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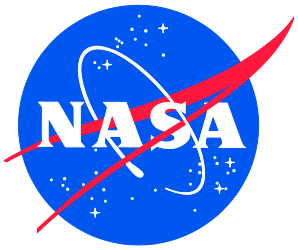

Proceedings of the NASA Technical Interchange Meeting on Active Optical Systems for Supporting Science, Exploration, and Aeronautics Measurements Needs

Edited by

Upendra N. Singh/NESC, and Stephen J. Horan
Langley Research Center, Hampton, Virginia

November 2019

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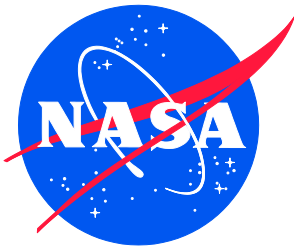

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Active Optical Systems for Supporting Science, Exploration, and
Aeronautics Measurements Needs
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and held in Columbia, Maryland
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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

November 2019

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I Introduction

NASA Active Optical Technical Interchange Meeting on Active Optical Systems for Supporting Science, Exploration, and Aeronautics Measurements Needs

I.1 Meeting Purpose

Active optical (Laser/Lidar) measurement techniques are critical for the future National Aeronautics and Space Administration (NASA) Earth, Planetary Science, Exploration, and Aeronautics measurements. The latest science decadal surveys recommend a number of missions requiring active optical systems to meet the science measurement objectives and the aeronautics community continues to use Laser/Lidar technologies to meet the aeronautics measurement objectives. With these drivers, the NASA Agency Program Management Council (APMC), chaired by the NASA Associate Administrator, has tasked the NASA Sensors and Instrumentation (S&I) Capability Leadership Team (CLT) Leader to determine if the Agency has the necessary expertise and capabilities to execute successfully the active optical-based systems necessary to make the required measurements for Science, Exploration, and Aeronautics. This NASA Technical Interchange Meeting (TIM) was a forum to exchange perspectives on the current state of the discipline's technologies and the direction NASA needs to take in the future to raise the Technical Readiness Level (TRL) of the measurement technologies to meet these measurement needs in the applications domains. The information developed at this TIM was used in formulating the Agency-level strategy and solutions for advancing high-risk Laser/Lidar technologies that are not currently being sufficiently planned, developed, or risk-reduced to meet NASA's mission requirements. Given the cross-cutting synergies in critical Active Optical measurements for NASA Science, Exploration, and Aeronautics, a strategic approach is needed to identify areas where NASA should "lead, leverage or collaborate" with existing national and international industries to meet its future needs. The TIM aimed at focusing NASA's directions to attain the necessary TRLs to meet the Agency-level priority Active Optical measurements in Space and Aeronautics. The TIM presentations and strategic inputs were synthesized by the NASA Active Optical Tiger Team for presentation to the NASA APMC with a suggested strategy to address the Agency's needs in a crosscutting, synergistic and cost-effective manner.

I.2 Active Optical Assessment Strategy

Given the charter from the APMC, the S&I NASA Technical Fellow assembled a core team to realize the assessment. The Active Optical assessment process utilized a multi-directorate teaming of the Science, Human Exploration and Operations, Aeronautics Research, and Space Technology Mission Directorate representatives to provide the guidance and list of priority measurements requirements to meet their critical future needs.

An Active Optical Tiger Team consisting of mission directorate representatives, S&I capability and technical leads/co-leads, and an external assessment team worked together to seek national and international community inputs to formulate an integrated Agency-level strategy. The international community inputs were based on the presentations at the Second International IEEE-GRSS Workshop on Space-based Lidar Remote Sensing Techniques and Emerging Technologies held June 4–8, 2018 at Milos Conference Center, Adamas, Milos Island, Cyclades, Greece. This Workshop brought together Active Optical experts from NASA, European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), Centre National d'Etudes Spatiales (CNES), and Deutschen Zentrums für Luft- und Raumfahrt (DLR) policy makers and experts from various Agencies engaged in advancing space missions/measurements in Active Optical area for Science and Exploration.

An essential part of the assessment strategy was to engage with other U.S. Government entities, as well as industry and academia, to leverage common Active Optical interests and complementary skills/expertise resident in those sectors.

The Active Optical Assessment and Recommendation Team (AOART) was charged with developing an integrated technology development and investment plan, which will address each directorate Agency's requirements in a crosscutting, synergistic and cost-effective manner, to meet the Agency-level, priority Active Optical space based measurements/missions.

The Active Optical Tiger Team members were

- **S&I Tech Fellow Team:** Upendra Singh, S&I NASA Technical Fellow, Stephen Horan, Technical Discipline Team (TDT) Deputy, and Terence Doiron, CLT Deputy
- **Active Optical Advisory Tiger Team (AOATT):** Michael Seablom, Science Mission Directorate (SMD); Prasun Desai, Space Technology Mission Directorate (STMD); Jason Crusan, Chris Moore, and Phil Liebrecht, Human Exploration and Operations Mission Directorate (HOEMD)
- **Active Optical Assessment and Recommendation Team (AOART)** – S&I TDT Members
    - Dr. Robert T. Menzies – Retired Jet Propulsion Laboratory (JPL), Chair, AOART
    - Dr. T. Y. Fan, Massachusetts Institute of Technology (MIT) Lincoln Lab
    - Dr. Michael Hardesty, Boulder Lidar Associates
    - Dr. David Tratt, The Aerospace Corporation
    - Dr. Denis Killinger, SenOptics LLC

I.3 Information Gathering

Through a call for papers, the TIM organizers requested relevant, four-page position papers to address the Active Optical Priority Measurements for NASA's critical Active Optical needs in Science, Exploration, and Aeronautics. The organizers instructed the authors to address the following points:

1. The technology needs and current limitations for the specific topic area drawn from the Priority Topic list in Section I.6 emphasizing the measurement approach (not a discussion of the final science data product) to describe the state of the art, a projected time line to develop/mature technologies, and to show the path necessary to reach the TRL required to make the measurement in the specific domain area
2. Gap areas in need of development to reach the required TRL
3. Opportunities within NASA Centers, industry, academia, Federally Funded Research and Development Center (FFRDC), National Labs, and other Government Agencies to capture capabilities where NASA can strategically lead, leverage, and partner to address critical gap areas to achieve the TRL necessary for the measurements
4. Potential partnerships, synergies, and crosscutting applications of the measurement technology

At the end of each TIM session, there was a panel discussion between the session presenters and the Active Optical Assessment Team members. Time permitting, audience members could also ask questions of the presenters. The Active Optical Assessment Team used these position papers and presentations as input to develop an Agency-level Active Optical Strategy and recommendation to the NASA APMC for planning purposes.

I.4 Meeting Organizing Committee

The Organizing Committee for the TIM included the following members:

- Chair: Upendra Singh (NASA S&I NASA Technical Fellow and CLT/TDT Leader, NASA Engineering and Safety Center (NESC))
- Co-Chair: Terence Doiron (S&I CLT Deputy, Goddard Space Flight Center (GSFC))
- Co-Chair: Stephen Horan (S&I TDT Deputy, Langley Research Center (LaRC))

- Local Host: Nicholas White (Sr. Vice President for Science, Universities Space Research Association)

I.5 Meeting Technical Program Committee

Technical Program Committee for the TIM included:

- Ralph Roe (NASA Chief Engineer)
- Tim Wilson (Director, NESC)
- Teresa Spagnuolo (Office of the Chief Engineer (OCE))
- Lisa Callahan (Office of the Chief Technologist)
- Michael Seablom (Chief Technologist, SMD), AOATT Member
- Prasun Desai (STMD, NASA Headquarters (HQ)), AOATT Member
- Jason Crusan (HEOMD, NASA HQ), AOATT Member
- Chris Moore (HEOMD, NASA HQ), AOATT Member
- Phil Liebrecht (HEOMD, NASA HQ) AOATT Member
- Robert T. Menzies, Retired JPL, AOART Chair
- T. Y. Fan, MIT Lincoln Lab., AOART Member
- Michael Hardesty, University of Colorado Boulder, AOART Member
- David Tratt, The Aerospace Corporation, AOART Member
- Dennis Killinger, University of South Florida, AOART Member
- Jack Kaye, (Earth Science Division, SMD, NASA HQ)
- Jonathan Rall (Planetary Science Division, SMD, NASA HQ)
- Michelle Munk (STMD, NASA HQ)
- Pamela Millar (Earth Science Technology Office (ESTO), NASA HQ)
- Parminder Ghuman (ESTO, NASA HQ)
- Steven Scott, GSFC
- James Garvin, GSFC
- James Abshire, GSFC
- Mathew McGill, GSFC
- Michael Krainak, GSFC
- Azita Valinia, GSFC
- Chris Hostettler, LaRC
- Chris Edwards, LaRC
- Paul Danehy, LaRC
- Ajay Misra, Glenn Research Center (GRC)

I.6 Priority Active Optical-Based Measurement Areas and Technical Sessions

I.6.1 Mission Area I: Earth Science Focused Measurement Topic Areas

The suggested Earth Science focus topics for consideration included the following:

- Atmospheric Composition sounding measurements in the troposphere including aerosol and cloud properties and profiling, water vapor profiling, and Planetary Boundary Layer height.
- Earth's Surface and Interior via geodetic imaging including wide-swath laser altimetry.

- Climate Effect Monitoring including ice mass changes, global ice characterization, snow depth, and snow-water equivalent measurements;
- Weather including global tropospheric Lidar wind measurements for planetary boundary layer energy, momentum, and mass exchanges; forecasting; convection; fluxes of heat, momentum, water vapor and other gases; and model validation and improvement.
- Carbon, Ecosystems, and Biogeochemistry including measurements of CO_2 and CH_4 fluxes and trends, vegetation 3D structure, biomass, and disturbance, ocean mixing layer.

I.6.2 Mission Area II: Space Science and Exploration Focused Measurement Topic Areas

The suggested Space Science and Exploration focus topics for consideration included:

- Lunar Exploration including landing navigation and hazard avoidance, and surface exploration and characterization
- Jovian Moons including surface features and characterization, and tidal signatures
- Jovian Environment including atmospheric cloud and wind structure, and atmospheric composition
- Mars Exploration including atmospheric winds, density, and dust profiling, surface topography, surface exploration and characterization, search for organic signatures, moisture distribution, and cloud characterization
- Martian Mission Support including precision landing, navigation, and hazard avoidance, sample return rendezvous and capture, and atmospheric characterization to support Entry, Descent, and Landing (EDL)
- Titan and Venus including balloon-borne active optical instrumentation
- Situational awareness of space weather phenomena
- Laser interferometry, active-optical sensing of telescope and satellite swarm elements to enable observations

I.6.3 Mission Area III: Aeronautics Focused Measurement Topic Areas

The suggested Aeronautics focus topics for consideration included the following:

- Turbulence detection on flight vehicles
- Situational awareness detection of atmospheric hazards including volcanic ash, ice, and snow
- Sense and avoidance for autonomous Unmanned Aerial Vehicles (UAVs) and future autonomous urban mobility aircraft
- Airport ground control management for taxiing, takeoff, and landing—including wake vortex detection
- UAV-based target imaging
- Sensing and avoiding hazards in the National Air Space including miniaturized, low-power active-optical sensors and instrumentation for UAV and personal air vehicles
- Quantification of flow field and surface parameters in ground-based wind tunnel testing of Aero vehicles

I.7 Meeting Information

The NESC and the NASA OCE sponsored the development and operation of the TIM. The Universities Space Research Association (USRA) hosted the TIM at the USRA headquarters in Columbia, Maryland on July 31 through August 2, 2018. Table I-1 shows the meeting agenda for the 3 days. Figure I-1 shows the meeting participants from the first day.

Table I-1. Meeting Agenda for the NASA Technical Interchange Meeting on Active Optical Systems for Supporting Science, Exploration, and Aeronautics Measurements Needs

Day 1 -- July 31					
Start Time	8:30AM				
	Paper #	**Session Title**	**Session Chair Full Name**	**Authors**	**Title**
8:30AM	P-0	Plenary	Upendra Singh	Upendra Singh	TIM Welcome
				Dr. Nick White, USRA's Senior Vice President for Science	USRA Welcome
				Stephen Horan	Logistics
9:00AM	P-1	Plenary	Upendra Singh	Stephen Jurczyk, NASA HQ	Agency Perspective
	P-2	Plenary	Upendra Singh	George Jackson	Optics at GSFC
9:30AM	P-3	Plenary	Upendra Singh	Jack Kaye, SMD	Earth Science Overview
10:00AM	P-4	Plenary	Upendra Singh	Pamela Millar and Parminder Ghuman, NASA GSFC	ESTO's Investments in Lidar Technologies relative to the 2017 Earth Science Decadal Survey Lidar-based Measurements
10:30AM	COFFEE				
10:50AM	S1-1	Clouds, Aerosols, and Ocean	Jack Kaye/Chris Hostetler	Matthew McGill, NASA GSFC	Goddard Space Flight Center Earth Science Perspective on Lasers and Lidar Development
11:10AM	S1-2	Clouds, Aerosols, and Ocean	Jack Kaye/Chris Hostetler	Johnathan Hair, NASA LaRC	Aerosols, Clouds and Ocean Profiling High Spectral Resolution Lidar
11:30AM	S1-3	Clouds, Aerosols, and Ocean	Jack Kaye/Chris Hostetler	Floyd Hovis, Fibertek	Laser Development for the Next Generation of Cloud, Aerosol, and Ocean Lidar Systems
11:50AM	S1-4	Clouds, Aerosols, and Ocean	Jack Kaye/Chris Hostetler	Richard J. Hare and John A. Smith, NASA LaRC	Detectors for Spaceborne Aerosol-Cloud-Ocean

					Lidar: Past, Present and Future Directions
12:10PM	LUNCH				
1:10PM	S1-Panel	Clouds, Aerosols, and Ocean	Jack Kaye/Chris Hostetler	All Paper Presenters	
1:30PM	S2-1	Greenhouse and Trace Gases Measurements	Ken Jucks	Ken Jucks, NASA SMD	Overview
1:50PM	S2-2	Greenhouse and Trace Gases Measurements	Ken Jucks	James B. Abshire[1], Haris Riris[1], Graham R. Allan[2], Jianping Mao[3], William E. Hasselbrack[2], Kenji Numata[1], Jeffrey Chen[1], Randy Kawa[1], Xiaoli Sun[1] [1]NASA GSFC; [2]Sigma Space Inc.; [3]University of Maryland	The CO_2 Sounder Lidar Development for Airborne Science Campaigns and as a Candidate for the ASCENDS Mission
2:10PM	S2-3	Greenhouse and Trace Gases Measurements	Ken Jucks	Mulugeta Petros[1], Upendra N. Singh[2], Tamer Refaat[1], Charles Antill[1], Ruben Remus[1], Jirong Yu[1], Teh-Hwa Wong[3], Doug Taylor[3], Jane Lee[3], Karl Reithmaier[3], Stephen Bowen[1], Angela Welters[1], Syed Ismail[3] and Kenneth Davis[4] [1]NASA LaRC; [2]NASA NESC; [3]Science System & Applications, Inc; [4]The Pennsylvania State University	Ground and Airborne Testing of an Advanced 2-micron Triple-pulse IPDA for Atmospheric Carbon Dioxide and Water Vapor Active Optical Remote Sensing
2:30PM	S2-4	Greenhouse and Trace Gases Measurements	Ken Jucks	Haris Riris[1], Kenji Numata[1], Stewart Wu[1], Molly Fahey[1], Brayler Gonzalez[1], Jianping Mao[2], Michael Rodriguez[3], Stan Scott[1], and Xiaoli Sun[1] [1]NASA GSFC, [2]University of Maryland, [3]Sigma Space.	Measuring Methane from Space and Airborne Platforms

2:50PM	S2-5	Greenhouse and Trace Gases Measurements	Ken Jucks	Amin Nehir, NASA LaRC	Technology Development for Advanced Greenhouse Gas Lidar Systems
3:10PM	S2-Panel	Greenhouse and Trace Gases Measurements	Ken Jucks	All Paper Presenters	
3:30PM	COFFEE				
3:50PM	S3-1	Wind Measurements	Tsengdar Lee	Tsendgar Lee, NASA SMD	Overview
4:10PM	S3-2	Wind Measurements	Tsengdar Lee	Michael J. Kavaya and Jirong Yu, NASA LaRC Sammy W. Henderson, Beyond Photonics G. David Emmitt, Simpson Weather Associates	Global Wind Measurement with a Pulsed, Coherent-Detection, Lidar System: Technology Status, Development Needs, and Partnering Opportunities
4:30PM	S3-3	Wind Measurements	Tsengdar Lee	Sara Tucker, Ball Aerospace	Direct Detection Doppler Wind Lidar: Recent progress, technical needs, and future applications
4:50PM	S3-4	Wind Measurements	Tsengdar Lee	Dominique Fourguette[1], David Johnson[1], Mike Fleck[2], Matt Wiebold[2], Mike Fan[2] [1] Michigan Aerospace Corporation; [2]Honeywell International	High Altitude LIDAR Atmospheric Sensing
5:10PM	S3-5	Wind Measurements	Tsengdar Lee	Michael A. Krainak[a], Anthony W. Yu[a], Steven X. Li[a], Yingxin Bai[a], Kenji Numata[a], Jeffrey R. Chen[a], Molly E. Fahey[a], Frankie Micalizzi[a], Oleg A. Konoplev[b], Diego Janches[a], Chester S. Gardner[c], Graham R. Allan[d] [a]NASA GSFC; [b]SSAI; [c]University of Illinois; [d]Sigma Space	Proposed Space-based Sodium Lidar Technology
5:30PM	S3-Panel	Wind Measurements	Tsengdar Lee	All Paper Presenters	

Day 2 -- August 1					
Start Time	8:30AM				
	Paper #	**Session Title**	**Session Chair Full Name**	**Speaker**	**Title**
8:30AM	S4-1	Topography, Cryosphere, and Biomass	Tom Wagner	Tom Wagner, NASA SMD	Overview
8:50AM	S4-2	Topography, Cryosphere, and Biomass	Tom Wagner	Nicholas Sawruk, Patrick Burns, Ryan Edwards, Viatcheslav Litvinovitch, and Floyd Hovis, Fibertek	Flight Laser Transmitter Development for NASA's Ice Topography ICESat-2 Space Mission
9:10AM	S4-3	Topography, Cryosphere, and Biomass	Tom Wagner	Paul R. Stysley, D. Barry Coyle, Furqan Chiragh, Erich Frese, NASA GSFC	The Global Ecosystems Dynamics Investigation (GEDI) Lidar Mission
9:30AM	S4-4	Topography, Cryosphere, and Biomass	Tom Wagner	Xiaoli Sun, NASA GSFC	Advanced Single Photon Detectors for Active Remote Sensing from Space
9:50AM	S4-5	Topography, Cryosphere, and Biomass	Tom Wagner	Roman Machan, Sigma Space LLC	Single Photon Lidar Measurement Technologies
10:10AM	S4-Panel	Topography, Cryosphere, and Biomass	Tom Wagner	All Paper Presenters	
10:30AM	COFFEE				
10:50AM	S5-1	Planetary Science	Jonathan Rall	Jonathan Rall	Overview
11:10AM	S5-2	Planetary Science	Jonathan Rall	James B. Abshire[1], Graham R. Allan[2], X. Sun[1], Daniel Cremons[3], Scott D. Guzewich[1], Anthony Yu[1], Floyd Hovis[4], Michael D. Smith[1], H. Riris[1], Bruce M. Gentry[1] [1]NASA GSFC; [2]Sigma Space Corporation; [3]Universities Space Research Association; [4]Fibertek Inc.	MARLI: MARs Lidar for Global Wind and Aerosol Profiles from Orbit

11:30AM	S5-3	Planetary Science	Jonathan Rall	Anupam K. Misra, Tayro E. Acosta-Maeda, John N. Porter, Shiv K. Sharma, Macey Sandford, Miles Egan, University of Hawai'i	Standoff, Active, Non-contact, Non-destructive "Search for Life" Systems with Fast Detection
11:50AM	S5-4	Planetary Science	Jonathan Rall	Barry Coyle, NASA GSFC	A Mission-enabling UV Laser for Mass Spectrometry (UVMS) with Continuously Selectable Output for in situ Planetary Exploration
12:10PM	LUNCH				
1:10PM	P-SC	Automotive LiDAR: Challenges and Opportunities	Lute Maleki GM/Cruise Automation		
1:30PM	S5-Panel	Planetary Science	Jonathan Rall	All Paper Presenters	
1:50PM	S6-1	EDL Technologies	Michelle Munk	Michelle Munk, NASA LaRC	Overview
2:10PM	S6-2	EDL Technologies	Michelle Munk	Carolina Restrepo, Johnson Space Center (JSC)/GSFC	SPLICE
2:30PM	S6-3	EDL Technologies	Michelle Munk	Farzin Amzajerdian[1], Glenn D. Hines[1], Diego F. Pierrottet[2], Bruce W. Barnes[1], Aram Gragossian[2], Mitchell J. Davis[1], Tak-kwong Ng[1], Alexander D. Scammell[1], Adam Ben Shabat[1], Larry B. Petway[1], Jacob J. Follman[1], and John M. Carson III[3] [1]NASA LaRC; [2]Coherent Applications, Inc.; [3]NASA JSC	Navigation Doppler Lidar for Autonomous Precision Landing
2:50PM	S6-4	EDL Technologies	Michelle Munk	Manoranjan Majji, Texas A&M University	Recent Advances in Relative Navigation of Aerospace Systems
3:10PM	COFFEE				

3:30PM	S6-5	EDL Technologies	Michelle Munk	Andrew Johnson, JPL	Terrain Relative Navigation: Mars 2020 and Future Systems
3:50PM	S6-6	EDL Technologies	Michelle Munk	A. Miguel San Martin, E. David Skulsky, Nikolas Trawny, and Anup Katake, JPL	A Hazard Detection Sensor for Landing on Europa
4:10PM	S6-7	EDL Technologies	Michelle Munk	Dominique Fourguette[1] and Volkan Ötügen[2] [1]Michigan Aerospace Corporation; [2]Southern Methodist University	Speed Sensor for Planetary EDL: "SPRY"
4:30PM	S6-Panel	EDL Technologies	Michelle Munk	All Paper Presenters	

Day 3 -- August 2					
Start Time	8:30AM				
	Paper #	**Session Title**	**Session Chair Full Name**	***Speaker***	***Title***
8:30AM	S7-1	Exploration	Chris Moore	Chris Moore	Overview
8:50AM	S7-2	Exploration	Chris Moore	Don Cornwell, NASA SCaN	NASA's Optical Communications Program for 2018 and Beyond
9:10AM	S7-3	Exploration	Chris Moore	Antonios Seas[1], Bryan Robinson[2], Tina Shih[2], Farzana Khatri[2], and Mark Brumfield[1] [1]NASA GSFC; [2]MIT Lincoln Laboratory	Optical Communication Activities through the Laser-Enhanced Mission Communications Navigation and Operational Services (LEMNOS) Office
9:30AM	S7-4	Exploration	Chris Moore	Abhijit Biswas, JPL	Deep Space Optical Communications (DSOC)
9:50AM	S7-5	Exploration	Chris Moore	Bo Naasz, NASA GSFC	Active Sensors for NASA Rendezvous and Capture Missions

10:10AM	S7-6	Exploration	Chris Moore	Farzin Amzajerdian, Paul F. Brewster, Vincent E. Roback, and Glenn Hines, NASA LaRC	3-D Imaging Flash Lidar for Autonomous Safe Landing and Spacecraft Proximity Operation
10:30AM	COFFEE				
10:50AM	S7-Panel	Exploration	Chris Moore	All Paper Presenters	
11:20AM	S8-1	Aeronautics	Greg Adamovsky/Paul Danehy	Session Chairs	Overview
11:40AM	S8-2	Aeronautics	Greg Adamovsky/Paul Danehy	Hyun Jung Kim[1] and Thomas Jones[2] [1]National Institute of Aerospace; [2]NASA LaRC	Unique Capabilities within the Advanced Measurement and Data Systems Branch at NASA LaRC
12:00PM	LUNCH				
1:00PM	S8-3	Aeronautics	Greg Adamovsky/Paul Danehy	Paul Danehy	Active Optical Sensing for Flow Quantification in Wind Tunnels in support of Aeronautics, Science and Exploration
1:20PM	S8-4	Aeronautics	Greg Adamovsky/Paul Danehy	Ivan Clark, NASA LaRC	Active Optical Systems for Aeronautics
1:40PM	S8-5	Aeronautics	Greg Adamovsky/Paul Danehy	Richard J. Schwartz[1], Carey F. Scott[1], Meaghan L. McCleary[2] [1]AMA Inc; [2]Iowa State University	SAMI, the SCIFLI Airborne Multispectral Imager: An Airborne Platform to Support Development and Testing of Active Optical Components and Sensors
2:00PM	S8-6	Aeronautics	Greg Adamovsky/Paul Danehy	Grady Koch, Ivan Clark, Fred Proctor, and Narasimha Prasad, NASA LaRC	Wind Lidar for Aviation Safety and Enhanced Efficiency
2:20PM	S8-7	Aeronautics	Greg Adamovsky/Paul Danehy	Mark R. Woike, NASA GRC	Advanced Optical Instrumentation for the NASA Glenn Research

					Center's Aeronautical Test Facilities
2:40PM	S8-Panel	Aeronautics	Greg Adamovsky/Paul Danehy	All Paper Presenters	
3:10PM	COFFEE				
	S9-1		Mike Seablom/Denise Podolski	Mike Seablom	Overview
3:30PM	S9-2	Innovations	Mike Seablom/Denise Podolski	Nan Yu, JPL	Laser and Optical Systems for Atomic Clocks, Sensors, and Quantum Applications in Space
3:50PM	S9-3	Innovations	Mike Seablom/Denise Podolski	Paul Suni, Lockheed Martin Space	Photonic Integrated Circuits for Active Optical Sensing in Space
4:10PM	S9-4	Innovations	Mike Seablom/Denise Podolski	Kenji Numata, Anthony Yu, Hua Jiao, Scott Merritt, Frankie Micalizzi, Molly Fahey, Jordan Camp, and Michael Krainak NASA GSFC	Laser System for the Laser Interferometer Space Antenna (LISA)
4:30PM	S9-5	Innovations	Mike Seablom/Denise Podolski	Abigail Licht, MIT Lincoln Laborarory	Geiger Mode Avalanche Photodiode Development at MIT Lincoln Laboratory
4:50PM	S9-6	Innovations	Mike Seablom/Denise Podolski	David D. Smith and Andrew Keys, NASA Marshall Space Flight Center (MSFC)	Prospects for the Development of Fast-Light Inertial Sensors
5:10PM	S9-7	Innovations	Mike Seablom/Denise Podolski	Jennifer Inman, NASA LaRC and Ian Miller, N&R Engineering	Ocular Hazard Risk Management for Airborne and Spaceborne Active Optical Systems
5:30PM	S9-Panel	Innovations	Mike Seablom/Denise Podolski	All Paper Presenters	



Figure I-1. Attendees at the Active Optical TIM held at USRA Headquarters in Columbia, MD. July 31, 2018.

R Assessment Report

Active Optical Assessment and Recommendation Team (AOART) Report on NASA Technology Development, Maturation, and Infusion into Future Missions

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July 2019

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Executive Summary

At the National Aeronautics and Space Administration (NASA) Agency Program Management Council (APMC) meeting held September 13–14, 2017, Dr. Upendra N. Singh, the Lead for the Sensors and Instrumentation (S&I) Capability Leadership Team (CLT), provided a Baseline Assessment of the S&I capability health. Included in this report were several CLT findings relating to the health of Active Optical (AO) technologies. A formal Action was issued to charter a multi-Directorate Active Optical Tiger Team to provide an Agency-level strategy and solutions for advancing high-risk laser/Lidar technologies. The approach that followed included the formation of a tiger team and an external assessment team to work together to seek community input and formulate an integrated Agency-level strategy for responding to the CLT findings.

The Active Optical Assessment and Recommendation Team (AOART) is the external assessment team that has been charged to work together with NASA Mission Directorate representatives and CLT leads/co-leads to participate in formulating a NASA strategy for laser-based instrument development and usage for scientific and engineering purposes. The AOART has relied on the NASA Earth Science Decadal Survey (ESDS), the Planetary Science Decadal Survey (PSDS), and the PSDS Mid-Term Assessment (all available from the National Research Council (NRC) library) to provide the basis for understanding and prioritizing the AO instrument development needs for the next several years.

Toward this end, a Technical Interchange Meeting (TIM) was organized and held July 31 through August 3, 2018 in Columbia, Maryland. This TIM consisted of over 80 technical presentations that provided a wide-ranging coverage of NASA AO developments and current activities. It served as the kickoff for the AOART assessment activities, and its session organization offered a template for categorizing the NASA AO activities and goals. The TIM Plenary Session topics included the NASA perspective, the tenets and rationale for the formation of the AOART, the Science Mission Directorate (SMD) Earth Science overview, and the Earth Science Technology Office (ESTO) investments in Lidar technologies.

The AOART assessments and recommendations began with guidance from prior S&I CLT findings and were summarized in Dr. Upendra Singh's Plenary Session presentation. We refer to these findings as the ten postulated tenets, tenets that the AOART has deemed to be particularly valid, relevant, and actionable.

Following the TIM, the AOART engaged in additional investigations and interviews with TIM presenters associated with the SMD, the Space Technology Mission Directorate (STMD), and the Human Exploration and Operations Mission Directorate (HEOMD), who provided additional active optical technology development insights.

Postulated Tenets

The ten tenets guiding the review process are as follows:

1. Active Optical is critical for future recommended missions.
2. Modest NASA investment in Active Optical can have significant impact on future mission planning.
3. Risk in Lidar missions can be significantly reduced by advancement/maturation of a few key technologies.
4. The existing competitive model to fund technologies to advance the Technology Readiness Level (TRL) is not working. (Finding from the CLT Assessment: "The existing competitive model to fund technologies to develop, mature, advance, and demonstrate TRL advancement in a relevant environment is not working and often results in massive cost growth and schedule slips for Laser/Lidar missions.")
5. The current means for TRL advancement have a poor track record of successfully advancing to sensor system-level TRL 6 or TRL 7, at which point further advancement would be implemented by spaceflight projects.
6. Inter-Center collaboration is a means to reach the desired outcomes. (Finding from the CLT Assessment: "Need to enhance inter-Center collaboration and leveraging between SMD and HEOMD missions.") NASA can benefit from engaging in collaborative opportunities with other U.S. Agencies and international space Agencies.
7. Leveraging among SMD, STMD, and HEOMD is advantageous for implementing their roadmap priorities.
8. TRL 1-2 (research) opportunities are limited.
9. Participation of academia in Active Optical Research and Development (R&D) that is relevant to NASA has been dwindling over the years instead of growing.
10. There are limited opportunities for [recruiting and training] new hires.

The AOART assessments and recommendations sections in this report are based on the TIM, additional investigations and interviews, and collective AOART member experience. The assessments are responsive to each of these tenets.

Of the ten postulated tenets, the AOART believes that tenet #5 is the key issue to address. The postulated tenet #4 can be considered a contributor to this issue. The need to address tenet #5 forms the key action for the AOART. Pertinent assessments are as follows:

1. NASA Headquarters (HQ) Program Office leadership can effectively enable continuous advancement of TRL for technologies that are realized as high priority in future mission implementations and scientific investigations, by means of effective oversight and funding levels. A recent example of success is Optical Communications maturation, supported primarily by HEOMD and STMD Program Office collaboration, with technology developments coming from several organizations. Project funding of technology maturation is beneficial but should be considered as a supplement, since projects have focused requirements, limited lifetimes, and an incentive to avoid risk.
2. The Safe and Precision Landing – Integrated Capabilities Evolution (SPLICE) precision landing project, funded by the STMD Game Changing Development Program, is a prominent example of a multi-Center collaborative effort with Directorate-level oversight and specific plans for maturing the active optical technology readiness to TRL 6/TRL 7 and infusing it into missions in the next decade.
3. Attempting to maintain sustained development and maturation of active optical technologies by means of a year-to-year competitive selection process does not work well, particularly when resources are needed to demonstrate TRL 6.
4. The ESDS, a guidance document for SMD, calls for spaceflight Lidars of specific types that can uniquely contribute to scientific objectives. For these Lidars to be selectable in proposals submitted to SMD opportunities, the TRL must be at TRL 6.

5. ESTO has been successful in supporting technology development from TRL 3 to TRL 5, but not to TRL 6. ESTO Instrument Incubator Programs (IIPs) rarely reach credible, system-level TRL 6 at the exit point.
6. The Airborne Instrument Technology Transition (AITT) Program enables airborne demonstration of the scientific value of new instrument concepts and capabilities and assist in enabling calibration/validation of satellite instruments. However, AITT is underfunded for this purpose. AITT is not meant for developing and testing engineering models of lasers/Lidars that can withstand the rigors of spaceflight environmental testing.
7. NASA Earth Science Division (ESD) has very few existing programs dedicated to engineering design and demonstration of system-level TRL 6 for risk-reduction of large active optical instruments (i.e., Lidars). NASA Centers and the Jet Propulsion Laboratory (JPL) often use internal funds to help proposed instruments reach a credible system-level TRL 6. These funding levels are often considered to be competition sensitive and proprietary.

Additional AOART assessments relating to the other tenets are found in the body of the report.

Specific Recommendations by the AOART

(1) The AOART stresses the importance of SMD, STMD, and HEOMD leadership at NASA HQ taking a decisive role in managing the development, maturation, and infusion of active optical technologies into future missions, with collaborative program office oversight that effectively enables continuous advancement of TRL for high priority technologies. These are technologies that are realized as high priority in mission implementations and scientific investigations. A more continuous process with regularly scheduled assessments and modifications of programs is needed to appropriately manage the activity. The assessment activity is particularly important.

(2) Within the SMD, the AOART strongly endorses the ESDS recommendation to fund the ESD Technology Investment Program at a level of approximately 5% of the total ESD budget, with a large fraction of the investment targeted toward the Earth observations that NASA intends to implement over the course of the next decade (see Appendix A). Some of this should be focused, per the ESDS, on greater efficiency as a means of lowering the cost and risk of active optical approaches for sustained observations. There should be a tighter focus on technologies needed to meet ESDS measurement priorities.

(3) The tech development/maturation funding priorities of the STMD, HEOMD, and ESD should be increased at the high end (TRL 6 and 7) and the low end (TRL 2 and 3). We recommend a funding increase to universities and other research laboratories for TRL advancement in the low TRL research neighborhood, encouraging innovation. We also recommend a funding increase to concentrate on the maturation of the AO instruments to system-level TRL 6 relevant to the spaceflight environment, followed by opportunities for tech demo flights as appropriate.

(4) NASA ESD should establish a program office dedicated to demonstration of system-level TRL 6 for risk-reduction of large AO instruments (i.e., Lidars). Maturation to TRL 6 requires engineering resources as well as the continuing involvement of the technologists. In this regard, we recommend that a new program office be established at NASA HQ to manage this technology maturation to TRL 6 for spaceflight opportunities.

(5) This NASA program office and the Centers should collaborate and form partnerships with outside partners (Department of Defense (DoD), Federally Funded R&D Center, Industry, etc.) in order to utilize existing resources and expertise. The use and leveraging of relevant non-NASA assets and capabilities in the private sector and in other research organizations provide extensive advantages to NASA. The DoD has been investing significant resources in AO systems and technologies, and the Agency should be doing more to leverage these investments. Leveraging is often hampered by a lack of knowledge and outreach.

(6) NASA HQ Mission Directorates should take a leadership role in improving collaboration and transparency among NASA Centers. NASA Centers are often reluctant to do this on their own. Previous external reviews of NASA Lidar efforts have made similar recommendations, with only tepid moves at best toward a better model.

(7) NASA HQ should also prioritize establishing improved collaborations with international organizations that are advancing AO technologies and leverage the relevant technology advances that are supported and stimulated by those organizations. Joint planning groups could explore joint missions that employ active optics technologies, with an aim to reduce risk, cost, and development time.

(8) NASA should look for future Lidar/AO hires within non-Lidar but growing active-optical/laser university research groups such as nanophotonics, laser telecommunication, femtosecond laser spectroscopy, nanomaterials, integrated photonics, and quantum optics. NASA should (1) increase specific AO Sensor funding from NASA to university research groups involving TRL 1 and 2 level research efforts, (2) increased NASA graduate student fellowships and stipends, and (3) increased faculty/graduate student short-term internships at NASA Centers to help introduce faculty and graduate students to NASA Missions.

(9) NASA should formulate a response to this assessment along with intended actions within a specific time frame following formal submission of this report. (Six months is recommended.) Previous panel reports on NASA AO activities have not had as much impact as they should have because of weak or un-sustained follow through.

R.1 Introduction

R.1.1 Background: AO Sensing and Formation of the AOART

AO sensing involves probing an environment external to the instrument with transmitted laser radiation. The instrument includes a receiver that detects the laser radiation that returns, due to a backscattering mechanism. In many ways AO sensing is analogous to radar, with the capability to operate at ultraviolet, visible, and infrared wavelengths. This capability provides numerous opportunities to explore the environment. Why is AO sensing technology critical for NASA in particular? It provides numerous capabilities that enable science and exploration missions that are on the NASA roadmaps for the future. The wide variety of capabilities include applications to rendezvous and capture, landing site searches, and scientific studies relevant to atmospheric chemistry, weather, climate, and environmental quality. These application areas are summarized in this report beginning with the summary of the structure and outcomes of the TIM held during the summer of 2018.

A Baseline Assessment of the NASA Sensor and Instrumentation State of Capability was conducted in 2017 by the S&I CLT, led by Dr. Upendra N. Singh and presented to the Agency Program Management Council (APMC) during their September 13–14 meeting at NASA HQ. The CLT Assessment included findings related to the state of capability of AO technologies, followed by a recommendation to respond to these findings. This led to the following Formal Action Item from the APMC:

"Charter an AO (Laser/Lidar) Tiger Team, which includes representation from SMD, STMD and HEOMD to address an increased emphasis on AO technology which is critical for future NASA Earth, Planetary Science, and Mars Exploration. The Team will provide Agency-level strategy and solutions for advancing high-risk Laser/Lidar technologies that are not currently being sufficiently planned or developed or risk reduced to meet NASA missions requirements."

The approach that followed included the formation of the Tiger Team and an external assessment team (the AOART) to work together to seek community input and formulate an integrated Agency-level strategy for responding to the CLT findings.

R.1.2 AOART Purpose and Scope

The AOART is the external assessment team that has been charged to work together with NASA Mission Directorate representatives and CLT leads/co-leads to participate in formulating a NASA strategy for laser-based instrument development and usage for scientific and engineering purposes.

The AOART seeks and evaluates input from national and international communities, to use as a basis for making assessments and offering recommendations.

The AOART relies on the NASA ESDS, the PSDS, and the PSDS Mid-Term Assessment (all available from the NRC library) to provide the basis for understanding and prioritizing the AO instrument development needs for the next several years.

As stated by Dr. Upendra Singh, the NASA Technical Fellow for S&I, the AOART recommendations will be folded into an integrated technology development and investment plan that addresses NASA Mission Directorate requirements in a crosscutting, synergistic and cost-effective manner, to meet the priority AO measurements and missions.

R.1.3 The Assessment Strategy

The AOART has organized prior findings from the CLT that are summarized in Dr. Upendra Singh's TIM Plenary session presentation[1] and has engaged in assessment and prioritization of what we call the ten postulated tenets. These assessments and prioritizations, which are articulated in the following sections, led

to several recommendations. The emphasis in this report is on the following postulated tenets that the AOART deemed to be particularly valid, relevant, and actionable.

In addition to formal presentation by practitioners, the AOART engaged in additional investigations and interviews with selected practitioners associated with SMD, STMD, and HEOMD, who provided additional AO technology development insights.

R.1.3.1 Postulated Tenets

The ten tenets guiding the review process are as follows:

1. AO is critical for future recommended missions.
2. Modest NASA investment in AO can have significant impact on future mission planning.
3. Risk in Lidar missions can be significantly reduced by advancement/maturation of a few key technologies.
4. The existing competitive model to fund technologies to advance TRL is not working. (Finding from the CLT Assessment: "The existing competitive model to fund technologies to develop, mature, advance, and demonstrate TRL advancement in a relevant environment is not working and often results in massive cost growth and schedule slips for Laser/Lidar missions.")
5. The current means for TRL advancement have a poor track record of successfully advancing to system-level TRL 6 or TRL 7, at which point further advancement would be implemented by spaceflight projects.
6. Inter-Center collaboration is a means to reach the desired outcomes. (Finding from the CLT Assessment: "Need to enhance inter-Center collaboration and leveraging between SMD and HEOMD missions.") NASA can benefit from engaging in collaborative opportunities with other U.S. Agencies and international space Agencies.
7. Leveraging among SMD, STMD, and HEOMD is advantageous for implementing their roadmap priorities.
8. TRL 1–2 (research) opportunities are limited.
9. Participation of academia in AO R&D that is relevant to NASA has been dwindling over the years instead of growing.
10. There are limited opportunities for (recruiting and training) new hires.

A TIM was organized and held July 31–August 3, 2018 in Columbia, MD (see the Introduction for the TIM announcement). This TIM provided wide-ranging coverage of NASA AO developments and current activities. It served as the kickoff for the AOART assessment activities, and its session organization offered a template for categorizing the NASA AO activities and goals. This session topical organization serves as the AO categorization that the AOART will use in further discussion. The categorization is as follows:

- Clouds, Aerosols, and Ocean Science
- Greenhouse and Trace Gas Measurements
- Wind Measurements
- Topography, Cryosphere, and Biomass
- Planetary Science
- Entry, Descent, and Landing (EDL) Technologies
- Automotive Lidar
- Exploration
- Aeronautics
- Innovations

This report is organized as follows. In the next section, we cite source materials. We emphasize the Decadal Survey and Strategic Plan materials as required reading, for they provide the context that provides the impetus for AO technology development and maturation.[2-9] In addition, some of these reports and

discussions refer back to several similar Lidar and AO system review panel reports conducted to enhance Lidar and laser technical maturity and capability.[10,11] The section on observations and assessments deriving from the TIM follows. TIM Plenary Session topics included the NASA perspective, the basic tenets and underlying reasons for the formation of the AOART, the ESD overview, and the ESTO organization. The TIM section is followed by assessment sections on the role of ESTO, the role of Industry, NASA internal and external collaborations, the role of competition, and the assessment of the AO research environment. Finally, we have a distillation of the AOART assessments and findings, followed by recommendations. The reference list and appendices can be found after the Recommendations section.

The assessments in each section have a connection with one or more of the tenets. As stated above, some tenets are given more consideration than others. The need to address tenet #5 forms the key action for the AOART.

R.2 The NASA Future Decade – Surveys and Plans

The AOART is relying on the following materials (including the "Decadal Surveys") to provide the basis for understanding the AO instrument development needs for the next several years:

- AOART reading material: (1) 2017 ESDS; (2) 2013 PSDS and 2018 Mid-Term Assessment; (3) ESD/ESTO 2016 Lidar Technologies Review and Strategy;[2-10] (4) Online Exploration and Space Technology materials that pertain to AO instruments.
- ESDS elements/plans that directly relate to AO/links to and dependencies on particular AO technology advancement/maturation, e.g., spaceflight Lidars.
- PSDS elements/plans that directly relate to and rely on AO (EDL, Hazard Avoidance, as applicable to Mars and asteroid missions, Europa Lander, also Exploration objectives, e.g., Moon landings, Mars landings.
- Exploration and Space Technology elements/plans that directly relate to AO, with technologies that have overlap with NASA SMD technologies.

These provide key context and direction to the materials provided by the TIM presenters.

R.3 Technical Interchange Meeting: Observations and Assessments

The NASA TIM on AO Systems for Supporting Science, Exploration, and Aeronautics Measurement Needs was a forum to exchange perspectives on the current state of the AO technologies and the direction NASA should take to raise the TRL of the measurement technologies to meet the current and future needs in the Earth Science, Planetary Science, Exploration, and Aeronautics applications domains. The TIM description can be found in the Introduction section of this document. The presentations and list of speakers are also contained in the Introduction. The TIM covered a wide range of AO technologies within the NASA context. However, the open format of the TIM limited the AOART insight from technologies considered classified in the DoD community, ITAR-sensitive, or industry-proprietary activities. As such, AOART assessments and recommendations are based on consideration of technologies that are in the open domain. However, we note in the recommendations section the need to develop ways to engage with organizations whose input was not included in this TIM.

The objective is that the "TIM inputs are to be used in formulating the Agency-level strategy and solutions for advancing high-risk laser/Lidar technologies that are not currently being sufficiently planned, developed, or risk-reduced to meet NASA mission requirements." (Upendra Singh, TIM Plenary Session)

"Workshop inputs are also to be used to incorporate international synergies and collaborative opportunities between NASA and other international space Agencies, for consideration in future planning." (Upendra Singh, TIM Plenary Session)

The TIM was organized such that the AOART assessments were grouped into three main categories, namely Earth Science, Planetary Science and Exploration, and Aeronautics, plus a session describing six innovative technologies that offer the possibility of broad application to various NASA interests.

This TIM section of the AOART Report includes a compilation of AOART panel member Observations and Assessments organized by TIM session, and/or followed by a set of broad Findings and Assessments that pertain to the postulated tenets and NASA context that were presented during the TIM Plenary session.

R.3.1 Plenary Session

The TIM began with a Plenary Session to set the stage for meeting. This was aimed at providing key direction and context for the participants from the NASA HQ point of view.

R.3.1.1 Observations

Mr. Stephen Jurczyk, NASA Associate Administrator, enunciated the context of the Agency perspective that underlies the purpose of the TIM. He articulated the viewpoint that NASA's technology development investment should focus on those technologies that are important from a systems capabilities point of view, closely linked to mission requirements. Dr. Jack Kaye followed with an overview of ESD's current status and future plans relevant to scientific observational goals and related measurement needs. He outlined the mission/measurement guidance from the recently released ESDS. Ms. Pamela Millar and Mr. Parminder Ghuman then presented ESTO's investments in AO technologies.

R.3.1.2 Assessments

The current competitive model works to the benefit of NASA in some cases; however, in other cases it is a detriment. It is clear that there is a need to enhance inter-Center collaboration—a need for more openness sharing of knowledge and resources, and more leveraging of the technical advances across the Centers.

1. The NRC ESDS provides a general sensor roadmap, but more specific measurement and sensor performance parameters were not provided, leaving the particulars to be assumed by others or developed at a later date.
2. Funding levels from ESTO on laser/Lidar technology development are significant but lack longer-term continuity, with appearance of lack of coordination and lack of transparency in some cases.

R.3.2 Session 1: Clouds, Aerosols, and Ocean

R.3.2.1 Observations

Airborne Lidar is an active, seemingly healthy component in this particular category. The vehicle for maturation of airborne Lidars often appears to be science campaigns instead of ESTO or the AITT Program. This is not healthy in general, although in this backscatter Lidar category it appears to be a viable alternative, and the investigators have often made it work. Support for engineering checkout flights should be inserted in the technology maturation path on the way towards instrument inclusion in airborne science campaigns. Airborne Lidar programs do not address TRL advancement to TRL 6 when the "relevant environment" is that encountered in a spaceflight application.

The lack of graduates trained in Lidar was cited as a "barrier" to development. The AOART's assessment is that this is a canard. Most graduate students are very adaptable and often migrate into fields different from those in which they qualified. The real driver for attracting fresh talent into the field is the prospect of involvement in healthy and meaningful projects. It is important to note that university research levels in optics/materials/physics/engineering are very successful and dynamic and the number of graduate students in the physical sciences and relevant engineering disciplines continues to expand. However, bringing in smart young people and training them to be Lidar scientists requires that NASA manage its workforce so

that the experienced scientists are around to ensure that the new scientists get good training. This is relevant to Tenets 8, 9, and 10. More on this topic can be found in the University Research, Education, and Hiring Environment section (Section R.4.8).

Continuity of funding is certainly desirable; however, largely due to the competitive environment, many investigators take a dim view of those few who actually get repeat awards year after year. This is part of the issue of clarifying to the community how much technology development funding is to be directed to support specific mission requirements.

Both Goddard Space Flight Center (GSFC) and Langley Research Center (LaRC) have very active aerosol research programs investigating somewhat different Lidar approaches for measuring aerosol properties from space. Although both teams do excellent work, under the constraint of limited resources some cost advantages and focus might be gained by selecting one of the two approaches for technology development aimed at deployment in space. A separate selection might be implemented for development of instruments for airborne aerosol science.

R.3.3 Session 2. Greenhouse and Trace Gas Measurements

R.3.3.1 Observations:

The Active Sensing of CO_2 Emissions over Nights, Days, & Seasons (ASCENDS) pre-formulation activity, which has funded flights of multiple Lidar instruments for CO_2 measurement for several years, concluded in FY18—no further NASA funding is projected under the umbrella of ASCENDS. The panel agrees with the termination of ASCENDS, given the progress being made with passive instruments and the challenges for AO approaches to meet extremely high precision CO_2 measurement demands.

A more convincing case can be made for Earth-orbiting Lidar measurements of methane (CH_4). The joint Deutschen Zentrums für Luft- und Raumfahrt (DLR) - Centre National d'Etudes Spatiales (CNES) Methane Remote Sensing LIDAR Mission (MERLIN) mission implementation that includes the CO_2 and CH_4 Atmospheric Remote Monitoring-Flugzeug (CHARM-F) airborne demonstrator is progressing. Should NASA emulate the MERLIN mission? In the near-term, NASA ESD should consider collaboration, e.g., with support of an airborne methane Lidar.

R.3.4 Session 3. Wind Measurements

R.3.4.1 Observations

For winds, it is critical that science requirements and technology objectives co-align. Coherent systems provide good boundary layer winds, but are the spacing and resolution sufficient to provide science value? Direct-detection systems are larger (more demanding spacecraft resource requirements) and less sensitive to aerosols, but offer the capability of measurements from low-aerosol regions, particularly relevant to middle and upper tropospheric regions. It is essential that the ESDS science requirements be well specified before choosing a preferred technology development direction.

NASA currently has access to two airborne wind Lidar assets, representative of the two fundamental Doppler Lidar technical approaches for tropospheric 3D wind measurements. Airborne operation of these assets can provide valuable experience in assessing capabilities, developing data analysis algorithms, and gaining further understanding of performance in various atmospheric conditions. To date, a satisfactory airborne comparison of coherent and direct-detection systems has not been carried out. Because these approaches have comparative advantages and disadvantages for meeting ESDS science objectives, more frequent flights should be supported to gain experience on their relative capabilities. The airborne wind Lidar data will be valuable for understanding the system requirements as the ESDS mission is better defined. In addition, the possibility exists of using them for Atmospheric Dynamics Mission (ADM) Aeolus correlative validation measurements, and this should be encouraged.

Benefits of Combined active Doppler Lidar winds and passive Atmospheric Motion Vector (AMV)-derived winds have not been well studied. Observation System Simulation Experiments (OSSEs) could provide some insights into benefits of this approach, and impact choice of a Doppler Lidar technology.

The European Space Agency (ESA) recently launched their ultraviolet wavelength direct-detection ADM Aeolus wind Lidar. This is a milestone for the wind Lidar community. Open channels of communication with ESA can provide useful insights into their decision making and lessons learned, and can be used to explore future collaborations. A vehicle for communication exists through the NASA-ESA Joint Program Planning Group (JPPG). A current opportunity to gather comparative information on performance of potential future space systems exists through Aeolus Calibration and Validation (cal-val). Collaboration with ESA for Aeolus cal-val, through underflights of the satellite track with NASA-funded aircraft-mounted Doppler Lidars would be extremely useful for evaluation of next-generation winds systems. More detail on collaboration with ESA is provided in Section R.4.

R.3.5 Session 4: Topography, Cryosphere, and Biomass

R.3.5.1 Observations

Post-award mission creep on the Ice, Cloud, and land Elevation Satellite (ICESat) 2 Program was not adequately propagated into GSFC's risk posture, consequently resulting in excessive cost and schedule variances during development of the laser transmitter subsystem in particular. One speaker seemingly stated "hey, the mission expanded because we are scientists and that is what scientists do—always want more." The extent to which this attitude drove laser risk and cost on ICESat-2 suggests insufficient rigor in program management and project execution. The tension between investigator teams and project management is natural and widespread, of course. In the case of ICESat 2, project management knowingly took on an inordinate amount of technical risk by committing to a laser transmitter subsystem with limited heritage that had not been developed and tested.

Industry played a significant role in the ICESat 2 laser development, which brings to the forefront the role of NASA collaborations with Industry, particularly in advancing technological maturity to TRL 6 or TRL 7. Fibertek is of unique value to the Lidar community. Fibertek has consciously positioned themselves as a custom laser house with a particular expertise in 1-µm laser systems and is perceived to be more flexible to evolving requirements and circumstances than competing suppliers. Perhaps for this reason they are viewed by NASA as a favored source. This is not strategically wise, but given the historical NASA funding patterns, what is the alternative?

Lack of continuity of funding and departures from previously assumed funding profiles in the AO (Lidar) technologies creates decision-making problems in managing Industry commitments to NASA. Inevitably, the result is that the schedule slips and the costs rise. This issue is not unique to ICESat 2. For various reasons, it has been present in other Lidar projects, e.g., the Lidar In-space Technology Experiment (LITE) shuttle Lidar, the ICESat mission, and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) Mission.

The presentation on Global Ecosystem Dynamics Investigation (GEDI) noted that much of the laser technology was developed through the Laser Risk Reduction Program (LRRP), which aimed to foster development of selected laser technologies deemed necessary for projected Earth Science missions. During ensuing discussion of the LRRP, it became apparent that the LRRP remains controversial. (For further comments, see the LRRP-related material in Section R.4.4.) However, some version of targeting for advancement of specific technologies that will meet the performance specifications for future missions seems necessary to ensure that the technology is ready when needed.

R.3.6 Session 5: Planetary Science

R.3.6.1 Observations:

The session chair (Dr. Jonathan Rall) was in an upbeat mood and expects a technology funding increase in the near future. This must reflect the commitment of the Planetary Science Division (PSD) to invest 6–8% of its budget in technology development, in accord with the PSDS.

The NRC PSDS report "Vision and Voyages for Planetary Science in the Decade 2013–2022" contains only a few mentions of AO sensing for scientific observations. These are in the categories of laser ranging/topography, Raman spectroscopy, and Laser-Induced Breakdown Spectroscopy (LIBS), the latter being restricted to short-range observations. There is no sense from that document of the value added by atmospheric Lidar. Rather, the AO technology emphasis is on mission-critical engineering sensors for EDL applications.

On the other hand, significant thought and effort has been directed towards utilizing Lidar methods and techniques with origins in Earth science for Mars science applications (e.g., the Abshire presentation on Mars wind Lidar, Presentation 5.2).

R.3.7 Session 6: EDL Technologies

R.3.7.1 Observations

The applications and sensor performance requirements are well formulated. Technology maturation progress is obvious. Plans are in place for increased reliance on AO for EDL and hazard detection and avoidance. AO technology has unique spatial resolution capabilities.

Collaboration among the NASA Centers and JPL is healthy in this area. U.S. industry and international capabilities can benefit NASA. The DoD has developed Lidars and Lidar technology (e.g., under the Defense Advanced Research Projects Agency (DARPA) Jigsaw Program) that are likely relevant for the EDL application, and the NASA Centers could do more to leverage these developments.

A strong need exists for incorporating advances in integrated photonics in order to reduce mass, power, and size, and increase reliability. These technologies enable non-mechanical laser beam steering, which will increase reliability and is expected to reduce Size, Weight, and Power (SWaP). Note that these are primarily "engineering sensors" that are mission-enabling, where reliability and SWaP are major drivers. Advances in integrated photonics for these sensor applications can enable new science instrument concepts also.

Collaboration between HEOMD and SMD has obvious advantages here, to facilitate leveraging the resources required to implement mission priorities.

R.3.8 Session 7: Exploration (optical communications, rendezvous and capture, and proximity operations)

R.3.8.1 Observations

In all these categories, the development and applications roadmaps that were presented are well articulated and appear to be credible. The technology development and maturation priorities are well recognized.

During the speaker panel Q&A at the end of this session, the speakers made the point that leveraging technology investments among STMD, HEOMD, and SMD is recognized to have obvious payoff in the future. The SMD benefits from Exploration technologies that enable future missions. On the other hand, Exploration-funded technology demonstrations can get opportunities to be in the payload of an SMD mission spacecraft.

The optical/laser communications enterprise sets the gold standard that can be aspired to in combining NASA capabilities, partnering with outside (non-NASA) organizations, and leveraging both commercial and DoD-developed technologies for NASA use.

The Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-Rex) Mission to asteroid 101955 Bennu is an excellent example of AO technologies applied to Rendezvous and Capture (R&C), and proximity operations. In this case, NASA has relied on international (Canadian) laser altimetry capabilities, applied to the NASA mission objectives. Arrival at the Bennu asteroid was in December 2018.

R.3.9 Session 8: Aeronautics

R.3.9.1 Observations:

AO technologies are enabling several useful diagnostic tools in aeronautics. The aeronautics investigators rely heavily on commercial AO products. Utilization of AO sensors that have been developed and matured in-house is rare.

Aeronautics suffers from serious investment constraints. Many existing NASA resources are active as service centers (e.g., at Glenn Research Center, LaRC) with customer business. However, there is a lack of resources for continuing development in some areas, e.g., wind tunnel investigations. Also, it appears that NASA is not investing adequately in the future aeronautics workforce.

The use of wind Lidar in aviation safety should be vitalized with incorporation of recent laser and photonics technology developments. This is an area of important partnership with and within the private sector.

International collaboration is beneficial in this area. International developments that utilize AO technologies are advancing, and NASA should be aware and make use of these continuing international developments.

R.3.10 Session 9: Innovations

R.3.10.1 Observations

The Geiger-mode Avalanche Photodiode (APD) focal plane array technology is an example of the benefits of NASA collaboration with other U.S. Agencies and research organizations. Potential applications in Deep Space Optical Communication (DSOC) and Hazard Avoidance Lidar are being investigated. The extremely compact "Lidar on a chip" concept takes advantage of advances in integrated photonics technologies. NASA can and should be more aware of and leverage advances that are taking place in external organizations. NASA should encourage its staff to attend technical conferences that are heavily represented by investigators at other Agencies and the DoD, including closed conferences.

Dr. Jennifer Inman's work on "Laser Ocular Hazard Risk Management for Airborne/Spaceborne Active Optical Systems" is definitely worthwhile for Lidar missions and should be communicated broadly to the community, including external Agencies. This approach should be utilized within the NASA community, where applicable, along with the American National Standards Institute (ANSI) standards to optimize Lidar designs and operations.

R.4 Additional Investigations/Actions by the AOART

The AOART gathered additional information from speakers and studied additional issues related to NASA AO programs that have a bearing on some of the TIM topics. Additional information was solicited involving areas covered in Sessions 6 and 7, where AO sensor technologies are being developed for use in "engineering" applications critical for mission implementation. It is important to understand how technology development in these areas, supported by programs within the STMD and HEOMD, compare and contrast with management and implementation of technology development within the SMD.

The other subjects of additional study that we include in this report are primarily the role of ESTO, the role of Industry, NASA internal and external collaborations, advantages and disadvantages of competition, and the university research, education, and hiring environment.

AO Sensor Technologies for Mission Implementation Purposes

Beyond the explicit coverage within the TIM, and using the session organization of the TIM as a guide, we include in this category the expanded AO sensor usage in (1) optical communications, (2) Rendezvous and Capture operations, and (3) EDL operations. In the latter two areas, we have benefitted from very informative conversations with Mr. Bo Naasz, leader of the Rendezvous and Capture System Capability Leadership Team (SCLT) within STMD, Mr. Scott Cryan representing R&C, and Ms. Michelle Munk, SCLT Leader for EDL within STMD. They provided materials to the AOART that expanded on the knowledge gained at the TIM.

A key AOART observation is that management and oversight at the NASA Headquarters Mission Directorate level is critical for enabling the timely technology development, maturation, and infusion into flight missions. When program offices exist for the purpose of maturing and infusing new technologies into these missions, progress is more steady and dependable. All three areas have experienced periods of funding that were insufficient for the pace of technology maturation needed to actualize AO sensors in space. Optical Communications is an example of a technology that was labelled as promising for decades, but experienced persistent delays in reaching operational maturity, notwithstanding efforts in the last decade toward that goal by the national security community.[12] Available laser technology was a factor for several years, but a low level of NASA programmatic support and the risk aversion of project management were major contributors. Now the picture is brighter. The optical/laser communications enterprise is exemplary in combining NASA capabilities, partnering with outside (non-NASA) organizations, and leveraging both commercial and DoD-developed capabilities and technologies for NASA use. Program management at NASA HQ in this area is robust and effective.

In the following paragraphs, we first note a perceived distinction from science instrument technology infusion in the expectations and manner in which new technologies are tested for space flight mission readiness, specifically in the TRL 6 and TRL 7 maturation levels.

Requirements for Active Sensors critical to mission success in applications such as EDL, R&C, and Optical Communications are formulated by means of close coupling among STMD and HEOMD principal technologists, mission planners, capability leadership teams, and directorate staff. These groups are responsible for evaluation of the technology maturation levels, the technology infusion into mission planning, and the need for further investment in technology maturation. This is a departure from the science panel roles in prioritizing active sensors for SMD investment.

Requirements placed on these “mission engineering active sensors” are strongly driven by the high value placed on low mass, low power draw, compactness, lifetime, and the performance criticality to mission success. In this respect, there is more similarity with planetary science active sensors. However, the mission engineering active sensor technology can gravitate to the most robust, most efficient, least complex sensor technologies (e.g., 1060 and 1550 nm fiber lasers and photon-counting detector arrays) without compromising the sensor capabilities, whereas for the Lidars that have scientific applications the science requirements may drive the required laser technology to less mature, more complex systems at different wavelengths. Lidars for mission implementation purposes also differ from those applied for Earth atmospheric science purposes, where the lasers employed typically require higher output power and pulse energy levels.

The requirements for attainment of TRL 6 receive more critical and thorough attention than those for science payload instruments, although in some cases the mission criticality of a science instrument in the payload leads to similar treatment. The same can be said for the testing sequence that precedes the build of

the flight unit. Also of high importance, if not mandatory, are technology demonstration flights and the attainment of TRL 7.

R.4.1 Rendezvous and Capture

R.4.1.1 Observations

Plans and schedules for various missions in pre-formulation or formulation dictate the AO sensor (Lidar) technology maturation schedules, e.g., the Engineering Design Unit's need date and the Flight Unit's need date. For R&C, active sensor technology development funding has been highly dependent on project support.

Active sensors (Lidars) can be classified by a combination of range-to-target type as well as target type. Two AO sensor classes in terms of range to target are: (1) Rendezvous Lidars, with long operating range to target, and (2) Proximity Lidars with range to target being no more than a few meters. The target type can be classified into three categories: (1) Cooperative (corner cubes), (2) Non-cooperative (e.g., target material gold multi-layer insulation), and (3) small body/asteroid surface, where Lidar requirements are more challenging due to the low target reflectance.

Is there sufficient synergy to implement a common sensor suite for Autonomous Rendezvous and Docking, with a set of common sensor specs? An HEOMD-issued study examined this question. A common sensor suite was defined as consisting of a Lidar, an infrared camera, and a visible-light camera. Respondents to the solicitation noted difficulty in achieving specifications for different mission scenarios in a single unit. Although looking for commonality in technologies and requirements across different application areas is worthwhile, there are downsides and challenges to this approach. At the system level, different applications likely have incompatible requirements. A modular approach can potentially alleviate this incompatibility. Unfortunately, this means that the first user (first project) must pay for the initial modular development and may not be willing to invest the extra funds needed to build in functionality that benefits other projects. The recommendation is to elevate ownership of the common sensor specification to the Agency level where a broader assessment of requirements across multiple missions can be taken.

Collaboration is very useful and important in some cases. One can cite some examples of collaboration among Centers and with Industry being critically important. The Hubble Robotic Servicing, the Dextre Pointing Package, and the Vision Navigation System for Orion are examples of inter-Center collaborations, Industry-provided optical systems, and international space Agency collaborations that resulted in flight testing of new active and passive optical/vision systems that represented advances in technology.

Infusing new AO R&C sensor technology into a project that is selected through a competitive proposal process (e.g., Discovery, New Frontiers) is difficult because these projects are cost-capped, and the proposed schedules are tight. This results in a huge disincentive to rely on new sensor technology.

Two bottom lines come from Mr. Naasz:

1. There is very little programmatic stability, it is difficult to predict what future missions will be funded, and therefore perhaps unwise to plan (and pay) for those enhanced capabilities to support uncertain future missions. (Fixing this requires money (see item 2) and better long-term planning).
2. The need for an AO sensor to satisfy a Level-1 requirement in a project is essential in order to get funding for that sensor. Projects are the only organizations with sufficient money to develop this hardware, and they have no motivation (in fact they have a counter-motivation) to build-in capability they do not directly need to meet their mission requirements.

R.4.2 Entry, Descent, and Landing

R.4.2.1 Observations

Ms. Munk represents the SPLICE Project that is funded from the NASA STMD Game-Changing Development (GCD) Program. To repeat, this funding source is from a NASA HQ program, not a specific flight project. It is a multi-Center project, selected in a competitive environment in response to a call for proposals. There is also industry involvement. SPLICE provides critical funding for high-priority technology development and demonstration. Still, funding limitations require choices, that is, "down-selections," that result in dropping some good ideas or putting them on the shelf.

For Precision Landing, it is essential to understand and mature the whole end-to-end set of capabilities together in order to meet the mission requirements. Integrated Capabilities implies cooperative involvement of multiple organizations that can contribute areas of expertise. SPLICE includes collaborations with other government entities and industry involvement: STMD programs are starting to commercialize component technologies like the Navigation Doppler Lidar and the Terrain Relative Navigation (TRN). SPLICE is an early adopter of the High Performance Spaceflight Computing (HPSC) Project deliverables, a collaboration with the United States Air Force, with industry contracts, to build chips that enable faster processing. NASA partners with Draper Labs for TRN algorithm developments that are "ripe for commercial applications."

The expertise unique for the EDL-related applications resides in house for the most part. Funding for the NASA Centers and JPL is therefore very important for sustaining the NASA capability for the future. Also, to meet the lunar landing timeline schedule and the feed-forward to Mars, the existing NASA-internal efforts are critical. TRN on Mars2020 is the first step. Ms. Munk states that "it is vital that Mars 2020 TRN work properly (and we have been wanting to do that since 2001!)" The TRN of the future includes the infusion of Lidar into the TRN system.

Relating to further technology maturation—in the TRL 6/TRL 7 range—for pinpoint landing, there is a need to get relevant ground and flight test experience and fly demonstrations to the Moon and Mars. A next step is infusion and demonstration of Lidar TRN technology. The Lidar requirements for some of the EDL scenarios are very challenging because of the combination of high resolution, large area coverage rates, short timelines, and small mass, volume, and power allocations. This drives a need to be investing in high-efficiency components and Lidar approaches.

On the topic of Programmatic Stability for supporting technology development and infusion into flight missions, is this an issue with EDL technologies? STMD is one of the more stable directorates that have technology-development programs that provide opportunities for tech developments with multi-year funding profiles.

Continuity in human resources is also a key to achieving the technology maturation objectives in a timely manner. This entails early-career hiring and mentoring at a level that is adequate for maintaining the in-house technology development expertise. On the topic of university provision of early-career hires, Michelle Munk stated that funding for several years was inadequate for feeding the future missions. Currently there is "project pull" as well as more program office support. STMD fellowships and grant mechanisms are useful tools to attract talent. Staff members that are engaged in EDL technologies are working with groups at 3–4 universities. For example, Johnson Space Center (JSC) works with Texas A&M. For interns and early-career hires, NASA needs to provide mentoring and application experience to build up the in-house skill sets. It takes years to mature experts in these systems.

International cross-fertilization: In the EDL area, this happens at the annual International Planetary Probe workshops. Offering special facilities to international collaborators is beneficial. For example, DLR has special testing facilities that NASA can access. International agreements enable working together at the more technical levels. Collaboration at the technical levels is of great importance for the advancement of these technologies.

R.4.3 Optical Communications

R.4.3.1 Observations

The successful performance of the Lunar Laser Communications Demo (LLCD) on board the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft, launched in 2013, was a technology demonstration breakthrough. NASA HQ oversight and funding were provided by the Space Communications and Navigation (SCaN) Program. This was also a successful demonstration of collaboration, including international collaboration. Massachusetts Institute of Technology's Lincoln Laboratory and GSFC were key implementing organizations. Also contributing were NASA Ames Research Center (LADEE Mission management), JPL, and ESA.

The SCaN Program Office, in the HEOMD, is providing oversight and support for development and demonstration of the Laser Communications Relay Demonstration (LCRD), to be placed in Earth orbit, and will demonstrate a communications relay between geostationary orbit and two ground terminals. A 2019 launch is scheduled. The DSOC technology demonstration will be aboard the Psyche spacecraft, scheduled for launch in 2022. Funding came from the STMD GCD Program and the HEOMD/SCaN Program office at NASA HQ. The SMD Discovery Program supports the accommodation on the Psyche spacecraft.

These examples and several others in the coming decade are on the SCaN technology demonstration roadmap.

R.4.4 Role of ESTO

R.4.4.1 Observations

NASA ESD has traditionally not asserted priorities against solicitations issued by ESTO, with the underlying philosophy being to not artificially restrict the flow of innovation issuing from the technology development enterprise. However, there was a sense from some TIM attendees that this unfiltered policy led to outcomes whereby first-past-the-post technology developers tend to dominate awards, sometimes in a serial fashion. ESTO stresses that the periodic ESDS reports are their primary guiding documents and ESD's strategy for meeting its recommendations is continually monitored and updated through weekly leadership team meetings between ESD science program managers and ESTO.

In response to the questions and comments that were posed at the TIM regarding lack of focus in the solicitations, ESTO management states that this approach is working satisfactorily, so that a more priority-driven approach is not seen as necessary or desirable, and is well regarded by other elements within SMD. To this extent, it was used as the model for the recently established Planetary Exploration Science Technology Office (PESTO), managed out of the NASA Glenn Research Center.

ESTO also encourages investigators to adopt a more aggressive, less conservative approach to technology development with greater risk acceptance. In cases where such an approach might flounder, ESTO's policy of "Active Management" would intervene to either chart a course forward or recommend cancellation. It is possible to imagine that an increased threat of cancellation might discourage developers from accepting this approach, but by way of example, Total and Spectral Solar Irradiance Sensor (TSSIS) was offered as a success story case in point by virtue of the fact that it was completed in 18 months from initiation. To complement this more risk tolerant approach, ESTO is also increasing support to low TRL research and development that could reduce risk in key areas.

ESTO could use more outside reviewers from the DoD, the National Science Foundation (NSF), etc. to help guide decisions and be more aware of outside research. Although ESTO does encourage collaboration between Centers and non-NASA labs and institutions during the solicitation phase, it would be beneficial to expand the number of funded projects that reflect such collaboration.

It is useful at this point to recall the lessons learned from the LRRP, an effort in the 2000s to advance laser technology and reduce the risk for Lidar instruments in Earth Science applications, as the technology needs have aspects that are NASA specific and are not developed by others. The AOART reviewed limited documentation available to us on the LRRP (technical subcommittee report in 2004[11] and limited access external panel review reports on the efforts at LaRC and GSFC) in an attempt to understand the impact of LRRP and the reasons for the mixed feelings about the program. Impetus for establishment of the LRRP was an external review panel convened by Code Y and prepared for NASA LaRC in 2000 to recommend ways to reduce the risks for space missions utilizing laser technology. (The Executive Summary is in Appendix C.) Although the scope of this AOART is broader, there are similarities between the charges to the 2000 panel and the AOART panel, which make evident that many of the challenges identified in the 2000 time frame remain to be resolved. As noted earlier, the LRRP that was established after the 2000 panel was controversial.

It is clear that significant technology advances were made under LRRP funding. These advances include improved 2-micron laser technology for wind sensing, maturing of 1-micron laser technology for altimetry, and critical advances in diode laser array qualification testing for spaceflight applications. It also helped foster a better working relationship between LaRC and GSFC and a long-term partnership with Industry. However, the panel reviews also indicate that LRRP suffered from inadequate management and oversight at the Centers, insufficient focus on addressing the stated priority goals of LRRP, and an execution approach that was too Center centric. Additionally, it is perceived that the cost of the LRRP, on the order of $70 M, was incommensurate with the progress made under the program. A more tightly focused emphasis on risk reduction of the critical technologies in the later years would have improved efficiency in use of resources. While the AOART believes that the fundamental reason for the LRRP was valid (and remains so today), any future focused investments ought to have more continuous oversight, be well aligned with and focused on decadal survey needs, and be more open to variety of organizations for execution.

During the workshop, the point was made by Mr. Michael Seablom that during the course of ESTO's existence approximately **$350M** has been invested in laser/Lidar related research and development efforts, with few of these having resulted in a direct contribution to an eventual space implementation. However, it is not clear how this finding compares to the performance of other technology classes within the portfolio, i.e., whether it is a consequence of a broader based barrier. It is apparent from Figure R-1[13] that getting to the "system-level TRL 6" that is expected for a credible space flight instrument or mission proposal is rare for ESTO-funded efforts.

R.4.5 Role of Industry

R.4.5.1 Observations

Laser physics and engineering, as applied to Lidar systems, does exist in industry. NASA's efforts to partner with industry are uneven. The expertise in industry has direct application to risk reduction. (Tenet #3).

Fibertek has had a major role in maturation of NASA-related spaceflight laser technology for the past two decades, predominantly with neodymium-based Lidar laser transmitters, although Fibertek has interest in developing and testing spaceflight lasers at other wavelengths. Raytheon, Northrup Grumman, Lockheed, and General Atomics, major government prime contractors, are all viable alternatives to Fibertek on a laser/Lidar technological capability level. They also have deeper engineering bench strength. These organizations rely on a different customer base for their products. Fibertek operates with leaner management and systems engineering than the major government prime contractors that generally have a more formal system with greater up-front scrutiny of the stated Requirements and Statement of Work.

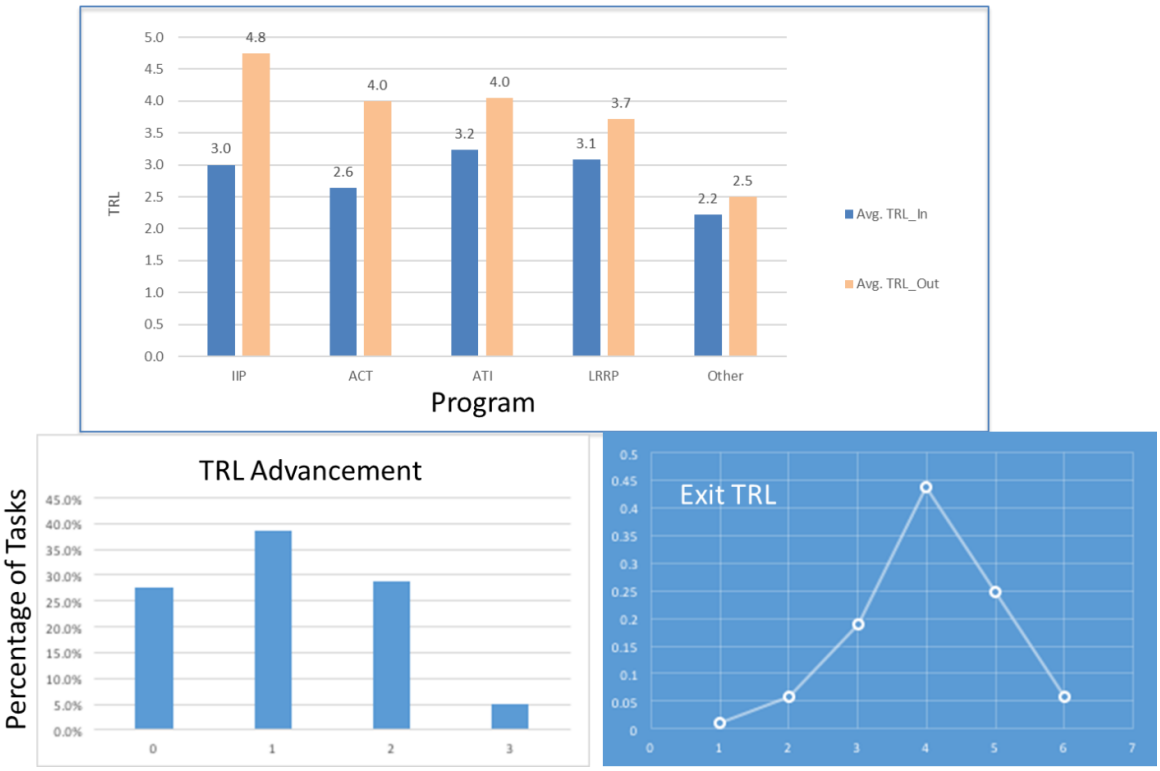

Figure R-1. TRL advancement statistics for ESTO R&D programs, 1998–2016.

There are cost-associated reasons underlying NASA's AO business with Fibertek. The primes noted above tend to spend a large portion of the contract up front to figure out exactly what the product will look like and bid/build accordingly. If NASA requests changes that invalidate a large amount of prior testing and analysis that then needs to be repeated, this results in considerable costs for the contract modification. Fibertek is more amenable to adjusting to changing requirements. While Fibertek is often willing to forgo performing such regression testing or analysis, upper management at the primes will not allow their reputation to be put at risk over equipment that has not been properly tested and analyzed to perform as required (and they have a strong business incentive not to forgo such additional work). Fibertek has historically been more accommodating of these fluctuations than the major primes that are willing to walk away rather than take a loss on a contract.

It is noted that NASA acts as a research organization, with budget and priorities subject to more insistent political pressures, and mission/instrument/subsystem requirements that are for various reasons more fluid than for typical DoD contracting.

Because of the importance of maintaining and facilitating a strong relationship between NASA and the private sector, the AOART contacted a limited number of companies that participated in the TIM, to probe their perspectives on how to optimize the NASA-industry relationship to advance AO technology. The perspectives offered reflected both systems and component-oriented organizations.

One common assessment among the organizations contacted is that a major obstacle, representing a change in culture that has developed over the last several years in the Earth Science community, is the exclusion of industry during the early stages of the mission-formulation planning process. Current Organizational Conflict of Interest rules are interpreted by some groups to prohibit industry's participation at the concept design stage. Industry feels that they are placed in a competitive disadvantage by this approach because these rules are not equally applied to internal NASA groups. The perception from industry is that NASA appears to prioritize keeping the civil servants at the Centers employed to the detriment of taking advantage of expertise in the companies. The companies believe that this not only puts them at a disadvantage for later

competitive stages, but also limits innovation within NASA because ideas and approaches developed externally are not fully considered. One company felt that many of the troubles associated with development of the ICESat 2 instrument could potentially have been reduced if more industrial instrument system expertise had been incorporated into the process. An alternative approach is followed within the Astrophysics community, where Phase A studies are typically competed to provide an opportunity for industry participation at early stages in the process. Earth sciences should consider more use of the Partnering Opportunity concept, in which NASA issues an Announcement of Opportunity for partnering ideas early in the mission development process, then selects a partner based on a competitive process. Adopting this approach where applicable would broaden the available field of ideas to include those developed external to NASA while mitigating potential Conflict of Interest issues. Presumably, internal NASA groups would be invited to participate in such competitions as well.

Another issue on which the companies agreed is the evolution over recent years of a change in the Earth Science Small Business Innovative Research (SBIR) Program. From their perspective, the program was historically more innovative and open for new ideas, but has evolved to the point where the Centers often go out on SBIR calls for very specific tasks or instruments that have more resemblance to directed contracts. From the perspective of the companies, this inhibits creativity and limits opportunity for diverse external input and, to some extent, violates the intent of the program aimed at encouraging small businesses to develop new innovative approaches that can eventually be commercialized. Although NASA is expected to direct the SBIR Program toward mission-oriented applications, the program should give priority to supporting new innovative approaches rather than supplying well-defined products.

It is clear that private-sector companies should be valued and their resources utilized to a greater extent in the NASA active optics programs. With their engineering and environmental testing resources and experience, they can and should be partners in the risk reduction phases of technology maturation, getting through the "valley of death." As partners in bringing AO sensor systems to fruition as key elements of NASA missions, they often face inconsistent relationships with NASA entities. One adverse result is the threat to continuity of funding and staffing. (More on this topic in the Collaboration and Competition Sections R.4.6 and R.4.7.)

R.4.6 NASA Internal and External Collaborations

R.4.6.1 Observations

Improved partnering and collaboration with Industry, Government entities, and Federally Funded Research and Development (FFRDC)-type organizations would benefit the NASA AO community. The gold standard for partnering and collaboration within this community is being set by the optical communications activities. This area appeared to be the most healthy and dynamic of all those presented at the TIM. NASA has effectively leveraged capabilities, technologies, and systems developed by the DoD and commercial industry; partnered and collaborated with outside organizations (FFRDCs); and combined this with NASA-developed technology to develop a capability for NASA-system-driven, high-bandwidth communications links. This serves as a model to emulate by others.

In the Lidar area, the DoD continues to put significant resources to develop Lidar systems and component technologies. Although the DoD applications and missions are different from NASA's, it should be possible to adapt some DoD technologies and instruments for the benefit of NASA. To this end, it is incumbent on NASA personnel in the Lidar area become more knowledgeable about DoD activities, many of which are not in the public domain. In the optical communications area, NASA was aware of classified DoD activities, and this awareness enabled NASA to leverage DoD investments. Even at the unclassified level, there is significant DoD work in Lidar systems and technology that is considered sensitive and not available in the public domain. NASA's improved awareness could provide similar pay-offs to that derived in the optical communications area. Unfortunately, the NASA TIM was an entirely open forum, with no closed sessions. This had the effect of eliminating presentations and discussions of export controlled, International Traffic

in Arms Regulations (ITAR)-restricted, and proprietary systems and technologies developed for the DoD and others. A possible way of NASA accessing some of this information would be to hold future TIMs with closed sessions. Another avenue is to have more NASA participation at a highly relevant source of information of DoD activities in the Lidar area such as the Military Sensing Symposium Active Electro-Optical Systems Conference. This conference is held at the classified secret level and would require additional NASA personnel to acquire security clearances. Finally, NASA personnel, particularly in the Lidar areas, should be more proactive in finding relevant non-NASA-developed technologies and capabilities to leverage for NASA's benefit.

There was a mix of inter-Center collaboration and competition observed during the TIM. An example of inter-Center collaboration (with multi-Directorate funding) is the SPLICE Project discussed above. In the area of Lidars for Earth science, there was more of a sense of inter-Center competition. Both inter-Center collaboration and competition have healthy aspects: collaboration can lead to a more efficient use of resources, while competition can lead to better concepts and ideas. Even within areas of competition, there is room for increased collaboration to make better use of Agency resources. Increased transparency on internally funded technology development by the Centers should enable earlier and wider use of these developments for the benefit of the Agency as a whole. Improved communications and transparency, even in areas of competition, also provides mechanisms for development of collaborations that make better use of Agency resources. In other parts of the Government, there are examples of better transparency and collaboration within the competitive model. Typically, in DoD research programs, Government laboratory and FFRDC competitors are expected to share technical information and collaborate for the benefit of the Department. Program managers in DARPA will broker collaborative arrangements among competitors when it is viewed as in the interest of the Government. The NSF has their Engineering Research Centers Program and the Industry-University Cooperative Research Centers Program that develop long-term partnerships between academia and industry and can involve international collaborations where appropriate. An example was the MIRTHE+ tunable Quantum Cascade Laser sensing NSF program at Princeton University. This program involved more than five universities over a 7- to 10-year period and had over a dozen industries on their industrial board. It would behoove the NASA Centers to adopt these models and culture of greater collaboration and transparency, even in the competitive context, for the good of the Agency. It will be challenging for NASA Centers to do this left to themselves, as previous external reviews of NASA Lidar efforts have made similar recommendations, with only tepid moves at best toward a better model. This is a topic that NASA HQ likely needs to take a leadership role to foster and champion.

Collaboration with Industry is of great value, yet there is room for improvement, starting with some specific steps that NASA can take. Although the open forum of the TIM eliminated presentations from many private firms doing research on ITAR-controlled technologies, a limited number of companies discussed active optics research and offered opinions on the impact of structural mechanisms and procedures on progress in active optics. One opinion that surfaced, particularly in the Earth sciences, was the difficulty private companies are faced with resulting from the inconsistent relationship between industry and NASA, where NASA is a partner on some projects and a competitor on others. It was noted that maintaining continuity and corporate memory in core areas was challenging for NASA's industrial partners, especially when the number of opportunities available through the Advanced Component Technologies (ACT) and IIP programs is limited. In areas where private industry competes with NASA Centers for technology research and development funding, the uncertain availability of funding for industry can put the companies at a disadvantage relative to the Centers, where support is much more consistent. Although competition can lead to new ideas and is therefore an important component of state-of-the-art research programs, opportunities for partnerships with industry as well as among the Centers should be encouraged, perhaps with incentives or rewards where appropriate, and care should be taken to ensure that in open competitions the NASA Centers do not have a significant competitive advantage. An approach that has been used in the past is to issue partnering opportunities that would enable industrial partners to bring ideas and concepts to early stages of the planning process. NASA's private-industry partners represent a key element of active optics programs within the Agency, both at the component and systems levels, and the Agency needs to

ensure that policies encouraging and supporting the participation of these partners are implemented and assessed. For specific areas where expertise resides primarily outside of NASA, it is important that the Agency take appropriate steps to ensure that expertise is maintained and not allowed to dissipate because of irregularities in funding or becoming too dependent on a single source or vendor.

International partnerships represent another opportunity for NASA to attain its science goals while spreading risk and managing cost. The fundamental challenge of developing and cost-managing AO technology for deployments in space is recognized as an important issue in ESA as well as NASA. Direct international cooperation in active optics technology development is inherently problematic because of exchange of funds issues and ITAR limitations on sharing and cooperation on key, state-of-the-art technologies. However, the difficulty and expense of developing key technologies for space-based missions suggests that exploring creative ways to move forward collaboratively should be aggressively explored where possibilities exist. ESA, Japan Aerospace Exploration Agency (JAXA), and NASA are all investigating future missions for which there is significant technological overlap, so agreements for joint missions in which different Agencies take responsibility for different technologies, subsystems, or instruments could offer a way to cooperate without violating technology-sharing restrictions. Sentinel 6, where Europe took responsibility for the platform, altimeter and Falcon launch vehicle while the U.S. provided the microwave radiometer, occultation instrument, and processing, is one workable model for such a program. Although this approach requires significant early-stage planning and introduces new risks, such as lack of progress or funding from one or more of the partners that jeopardizes the entire mission, a go-it-alone model also introduces significant risk and limitations in that availability of funding limits the number of missions and hence the science that can be done.

An example of international collaboration was the recent International IEEE-GRSS Workshop on Space-based Lidar Remote Sensing Techniques and Emerging Technologies, held June 4–8, 2018 at a venue in Greece[14]. This Workshop brought together about 100 AO participants from NASA, ESA, JAXA, CNES, and DLR, including policy makers and technical experts from these Agencies who are engaged in advancing space missions/measurements in AO sensing for science and exploration. Workshop discussions identified potential international synergies and collaboration opportunities between NASA and other international space Agencies for consideration in future planning of AO missions. Although workshops such as this require considerable effort to organize and implement, they should be encouraged. Follow-up actions involving smaller joint working groups that prioritize AO developments should be maintained.

R.4.7 Competition

R.4.7.1 Observations

In certain contexts, competition is healthy, both among the Centers as well as with private industry. The ESDS encourages competition. Competition breeds innovation. Competitive responses to solicitations in the lower TRL environment appear to be healthy; however, as stated above, sharing technology advances in the open forums and in the open literature should be encouraged or even mandated in some cases. The existing competitive environment at the TRL 5 to TRL 6 transition is not effective. Among the responses to NASA solicitations aimed at this TRL 5–TRL 6 range, the selection percentages are very low. NASA program offices make funding decisions based on priorities that are not always transparent to the community of technologists. To fill gaps in technology maturation to system-level TRL 6, respondents to NASA Announcements of Opportunity often resort to spending internal funds, which engenders the attitude that the results should remain "competition sensitive," hence closed to the "outside community." This is not healthy in the NASA environment.

R.4.8 University Research, Education, and Hiring Environment

R.4.8.1 Observations

Tenets 8, 9, and 10 are different manifestations of the same general problem and observation within NASA that it is harder to replace retiring atmospheric Lidar researchers with new hires, especially at the graduate level. Also, there appears to be fewer research collaborations in atmospheric Lidar between NASA Centers and University research groups as compared to several decades ago. The AOART feels that this is true on the surface as regards research in atmospheric Lidar, but it is an over simplification in respect to the overall field of optics, lasers, Lidar, physics, materials science, instrumentation, and atmospheric science. Specifically, we observe

(1) It is true that there are fewer research opportunities at the basic science level (i.e., TRL 1 and 2) within NASA and NASA-sponsored research at universities; but this is also true within DoD, Department of Energy (DoE), and Industry in that there are fewer 6.1 and 6.2 basic research programs now than a few decades ago. However, the overall level of funding to university research programs has increased over the past decade as seen in Figures R-2 and R-3. This increase is in the engineering and physical sciences, especially in laser communication, nanophotonics, quantum simulations, and bio-optics. It should be noted specifically that funding and research activities within physics and engineering university departments are relatively robust, healthy, and have grown significantly over the past decade. It has not just occurred within traditional atmospheric Lidar groups, but rather in new fields such as femtosecond laser spectroscopy, nanomaterials, integrated photonics, quantum optics, optical sensing, and lasers. As an example, this growth is reflected in the research interests of most of the major Optics Centers including the optics colleges at University of Arizona, University of Central Florida, and University of Rochester. Finally, anecdotally, it should be mentioned that there are fewer "atmospheric Lidar" university groups (located in physics, atmospheric sciences, engineering) now than there were 20 years ago, but the new explosion in autonomous vehicle Lidar and drone survey Lidar research and applications have resulted in increased "mapping Lidar" university research groups primarily within other departments such as forestry, geography, anthropology, and industrial engineering.

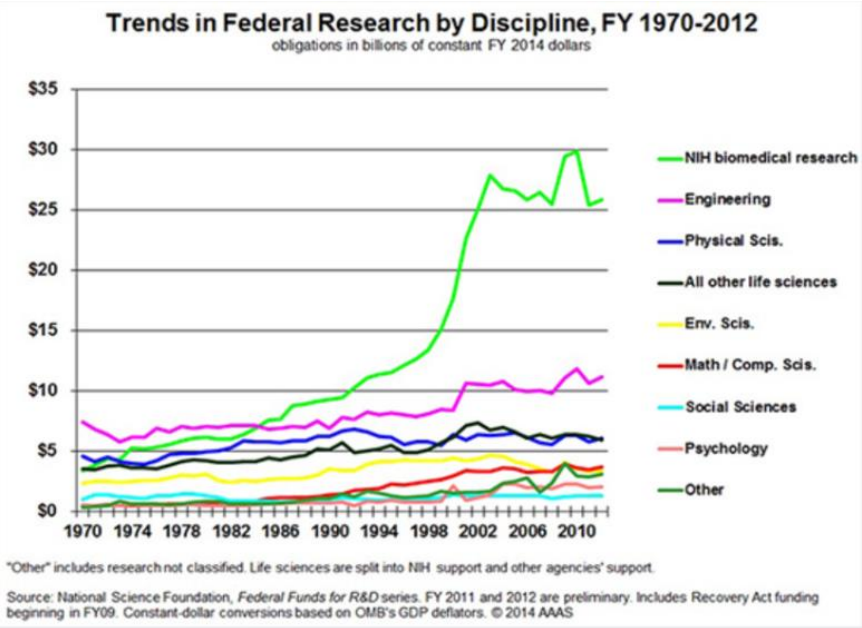

Figure R-2. Federal research funding by discipline from 1970 to 2012.

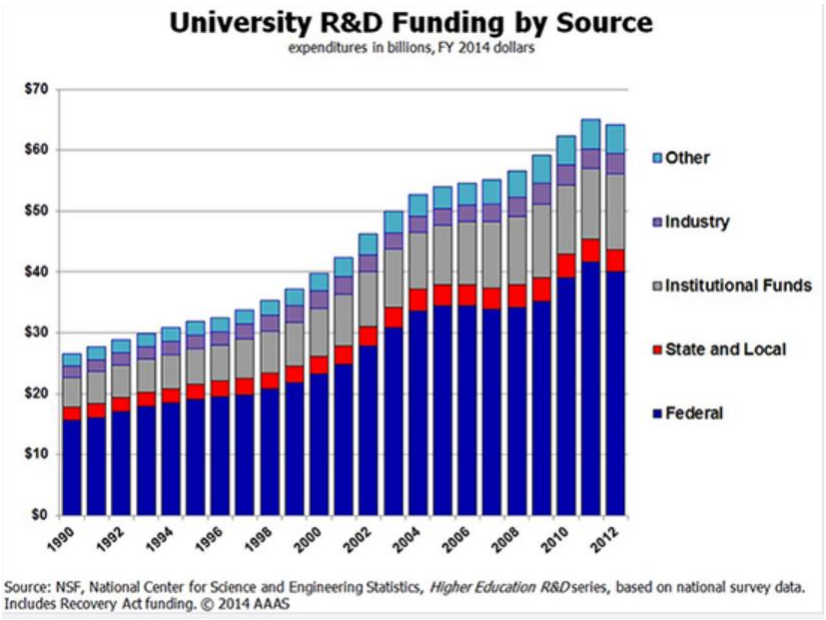

Figure R-3. University funding for research and development by source from 1990 to 2012.

(1) In order to facilitate hires within NASA AO groups, based upon the above observations, it is important that NASA recruit optical and laser scientists from non-Lidar research groups who can be trained in Lidar sensing and related instrumentation. The new hires can be integrated into NASA AO groups to be mentored and motivated.

(2) Finally, it is important that NASA increase basic research grants to universities and use other incentives for university/NASA research and collaboration in order to help direct and channel research in NASA-related AO Sensing. Basic research increases would involve new laser system development, spectroscopic techniques, ground-based Lidar atmospheric measurements, and airborne instrumentation development. NASA/University incentives could include several specific areas including (1) increased specific AO Sensor funding from NASA to university research groups involving TRL 1 and 2 research efforts, (2) increased NASA graduate student fellowships and stipends, and (3) increased faculty/graduate student short-term internships at NASA Centers to help introduce faculty and graduate students to NASA Missions. While the university optical centers and faculty are doing very well at present, such collaboration would better introduce and tie NASA research to that research within these university groups.

R.5 Summary of Findings/Assessments

R.5.1 Assessment Related to Tenet #1:

The AOART is in total agreement that AO technologies are critical for future recommended missions. This is a "given." One example can be found in the ESDS Summary in Table S.2 (p.S-8, 9).[2] This table outlines 14 Targeted Observables (such as Greenhouse Gases, Planetary Boundary Layer, etc.) of which 8 have Lidar or AO sensing as the Candidate Measurement Choice. Many other examples are reported in the preceding sections.

R.5.2 Assessment Related to Tenet #2:

The impact of modest NASA investments in AO programs is particularly relevant to the support of research at universities. Modest investments enable basic research and TRL advancement at early levels. In addition,

these investments can prepare graduate students for the NASA workforce of the future (see the assessments related to Tenets 8, 9, and 10 below).

Small business resources are supported through the SBIR Program. Of course, SBIR funding is meant for innovative research. The solicitation process encourages innovative ideas that have general relevance to NASA areas of interest. Quite often, it appears that these funds are used to support very focused objectives, apparently because there are no other funding avenues to support accomplishing those focused objectives.

R.5.3 Assessment Related to Tenet #3:

Risk is a significant factor in cost estimation of spaceflight instruments. High risk imposes high performance margins, and high schedule and cost reserves in flight instrument projects. Risk is linked with lack of experience—lack of heritage. Since the laser subsystem is viewed as the high-risk item in an AO instrument, the maturation of the laser-related technologies that are specific to the instrument will significantly reduce risk.

R.5.4 Assessments/Findings Related to Tenets #4 and #5 – Valley of Death

Of the ten postulated tenets, the AOART believes that tenet #5 is the key issue to address. The postulated tenet #4 can be considered a contributor to this issue. The need to address tenet # 5 forms the key action for the AOART.

1. NASA HQ Program Office leadership can effectively enable continuous advancement of TRL for technologies that are realized as high priority in future mission implementations and scientific investigations by means of effective oversight and continuity of necessary funding levels. A recent example of success is Optical Communications maturation, supported primarily by HEOMD and STMD Program Office collaboration, with technology developments coming from several organizations. Project funding of technology maturation is beneficial, but should be considered as a supplement, since projects have focused requirements, limited lifetimes, and an incentive to avoid risk.
2. The SPLICE precision landing project, funded by the STMD GCD Program, is a prominent example of a multi-Center collaborative effort with Directorate-level oversight and specific plans for maturing the AO technology readiness to TRL 6/TRL 7 and infusing it into missions in the next decade.
3. Attempting to maintain sustained development and maturation of AO technologies by means of a year-to-year competitive selection process does not work well, particularly when resources are needed to demonstrate TRL 6.
4. The ESDS, a guidance document for SMD, calls for spaceflight Lidars of specific types that can uniquely contribute to scientific objectives. For these Lidars to be selectable in proposals submitted to SMD opportunities, the TRL must be at TRL 6.
5. ESTO has been successful in supporting technology development from TRL 3 to TRL 5, but not to TRL 6. ESTO IIP's rarely reach credible system-level TRL 6 at end point.
6. To fill gaps in technology maturation to system-level TRL 6, respondents to NASA Announcements of Opportunity often resort to spending internal funds, which engenders the attitude that the results should remain "competition sensitive," hence closed to the "outside community." This is not healthy in the NASA environment.
7. AITT selections (which are thought of as the next step after IIP for airborne instruments) are not pointed at developing and testing engineering models of lasers/Lidars that can withstand the rigors of space flight environmental testing.
8. AITT funds airborne instrument maturation so that the instrument can be ready to fly in any number of airborne science campaigns while reducing the necessary maintenance resources. This is certainly worthwhile. It enables demonstration of the scientific value of new instrument concepts and capabilities and assists in enabling cal/val of satellite instruments. However, AITT is underfunded for this purpose.
9. AITT does not lead to demonstration of TRL 6 when the "relevant environment" is the launch and operation in a spaceflight environment.

10. ESTO In-Space Validation of Earth Science Technologies (InVEST) is for small instruments – worthwhile investments but not applicable to Lidars of the size that the ESDS has in mind.
11. Earth Venture (EV) technology funding is helpful in developing and demonstrating technology readiness. This is an alternate path without science. However, it is enormously impractical, because an organization must expend the resources required to develop a competitive EV proposal in order to be considered for EV technology funding.
12. NASA ESD has very few existing programs dedicated to engineering design and demonstration of system-level TRL 6 (by means of environmental tests) for risk-reduction of large AO instruments (i.e., Lidars). NASA Centers and JPL often use internal funds to help proposed instruments reach a credible system-level TRL 6. These funding levels are often considered to be competition sensitive and proprietary.

R.5.5 Observations/Assessments Related to (expanded) Tenet #6: Collaboration

1) Some parts of the AO enterprise (e.g., Earth science sensing) could benefit from more collaboration and partnering.
    a. There will always be competition among new ideas and concepts.
    b. Collaboration can lead to more efficient execution and use of resources.
2) The optical communication activities have set the gold standard for collaboration and partnering that should be used as a model for other AO activities.
    a. Significant partnering with non-NASA organizations
    b. Leveraging DoD-developed and commercial capabilities to build a robust and successful enterprise
3) Improved visibility is needed to adopt/adapt technology and systems for NASA's benefit.
    a. Need better awareness of ITAR and proprietary technologies
    b. Need better and more timely transparency of technology being developed with help from internal Center funding to allow earlier adoption for benefit of the Agency

R.5.6 Findings and Assessments for Tenets 8, 9, 10 on AO Research, Education, and Hiring Environment

There are two general reasons for increasing research at lower TRLs:

1) To enhance development of new technologies and research at the more basic levels (both in academia and at Government/industrial labs) so that NASA instrumentation development is at the leading edge of research.
2) To enhance academic interactions between NASA programs and university faculty/grad students in order to increase hiring of students; this also acknowledges the fact that most academic research has to be done at the lower TRLs so that original publishable papers and PhD theses can be written based upon the research.

Toward these goals:

a. NASA could look for future Lidar/AO hires within non-Lidar but growing AO/laser university research groups such as nanophotonics, laser telecommunication, femtosecond laser spectroscopy, nanomaterials, integrated photonics, and quantum optics.
b. NASA could also increase specific AO Sensor funding from NASA to university research groups involving TRL 1 and 2 level research efforts, graduate student fellowships and stipends, and faculty/graduate student short-term internships at NASA Centers.

R.6 Recommendations

Based upon the above assessments, the AOART makes the following recommendations:

1. The AOART stresses the importance of SMD, STMD, and HEOMD leadership at NASA HQ taking a decisive role in managing the development, maturation, and infusion of AO technologies into future missions, with collaborative program office oversight that effectively enables continuous advancement of TRL for high-priority technologies. These are technologies that are realized as high priority in mission implementations and scientific investigations. A more continuous process with regularly scheduled assessments and modifications of programs is needed to manage the activity appropriately. The assessment activity is particularly important.
2. Within the SMD, the AOART strongly endorses the ESDS recommendation to fund the ESD technology investment program at a level of approximately 5% of the total ESD budget, with a large fraction of the investment targeted toward the Earth observations that NASA intends to implement over the course of the next decade (see Appendix A). Some of this should be focused, per the ESDS, on greater efficiency as a means of lowering the cost and risk of AO approaches for sustained observations. There should be a tighter focus on technologies needed to meet ESDS measurement priorities.
3. The tech development/maturation funding priorities of the STMD, HEOMD, and ESD should be increased at the high end (TRL 6, 7) and the low end (TRL 2, 3). We recommend a funding increase to universities and other research laboratories for TRL advancement in the low TRL research neighborhood, encouraging innovation. We also recommend a funding increase to concentrate on the maturation of the AO instruments to system-level TRL 6 in two categories: (1) relevant to airborne operations for use in scientific investigations, and (2) relevant to the spaceflight environment, followed by opportunities for tech demo flights as appropriate.
4. NASA ESD should establish a program office dedicated to demonstration of system-level TRL 6 for risk reduction of large AO instruments (i.e., Lidars). Maturation to TRL 6 requires engineering resources as well as the continuing involvement of the technologists. In this regard, we recommend that a new program office be established at NASA HQ to manage this technology maturation to TRL 6 for spaceflight opportunities.
5. This NASA Program Office and the Centers should collaborate and form partnerships with outside partners (DoD, FFRDC, industry, etc.) in order to utilize existing resources and expertise. The use and leveraging of relevant non-NASA assets and capabilities in the private sector and in other research organizations provide extensive advantages to NASA. NASA should encourage its staff to attend technical conferences that are heavily represented by investigators at other Agencies and the DoD, including closed conferences. The DoD has been investing significant resources in AO systems and technologies, and the Agency should be doing more to leverage these investments; currently leveraging is often hampered by a lack of knowledge and outreach.
6. NASA HQ Directorates should take a leadership role in improving collaboration and transparency among NASA Centers. NASA Centers are often reluctant to do this on their own. Previous external reviews of NASA Lidar efforts have made similar recommendations, with only tepid moves at best toward a better model.
7. NASA HQ should also prioritize establishing improved collaborations with international organizations that are advancing AO technologies and leverage the relevant technology advances that are supported and stimulated by those organizations. Joint planning groups could explore joint missions that employ active optics technologies, with an aim to reduce risk, cost, and development time.
8. NASA should look for future Lidar/AO hires within non-Lidar but growing AO/laser university research groups such as nanophotonics, laser telecommunication, femtosecond laser spectroscopy, nanomaterials, integrated photonics, and quantum optics. NASA should (1) increase specific AO Sensor funding from NASA to university research groups involving TRL 1 and 2 level research efforts, (2) increased NASA graduate student fellowships and stipends, and (3) increased faculty/graduate student short-term internships at NASA Centers to help introduce faculty and graduate students to NASA Missions.

9. NASA should formulate a response to this assessment along with intended actions within a specific time frame of formal submission of this report. (Six months is recommended.) Previous panel reports on NASA AO activities have not had as much impact as they should have because of weak or un-sustained follow through.

R.7 References

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14. Second International IEEE-GRSS Workshop on Space-based Lidar Remote Sensing Techniques and Emerging Technologies (Upendra N. Singh and Georgios Tzeremes Co-Chairs) Milos Island, Greece, June 4-8, 2018, https://www.lidar-workshop-2018.com.

R.8 Appendices

Appendix A. Pertinent sections from the Earth Science Decadal Survey (ESDS) that impact NASA Active Optical Programs and the AOART Report

The paragraph below is from pages 4-24 and 4-25 of the ESDS[2] and is part of the recommendation that the ESTO budget be increased. The ESDS recommends that some of the technology funds specifically go to lowering cost and risk to better enable sustained observations.

> *The Balance Among Technology Development Phases.* Investments in innovation are critical to the success of this new program. Earth system science and applications rely on long-term (sustained) observations of many key aspects of the Earth system. Yet, there is at present currently no mechanism to fund early-stage innovation that might lead to lowering the cost of providing for long-term observations. Instead, teams are currently incentivized to improve upon state-of-the-art to qualify for consideration in competitive funding solicitations that are targeted to new scientific investigations. Put simply, there is no incentive to drive for efficiency. The committee therefore proposes that ESTO establish a competitive call to incentivize development of game-changing technologies to lower the cost and risk associated with provision of sustained observations needed for Earth system science. The ESTO budget is currently at the low end of its historical range as a percentage of ESD's budget. The committee recommends (Recommendation 4.6) that the ESTO budget be increased to 5% of the ESD budget, which remains within the historical range of ESTO funding (Table 4.4).

This next paragraph is from page 4-26 and argues that less expensive measurement technologies are critically important.

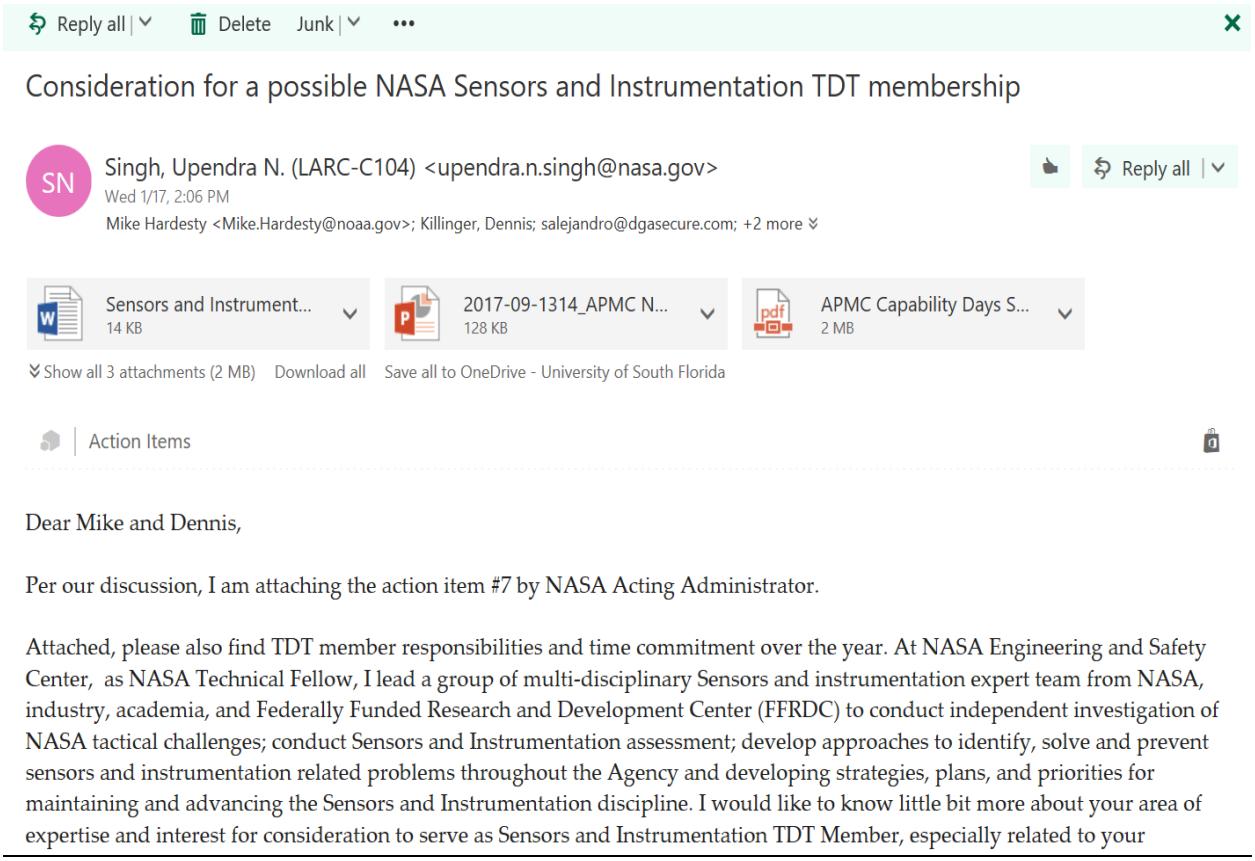
> *The Balance Between Heritage Technology and New Technology.* The development of advanced technology can provide novel measurement capabilities and the ability to make needed measurements at reduced cost. Less expensive measurement technologies are critically important if NASA ESD is to innovate to obtain the most critical measurements within its expected budget. In a balanced program, new technology is continuously introduced into space-based measurements, and innovation to improve existing measurements and measure new variables of importance is implemented. New technologies do require investment, however, and their successful adoption requires demonstrated capabilities to achieve measurement objectives. In the meantime, heritage technologies are essential for the achievement of observation objectives until such time as reliable transition to new capabilities can be accomplished.

In our opinion, NASA should emphasize and endorse these points. Lidar missions, even ones to continue the existing measurements like altimetry and aerosols, need to become less expense if there are going to be sustained observations.

Finally, it is essential to recognize the importance of AO and Lidar sensing technology within the ESDS. For example, the Summary in Table S.2 (p.S-8,9) outlines 14 Targeted Observables (such as Greenhouse Gases, Planetary Boundary Layer, etc.) of which 8 have Lidar or AO sensing as the Candidate Measurement Choice.

Appendix B. Original NASA Sensors and Instrumentation TDT Instructions

The original instructions to the AOART Panel consisted of previous NASA documents dated September 13, 2017, and sent to the panel members on January 17, 2018 in an email from Upendra Singh.



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Consideration for a possible NASA Sensors and Instrumentation TDT membership

SN Singh, Upendra N. (LARC-C104) <upendra.n.singh@nasa.gov> Reply all

Wed 1/17, 2:06 PM

Mike Hardesty <Mike.Hardesty@noaa.gov>; Killinger, Dennis; salejandro@dgasecure.com; +2 more

Sensors and Instrument... 14 KB | 2017-09-1314_APMC N... 128 KB | APMC Capability Days S... 2 MB

Show all 3 attachments (2 MB) Download all Save all to OneDrive - University of South Florida

Action Items

Dear Mike and Dennis,

Per our discussion, I am attaching the action item #7 by NASA Acting Administrator.

Attached, please also find TDT member responsibilities and time commitment over the year. At NASA Engineering and Safety Center, as NASA Technical Fellow, I lead a group of multi-disciplinary Sensors and instrumentation expert team from NASA, industry, academia, and Federally Funded Research and Development Center (FFRDC) to conduct independent investigation of NASA tactical challenges; conduct Sensors and Instrumentation assessment; develop approaches to identify, solve and prevent sensors and instrumentation related problems throughout the Agency and developing strategies, plans, and priorities for maintaining and advancing the Sensors and Instrumentation discipline. I would like to know little bit more about your area of expertise and interest for consideration to serve as Sensors and Instrumentation TDT Member, especially related to your

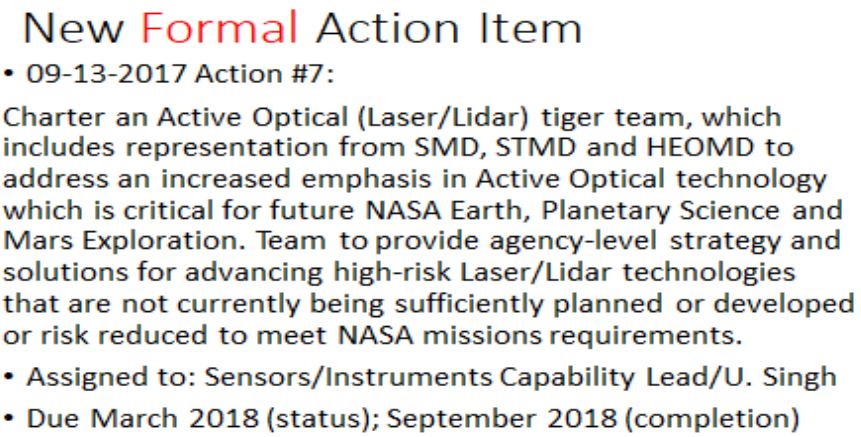
Attachments

Sensors and Instrumentation Technical Discipline Team Member Responsibilities

- Participate as sensors and instrumentation experts in multi-discipline independent investigations and other activities
- Conduct sensors and instrumentation assessments (formal investigations with documented final reports)
- Provide sensors and instrumentation technical support (informal program support without final report)
- Support NASA Technical Fellow in identifying sensors and instrumentation experts for staffing NASA Engineering and Safety Center (NESC) assessment and technical support teams
- Provide critical reviews for Sensors and Instrumentation-related technical input
- Act as a technical resource for the discipline
- With NESC Review Board approval, develop approaches to identify, solve and prevent sensors and instrumentation related problems throughout the Agency
- Participate in Sensors and Instrumentation Community of Practice
- Support NASA Technical Fellow in developing strategies, plans, and priorities for maintaining and advancing the Sensors and Instrumentation discipline

- Support NASA Technical Fellow in developing lessons learned, best practices, and/or knowledge capture products for NESC Academy
- Basic support
    - Monthly Technical Discipline Team (TDT) teleconference (~2 hours)
    - Annual Face-to-Face TDT Meeting (NESC provides travel funding)
    - Occasional development of initial assessments, peer reviews, and related items.
    - NESC provides funding for ~88 hours/year
- Additional time for technical support or assessments are budgeted and negotiated separately

Attachment sent by email on January 22, 2018:



Appendix C. Earth Science Independent Laser Review Panel Report

November 27, 2000

Panel Members:

Steven B. Alejandro, Air Force Research Laboratory, Chair

Michael Hardesty, National Oceanic and Atmospheric Administration

John Hicks, National Reconnaissance Office

Dennis Killinger, University of South Florida

Marshall Lapp, Sandia National Laboratories

EXECUTIVE SUMMARY

In order to reduce the risks associated with missions utilizing laser technology, a review panel was commissioned by CODE Y that was composed of experts from outside of NASA. The panel was charged with performing an independent assessment of the laser systems, related technologies, and associated program management of the PICASSO-CENA, GLAS, and VCL Programs. The SPARCLE and LITE programs provided brief overviews as well to provide further background in NASA practices. Over a two day period the panel received briefings from each of these programs which, combined with an extensive amount of additional materiel in the form of program PDR, CDR, and progress reports, formed the foundation upon which this report is based.

COMMON ISSUES

All of the briefings were extremely well composed and professional. As they progressed, a number of common issues began to emerge. Overall, it became clear that the NASA ESSP and ICESAT programs have generally underestimated the time, expense, and technology hurdles associated with carrying out the GLAS, VCL, and PICASSO laser-based missions. The somewhat strict budget and time limitations set forth for these programs were unrealistic, given the state of the art of diode-pumped laser systems (PICASSO to a large extent overcame this hurdle by applying Langley internal funds for the Risk Reduction Laser (RRL)). This underestimation of the magnitude of the task involved, especially the challenges involved in engineering the technology to the level of robustness and reliability required for spaceflight, was also characteristic of the proposals submitted by the mission teams. As a result, the programs have been somewhat predestined to falter from the beginning. The panel felt that the other major factor impacting mission progress was different program management and technology development approaches. In particular, problems with communication within a program, and/or between programs, which hampered exchange of important technical information, were recurring points that emerged repeatedly to one degree or another for each program.

PICASSO-CENA

Based upon the presentation presented to the panel, PICASSO-CENA appears to be moving steadily toward a well-characterized flight system. This is due in large part to the RRL effort initiated prior to the formal start of the program. The RRL resulted in an overall reduction in technology uncertainty and technical program risk. The conservative management approach of budgeting a laser management reserve, fostering communication between the science and engineering teams, and approach to contamination control and laser lifetime seem to have benefited the program. However, much of the experience gained and successes achieved were not communicated to either GLAS or VCL programs.

GLAS

The panel felt that the GLAS program work accomplished by GSFC with regard to the laser design, development, and fabrication is excellent. But much of this R&D should have been completed prior to initiating the program. It seems unlikely that the flight lasers will be ready in time for the scheduled launch and that the 5 year mission lifetime is optimistic given the current state of the art demonstrated. With the

proper support to addressing the key problems, the panel felt GLAS would be a success, and as such, should be appropriately supported.

VCL

VCL was the least mature program reviewed. In addition to laser technology problems, the program has also been plagued by management problems. Communication between the science and technical/engineering teams seemed nearly non-existent. Thus, science requirements excessively drove the laser system requirements since little, if any, trade-space analysis or dialogue seems to have occurred. Laser R&D under an SBIR, which was to have formed the foundation of the program, proved unsuccessful. This left major key technology elements undemonstrated prior to mission commitment. Further, the flight testing of hardware for this program is a serious concern and spacecraft power and thermal management issues are still not resolved. This program appears to be a long way from being ready for flight.

KEY TECHNOLOGY ISSUES

The key technology issue that surfaced in every program was that the laser technology was considerably less mature than believed and the engineering for spaceflight was much more formidable than expected. Laser technology for spaceflight is still in its infancy compared to many other technologies. The next generation of instruments envisioned by the Earth Science Enterprise will be significantly more complex compared to those reviewed here. As a result, the science objectives and/or requirements need to be carefully considered to achieve the acceptable level of cost and risk. Until the technology experience in space has developed further, and to preclude failures that doom the further exploitation of the technology, the objective for these programs should not just be "Faster, Better, Cheaper," but must include the concepts of achievability and reliability within the realistic constraints of available resources.

RECOMMENDATIONS

NASA HQ must support a campaign to move laser transmitter technology from low technical readiness levels to the higher levels required for space missions. It must take the lead role in organizing how the centers apply their core competencies in a constructive and synergistic manner rather than a destructively competitive and stove-piped manner. Maintaining the existing moderate in-house space laser expertise and R&D capability is considered vital if NASA hopes to have access to capable program Contract Officer's Technical Representatives (COTAR) and to competently evaluate commercial technology proposals and programs. The organization of a "Space Laser Super Center" composed of the LaRC and GSFC, MSFC, JPL and other laser technology teams, but managed as a single organization at the NASA HQ level, should be considered. HQ would control the funding and provide direction and oversight of the organization to de-couple it from Center political and funding distractions while fostering cooperation and maximizing utilization of facilities and resources. This Super Center would also allow more efficient pursuit of development efforts not profitable enough for the commercial sector to pursue, while at the same time, provide a better interface and teaming arrangement with industry to leverage the greater pool of resources and expertise it can provide in other areas. The Super Center should also be open to supporting programs that involve the DOD, DOE and other federal organizations.

Investments must be made to address other issues that have long been resolved and taken for granted with other technologies. Lasers do not have the standards, databases, and procedures established to serve as references and guides to developing a space qualified sensor. Testing requirements for spaceflight certification, cleanliness and contamination control standards and procedures, and lifetime testing requirements for lasers, diode pumps, and optical components as well as the complete flight-ready laser-Lidar must be established. These are now being done on a case by case basis with the resulting risk to the individual programs. These need to be developed outside of specific mission programs and established as standards for all programs to abide by.

The value of laser based sensors has been demonstrated repeatedly in ground and aircraft missions. The extension of this capability to space is required if important science goals are to be met that cannot be satisfied by passive sensors. The new capabilities of laser based sensors also brings with it the embarking

upon a new frontier of science and spaceflight challenges. New challenges have never been cheap or without risks, and abandoning the pursuit of laser sensors because of cost and risk would be contrary to NASA's heritage. NASA HQ and the centers must accept the responsibility for the required technology, program management, oversight, and teaming that will mitigate the costs and risks to a level that is acceptable with achieving the science goals.

Appendix D. Acronyms

ACT	Advanced Component Technologies
ADM	Atmospheric Dynamics Mission
AITT	Airborne Instrument Technology Transition
AMV	Atmospheric Motion Vector
ANSI	American National Standards Institute
AO	Active Optical
AOART	Active Optical Assessment and Recommendation Team
APD	Avalanche Photodiode
APMC	Agency Program Management Council
ASCENDS	Active Sensing of CO_2 Emissions over Nights, Days, & Seasons
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
cal-val	Calibration and Validation
CH_4	Methane
CHARM-F	CO_2 and CH_4 Atmospheric Remote Monitoring - Flugzeug
CLT	Capability Leadership Team
CNES	Centre National d'Etudes Spatiales
COTR	Contract Officer's Technical Representatives
DARPA	Defense Advanced Research Projects Agency
DLR	Deutschen Zentrums für Luft- und Raumfahrt
DoD	Department of Defense
DoE	Department of Energy
DSOC	Deep Space Optical Communications
EDL	Entry, Descent, and Landing
ESA	European Space Agency
ESD	Earth Science Division
ESDS	Earth Science Decadal Survey
ESSP	Earth System Science Pathfinder
ESTO	Earth Science Technology Office
EV	Earth Venture
FFRDC	Federally Funded Research and Development Center
GCD	Game-Changing Development
GEDI	Global Ecosystem Dynamics Investigation
GSFC	Goddard Space Flight Center
HEOMD	Human Exploration and Operations Mission Directorate
HPSC	High Performance Spaceflight Computing
HQ	Headquarters
ICESat	Ice, Cloud, and land Elevation Satellite
IIP	Instrument Incubator Program
InVEST	In-Space Validation of Earth Science Technologies
ITAR	International Traffic in Arms Regulations
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
JPPG	Joint Program Planning Group
JSC	Johnson Space Center
LADEE	Lunar Atmosphere and Dust Environment Explorer
LaRC	Langley Research Center
LASER	Light Amplification by Stimulated Emission of Radiation
LCRD	Laser Communications Relay Demonstration
LIBS	Laser-Induced Breakdown Spectroscopy

LIDAR	Light Detection And Ranging
LITE	Lidar In-space Technology Experiment
LLCD	Lunar Laser Communications Demo
LRRP	Laser Risk Reduction Program
MERLIN	Methane Remote Sensing Lidar Mission
NASA	National Aeronautics and Space Administration
NESC	NASA Engineering and Safety Center
NRC	National Research Council
NSF	National Science Foundation
OSIRIS-Rex	Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer
OSSE	Observation System Simulation Experiment
PESTO	Planetary Exploration Science Technology Office
PICASSO-CENA	Pathfinder Instruments for Cloud and Aerosol Spaceborne Observations - Climatologie Etendue des Nuages et des Aerosols
PSD	Planetary Science Division
PSDS	Planetary Science Decadal Survey
R&C	Rendezvous and Capture
R&D	Research and Development
RRL	Risk Reduction Laser
S&I	Sensors and Instrumentation
SBIR	Small Business Innovative Research
SCaN	Space Communications and Navigation
SCLT	System Capability Leadership Team
SMD	Science Mission Directorate
SPARCLE	Space Readiness Coherent Lidar Experiment
SPLICE	Safe and Precision Landing – Integrated Capabilities Evolution
STMD	Space Technology Mission Directorate
SWaP	Size, Weight, and Power
TDT	Technical Discipline Team
TIM	Technical Interchange Meeting
TRL	Technology Readiness Level
TRN	Terrain Relative Navigation
TSSIS	Total and Spectral Solar Irradiance Sensor
VCL	Vegetation Canopy Lidar

P Plenary

The Plenary session is designed to provide a motivation for the meeting as a whole. The talk from Mr. Jerczyk was to place active optical techniques in the Agency context and highlight the historical and future importance. Two papers gave Agency science mission overviews from the Agency perspective. There was a presentation on automotive Lidar to show how industry is using these techniques. Table P-1 lists the session papers. See Section 3 of the Assessment Report for observations and assessment comments.

Table P-1. Plenary Session Papers

Paper Number	Author	Title	Paper	Presentation
P-0	Upendra Singh, NESC	NASA Technical Interchange Meeting on Active Optical Systems for Supporting Science, Exploration, and Aeronautics Measurements Needs		☑
P-1	Stephen Jurczyk, NASA HQ	Agency Perspective		
P-2	George Jackson	Optics at GSFC		☑
P-3	Jack Kaye, SMD	Earth Science Overview		☑
P-4	Pamela Millar and Parminder Ghuman, NASA GSFC	ESTO's Investments in Lidar Technologies relative to the 2017 Earth Science Decadal Survey Lidar-based Measurements		☑
P-SC	Lute Maleki, GM/Cruise Automation	Automotive Lidar: Challenges and Opportunities		☑

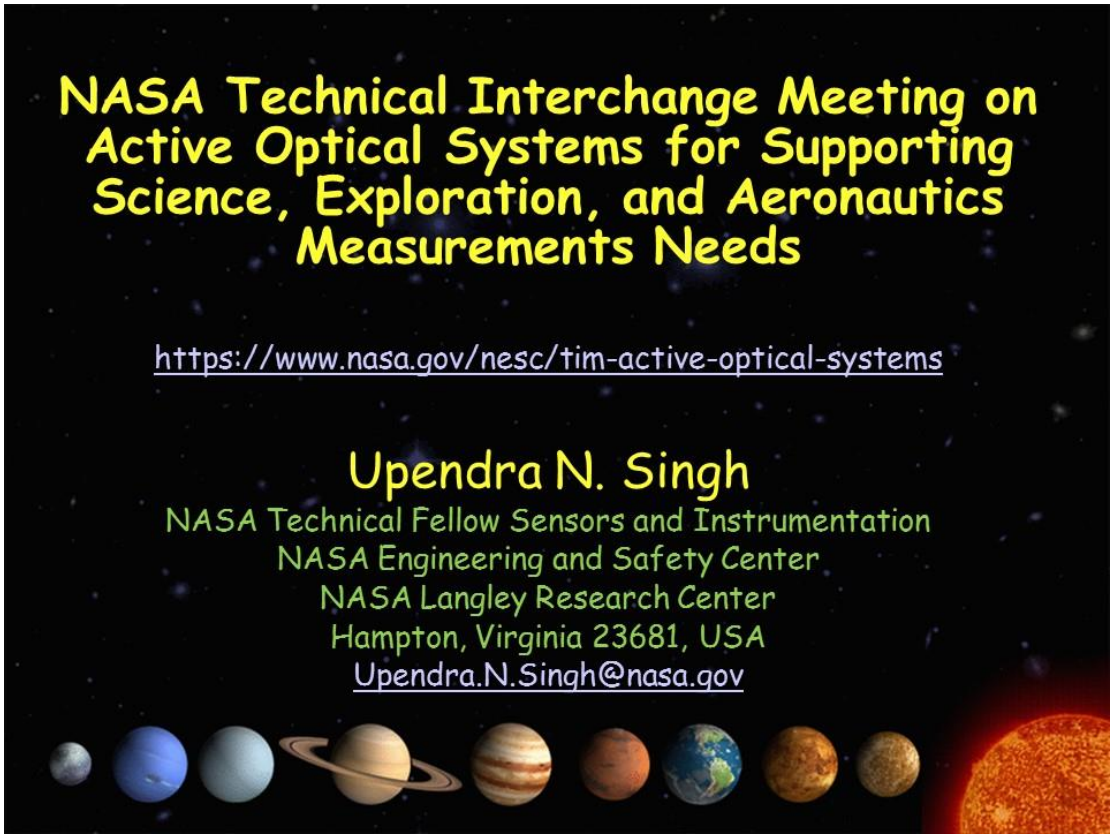
List of presentations

P.1 NASA Technical Interchange Meeting on Active Optical Systems for Supporting Science, Exploration, and Aeronautics Measurements Needs..... P-2
P.2 Agency Perspective P-11
P.3 GSFC Active Optical Systems P-12
P.4 NASA’s Active Optical Remote Sensing Activities: Results, Plans and Implications for Earth System Science..... P-14
P.5 An Overview of NASA Earth Science Technology and Lidar Investments..... P-33

P.1 NASA TECHNICAL INTERCHANGE MEETING ON ACTIVE OPTICAL SYSTEMS FOR SUPPORTING SCIENCE, EXPLORATION, AND AERONAUTICS MEASUREMENTS NEEDS

Upendra N. Singh

NASA Technical Fellow Sensors and Instrumentation, NASA Engineering and Safety Center, NASA Langley Research Center, Hampton, Virginia 23681, USA, Upendra.N.Singh@nasa.gov



Capability Leadership Team Assessment, 2017
Sensors and Instrumentation

- **Findings:**
  - **Active optical (Laser/Lidar)** is critical for future NASA Earth, Planetary Science, and Mars Explorations. Six out of fifteen missions recommended by 2007 NRC Earth Science Decadal Survey require active optical remote sensing for successful mission implementation. Laser/Lidar is also critical for enabling human-rated EDL capabilities for a crewed Mars mission
  - The existing competitive model to fund technologies to develop, mature, advance, and demonstrate TRL advancement in a relevant environment is not working and often results in massive cost growth and schedule slips for Laser/Lidar missions.
  - Need to produce more flight-ready Laser/Lidar technologies ready for mission infusion with the accompanying reduction in mission cost, schedule slips, and performance degradation.
  - Need to enhance inter-Center collaboration and leveraging between SMD and HEOMD missions.

New Formal Action Item - APMC

- **09-13-2017 Action #7:**
- Charter an Active Optical (Laser/Lidar) tiger team, which includes representation from SMD, STMD and HEOMD to address an increased emphasis on Active Optical technology which is critical for future NASA Earth, Planetary Science and Mars Exploration. Team to provide agency-level strategy and solutions for advancing high-risk Laser/Lidar technologies that are not currently being sufficiently planned or developed or risk reduced to meet NASA missions requirements.
- **Assigned to: Sensors/Instruments Capability Lead/Upendra Singh, NASA Tech Fellow S&I**
- Due March 2018 (status); September 2018 (completion)

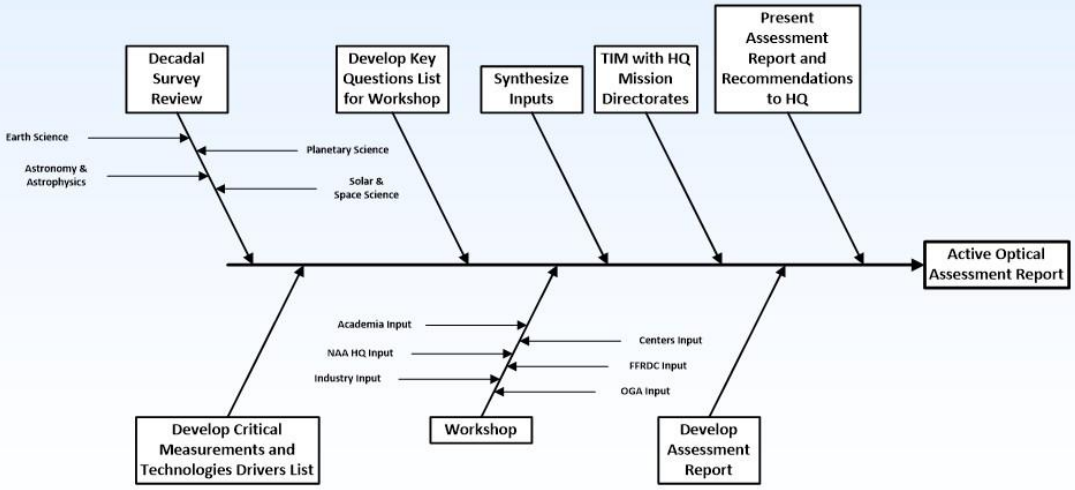
Active Optical Strategy Approach

- Active Optical will be a **multi-directorate teaming** of the Science Mission, Human Exploration and Operation Mission, Aeronautics Research Mission Directorate and Space Technology Mission representatives to provide the guidance and list of priority measurements requirements to meet their critical future needs.
- An Active Optical Tiger team consisting of MD's representatives, CLT/TDT leads/co-leads and an external assessment team will work together to seek national and international community inputs to formulate an integrated Agency level strategy
- An essential part of the augmentation strategy will be to engage with other US Government entities, as well as industry and academia, to leverage common Active Optical interests and complementary skills/expertise resident in those sectors
- Develop a cross-cutting strategy based on **"Lead, Leverage and Collaborate"** approach with NASA and external entities, national and international, to meet NASA Science, Aeronautics and Exploration needs
- An **integrated technology development and investment plan**, which will address each directorate agency's requirements in a cross-cutting, synergistic and cost-effective manner, to meet the Agency-level, priority Active Optical space based measurements/missions.

Active Optical Tiger Team

- **S&I Tech Fellow Team** – **Upendra Singh**, S&I Tech Fellow, **Steve Horan**, Deputy, TDT and **Terence Doiron**, Deputy, CLT
- **Active Optical Advisory Tiger Team (AOATT)** – SMD: **Michael Seablom** (SMD); **Prasun Desai** (STMD); **Jason Crusan, Chris Moore, Phil Liebrecht** (HOEMD)
- **Active Optical Assessment and Recommendation Team (AOART) – S&I TDT Member**
  - Dr. Robert T. Menzies – Retired JPL (IEP), Chair, AOART
  - Dr. T. Y. Fan, MIT Lincoln Lab
  - Dr. Michael Hardesty, Boulder Lidar Associates
  - Dr. David Tratt, Aerospace Corp.
  - Dr. Denis Killinger, SenOptics LLC

Work Plan Flow Chart



International and National Community Inputs

- **Second International IEEE-GRSS Workshop on Space-based Lidar Remote Sensing Techniques and Emerging Technologies**

  Chairs: Upendra N. Singh[1] and Georgios Tzeremes[2]
  [1]NASA Langley Research Center, USA; [2]European Space Agency, ESTEC, The Netherlands

  - **June 4-8, 2018** at Milos Conference Center, Adamas, Milos Island, Cyclades, Greece
  - Workshop will bring together Active Optical Experts from NASA, ESA, JAXA, CNES, and DLR policy makers and experts from various agency engaged in advancing Space missions/measurements in Active Optical area for Science and Exploration

  https://www.lidar-workshop-2018.com

- **NASA Technical Interchange Meeting (TIM) on Active Optical Systems for Supporting Science, Exploration, and Aeronautics Measurements Needs**

  Chairs: Upendra N. Singh,[1] Steve Horan[1] and Terence Doiron[2]
  [1]NASA Langley Research Center, USA; [2]NASA Goddard Space Flight Centers, USA

  - **July 31-August 3, 2018**
  - Universities Space Research Association (USRA) Headquarters, Columbia, MD 21046
  - TIM will bring together Active Optical experts from NASA Centers, NASA HQ, Industry, Academia, National Labs, and DoD who are engaged in developing concepts and systems to support NASA measurements needs

  https://www.nasa.gov/nesc/tim-active-optical-systems

Purpose for TIM and Workshop

- TIM is a forum to exchange perspectives on the current state of the discipline's technologies and the direction NASA needs to take in the future to raise the TRL of the measurement technologies to meet these measurement needs in the applications domains
- The TIM aims at focusing NASA's directions to attain the necessary technology TRL levels to meet the Agency-level priority Active Optical measurements in Science, Explorations and Aeronautics and identify capabilities, internal and external to NASA, to **lead, leverage and collaborate** to meet NASA current and future needs
- TIM inputs will be used in formulating the agency-level strategy and solutions for advancing high-risk Laser/Lidar technologies that are not currently being sufficiently planned, developed, or risk reduced to meet NASA missions requirements
- The TIM presentations and strategic inputs will be synthesized by the NASA Active Optical Tiger Team and presented to the NASA APMC with a suggested strategy to address the Agency's needs in a cross-cutting, synergistic and cost-effective manner
- Workshop inputs will be used to incorporate international synergies and collaborative opportunities between NASA and other international space agencies, for consideration in future planning

NASA Technical Interchange Meeting on Active Optical Systems for Supporting Science, Exploration, and Aeronautics Measurements Needs

July 31- August 3, 2018
University Space Research Association, Columbia, Maryland, USA

Mission Area I: Earth Science

Session 1: Clouds, Aerosols and Ocean
Session 2: Greenhouse and Trace Gases Measurements
Session 3: Wind Measurements
Session 4: Topography, Cryosphere and Biomass

Mission Area II: Space Science and Exploration

Session 5: Planetary Science
Special: Automotive Lidar
Session 6: EDL Technologies
Session 7: Exploration

Mission Area III: Aeronautics

Session 8: Aeronautics – Turbulence Detection, Hazard, Autonomous UAV

Mission Area IV: Innovations

Session 9: Innovations

Panel Discussions of the Session Chairs and Active Optical Tiger Team and Active Optical Assessment and Recommendation Team

https://www.nasa.gov/nesc/tim-active-optical-systems

Questions?



Conclusions

- Active optical remote sensing is making significant contributions to NASA's Earth Science, Planetary Science and being targeted for future Mars and Lunar explorations space-based observations
- The integration of active optical remote sensing with other observing approaches is providing new knowledge in a broad set of disciplines.
- An Agency level active optical strategy effort will align NASA efforts for Science, Exploration and Aeronautics
- Industry, academia, OGA and international partners are key contributors in advancing the active optical capability
- Active optical remote sensing can be expected to play an increasing role in the future and will benefit from investments in lidar technology by NASA and our industry, interagency and international partners

Mission I - To Understand and Protect our Home Planet
Earth Science Foci

- *Atmospheric Composition* sounding measurements in the troposphere including aerosol and cloud properties and profiling, water vapor profiling, and Planetary Boundary Layer height
- *Earth's Surface & Interior* via geodetic imaging including wide-swath laser altimetry
- *Climate Effect Monitoring* including ice mass changes, global ice characterization, snow depth, and snow-water equivalent measurements
- *Weather* including global tropospheric lidar wind measurements for planetary boundary layer energy, momentum, and mass exchanges; forecasting; convection; fluxes of heat, momentum, water vapor and other gases; and model validation and improvement
- *Carbon, Ecosystems, & Biogeochemistry* including measurements of CO_2 and CH_4 fluxes and trends, vegetation 3D structure, biomass, and disturbance, ocean mixing layer

Mission II - To Explore the Universe and Search for Life
Planetary and Exploration of Mars, Lunar and Outer Planets foci

- *Lunar Exploration* including landing navigation and hazard avoidance, and surface exploration and characterization
- *Jovian Moons* including surface features and characterization, and tidal signatures
- *Jovian Environment* including atmospheric cloud and wind structure, atmospheric composition
- *Mars Exploration* including atmospheric winds, density, and dust profiling, surface topography, surface exploration and characterization, search for organic signatures, moisture distribution, and cloud characterization
- *Martian Mission Support* including precision landing, navigation, and hazard avoidance, sample return rendezvous and capture, atmospheric characterization to support entry, descent, and landing
- *Titan and Venus* including balloon-borne active optical instrumentation
- *Situational awareness of space weather phenomena*
- *Laser interferometry, active –optical sensing of telescope and satellite swarm elements to enable observations*

Mission III: Active Optical for Aeronautics

- *Detection of turbulence* (current activities by Boeing and JAXA)
- *Detection of and situational awareness for atmospheric hazards* (e.g., volcanic ash, ice, snow)
- *Sense and avoidance for autonomous UAVs and future autonomous urban mobility aircraft*
- *LIDARs on airport ground to control taxing, takeoff, and landing of aircraft* (eg.,wake vortices)
- *Imagery of various targets using UAVS*
- *Miniaturized, low power active optical sensors and instrumentation* for Unmanned and Personal Air Vehicles for sensing and avoiding hazards in the National Air Space

AORS Strategies

- Laser based instruments are applicable to a wide range of NASA's Earth Science, Planetary Science, Aeronautics, and Human Explorations and Operation Mission Directorate needs
- Risk in lidar missions can be significantly reduced by progress in a few key technologies
- Modest NASA investment towards proposed strategy will have significant impact on future space-based active remote sensing missions
- Strategic alliance with other government organizations, industry, and academia for leveraging and accelerating advancement of key technologies

S&I Technology Challenges

- **Findings:**
  - Opportunities for TRL 1-2 Sensor/Instrument development funding are limited
  - Opportunities for academia to participate in basic research to advance capabilities are limited and have shrunk over the years (e.g. GSRP and NASA/ASEE faculty fellowship programs are going away)
  - On-boarding new hires with chances to develop their careers through growing new technologies and applying them to mission concepts is limited
  - Improving methods for crossing the "Valley of Death" will result in reductions in both the rate and the magnitude of cost overruns occurring during mission development.
  - Improved methods for technology maturation will likely require increased technology investment in the early stages of mission development, but will result in significant risk reduction for missions/instruments. In turn, this will reduce both schedule and budget overruns, likely resulting in net savings. Further, it will enable an increased cadence for world-leading science missions.
- **Forward Work:**
  - Partner with OCT to review current S&I roadmap, review valley of death and assess distribution of TRL funding to work through these challenges

Outline

- Introduction
- NASA Sensors and Instrumentation Capability
  - Assessments, findings, and challenges
  - APMC Formal Action Item
  - Active Optical Tiger Team
  - Leveraging National and International Capabilities
  - Active Optical Strategy Formulation, Work Plan and Recommendations
- Conclusions

P.2 AGENCY PERSPECTIVE

Stephen Jurczyk, NASA Associate Administrator at NASA Headquarters, gave an oral presentation.



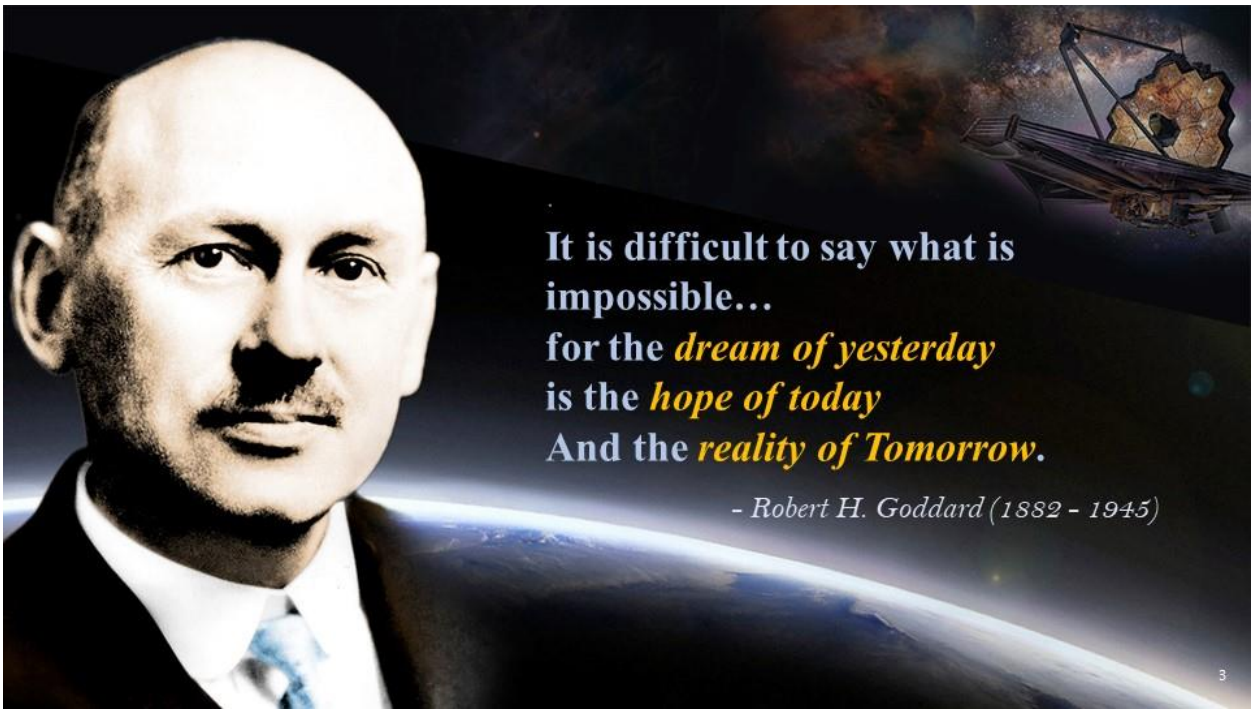
P.3 GSFC ACTIVE OPTICAL SYSTEMS

George L. Jackson (on behalf of Chris Scolese)

Deputy of Director of Engineering, Goddard Space Flight Center, Greenbelt, Maryland





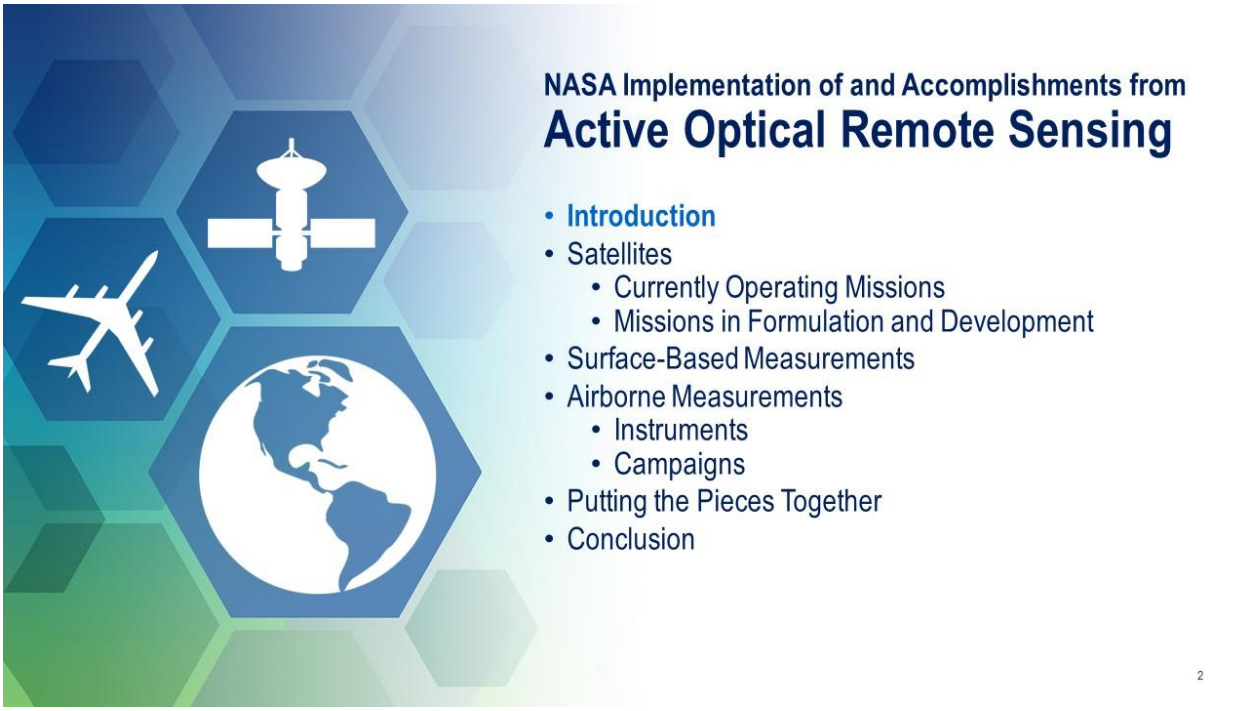

It is difficult to say what is
impossible…
for the dream of yesterday
is the hope of today
And the reality of Tomorrow.
- Robert H. Goddard (1882 - 1945)
3

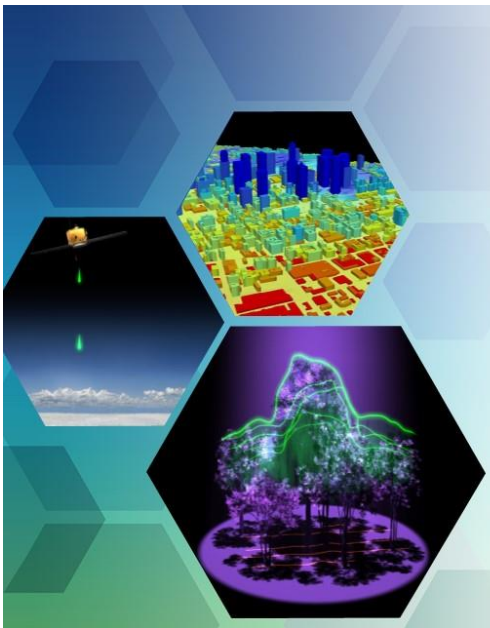
P.4 NASA'S ACTIVE OPTICAL REMOTE SENSING ACTIVITIES: RESULTS, PLANS AND IMPLICATIONS FOR EARTH SYSTEM SCIENCE

Jack A. Kaye

Earth Science Division, Science Mission Director, NASA Headquarters, Washington, D. C.







Introduction

- **Lidar** is an important technique that contributes to NASA's overall efforts in Earth System Science.
- **Lidar** can make unique contributions, especially in terms of high vertical resolution (accurate time measurements → accurate height measurements).
- Since **lidar** involves "bring your own signal" (or "create your own") there is a possibility of obtaining results not available from passive measurements that utilize "the signal nature gives you."
- **Lidar** measurements can be important complements and/or validation measurements for those from other approaches.
- **Lidar** technology has advanced to the point that deployment from surface, aircraft and satellites is now possible; continuing advances offer even greater possibilities in the future.
- NASA has strong scientific and technical capabilities that are applied to development and utilization of **lidar** approaches.

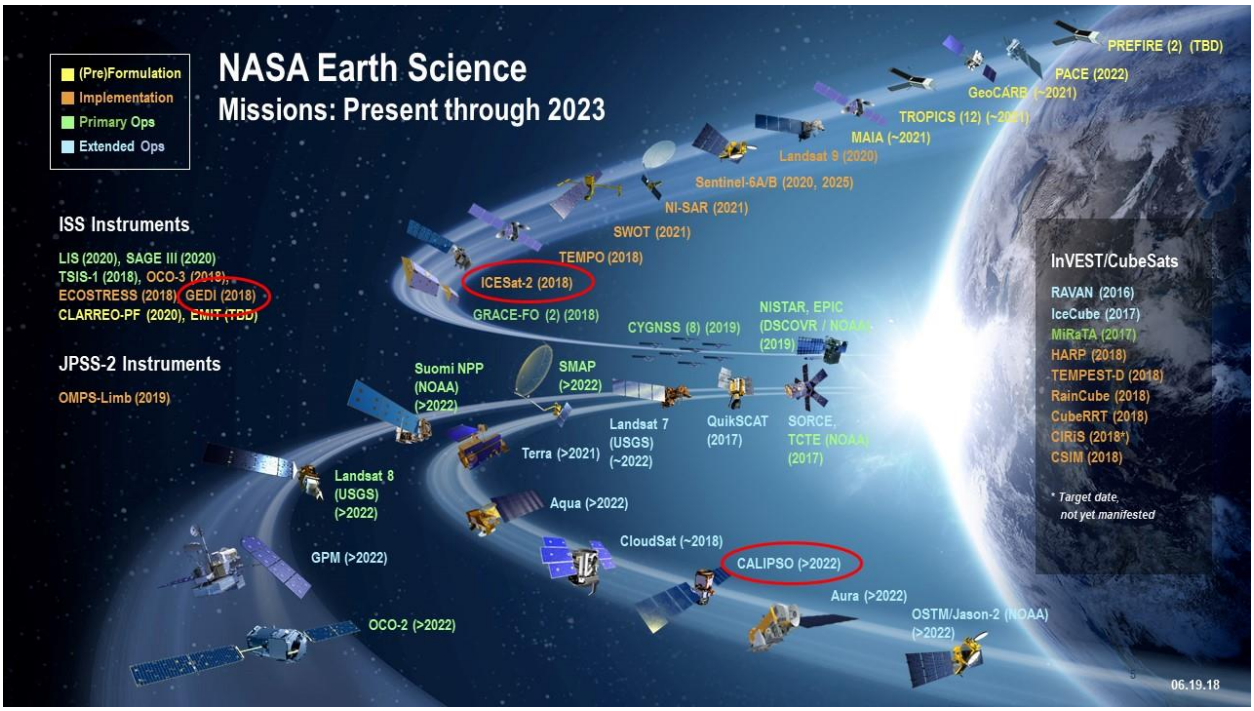
3



NASA Implementation of and Accomplishments from
Active Optical Remote Sensing

- Introduction
- Satellites
  - Currently (& Past) Operating Missions
  - Missions in Formulation and Development (not just NASA!)
- Surface-Based Measurements
- Airborne Measurements
  - Instruments
  - Campaigns
- Putting the Pieces Together
- Conclusion

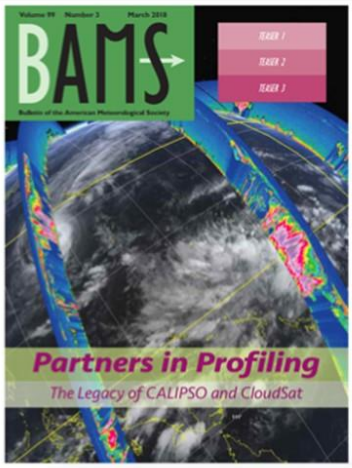
4



CALIPSO Mission Background

KeyFeatures

- Dual wavelength, polarization backscatter lidar (532 * 1064 nm)
- Infrared Imaging Radiometer (IIR) at 8.65, 106, 12.05 mm
- Wide Field-of-view Camera at 645 nm
- Member of A-Train satellite constellation (to exit to “C-Train” shortly)
- Launch date: 28 April 2006
- End of Prime Mission: 28 April 2009
- Extended mission approved through September, 2020
- Partnership with CNES (spacecraft, IIR, on-orbit operations)



Science

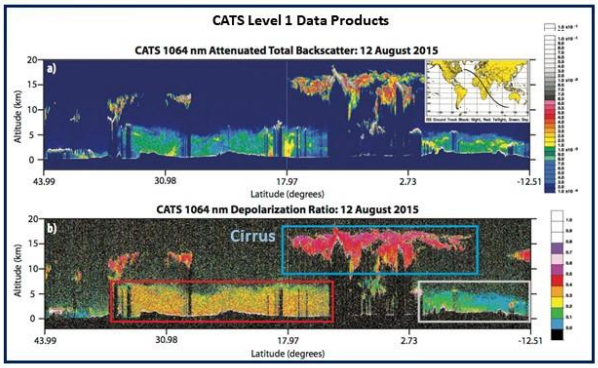
- Produce a global uniformly-calibrated aerosol and cloud data set
- Identify cloud ice-water phase and aerosol type
- Improved understsanding of aerosol and cloud effects on Earth’s radiation budget
- Improve aerosol and cloud information from other A-Train sensors
- Improved predictive capability for climate, weather, air quality

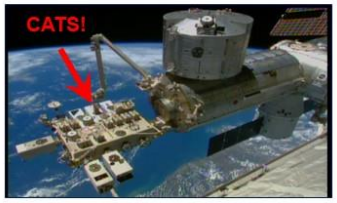
6

CATS (*formerly*) on the ISS

Cloud-Aerosol Transportation System (CATS) utilized ISS as an affordable platform to:

- Complement the lidar data record with diurnally varying cloud and aerosol vertical profiles.
- Monitor dynamic events (wildfires/volcanic eruptions).
- Demonstrate new technologies for future missions.
- Demonstrate build-to-cost project development.





CATS launched in January 2015 and operated for 33 months. It was, among other things the first:

- **High repetition-rate, photon-counting lidar in space.**
- **Space-based lidar to provide data products in near real time.**

Its data remain freely available at:

- **www.cats.gsfc.nasa.gov.**

7



ICESat-2: Next Generation Altimetry from Space

ICESat-2

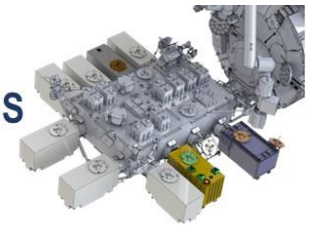
- Scheduled for launch in 2018.
- Near-polar orbit, ~500 km altitude.
- 92-degree inclination (max latitudes of +/- 88 degrees).
- Year-round operation planned.

Advanced Topographic Laser Altimeter System (ATLAS)

- Six beams, 532 nm (green).
- Single laser fires 10K shots per second, split into 6 beams.
- Spots on surface 17 m in diameter, 70 cm separation.
- Photon-counting detectors.
- Beam pairs allow direct local slope determination.

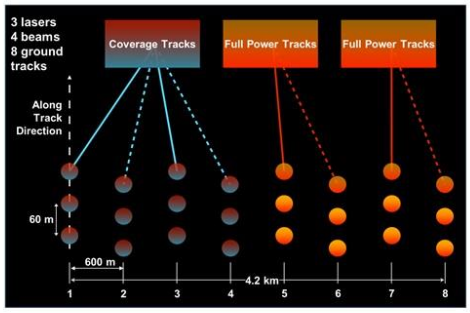
8

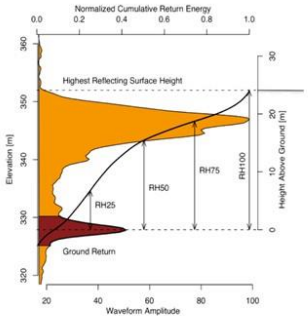
GEDI: High Resolution Laser Ranging Of Earth's Forests and Topography on ISS

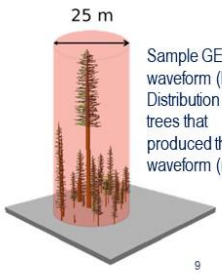


- NASA's Global Ecosystem Dynamics Investigation (GEDI) is a full waveform lidar system that will launch to the International Space Station in late 2018.
- GEDI's 3 lasers will return 8 tracks of ~25 m waveform samples, providing ~10 billion cloud-free surface structure observations.

GEDI ECOSYSTEM LIDAR







Sample GEDI lidar waveform (left). Distribution of trees that produced the waveform (right).

9

Aeolus Launch Date Confirmed

esa

21 Aug. 2018

Wind Mission
First ever UV LIDAR in Space

From ESA Presentation at CGMS-46 meeting

European Space Agency

ESA/JAXA EarthCare Satellite

Payload:

- The Atmospheric Lidar (ATLID) provides vertical profiles of aerosols and thin clouds. It operates at a wavelength of 355nm and has a high-spectral resolution receiver and depolarisation channel.
- The Cloud Profiling Radar (CPR) provides vertical profiles measurements of clouds and has the capability to observe vertical velocities of cloud particles through Doppler measurements. It operates at 94GHz.
- The Multi-Spectral Imager (MSI) provides across-track information on clouds and aerosols with channels in the visible, near infrared, shortwave- and thermal infrared.
- The Broad-Band Radiometer (BBR) provides measurements of top-of-the-atmosphere radiances and fluxes. It has one short-wave and one long-wave channel with three fixed viewing directions pointing in nadir and aft-directions.



Courtesy of ESA

From JAXA Presentation at CGMS-46

https://earth.esa.int/web/guest/missions/esa-future-missions/earthcare

11

MERLIN Satellite (DLR/CNES)

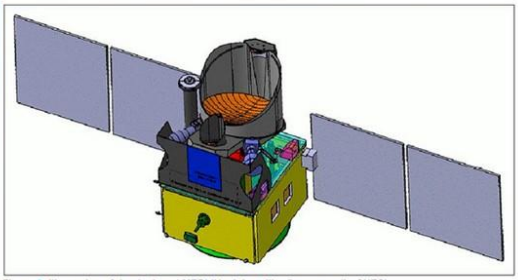


Figure 2: Illustration of the deployed MERLIN minisatellite (image credit: CNES)

Spacecraft launch mass	430 kg
Platform mass	260 kg
Platform size (stowed)	570 mm x 980 mm x 1020 mm (external appendices not included)
Power generation	500 W, (platform + payload), 150 W allocated for payload
Power units	Deployable solar array and battery
AOCS elements	Star tracker, reaction wheels, ..
Propulsion	28 kg of hydrazine fuel
RF communications	X-band downlink of payload data at 180 to 310 Mbit/s S-band downlink of TT&C data at 625 kbit/s S-band uplink of TT&C data at 16, 32 and 64 kbit/s Onboard mass memory: 512 Gbit

Launch expected ~ 2021

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https://directory.eoportal.org/web/eoportal/satellite-missions/m/merlin

NASA Implementation of and Accomplishments from

Active Optical Remote Sensing

- Introduction
- Satellites
  - Currently Operating Missions
  - Missions in Formulation and Development
- **Surface-Based Measurements**
- Airborne Measurements
  - Instruments
  - Campaigns
- Putting the Pieces Together
- Conclusion

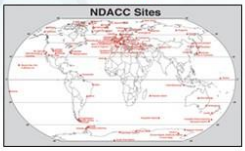
13

Examples of NASA-Supported Ground Networks

AGAGE



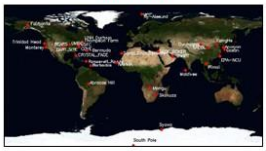
NDACC



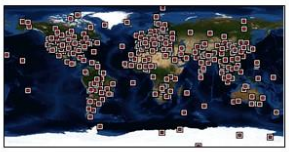
ILRS



MPLNet



AERONET



SHADOZ



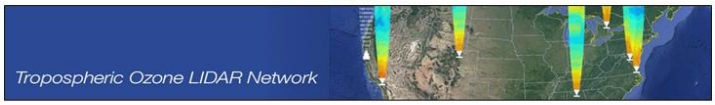
TCCON



PANDORA



TOLNet



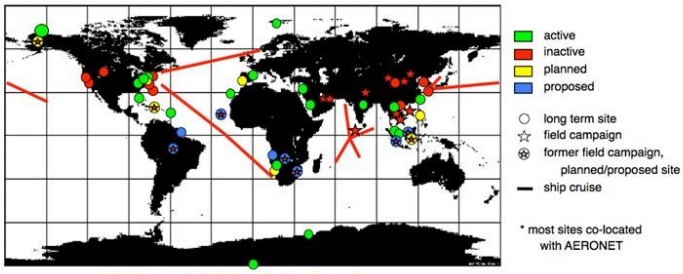
14

The Micro Pulse Lidar Network (MPLNET): 2000-Present

- Objective: Long term, global lidar network to profile aerosol and cloud vertical distribution and properties.
- Most sites co-located with AERONET, close interaction between the networks.
  - Provide both NRT and QA Level 2 data in support of various NASA missions, programs and modeling.
  - Support other domestic and international aerosol and cloud research activities.
  - Develop capability to support operational aerosol and air quality forecasting.

- MPLNET is a federated network built on the AERONET model: utilize standard instruments, calibrations, operations, and processing.
- MPLNET is a member of the WMO Global Atmospheric Watch (GAW) Aerosol Lidar Observation Network (GALION). Welton is co-chair.
- Nearing completion of our new Version 3 system with polarized MPL, and enhanced data products.

MPLNET Sites: 2000-present
- 19 long-term sites (17 upgraded with polarized lidars).
- 7 sites have 10+ years of data, significant number have 5+ years and going.
- 5 more sites in planning stages, install by end of 2017-early 2018.



New Version 3 Website: http://mplnet.gsfc.nasa.gov

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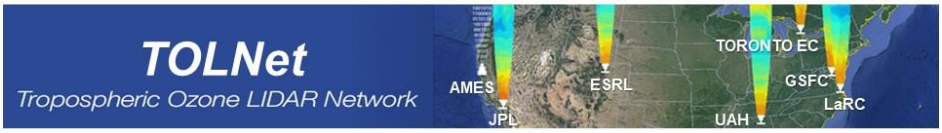
TOLNet Overview

- 5 Tropospheric ozone lidars in U.S. (3 mobile, 1 in transition to mobile).
- Interagency and university: JPL/TMF, NOAA/ESRL, UAH, NASA/GSFC, NASA/LaRC.
- 1 autonomous, mobile lidar (O3 and aerosol) in Canada ECCC/Toronto.
- A modeling hub at NASA/ARC and a NASA data center at NASA/LaRC.
- TOLNet is a critical adjunct to the future geostationary air-quality satellite, TEMPO, for validation and profile measurement.
- TOLNet is a significant component of NASA ground-based profiling assets.
- Validated to better than 10% in the tropospheric ozone profile (SCOOP/Leblanc et al.).
- Participated in many campaigns: DISCOVER-AQ/Houston & Colorado, KORUS/AQ, LVOS, FAST LVOS, SJV, CABOTS, SEAC^{4}RS, SOAS, OWLETS.
- High time- and space-resolution measurements of many scientific phenomena: STE, Free Tropospheric Lamina, PBL diurnal evolution, FT/PBL interaction, Nocturnal Jet Transport, Front Range Recirculation, Urban Plume Evolution, Background Ozone, et al.



16

ILRS currently tracks more than 90 satellites.



Over 40 years of SLR to the LAGEOS satellites have significantly contributed to our understanding of the Earth's shape, orientation, and gravity.



SLR Science, Applications and Instrument Development

- **Measurements**
  - Precision Orbit Determination (POD).
  - Time History of Station Positions and Motions.
- **Products**
  - Terrestrial Reference Frame (Center of Mass and Scale).
  - Plate Tectonics and Crustal Deformation.
  - Static and Time-varying Gravity Field.
  - Earth Orientation and Rotation (Polar Motion, length of day).
  - Orbits and Calibration of Altimetry Missions (Oceans, Ice).
  - Total Earth Mass Distribution.
  - Space Science – Tether Dynamics, etc.
  - Relativity Measurements and Lunar Science.
- **Next Generation SLR**
  - Millimeter ranging precision.
  - Day and nighttime tracking of satellites up to 22,000 km altitude.
  - Capable of producing over 50,000 satellite measurements per year.
  - Automated operations.
  - Modular design for simplified maintenance and upgrades.
- **New SLR Systems Under Development**
  - Based on protoyype system at Goddard (day and nighttime tracking, 1 mm-level range precision and stability, fast target acquisition and normal point generation, near-autonomous operations)

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NASA Implementation of and Accomplishments from Active Optical Remote Sensing

- Introduction
- Satellites
  - Currently Operating Missions
  - Missions in Formulation and Development
- Surface-Based Measurements
- **Airborne Measurements**
  - **Instruments**
  - **Campaigns**
- Putting the Pieces Together
- Conclusion

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Summary of NASA Airborne Lidar Instruments (1 of 2)

Lidar	Inst. Home	Wavelength (nm)	Platform(s)	Key Objective (s)	Key Characteristics	Recent Campaign(s)
ATM	WFF	532	P3, C-130, DC-8, TO	Elevation glaciers, ice sheets, sea ice	Digital waveform recording	OIB
LVIS	GSFC	1064	ER-2, B-200	Large area geodetic mapping	5-10 m footprints, 10 cm vertical accuracy	AvriSAR, OBI, ABoVE
CPL	GSFC	255, 532, 1024	ER-2, WB-57, C-130	Vertical profiles of clouds and aerosols	Fully autonomoous backscatter, depolarization-1024	SEAC4RS, HS3, ATTREX
ACATS	GSFC	532	ER-2	Cloud/aerosol extinction profiles and winds	Particulate extinction/lidar ratio; wind measurements	Ready for campaign use
LASE	LaRC	815	DC-8, P-3, ER-2	Aerosol and water vapor profiling	Nadir and zenith viewing DIAL	PECAN
DIAL-O3	LaRC	289,300 or 301, 311		Aerosol and ozone vertical profiling	Both upward and downward pointing	
DAWN	LaRC	2000	DC-8	Vertical profiles of wind components	1- Hz with 250 mJ pulses of 200 nsec	CPEX
HSRL-1	LaRC	532, 1064	B-200, P-3, C-130, DC-8	Multiple aerosol and ocean properties	Nadir pointing atmosphere and ocean profiling	SEAC4RS, NAAMES, SABOR
HSRL-2	LaRC	355, 460, 532, 650, 680, 1064, 290, 300	ER-2, B-200, P-3, DC-8	Multiple aerosol and ocean profiles	Nadir pointing atmosphere and ocean profiling	DISCOVER-AQ, ORACLES

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Summary of NASA Airborne Lidar Instruments (2 of 2)

Lidar	Inst. Home	Wavelength (nm)	Platform(s)	Key Objective (s)	Key Characteristics	Recent Campaign (s)
CAMAL	GSFC	355, 532, 1024	ER-2	Vertical profiles of clouds/aerosols in 10 km swath	Backscatter at 3 wavelengths; depolarization at two	Still under constructions
HALO	LaRC	1645, 935, 820, 532, 1064, 355	UC-12, B-200		Single receiver for H2o + HSRL or CH4 DIAL + HSRL	Being integrated for B-200
GSFC CO_2 sounder	GSFC	1572	DC-8 or lower	Airplane to surface or cloud top total column CO_2	Samples across CO_2 line; 10 kHz pulse rate; new HgCdTe detector	Soon fly on ASCENDS flights in ABoVE
MFFL and ACES CO_2 sounders	LaRC/ Harris	1572	DC-8 or lower	Airplane to surface or cloud top total column CO_2	CW laser systems using amplitude modulation for altitude information	Soon fly on ASCENDS flights in ABoVE
CO_2 LAS	JPL	2060	DC-8 or lower	Airplane to surface or cloud top total column CO_2	CW laser heterodyne system for better surface characterization	Soon fly on ASCENDS flights in ABoVE
G-LiHT	GSFC	1550	B-200/UC12-B, lower	Vegetation structure, bare Earth elevation	Scanning, small-footprint lidar	CMS, NASA/ESA fluorescence, FLARE
ASO-Riegel Q1560	JPL	1064	A-90 King Air	Snow depth with < 10 cm vertical accuracy	Commercial instrument; full waveform, dual channels,	ASO 2013-2017

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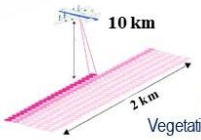
LVIS Airborne, Swath-mapping Lidar Facility

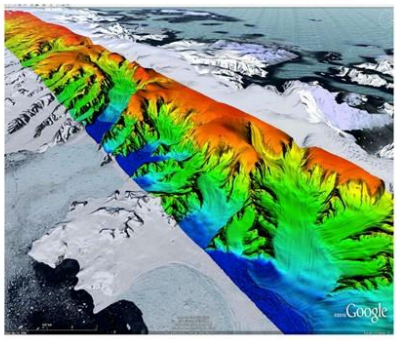
Wide-swath, Full-waveform, High-accuracy Laser Altimeter for Large Area Geodetic Mapping

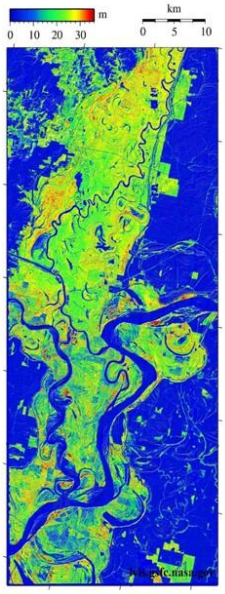
- Full transmit and receiver waveforms.
- Mature instrument & measurement concept.
- Serves multiple science measurement goals: ecology, cryosphere, carbon cycle, biodiversity, hydrology, natural hazards.
- Capable of mapping 100,000's of sq. km.
- Proven capability over numerous flight missions.
- 5-10 m footprints.
- 10 cm vertical accuracy.
- 1 m horizontal accuracy.
- Multi-aircraft support.
- First deployments to Alaska (ABoVE) and Greenland in 2017.

Contact: Bryan Blair
Code 61A, Geodesy and Geophysics Lab
NASA/GSFC



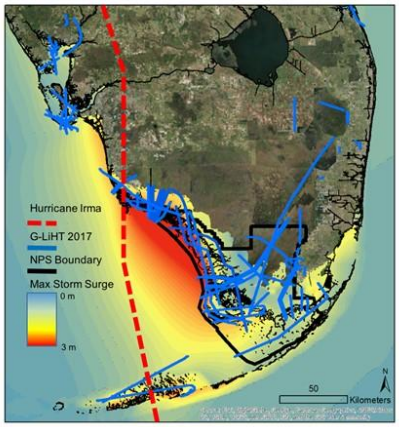
LVIS Data Examples: Vegetation Height in Arkansas (right) and Ice Surface Topography over the Antarctic Peninsula (below).





G-LIHT Payload

1) G-LiHT provides *fine-resolution* (3 cm to 1 m) *multi-sensor* (lidar, VNIR imaging spectroscopy and thermal imagery) data that are needed to quantify:
   - *defoliation and mortality* in terrestrial ecosystems; and
   - *changes in elevation* due to coastal erosion.
2) Pre- and Post-Hurricane Irma *G-LiHT imagery was acquired in South FL in 2017 and 2018, respectively*.
3) Pre- and Post-Hurricane Maria G-LiHT imagery was also obtained in Puerto Rico in 2017 and 2018, respectively.
4) G-LiHT compliments UAVSAR, AVIRIS, Landsat, MODIS and commercial high-resolution imagery that provide greater coverage at a coarser spatial resolution.
5) Open access to G-LiHT data and data products is made available through *https://gliht.gsfc.nasa.gov*. Turnaround on Level 3 products is 60 days.



Hurricane Irma had a major impact on mangrove forests in the Florida Everglades



Before & After Hurricane Maria Puerto Rico G-LiHT Flight Lines
2017 & 2018
2018 only

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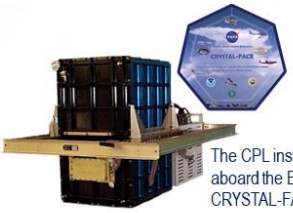
Examples of LIDAR Use in Major Airborne Field Campaigns



Monitoring LASE data aboard a DC-8 during the 2006 NAMMA mission.



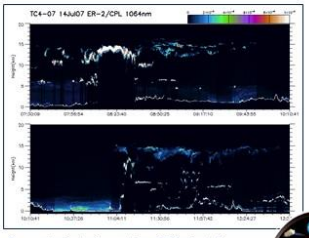
Cleaning the glass over the lidar on NASA's King Air B-200 for the 2008 ARCTAS mission. The HSRL and DIAL instruments flew aboard the B-200 and DC-8, respectively, as part of ARCTAS.



The CPL instrument flew aboard the ER-2 in CRYSTAL-FACE, 2002.



The DIAL and HSRL instruments flew during 2006's INTEX-B campaign aboard the DC-8 (seen here arriving at Diamond Head, Hawaii) and B-200, respectively.



Sample data from the CPL that flew aboard an ER-2 during the TC4 campaign of 2007. The DIAL and LASE instruments flew aboard the DC-8 during TC4.

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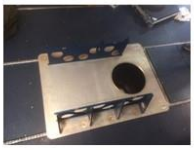
Examples of LIDAR Use in Major Airborne Field Campaigns



The ER-2 and DC-8 ready for deployment to the SEAC^{4}RS campaign, 2013. DIAL-HSRL flew on the DC-8 and the CPL flew on the ER-2.



A post-flight check of the CPL on the Global Hawk platform (data acquisition 2012-2014) in the ATTREX campaign.

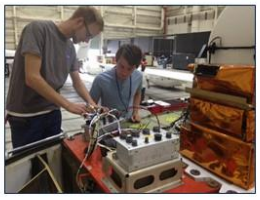


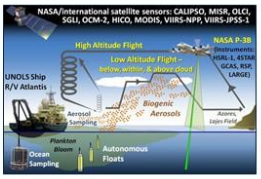
The HSRL2 Instrument flew on the P3B platform (data acquisition 2016-2018) in the ORACLES campaign.



The HSRL instrument flew on the C-130 platform (data acquisition 2016-2018) in ACT-AMERICA.

Installing the CPL on one of the Global Hawk platforms (data acquisition 2012-2014) in the HS3 campaign.





The HSRL instrument flew on the C-130 platform (data acquisition 2016-2018) in the NAAMES campaign.



Researchers used the HSRL instrument on the UC-12 during the SABOR campaign of 2014.



The CPL Instrument flew in on the B-200 (data acquisition 2011-2014) in DISCOVER-AQ .

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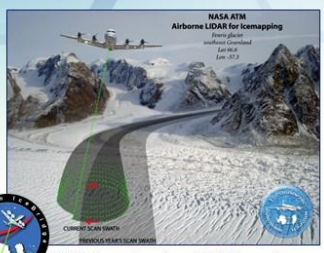
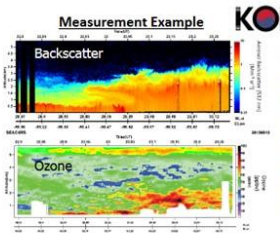
Examples of LIDAR Use in Major Airborne Field Campaigns



ATM (shown here) and LVIS have flown as part of Operation Ice Bridge starting in 2009 on multiple platforms.

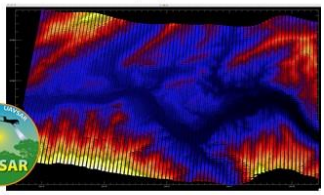


The 2017 ABoVE campaign collects data in Alaska (pictured) and Canada from space and air, including LVIS on the B-200 and ASCENDS lidar on the DC-8.



KORUS-AQ

Sample measurements from the DIAL/HSRL instrument, such as the one that flew aboard the DC-8 in the 2016 KORUS-AQ campaign.



A sample LVIS scan and beam pattern. A LVIS instrument flew aboard the B-200 in AfriSar in 2016.





The LASE instrument flew on the DC-8 as part of PECAN in 2015.



The DAWN wind lidar on the DC-8 as it flew in the 2017 CPEX campaign.

CPEX

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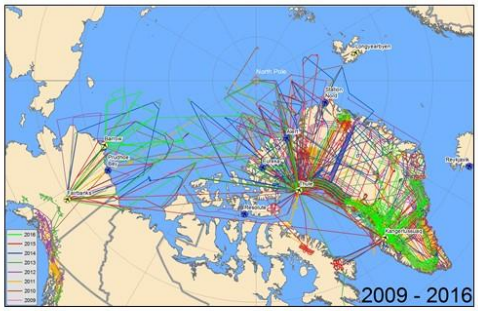
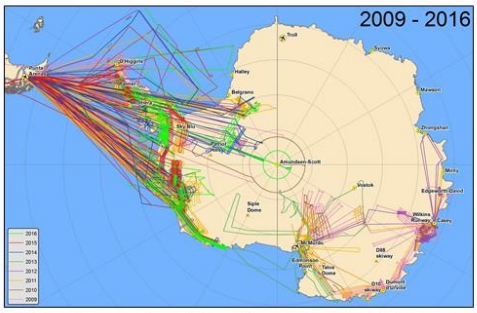
OIB Arctic and Antarctic Campaigns

- Arctic campaigns (below) have taken place in March through May of each year since 2009.
- They survey sea ice in the Arctic Ocean and the Greenland Ice Sheet, with a special focus on rapidly changing outlet glaciers.
- Missions are flown out of Thule and Kangerlussuaq in Greenland, and Fairbanks, Alaska. There is also a smaller component surveying glaciers in southeast Alaska.
- To date, these combined efforts have yielded nearly **910,000 km** of science data.

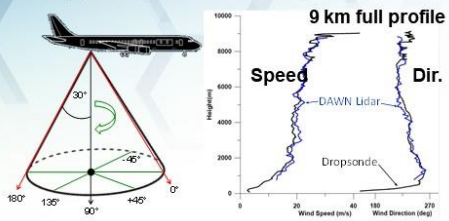




- Antarctic campaigns (above) have taken place in November through December of each year since 2009.
- They survey rapidly changing areas along the coast of West Antarctica, as well as major ice shelves, and seasonal sea ice.
- Missions are flown out of Punta Arenas in Chile, and McMurdo Station in Antarctica. There was a significant component flown in East Antarctica in collaboration with NSF's ICECAP program.
- To date, these combined efforts have yielded nearly **520,000 km** of science data.

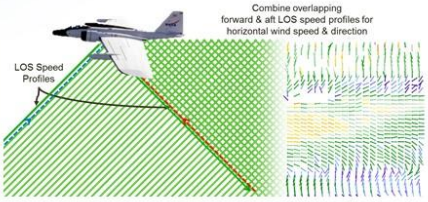
NASA Supported Wind Lidars

Doppler Aerosol WiNd lidar (DAWN)



- Coherent detection wind lidar at 2 microns
- Participated in GRIP (2010), Polar Winds (2014-15), CPEX (2017) science campaigns on DC-8
- Aerosol backscatter, accurate winds, eyesafe, equal day/night performance
- Conical scan, choice of no. azimuth angles (for cloud mitigation) & laser shots averaged
- Data may be re-processed often trading resolution, minimum aerosol concentration (i.e., atmospheric coverage), maximum range & probability of success
- 3-yr funded effort to advance coherent lidar technology towards space readiness

Optical Autocovariance Wind Lidar (OAWL)



- Direct detection wind lidar based on CALIPSO lidar technology (high TRL)
- Operates at 532 nm and/or 355 nm (like Aeolus)
- Two continuous lines of sight provide two constraints on the vector wind field
- 2016 Airborne measurements provided demonstration of technology capabilities
- "Scaling to space" performed for a space-based mission concept ("ATHENA-OAWL")
- Molecular channel in development (IRAD) to measure winds from upper troposphere
- OAWL Airborne system ready for DC-8

CPEX 2017: A Field Experiment to study Convective Processes in the Tropics

25 May-24 June 2017

DC-8 based in Fort Lauderdale, Florida

DAWN, APR-2, HAMSR, MTHP, Dropsondes, MASC

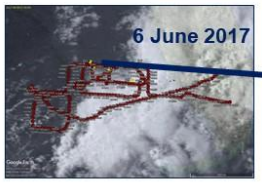
CPEX Science Objectives

1. Improve understanding of convective processes including cloud dynamics, downdrafts, cold pools and thermodynamics during initiation, growth, and dissipation.
2. Obtain a comprehensive set observations, especially from DAWN, in the vicinity of scattered and organized deep convection in all phases of the convective life cycle.
3. Improve model representation of convective and boundary layer processes over the tropical oceans using a cloud-resolving, fully coupled atmosphere-ocean model.
4. Improve model assimilation of the wind, temperature and humidity profiles from the wind lidar and dropsondes into numerical weather prediction models.

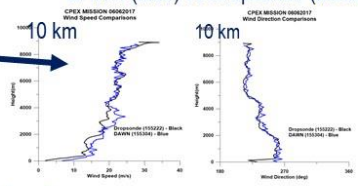
LaRC DAWN on NASA DC8



- DAWN is NASA's most capable airborne wind-profiling lidar
- Previously participated in NASA GRIP (2010) and Polar Winds (2014-15) airborne campaigns.
- Laser pulses at 2-micron wavelength and 10 Hz are eyesafe at any range; daytime observations not compromised by solar background.
- Data may be post flight processed multiple times with various number of shots accumulated (horizontal resolutions), vertical resolutions, and wind search bandwidths for maximum information extraction.
- CPEX science flights indicate excellent vertical coverage and agreement with dropsonde winds (e.g. from 9.5km in plots below).



DAWN (blue) vs Dropsonde (black)



Each red circle is a DAWN sounding location.

28

Considerations for Future AEOLUS Cal/Val

- Aim for collocated and/or synergistic calval activities addressing key geographical regions (e.g. tropics, arctic) and scientific questions
- Possibly include stronger data analytics and modeling components
- NASA/LaRC is completing work authorized in 2017 & 18to make DAWN instrument more reliable and robust (e.g., replacing old electronics)
- Coordination of NASA underflights during commissioning phase (e.g. testing of upgraded NASA DAWN and fitting of OAWL airborne instruments in 2019)
- In longer term, NASA to possibility flying DAWN and OAWL (with other instruments TBD) during FY20 time period and link with ESA-planned activities in tropics or polar regions (currently considering EUREC4A or CPEX2)



NASA Implementation of and Accomplishments from
Active Optical Remote Sensing

- Introduction
- Satellites
  - Currently Operating Missions
  - Missions in Formulation and Development
- Surface-Based Measurements
- Airborne Measurements
  - Instruments
  - Campaigns
- **Putting the Pieces Together**
  - **Active/Passive**
  - **Lidar/Radar(!)**
  - **Satellite/Airborne**
- Conclusion

30

Contribution to the WMO Ozone Assessment Reports and Satellite Data Validation

Four JPL Lidars for NDACC (Network for the Detection of Atmospheric Composition Change).
(T. Leblanc, JPL-TMF)

Ozone trends with the contributions of five NDACC stratospheric ozone lidars (in red) (WMO Ozone Assessment Report)

Two lidars from NASA-JPL Group:

- Table Mountain Facility (California, 35N).
- Mauna Loa Observatory (Hawaii, 19.5N).

Ozone positive trend (recovery) began in early 2000s:

- +1.%/decade at Mauna Loa in the upper stratosphere.
- +2%/decade at Table Mountain Facility in the upper stratosphere.
- Non statistically significant positive trends in the lower stratosphere (not shown).

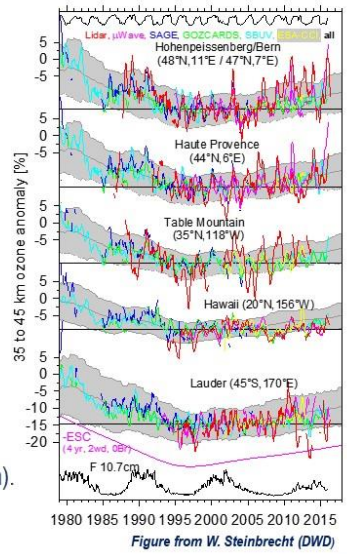
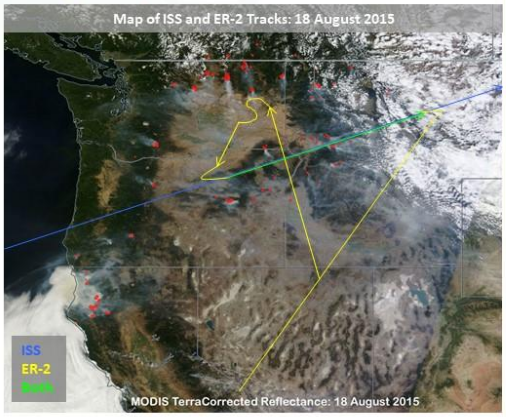


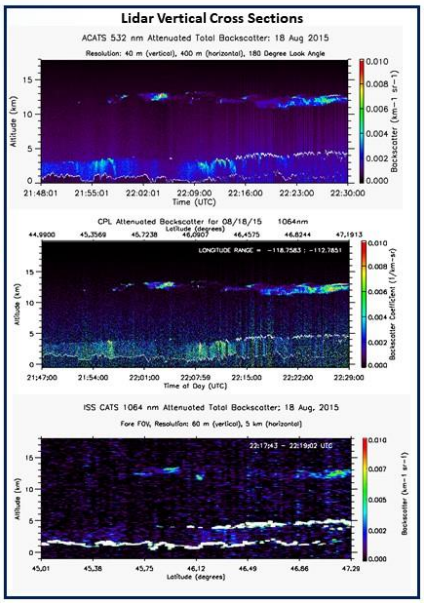
Figure from W. Steinbrecht (DWD)

31

Triple Lidar Measurements of Smoke

Coincident backscatter measurements of smoke from wildfires in the Pacific Northwest from ACATS (top panel) and CPL (middle) on board the NASA ER-2 are used to validate measurements from CATS (bottom) located on the ISS.





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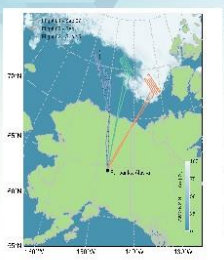
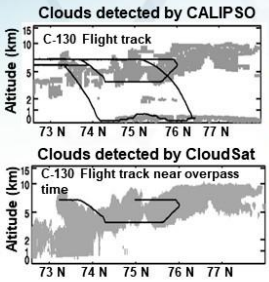
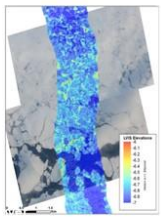
Satellite and Airborne Lidar Support ARISE Field Campaign

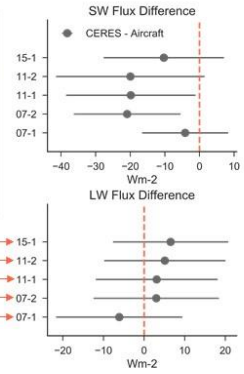
Arctic Radiation-IceBridge Sea & Ice Experiment: improved understanding of cloud and sea-ice radiative interactions

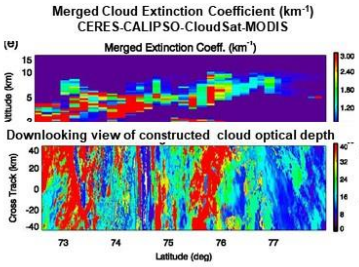




Lidar data provides important detail on cloud vertical structure and surface characteristics.







- LW flux shows good agreement for all grid-boxes.
- SW flux shows agreement within 2σ uncertainty for 4/5 grid-boxes.
- Surface fluxes less certain – evaluations in progress.

ARISE C-130 Grid-box Experiments

- Test popular CERES TOA/Surface radiative flux products.
- Flown over wide range of cloud/surface conditions.
- Anchored to CALIPSO overpasses.

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Many Upcoming Missions Will Provide Data That Will Be Used to Map Biomass

	ICESAT-2	GEDI	NISAR	ESA's BIOMASS
Launch Date	Sept. 2018	Late 2018	2022	2022
Wavelength	532 nm (green)	1064 nm (near IR)	S & L Band	P band
Coverage	Global	+/- ~ 50°	Global	Global (except W Europe and North America)
Measurement Strategy	6 tracks with 1 laser	10 tracks with 3 lasers	Wall-to-wall	Wall-to-wall

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  - Active/Passive
  - Lidar/Radar(!)
  - Satellite/Airborne
- **Conclusion**

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Conclusions

- Active optical remote sensing is making significant contributions to NASA's Earth Science Programs through surface-, aircraft- and space-based observations.
- Significant new capability has been developed and new plans implemented in the last few years in all areas.
- The new (January, 2018) NASEM Decadal Survey for Earth Science makes multiple mentions of lidar (see next chart!)
- The integration of active optical remote sensing with other observing approaches is providing new knowledge in a broad set of disciplines.
- The ingenuity of NASA scientists and grantees is demonstrating new uses of lidar data while advancing technology for the future.
- Active optical remote sensing can be expected to play an increasing role in the future and benefit from investments in lidar technology by NASA and our interagency and international partners (note ADM-Aeolus, EarthCares, and MERLIN).

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NASA Observing System Priorities as Identified in 2018 NASEM Decadal Survey

TARGETED OBSERVABLE	SCIENCE/APPLICATIONS SUMMARY	CANDIDATE MEASUREMENT APPROACH	Designated	Explorer	Incubation
Aerosols	**Aerosol properties, aerosol vertical profiles, and cloud properties** to understand their direct and indirect effects on climate and air quality	Backscatter lidar and multi-channel/multi-angle/polarization imaging radiometer flown together on the same platform	x		
Clouds, Convection, & Precipitation	**Coupled cloud-precipitation state and dynamics** for monitoring global hydrological cycle and understanding contributing processes	Radar(s), with multi-frequency passive microwave and sub-mm radiometer	x		
Mass Change	**Large-scale Earth dynamics** measured by the changing mass distribution within and between the Earth's atmosphere, oceans, ground water, and ice sheets	Spacecraft ranging measurement of gravity anomaly	x		
Surface Biology & Geology	**Earth surface geology and biology,** ground/water temperature, snow reflectivity, active geologic processes, vegetation traits and algal biomass	Hyperspectral imagery in the visible and shortwave infrared, multi- or hyperspectral imagery in the thermal IR	x		
Surface Deformation & Change	**Earth surface dynamics** from earthquakes and landslides to ice sheets and permafrost	Interferometric Synthetic Aperture Radar (InSAR) with ionospheric correction	x		
Greenhouse Gases	**CO_2 and methane fluxes and trends,** global and regional with quantification of point sources and identification of source types	Multispectral short wave IR and thermal IR sounders; or lidar**		x	
Ice Elevation	**Global ice characterization** including elevation change of land ice to assess sea level contributions and freeboard height of sea ice to assess sea ice/ocean/atmosphere interaction	Lidar**		x	
Ocean Surface Winds & Currents	**Coincident high-accuracy currents and vector winds** to assess air-sea momentum exchange and to infer upwelling, upper ocean mixing, and sea-ice drift.	Radar scatterometer		x	

Ozone & Trace Gases	**Vertical profiles of ozone and trace gases** (including water vapor, CO, NO_2, methane, and N_2O) globally and with high spatial resolution	UV/IR/microwave limb/nadir sounding and UV/IR solar/stellar occultation		x	
Snow Depth & Snow Water Equivalent	**Snow depth and snow water equivalent** including high spatial resolution in mountain areas	Radar (Ka/Ku band) altimeter; or lidar**		x	
Terrestrial Ecosystem Structure	**3D structure of terrestrial ecosystem** including forest canopy and above ground biomass and changes in above ground carbon stock from processes such as deforestation & forest degradation	Lidar**		x	
Atmospheric Winds	**3D winds in troposphere/PBL** for transport of pollutants/carbon/aerosol and water vapor, wind energy, cloud dynamics and convection, and large-scale circulation	Active sensing (lidar, radar, scatterometer), passive imagery or radiometry-based atmos. motion vectors (AMVs) tracking; or lidar**		x	x
Planetary Boundary Layer	**Diurnal 3D PBL thermodynamic properties and 2D PBL structure** to understand the impact of PBL processes on weather and AQ through high vertical and temporal profiling of PBL temperature, moisture and heights.	Microwave, hyperspectral IR sounder(s) (e.g., in geo or small sat constellation), GPS radio occultation for diurnal PBL temperature and humidity and heights; water vapor profiling DIAL lidar; and lidar** for PBL height			x
Surface Topography & Vegetation	**High-resolution global topography** including bare surface land topography ice topography, vegetation structure, and shallow water bathymetry	Radar; or lidar**			x

** Could potentially be addressed by a multi-function lidar designed to address two or more of the Targeted Observables

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Other ESAS 2017 Targeted Observables, not Allocated to a Flight Program Element

Aquatic Biogeochemistry	Radiance Intercalibration
Magnetic Field Changes	Sea Surface Salinity
Ocean Ecosystem Structure	Soil Moisture

P.5 AN OVERVIEW OF NASA EARTH SCIENCE TECHNOLOGY AND LIDAR INVESTMENTS

Pamela Miller and Parminder Ghuman

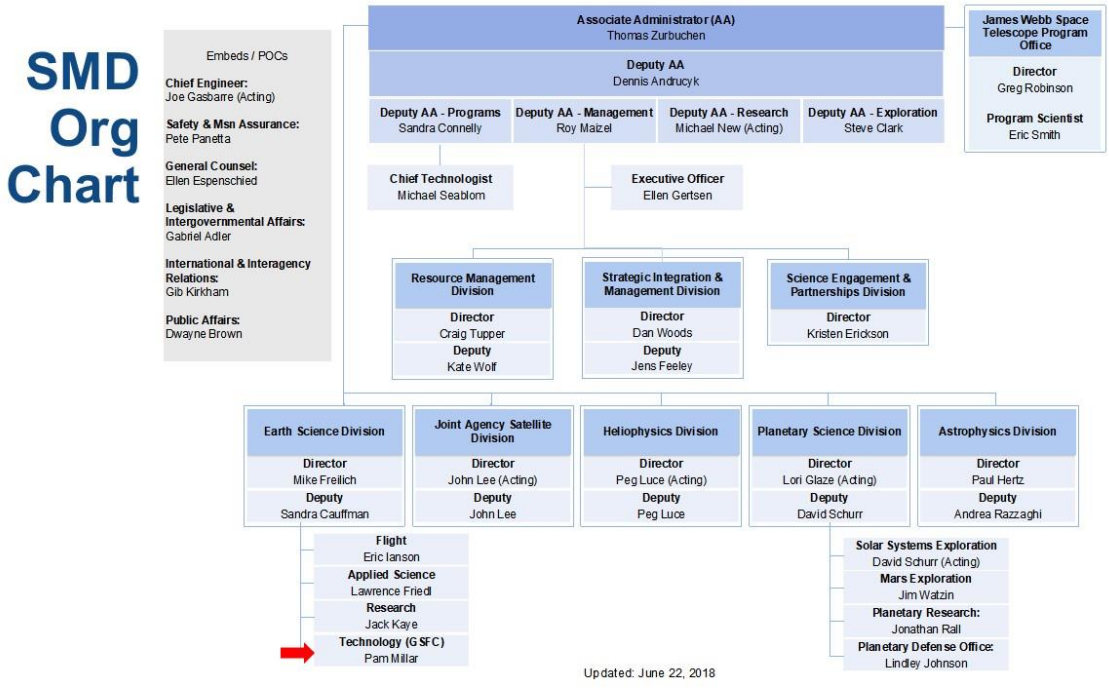
Earth Science Technology Office, Goddard Space Flight Center, Greenbelt, Maryland



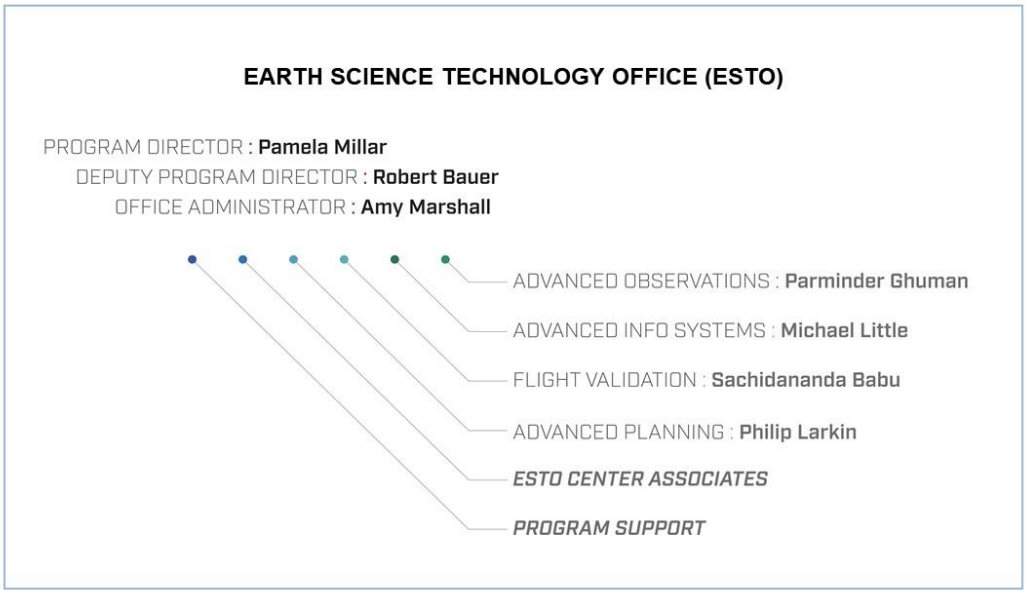


Overview
Earth Science Technology Program

SMD Org Chart



ESTO Org Chart



5

A Flexible, Science-driven Strategy

- Competitive, peer-reviewed proposals enable selection of best-of-class technology investments
- Risks are retired before major dollars are invested: a cost-effective approach to technology development and validation
- Successful partnering establishes leveraging opportunities
- This approach has resulted in:
  - a portfolio of emerging technologies that will enhance and/or enable future science measurements
  - a growing number of infusion successes into science campaigns, instruments, applications, ground systems, and missions

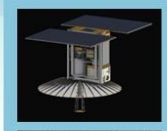
ESTO Enables – Science Selects

6

Earth Science Technology Program Elements

ESTO manages, on average, 120 active technology development projects. Most are funded through the primary program lines below. Nearly 800 projects have completed since 1998.

Advanced Technology Initiatives (ATI)



In-Space Validation of Earth Science Technologies (InVEST)
on-orbit technology validation and risk reduction for small instruments and instrument systems that could not otherwise be fully tested on the ground or airborne systems
(average award: $1-1.8M per year over three years)



Advanced Component Technologies (ACT)
critical components and subsystems for advanced instruments and observing systems
(average award: $400K/$600K per year over two/three years)



Instrument Incubator Program (IIP)
innovative remote sensing instrument development from concept through breadboard and demonstration
(average award: $1.5M per year over three years and $750K for 18 months for instrument concepts)



Advanced Information Systems Technology (AIST)
innovative on-orbit and ground capabilities for communication, processing, and management of remotely sensed data and the efficient generation of data products
(average award: $600K per year over two years)

7

Technology Program Budget and Schedule

($M)	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23
Q	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
ROSES Solicitations	△	△	△	△	△	△	△	△
ATI – ACT & InVEST Solicitation NRA Release		ACT-17	InVEST-17		ACT-20	InVEST-20		ACT-23
Budget								
IIP Solicitation NRA Release	IIP-16			IIP-19			IIP-22	
Budget								
AIST Solicitation NRA Release		AIST-16		AIST-18		AIST-20		AIST-22
Budget								
In-Guide Totals ($M)	60.7	62.8	60.4	59.7	61.5	64.2	67.8	
Total ESD Budget ($M)	$1,926	$1,907	$1,754	$1,784	$1,784	$1,784	$1,784	
% of ESD Budget	3.2%	3.3%	3.4%	3.3%	3.5%	3.6%	3.8%	

8

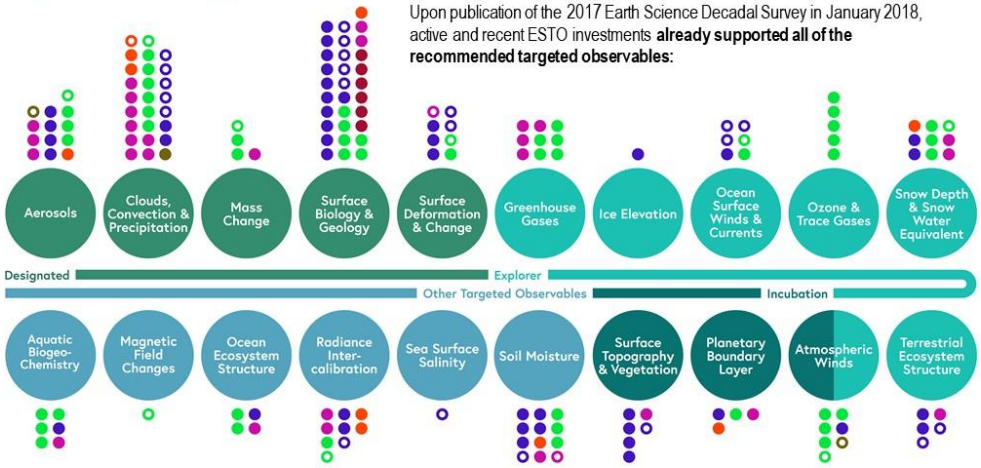
2017 Earth Science Decadal Survey
Technologies for New Observations

2017 ES Decadal Survey – Implications for ESTO

- ESTO is closely involved with ESD planning to translate the recommendations into an executable program over the next 12-18 months
- We have done a preliminary mapping of the targeted observables, and as expected, **don't see many technology deficiencies**
- Decadal has recommended small changes in balance with more resources on technology
- Plans for how to implement the incubation are in formulation, not a big challenge but needs careful consideration – being done in concert with Flight and R&A
- We see a need to emphasize bringing in early career researchers for succession planning in our future solicitations (**especially for Incubation**)

Responding to the 2017 Decadal Survey

Upon publication of the 2017 Earth Science Decadal Survey in January 2018, active and recent ESTO investments **already supported all of the recommended targeted observables:**



- Advanced Component Technologies
- Advanced Information Systems Technology
- Instrument Incubator Program
- In-Space Validation of Earth Science Technologies
- Sustainable Land Imaging - Technology
- Earth Venture Technologies
- Solid circle indicates active project
- Ring shape indicates recently completed project

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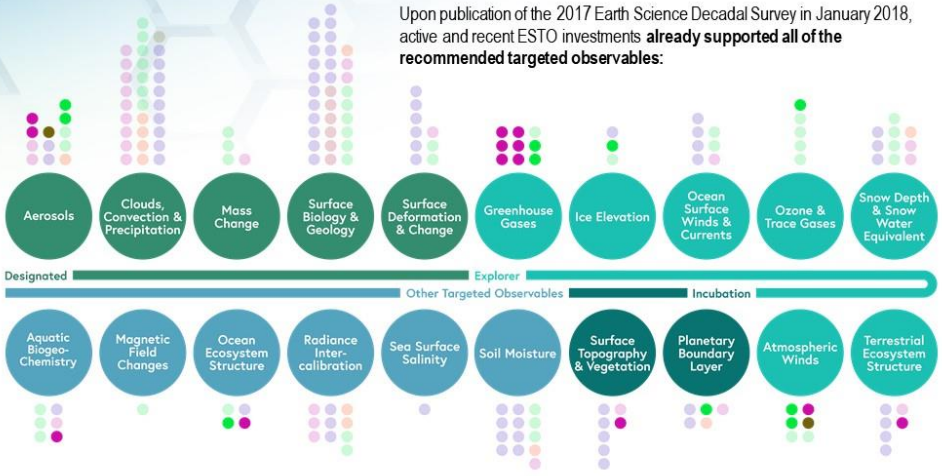
2017 Decadal Survey Mapping for Laser/Lidar Measurements

Upon publication of the 2017 Earth Science Decadal Survey in January 2018, active and recent ESTO investments **already supported all of the recommended targeted observables:**



- Components
- Information Systems
- Instruments
- In-Space Validation
- Sustainable Land Imaging
- Earth Venture Technologies

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Laser/Lidar Technologies (ESTO: ~$50M + SBIR: $14M)
Advanced Sensors

❑ Atmospheric Sciences
- Clouds and Aerosols
- Greenhouse, Ozone & Trace Gases

❑ Weather
- Atmospheric Winds

❑ Carbon Cycle & Ecosystem
- Aquatic Biogeo-Chemistry
- Ocean Ecosystem and Terrestrial Structure
- Surface Vegetation and Topography

Atmospheric Sciences

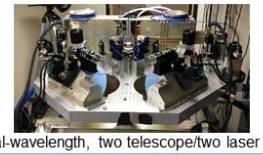
Lidar Investment Highlights for Atmospheric Sciences

- TRL 6, low cost, efficient, high repetition rate laser transmitter (4.5 mJ and 4.5 kHz at 1064 nm) and electronics for ESPA class satellite bus for clouds and aerosols. *(PI: William Austin/LiteSpar, Inc.)*: *Completed*



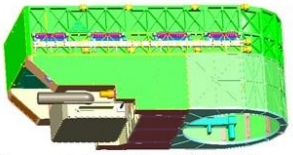
Laser optical head and preliminary power/control electronics

- TRL 4, 355 and 532-nm lidar system that uses a-thermal interferometer and auto-covariance technique for simultaneous measurement of winds and aerosol properties required for the study of aerosol-wind-cloud interactions. *(PI: Sara Tucker/Ball Aerospace)*: *Completed*



Packaged dual-wavelength, two telescope/two laser system

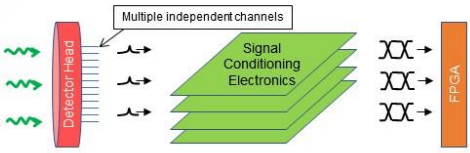
- TRL 4, Multi-wavelength (355, 532, 1064 nm) high resolution lidar system (HSRL) for clouds, aerosols, and ocean color measurements. *(PI: Chris Hostetler/NASA, LaRC)*: *Scheduled to be completed*



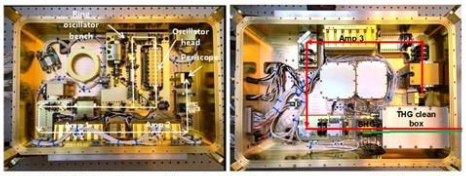
Ocean-optimized airborne HSRL

Lidar Investments Highlights for Atmospheric Sciences (cont'd)

- TRL 2, A GHz photon counting system that uses MCP-PMT detectors for HSRL system to enable measurement of clouds, aerosols, and ocean color. *(PI: John Smith/NASA, LaRC)*: scheduled to be completed

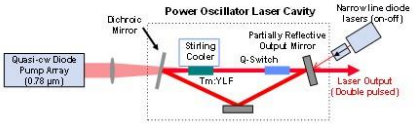


- TRL 5 , ~90 mJ 355-nm laser that is life tested in excess of 2B shots. *(PI: Floyd Hovis/Fibertek, Inc.)*: completed



As built HEUVD optics modules showing the key components of the internal laser compartments

- TRL 4, an efficient high power laser transmitter at 816 nm based on newly emerging Tm:YLF laser crystals to meet space-based requirements for H_2O. *(PI: Tso Yee Fan/MIT/LL)*: scheduled to be completed



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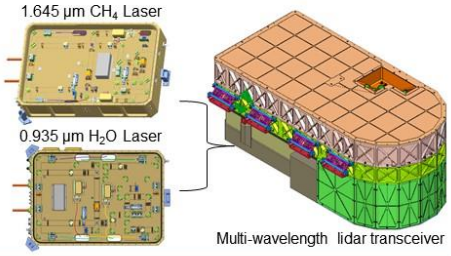
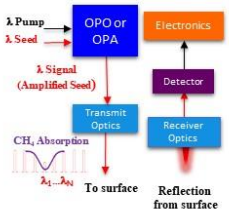
Lidar Investments Highlights for Atmospheric Sciences (cont'd)

- TRL 4, combined DIAL and HSRL lidar system to enable observations of atmospheric H_2O, CH_4, and aerosols from an aircraft platform. *(PI: Amin Nehrir/NASA, LaRC)*: scheduled to be completed



Multi-wavelength lidar transceiver

- TRL 4, laser to enable methane and water vapor measurements at 1651 nm and 1652 nm respectively from airborne and spaceborne platforms. *(PI: Harris Riris/NASA, GSFC)*: scheduled to be completed



Instrument Concept

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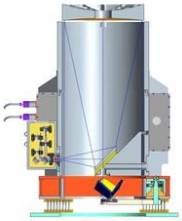
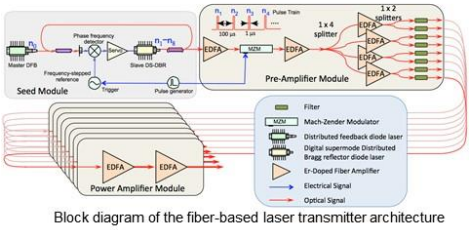
Lidar Investments Highlights for Atmospheric Sciences (cont'd)

- TRL 5, Triple-Pulsed 2-µm direct detection airborne lidar for simultaneous and independent CO_2 and H_2O Column Measurement. (*PI: Upendra Singh NASA, LaRC):* completed



Integrated 2-µm CO_2 and H_2O airborne packaged IPDA lidar

- TRL 4, 1.5µm fiber-based master oscillator power amplifier (MOPA) architecture for modularity and performance spaceborne platforms to measure CO_2. *(PI: Mark Stephen/NASA, GSFC):* scheduled to be completed



Block diagram of the fiber-based laser transmitter architecture

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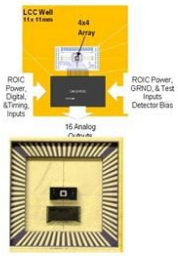
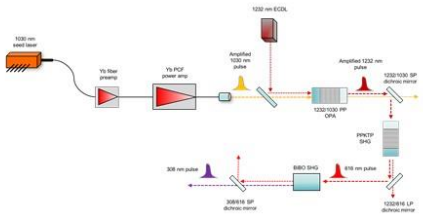
Lidar Investments Highlights for Atmospheric Sciences (cont'd)

- TRL 6, radiation tested 4x4 pixel array HgCdTe e-APD FPA for both 1.5 and 2-µm CO_2 lidars. A fully packaged detector and electronics were delivered to LaRC for their 2-µm CO_2 system. (*PI: Xiaoli Sun/NASA, GSFC):* completed



Detector Chip

- TRL 3, tunable fiber laser to measure OH columns at 308 nm with performance goals of <0.05 pm linewidth, 100 kHz pulse repetition rate, 250 Hz tuning rate, and >3W average power. (*PI: Thomas Hanisco/NASA, GSFC):* scheduled to be completed



Tunable fiber laser for OH IPDA LIDAR

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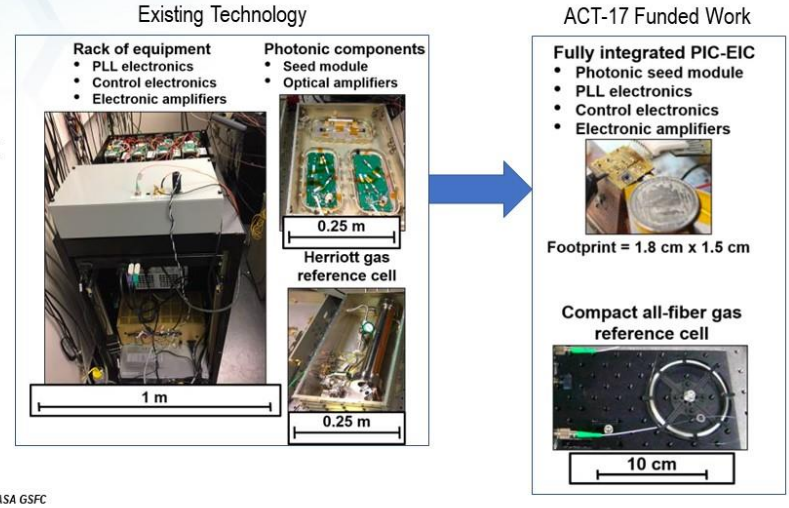
Integration of Photonics Integrated Circuits in Lidar Systems – *emerging technology for next decade and beyond*

➢ CO_2 using PICs

Photonic Integrated Circuits (PICs) will enable more frequent and lower cost missions for remote Earth science sensing from small craft and small satellite platforms.



Collaboration between Univ. of California, Santa Barbara and NASA GSFC

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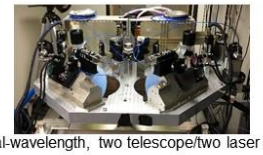
Weather

Lidar Investments for Weather

- TRL 4, 355 and 532-nm lidar system that uses a-thermal interferometer and auto-covariance technique for simultaneous measurement of winds and aerosol properties required for the study of aerosol-wind-cloud interactions. *(PI: Sara Tucker/Ball Aerospace)* *(also for atmospheric): completed*



Packaged dual-wavelength, two telescope/two laser system

- TRL 7, Two-telescope (30cm), two-laser (capable of >30 mJ/pulse of 532 at 200Hz) configuration of the OAWL instrument to demonstrate airborne LOS wind measurements. (*PI: Michael Hardesty/Sara Tucker/Univ. of Colorado/Ball Aerospace, Inc.): completed (Venture Tech Award)*



ATHENA-OAWL Airborne Demonstrator installed in the NASA WB-57 pallet

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Lidar Investments for Weather (cont'd)

- TRL 4, 2-μm high repetition rate pulsed coherent two-telescope lidar system for wind measurement from space. *(PI: Michael Kavaya/NASA LaRC): scheduled to be completed*
  - *SBIR Investments*
    - *Beyond Photonics*
    - *Fibertek*



Notional wind lidar profiling horizontal vector wind on both sides of track

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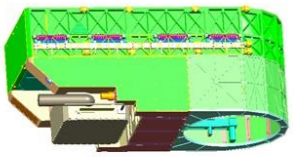
Carbon Cycle & Ecosystems

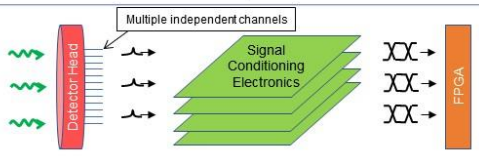
Lidar Investments for Carbon Cycle and Ecosystems

- TRL 4, Multi-wavelength (355, 532, 1064 nm) high resolution lidar system (HSRL) for clouds, aerosols, and ocean color measurements *(PI: Chris Hostetler/NASA, LaRC):* *scheduled to be completed (also for Aerosols)*



Ocean-optimized airborne HSRL

- TRL 2, A GHz photon counting system that uses MCP-PMT detectors for HSRL system to enable measurement of clouds, aerosols, and ocean color. *(PI: John Smith/NASA, LaRC):* *scheduled to be completed*



- TRL 3, Evaluate the HgCdTe avalanche photodiodes (APD) arrays from Selex/Leonardo for higher speed Lidar receiver applications. *(PI: Xiaoli Sun/NASA GSFC):* *scheduled to be completed*



Packaged APD detector LCC pack in a LN2 Dewar for electro-optical tests



Packaged APD detector with preamplifier in a LCC pack

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Laser Investments in SBIR Program

Proposal Number	Proposal Title	Email	Phase	Firm	Award Amount	State	Center	Year
S1.11-8294	Compact UV Laser	green@qpeak.com	Phase II	Q-Peak Inc.	$754,970	Massachusetts	GSFC	2017
S1.10-8423	Cold Atom Laser Module (CALM)	jburke@aosense.com	Phase II	AOSense Inc.	$749,927	California	GSFC	2017
S1.01-9205	Compact Integrated DBR Laser Source for Absorption Lidar Instruments	kgoodwin@photodigm.com	Phase II	Photodigm Inc.	$748,277	Texas	LaRC	2017
H9.01-8624	High Power (50W) WDM Space Lasercom 1.5um Fiber Laser Transmitter	tperinis@fibertek.com	Phase II	Fibertek Inc.	$749,787	Virginia	JPL	2017
S1.11-8595	WOLFEChip: Wholly-Integrated Optofluidic Laser-Induced Fluorescence Electrophoresis Chip	N.Bramall@LeidenTechnology.co	Phase II	Measurement Technology LLC	$749,967	California	JPL	2017
S1.01-8484	1.57 Micron High Pulse Energy Single Frequency Fiber Laser	sjiang@advaluephotonics.com	Phase II	AdValue Photonics Inc.	$748,893	Arizona	GSFC	2017
A2.01-8971	Tunable Laser for High-Performance Low-Cost Distributed Sensing Platform	seeleyr@sequentlogic.com	Phase II	Sequent Logic LLC	$754,929	Utah	AFRC	2017
S1.04-9669	Tunable High-Power Terahertz Quantum Cascade Laser Local Oscillator	wilt_kao@longwavephotonics.com	Phase II	LongWave Photonics LLC	$750,000	California	JPL	2017
					$6,006,750			
S4.01-8277	Ultra Compact Laser for 3D Imaging LIDAR	green@qpeak.com	Phase II	Q-Peak Inc.	$754,923	Massachusetts	JPL	2016
S1.01-7662	Lidar	bleile@bridgerphotonics.com	Phase II	Inc.	$749,848	Montana	LaRC	2016
S1.01-8414	Spaceflight 1.94 Micron Tm Fiber Laser Transmitter	tperinis@fibertek.com	Phase II	Fibertek Inc.	$749,950	Virginia	LaRC	2016
S1.07-7358	Widely Tunable Semiconductor Laser at 1650nm for Greenhouse Gas LIDAR Detection	mashan@freedomphotonics.com	Phase II	Freedom Photonics LLC	$749,994	California	GSFC	2016
S1.01-7855	Space-Hardened Seed Laser for Use in High Spectral Resolution Lidar Systems	heckel@advr-inc.com	Phase II	ADVR Inc.	$749,993	Montana	LaRC	2016
					$3,754,708			
S1.09-8809	Stabilized Portable External Cavity Laser (SPECL)	byoung@aosense.com	Phase II	AOSense Inc.	$749,925	California	GSFC	2015
S1.01-9731	Integrated Miniature DBR Laser Module for Lidar Instruments	kgoodwin@photodigm.com	Phase II	Photodigm Inc.	$747,306	Texas	LaRC	2015
S1.09-8674	Robust Frequency Combs and Lasers for Optical Clocks and Sensing	rommel@vescent.com	Phase II	Vescent Photonics Inc.	$748,310	Colorado	JPL	2015
S1.01-9914	Novel Solid State Lasers for Space-Based Water Vapor DIAL	tperinis@fibertek.com	Phase II	Fibertek Inc.	$749,985	Virginia	LaRC	2015
S1.01-9021	High-Power Tunable SeedLaser for Methane LIDAR Transmitter	mitzler@princetonlightwave.com	Phase II	Princeton Lightwave Inc.	$737,758	New Jersey	GSFC	2015
H9.01-8772	Non-Mechanical Electro-Optic Beamsteerers for Space Based Laser Communications	rommel@vescent.com	Phase II	Vescent Photonics Inc.	$747,038	Colorado	JPL	2015
					$4,480,322			

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Summary

- The Earth Science Technology Program inherently enables the implementation of the Decadal Surveys
- Continuous pursuit of miniaturization and reducing SWaP translates to:
  - improving affordability and sometimes simplification
  - enabling implementation options, such as constellations, that can improve spatial coverage and temporal frequency
- ESTO is investing in new observation systems strategies which combines different measurement techniques (combined active and passive instruments) and platforms (ground, airborne, and space)
- The ESTO strategy of investing in laser and lidar technology is through
  - Competitive solicitations
  - Occasionally directed funding for cross-cutting investments
  - Partnerships (cost sharing): NASA Centers, SBIR, R&A
- There will be future opportunities such as through Incubation program to mature lidar technologies for use in the next decade, 2027 and beyond (PBL, SV&T)
- Current Investment Strategy is working well, there's no compelling reason to change at this time

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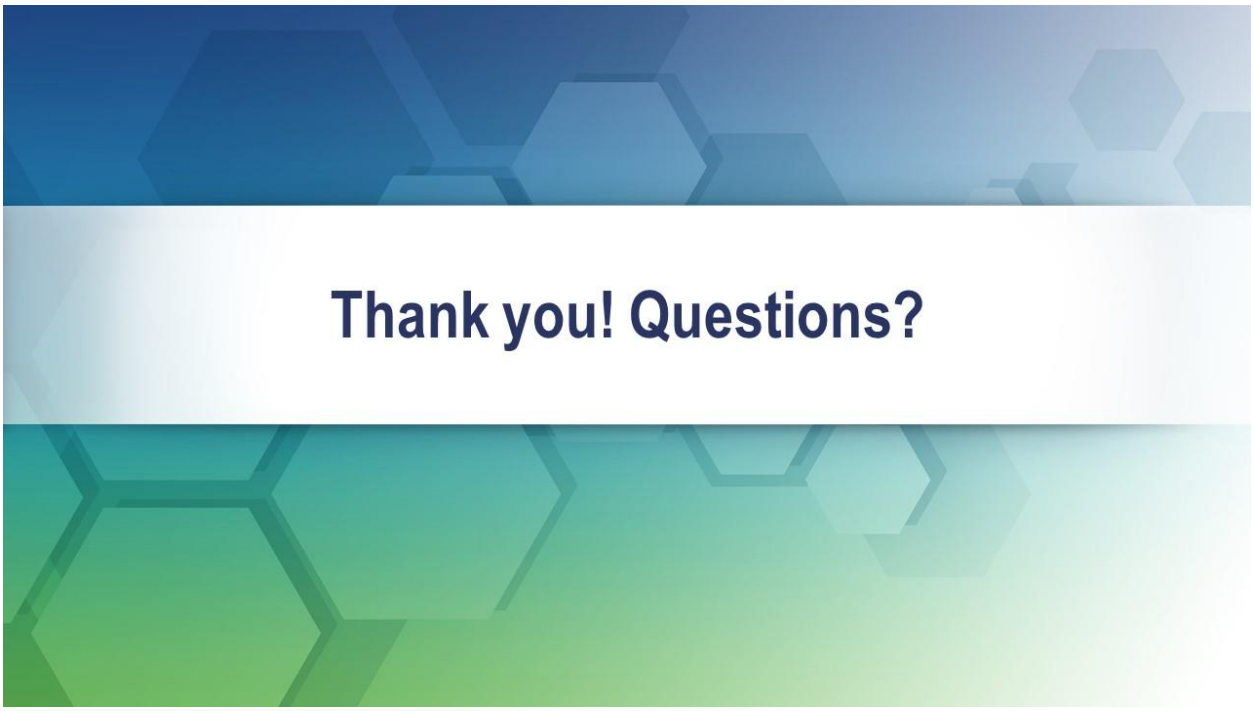

Thank you! Questions?

1 Session 1

Clouds, Aerosols and Ocean was designed to examine perspectives and issues in measuring the characteristics of cloud and ocean systems. A total of four presentations from GSFC, LaRC, and Fibertek was received. Table 1-1 lists the session papers. See Section 3 of the Assessment Report for observations and assessment comments.

Table 1-1. Session 1 Papers

Paper Number	Author	Title	Paper	Presentation
S1-1	Matthew McGill, NASA GSFC	Goddard Space Flight Center Earth Science Perspective on Lasers and Lidar Development		☑
S1-2	Johnathan Hair, NASA LaRC	Aerosols, Clouds and Ocean Profiling High Spectral Resolution Lidar		☑
S1-3	Floyd Hovis, Fibertek	Laser Development for the Next Generation of Cloud, Aerosol, and Ocean Lidar Systems	☑	☑
S1-4	Richard J. Hare and John A. Smith, NASA LaRC	Detectors for Spaceborne Aerosol-Cloud-Ocean Lidar: Past, Present and Future Directions		☑

List of presentations

1.1 Goddard Space Flight Center Earth Science Perspective on Lasers and Lidar Development 1-2
1.2 Aerosol-Cloud-Ocean High Spectral Resolution Lidar Requirements and Technical Overview 1-11
1.3 Laser Development for the Next Generation of Cloud, Aerosol, and Ocean Lidar Systems.....1-25
1.4 Detector for Spaceborne Aerosol-Cloud-Ocean Lidar: Past, Present, and Future Directions 1-45

1.1 GODDARD SPACE FLIGHT CENTER EARTH SCIENCE PERSPECTIVE ON LASERS AND LIDAR DEVELOPMENT

Matthew McGill

Earth Science Division Chief Technologist, Goddard Space Flight Center, Greenbelt, Maryland



Goddard SPACE FLIGHT CENTER

This TIM

2

Stated goal of this TIM:

"…the NASA Agency Program Management Council (APMC), chaired by the NASA Associate Administrator, has tasked the NASA Sensors and Instrumentation Capability Leadership Team Leader to determine if the Agency has the necessary expertise and capabilities to successfully execute the active optical-based systems necessary to make the required measurements for Science, Exploration, and Aeronautics. This NASA Technical Interchange Meeting (TIM) is **a forum to exchange perspectives on the current state of the discipline's technologies and the direction NASA needs to take** in the future to raise the TRL of the measurement technologies to meet these measurement needs in the applications domains. The information developed at this TIM will be used in formulating the agency-level strategy and solutions for advancing high-risk Laser/Lidar technologies that are not currently being sufficiently planned, developed, or risk reduced to meet NASA missions requirements.

Overview

My goals for this presentation are as follows:

1. Represent some GSFC interests that are not explicitly addressed at this TIM with individual presentations
2. Address readiness/needs for GSFC cloud/aerosol lidar going forward
3. Address barriers to laser/lidar development

GSFC Earth Science Activities

Goddard Earth Sciences Division is heavily involved in lidar developments, including:

- Ground-based instruments and tech developments
- Airborne demonstration and "facility-class" instruments
- Flight instruments

GSFC Ground-based Activities

Ground-based instruments

MicroPulse Lidar (MPLNet)

Tropospheric Ozone Differential Absorption Lidar (TropOz)

Stratospheric Ozone Lidar Trailer Experiment (STROZ LITE)

Goddard Lidar Observatory for Winds (GLOW)

Tech developments

Wide range of component technology developments, including

- lasers and laser components
- detectors
- optical components
- advanced data systems and processing

This is key – we must remember this is about systems/instruments, *not* just lasers !

GSFC Airborne Activities

Airborne instruments

Airborne demonstration and "facility-class" instruments, serving as science tools, technology demonstrators, and spaceflight precursors (not a comprehensive list!)

Cloud Physics Lidar (CPL), Airborne Cloud/Aerosol Transport System (A-CATS), and Cloud-Aerosol Multi-Angle Lidar (CAMAL) cloud/aerosol lidar instruments https://cpl.gsfc.nasa.gov



Land, Vegetation, and Ice Sensor (LVIS and LVIS Facility) laser altimeter for surface topography and 3-D structure https://lvis.gsfc.nasa.gov

Goddard Lidar Hyperspectral and Thermal (G-LiHT) for mapping of composition, structure, and function of terrestrial ecosystems https://gliht.gsfc.nasa.gov

Multiple Altimeter Beam Experimental Lidar (MABEL) as an ICESat-2 demonstrator

CO2 lidar

CH4 lidar

Formaldehyde and OH

GSFC Flight Activities

Flight instruments

ICESat, ICESat-2 altimetry for ice sheets
https://icesat-2.gsfc.nasa.gov/

Cloud-Aerosol Transport System (CATS) on ISS for cloud/aerosol profiling
https://cats.gsfc.nasa.gov

Global Ecosystem Dynamics Investigation (GEDI) on ISS for surface topography and 3-D structure
https://gedi.umd.edu

Going forward, Decadal Survey 'Designated Observable' for aerosols (next slides)

GSFC Cloud/Aerosol Lidar

GSFC researchers have a long history of developing elastic backscatter lidar instruments and technologies for study of clouds/aerosols.

GSFC approach tends to photon-counting, which means we develop technologies for high rep-rate/low pulse energy lasers, single photon sensitive detectors, and efficient optical systems.

Past examples include GLAS atmospheric channels on ICESat, MPL for ground-based studies, and CPL for airborne applications.

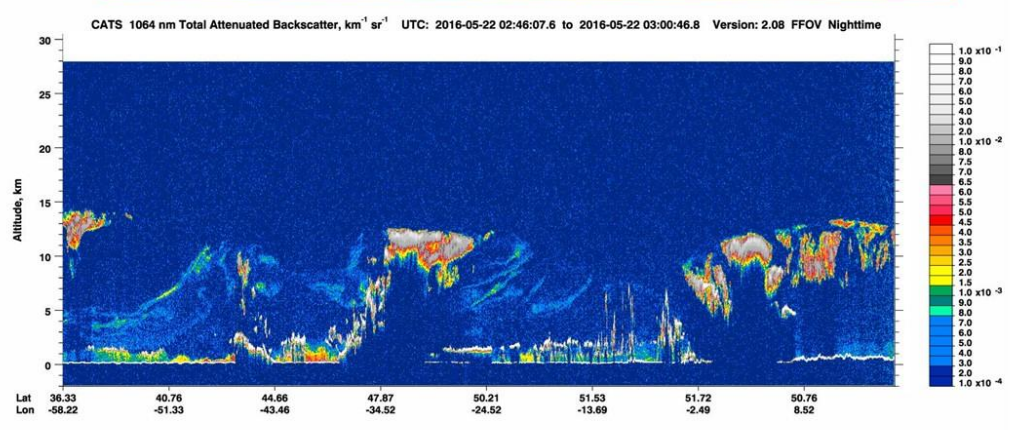
"Elastic backscatter lidar" is a cost-effective approach to cloud/aerosol profiling

There are two approaches for backscatter lidar, both have been proven to work in-space:

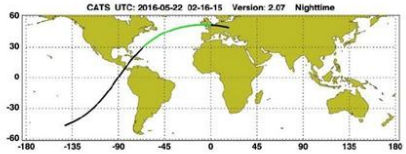
"CALIPSO-like" with big laser pulses, low repetition rate, and analog detection
- analog detectors drive need for big laser pulses, to overcome detector noise threshold
- big laser pulses drives to lower repetition rate (reality of power/fluence limits)
- 100 mJ at 20-100 Hz repetition rate is about the practical limit

"CPL-like" with small laser pulses, high repetition rate, and photon-counting detection
- sensitive photon-counting detectors would saturate with big laser pulses
- less energy per pulse compensated with higher repetition rate
- 2-8 mJ at 4-5 kHz repetition rate (5 kHz about as fast as practical to avoid aliasing)

High Rep-Rate Example



CATS provides excellent on-orbit demonstration of high repetition-rate, photon-counting lidar. This raw data shows excellent detail and fine structure at raw resolution with only ~1 mJ pulse energy (at least at night).



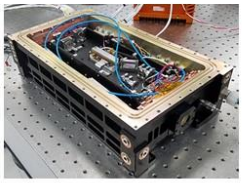
GSFC Cloud/Aerosol Lidar

The photon-counting approach has been demonstrated to provide high detection sensitivity and the GLAS and CATS-ISS demonstrations provide in-space demonstration.

Going forward, the Aerosols "Designated Observable" in the new Decadal Study calls for a lidar to measure aerosol properties. We believe the GSFC heritage, coupled with prior on-orbit demonstrations, provides a solid path for the Aerosols mission.

This is moreso when realities of budget limitations are considered. It is entirely possible that future missions will embrace SmallSat architecture, and the GSFC approach is well suited to both large and small platforms.

Very modest ESTO funding permitted demonstration of a flight-qualified transmitter aimed at SmallSat applications. Commercial partners Litespar, Inc. and Sigma Space Corp. developed the hardware.



Optical head. 16" x 9" x 4.5" and 26 lbs



Electronics box. 2 full units in one box. 12" x 16" x 4" and 24 lbs

4 mJ/pulse at 1064 nm
4 mJ/pulse at 532 nm
4.5 kHz rep rate
vibration tested to >16 G_{RMS}
thermal cycled -30C/+60C

Lessons learned from CATS

CATS provided valuable insight to inform a path forward that optimizes science return versus cost.

Algorithm development – for either CATS or CALIPSO approaches, algorithms are mature.

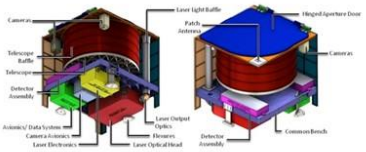
Real-time data flow critical for future model needs, applications, and hazard events → any future system will have to include this.

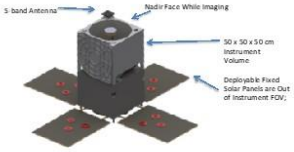
Cloud diurnal variability studies speak to using a constellation of SmallSats to secure optimal sampling. Value of multiple beams also speaks to alternate implementation or multiple SmallSats operating together.

The future is SmallSats and, yes, backscatter lidar can be scaled to SmallSat implementation – strong heritage from CATS hardware and data

Can get CATS-like performance at 600 km orbit, single wavelength with depolarization

The barrier is lack of opportunities!!!!







Barriers to Laser/Lidar Development

There has been significant investment in laser/lidar technical readiness through

- ESTO
- SBIR
- Center investments
- 2007 D.S. study team funding (e.g., ACE, ASCENDS, etc.)
- Mission funding (e.g., ICESat-2)

Moreso than limitations of technology funding, 5 key areas seem to be substantial barriers to development of active optical remote sensing instruments:

- Difficulty developing new talent
- Awards repeatedly focused on same technologies
- The TRL gap to flight
- Evaluation criteria applied to laser/lidar proposals
- Measurement requirements in Earth Science

Barrier #1: New Talent

Difficulty developing new talent

 This is a people/pipeline problem

It starts with Universities!

Many of the Universities historically involved in active lidar programs (Michigan, Arizona, Fairbanks, etc.) have de-emphasized that work as the primary researchers have retired.

Why is this? One belief: the volume of earth science data now available (thanks largely to EOS) means most PhD candidates sit and look at data and develop models – not working on/with instrumentation. It's far less expensive to "mine" EOS data than to build new sensors. This is a problem across Earth Science but seems particularly acute in the lidar area.

Barrier #2: Repeat Awards

Past awards have focused on the same technologies and research groups at the expense of new or emerging concepts or groups

 This is a lack of vision problem

Increasingly, it seems that "follow on" funding is the norm (i.e., multiple program awards to get to successful conclusion). This is partly a reflection of the true cost of developing remote sensing instruments, but also drags out timelines, (in some cases) rewards poor performance, and precludes innovation.

How many of the same thing do we need to fund? How do new groups break in when an established group is repeatedly funded as "the" group?

One suggestion: more IIP awards. IIP is the *only* opportunity to develop new earth science instruments, once every three years, maybe 10 awards, maybe 2 of those lidar…chances are slim. Could also increase the frequency of solicitation or dollar value of IIP awards (3 years to complete an IIP is okay but complex instruments often cost >$4-5M). Or, more ACT and IIP awards, on strict two year cycle, alternating between ACT and IIP each year. For spaceborne application, more/more frequent Earth Venture awards (perhaps lower $ value EVM-like program specifically for SmallSats?).

Barrier #3: TRL Gap to Flight

The TRL gap to Flight is a problem for more than just lasers and lidar. ESTO's charter allows them to fund to a TRL that is short of what Flight Projects want; Flight Projects don't want to accept risk/cost of advancing the TRL.

☞ This is a funding/budget problem

For Earth Science, ESTO does a good job funding technologies to TRL 5, sometimes TRL 6 depending on definition and aircraft demonstration, etc. However, the gap to infusion into Flight Projects is huge – the perceived risk and cost to fully develop or qualify hardware is not easily accommodated (i.e., cost is typically greater than ESTO awards allow).

One suggestion: In relevant cases, augment ESTO funding to permit advancement. Specific example is 1.5 micron laser for CO2 sensing, where ESTO paid for hardware costs and GSFC partnered with labor contribution. Total cost is >$8M but there was no other identified mechanism to get the candidate laser to TRL 6.

Barrier #4: Proposal Evaluation Criteria

It can be argued that overly conservative evaluation criteria gets imposed on laser-based proposals.

Stated differently, it is felt that laser/lidar proposals are more critically reviewed and held to higher standard. New researchers, new companies, new technologies have disadvantage convincing reviewers that concepts and technologies are mature and appropriate.

☞ This is a programmatic problem

A specific example: a proposal to EV-I proposing to use a laser that has been developed (with ESTO funding) for use in space and tested/qualified to TRL 6. Evidence provided in proposal, even showing the laser being environmentally tested.
TMCO response: "major weakness" because "A detailed laser optical layout with all components designated and described is not provided. Design details on the laser pumping scheme are not evident…" Why should this level of detail matter, especially for a Class D instrument? The review criteria is over-stringent and the risk posture of Class D is ignored.

Suggestion: HQ, TMCO, and external reviewers need to be more flexible, especially if dealing with proposals for Class D, SmallSats, and CubeSats. This is an area where NESC could evaluate the TMCO evaluation process for lasers/lidar and educate them on appropriate evaluation criteria.

Barrier #5: Earth Science Measurement Requirements

The abundance of Earth Science data and models means Earth Science instruments need to be capable of either more accurate measurements or higher-order data products.



This is a reality versus expectations problem

Examples: In the old days, postulating wind lidar measurements over large grid squares with large error bars was okay and had a positive impact on forecasting accuracy (because models were not so good and other data sources did not exist). These days models are so good that any wind lidar has to provide high accuracy over small grid squares – a need that significantly drives power-aperture product (and thus cost) and is in direct conflict with desires for smaller, less expensive instruments.

Same example can apply to CO2. Same example can apply to aerosol lidar if we want to push beyond backscatter to higher-order data products.

Suggestion: This is a real challenge. The physics of the atmosphere does not change, but the measurement requirements become more stringent. HQ stands up these big mission study teams, who want everything and with stringent measurement requirements…perhaps "academic scientists" have to be willing to accept less and stop pushing so far to highest levels of fidelity.

Summary

- Specific to cloud/aerosol lidar, NASA is well positioned to pursue the Aerosol mission identified Decadal mission
- To advance lidar remote sensing in Earth Science, the barriers to be overcome are not necessarily just funding
- Investments in lasers and lidar have not been ignored….ESTO has done a good job, within their funding limitations
- A "Laser Risk Reduction Part 2" is absolutely *not* what is needed. Nor is a new lidar-specific program necessarily a solution
- Instead, additional ESTO awards via ACT and IIP could substantially bolster the scope of work being done and expand the innovative nature of lidar research…more EV opportunities would help, too
- We need fair review of proposals submitted to Earth Venture or AO opportunities (e.g., those reviewed by TMCO) *especially* for Class D opportunities
- Indeed, if the future is SmallSat or "alternative architectures" then the review criteria applied needs to quickly and substantially evolve
- And we need to revitalize the pipeline of new talent…which will take time

1.2 AEROSOL-CLOUD-OCEAN HIGH SPECTRAL RESOLUTION LIDAR REQUIREMENTS AND TECHNICAL OVERVIEW

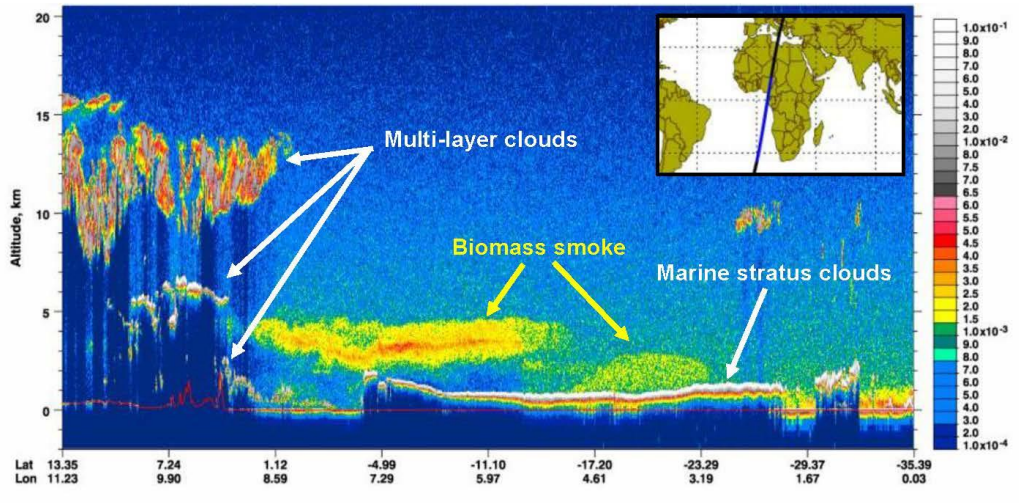
John Hair, Chris Hostetler, Rich Ferrare, Richard Hare, John Smith, Sharon Burton, + many others

NASA Langley Research Center, Hampton, Virginia

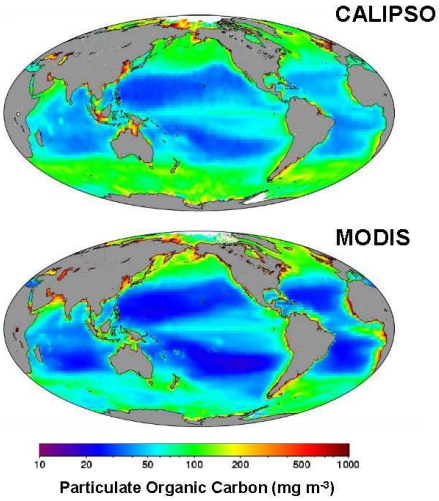
Aerosol-Cloud-Ocean High Spectral Resolution Lidar Requirements and Technical Overview

John Hair, Chris Hostetler, Rich Ferrare, Richard Hare, John Smith, Sharon Burton, + many others

CALIPSO was a huge success (12.5 years and going!) but has identified future measurement needs



The unexpected application: CALIPSO ocean measurements



- Particulate Organic Carbon (POC) retrieved from CALIOP spaceborne lidar compared favorably to the MODIS product
- CALIOP retrievals pioneered by Yongxiang Hu
- CALIOP retrievals are vertically-integrated (i.e., not vertically-resolved) due to coarse vertical resolution

From Behrenfeld et al., 2013, Space-based lidar measurements of global ocean carbon stocks, GRL.

Also see Behrenfeld et al., 2016, Annual boom-bust cycles of polar phytoplankton biomass revealed by space-based lidar, Nat. Geosci.

Data in each panel are climatological annual averages for the 2006 to 2012 period. Data are binned to 2° latitude by 2° longitude pixels.

Motivation – Aerosol, Cloud, and Ocean Lidar

Aerosols & Clouds are "Designated Observables" in the 2017 Decadal Survey

- Interdisciplinary/cross-cutting Science – Climate & Radiation, Air Quality, and Ocean Ecosystems
- Measurement objectives extend beyond what CALIPSO has (still) providing over 12+ years
- Integrated with polarimeter column measurements

Aerosols – vertically resolved

- Accurate backscatter and extinction to improve aerosol radiative forcing estimates
- Aerosol type and microphysics to improve chemical transport models and air quality forecasts
- Spatial and vertical information through combined active and passive sensors measurements

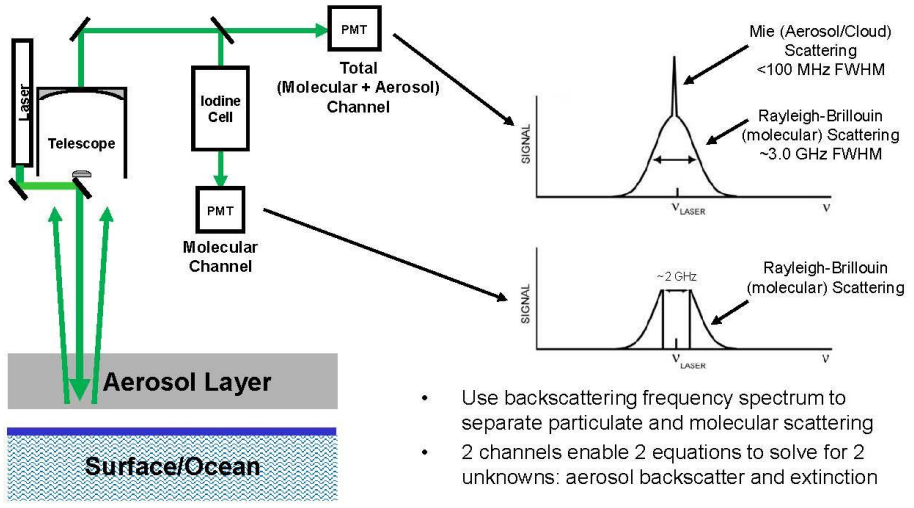
Clouds

- Cloud heights
- Tenuous cloud vertical structure and optical depth
- Cloud phase and ice water content
- Aerosol and cloud separation
- Microphysics – combined data products (HSRL, polarimeter)

Ocean Ecosystems – vertically resolved

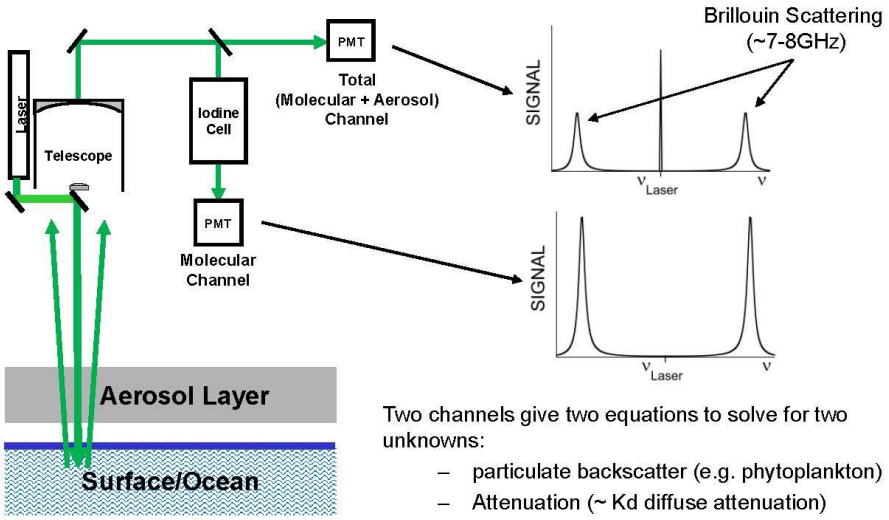
- Global 3-D distribution of marine biomass within the euphotic zone
- Subsurface optical properties for estimates of POC, C_{phyto}, and NPP
- Critical for understanding ocean biomass in high-latitude oceans

High Spectral Resolution Lidar (HSRL) technique for aerosol profiling



- Use backscattering frequency spectrum to separate particulate and molecular scattering
- 2 channels enable 2 equations to solve for 2 unknowns: aerosol backscatter and extinction

High Spectral Resolution Lidar (HSRL) technique for ocean profiling



Two channels give two equations to solve for two unknowns:

- particulate backscatter (e.g. phytoplankton)
- Attenuation (~ Kd diffuse attenuation)

Why HSRL?

- Overall accuracy of the measurements
  - Internally calibrated (improved calibrations at non-HSRL wavelengths i.e. 1064nm)
  - Provides independent backscatter and extinction
  - Backscatter determined from simple ratio at each altitude (no vertical integration required)
  - Improves information content to infer aerosol type
- Standard backscatter lidar retrievals are most uncertain near the surface
  - Most aerosols are distributed near the surface
  - Measurements in the boundary layer are critical for air quality
- Improves cloud measurements
  - Transmission method to determine cirrus cloud optical depth
  - Normalization above warm clouds for integrated cloud products.
- Enables retrieval of aerosol microphysical parameters
  - Improved performance of vertically resolved aerosol typing
  - Accurate lidar measurements combined with passive remote sensor measurements allow retrieval of microphysics
  - Relevant to aerosol-cloud interactions and air quality (i.e. Number concentrations)
- Enables accurate profiling of ocean subsurface
  - New frontier in satellite lidar remote sensing and noted as one of the 'most important' observables from the Marine and Terrestrial Ecosystems panel (Chapter 8) of the DS2017

Airborne LaRC High Spectral Resolution Lidar Systems: History and Value

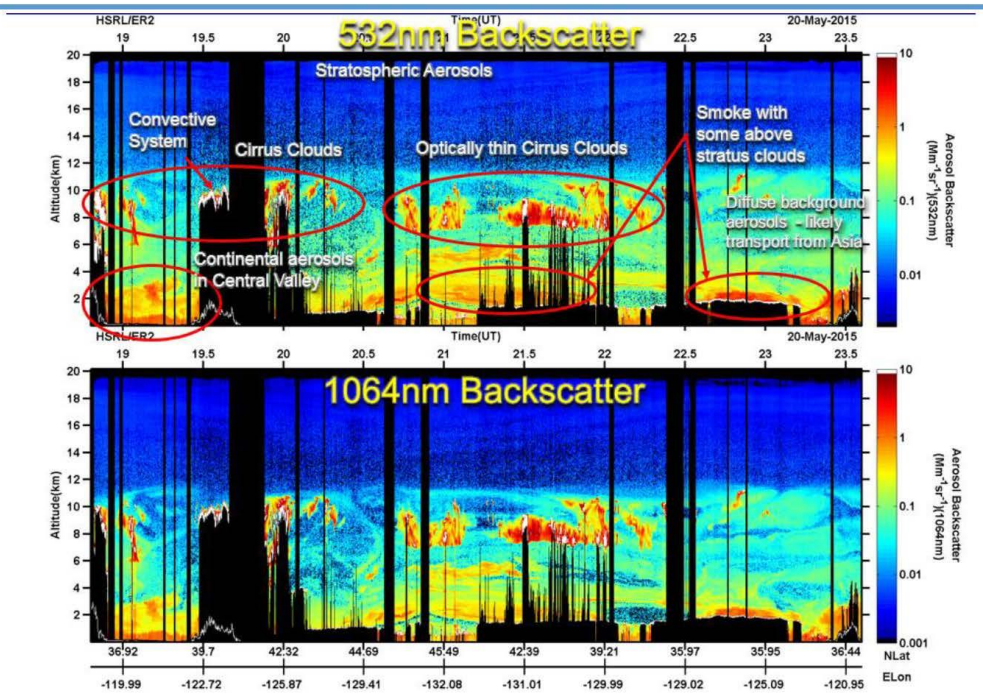




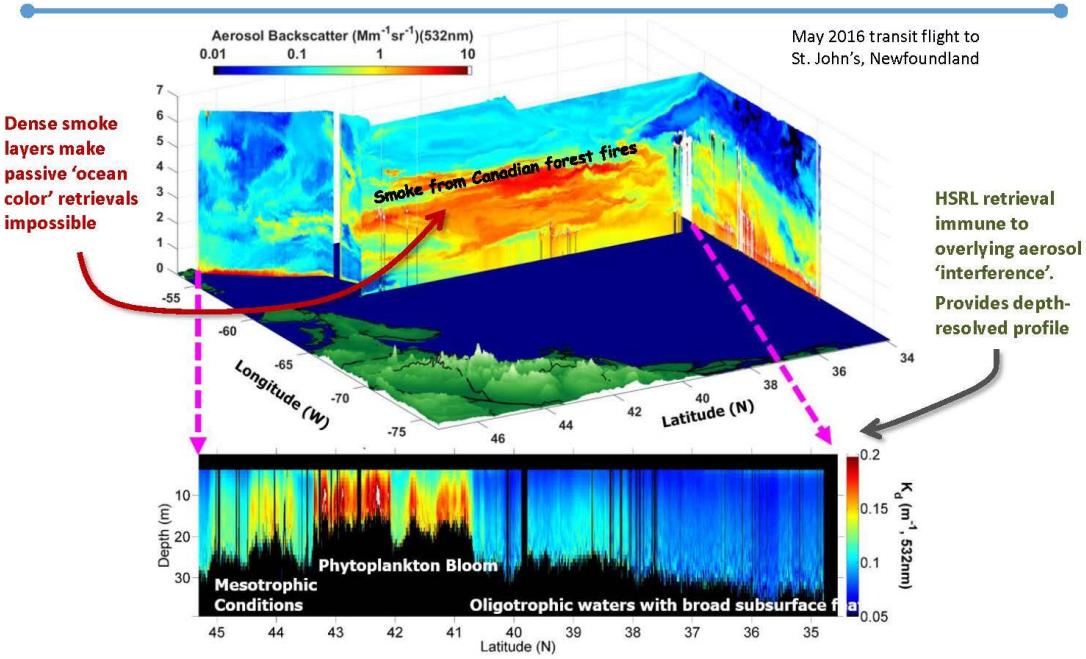


- **Demonstration of measurement concept**
  - Airborne provides a relevant environment over a range of conditions (low/high aerosol loading, cloud types) and locations (oceanic, arctic, continental)
  - Demonstrate the robustness of the instrument and measurements, aircraft can be more demanding than space for specific environmental states (i.e. vibration, temperature variations)
- **Development of retrieval algorithms**
  - Develop lidar only retrievals of fundamental products (backscatter, extinction, depolarization)
  - Develop advanced and combined active-passive retrievals
- **Performance analysis and comparisons**
  - Allows direct comparisons to state-of-the-art remote and in situ measurements (aerosols, clouds, and ocean profiles)
- **Evaluation of emerging technology**
  - Relative fast integration and demonstration of emerging subsystem technologies
- **Integration of capability by the science community**
  - Demonstrate the value and closely work with the science community to integrate measurements in research and modeling

Airborne High Spectral Resolution Lidar (HSRL) measurements from the ER2



Atmosphere-ocean example from the NAAMES EVS mission



Technology and Driving Requirements

Technology challenges: from CALIOP to HSRL



- Laser (F. Hovis)
  - High energy lower repetition rates
  - Injection seeded lasers for single frequency operation.
  - Multiwavelength (1064, 532, 355nm)
- Detectors (R. Hare)
  - Improvements in detector efficiency can reduce laser power and telescope size thereby reducing overall mission cost
  - Increasing resolution and dynamic range enables new science – clouds and ocean
- Receiver
  - Spectral Filters - interferometers

Also, Jennifer Inman will present later in the workshop on laser eye-safety assessments.

Laser pulse-energy/rep-rate regimes



- Bookend transmitter options
  - High-pulse-energy and low-rep-rate
  - Low-pulse-energy and high-rep-rate

- Langley approach: High-pulse-energy and low-rep-rate
  - Dates back to LITE, then CALIPSO
  - Current approach for Langley's Decadal Survey concepts

- Why?
  - Daytime performance is optimized

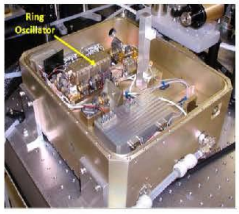
Daytime measurements are critical!

- **Aerosol Science**
  - Aerosol vertical structure, particularly near the surface, differs between night and day and is critical to understand for air quality
  - Direct radiative effect and aerosol-cloud-interactions deal with scattering and absorption of sunlight
- **Cloud science**
  - Clouds have a large diurnal variation in spatial distribution
  - Two parts to cloud radiative effects:
    - Absorption and emission of longwave radiation: occurs both day and night
    - Reflection of sunlight back to space: daytime only
- **Combined lidar and passive sensors**
  - A-Train demonstrated the huge benefit of integrating data from CALIPSO and passive sensors, i.e., CALIPSO and MODIS day vis and NIR observations.
  - Decadal Survey: A&CCP recommends lidar and polarimeter
    - Lidar profile (vertical dimension) & polarimeter column (horizontal dimension)
      - Aerosol, cloud, and ocean phytoplankton distributions
      - Detailed aerosol optical and microphysical characteristics
      - Polarimeter provides aerosol measurements in the visible only during the daytime

High-Energy Laser Development Path

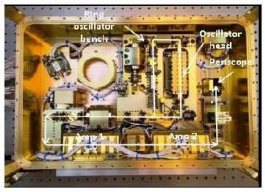
- Past: Airborne HSRL (IRAD, ESTO, R&A, SBIR)
  - Development and demonstration of HSRL approach
  - Iterations allow simplification of approach and scaling of laser energy and power
  - Provided the basis for a risk reduction laser for space

HSRL-2 Pulsed Laser



- Present: Risk Reduction Laser Development (ESTO)
  - Cross cutting in applications (Aerosol/Cloud/Ocean and Winds)
  - Multiple wavelength (1064, 532, 355nm)
  - A component of effort addresses lifetime for UV wavelengths. UV adds science capability but is not required for HSRL approach
  - ETSO funded and managed with input from the end users

HEUVD Pulsed Laser



- Present: Lifetime testing of pump diodes (IRAD)
- Future: blue laser for ocean profiling

Detectors: advances in performance can have large impact on science and mission cost and risk

- Atmospheric Measurements
  - PMT detectors (CALIPSO, ICE-Sat II 532nm)
  - APD detectors (CALIPSO 1064nm)
- Ocean Measurements (Rich Hare)
  - Higher vertical resolution (~10x over atmosphere)
  - Higher dynamic range
  - Low transient response error from ocean surface return
    - Airborne Measurements (tilted instrument to reduce specular reflection) and used Hybrid Photomultiplier Detectors (HPDs)
  - Also enables new opportunities for profiling into clouds
- New detector technology exists and has a path to TRL 6

HSRL interferometric optical filter is the baseline for space applications

Interferometers (ESTO, R&A, IRAD)

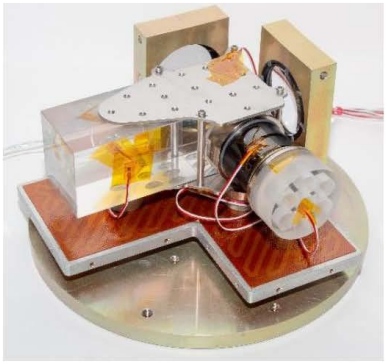
- photon efficient
- applicable at different wavelengths
- high-rejection of aerosol scattering
- applicable to atmospheric and ocean measurements

LaRC Development Timeline
(ESTO – IIP/QRS and IRAD)

2006	Concept and performance studies
2007	Design and build interferometer (532nm)
2009	Atmospheric comparison tests (532nm)
2010	Delivery of 355nm Intf. (piezo tuned)
2012	Flight demonstration 355nm piezo tuned
2013	Delivery of 355nm Intf. (pressure tuned)
2015	Flight demonstration 355nm press. tuned
2017	Environmental and Vibe testing 355nm

Development cycle took nearly a decade to from concept to final iteration.

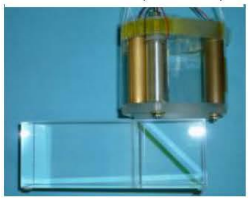
Space EDU Interferometer
TRL 6



Space version of HSRL interferometer now at TRL6

Aircraft Versions

Piezo-Tuned (HSRL-2)



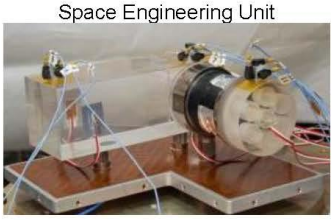
Pressure/Temperature Tuned (HSRL-2)



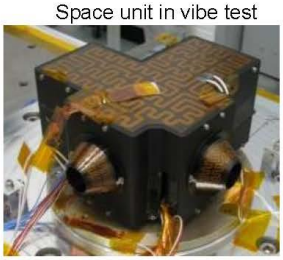
Performance exceeds ATLID interferometer by 10X

Space Version

Space Engineering Unit



Space unit in vibe test



Funded through multiple programs: NASA ESTO(IIP,QRS), R&A, and IRAD

Challenges and Summary

Challenges (1 of 2)



- NASA can't do it all – requires capable industry partners.
- NASA's main role is defining science requirements and lidar systems engineering and performance testing
- Challenge is that these are low volume applications.
  - Need to target companies willing to work in this low volume R&D market and maintain corporate knowledge.
  - How to keep these companies funded and advancing key lidar technologies?
- Competition is good, but can't spread the limited funding too thin.

- Successful HSRL industry partnerships
  - Seed laser development - SBIR
  - Pulsed laser development – ESTO and SBIR
  - Interferometer development and demonstration - ESTO, R&A and IRAD
  - Detectors – ESTO and SBIR

Challenges (2 of 2)



- Funding requires interleaving support though multiple competitive programs supported by ESTO, R&A, and SBIR.

- Funding for specific programs (i.e. IIP, ACT) are offered on 3 or 4-year cycles which may not align with the development cycle.

- Funding gap exists for subsystem technology maturation to TRL 6.
  - ACT Program targets low TRL. Need follow-on program to mature successful development of subsystems to TRL 6.

- Recruitment of early career personnel and obtaining funding for training and integration into lidar program.
  - Our group has leveraged the NPP (Post-doctoral Program), however only a few university programs offering lidar remote sensing R&D programs.

Summary



- Decadal Survey calls for lidar capability beyond CALIOP and the A-train
- The HSRL technique is mature as demonstrated for 12+ years via airborne prototypes to flesh out requirements and to advance technology
- The main subsystems that enable the HSRL technique are mature
- Technology advances in detector performance would:
  - reduce overall mission cost and risk
  - Create new and cross-cutting science capabilities (ocean and cloud profiling capabilities)
- Near-term (~4 years) advancement of technology readiness will enhance the Aerosols, Cloud, and Ocean Mission or buy down the overall cost and risk.

Backup Slides

Langley HSRL Instrument Timeline

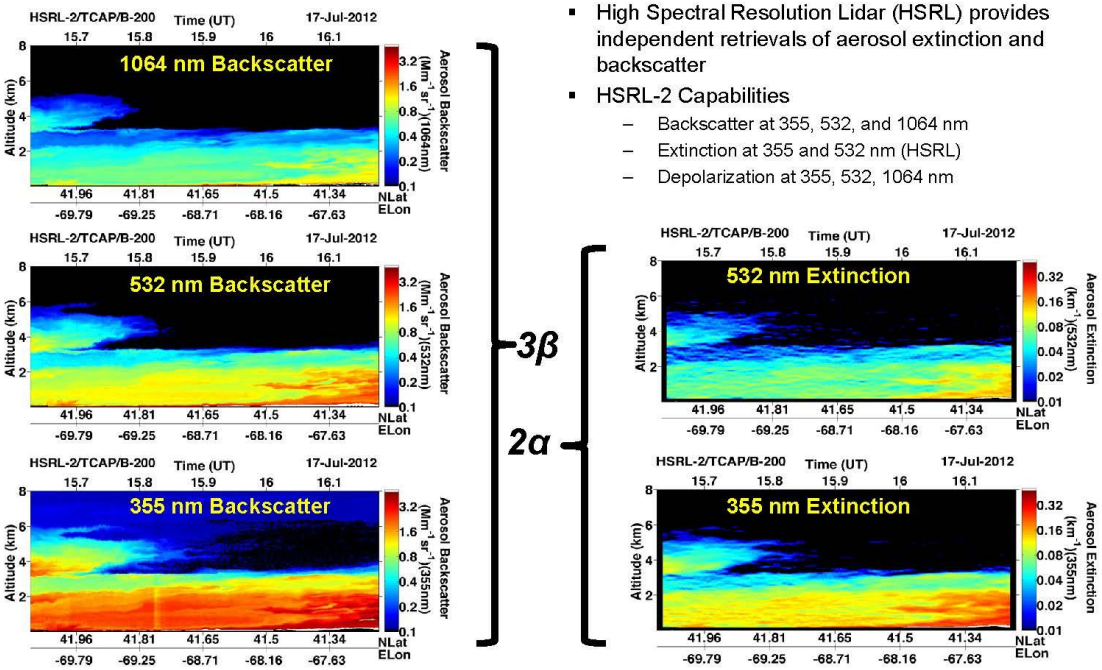
1st Generation HSRL

- Summer 2000 – Concept development.
- 2001 through 2003 – Instrument Development.
- Dec 2004 – First test flight on Learjet
- March 2006 – First flight mission on B200 (Mexico City).
- 2006 to Present – Various flight campaigns.
- 2011 to Present – Ocean subsurface measurements.

2nd Generation HSRL

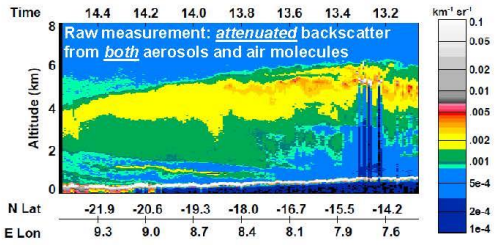
- 2006 to 2009 – Instrument Development.
- 2009 to Present – Automate HSRL for ER2 aircraft.
- 2012 to Present – Field campaigns on B200 aircraft.
- 2015 to Present – Flight demo and field campaigns on ER2.

Airborne multi-wavelength "3β+2α" HSRL



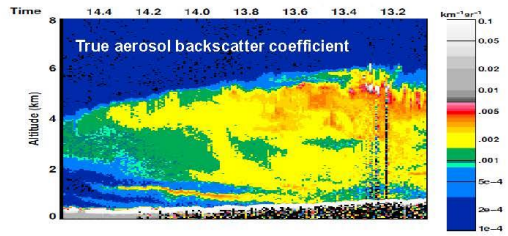
- High Spectral Resolution Lidar (HSRL) provides independent retrievals of aerosol extinction and backscatter
- HSRL-2 Capabilities
  - Backscatter at 355, 532, and 1064 nm
  - Extinction at 355 and 532 nm (HSRL)
  - Depolarization at 355, 532, 1064 nm

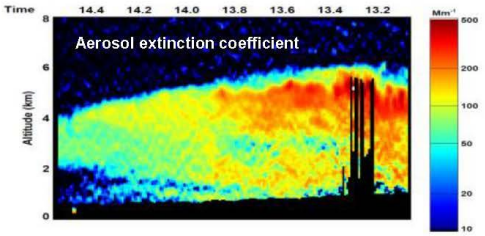
Advanced technique (HSRL) provides greater accuracy



- **Problem:**
  - CALIPSO measures the *attenuated* backscatter coefficient
  - What we actually want is
    - The *true* aerosol backscatter coefficient
    - And the aerosol extinction coefficient
  - To get these, we must somehow correct for extinction as the retrieval proceeds downward through the profile
    - This correction can have significant (30-100%) errors
    - The errors accumulate with integration and are largest near the surface.

- **Solution: High Spectral Resolution Lidar**





HSRL ocean retrievals validated against ocean color and in situ measurements

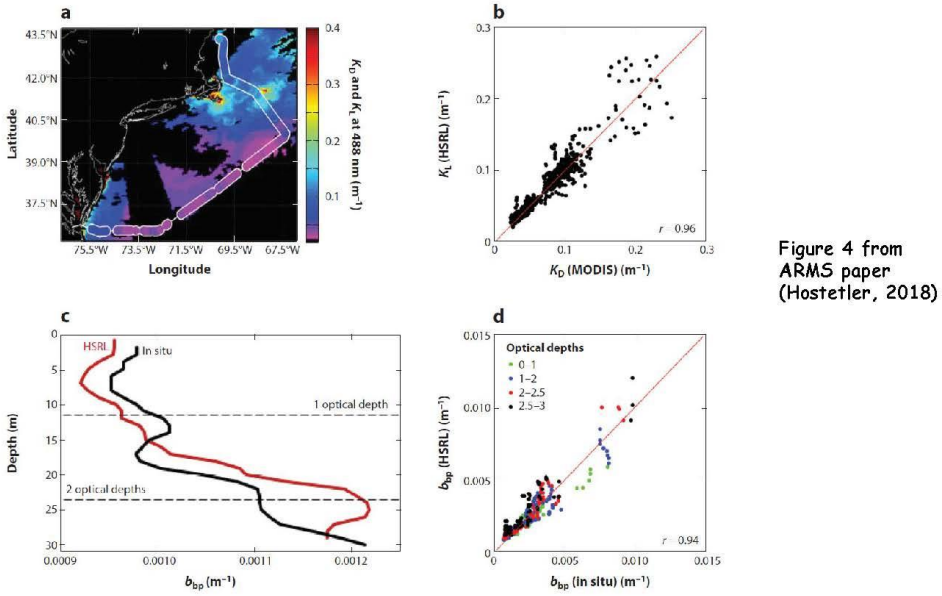


Figure 4 from ARMS paper (Hostetler, 2018)

1.3 LASER DEVELOPMENT FOR THE NEXT GENERATION OF CLOUD, AEROSOL, AND OCEAN LIDAR SYSTEMS

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ABSTRACT

The 2017 Earth Science Decadal Survey [1] has identified clouds, convection, & precipitation and aerosols as two of the designated space-based measurements. We provide a brief survey of this class of measurements and discuss approaches and barriers to the next generation of laser transmitters needed to make these measurements.

1 INTRODUCTION

The space-based Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) [2] and the Cloud-Aerosol Transport System on the International Space Station (CATS-ISS) [3] lidar instruments have demonstrated the value of space-based cloud and aerosol measurements in providing new insight into the role that clouds and atmospheric aerosols play in regulating Earth's weather, climate, and air quality. This assessment is reinforced by the recent Earth Science Decadal Survey in which aerosols plus clouds, convection, and precipitation were two of the five targeted observables in the highest priority Designated category. With CATS now decommissioned and CALIPSO at 12 years of an originally planned 3-year mission, it is important for NASA to be preparing for the next generation of these measurements. A key part of this preparation is the development and TRL advancement of the laser transmitters needed for the next generation of space-based cloud and aerosol lidar systems.

Two obvious areas for improvements in the laser transmitters are higher efficiency and lower mass. Additional areas for development include incorporation of injection seeding to achieve the narrowed linewidths needed for high spectral resolution lidar systems, the addition of a long-lived UV channel to allow more accurate measurements of the micro-physical properties of the clouds and aerosols, shorter pulsewidths for enhancements to subsurface ocean measurements demonstrated with CALIPSO data, and the addition of a blue channel for better ocean penetration to further enhance subsurface ocean measurements. These transmitter upgrades will require a significantly higher level of investment than was made with the CALIPSO Risk Reduction Laser. We will provide an overview of current NASA supported cloud and aerosol transmitter development that includes a summary of ongoing activities, suggestions for future support, and an evaluation of how the transmitter development for cloud and aerosol lidar systems can be leveraged for use in other active space-based lidar measurements.

2 CURRNT TECHNOLOGY AND MISSIONS

2.1 LIDAR IN-SPACE TECHNOLOGY EXPERIMENT (LITE)

LITE (Fig.1) was a three wavelength (1064nm/ 532nm/355nm) backscatter lidar flown on a short duration Space Shuttle mission that demonstrated the possibility and value of space-based cloud and aerosol measurement [4]. The laser technology used was a flash lamp pumped transmitter that was appropriate for a 2 week duration mission but that would need to be upgraded to diode pumping for a long duration space-based mission. The results from the LITE mission were important in demonstrating that useful cloud and aerosol lidar measurements could be made from space.

2.2 CALIPSO

CALIPSO (Fig. 2) was a successful demonstration of the high energy, low repetition rate approach to cloud and aerosol measurements from space. It was based on Fibertek built transmitters using diode-pumped laser technology that were capable of 110 mJ/pulse at both 1064 nm and 532 nm at a repetition rate of 20 Hz. CALIPSO was launched in 2006 and is still operational. It has provided an extensive and long duration record of the world wide distribution and composition of clouds and aerosols. It has also shown that a space-based lidar could support long duration measurements from space.

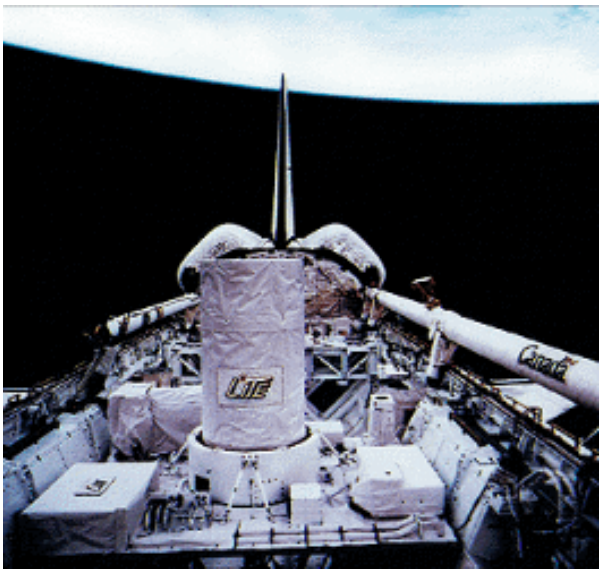

Figure 1. LITE instrument on the space shuttle

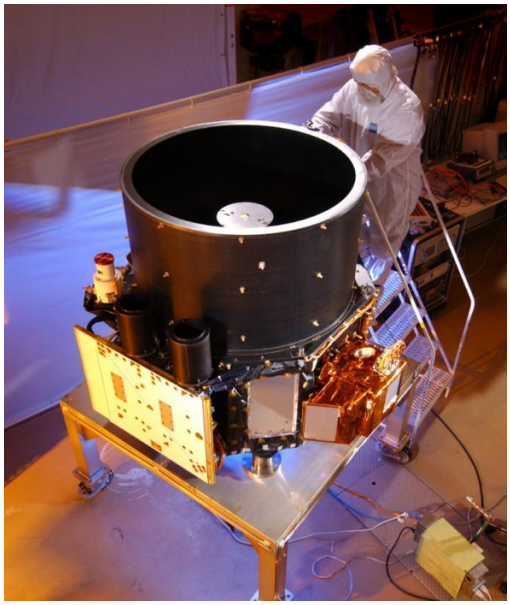

Figure 2. CALIPSO lidar before integration with the spacecraft bus

2.3 CATS-ISS

CATS-ISS (Fig.3) was an international space-station based lidar remote sensing instrument for range-resolved profile measurements of atmospheric aerosols and clouds. It incorporated Fibertek built high repetition rate lasers to derive the properties of cloud and aerosol layers including layer height and thickness, optical depth, extinction, and depolarization-based particle type discrimination. It including two lasers, one of which was injection seeded, whose properties are summarized in Table 1. CATS-ISS was a successful demonstration of the low energy, high repetition rate approach to cloud and aerosol measurements from space.

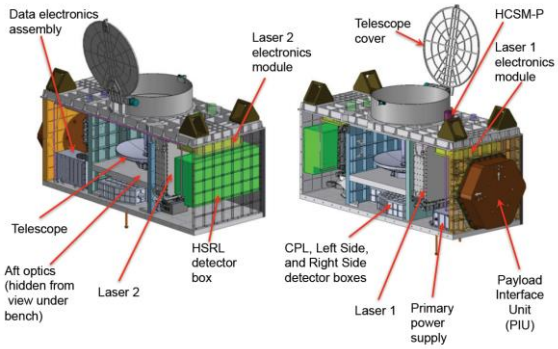

Figure 3.Views of the CATS-ISS lidar system

Table 1. Key performance parameters of the two lasers CATS-ISS lidar system

Parameter	Laser #1	Laser #2
Total Energy (mJ)	5.4	5.8
Rep Rate (Hz)	5,000	4,000
1064 nm (mJ)	2.6	2.3
532 nm (W)	2.8	1.2
355 nm (W)	NA	2.3
Linewidth (pm)	0.1-0.3	Single-ν

2.4 EARTH CLOUDS, AEROSOLS, AND RADIATION EXPLORER (EARTHCARE)

EarthCARE (Fig.4) is a multi-instrument cloud and aerosol mission currently being developed by the European Space Agency (ESA). It includes an atmospheric lidar, a cloud profiling lidar, a multi-spectral imager, and a broadband radiometer. The lidar instrument is based on a single-frequency 355 nm laser that provides 38 mJ/pulse at 51 Hz. Single frequency operation allows the separation of particle and molecular Rayleigh scattering.

The lasers have been delivered for instrument integration. ESA invested significantly in diode laser qualification and in mitigating laser induced damage and laser induced contamination to accomplish this.



Figure 4. Artist conception of the EarthCARE satellite

3 CLOUD & AEROSOL LASER TECHNOLOGY DEVELOPMENT

The NASA Earth Science Technology Office (ESTO) has been funding laser technology development for space-based lidar systems for over two decades. In this section we briefly review currently funded ESTO programs that are focused on developing the laser transmitter technologies needed for the next generation of space-based cloud and aerosol lidar systems.

3.1 HIGH ENERGY UV DEMONSTRATOR (HEUVD)

Fibertek has been funded by ESTO to develop a UV laser for a next generation cloud and aerosol mission that incorporates a high spectral resolution lidar system. The key laser performance and program goals are listed below.

- Injection seeded
- 150 Hz, 250 mJ total energy
- 100 mJ @ 355 nm
- 60 mJ @ 532 nm
- 90 mJ @ 1064 nm
- Lifetime >10 billion shots
- Full conductive cooling
- Evaluate impact of reduced contamination on lifetime by the incorporation of an ultra-clean UV conversion module

The laser transmitter needed to accomplish these goals (Fig. 5) has been built and subjected to a number of lifetime tests. These include an initial 20 kHz UV screening test, a full power 532 nm life test (125 mJ at both 1064 nm and 532 nm), a half power (50 mJ @ 355 nm) UV life test, and a full power (100 mJ @ 355 nm) UV life test. Thermal/vacuum and vibration testing are still needed to advance the laser to TRL 6.

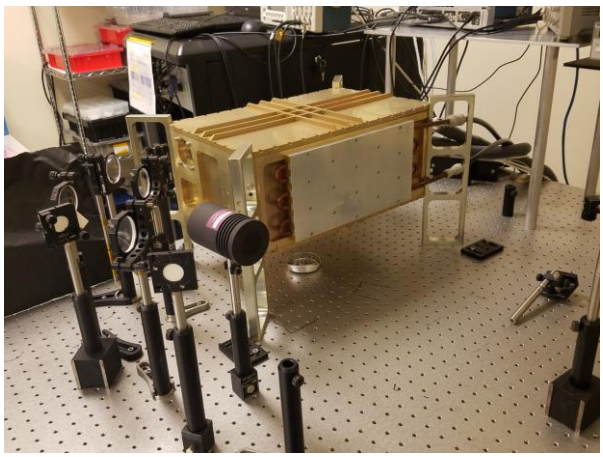

Figure 5. Lifetime testing of the HEUVD laser

The successful UV lifetime tests showed that a high level of contamination control is a key element of achieving a long lived UV laser. The testing also reinforced surfaced the need for continued attention to pump diode lifetimes and optical coatings external to the ultra-clean environment of the UV conversion module.

At a programmatic level our conclusion from the HEUVD program is that ESTO funding is important for advancing the TRL of lidar technology, but more support is needed. Our preferred approach is enhanced funding through ESTO vehicles (ACT, IIP, Phase III SBIRs, …). This approach better allows for and enhances participation of the full technical community, i.e. NASA centers, universities, and industry

3.2 CATS ELECTRONICS

ESTO is also providing funding for the next generation of laser transmitters needed for the low pulse energy, high repetition rate approach to a space-based cloud and aerosol lidar. The laser transmitter (Figure 6) was built by Litespar with NASA SBIR funding. It is design for 4.5 kHz operation and provides 4 mJ/pulse at both 1064 nm and 532 nm. ESTO is funding the development of the electronics module needed to run the laser (Figure 7). The overall system is designed for lower weight and higher efficiency and has been

vibration tested to >16 G_{rms} and thermally cycled from -30°C to +60°C.



Figure 6: SBIR funded 4.5 kHz laser optical head. 16" x 9" x 4.5" and 26 lbs.



Figure 7: ESTO funded electronics for the 4.5 kHz laser in Figure 6. 12" x 16" x 4" and 24 lbs.

4 CRITICAL TECHNOLOGY CHALLENGES

4.1 GENERAL CHALLENGES FOR CLOUD & AEROSOL LIDAR TRANSMITTERS

Optical damage is one of the key issues that the must be taken into account in the design of the pulsed laser transmitters used in space-based cloud and aerosol lidar systems. Optical designs must be careful to limit susceptibility to laser induced damage by ensuring all of the optics in the transmitter have damage thresholds that provide margin relative to the peak fluences they experience. In CALIPSO the margins relative to measured optical damage thresholds were 3X. Damage thresholds are strongly wavelength dependent and can be more than 4X lower at 355 nm than at 1064 nm.

Since laser transmitters are effectively active interferometers, they have a sensitivity to misalignment from a few to a few tens of µrad. The opto-mechanical designs must be stiff and well analyzed to ensure that they will maintain alignment after launch level vibration and during the thermal cycling that can occur on orbit.

Clouds and aerosols are diffuse, extended targets that are much more difficult to observe than the hard targets of topographic lidar systems. The optimum system design is a trade between pulse energy, detector sensitivity, amount of signal averaging, and transmitter efficiency.

Many laser systems require custom/specialized materials. Laser and optical materials for 1 µm and 0.5 µm are relatively mature with well-established supply chains, but other wavelengths require less mature materials or have a limited number of vendors. Some electro-optic crystals such as RTP, KTP, KD*P, & BBO that are needed for both q-switches electro-optic modulators are relatively mature but still have challenges due to bias induced absorption, color center formation, and high-voltage packaging.

Although the addition of a UV channel would enhance lidar measurements of clouds and aerosols, they have yet to be deployed in a long duration space-based mission due to long term degradation of the optics. UV optics need special design and process attention to control long term contamination damage effects.

4.2 OPTICAL COATINGS AND COMPONENTS

Procuring the high damage threshold coatings needed for space-based lasers requires significant effort for each mission. The coatings are typically done by small companies with relatively high turn-over and consolidation rates. For example, ICESat-2 started with two optical coating vendors who were then both acquired and consolidated. Our goal of two independent sources was compromised as a result of this change. A consideration of these types of issues leads to the conclusion that optics qualification will most likely need to be done on an individual mission basis.

Optical rotators are used in ring oscillators to enforce unidirectional operation and are the key component in the optical isolators needed to prevent feedback between the stages of a multi-stage laser transmitter. COTS rotators are available, but they do not typically meet the requirements of a long duration space-based

mission. They can be qualified but effort can be significant. This was the approach taken on both CALIPSO and ICESat-2.

Laser gain media and nonlinear conversion crystals continue to be key components of the lasers used in cloud and aerosol lidar transmitters. The COTS supply chain for a number of the key crystals (Nd:YAG, Nd:YVO_4, LBO, KTP) is good, but attention must be paid to getting high damage threshold coatings. A growing issue is that an increasing percent of the vendors for these materials are outside of the U.S.

Several key transmitter components and technologies will likely continue to only be available through the commercial supply chain. Plans to qualify them should be made early in the mission planning.

4.3 Laser Diode Space Qualification

Space-flight qualified laser diodes are generally not available as commercial-off-the-shelf (COTS) components. The commercial market has shifted toward high-power, fiber-coupled, CW sources that are useful for high repetition rate systems. The commercial and DoD market for the multi-billion shot QCW arrays needed for high energy systems is limited. Because there are no space-qualified diodes available on the market, A unique certification & qualification plan must be developed for each COTS diode laser. The baseline for laser diode space certification and qualification program should include the following.

- Technology plausibility study
- Component and system pedigree reviews
- Environmental acceptance testing
- Extensive life testing
- Laser diode qualification and capability testing
- Statistical up-screening of COTS laser diodes

5 AREAS FOR FURTHER TECHNOLGY DEVELOPMENT

5.1 Fiber Lasers & Components

Fiber lasers have increasing utility for space missions due to advantages in efficiency & compactness. They are being developed for the LISA gravitational wave mission, the ASCENDS CO_2 mission, and for multiple programs developing sources for laser communications. Although promising as sources for space-based lidar, fiber lasers do have challenges to overcome. These include the fact that they peak-power limited, have power dependent linewidths (~10 kW narrow-linewidth, ~100 kW broad-linewidth), and may issues with radiation hardness. In spite of these limitations fiber lasers have a high potential for impacting lidars and other instruments that can use high average power cw or low energy pulsed lasers due to their high beam quality and higher efficiency than bulk solid-state lasers.

Fiber only systems seem less likely to impact future space-based cloud & aerosol lidars due to their peak power limitations. Hybrid fiber/bulk solid state may provide waveform flexibility to enable multi-mission utility and further work on radiation hardening will be important for use in long duration space missions.

COTS components developed for the telecom & laser manufacturing industries may enable low-cost high-power systems.

Continued NASA support for fiber laser technology development through the SBIR program should be given high priority

5.2 Injection Seeded Laser Technology

A high spectral resolution-based cloud and aerosol lidar will need to incorporate a single-frequency laser source and injection seeding is the most likely approach for line narrowing. The implementation of injection seeding will require the development of space-qualified seed sources. The most commonly used 1064 nm source for fielded airborne lidars are COTS lasers based on is based on nonplanar ring oscillator technology, but currently no domestic suppliers are willing to develop space-qualified versions. There are available European sources are available, but they are expensive. Diode based sources are promising alternatives but still need further development for use in long duration space missions.

Continued NASA support through the SBIR program is needed to mature seed laser technology

5.3 Long-Lived UV Transmitters and Transport Optics

High power UV lasers are more susceptible to damage from both laser induced optical damage

and laser induced contamination damage. Laser induced optical damage tends to be abrupt and catastrophic, but laser induced contamination damage is a longer-term effect that is worse in vacuum where there is no O_2 to suppress the deposition of contaminants. Enhanced contamination control procedures and polymer free operating environments are needed mitigate of laser induced optical damage.

Additional work to better understand and quantify both types of damage should be supported. Normal laboratory levels of gas phase contaminants can result in rapid laser induced contamination. Vacuum operation lowers laser induced optical damage threshold and accelerates laser induced contamination damage. ESA supported significant efforts in these areas during the build and qualification of the space-based Aeolus wind lidar and ATLID aerosol and cloud lidar and NASA needs to do the same.

More basic research on the mechanisms of contamination induced damage is needed. This is a good area for partnership with universities.

5.4 Power Scaling to > 50 W

Higher powers from both higher energies and higher repetition rates will be important for future space-based lidar systems for better SNR, better vertical resolution, and higher density horizontal area sampling. Improved efficiencies are needed to significantly improve our ability to power scale new laser designs. ICESat-2 and CATS technology provide a path to power scaling to ~100 W without major design changes. Fiber lasers can be readily scaled to >100 W but need additional work on component technology and radiation hardness. Additional support of beam combining technology is a possible path to the higher energies needed for space-based applications.

Power scaling is an area where leveraging DoD R&D is likely to be productive

5.5 Efficient Blue Lasers for Improved Subsurface Ocean Measurements

Progress in the development of robust and efficient blue lasers for underwater lidar systems has been slow in spite of decades of R&D effort. Nonlinear mixing schemes have been demonstrated but tend to be complex and inefficient. Robust fundamental pump lasers that could be doubled or tripled to blue have yet to materialize. Significant advances in laser or nonlinear optical materials are needed.

More support and ideas for low TRL development activities on blue laser technologies are needed

6 COLLABORATION, PERSONNEL, AND RESOURCE ISSUES

6.1 Small Company Perspective on Industry/NASA/Academia Collaboration

Collaboration is necessary for successful NASA missions. We have observed that the following set of overall responsibilities by organization has somewhat organically developed.

- NASA: Mission science & prioritization, end-to-end expertise
- Large contractors: Large systems engineering & integration
- Small business: Technology enablers & specialty engineering
- Academia: Innovative phenomenology & science motivation

Fibertek's experience in collaboration has tended to be positive and includes some successful examples.

- CALIPSO → collaboration between NASA, Ball Aerospace, and Fibertek
- ICESat-2 → collaboration between GSFC, Lucent Government Systems, and Fibertek

We have also has found the SBIR/STTR program to be effective in promoting partnerships with both NASA centers and universities

Although our collaboration experiences have been generally positive, one of the barriers to effective collaboration we have experience is the case where the overlap of technical regions of interest result in our NASA colleagues being both customers and competitors.

An open dialogue on how to deal with the intrinsic conflicts that can develop since NASA is both a competitor and partner with industry would be helpful

6.2 PERSONNEL AND OTHER RESOURCE ISSUES

Fibertek's experience in maintaining staff between CALIPSO and ICESat-2 was very good, with a large percent of key personnel having worked on both programs. Due to the relatively long lag between fight missions this in not likely to be repeated. Going forward, our corporate memory must be maintained by developing designs and processes that can be used on other projects. This will both help to span the relatively long times between flight missions and to make results more readily applicable to more than NASA programs. Increasing mobility of personnel is an additional motivator for better process development.

One of the downsides to having primarily NASA, DoD, and aerospace primes as our main customer is that the resulting focus on primarily custom work has led to periodic significant oscillations in our business base. This is likely an issue for many small companies with a NASA/DoD business focus. The issue is aggravated by the deceasing pool of lidar available scientists and engineers.

A DoD like approach of targeting funding to university groups involved in lidar R&D should be considered by NASA

7 CONCLUSIONS

A high-level summary of our observations and conclusions is given below.

- The value of lidar systems as a component of a cloud & aerosol mission is well demonstrated by the LITE, CALIPSO and CATS-ISS missions.
- The next space-based cloud & aerosol lidar will likely be on the ESA multi-sensor EarthCARE mission.
  - Even a 3-year slip from the currently projected August 2019 launch date will be well before the current projection for the Decadal Survey designated missions.
- ESTO is supporting the technology development needed to advance the TRL of space-based remote sensing (including active optical systems).
  - Additional funding is needed for more frequent ACT and IIP (or similar) calls.
- COTS components are likely to be key components for active optical for the foreseeable future.
  - Work is needed to streamline the processes for qualification COTS components.
- Strong support for new active remote sensing technology through the SBIR and STTR programs needs to be maintained.
- There have been many successful industry/NASA mission collaborations, but work is needed in areas where NASA is both a competitor and partner.
- Maintaining knowledge and staffing between mission needs more attention.
- New programs to increase the pool of lidar scientists & engineers are needed.
  - Focused development programs with universities is one possibility.

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17. McGill, M. J., Yorks, J. E., Scott, S., Kupchock, A. W., and Selmer, P. A., "The Cloud-Aerosol Transport System (CATS): a technology demonstration on the International Space Station", Proc. SPIE 9612, Lidar Remote Sensing for Environmental Monitoring XV, San Diego, CA, 2015.
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Laser Development for the Next Generation of Cloud, Aerosol, and Ocean Lidar Systems

Fibertek, Inc.
13605 Dulles Technology Drive
Herndon, VA 20171

Agenda

- Previously flown systems
- Currently ESTO funded technology development
- ESA next generation cloud & aerosol mission
- Critical technology challenges
- Technical areas for future development
- Collaboration, Personnel, and Resource Issues

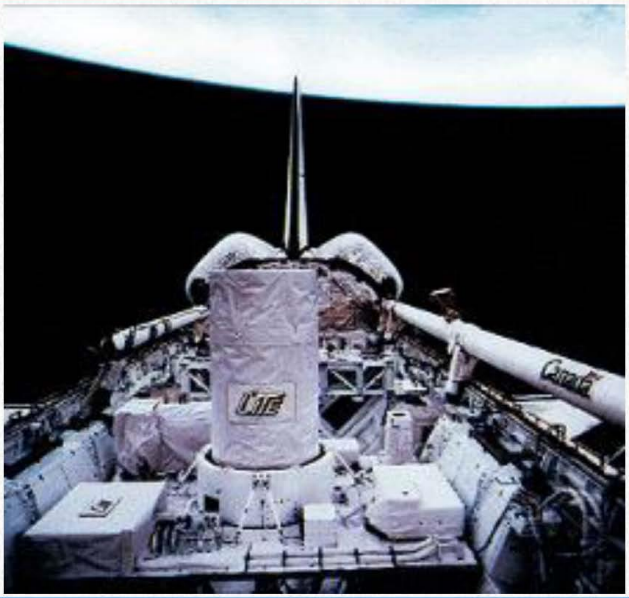
FIBERTEK, INC.

Previously Flown Space-Based Cloud & Aerosol Lidar Systems

Lidar In-space Technology Experiment (LITE)

FIBERTEK, INC.

- Three wavelength (1064nm/ 532nm/355nm) backscatter lidar that demonstrated the possibility and value of space-based cloud and aerosol measurement
- Flash lamp pumped transmitter was appropriate for a 2 week duration mission

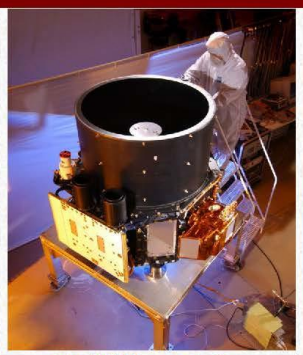


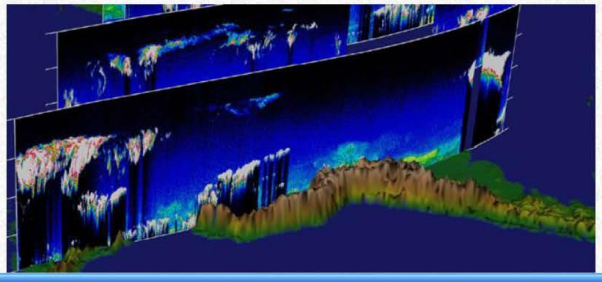
The results from the LITE mission were important in demonstrating that useful cloud and aerosol lidar measurements could be made from space

4

CALIPSO Flight Lasers



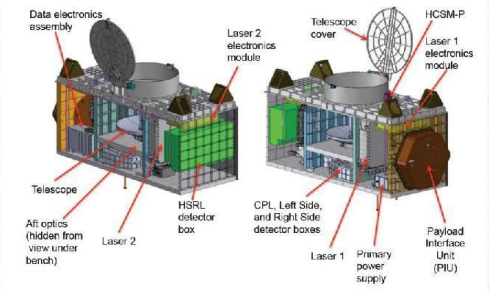




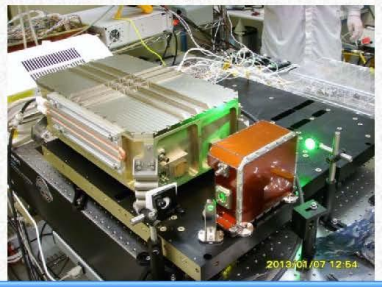
Fibertek Built CALIPSO Flight Lasers
Lasers delivered in 2002
CALIPSO launched in 2006
Space-based aerosol measurements
Nd:YAG x2 Total energy 220 mJ @ 20 Hz 110 mJ @ 1064 110 mJ @ 532 nm
3 yr mission completed with laser SN #2 Laser SN #1 has operated for additional 9 years, 5.5×10^9 shots on orbit

CALIPSO was a successful demonstration of the high energy, low repetition rate approach to cloud and aerosol measurements from space

ISS Cloud-Aerosol Transport System (CATS)



Laser #2 on the Flight Optical Bench



- **LiDAR remote sensing instrument for range-resolved profile measurements of atmospheric aerosols and clouds.**
- **Incorporated a high repetition rate lasers to derive properties of cloud and aerosol layers**
  - Layer height & thickness
  - Optical depth
  - Extinction
  - Depolarization-based particle type discrimination

Key Fibertek Laser Performance Parameters

Parameter	Laser #1	Laser #2
Total Energy (mJ)	5.4	5.8
Rep Rate (Hz)	5,000	4,000
1064 nm (mJ)	2.6	2.3
532 nm (W)	2.8	1.2
355 nm (W)	NA	2.3
Linewidth (pm)	0.1-0.3	Single-v

CATS-ISS was a successful demonstration of the low energy, high repetition rate approach to cloud and aerosol measurements from space

FIBERTEK, INC.

ESA Next Generation Cloud & Aerosol Mission

ESA Earth Clouds, Aerosols, and Radiation Explorer (EarthCARE)

FIBERTEK, INC.

- **Atmospheric Lidar (ATLID)**
  - 38 mJ @ 355 nm
  - 135 mJ total
  - 51 Hz
  - 20 ns
  - Single frequency to allow separation of particle and Rayleigh scattering
- **Cloud Profiling Radar**
- **Multi-Spectral Imager**
- **Broad-Band Radiometer**



Lasers have been delivered for instrument integration. ESA invested significantly in diode laser qualification and in mitigating laser induced damage and laser induced contamination to accomplish this.

8

FIBERTEK, INC.

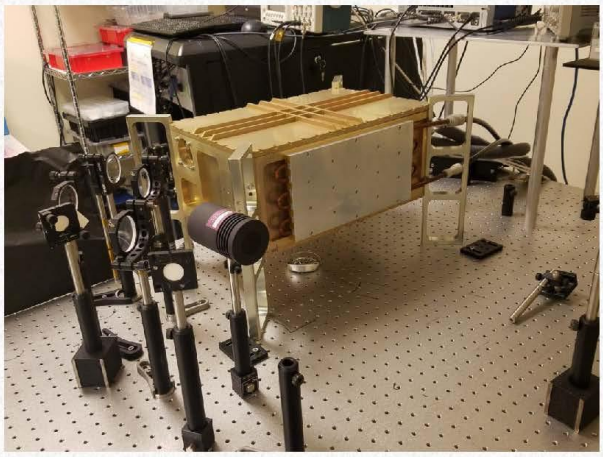
Currently Funded ESTO Cloud & Aerosol Laser Technology Development

High Energy UV Demonstrator

Program Objectives & Approach

FIBERTEK, INC.

- **Fibertek program to develop a space-qualifiable UV laser**
  - Injection seeded
  - 150 Hz, 250 mJ total energy
    - 100 mJ @ 355 nm
    - 60 mJ @ 532 nm
    - 90 mJ @ 1064 nm
  - Lifetime >10 billion shots
  - Conductively cooled
  - Evaluate impact of reduced contamination on lifetime
- **Initial 20 kHz UV testing**
- **Full power 532 nm life testing**
- **Half power UV life testing**
- **Full power UV life testing**
- **Environmental testing to advance TRL**
  - Thermal-vacuum & vibration



Lifetime testing of HEUVD

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HEUVD Summary

FIBERTEK, INC.

- **A conductively cooled, single-frequency UV demonstrator laser was built and tested**
  - 100 mJ/pulse, 150 Hz @ 355 nm
  - Successfully completed life testing
    - 1.3 billion shot, full power 532 nm
    - 1.5 billion shot, 50 mJ 355 nm
    - 1.35 billion shot, 100 mJ 355 nm
      - Still needs root cause determination for seeding anomaly late in the test
  - Successful UV tests show importance of enhanced contamination control
  - Surfaced need for more attention to pump diodes and optics coatings outside of UV clean box
  - Environmental testing to follow final full power UV lifetest to advance to TRL-6
- **Designed to support multiple future lidar missions**
  - Next generation high energy, low rep rate, cloud, aerosol, & ocean lidars
  - Direct detection winds
  - Pump for trace gas detection

ESTO funding is important for advancing the TRL of lidar technology, but more support is needed. Our preferred approach is enhanced funding through ESTO vehicles (ACT, IIP, Phase III SBIRs, …). This approach better allows for and enhances participation of the full technical community, i.e. NASA centers, universities, and industry

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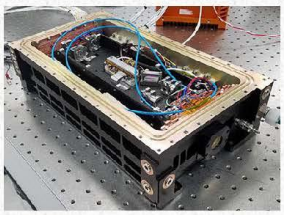
CATS Follow-On Technology Development

FIBERTEK, INC.

- **ESTO funding permitted demonstration of a flight-qualified transmitter aimed at SmallSat applications**
  - GSFC's commercial partners Litecycles, Inc. and Sigma Space Corp. developed the hardware



Optical head. 16" x 9" x 4.5" and 26 lbs



Electronics box. 2 full units in one box. 12" x 16" x 4" and 24 lbs

4 mJ/pulse at 1064 nm
4 mJ/pulse at 532 nm
4.5 kHz rep rate
vibration tested to >16 G_{RMS}
thermal cycled -30C/+60C

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FIBERTEK, INC.

Critical Technology Challenges

General Challenges of Lasers for Cloud & Aerosol Lidars

FIBERTEK, INC.

- **Optical Damage**
  - Optical designs must be careful to limit susceptibility to laser induced damage
    - Strongly wavelength dependent
- **Alignment sensitivity**
  - Laser are active interferometers
  - Requires stiff, well analyzed structures
- **Clouds and aerosols are diffuse targets**
  - Optimum system design is a trade between between pulse energy, detector sensitivity, amount of signal averaging, and transmitter efficiency
- **Many required custom/specialized materials**
  - Laser and optical material for 1 μm and 0.5 μm are relatively mature with well established supply chain
    - Other wavelengths are less mature
  - Electro-optic crystals
    - RTP, KTP, KD*P, & BBO are relatively mature
      - Still have challenges due to bias induced absorption, color center formation, and high-voltage packaging
  - UV optics need special attention to control long term contamination damage effects

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Optical Coatings & Components

FIBERTEK, INC.

- **Procuring the high damage threshold coatings needed for space-based lasers requires significant effort for each mission**
  - Typically done by small companies with relatively high turn over and consolidation rates
  - ICESat-2 started with two vendors who were then both acquired and consolidated
  - Optics qualification will most likely need to be done on an individual mission basis
- **Optical rotators**
  - Needed for isolation stages
  - COTS components can be qualified but effort can be significant
- **Laser and Nonlinear Crystals**
  - COTS supply chain for a number of the key crystals (Nd:YAG, Nd:YVO_4, LBO, KTP) is good
  - Attention must be paid to getting high damage threshold coatings
  - Many sources are non-US
- **Q-switch assemblies**
  - COTS parts had issues on ICESat-2
  - Attention to lessons learned from ICESat-2 can be used to mitigate future problems

A number of key transmitter components and technologies will likely continue to only be available through the commercial supply chain. Plans to qualify them should be made early in the mission planning.

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Laser Diode Space Certification & Qualification

FIBERTEK, INC.

- **Space-flight qualified laser diodes are generally not available as commercial-off-the-shelf (COTS) components**
  - The commercial market has shifted toward high-power, fiber-coupled, CW sources
    - These are useful for high repetition rate systems
  - The commercial and DoD market for the multi-billion shot QCW arrays needed for high energy systems is limited
- **A unique certification & qualification plan must be developed for each COTS diode laser**
- **The baseline for laser diode space certification and qualification program should include several phases**
  - Technology plausibility study
  - Component and system pedigree reviews
  - Environmental acceptance testing
  - Extensive life testing
  - Laser diode qualification and capability testing
  - Statistical up-screening of COTS laser diodes

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FIBERTEK, INC.

Areas for Further Technology Development

Fiber Lasers & Components

FIBERTEK, INC.

- **Increasing utility for space missions due to advantages in efficiency & compactness**
  - Currently being developed for LISA gravitational wave and ASCENDS CO_2 missions
  - Multiple programs developing sources for laser communications
- **Primary challenges:**
  - Peak-power limited: ~10 kW narrow-linewidth, ~100 kW broad-linewidth
  - Radiation hardness
- **High potential for impacting lidars and other instruments that can use high average power cw or low energy pulsed lasers**
  - Good beam quality and higher efficiency than bulk solid-state lasers
  - Fiber only systems less likely to impact future space-based cloud & aerosol lidars due to peak power limitations
  - Hybrid fiber/bulk solid state may provide waveform flexibility to enable multi-mission utility
  - Further work on radiation hardening will be important for long duration space missions
- **COTS components developed for the telecom & laser manufacturing industries may enable low-cost high-power systems**

Continued NASA support for in fiber laser technology development through the SBIR program should be given high priority

Injection Seeded Laser Technology

FIBERTEK, INC.

- **A high spectral resolution based cloud and aerosol lidar will need to incorporate a single-frequency laser source**
  - Injection seeding is the most likely approach for line narrowing
- **Space-qualified seed sources will be required**
  - Most commonly used 1064 nm source for fielded airborne lidars are COTS lasers based on is based on nonplanar ring oscillator technology
    - Currently no domestic suppliers are willing to develop space-qualified versions
  - European sources are available but are expensive
  - Diode based sources are promising alternatives but still need further development for use in long duration space missions

Continued NASA support through the SBIR program is needed to mature seed laser technology

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FIBERTEK, INC.

- **High power UV lasers are more susceptible to damage from both laser induced optical damage and laser induced contamination damage**
  - Laser induced optical damage tends to be abrupt and catastrophic
  - Laser induced contamination damage is a longer term effect and is worse in vacuum where there is no O_2
- **Enhanced contamination control procedures and polymer free operating environments mitigate of laser induced optical damage**
- **Additional work to better understand and quantify both types of damage should be supported**
  - Levels of gas phase contaminants in normal lab air can result in relatively rapid laser induced contamination
  - Vacuum operation tends to lower laser induce optical damage threshold and accelerate laser induced contamination damage
  - ESA supported significant efforts in these areas during the build and qualification of the space-based Aeolus wind lidar and ATLID aerosol and cloud lidar

More basic research on the mechanisms of contamination induced damage is needed. This is a good area for partnership with universities.

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Power Scaling to > 50 W

FIBERTEK, INC.

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  - Better SNR
  - Better vertical resolution
  - Higher density horizontal area sampling
- **Improved efficiencies can significantly improve our ability to power scale new laser designs**
- **ICESat-2 and CATS technology can be scaled to ~100 W without major design changes**
- **Fiber lasers can be readily scaled to >100 W but need additional work on component technology and radiation hardness**
  - Additional support of beam combining technology is a possible path to the higher energies needed for space-based applications

Power scaling is an area where leveraging DoD R&D is likely to be productive

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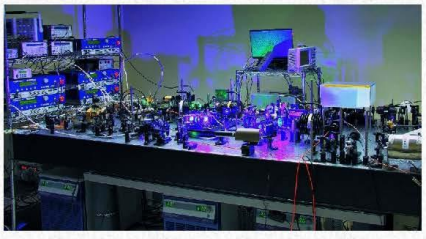
Efficient Blue Lasers for Improved Subsurface Ocean Measurement

FIBERTEK, INC.

- **Progress in the development of robust and efficient blue lasers for underwater lidar systems has been slow in spite of decades of R&D effort**
  - Nonlinear mixing schemes have been demonstrated but tend to be complex and inefficient
  - Robust fundamental pump lasers that could be doubled or tripled to blue have yet to materialize
- **Significant advances in laser or nonlinear optical materials are needed**



Fibertek 7 W blue laser based on 355 nm pumped OPO technology



Fibertek 13 W, 62 Hz blue laser demonstrator

More support and ideas for low TRL development activities on blue laser technologies are needed

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FIBERTEK, INC.

Collaboration, Personnel, and Resource Issues

Small Company Perspective on Industry/NASA/Academia Collaboration

FIBERTEK, INC.

- **Collaboration is necessary for successful NASA missions:**
  - NASA: Mission science & prioritization, end-to-end expertise
  - Large contractors: Large systems engineering & integration
  - Small business: Technology enablers & specialty engineering
  - Academia: Innovative phenomenology & science motivation
- **Successful examples:**
  - CALIPSO → collaboration between NASA, Ball Aerospace, and Fibertek
  - ICESat-2 → collaboration between GSFC, Lucent Government Systems, and Fibertek
- **Fibertek has found the SBIR/STTR program to be effective in promoting partnerships with both NASA centers and universities**
- **Barriers to effective collaboration:**
  - Overlap regions generate customer-competitor conflicts of interest

An open dialogue on how to deal with the intrinsic conflicts that can develop since NASA is both a competitor and partner with industry would be helpful

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Personnel and Other Resource Issues

- **Fibertek's experience in maintaining staff between CALIPSO and ICESat-2 was very good**
  - A large percent of key personnel worked on both programs
- **Going forward, corporate memory must be maintained by developing designs and processes that can be used on other projects**
  - Helps to span the relatively long times between flight missions
  - Applicable to more than NASA programs
  - Increasing mobility of personnel is an additional motivator for process development
- **A focus on primarily custom work has led to significant oscillations in our business base**
  - This is likely an issue for many small companies with a NASA/DoD business focus
- **Pool of lidar scientists and engineers is decreasing**
  - A DoD like approach of targeting funding to university groups involved in lidar R&D should be considered by NASA

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Summary

- **The value of lidar systems as a component of a cloud & aerosol mission is well demonstrated by the LITR, CALIPSO and CATS-ISS missions**
- **The next space-based cloud & aerosol lidar will likely be on the ESA multi-sensor EarthCARE mission**
  - Even a 3 year slip from the currently projected August 2019 launch date will be well before the current projection for the Decadal Survey designated missions
- **ESTO is supporting the technology development needed to advance the TRL of space-based remote sensing (including active optical systems)**
  - Additional funding is needed for more frequent ACT and IIP (or similar) calls
- **COTS components are likely to be key components for active optical for the foreseeable future**
  - Work is needed to streamline the processes for qualification COTS components
- **Strong support for new active remote sensing technology through the SBIR and STTR programs needs to be maintained**
- **There have been many successful industry/NASA mission collaborations but work is needed in areas where NASA is both a competitor and partner**
- **Maintaining knowledge and staffing between mission needs more attention**
- **New programs to increase the pool of lidar scientists & engineers are needed**
  - Focused development programs with universities is one possibility

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1.4 DETECTOR FOR SPACEBORNE AEROSOL-CLOUD-OCEAN LIDAR: PAST, PRESENT, AND FUTURE DIRECTIONS

Rich Hare, John Smith, Chris Hostetler, John Hair, Kathy Powell

NASA Langley Research Center, Hampton, Virginia



Detector for Spaceborne Aerosol-Cloud-Ocean Lidar: Past, Present, and Future Directions

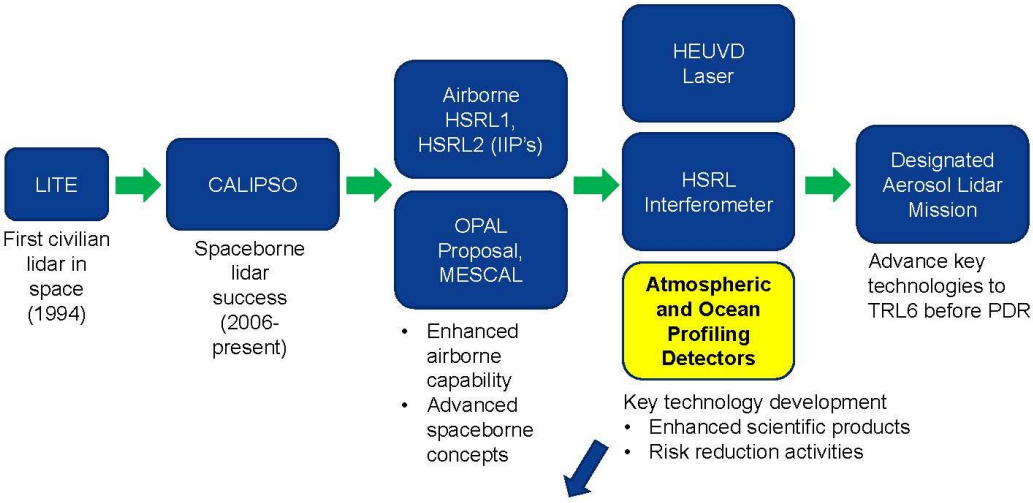
Rich Hare, John Smith, Chris Hostetler, John Hair, Kathy Powell

NASA Langley Research Center

July 31, 2018

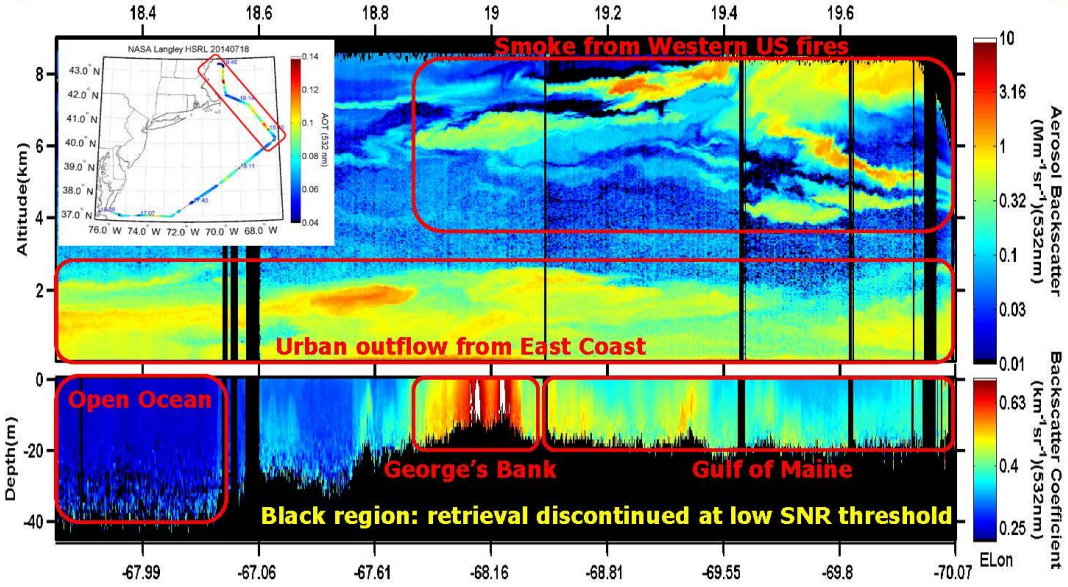
Technical Interchange Meeting on Active Optical Systems for Supporting Science, Exploration, and Aeronautics Measurements Needs

Future Aerosol Lidar Mission Technology Development at LaRC

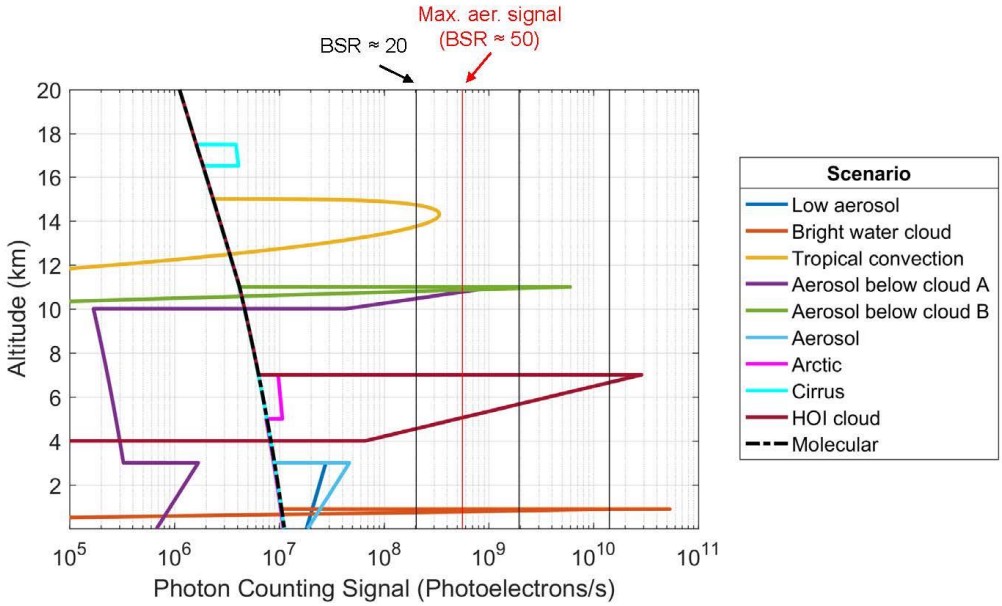


Why invest in Lidar Detector Technology?
Moderate Investment, High Reward
(Significant performance improvements with potential to reduce cost and risk)

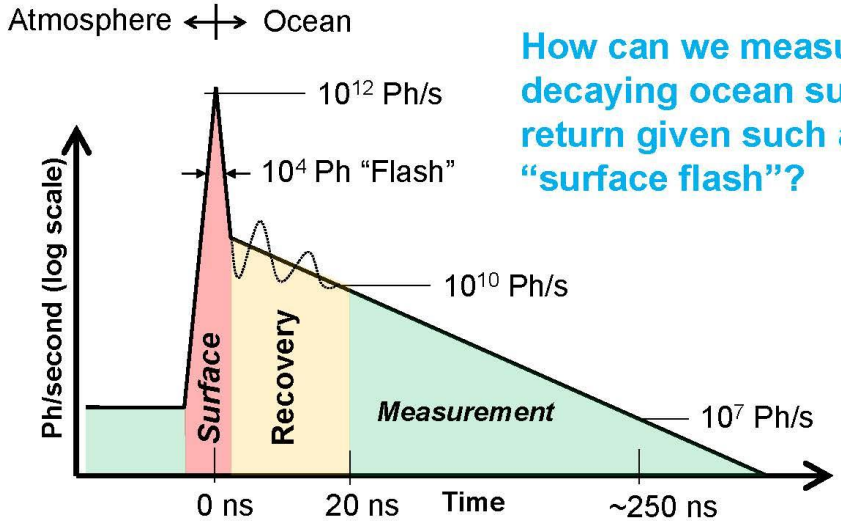
Aerosol-Ocean Application Example



Aerosol and Cloud Simulations



Ocean Measurement Challenge

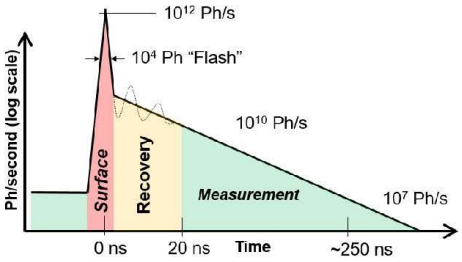


How can we measure rapidly decaying ocean subsurface return given such a large "surface flash"?

Detection Requirements

Airborne & Spaceborne Detectors

- Low afterpulsing
- Wide dynamic range
- Fast transient recovery from ocean surface flash
- Ability to accurately profile rapidly decaying subsurface signal
- High SNR/spatial resolution
  - High photon detection efficiency
  - Low excess noise

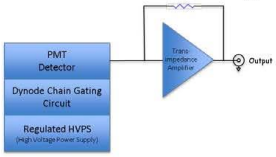


Spaceborne Detectors

- Radiation tolerant
- Magnetic Field Immune
- Low power consumption
- Good linearity, high current rating
- Long lifetime

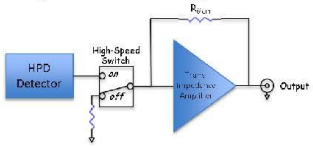
Subset of Options Evaluated ESTO HSRL-2 IIP

PMT Detector Gating



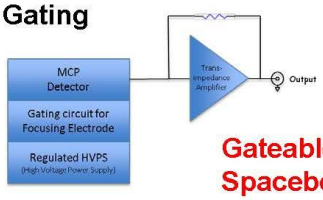
Exhibited long term gain recovery issues after gate turn on. Also, PMT after-pulsing not sufficiently reduced.

Amplifier Gating



Various methods of gating the amplifier instead of the detector were attempted including gating the amplifier input, amplifier feedback, and amplifier output. Residual glitch from switching the gate off and on was too strong to make subsurface measurement.

MCP Detector Gating



MCP detector has gating/focusing electrode allowing fast gating without strong residual switching noise. Also, the gate is ac coupled allowing low voltage gate drive signal which further decreases switching noise.

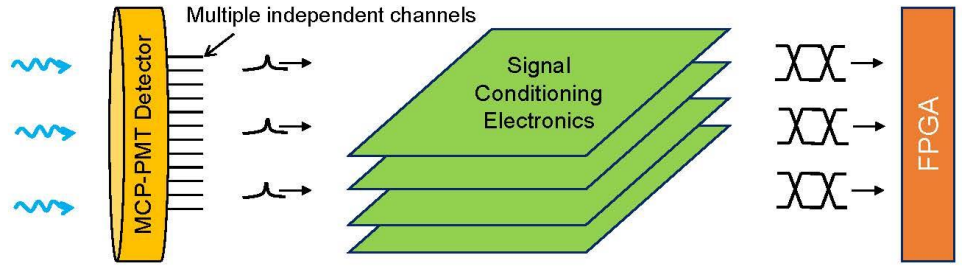
Gateable MCP is a good solution for Airborne Lidar, however, Spaceborne Lidar requires a higher performance solution.

Suitability of Detector Technologies for **Spaceborne Ocean/Atmosphere Lidar**

	CALIPSO, LITE	GLAS	ATLAS	Giga-PAD
Detector type	EMR Single Anode PMT	Perkin-Elmer SPCM	Hamamatsu Multi-Anode PMT	Photonis Multi-Anode MCP PMT
Detection efficiency	13% [1]	65% [2]	12% [3]	20-25% [4]
Pulse response rise time	10ns [1]	-	1.6ns [3]	< 800 ps [4]
Max Synchronous Count Rate (detector limited)	N/A	< 22 Mcps (45ns deadtime [2])	300 Mcps [3] / channel	> 600 Mcps [4] / channel
Number of outputs	1	1	16	61
Dark count rate	<1,500 cps [1]	300 cps + ~18,000 cps/year [2]	6,250 cps [3]	< 10,000 cps [4]
Radiation tolerance	Excellent	Poor	Excellent	Excellent
Afterpulsing	Poor	N/A	Poor	Excellent

1 Internal LaRC EMR PMT Test Data.
2 Data from published conference proceedings.
3 Typical values inferred from vendor datasheets, for comparison purposes only.
4 Projected performance, will be verified early 2019.

Giga-PAD High-level concept

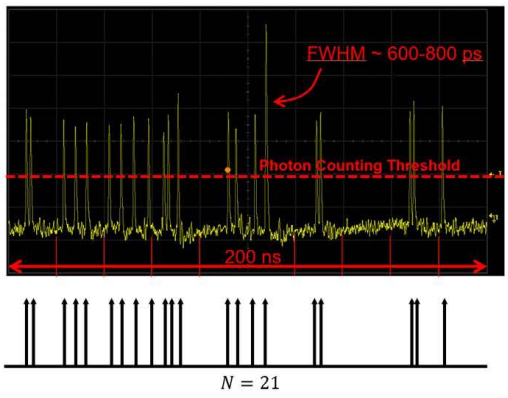


Detector Head
- Semi-custom Photonis MCP-PMT, with the following modifications:
  - Tube modified to reduce charge sharing/crosstalk
  - Improved photocathode quantum efficiency
  - Space-grade packaging

Signal Conditioning Electronics
- Array of high speed amplifiers and discriminators realized in discrete components with path to space
- Employs special technique to enable accelerated recovery following surface flash
- Implements circuitry to limit power consumption

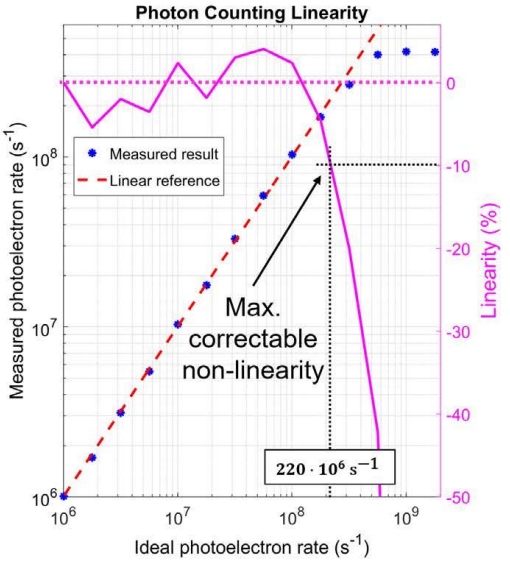
FPGA
- Advanced firmware synthesizes a large array of GHz-class counters
- Configured to reduce power consumption
- Profile binning and averaging performed on chip

Maximizing Photon Counting Linearity



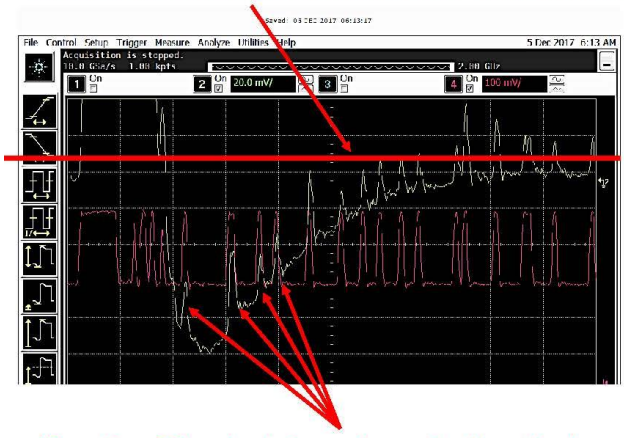
Corresponding count rate for example above:

$$\frac{21}{200\ \text{ns}} = 105 \cdot 10^6\ \text{s}^{-1}$$



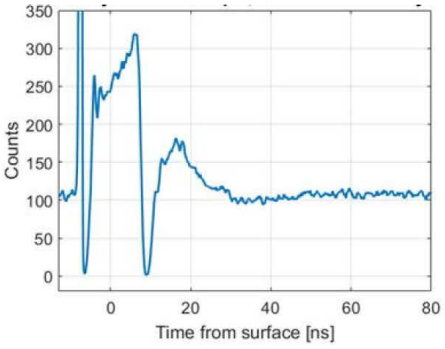
Advantage of Photon Counting for the Ocean, Cloud, and Aerosol Measurements

Fixed threshold misses pulses after surface flash

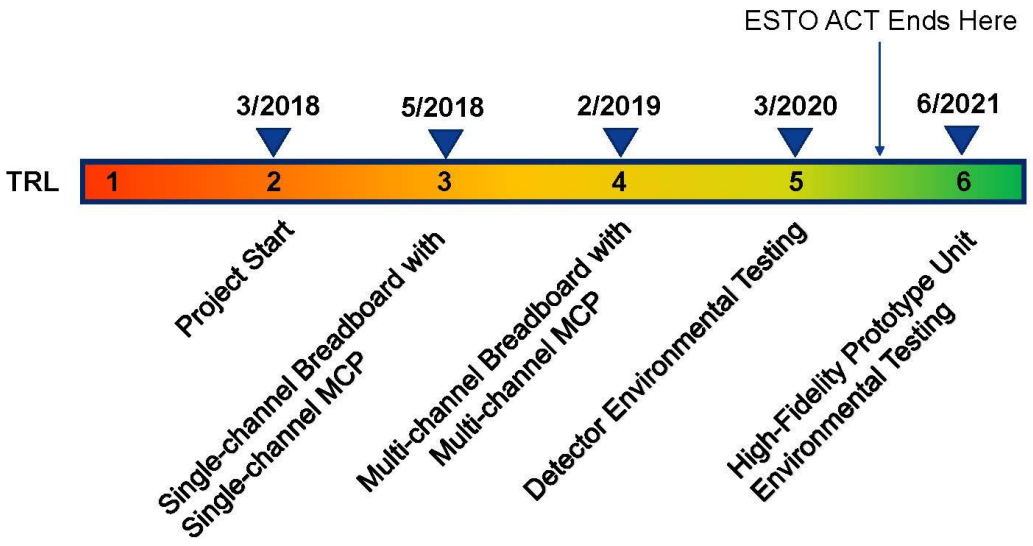


Baseline Filter technique dynamically adjusts threshold so that pulses immediately after surface flash are registered

Histogram of Accumulated Counts: Baseline Filter Technique



Giga-PAD Technology Readiness Timeline: TRL6 Before PDR of D.S. Aerosols Mission



Vision for Future Detector Technology Development

- **Single Photon Avalanche Detector (SPAD) Array and Readout Integrated Circuit (ROIC) Technology**
- Desired **Detector Specifications**
  - Increased Detection Efficiency at 532nm > 50%
  - >10,000 Channels, "Massively Parallel" Photon Counting Outputs
  - Gain > 1E4 A/A
  - Short deadtime, fast reset (<10ns per pixel)
  - Low Probability of Afterpulsing
  - Low Dark Count Rate
  - Radiation Tolerant
  - Compatible with 3D wafer integration/hybridization to ROIC
  - Non-Cryogenic Cooling

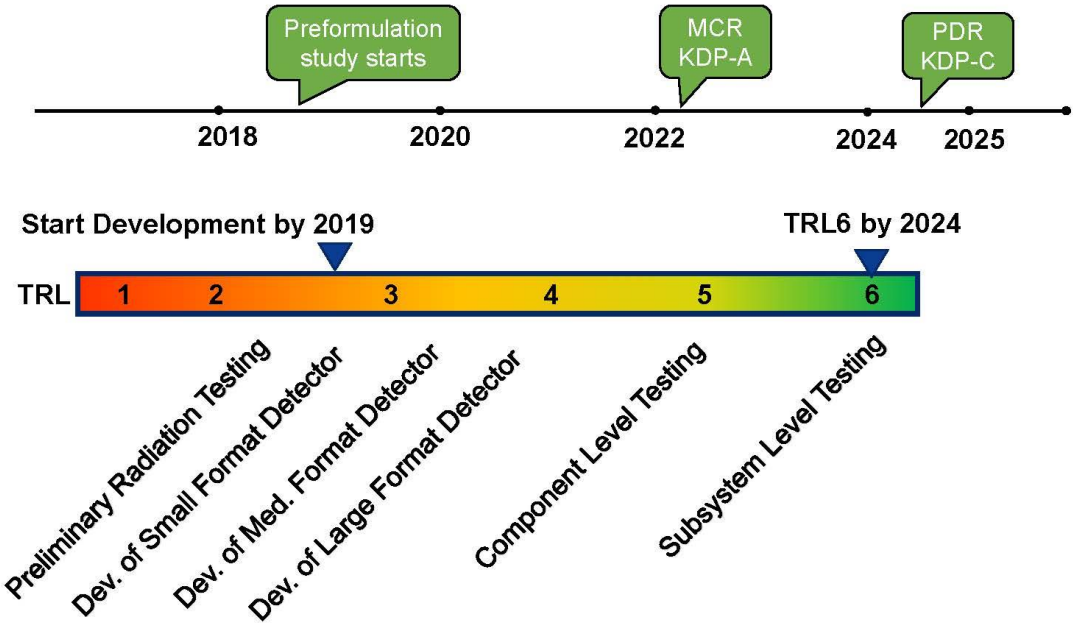
  - **Want to develop a 532nm detector that provides breakthrough capability for a multitude of lidar applications.**

Vision for Future Detector Technology Development

- Desired **Readout Integrated Circuit (ROIC) Specifications**
  - >10,000 Channels, "Massively Parallel" Photon Counting Capability
  - >100MHz per channel synchronous count rate capability
  - Variable Range Resolution of ~1m, 30m, etc.
  - Range > 120km
  - Radiation Tolerant
  - Low Power
  - Compatible with 3D wafer integration/hybridization to Detector

  - **Using the same detector, various groups would only need to develop a custom ROIC to meet their programs specific requirements.**
  - **Lowered development cost by reusing detector and leveraging previously developed IP that is generic to the ROIC design.**

Notional SPAD Array Development Timeline: TRL6 By PDR for the D.S. Aerosols Mission



What are we currently doing to get there?



- **Leveraging SBIR Program** (slow, limited funding)
  - SPAD Array Phase I
  - ROIC Phase I

- **IRAD and ESTO ACT for Giga-PAD**
  - Only covering initial feasibility type studies.
    - Small Form Factor SPAD Array procurement and testing.
  - Leveraging the knowledge of science/engineering requirements for Giga-PAD to guide direction of future SPAD Array Detector.

- **More funding needed to develop a large format end-to-end solution including both detector and readout.**

Suggested Programmatic Changes



- ESTO ACT program as conceived is working well for subsystem developments, but is *woefully underfunded and does not enable advancement to TRL6*.
- Create two-Phase ACT Program:
  - Phase I: ~$2.5M, (TRL2 to TRL4-5)
  - Phase II: ~$2.5M (TRL 4-5 to TRL 6)

(Alternative Option)

- Modify the ESTO IIP Program:
  - Allow for subsystem technology development rather than only entire instruments.

Interagency and Industry Partnerships



- **Each group leveraging their strengths**
  - NASA LaRC Strengths:
    - Translation of Science Requirements into Engineering Requirements.
    - Application of this understanding to guide industry partners towards solutions that best meet NASA's needs.
    - Airborne systems for technology maturation, science algorithms development/validation.
    - Lidar Metrology and Validation of Detector Performance.
    - Lidar System Performance Optimization.
    - Custom discrete readout solutions.
  - Other NASA Centers:
    - Many areas for possible collaboration.
  - Industry Strengths:
    - Cutting edge Detector Design and Fabrication.
    - Custom ROIC Design and Fabrication.
    - Detector Packaging and Cooling.

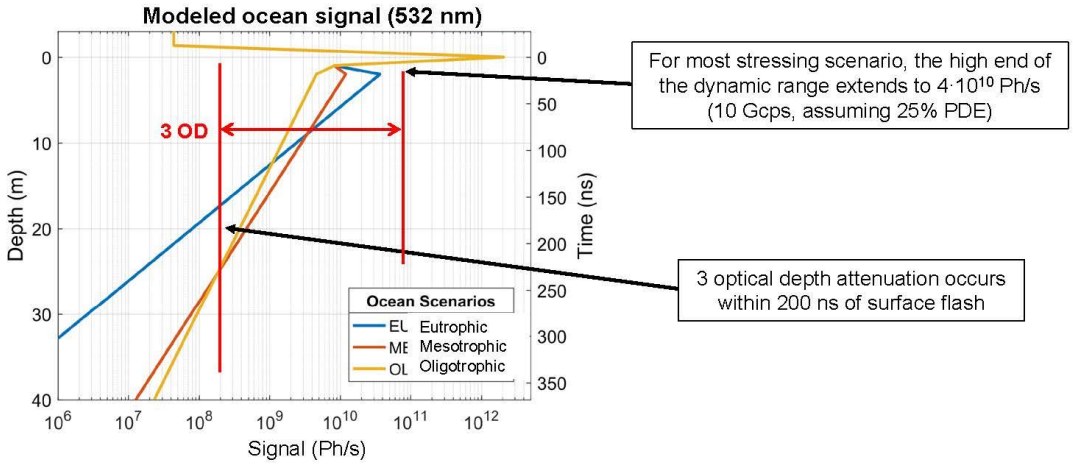
Summary



- Development of detection technology for aerosol, cloud, ocean lidar applications requires closely integrated science and engineering teams.
- Availability of high-performance 532-nm lidar detectors will reduce cost and increase performance for future missions, including the Decadal Survey Aerosols Mission.
- Collaboration with Industry partners and NASA is critical to advancing detector technologies for lidar.
- Programmatic changes are needed to bridge "valley of death" to TRL-6 for *subsystems.*

Backups

MESCAL reference ocean scenarios



2 Session 2

Greenhouse and Trace Gases Measurements was designed to examine the applications and issues for measuring greenhouse gasses from airborne platforms and spacecraft. The Session Chair, Ken Jucks, gave an overview presentation of the area to start the session. A total of four research presentations representing the work of researchers at GSFC and LaRC along with their industry and academic partners was received. Table lists the five session papers. See Section 3 of the Assessment Report for observations and assessment comments.

Table 2-1. Session 2 Papers

Paper Number	Author	Title	Paper	Presentation
S2-1	Ken Jucks, NASA SMD	Overview		☑
S2-2	James B. Abshire[1], Haris Riris[1], Graham R. Allan[2], Jianping Mao[3], William E. Hasselbrack[2], Kenji Numata[1], Jeffrey Chen[1], Randy Kawa[1], Xiaoli Sun[1] [1]NASA GSFC; [2]Sigma Space Inc.; [3]University of Maryland	The CO2 Sounder Lidar Development for Airborne Science Campaigns and as a Candidate for the ASCENDS Mission		☑
S2-3	Mulugeta Petros[1], Upendra N. Singh[2], Tamer Refaat[1], Charles Antill[1], Ruben Remus[1], Jirong Yu[1], Teh-Hwa Wong[3], Doug Taylor[3], Jane Lee[3], Karl Reithmaier[3], Stephen Bowen[1], Angela Welters[1], Syed Ismail[3] and Kenneth Davis[4] [1]NASA LaRC; [2]NASA NESC; [3]Science System & Applications, Inc; [4]The Pennsylvania State University	Ground and Airborne Testing of an Sdvanced 2-micron Triple-pulse IPDA for Atmospheric Carbon Dioxide and Water Vapor Active Optical Remote Sensing	☑	☑
S2-4	Haris Riris[1], Kenji Numata[1], Stewart Wu[1], Molly Fahey[1], Brayler Gonzalez[1], Jianping Mao[2], Michael Rodriguez[3], Stan Scott[1], and Xiaoli Sun[1] [1]NASA GSFC, [2]University of Maryland, [3]Sigma Space.	Measuring Methane from Space and Airborne Platforms	☑	☑
S2-5	Amin Nehir, NASA LaRC	Technology Development for Advanced Greenhouse Gas Lidar Systems		☑

List of presentations

2.1 Greenhouse and Trace Gas Measurements.....2-2
2.2 Development of the CO_2 Sounder Lidar for Airborne & Space Missions.....2-7
2.3 Ground and Airborne Testing of an Advanced 2-micron Triple-Pulse IPDA for Atmospheric Carbon Dioxide and Water Vapor Active Optical Remote Sensing.....2-19
2.4 Measuring Methane from Space and Airborne Platforms.....2-36
2.5 Technology Development for Advanced Greenhouse Gas Lidar.....2-58

2.1 GREENHOUSE AND TRACE GAS MEASUREMENTS

Ken Jucks

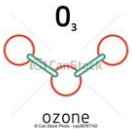
NASA Science Mission Directorate, NASA Headquarters, Washington, D. C.

Greenhouse and Trace Gas Measurements

Intro…

What GHGs and/or trace gases CAN be measured with a Lidar system?

- Ozone…we've been doing that for 30ish years now from aircraft and ground.
- H_2O…we've been doing this for less time from both, but still well established.
- CO_2…really a column measurement as there is no direct "Ranging" in these observations. These systems have been around for 12ish years now from aircraft.
- CH_4…This is a more recent capability…and we will hear about it more today.
- As far as I can tell, this is it as other gases don't have the atmospheric absorption characteristics to really allow a laser based remote sensing approach.



Ozone

- These observations have been a powerful tool on aircraft missions since the 1980s.
  - Obtaining height resolved concentrations both above and below an aircraft is almost an essential for most tropospheric composition missions these days.
  - Because these observations are made in the UV, Rayleigh scattering naturally provides the scattering needed to "range".
- Ground based Ozone lidars have operated both for the stratosphere through NDACC and now the troposphere through TOLNet and others.
- The Decadal survey did not call for anything like an Ozone lidar from space. Ozone is part of the future program of record in the form of OMPS (and OMPS-Limb), and possibly part of an explorer class mission.



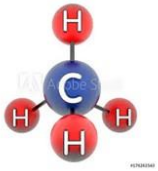
Water

- A number of ground based Raman Lidar systems are operational and are part of NDACC.
  - Again, Raman works in the UV, allowing scattering (that's inelastic as opposed to elastic) and thus get's ranging.
  - Because there are PLENTY of options to obtain water column exist out there that are highly precise, ranging is required for a "lidar" to be worth while.
  - High powered lasers are required for these experiments.
- DIAL systems do operate from aircraft.
  - These require some particles to scatter as they operate where water directly absorb in the near IR.



CO_2

- Numerous groups have been developing CO_2 "lidar" systems for a number of years not, using both CW and pulsed lasers operating near 1.6 and 2.0 microns…the primary CO_2 absorption features in the near infrared.
  - These observations have provided interesting results to date, and show significant promise, at least for aircraft observations.
  - One set of observations are currently part of ACT-America, an Earth Venture Suborbital mission.
  - Others have proven useful for observing fine scale features from emission sources and localized uptake.
- The Primary challenge for CO_2 is the small dynamic range of the variations in the atmosphere, requiring very high precision with very low bias for the measurements! More later…



CH_4

- Three groups (that I know of) have developed "lidars" to obtain CH4 abundances.
  - 2 of these are NASA-Based and you will hear from them today
  - 1 is from DLR
- This DLR group is also developing a spaced based version for the MERLIN mission.
- CH_4 also has tight requirements for precision and bias, but not as tight as that for CO_2.

What did the past Decadal Survey say regarding GHG observations?

- Since that initial Decadal Survey went all the way to recommending missions as opposed to "Observables", they recommended for NASA to develop the ASCENDS mission.
  - NASA, for a number of reasons, never got to developing such a mission.
  - ASCENDS was "stuck" in pre-formulation phase where there was pre-formulation money to further advance the technology, define requirements, and map out what the mission may look like.
  - There was NO decision made as to what wavelength or technique was the "best" technique for going forward for ASCENDS.

What is part of the program of record (both within NASA and other agencies)?

- OCO-2 is in its 4th year of operation.
  - Operations are nominal with no immediate life limiting issues
- OCO-3 launches to ISS in February.
  - 3 year prime mission.
- GeoCARB has it's PDR in 2 weeks, with KDP-C planned in ~2 months.
- GOSAT has been in operation for 9 years (CO_2 & CH_4)
- GOSAT-2 is due to launch soon (CO_2 & CH_4)
- Sentinel 5P is now in prime mission (CH_4)
- MicroCarb is in development now.
- Sentinel 7 is in discussion in Europe.

What does the NEW Decadal Survey say regarding GHG gas observations?

- THIS Decadal Survey does indeed recognize the need/desire to continue GHG gas observations. It was listed within the group of 6 eligible observables to be considered for "Explorer Class".
  - These Explorer Class missions will be competed, much like the Venture Class observables that came out of the last Decadal Survey.
  - The assumed budget for the next decade suggest that NASA could afford to solicit for up to 3 of these observables in that time frame, assuming a cost cap of $350M/mission.
  - Because these are **competed** observables, it is unclear right now how much, if any, NASA investment will be put into any concepts within the pre-formulation budgets that NASA is carrying forward. Right now, there is no directed budget for investing into these concepts.

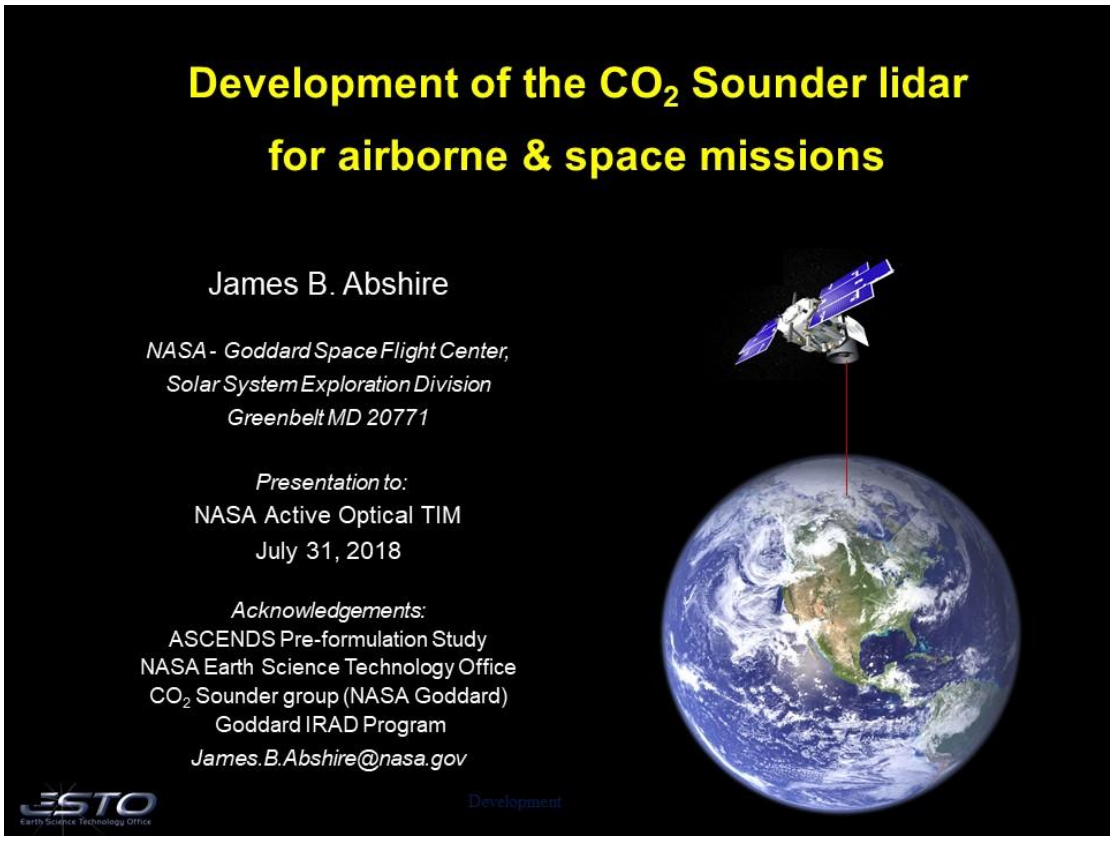
Open questions?

- Can a CH_4 and CO_2 laser based system fit within an "Explorer Class" box?
- Can such a system have measurement characteristics that can match or better the passive sensing systems?
  - Not necessarily single shot precision, but overall quality (i.e., bias).
- What science CAN and SHOULD be done with these airborne systems that cannot be done better with the in situ observations?

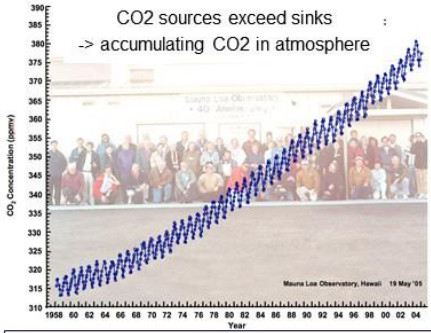
2.2 DEVELOPMENT OF THE CO_2 SOUNDER LIDAR FOR AIRBORNE & SPACE MISSIONS

James B. Abshire

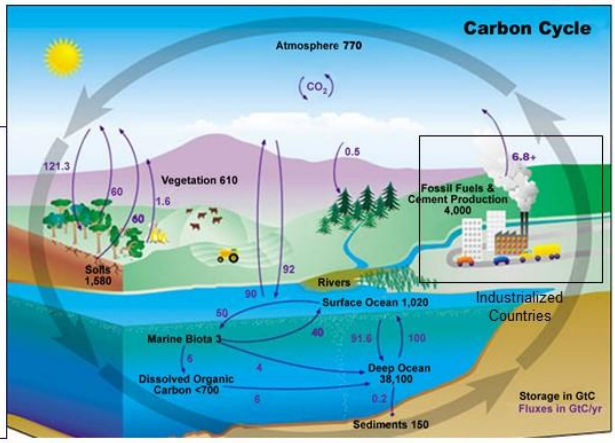
NASA - Goddard Space Flight Center, Solar System Exploration Division, Greenbelt, Maryland



Atmospheric CO2 & Earth's Carbon Cycle



Major Questions about CO2 Sinks:
Considerable uncertainty in locations, strengths, dynamics & evolution with time
=> Space Observations (OCO, ASCENDS)



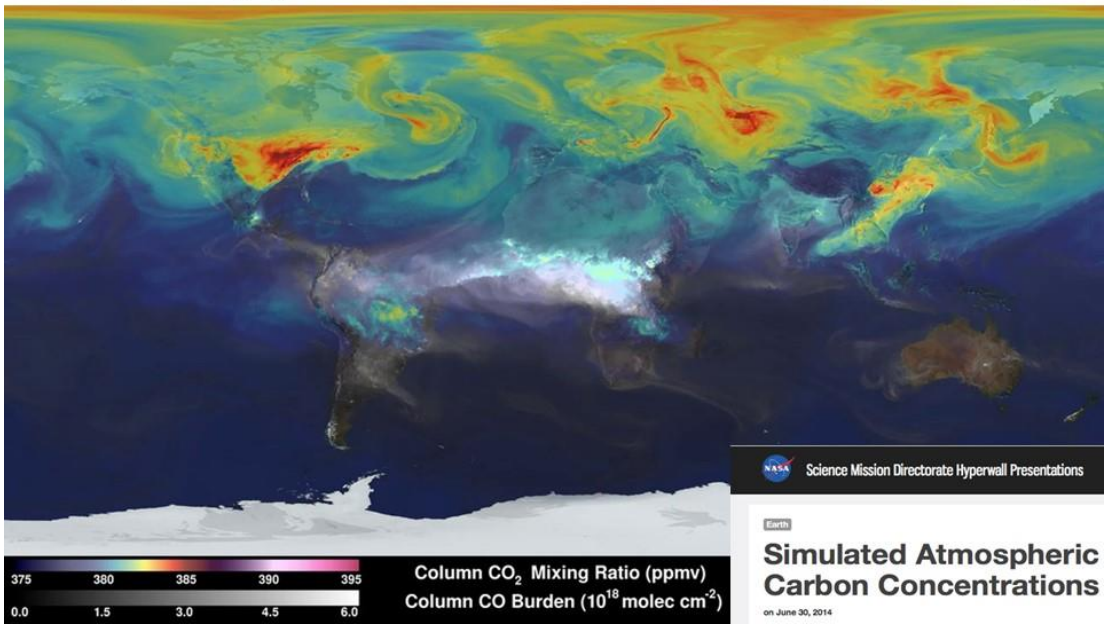
Challenges:

- Fluxes of great interest produce only very small signatures in atmospheric CO_2 (typ. < 1 of 400 ppm, or < 0.25%)
- Areas of interest are distributed globally (including high latitudes, often with haze or clouds
- Arctic and southern oceans are in darkness almost half of each year

Targeted CO_2 Fluxes produce only very small signatures (typ. < 1 of 400 ppm) in Atmospheric CO_2

http://svs.gsfc.nasa.gov/vis/a030000/a030500/a030515/

Very challenging to measure accurately with clouds, aerosols, varying sun angles



NASA's planned ASCENDS Mission

GSFC

ASCENDS

Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) Mission

Science Mission Definition Study

Draft

ASCENDS Ad Hoc Science Definition Team:

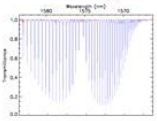
Avail from:
http://cce.nasa.gov/ascends_2015/index.html

April 15, 2015

Addresses:

- Science questions
- Simulation Studies (OSSE's)
- Required knowledge of atmosphere
- Measurement Requirements
- Technique & technology demonstrations
- Mission Study & next steps

Measures:
- CO2 tropospheric column
- O2 tropospheric column
- Cloud backscattering profile



Target Requirements for XCO2:

Random error **: ~ 1ppm in 1 sec, deserts (1 part in 400)**

Bias errors: **< 0.4 ppm (~ 1 part in 1000)**

High precision and accuracy !

CO_2 Sounder Lidar
A pulsed IPDA lidar for CO_2 - here on NASA DC-8

GSFC



Developed as space lidar Simulator

- 25 uJ/pulse at 10 KHz (250 mW)
- 30 λ's/line, 300 Hz sweep rate
- 20 cm dia. receiver telescope
- Detector & backscatter profile recorder:

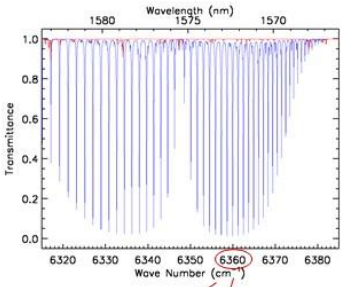
- HgCdTe APD (QE ~70%)
- 100 MHz analog digitizer (10 Hz)

2011, 2013, 2014, 2016 ASCENDS Flights

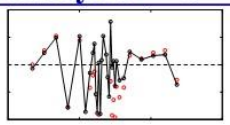
Objectives: Measure CO2 columns over a variety of topographic targets & under varying atmospheric conditions with lidar candidates & in-situ sensors



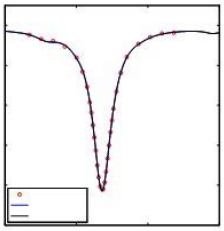
CO_2 Sounder Approach: Airborne CO_2 Line Sampling & Absorption line analysis

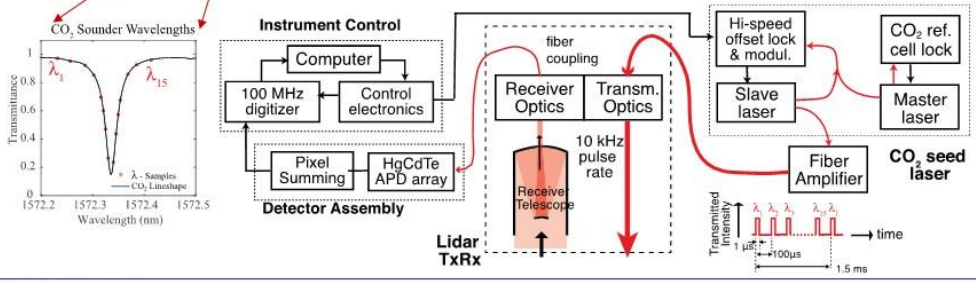


- *Lidar* measures "dots" (wavelength samples) to all scattering surfaces



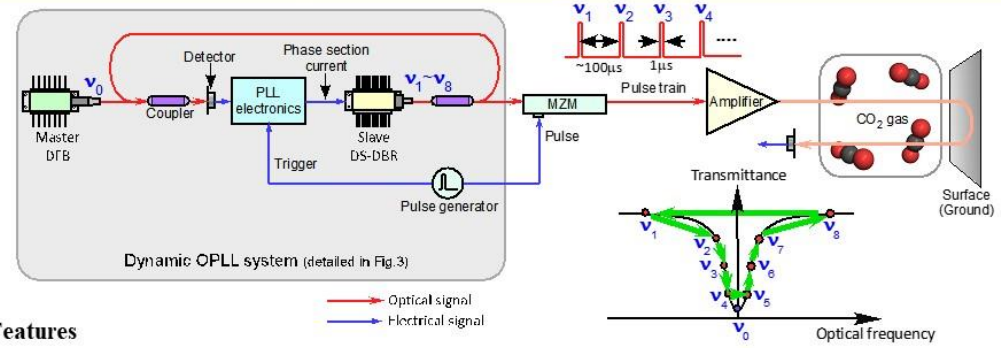
- *Post flight Retrievals "line shape"* (based on model atmosphere)
- Calculate:
  - Range,
  - Normalized line shapes
  - Solves for best fit CO2 concentration (XCO2)





Precision Step-Locked CO2 seed laser

(Jeff Chen and Kenji Numata)



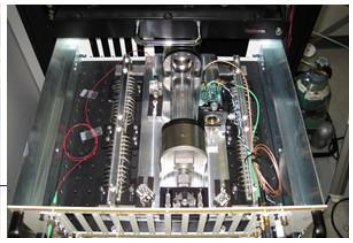
Features

- DS-DBR laser is dynamically offset-locked to master DFB laser using optical phase-locked loop
- Frequency-stepped pulse train carved by MZM and subsequently amplified.
- Effective optical frequency noise of laser < 0.2 MHz

Step locked laser in DC-8 rack



CO2 cell for master laser locking

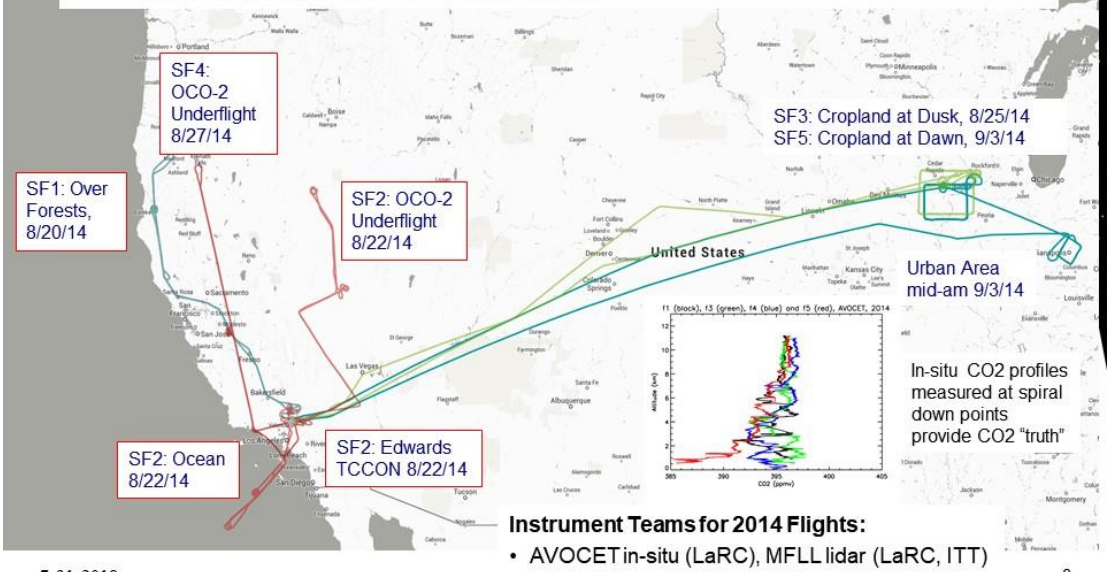


Status:

- **Used successfully with 30 λ's in CO2 Sounder in FY14 campaign**
- **Flexible in # of wavelengths & their set points**

ASCENDS Airborne Campaigns (example from 2014)

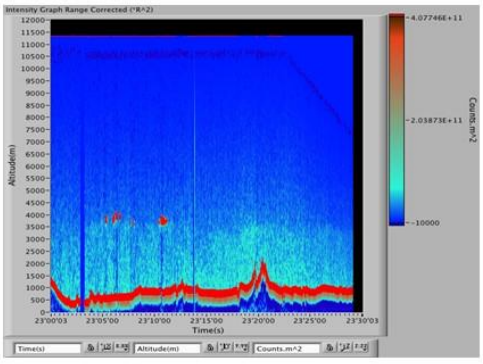
- Targets: forests in CA, growing agriculture at dusk and dawn over Iowa, & urban area
- IPDA lidar allows measurements under conditions that are difficult for passive sensors.
- Two flights under flew the OCO-2 satellite track



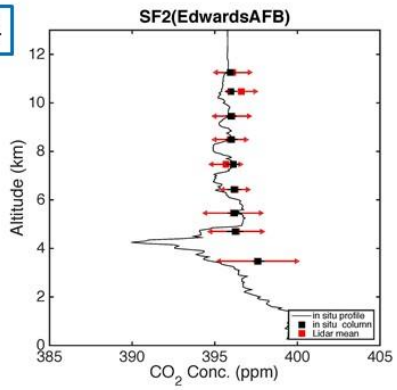
Instrument Teams for 2014 Flights:

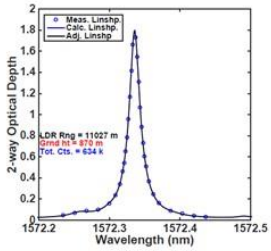
- AVOCET in-situ (LaRC), MFLL lidar (LaRC, ITT)
- CO2 LAS lidar (JPL), CO2 Sounder lidar (GSFC)

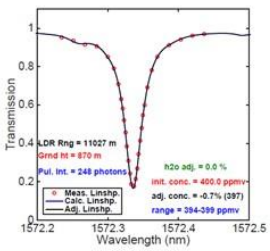
Accurate Column Retrievals over desert - through aerosol layers



8/22/2014



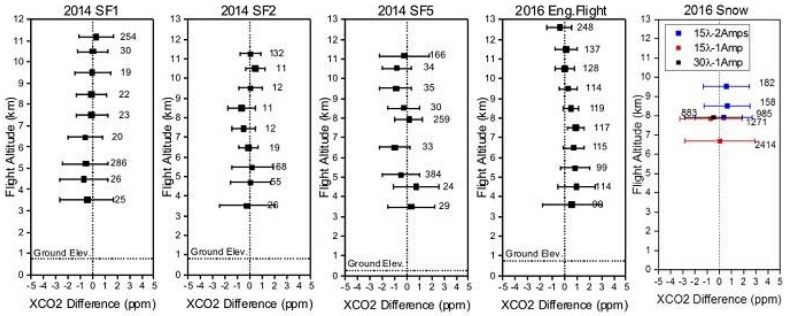




- Range-resolved measurements allow timing gating to minimize impact from atmospheric scattering
- Allow robust retrievals with low bias
- Minimizes retrieval errors over rough surfaces (terrain, and tree cover)

2014 & 2016 ASCENDS Airborne Campaign Summary

Flight Designation	Date	Location (in US)	Focus of measurements	Aircraft Altitude Range (km)	Ave. time per measurement (sec)	Number of Lidar measurements
2014 SF1	20-Aug-14	North CA Coastal forests	Forests on low mountains	2.89 - 11.19	10	712
2014 SF2	22-Aug-14	Near Edwards AFB, CA	Desert through haze	3.50 - 11.25	10	446
2014 SF5	3-Sep-14	Eastern Iowa	XCO2 over cropland	2.62 - 11.16	10	1010
2014 SF3G1	25-Aug-14	Colorado to Iowa (outbound)	East-West XCO_2 gradients	11.2	50	43
2014 SF3G2	25-Aug-14	Iowa to Colorado (return)	East-West XCO_2 gradients	5.6, 6.3, 10.8	50	67
2016 Desert	10-Feb-16	Edwards AFB, CA	Desert	3.59 - 12.60	1	1281
2016 Snow	11-Feb-16	Eastern Nevada	Recent cold snow	6.68 - 9.52	1	5893

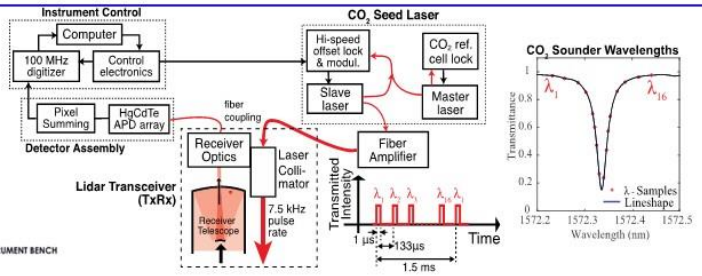


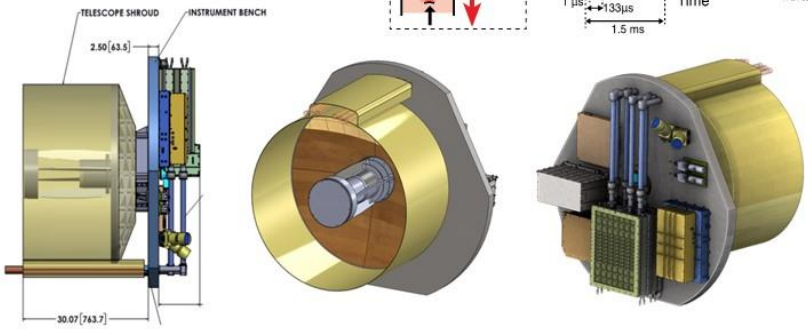
The dots are the mean value of the XCO_2 from the lidar minus that computed from the in situ sensor. They are plotted at the altitude from which they were measured, and the average ground elevations are also shown. The 2014 statistics are from data using10-s averaging and the 2016 measurements used 1-s averaging. The error bars are those of the lidar data set, and the numbers shown are the number of lidar observations in that set.

CO_2 Sounder lidar – Approach for Space

Space lidar is very similar to airborne lidar:

- **Added laser stage(s)**
- **Larger telescope**



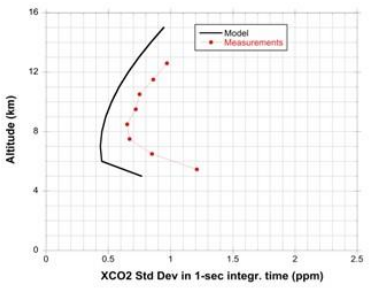


Preliminary layouts for a space version of the CO_2 Sounder lidar that uses a 1-m diameter Be receiver telescope, like that used for ICSat/GLAS and Calipso lidar. The largest box (with the tubes) is that for the laser amplifier, with others for the laser stages and absoption cell, the detector assembly, the electronics box and the power supply, and two small star cameras. The star camera light baffles are not shown and the layout is not yet optimized

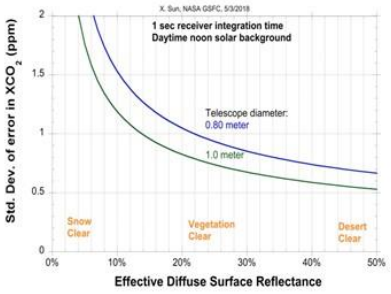
Model shows random errors meet requirements for space for ASCENDS (Xiaoli Sun)

GSFC

Airborne over desert
Model & Measurements



Same model with parameters for space



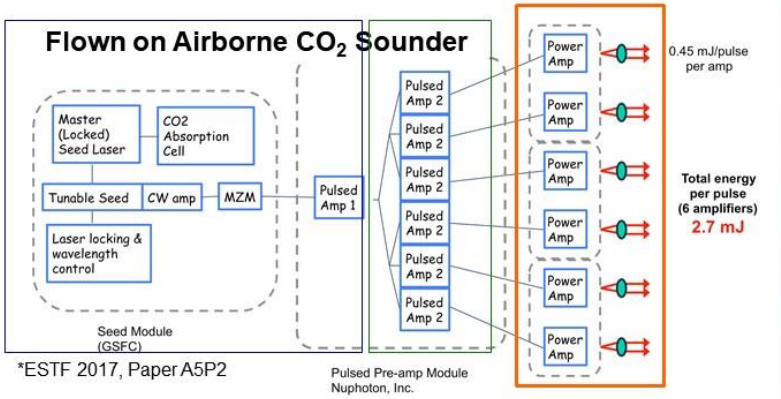
Parameter	Value	Parameter	Value	Parameter	Value
Orbit Altitude	400 km	Laser wavelengths/scan	16	Receiver optical transmission	50%
Laser pulse energy	2.67 mJ	Off-line atmosphere trans.	70%	Detector effective QE	67%
Laser pulse rate	7.5 kHz	Surface reflectivity	varies	Detector APD gain	500
Laser pulse width	1.0 usec	Telescope diameter	0.8 and 1.0 m	Detector dark current	5 fA
Laser divergence	150 urad	Telescope FOV	225 urad	Detector bandwidth	~ 6.5 MHz

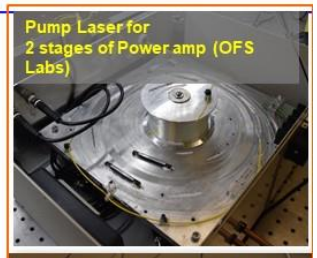
(Left top) Comparison of the predicted XCO_2 error and the measurements for the 2016 airborne measurements over Edwards CA that used 1-sec averaging. *(Right top)* Predicted XCO_2 error of the CO_2 Sounder model versus surface reflectivity for 1-sec averaging and space. The effective diffuse surface reflectivity for RRV is 55%. *(Bottom)* Some parameters used in the space calculation.

Laser Pathway to Space

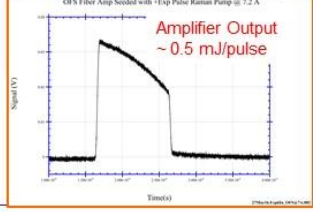
(ESTO/ GSFC IRAD Development– led by Mark Stephen)

GSFC



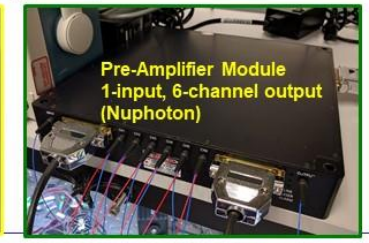






New Technology Developments

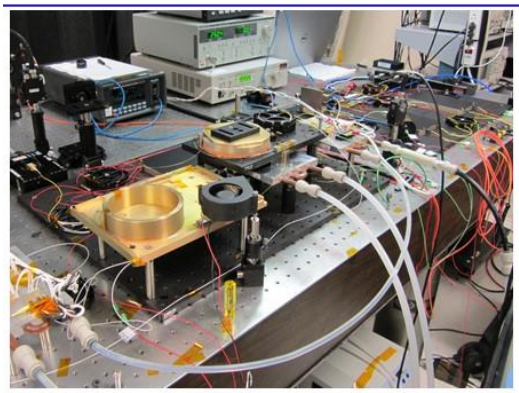




Options/Tradeoffs for Laser Power Amplifier

(both demonstrated at 1572 nm, 1 usec pulses, 7.5 kHz rate)

GSFC

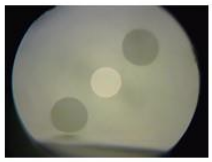


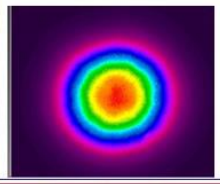
Fibertek – Option 1

- Approach 1st demonstrated under 2010 CO_2 IIP
  - 4 amp stages using 25 µm core PM fiber
  - Cladding pumped at ~ 970 nm
  - Recently demonstrated:
    - > 330 µJ (TL)
    - **> 440 µJ (100 MHz BW)**

OFS Laboratories – Option 2

- Very-large-mode (VLMA) fiber amplifier
- Step index Er-doped PM fiber, 50 um core diameter
- Core-pumped - single mode 1480 nm Raman fiber laser
- Approach:
  - Keeps amplifier fiber < 4 m, reduces nonlinearity
  - Single stage power amplifier
- Recently demonstrated:
  - > 600 W peak power, **~430 uJ pulse**
  - Good spatial beam quality, M^2 < 1.2





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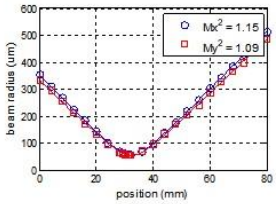
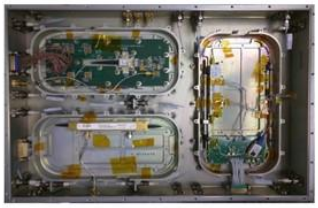


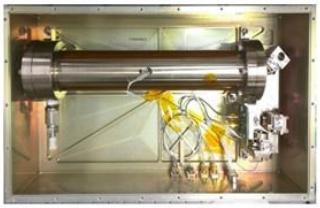
Both amplifier approaches showed margin on key specifications

Laser Technology developed for Space

(Mark Stephen, Tony Yu, Kenji Numata, Jeff Chen, Xiaoli Sun)

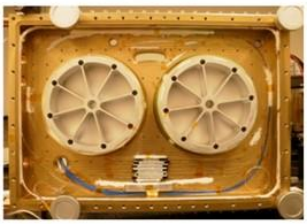
GSFC

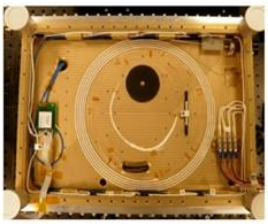


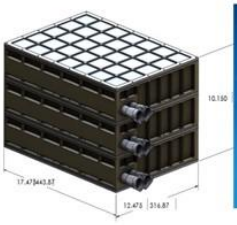




(Left) The completed seed laser module with reference laser, tunable laser and Mach-Zehnder modulator. *(Middle)* Photo of the Herriot cell filled with CO_2 gas with integration optics in a ruggedized package to lock the reference laser to an absolute wavelength standard. Gas cell module dimensions are 25.5-cm x 12.5-cm x 10-cm. *(Right)* Photo of the preamplifier.





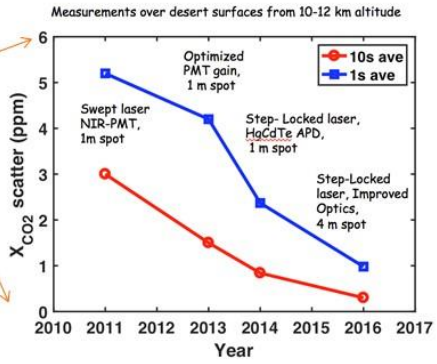




(Two left figures) Photos of the prototype VLMA fiber laser power amplifier. The left photo shows the two spools of the Raman pump fiber laser. The right photo shows the top half of the box with the VLMA fiber spiral. The the spiral groove easy to visualize. The dual output power amplifier module dimensions are 44 x 32 x 9-cm. *(Middle)* Drawing of the stack of 3 laser amplifier assemblies containing the 6 parallel laser outputs that are co-aligned. When summed on the ground spot, the total pulse energy is 2.7 mJ. *(Right)* Photograph of a DRS 16-element HgCdTe APD detector inside the IDCA.

Development Summary

- CO_2 Sounder lidar provides a robust & accurate measurement of XCO_2
- Steadily improved airborne performance since 2011
- Developed an instrument model and XCO_2 retrieval algorithm and verified them with airborne data
- Airborne biases < 1 ppm
- Model shows space lidar has smaller random error than required by ASCENDS
- Developed space lidar technology to ~ TRL 6
- **Logical next step: Space Mission**



We acknowledge the outstanding work of our team
and the support from ESTO, GSFC Earth Science Division, and ASCENDS SDT



CO_2 Sounder Lidar - Development History

Key support: ESTO, ASCENDS Pre-formulation, Goddard IRAD

- ESTO* ATIP (2001)
- ESTO* IIP-04
- ESTO* IIP-07, ASCENDS pre-formulation
- ESTO* IIP-10, ASCENDS pre-formulation
- ESTO* IIP-13, ASCENDS pre-formulation
- ESTO* AIST & Goddard IRAD – space laser development-> TRL 6
  ASCENDS pre-formulation (ASCENDS 2016 & 2017 airborne campaigns)

where:

* - ESTO: lidar measurement approach, instrument & laser technology

** - ASCENDS pre-formulation: retrievals, airborne campaigns, data analysis

- Goddard IRAD - for science, OSSEs, retrievals & early stage technology/risk reduction for a laser CO2 mission (ASCENDS) for most of time

Lidar development process for Earth Science (my views)

- Competition isn't perfect, but is "least bad" approach:
  - Makes program responsive to technological changes
  - It keeps awardees focused & on their toes
  - Is incentive to keep an eye out for partners & better technologies
- Whether to collaborate or not is best done at investigator level
- Opportunities for early (ACT) and later phase (IIP) developments is good
- Are many conferences to learn of other activities/ technologies/ etc.

Challenges:

- Continuity of effort
- Lack of options for space demonstrations (EVI's are "science missions")
- NASA's competitive mission selection process -> many uncertainties:
  - which mission, when & whose instrument ?

My recommendations for this meeting

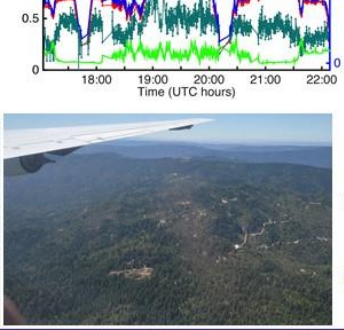
- Support the laser/lidar development within ESTO via ACT & IIP programs
- ***Augment the programs:*** **bring in more $'s for laser & lidar development**
- *Use additional $'s to increase the cadence* for ACT & IIP solicitations -> every 2 years

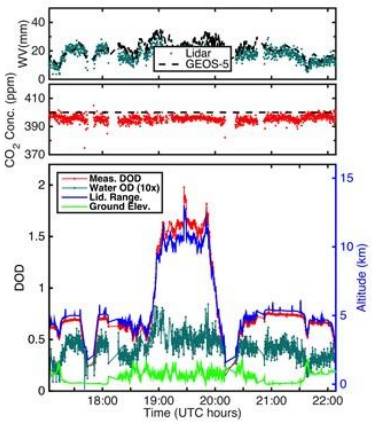
BACKUP

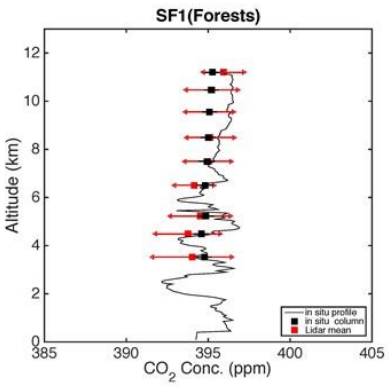
CO2 Sounder: Tall forests in Coastal California
(Redwood forests on several km high mountains)











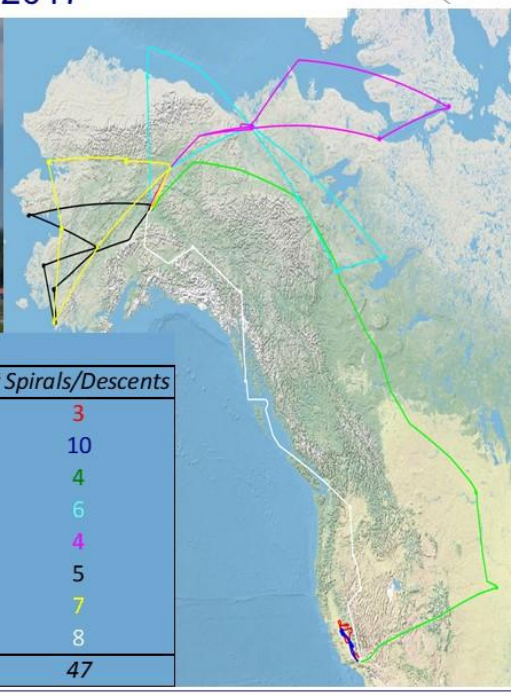
Why ?: Accurate CO_2 measurements over Amazon, Congo & Boreal forests are important for ASCENDS

- Varying tree canopy & terrain -> rapid change in column length
- **Results show accurate (very low bias) measurements in challenging conditions**

Overview - 2017 ASCENDS Airborne Campaign
Jul 20- Aug 8, 2017

GSFC





Flights & Legend:

Dates	*Name*	*Duration (hrs)*	*# Spirals/Descents*
20-Jul	Engineering	4.4	3
21-Jul	Calibration	5.6	10
27-Jul	Northbound science/transit	9.4	4
31-Jul	Western NWT	8	6
2-Aug	Northern NWT	6.6	4
5-Aug	South-Central Alaska	6.2	5
6-Aug	Central Alaska	7	7
8-Aug	Southbound science/transit	8.1	8
8	*Totals:*	*55.3*	*47*

2.3 GROUND AND AIRBORNE TESTING OF AN ADVANCED 2-MICRON TRIPLE-PULSE IPDA FOR ATMOSPHERIC CARBON DIOXIDE AND WATER VAPOR ACTIVE OPTICAL REMOTE SENSING

Mulugeta Petros[1]*, Upendra N. Singh[2], Tamer F. Refaat[1], Charles Antill[1], Ruben Remus[1], Teh-Hwa Wong[3], Doug Taylor[4], Jane Lee[3], Karl Reithmaier[3], Stephen Bowen[1], Angela Welters[1], Syed Ismail[4] and Kenneth Davis[5]

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ABSTRACT

An advanced triple-pulse 2-micron integrated path differential absorption (IPDA) lidar has been developed at NASA Langley Research Center. This instrument relies on a high-energy triple-pulse laser transmitter operating at 50 Hz, with 200 μs pulse separation. The IPDA measures both carbon dioxide (CO_2) and water vapor (H_2O), the two dominant greenhouse gases, simultaneously and independently. This is achieved by wavelength tuning of each transmitted pulse separately. The first two pulses are tuned to strong H_2O and CO_2 absorption lines, while the third pulse is tuned to low absorption. This enhances CO_2 and H_2O measurement capabilities, while eliminating interferences. In addition, this technique results in saving complexity and cost required to build two separate instruments for sensing two different species. Modeling of a space-based IPDA was conducted to demonstrate CO_2 measurement capability and to evaluate random and systematic errors. Projected performance shows 0.5 ppm precision and 0.3 ppm bias in low-tropospheric column CO_2 mixing ratio measurements from space for 10 second signal averaging over the Railroad Valley (RRV) reference surface. This paper presents the ground and airborne engineering flight results for this IPDA lidar. IPDA tuning capabilities, future science campaign and potential space applications will be addressed towards accurate carbon dioxide measurements.

1 INTRODUCTION

Continuous and accurate column measurements of CO_2 from space are required to improve estimates of regional and global scale sources and sinks. This is important for improving carbon-climate interactions models. Critical regions that could be covered using CO_2 active optical remote sensing include high latitude, tropical ecosystems and Southern Ocean. The need for space-based IPDA measurements has been advocated by Active Sensing of CO_2 Emission over Nights, Days, and Seasons (ASCENDS) [1] and Advanced Space Carbon and Climate Observation of Planet Earth (A-Scope) [2] studies, and supported by the 2017 Earth Science and Applications from Space study [3]. Technology developments are in progress to provide high pulse energy 2-μm IPDA that enables optimum, lower troposphere weighted column CO_2 measurements from space. This system provides simultaneous ranging; information on aerosol and cloud distributions, measurements over region of broken clouds, and reduces influences of surface complexities. The IPDA lidar transmitter is based on a high-energy, tunable, triple-pulse 2-μm laser developed at NASA LaRC. The IPDA lidar receiver is based on commercial InGaAs pin detector and an advanced HgCdTe (MCT) electron-initiated avalanche photodiode (e-APD) detection systems.

The performance of the 2-μm triple-pulse laser transmitter is critical for achieving measurement sensitivity, accuracy, and range. Unique features of this laser include producing triple Q-switched pulses, separated by 200 μs, using a single pump pulse. The laser is based on Ho:Tm:YLF crystal technology [4]. The three pulses are seeded with different wavelengths using a single seed laser. Other transmitter enhancements include timing control, seeding, locking, and narrowing frequencies for CO_2 measurements. The wavelength control of the current triple-pulse laser provides any offset-locked frequency within 32 GHz with respect to the CO_2 R30 line center (λ_C), as shown in figure 1 [5].

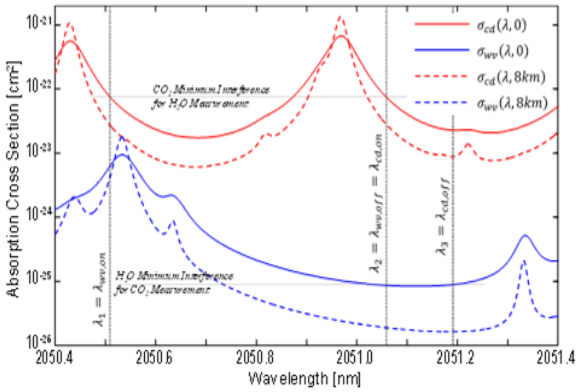

Figure 1. Comparison of the H_2O and CO_2 absorption cross-section spectra, σ_{wv} and σ_{cd}, respectively, at ground (0 km) and mid-altitude aircraft (8 km). Temperature and pressure profiles used in the calculation were obtained from the US Standard atmospheric model. Vertical lines mark the instrument operating wavelengths for CO_2 and H_2O independent measurements. Note that λ_1 is the H_2O on-line, λ_2 serves as the H_2O off-line, and the CO_2 on-line and λ_3 is the CO_2 off-line. The horizontal lines point to minimization of molecular interference errors.

The direct-detection IPDA receiver based on two detection channels. The first relies on mature InGaAs pin detector technology, which was successfully demonstrated using CO_2 double-pulse IPDA lidar [6]. The second detection system is based on state-of-the-art, very low noise, 4×4 pixels MCT e-APD array [7]. This e-APD detection system was developed and tested at NASA Goddard Space Flight Center for 1.6-μm pulsed IPDA lidar for different atmospheric trace gases such as CO_2 and methane (CH_4).

2 IPDA DEMONSTRATION

The triple-pulse IPDA lidar was integrated and tested on ground before airborne validation. The primary objective of the ground test was to integrate the various sub-systems of the IPDA and align the instrument. This was done in the mobile lidar trailer, which is designed for such application. The triple pulsed lidar is mounted in a nadir looking configuration, with a 0.6 m diameter mirror set at 45° that steers the beam for horizontal operation. Calibrated targets with various reflectivity, ranging from 4 to 55%, are placed 981 meters away for evaluating the lidar performance.

After the lidar is integrated, operating parameters tests were conducted, such as detector gain and bandwidth settings, to evaluate the data acquisition performance. Table 1 shows the summary of the triple pulsed lidar differential optical depth both for CO_2 and H_2O. The primary product of the IPDA lidar is optical depth, which is obtained by the natural logarithm of ratio of the transmitted and received off- and on-line signals for each of the species of interest. The result shows the values for single shot, 1 second and 10 second averages compared to meteorological model and US Standard model. To obtain the column average dry mixing ratios, other ancillary data including atmospheric pressure, temperature and relative humidity, are obtained from CAPABLE meteorological station located between the lidar and the target.

Table 1 Summary of IPDA ground test Results

	CO_2	***H_2O***
Differential Optical Depth		
Single shot	0.0955 ± 0.0215	0.1408 ± 0.0361
50 shots	0.0986 ± 0.0049	0.1384 ± 0.0182
500 shots	0.0987 ± 0.0015	0.1382 ± 0.0134
Met. Model	0.1045 ± 0.0001	0.1759 ± 0.0005
US Standard	0.1029	0.1866
Column Dry-air Mixing Ratio		
Single shot	392.3 ± 71.9	•5057.8 ± 1398.8
50 shots	•436.9 ± 19.8	•5037.1 ± 673.2
500 shots	•425.9 ± 6.0	•5353.2 ± 496.6
Met. Model	•422.0 ± 0.4	•6481.9 ± 17.5
US Standard	•422.0	•7750.0
Single shot	392.3 ± 71.9	•5057.8 ± 1398.8

Table 2 Summary of airborne data sample

	Differential Optical Depth	
	CO_2	***H_2O***
Single shot	•0.3692 ± 0.1609	•0.1709 ± 0.2124
50 shots	•0.3724 ± 0.0224	•0.1840 ± 0.0284
500 shots	•0.3704 ± 0.0079	•0.1864 ± 0.0124
Met. Model	•0.4026	•0.1853
US Standard	•0.3895	•0.5623

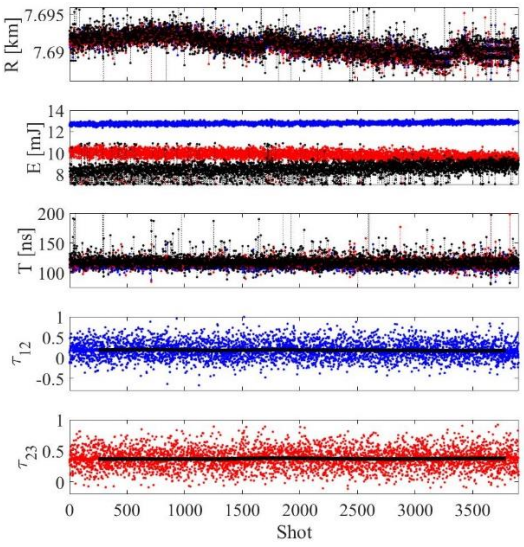

Figure 2 Airborne 2-μm triple-pulse IPDA measurements sample, including range, R, energy, E, and return pulse width, T. Simultaneous, single-shot H_2O (τ_{12}) and CO_2 (τ_{23}) differential optical depth measurements are shown in bottom two plots. IPDA operated from the NASA B-200 at 7.7 km altitude over ocean, East Cape May, NJ, on February 27, 2018.

The main objective of the airborne testing is to demonstrate the instrument capability to measure two different atmospheric species using a single instrument. Four flights were conducted for various specific objectives. The first flight was to verify instrument performance using the highest altitude. The second flight was conducted over ocean targeting clear, broken cloud and cloudy conditions. The third flight was coordinated with NOAA and university of Maryland. The fourth flight was conducted over power plant during day and night. The instrument performance met the design objective, demonstrating the measurements of two atmospheric specie simultaneously and independent from a single airborne instrument. Table 2 lists a summary of airborne data sample, shown in figure 2.

3 SPACE-BASED ANALYSIS

Analysis of both random error, associated with IPDA, and systematic errors, from atmospheric and instrument biases, were estimated assuming a space-based platform. Residual systematic errors in CO_2 measurement arise due to uncertainties in the knowledge of atmospheric and the IPDA instrument capabilities are shown in figure 3. The estimated CO_2 differential optical depth error from atmospheric effects include uncertainties in temperature (0.5°C), pressure (100 Pa), relative humidity (10%) and H_2O interference. A normally distributed random number generator was used to simulate the variability of these fields to evaluate the systematic error. CO_2 differential optical depth bias errors resulting from the IPDA transmitter uncertainties includes on- and off-line laser position jitter (650 kHz) and spectral profiles.

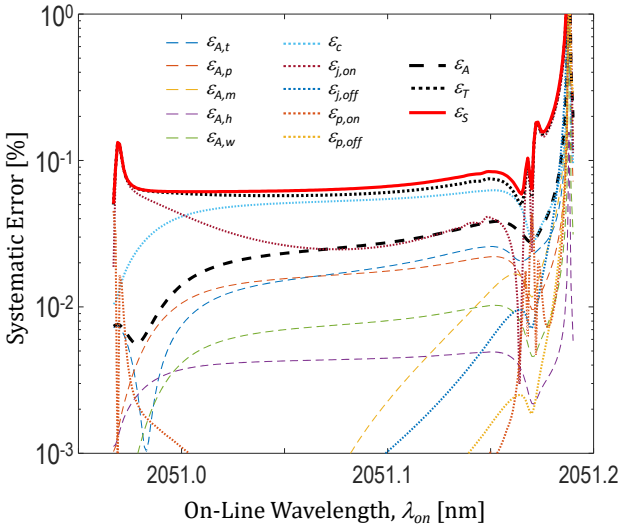

Figure 3 Space-based 2-μm CO_2 IPDA lidar total systematic error compared to atmospheric and instrument errors, presented for scenario 1 (RRV reference) as a function of on-line wavelength. Total systematic error is dominated by instrument errors in terms of on-line jitter and ranging closer and away from the line center, respectively.

Random errors for different on- and off-line transmitted energies combinations and the total (random + systematic) errors are computed. With the triple-pulse system, CO_2 measurements with two weighting functions, at 50 Hz each, can be accomplished using two on-lines and a common off-line. The near optimum random error for each pair is < 0.12% (< 0.5 ppm), and the residual systematic error is < 0.07% (0.3 ppm). Measurements can be optimized by tuning on-lines based upon ground target scenarios, environment and science objectives. With 10 MHz detection bandwidth, surface ranging with an uncertainty of less than 3 m can be achieved as demonstrated from earlier airborne flights [8].

4 TECHNOLOGY ROADMAP

A technology development roadmap over the next decade is shown in Figure 5. Projected forward path for the next steps are:

1) system optimization and testing for high accuracy CO_2 measurements from the trailer and NASA B-200 aircraft. This will also allow validation of CO_2 using in-situ sensors and full diagnosis of systematic and random errors.

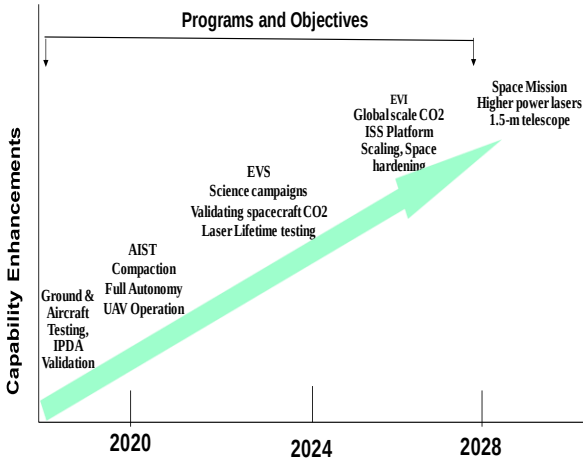

Figure 5 IPDA technology development roadmap leveraging existing NASA programs.

2) Packaging the system to fit within high altitude, long-range and long-duration aircraft or UAV environment with full autonomous operation.

3) Participation in science measurement campaigns, and involve in satellite CO_2 measurement validations from OCO-2 and GOSAT. Simultaneous laser lifetime testing could be conducted.

4) Meeting one of the objectives of ESAS 2017, "Quantify the fluxes of CO_2 and CH_4 globally at spatial scales of 100-500 km and monthly temporal resolution with uncertainty <25% between land ecosystems and atmosphere and between ocean ecosystems and atmosphere". This is the objective of an Explorer class mission identified by the ESAS 2017 recommendation. This can be accomplished under NASA EV-I program during 2026-2028-time frame. This will also allow maturation of the IPDA for operation on free flyer science mission with potential future international collaboration.

5 CONCLUSIONS

Triple-pulse 2-μm IPDA lidar has been developed at NASA LaRC. The development focused on measuring both H_2O and CO_2 simultaneously and independently. This IPDA lidar was demonstrated from ground and airborne platforms. The IPDA lidar design allows measurement adaptability over variety of target and atmospheric conditions. Projected capability of high pulse energy 2-μm laser and MCT e-APD detection system were incorporated for modeling the performance of a space-based IPDA. Random and systematic errors from the instrument and atmospheric effects were evaluated. High precision and low bias weighted dry-air column CO_2 mixing ratio measurements can be made from space with total error of <0.8 ppm. IPDA Technology development roadmap to meet the objectives of ESAP-2017 was addressed.

ACKNOWLEDGEMENTS

This work was funded and supported by NASA Earth Science Technology Office.

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2. Earth Science and Applications from Space 2017.
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7. X. Sun, et al., Opt. Exp. 25, 16589-16601 (2017).
8. U. Singh, et al., Appl. Opt. 56, 6531-6547 (2017).



Ground and airborne testing of an advanced 2-micron triple-pulse IPDA for atmospheric carbon dioxide and water vapor active optical remote sensing

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[3]*Science System & Applications, Inc, Hampton, Virginia 23666*
[4]*The Pennsylvania State University, Pennsylvania 16802*

NASA Technical Interchange Meeting on Active Optical Systems for Supporting Science, Exploration, and Aeronautics Measurements Needs, July 31- August 3, 2018, Columbia, Maryland

Acknowledgement: This work is funded by NASA Earth Science Technology Office

Objectives and Outline

Objectives

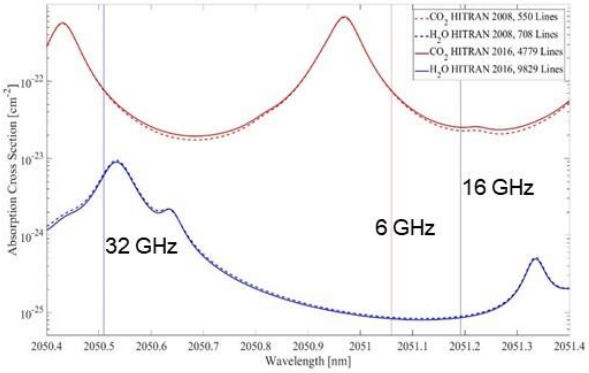
- Demonstration of an airborne triple-pulse, 2-μm, IPDA lidar for simultaneous and independent measurement of the weighted-average column dry-air mixing ratios of carbon dioxide (XCO2) and water vapor (XH2O)
- Scaling IPDA lidar technology for the assessment of space-based global XCO2 measurement

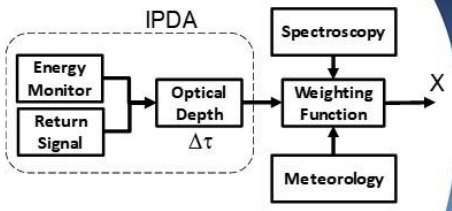
Outline

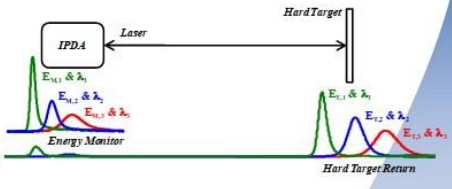
- Methodology
- Technology Development
- Ground and Airborne Measurement Demonstration
- IPDA Space-Based Scaling
- IPDA Roadmap
- Conclusions

Methodology

US Standard Atmosphere at surface







- Optical depth is the main IPDA product
- Other IPDA products include ranging and target surface height
- Meteorological data are required to obtain mixing ratios
- Meteorological data obtained from other sensors or models (US Standard Atmosphere)
- Triple-pulse independent wavelength tuning defines H_2O & CO_2 differential optical depth simultaneously and independently

Technology Development and Demonstration Objectives

Technology Development

- Development of space-qualifiable, fully conductively-cooled, triple-pulsed, 2-µm laser transmitter
- Development of wavelength control system for rapid and fine tuning of three locked sensing for CO_2 and H_2O IPDA lidar transmitter
- Integrate transmitter with receiver and data acquisition to develop the triple-pulsed 2-µm direct detection IPDA lidar

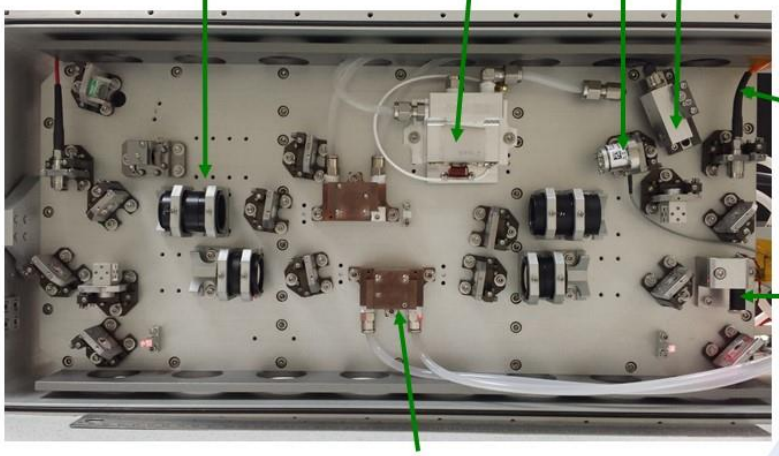
Technology Demonstration

- Integrate IPDA lidar in mobile trailer and perform extensive ground testing to test laser transmitter, receiver, detector and data acquisition system
- Integrate IPDA Lidar in NASA B-200 Aircraft and conduct 15-20 hrs of engineering flight testing
- Coordinate and conduct flight measurement inter-comparison with other airborne CO_2 sensing passive instruments

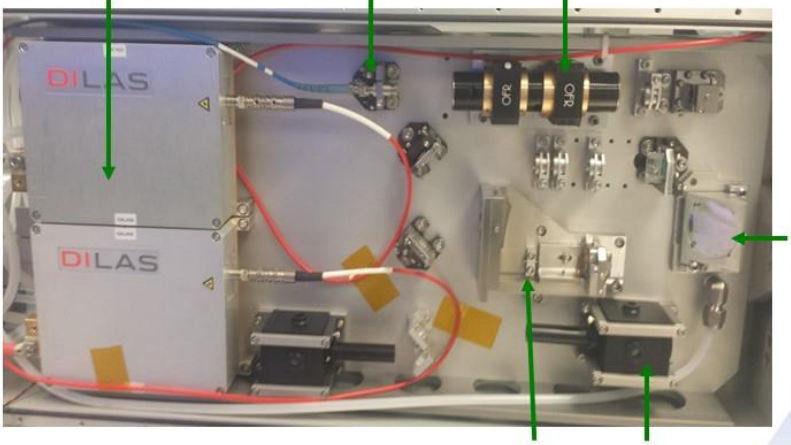
2-micrion Triple-Pulse IPDA Lidar System

Seed Laser	Wavelength Control	Oscillator	IPDA Transmitter	IPDA Receiver
Semiconductor Laser JPL/ESTO	➢ Designed to inject 3 wavelengths from a single laser ➢ Novel Electro-optics modulators and fiber filters based design	➢ In-house laser development ➢ Conductive cooling ➢ Slab architecture ➢ End-pump ➢ 2.5ms pumping at 50 Hz, 80mJ output 3 pulses, injection seeded ➢ Airborne flight hardened	Beam Expander Divergence 0.18mrad Steering Optics	➢ Mercury-Cadmium-telluride (MCT) eAPD GSFC/ESTO ➢ Extended spectral responsivity (2.6μm) InGaAs PIN diode

Laser Bench Side 1



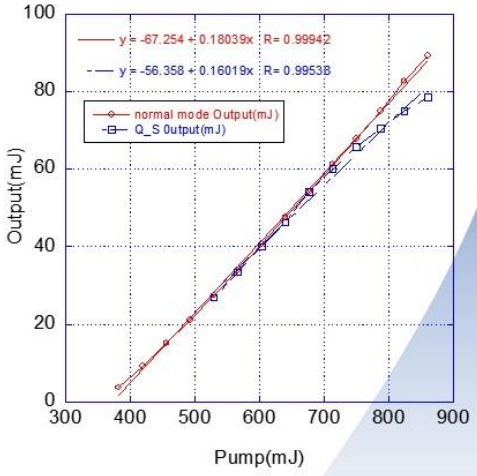
Laser Bench Side 2



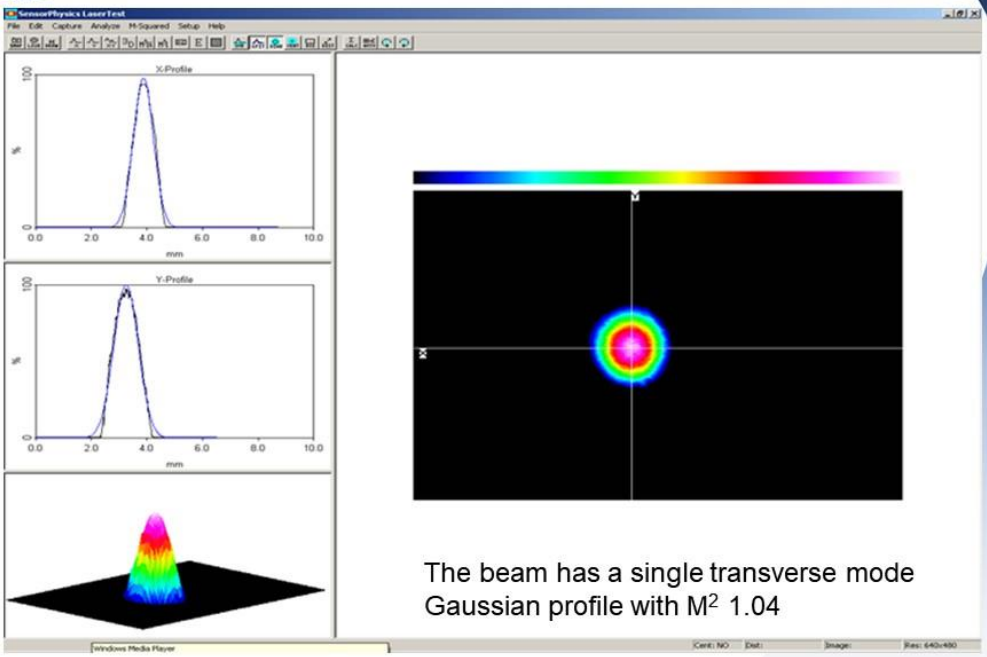
Laser Transmitter: Highlights

For the three Q-Switched pulses

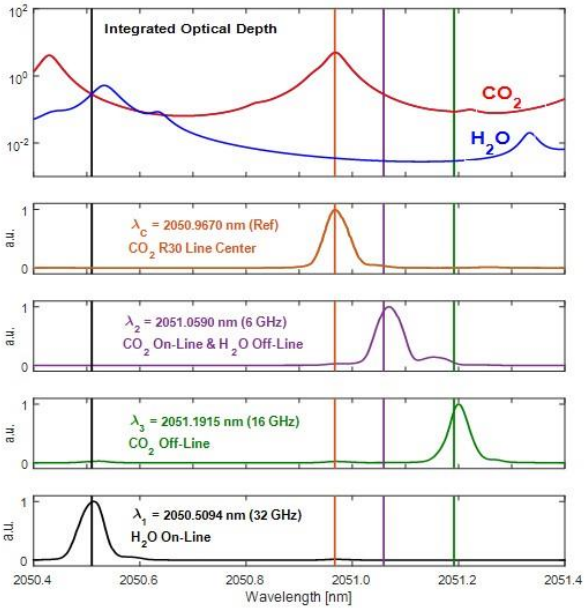
- The distribution of the energy between pulses is **40, 26, 14 mJ (80 mJ total)**
- Slope efficiency is 16%
- The operating temperature of the rod is 9° C
- The optical to optical efficiency is **9.11%**
- The electrical to optical efficiency is **3.64%**



Near Field Beam Profile



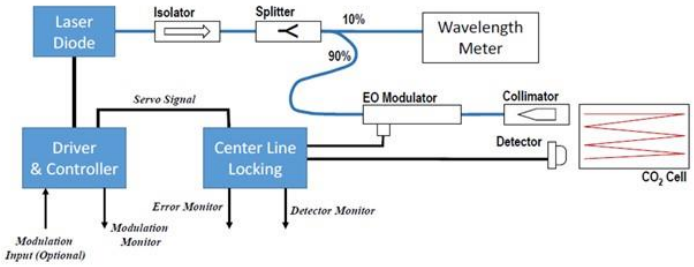
Triple-Pulsed 2-µm IPDA Airborne Lidar Simulation
CO_2 and H_2O Optical Depth



A novel measurement approach:

- Single Seed Laser
- Single Laser/Lidar
- Three Different Locked Wavelengths
- Two Species Measurements
- Independent and Simultaneously

Center Line Locking



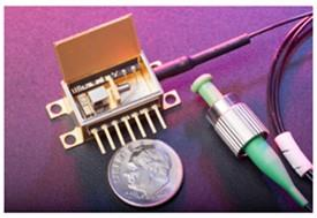
The center line locking scheme is based on all fiber optics design. The center line is locked to less than a MHz jitter

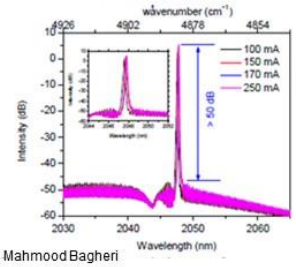


The center locked wavelength is fed into a wavelength control unit where the three wavelengths are generated for seeding.



2-µm Semiconductor Seed Laser from JPL





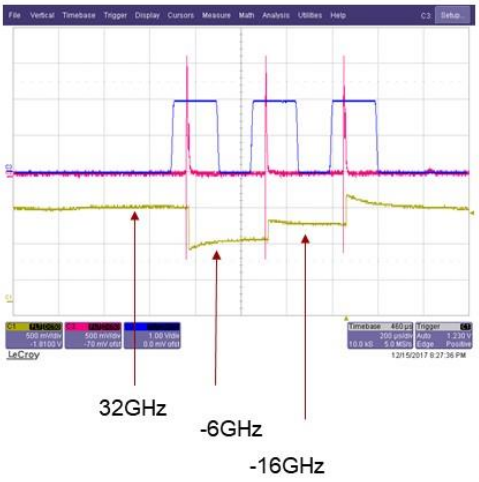
Courtesy, JPL Micro-devices Lab. Mahmood Bagheri
mahmood.bagheri@jpl.nasa.gov

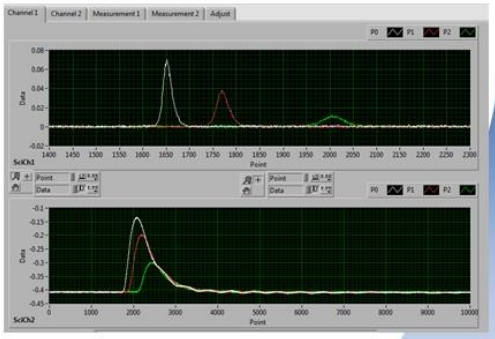
- Butterfly package with integrated optical isolator
- Operates near 2051 CO_2 absorption lines
- 15 mW output power
- <50KHz line width
- Polarization maintaining (PM) fiber
- Fast wavelength tuning capability (>100GHz)

- **Designed a new low noise laser driver, and TEC controllers.**
- **For enhanced performance and stability, temperature is controlled to <0.001K.**



Switching Wavelength for Injection Seeding



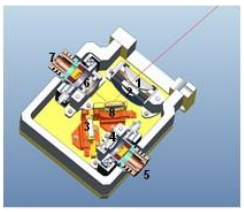


Frequency change occurs after the Q-S is fired

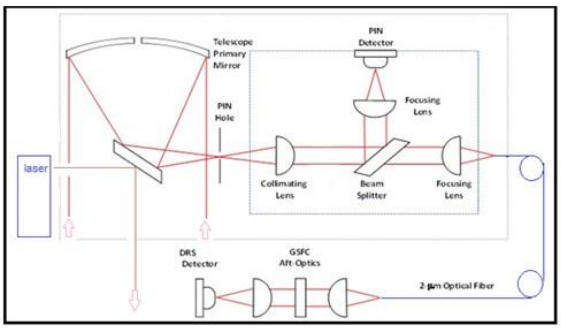
Lidar Receiver System

Receiver System Optics

2-Channels Aft-Optics



1 Collimating Lens
2 Optical Filter
3 HR mirror
4 Focusing Lens
5 10% Detector (Double-Pulse)
5 Fiber Input to DRS (Triple-Pulse)
6 Focusing Lens
7 90% Detector
8 Beam Splitter

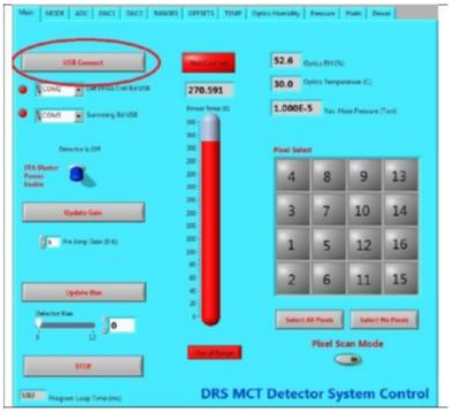


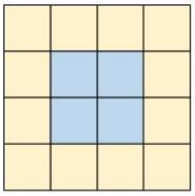
Detectors

InGaAs Hamamatsu, Inc.	MCT e-APD DRS/GSFC
• Characterized • Validated • Reference • Uses simple AFT-optics • 2 Channels, one for InGaAs the other fiber coupled to MCT DRS/GSFC detection system	• Mechanical repackaging • No electronics design required • Factory Hardware modification needed for filter • Operates in cryogenic temp. • Requires AFT optics modification

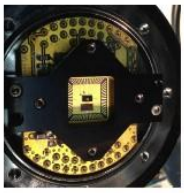
1/15/2019

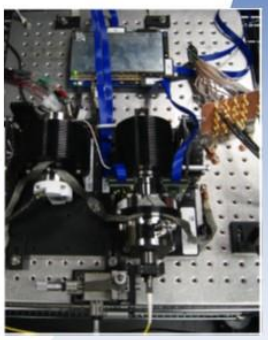
MCT e-APD Detection





MCT e-APD
4x4 Pixel





X. Sun, et al., Proc. of SPIE, 9114, 91140K, (2014).

- DRS/GSFC MCT e-APD
- 4 by 4 pixel format
- Access to each pixel
- GSFC provides read-out electronics for combining pixels.

IPDA Integration and Ground Testing

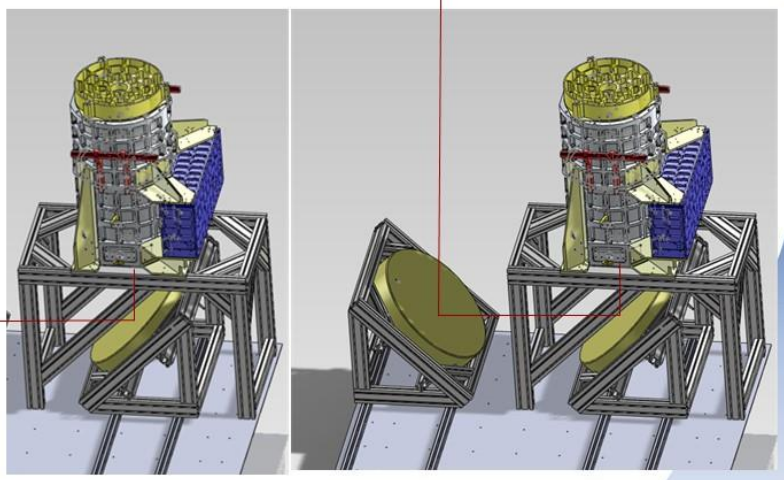
Mobile IPDA lidar trailer has been operational for use as test bed throughout the IIP duration to integrate the instrument and test new techniques.

- Basic CO_2 and H_2O IPDA measurement concept verified
- New detector performance evaluation (MCD)
- CO_2 and H_2O independent and simultaneous column measurement
- Long path IPDA measurements with cloud as hard target (up looking)
- Triple-pulsed IPDA measurements with various calibrated targets
- Testing of different AFT optics and detector alignments
- Installation and testing of data acquisition system for real-time display and analysis
- Clouds up to 6.6 km were detected using the up look configuration

Ground Testing Setup

6 km clouds

897m
To target



Horizontal Zenith

IPDA Lidar Integration in NASA B-200 Aircraft

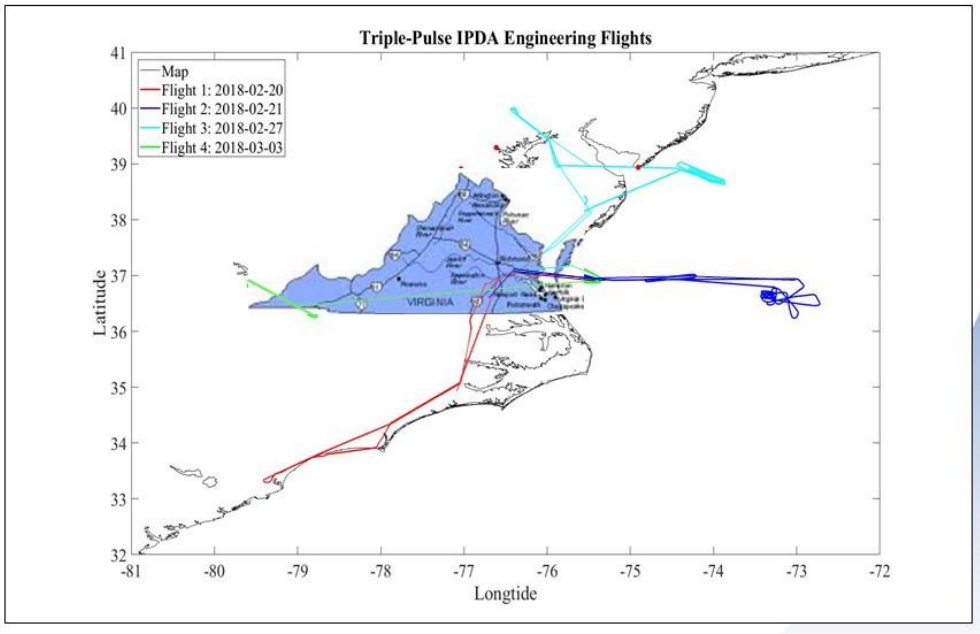


Airborne IPDA Performance Demonstration

Engineering Flight Tests:

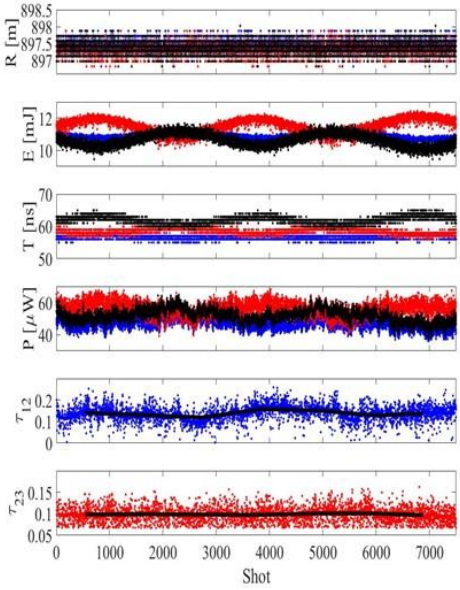
- Verified instrument performance from maximum altitude of 28K feet
- Collected data from Cloud return, broken cloud return, ocean return
- Coordinated flight with NOAA and NIST
- Conducted plume migration detection at power plant and diurnal cycle test during evening flights
- Direct CO_2 and H_2O validation will be achieved by comparison with in situ sensors (Picarro, Inc.,) which is included in the aircraft. Additional H_2O validation will be achieved by comparison to relative humidity profiles obtained from meteorological sonde launches.
- Inertial Navigation System instrument provides position and orientation of the aircraft

IPDA Engineering Flight Path (Feb-March 2018)



Technology Demonstration

Preliminary Ground Testing



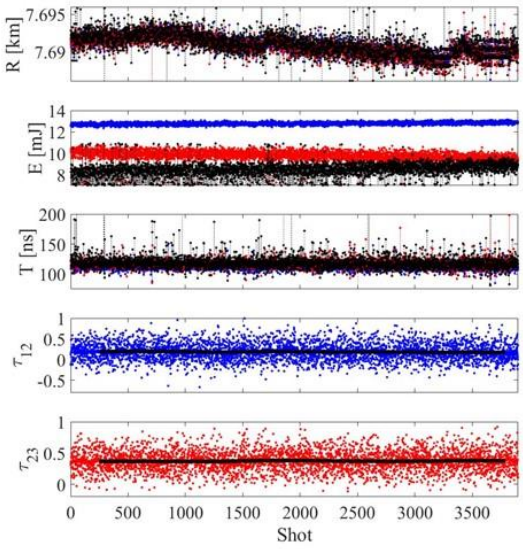
	$(CO_2)\ \tau_{23}$	$(H_2O)\ \tau_{12}$
Single-Shot	0.0955 ± 0.0215	0.1408 ± 0.0361
50 Shots (1s)	0.0986 ± 0.0049	0.1384 ± 0.0182
500 Shots (10s)	0.0987 ± 0.0015	0.1382 ± 0.0134
Met. Model	0.1045 ± 0.000	0.1759 ± 0.0005
US Standard Model	0.1029*	0.1866

	XCO2	XH2O
Single-Shot	392.3 ± 71.9	5057.8 ± 1398.8
50 Shots (1s)	436.9 ± 19.8	5037.1 ± 673.2
500 Shots (10s)	425.9 ± 6.0	5353.2 ± 496.6
Met. Model	422.0 ± 0.4	6481.9 ± 17.5
US Standard Model	422.0*	7750.0

- Conducted January 10, 2018
- Tuned to 32, 6 and 16 GHz seeding
- 2.5 min. records (7500 shots)
- IPDA range (897m) consistent with Rangefinder measurement (894m)
- IPDA range uncertainty of 0.2 m is consistent with the sampling rate (0.15 m)
- Results compared to US Standard Atmosphere and Meteorology models

Technology Demonstration

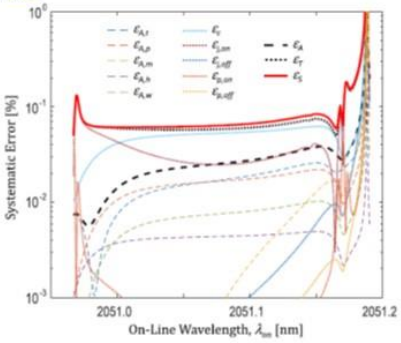
Preliminary Airborne Testing



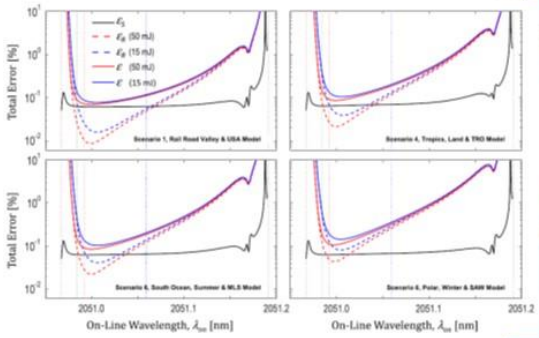
	$(CO_2)\ \tau_{23}$	$(H_2O)\ \tau_{12}$
Single-Shot	0.3692 ± 0.1609	0.1709 ± 0.2124
50 Shots (1s)	0.3724 ± 0.0224	0.1840 ± 0.0284
500 Shots (10s)	0.3704 ± 0.0079	0.1864 ± 0.0124
US Standard Model	0.3895	0.5623

- Conducted on February 27, 2018
- Flight over ocean at Cape May, NJ
- NOAA co-flight
- Tuned to 32, 6 and 16 GHz seeding
- 5 min. records (15.5k shots)
- IPDA range (7.7 km) is consistent with GPS.
- High return pulse width due surface wave elevation.

Space Feasibility Study*



Systematic Errors Analysis



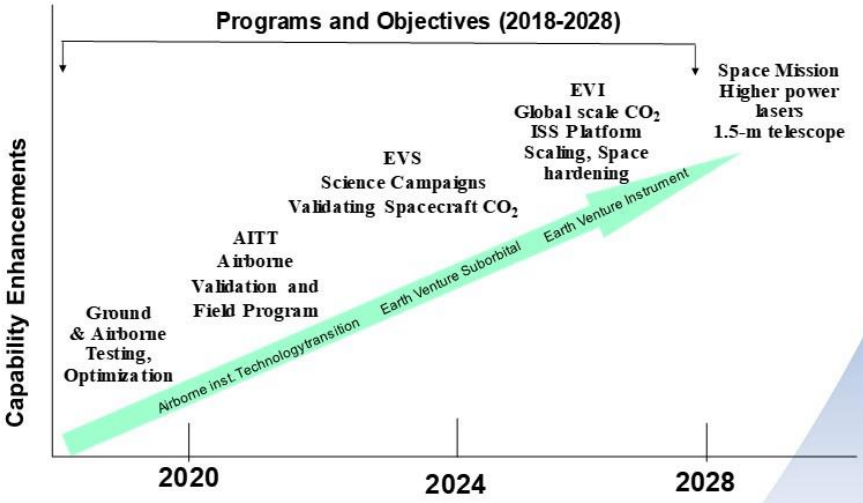
Total Error for Different Scenarios

- Analysis assumes 400 km platform altitude, 10 s integration time, different standard atmospheric models and aerosol loading.
- US standard model and Rail Road Valley as reference surface condition with 0.51 reflectivity.
- Total random error is <0.12% (<0.5 ppm), and the residual systematic error is <0.07% (0.3 ppm).
- Adaptive targeting can optimize the measurements by tuning the on-line wavelengths (weighting function) based upon ground target scenarios, environment and science objectives

* U. Singh *et al.*, *Applied Optics* 56(23), 6531-6547 (2017)

IPDA Roadmap

CO_2 IPDA Lidar Technology Development Roadmap



➢ Projected triple-pulse, 2-μm IPDA lidar technology development roadmap for active optical remote sensing of global carbon dioxide from space

Conclusions

- An airborne tripled-pulsed IPDA lidar was developed at NASA LaRC for simultaneous and independent measurement of column water vapor and carbon dioxide
- This IPDA is based on a state-of-the-art triple-pulse 2-μm laser transmitter, seeded with tunable and locked wavelength for each pulse
- Ground and airborne testing indicated successful IPDA operation
- Modeling of space-based 2-μm IPDA to evaluate random and systematic errors and demonstrate performance capability, while focusing on carbon dioxide measurement
- IPDA capabilities includes carbon dioxide measurements with different weighting functions simultaneously; and tunablity to adopt to specified environmental conditions
- Estimated <0.35 ppm precision 0.3 ppm bias in low trop column CO_2 optical depth equivalent measurements with 10 s signal averaging Railroad Valley Reference surface condition
- Using reanalysis of global meteorological surface pressure data, CO_2 column mixing ratio measurements with high precision (0.5 ppm), and high accuracy (0.5 ppm) can be achieved to meet science objectives

2.4 MEASURING METHANE FROM SPACE AND AIRBORNE PLATFORMS

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ABSTRACT

The global and regional quantification of methane fluxes and identification of its sources and sinks has been highlighted as one of the goals of the NASA 2017 Earth Science Decadal Survey. Detecting methane from space and airborne platforms with an active (laser) remote sensing instrument presents several unique technology and measurement challenges. The instrument must have a single frequency, narrow-linewidth light source, and photon-sensitive detector at the right spectral region to make continuous measurements from orbit, day and night, all seasons and at all latitudes. It must have a high signal to noise ratio and must be relatively immune to biases from aerosol/cloud scattering, spectroscopic and meteorological data uncertainties, and instrument systematic errors.

At Goddard Space Flight Center (GSFC), in collaboration with industry, we have developed an airborne instrument to measure methane. Our instrument is a nadir-viewing lidar that uses Integrated Path Differential Absorption (IPDA), to measure methane near 1.65 μm. We sample the absorption line using multiple wavelengths from a narrow linewidth laser source and a sensitive photodetector. This measurement approach provides maximum information content about the CH4 column, and minimizes biases in the XCH4 retrievals.

In this paper, we will review our progress to date and discuss the technology challenges, options and tradeoffs to measure methane from space and airborne platforms.

Keywords: lidar, spectroscopy, methane, airborne instruments

1 INTRODUCTION

Methane (CH4) is the second most important anthropogenic greenhouse gas (GHG) with a higher radiative forcing potential than Carbon Dioxide (CO2) on a per molecule basis[1], making anthropogenic CH4 a critical target for mitigation. The current CH4 global mixing ratio is 1852 parts per billion (ppb)[2, 3]. Anthropogenic CH4 is responsible for a significant portion of the global warming produced by all well-mixed greenhouse gases and contributes to the formation of ozone[4], another GHG and air pollutant. The existing CH4 observing network has proven inadequate to constrain global and regional sources, and explain observed trends and variation in atmospheric CH4 over the last few decades. Part of the year-to-year, variations in methane's global growth rate are likely from variations in wetland or Artic emissions and part of the recent increasing trend in methane's growth rate may be associated with increased energy extraction activities[5, 6]. The importance of measuring CH4 is also reflected in the recent Earth Science Decadal Survey[7] and the recent report by the Carbon Climate Workshop[8].

Our current understanding of CH4 distributions and processes is founded mostly on precise and accurate ground-based, in-situ measurements from global monitoring networks[9, 10]. The location and frequency of these measurements is, however, very sparse on a global scale and is even sparser at high latitudes where the thawing Arctic permafrost is of particular concern. Large quantities of organic carbon are stored in the Arctic permafrost and a warming climate can induce drastic changes in carbon emissions and a subsequent positive feedback mechanism that can significantly accelerate climate change[11]. Global measurements from satellites are available from passive optical sensors AIRS[12], SCIAMACHY[13], [14], TES[15], IASI[16], and GOSAT[17], but currently lack the required sensitivity to derive regional CH4 sources. Passive sensors measuring reflected sunlight are limited to sunlit areas of the planet and their sensitivity falls off at low sun angles, increasing cloud cover, aerosol scattering, and low surface reflectivity. Recent observations indicate

that the thawing Arctic permafrost is active even during the cold season[18] highlighting the need for continuous sampling at high latitudes even in the winter months.

Active (laser) remote sensing technology will be a key step in obtaining CH4 measurements to supplement existing observations from passive satellite instruments and the sparse surface monitoring network. Active measurements will enable accurate CH4 observations at high latitudes, during all seasons and at night, over land and water surfaces, in the presence of scattered or optically thin clouds and aerosols, and with higher coverage than passive instruments. Together, data from an observational suite of active, passive and in situ instruments will provide sufficient coverage, sampling, and precision to constrain emissions on global and regional scales and potentially some sectoral CH4 emission sources (e.g., oil and natural gas exploration in the central U.S.).

The only active trace gas mission currently in development is the Franco-German MEthane Remote sensing LIdar missioN (MERLIN) by the French Centre National d'Etudes Spatiales (CNES) in collaboration with the German Aerospace Centre (DLR) scheduled for launch in 2021[19, 20]. The MERLIN mission targets an 8-36 ppbv relative random error in the methane column abundance with a 50 km horizontal resolution.

At NASA Goddard Space Flight Center (GSFC), we have also been developing an active, airborne lidar to measure atmospheric methane using Integrated Path Differential Absorption (IPDA) as a precursor to a space mission to measure CH4 from orbit.

2 GSFC MEASUREMENT APPROACH

An IPDA lidar measures the absorption of laser pulses by a trace gas when tuned to a wavelength coincident with an absorption line[21-31]. Using the instrument in a sounding (surface reflection) mode which enables integrated column trace gas measurements from orbit with relatively modest laser power. Although in principle, only two wavelengths ("on" and "off" the absorption line) are needed to determine the transmittance through the atmospheric column, our technique uses multiple wavelengths to probe the absorption feature.

CH4 has absorption lines in the near infrared spectral region at 3.3, 2.4 and 1.65 µm. The lines at 1.65 µm are best suited for active remote sensing from space because they have the right linestrengths and there is very little interference from other molecules. Unfortunately, there are no commercially available lasers in this spectral region.

There are two primary candidate lines can be used for CH4 monitoring: One at 1650.96 nm and one at 1645.55 nm. The GSFC IPDA lidar uses a tunable, narrow-linewidth light source and a photon-sensitive detector coincident with the CH4 absorption at 1650.96 nm. The CH4 line is mostly isolated from adjacent CO2 lines and there is very little water (H2O) vapor interference. The MELRIN line at 1645.55 nm is not as well less suited to our technique because it is interfered with by H2O vapor at ~1645.47 nm and it is wider than our line (~56 pm vs. ~36 pm), an important consideration because it increases the tuning requirement for our laser transmitter. Fig. 1 shows the two-way atmospheric transmittance spectrum for the two lines from a 400 km orbit using the 2008 HITRAN database[32] and a US standard atmosphere.

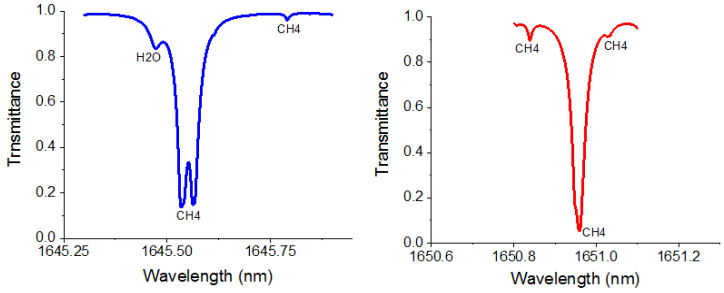

Figure 1 Atmospheric transmittance at 1645.5 nm (left) and 1650.9 nm (right) wavelengths using a US Standard Atmosphere and the HITRAN 2008 database.

The GSFC lidar (Figure 2) uses multiple wavelengths to probe the CH4 absorption feature. Our IPDA approach has been validated experimentally over several years in multiple airborne campaigns and extensive ground tests with our CO2, O2, and CH4 IPDA lidars. Using multiple wavelengths can reduce errors that may affect the measurement precision[33], measure the spectral shift of the line with changing atmospheric pressure[34], generate atmospheric backscatter profiles of the entire column[35], and enable retrievals of trace gas mixing ratios above and below the planetary boundary layer[36].

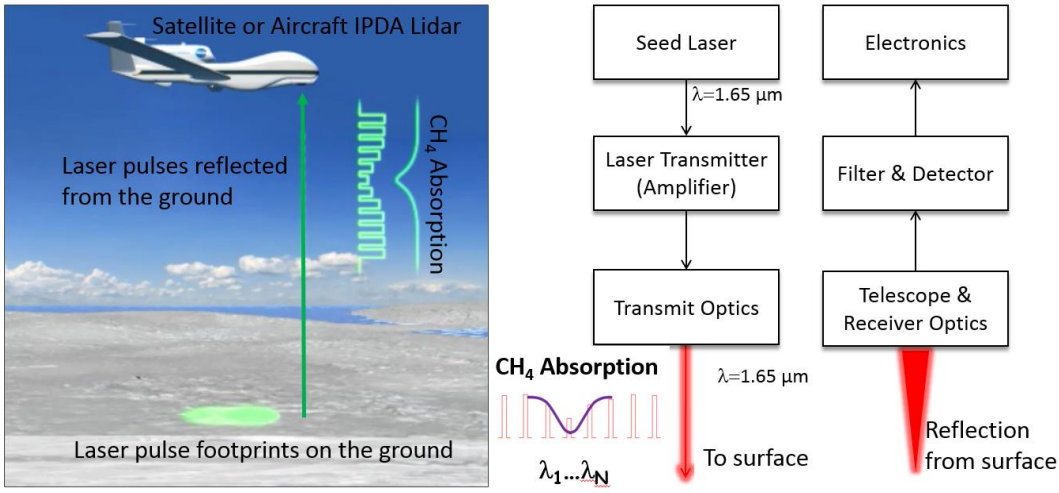

Figure 2. (Left) An Integrated Path Differential Absorption (IPDA) lidar measures the absorption of laser pulses by a trace gas at multiple wavelengths. (Right) Simplified functional block diagram of the CH4 IPDA lidar.

In late 2015, we flew the CH4 lidar instrument on NASA's DC-8 airborne laboratory. The airborne IPDA lidar used two different laser transmitters. The first was an Optical Parametric Amplifier (OPA)[37, 38] and the second was an Optical Parametric Oscillator (OPO)[39]. Only one laser transmitter was used at a time by using a movable mirror to select the desired transmitter.

The OPA, used 20 wavelengths, and was simpler to implement than the OPO, because it did not require an optical resonator cavity, was easier to align and tune, and used only two seed lasers (master and slave). The OPO used 5 wavelengths and required a separate seed laser for each wavelength. Table 1 summarizes the major parameters of the 2015 airborne IPDA lidar and Figure 3 shows the instrument in the DC-8 prior to flight. Both the OPO and OPA used a master seed laser locked on the CH4 absorption peak at ~ 1650.96 nm. The locking technique is the same for both the OPA and OPO, and is described by Numata[40]. It is based on the technique used by Pound–Drever–Hall[41] and is similar to the technique used by Fix[42]. The detector was developed by ESTO and has flown in multiple airborne missions[43-45].

Our retrieval algorithm used a least squares fit to minimize the root mean squared error between the IPDA lidar measurements and the model prediction and is similar to the approach used by Abshire et.al.[46] in their CO2 retrievals. The remaining design details of our instrument and results of our airborne demonstration were summarized in a recent publication.[47]

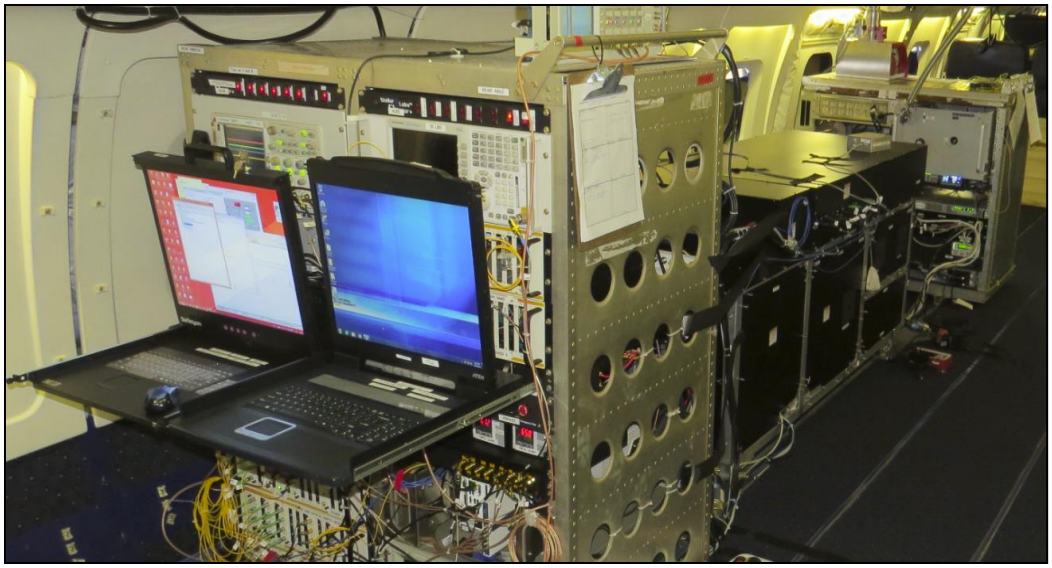

Figure 3 The 2015 GSFC CH4 IPDA Lidar in the DC-8 prior to flight.

Table 1 2015 CH4 Airborne Lidar

Parameter	OPA	OPO
Center Wavelength	1650.958 nm	1650.958 nm
Number of wavelengths used	20	5
Transmitter Energy/pulse	~25-30 µJ	~250 µJ
Transmitter Pulse rate	10 kHz	5 kHz
Transmitter divergence	~150 µrad	~150 µrad
Spectral Linewidth	~500 MHz	<300 MHz*
Number of seed lasers used	2	5
Pump laser	Burst mode Yb Fiber	Single pulse Nd:YAG
Pump laser energy	350 µJ	1.2 mJ
Receiver diameter	20 cm	20 cm
Receiver Field of view	300 µrad	300 µrad
Receiver band pass	0.8 nm (FWHM)	0.8 nm (FWHM)
Detector	4x4 HgCdTe e-ADP	4x4 HgCdTe e-ADP
Detector Pixel Pitch	80 µm	80 µm
Detector QE	~ 90%	~ 90%
Detector Temperature	80K	80K
Detector bandwidth	7 MHz	7 MHz
Averaging time	1/16 sec	1/16 sec

3 LASER TECHNOLOGY

Most of the key technologies for a space CH4 lidar have a long heritage, and most have been demonstrated in previous space missions. Telescopes of various sizes (1.0 and 0.7 m diameter) for lidar missions have flown on the Ice, Cloud, and land Elevation Satellite (ICESat-I and soon ICESat-II), Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (Calipso), and Cloud-Aerosol Transport System (CATS). The command & control and data acquisition electronics will be similar to other lidar missions. The only remaining low technology readiness level component of the instrument is the laser transmitter.

The laser transmitter must have high energy, narrow linewidth and must be rapidly tunable over the absorption line. Depending on the receiver size and other instrument parameters we calculate that approximately 600 µJ is needed to obtain a measurement with a 0.5% precision from space.

The primary means to generate 1.65-µm laser radiation has been to use non-linear optical parametric techniques: optical parametric amplifiers (OPA) or oscillators (OPO)[48]. MERLIN uses a two-wavelength

OPO. Our airborne OPA, which used 20 wavelengths, was simpler to implement than the OPO because it did not require an optical resonator cavity, and was easier to align and tune. However, it is extremely difficult to scale the OPA energy to that needed for space (~ 600 µJ depending on the receiver size and other instrument parameters) and maintain a narrow linewidth. The highest energy we obtained in the laboratory with our OPA was 290 µJ using a two-stage OPA, and the burst-mode Yb fiber laser amplified by a custom solid-state amplifier as a pump. However, at high energies, the OPA output spectrum typically consists of sharp peak near the seed wavelength and a broad side lobe, when the parametric gain is high. In that case, we cannot clearly define the linewidth but it is generally too wide for accurate CH4 IPDA lidar measurements. In addition, for a space mission we are aiming for a simple and efficient single stage - not a complex multi-stage - OPA based on quasi-phase matching (QPM). In this configuration, we have observed that the OPA output linewidth does not fully converge to the seed linewidth, giving wide side lobes, especially when pump and seed fluences are high and low, respectively[49]. Back-conversion and parametric amplification of the seed's side lobes are possible causes. If the seed laser power can be significantly scaled up then it may be possible to achieve energies of 600 µJ out of the OPA with a narrow linewidth. With the existing seed and pump laser technology, we do not see a path to space for the OPA in the near future. However, it remains a viable transmitter for CH4 measurements from an airborne platform.

In the OPO, narrow linewidth was achieved by using an optical resonator cavity, which also enhances the energy of the non-linear conversion. Our 5-wavelength OPO used a 1.2 mJ GSFC-built solid-state pump laser and a triangular optical ring cavity. We have since replaced the GSFC-built solid-state pump laser with a smaller, compact Yb fiber laser and redesigned the OPO to improve stability (Figure 4-left). We integrated the new OPO into a new airborne sensor that has dual beam capability ((Figure 4-right).

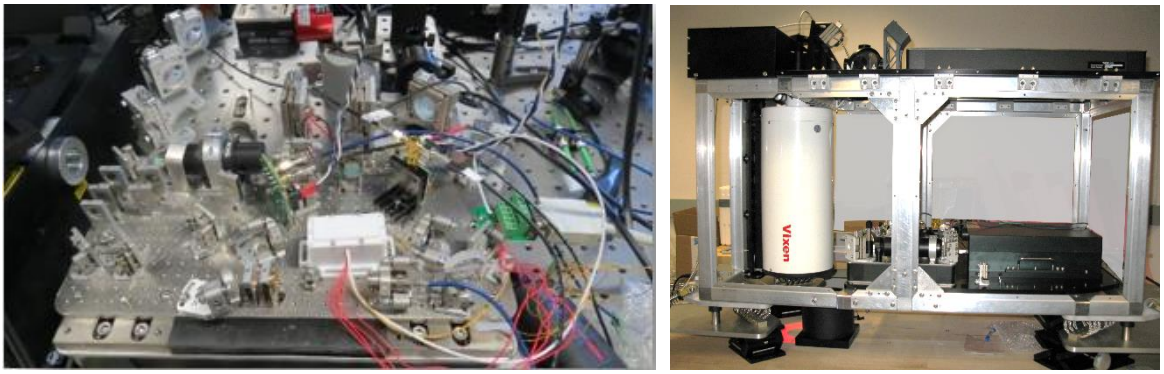

Figure 4 (Left) Our airborne 5-wavelength OPO used a 1.2 mJ GSFC-built solid-state pump laser and a triangular optical ring cavity. We have since replaced the GSFC-built solid-state pump laser with a smaller, compact Yb fiber laser and used a single DBR seed laser that step-tunes over the CH4 absorption line. (Right) Redesigned airborne instrument is lighter, smaller, and can transmit and receive two different beams simultaneously making it ideal for joined CH4/CO2 or H2O missions.

We also replaced the five seed diode lasers with a single custom-made DBR laser that is stepped tuned over the absorption line. We now use sixteen wavelengths to tune over the CH4 absorption line with just two lasers (master and slave). These changes simplified the OPO design considerably. In the laboratory we demonstrated energies of ~250 µJ at 5 kHz with a narrow (transform limited) linewidth. The multi-wavelength OPO energy could be scaled to space and remains our baseline approach. However, it still requires optical phase-lock loop and cavity control.

In recent years, resonantly pumped Erbium (Er) doped YAG, Er:YAG and Er:YGG, lasers, which directly emit at 1645.5 and 1650.96 nm, respectively offer another option for a CH4 transmitter. Using Er:YAG for CH4 detection dates back to 1972[50]. In recent years, successful demonstrations and commercialization of high power and high spectral brightness pump sources at 1470 nm and 1532 nm, driven in large part by the various industries including defense, telecommunications and medical, have afforded the realization of resonant pumping of of Er:YAG [51-54] and Er:YGG [55, 56] lasers. The emission cross-section of Er:YAG crystal

is centered near 1645.3 nm and falls off rapidly at 1650.96 nm. It is near the MERLIN lines at 1645.55 nm which are relatively wide (~56 pm). Our CH4 line at 1650.96 nm is narrower (~36 pm) which makes fast tuning easier. Unfortunately, Er:YAG cannot be used as a gain medium at 1650.96 nm but Er:YGG can be used as a potential medium for lasing at that wavelength. Our preliminary radiative transfer calculations show that both lines (Er:YAG at 1645.55 nm and Er:YGG at 1650.96 nm) have similar temperature sensitivity and are well suited for CH4 measurements. Recent high accuracy spectroscopic measurements indicate that line mixing effects in the Er:YAG 1645.55 nm line[57] should also be taken into account. We expect similar effects to be present for the Er:YGG line at 1650.96 nm.

Both materials are good candidates for a space CH4 laser transmitter but Er:YAG is more readily available. Power scaling for both materials, and most importantly multi-wavelength operation and tuning considerations remain. For both materials, the gain peak is slightly off the CH4 absorptions lines requiring the use of a tuning element, such as an etalon, in the cavity. However, for a multi-wavelength IPDA that introduces yet another element that needs to be aligned, tuned and controlled at high precision. Our laser technology roadmap and final design summarizing the current technology roadmap is shown in Figure 5.

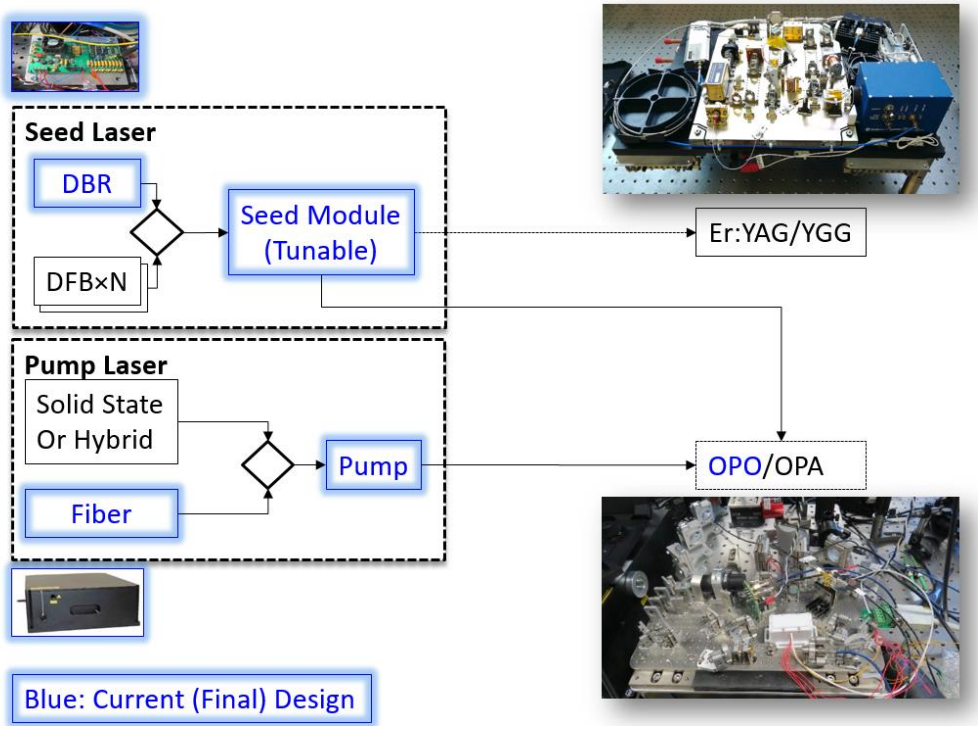

Figure 5 Laser technology roadmap and final design

4 SUMMARY

Anthropogenic CH4 is responsible for a significant portion of the global warming produced by all well-mixed greenhouse gases. Despite the critical importance of CH4 for climate, the existing CH4 observing network has proven inadequate to constrain global, regional, and sectoral sources, and explain observed trends and variation in atmospheric CH4 over the last few decades. An adequate CH4 observing network is necessary to monitor the interaction between the carbon cycle and climate change, such as the potential release of CH4 from stored carbon reservoirs (e.g., Arctic and boreal soils) and changes in natural emissions. Identifying methane and quantifying regional-scale emissions from specific sources will require substantial investments in CH4 monitoring technology. These technologies need to be able to resolve CH4 concentration uncertainties over global and regional scales, at all latitudes throughout the year.

At GSFC, we developed a multi-wavelength IPDA lidar and demonstrated CH4 column measurements using an optical parametric oscillator (OPO) and optical parametric amplifier (OPA) laser transmitter and

sensitive avalanche photodiode detector. The lidar measured the atmospheric CH4 absorption at multiple, discrete wavelengths near 1.65 μm. The stability and reliability of the laser transmitters need to improve considerably but the basic measurement approach has been demonstrated. However, many technical challenges remain to scale the space.

Generally, an OPA is simpler to implement than an OPO because it does not require an optical resonator cavity and is easier to align and tune. However, it is extremely difficult to scale the power of the OPA and maintain a narrow linewidth. After extensive testing, we have concluded that it is not feasible to scale the OPA laser energy to the level needed for space without significant improvements considerable investments in the seed and pump laser.

In an OPO, a narrow linewidth is achieved by using an optical resonator cavity, which also enhances the energy of the non-linear conversion. Our new multi-wavelength OPO is scalable to space, but still requires phase-locking loops and cavity tuning. The OPO will remain the baseline option until other approaches can be convincingly demonstrated.

It would seem that the simplest and most promising technology at this wavelength range is Er:YAG/Er:YGG. The lasing occurs near (but unfortunately not exactly) at the CH4 absorptions 1645 and 1651 nm. Power scaling has already been demonstrated with the desired spectral characteristics but without fast tuning and only at one or two wavelengths. The Er:YAG/Er:YGG still require a tuning element in the cavity to lase at the right wavelength. If the tuning problem can be solved this technology may be the most promising.

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Measuring Methane from Space and Airborne Platforms

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NASA Technical Interchange Meeting on Active Optical Systems for Supporting Science, Exploration, and Aeronautics Measurements Needs

Paper: S2-4, July 31st 2018, Columbia, MD

Supported by:

NASA ESTO ACT, STMD GCD, GSFC IRAD and SBIR programs

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Outline

- Why measure Methane with a lidar?
- GSFC measurement approach
- Technology challenges and progress
- Summary and future steps

WHY MEASURE METHANE FROM ORBIT WITH A LIDAR?

Methane and the 2017 Earth Science Decadal Survey

TARGETED OBSERVABLE	SCIENCE/APPLICATIONS SUMMARY	CANDIDATE MEASUREMENT APPROACH	Designated	Explorer	Incubation
Greenhouse Gases	**CO_2 and methane fluxes and trends,** global and regional with quantification of point sources and identification of source types	Multispectral short wave IR and thermal IR sounders; or lidar**		x	

QUESTION W-8. What processes determine observed atmospheric methane (CH4) variations and trends and what are the subsequent impacts of these changes on atmospheric composition/chemistry and climate?

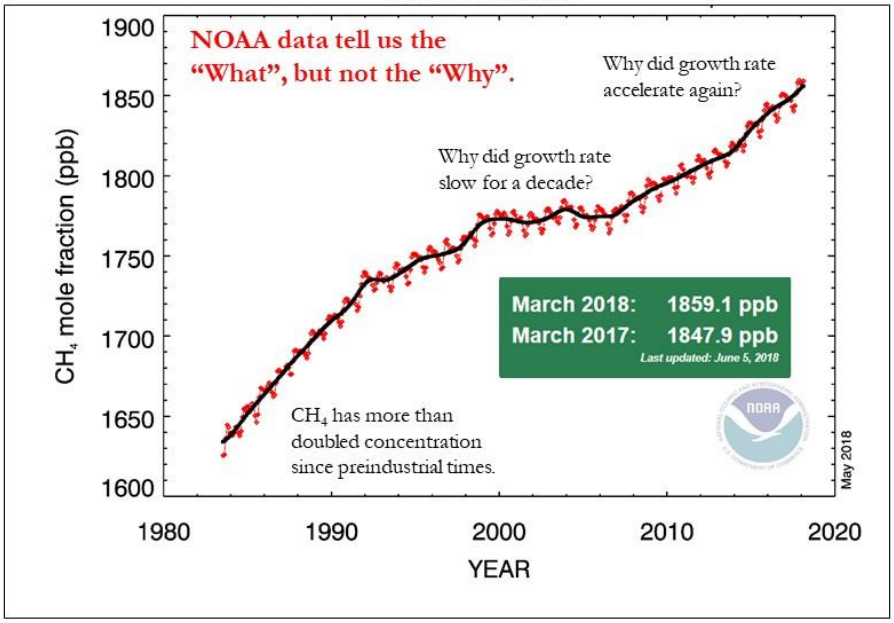
W-8a. Reduce uncertainty in tropospheric CH4 concentrations and in CH4 emissions, including regional anthropogenic sources and from a process level for natural sources.

QUESTION C-8. What will be the consequences of amplified climate change already observed in the Arctic and projected for Antarctica on global trends of sea level rise, atmospheric circulation, extreme weather events, global ocean circulation, and carbon fluxes?

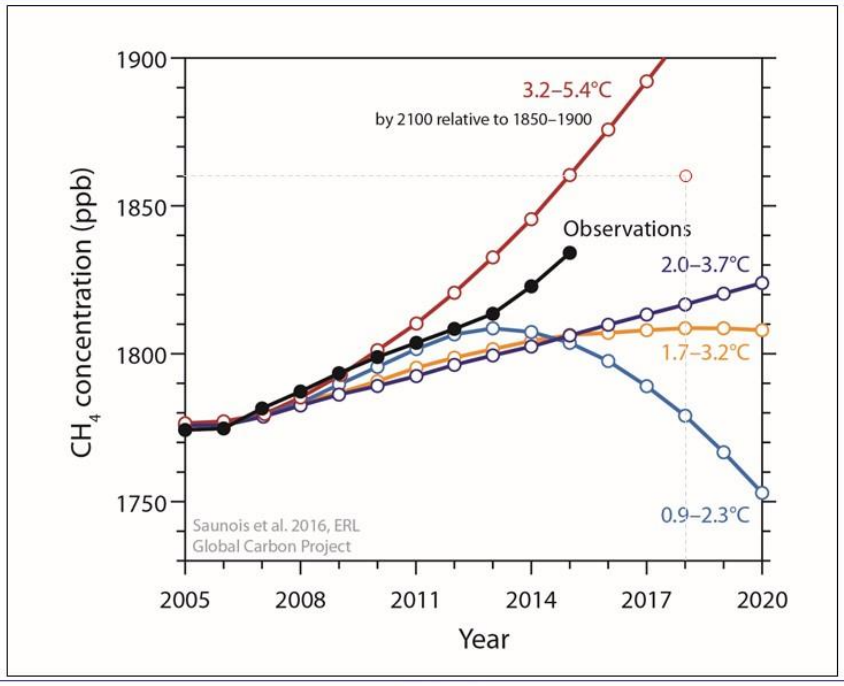
C-8f. Determine how permafrost-thaw driven land cover changes affect turbulent heat fluxes, above and below ground carbon pools, resulting greenhouse gas fluxes (carbon dioxide, methane) in the Arctic, as well as their impact on Arctic amplification.

Also: Sellers, Piers J., David S. Schimel, Berrien Moore, Junjie Liu, and Annmarie Eldering. "Observing carbon cycle–climate feedbacks from space." Proceedings of the National Academy of Sciences (2018)

Why measure Methane?



Observed Concentrations Compared to IPCC Projections



Source: www.globalcarbonproject.org

Methane Space Missions

CH4 Mission	Agency	Cov. (days)	Spatial Res. (km²)	Swath (km)	Err.	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	+
Solar backscatter (1.65 nm or 2.3 nm)																								
SCIAMACHY	ESA	6	30x60	960	1.5%																			
GOSAT TANSO-FTS	JAXA	3	10x10	520	0.7%																			
Sentinel-5P Tropomi	ESA	1	7x7	2600	0.6%																			
GOSAT-2 (3)	JAXA	3	10x10	632	0.4%																			
MetOp Sentinel 5	ESA		7x7	2600																				
CarbonSAT	ESA	5-10	2x2		0.4%																			
Thermal emissions (8.0 µm)																								
IASI	CNES	0.5	12x12	100	1.2%																			
AIRS	NASA	0.5	45x45		1.5%																			
TES	NASA		5x8		1.0%																			
CrIS	NOAA		14x14		1.5%																			
IASI-NG	CNES	0.5	12x12																					
Active (lidar)																								
MERLIN	DLR-CNES			100	1-2%																			
Geostationary / CUBESAT / ISS (1.65 nm or 2.3 nm)																								
geoCARB	NASA	2 hours	3x3 +		1%																			
ghgSAT	Private	targets	0.05x		1-5%																			
Bluefield (COOL)	Private	targets	0.02x	38																				
methaneSAT	Private																							
HISUI	JAXA																							

Table courtesy of Dr. Benjamin Poulter (GSFC)

Why use a laser?

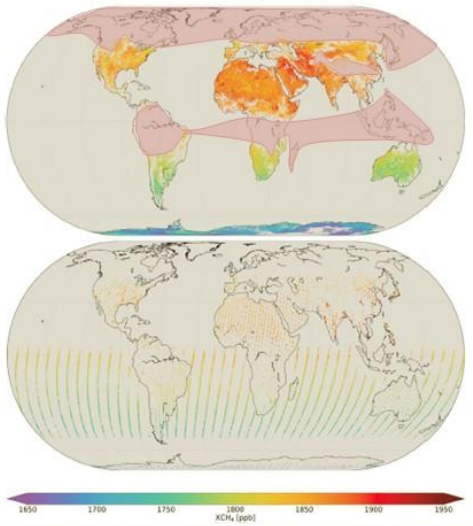
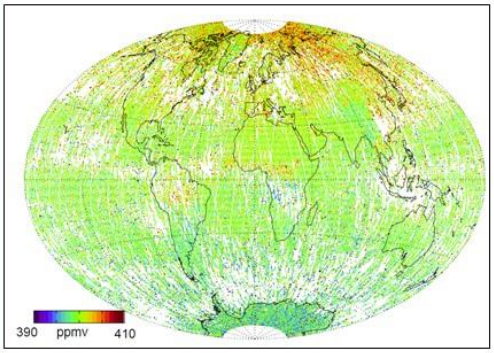


Figure 2. Global XCH_4 distribution as obtained with TROPOMI (top) and GOSAT (bottom) measurements averaged over the period of 12 November to 30 December 2017. Please note that for TROPOMI we have only used the observations over land so far. The GOSAT CH_4 product also contains observations over ocean for sunglint geometries.

Hu, Hailí, et.al. "Toward global mapping of methane with TROPOMI: first results and intersatellite comparison to GOSAT." Geophysical Research Letters 45, no. 8 (2018): 3682-3689.

No coverage in the Artic during the winter
Sparse coverage in tropical regions (wetlands)

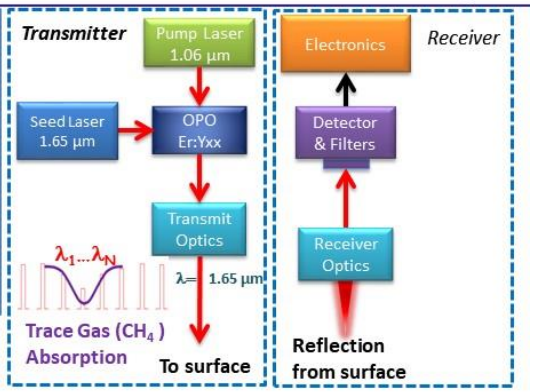
Lidar can address data gaps in important source regions (arctic and tropics).
Simulated CO_2 Lidar (ASCENDS) coverage for December 16-31 2015. (Simulation provided by Dr. Stephan R. Kawa, GSFC). CH_4 Lidar will be similar.

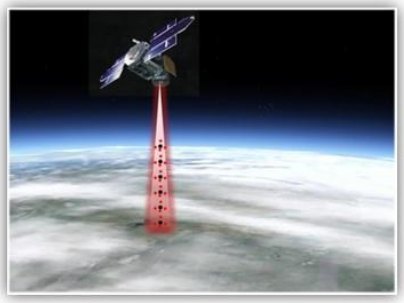


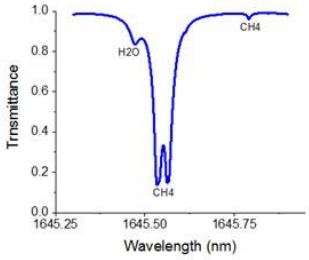
GSFC MEASUREMENT APPROACH

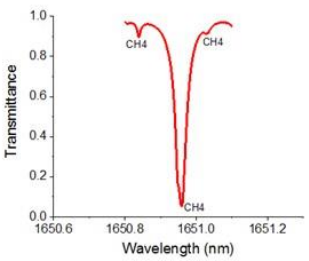
GSFC CH_4 Integrated Path Differential Absorption Lidar

- ***Transmitter (Laser) technology***
  - **Optimum wavelength for CH_4 Earth Detection: ~1.64-1.66 µm**
  - **Optical Parametric Oscillator (OPO) is the "baseline" solution for the transmitter.**
  - **Other options (Er:YAG and Er:YGG) available.**
- ***Receiver (Detector) Technology***
  - **DRS e-APD (ESTO)**

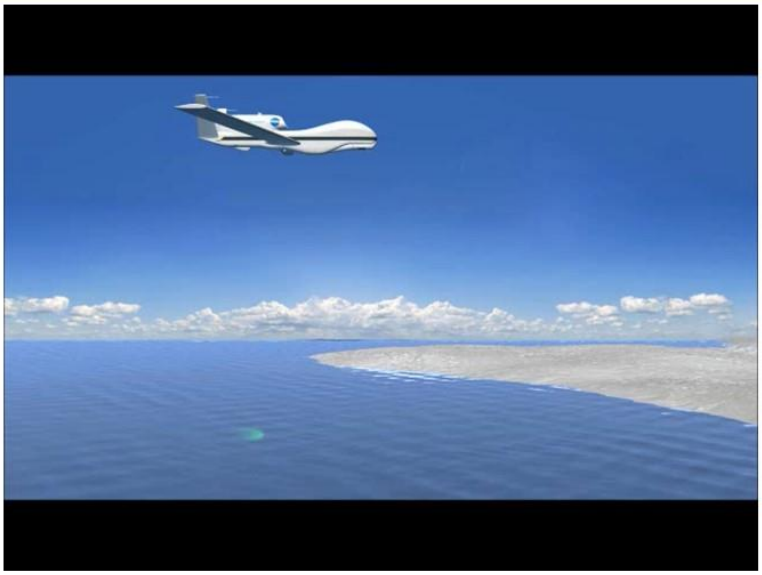




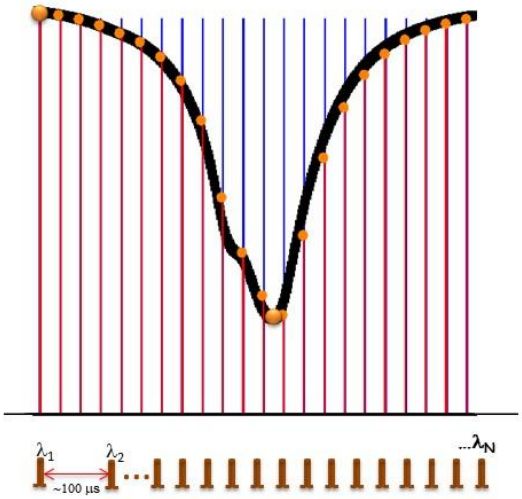




GSFC CH_4 IPDA Lidar Measurement Approach



Why use multiple wavelengths?



"Ideal" Instrument – has only random noise which can be averaged indefinitely.
Two wavelengths can adequately sample the lineshape. Averaging always helps.
Real Instrument – has random and non-random noise which can NOT always be averaged.
Two wavelengths can not adequately sample the lineshape if there are biases.
Nicely, J. M., T. F. Hanisco, and H. Riris. "Applicability of neural networks to etalon fringe filtering in laser spectrometers." Journal of Quantitative Spectroscopy and Radiative Transfer 211 (2018): 115-122.





TECHNOLOGY CHALLENGE AND CURRENT STATUS



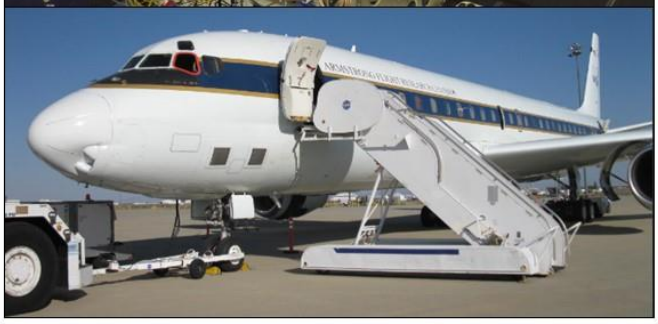
Laser transmitter is the biggest challenge



- "Requirements":
- Emission wavelength must coincide with suitable CH_4 absorption lines (1645.5 nm or 1651 nm)
- Must have high pulse energy (~600 μJ) and high pulse repetition rate. Depending on the receiver size and other instrument parameters we calculate that approximately 600 μJ is needed to make a measurement with a 0.5% precision.
- Must be tunable (~300-500 pm) and scan rapidly (0.5-1 KHz) over the CH_4 absorption line
- Must have narrow linewidth (~100 MHz).

2015 CH_4 Airborne Instrument

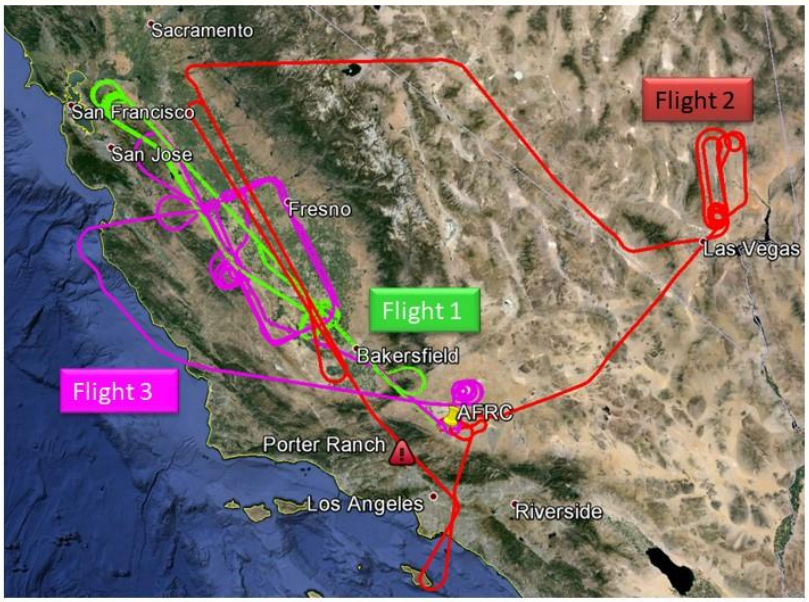




Parameter	Value (OPA/OPO)
Center λ.	1650.9 nm
Number of λ.	20/5
Pulse Width	~700/80 ns
Energy/pulse	~25/250 µJ
Bin width	4 ns
Divergence	~150 µrad
Receiver diam.	20 cm
Field of view	300 µrad
Receiver BP	0.8 nm (FWHM)
Averaging time	1/16 s *
Detector Resp.	~1-1.5 x10^9 V/W

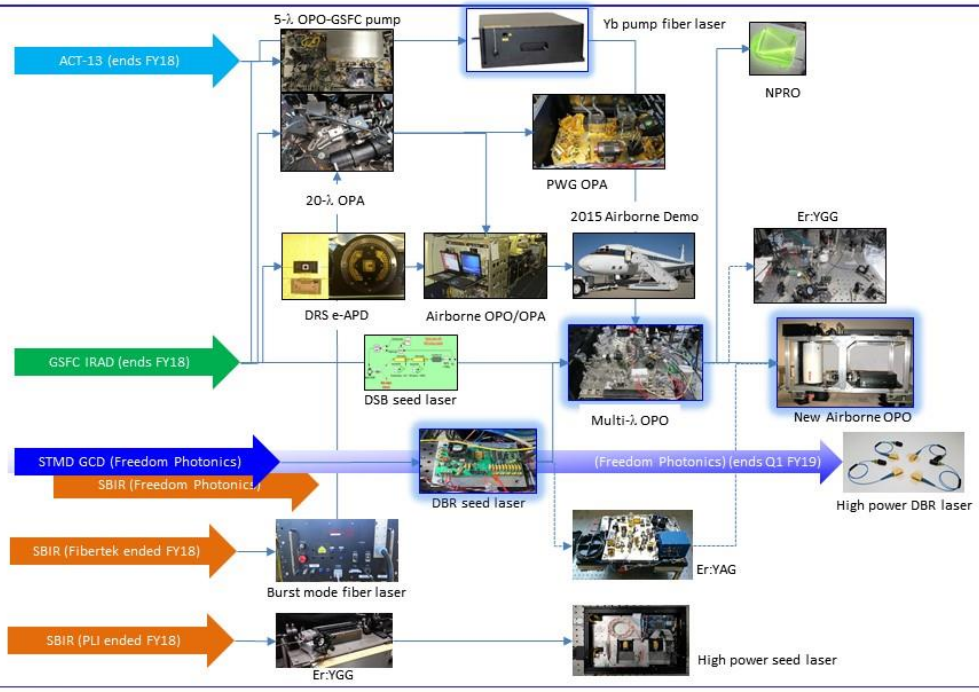
*Data analysis uses 1s averages

2015 Airborne Demonstration Flight Tracks

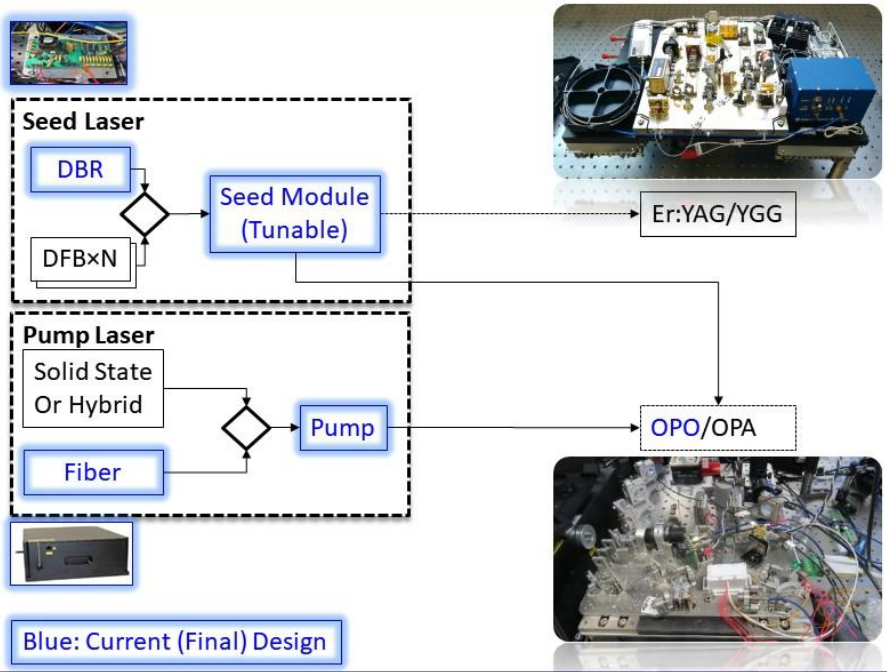


Better than 1% precision. Riris, Haris, Kenji Numata, et.al. Journal of applied remote sensing 11, no. 3 (2017): 034001.

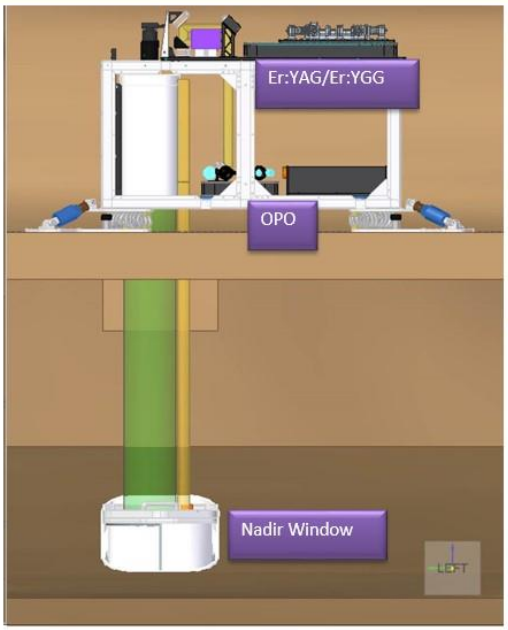
Technology Development

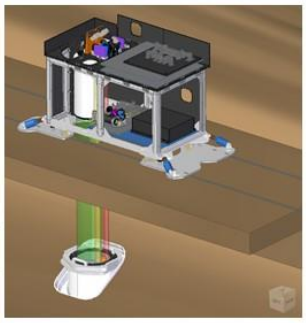


CH_4 Laser Transmitter Final Design for space and airborne science

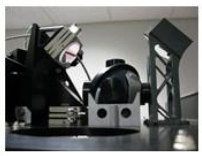


New (improved) airborne sensor







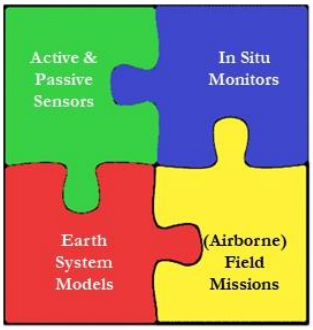


Smaller, lighter, easier to operate and align
Simultaneous dual beam capability
OPO completed and aligned
Er:YAG in almost complete
Ready to fly!

GSFC laser transmitter current status

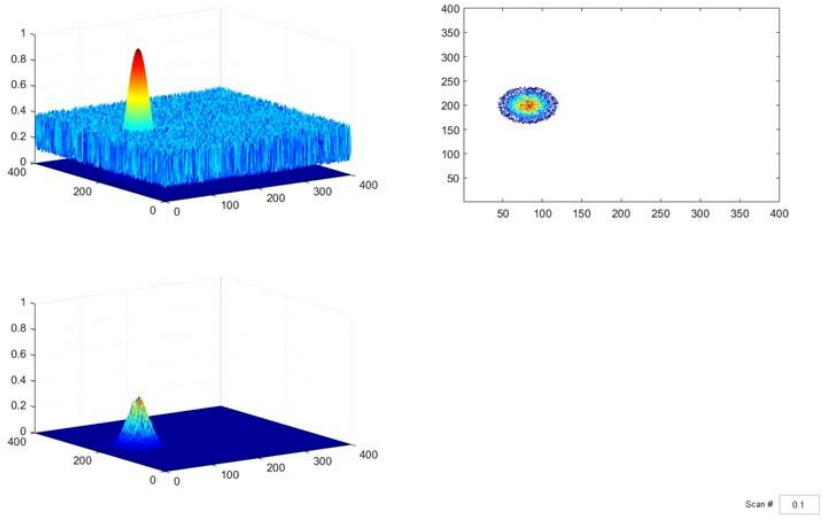
- Many different approaches for the laser transmitter have been investigated.
- Demonstrated CH_4 airborne measurements using two lidar transmitters
- Fast-tuned seed laser
  - 16-wavelength locked seed laser now combined with the OPO
  - ***Fast-tuned seed laser is applicable to all designs***
- Multi-wavelength OPO
  - Successful seeding with step-tuned DBR (FP) laser
  - Open path measurements started.
- Er:YAG
  - Er:YAG laser (Fibertek) delivered in June
  - Open path measurements this summer with two or more wavelengths
- Er:YGG
  - Testing Er:YAG NPRO possible alternative to Er:YAG
- OPA
  - On hiatus – available for airborne experiments.
- ***New airborne instrument ready to fly.***

Summary

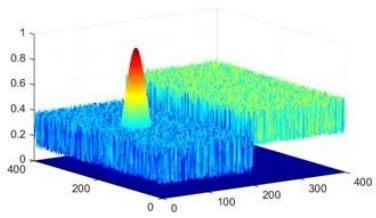


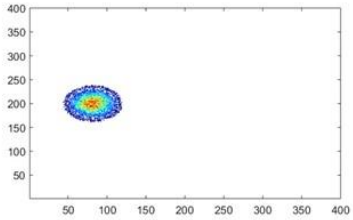
- Our present and near future observations are not adequate to constrain CH_4 budget or to monitor future releases.
- Space observations and budgets will require multi-agency, commercial and multi-national cooperation.
- Airborne campaigns maybe able to constrain models and allow us to model and predict how fluxes may respond in a warming world.
- *We would like to thank ESTO, GSFC IRAD, STMD and SBIR for their support.*

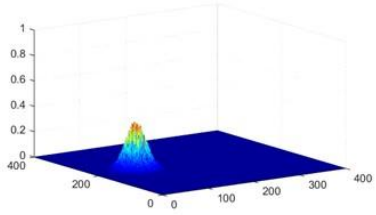
Multi-wavelength simulation



Multi-wavelength simulation

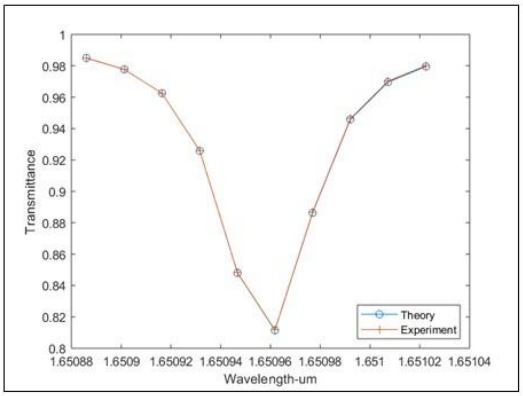


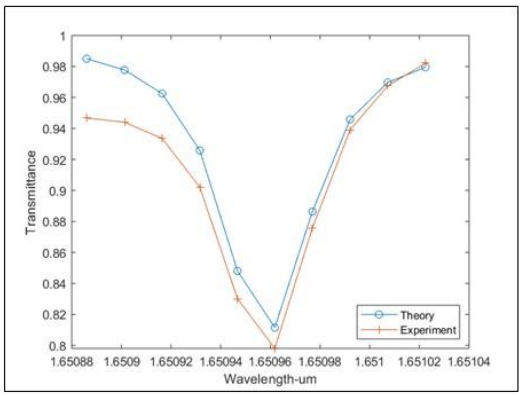




Scan # 0.1

Averaged Line shapes





2.5 TECHNOLOGY DEVELOPMENT FOR ADVANCED GREENHOUSE GAS LIDAR

Amin Nehrir

NASA Langley Research Center, Hampton, Virginia

Technology Development for Advanced Greenhouse Gas Lidar

Amin Nehrir

&

HSRL-DIAL Team

NASA Langley Research Center

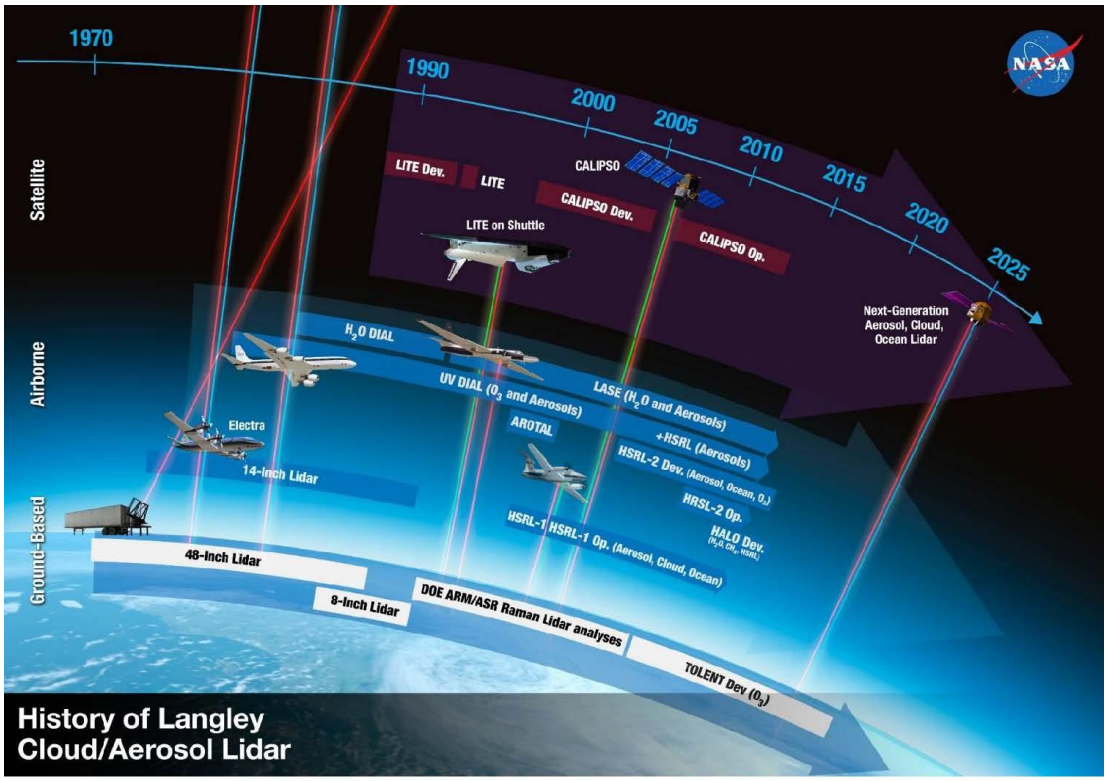
&

Industry, Govt., and Academic Labs

NASA Active Optical Technical Interchange Meeting

Columbia, MD

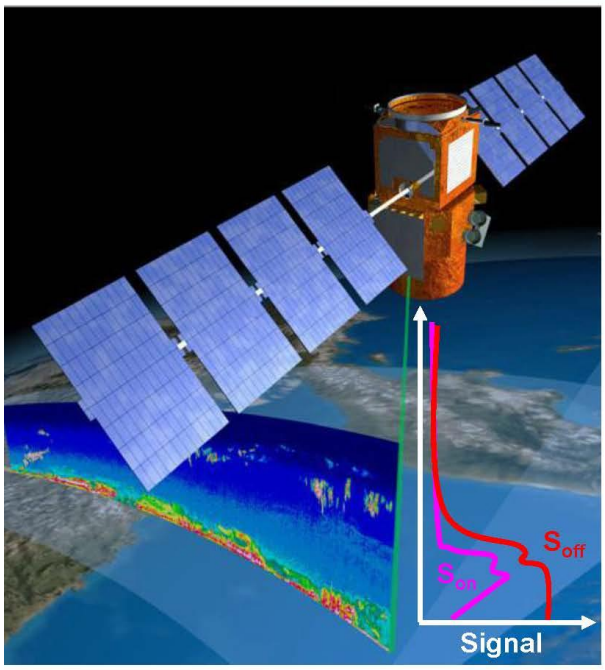
July 31, 2018

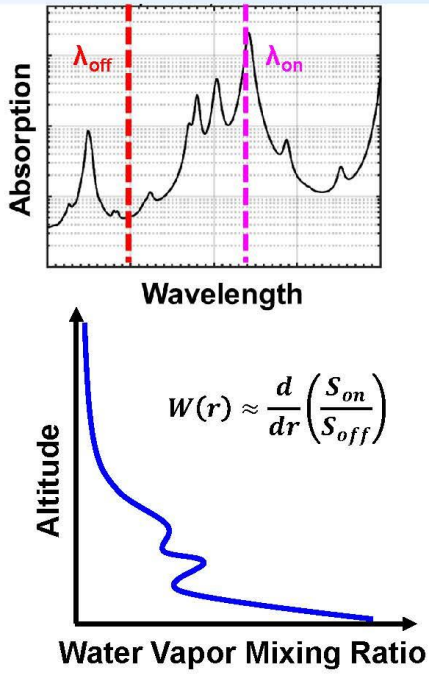


Motivation- Water Vapor, Methane

- **High resolution and accurate water vapor profile is the most cited "Target Observable" in the 2017 Decadal Survey**
  - Interdisciplinary/cross cutting science across four of the five 2017 Decadal Survey panels
- **D.S. recommendation to advance water vapor DIAL technologies through Incubation class investment for readiness in next decade**
  - Sustained technology maturation programs spanning all lidar subsystems
  - Demonstrate technologies and utility of operational retrievals in airborne science campaigns
- **Methane emissions/fluxes also identified as "Target Observable" in Explorer class**
- Technology advancements may enable cross-cutting mission simultaneously targeting methane columns and water vapor profiles

Differential Absorption Lidar for Trace Gas Profiling



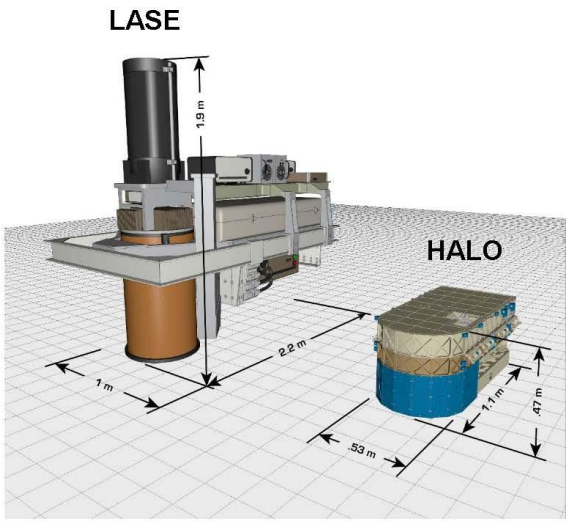


Why the DIAL Approach-Enables Profile Measurements

- **Enables direct measurements of water vapor profiles throughout the troposphere**
  - Increased spatial resolution and sensitivity to near surface atmosphere
  - Capability to resolve above cloud tops as well as through and below thin clouds
  - Can profile between broken clouds
  - Multi-line approach provides sensitivity from upper troposphere down to surface
- **Overall accuracy of the measurements**
  - Inherently self calibrating
  - Low sensitivity to uncertainties in atmospheric state parameters (e.g., temperature)
  - Immune to contamination from aerosol and cloud layers
- **Passive visible and infrared sensors are most uncertain near the surface**
  - Over 90% of water vapor is near the surface
  - Land-atmosphere exchange processes occur near the surface
- **Cross-cutting applications**
  - Simultaneous information on aerosol and cloud distributions (CALIPSO continuity)
  - Retrieval of mixed layer heights
  - Absolute reference for calibration of passive sensors

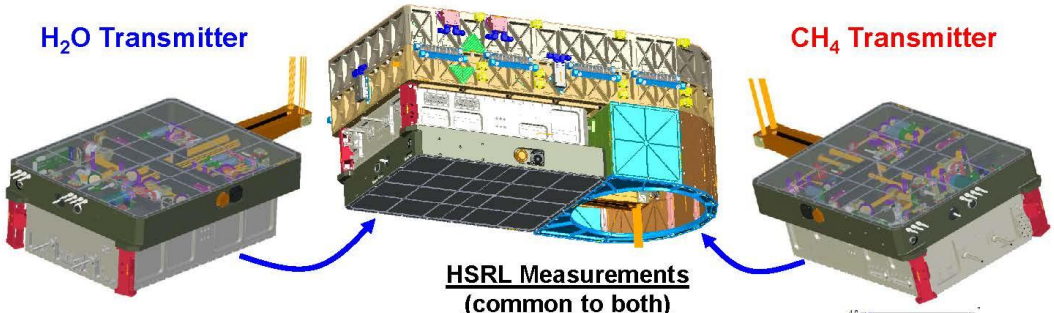
Motivation- Advanced Airborne Demonstrator

- New capability to measure H_2O profiles from smaller and high altitude airborne platforms
  - Currently: LASE is only capable of going on large aircraft (DC-8)
  - Development of more compact H_2O DIAL system with additional (CH_4) DIAL and HSRL measurement capabilities
- DIAL measurements along with measurements of aerosol/cloud properties combines many of the measurement requirements for airborne campaigns and satellite calibration and validation
- **Technology test-bed for maturing technologies and algorithms required for future DIAL missions**

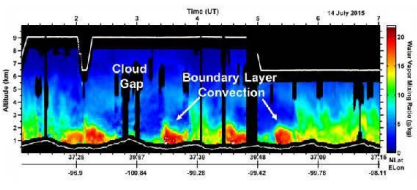


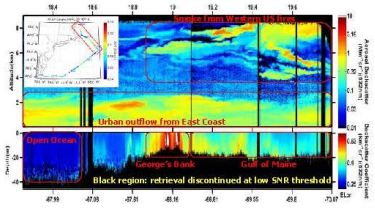
HALO Architecture

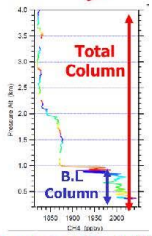
Interchange two common architecture lasers and single receiver to enable H_2O DIAL+HSRL or CH_4 DIAL+HSRL measurements



HSRL Measurements (common to both)





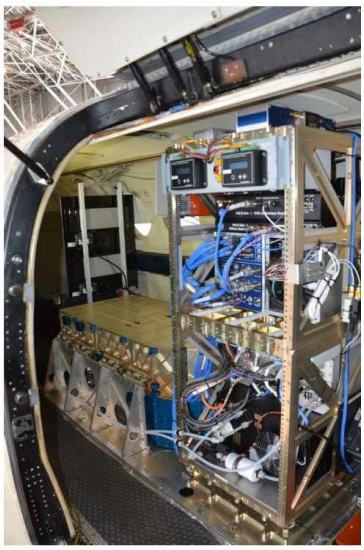


- **Water vapor profiles**
- **Total perceptible water**
- **Aerosol, cloud, and ocean profiling**
- **Column weighted XCH_4**
- **Multi-layer XCH_4 retrieval**

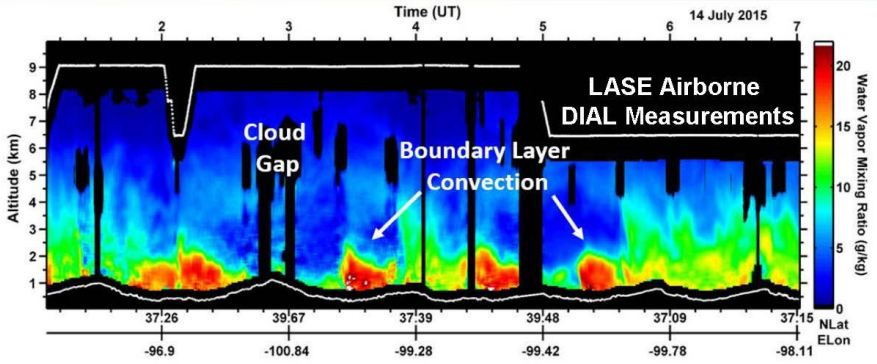
Timeline for HALO Development

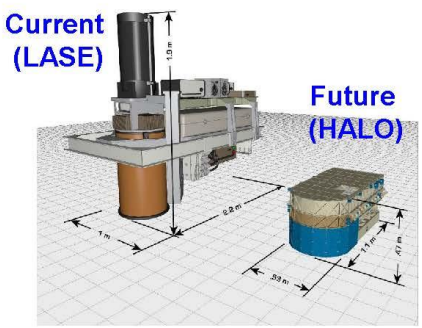


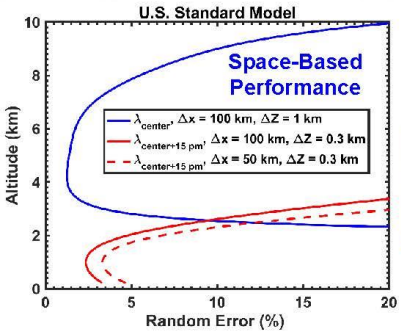
- **~3.5 year development cycle for three measurements**
  - Enabled by adapting heritage designs and algorithms from LaRC HSRL/DIAL instruments
  - SBIR and ESTO investments prior to start of program
- **Methane laser technology was more straightforward and came first…we are currently flying**
  - First demonstration of an injection seeded OPO on prop aircraft
  - First airborne demonstration of range resolved CH_4 absorption
  - Flying on the B200 as a part of the Long Island Sound Tropospheric Ozone Study mission
- **Water vapor measurements coming up in spring 2019**



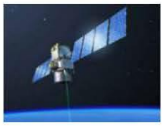
Water Vapor DIAL: Current and Future Prospects



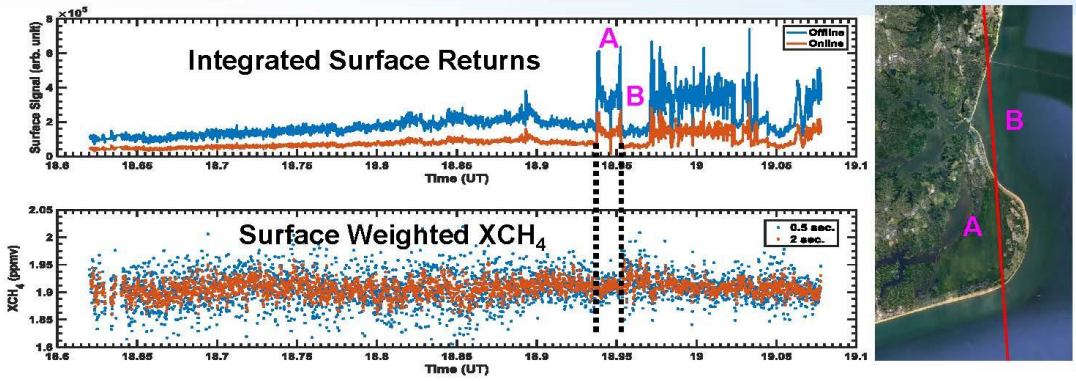


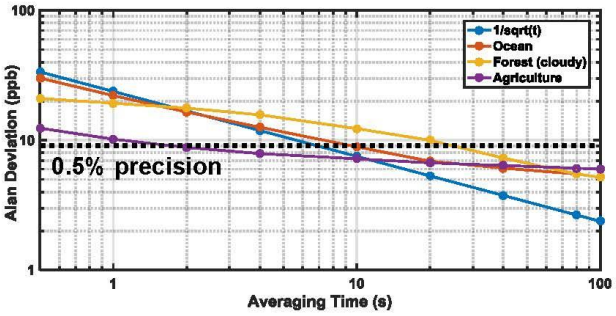


ESTO ACT Fan 2017



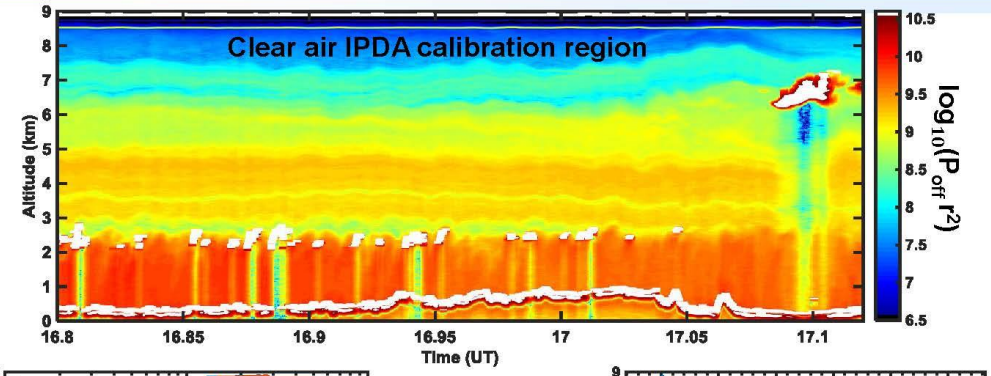
High Accuracy and Precision CH_4 Columns

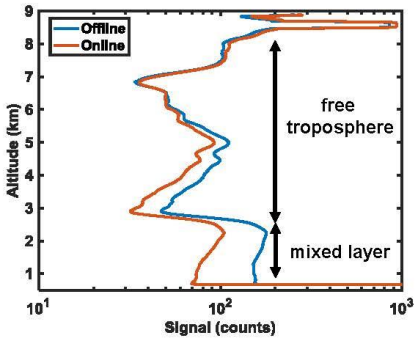




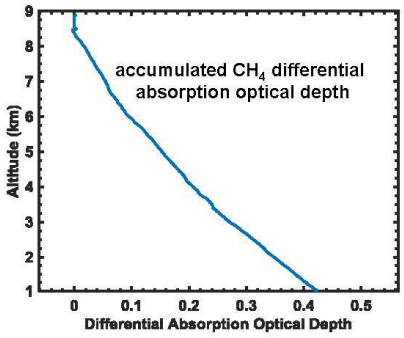


Preliminary CH_4 DIAL Products





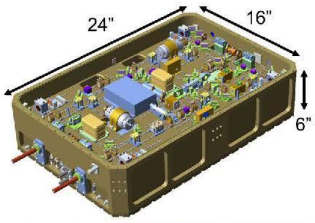
$$OD_{CH_4}(r) \propto \frac{P_{on}(r)}{P_{off}(r)}$$



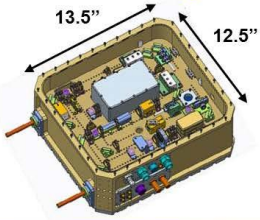
Technology Advancements and Challenges

Pulsed Laser Development: Water Vapor

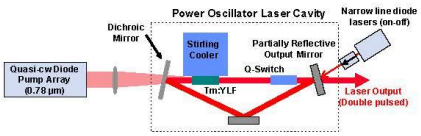
Fibertek
935 nm OPO



Fibertek
822 Er:YAG (H_2O+CH_4)



MIT L.L.
822 nm Tm:YLF



Airborne → Airborne/Space → Space

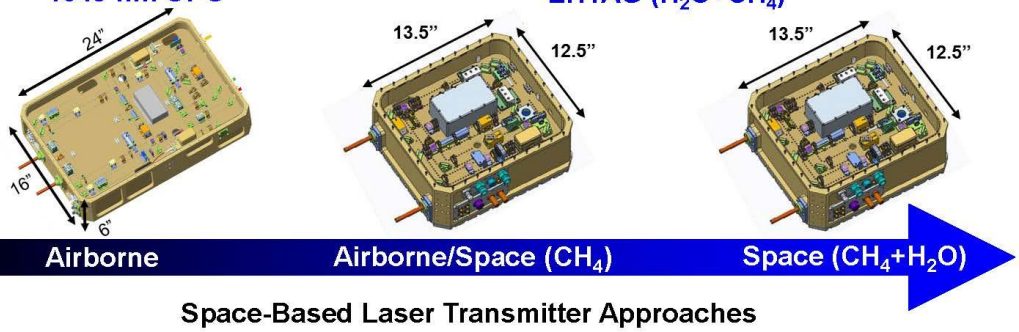
Space-Based Laser Transmitter Approaches

	Laser	λ (nm)	Efficiency	Pulse Energy	Power	Complexity	Scalability	Maturity
Current	Ti:S	817	<1-3%	~100 mJ	1W			
Current	Nd:xxx	940	~2%	~10-20 mJ	1W			
Transitional	OPO	700-950	<2%	70-100 mJ	10W			
Emerging	Er:YAG	822	~3-5%	4 mJ	16W			
Emerging	Tm:YLF	812-817	~5-8%	~100 mJ	10-20W			

Pulsed Laser Development: Methane

Fibertek
1645 nm OPO

Fibertek
Er:YAG (H_2O+CH_4)



Space-Based Laser Transmitter Approaches

Laser	λ (nm)	Efficiency	Pulse Energy	Power	Complexity	Scalability	Maturity
OPO	1645	<2%	2-4 mJ	2-4W			
Er:YAG (CH_4)	1645	~3-5%	7 mJ	7W			
Er:YAG (CH_4+H_2O)	1645/822	~3-5%	7 mJ	28W			

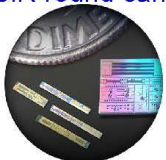
Er:YAG laser technology fostered with Fibertek through SBIR starting in 2015
Scaling laser average power will enable methane and water vapor pathfinder mission

Seed Lasers Technologies

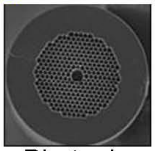
- Seed laser technologies have been demonstrated on airborne prototypes
- Investments are required to develop critical technologies with the required form factor and radiation tolerance
  - Semiconductor lasers
  - Low loss optical isolators
  - Photonic gas cell and etalon frequency references
  - Integrated RF and photonic systems
- SBIR awards backed by ESTO have been heavily leveraged, but resources are spread too thin amongst other sub topics
- ACT funding cycle and model makes continuous development a challenge
- Missing one SBIR round can set progress back 2 years



Semiconductor Lasers



Integrated Photonics



Photonic Gas Cells

HALO Seed Lasers

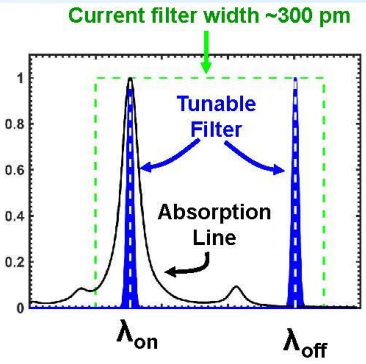


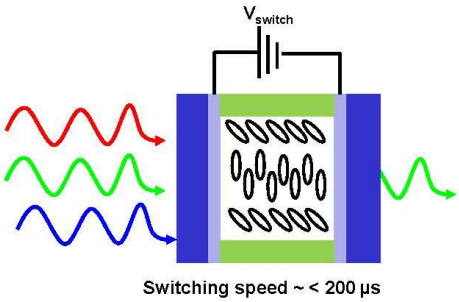




Receiver Technologies

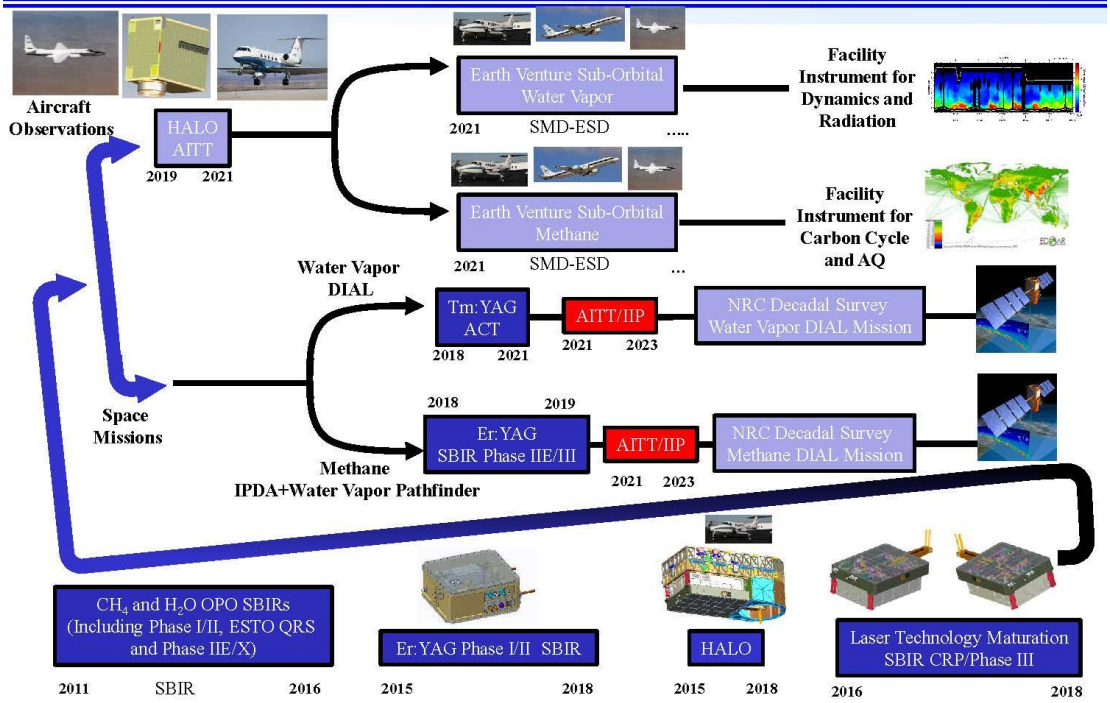
- **Frequency agile optical filtering**
  - Multi-wavelength DIAL approach requires use of broad band optical filters compared to CALIPSO- 300 pm vs 30 pm
  - Frequency agile filter that tracks the transmitted pulsed laser wavelength significantly reduces (30x) solar background
  - Partnership with industry through SBIR (TRL2)
  - Funding cycle poses development challenges
- **Detector technologies**
  - High quantum efficiency
  - Low noise
  - Large dynamic range (driven by cloud requirements)
  - Sun, Smith/Hare et al....





Switching speed ~ < 200 µs

Technology Roadmap-Airborne to Space



Challenges

- NASA can't do it all – requires capable industry partners
- NASA's main role is defining science requirements, lidar systems engineering, development of focused subsystems, and performance test
  - No funding available to conduct performance simulations/OSSES
- Challenge is that these are low volume applications
  - Need to target companies willing to work in this low volume R&D market and maintain corporate knowledge
  - How to keep these companies funded and advancing key lidar technologies?
- Competition is good, but can't spread the limited funding too thin
- Successful DIAL industry partnerships
  - Seed laser integrated photonics development - SBIR
  - Pulsed laser development – ESTO, SBIR, IRAD
  - Filter opto-electronics – SBIR, IRAD
  - Detectors – ESTO and SBIR (leveraged from other developments)

Challenges

- Funding requires support though multiple competitive programs supported by ESTO, R&A, and SBIR
- Funding for specific programs (i.e. IIP, ACT) are offered on 3 or 4-year cycles which may not align with the development cycle.
  - Missing one ACT cycle can set you back 3-4 years. One SBIR round is 1-2 years
- Funding gap exists for subsystem technology maturation to TRL 6.
  - ACT Program targets low TRL. Need follow-on program to mature successful development of subsystems to TRL 6.
- Recruitment of early career scientists and engineers and obtaining funding for training and integration into lidar program.
  - Our group has leveraged the NPP (Post-doctoral Program) and pathway programs, however only a few university programs offering lidar remote sensing R&D programs.
  - Limited funding at universities to sustain lidar programs

Summary



- Decadal Survey calls for advancing technologies to enable water vapor DIAL in the next decade
- The DIAL technique is mature as demonstrated for 30+ years via airborne prototypes to flesh out requirements and to advance technology
- Technology advancement required to enable/scale airborne prototypes to space
  - Funding for lidar simulations/OSSES, power scaling of pulsed lasers, development of seed laser optics and photonics, frequency agile filtering, high efficiency and low noise detectors
- Sustained technology investments now for water vapor DIAL will enable flight missions in the next decade
- Short term investments in emerging technologies may enable cross-cutting methane explorer class mission with simultaneous path finder water vapor DIAL measurements



Acknowledgments

This work is supported by NASA ESTO, SBIR, and the Earth Science Division Research and Analysis program. We thank Fibertek Inc. for their dedicated support and internal investments on the laser development effort. We also thank NASA Langley Research Center for internal support.

3 Session 3

Wind Measurements was designed to examine applications and issues for measuring Earth atmospheric winds from airborne platforms and spacecraft. The Session Chair, Tsendgar Lee, gave an overview presentation of the area to start the session. A total of four research presentations representing the work of researchers at GSFC and LaRC along with their industry and academic partners, and work of industry groups was received. Table 3-1 lists the five session papers. See Section 3 of the Assessment Report for observations and assessment comments.

Table 3-1. Session 3 Papers

Paper Number	Author	Title	Paper	Presentation
S3-1	Tsendgar Lee, NASA SMD	Overview		☑
S3-2	Michael J. Kavaya and Jirong Yu, NASA LaRC Sammy W. Henderson, Beyond Photonics G. David Emmitt, Simpson Weather Associates	Global Wind Measurement with a Pulsed, Coherent-Detection, Lidar System: Technology Status, Development Needs, and Partnering Opportunities	☑	☑
S3-3	Sara Tucker, Ball Aerospace	Direct Detection Doppler Wind Lidar: Recent Progress, Technical Needs, and Future Applications		☑
S3-4	Dominique Fourguette[1], David Johnson[1], Mike Fleck[2], Matt Wiebold[2], Mike Fan[2] [1] Michigan Aerospace Corporation; [2]Honeywell International	High Altitude LIDAR Atmospheric Sensing	☑	☑
S3-5	Michael A. Krainak[a], Anthony W. Yu[a], Steven X. Li[a], Yingxin Bai[a], Kenji Numata[a], Jeffrey R. Chen[a], Molly E. Fahey[a], Frankie Micalizzi[a], Oleg A. Konoplev[b], Diego Janches[a], Chester S. Gardner[c], Graham R. Allan[d] [a]NASA Goddard Space Flight Center; [b]SSAI; [c]University of Illinois; [d]Sigma Space	Proposed Space-based Sodium Lidar Technology	☑	☑

List of presentations

3.1 Wind Measurement for NASA's Weather Focus Area 3-2
3.2 Global Wind Measurement with a Pulsed, Coherent-Detection, Lidar System: Technology Status, Development Needs, and Partnering Opportunities.....3-6
3.3 Direct Detection Doppler Wind Lidar: Recent Progress, Technical Needs, and Future Applications.....3-30
3.4 High Altitude Lidar Atmospheric Sensing.....3-50
3.5 Proposed Space-Based Sodium Lidar Technology 3-67

3.1 WIND MEASUREMENT FOR NASA'S WEATHER FOCUS AREA

Tsengdar Lee

Weather Focus Area Lead, Earth Science Division, Science Mission Director, NASA Headquarters, Washington, D. C.

Wind Measurement for NASA's Weather Focus Area

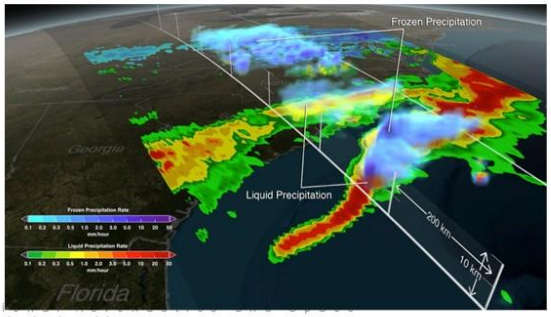
Tsengdar Lee
Weather Focus Area Lead
Presented at
NASA Technical Interchange Meeting on Active Optical Systems
July 31, 2018

National Aeronautics and Space Administration

1

NASA's Weather Programs

- Atmospheric Dynamics
- Precipitation Science
- Sounders Science
- Joint Center for Satellite Data Assimilation
- Short-term Prediction Research and Transition Center
- Heavily leveraging Modeling and Analysis Program





National Aeronautics and Space Administration

2

Topics in 2015 Weather Focus Area Workshop

Weather Prediction and Predictability:

- Expand range of NWP up to 4 weeks.
- Improved prediction of extreme weather.

Convection and Precipitation:

- Interaction between convective and larger scale circulations.
- Mesoscale organization, internal structure and dynamics, life cycle of convection.
- Rate of intensification.
- Processes and interactions which control precipitation.

PBL/Land surface/Ocean surface:

- Moist convective process interaction with BL and surface.
- Mechanisms controlling BL clouds.
- Unify parameterization of moist and dry turbulence, covection and clear air turbulence.

Clouds and Radiation:

- Processes determining cloud microphysical properties, connection to aerosols and precip.
- Spatio-temporal structure of cloud systems.

Critical Capabilities Identified

OSSEs:

Take ownership of NASA Earth Science OSSE capability designed for mission trade studies

Wind measurements:

Additional trade studies may be needed to design cost-effective strategy for wind measurements (based on lidar, radar, and atmospheric motion vector)

Temperature and Humidity measurements:

Better measurements from space of the temperature, water vapor, and wind in the boundary layer.

Cloud and Precipitation measurements

Focus on higher spatial and temporal resolution, and synergistic measurements involving multiple instruments (e.g., radar, radiometer, and lidar observations), and different platforms (geosynchronous, low-Earth orbit, and airborne).

Modeling:

Pursue convective permitting (grid size 1-5 km) modeling

Data assimilation:

Pursuit cutting-edge data assimilation issues such as hybrid ensemble-based 4D-Var, all-sky radiance assimilation, assimilation of properties related to clouds and radiation, land surface emissivity, coupled DA of the atmosphere-ocean-land-ice system, and DA evaluation metrics.

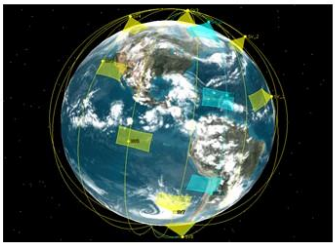
Computing:

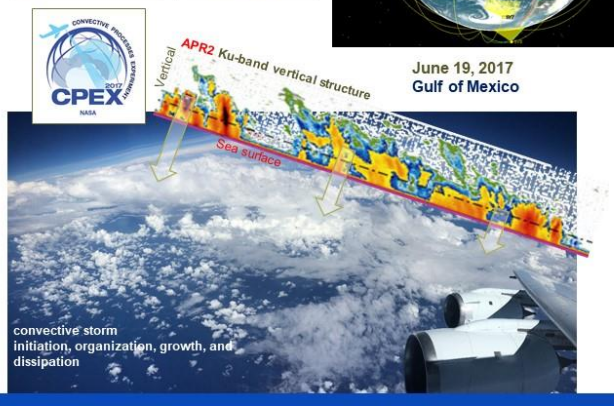
Match the supercomputing capability and capacity with the growth in a sustained, high-resolution modeling capability directed at using all observations to their fullest extent in weather prediction and at planning for new global observations

Some Notable WFA Activities Since 2015









- Published WFA Workshop report
- Two OSSE Workshops (2016 &17)
- One MISTiC OSSE study
- One AMV OSSE study
- Convective Storm ROSES call
- CPEX campaign
- Participated in the NOAA NGGPS working groups
- Continued investment in precipitation science
- Invested in Joint Effort for Data assimilation Integration (JEDI) at JCSDA

Decadal Survey Recommendations

Science questions

(W-1) What planetary boundary layer (PBL) processes are integral to the air-surface (land, ocean and sea ice) exchanges of energy, momentum and mass, and how do these impact weather forecasts and air quality simulations?

(W-2) How can environmental predictions of weather and air quality be extended to forecast Earth System conditions at lead times of 1 week to 2 months?

(W-4) Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?

(W-5) What processes determine the spatio-temporal structure of important air pollutants and their concomitant adverse impact on human health, agriculture, and ecosystems?

(W-3) Influence of Earth surface variations on weather and air quality

Atmospheric Wind Observations

3D winds in troposphere/PBL for transport of pollutants/carbon/aerosol and water vapor, wind energy, cloud dynamics and convection, and large-scale circulation

Active sensing (lidar, radar,scatterometer); or **passive imagery** or **radiometry-based atmos. Motion vectors** (AMVs) tracking; or lidar**

** Could potentially be addressed by a multi-function lidar designed to address two or more of the Targeted Observables

Several Science Drivers for Wind Measurement



- Numerical Weather Prediction
  - Large scale wind at mid-latitude is well understood
  - Wind in the tropics, where the mass balance relation fails, is still a challenge and not well measured
- Planetary Boundary Layer
  - Interaction with tropical convection system
  - Modulation in dynamical oscillations
  - Initiation of mesoscale convective systems
  - Ventilation of boundary material (e.g. water vapor, aerosol) and energy into the troposphere
- Transport of aerosols
  - Connection of aerosol-cloud-radiation feedback processes
- Transport of mass
  - Constraining the convective mass flux, a key source of uncertainty in cumulus parameterization, which is critical in the Earth System Modeling

3.2 GLOBAL WIND MEASUREMENT WITH A PULSED, COHERENT-DETECTION, LIDAR SYSTEM: TECHNOLOGY STATUS, DEVELOPMENT NEEDS, AND PARTNERING OPPORTUNITIES

Michael J. Kavaya[1]*, Jirong Yu[1], Sammy W. Henderson[2], and David Emmitt[3]

*[1]NASA Langley Research Center, USA, *michael.j.kavaya@nasa.gov*
[2]Beyond Photonics, USA
[3]Simpson Weather Associates, USA

ABSTRACT

The 2017 NRC Earth Science Decadal Survey stressed the urgent need for global measurements of wind, repeating the 2007 Decadal Survey conclusions, and included global winds in its 14 "Priority Targeted Observables". The 35 "Most Important Science and Applications Questions" included questions from the Weather Panel about the planetary boundary layer, convective processes, and weather prediction. The Weather Panel stated global winds would be a transformative new measurement. One of the most promising sensors to deliver global winds in the presence of clouds and in the atmospheric boundary layer is the pulsed, 2-micron, coherent-detection, Doppler lidar technology which utilizes backscattered light from airborne aerosols moving with the wind. Within NASA, the Langley Research Center (LaRC) has been developing the required laser and lidar technology for both airborne and space applications. Langley is working with several industry partners to enable a space mission. The technology status, current programs, further development needs, the space mission concept, and partnering ideas will be presented.

1 ADVOCACY FOR GLOBAL WINDS

The "science pull" for global wind measurement is very strong. WMO advocacy began at least as early at 1992 and its requirements database lists 13 entries for horizontal winds in the troposphere and lower stratosphere for 7 different application areas [1]. The 2017 NRC Earth Science Decadal Survey stated that "In particular, three-dimensional horizontal wind vector measurements from space-borne wind profilers (Baker et al, 2014) would be transformative to weather and air quality forecasting, both in the PBL and the free troposphere. High temporal resolution vertical profiling of the PBL and troposphere on a global scale would improve severe weather (a national priority, H.R.353, 2017) and air quality forecasting." [2, 3]. A 2015 workshop for the NASA Weather Focus Area gathered about 70 weather researchers and stated "Global measurements of the spatio-temporal (four-dimensional) evolution of large-scale horizontal wind vectors are urgently needed. It is important to avoid all or nothing strategies for the three-dimensional wind vector measurements, as important progress is possible with less than comprehensive observing strategies." [4]. A 2018 NOAA study listed 3D Wind Lidar in the "High Leverage/High Impact" category, ranked it high in value per unit cost, and included it in the highest scoring Constellations [5].

2 SPACE MISSION CONCEPT

Global wind measurement using pulsed Doppler lidars has been discussed since the 1970s. Several space mission studies have been performed for lidar systems employing coherent detection, direct detection, and a combination of both, the "hybrid Doppler lidar" [6]. A typical mission concept is depicted in Figure 1. The satellite and lidar are moving to the right. Two fixed telescopes are both aimed 30 deg. from nadir with top view azimuth angles of 45 (blue "fore" beam) and 135 (red "aft" beam) deg. The laser is directed to the fore azimuth telescope for a time interval determined by the desired along-track horizontal resolution. During this time data from multiple laser shots are acquired to be combined into a single line-of-sight (LOS) range profile of the 3-D wind projected along the beam direction. The grayed data curtain in the figure depicts vertical profiles of LOS winds measured at that time only from the fore direction. The backscattered signal from each laser shot is divided into consecutive time or "range gate" intervals, which lead to height intervals and the resultant vertical profile. After the shot accumulation time interval, the laser is directed to the aft azimuth telescope and measures wind in an

air volume that was previously measured from the fore direction about 46 sec. earlier. The colored data curtain in the figure depicts completed vertical profiles of horizontal vector (magnitude and direction) wind that are calculated from the two LOS perspectives. Switching between beam directions is timed to overlay the fore and aft LOS wind measurements.

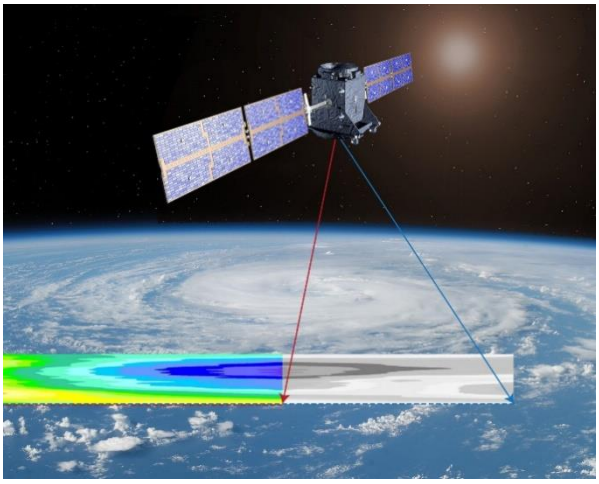


Figure 2 Depiction of "sheet" of wind vertical profiles

3 COHERENT LIDAR MEASUREMENT OF WIND

Pulsed coherent detection lidar is well suited for remote sensing of wind from earth orbit. The use of a local oscillator (LO) laser, the optical detector as a signal-LO mixer, data processing in software, and aerosols as the backscattering target together yield several benefits. Table 1 relates aspects of the measurement technique to the resulting benefits.

The software estimation of frequency in the signal's frequency domain leads to two figures of merit (FOM) for the wind measurements [7, 8]. The first FOM is the usual velocity precision. Coherent detection has excellent precision (order 1 m/s) for all wind estimates that are not outliers. The second FOM, is the probability of outlier wind estimates. The outliers result from the combination of low SNR, the stochastic behavior of the signal and noise, and frequency domain estimation; they occur when a noise spectral peak is mistaken for the wind velocity peak. The outlier probability falls from 50% to 1% with less than 5 dB increase in SNR. The mission design point will specify the probability of outliers, for example, 10%. The value of aerosol backscatter required for the design probability is determined by the coherent lidar, data processing, and atmospheric parameters. [9, 10, 11]; and is a key parameter that determines atmospheric coverage.

Table 1 Coherent detection aspects & benefits

Aspects of Technique	Resultant Benefits
Active remote sensing	Any sun geometry
LO rejects background light	Equal day/night performance
LO eliminates most noise sources	Very photon & electrically efficient
Software controlled narrow detection BW	Better vertical and horizontal resolution due to efficiency
Frequency estimation not light intensity	Excellent velocity estimation precision
Aerosols much less Brownian velocity than molecules	Wind turbulence also obtained
Signal spectrum mixed to MHz & digitized to computer	Data may be re-processed repeatedly to optimize spatial resolution

One of the benefits of coherent detection listed in Table 1 is **the ability to repeatedly re-process the data for optimization to the measurement conditions and science priorities.** Figure 2 shows some of the parameters that trade with the required aerosol backscatter, and with each other. Sensitivity to lower backscatter β is desired. The first right hand side term is the receiver diameter D. The second term includes the laser pulse energy E, pulse rate f, pulse duration τ, and laser beam quality parameter M^2; and is the laser FOM for considering the required aerosol backscatter. The first two terms together are often called the lidar FOM; which permits quick lidar comparisons but does not attempt to be inclusive of all parameters affecting minimum backscatter sensitivity. The third term comprises the key science parameters of horizontal h and vertical z resolution; the velocity search bandwidth V_{SRCH}, and outlier wind estimate probability b. V_{SRCH} may be able to be minimized using contextual information including other sensors. The spacecraft velocity combined with the design horizontal resolution sets the number of

laser shots averaged for an LOS wind profile, a key aerosol sensitivity parameter.

$$\frac{1}{\beta_{MIN}} \propto D^2 \cdot \frac{E\sqrt{f}\,\tau^{0.285}}{1+\left(M^2\right)^2} \cdot \frac{\sqrt{\Delta h \bullet \Delta z}}{V_{SRCH}^{0.4}\left[2.5-\ln(b)\right]}$$

Figure 2 Lidar and data processing trade equation for the required aerosol backscatter coefficient

The design vertical resolution and the laser beam nadir angle at the wind measurement location set the range gate length, another key aerosol sensitivity parameter. The τ and V_{SRCH} exponents, and the algebraic expression for b in Figure 2 are only illustrative examples; they will change under different conditions. Multiple re-processing of the data will also permit reduction of V_{SRCH}, and permit different science emphases depending on conditions and applications.

4 AIRBORNE TECHNOLOGY STATUS

Pulsed-laser, coherent-detection (heterodyne), remote sensing of wind velocity began with the CO_2 laser in 1970; first flew on an aircraft in 1972; advanced to solid-state lasers in 1988 using Nd:YAG [12]; and then the eye safe 2-micron Tm,Ho:YAG in 1990 [13]. Aircraft demonstration at 2 microns followed in 1993. The laser used for the 1990 demonstration operated at 22 mJ pulse energy at 3.2 Hz. NASA was developing global wind mission concepts using 2-micron lasers and challenged the laser group at LaRC to increase the 2-micron pulse energy. **The LaRC laser team invented the 2-micron Tm,Ho:LuLF laser** which quantum mechanical models predicted [14] and experiments showed had higher efficiency than YAG and YLF based lasers. Langley steadily demonstrated greater pulse energies up to 1,000 mJ in 2003, a factor of 50 increase [15]. The successful development of this and other 2-micron lasers at Langley has been documented [16].

During the laser development LaRC developed a compact, rugged, 2.053 micron, 250 mJ, 10 Hz, 200 ns, Tm,Ho:LuLF MOPA laser. The optical-to-optical efficiency is about 2.4%; which gives 1.2% electrical-to-optical efficiency assuming 50% laser diode array efficiency. With the compact laser they developed an airborne 2-micron pulsed coherent wind lidar called the Doppler Aerosol WiNd (DAWN) lidar system [17]. DAWN has flown in four NASA airborne science campaigns to date: GRIP in 2010, Polar Winds – Greenland in 2014, Polar Winds – Iceland in 2015, and CPEX in 2017 [18 – 23]. Results from the 2017 CPEX science campaign demonstrated that DAWN: 1) produced vertical profiles of horizontal vector wind with many complete horizontal wind profiles from 10 km to the surface with 1 second integration; 2) was validated to provide accurate winds with very low bias by comparison with dozens of dropsondes; 3) made valuable wind measurements in cloudy skies including cloud tops, through low optical density clouds, and through holes between clouds; and 4) was very complementary to the JPL APR-2 radar as the atmosphere transitioned between clear air/thin clouds and thick clouds. **The DAWN coherent wind lidar technology is TRL 9 for aircraft flight.**

5 TECHNOLOGY ADVANCEMENT

LaRC recently began a program to advance the pulsed 2-micron coherent wind lidar technology beyond the successful aircraft validation and towards a space mission. LaRC's partners in this program are Beyond Photonics (BP), Simpson Weather Associates (SWA), and Fibertek.

There are several coherent wind lidar components and component functions that are needed for space but have not been needed for aircraft operation. We will develop and demonstrate these components and features, and package them in a rugged, compact transceiver for ground demonstration of wind measurement. The transceiver will consist of the pulsed transmit laser, three continuous-wave (CW) lasers, small discrete and fiber optics, the main dual-balanced heterodyne detector, and several monitoring detectors. A schematic of the key laser and optical coherent wind lidar components for space is shown in Figure 3. In addition to the transceiver, Figure 3 depicts the fiber pump laser and the two fore/aft telescopes. The transceiver components are outlined in green. Yellow shading indicates components to be advanced towards space in this program. Not shown outside the transceiver are small beam routing optics, power supplies, control circuits, thermal subsystem, mechanical structures, and control/data acquisition computers.

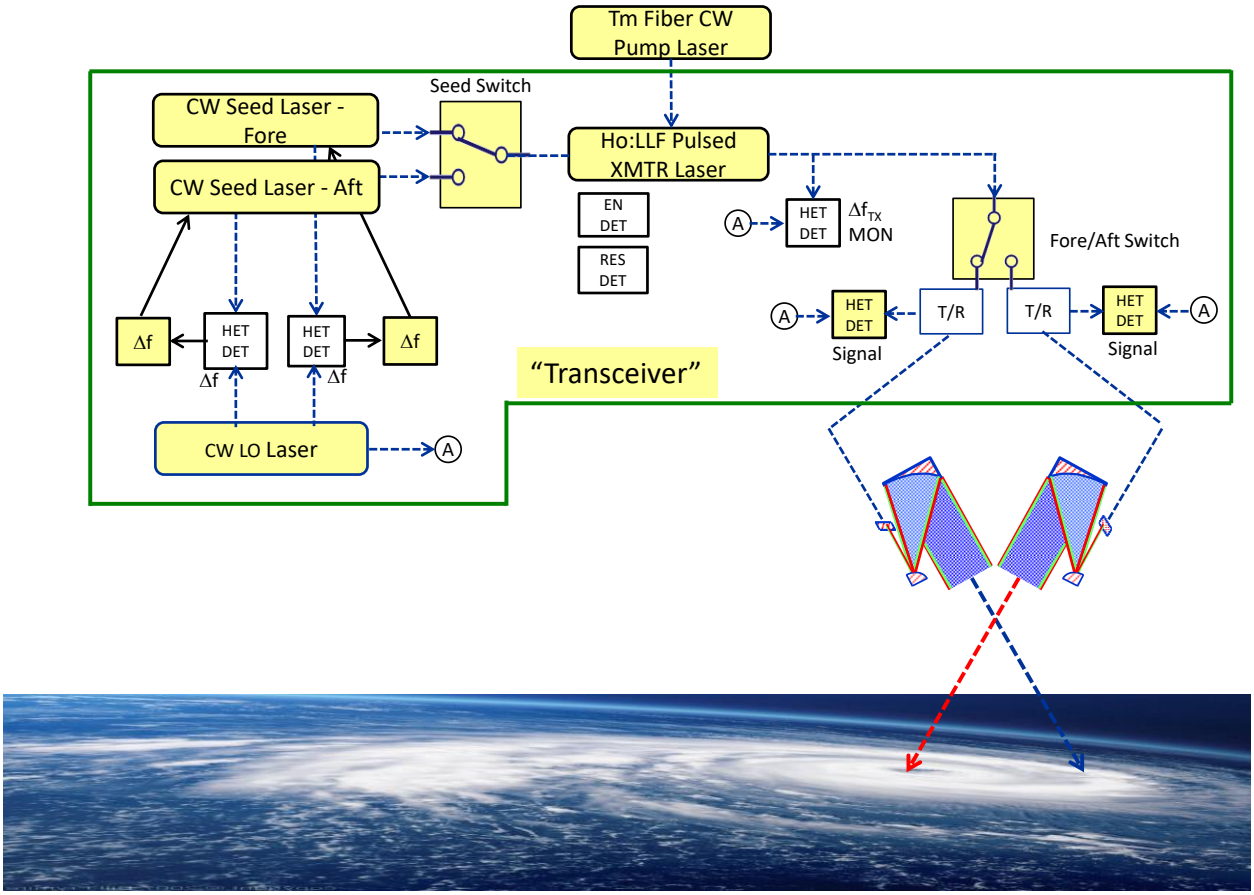


Figure 3. Simplified Schematic of Space-Based Pulsed Coherent Wind Lidar

6 STATUS OF KEY TECHNOLOGIES

Tm:fiber pump laser

The overall transmit laser architecture is a Ho:LuLF laser in-band pumped by a Tm:fiber laser. This has the advantage of significantly lowering the thermal load in the Ho laser allowing for higher average power while maintaining good beam quality. Fibertek is currently developing a space-qualifiable, high-reliability 100 W Tm:fiber laser for delivery to LaRC. Fibertek is developing this laser based on their previous heritage with high power erbium laser communications and CO_2 lidar space packages**. It will have estimated wall-plug efficiency of 23.2%, size of 14 x 11 x 4.4 inches, and mass of 13.7 kg.** Future work will include space qualification testing.

Pulsed transmitter laser

The transmit laser, being developed at LaRC, is planned at a higher pulse rate than the 10 Hz DAWN, nominally 100 – 200 Hz. Since cloudy skies are prevalent on earth, a higher pulse rate will increase the probability of passing through holes in the cloud deck and thereby increase the successful wind measurements from clouds, in clouds, and in high backscatter regions below clouds. With coherent detection and frequency estimation, any laser shots blocked by clouds will raise the minimum detectable aerosol backscatter at lower altitudes. However, when the backscatter is above the minimum detectable level the velocity estimation precision will be almost unchanged. Typically, the lower altitudes have increasing amounts of aerosols. Moving from side pumping to end pumping increases the optical-to-optical efficiency and increases the laser crystal surface area available for heat removal. The lower pulse energy needed with higher pulse rate for equal wind measurement performance decreases the chance of optical damage from the pulse or from contamination.

The baseline laser FOM will match DAWN's FOM; keeping the minimum required aerosol backscatter the same. **SWA has utilized space mission performance simulations to formulate**

pathfinder space mission concepts which provide several exciting science products consistent with the priorities in the 2017 Decadal Survey [2, 24]. The laser Q-switch in DAWN is an AOM. BP is developing an electro-optic Q-switch for use in the new transmit laser with the potential to save 150 – 200 W wall power vs. an AOM.

The current transmit laser goals are Ho:LuLF, Tm fiber end pumped, 56 mJ, 200 Hz, and 180 ns. Overall electrical-to-optical efficiency, including the estimated 23.2% of the Tm:fiber pump laser, and the estimated 16% transmit laser optical-to-optical efficiency, is estimated at 3.7%. Beam quality is estimated to be better than 1.1. **BP is developing auto-alignment technology for the transmit laser.** Future (currently-unfunded) work includes aircraft validation, lifetime testing, and space qualification testing.

Local oscillator CW laser
Stable CW 2-micron 100 mW lasers have been a COTS product and used at LaRC for many years. BP is developing a new smaller, more efficient, stable, single-frequency, 2-micron laser. A 100 mW prototype has been previously delivered to LaRC. For the wind lidar application the LO laser will nominally operate at about 25 mW and only a few watts of prime power including all control electronics. Future work includes aircraft validation and space qualification testing.

Dual frequency-tunable seed CW lasers
For ground and aircraft flights the dual seed lasers are identical to the local oscillator laser; or one laser may serve both functions as in DAWN. The seed laser injects the transmit laser, which is fired when seed laser resonance with the transmit laser cavity is detected. This resonant injection seeding drives the transmit laser into single frequency operation. For space, BP is developing small, efficient lasers that will widely tune in frequency and be frequency offset locked to the local oscillator over a ±5 GHz range. One seed laser will be used for forward looking laser shots, and the second laser used for aft looking shots. The offset frequency will be controlled to remove the majority of the backscattered light's Doppler shift from the spacecraft and earth rotation velocities, adjusted for changes in spacecraft attitude. The seed lasers are expected to nominally operate at 25 mW power with each requiring only a few watts of prime power including control electronics and the frequency-offset locking circuitry. Future work includes aircraft validation and space qualification testing.

Seed laser optical switch
Two seed lasers are envisioned to handle the fore and aft laser shots. This will alleviate the need for multi-GHz swings of the offset frequency for every change in laser direction. The seed laser switch will select which laser seeds the transmit laser synchronously with using fore and aft telescopes. BP is implementing the seed laser switch as part of the fiber optic network. Future work includes aircraft validation and space qualification testing.

Fore/aft optical switch
At present, two beam-expanding telescopes are envisioned which aim the laser to the fore and aft directions without any scanning or motion. The fore/aft switch selects between the fore and aft direction telescopes synchronously with the seed laser switch. This enables the required dual-LOS wind measurement of each air mass for horizontal wind profiling without requiring simultaneous operation of two lidar systems. BP is developing a compact and efficient fore/aft switch using and EO modulator, polarizer, and a fiber-based LO polarization switch. The details of the planned technique are grossly oversimplified in Figure 3, which shows only a switch symbol. The technique will only require one transmit/receive switch and heterodyne detector. Future work includes aircraft validation and space qualification testing.

Lag angle removal optics
The lag angle removal optics adjust for the alignment error of the receiver optical axis compared to the transit optical axis due to spacecraft orbit or platform rotation during the round-trip time of light. The exact amount of adjustment and the direction of the misalignment will depend on the spacecraft attitude and the varying range to the surface. BP is developing an optical subsystem to perform this function. The system will have the additional benefit of allowing any misalignment of the transmitter and receiver optical axes to be automatically corrected to maintain near peak lidar performance. Future work includes aircraft validation, laboratory testing of large lag angles, and space qualification testing.

Transceiver bench and transceiver enclosure
The transceiver lasers, optics, and detectors are kept in alignment by the transceiver bench in a hermetically-sealed enclosure. These components are being developed by BP. The current design of the temperature-controlled dimensionally-stable transceiver bench is about 22 x 11 x 2 inches. The enclosure housing the transceiver bench is about 25 x 14 x 9 inches. The transceiver bench is mounting in the enclosure using flexures which ensure the dimensional stability of the bench even with significant temperature change or other dimensional warpage of the outer enclosure. The enclosure will be hermetically sealed and filled with very dry and clean air needed to ensure stable laser operation and reduce the probability of laser-induced optical damage. Future work includes aircraft validation, upgrade to full conductive cooling, and space qualification testing.

Telescopes
The two telescopes will be on the order of 60 cm diameter in space to partially compensate for the much greater inverse range squared signal loss compared to aircraft operation. They are planned as off-axis, reflective, afocal beam expanders. DAWN has demonstrated 15 cm diameter in aircraft. Many large telescopes have flown in space. We plan to use existing spare 15-cm telescopes for the ground demonstration at the end of the current program. Future work includes a more detailed design of the space telescopes which includes minimizing mass and fiducial aids to optimize lidar-to-telescope alignment.

Other subsystems
A space mission requires accurate laser individual shot pointing knowledge with and without available earth surface returns. **DAWN and other airborne coherent lidar systems have successfully demonstrated the use of land returns to obtain velocity errors well below 1 m/s.** The GSFC GLAS altimeter in space demonstrated a method using a star tracker for a 532 nm laser [25]. Future work includes investigation of utilizing the GLAS technique at 2 microns, and development of a concept of operations for the use of intermittent land and water surface signals.

We envision ground support equipment (GSE) to permit validation of lidar alignment and beam collimation consistent with targets at ranges of several 100 km. A method has been demonstrated for the transceiver small beam output without including the beam expander. The beam expander greatly increases the distance to the optical far field, making long-path validation on the ground impractical. The GSE will include a high-quality beam expander used in reverse to re-shrink the laser beam permitting calibration targets in the (closer) optical far field. Future work includes a demonstration of this technique.

A space mission will necessarily require specification of the misalignment, aberration, and polarization effect tolerances of all the lidar's optical elements. An extremely useful tool would be optical design software that models imperfections of the optics and calculated the overall loss of far-field, diffuse-target (aerosols) coherent lidar SNR. The theory to perform this calculation is known. At least one optical modeling software vendor has expressed interest in adding this capability to their software. Having this software tool would reduce mission risk while saving the cost of the over-specification that may result from not having the tool. Future work includes procuring this upgrade to an optical modeling software product.

Autonomous operation should be implemented and aircraft validated.

7 PARTNERSHIPS, SYNERGIES, AND CROSS-CUTTING APPLICATIONS

The current program partners would be a strong team starting point for a coherent lidar space mission such as a pathfinder mission providing primarily boundary layer science and atmosphere/earth characterization for later missions. Such a mission would naturally provide cloud winds and cloud top heights to enhance cloud tracking wind sensors. NASA could benefit by partnering with Japan/JAXA and India/ISRO. JAXA, working with agencies such as NICT and NIES, has been developing 2-micron coherent wind lidar for the last 20 years. JAXA and their industries have indicated a willingness to collaborate with NASA on a 2-micron aerosol DWL mission. In India, both ISRO and the MOES have indicated a desire to work with NASA on a 2-micron coherent DWL mission. Although India does not have the laser or lidar technology, they

have very advanced launch and spacecraft capabilities. Future NWP missions require the atmospheric coverage delivered by both an aerosol and molecular wind lidar. 355 nm is the optimum candidate for molecular backscatter. ESA is close to launching a direct detection molecular wind lidar into space. In the US, Ball Aerospace is developing direct detection molecular wind lidar technology.

8 CONCLUSIONS

Pulsed, 2-micron, coherent-detection lidar for profiling horizontal wind vectors is TRL 9 for aircraft flight. Spaceflight requires demonstration of space-unique components and functions. A government-industry partnership is currently working on this demonstration. Future work includes hardware space qualification and model demonstration of key subsystems.

Acknowledgements

Many colleagues at Langley and at our contractor partners have performed the technology and mission concept work. We thank Dr. Upendra Singh for numerous technical and mission formulation contributions. We gratefully acknowledge the support of NASA Science Mission Directorate, Earth Science Division; the Earth Science Technology Office, and the Langley Science and Engineering Directorates.

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Global Wind Measurement with a Pulsed, Coherent-Detection, Lidar System: Technology Status, Development Needs, and Partnering Opportunities

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and many colleagues at our organizations

NASA Technical Interchange Meeting on Active Optical Systems for Supporting Science, Exploration, and Aeronautics Measurements Needs

Columbia, MD

July 31 – August 3, 2018

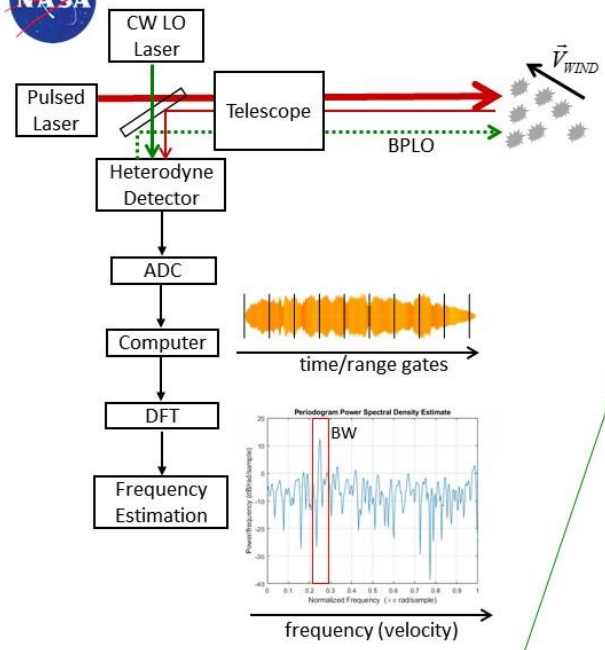
Multi-Decade Desire for Global Wind Measurements

A Very Strong Science Pull

- 2018 – National Research Council Earth Science "Decadal Survey"
  - **3-D Winds** & **Planetary Boundary Layer** in 14 Priority Targeted Observables (Table 3.5)
  - **3-D Winds** in 7 recommended Explorer missions
  - **3-D Winds** in 3 recommended Incubation Observables (NASA removed)
- 2018 – NOAA, NOAA Satellite Observing System Architecture (NSOSA) Study
  - **3-D Winds** in 14 "Earth Weather" observations; "High Leverage/Impact Category"
- 2018 – WMO, Observing Systems Capability Analysis and Review (OSCAR) Tool Data Base
  - 24 entries for **"Wind, Horizontal"**
- 2016 – Xubin Zeng, Tsengdar Lee, et al, "Challenges and Opportunities in NASA Weather Research," BAMS 97 (7), ES137
  - Global measurements of ... **horizontal wind vectors are urgently needed**"
- 2007 – National Research Council Earth Science "Decadal Survey"
  - **3-D Winds** in 15 missions recommended to NASA
- 1999 – European Space Agency, "Reports for Mission Selection. The Four Candidate Earth Explorer Core Missions. Atmospheric Dynamics Mission. Atmospheric Dynamics Mission" SP-1233 (4)
  - "There is a clear requirement for a high-resolution observing system for **atmospheric winds** with full global coverage"
  - **AEOLUS launch scheduled for August 2018!**



Pulsed 2-Micron Coherent Wind Lidar Features



e.g. $\frac{1}{\beta_{MN}} \propto \frac{D^2}{R^2} \times \frac{E\sqrt{f}\,\tau^{\sim 0.285}}{1+(M^2)^2} \times \frac{\sqrt{\Delta h\,\Delta z}}{V_{SRCH}^{\sim 0.4}\left[\sim 2.5 - \ln\left(\Pr\{outliers\}\right)\right]}$

Active Remote Sensing
- ➢ Any sun, limb geometry
- ➢ Eye safe

Local Oscillator (LO) Laser
- Defines very narrow antenna pattern for immunity to background light
- ➢ Equal day/night performance
- "Shot noise" limited "eliminates" all other noise
- ➢ High photon/electrical efficiency

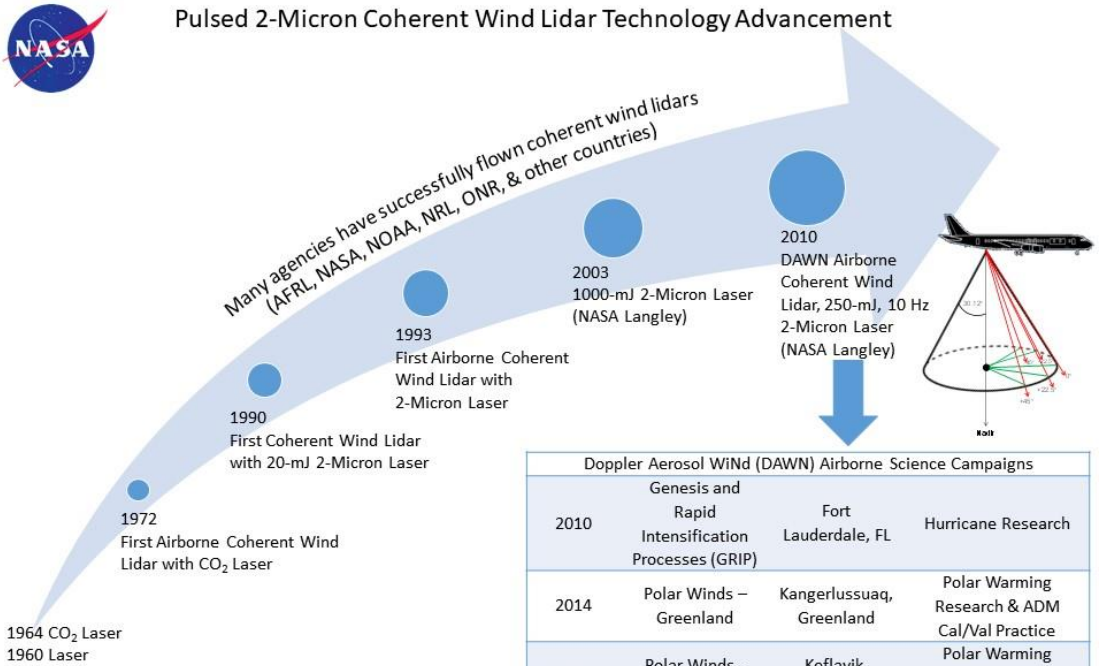
Heterodyne Detection
- Mixes 150 THz to MHz, sampled into computer
- Entire signal spectrum available
- ➢ More science, e.g., wind turbulence
- ➢ May reprocess data many times to maximize science for particular conditions

Frequency Estimation in Frequency Domain
- Shot noise power spread out on frequency axis,
- Very narrow effective detection BW, less noise
- ➢ High photon/electrical efficiency can be traded for improved vertical & horizontal resolution
- ➢ Multiple velocity products possible: wind, hydrometeors, waves, current, etc.

Aerosols much heavier than molecules
- Signal spectral width not widened by molecular motion (~300 m/s)
- ➢ Excellent velocity estimate precision with less photons

3

Pulsed 2-Micron Coherent Wind Lidar Technology Advancement



Doppler Aerosol WiNd (DAWN) Airborne Science Campaigns			
2010	Genesis and Rapid Intensification Processes (GRIP)	Fort Lauderdale, FL	Hurricane Research
2014	Polar Winds – Greenland	Kangerlussuaq, Greenland	Polar Warming Research & ADM Cal/Val Practice
2015	Polar Winds - Iceland	Keflavik, Iceland	Polar Warming Research & ADM Cal/Val Practice
2017	**CPEX**	**Fort Lauderdale, FL**	**Convection Research**
2018	**3 NASA Earth Venture Suborbital Proposals**		

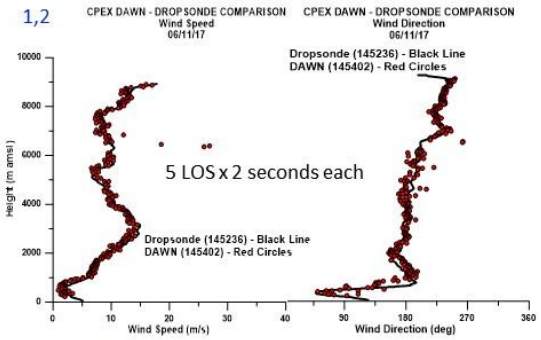
2017 - 2020
Coherent 2-Micron Technology Advancement for Space (Wind-SP)

4

DAWN Performance in 2017 CPEX Campaign

1. Produced vertical profiles of horizontal vector wind with many complete horizontal wind profiles from 10 km to the surface with 1-2 second integration
2. Validated to provide accurate winds with very low bias by comparison with dozens of dropsondes
3. Valuable wind measurements in cloudy skies including cloud tops, through low optical density clouds, and through holes between clouds
4. Very complementary to the JPL APR-2 radar as the atmosphere transitioned between clear air/thin clouds and thick clouds

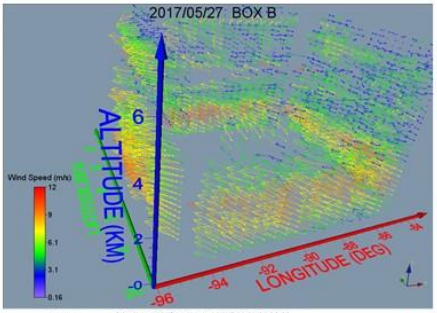
1,2



3



3



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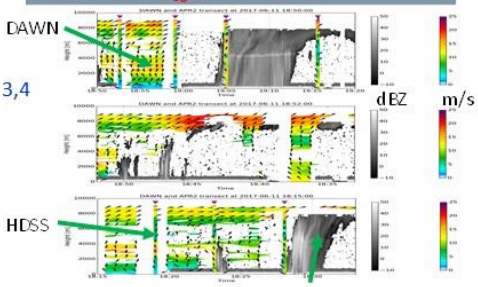
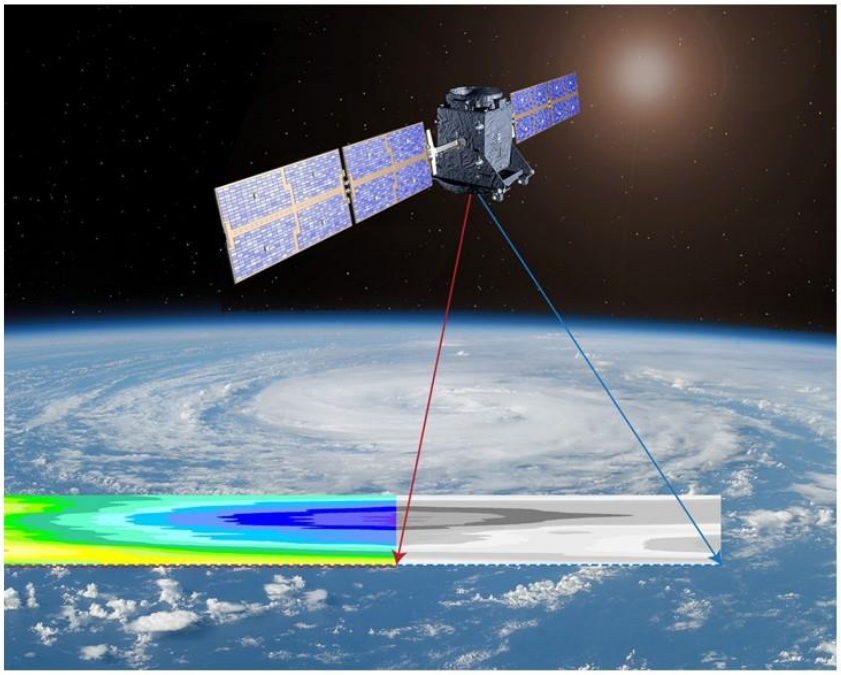


Provided by Shuyi Chen APR2

5

Space Mission Concept: Vertical Profiles of Horizontal Winds



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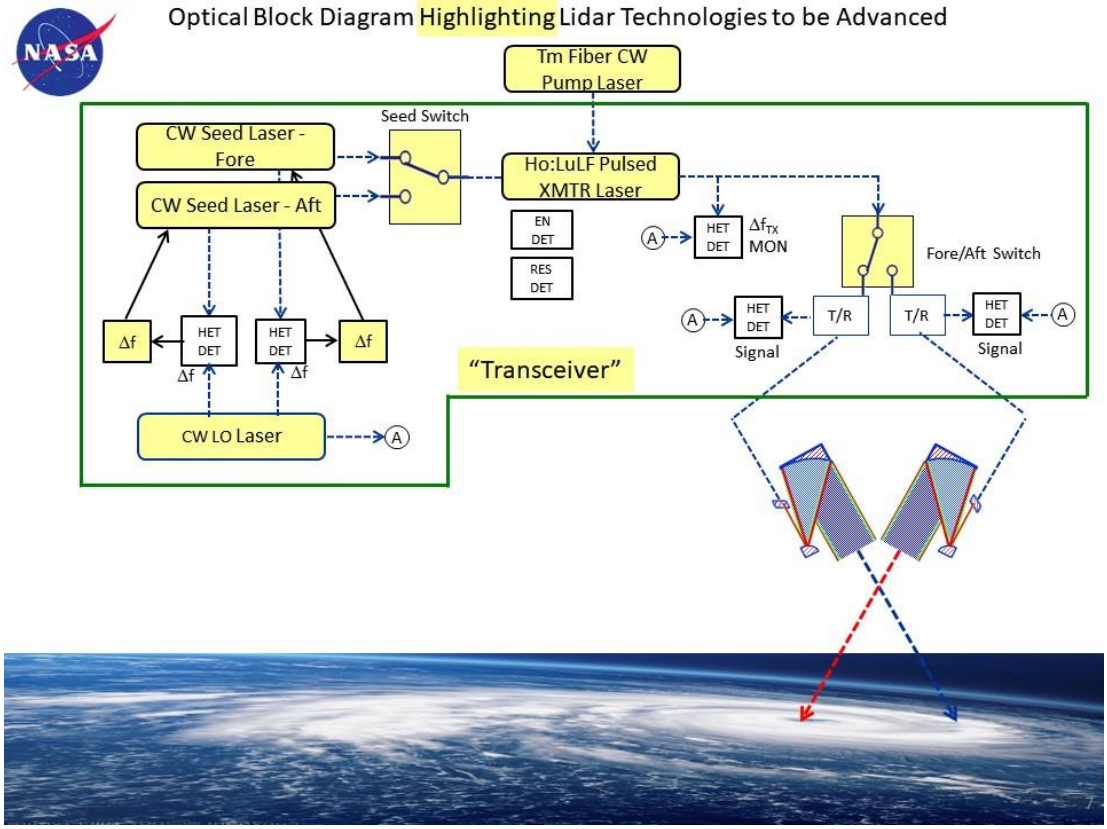
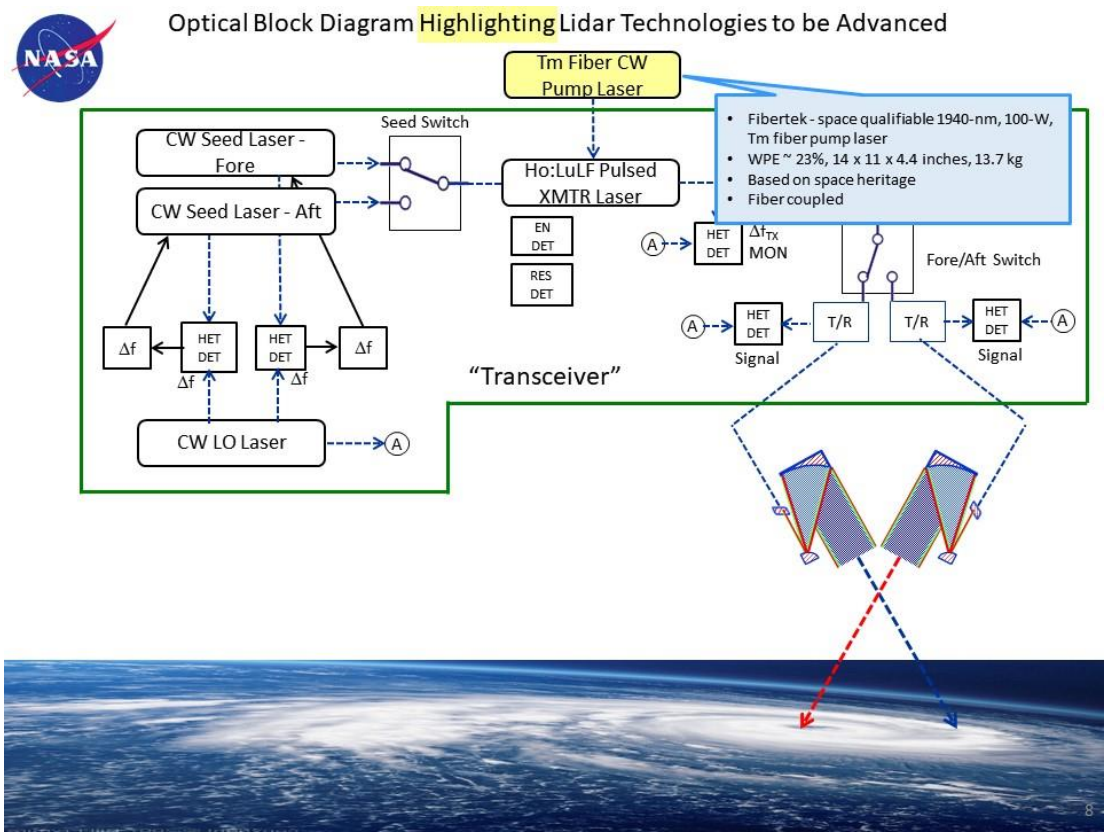

Optical Block Diagram Highlighting Lidar Technologies to be Advanced
Tm Fiber CW Pump Laser
Seed Switch
CW Seed Laser - Fore
CW Seed Laser - Aft
Ho:LuLF Pulsed XMTR Laser
EN DET
RES DET
HET DET
Δf_{TX} MON
Fore/Aft Switch
T/R
T/R
Signal
Signal
Δf
"Transceiver"
CW LO Laser
A


Optical Block Diagram Highlighting Lidar Technologies to be Advanced
Tm Fiber CW Pump Laser
Fibertek - space qualifiable 1940-nm, 100-W, Tm fiber pump laser
WPE ~ 23%, 14 x 11 x 4.4 inches, 13.7 kg
Based on space heritage
Fiber coupled
Seed Switch
CW Seed Laser - Fore
CW Seed Laser - Aft
Ho:LuLF Pulsed XMTR Laser
EN DET
RES DET
HET DET
Δf_{TX} MON
Fore/Aft Switch
T/R
T/R
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Signal
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"Transceiver"
CW LO Laser
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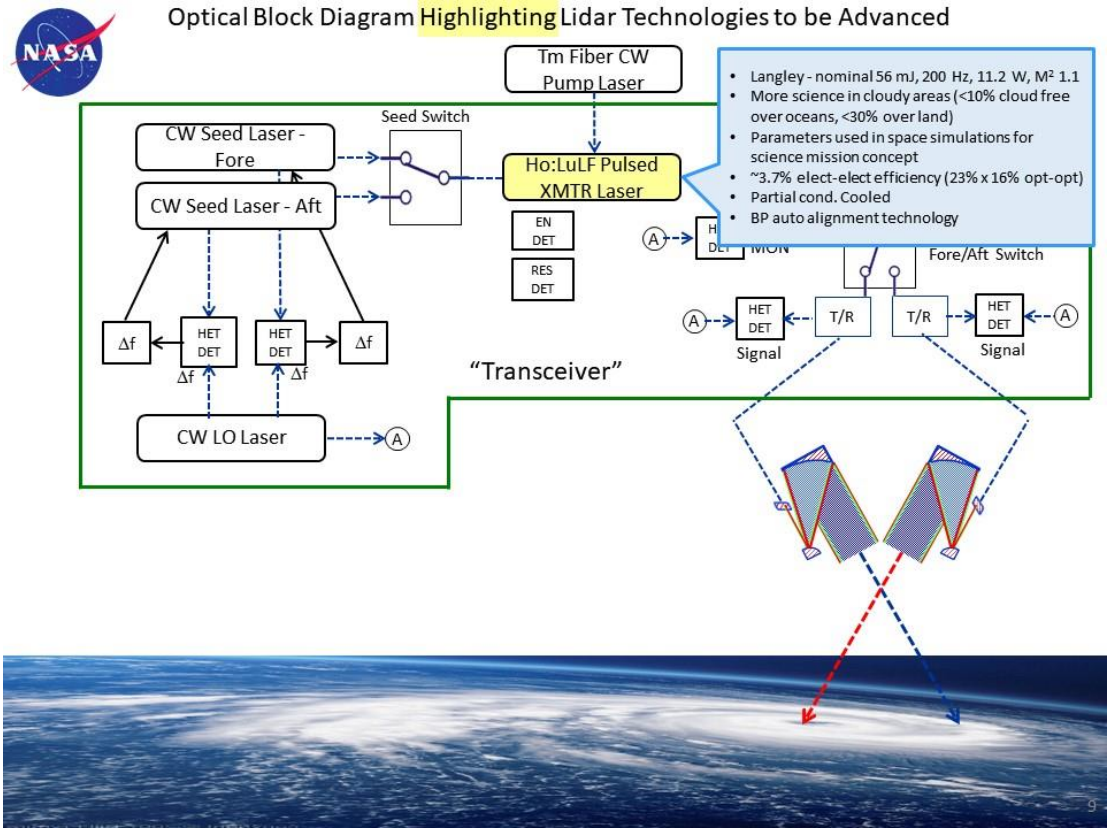
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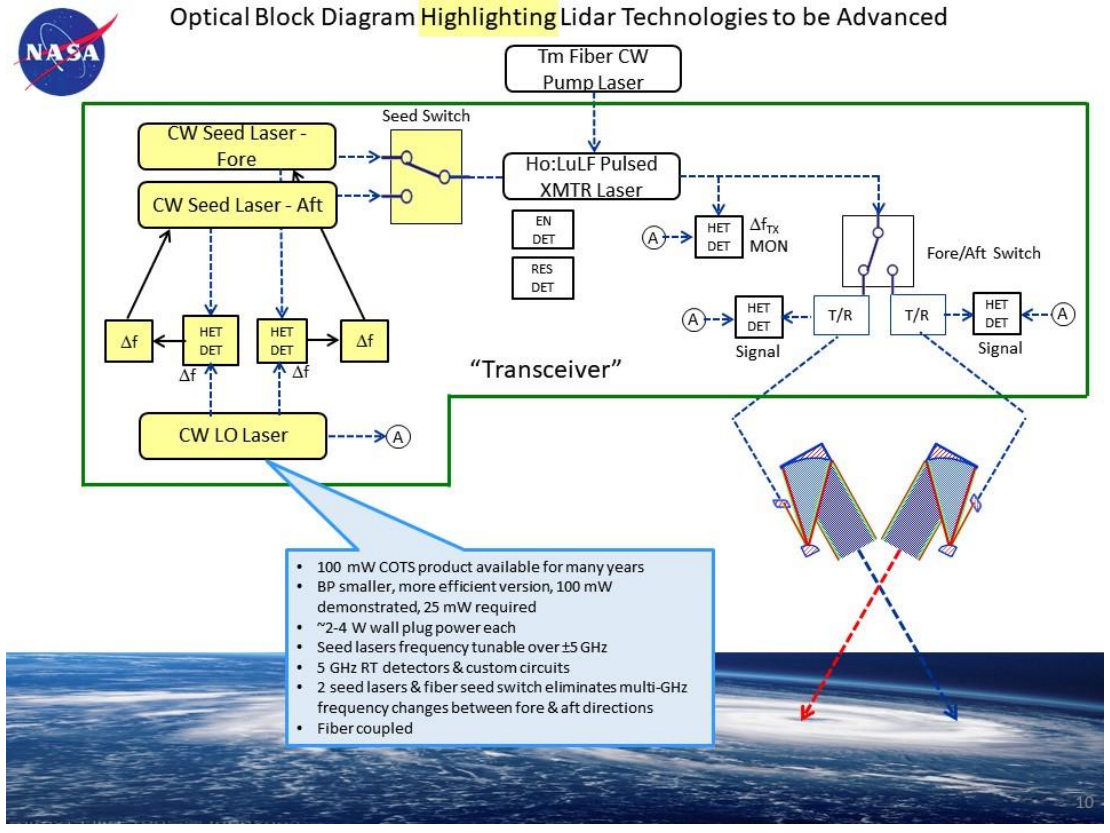
EN DET
RES DET
Δf
HET DET
CW LO Laser
A
MON
Fore/Aft Switch
T/R
Signal
"Transceiver"
Langley - nominal 56 mJ, 200 Hz, 11.2 W, M² 1.1
More science in cloudy areas (<10% cloud free over oceans, <30% over land)
Parameters used in space simulations for science mission concept
~3.7% elect-elect efficiency (23% x 16% opt-opt)
Partial cond. Cooled
BP auto alignment technology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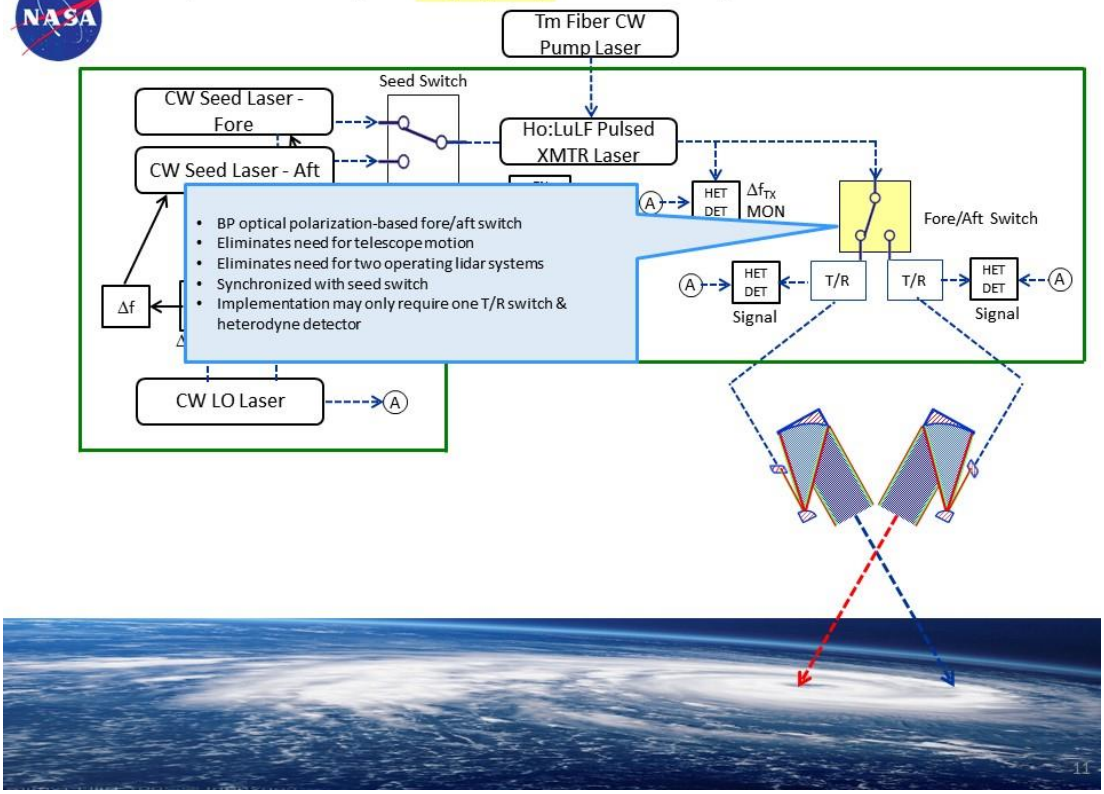
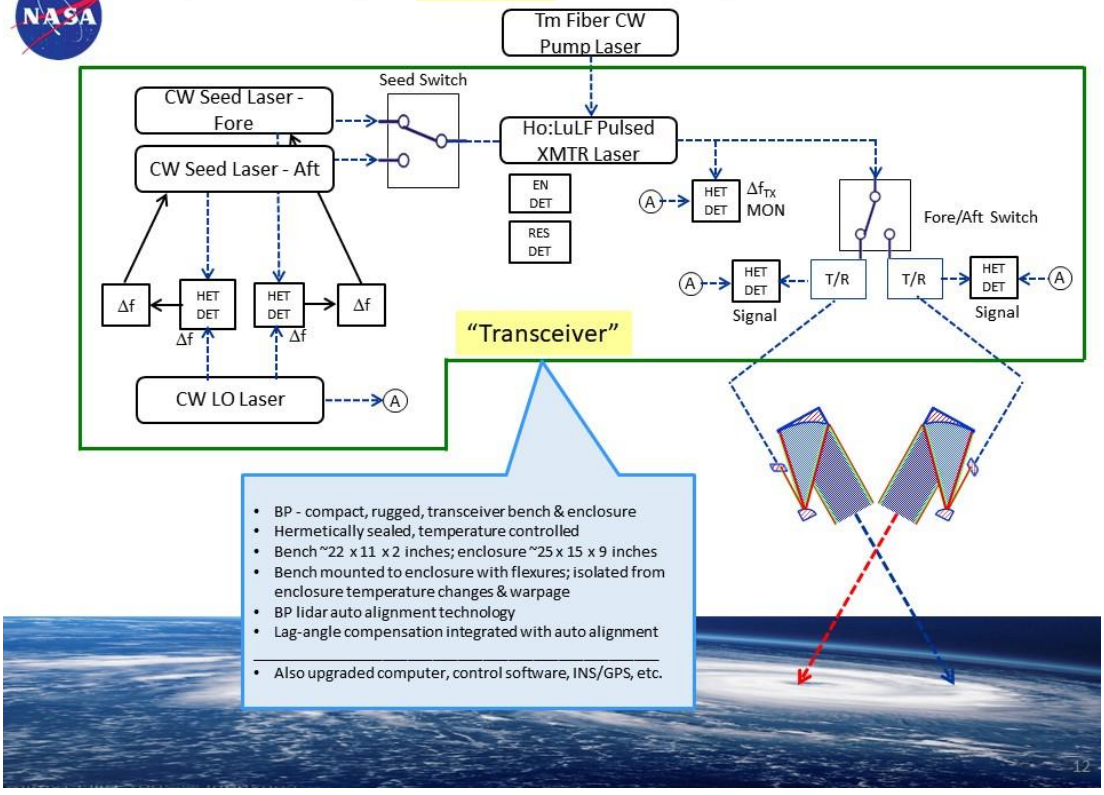
RES DET
Δf
HET DET
CW LO Laser
A
Δf_Tx MON
Fore/Aft Switch
T/R
Signal
"Transceiver"
100 mW COTS product available for many years
BP smaller, more efficient version, 100 mW demonstrated, 25 mW required
~2-4 W wall plug power each
Seed lasers frequency tunable over ±5 GHz
5 GHz RT detectors & custom circuits
2 seed lasers & fiber seed switch eliminates multi-GHz frequency changes between fore & aft directions
Fiber coupled

Optical Block Diagram Highlighting Lidar Technologies to be Advanced



Optical Block Diagram Highlighting Lidar Technologies to be Advanced



Path Forward for Space Mission

- Tm:fiber laser
  - Aircraft validation
  - Space qualification
- Transmit laser with auto-alignment
  - Aircraft validation
  - Life testing
  - Space qualification
- LO laser & frequency-tunable seed lasers
  - Aircraft validation
  - Space qualification
- Seed & fore/aft telescope optical switches
  - Aircraft validation
  - Space qualification
- Lidar auto-alignment & lag angle compensation
  - Aircraft validation
  - Lab test for large realistic lag angles
  - Space qualification
- Transceiver bench & enclosure
  - Aircraft validation
  - Upgrade to full conductive cooling
  - Space qualification
- Dual ~60-cm class off-axis telescopes
  - More detailed design with mass reduction and alignment fiducials
- Autonomous operation demonstration
- Laser shot pointing knowledge
  - Subsystem design study (adapt GLAS stellar reference system?)
  - Land/ocean concept of operations
- Pre-launch alignment/collimation validation
  - Procure GSE beam expander
  - Demonstrate technique on ground
- Telescope/optics specifications tool
  - Commission optical software module
  - Provide theoretical basis to vendor

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Partnerships and Synergies

- The current program partners comprise a strong team starting point for a coherent wind lidar space mission
- An envisioned first pathfinder wind mission would perform primarily boundary layer science; but would frequently profile wind above the BL, would provide cloud top heights and winds for AMV investigations; and would characterize the aerosol backscatter, cloud porosity, cloud thickness, and surface reflectance statistics for future wind lidar missions. It would also validate and improve coherent wind lidar performance models
- NASA would greatly benefit from international partnerships. JAXA and their industries have indicated a willingness to collaborate with NASA on a 2-micron coherent with lidar mission. In India, both ISRO and the MOES have indicated a desire to contribute advanced launch and spacecraft capabilities to such a mission.
- Future NOAA NWP missions would likely require the atmospheric coverage from both aerosols and molecules. Direct detection at 355 nm is the optimum molecular wind lidar candidate. ESA plans to launch a single LOS lidar of this type later this summer. In the US, Ball Aerospace is developing this type of wind lidar system.

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Conclusions

- Global measurement of wind is a highly desired missing observable. Both NRC earth science "Decadal Surveys" have asked NASA to enable this measurement for boundary layer and NWP applications
- Pulsed 2-micron coherent detection wind lidar has many attractive features for wind measurements from space
- A long history of airborne pulsed coherent wind lidars has led to the airborne DAWN wind lidar; which has been validated in the 2017 CPEX campaign
- Coherent lidar component functions required for space operation, but not needed to date on aircraft, are being developed by the existing Wind-SP program
- The current program team members are a strong team starting point for a space mission. They have formulated a pathfinder, primarily boundary layer mission consistent with the NRC recommendations and the technology being developed
- Follow-on technology tasks to further prepare for space have been identified; which are unfunded at this time
- International partnerships are possible for a coherent wind lidar space mission; providing cost savings to NASA
- A NWP mission would also require a molecular backscatter lidar for vertical coverage. This lidar could be provided by US industry or by ESA

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The Wind-SP Team

NASA Langley	Beyond Photonics	Simpson Weather Assoc.	Fibertek	NASA/ESTO
Bruce Barnes	Dale Bruns	David Emmitt	Floyd Hovis	Pamela Millar
Kris Bedka	Charley Hale	Steve Greco	Mark Storm	Parminder Ghuman
Songsheng Chen	Sammy Henderson	Sid Wood		Keith Murray
Connor Huffine	Pat Kratovil			
Michael Kavaya				
Jane Lee				
Zhaoyan Liu				
John Marketon				
Anna Noe				
Larry Petway				
Diego Pierrottet				
Teh-Hwa Wong				
Jirong Yu				
Chris Edwards				
Glenn Hines				
David Macdonnell				
Upendra Singh				

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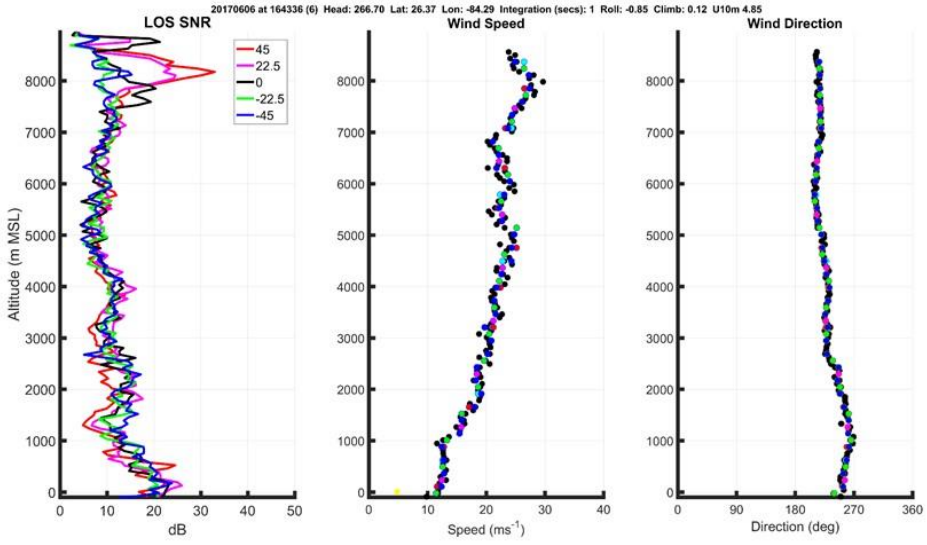
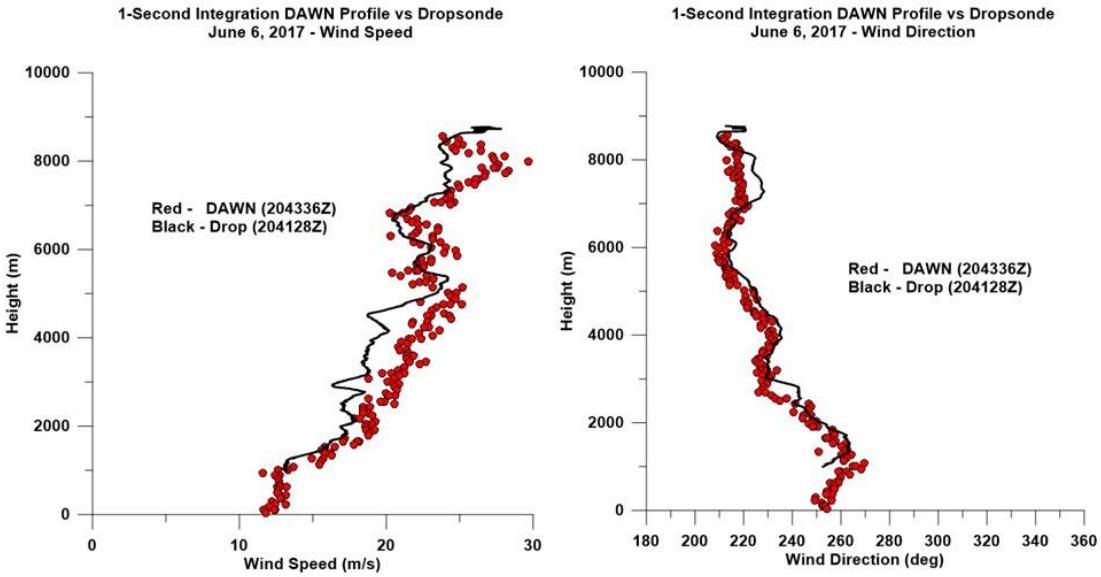
Extra Slides

5 LOS x 1 second each



5 LOS x 1 second each



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Pathfinder Science Experiments

- The following represent an initial set of science experiments/objectives
  - Investigate inter-hemispherical transports via LLJs and within tropical convergence zones (ITCZ); How prevalent and energetic are LLJs over the oceans?
  - Develop improved parameterization schemes for PBL depths and growth rates for use in global weather and climate models…especially marine BLs.
  - Investigate the role of vertical shear of the horizontal wind in regions of deep convection and in tropical cyclone maintenance and suppression.
  - Investigate dynamic impacts such as speed and directional shear on the global trans-oceanic transport of pollution.

Courtesy Dr. David Emmitt, SWA

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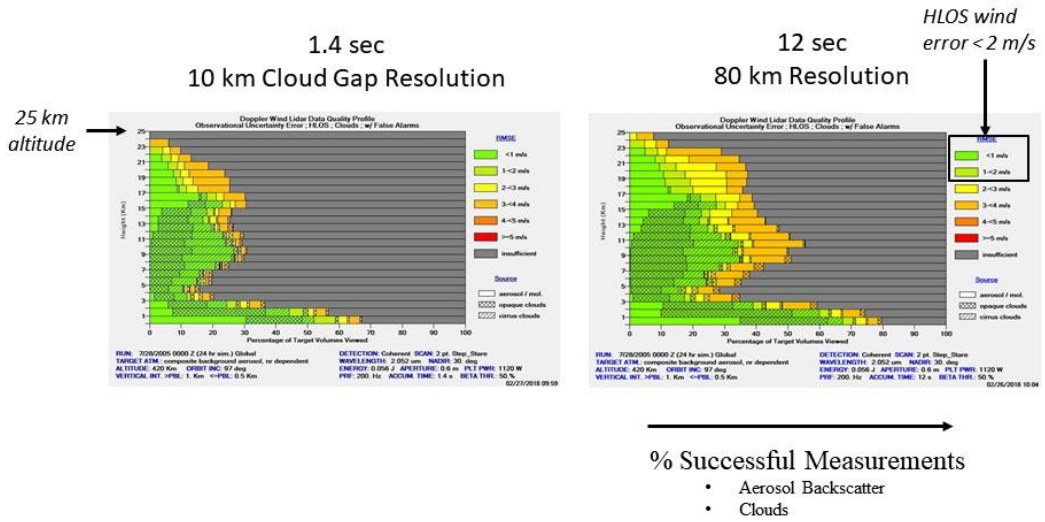
Example of Pathfinder Mission Concept Wind Products & Coverage

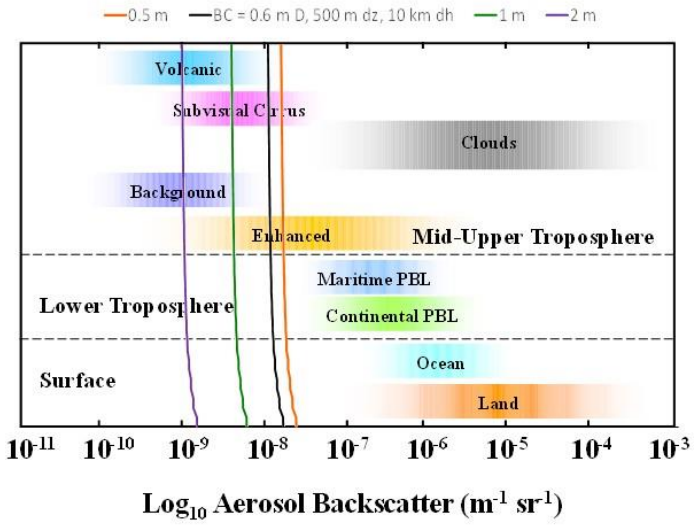
(420 km, 30 deg nadir, 60 cm, 56 mJ, 200 Hz, 1 km vertical resolution)



Courtesy Dr. David Emmitt, SWA

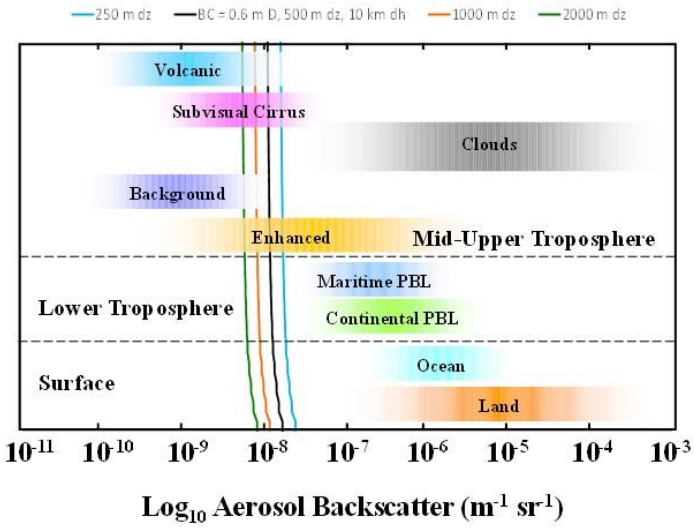
21

Varying Receiver Diameter D



22

Varying Vertical Resolution dz



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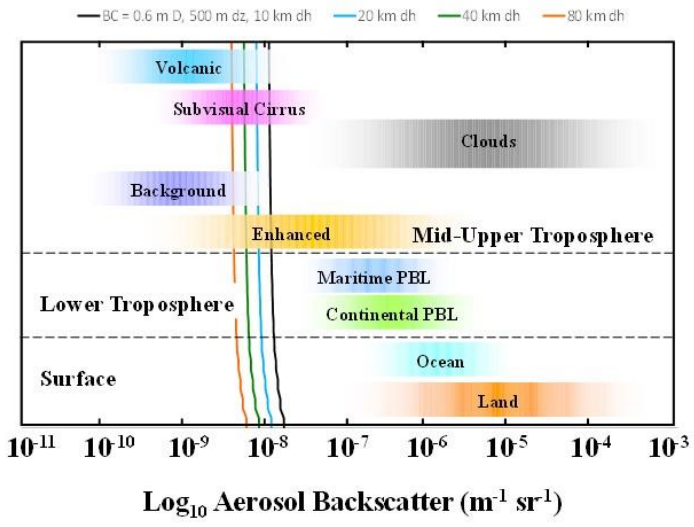
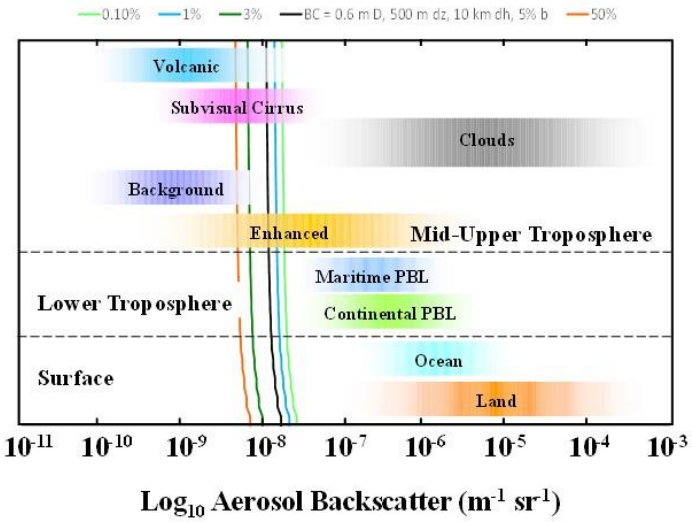
Varying Horizontal Resolution dh



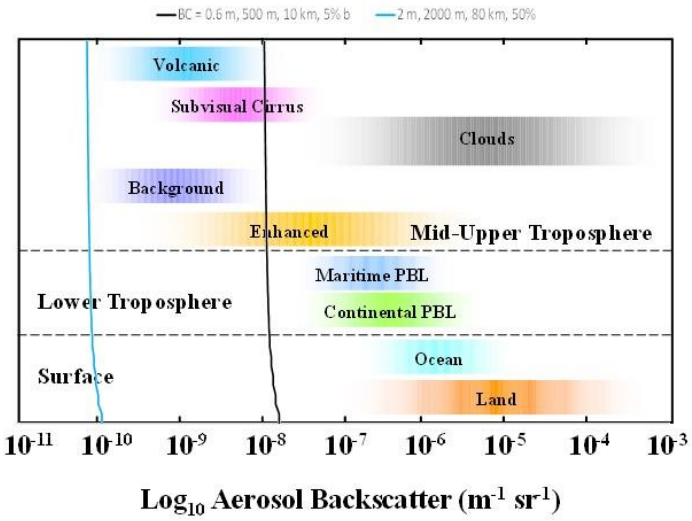
24

Varying Probability of Outlier Wind Estimates b



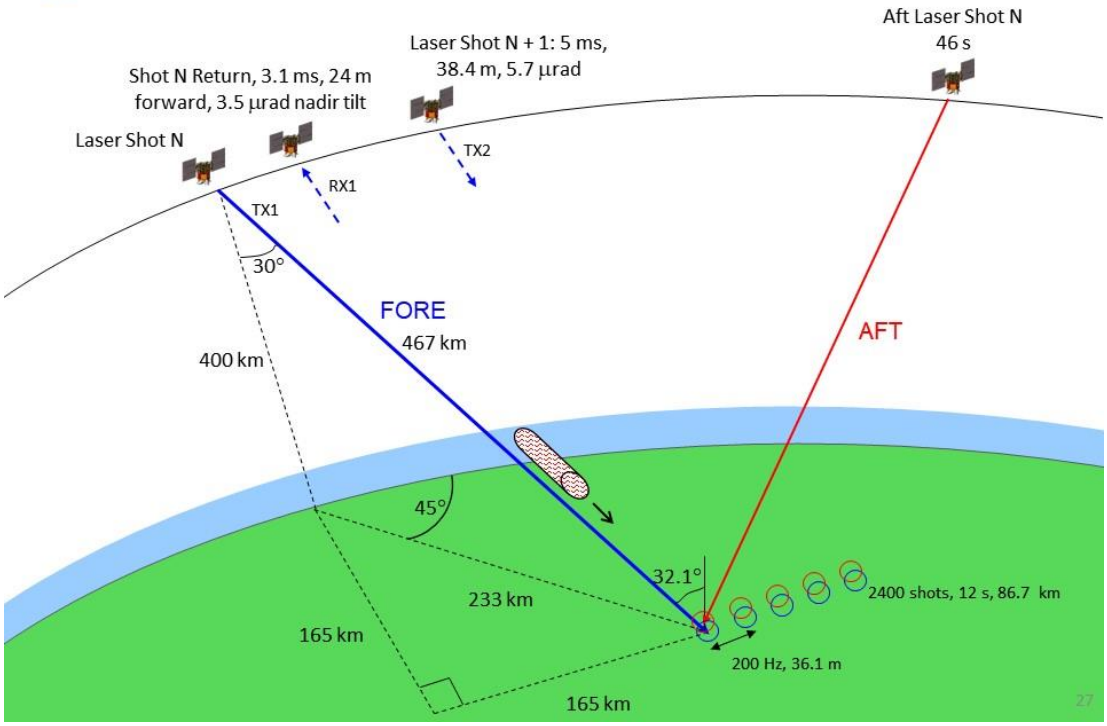
25

Pulling Out All Stops for Aerosol Sensitivity

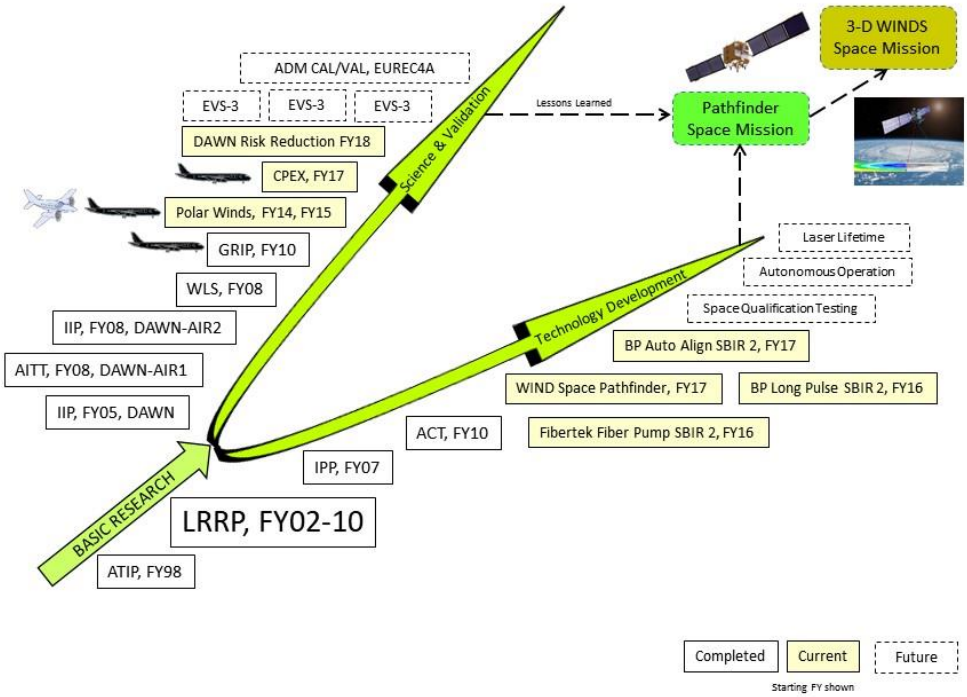


26

Space Mission Concept: Measure Air Mass from Two Perspectives



Steps to Coherent Doppler Lidar 3-D Winds Mission Readiness



Coherent Wind Lidar has Two Wind Measurement Figures of Merit Not Just Velocity Accuracy

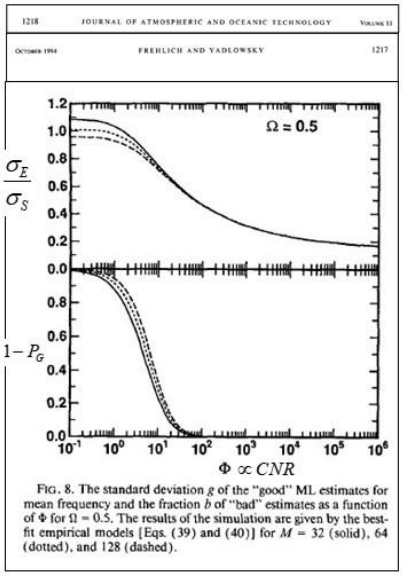


FIG. 8. The standard deviation g of the "good" ML estimates for mean frequency and the fraction b of "bad" estimates as a function of Φ for $\Omega = 0.5$. The results of the simulation are given by the best-fit empirical models [Eqs. (39) and (40)] for $M = 32$ (solid), 64 (dotted), and 128 (dashed).

- Φ which is $\propto CNR_{IF}$, is a better parameter than SNR for coherent lidar wind estimation
- Over seven (7) orders of magnitude of Φ (e.g., aerosol backscatter):
- Velocity error σ_E stays between 20% and 110% of the signal spectrum width σ_S, which is an accurate wind estimate
- More important than velocity error, the fraction of wind estimates P_G that are "good", i.e., grouped near the true wind value steeply falls from 1 to 0 within two orders of magnitude (typical P_G requirement is 50% - 90%)
- In the case shown $P_G = 0.5$ corresponds to $\Phi \approx 50$ and $\sigma_E/\sigma_S \sim 80\%$. Or $P_G = 0.9$ corresponds to $\Phi \approx 107$ (approx. doubled) and normalized error $\sigma_E/\sigma_S \sim 50\%$.

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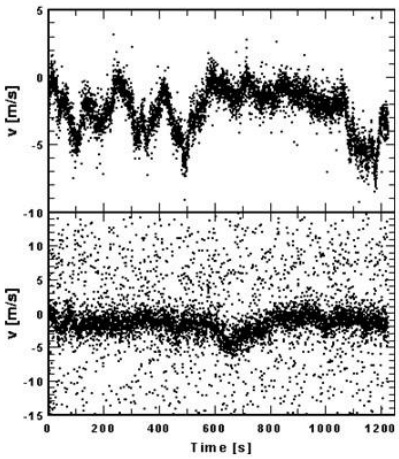
Coherent-Detection Wind Measurement Visualizing the Probability of a "Good" Estimate PG

Actual lidar data (not DAWN) – velocity estimate vs. pulse; 6000 shots at 4.9 Hz



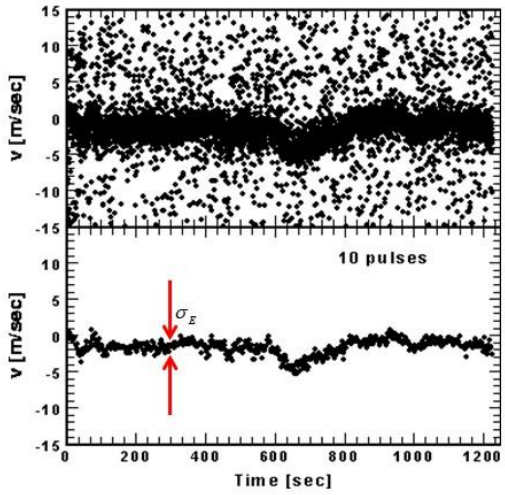
Higher Φ at R = 1 km

Lower Φ at R = 5 km

- 6,000 wind estimates over 1,200 seconds reveal how increasing Φ increases probability of a good estimate, and reduces wind estimate error
- The "bad" wind estimates are uniformly distributed over the processing algorithm's allowed velocities

30

Coherent-Detection Wind Measurement Improvement From Shot Averaging



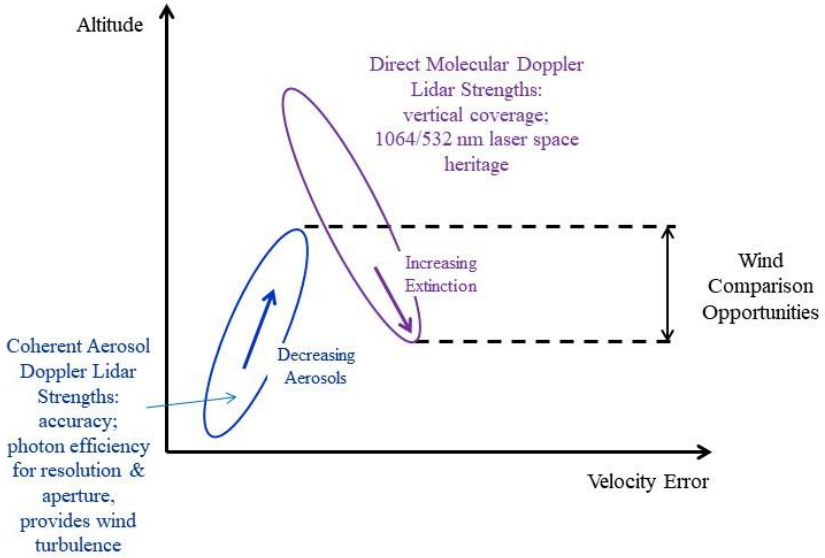
1 laser pulse

10 laser pulses averaged

- Actual lidar data (not DAWN) – velocity estimate vs. pulse; 6000 shots at 4.9 Hz; R = 5 km "lower F"
- Shot accumulation improves both "good" probability and velocity accuracy

31

Depiction of Complementarity of a Space-Based Hybrid Wind Lidar



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3.3 DIRECT DETECTION DOPPLER WIND LIDAR: RECENT PROGRESS, TECHNICAL NEEDS, AND FUTURE APPLICATIONS

Sara Tucker

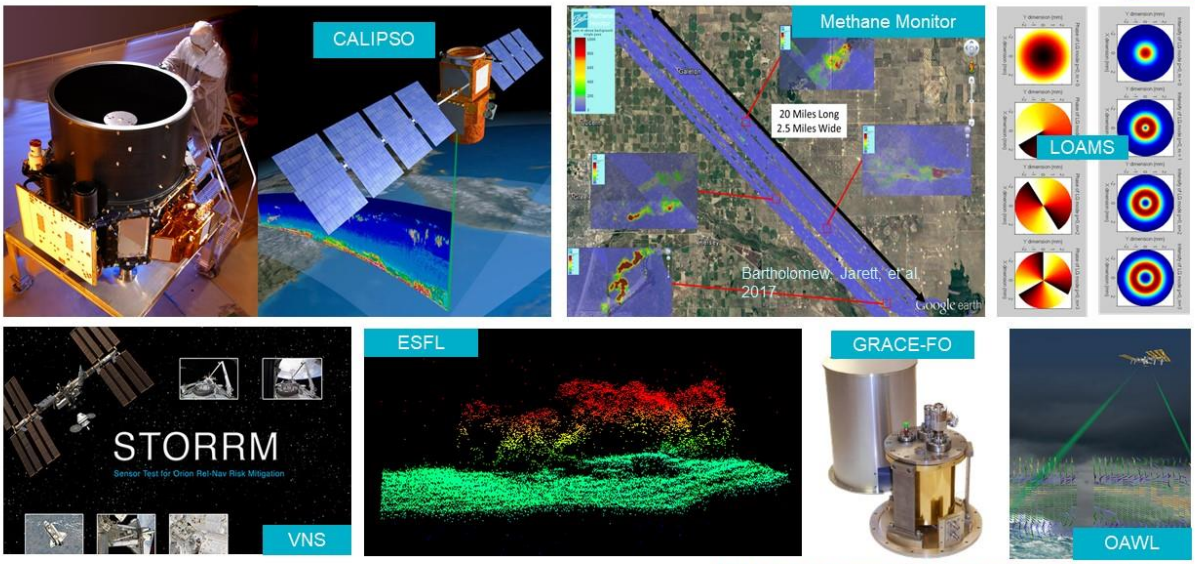
Ball Aerospace, Boulder, Colorado

DIRECT DETECTION DOPPLER WIND LIDAR: RECENT PROGRESS, TECHNICAL NEEDS, AND FUTURE APPLICATIONS

Sara Tucker – Ball Aerospace

NASA Active Optical Systems Technical Interchange Meeting, 1-2 August 2018 1

A subset of Ball Active Optical System Activities



NASA Active Optical Systems Technical Interchange Meeting, 1-2 August 2018 2

Ball Participation in Active Remote Sensing at NASA

- CALIPSO
  - Ball funded the CALIPSO risk reduction laser development at Fibertek through IRAD with some support from LaRC.
  - CALIOP lidar was built collaboratively with NASA LaRC, Fibertek and Ball
  - CALIOP is still operating, 12 years into its 3 year mission
- ESTO-funded & managed projects – building on years of internal Ball investments
  - Winds & HSRL: OAWL IIP, HOAWL ACT, FIDDL ACT, HAWC-OAWL IIP
  - Adaptive lidar (ESFL) was developed under ESTO IIP, AITT, and AIST, plus other SMD funds to address vegetation/topography lidar needs: directly supports the new ESDS Incubation Observable "Surface Topography & Vegetation
  - LOAMS ACT to study physics of optical angular momentum for lidar remote sensing.
  - GRACE-FO laser stabilization optical cavities (with JPL)
- Lidar Winds
  - Started developing OAWL theory in 2004 (based on Schwiesow's 1995 concept)
  - Years of Ball funded IRAD – first interferometer in 2009 – more throughout this talk.

(small-to-mid-size Aerospace) Industry Perspective

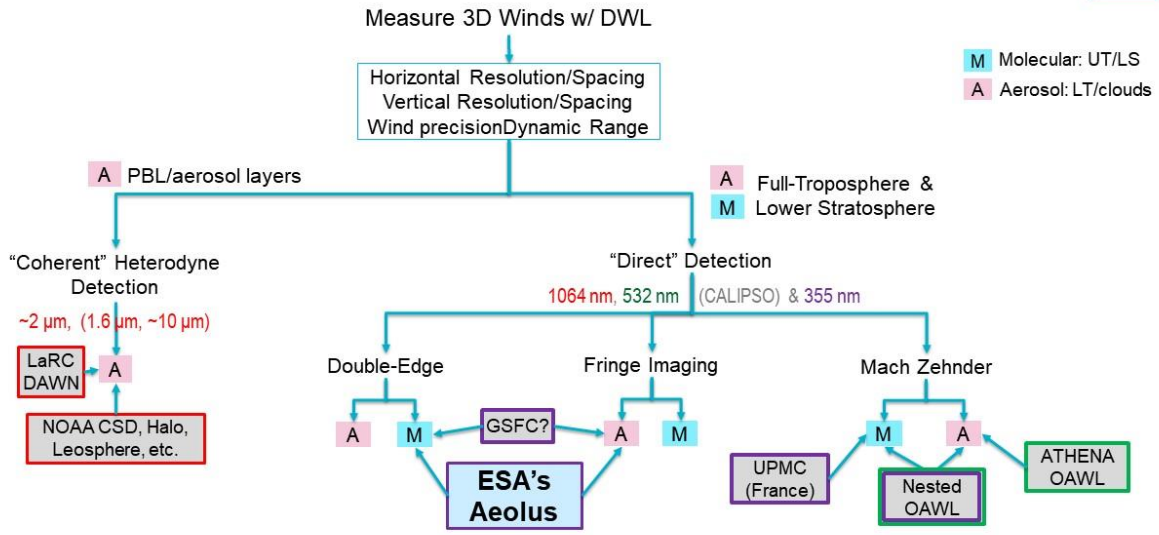
Challenges

- No continuity in funding like at federally funded centers
  - Risk of losing staff & their knowledge to other programs.
- Grant Contracts (e.g. ESTO)
  - No profit for grants – investment.
  - Industry cannot keep any hardware without transferring or purchasing it.
- Industry held fully accountable for delays, losses, etc. Sometimes results in "blacklisting".
- Industry often feels "exercised" by NASA – investing lots of funding to develop ideas and write proposals, but then not awarded, then excluded from future proposals.
- NASA Coopetition with industry on engineering (and academia on science).

Opportunities

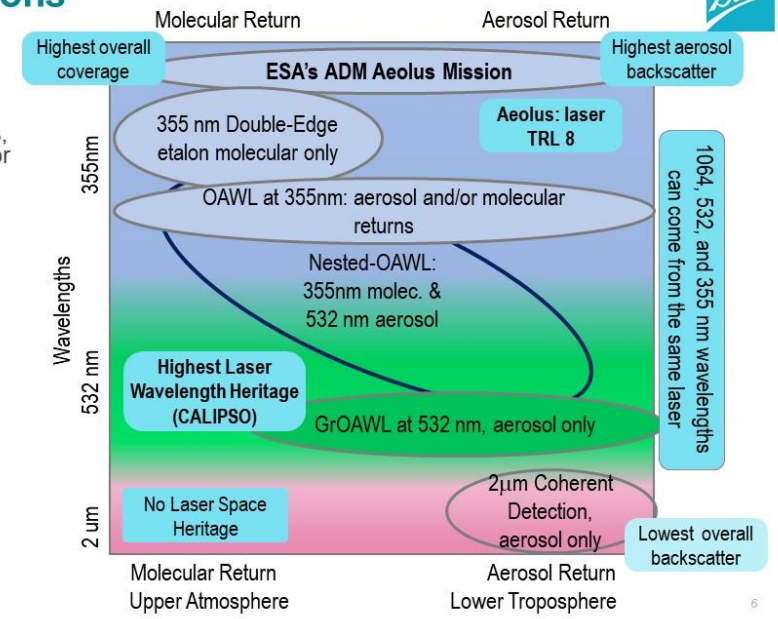
- Working with Industry expands access to larger pool of excellent engineers with focused or broad skill sets, as needed.
- Competition pushes innovation
- Perceived cost differences mitigated by:
  - Industry (Ball) wants to keep the customer happy – our job is to deliver results.
  - Industry doesn't afford those who don't help pull the weight – layoffs, etc. can happen.
  - Contracts mechanisms exist to address costs – e.g. firm fixed price for some efforts (not something seen at centers)
- Spreading mission work across multiple states increases congressional support: keeps the mission sold!

Taxonomy: Wind Lidar Concepts for Space

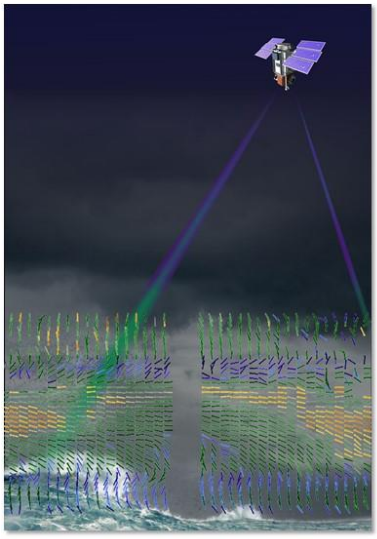


Wind Lidar Comparisons

- Direct Detection
  - Highest TRL (lasers, telescopes, detectors, data systems, etc.) for space.
  - Greater coverage from aerosol backscatter
  - Includes molecular backscatter (most coverage)
- Coherent detection
  - high sensitivity when sufficient aerosols are present
  - Eyesafe for aircraft applications
  - >40 years of airborne demonstrations

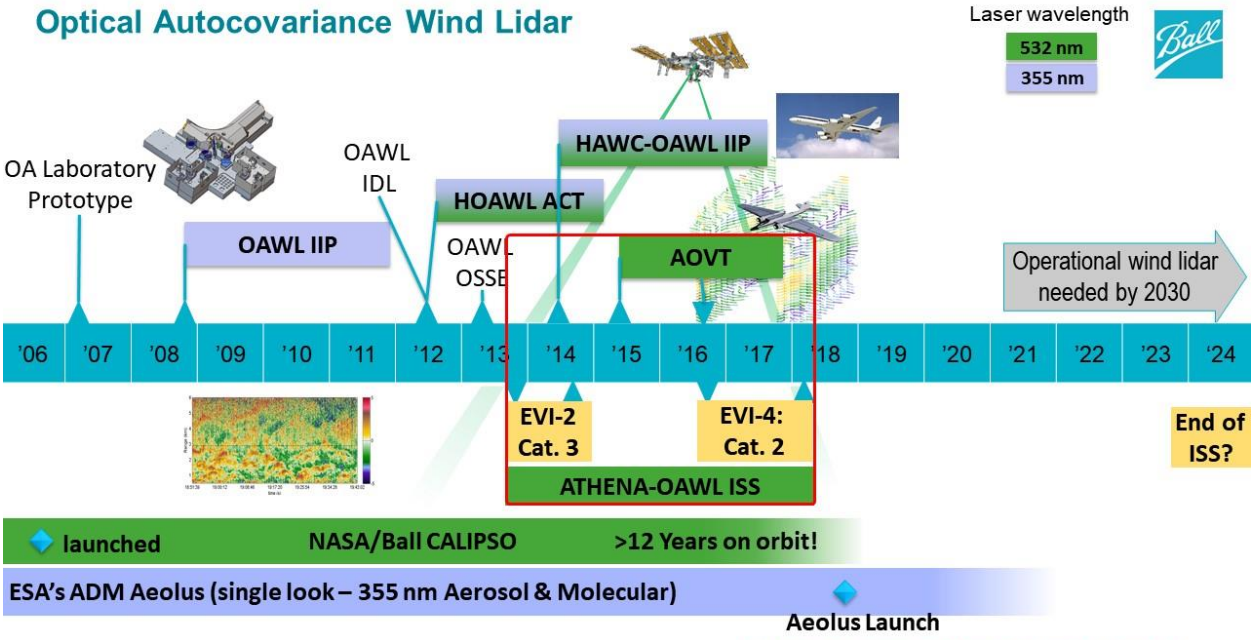


What (Whooo) is OAWL? Optical Autocovariance Wind Lidar



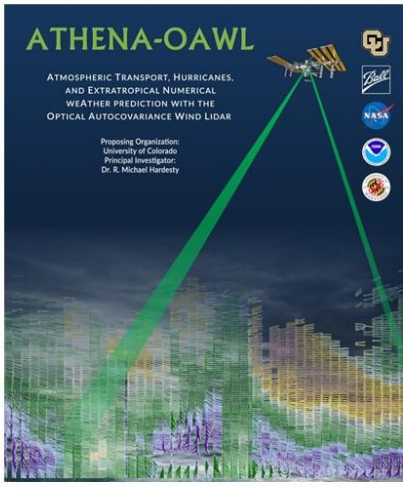
- Alternative type of direct detection wind lidar
  - Can be built to operate at any lidar wavelength – but demonstrated at 355 nm and 532 nm wavelengths
- ***Aerosol and/or Molecular*** winds
  - Aerosol winds demonstrated since 2011 using long optical path difference (OPD) interferometer
- Uses a patented, field-widened, four-channel, Mach-Zehnder interferometer to measure fringes in laser light
  - Measures Doppler shifts by measuring changes in interferometer fringe phase
  - Similar approach described by Bruneau & Pelon, 2003
  - Can operate a two wavelengths
  - Field widening reduces telescope wavefront requirements, allowing larger telescopes at lower cost.

Optical Autocovariance Wind Lidar



ATHENA-OAWL: path-finding science mission concept for next-generation global weather prediction and climate analysis

- **ATHENA-OAWL:** **A**erosol **T**ransport, **H**urricanes, and **E**xtra-tropical **N**umerical we**A**ther using **OAWL.**
  - Co-located wind and aerosol profiles for NWP and climate studies
- ***Design-to-cost approach*** to NASA Earth Venture Instrument (EVI) opportunities based on heritage systems (mostly CALIPSO) and ISS hosting
- EVI– *first proposed in 2013* was the first full US wind lidar mission concept developed, costed, and proposed in decades: Rated **Category 3**, eligible for Venture Technology development funding.
- Re-proposed in 2016. Announced February 2018, rated **Category 2 (Selectable** – but not selected**)**.
- EVI-5: ISS not allowed. A missed opportunity for winds

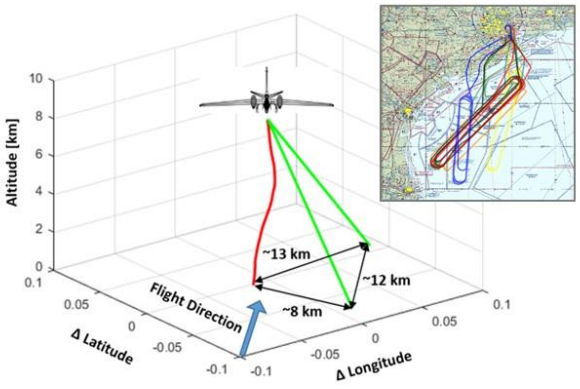


ATHENA-OAWL Venture Tech:

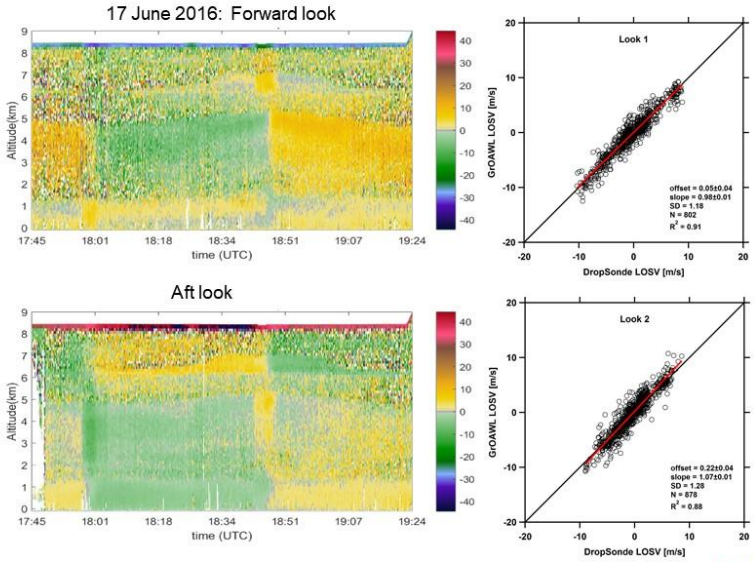
- Built and flew the "GrOAWL" airborne demonstrator for the ATHENA-OAWL DWL mission approach
- Demonstrated 2-LOS wind measurement capabilities
- Validated measurement accuracy using dropsondes/radiosondes
- Verified OAWL precision/performance using aerosol (GEOS5) models
- Scaled performance to space-based operation
- 2x Papers in review at *Journal of Atmospheric & Oceanic Science*.



NASA WB-57 jet



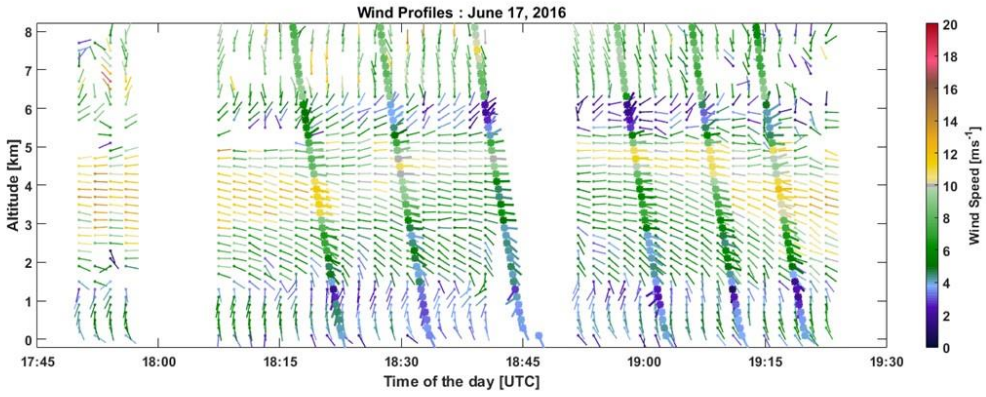
GrOAWL Simultaneous two-look LOS wind speed profiles

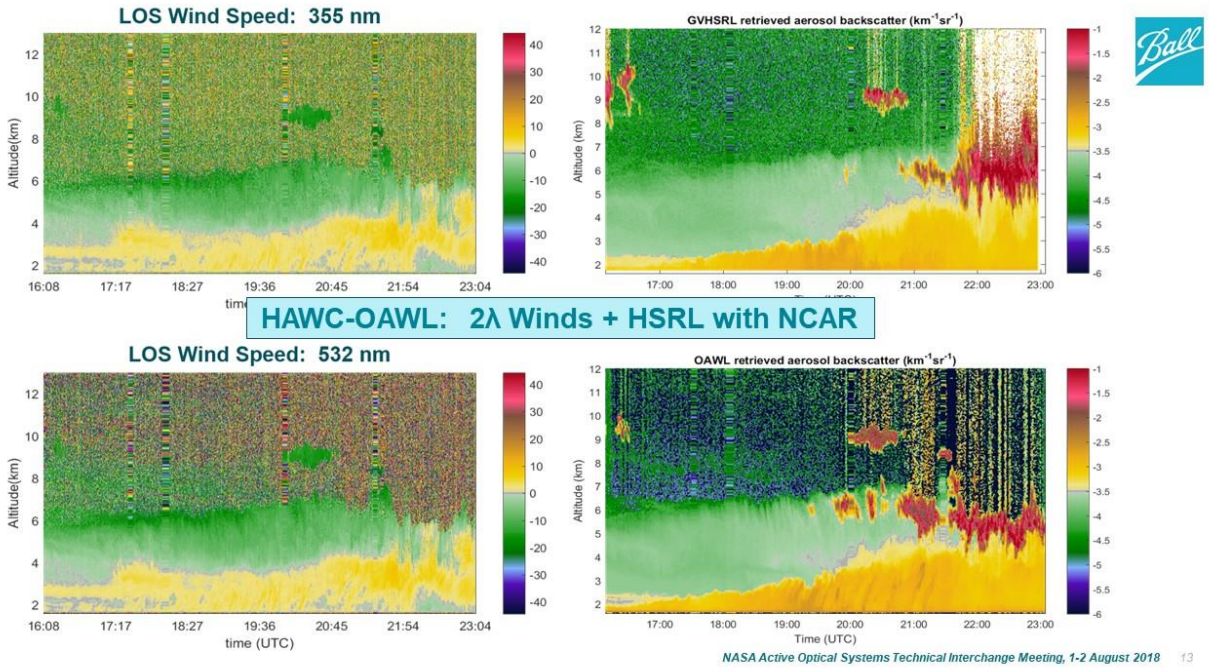


- Line of sight wind speed data
  - 8.5-10km flight altitudes,
  - 45° slant path angles
  - <1.5 mJ/pulse, 532 nm
  - 27 cm eff. diameter telescopes
  - 1-10s data accumulation
  - Daytime flight w/ scattered clouds.
  - Clean atmosphere/low aerosol backscatter (GEOS5 model)
- Continuous coverage with each look, *no switching or scanning required*
- Validated using 21 dropsondes from 3 validation flights

Wind Profiles: June 17 2016

- Can assimilate vertically resolved winds from separate lines-of-sight
- Can also combine 2 look LOS winds to retrieve wind speed and direction profiles
- Retrieval is based on classic radar/lidar "VAD" techniques





ADM-Aeolus Mission: ALADIN: Atmospheric LAser Doppler Instrument



Single-look
(60%-70% of 2 looks)

Two Direct Detection channels:
Aerosol & Molecular (full troposphere) - both at 355 nm

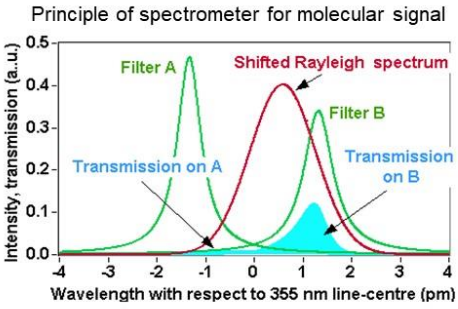
Launch scheduled for
21 August 2018!!

Sun-synchronous, dusk/dawn orbit, 320 km

3 year mission (consumables) - no follow-on



Courtesy Anne Grete Straume



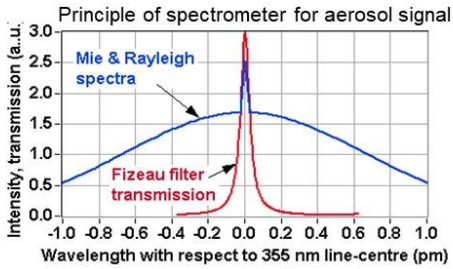
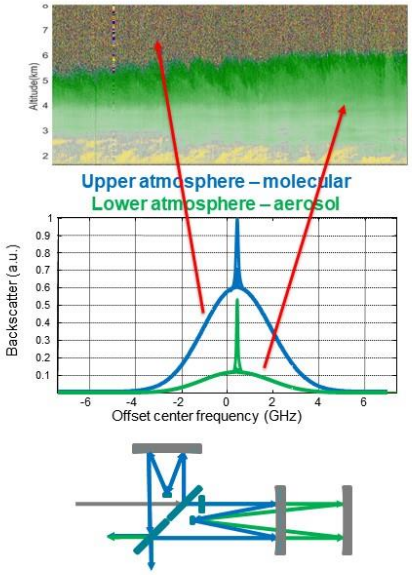


Fig. U. Paffrath

Principle of wind measurement with **A**tmospheric **LA**ser **D**oppler **In**strument: ALADIN

- Direct-Detection Doppler Lidar at 355 nm with 2 spectrometers to analyse backscatter signal from molecules (Rayleigh) and aerosol/clouds (Mie)
- **Molecular:** sequential implementation of Double edge Fabry Perot for spectrally broad molecular returns
- **Aerosol:** Fizeau spectrometer for spectrally narrow aerosol/cloud returns
- Uses Accumulation CCD as detector => high quantum efficiency >0.8 and quasi-photon counting mode
- ALADIN provides High-Spectral Resolution Lidar HSRL with 3 channels: 2 for molecular signal, 1 for aerosol/cloud signal => retrieval of profiles of aerosol/cloud optical properties possible

OAWL for Full Atmosphere Wind Profiling



OAWL path to *full* atmospheric wind profiles

- Measure aerosol winds @ 532 nm – more precision using the ***existing*** long OPD
- Measure molecular winds @ 355 nm – more coverage using the new short OPD
- Both wavelengths can be simultaneously generated in the same laser
- BOTH measurements made simultaneously using a “nested” OAWL interferometer (patent pending).

Wind lidar measurements from space: Aerosols, molecules, and scales

Like Aeolus, the OAWL approach offers a path to *full* atmospheric wind profiles:

Two wavelengths (same laser) used to measure winds from both aerosols AND molecules

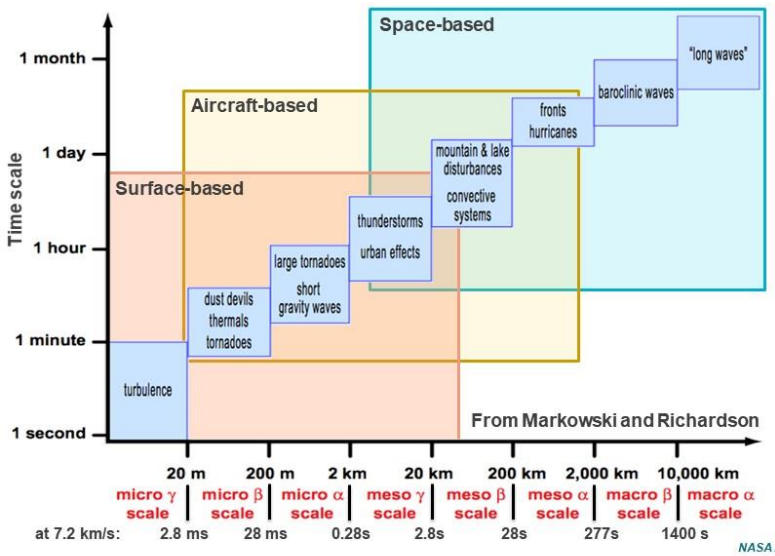
- @ 532 nm – provides precision using ***aerosol returns***
- @ 355 nm – provides coverage using ***molecular returns***

High altitudes: fewer aerosols & clouds, so UV wavelengths are used to measure winds using lidar returns from just molecules (e.g. ESA's Aeolus mission, UV OAWL)

Aerosol-DWL's (Green-OAWL, Coherent detection) provide good returns in lower troposphere and where aerosol layers or thin clouds are present

Airborne & ground DWLs are best for boundary layer studies at scales that would be smeared by space-based orbit speeds (~7.2 km/s)

Matching space-based lidar wind observations to atmospheric process time and space scales



- Lidar wind measurement of many important weather processes from space is challenging
  - Satellite speed (~7 km s^{-1})
  - Multi-pulse accumulation
  - Measurement curtain
  - Long revisit times
- Space-based Lidar winds (e.g., Aeolus) are well-matched to synoptic scales and perhaps long term wind statistics
- Impactful measurements for smaller scale processes is difficult
- Need full atmospheric profiles to understand processes.
- Useful to investigate observation capability at sub-synoptic scales

Next for OAWL – pending funding

An aerosol wind lidar mission at 532 nm is ready for Phase A.

The following additions are continuing improvements, size reduction, additional capability, etc.

- Continue with HEUVD laser testing and development at Fibertek
  - Alternative OAWL system designs being studied/proposed to reduce laser requirements (and thus size and risk)
- Build new compact interferometer design (proposed for MATISSE)
- Validate calibrated HSRL data products
- More airborne demonstrations (e.g. Aeolus CalVal)
- Optical bench modifications/improvements (e.g. bench layout/size, transmit beam expansion, background filters)
- Ball Internally funded
  - Nested OAWL TRL 2-3 demonstration this fall
  - HSRL demonstrations & calibration
  - Ongoing mission concept development

Recommendations

"how to maintain an active remote sensing program and how to integrate measurement techniques & technology within NASA."

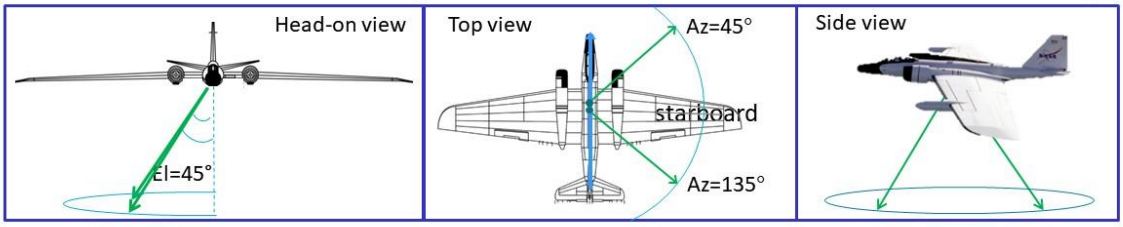
- Clearly define NASA's own objectives: What is NASA's mission with respect to active optical systems, especially lidar?
  - Internal lidar program vs. competed funding?
  - Input from Academia?
- Increase transparency and levelness:
  - Industry invests a lot of their own time and energy developing and proposing new and beneficial technologies to meet perceived NASA mission – but we can't give them away for free.
  - When funding so often stays within NASA & FFRCs, industry starts to feel "exercised."
- Increase diversity - good engineering, science, and support comes from differences in people, sectors, and locations.
- Increase accountability for work at centers: program review panels that include external reviewers
- Reward collaboration – current NASA (SMD? ESD?) model often sets up NASA centers as competitors ("coopetition" or "competimates") with industry and academia.
  - NASA centers often reluctant to allow collaboration unless they are the lead – at all levels, from IIP to Earth Venture.
- ESTO has the right idea (though sometimes not enough autonomy). Consider more ESA/NSF/DARPA-like models at NASA: PMs managing external programs, with some rotations like HQ positions – avoid the biases (e.g. friendships, center politics) that impact success.

Conclusions

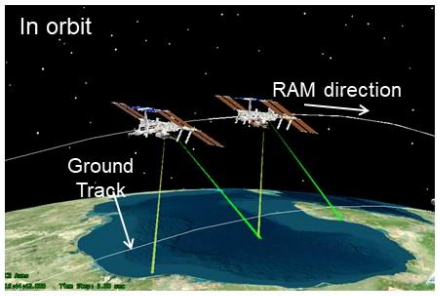
- Wind lidar technology is ready for space-based operation
  - Aeolus launching August 21, 2018: US CalVal activities in development
  - ATHENA-OAWL
    - technology demonstrations and validation performed using airborne demonstrator,
    - the EVI4 mission concept was rated selectable: Non ISS lidar missions are challenging in EVI cost cap
  - CALIPSO lidar still operating – 12 years on orbit
- NASA funding ceased for OAWL in 2017
  - R&A-based funding, like that provided for centers, can provide more OAWL demonstrations, validation, and interactions with scientists.
  - NASA could make additional technical investments (on top of Ball's current IRAD) to increase coverage (full troposphere), and reduce size, mass, and cost risk
- Public-private partnership between NASA and Ball has provided high TRL, low risk technologies for active remote sensing missions.
- Ball is still here, wanting to partner with NASA to develop space-systems for more great missions.

EXTRAS

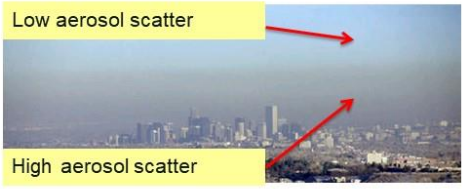
Both eyes open: Two-look, two-laser system parameters



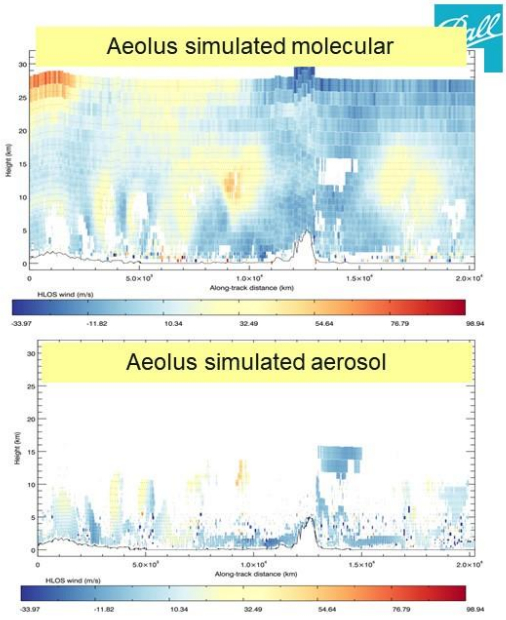
Parameter	Airborne System Value
Pulse Energy 532 nm	200 µJ – 2.5+ mJ (*nom. 1.5 mJ*)
Pulse Energy 355 nm (HAWC)	10-11 mJ
Laser Pulse Repetition	200 Hz per look
Cassegrain Telescopes	~27 cm eff. Diameter w/ obsc.
Sample Rate	140 MHz (1.07 m)
Interferometer OPD	~0.9 meters
Off-Nadir pointing	45°
Azimuth pointing (from forward)	Look 1/Look2: 45° / 135°



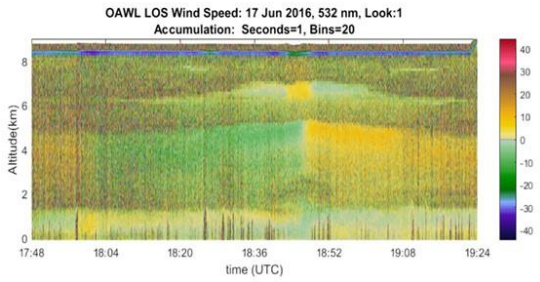
Moving beyond Aeolus: getting the second look

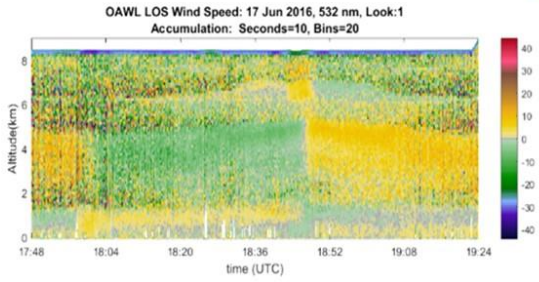


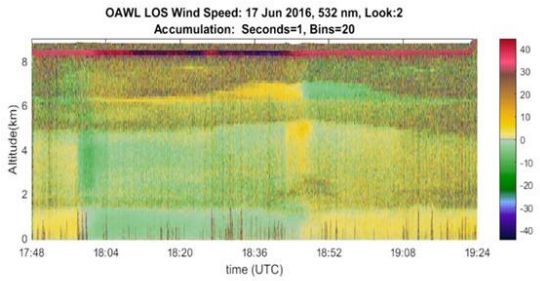
- Future missions will require *full atmospheric* wind profiles for high global NWP impact
- Moving beyond Aeolus to two looks will require higher overall efficiency,
- Building on CALIPSO & Aeolus technologies: Optical Autocovariance Wind Lidar (OAWL)-based designs offer *aerosol and molecular* winds in a single, more efficient receiver with less complexity and lower risk

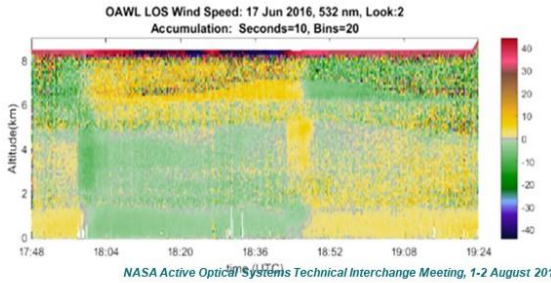


GrOAWL: 1s and 10 s average airborne profiles

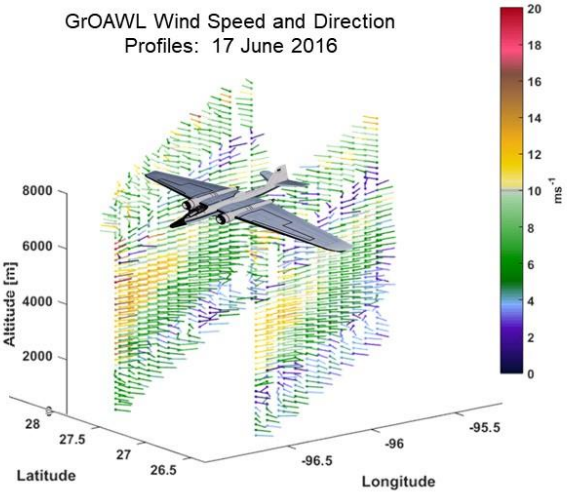


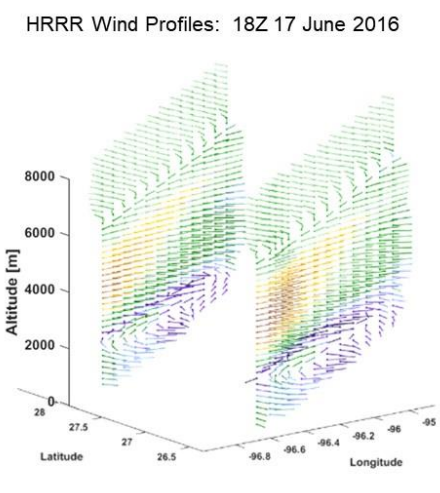






GrOAWL measurements captured the spatial variability predicted by the HRRR over the Gulf of Mexico.





Why OAWL?

From Space

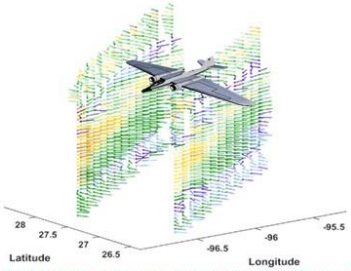
OAWL is the only US Doppler Wind Lidar with a *high heritage* path to space

- High TRL components based on CALIPSO (direct detection): wavelength, optics, filters, etc.
- Field widened receiver works well with large telescopes; diffraction limited not required. 1-λ aberrations OK.
- Nd:YAG – (including 532 nm) laser technology already proven in space: 10+ years on CALIPSO
  - Slightly higher power and single mode operation being demonstrated on HEUVD
- OAWL can also operate at 355 nm –(Aeolus & HEUVD qualifying the laser)
- 355 and 532 nm wavelengths see scattering/returns from large portions of the atmosphere.
- OAWL offers a full atmosphere solution

From Aircraft

OAWL wavelengths and autonomous operation enable high altitude airborne studies

- ESA's 355 nm Aeolus CalVal
  - OAWL is the only validated US 355 nm aerosol wind lidar for Aeolus aerosol channel validation
- Suborbital Science missions
  - OAWL's small wavelengths scatter from smaller aerosol modes, like those found in the arctic and at higher altitudes
  - OAWL's autonomous real-time winds can provide immediate feedback to mission science



Example of MZI with short OPD: Molecular returns

- Bruneau et al., 2004 – show MZI data from 10 to 40 km Altitude
- Mach Zehnder Interferometers (MZI) have more throughput than Fabry Perot interferometers, and are self referencing.
- Additional Double Edge & MZI comparison info available on request

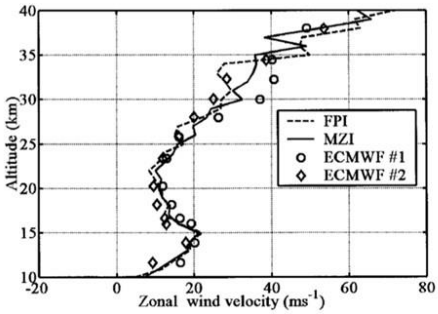


Fig. 8. Zonal wind-velocity profiles. ECMWF #1 is the numerical analysis on 16 January 2003, 18:00, and ECMWF #2 was on 17 January 2003, 0:00.

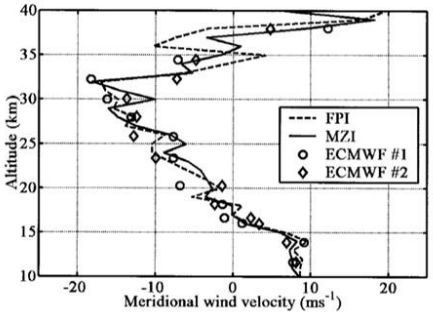
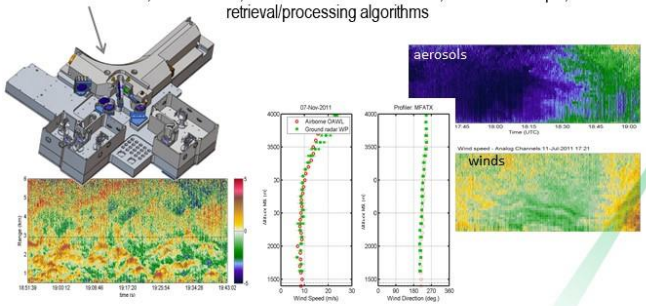


Fig. 7. Meridional wind-velocity profiles. ECMWF #1 is the numerical analysis on 16 January 2003, 18:00, and ECMWF #2 was on 17 January 2003, 0:00.

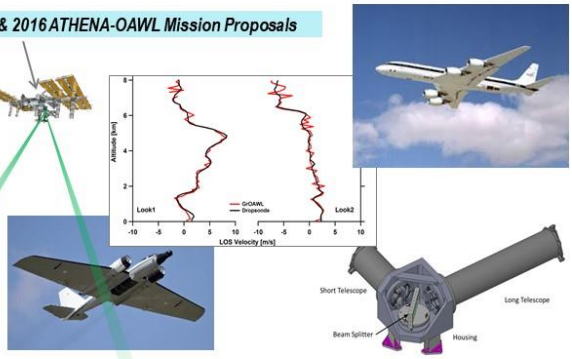
The Evolution of OAWL

Since 2003, Ball has worked in a public-private partnership with NASA and weather/wind lidar communities to advance space-based wind lidar technology and fill the global wind measurement gap.

1999-present: Ball designs, mission concepts, build and test of OAWL patented, field-widened, four-channel, Mach-Zehnder interferometer, mission concepts, and retrieval/processing algorithms



2013 & 2016 ATHENA-OAWL Mission Proposals



2008-2012: OAWL IIP-07
- Breadboard system
- 355 nm only, 4x channels
- Single look 12" telescope
- Ground validation with NOAA Coherent system
- Autonomous flight tests on NASA WB-57

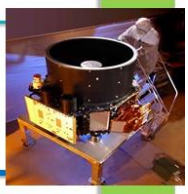
2012-2015: HOAWL ACT
- Breadboard System
- Demonstrate 532 nm wavelength channels & depolarization channels
- Total 10 channels
- HSRL Aerosol retrieval algorithms

2015-2017: ATHENA-OAWL Venture-Tech: GrOAWL
- Airborne demonstrator System (WB-57)
- 2-lasers = 400 Hz eff. PRF
- 4x 532 nm channels
- 2 looks, 2 telescopes to demonstrate geometry for space-based operation

2014-2017: HAWC-OAWL IIP
- Two look airborne system (build on GrOAWL)
- Dual Wavelength + depol. Channels
- Athermal interferometer build and demonstration
- DC-8 hardware design/build

TRL	1	2	3	4	5	6	7	8	9
Receiver	Concept	Lab demos		Ground demos	2λ Winds; Aircraft Demos; Performance scaling to space	**Brassboard IFO EDU build & test**; **Environmental Test**	CALIPSO & ICESAT telescopes, detectors	System Thermal/Vacuum/ Shock/Vibe Testing	**NASA/Ball CALIPSO**
Laser				HSRL, GOLD, & TWiLiTE	**HEUVD**; OAWL1& GrOAWL lasers; Lifetime-testing	**Thermal/vacuum/ shock/vibe test**			
Elect. & SW			National Instruments/ Labview	Payload Controller (PC) & data acq. development	PC EDU w/ space-qualified equivalents	**PC w/ Space-qualified parts**; **Thermal/vacuum/ shock/vibe test**			
Data & Science	OSSEs			Real-time processed winds (FPGA)	355 OSSE; **2λ synergy studies**	**2λ OSSE**	Science Implementation Plan; **ATBD**; Cal-Val planning	ESA's Aeolus (355 nm lasers)	**>11 Years on orbit!**
Mission	Ground Validation	Airborne Validation	Instrument Design Lab	EVI-2 (2013) proposal	EVI-4 (2016) proposal	**Airborne flight tests**; **Free-flyer mission designs**			

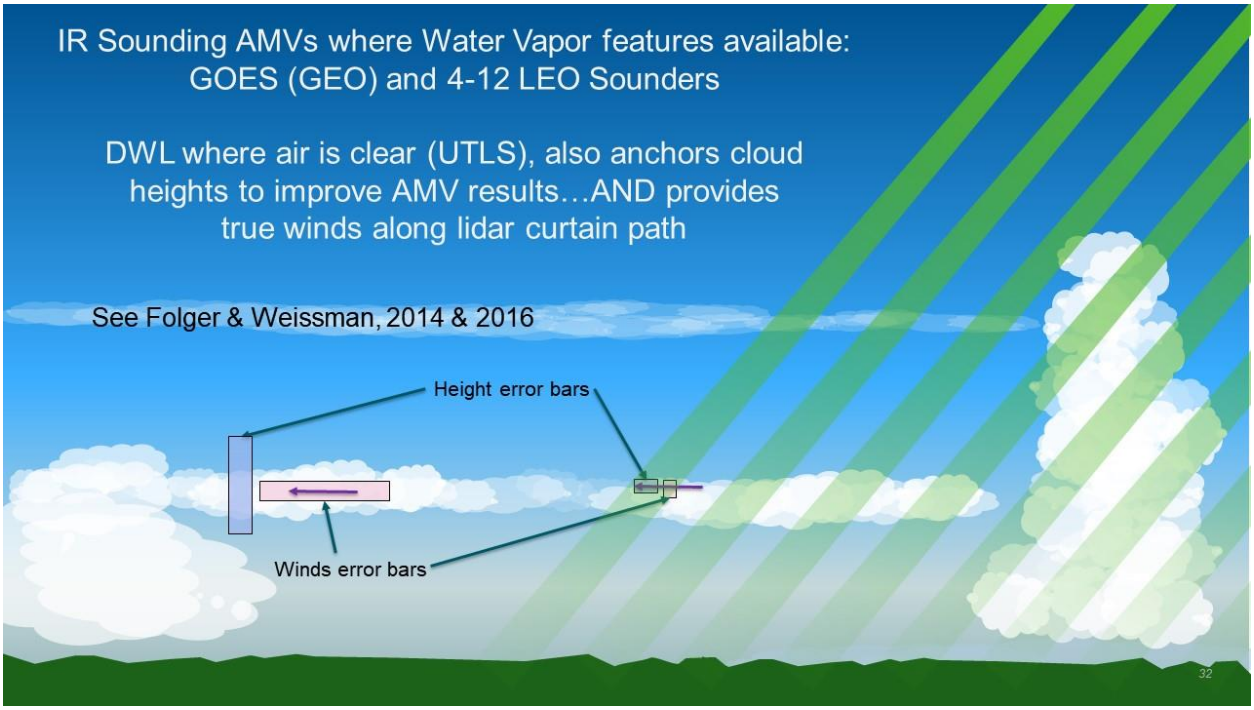




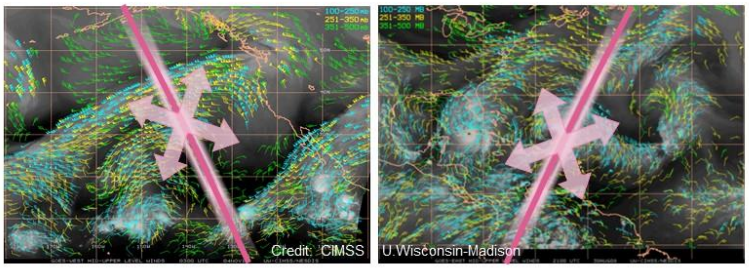


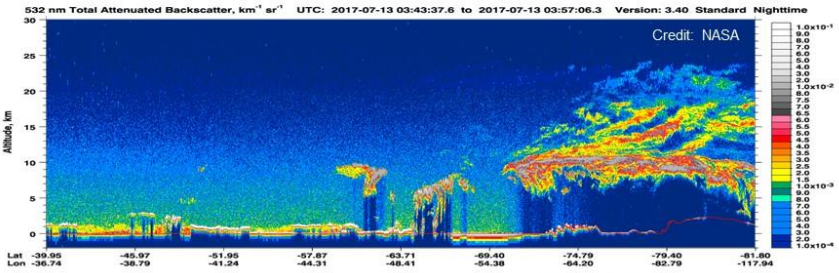
Aeolus Calibration/Validation: US participation

- ESA will share data – proposal required (but no funding provided)
- US CalVal team – proposal to ESA led by Mike Hardesty, consists of multiple US Investigators from all sectors. US funding pending.
- NOAA (NESDIS, AOML, etc.): DA, impact studies, US Cal/Val coordination
  - JCSDA coordination?
- NASA Weather Focus Area: Possible airborne Cal/Val campaigns (WFA)
  - NASA Langley 2um Coherent Detection DWL System
  - Ball/NASA OAWL 355 nm (like Aeolus) and 532 nm (aircraft pending) DWL System
  - NASA Langley HSRL and Water Vapor Dial lidar systems
- Other US activities?

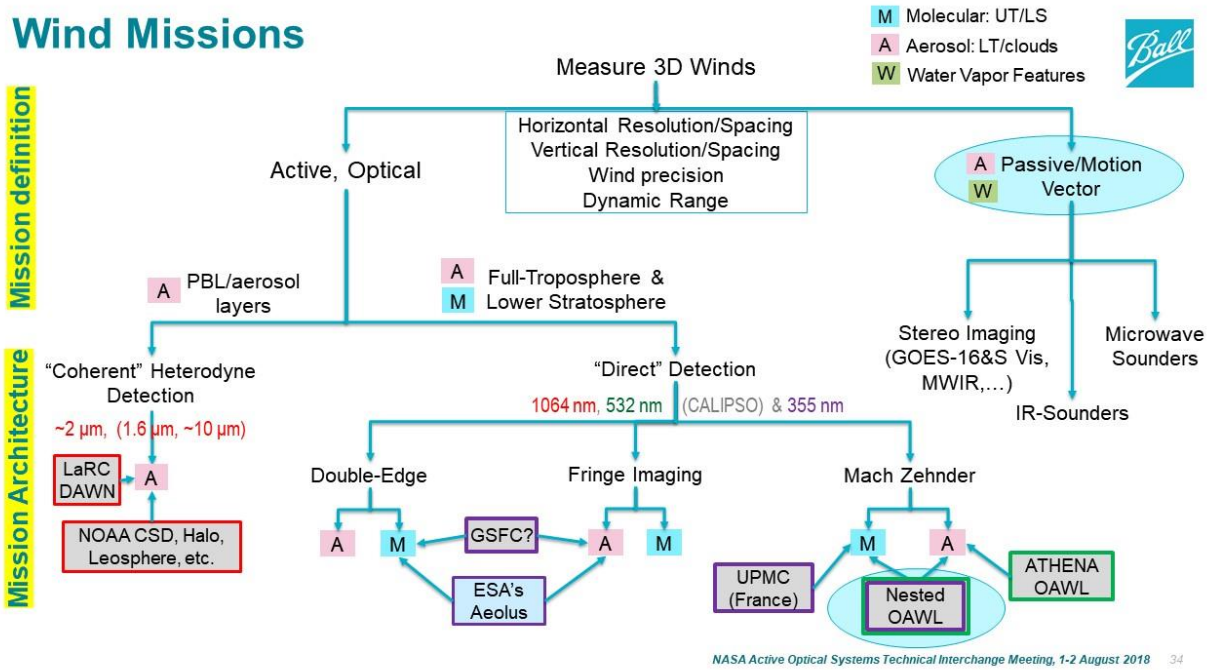


Lidar winds: Studies on the swath of AMV improvement when anchored?



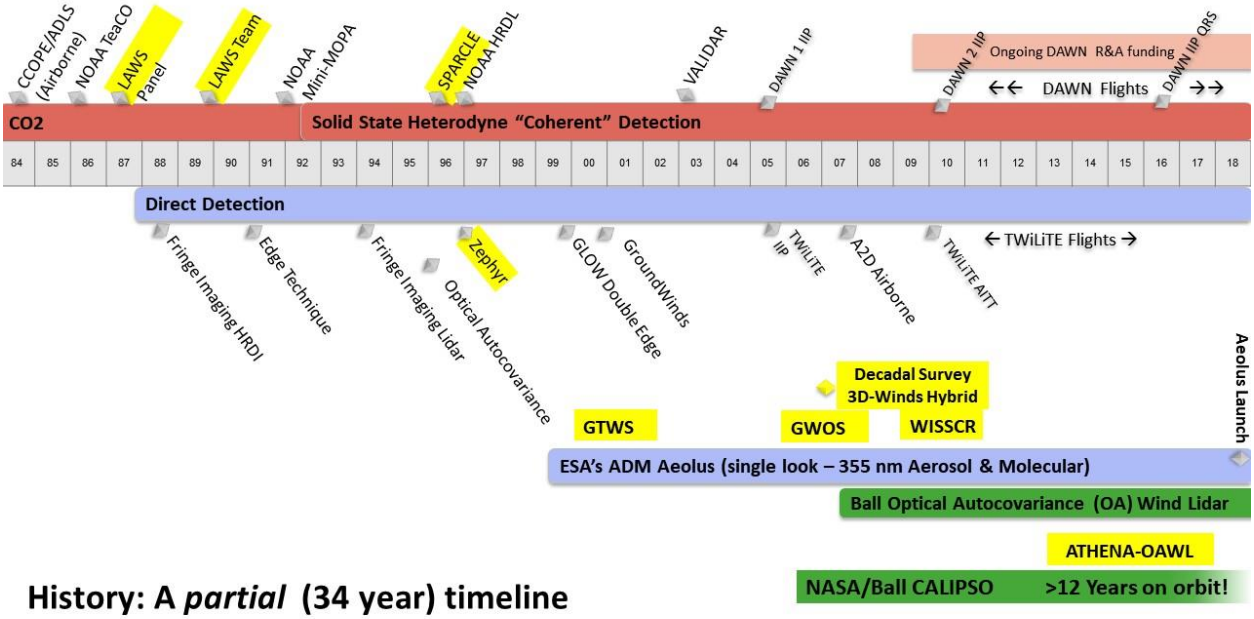


Wind Missions

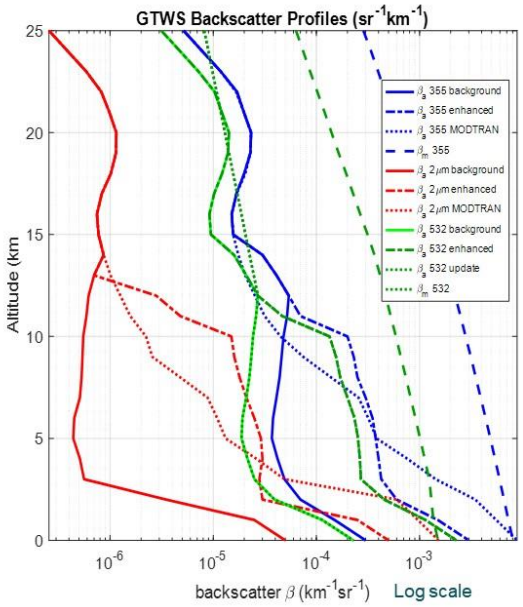


Atmospheric Winds in the 2017 Earth Science Decadal Survey: Thriving on our Changing Planet

- Atmospheric Winds listed in “Incubation” and “Explorer” categories: to possibly be addressed by Wind Lidar
- “Recognizing the cross-panel importance of the PBL and the challenges of obtaining 3D measurements of horizontal wind, temperature, humidity, and aerosol and trace gases in the PBL, optimal approaches could be:
  - To combine Doppler lidar wind profiling with hyperspectral infrared sounding to provide the 3D structure of horizontal wind. This can be further combined with near-surface microwave scatterometer wind over ocean, and ground-based wind profiling, high vertical resolution profiles from radiosondes and commercial aircraft measurements during taking off and landing. …
  - To bring Doppler Lidar and hyperspectral infrared observations together in a dynamically consistent way through data assimilation and numerical modeling. “



History: A *partial* (34 year) timeline of space-based Doppler wind lidar



Atmospheric Backscatter

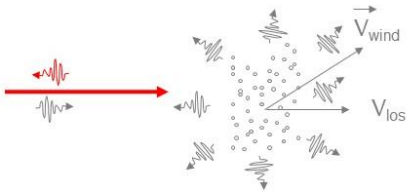
- Longer wavelengths (e.g. 2 µm)
  - Larger aerosols present in the PBL & aerosol/cloud layers
  - Less atmospheric extinction, but less coverage
- Shorter wavelengths (532 & 355 nm)
  - More scattering from aerosol/cloud layers
  - Scattering off of smaller particles present in Upper-troposphere/Lower-Stratosphere
  - Molecular scattering
  - High TRL lasers, telescopes, & detectors

These properties factor strongly into which lidars are best for a given application

Atmospheric Scattering

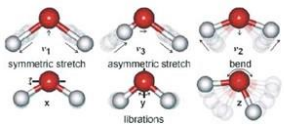
Aerosol Scattering

- Aerosols (dust, cloud droplets, etc.) move with the wind
- Backscattered laser light picks up a Doppler shift based on the wind speed.

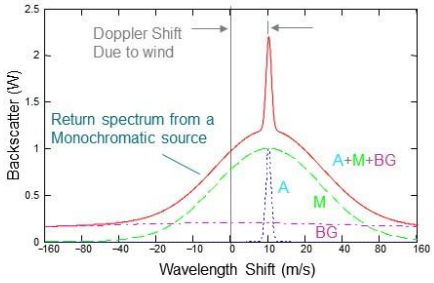


Molecular Scattering

- Molecules move with the wind…
- … AND they vibrate (at frequencies based on temperature & pressure).
- Backscattered laser light picks up Doppler shift(s) from wind speed AND molecular vibrations
- Molecular scatter is “Doppler Broadened”



Bandwidth of atmospheric lidar return



As a result….

- Aerosol return has approximately the same narrow bandwidth as the outgoing laser pulse
  - easier to resolve precise frequency shifts,
  - inconsistent opportunities.
- Molecular return has a wide bandwidth due to all the Doppler shifts from the molecular vibrations (Doppler broadening)
  - More difficult to resolve precise frequency shifts
  - Molecules always available (full coverage)

3.4 HIGH ALTITUDE LIDAR ATMOSPHERIC SENSING

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ABSTRACT

Michigan Aerospace Corporation and Honeywell have designed and tested a LiDAR (light detection and ranging) system (HALAS: High Altitude LiDAR Atmospheric Sensing) capable of wind, density, aerosol extinction, temperature and water content measurements in the troposphere and lower stratosphere. The intent of this integrated, high-altitude atmospheric quantities measurement instrument is to provide the near real-time measurement of parameters critical to launch facilities, test programs, modeling and predictions.

The current methodology for determining atmospheric conditions includes the integration of balloon sonde data along with conventional instrumentation into a predictive model. Temporal and spatial variation associated with balloon sonde data can provide significant uncertainty when determining the Best Estimate Atmosphere. The HALAS system provides near real-time measurements of atmospheric quantities prior and during operations. By reducing spatial and temporal variation in measurements, and providing a continuous data stream, HALAS has the potential to improve characterization of atmospheric dynamics from the boundary layer to the stratosphere.

HALAS is an ultraviolet-based direct detection LiDAR system for wind and temperature measurements, combined with a Raman channel to measure nitrogen, water concentration and temperature in the troposphere and stratosphere. HALAS is based on the direct detection technology developed and demonstrated by Michigan Aerospace (in conjunction with NOAA support and in partnership with the University of New Hampshire) on a system based on Mauna Loa (HI) that has delivered reliable wind, density and temperature measurements. In addition to the direct quantities measured, derived quantities include extinction, cloud height, and aerosol content.

So far, the HALAS system has been tested at three sites, among them NASA Armstrong Flight Research Center (Edwards AFB, CA) in high desert conditions, and along the West Coast at Vandenberg AFB in a littoral environment. The instrument is currently being tested at Pt Mugu NAS. The instrument can be disassembled and prepared for transport within a day; reassembly and preliminary tests take a week on average. The instrument can operate on generator power and satellite link, and therefore in locations with limited infrastructure.

HALAS has paved the way for the next generation LiDAR, which Honeywell International is co-developing with Michigan Aerospace. The end system will be a versatile platform that supports a wide variety of atmospheric and meteorological missions. There are opportunities to calculate secondary or derived data products from the fundamental data gathered by HALAS, which vary based on the end application. For example, optical turbulence can be derived from several primary data products, which can be fused for more accuracy and robustness.

1 INTRODUCTION

The Test Resource Management Center (TRMC), a component of the Office of the Under Secretary of Defense for Acquisition, Technology and Logistics, funded and managed the LiDAR development. The TRMC Test & Evaluation/ Science & Technology program develops new technologies to advance DoD T&E capabilities. High Speed Systems Test (HSST) is one of eight Test Technology Areas in the program.

HSST, located at the Arnold Engineering Development Complex on Arnold Air Force Base in Tennessee, develops T&E technologies, tools, and methodologies for ground test, flight test, instrumentation, and computational modeling and simulation of high-speed and hypersonic vehicles. The goal of HSST is to provide high speed and hypersonic programs with T&E capabilities. In addition to support to hypersonic research programs, HALAS applications also include

atmospheric characterization, winds for vehicle re-entry phase for instance, and atmospheric dynamics for climate research.

The High Speed Systems Test group conceived the HALAS LiDAR, a ground-based, ultra-violet LiDAR, to gather near real-time meteorological data, including:

- Density, temperature, wind velocity/direction, and N2 and H2O mass fractions,
- Measurements over the range of 0.6-to-40+ kilometers,
- Scans 0-360o in the azimuthal direction, and
- Scans 0-90o in elevation.

The HALAS LiDAR instrument is a Direct Detection Lidar, equipped with a Fabry-Perot interferometer to obtain density and wind vector, wind shear, as well as a vibrational Raman channel to collect N_2 and H_2O mass fraction, and pure rotational Raman channel to measure temperature. Over the past 5 years, the LiDAR has been tested at several sites, including Kwajalein Atoll (RMI), NASA Armstrong Flight Research Center, and Vandenberg AFB. The LiDAR is currently located at Pt Mugu NAS. Figure 1 shows a photograph of HALAS during its first deployment at the Kwajalein Atoll.



Figure 1 HALAS first deployment at Kwajalein Atoll (RMI)

The HALAS system utilizes a laser operating at 355nm (invisible and does not focus in the eye), which enables atmospheric measurements of wind speed, wind direction, temperature and air density.

The instrument measures winds by looking at the laser backscatter from both aerosols and air molecules. It is a proven technology that has been demonstrated for both short- and long-range applications. To improve density profile accuracy, recycled light from the interferometer is directed to a series of light intensity splitters and photon counting PMTs. These channels provide the elastic scattering from the LiDAR, i.e., molecular and aerosol, returns. Pure rotational Raman and vibrational Raman light contributions are extracted from the LiDAR return and directed to a spectrograph in the case of the pure rotational Raman, and photon counting PMTs in the case of N_2 at 387 nm, and H_2O at 407 nm. Table 1 lists the main LiDAR components.

Table 1 LiDAR Components

Laser Wavelength	354.7 nm
Laser Power	12 W (18 W)
Telescope Diameter	0.5 m
Telescope Configuration	Dall-Kirkham
Optical Bandwidth	345 nm to 410 nm
Beam Scanner Az	0 - 360º
Beam Scanner El	0 - 90º
Fabry-Perot CCD	Andor
Temperature:	Spectrograph
N_2	Photon counting PMT
H_2O	Photon counting PMT

2 METHODOLOGY

2.1 STATE OF THE ART

The current methodology for determining wind and density during a flight test, launch, or re-entry involves balloon launches combined with conventional ground instrumentation (MET towers, wind profilers, models) prior to and during the launch/flight. Balloon sondes afford high altitude measurements but data accuracy is often affected with uncertainty caused by balloon drift.

2.2 NEW APPROACH

While the LiDAR system such as HALAS does not claim to replace existing measurement techniques at this time, the high-altitude LiDAR can make

significant improvements to the current atmospheric characterization process. The LiDAR:

- Provides measurements locally in a *controlled* spatial domain.
- Delivers continuous data that can be input into models. The continuous data stream can be exploited to identify subtle changes in a short period of time.
- Is versatile. Emphasis on density or winds can be selected at any time.

2.3 DESCRIBE THE FUTURE STATE

A network of such LiDARs will deliver 24/7 measurements of aerosol content and cloud structure, water content and temperature, and how water vapor, clouds, and aerosols interact, all critical data for climate research. This network will also contribute data to field campaigns and long term climate data records.

Finally, the wealth of data obtained from such LiDAR network will be useful to improve the reliability and reduce uncertainty of climate model projections.

2.4 RISKS AND REWARDS

At the onset of the program, the concept and development afforded high risks because of the high expectations, but high rewards. If successful, the program would deliver the capabilities described in Section 2.3. The prototype LiDAR and software are in their fourth year of development and have already demonstrated density, wind, temperature and extinction measurements up to the lower stratosphere region. As a result, the early phases of the program that are traditionally associated with high risk have been demonstrated successfully. The HALAS LiDAR is still considered a working prototype but the instrumentation development has yielded a wealth of knowledge that will be carried forward in the final instrument development.

3 PROGRAMMATICS

3.1 DEVELOPMENT PLANS

The project started in 2013 with a demonstration using an existing LiDAR (located at Mauna Loa) based on the Direct Detection technique, to mitigate risk. Following a successful technology demonstration, a prototype instrument, the current HALAS, was designed and assembled for capability demonstration. A transportable version and a fixed version of the LiDAR is in development.

An airborne version of the instrument is currently being integrated on a Gulfstream IV and will be demonstrated in August 2018. The following and last step of the program will be the integration of the airborne version on a Global Hawk by 2020.

3.2 DEVELOPMENT MILESTONES AND DATES

Figure 2 shows the project timeline from the technology demonstration with an existing ground-based LiDAR to a LiDAR-instrumented Global Hawk flight demonstration.

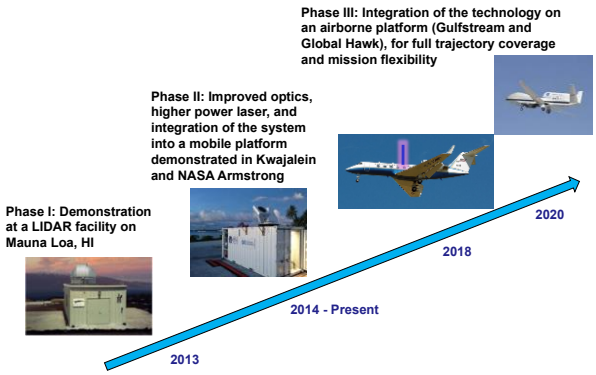

Figure 2 Project timeline

The ground-based LiDAR validation and demonstration phase will continue through the end of 2018. A flight worthy version of the ground-based system is currently being installed on a Gulfstream IV and demonstration flights will occur in August 2018. The flight demonstration on the Global Hawk is expected to take place in 2020.

3.3 PARTNERING

Michigan Aerospace Corporation has teamed with Honeywell Aerospace to co-develop the HALAS system for greater use and access. Our team will continue to showcase the HALAS system to pre-identified ranges and demonstrate its compatibilities and operations. Furthermore, we are collaborating to develop the next generation HALAS system called Honeywell Extended Range Atmospheric LiDAR. This next generation system will be equipped with improved and ruggedized optics and its core design will be modular to be integrated on a multitude of platforms ranging from airborne, maritime, and ground based systems.

Michigan Aerospace Corporation and Honeywell Aerospace will continue to work closely with the High Speed Systems Test (HSST) group. HSST will continue to help define the measurement needs and establish the technology milestones and roadmap.

Our team solicits NASA's input on measurement requirements and user experience to potentially support future NASA missions.

3.4 OVERCOMING THE VALLEY OF DEATH

Michigan Aerospace Corporation has partnered with Honeywell Aerospace with an objective of productizing and manufacturing the next generation HALAS system in support of ranges and hypersonic vehicle testing. Honeywell Aerospace is investing in this technology and will continue to do so to bridge the valley of death and bring a product to market. As part of Honeywell's industrialization effort, the system will be engineered for ruggedization and manufacturability, a supply chain will be established, and maintenance & services will be trained. Honeywell will pass on cost savings from volume production to customers and incorporate the Honeywell User Experience into the system design to facilitate operation.

4 WIDER VISION

The development of a modular core technology enables the deployment of Extended Range Atmospheric LiDAR systems on multiple platforms. Due to its versatility and breadth of data products, Honeywell's product has the potential to support numerous DOD missions and commercial applications. A network of LiDAR systems can be connected enabling a stitched field and augmented performance due to overlapping interrogation regions.

5 CONCLUSIONS

HALAS is a state of the art direct detection LiDAR system that offers a breadth of data products simultaneously, measured when and where the user desires. This system provides unique benefits to those interested in atmospheric characterization in a number of fields, including hypersonic test and launch support. Further development of HALAS, in conjunction with Honeywell, will lead to a mobile, modular, connected LiDAR system to serve NASA's and other agencies' needs well into the future.

Acknowledgements

The authors gratefully acknowledge the support of HSST, under the guidance of Mr. Wade Burfitt and Mr. Rick Hutchings.

Test & Evaluation/Science & Technology Program
High Speed Systems Test (HSST)

HALAS

High Altitude LIDAR Atmospheric Sensing

NASA Technical Interchange Meeting
July 2018
Columbia, MD

Honeywell Internal
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Agenda

- Introduction/Overview
- HALAS-Ground Description
- User Interface
- Ground LIDAR Results
- HALAS Airborne
- Moving Forward

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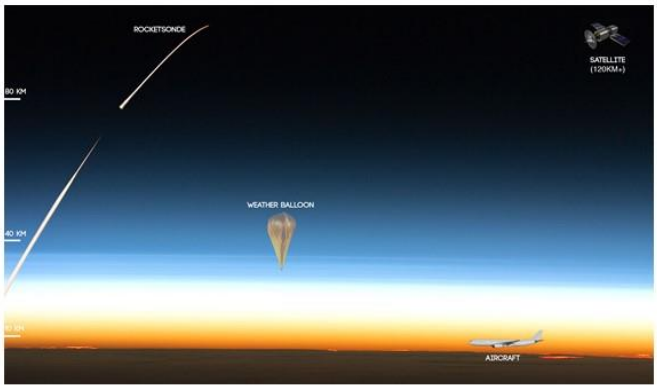
Problem Statement

Honeywell
THE POWER OF CONNECTED
MICHIGAN AEROSPACE

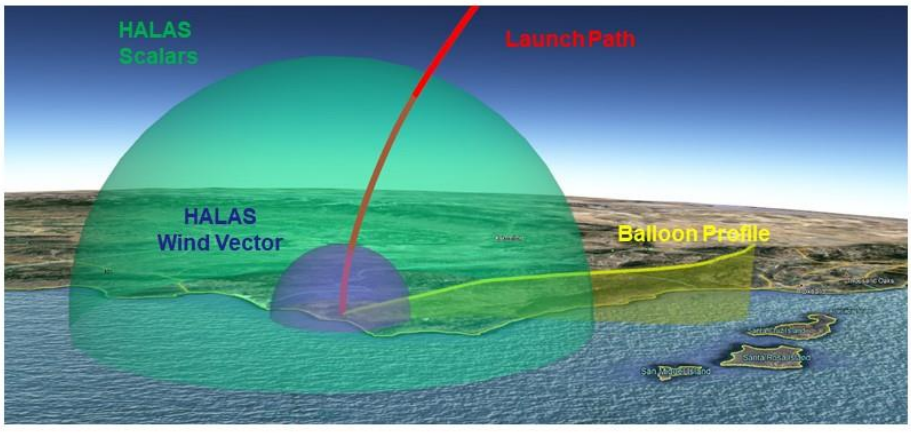
Current measurement techniques and models to support range operations such as hypersonic vehicle testing suffer from:

- **High Uncertainties**
  - **Density uncertainties of 10% to 20% at high altitudes (>15 km)**
  - **High density uncertainty increases uncertainties in calculated vehicle aerodynamic performance (lift, drag, etc)**
- **Limited coverage**
  - **Current Best Estimated Atmosphere (BEA) methodology combines sparse data from balloons and satellites with weather model outputs which results in high uncertainties**



Problem Statement

Honeywell
THE POWER OF CONNECTED
MICHIGAN AEROSPACE



Weather balloons ascend slowly, and travel downwind causing uncertainty and latency in critical atmospheric data.

A technology that could deliver critical atmospheric data parameters, orders of magnitude faster, more accurately, and precisely where the measurement is needed

HALAS

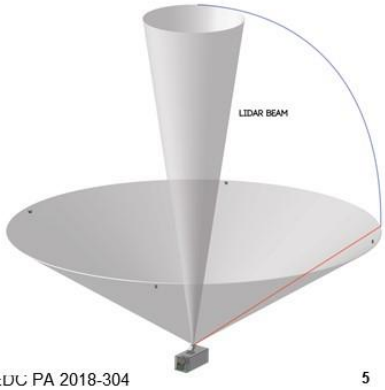
High Altitude LIDAR Atmospheric Sensing

HALAS provides improved capabilities for flight test, meteorological characterization and launch operations

HALAS is a ground-based, UV LIDAR and scanner system for making near real-time, high altitude atmospheric measurements along an aircraft or missile's flight path

The system will provide significantly reduced uncertainties compared to current techniques and is calibrated to NIST instrumentation standards





HALAS Capabilities

- **Provide Lower Uncertainties**
- **Enhanced coverage – ground and airborne**
  - Multiple profiles optimized for intended trajectories or mission goals
  - Provide hundreds of measurement profiles a day with a single system
  - Airborne implementation will provide direct coverage of intended trajectory or area of interest
- **Multiple data products**
  - Direct measurement of density, wind speed/direction, temperature, oxygen, nitrogen, and water content
- **Capable of ~40km+ (131,234ft+) measurement range**

* Range and accuracies dependent on aerosol loading and integration time

Program Phases

Phase III: Integration of the technology on an airborne platform (Gulfstream and Global Hawk), for full trajectory coverage and mission flexibility



Phase II: Improved optics, higher power laser, and integration of the system into a mobile platform demonstrated in Kwajalein and NASA Armstrong





Phase I: Demonstration at a LIDAR facility on Mauna Loa, HI



HALAS Test Sites





Reagan Test Site Aug

Vandenberg AFB Oct

2014 | 2015 | 2016 | 2018

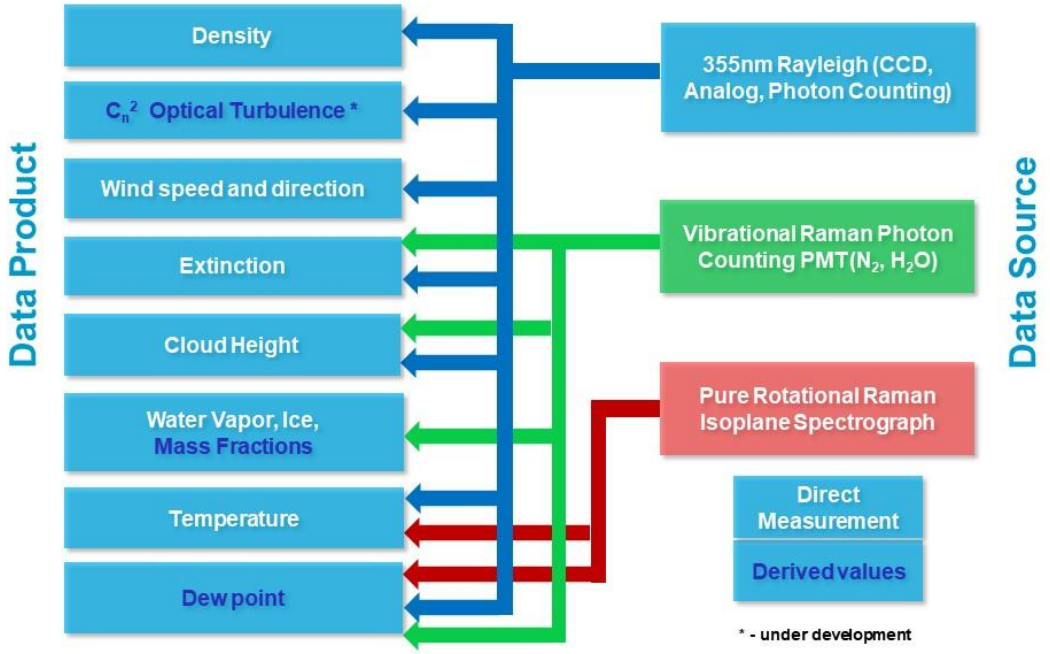
Oct NASA Armstrong

May Pt. Mugu



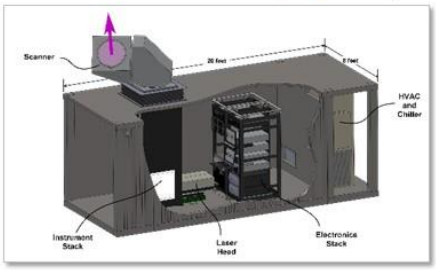


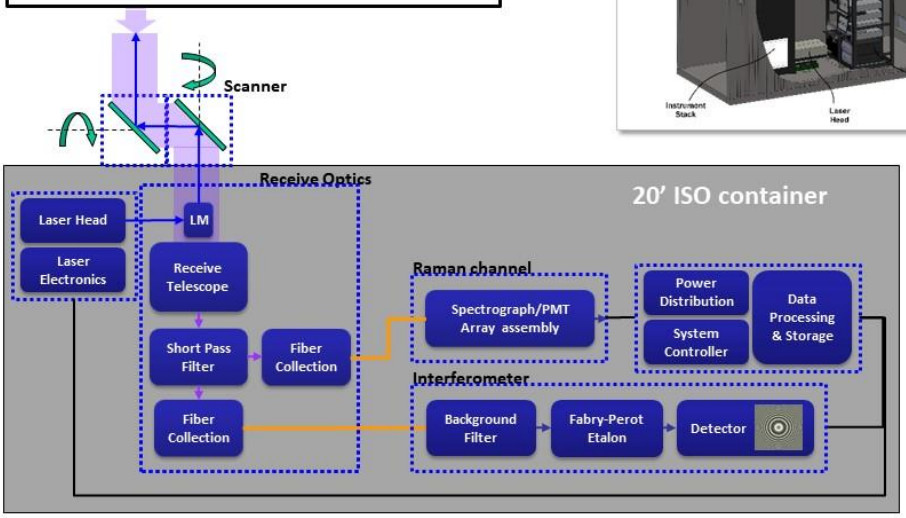
HALAS Data Products



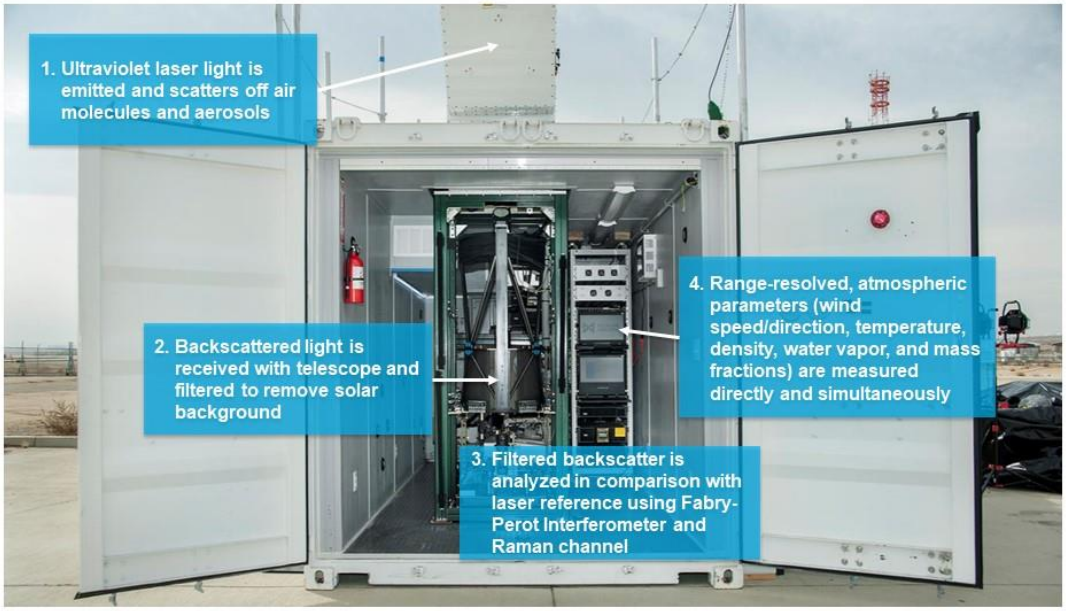
HALAS: Ground System

- Full hemispheric pointing
- Power via direct line or generator
- Capable of remote operation
- Transportable by cargo aircraft and flatbed truck





HALAS Components



Data Output Files

- **Data files can be modified to suit user needs**

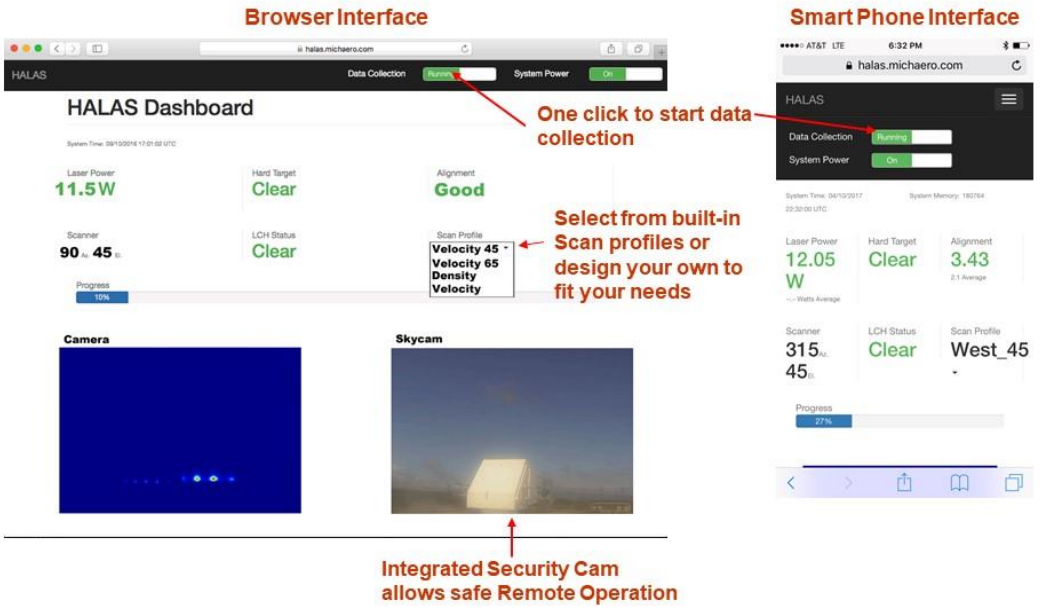
Wind results file
HALAS_640_2016_06_21_1240Z.txt

```
# HALAS DATA, SOFTWARE Version 1.1
# DFRC
# Lat  34.9588
# Lon -117.882
# 1240Z  21 JUL 2016
#
# HALAS LEVEL OUTPUT
# Index     Height     Speed      Dir        u          v
# int        mtrs       m/s       deg       m/s        m/s
#
#
        0  739.3249     2.0687   23.0444    0.8098     1.9036
        1   807.251      3.425   29.4309    1.6829      2.983
        2   875.177     4.7701    31.574    2.4976     4.0639
        3   943.103     6.0631   32.0364    3.2162     5.1398
        4  1011.029     7.2865   32.6255    3.9285     6.1368
```

Density, Pressure, Temperature results file
HALAS_density_617_IT_140_2016_06_07_1202Z_az_0.0_elv_90.0_scan_0.txt

```
# HALAS DATA, SOFTWARE Version 1.0, values = -999.99  imply data not
available, temps from rows above 298 are from balloon
GP021591728_Set617_Set618_Set619_Set620.txt
# DFRC, integration-time 140 sec, azm 0 deg, elv 90 deg
# Lat  34.9588
# Lon -117.882
# 1202Z  07 JUL 2016
#
# HALAS LEVEL OUTPUT
# Index    Height[MSL]   Density    Pressure   Temperature   Pressure-Altitude
# int        meters      kg/m^3     Pascals      Kelvin          meters
#
#
        0     695.173      1.105     92573.4     291.8456        755.3905
        1     725.1522     1.1019    92248.89    291.6462        784.495
        2     755.1315     1.0988    91925.29    291.4468        813.5999
        3     785.1107     1.0957    91602.61    291.2474        842.7053
        4      815.09      1.0926    91280.84    291.0478        871.8111
```


HALAS Control Designed for Ease of Use



HALAS Sample Data

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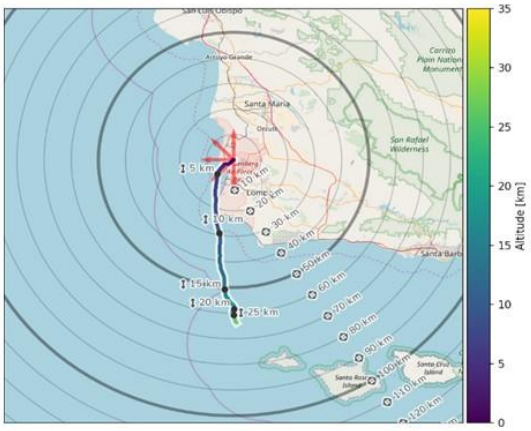
HALAS Coverage

HALAS Start	01/14/2017 1200Z
Collection Duration	92 min
Sonde Launch	01/14/2017 1158Z
Sonde Max Alt	27.4 km
Laser Power	8 W
Elevation(s)	45°
Azimuth(s)	0°, 315°, 270°, 225°, 180°
Launch Conditions	Marginal
Details	High Ground Winds



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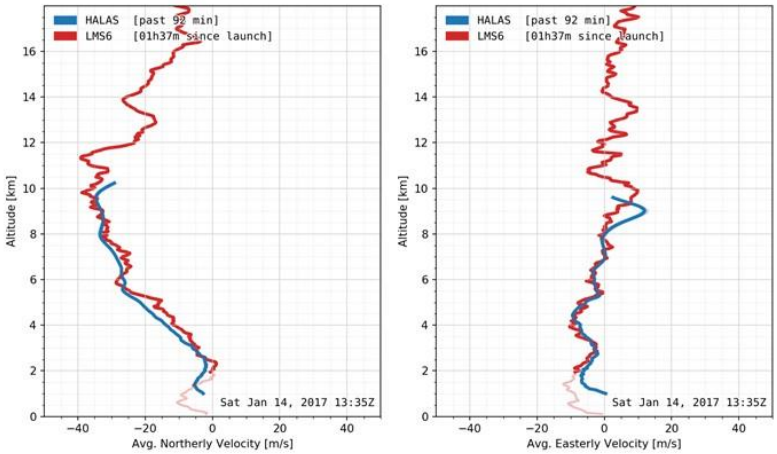
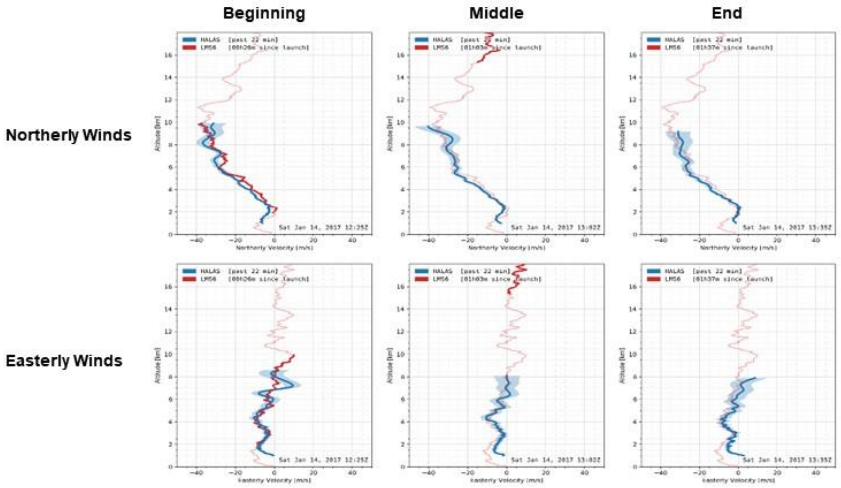
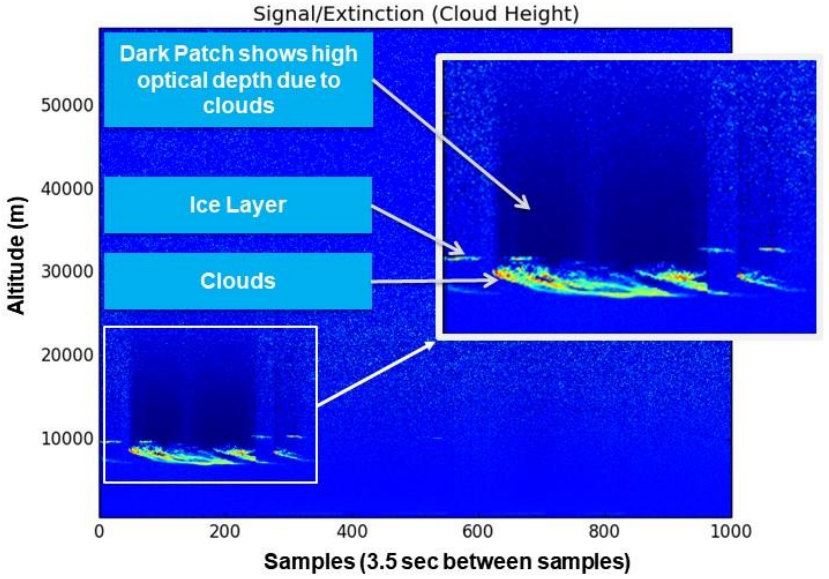
Sample Winds
Average Winds



Sample Winds
Wind Evolution



Extinction/Cloud Height

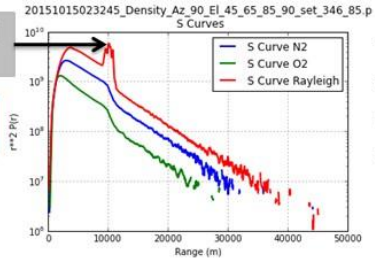


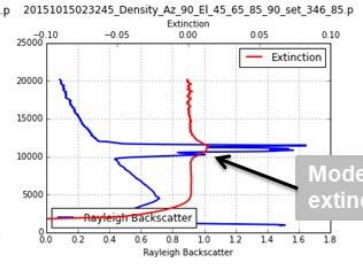
Extinction
Moderate and Heavy Clouds

Cloud extent & high altitude clouds are characterized using the same technique

Aerosol peak

Cloud with moderate extinction

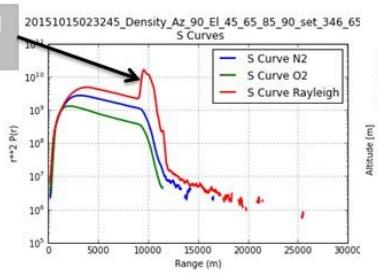


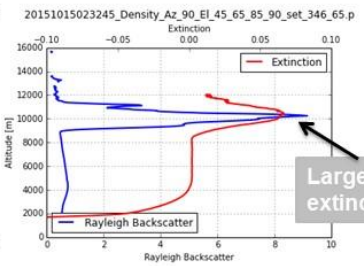


Moderate extinction

Aerosol peak

Large extinction, Nearly complete beam attenuation

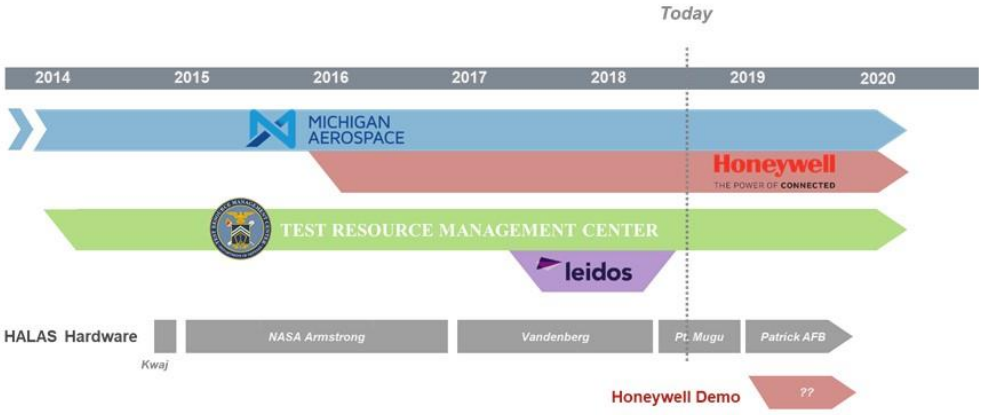




Large extinction

Honeywell/MAC Relationship

- Honeywell licensed technology from MAC
- Honeywell will bring product to market to meet needs of launch community
- Working closely with MAC, AEDC, TRMC, test ranges and launch sites



Multiple Platform Assets



- Development of airborne HALAS underway.
- The system is being designed for NASA Global Hawk with the proof-of-concept demonstration and check out on a Tempus-AS Gulfstream III beginning in the summer of 2017
- Significantly enhanced atmospheric data coverage
- Greater mission flexibility
- Improved measurement opportunity by beginning measurement above boundary layer and majority of cloud cover



- Potential future capability is development of a maritime HALAS system
- The system is being designed to incorporate platform stabilization to ensure pointing stability and accuracy
- Greater mission flexibility
- Cheaper means of Met data collection in maritime environment

Summary

HALAS has demonstrated unique capability to provide critical atmospheric data and has been shown to compare well with balloonsonde data

Demonstrations performed at Kwajalein, NASA Armstrong (Edwards AFB), and Vandenberg AFB

System has shown great promise towards being able to fulfill multiple mission needs for test ranges and launch facilities

HALAS demonstrated NIST traceable density uncertainty of < 2% from 0km to 40km+

- **Range and uncertainties depend on aerosols and integration time**
- **Typical balloonsondes have shown uncertainties of 0.5% to 30% over the range of 0km to 40km**
- **Other parameters such as wind speed/direction, temperature and water vapor are provided simultaneously**





Moving Forward

HALAS provides unique atmospheric data enabling support of multiple CONOPS for fixed test range locations as well as airborne assets with highly flexible coverage capability

Continuing demonstration of HALAS ground based prototype and identifying needs of each test range for input into Honeywell's Extended Range Atmospheric Lidar product design

Systems can be completely stand alone and secure, or networked depending on the application

Continuing development of a mobile, airborne, and maritime asset that will increase mission flexibility and opportunities

The airborne HALAS system is being designed with a path toward Global Hawk; The airborne HALAS system is installed and will be tested on a Gulfstream IV in August 2018.

Backup Slides

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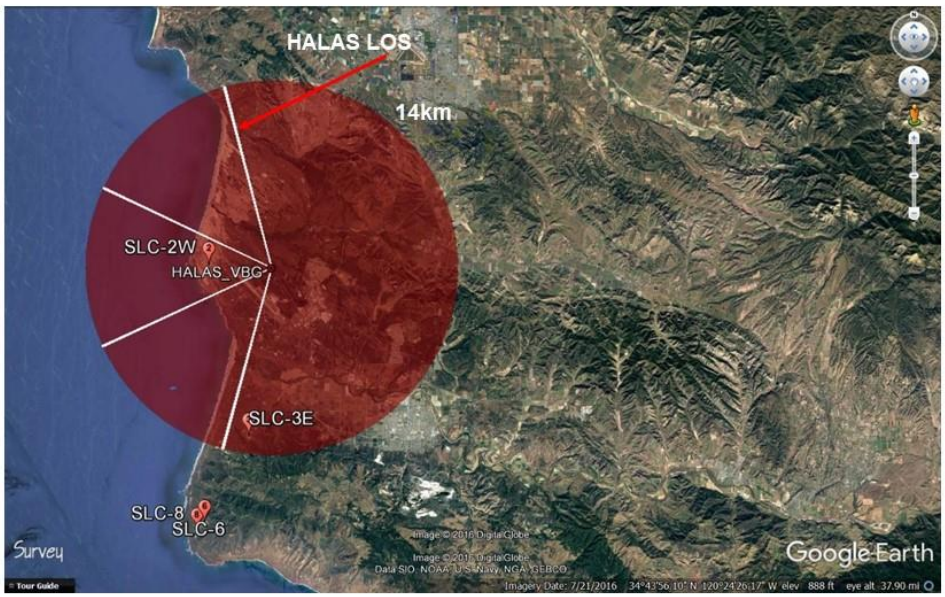
HALAS Vandenberg Coverage



HALAS Scan angles can be adjusted based on flight trajectory

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HALAS
Pt. Mugu Coverage



HALAS Field Experience Through TRMC

Reagan Test Site (RTS) 2014 August (8 days)		• First Gen Interferometer, Filter box • Vibrational Raman: Night time operation • Rotational Raman: N/A • Laser Clearing House: Automated	
NASA Armstrong (AFRC) 2014 - 2016 (24 months)		• Second Gen Interferometer, Filter box • Vibrational Raman: Night time operation • Rotational Raman: N/A • Laser Clearing House: PAM file enabled	**Improvement** • Max wind vector range: +20%
Vandenberg AFB 2016 - 2018 (10 months)		• Second Gen Interferometer, Filter box • Fully automated data collection with HALAS Live • Vibrational Raman: Night time operation • Rotational Raman: N/A	**Improvement** • Max air density range: +15%
NAS Point Mugu 2018 May -		• Third Generation Filter box • Vibrational Raman: Nighttime and daytime operation • Rotational Raman: Enabled • Upgraded laser crystal • Mobile generator	**Improvement*** • Max wind vector range: +33% • Max N_2, H_2O range: +50% • Max air density range: +50% • Max temperature range: improvement

*Calculated output ranges based on anchored models

3.5 PROPOSED SPACE-BASED SODIUM LIDAR TECHNOLOGY

Michael A. Krainak[1], Anthony W. Yu[1], Steven X. Li[1], Yingxin Bai[1], Kenji Numata[1], Jeffrey R. Chen[1], Molly E. Fahey[1], Frankie Micalizzi[1], Oleg A. Konoplev[2], Diego Janches[1], Chester S. Gardner[3], Graham R. Allan[4]

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ABSTRACT

We propose a nadir-pointing space-based Na Doppler resonance fluorescence LIDAR on board of the International Space Station (ISS). The science instrument goal is temperature and vertical wind measurements of the Earth Mesosphere Lower Thermosphere (MLT) 75-115 km region using atomic sodium as a tracer. Our instrument concept uses a high-energy laser transmitter at 589 nm and highly sensitive photon counting detectors that permit range-resolved atmospheric-sodium-temperature profiles. The atmospheric temperature is deduced from the linewidth of the resonant fluorescence from the atomic sodium vapor D2 line as measured by our tunable laser. We are pursuing high power laser architectures that permit limited day time sodium lidar observations with the help of a narrow bandpass etalon filter. We discuss technology, prototypes, risks and trades for two 589 nm wavelength laser architectures: 1) Raman laser 2) Sum Frequency Generation.

1 INTRODUCTION

One of the most critical science questions facing the Earth Ionosphere - Thermosphere - Mesosphere (ITM) community is: "How do small-scale waves, that are generated in the lower atmosphere and propagate upward, control the large-scale circulation and structure of the Earth's Mesosphere and Lower Thermosphere (MLT)?". There is a pressing need in the ITM community for high-resolution measurements that can characterize small-scale dynamics (viz. Gravity Waves with horizontal wavelengths smaller than a few hundred kilometers) and their effects in the MLT on a global basis. This is compelling because these waves are believed to be the dominant contributors to momentum, heat and constituent transport in the MLT, where they largely drive the global circulation, modify the thermal structure and control interactions with the tides and planetary waves in this region. A space-borne sodium (Na) LIDAR will provide these critical measurements by enabling acquisition of global Na density and temperature in the MLT with the spatial and temporal resolution required to resolve issues associated with the structure, chemistry, dynamics, and energetics of this region. Our science goal is to measure range-resolved atmospheric-sodium-temperature profiles from Low-Earth-Orbit (LEO). The atmospheric temperature is deduced from the linewidth of the resonant fluorescence from the atomic sodium vapor D2 line as measured by a tunable laser as shown in Figure 1. We propose to adapt a laser with spaceflight heritage to probe, in the proposed mission, the mesospheric Na layer between 80 and 100 km. By power scaling each of the two lasers to 4.5 W and electronically tuning it to multiple frequencies within the Na fluorescence line (589 nm), the instrument will acquire high-resolution measurements of Na density and temperature.

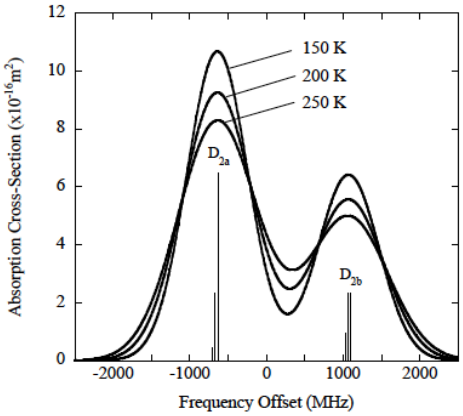

Figure 1. The sodium D2 resonance line is a Doppler broadened doublet composed of six hyperfine lines of atomic sodium at 589.159 nm wavelength. The Doppler broadening of the lines is a function of temperature and the ratio of the D2a peak (ν_{pk}) to the value at the minimum between the peaks (ν_{min}) is a very sensitive function of temperature (from Reference 1).

We conducted a trade study on various approaches for laser development to measure mesospheric sodium. The laser requirements are listed in Table 1. Two approaches allow leverage from previous space-qualification work, 1) A Raman shifted Nd:YVO4/GdYVO4 frequency-doubled laser, 2) mixing the output of two Nd:YAG lasers – one at 1064 nm and one at 1319 nm. We are developing prototype lasers for each approach.

Table 1 - Sodium lidar laser requirements

Wavelength (nm)	589.2 nm ± 0.1 nm
Optical Power (@589 nm)	4.5 W per laser (Two lasers total)
Pulsed	Yes
Wall-plug efficiency	>2%
Pulse width	10 - 100 ns
Spectral width	< 200 MHz
Tuning range	0.5 nm
Tuning speed	< 10 microseconds per GHz
Beam Quality (M^2)	< 4

2 METHODOLOGY

2.1 RAMAN LASER APPROACH

A Raman laser has several interesting features: 1) Raman beam cleanup - the Raman gain itself acts as an intra-cavity gain-aperture that spatially filters the oscillating Stokes field on every pass through the Raman gain medium; 2) high conversion efficiency; 3) single-longitudinal mode operation - gain saturation occurs via a distinctly different process than inversion lasers. There is no energy storage in the Raman medium so that the gain is not necessarily spatially modulated in the same manner as inversion lasers. This provides an avenue for single-longitudinal-mode operation with the proper management of thermal effects. 4) operation at unique wavelengths where direct laser transitions are unavailable, inefficient or restricted to low output-energy. These features have led to continuing research on the development of a 589-nm-wavelength Raman laser that is resonant with the sodium D2 line for laser guide-stars and lidars. A summary of recent near 589-nm wavelength pulsed solid-state Raman laser work follows. A 7.9W output power, 110 kHz repetition rate, Q-switched, 18-ns pulse width, 30% diode-to-yellow efficiency Raman laser operating at 588-nm wavelength was demonstrated[2]. A Q-switched 589 nm wavelength Raman laser was demonstrated[3] with 4.3 W output power, 38-ns pulse-width, 10 kHz repetition-rate, 3.5% diode-to-yellow efficiency and possible high temperature tuning to the sodium line, but with a broad linewidth (0.2 nm) and large M2~5. The required resonant-wavelength (operation at the sodium D2 line) was demonstrated in a quasi-CW Raman laser[4] with macro-pulse repetition rate of 300 Hz, micro-pulse repetition rate of 33 kHz, a pulse-width of 13.6-ns, less than 0.05 nm linewidth and 3% diode-to-yellow efficiency.

Tuning the laser operating wavelength to the sodium D2 line resonance can be challenging. The Raman effect relies on absorbed pump power that heats the Raman shifter. Excessive heating or cooling the Raman shifter crystal can lead to strong temperature gradients causing possible reliability issues, thermal lensing and temperature-induced birefringence. To reduce the burden of temperature tuning, the value of the Raman shift can be tailored with crystal composition[5]. Specifically, the Raman shift of mixed $Y_xGd_{1-x}(VO4)$ crystal can be varied (engineered) from 885 cm-1 to 895 cm-1 by adjusting the Yttrium to Gadolinium composition ratio. Our recent experiment indicates that the Raman shift of mixed $Y_xGd_{1-x}(VO4)$ crystal is 0.2 nm from pure YVO4 crystal for a mixed crystal of $Gd_{0.2}Y_{0.8}VO4$. Figures 2 and 3 show the temperature tuning and operation at the sodium D2 line for the $Gd_{0.2}Y_{0.8}VO4$ (at 38 C) Raman laser. Further details on our Raman laser are presented by Li[6] and Konoplev[7]. A very high electrical-efficiency sodium-D2-resonant wavelength Raman laser approach will be to use the self-Raman effect in a compositionally engineered Nd:YxGd1-x(VO4) crystal.

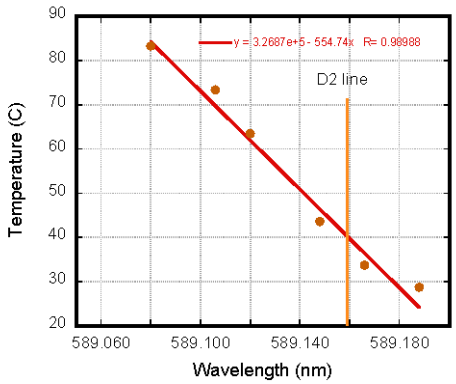

Figure 2. Experimental temperature tuning of the $Y_{0.8}Gd_{0.2}VO4$ Raman laser.

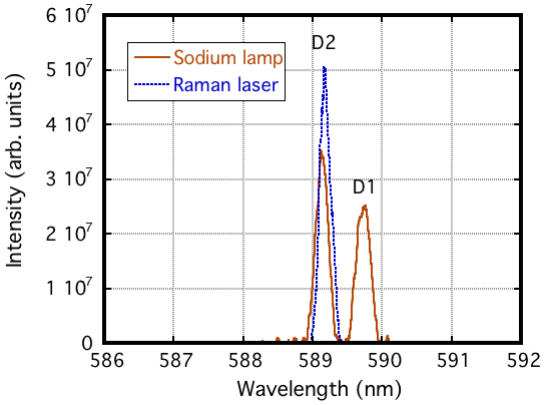

Figure 3. Experimental $Y_{0.8}Gd_{0.2}VO4$ Raman laser operation at the D2 line (spectral resolution limited by Optical Spectrum Analyzer resolution of 0.05 nm).

2.2 SUM-FREQUENCY GENERATION LASER APPROACH

Numerous 589-nm-wavelength lasers using Sum-Frequency-Generation (SFG) have been constructed. An excellent fielded sodium-lidar SFG diode-pumped laser was recently reported by Kawahara[8]. Their output power is ~4W at one of 3 tunable wavelengths, with 4 mJ/pulse at 1000 Hz repetition rate. Their pulse width is 35 ns with linewidth < 200 MHz.

We have purchased and tested commercial high-energy laser modules for operation at 1064 nm and 1319 nm. The commercial modules are Northrop-Grumman RBAT RBAT20-2P200H-WA1-0110 (1064 nm) with 140 Amp 804-nm pump-diode current and a slope efficiency of 8.65 W/A and RBAT RBAT20-2P200H-WA1-0111 (1319 nm) with 140 Amp 805-nm pump-diode current and a slope efficiency of 8.66 W/A. Our tested long-pulse (150 μs) measurement is >60 W average power (>125 mJ) at 500 Hz at 1064 nm and >50 W average power (>100 mJ) at 500 Hz at 1319 nm.

2.3 FUTURE STATE

NASA-GSFC is leading the development of a sodium lidar - Atmospheric Coupling and Dynamics Across the Mesopause (ACaDAME) - to propose on the ISS to understand the middle and upper atmosphere chemistry, structure and dynamics. A key science goal is the impact of gravity waves – the parameterization of which is a fundamental issue in current atmospheric modeling for climate and meteorology. We have demonstrated operation at the sodium D2 line with a Nd:YVO4 pumped Raman laser. The Raman crystal $Gd_{0.2}Y_{0.8}VO4$ wavelength shift can be engineered with crystal composition. We demonstrated single-frequency tunable injection-seeded operation. The ultimate wall-plug efficiency could possibly be achieved with a self-Raman Nd:GdYVO4 laser. We demonstrated high-power 1064 nm and 1319 nm oscillators with preliminary SFG yellow (D2 resonant) operation (Figure 4).

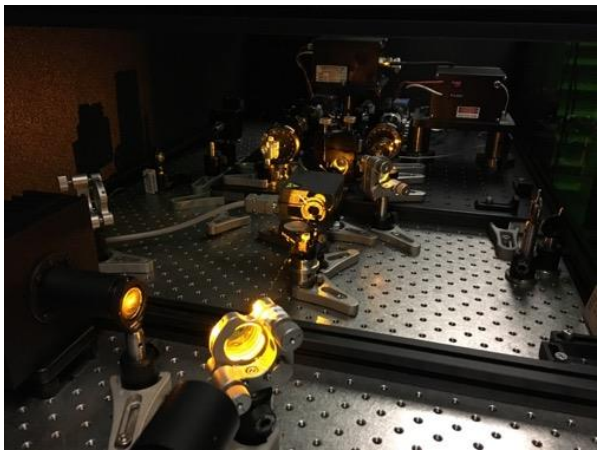

Figure 4. NASA-GSFC experimental Sum-Frequency Generation laser operation at the D2 wavelength (589 nm).

2.4 RISKS AND REWARDS

The major risks are cost and schedule. The major reward is new mesospheric science from a space-based sodium lidar. A more efficient 589 nm (sodium vapor resonant) laser technology enhances opportunities for an artificial guide-star, a temperature lidar and a remote sensing magnetometer system.

3 PROGRAMMATICS

We will build a power oscillator laser breadboard to demonstrate the required 9W at 589 nm for the sodium lidar instrument. We will also leverage our in-house space flight laser design heritage to produce a space-qualifiable laser transmitter engineering test unit (ETU) that we will environmental test for TRL 6.

4 WIDER VISION

The 589 nm (sodium vapor resonant) laser technology can be used for an artificial guide-star, a temperature lidar and a remote sensing

magnetometer system. We held discussions with the US Air Force on a transportable combined mesospheric lidar and artificial guide-star. The astronomy community routinely conducts ground-based science, architecture (e.g. telescope arrays) and instruments and can greatly benefit with adaptive optics enabled by an artificial guide-star.

5 CONCLUSIONS

There is a pressing need in the Earth Ionosphere - Thermosphere - Mesosphere (ITM) community for high-resolution measurements that can characterize small-scale dynamics (viz. Gravity Waves with horizontal wavelengths smaller than a few hundred kilometers) and their effects in the MLT on a global basis. A space-borne sodium (Na) LIDAR will provide these critical measurements by enabling acquisition of global Na density and temperature in the MLT with the spatial and temporal resolution required to resolve issues associated with the structure, chemistry, dynamics, and energetics of this region. We have demonstrated operation at the sodium D2 line with a Nd:YVO4 pumped Raman laser. The Raman crystal $Gd_{0.2}Y_{0.8}VO4$ wavelength shift can be engineered with crystal composition. We demonstrated single-frequency tunable injection-seeded operation. The ultimate wall-plug efficiency could possibly be achieved with a self-Raman Nd:GdYVO4 laser. We demonstrated high-power 1064 nm and 1319 nm oscillators with SFG yellow (D2 resonant) operation.

Acknowledgements

We are grateful for support from the NASA HTIDS, NASA-GSFC IRAD and B&P programs.

References

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3. Shen, Hongbin; Wang, Qingpu; Zhang, Xingyu; et al. “Intracavity frequency-doubled Nd:YAG/KLu(WO4)(2) Raman laser at 589 nm: A potential source for sodium D-2 resonance radiation” Optics And Laser Technology 45, 142-146 (2013).
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5. Zhang, Nana; Wang, Jiyang; Hu, Xiaobo; et al. “Phonons in isostructural (ND,Yb):YxGd1-x(VO4) laser crystals: A Raman scattering study” Journal Of Solid State Chemistry 184(4), 905-910 (2011).
6. Steven X. Li, Anthony Yu, Michael Krainak, Yingxin Bai, Oleg Konoplev, Kenji Numata, Molly Fahey, Ronny Huang, “Progress on Raman laser for sodium resonance fluorescence lidar,” SPIE Photonics West 2018.
7. Oleg A. Konoplev, Anthony W. Yu, Steven X. Li, Michael A. Krainak, Yingxin Bai, Molly E. Fahey, Wenqian R. Huang, Diego Janches “Scaling the average power of 1066-nm end-pumped c-cut Nd:YV04 laser for sodium lidar development project”, SPIE Photonics West 2018.
8. Kawahara, T. D.; Nozawa, S.; Saito, N.; et al. “Sodium temperature/wind lidar based on laser-diode-pumped Nd:YAG lasers deployed at Tromso, Norway (69.6 degrees N, 19.2 degrees E)” Optics Express 25(12), A491-A501 (2017).

Proposed space-based sodium lidar technology
July 31, 2018

ACADAME

Atmospheric Coupling and Dynamics Across the Mesopause

Michael A. Krainak, Anthony W. Yu, Diego Janches, Steven X. Li, Kenji Numata, Jeffrey R. Chen, Molly E. Fahey, Oleg A. Konoplev, Frankie Micalizzi1, Yingxin Bai, Chester S. Gardner, Graham R. Allan

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SODIUM LASER TECHNOLOGY AGENDA

ACADAME

Atmospheric Coupling and Dynamics Across the Mesopause

- SODIUM LIDAR – MISSION OVERVIEW
- LASER APPROACHES
  - Sum-Frequency-Generation
  - Raman
- ACTIVE OPTICAL TIM TARGETS

2

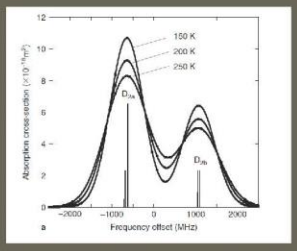
HELIOPHYSICS SCIENCE

- Critical science questions facing the Earth Ionosphere - Thermosphere - Mesosphere (ITM) community is: "How do small-scale waves, that are generated in the lower atmosphere and propagate upward, control the large-scale circulation and structure of the Earth's Mesosphere and Lower Thermosphere (MLT)?"
- There is a pressing need in the ITM community for high-resolution measurements that can characterize small-scale dynamics (viz. Gravity Waves with horizontal wavelengths smaller than a few hundred kilometers) and their effects in the MLT on a global basis. This is compelling because these waves are believed to be the dominant contributors to momentum, heat and constituent transport in the MLT, where they largely drive the global circulation, modify the thermal structure and control interactions with the tides and planetary waves in this region.
- A space-borne sodium (Na) LIDAR will provide these critical measurements by enabling acquisition of global Na density and temperature in the MLT with the spatial and temporal resolution required to resolve issues associated with the structure, chemistry, dynamics, and energetics of this region. Our science goal is to measure range-resolved atmospheric-sodium-temperature profiles from Low-Earth-Orbit (LEO). The atmospheric temperature is deduced from the linewidth of the resonant fluorescence from the atomic sodium vapor D2 line.

3

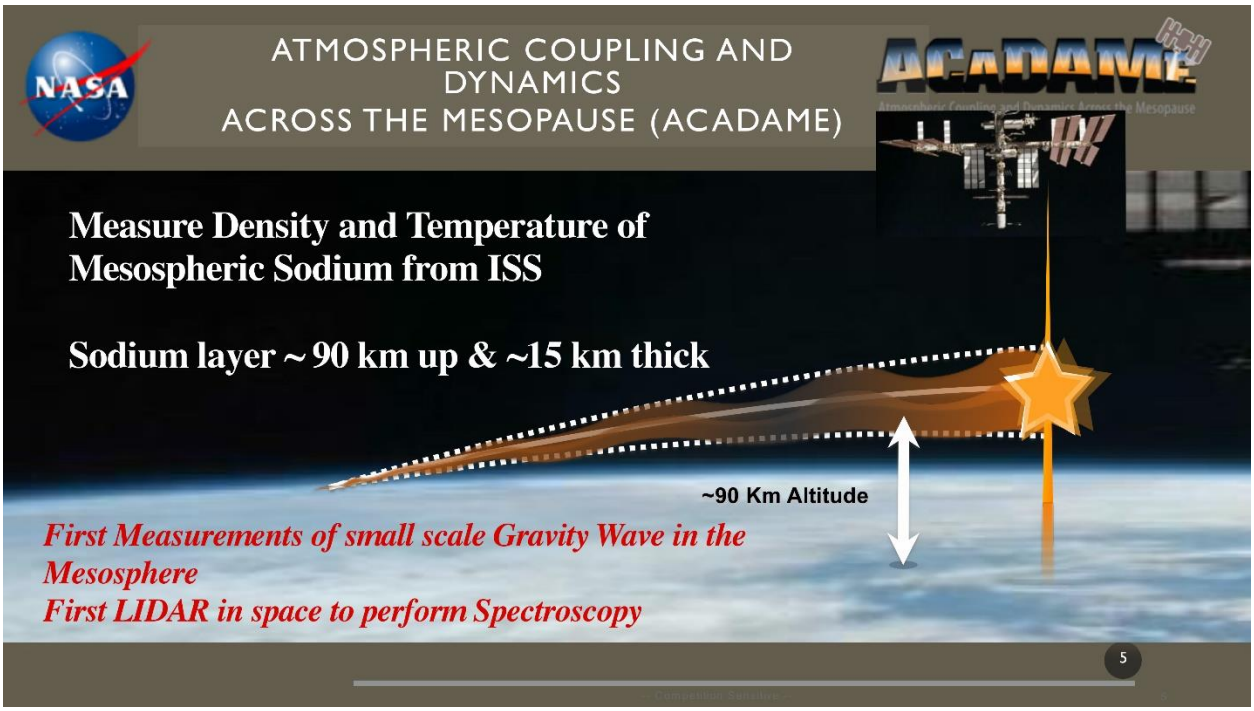
ATMOSPHERIC SODIUM SPECTRA
TEMPERATURE EFFECTS

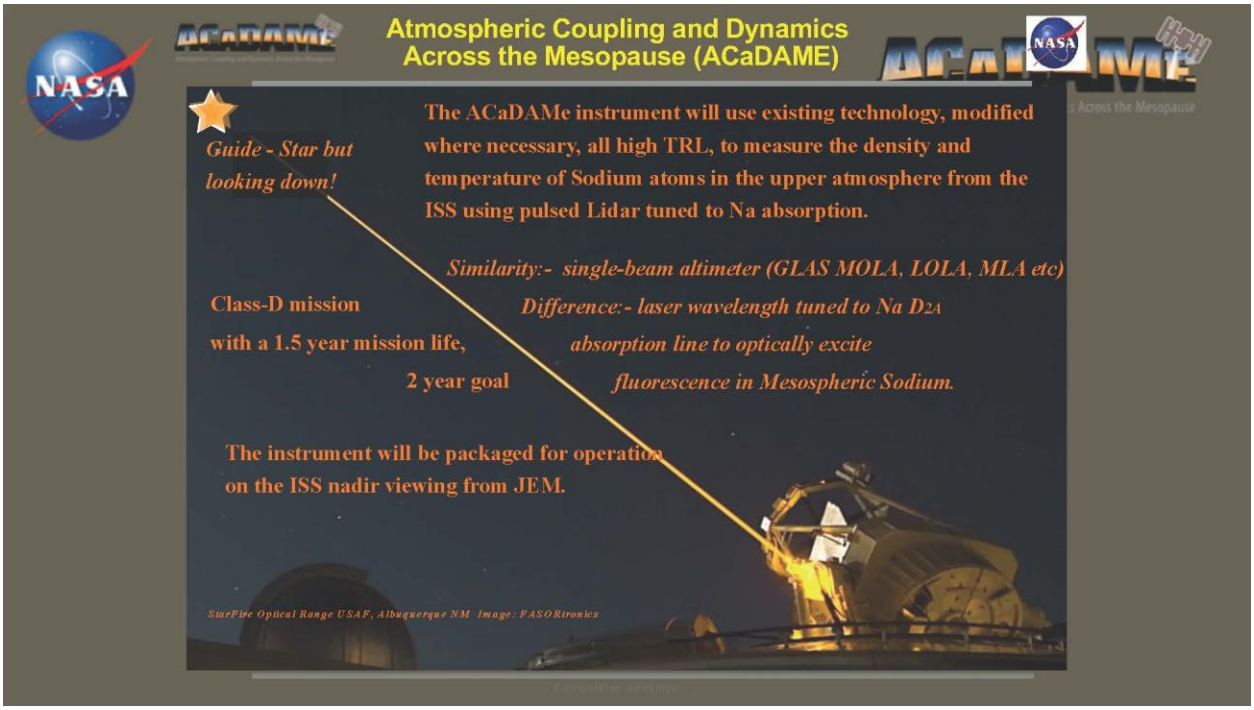
- The D2 resonance line of atomic sodium is **589.159 nm**
- The D2 resonance line of Na is a Doppler broadened doublet composed of six hyperfine lines as shown below.



- The Doppler **broadening of the lines** is a **function of temperature** and the ratio of the D2a peak to the value at the minimum between the peaks is a very sensitive function of temperature.

4


ATMOSPHERIC COUPLING AND DYNAMICS ACROSS THE MESOPAUSE (ACADAME)
ACaDAME
Measure Density and Temperature of Mesospheric Sodium from ISS
Sodium layer ~ 90 km up & ~15 km thick
~90 Km Altitude
First Measurements of small scale Gravity Wave in the Mesosphere
First LIDAR in space to perform Spectroscopy
5


Atmospheric Coupling and Dynamics Across the Mesopause (ACaDAME)
ACaDAME
Guide - Star but looking down!
The ACaDAMe instrument will use existing technology, modified where necessary, all high TRL, to measure the density and temperature of Sodium atoms in the upper atmosphere from the ISS using pulsed Lidar tuned to Na absorption.
Similarity:- single-beam altimeter (GLAS MOLA, LOLA, MLA etc)
Difference:- laser wavelength tuned to Na D2A absorption line to optically excite fluorescence in Mesospheric Sodium.
Class-D mission with a 1.5 year mission life, 2 year goal
The instrument will be packaged for operation on the ISS nadir viewing from JEM.
StarFire Optical Range USAF, Albuquerque NM Image: FASORtronics

LASERS REQUIREMENTS

Property	Laser 1	Laser 2
Pulse Energy	15 mJ	15 mJ
Repetition Rate	300 Hz	300 Hz
Average Power	4.5 W	4.5 W
Wavelength (Vacuum)	589.1590 ± 0.010 nm	589.1579 ± 0.010 nm
RMS Pulse Bandwidth	150 MHz	150 MHz
Pulse width	< 35 ns	< 35 ns
Laser Frequency Stability (rms)	< 1 MHz @ 1 s average	< 1 MHz @ 1 s average
Laser Bandwidth Stability (rms)	< 3 MHz	< 3 MHz
Divergence (Full width @ $1/e^2$)	400 ± 10 μrad	400 ± 10 μrad
Laser Beam Pointing Jitter (rms)	20 μrad	20 μrad
Spatial Mode, M^2	< 2	< 2

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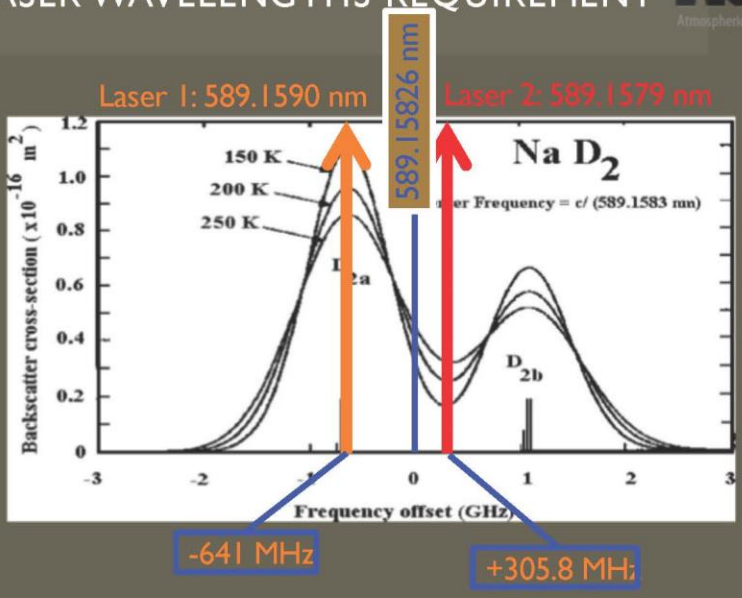
LASER WAVELENGTHS REQUIREMENT



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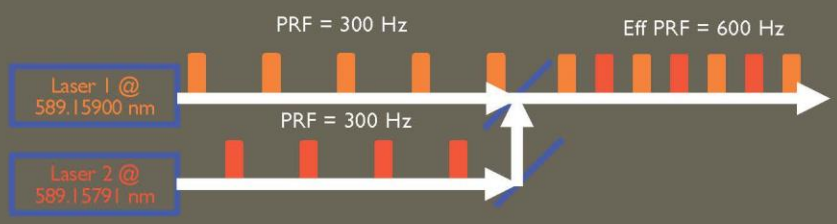
TIME MULTIPLEXED APPROACH



Time multiplexed of two 300 Hz lasers for an effective 600 Hz lidar instrument

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SODIUM LASER TECHNOLOGY AGENDA

- SODIUM LIDAR – MISSION OVERVIEW
- LASER APPROACHES
  - Sum-Frequency-Generation
  - Raman
- ACTIVE OPTICAL TIM TARGETS

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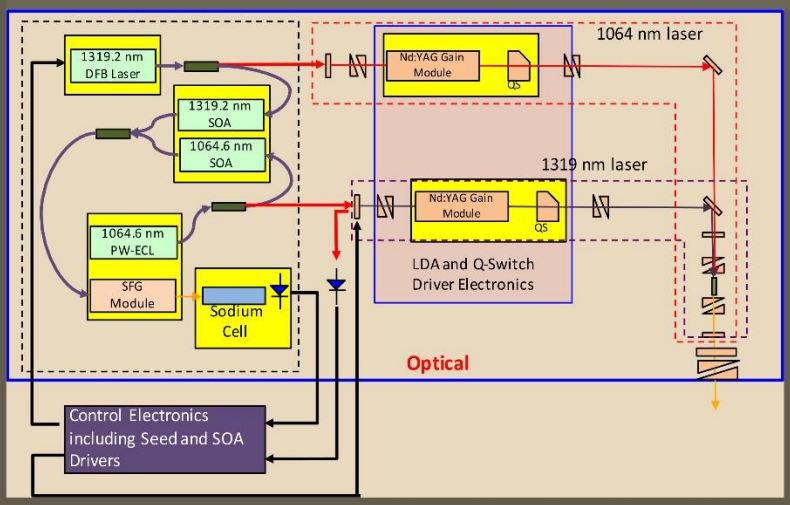
SUM-FREQUENCY-GENERATION APPROACH



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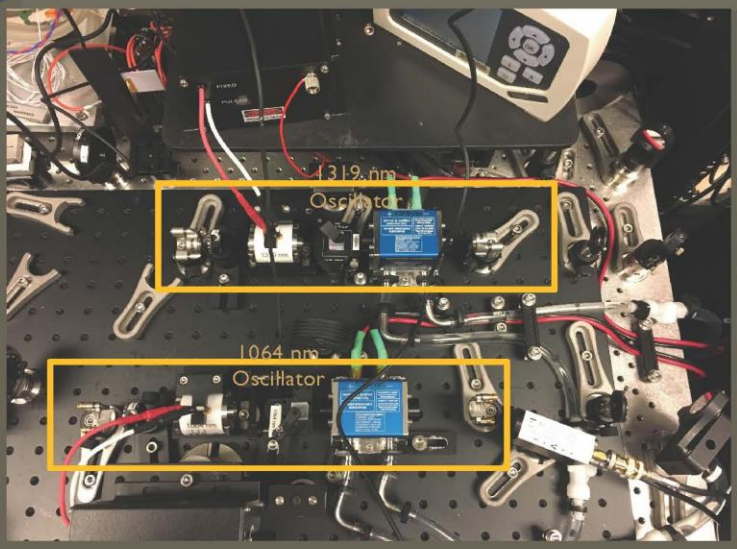
SUM-FREQUENCY-GENERATION LASER



Our tested long-pulse (150 μs) measurement:

- >60 W average power (>125 mJ) at 500 Hz at 1064 nm
- >50 W average power (>100 mJ) at 500 Hz at 1319 nm

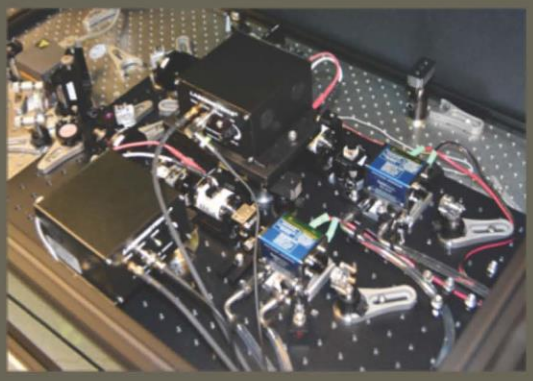


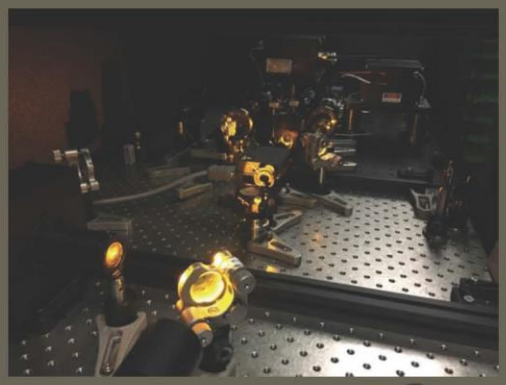
12

SUM-FREQUENCY-GENERATION LASER

Our tested long-pulse (150 μs) measurement:

- >60 W average power (>125 mJ) at 500 Hz at 1064 nm >50 W average power (>100 mJ) at 500 Hz at 1319 nm
- Below: Q-switched 589 nm SFG laser. Next step: Insert high power tolerant 1319 Q-switch (received on June 4).





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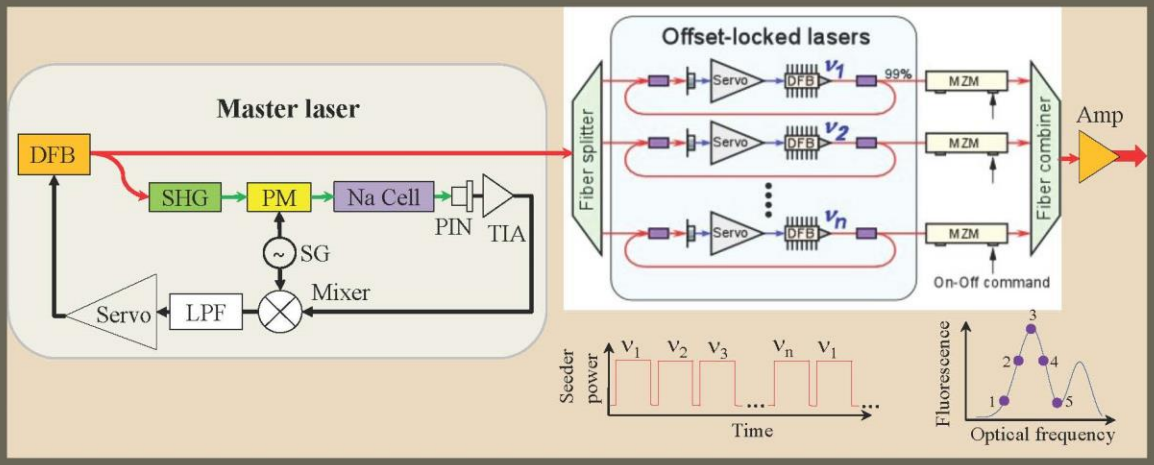
SEEDING AND LOCKING LASER ARCHITECTURE



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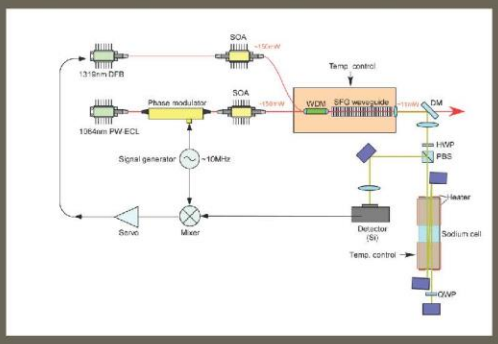
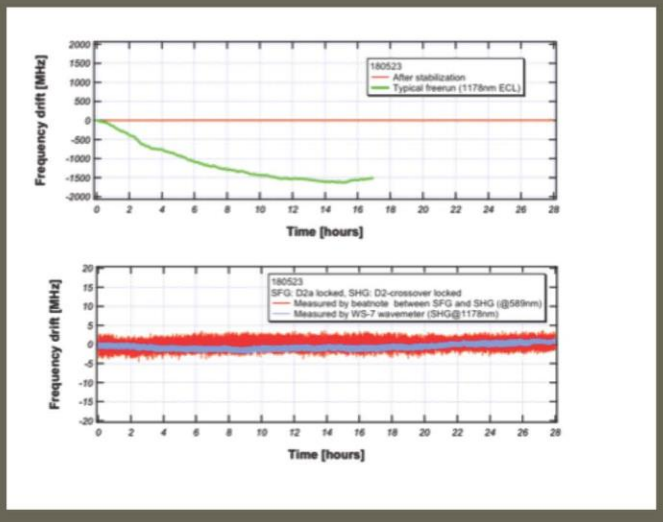
SFG LASER SEEDING, TUNING & LOCKING





SFG LASER SEEDING, TUNING & LOCKING



COMPOSITIONAL ENGINEERING OF PHONON MODES (RAMAN SHIFT)

Journal of Solid State Chemistry 184 (2011) 905–910

Phonons in isostructural (ND,Yb):$Y_xGd_{1-x}(VO_4)$ laser crystals: A Raman scattering study

Nana Zhang [a,b], Jiyang Wang [a,**], Xiaobo Hu [a], Huaijin Zhang [a], C.C. Santos [c], A.P. Ayala [b], I. Guedes [b,*]

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[b] Departamento de Física, Universidade Federal do Ceará, Campus do Pici, CP 6030, Fortaleza CE 60455-760, Brazil
[c] Departamento de Física, CCET, Universidade Federal do Maranhão, 65085-580 São Luis, MA, Brazil

"No appreciable changes in the phonon wavenumbers were observed for Yb:GdVO4 (Yb1⁄40.008, 0.015, 0.020, 0.025, and 0.035), indicating that the force fields in the GdVO4 lattice are not strongly altered by Yb doping at the Gd site. **However, most of the phonon wavenumbers in the systems (Nd,Yb):$Y_xGd_{1-x}(VO4)$ shifts upwards (one-phonon-like behavior) when Y replaces for Gd.** "

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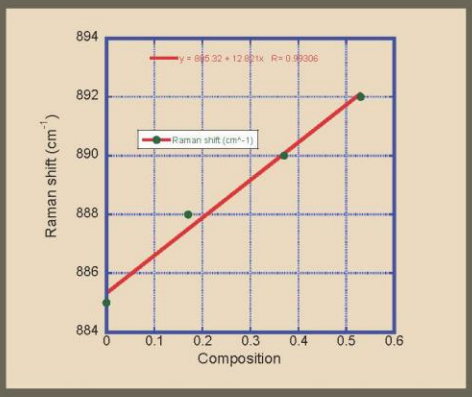
ENGINEERING RAMAN SHIFT (FROM ZHANG ET AL. 2011)



Sodium D2 line: 589.158 (x 2 = 1178.316)

$1/(1178.316\ nm) = 8486.68\ cm^{-1}$
$1/(1066.6\ nm) = 9375.58\ cm^{-1}$
$9375.58\ cm^{-1} - 8486.68 cm^{-1} =$ **888.9** cm^{-1}

To insure above room temperature operation (with high-power Raman pumping) we chose:

$Gd(0.2)Y(0.8)VO4$

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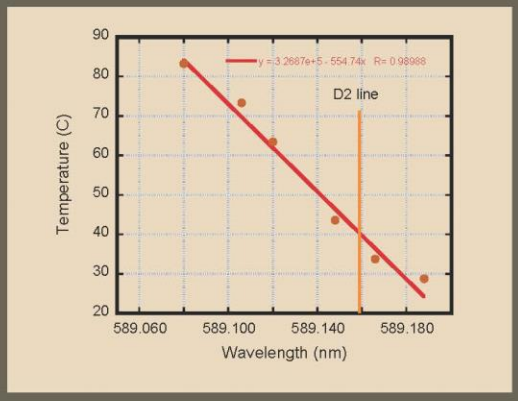
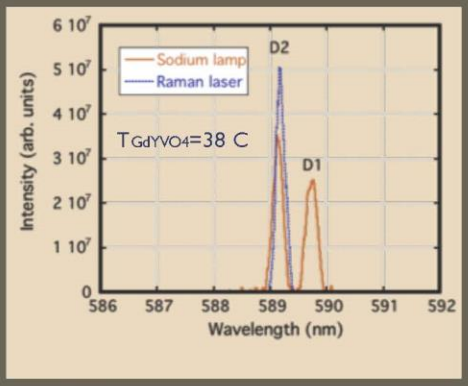
RAMAN LASER OPERATION AT THE D2 SODIUM LINE



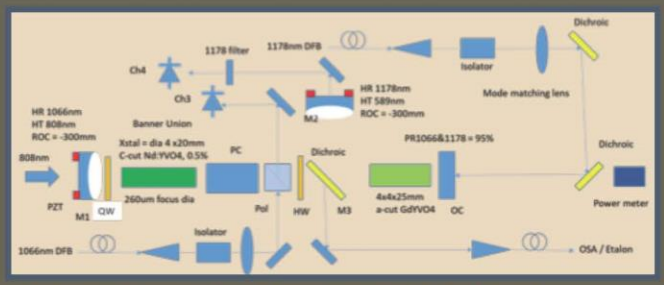
Temperature tuning of GdYVO4 Raman laser



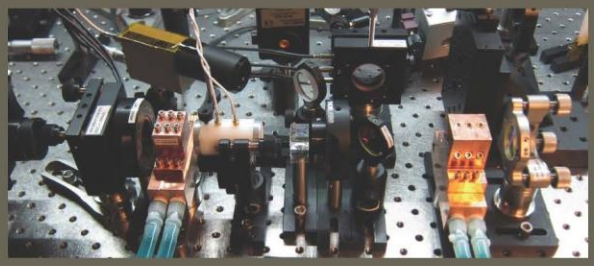
OSA trace with simultaneous sodium lamp and Raman laser

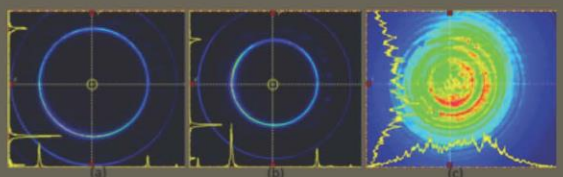
20

INJECTION-SEEDED (SINGLE FREQUENCY) RAMAN LASER



Reference (at this Conference):
"Progress on Raman Laser for Sodium Resonance Fluorescence Lidar"
Steven X. Li, et al.
Solid State Lasers XXVII: Technology and Devices
Session 11:Novel Laser Concepts
Wednesday 31 January 2018
Paper 10511-53

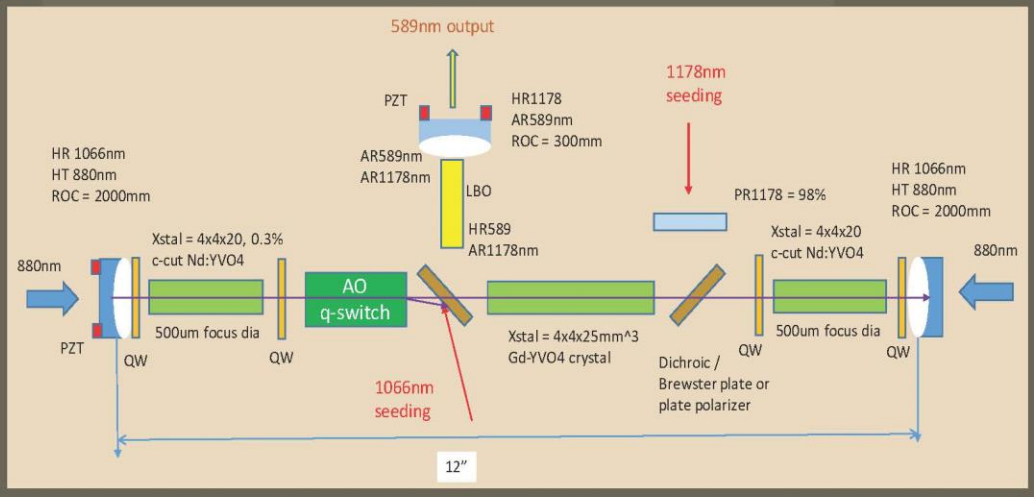




SEEDED UNSEEDED

21

RAMAN LASER APPROACH



22

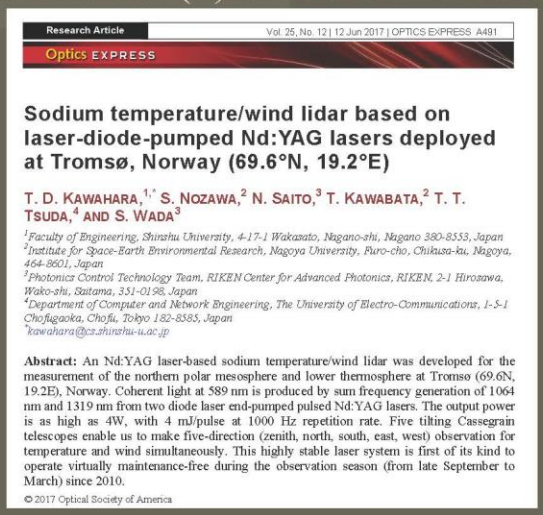
SODIUM LASER TECHNOLOGY AGENDA

- SODIUM LIDAR – MISSION OVERVIEW
- LASER APPROACHES
  - Sum-Frequency-Generation
  - Raman
- ACTIVE OPTICAL TIM TARGETS

23

SODIUM LIDAR
ACTIVE OPTICAL TIM TARGETS (1)

- Technology needs
  Space-qualified, 4.5 W, 589 nm wavelength, Q-switched laser
- Current limitations
  Financial resources.
- Current measurement state-of-the-art
  Ground-based sodium lidars. Example



Research Article | Vol. 25, No. 12 | 12 Jun 2017 | OPTICS EXPRESS A491

Optics EXPRESS

Sodium temperature/wind lidar based on laser-diode-pumped Nd:YAG lasers deployed at Tromsø, Norway (69.6°N, 19.2°E)

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[2]*Institute for Space-Earth Environmental Research, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8601, Japan*
[3]*Photonics Control Technology Team, RIKEN Center for Advanced Photonics, RIKEN, 2-1 Hirosawa, Wako-shi, Saitama, 351-0198, Japan*
[4]*Department of Computer and Network Engineering, The University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan*
[*]*kawahara@cs.shinshu-u.ac.jp*

Abstract: An Nd:YAG laser-based sodium temperature/wind lidar was developed for the measurement of the northern polar mesosphere and lower thermosphere at Tromso (69.6N, 19.2E), Norway. Coherent light at 589 nm is produced by sum frequency generation of 1064 nm and 1319 nm from two diode laser end-pumped pulsed Nd:YAG lasers. The output power is as high as 4W, with 4 mJ/pulse at 1000 Hz repetition rate. Five tilting Cassegrain telescopes enable us to make five-direction (zenith, north, south, east, west) observation for temperature and wind simultaneously. This highly stable laser system is first of its kind to operate virtually maintenance-free during the observation season (from late September to March) since 2010.

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SODIUM LIDAR
ACTIVE OPTICAL TIM TARGETS (2)

- Desired future measurement needs
  Global Earth Mesosphere temperature and wind profiles
- Critical gaps in raising the TRL
  Funding profile
- How will NASA "lead, leverage, or collaborate" between Centers, OGAs, FFRDC, academia, and industry to achieve the TRL necessary for the measurements?

Industry: Gats, Inc. and Partnership Agreement with Industry.
FFRDC: National Center for Atmospheric Research
OGA: Naval Research Laboratory
University: University of Illinois at Urbana-Champaign
International: Deutsches Zentrum für Luft- und Raumfahrt - DLR

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SODIUM LIDAR
ACTIVE OPTICAL TIM TARGETS (3)

- Cross-cutting or synergistic opportunities that are expected to arise from this technology advancement



Optical communication sodium guide star

Opportunity with US Industry, OGAs, DoD



Sodium guide star for Ground-based Very Large Telescope (VLT)

Opportunity with Astronomy community

26

4 Session 4

Topography, Cryosphere and Biomass was designed to discuss issues related to making Earth ice measurements from space. The Session Chair, Tom Wagner, gave an overview presentation of the area to start the session. A total of four research presentations representing the work of researchers at GSFC and industry was received. Table 4-1 lists the five session papers. See Section 3 of the Assessment Report for observations and assessment comments.

Table 4-1. Session 4 Papers

Paper Number	Author	Title	Paper	Presentation
S4-1	Tom Wagner, NASA SMD	Overview		☑
S4-2	Nicholas Sawruk, Patrick Burns, Ryan Edwards, Viatcheslav Litvinovitch, and Floyd Hovis, Fibertek	Flight Laser Transmitter Development for NASA's Ice Topography ICESat-2 Space Mission	☑	☑
S4-3	Paul R. Stysley, D. Barry Coyle, Furqan Chiragh, Erich Frese, NASA GSFC	The Global Ecosystems Dynamics Investigation (GEDI) Lidar Mission	☑	☑
S4-4	Xiaoli Sun, NASA GSFC	Advanced Single Photon Detectors for Active Remote Sensing from Space	☑	☑
S4-5	Roman Machan, Sigma Space LLC	Single Photon Lidar Measurement Technologies	☑	☑

List of presentations

4.1 Cryosphere and Biomass Programs: NASA's Research Needs for Lidar or Is lidar the burger or the fries? Or is it both? 4-2
4.2 Flight Lasers Transmitter Development for NASA Ice Topography Icesat-2 Space Mission 4-20
4.3 Development of the Solid-State Laser System for the GEDI Mission 4-34
4.4 Advanced Single Photodetectors for Active Sensing from Space 4-58
4.5 Single Photon Lidar Measurement Technologies 4-78

4.1 CRYOSPHERE AND BIOMASS PROGRAMS: NASA'S RESEARCH NEEDS FOR LIDAR OR IS LIDAR THE BURGER OR THE FRIES? OR IS IT BOTH?

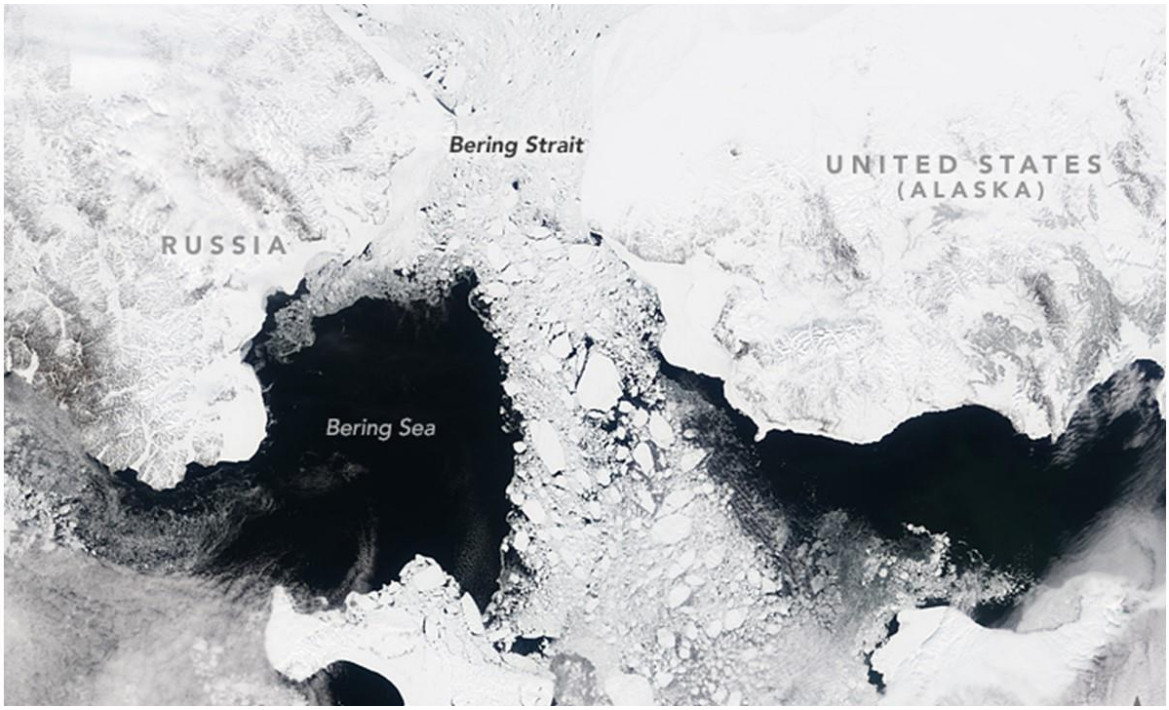
Thomas Wagner and Colene Haffke

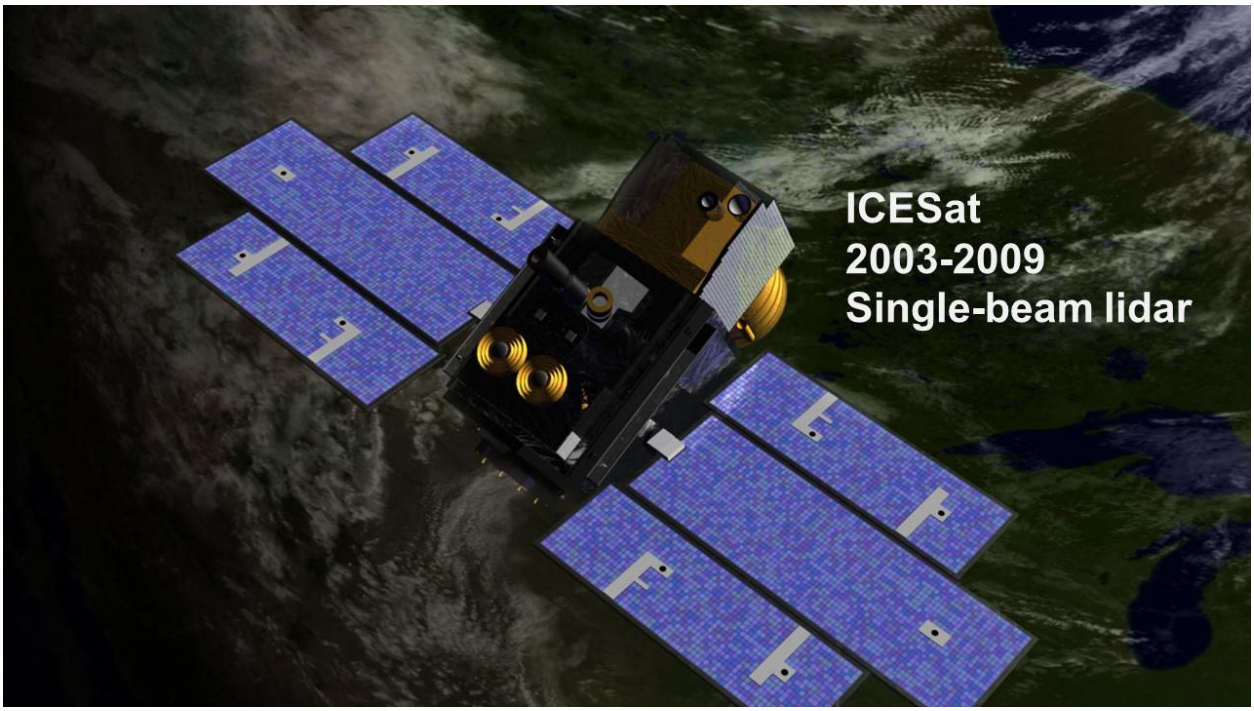
NASA Science Mission Directorate, NASA Headquarters, Washington, D. C.

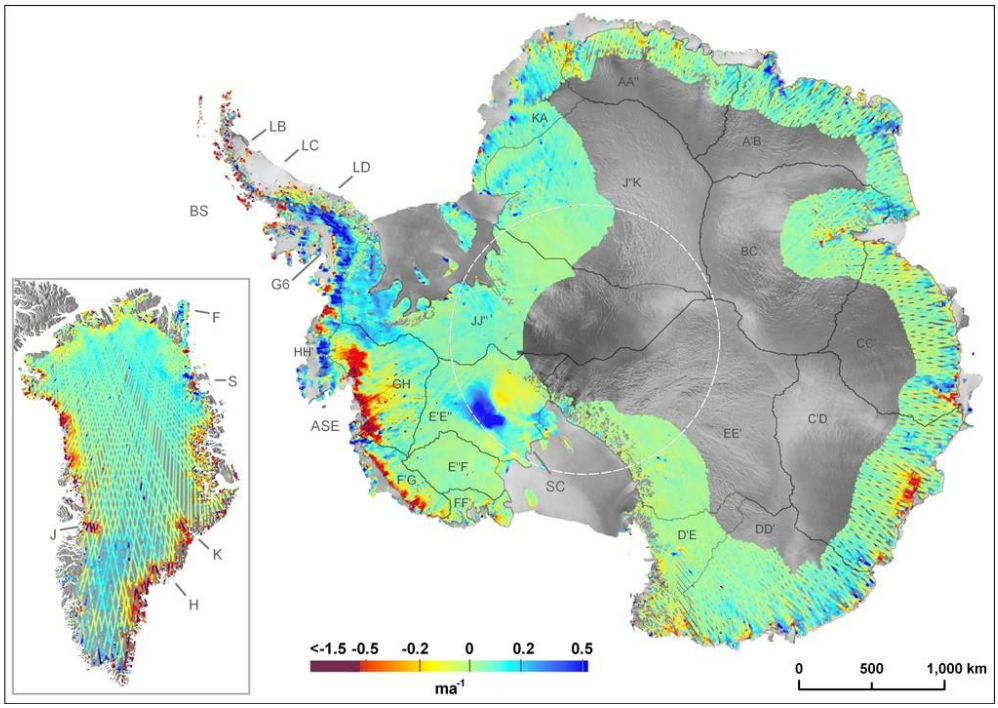







Bering Strait
UNITED STATES
(ALASKA)
RUSSIA
Bering Sea


ICESat
2003-2009
Single-beam lidar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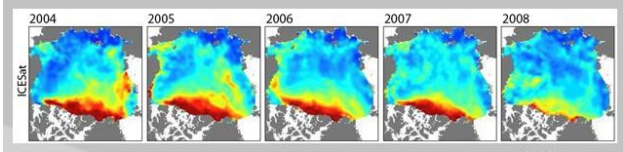
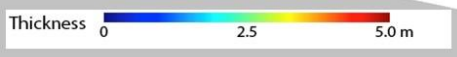
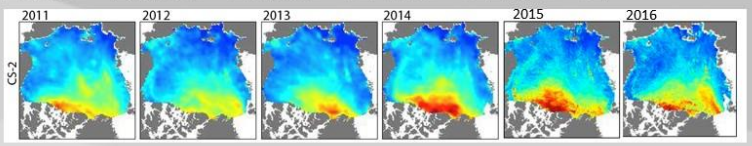
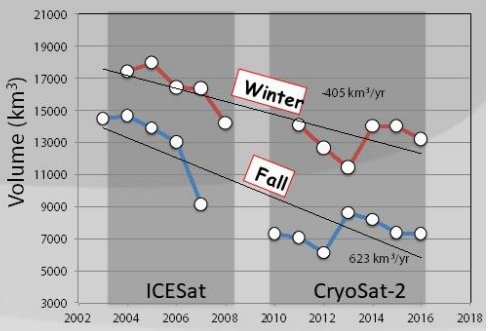
0 500 1,000 km

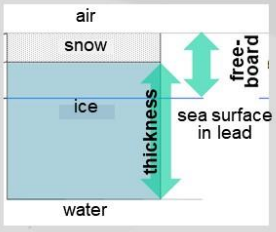
Trends in Arctic Sea Ice Volume from ICESat (laser) and CryoSat-2 (radar)





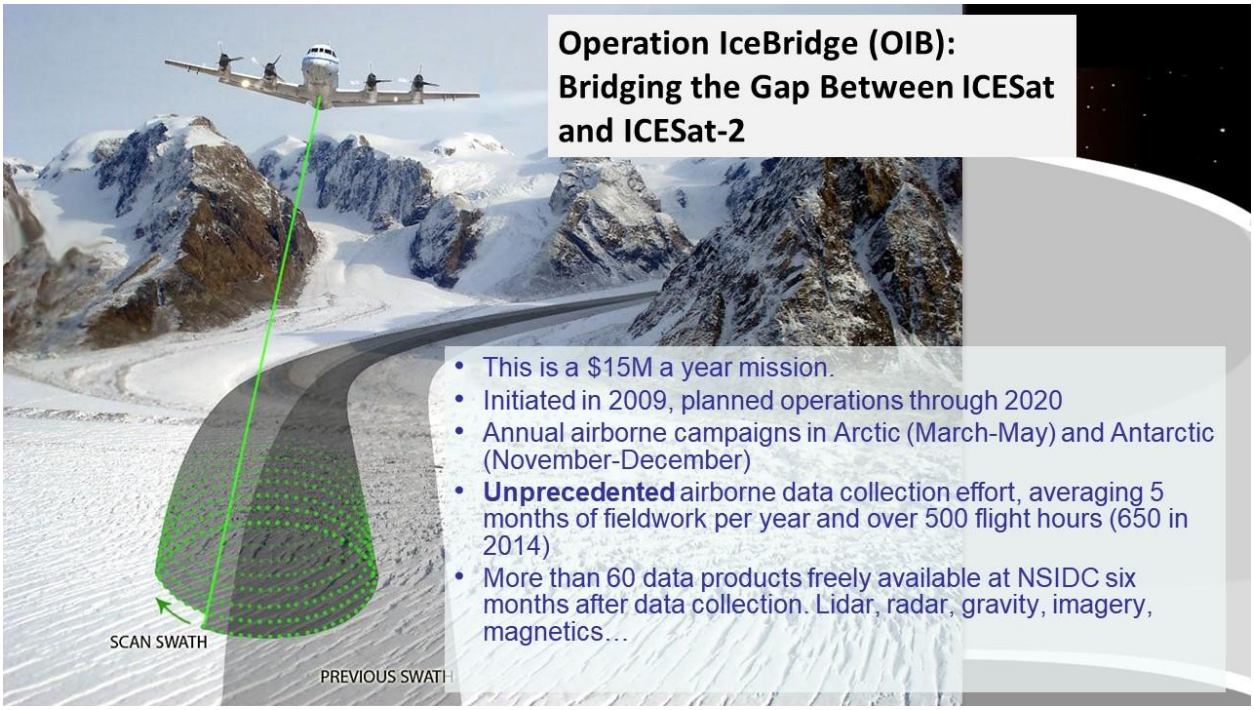






- Height of sea ice above water (freeboard) provides estimate of ice thickness.
- Thickness estimate is combined with extent to obtain volume.
- Snow thickness and density inferred from climatologic modeling

Image credit: R. Kwok, JPL-Caltech

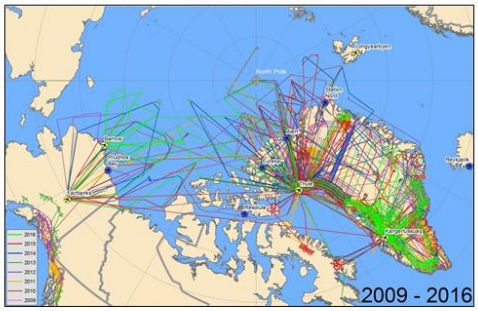


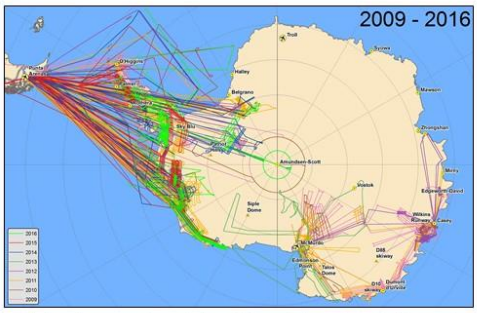
Operation IceBridge (OIB): Bridging the Gap Between ICESat and ICESat-2

- This is a $15M a year mission.
- Initiated in 2009, planned operations through 2020
- Annual airborne campaigns in Arctic (March-May) and Antarctic (November-December)
- **Unprecedented** airborne data collection effort, averaging 5 months of fieldwork per year and over 500 flight hours (650 in 2014)
- More than 60 data products freely available at NSIDC six months after data collection. Lidar, radar, gravity, imagery, magnetics…

OIB Arctic and Antarctic Campaigns

- Arctic campaigns (below) have taken place in March through May of each year since 2009.
- They survey sea ice in the Arctic Ocean and the Greenland Ice Sheet, with a special focus on rapidly changing outlet glaciers.
- Missions are flown out of Thule and Kangerlussuaq in Greenland, and Fairbanks, Alaska. There is also a smaller component surveying glaciers in southeast Alaska.
- To date, these combined efforts have yielded nearly **910,000 km** of science data.





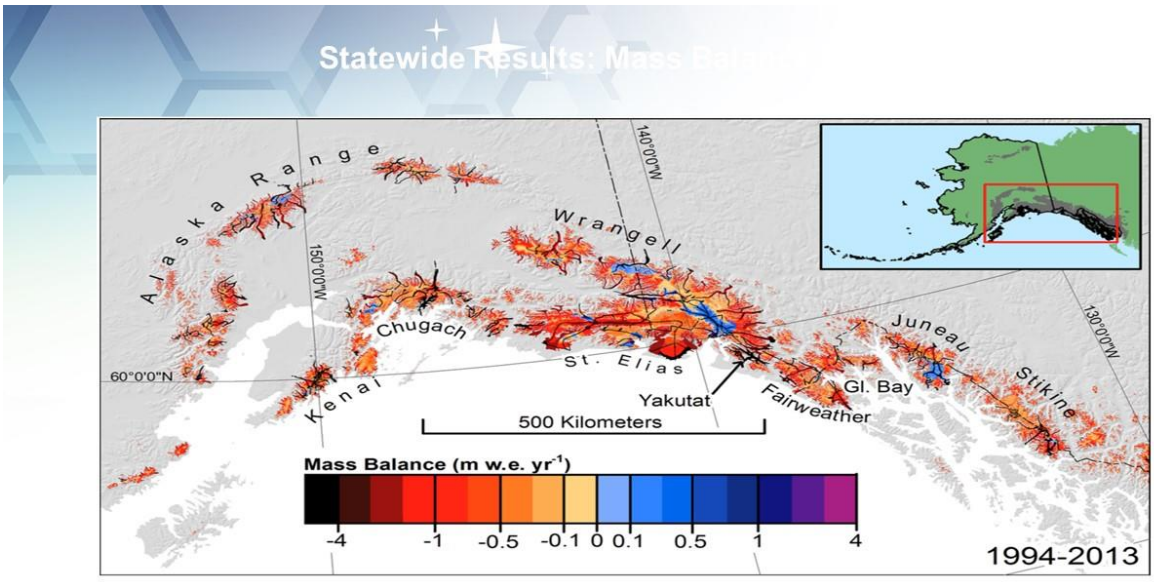
- Antarctic campaigns (above) have taken place in November through December of each year since 2009.
- They survey rapidly changing areas along the coast of West Antarctica, as well as major ice shelves, and seasonal sea ice.
- Missions are flown out of Punta Arenas in Chile, and McMurdo Station in Antarctica. There was a significant component flown in East Antarctica in collaboration with NSF's ICECAP program.
- To date, these combined efforts have yielded nearly **520,000 km** of science data.

OIB-Alaska
Aircraft: DHC-3 Single Otter
Instrumentation:
- UAF lidar (dh/dt elevation change)
- UAF/UT/UA HF radar (depth sounding)
- KU Snow Radar (accumulation)



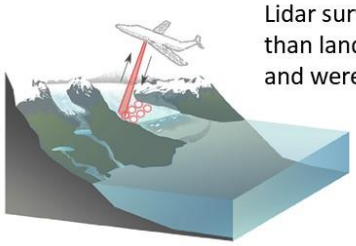


Accumulation + elevation change + basal geometry (+ velocities) = complete picture of mass balance and future retreat scenarios for Alaskan glaciers . From one airplane. (plus a few satellites.) For the first time.



Surface melt dominates Alaskan glacier mass balance

Larsen, Burgess, Arendt, O'Neel, Johnson, Kienholz (2015), Geophysical Research Letters

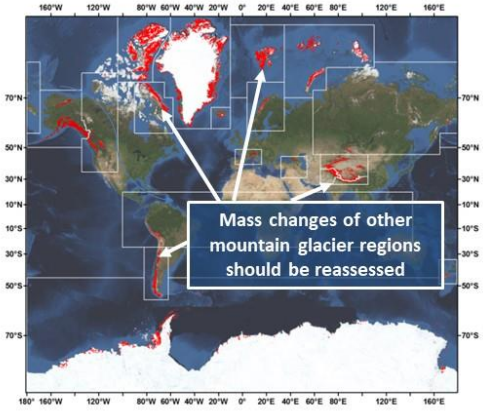


Lidar surveys of Alaskan glaciers show tidewater glaciers are losing mass at slower rates than land-terminating glaciers. Tidewater glaciers had undergone rapid retreat in the past and were thought to dominate the current mass loss signal.

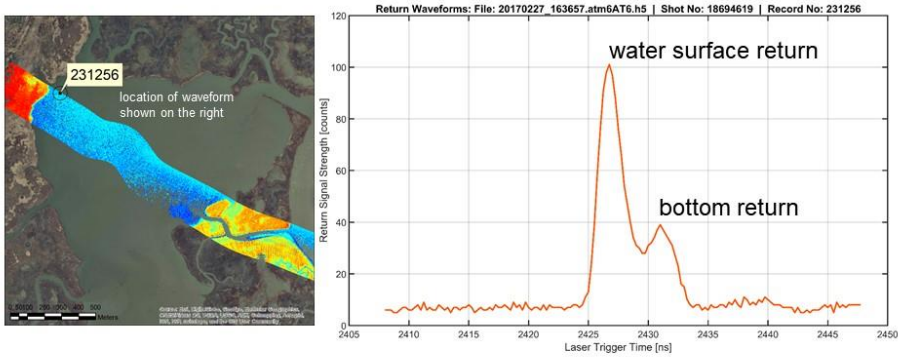
Future sea-level contributions will be driven by surface melt and accumulation rather than ice-ocean interactions.

Mountain glaciers account for < 1% of the world's ice volume but their rapid mass loss contributes 1/3 of current sea level rise.

NOT JUST GREENLAND AND ANTARCTICA, Surface mass balance dominates Arctic glacier and icecap budget.



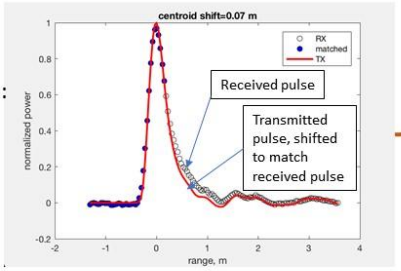
Shallow Coastal Bathymetry Mapping



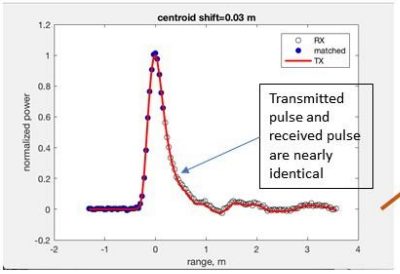
- This bathymetry example over water with high sediment contents has stronger water attenuation and therefore weaker bottom returns compared to sea ice melt ponds and supraglacial lakes.
- The low reflectance of the bottom weakens the signal strength compared to reflective melt pond bottoms.

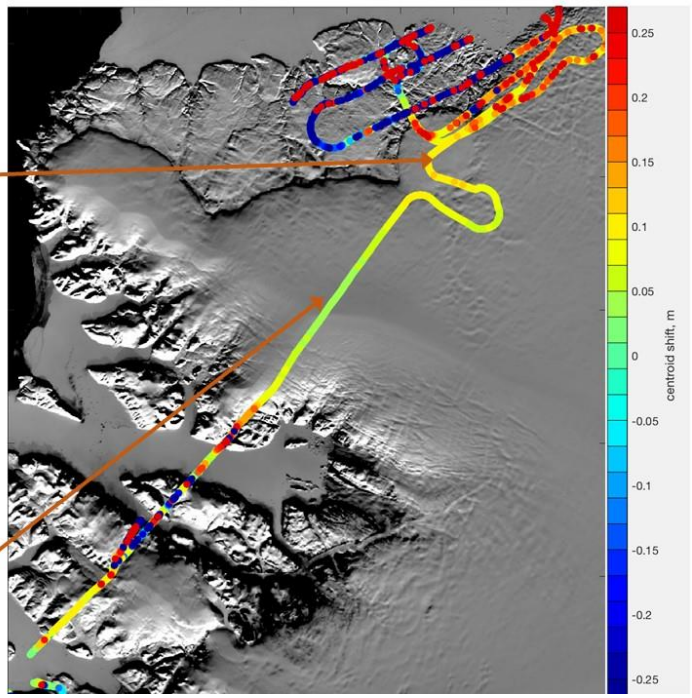
13

Low elevation, melting surface: coarse grains lead to 7-10 cm centroid shift



High elevation, cold surface: fine grains lead to 2-3 cm centroid shift

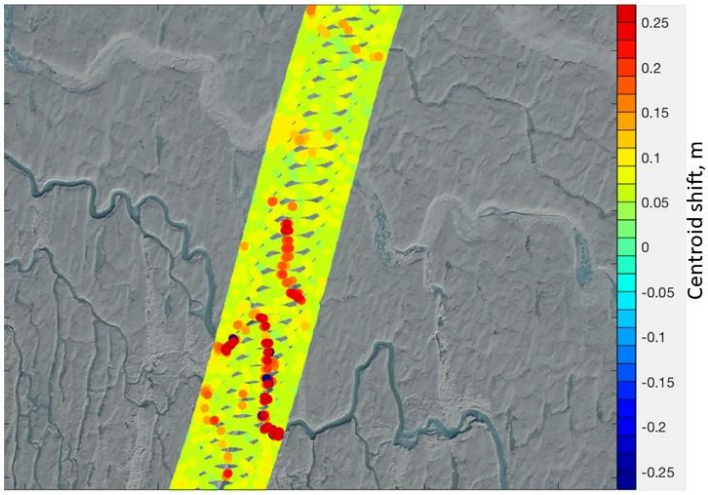




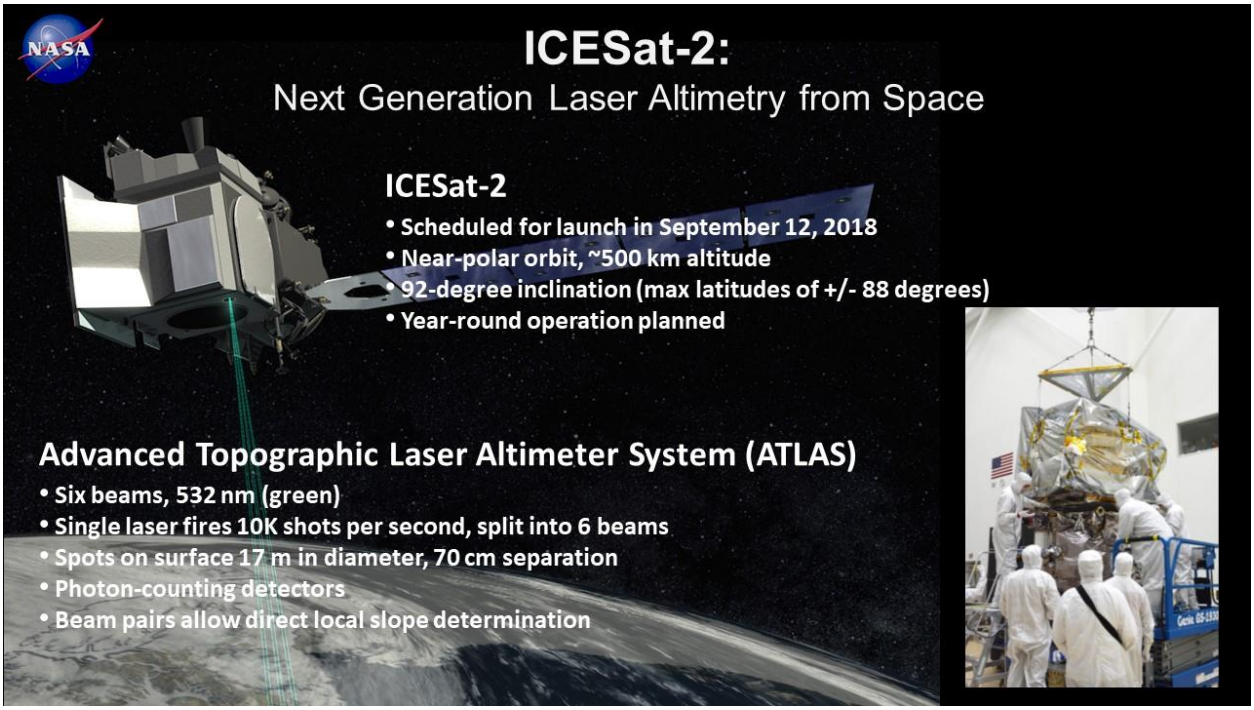
Ben Smith, University of Washington

Melting surfaces: Rotten ice and supraglacial water

- Modeling suggests large (20+ cm) range delays for bubbly ice
  - Implies problems with green-light altimetry for Greenland melt surfaces
- Measurements show:
  - 5-10 cm delays over melting surfaces
    - Drained "Rotten ice" layers at the surface (mm-scale grain size) limit biases
  - 20-40-cm delays over supraglacial lakes and streams
    - Stream/lake bottoms made up of water-saturated rotten ice, or exposed bubbly ice

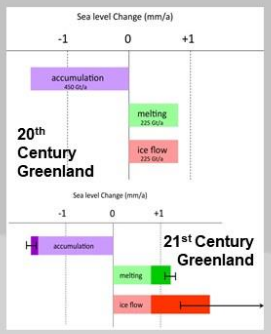


DMS image with ATM scan

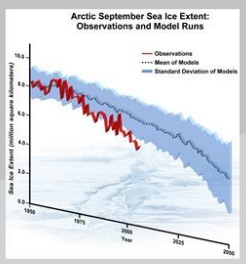


ICESat-2 Science Objectives

- Quantify polar ice-sheet contributions to current and recent sea-level change and the linkages to climate conditions.
- Quantify regional signatures of ice-sheet change to assess driving mechanisms and improve predictive ice sheet models.
- Estimate sea-ice thickness to examine ice-ocean-atmosphere exchanges of energy, mass, and moisture.
- Measure vegetation canopy height as a basis for estimating large-scale biomass and biomass change.
- **ICESat-2 will make measurements over the world's oceans, land surfaces, and inland water, providing new data at unprecedented resolution for a wide range of scientific investigations.**



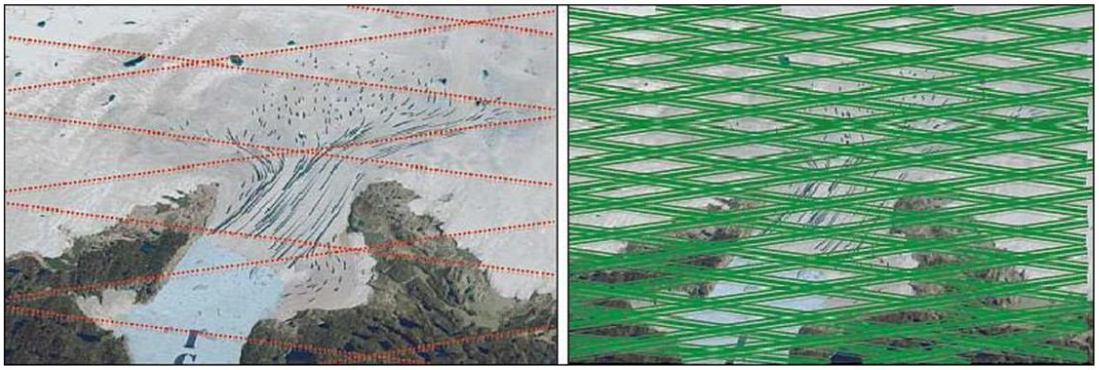
The Greenland ice sheet changed from a state of balance, to substantial imbalance, with large error bars.

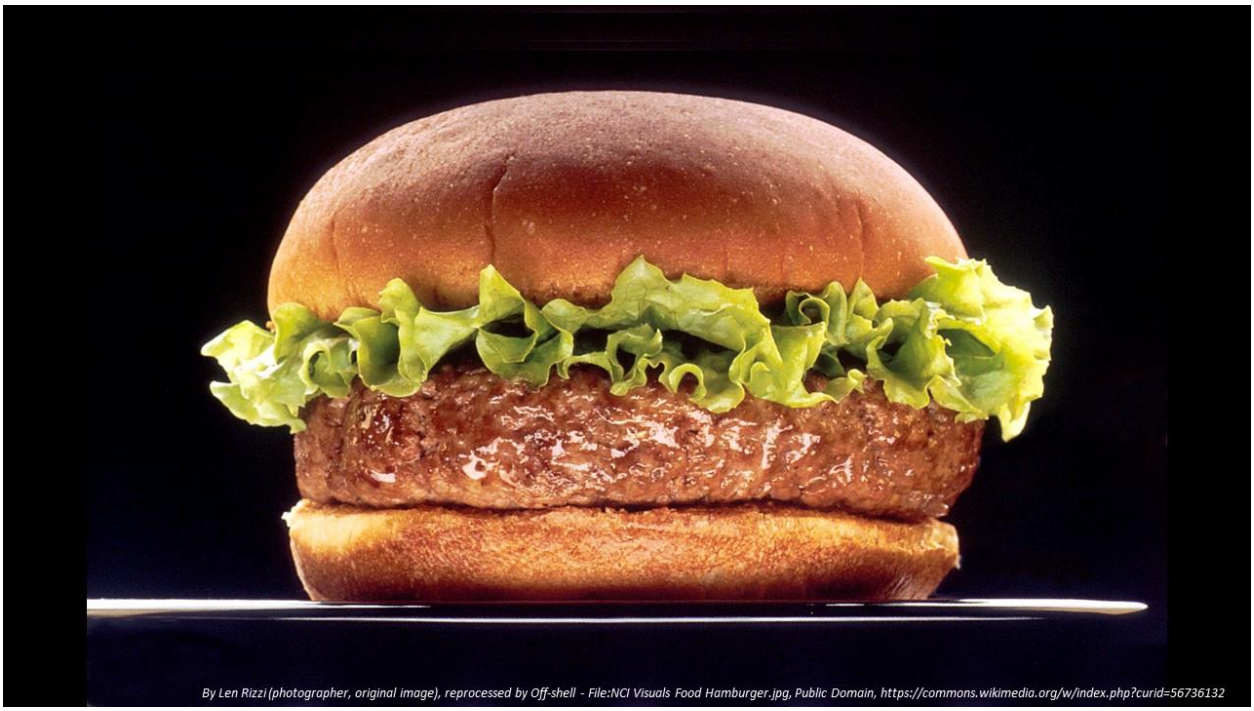


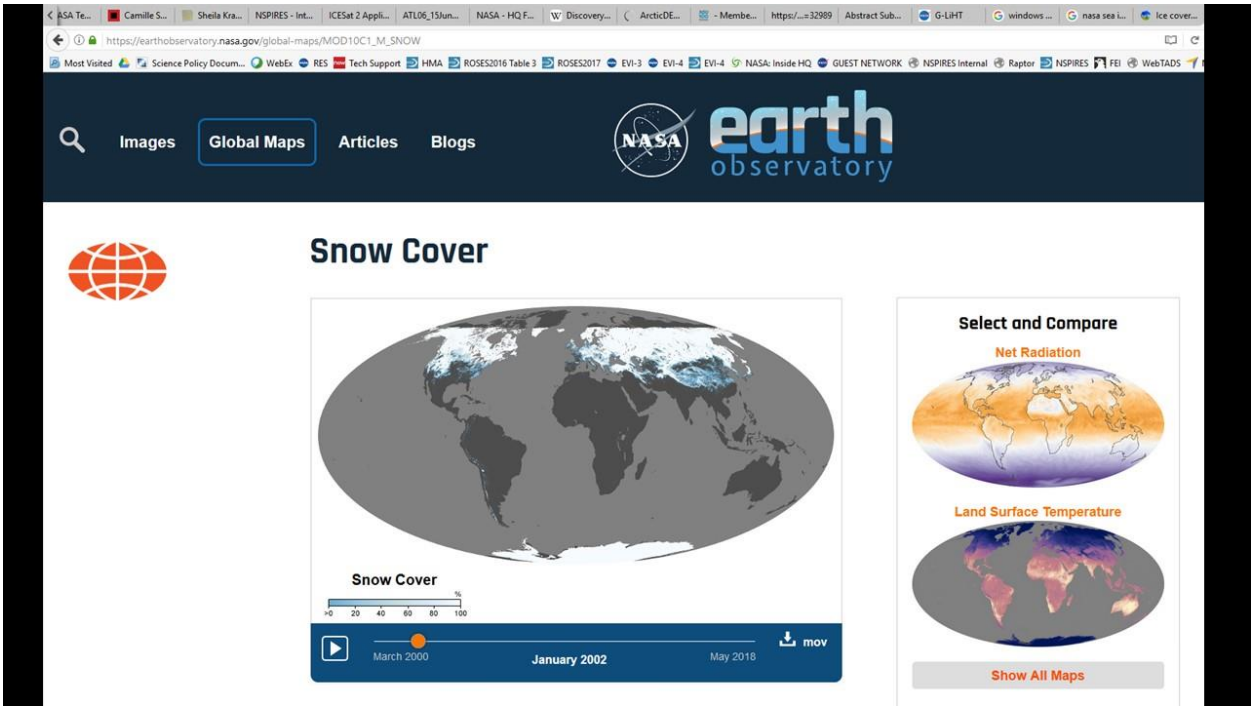
Sea ice extent has decreased faster than models predict. Sea ice thickness remains a major unknown.

ICESat-2 Improved Mapping

ICESat-1 ICESat-2




By Len Rizzi (photographer, original image), reprocessed by Off-shell - File:NCI Visuals Food Hamburger.jpg, Public Domain, https://commons.wikimedia.org/w/index.php?curid=56736132


https://earthobservatory.nasa.gov/global-maps/MOD10C1_M_SNOW
Images
Global Maps
Articles
Blogs
NASA
earth observatory
Snow Cover
Snow Cover
March 2000
January 2002
May 2018
mov
Select and Compare
Net Radiation
Land Surface Temperature
Show All Maps

Snowmelt Runoff Forecasting

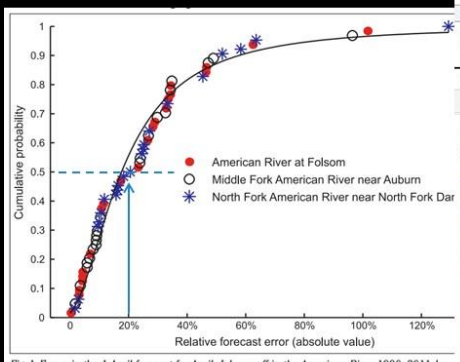


Fig. 1. Errors in the 1 April forecast for April–July runoff in the American River, 1990–2011, base on gauges at Auburn and Folsom, in California. Note that the median error is 18% and the 80t percentile (1 year in 5) error is 39%. The plot was generated from information from the Califo Data Exchange Center.

Dozier 2012

In 1 of 5 years, forecast errors are greater than 40%. Half the time, they are greater than 20%. These come from poor data and poorly constrained science.



The New York Times

U.S.

In California, Reading the Snow to Tell the Future for the Water Supply

Max Whittaker for The New York Times

Frank Gehrke, center, has led snowpack surveys in California for a quarter-century. The state's multibillion-dollar agricultural industry pays close attention.

By NORIMITSU ONISHI
Published: February 7, 2013

JPL Airborne Snow Observatory: ASO

Imaging Spectrometer
0.35-1.05 µm
2 m spatial resolution from 4000 AGL

Albedo

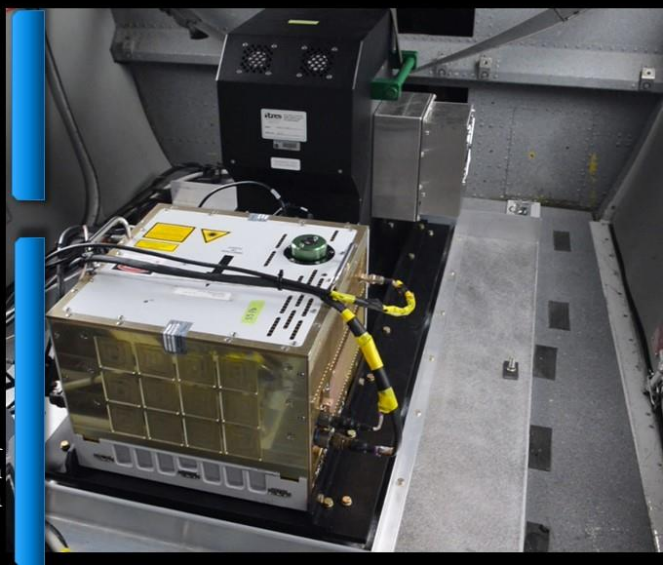
Uncertainty < 2%

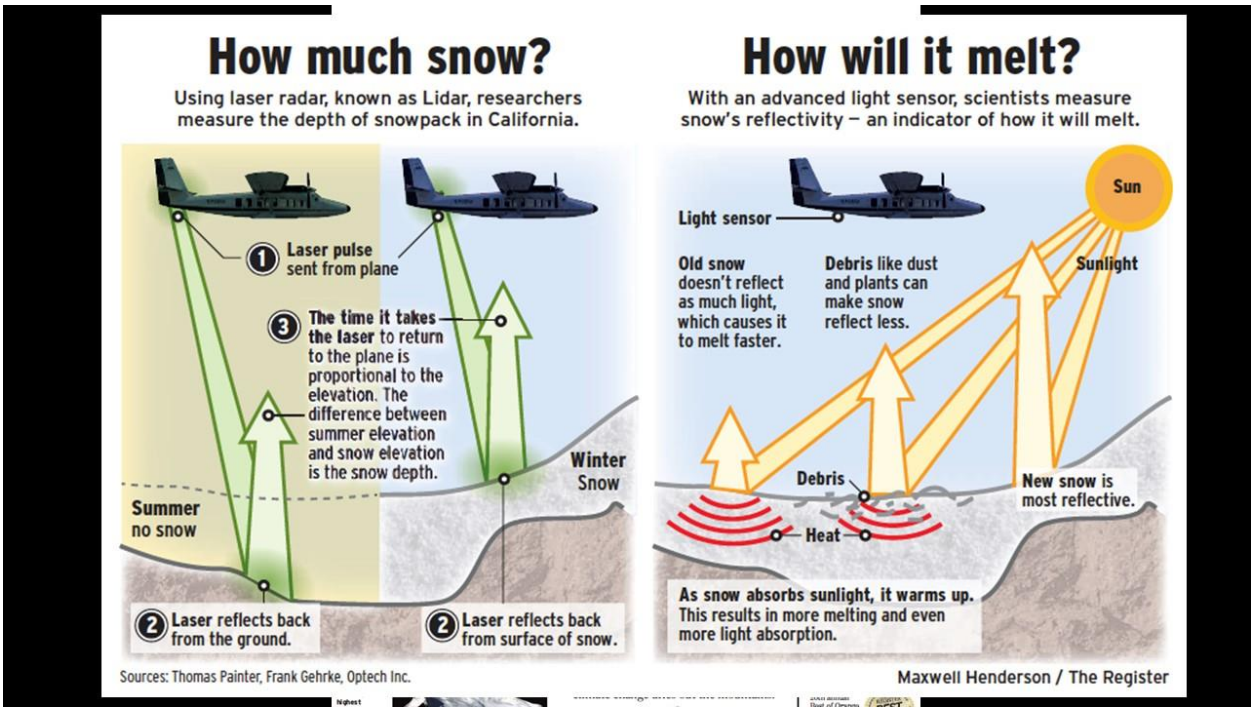
ASO

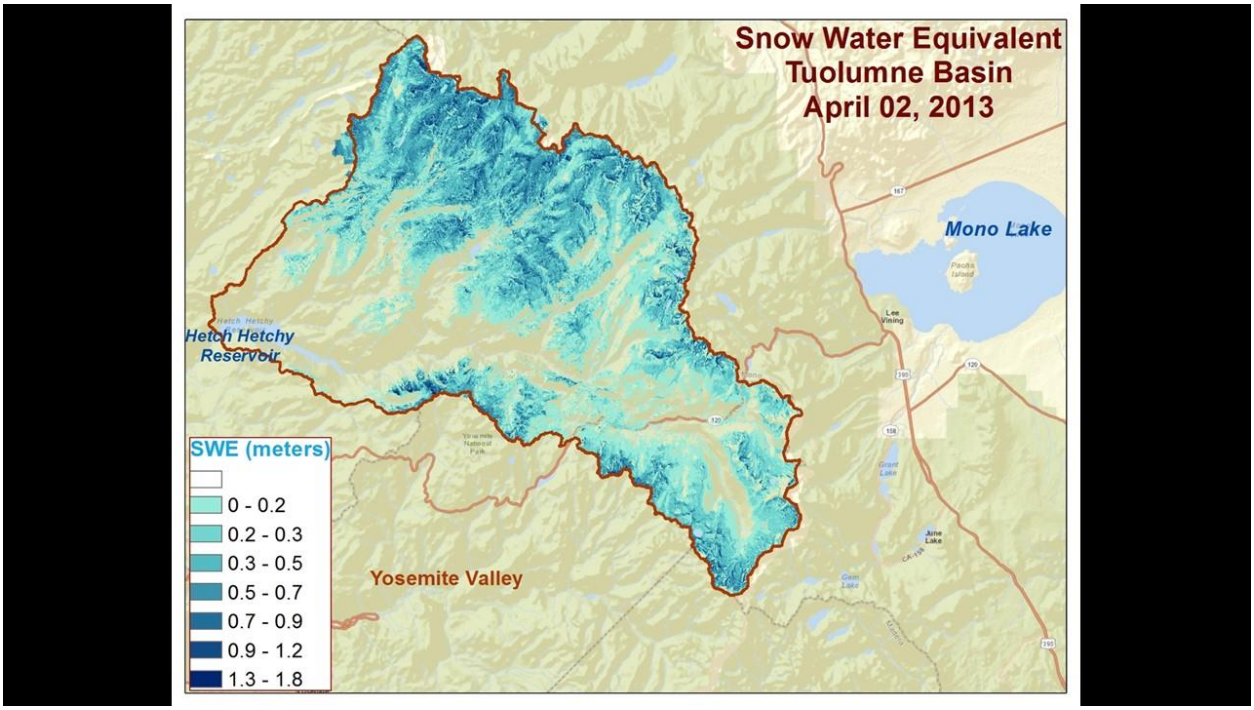
SWE

Uncertainty < 5 cm

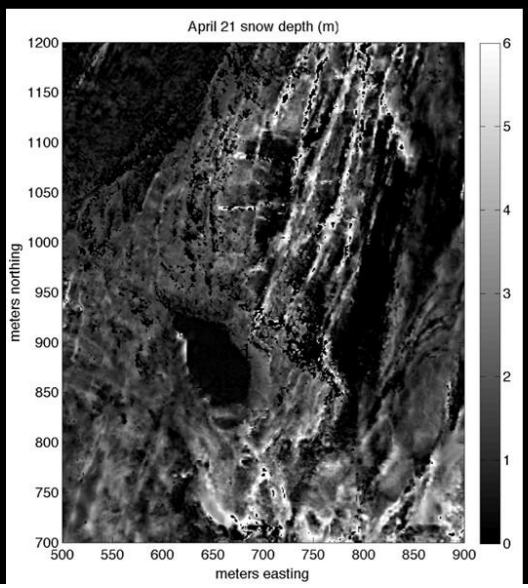
3D Scanning LiDAR
1064 nm
1 m spatial resolution




How much snow?
Using laser radar, known as Lidar, researchers measure the depth of snowpack in California.
1 Laser pulse sent from plane
3 The time it takes the laser to return to the plane is proportional to the elevation. The difference between summer elevation and snow elevation is the snow depth.
Winter Snow
Summer no snow
2 Laser reflects back from the ground.
2 Laser reflects back from surface of snow.
How will it melt?
With an advanced light sensor, scientists measure snow's reflectivity – an indicator of how it will melt.
Light sensor
Sun
Sunlight
Old snow doesn't reflect as much light, which causes it to melt faster.
Debris like dust and plants can make snow reflect less.
Debris
Heat
New snow is most reflective.
As snow absorbs sunlight, it warms up. This results in more melting and even more light absorption.
Sources: Thomas Painter, Frank Gehrke, Optech Inc.
Maxwell Henderson / The Register

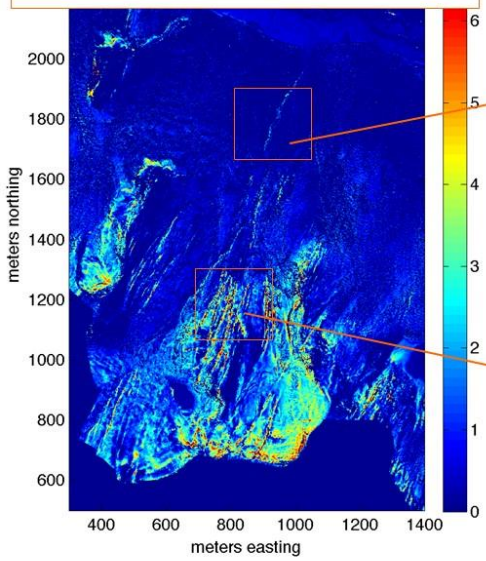

Snow Water Equivalent
Tuolumne Basin
April 02, 2013
Mono Lake
Hetch Hetchy Reservoir
Yosemite Valley
SWE (meters)
0 - 0.2
0.2 - 0.3
0.3 - 0.5
0.5 - 0.7
0.7 - 0.9
0.9 - 1.2
1.3 - 1.8

New observations = new science and applications

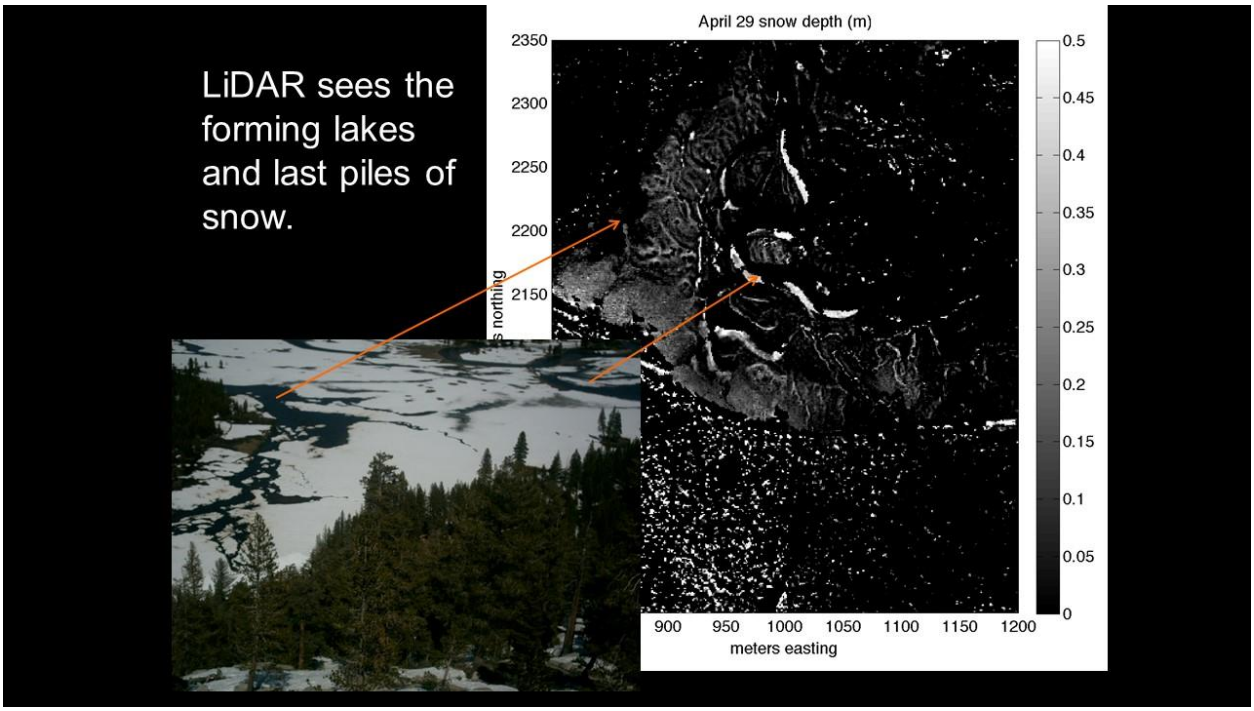


- Better forecasts for water managers
- Seeing snow in space and time in a manner never possible before
- Many applications to be discovered

Landscape is full of fissures that fill with snow





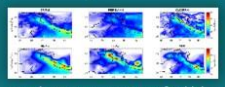


NASA High Mountain Asia Team (HiMAT): Key Science Results

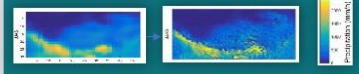
Climate

| Precipitation

- Intercomparison of over 10 existing precipitation products will enable us to choose which is best for subsequent modeling work:



- Existing products are too coarse for high resolution land surface modeling. We are downscaling to 1 km using dynamical and other methods:

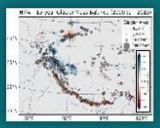


- There are numerous models being used by HiMAT (WRF, GCMs, MAR). We are conducting a intercomparison exercise using statistical methods to identify outliers.
- When the ground data arrive, we will do a more robust validation to ground data.
- GCM simulations are nearly complete: optimized for precipitation intensity (landslides) and the aerosol work.

Cryosphere

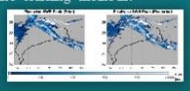
| Glaciers

- High-res + historical DEMs providing new insight on mass balance of the region's glaciers

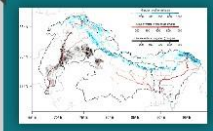


| Snowpack

- New high-resolution snow climatology datasets using remote sensing, dynamical downscaling, assimilation and machine learning methods.



Land Surface Models

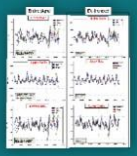


Comparison of several high resolution land surface models (NASA LIS, UNH model, etc) to represent water balance of HMA.

- Exploring the routing and retention of water across the region in relation to groundwater depletion, hydropower.

Remote Sensing

Numerous remote sensing products (GRACE, MODIS, TRMM, GPM, Landsat) used for model cal/val. E.g. GRACE comparisons to modeled water balances:



Process Studies and Impacts

Dust and aerosols: comparing GCM and local observations.



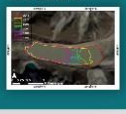
New maps of landslide occurrances and relation to extreme precip events.



Relating runoff to fisheries and hydropower in Nepal.

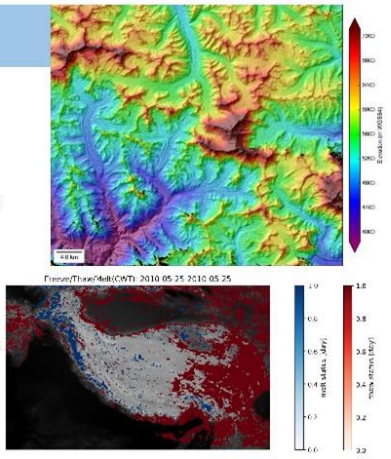


Assessing glacier lake hazards.



Early HiMAT data products

- Digital Elevation Models (DEMs) from U. Washington
  - Published in the NSIDC DAAC
  - Browse products and index files also available
  - Use examples: glacier thickness changes, hydrological routing, landslide analysis
- High Mountain Asia ASCAT Freeze/Thaw/Melt Status
  - Sample data provided to NSIDC DAAC
  - Use examples: meltwater infiltration, surface energy ba check on model results
- MODSCAG/MODDRFS (Tom Painter's snow products)
  - Data being repackaged into NetCDF at JPL
  - Use examples: model input for snow cover, snow-water equivalent
- Geodetic mass balance measurements (Summer Rupper)
  - Not yet provided to NSIDC DAAC
  - Use examples: glacier contribution to streamflow, check on glacier mass balance model results



2



NASA Terrestrial Ecology Program
Hank Margolis, Program Manager

The goals of the NASA Terrestrial Ecology Program are to improve understanding of how human interventions and environmental change impact the:

- Structure, function, and productivity of terrestrial ecosystems across the globe;
- Interaction of terrestrial ecosystems with the atmosphere and hydrosphere;
- Role of terrestrial ecosystems in biogeochemical cycles, e.g., carbon and water cycles

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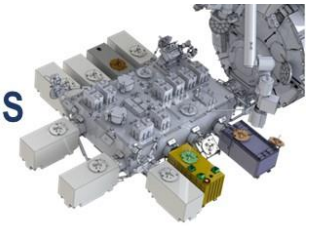
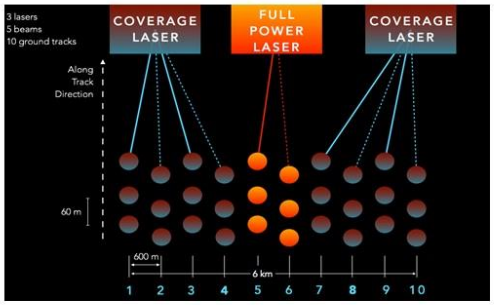
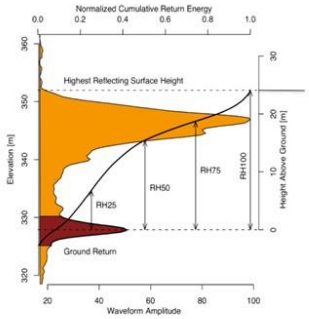
GEDI: High Resolution Laser Ranging Of Earth's Forests and Topography on ISS

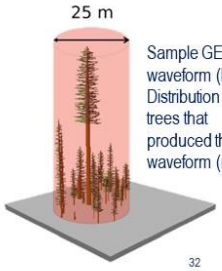


- NASA's Global Ecosystem Dynamics Investigation (GEDI) is a full waveform lidar system that will launch to the International Space Station in late 2018.
- GEDI's 3 lasers will return 10 tracks of ~25 m waveform samples, providing ~15 billion surface structure observations.

GEDI ECOSYSTEM LIDAR



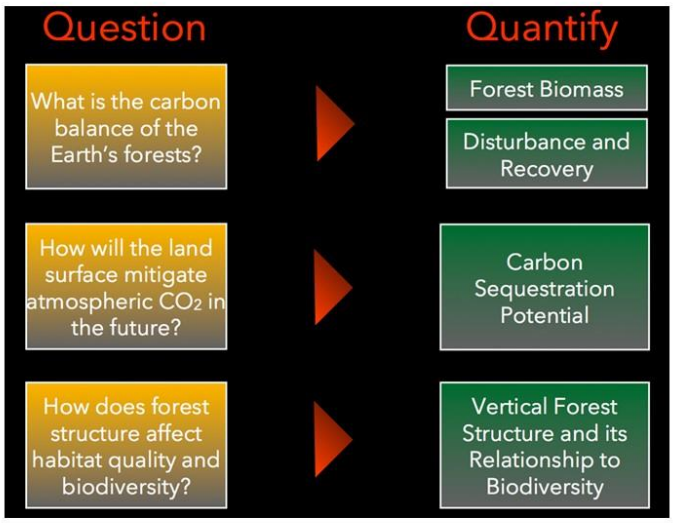




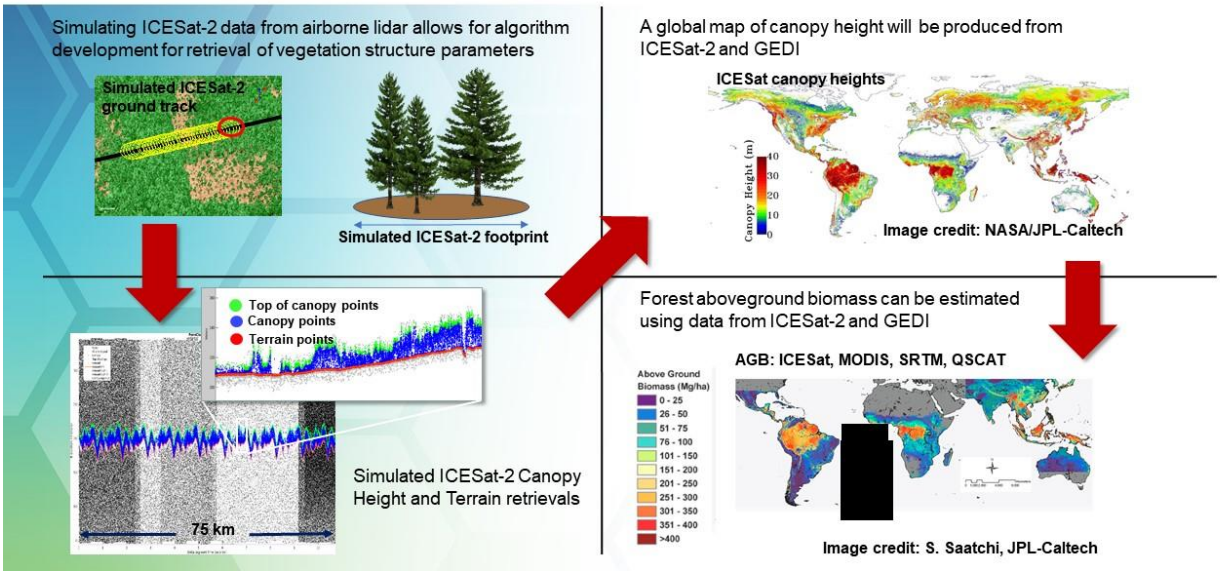
Sample GEDI lidar waveform (left). Distribution of trees that produced the waveform (right).

32

GEDI Science Objectives



ICESat-2 & GEDI: Global Vegetation Height and Biomass





Notes

- As per as the overview by Session Chairs are concerned, you could certainly highlight ESD vision active sensing for **Topography, Cryosphere and Biomass** and ESAS NRC Decadal survey 2017 observations and recommendations.
-
- Then you can briefly describe the NASA sponsored ongoing efforts at NASA, industry and academia and convey your and ESD vision for future space based formulation, as designated mission, with support from NASA Centers, industry, academia and possible collaborations opportunity with international space agency partners. You could also briefly provide, in your estimate, where the TRL Level of the technologies are, what do you see as tall poles, and what is the path forward to advance the TRL and mature the candidate technologies to ensure the success of the mission.

- Co-chair Ralph Dubayah – PI for GEDI

4.2 FLIGHT LASERS TRANSMITTER DEVELOPMENT FOR NASA ICE TOPOGRAPHY ICESAT-2 SPACE MISSION

Nicholas Sawruk, Patrick Burns, Ryan Edwards, Viatcheslav Litvinovitch and Floyd Hovis

Fibertek, Inc., 13605 Dulles Technology Drive, Herndon, VA 20171

ABSTRACT

We report on the completion of the development, space-qualification and delivery of the flight lasers for NASA Goddard Space Flight Center's Advanced Topographic Laser Altimeter instrument.

***Index Terms*—** Nd:YVO_4 lasers, diode pumped solid state lasers, space-based lasers, TRL 6 lasers, diode-pumped lasers

1 INTRODUCTION

The Advanced Topographic Laser Altimeter System (ATLAS) is the sole instrument on the ICESat-2 mission. It is comprised of a multiple-beam laser altimeter utilizing a high repetition, short pulse width, 532 nm laser transmitter [1]. In terms of space qualified laser systems, the ATLAS laser represents a significant jump in space qualified laser technology (short pulse width, moderate average powers, frequency tunable and laser shot count). The ATLAS instrument is required to run continuously for 3 years on-orbit and the required laser shot count (~1 trillion) is ~ 3 orders of magnitude greater than in any previous NASA spaceflight mission [2].

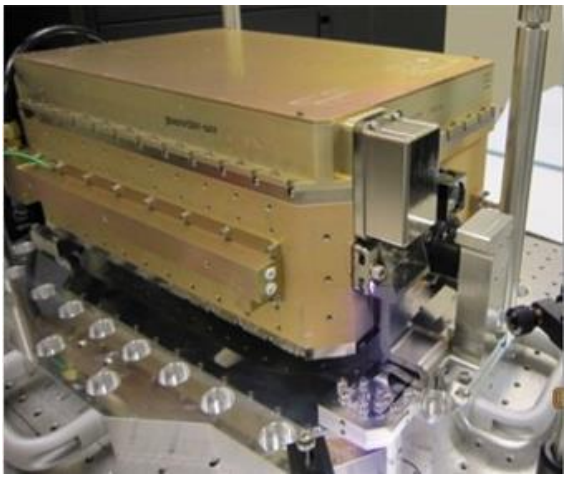


Figure 1. The ATLAS laser system.

Fibertek delivered three laser transmitters, including the one shown in Figure 1, that meet the demanding performance and reliability requirements for the ATLAS instrument, including two flight units and one spare. The lasers consists of two major sub-assemblies. The Laser Optical Module (LOM) is a sealed and pressurized module housing all of the optical components and laser diode modules. The Laser Electronics Module (LEM) is integrated to the LOM and is a vented module housing the laser power and command and control electronics.

1.1 LASER OPTICAL MODULE

A mature diode pumped solid Master Oscillator Power Amplifier (MOPA) architecture was selected in order to minimize schedule, cost and technical risks. End-pumped crystals gain heads are used in the oscillator and three subsequent amplifiers. The end-pumped gain heads are designed with methodology similar to mature geometries used broadly in commercial laser systems.

The master oscillator generates 200 μJ infrared pulses with < 1.5 ns full width half max pulse widths with narrow (< 5 pm) linewidth tunable over a >50 pm wavelength range. The oscillator's output is amplified via three stages to more than 1.8 mJ at 10 kHz pulse repetition frequency while preserving the near diffraction-limited beam quality (M^2 < 1.4) and short pulse widths of the oscillator output. The 1064 nm amplifier output is frequency doubled to 532 nm via a critically phased matched lithium triborate (LBO) crystal.

The ATLAS lasers generate 532 nm output pulses with user-selectable energies from 250 μJ to 1.2 mJ with near-diffraction limited beam quality and < 1.5 ns pulse widths. Additional system design details have been previously published [3,4,5].

The ATLAS lasers systems successfully completed a proto-flight qualification program including electromagnetic interference testing, vibration testing and thermal vacuum testing, specific testing details are published [6]. In addition, three early system prototypes completed >25,000 hour life tests demonstrating the laser design was capable of meeting the mission operational run time requirement [7]. A summary of the key laser requirements and achieved performance is listed in Table 1.

Table 1. Key laser requirements and performance.

Parameter	Requirement	Flight Lasers
Energy (µJ)	250-900	250-1,370
Pulse Rate (kHz)	10	10
Pulse Width (ns)	1.5	<1.3
Divergence (µrad)	<130	91
Wavelength (nm)	532.272	532.272
Linewidth (pm)	<30	<5
Efficiency	>5%	8.2%
Operational Run-Time	3.5 years (> 1 trillion shots)	Prototype Systems (> 1 trillion shots)

1.2 LASER ELECTRONICS MODULE

The electronic design was started early in the program mitigating design surprises and long lead Electrical, Electronic and Electromechanical (EEE) part procurement schedules. The integrated ATLAS electronics included the following major electronic boards.

Laser Control Board: Provides high speed communications with the payload, to monitor numerous laser health and diagnostic sensors (14 temperature sensors, four internal energy monitors, two pressure sensors, other housekeeping telemetry) while providing the critical timing parameters needed for a laser capable of 12 user selectable energy modes.

Diode Power Module: A custom high efficiency (>87%) DC-DC converter purpose built to provide power conditioning to four custom pulsed diode drivers.

Pulsed Diode Driver: Four pulsed diode drivers generating the programable current waveforms with a peak current of 4 A, ~28 VDC at 10 kHz with µsec class rise and fall times, and 85% efficiency.

2 ATLAS LASER DEVELOPMENT

2.1 LASER DIODE MODULE – SPACE QUALIFICATION

A laser diode module (LDM) space certification and qualification program was developed and executed. The test centric LDM space certification and qualification programs consisted of several key phases including a technology plausibility study, laser diode and LDM pedigree reviews, environmental acceptance and qualification testing, and extensive life testing [8,9,10]. The intent of the plausibility study was to analytically and experimentally attest that a commercial-off-the-shelf (COTS) LDM design was capable of being space-certified. A pedigree review of the laser diode (single emitter) population was conducted to reject out-of-family laser diodes from the population prior to integration into the multi-emitter LDM. All LDMs underwent environmental acceptance testing including vibration, thermal cycling and an extended burn-in. Multiple LDMs are being life tested under flight-like conditions and show no signs of degradation. Figure 2 shows four LDMs with run times of ~50,000 hours, well over the 27,000 hour mission life.

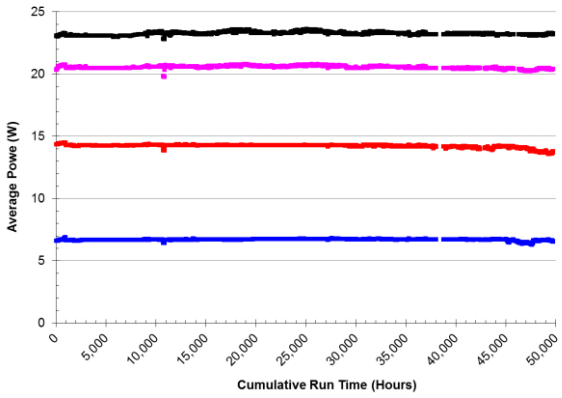


Figure 2. Four LDM with a run time of approximately 50,000 hours operating at nominal flight conditions.

2.2 DETAILED AND CORRELATED SYSTEM LEVEL ANALYSIS

The STOP analysis consists of four modules, optical ray-trace model, finite element (FE) model of the system, thermal lensing model and laser dynamics model [11]. The system ray trace model was constructed in Zemax and linked to the solid engineering model and FE model. The FE model subjects a detailed structural model to expected loads (pressure, thermal, vibration, etc.) and calculates the displacement and rotations of the optical. The end-to-end STOP and laser performance model were correlated to the performance of a laser engineering model prototype. The analysis package was used to optimize the flight laser design and to validate the design for conditions that are difficult to test such as end-of-life thermal conditions, gravity release, acoustic sensitivity, and rapid de-pressurization of the laser enclosure. All of the flight laser systems performed as predicted throughout proto-flight environmental testing.

2.3 Optical Component Selection & Qualification

The optical components were carefully selected for optimal performance and laser damage threshold. The laser damage threshold was measured for each coating run via the standard S-on-200 laser damage test to screen out erroneous coatings at the batch level. In addition to the lot certification, NASA GSFC experimentally investigated the effects of long term exposure to 532 nm on the performance of multilayer optical coatings [12]. The test results indicated that low cost e-beam evaporated mirror coatings at 532 nm failed after 150 billion shots, while an ion beam sputter (IBS) coated mirror maintained peak reflectivity over the full 1 trillion shots. The test samples showed laser-induced contamination and cavitation of the surface but the optical performance was not affected.

The peak optical fluences on all surfaces were limited by design to be 5x below the lowest measured laser damage threshold. The low fluence design successfully mitigated laser induced damage throughout the program.

2.4 Laser Test Program

The laser development program was heavily test centric including five system level laser engineering models, and several sub-system (oscillator, diodes, q-switch) test units. Figure 3 shows the various engineering models through the final TRL-8 lasers integrated on the ATLAS instrument. The early prototype units confirmed the laser design, performance over vibration testing and thermal vacuum testing and electro-magnetic interference qualification. Three of the five system level engineering models completed mission equivalent life tests, running over 25,000 hours and accumulating over 1 trillion laser shots each. The early life tests surfaced several design improvements including an updated oscillator design less susceptible to pre-lasing and reduced laser fluence on the 532 nm optics minimizing laser-induced photo contamination degradation.

During the ATLAS instrument (full lidar system) thermal vacuum testing the output pulse energy of one of the flight lasers dropped suddenly as reported by both the internal and external energy monitors. The output energy oscillated and eventually settled out at 20-30% lower pulse energy. All system telemetry and ATLAS level performance were unaffected. The observed energy oscillations and drop were later determined to be caused by a Nd:YVO_4 crystal fracture in the Pre-Amplifier gain head [13]. The probable cause of the flight laser's slab fracture multiple years after assembly and >1,000 hours of operation is due to an unexpectedly high initial preload combined with a time dependent gold indium intermetallic growth further increasing the preload resulting in tensile stress on the surface of the crystal exceeding its local strength.

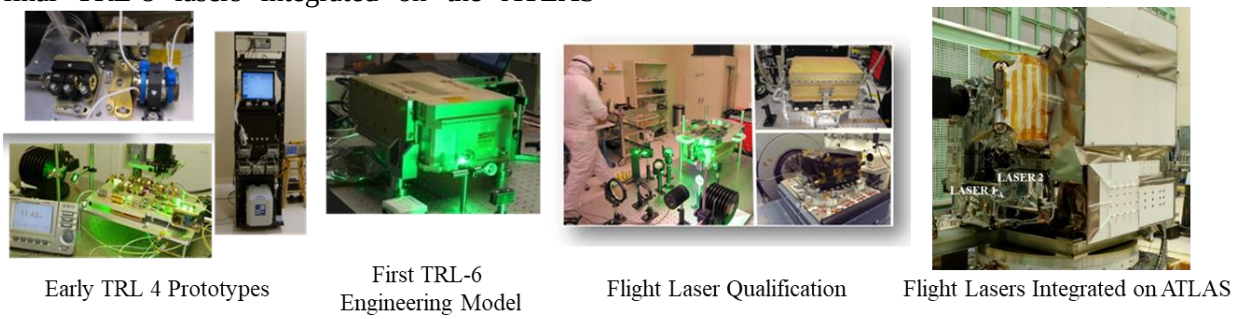


Figure 3. The ATLAS laser development from TRL 3 to TRL 8.

Several design changes were identified and implemented for the flight laser systems, resulting in substantially reduced likelihood of fracture over the 3-year mission life. Design changes include reduced gold metallization, and a constant-stress mounting scheme that limits stress concentration over changing temperature and deformation conditions. Figure 4 shows the updated amplifier mount with reduced gold metallization. constant load fasteners and the resulting operational crystal stress.

Ideally, the early test programs and flight laser proto-flight testing were designed to surface systematic and workmanship failure mechanisms. However, due to a subtle design change increasing the gold plating thickness on the flight laser

amplifier assemblies compared to all the previous test units the previous testing was not effective for this time dependent failure mechanism. It's worth noting, the overall test campaign, served its purpose, identifying the systemic issue prior to launch with adequate reserves to implement the corrective actions.

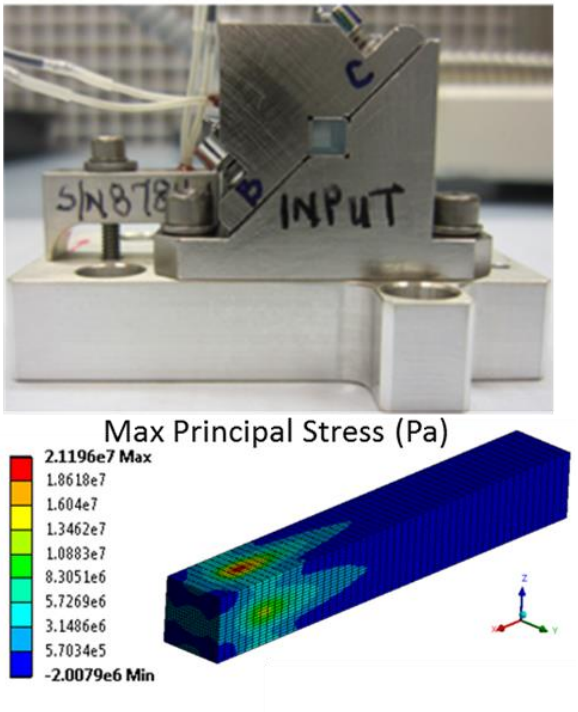


Figure 4. (top) New flight amplifier assembly. (bottom) FE analysis stress results for an amplifier crystal in normal operation in the improved amplifier assembly under normal lasing operation.

The new amplifiers were installed in the flight lasers and the lasers subsequently passed proto-flight testing (vibration and thermal vacuum). The flight lasers have been run for over 1,000 hours without signs of degradation or damage.

3 SUMMARY

The ATLAS lasers are complete and integrated on the ATLAS instrument. The overall program carried out the goal of space-qualifying a next generation laser capable of over 1 trillion >600 kW peak power 532 nm pulses in a near-diffraction limited beam. ICESat-2 is on track to launch in 2018.

Acknowledgements

This work was supported by funding from the NASA Goddard Space Flight Center, ICESat-2 mission. In particular, we would like to thank ATLAS team for the expertise and resources during the execution of the flight laser program.

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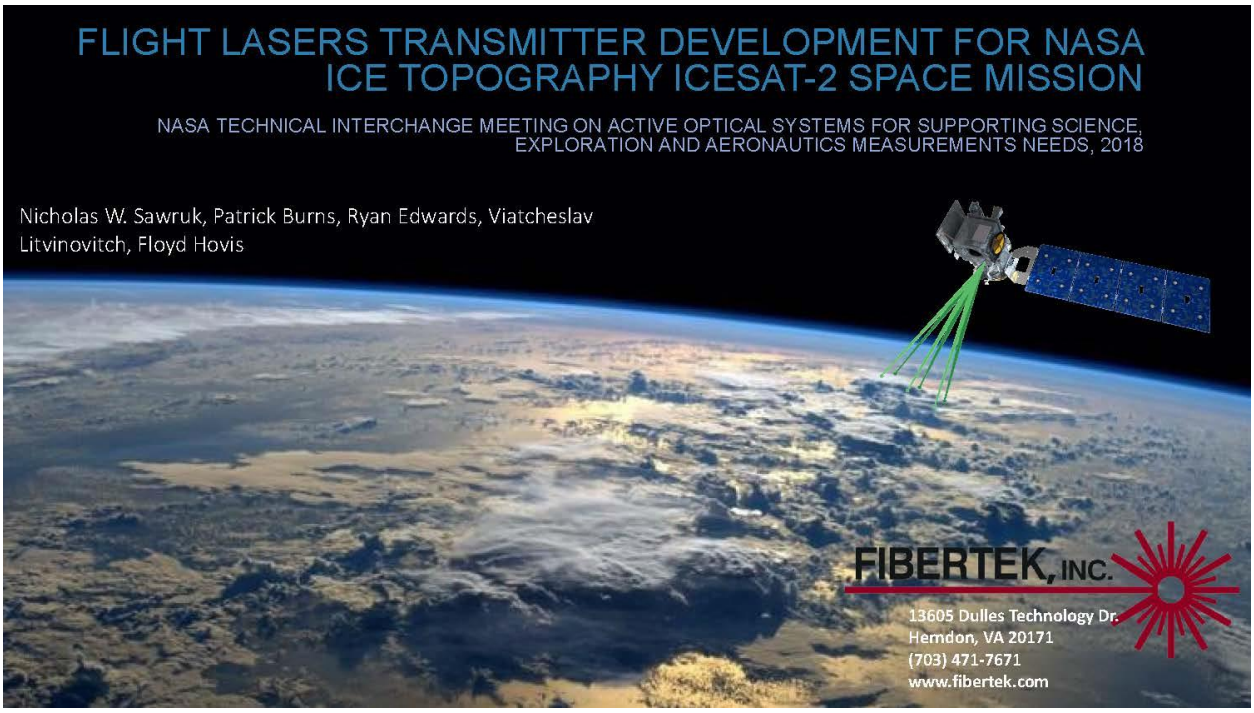
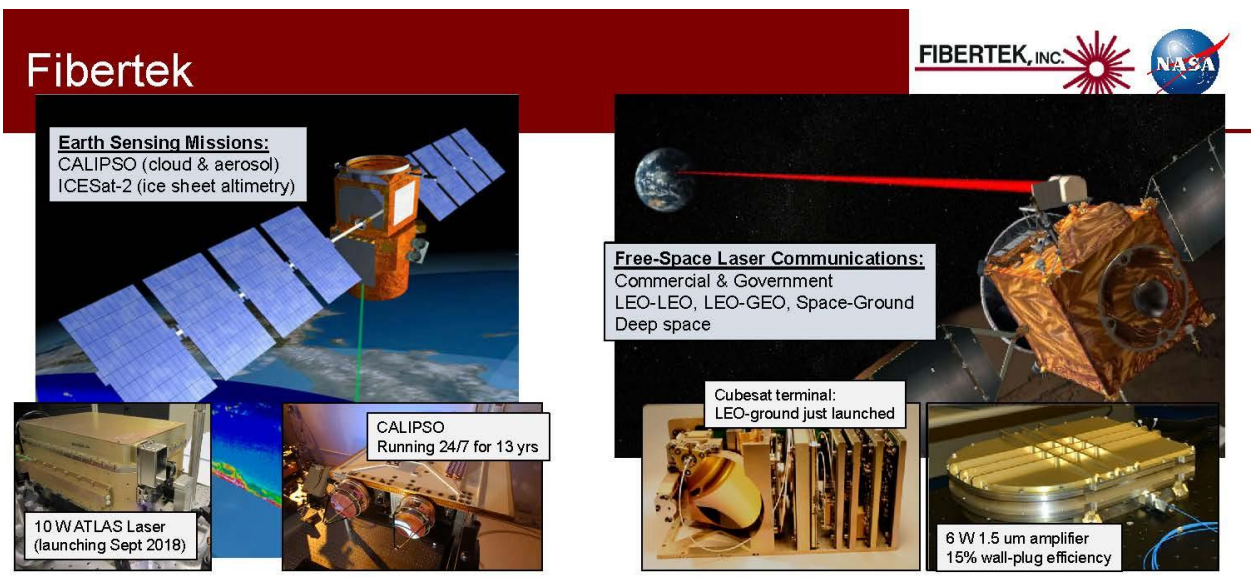




Fibertek has been developing enabling component technologies for active optical systems for space (and airborne and ground) for 30 years.

Presentation Summary



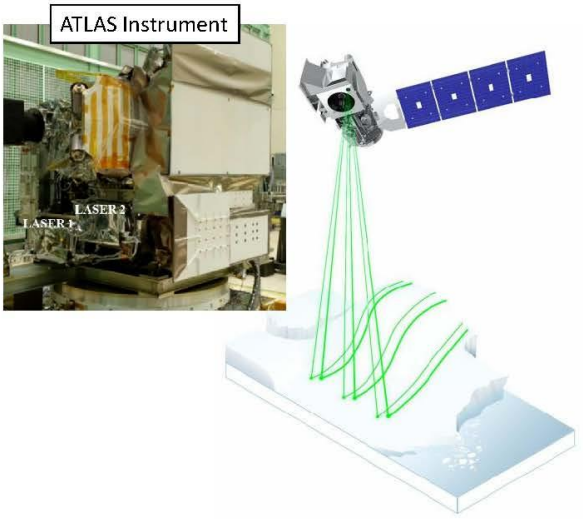
- ICESat-2 Mission Overview
- ATLAS (ICESat-2) Lasers
  - Laser Overview
  - Design Features
  - Driving Requirements
- Noteworthy Program Achievements
  - Pump Diode Space Qualification
  - Correlated Structural Thermal Optical Performance Model
  - Flight Component Supply Chain Management
  - Test Centric Development & Qualification Program
- ICESat-2 Laser Versatility

3

NASA ICESat-2 Mission Overview

Ice Cloud and land Elevation Satellite

- ICESat-2 carries a single instrument – the Advanced Topographic Laser Altimeter System (ATLAS).
  - ATLAS measures the travel times of lasers pulses to calculate the distance between the spacecraft and Earth's surface
  - ATLAS carries two redundant lasers, one primary and one backup.
- The four ICESat-2 science objectives are
  - Measure melting ice sheets and investigate how this effects sea level rise
  - Measure and investigate changes in the mass of ice sheets and glaciers
  - Estimate and study sea ice thickness
  - Measure the height of vegetation in forests and other ecosystems worldwide



4

Fibertek's ICESat-2 Contributions

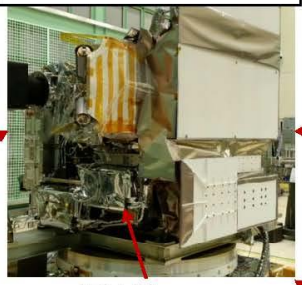
Photon Counting Electronics
RF CFD circuits
(120 PMT Channels)





Altimeter precision relies on wide-bandwidth, high-precision detection circuitry

NASA ICESat-2 ATLAS



ATLAS Lasers



Generates short, high-energy laser pulses for precision time of flight measurement

Start Pulse Detector
Altimeter T_o Signal



Detection of returns is measured relative to high-precision knowledge of the timing for transmitted pulses

Laser Wavelength Control
Electronics (Integrate and Test)

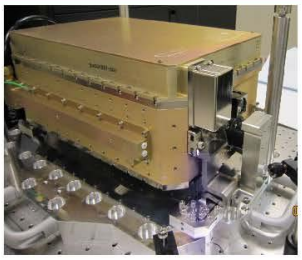


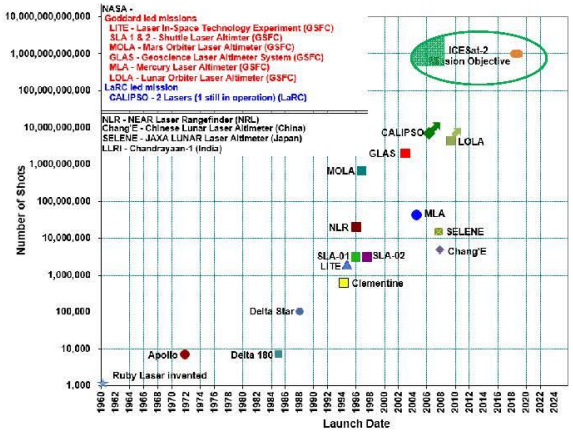
Narrow-linewidth filters suppress solar background, and so suppression of wavelength drift is critical to maintaining signal to noise

Presentation Summary

- ICESat-2 Mission Overview
- ATLAS (ICESat-2) Lasers
  - Laser Overview
  - Design Features
  - Driving Requirements
- Noteworthy Program Achievements
  - Pump Diode Space Qualification
  - Correlated Structural Thermal Optical Performance Model
  - Flight Component Supply Chain Management
  - Test Centric Development & Qualification Program
- ICESat-2 Laser Versatility

ICESat-2 Laser Overview





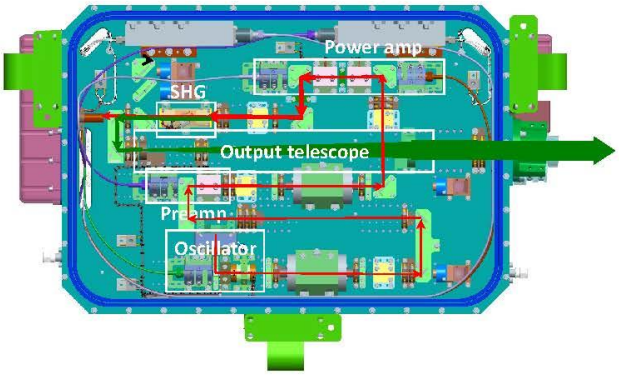
- **Integrated and ruggedized packaging – single unit with power and command inputs and 532 nm photons out.**
  - 30 cm x 50 cm x 15 cm, 19 kg
  - Flexure mounted laser system with hermitically seal laser module and vented electronics module in a single unit.
- **ICESat-2 lasers are State-of-the-Art space qualified lasers simultaneously requiring short pulse width, high average power, frequency tunability, near diffraction limited beam quality and a minimum life time shot count of 1 Trillion shots.**

ICESat-2 mission requires ~3-orders of magnitude more laser shots, with the most stringent wavelength control and temporal pulse width requirements of any NASA spaceflight laser altimeter to date.

ICESat-2 Laser Design Features

- **Short, electro-optical Q-Switched oscillator generating key performance:**
  - Short pulse widths, diffraction limited BQ, 10 kHz PRF, and wavelength tunable w/ narrow linewidth.
- **End-Pumped amplifier chain**
  - Excellent Efficiency (40% Optical to Optical)
  - Preserves beam quality (M^2 ~1.3)
  - Enable by high brightness fiber coupled diode pumps.
- **Pulsed-Pumped w/ variable phasing and pump duration**
  - Energy tuning from 250 µJ to > 1,000 µJ
  - Constant thermal loading, i.e. minimal changes in beam divergence, pointing, & position.
- **High efficiency frequency conversion via critically phased match LBO**
- **Wall Plug Efficiency @ Full Energy: >7%**

1064 nm Master Oscillator Power Amplifier Frequency Doubled to 532 nm



ICESat-2 Laser Driving Requirements & Resulting Enabling Capability

Parameter	Requirement	Flight Lasers	Enabling Lidar Capability
Energy (μJ)	250-900	250-1,370	Required pulse energy for multi-beam (6x) altimeter per laser shot, i.e. single output beam is split into 6 beams providing dense cross track sampling required for surface slope measurements.
Pulse Rate (kHz)	10	10	Fine ground sampling distance, measurements every 70 cm.
Pulse Width (ns)	1.5	<1.3	Fine height measurement resolution.
Divergence (μrad)	<130	91	<1.5x diffraction limited BQ – Minimal illuminated spot on the ground.
Tunable Wavelength (nm)	532.27±0.015	532.27±0.015	Absolute wavelength tunable to match etalon receiver transmission – minimizing background contributions.
Linewidth (pm)	<30	<5	Enables a narrow linewidth receiver filter – minimizing background contributions.
Efficiency	>5%	8.2%	High efficiency – reducing spacecraft thermal management & power distribution requirements.
Operational Run-Time	3.5 years (> 1 T shots)	Life test Lasers (> 1 T shots)	Demonstrate reliability required for long duration lidar missions – allows for long term trend measurements.

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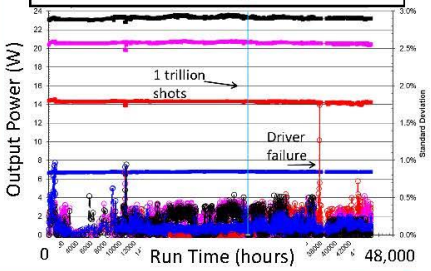
Laser Diode Pump Module Qualification

Component Qualification	Component Certification	Module Certification	Module Qualification	Module Capability Testing
Qualify component reliability and robustness in terms of particular mission requirements. **GOAL: Demonstrate plausibility the system will satisfy mission environmental and reliability requirements.**	Lot certification of components used in module builds. If lot certification is not feasible, 100% screen and select. **GOAL: Certify all components used in flight modules are of the highest quality and free of anomalies.**	100% test & screen of modules required. **GOAL: Certify modules for the mission via 100% unit testing and screening.**	Qualify a subset of modules to demonstrate reliability and robustness in terms of particular mission requirements. **GOAL: Demonstrate module design is capable of meeting the mission environmental and reliability requirements.**	Capability testing above and beyond mission requirements to demonstrate design margin. **GOAL: Demonstrate and understand the module's headroom above mission requirements.**
Subset of Components for Flight Modules	**100% of Components for Flight Modules**	**100% of Flight Modules**	**Subset of Certified Modules**	**Subset of Qualification Modules**
Radiation Testing	Lot Certify Components	Lot Certify if Possible or 100% Test & Screen	Environmental Tests (Vibe, Shock, Thermal, Radiation, etc.)	Test Subset of Modules to Failure (or sufficiently beyond mission requirements)
Component Accelerated Life Testing	Chiplet Burn-In	Acceptance Level Environmental Tests		
Compliant w/ Operational Environment (high vac, etc.)	Pedigree Review	Additional Module Burn-In At Elevated Conditions		
Chiplet Multicell Testing	Active Component Burn-In (fibers, optics, etc.)	Detailed Pedigree Review (Out of Family Modules Discarded)		

N. W. Sawruk, et al, "Space certification and qualification programs for laser diode modules on the NASA ICESat-2 Mission," SPIE 8872, 2013.

Diode Life Test (QTY 4 Units)

<0.5 % drop in output power over >45,000 hrs & 1.6 trillion shots -- 1.6 times planned mission life.



A test centric diode laser space certification program consisting of several key phases including a technology plausibility study, component and LDM pedigree reviews, and environmental acceptance was developed and successfully executed.

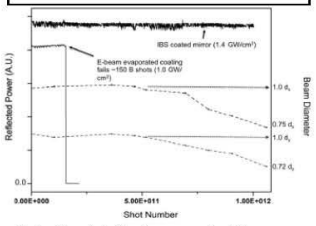
This program is well documented & adaptable to future space missions.

Supply Chain Management of Optical Components for Space

- **Space qualified optical components are not a commodity, lacking industry accepted standardized processes and/or certification procedures common to electronic components for space applications.**
  - Typically small companies with relatively high turn over and consolidation rates complicate reuse of the developed supply chain.
  - Optical component supply chain management is challenging requiring a balance between design updates and maintaining an established process.
- **Optical coating technology, lot certification and qualification.**
  - Vendor survey & down select based on coating requirements.
- **Faraday Rotators compatible with environments were not commercially available.**
  - Incompatible materials, not vacuum compatible and not robust to GEVS random vibe.
  - Worked closely with the rotator vendor and collaboratively upgraded the rotator design and executed a qualification program.

IBS & e-beam vs Shot Count

e-beam damaged @ ~150B shots



D. Poulios, et al, "Performance of multilayer optical coatings under long term 532 nm laser exposure," *Proc. SPIE 8885*, 2013.

Faraday Rotator

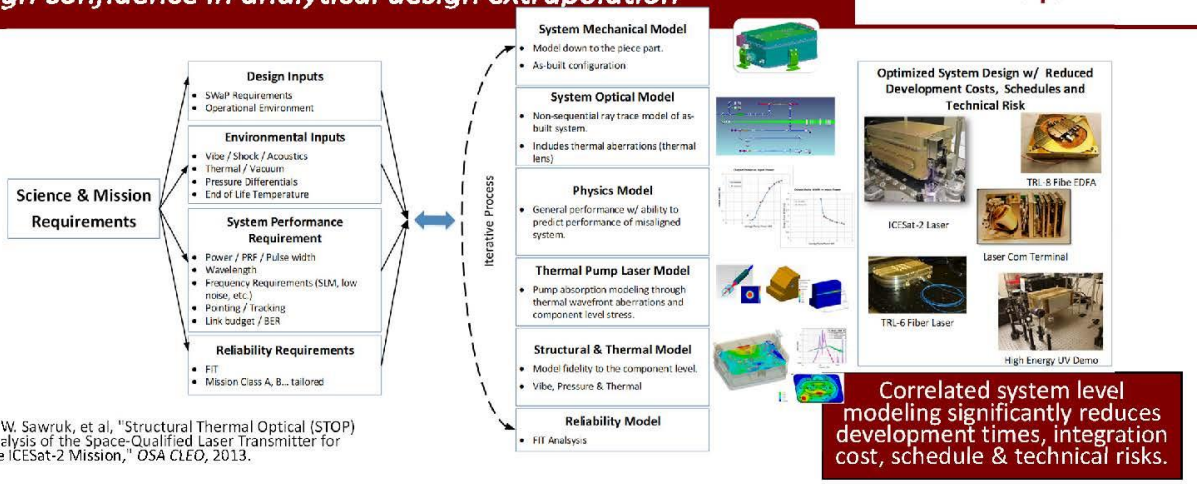
Space-Qualified



Fibertek & NASA successfully developed screening procedures and guided designs of key optical components from commercial vendors.

Correlated Advanced Analysis Capabilities

High confidence in analytical design extrapolation



N. W. Sawruk, et al, "Structural Thermal Optical (STOP) Analysis of the Space-Qualified Laser Transmitter for the ICESat-2 Mission," *OSA CLEO*, 2013.

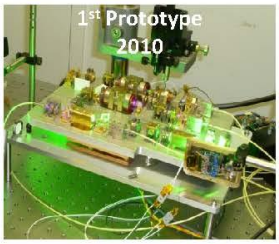
Correlated system level modeling significantly reduces development times, integration cost, schedule & technical risks.

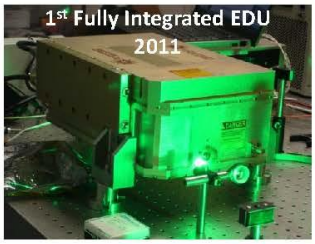
The ICESat-2 Structural Thermal Optical Performance model was validated using sub-system and full system test units resulting in robust flight lasers meeting all performance requirements.

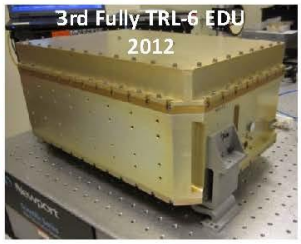
The modeling tools are well documented and applicable to future space qualified laser programs.

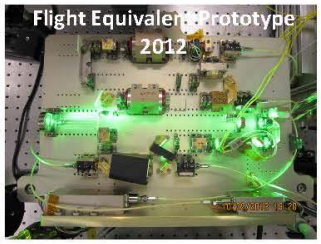
Robust & Systematic Laser Development Program

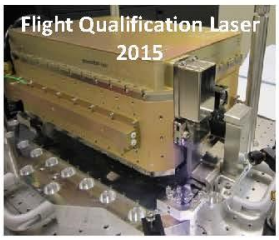
Test-Centric Development Program













- Incremental design changes validated via analysis and system level testing.
- Several full system life tests completed demonstrating the 27,000 hour mission life requirement.

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ICESat-2 Laser Derived Technologies

Derived Technology	Capabilities	Utility
Short Pulse Width Master Oscillator	Ruggedized packaging of the short pulse width oscillator for SWaP constrained lidar missions (200 µJ, 10-25 kHz, <1.1 ns).	Planetary landing lidars, laser range finders for proximity operations, short range topology lidar.
High Power Bulk-Solid State 1064 nm Amplifiers	Scalable & reliable 1064 nm amplifier chain to average powers >100 W, peak powers > 1 MW, and PRFs kHz to CW. Supports efficient amplification of single frequency input, swept waveforms and excellent beam quality.	Supports a wide variety of lidar missions requiring > 1 kHz Pulse Repetition Frequencies. 1064 nm engine for NLO stages providing wavelength diversity from the UV to IR.
High Efficiency Space Qualified Electronics	FPGA Laser Controller, high efficiency (>85%) pulsed diode drivers, energy monitors and high voltage QS driver.	Designs leveraged across Fibertek laser programs – reduced development and qualification costs.
Ruggedized Packaging	Conductively cooled (w/ no internal heat pipes) and flexure mounted packaging designed for GEVS random vibration.	Quick adaptation of design updates using correlated modeling tools – reduced development schedules and cost.

The ICESAT-2 laser is versatile and adaptable to wide a performance envelope enabling future lidar mission capabilities.

Fibertek's Space Systems Business
Perspective & Challenges

- **Fibertek's core business is developing and delivering space-qualified electro-optical systems including electronics, lasers and optical communication terminals.**
  - We are committed to serving the NASA active sensing community.
- **Our focus on primarily custom work provides a rich technology portfolio and advanced engineering know-how.**
  - Fibertek has a unique partnership with NASA's active sensing community through continuous technology and TRL advancements on SBIR/STTR, Risk Reduction, ACT, & etc. programs.
  - Our business model is compatible with volatility of the space business and is supplemented with synergistic DoD and commercial programs.
  - Well communicated technology roadmaps, continuous development funding and SBIR/STTR participation allows for more predictable and stable business volume – NASA does this well.
- **Corporate memory must be maintained by developing designs and processes that can be used on other projects mitigating the loss of know-how over the relatively long times between flight missions.**
  - Developed & documented rigorous SMA program as part of ICESat-2 which will be tailored for future programs.
  - ISO 9001:2015 certified procedures – documented quality manual, processes and procedures.
  - Increasing mobility of personnel is an additional motivator for process development.
- **Pool of lidar scientists and engineers is limited – especially for space systems.**
  - The DoD Directed Energy Community provides a great example of a focused education out reach program fostering professional growth of current workers and providing education opportunities of the future DE researchers and engineers.

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ICESat-2 Laser Summary



- The overall program carried out the goal of space-qualifying a next generation laser capable of over 1 trillion, >600 kW peak power, 532 nm pulses in a near-diffraction limited beam.
  - The flight spare laser and qualification laser will continue life-testing post launch on the ground providing insights into the long term operation of the flight lasers.
- The ICESat-2 laser program was a successful collaboration between Fibertek, NASA and other industry partners.
- The lasers were fired for the last time prior to launch and final launch preparations are in progress.
  - ICESat-2 is on schedule to launch Sept 2018 out of Vandenberg Air Force Base in Southern California.
- We are ready for and looking forward to the next space mission!





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4.3 DEVELOPMENT OF THE SOLID-STATE LASER SYSTEM FOR THE GEDI MISSION

Paul R. Stysley[1], D. Barry Coyle[1], Erich A. Frese[2], Furqan L. Chiragh[3]

[1]NASA Goddard Space Flight Center, Laser and Electro-Optics Branch, Greenbelt, MD 20771
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ABSTRACT

The Global Ecosystems Dynamics Investigation Mission will employ 3 lasers systems internally developed, built, and tested by the NASA Goddard Space Flight Center. The lasers are a heritage Nd:YAG solid state design required to put out Q-switched pulses at a rate of 242 Hz with a minimum 10 mJ per pulse at a 1064 nm wavelength. We report on the technical and programmatic development plan and lessons learned that lead to the successful delivery of the flight lasers.

1 INTRODUCTION

The Global Ecosystems Dynamics Investigation (GEDI) Lidar Mission is a cost-capped class C mission part of the NASA Earth Venture Instrument program. Once installed on the Japanese Experiment Module (JEM) on the International Space Station (ISS), the lasers, each coupled with a Beam Dithering Unit (BDU) will produce three sets of staggered footprints on the Earth's surface to accurately measure global biomass. A multi-beam waveform generated from the laser returns will provide the ground elevation and vegetation canopy height and structure measurements on a global level [1]. These 3D data products are based on those that have been provided by the Land, Vegetation, and Ice Sensor (LVIS) facility on airborne lidar missions [2]. The GEDI instrument, at time of this publication, has been allocated a mass of 600 kg and volume of 1.7 m x 0.8 m x 0.866 m. It is planned to launch on a Space-X Dragon 9 vehicle in late 2018.

The GEDI lasers use the High Output Maximum Efficiency Resonator (HOMER) architecture, which was successfully designed and qualified by the Goddard Space Flight Center Laser and Electro-Optics Branch. The design was first conceived during the Vegetation Canopy Lidar (VCL) mission, matured through the Laser Risk Reduction Program (LRRP), and demonstrated Technology Readiness Level (TRL) 6 successfully during the Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI) mission before the GEDI mission was proposed [3]. The final flight version of this laser design was exhaustively modeled, carefully developed, characterized, and finally environmentally qualified to ensure their ability to survive the extreme vibrational and thermal stresses of launch and long term operation during the mission.

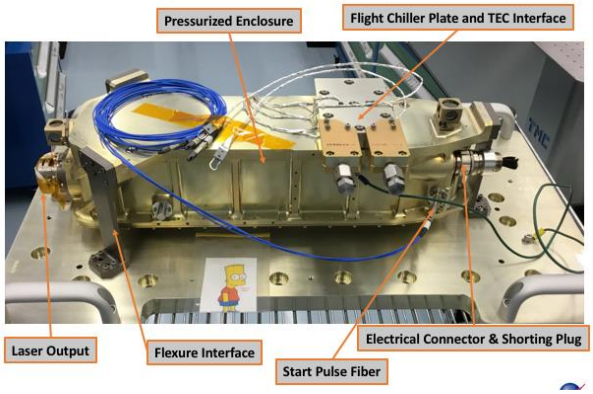

Figure 1: Flight GEDI Laser before delivery to the instrument

2 DESIGN OVERVIEW

2.1 DRIVING REQUIREMENTS

The driving laser requirements for the GEDI mission are shown in Table 1. The laser design was already TRL-6 qualified using GEVS standards when the mission was being formulated. This greatly informed the requirements flow down and allowed for informed modification of any performance specifications.

Table 1: Requirements used to drive qualification testing of the GEDI laser system

Requirement	Value
Wavelength	1064.5 nm ± 0.2 nm in vacuum
Output Energy	10 - 11.5 mJ fully captured beam at the output
Polarization	≥ 300:1
Far Field Div.	0.60 mrad ±0.08 mrad $1/e^2$
Pulse Energy Concentration	≤ 0.5% of $1/e^2$ central lobe per energy concentration
Pulse Rate	242 +/- 2 Hz

Pulse Width	≤ 16 ns full width half max
Lifetime	3.61 Billion Shots
Temperature	Operational and Qual 35°C±2°C (Diode set). Survival -10°C and 50°C.
Mass	≤ 10.5 kg

2.2 Flight Delivered State of the Art System Overview

The GEDI laser overview and interface summary can be seen in Figure 2. The laser assembly is primarily a pressurized aluminum enclosure 20.5" x 6.3" x 9.2" and 9.3 kg. The enclosure includes 3 titanium flexures that interface with the instrument optical bench. On the outer part of the enclosure is an optical assembly, consisting of a beam expander and Risley pair coupled with a half waveplate. This is used to align to the polarization sensitive BDU and the rest of the GEDI transmit path. Also on the enclosure is a chiller plate and Thermal Electric Cooler (TEC) that will hold the diodes to +/- 1 degrees Celsius. Inside the enclosure is the laser cavity, optical bench, and pump module. Also inside the enclosure includes, but is not limited to, the high voltage Q-switch electronics, start pulse pick-off, and internal telemetry sensors. Electrically, the laser primarily interfaces with the Laser Electronics Unit (LEU), which provides the Q-switch voltage and trigger along with diode current.

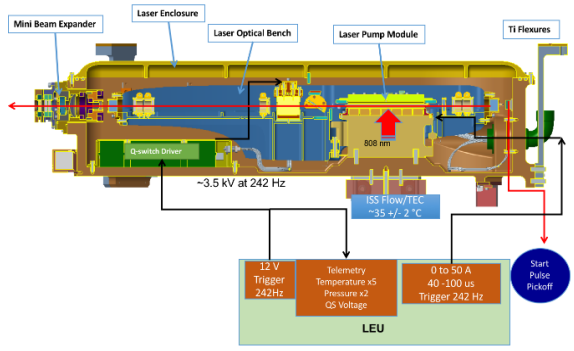

Figure 2:GEDI Laser functional interface overview

2.3 Development Approach

The development approach of the GEDI laser systems relied heavily on the heritage of the HOMER laser design summarized in Figure 3. This laser was designed in response to concerns about laser reliability, part count, and efficiency. Design decisions always begin with established models and are proven via the model output with bread board level experimental results. From there, the TRL can be matured carefully. The HOMER-1 EDU was a hardened breadboard unit that successfully completed a life test of over 2 billion shots in 2005. The TRL-6 engineering unit HOMER-2 completed GEVS environmental testing and a 15+ billion shot life test in 2012 [3]. Trade studies using HOMER on earlier programs or during the GEDI program emphasized avoiding change to preserve the heritage of the design. Any minor changes studied would be sure to avoid effecting more than one item in the system at a time. From there, the model could be modified to bound the effect of the change and then be confirmed again on the bread board units. As HOMER matured, those changes could then be iterated and studied in the engineering units to confirm performances from a more advanced systems perspective.

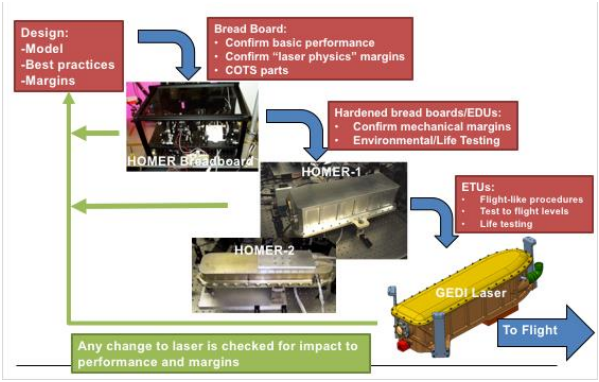

Figure 3: Overview of the GEDI flight development approach using HOMER class laser engineering units

Extensive component-level testing was also performed on the HOMER laser over time. Higher risk components were identified either through experimental results or lessons learned on other projects. Performance and environmental testing was then conducted on parts such as the diodes, laser slabs, and output coupler to burn down any risk. The component-level testing would be a collaborative effort between the laser team, the electro-optics branch, the Goddard Space Flight Center (GSFC) parts group, and various vendors.

2.4 Risks and Rewards

The HOMER laser development approach was inherently conservative and risk-adverse, focusing more on preserving TRL-6 heritage and long term performance of the system over the mission vs pushing technical envelopes. The primary

advantage of this approach; that the project can have very high confidence in the reliability of the laser system, cannot be over emphasized given the often problematic history of qualifying space flight lasers. When performance questions of the laser inevitably arose, the laser team or project leaned on a long history of experimental data and directed often difficult decisions. The primary downside was that the trade space for the HOMER laser was often closed or limited due to the priority of preserving the designs TRL status. Better technical choices from a purely laser physics perspective could be rejected in order to maintain consistency in performance with the heritage designs.

3 PROGRAMMATICS

3.1 DEVELOPMENT PLAN

The GEDI mission was awarded as a $90M cost capped mission using the HOMER class laser system. The HOMER laser was already successfully developed at GSFC during various programs mentioned in section 3.2 and had completed TRL 6 testing. Starting with a TRL-6 laser allowed the project to significantly reduce both cost and risk for the mission when finalizing the flight development plan. This included the delivery of one engineering test unit (ETU), three flight units, one flight spare, and all associated ground support equipment (GSE) for a final cost of approximately $10M. In order to close any open trades, prove out flight procedures and test plans, the GEDI mission built, qualified, and life tested an ETU. As a result, the flight build plan replicated the ETU effort while folding in all lessons learned. Figure 4 gives an overview of the ETU and flight development flow.

For all the deliverables, parts were purchased and fabricated using flight safety and mission assurance standards. Flight procurement was initiated as soon as the ETU acceptance testing was completed to a level where any lessons learned could be levied. As soon as parts arrive they immediately went through a comprehensive acceptance testing process which was heavily base on past component level testing on the HOMER laser or past project. Final acceptance required the approval from the GEDI team including input from various discipline leads, Systems Engineering, Quality Assurance, and external independent reviewers as needed.

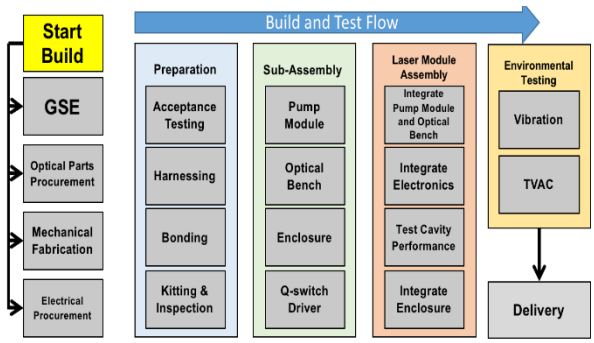

Figure 4:GEDI laser development flow

The sub-assembly of the laser is divided into four major areas: the enclosure, pump module, optical bench, and Q-switch driver. Each section could begin assembly independently allowing for significant schedule savings. Once all four sub-assemblies were completed they were fully integrated to form the laser module assembly. Full assembly and environmental testing of the flight lasers started once the ETU completed environmental qualification and initiated life testing. From here the laser assembly's performance was baselined against requirements and compared to the ETU's. Environmental testing was then successfully completed for each flight unit including vibration and Thermal Vacuum (TVAC) testing [5].

3.2 DEVELOPMENT MILESTONES AND DATES

The HOMER laser has been thoroughly studied and reviewed over the past 15 years, with very few changes in the overall optical design. Through these milestones, we have developed a results/success-based methodology of solid state laser development that achieves the highest confidence possible with any new application.

All hardware, optical, and operational decisions or modifications required laboratory demonstration and verification, with mathematical modeling support.

Table 2: Laser system delivery milestone summary

Program	Laser	Milestone Date
Laser Risk Reduction Program (LRRP)	HOMER-1	May 2002
TRL 6 Review	HOMER-2	January 2009
GEDI Start	GEDI Laser	November 2014

GEDI ETU Environmental	GEDI Laser-ETU	January 2016
GEDI Life test goal met	GEDI Laser-ETU	August 2017
GEDI Vibration	GEDI Flight	December 2017
GEDI TVAC	GEDI Flight	February 2018
GEDI Laser Delivery	GEDI Laser-Flight	March 2018

3.3 PARTNERING

Partnering with both internal GSFC organizations and outside vendors was key to the successfully development of the GEDI flight lasers. The laser mechanical and thermal designs were matured completely with the assistance of GSFC Code 540. Optical qualification was performed with help of Codes 551 and 562. Laser diode down-selection and qualification was accomplished using well-established Code 554 evaluation capabilities in collaboration with the vendor. The flight laser electronics were developed by a vendor with a long relationship with GSFC and monitored by Code 563 as a deliverable to the laser team.

As part of the development philosophy and programmatic limitations, the GEDI laser team relied on the vendors of various components to provide appropriate test data of their flight parts in order to assure appropriate reliability and performance of the flight units. Special focus was applied to the Q-switch optics, gradient reflectivity mirror, laser slabs, and laser diodes. A working relationship was already established with the vendors which included requiring testing that was identical to experimental setups at GSFC or site visits where GSFC personnel was comfortable with the test equipment the vendor had available. This created a qualification plan where vendor data could be trusted and "science projects" resolving any discrepancies to a minimum.

4 FUTURE VISION

Since three lasers have been successfully delivered to the GEDI project, this fundamental design can be considered for future projects as part of the Center's portfolio. If requirements are flowed down early on, design modifications can be implemented with robust testing and high confidence. Immediate modifications would include reducing the size of the cavity and pump module. This design has high diode operational derating that could be modified to boost efficiency and reduce the footprint of the system.

5 CONCLUSIONS

All three GEDI laser systems successfully completed the flight test plan with acceptable performance across all requirements. Knowing that the qualification of a space flight laser can be challenging, the GEDI instrument team was careful to design margin into the system so that there would be flexibility to adapt to any non-conformances found during laser testing. As a result, the GEDI project can be confident the lasers will produce an invaluable, multi-year, 3D global biomass data set.

Acknowledgements

The authors would like to acknowledge the GEDI project, GSFC, the individual component vendors, and all the past projects mentioned in the paper for continuing to support the laser and making the successful flight delivery possible.

References

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2. Blair, J. Bryan., "Laser Vegetation Imaging Sensor," https://lvis.gsfc.nasa.gov.
3. Paul R. Stysley, D. Barry Coyle, Greg B. Clarke, Erich Frese, Gordon Blalock, Peter Morey, Richard B. Kay, Demetrios Poulios, Michael Hersh, "Laser production for NASA's Global Ecosystem Dynamics Investigation (GEDI) lidar," Proc. SPIE 9832, Laser Radar Technology and Applications XXI, 983207 (13 May 2016).
4. Stysley, Paul, et. al, "Long term performance of the High Output Maximum Efficiency Resonator (HOMER) laser for NASA's Global Ecosystem Dynamics Investigation (GEDI) lidar," Optics & Laser Technology 68, 67-72 (2015).
5. Stysley, Paul, et. al, "Qualification of the solid state laser systems for the GEDI altimeter mission", Proc. SPIE 10636, Laser Radar Technology and Applications XXIII, 106360U (10 May 2018).

Development and Flight Qualification of the Global Ecosystem Dynamics Investigation (GEDI) Laser Transmitters

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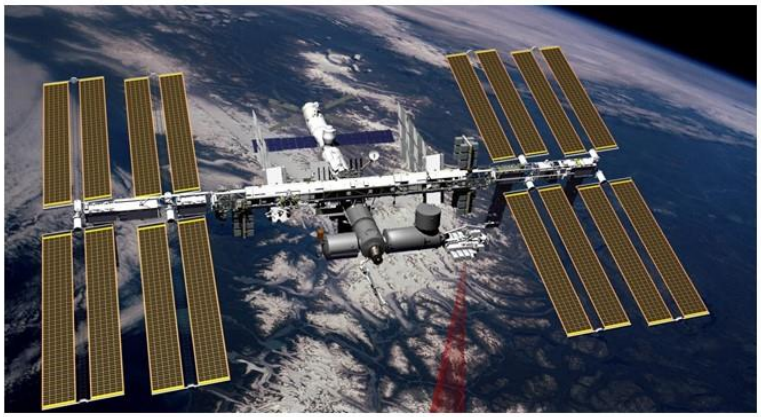
[b]ASRC, 7000 Muirkirk Meadows Dr #100, Laurel, MD, 20707
[c]Velos, Princess Anne, MD 21853

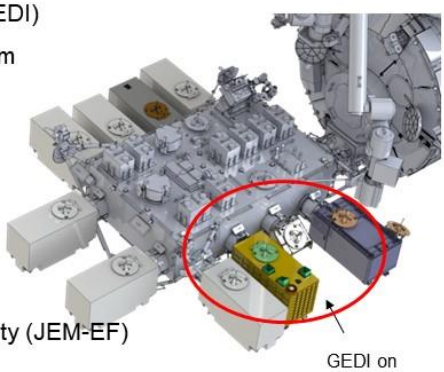


1

GEDI Mission Overview

GEDI Mission Overview (to date)

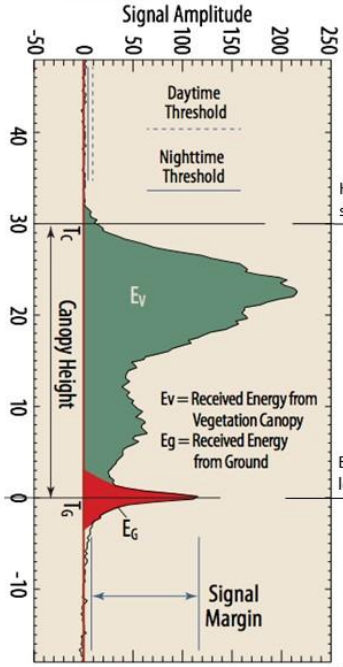
- Global Ecosystem Dynamics Investigation (GEDI)
- NASA Earth Ventures Instrument (EVI) program
- $90M, cost capped, "PI-Led" mission
- Class C, 2 year mission
- Multi-beam waveform Lidar experiment
- Launch Vehicle:
  Space-X Falcon 9/Dragon, or equivalent
- Platform: International Space Station
- Japanese Experiment Module- Exposed Facility (JEM-EF)
- Orbit: 415 km average; 51.6 degrees
  (440 km, max altitude; 447 km, max range)
- Payload / Allocations: 527kg / 600 kg.; 590W / 800 W; < 10 Mbps
- Planned 2018 launch



GEDI on JEM-EF

2015	2016	2017	2018		2019	2020
SRR 6-15	PDR 4-16	CDR 1-17	PER 8-17	PSR 5-18 / LRD 8-18	Primary Mission: 365 Days of Science Collection	Extended Mission to Account for ISS Induced Downtime

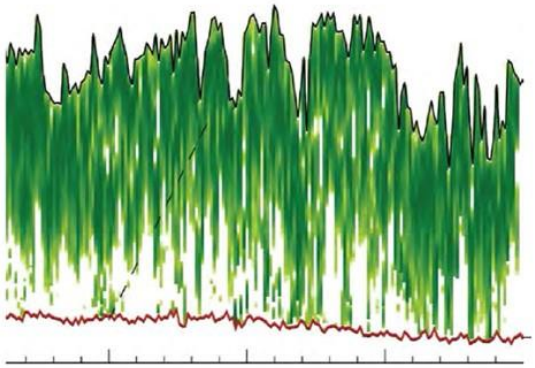
Waveform Altimetry for Global Biomass Volume



Full-waveform lidar is the **only remote sensing technique** that has demonstrated the ability to provide 3D canopy profile information at the required resolution and accuracy across the full range of canopy cover, density, and environmental conditions.

Highest reflecting surface elevation

Elevation of center of lowest mode



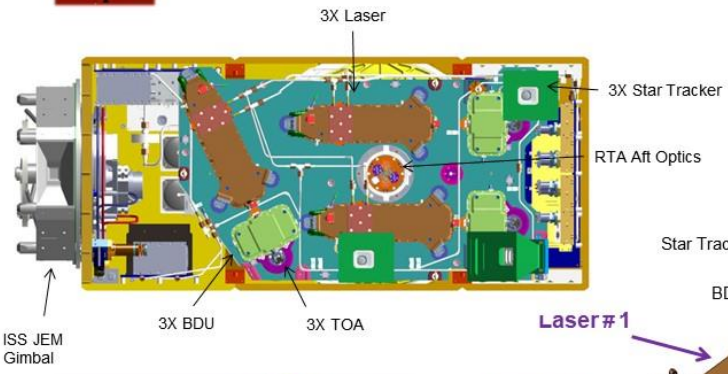
Canopy Profile From Lidar Waveforms

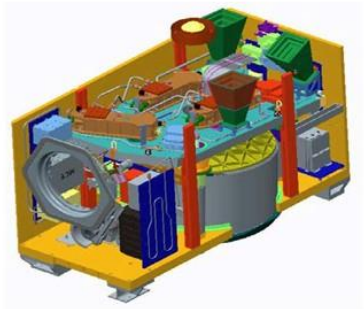
Each of GEDI's 8 laser tracks will generate 3D profiles of vegetation vertical structure, even in the world's densest canopies.

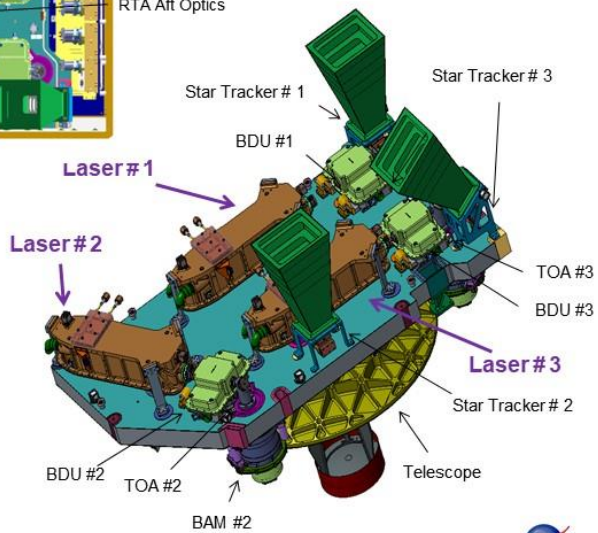
J. F. Weishampel, et. al., Volumetric lidar return patterns from an old-growth tropical rainforest canopy, Inter Journ of Remote Sensing, 21:2, 409-415

4

GEDI Top Level View







Global Ecosystem Dynamics Investigation (GEDI)

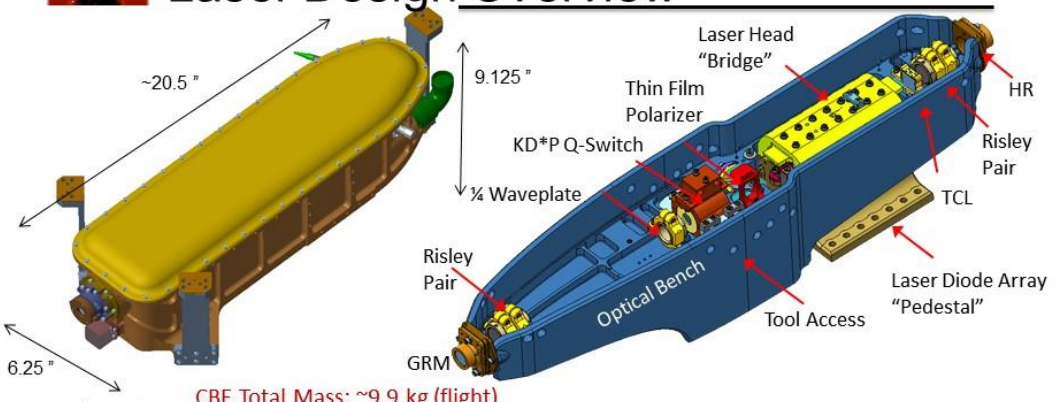
GEDI Laser Overview



GEDI Laser ETU and Flight Hardware Deliverables

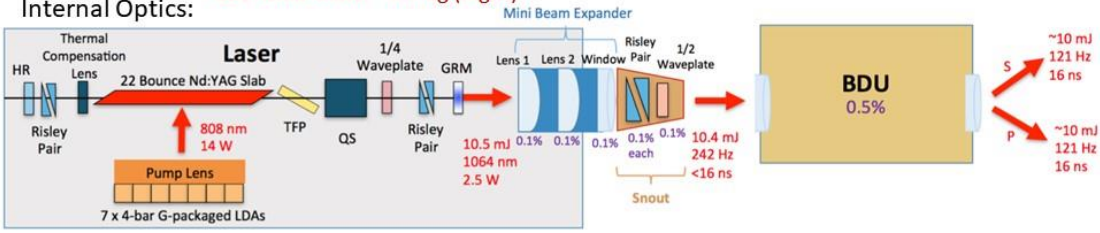
Type	Model Build	Purpose of Model	Facility and GSE	Build Strategy Plan
ETU Qty 1	Qual unit with flight parts	• Flight design • Flight qual testing (vibration, TVAC, EMC) • Finalize flight build procedures with core team • Implementing improvements from HOMER-2 effort • Interface test with BDU and LEU • Comprehensive performance tests (CPT) and life test	GSFC Bldg. 33/H009 GSE required: Beam imaging system, laser diagnostics, digital oscilloscope, laser drive electronics, thermal control, housekeeping sensors, CPU and software. Opto-mech infrastructure for ETU assembly and lifetest.	Labor- In-house laser build using primarily 554 labor and support as needed. QA – Limited. As needed to improve procedures for flight. ME Parts - Purchased with flight traceability and acceptance testing. EEE Parts – HV QS driver boards will be procured by 563. EEE parts approved by Parts group. Optical Parts – Purchased with flight traceability and acceptance testing.
Flight Qty 3	Flight deliverable	• Flight design • Flight qual testing and CPT (vibration, TVAC) • Implement procedure finalized on ETU	GSFC Bldg. 33/SLAC GSE required: (Same as ETU) X 3 Qty 1: Reference opto-mech and reference system for pre-post vibe tests.	Same as above but with additional QA as prescribed.
Spare Qty 1	Flight unit but will not fly	• Flight design • Flight CPT • Flight environmental optional • Implement procedure finalized on ETU	GSFC Bldg. 33/SLAC GSE required: Same as ETU.	Same as above but with additional QA as prescribed.

Laser Design Overview



CBE Total Mass: ~9.9 kg (flight)

Internal Optics:

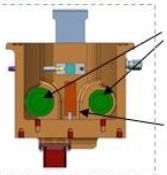


Laser Interface Overview

EICD: GEDI-ELEC-ICD-0009,
GEDI-ELEC-ICD-0017
TICD: GEDI-THRM-ICD-0007
MICD: 2275600
OICD: GEDI-OPT-ICD-0006

Electrical

Start Pulse (1x3 x 200 um fiber bundle)



Hermetic Connectors

Pressure Sensor Board

Optical

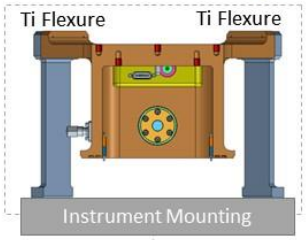
Output to BDU
1064 nm, 242 Hz,
~10.4mJ, <16 ns

SP Pickoff Reflector

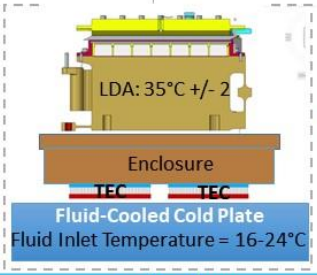


- **QS Driver:** 12 V DC Power, 242 Hz Trigger (3-4 kV to QS)
- **Diode Current Pump Pulse:** 35 us- 65 us, 0A-60A

Mechanical



Thermal



TEC Temp

DC Control Voltage to TEC

LEU (Diode driver, TEC controller)

Telemetry:

1. Pressure sensors (x2)
2. QS Temperature (AD590s), QSD PCB Temperature, QS HV Monitor
3. Laser temperature sensors (10k Thermistors x5)

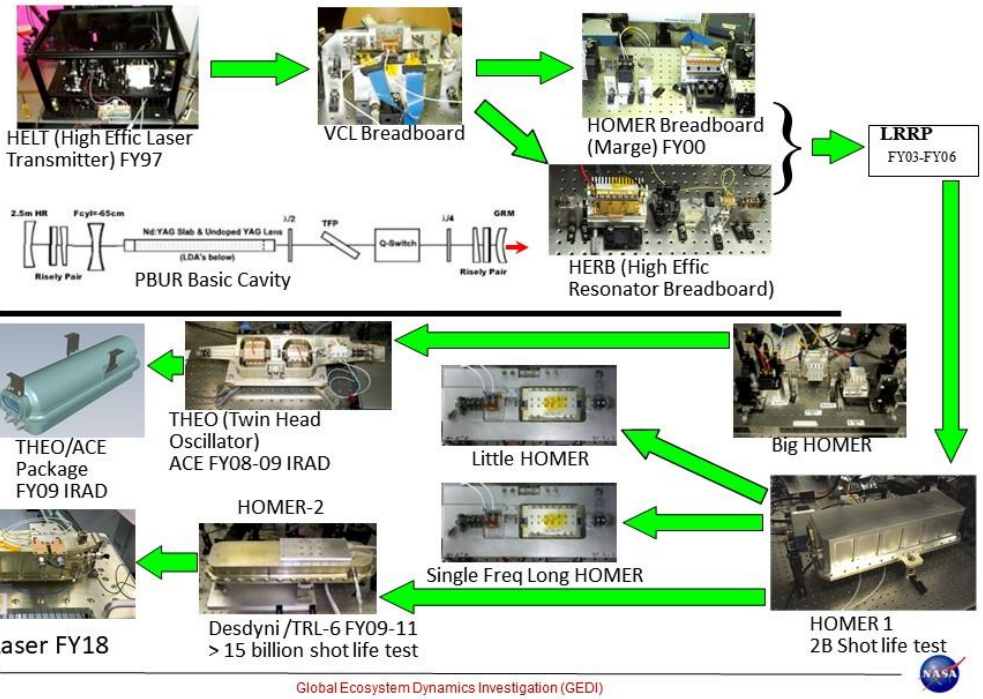
Controls Temp Range

IEU

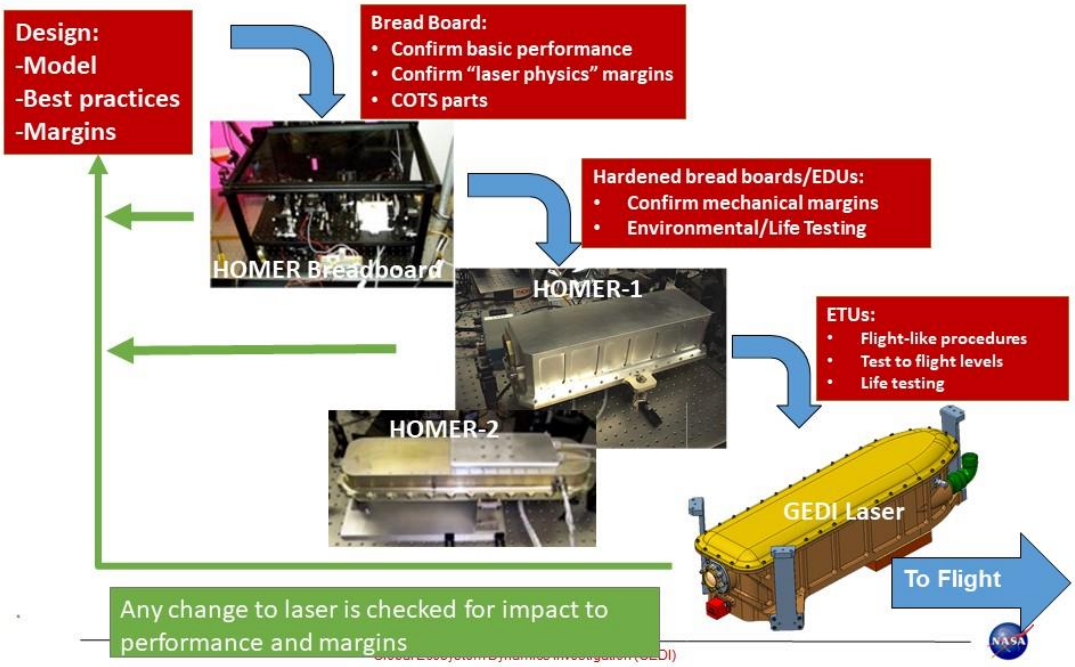
Coolant Flow

LEU – Laser Electronics Unit
IEU – Interface Electronics Unit

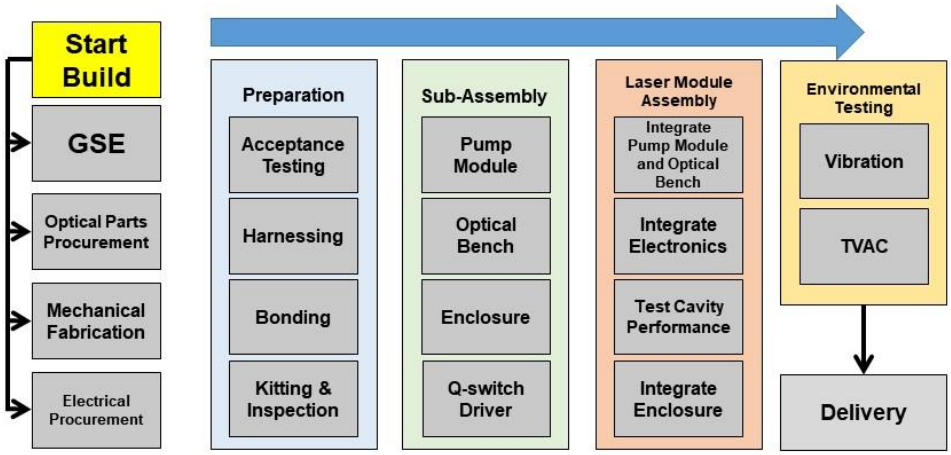
The High Output Maximum Efficiency Resonator (HOMER) Family Tree



HOMER Class Heritage and Philosophy



Flight Laser Development Flow

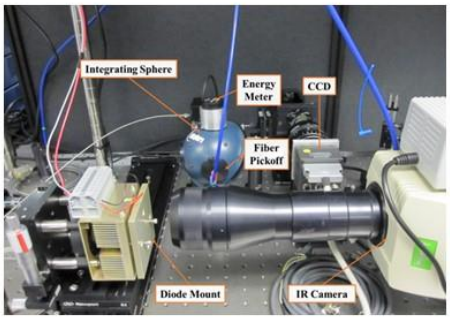


Note: ETU development plan was identical except it included life testing. ETU life testing completed mission life time of 3.6 billion shots at spec before flight environmental testing. Total life test shots to date is over 8 billion.

Component Level Testing

Laser Diode Array Testing



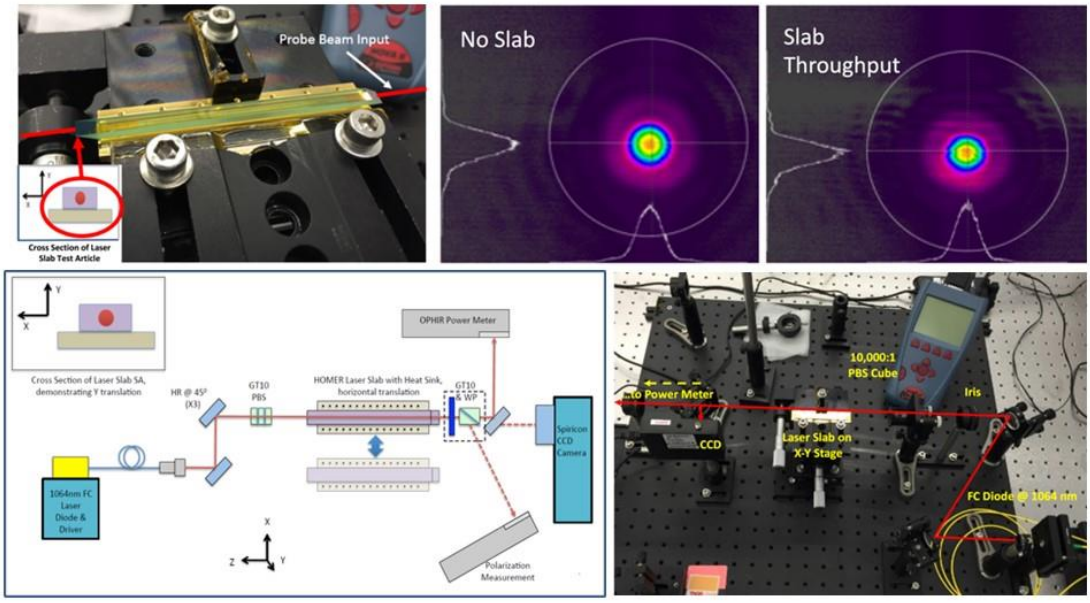


- Characterization/acceptance testing performed on all units
  - Energy
  - Peak Wavelength
  - Hot Spots
- DPA on spare units
- Life Tested ETU spares 4.3B shots before flight units
- Spare Flight Unit Life Test Shots = 5.54 Billion w/ 34092 ON/OFF Cycles
- Negligible loss in performance.



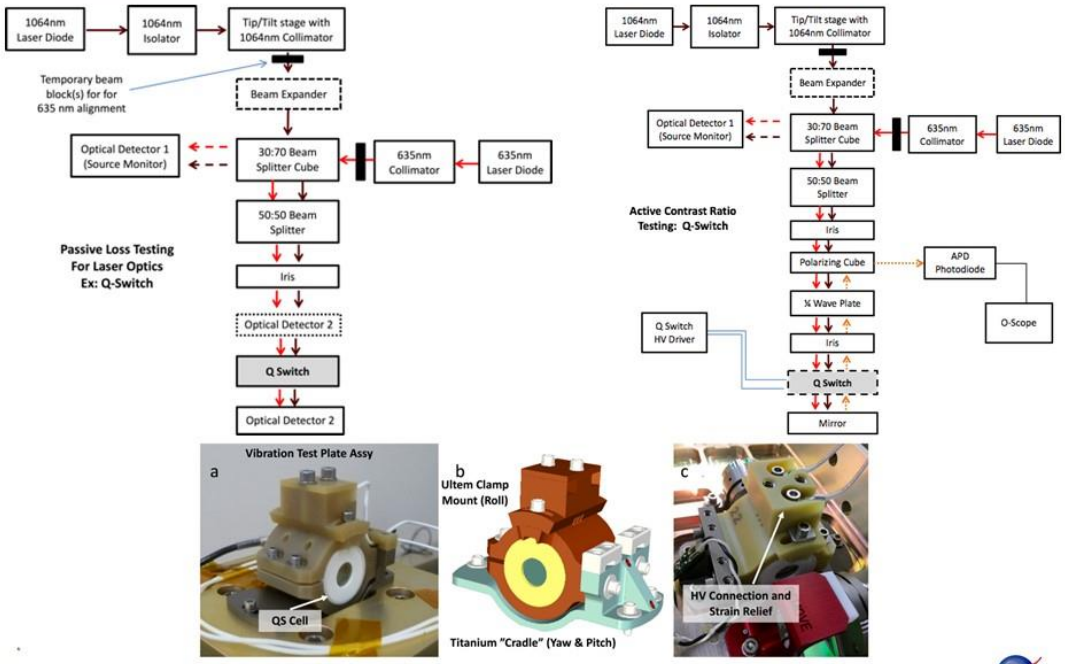
Results: Any laser diode array risk was abated with high derating settings, comprehensive acceptance tests, and successful life test.

Nd:YAG Slab Test Setup



Note: Identical setup used by vendor to check final cuts and quality before delivery

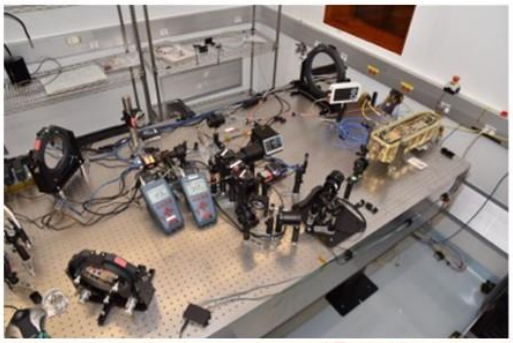
Optics Inspection & Testing



Test GSE and Facilities

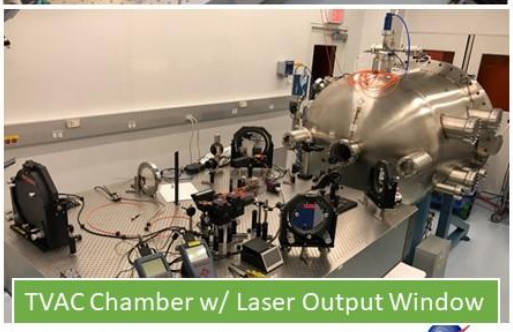
GSFC Space Laser Assembly Center (SLAC)

- Class 1K Cleanroom
- 3 Labs Including: TVAC, Laser Lab, and Prep/Inspection Room
- Designed for Laser Safety
- Optomechanical and Optical Inspection Part of Facility
- 10k Cleanroom Next Door to Support ETU and Optics Testing
- All GEDI Flight Lasers Built and Tested Here



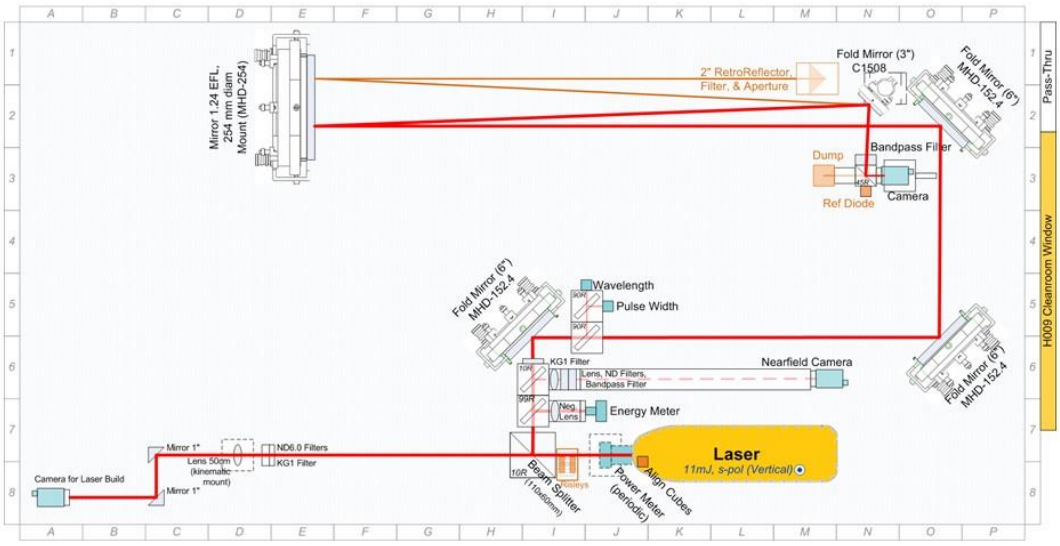


3 Tables for Each Flight Laser



TVAC Chamber w/ Laser Output Window

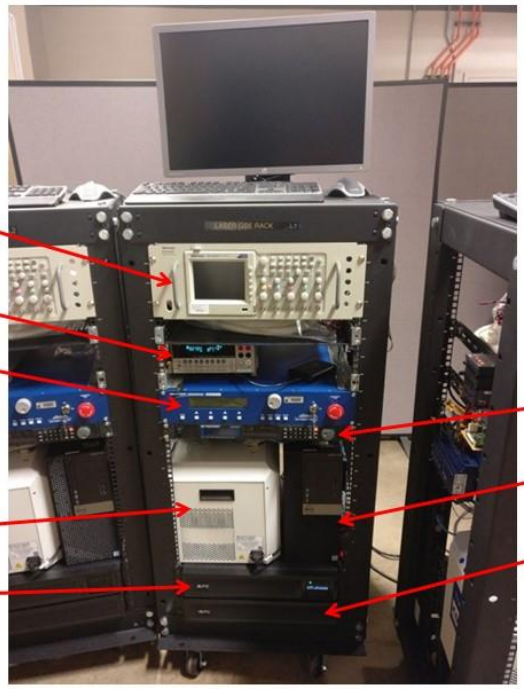
Optical Setup – Laser CPT/Lifetest



Laser & BDU Lifetest Optical Table (8' x 4')

Each laser was built in the GSFC Space Laser Assembly Center (SLAC). 3 lasers were

LASER GSE Rack Description (Front View)



A dedicated identical GSE rack for each flight and ETU laser

Laser Assembly and Testing

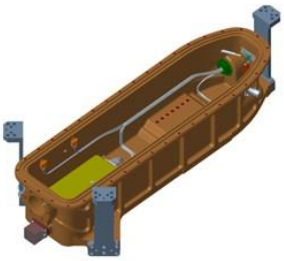


Flight Laser Assembly Flow

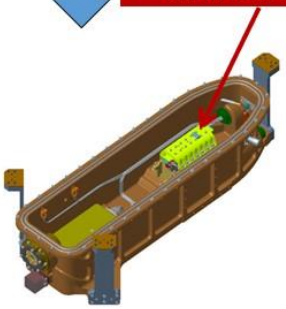
Workmanship Test
- Apply MAC* to inside lid
- Test pressure seal
- Vibration mule testing



Assemble bucket:
- Q-Switch Driver
- Harness
- Flexures
- Feedthroughs (electrical, purge/fill, and fiberoptic)



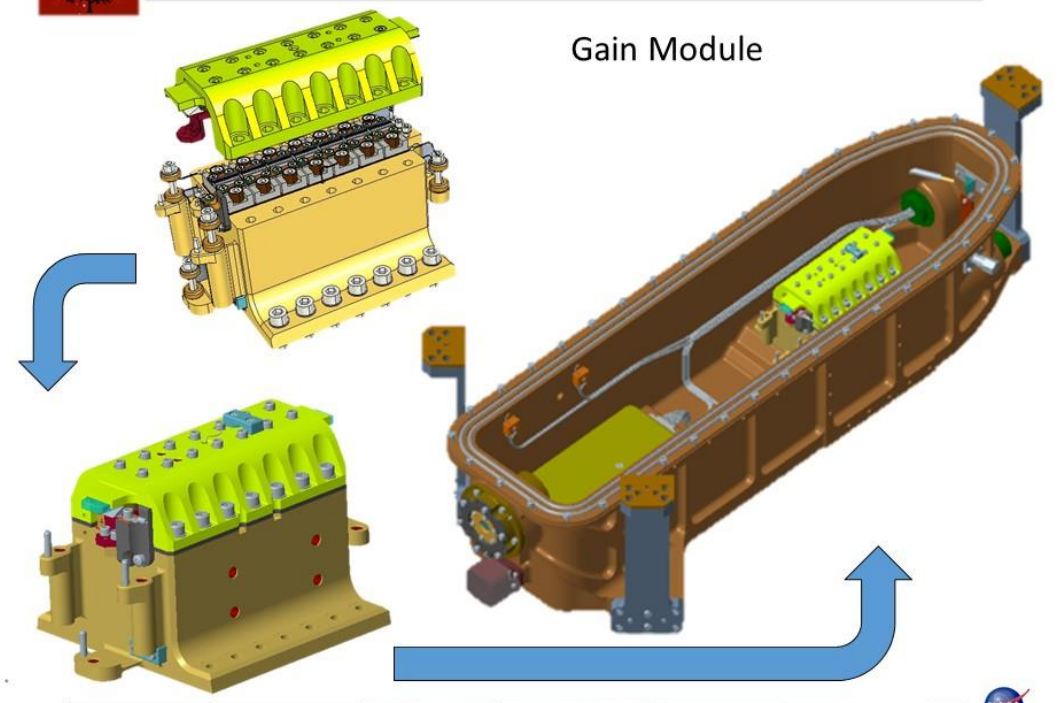
Add Pump Module:
- Safe-to-mate GSE
- Test Fire Diodes



- Molecular Adsorber Coating, developed and used for JWST

Nithin S. Abraham, et. al. SPIE Opt Eng & App, Vol 9952, (2016)

Flight Laser Assembly Flow

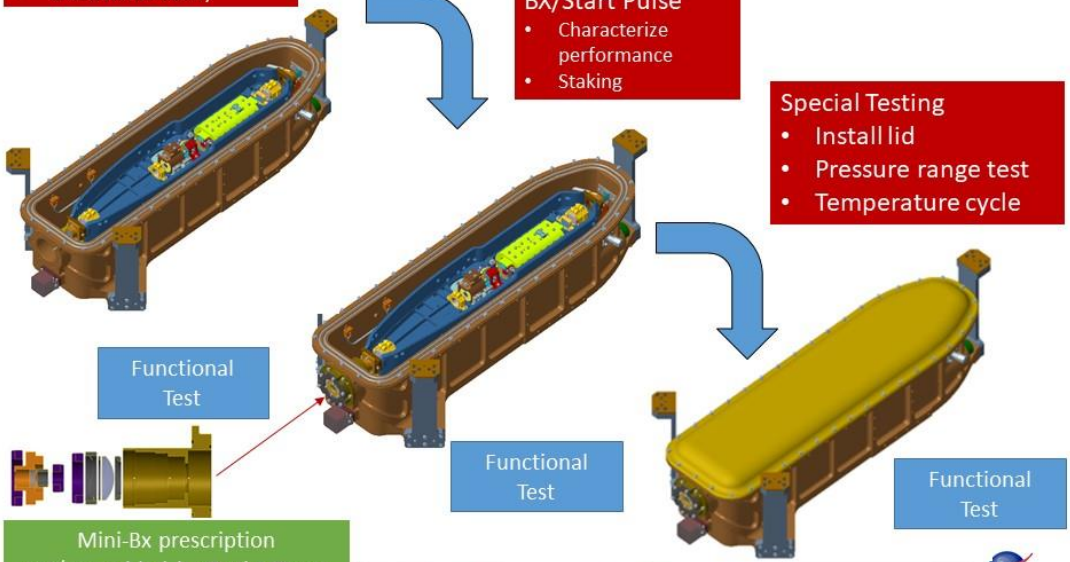


Flight Laser Assembly Flow

Laser Optical Bench
- Populate bench
- Finish harness connections
- Characterize cavity

Install Mini-BX/Start Pulse
- Characterize performance
- Staking

Special Testing
- Install lid
- Pressure range test
- Temperature cycle



Functional Test

Functional Test

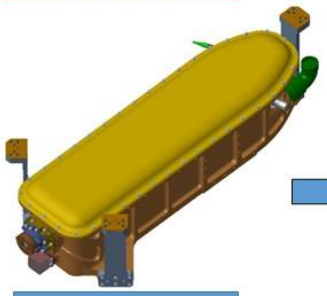
Functional Test

Mini-Bx prescription set/assembled by Optics Team

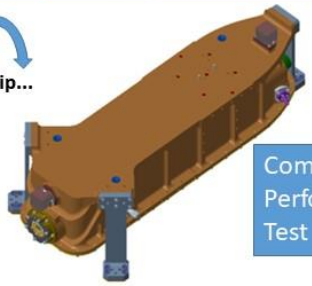
Laser Assembly Flow

Add Alignment Snout

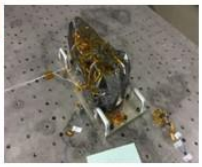
Final installation and Staking
Install TECs and Cold Plate (delivery from Thermal)
Full CPT
Complete staking



...flip...



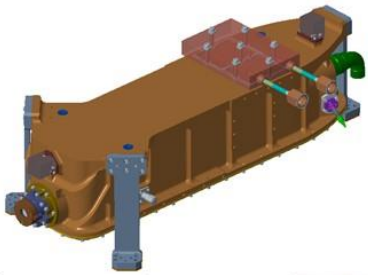
Comprehensive Performance Test



Environmental

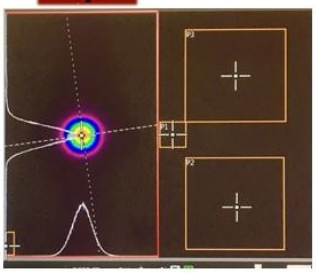


Functional Test

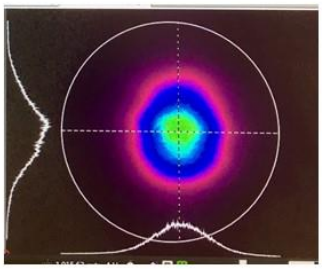


Add TEC and Cold Plate

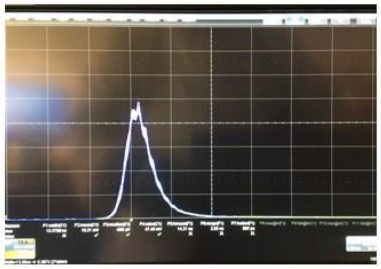
Laser Assembly Overview



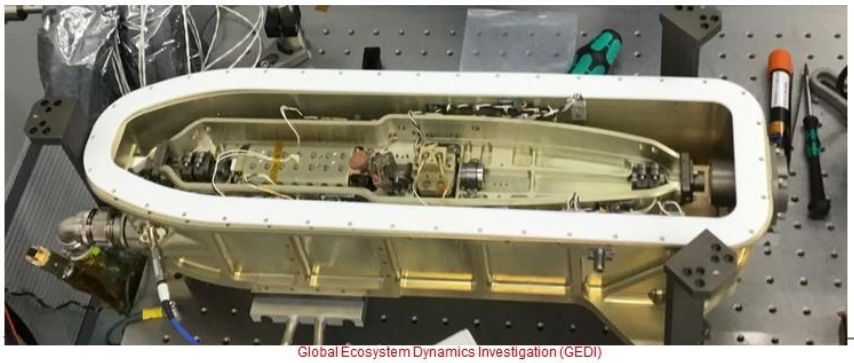
FF Divergence ~ 0.6 mR
(out of box)



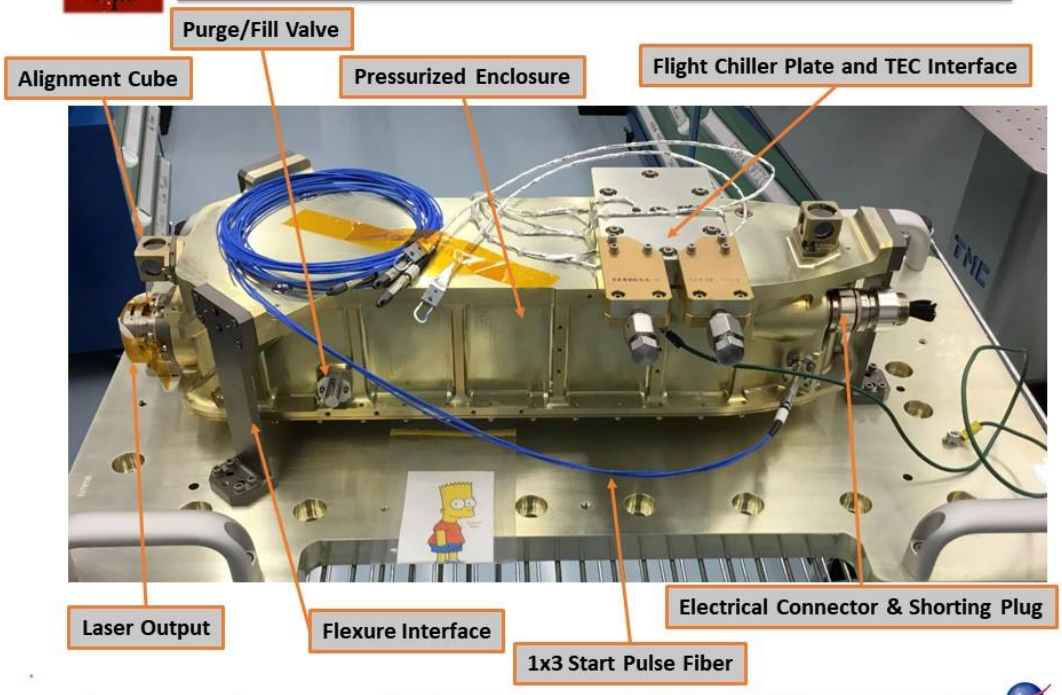
Real-Time Near Field
Beam Quality monitoring



QS Pulse Width ~ 12-13 ns

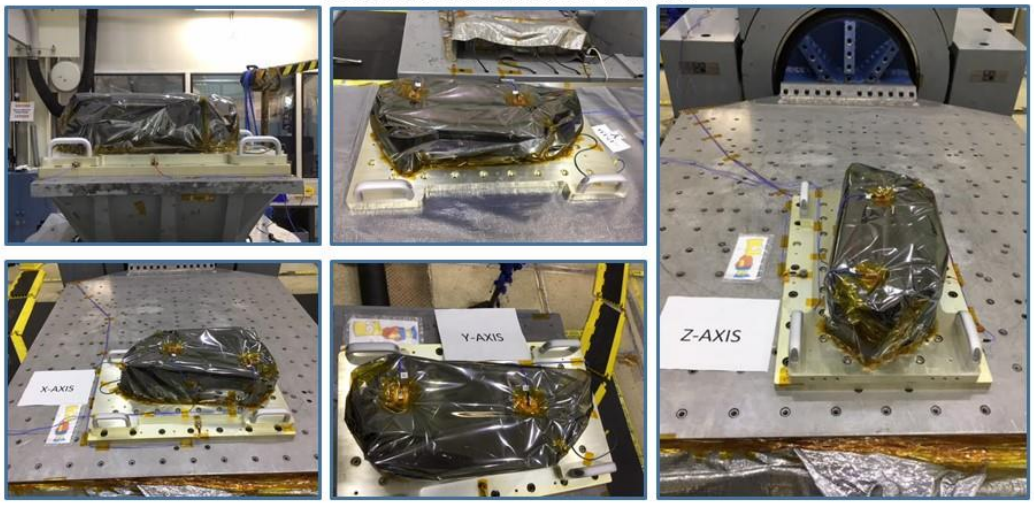


Flight Laser #1



Laser: Vibration Testing

Vibration Testing Conducted on ETU, Test Mule, and 3 Flight Lasers. CPTs Successfully Performed Before and After Vibration

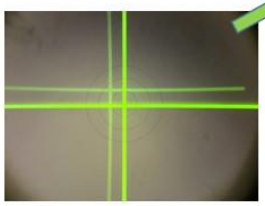


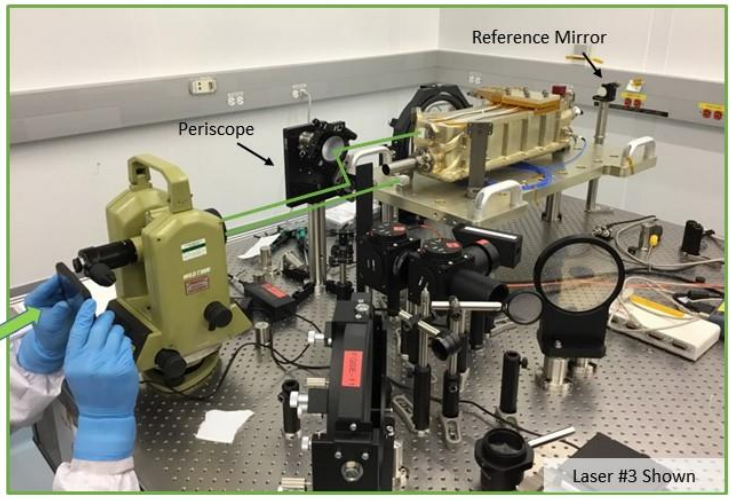
Laser: Vibration Testing

External Theodolite Measurement for Pre- and Post-Vibration Testing

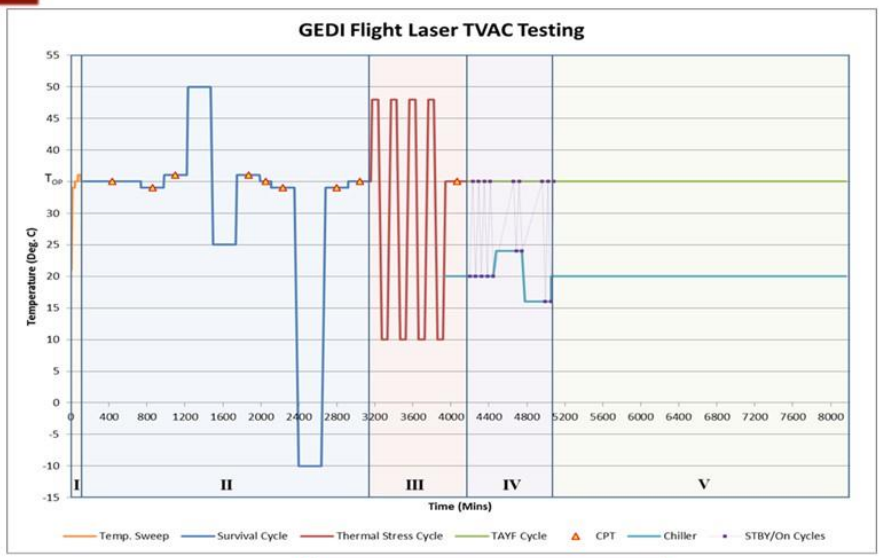
"Periscope" was required to bring the enclosure and plate alignment cubes into the Theodolite's field of view.

Reference mirror location was tracked before every measurement, prior to laser/plate placement into system.





Laser TVAC Testing Profile

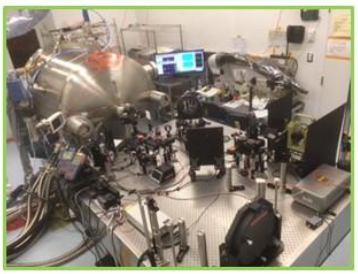


See GEDI-LAS-PROC-0182 for details

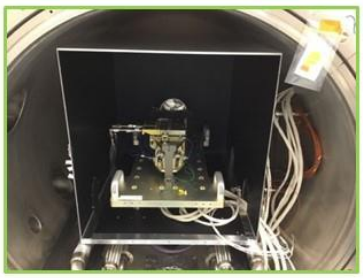
Survival = -10°C to +50°C. Operational temperatures were very tight (+/-1°C) so system was exercised in section III in order to confirm workmanship.

Thermal Vacuum Testing

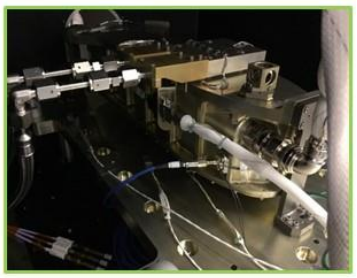
- Test Instrumentation
  - A thermistor placed on Laser 2's chiller plate (LTC4) was used as the temperature indication during testing.
  - 4 hour dwell times were maintained for temperature extremes



TVAC OGSE



Laser & Shroud in Chamber

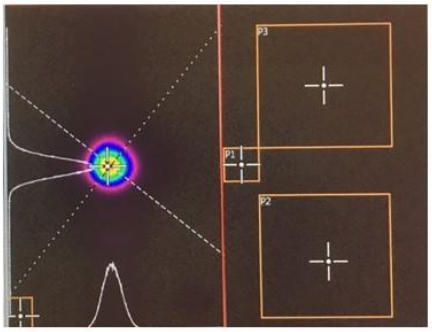


Laser & Chamber Output Window

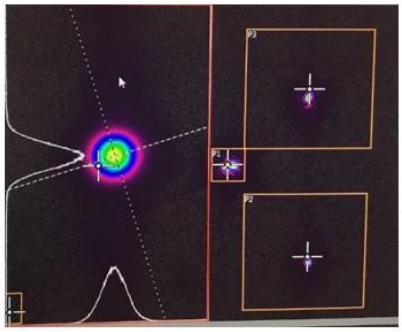
Another 5 temperature sensors added to laser hardware exterior and tracked.

Laser Performance Summary

Pre-Environmental



Post-Environmental

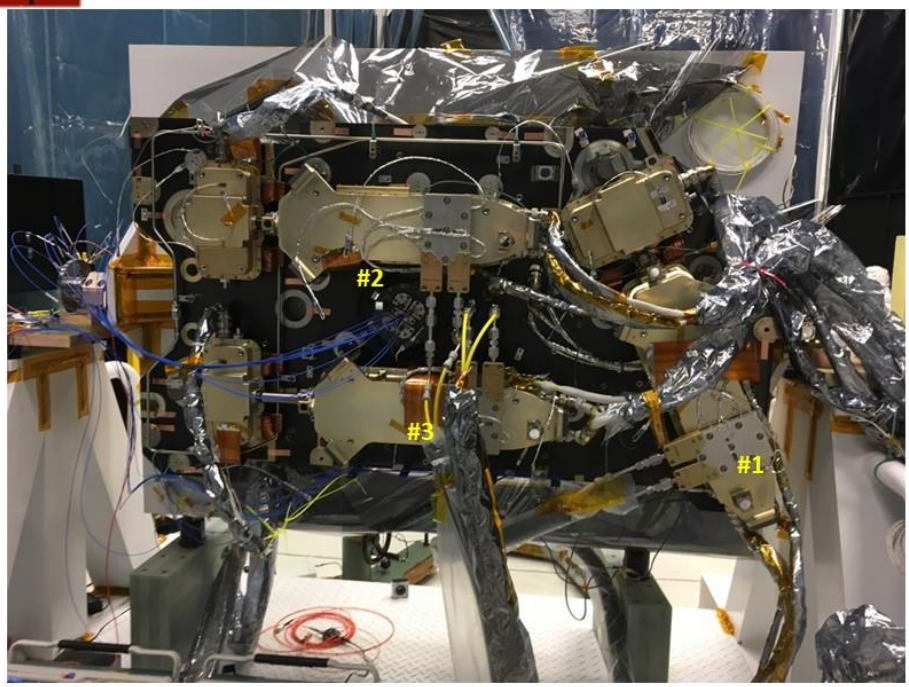


	Laser1		Laser 2		Laser 3	
Parameter	Pre	Post	Pre	Post	Pre	Post
Energy (mJ)	11.26	10.94	11.24	10.90	11.30	11.20
X/Y Divergence (mrad)	.58/.50	.56/.50	.68/.67	.62/.63	.58/.57	.58/.55
QS Pulse (ns)	15.24	15.39	12.99	12.55	12.90	13.33

GEDI Optical Bench Assembly



GEDI Lasers Installed GEDI Optical Bench



GEDI Integration with JEM Enclosure

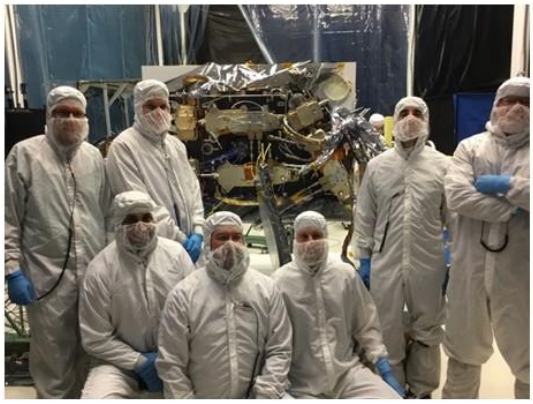
April 23, 2018



Conclusion and Future Work

- All three GEDI laser systems successfully completed the flight test plan with acceptable performance across all requirements.
- Knowing that the qualification of a space flight laser can be challenging, and incorporating lessons learned on prior flight laser development, the GEDI instrument team was careful to design margin into the system so that there would be flexibility to adapt to any non-conformances found during the testing of the lasers.
- As a result, the GEDI project can be confident the lasers will perform as required, produce an invaluable, 3D global biomass data set.
- GEDI laser can be modified to several of the in family HOMER options for a mission looking for a highly reliable and efficient in-house design.

Special Thanks the GEDI Laser Team!





Amazing team of highly skilled people from all disciplines: contamination, mechanical, tbermal, electrical, optics, lasers, fabrication, materials, software, analysis, systems, and quality assurance.

4.4 ADVANCED SINGLE PHOTODETECTORS FOR ACTIVE SENSING FROM SPACE

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NASA Technical Interchange Meeting on Active Optical Systems
Columbia, Maryland, July 31 to August 3, 2018

ABSTRACT

A brief overview of the photodetectors used in past and present space lidar is provided. A summary of the new technologies underdevelopment by NASA and industries is presented. A major bread-through in the near to mid infrared single photon detectors is described.

1 INTRODUCTION

Photodetector technologies play a vital role in space lidar and other types of active optical remote sensing from space. Single photon detectors are required to achieve the highest possible performance. Unlike imaging sensors, detectors for most of active remote sensing measurements have to provide instantaneous output instead of being read-out frame by frame. There are only limited choices in detector technologies for active remote sensing. Photomultiplier tubes (PMT) are still being used despite of their relatively large size, relatively low quantum efficiency and dynamic range. Silicon and InGaAs single photon avalanche photodiodes (SPAD) have high quantum efficiencies but nonlinearities that limits their use. HgCdTe avalanche photodiodes (APD) have recently become available which offer linear mode photon counting performance from visible to mid-infrared. They have demonstrated near quantum limited receiver performance in several airborne lidar measurement at near infrared wavelength. They also extend the lidar measurements from simple range measurements to simultaneous laser spectroscopic measurements for remote sensing of water ice and other volatiles on lunar surface and other airless bodies. These are pixelated arrays of linear mode photon detectors which extend the spatial resolution and coverage without increasing the instrument size. However, these new detectors are very expensive to produce and often have low yield. There are also other technologies which have to be matured, such as integrated detector cooler assemblies (IDCA) before these new photodetector technologies can be brought to fruition.

2 PHOTODETECTORS FOR ACTIVE REMOTE SENSING FROM VISIBLE TO NEAR INFRARED WAVELENGTH

Several types of single photon detectors are available that can be used in active remote sensing optical systems [1]. The following is a brief summary of those that have been used in space borne and airborne lidar.

2.1 PHOTOMULTIPLIER TUBES (PMT)

Ruggedized PMTs have long been used in space for passive spectrometers and later in space lidar. They are used in the Lidar In-space Technology Experiment (LITE) on the Space Shuttle launched in 1994, the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on the CALIPSO mission launched in 2006, and in the Advanced Topographic Laser System (ATLAS) on the ICESat-2 mission to be launched in September 2018. PMT's are widely used in passive spectrometers.

PMT's are made of thin metal plates and glass or ceramic housing. They have an internal photoelectron multiplication gain up to several millions which is sufficient to override electronics noises and achieve a shot noise limited performance. PMT's have been invented about 100 year ago and the technology are relative mature than other types of lidar detectors [2]. Segmented anodes can be used in a PMT to form an array detector in one package and produce pixelated output. Microchannel plate (MCP) can be used inside the PMT in places of the dynodes to allow more segmented anodes and hence more pixels, and smaller package size. One of the greatest advantages of PMT's is the combination of relatively large detector active area and wide electrical bandwidth, which is particularly important for active remote sensing instruments that needs a fast time response and a wide field of few (FOV).

PMT's have limited lifetime. The photocathodes degrade after a certain number of photoelectrons

drawn from the photocathodes. PMT's with MCP have a significant shorter lifetime than regular PMT's. However, the lifetime of regular PMT's are usually adequate for a multi-year space lidar mission such as ATLAS on ICESat-II. PMT's are widely used in passive spectrometers in various space missions and have a long heritage of space applications [3].

PMT's are far less susceptible to space radiation damage than semiconductor devices. The major radiation effects on PMT's is the scintillation and darkening of the glass housing.

However, PMT's are much large in size compared to semiconductor devices. Their quantum efficiency is relatively low, typically 10 to 25% and for the visible wavelength only. They have limited linear dynamic range and limited electrical bandwidth. PMT's have been gradually replaced by semiconductor photodetectors over the years. There are only a few non-US suppliers left and they do not offer space qualified or military standard devices. One has to purchase a large batch of devices and space qualify them by "up-screening" and testing on a case by case bases.

2.2 SILICON AVALANCHE PHOTODIODE (APD) IN ANALOG MODE OPERATION

Silicon APD's have been used in almost all space lidars over the past three decades. In particular the infrared enhanced reach-through type silicon APD's from Excelitas Canada (formally RCA, GE, EG&G, and PerkinElmer) [4][5]. They were used in analog mode with the bias voltage well below the breakdown voltage. They could detect laser pulses with about 100 photons at 1064 nm wavelength, which was the most sensitive detectors at the fundamental output wavelength of diode pumped Q-switched Nd:YAG lasers used for space lidar. A hybrid circuit was developed which consisted of a silicon APD chip, a high voltage regulator and temperature compensation circuit, and a high input impedance preamplifier circuit. The hybrid circuit was housed in a TO-8 type package and hermatically sealed. The leak rate was sufficiently low to ensure no arching from the high voltage for the mission lifetime. The devices were first developed for the US military to use in free space laser communications in the 1980's. Though the laser communication project was terminated in late 1980's, the residual devices were used with great success in the laser altimeter in the Clementine mission in 1994, the Near Earth Asteroid Rendezvous (NEAR) mission in 1996, the Mars Orbiter Laser Altimeter (MOLA) on the Mars Observer mission in 1992 and again on the Mars Global Surveyor (MGS) in 1996.

A new batch of the silicon APD preamplifier modules were made for lidar applications, using the same silicon APD chips from the original batch but replacing the high input impedance preamplifier with a transimpedance amplifier (TIA) to improve the electrical bandwidth, waveform fidelity, and linear dynamic range. These improved devices were successfully used in the Geoscience Laser Altimeter System (GLAS) on the ICESat mission launched 2003-2009, the near infrared channel of the CALOIP instrument on the CALIPSO mission 2006 to present, the Mercury Laser Altimeter (MLA) on the MESSENGER mission 2004-2014, the Lunar Orbiter Laser Altimeter (LOLA) on the LRO mission 2009 to present, and the Global Ecosystem Dynamics Investigation (GEDI) on the International Space Station to be launched in late 2018. The same detector module is also used in the BepiColombo Laser Altimeter (BELA) on the BepiColombo mission to Mercury by the European Space Agency (ESA) scheduled to be launched in October 2018.

Like other silicon electronics components, silicon APDs are radiation damage tolerate to a certain dose level. The major radiation damage is the displacement damage to the crystal and the creation of defect sites, which causes the dark current to increase over time. Usually the detectors are surrounded by optics in front, lens barrel on the side, and electronics on the back. The total radiation dose and fluence at the detector chip is much lower than at other part of the instrument. For example, the total dose at the detector chips of the GLAS SPCMs were only 3-5 krad(Si) over a five year mission based on a 3-D ray-tracing. Since the dark current of these silicon APDs is still high (picoamperes) and the noise from the preamplifier is a significant factor in the total noise, the radiation damage to the silicon APD only becomes apparent after 5-10 krad(Si). We saw little radiation damage to these analog silicon APDs from MOLA, MLA, and GLAS [6]. There has been a steady trend of the detector dark noise increases

from all five detectors on LOLA at 1-2% per year [7], possibly due to the fact that the LOLA detector assemblies are attached to the exterior of the instrument chassis and the amount of shielding is much less compare to previous missions.

These analog silicon APD preamplifier modules are still the best detectors at 1064 nm laser wavelength and are likely to continue to be used in space lidar for many years to come. However, the gain of the silicon APD's are still too low to override the preamplifier noise, the APD gain noise, called excess noise, is still high for photon counting operation, the dark currents are still overwhelming for single photon operation. They are single element detectors and not efficient for use with multi-beam swath mapping lidar with more than 10 laser beams or pixels.

2.3 GEIGER MODE SILICON APDS

Silicon APDs can also be used in the so-called Geiger mode, where the APD is based very close to the breakdown voltage that an incident photon can trigger an avalanche breakdown, resulting a large electrical pulse at the output. The avalanche process is then quenched and the bias restored for the next photon. These type of APD sometimes are also called single photon avalanche diode (SPAD). There are two types of quenching circuits, passive and active, with the latter offering a much faster recovery time and higher maximum count rate.

NASA GSFC has space qualified the single photon counting module (SPCM) with silicon APD and active quenching circuit by Excelitas, Canada [8][9]. These SPCMs have been successfully used in the 532 nm atmosphere backscattering measurement of the GLAS instrument on ICESat. They have a single photon counting efficiency as high as 70% at 532 nm laser wavelength, a recover time (dead-time) of about 40 ns, a dark count rate of <<1000 cts/s. The reliability of the commercial version of the SPCMs was greatly improved by incorporating design modifications used in the space qualified SPCMs. A number of commercial grade SPCMs were used in NASA's Clouds Aerosol Transport System (CATS) lidar on the International Space Station and all of them performed as expected during the entire mission time from September 2014 to March 2016.

Geiger mode silicon photon counters are also made by Micro Photo Device (MPD) in Italy [10]. They have slightly lower photon counting efficiency and longer dead-time compared to that of the SPCMs by Excelitas, but a much lower timing jitter of the output pulse, 10's picoseconds vs. 100's picoseconds. They are smaller in size and have a lower electrical power because the active quenching circuits and the silicon APD are all integrated in a silicon chip. However, the active area of these devices is smaller, 50 microns in diameter, compared to 170 microns of the SPCM's. They have not been used in space so far.

Another type Geiger mode silicon APDs that has been used in space is the SPAD from the Czech Technical University in Prague, Czech Republic [11]. They also have very low timing jitter and have been widely used in the satellite laser ranging (SLR) stations on Earth. They were first used in the lidar on board the ill-fated Mars'96. They were later successfully used in the Chinese Compass mission launched in 2010. These detectors need to be gated to maintain a low after-pulsing rate. They can only detect one event, incident photon or a dark current electron, within the gate interval. Another unique feature of these SPAD is the ability to resolve the number of photons in the received pulse if the pulse width is known or the pulse broadening can be neglected, such as in satellite laser ranging. While they work well for ranging to know targets such as satellites, they are difficult to use in lidar applications where the uncertainty of the target distance is much greater.

Geiger mode silicon APDs are more susceptible to space radiation damage since every electron of the dark current can trigger an avalanche breakdown and be counted [12-15]. Fortunately, the damage rate is still sufficiently low for a typical multi-year Earth orbiting mission. The dark count rate of the GLAS SPCMs increased from several hundred per second to several hundreds of thousands per seconds at the end of its 9-year mission [6].

2.4 MULTI-PIXEL GEIGER MODE SILICON APDS

Multi-pixel arrays of silicon APDs have been made and used in flash lidar demonstration by Massachusetts Institute of Technology (MIT) Lincoln Lab [16]. There is a finite fill factor for the array since each detector element has to be isolated from adjacent ones. Microlens arrays have been used to improve the fill factor. The silicon APDs

have to be gated. Each detector element can be triggered by the first photon, signal or background, and reinitialized at the beginning of the next gate interval. Since the background photons and dark current electrons can also trigger the detector and preempt the target return for that pixel, the gate time has to be set to close to the target return and the receiver collecting aperture and filter bandwidth have to be designed such that the background photon rate is much lower than the signal photon rate over the gate interval. The flash lidar has to build the 3-D image of the target through a number of exposures (laser shots).

A new type of Geiger mode silicon APD arrays has become available from several suppliers under the name of silicon photomultiplier (SiMP) [17-19]. They contain arrays of much smaller but more densely placed silicon APDs and the associated passive quenching resistor integrated on a silicon chip. The APDs are divided into subarrays with all elements in the subarray connected in parallel. The incident light is purposely defocused somewhat so that the photons are spread out over the subarray. When an incident photon triggered one APD element, an electrical pulse is produced and the APD is passively quenched and slowly recovered. If another photon incident on the subarray but a different APD, the output from the subarray becomes the sum of two APD outputs. Each APDs in SiMPs devices are small and has a much lower parasitic capacitance. As a result, the current draw from each avalanche breakdown is lower and the recovery time is much shorter compared to the discrete SPADs. The output pulse amplitude is also less random because of the lower current and the clamping of the supply current of the passive quenching. The pulse amplitude from subarray of the SiMP is the sum of pulse amplitude of each APD. If the received signal light is properly defocused on to the subarray such that only one photon can fall on one APD over its recovery time, the output of the subarray can be linear to the number of incident photons in the pulse. However, SiMPs are Geiger mode devices. They need to be gated to maintain a sufficiently low afterpulsing rate. They become nonlinear if the incident light is not properly defocused. They have not been widely used in active remote sensing.

3 PHOTODETECTORS FOR ACTIVE REMOTE SENSING IN INFRARED WAVELENGTH

There is a strong science need for space lidar to operate from near and mid infrared (IR) wavelengths. There are more spectral absorption lines of interested atmospheric constituents and surface element in this wavelength band that are easy to distinguish and measure, such as CO_2 and methane (CH_4) in Earth atmosphere and ice on planetary surface. There are more lasers available in short wave infrared (SWIR) which have been developed by the optical fiber communication and fiber laser industries. The laser eye-safety threshold is much higher than that in the infrared than in the visible. The solar background noise is much lower in the infrared. However, there are far fewer choices of lidar detectors in the infrared than in the visible. Thermal IR detectors have too slow a time response for active remote sensing. Cryo-coolers are often needed to achieve high receiver sensitivity [20].

3.1 INFRARED IMAGING SENSORS

There have been many advances in infrared imaging sensors over the past several decades. Some of them can detect extremely low level of light from faint celestial objects. Some of them have been used in gated imaging with laser illumination. They may be used in some of the laser absorption spectroscopic measurement. However, imaging sensors have to be read out frame by frame and cannot be easily used to detect laser pulses in active remote sensing. The range resolution is limited by the frame rate. The receiver integration time is limited by the exposure time which is usually orders of magnitude of the laser pulse width and not effective in gating out background light and detector dark noise.

3.2 INGAAS PHOTOCATHODE PHOTOMULTIPLIER TUBES

PMT's with InGaAs photocathodes are now commercially available. The photocathodes are made of semiconductor materials with special coating to allow photoelectrons to escape and be accelerated to the dynodes. The quantum efficiency of the device is typically a few percent from 1 to 1.6-micron wavelength. The highest reported quantum efficiency is 15-18% at 1.55-micron wavelength. With a dark count rate of a few

millions per second. There are still issues to be resolved, such as lifetime and space radiation damage, before they can be used in space borne instruments.

3.3 InGaAs Photocathode Hybrid Photomultiplier Tubes

A variant of the InGaAs PMT's is the hybrid PMT and APD. They use InGaAs photocathodes as in PMT's but an APD at the anode. Secondary photoelectrons are generated at the bombardments of primary photoelectrons on the APD active area [21-22]. The APD further multiplies the photoelectrons through the avalanche process. The photoelectron multiplication gain at the photoelectron bombardments is about 1000 at 8 kV high voltage. The APD avalanche gain is several tens. Together they multiply the primary photoelectrons by a gain of >10,000, which is sufficient to override the noise from a low-noise wide-bandwidth amplifier. The devices have been called hybrid PMT (HPMT), intensified photodiode (IPD), electron bombard APD, or vacuum APD. The greatest advantage of the device is the combination of wide electrical bandwidth (~1 GHz) and the relatively large active area (several mm in diameter). The electrical bandwidth is wider than those of regular PMT's because of the simpler and more deterministic photoelectron trajectory. Similar devices with regular photocathodes in the visibly wavelength have been commercially available.

However, hybrid PMT's with InGaAs photocathodes in the near IR are still in a research and development (R&D) stage. The reliability of the devices is still low, the cost is high, and the yield is uncertain at present.

3.4 Linear Mode InGaAs APDs

Linear mode InGaAs APD's have been the widely used in active remote sensing at present. They are different types with cut-off wavelength of 1.6, 1,9, 2.2, and 2.6 microns. The quantum efficiencies are relatively high. The cost of the devices is much lower compared to other type of IR detectors.

However, the avalanche gain of InGaAs APD's are much lower and the excess noise (randomness of the APD gain) is much higher compared to silicon APD's at present. The overall receiver noise is still dominated by the preamplifier noise. The APD dark current is also higher compared to silicon APDs. The noise equivalent power (NEP) of the detector system is typically several hundreds of $fW/Hz^{1/2}$ for a wide bandwidth device [23], which is at least 10 times the NEP of a silicon APD detector system.

InGaAs APD's in analog mode work well in active remote sensing instrument with high pulse energy, short pulse width, and low pulse rate lasers where the receiver performance is not dominated by the background light noise and detector dark noise. For low pulse energy and high pulse rate laser instrument, detectors with lower NEP are needed.

Multi-pixel InGaAs APD arrays are also available, which have been used in some of the terrestrial laser scanners in a combination of flash lidar and mechanical scanner. The receiver sensitivity is limited by the detector noise to tens or hundreds of times of the single photon detectors.

3.5 Geiger Mode InGaAs APDs

InGaAs APDs can also be used in Geiger mode to count single photons up to 2-micron wavelength. There have been many R&D efforts in this area over the past 20 years [24-25]. Like their linear mode counterpart, they have a relatively high quantum efficiency and are relatively low cost. They do not require high voltage biases and they do not need to operate at cryogenic temperatures. Most of these devices are already in multi-pixel array format. Several types of read-out integrated circuits (ROIC) have been developed that can produce a 3-D image of the target from a flash of the laser light on the scene. They have already been used in terrestrial laser scanners and flash lidar. They are commercially available in 32x32 and 32x256 pixel format at present [26].

A major disadvantage of Geiger InGaAs APDs is after-pulsing where sporous electrical pulses appeared randomly over tens of microseconds after the target return due to trapped charges from the avalanche. The detector has to be gated to allow the after-pulsing to die out before the gate is turned on for the next signal detection. Like in silicon Geiger mode APD's, the first event within the gate triggers the APD and no signal photons can be detected until the next gate interval. The devices are usually cooled to reduce the dark count rate, which further increase the after-pulsing time. The gate interval is typically a few microseconds (~100 m), which

make it difficult to use on a space borne platform where the target distance cannot be easily predicted to 100 m.

Another technical issue with the InGaAs APD's is radiation damage. All test results published so far showed InGaAs APD's are far more susceptible to radiation damage than silicon devices [27-28]. The devices have to be made small in order to reduce the radiation dose per detector element, which reduces the fill factor and makes it more difficult in the optical design. As a result, Geiger mode InGaAs APD have not been used in space borne instruments.

3.6 HgCdTe Avalanche Photodiodes

Recent progress in the HgCdTe APD arrays have emerged as a major breakthrough in infrared detector for space lidar. HgCdTe photodiodes have long been the superior materials for IR detectors from near IR to 20-micron wavelength [29-33], though a much cost than other type of detectors. They have high quantum efficiency and very low dark count rate when cooled to cryogenic temperature. The cutoff wavelength can be tailored by adjusting the alloy composition. HgCdTe photodiode arrays imaging sensors have been used in the Hubble Space Telescope and will be used in the James Webb Space Telescope. They have been used in various passive spectrometers in space. However, these are imaging sensors and have limited application in active remote sensing. HgCdTe APD arrays have recently been available which are capable of detecting laser pulses in space lidar with near quantum limited performance [34].

HgCdTe APD's are like silicon APD's in linear mode but with a much higher APD gain and much less excess noise factor (i.e. noiseless gain), and >90% quantum efficiency up to mid IR wavelength. The APD gain is sufficiently high to overcome the preamplifier noise without excess noise. The detector bulk dark current at 110K is almost negligible compared to other source of noise in a space lidar [35].

Small and low power space cryo-coolers are now available for HgCdTe APD arrays. One option is the micro-coolers, which is the miniaturized version of a long line of pulse-tube cryo-coolers used in several space missions [36]. Pulse-tube coolers have no moving parts. They are low power, low vibration, and expected to have a long lifetime in space. A lower cost option for the cryo-coolers is the mini-Stirling cooler used in weapon system, or "tactical cooler." They are designed to survive the vibration during rocket launches. They have also demonstrated multi-year lifetime [37].

NASA Earth Science Technology Office (ESTO) has funded GSFC to partner with Leonardo DRS, Dallas TX, to develop a multi-element HgCdTe APD focal plane array (FPA) with a built-in ROIC for the CO_2 lidar on Active Sensing of CO_2 Emission of Days, Nights, and Seasons (ASCENDS) mission. DRS has successfully developed a 4x4 element FPA with a near 90% quantum efficiency, 4.3-micron cutoff wavelength, <0.5 $fW/Hz^{1/2}$ noise equivalent power (NEP), and about 6 MHz electrical bandwidth [35]. One such detector system housed in a closed-cycle Dewar has been successfully tested in an airborne CO_2 lidar experiment by GSFC in 2014 and 2017. A similar detector system is tested in an airborne CH_4 lidar at 1.65-μm by GSFC in 2015 and another one in the CO_2 lidar at 2.05-μm wavelength by the NASA Langley Research Center (LaRC) in 2018 [38].

NASA ESTO has later funded GSFC to partner with Leonardo DRS under an Advanced Component Technology (ACT) program to mature the technology for a more advanced type of HgCdTe FPAs with reduced noise, much wider electrical bandwidth, and higher APD gain to enable linear mode photon counting (LMPC) [39]. Under this program, DRS produced a set of 2x8 pixel LMPC FPAs capable of detecting single photon events at >60% photon detection efficiency (PDE) at about 250 kcts/s dark count rates, and about 8-ns impulse response [40].

ESTO also funded Jet Propulsion Laboratory (JPL) and DRS to develop a new batched of the 2x8 pixel LMPD HgCdTe APD arrays for a passive photo-elastic modulator (PEM) based imaging polarimeter. Under this program DRS successfully develop a batch of the 2x8 pixel LMPC HgCdTe APD with 3.7-micron cutoff wavelength. DRS also improved the blocking of the light emitted by the ROIC to the APDs [41].

NASA ESTO later funded Aerospace, GSFC and DRS under an In-space Validation of Earth Science Technology (InVEST) program to develop an integrated detector cooler assembly (IDCA)

with these 2x8 pixel detectors with microlens arrays in tactical coolers for a CubeSat in-space demonstration. Though the CubeSat program was later suspended, two of these IDCA have been delivered to GSFC. DRS performed two vibration tests per NASA Goddard Environmental Verification Standard (GEVS), a thermal cycle test, and a thermal shock test. GSFC performed a full thermal cycle test and thermal vacuum test per GEVS. The IDCA's have passed these environmental tests with minor issues which could be fixed at the next iteration [42].

The United States Defense Advanced Research Projects Agency (DARPA) funded DRS after the start of the NASA ACT program to develop a larger array of the LMPC HgCdTe APD's with microlens array in a tactical cooler [43]. Both NASA and DARPA benefited each other and made significant improvement in the device design, fabrication, ROIC, and packaging. A significant improvement has been made to the ROIC bandwidth and the overall timing jitter of the detector output.

A series of radiation damage tests have been performed by NASA GSFC to these new HgCdTe APDs under several NASA ESTO Quick Response Study (QRS) programs [44]. A proton radiation damage test was first performed to the 4x4 pixel HgCdTe APD array itself with the ROIC in 2012. Another proton radiation damage test was performed to the 4x4 pixel HgCdTe APD array with the ROIC in 2013. A gamma ray radiation damage test to a 4x4 pixel HgCdTe APD array in 2015. A proton radiation damage test to the 2x8 pixel LMPC HgCdTe APD array in 2017. The most significant radiation effect was the increase of the APD dark currents. The detector quantum efficiency and the APD gain decreased only slightly at 100 krad(Si). The detectors produced a large current impulse in response to each proton hit and recovered within a microsecond. The increased dark current caused radiation damage was found to increased significantly after the devices were brought to room temperature. However, most radiation damage annealed after heating the device to 85°C for several hours. Therefore, these HgCdTe APD arrays can be used in a multi-year space mission provided they can be heated to 85°C periodically to anneal radiation damage.

NASA Science Mission Directorate (SMD) has funded the development of a 4x4 pixel HgCdTe APD array in a tactical cooler for a Mars climate lidar under a Maturation of Instruments for Solar System Exploration (MatISSE) program in 2017. This will advance the packaging of the 4x4 pixel HgCdTe APD arrays ready for space application.

NASA SMD has recently funded GSFC and DRS to develop a 2x30 pixel and 7x8 pixel LMPC HgCdTe APD arrays through a Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) program. It will bring the LMPC HgCdTe APD array to a much large array size with more pixels ready for a swath mapping lidar. It will further improve the performance of the existing 4x4 HgCdTe APD array with a much higher electrical bandwidth, higher APD gain, lower noise, and larger array size with more pixels.

There are other suppliers of HgCdTe APD arrays, including Raytheon Vision Systems (RVS) in the United States, Leonardo Airborne and Space Systems in United Kingdom (formally Selex), and Sofradir in France. The devices by Leonardo UK have demonstrated high APD gain and extremely low dark current [45]. They have been integrated with an imaging type of ROIC and used in astronomy. NASA ESTO has funded GSFC under a QRS program to procure and test one of the devices for potential use in active remote sensing.

These new LMPC HgCdTe APDs fill a gap in high speed single photon detectors from short to mid IR wavelength. They will have many future NASA applications, not only in active remote sensing but also passive remote sensing instruments in space.

4 PROGRAMMATICS

4.1 STRATEGIC APPROACH

Photodetector developments for active remote sensing is a long and costly process. Once a type of detectors was space qualified, they tend to be used again and again. It was fortunate that the Department of Defense (DoD) already developed and space qualified the linear mode silicon APD's before space lidar came to age. MOLA-1, Clementie lidar, NEAR Laser Ranger, and later MOLA-2 all used the residual detectors from the canceled DoD program. ICESat/GLAS made an incremental improvement by replacing the

preamplifiers with the one already used in a commercial product. The residual GLAS detectors have been used for MLA, LOLA. The same design was used in CALIPSO, BELA and later GEDI. ICESat/GLAS took considerable risk and finally succeeded to space qualified the commercial SPCM which became the first solid state photon counting detectors for atmosphere backscattering measurements. The same detectors were used in CATS and probably other cloud and aerosol lidar in the future.

There have been numerous of lidar detector development programs over the years but none has been used in space to date. NASA alone does not have to resources to develop a new detector technology and bring it to fruition because of the technical challenges and high cost of new detector developments.

The recent HgCdTe APD development has been a major breakthrough in the advanced photodetectors for space lidar and other active remote sensing instruments. They not only fill a void in the lidar detectors from short to mid infrared, but also offer a much better performance in the near infrared than the silicon APDs. NASA ESTO has funded the HgCdTe APD development through IIP, ACT, InVEST, and QRS programs since 2011. DoD has invested in the same detector technology for ground-based flash lidar. However, the progress under ordinary R&D programs has been slow. The selection rates of research proposals are low. Some proposals have to be submitted repeatedly or to different programs in order to continue advancing the technology to a point that a flight project can start to invest on it.

We need to produce larger size array with much more pixels in order for them to be useful and serve the larger active remote sensing community. As the array size increases, a switching matrix is also needed in the ROIC to combine and select sub arrays of the pixels for output, since there can only be a limited number of input/output (I/O) ports on a detector chip and the cryo-cooler vacuum feed throughs.

4.2 DEVELOPMENT PLANS

As mentioned earlier, we are currently funded by NASA SMD MatISSE program to integrate a 4x4 pixel HgCdTe APD array with a tactical cooler to bring the 4x4 pixel devices to a Technology Readiness Level (TRL) of 6 for a Mars wind lidar by the end of October 2019. The same detector assemblies can be used in the CO_2 and CH_4 lidar. We are also funded by the PICASSO program from now to 2021 to develop a 2x30 and 7x8 pixel linear mode photon counting HgCdTe APD arrays for planetary swath mapping lidar. We will continue to look for new funding sources to continue mature the technology.

4.3 DEVELOPMENT MILESTONES AND DATES

The new device to be developed under the PICASSO program is an intermediate step to grow even larger size arrays with many more pixels required by the next generation swath mapping lidar. We are hopeful but still do not have a funded potential flight projects which use the new HgCdTe APDs. There is no immediate milestones and dates.

4.4 PARTNERING

We have been partnering with all HgCdTe APD developers in the United States, including Teledyne Scientific Imaging, Raytheon Vision System, and Leonardo DRS in Dallas Texas. Lately, we have been collaborating with Leonardo DRS. The DRS HgCdTe APD's use a cylindrical device structure with certain advantages that are the most mature at this time. We are also evaluating HgCdTe APD arrays from Leonardo UK (formerly Selex) under a QRS program from ESTO. The devices from Leonardo UK are planer devices which has a near 100% fill factor, lower noise and potentially high speed.

4.5 OVERCOMING THE VALLEY OF DEATH

The HgCdTe APD array and the tactical cooler are now at TRL-6. However, the current detector array sizes, 4x4 and 2x8 pixels, are still too small for most of the lidar for Earth environmental monitoring and planetary mapping. They can only be considered as prototype devices and there is still a gap to actual space application. The TRL for larger size detectors are still too low for immediate space applications.

Flight projects tend to pick already mature detectors and usually do not have the time and resources to develop and qualify a new batch of HgCdTe APDs. Few R&D programs are intended to continue developing an already TRL-6 prototype detector array to a larger sized detector

array. We are now facing the possibility of the so-called "Valley of Death" in this technology development. We are trying every opportunity and funding source to continue developing this new detector technology.

5 WIDER VISION

There are potential cross-cutting benefits for the lidar detector technologies to help in other areas, especially the recent HgCdTe APD development. As mentioned earlier, these are the first ever photon counting detectors from short to mid infrared wavelength. They can be used not only in active remote sensing instrument but passive spectrometers. They have been used in astronomy to overcome the read noise and increase the frame rate. They can be used in the free space laser communications at 1550 nm laser wavelength to take advantages of the technology development in terrestrial optical fiber communication systems.

6 CONCLUSIONS

Photodetector technologies play a key role in active optical remote sensing from space where the signal is weak and the demand for the measurement precision is high. Despite of all the efforts, there are only a few types of photodetectors that are adequate for space applications, namely, photomultiplier tubes and silicon avalanche photodiodes. There is a need to develop new detector technologies with single photon sensitivity, multipixel array format, and from near to mid infrared wavelength for the next generation active optical remote sensing instrument. The recent HgCdTe avalanche photodiode arrays have been a major breakthrough in lidar detectors with linear mode photon counting output, wide dynamic range, and spectral response up to 5 microns. The prototype devices have achieved TRL-6 along with the packaging and cryo-cooler technologies. The next step is to increase the array size and the number of pixels. These new detectors will help to extend space lidar in receiver sensitivity, dynamic range, spatial coverage, and spectral range.

ACKNOWLEDGEMENTS

We thank all people who valued the importance of lidar detectors and supported detector technology development over the past 20 years. We thank NASA ESTO for the continued support in the HgCdTe APD development. We thank Leonardo DRS for collaborating with NASA to continuously improve the technology and the detector performance for NASA applications.

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Advanced Single Photodetectors for Active Sensing From Space

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Greenbelt MD 20771

NASA Technical Inerchange Meeting on
Active Optical Systems for Supporting Science Exploration, and Aeronautics Measurement Needs

University of Space Research Association (USRA)
Columbia, Maryland
July 31 to August 2, 2018

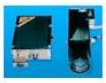
Active Optical Sensing from Space - Space lidar developed by NASA

GSFC

Apollo, - moon
NASA (1971-1972)
Ruby lasers,
5,000 shots



Clementine - moon
LLNL/NRL (1994)
Nd:YAG laser,
~72,000 shots



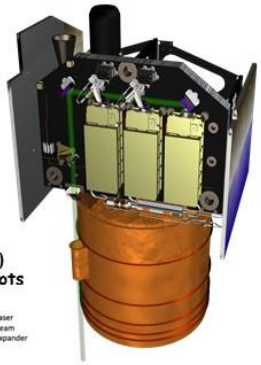
NEAR/NLR - Eros
JHU/APL (1996-2001)
Nd:YAG laser,
11 million shots



MGS/MOLA - Mars
NASA GSFC (1996 -2000)
Nd:YAG laser,
670 million shots



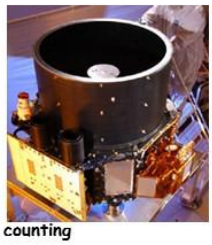
ICESat/GLAS - Earth
NASA GSFC (2003-2009)
Nd:YAG laser
~2 billion shots



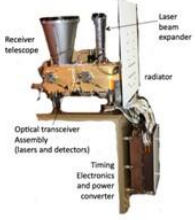
MESSENGER/MLA - Mercury
NASA GSFC (2004-present)
Nd;YAG laser,
35 million shots



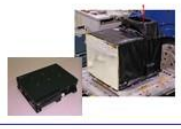
CALIOP/CALIPSO
- Earth
NASA LaRC
(2006-present)
Nd;YAG laser,
2 billion shots and counting



LRO/LOLA - moon
NASA GSFC (2009-present)
Nd;YAG laser, >4 billion shots



SELENE/LALT - moon
Japan (2007-present)
Nd;YAG laser,
13 million shots



Chang'E - moon
China (2007-present)
Nd;YAG laser
8 million shots

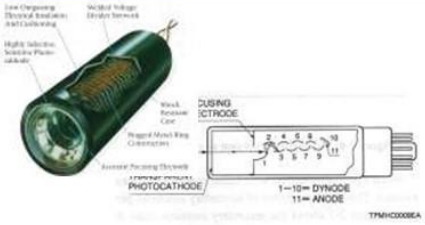


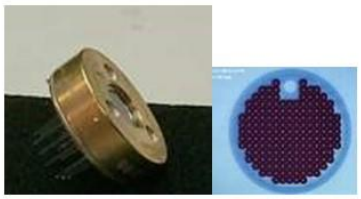
Candrayaan/LLRI
- moon
India (2008-2010)
Nd;YAG laser,
millions of shots



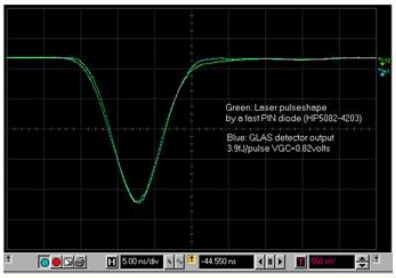
Detectors used in Space Lidar to Date
- PMT and IR Enhance Si APDs

- **Photomultiplier tubes (PMT) with Multi-alkali photocathodes:**
  - LITE, CALIPSO
- **Si avalanche photodiodes (APD), linear mode, IR-enhanced (1064 nm):**
  - Clemetine lidar, NEAR/LR, MOLA, GLAS/ICESat-1, CALIPSO, MLA, LOLA, GEDI, BELA



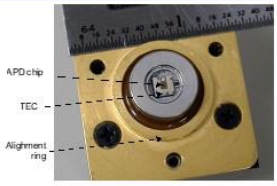


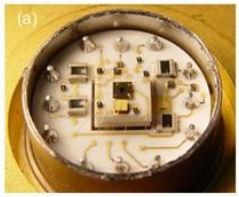




Detectors used in Space Lidar to Date
- Geiger Mode Silicon APDs

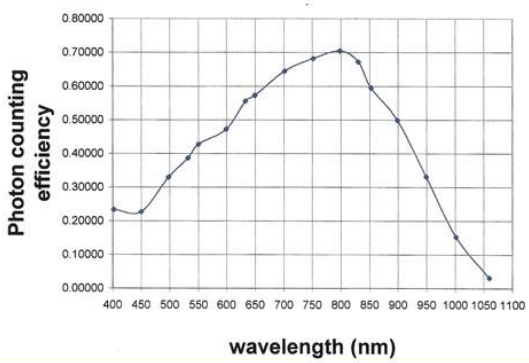
- **Geiger mode Si APD photon counters:**
  - GLAS/ICESat-1, CATS/ISS
- **PMT with Multialkali photocathodes and segmented anodes:**
  - ATLAS/ICESat-2, CATS







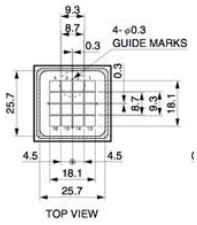


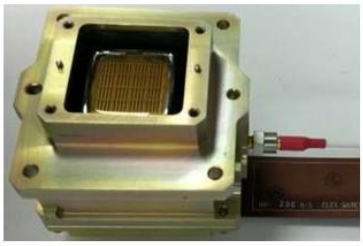


Detectors used in Space Lidar to Date
- PMT in ICESat-2/ATLAS

- Hamamatsu R7600-300-M16 with Extended Bi-alkali Cathode
- 15% QE at 532 nm, large active area, high speed
- 16-channel segmented anode to allow limited linear mode photon counting
- High optical damage threshold
- Ruggedized packaging
- Radiation tolerant to >30 krad(Si)







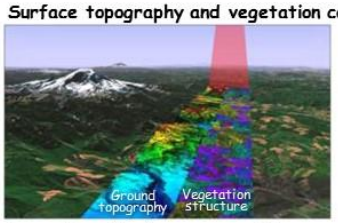
- Timing jitter <250 ps, Dead time: <3.3 ns
- Lifetime validated: >3.5 years continuous
- Burst mode pulsed laser damage threshold
  (>2 uJ per pulse with 30 consecutive pulses of a 10 kHz laser)

New Trends in Space Lidar

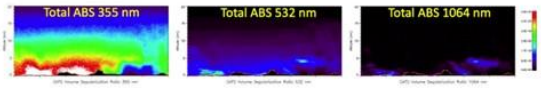
- Multi-beam swath-mapping surface and vegetation lidar
- Atmosphere backscatter profiling lidar at different wavelengths and polarizations
- Integrated Path Differential Absorption (IPDA) lidar for greenhouse gases, CO_2 CH_4, etc.
- Laser absorption spectrometer for surface composition studies (e.g., ice) for the moon, Mercury, comets, etc.

Multi-pixel lidar detector sensitive in short to mid infrared wavelengths

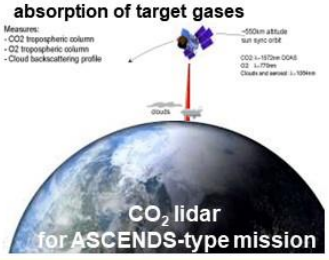
Surface topography and vegetation coverage



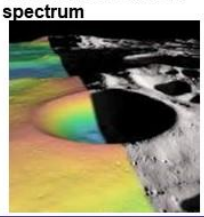
Atmosphere backscatter profiles



IPDA lidar - measures column absorption of target gases



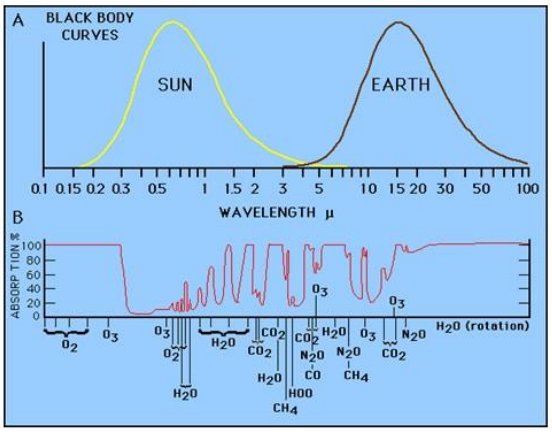
Lidar sampling of surface reflection/absorption spectrum



Advantages of lidar from Short to Mid-IR

- Low background from sunlight & low thermal emission from surface
- Rich in spectral absorption lines of interesting species
  - in atmosphere and on surface

e.g. for Earth



Some candidate laser wavelengths for sensing gases on Mars of high interest

Molecule	Wavelength (nm)
H_2O	3146.5
HDO	3613.5
CH_4	3260.2
C_2H_6	3360.9
N_2O	3884.5
SO_2	3985.1
H_2S	3753.6
H_2CO	3595.8
NH_3	3051.7
O_3	3298.3

http://objectivistindividualist.blogspot.com/2013/02/infrared-absorbing-gases-and-earths.html

Research and Development of Near to Mid IR Lidar Detectors

- **InGaAs APDs**
  - High noise
  - Space radiation damage
- **InGaAs PMTs**
  - Low quantum efficiency
  - Not available beyond 1.7 μm
- **HgCdTe photodiode array**
  - Imaging sensors with too low frame rate for lidar application
  - Lack of pulse shape information
- **HgCdTe avalanche photodiodes**
  - Quantum limited performance and wide linear dynamic range from visible to 5 μm
  - Several space cryo-coolers available
  - Radiation damage tolerant and can be annealable in orbit



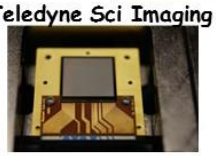


Many suppliers and low cost



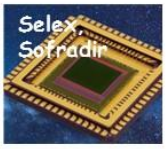


Teledyne Sci Imaging



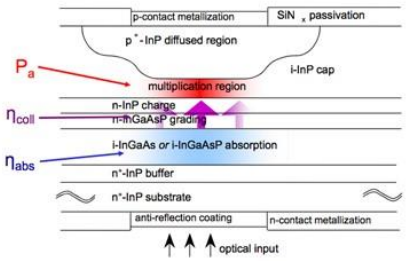






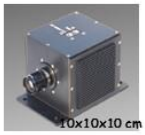
Single Photon Avalanche Photodiode (SPAD)

- InGaAs APDs have high quantum efficiency to 2 um, and they are small, inexpensive, and can be cooled with TEC
- InGaAs APDs in analog mode have APD gain of 10-50 with excess noise factor of 5-10.
- InGaAs APDs in Geiger mode can count single photons with gating to mitigate dead-time and afterpulsing
- On going research to improve performance, e.g., negative feedback, I^2E, high frequency gating, large array with built-in digitizers or timers, etc.
- More susceptible to radiation damage than Si detectors

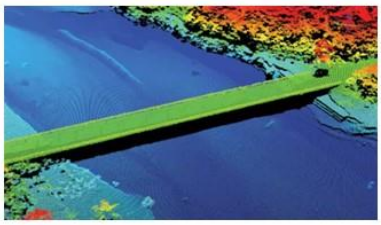


MIT/LL&PLI/Spectrolab SPAD arrays

- 32x32 pixels, 100 µ pitch
- Microlens array for high fill factor
  Built-in ROIC with 0.5 ns timing
- 20 KHz frame rate
- 2-8 µs range gate
- Used in ground based observations

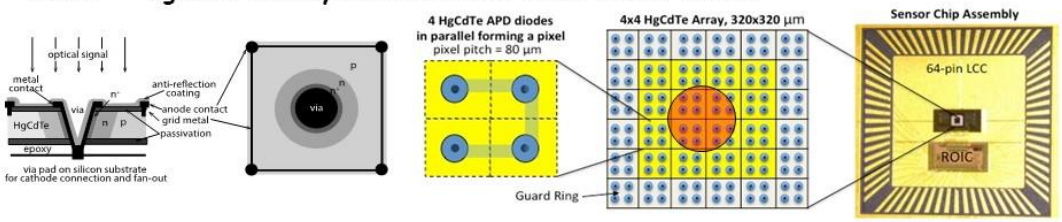


3-D lidar images of Haiti bridge and road condition assessment after 2010 earthquake

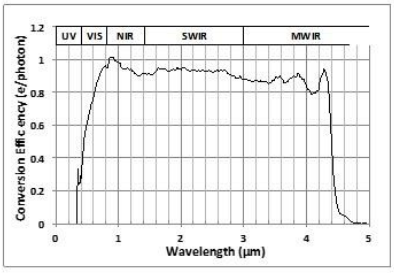


HgCdTe APD Arrays for Trace Gas Lidar

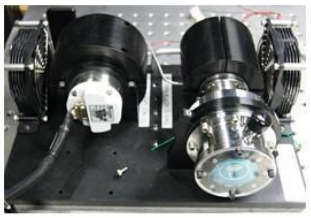
HDVIP™ HgCdTe APD by Leonardo DRS under ESTO IIP-10



HgCdTe APD for GSFC CO_2 lidar
80x80 µm pixel and 4x4 pixels
~90% Quantum efficiency from 0.7 to 4.3 µm



Closed-cycle cryocooler used for lab tests and aircraft



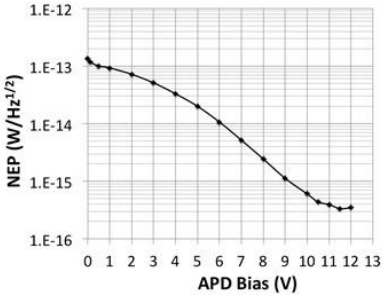
Packaged detector system for airborne lidar

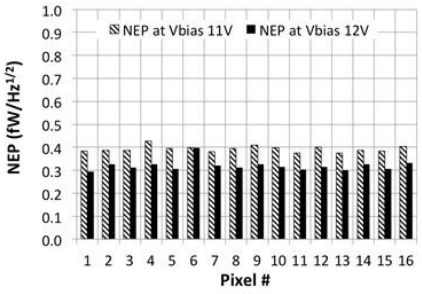


More details can be found in Beck *et al., J. Electron Materials*, 2014; Sun *et al. SPIE 9114*, 2014; Sun *et al., Optics Express*, 2017

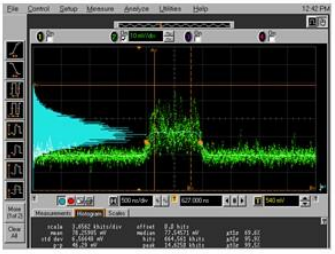
HgCdTe APD Arrays for Trace Gas Lidar - Performance

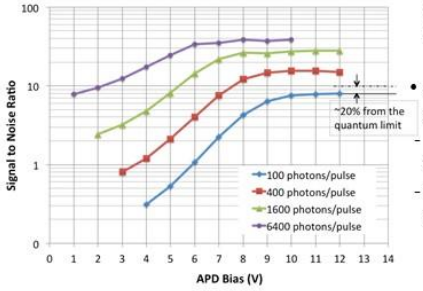
Lowest noise equivalent power





Analog waveform (100 photons/pulse



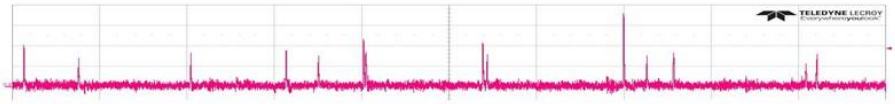


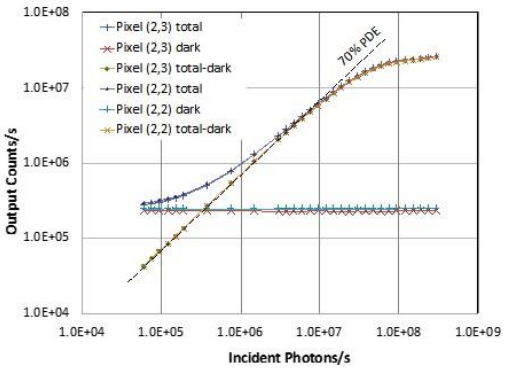
- Near quantum limited receiver performance in the GSFC 1.57 µm CO_2 Sounder lidar
- One unit is used in GSFC 1.65 µm CH_4 lidar
- One unit is now used in NASA LaRC 2-µm CO_2 Lidar
- Also used in GSFC's development of:
  - a Mars 1.064 µm climate lidar
  - a 3-µm lunar surface volatile lidar

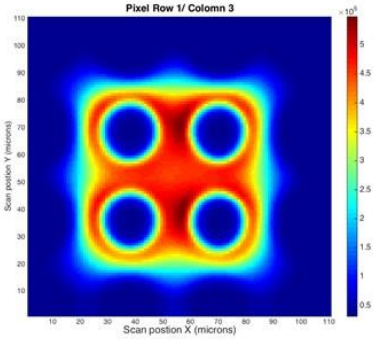
Sun et al. SPIE 9114, 2014; Sun et al., Optics Express, 2017

Advanced HgCdTe APD Arrays - Linear mode photon counting

Pulse waveforms from single photon detection under cw illumination.

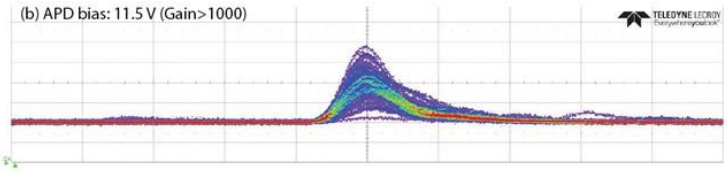




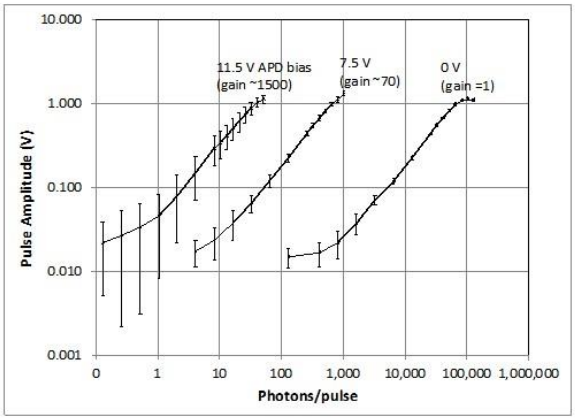


Advanced HgCdTe APD Arrays
- Linear mode single and multiple photon detection

GSFC



Pulse waveforms from multiple (~15) photons/pulse



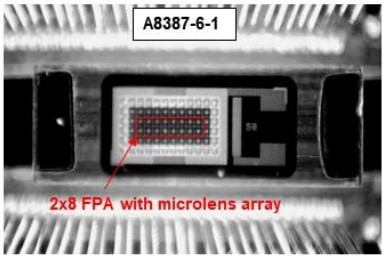
- **Output pulse amplitude can be used to estimate the received number of photons/pulse**
- **Estimated APD excess noise factor <1.3**

More details in Sun *et al.*, SPIE 10659, 2018

Advanced HgCdTe APD Arrays
- Integration of Microlens Arrays

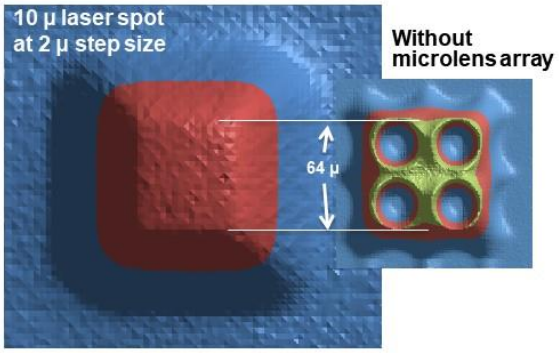
GSFC

Microlens array on HgCdTe APD array





Surface map shows the microlens array concentrated light on the center of the pixel and achieved ~100% fill factor at f/7.



Supported by ESTO InVEST program

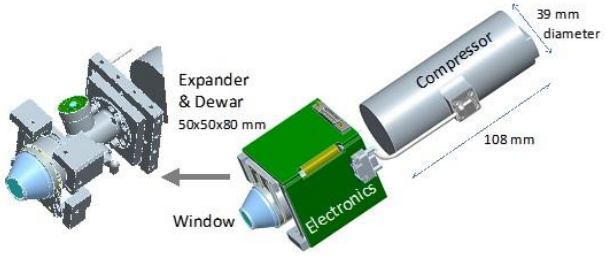
More details in Sun *et al.*, SPIE 10659, 2018

Integrated Detector Cooler Assembly*

GSFC

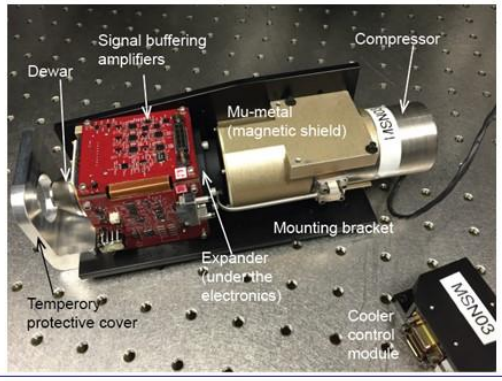
DRS 1/5W Mini-Stirling Cooler





- **Miniature Stirling cryo-cooler from DRS - multi-year life time**
- **Detector temperature : 80K or 110K**
- **Mass: ~0.8 kg cooler only and 1.4 kg with mounting bracket and Mu-metal magnetic shield for CubeSat**
- **Electrical power: 6-8 W with heat sink at 30˚C**

*** Supported by ESTO InVEST-12 program**

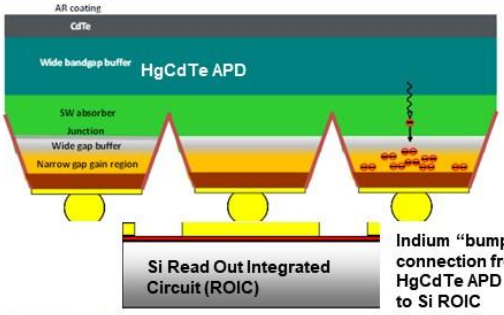


New HgCdTe APD Array by Leonardo UK

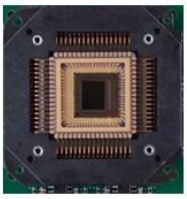
GSFC

- Developed under ESA SAPHIRA program for fast frame imaging in astronomy.
- Planar Metal-organic vapor phase epitaxy (MOVPE) multi-anodes mesa avalanche photodiode array (100% fill factor)
- Indium 'bump' connection to Si ROIC as in the H1RG in HST and H2RG in JWST
- 24 µm pixel size, 320x256 pixels
- Extremely low dark current
- Nominal APD gain = 80 at 12 V bias and up to 580 at 20 V.
- Spectral response 0.8-2.5 µm

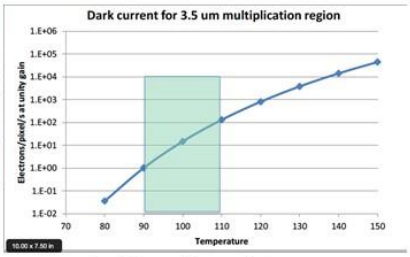
* To be evaluated under ESTO QRS-17



Indium "bump" connection from HgCdTe APD to Si ROIC



HgCdTe APD FPA operate from for high frame rate IR imaging for astronomy

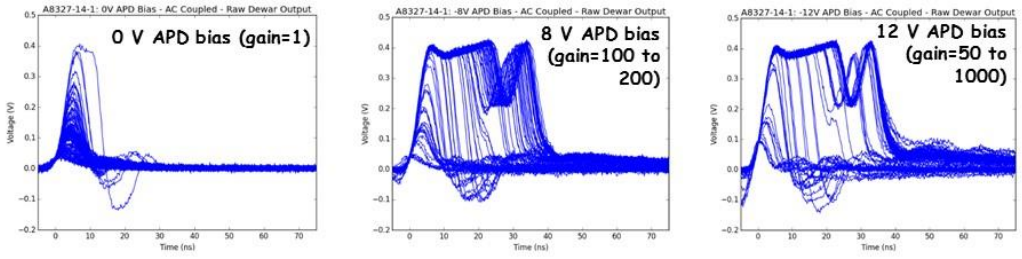


Dark Count Rate vs. Temperature

Baker *et al.*, SPIE 9915, 2016

Radiation Damage Test of DRS HgCdTe APD

Transient effects from proton hits: large output pulses, saturating the electronics but no latch-up, recovering within 1 μs.



Accumulated radiation effects tested with protons up to 100 krad(Si)

- **Slight decrease in quantum efficiency, 7% at 100 krad(Si)**
- **Likely no significant change in the APD gain**
- **Linear increase in dark currents with proton dose**
- **About 100x increase in dark currents after warming the device to room temperature and cooling down again**
- **Complete annealing by heating the detector to 85°C for 3 hours**

Summary and Recommendations

- PMT or silicon APDs have served us well in space lidar in the past 25 years and will continue to do so for visible to near IR wavelength 1 to <10 beam lidar
- New lidar detectors are needed for next generation space lidar
  - Higher quantum efficiency from visible to mid-wave IR
  - Linear mode photon counting with wide dynamic range
  - Continuous operation, no dead-time, after pulsing, or other nonlinear effects
  - Multi-pixel arrays
- Recently development of HgCdTe APD arrays is a major breakthrough in space and airborne lidar detectors with all the desired properties
- Several options available for the space cryo-coolers with small size and mass, moderate electrical power, and multi-year lifetime
- The HgCdTe APD technology has drawn new applications and funding from planetary science division
- Need additional funding to mature the technology in yield and ease of use, fabricate larger pixel arrays, and reduce cost for other NASA applications

4.5 SINGLE PHOTON LIDAR MEASUREMENT TECHNOLOGIES

Roman L. Machan[1], John J. Degnan[2], J. Marcos Sirota[2]

[1]Sigma Space LLC, Roman.Machan@sigmaspace.com
[2]Sigma Space LLC:USA

ABSTRACT

Sigma Space develops, produces, and deploys Lidar instruments suitable for a number of NASA priorities including terrestrial and planetary mapping, laser ranging, surface topography & vegetation, docking/landing, and ice elevation. Backscatter lidar instruments provide measurements of aerosols, clouds, boundary layer, and clear air wind profiles using various techniques such as multi-wavelength, polarization, scanning, and Doppler measurements. Sigma has teamed with Goddard, JPL and Langley on several missions to leverage its internal R&D investments and instrument experience for ground-based, airborne, and space flight missions. The measurement techniques extend to commercial and Department of Defense activities as well, allowing for cost savings and rapid development by cross-pollinating developments from different business segments. Our measurement approach uses single photon sensitive detectors in the 532nm and 1064 nm wavelengths paired with custom timing electronics optimized for the specific measurement concept. This has many advantages for NASA missions. Single photon sensitivity allows for the use of smaller, more reliable lasers that are better suited for space flight where volume, mass, power and cost are prime considerations. Custom FPGA-based timing electronics suitable for radiation environments allow for very compact solutions for a large number of independent channels that are ideal for mapping or landing applications. The compact size and low power solutions allow for new NASA instrument opportunities for active lidar sensors.

1 INTRODUCTION

Single Photon active sensing is a cross-cutting optical measurement technique that is being used or could be used for several of NASA's Decadal Survey targeted observables. Sigma's implementation of this technique is split into two approaches, both of which use single photon sensitive detectors.

The first, widely known as Single Photon Lidar (SPL) is used in ice elevation, snow depth, terrestrial structure, surface topography, vegetation, and general mapping or docking/landing applications. It uses short laser pulses (10 to 100's of Picoseconds) pixelated detector arrays (25 to 256 pixels) and, multi-stop, multi-channel precision timers, to time tag lidar return edges to a precision of between 3 to 20 ps rms.

The second technique, commonly used in atmospheric backscatter lidar, also uses single photon sensitive detectors and histograms the lidar return pulses into time bins that represent typically 5 to 70 meters of distance. These instruments can histogram up to 24 different channels simultaneously. The signal is integrated over a period ranging from 1 second to 15 minutes to extract the signal from the noise floor. NASA objectives such as aerosols, clouds, planetary boundary layer, and winds all use this measurement concept. Sigma played a key role in all the instruments cited below.

Ice Elevation: Using the SPL measurement concept, the Advanced Topographic Laser Altimeter System (ATLAS) instrument will measure ice sheet elevation change to less than 0.4cm per year and sea ice thickness from low Earth orbit using a 532 nm, 10 KHz laser, with 60 receiver channels, while also measuring global vegetation biomass. ATLAS will launch on the ICE-Sat2 (Ice, Cloud, and Land Elevation Satellite) mission in September 2018. The measurement concept was already validated in NASA's ER-2 and Proteus aircraft as part of MABEL (Multiple Altimeter Beam Experimental Lidar). The data was used to validate design and link margins from 60 kft and develop algorithms for ATLAS tree canopy measurements.

Snow Depth and Snow Water Equivalent: High resolution, wide area coverage, mapping lidar such as SPL can be used to map the same areas before and after snowfall, using the change in measured surface height to accurately compute the depth of

snow and equivalent volume of water, applying the same methodology currently used with much less efficient linear mode lidars.

Terrestrial Ecosystem Structure; Surface Topography and Vegetation: These observables have been grouped together. Sigma's SPL-100 instruments are actively mapping both forest canopy and above ground biomass from aircraft platforms for USGS and other organizations. High-altitude versions, SPL100-HA's, are currently mapping for the military, and ATLAS will soon map from low earth orbit over its 3-year mission, all using the same measurement concept. Recent flights over triple canopy vegetation in Hawaii have demonstrated excellent foliage penetration. This is due to the combination of low dead time detectors and Sigma's multi-stop timer capability. The same data sets could be processed to produce bare earth products and shallow-water bathymetry, which produces good results when using a 532 nm wavelength (figure 1). This capability could be important for coastline and floodplain mapping applications.

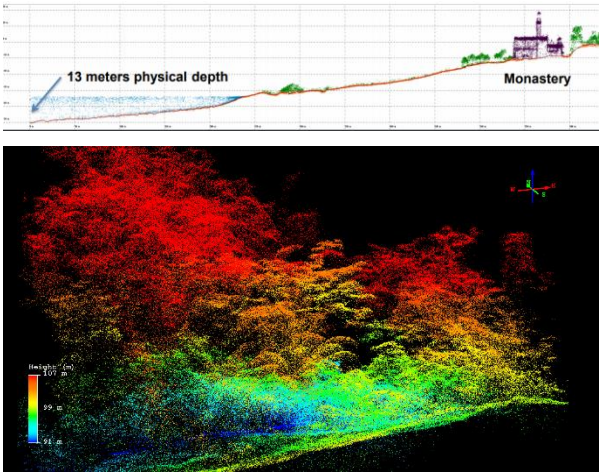


Figure 3 Water Penetration to 13 meters in Pt. Lobos, CA (top), and forest penetration in Oahu, HI.

Aerosols: Sigma's MicroPulse Lidar (MPL) and Mini-MPL products are ground-based backscatter lidars with a range of between 9 and 25 km depending on version and wavelength. They use either 532 or 1047 nm lasers and have polarization options. By measuring the boundary layer, MPL helps to support tracking of emissions and transport, another NASA targeted observable. Over 100 of these instruments are deployed worldwide as part of NASA's MPL-NET and for other commercial applications including volcanic ash and pollution monitoring.

Planetary Boundary Layer: By measuring aerosol structure, Sigma's MPL and Mini-MPL systems measure and monitor the real-time structure and dynamics of the planetary boundary layer. Measurement of transport and vertical mixing in the lower atmosphere provides better meteorological and urban canopy models.

Clouds: Cloud Physics Lidar (CPL) [1] is an airborne instrument that uses single photon counting and histogramming techniques. CPL has flown on the ER-2 and Global Hawk aircraft, collecting data from 60 kft. It uses 355, 532, and 1064 nm wavelengths along with multiple polarizations to produce products including cloud profiling, aerosol and boundary layer, cloud optical depth, cloud optical size, and depolarization ratio to determine the ice vs. water content of clouds.

Winds: Tropospheric Wind Lidar Technology Experiment (TWiLiTE) [2] is a direct detection scanning Doppler lidar designed to measure wind profiles in clear air. It has flown on the WB-57 and NASA's ER-2 aircraft, and uses the single photon counting and histogramming technique.

Rendezvous / Docking / Landing: Sigma is working with JPL to extend SPL technology for a landing / hazard avoidance application in the high radiation environments of the Jovian moons. These efforts require additional development of proven concepts to withstand primarily high energy electrons and secondary radiation effects that create excess noise not typically present in low Earth orbit (LEO) or terrestrial applications. Initial results show that with minor modifications, SPL techniques can be readily adapted for these environments.

Sigma has proposed a solid-state range finding solution for Restore-L. Rendezvous missions benefit from active lidar with photon-sensitive detectors, which can then easily perform the docking function as well.

2 METHODOLOGY

2.1 STATE OF THE ART

The SPL measurement technique uses a 5 to 10 watt laser, transmit optics, scanner, receive optics,

a single-photon sensitive pixelated detector, analog front end, and multi-channel, multi-stop timer implemented in a Field Programmable Gate Array (FPGA). We prefer the FPGA timer approach due to the flexibility afforded by small customizations for new missions, and the ability to quickly implement the same functionality in cost-effective commercial hardware or flight qualified FPGAs for space flight. New FPGA offerings from vendors allow continuous improvements with speed, new features and resolution improvements with minimal investment. Some applications such as docking, landing and military lidar require on-board real-time processing.

Lasers used for SPL applications have several desirable characteristics as shown in table 1-1. They are typically Q-switched, solid state, diode-pumped lasers most often with a 532 nm wavelength due to the combined efficiency of available laser and detector pairs. The line widths are typically around 0.1 nm, which enables the use of tight optical bandpass filters to further reduce solar noise, provided that the line width and filter are relatively stable with required mission temperatures.

Table 1-1 Typical Laser Characteristics for SPL measurements

Laser Specification	Value
Wavelength	532 or 1064 nm
Pulse Width	100 ps to 1ns FWHM
Pulse Repetition Rate	20 to 100 KHz
Laser Power	5 Watt (532nm) to 15 Watt (1064)

The lasers are not continuous wave, but rather output sub nanosecond, skewed Gaussian pulses. Depending on the distance, laser repetition rate, and the application, it may be desirable to have multiple pulses in the air simultaneously to increase data rates. The outgoing beam is often scanned with a single or dual wedge scanner, or with a fast steering mirror to cover a larger target area. Scanner selection depends on mission requirements. A single 15-degree half-angle wedge scanner is currently used to produce a conical scan for mapping applications at high AGL (above ground level).

Passing the outgoing beam through a diffractive optical element (DOE) produces an array of beamlets that can be imaged onto individual detector anodes after passing through a 5" telescope, for example, shared by the transmit and receive paths. A small field of view, matched between the transmit and receive optics, results in low solar noise and allows for operation in full daylight. Simple noise filtering algorithms easily remove noise and have a negligible effect on the probability of detecting the desired signals on all channels with each laser shot. Typically, between 25 and 256 detector and timer channels are used depending on signal strength and the desired rate of coverage.

The receiver optics need to correct for the pulse time of flight (if the distances are sufficiently large) to focus the individual beamlets on an array of single photon sensitive detector anodes.

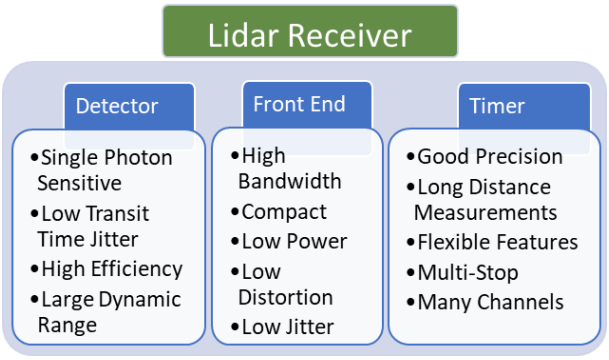


Figure 2 Lidar receiver components and desired features

The remaining key components of the lidar receiver are shown in Figure 2. To be considered single photon sensitive, the detector should have a minimum gain of 10^5, but more typically between $1x10^6$ and $6x10^6$. An additional amplifier with approximately 1 GHz bandwidth must create a large enough voltage pulse to create a low-jitter signal through a fast discriminator. The timer must be able to precisely time tag each rising edge on every channel simultaneously. Each channel may have multiple rising edges within 1 or 2 ns (the dead time) for approximately 32 edges per channel per pulse, for all 100 channels, for example. In addition, by measuring both the rising and falling edges of each pulse, we get a measure of the received energy in each return. This can be used to provide intensity information in a mapping application, or to remove intensity-based range

bias for more accurate measurements. It can also be used to control the detector bias voltage to improve operation over a dynamic range of six orders of magnitude.

The system will need a GPS, IMU and scanner position feedback with specifications for those components flowing down from standoff distance, desired accuracy, and other system level parameters. That data, along with the forward motion of the aircraft or spacecraft produces contiguous maps.

The SPL measurement technique makes the best use of the limited laser energy and good components are currently available for most missions. One photon produces one 3D measurement in the range of a few cm of range resolution. System errors from GPS, IMU, and scanner tend to limit overall geolocation accuracy to the 5 to 10 cm range. However, the same technique can measure to less than one millimeter by averaging over many returns to a stable satellite trajectory.

The SPL technique allows contiguous mapping to be done in a single pass. SPL measurements fit between linear mode and Geiger systems, and borrow some beneficial characteristics from both approaches. SPL is very flexible and can take advantage of stronger returns when available. For example, an imager that is ultimately used in a planetary landing application at the end of the mission can provide mapping while on orbit with single-photon sensitivity and make use of additional photons to improve accuracy or eliminate noise by raising the threshold above the single-photon threshold during the low-altitude mapping stage.

Solid state silicon detectors that maintain the low dead time through the use of many SPAD-like (Single Photon Avalanche Diode) microcells are a good alternative to Photo Multiplier Tubes (PMTs) in green wavelengths but are not efficient in the infrared wavelengths. Sigma is working to validate new options for missions that benefit from IR wavelengths through commercial and military programs, which may benefit NASA missions in the future.

Measurement goals are pushing the boundaries of available laser energy and pulse widths. More energy in small, efficient volumes that are suitable for aircraft or space flight are needed, with short pulse durations and high repetition rates with adequate link margin for large numbers of channels. 1 ns FWHM (full width half max) laser pulse widths are adequate. Five to 500 ps would be better if the repetition rates and pulse energy could be maintained. Suitable lasers for NASA missions fall into the range of 5 to 15 Watts in the 532 nm wavelength. More powerful lasers often must be liquid cooled, adding significant mass.

Detector transit time jitter performance is the largest source of timing error in these systems. Photomultiplier tubes have better transit time jitter specifications than Silicon Photo Multipliers (SiPMs), if they use a microchannel plate gain stage rather than dynode chains. See figure 3 for a comparison of detector technologies. But PMTs require high voltage and have limited lifetime as compared to SiPMs. PMTs are better for radiation effects and are often used for flight missions. SiPMs are not efficient enough at 1064 nm, so new detectors are being developed and tested to satisfy the IR wavelengths. Lasers at 1064 nm are available with acceptable specifications to meet most mission requirements.

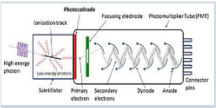
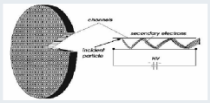
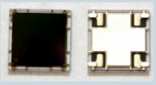
Detector Technology	Architecture	Key Advantage
PMT Photomultiplier Tube with dynode chain electron multiplication		Proven for space applications, with correct window and cathode materials
MCP-PMT PMT with microchannel plate electron multiplication		Improved timing (low transit time spread)
SiPM / MPPC Silicon Photo Multiplier Mulitple SPADs per pixel (channel), Geiger mode		Low cost, uniformity, solid state, low voltage, robust, acceptable timing

Figure 3 Suitable Detector Technologies for SPL Measurement Technique

Larger detector arrays (16x16) help with coverage in time constrained applications such as hazard avoidance. Much larger commercial arrays already exist in the Microchannel Plate Photomultiplier Tube (MCP PMT) detector technology, but some special considerations must be taken for high radiation environments. Some development is beneficial for future NASA missions. Note that

MCP PMTs naturally have a low dead time. In fact, the tubes are always ready to receive another photon and superimpose two events in an additive analog manner. The dead time comes primarily from the edge rates of the detector and the ability of the timer to discern the two edges with a fixed threshold discriminator. This is typically on the order of 1.6 ns, which is sufficiently fast to discern two objects that are close together in range or to prevent high noise rates from disabling the detector pixel.

Most of the key components have been verified to TRL-8 for the ICESat-2 mission to low Earth orbit, except for a scanner since it will be a "push broom" mapper and no scanner is required. A fast steering mirror has been identified as a suitable scanner for future missions with a TRL-9 level for LEO environments.

New Approach

Other approaches to the measurement concept include linear mode lidar and Geiger mode lidars. Many problems can be solved in multiple ways with different techniques. We feel that the primary reasons that our approach is well-suited for NASA missions:

- They are the most efficient 3D imagers possible since each range measurement requires only one detected photon as opposed to hundreds or thousands in conventional laser pulse time of flight (TOF) or waveform altimeters. [3]
- Their high efficiency enables orders of magnitude more imaging capability (e.g. higher spatial resolution, larger swaths and greater areal coverage). [3]
- Single photon sensitivity combined with fast recovery multi-stop timing capability enables the lidar to penetrate semi porous obscurations such as vegetation, ground fog, thin clouds, etc. Furthermore, the 532 nm operating wavelength is highly transmissive in water thereby permitting shallow water bathymetry and 3D underwater imaging. [3]
- Contiguous, high resolution topographic mapping and surveying on a single overflight becomes possible with very modest laser powers and telescope apertures – even from orbital altitudes. [3]
- Simple algorithms can be applied to a reasonable number of channels (25 to 256) in real time, enabling new missions such as docking or landing/hazard avoidance.

Suggested development priorities for NASA may include long-life scanning mechanisms that are ideal for a wide range of mission requirements. In addition, research in very short-pulse flight lasers in 532 or 1064 wavelengths, or suitable radiation hardened detectors in complimentary wavelengths would benefit the SPL measurement concept.

Single photon sensitivity and reasonably sized detector arrays and associated electronics have many advantages for NASA flight systems. They can take advantage of smaller lasers that are easier to build for space. Small lasers are inherently more reliable than high power lasers that can damage optical coatings and push the limits of SWAP constrained missions.

2.2 DESCRIBE THE FUTURE STATE

Future developments that would expand capability include on-board real-time processing, reductions in SWAP, operation in harsher environments, low dead time infrared and other wavelength detectors. Other incremental performance improvements such as shorter pulse and higher repetition rate lasers, detectors with lower time jitter and higher resolution timers could also improve performance and expand the application space.

For example, qualification of select components to higher radiation requirements would enable rendezvous/capture, landing, and planetary mapping applications in a Jovian radiation environment. Development of a front-end analog Application Specific Integrated Circuit (ASIC) and flight-qualified Risley prism (wedge) scanners could enable SWAP reductions.

2.3 RISKS AND REWARDS

Risks at this time are primarily toward qualifying the components such as the detector and front-end circuitry for high radiation levels beyond Low Earth Orbit (LEO) to expand the number of possible missions.

3 PROGRAMMATICS

3.1 DEVELOPMENT PLANS

Sigma continues to push the envelope on miniaturizing instrument systems and driving

down power requirements. We are currently developing a "Next-Gen" SPL lidar receiver which would be compatible with Cubesat-level SWAP.

Sigma continues to evolve the technique from 532 nm to 1064 nm laser and detector options to solve new commercial challenges such as high-speed train collision avoidance and military reconnaissance and surveillance needs where either eye safety or covert operations drive the non-visible wavelengths. Some of these technologies end up flowing back to NASA for future space mission concepts.

Under a NASA contract, we plan to develop a 16x16 (256-channel) detector and timer suitable for the harshest radiation environments.

We are also working with vendors and the government for advances in flight lasers. We have recently completed design and integration of flight laser electronics in a Goddard project.

3.2 Development Milestones and Dates

A key date will be the space flight validation of the technology in September 2018 with the launch of the ICESat-2 mission, eventually bringing it to TRL-9.

3.3 Partnering

We see NASA providing the science and mission engineering leadership while leveraging Sigma's technology insertion into future NASA missions. Sigma has partnered with NASA Goddard, JPL and Langley in multiple TRL-advancing efforts, as well as development of space flight systems. We have also worked with the Army Geospatial Center, United States Geological Survey, and multiple partners in industry, and many academic institutions worldwide both for our SPL systems, as well as our photon counting/histogramming cards and products. Future partners will likely consist of similar agencies.

Sigma's parent company, Hexagon, provides paths for partnering with other Hexagon subsidiaries such as Leica Geosystems. Leica produces high quality camera instruments, platform stabilization, and metrology systems that may be suitable for NASA needs, but space qualification efforts would be required.

3.4 Overcoming the Valley of Death

The SPL technology is beyond this development milestone and improvements are evolutionary at this point.

4 WIDER VISION

The cross-cutting benefits are evident from the number of NASA objectives that can be covered using this measurement technique. Multipurpose instruments can be designed for a single mission to maximize the science return per invested dollar. For example, the same instrument can be used for general altimetry, atmospheric science and planetary mapping at high altitudes and later used for hazard detection during landing. Also, the SPL technique has not yet been applied to extraterrestrial mapping, asteroid mapping or docking and hazard avoidance, yet it is a natural extension due to the small SWAP and capacity for real-time processing. MPL and wind lidar concepts verified in ground networks and airborne platforms can be extended to flight missions.

Also, if there are any science benefits to incorporating SPL-level timing techniques into wind, cloud, or aerosol or planetary boundary measurements, the relatively coarse counting and histogram binning could be augmented with much better precision, although there has not been customer demand to move in that direction.

5 CONCLUSIONS

Single Photon Lidar measurement techniques offer a powerful tool for flight missions due to the modest laser size/power needs and low mass/volume necessary to perform the measurements in a flight environment. We continue to expand the technology with our government partnerships and commercial customers to produce new timers with more channels, better precision, more features, smaller packaging of instrument electronics, and radiation hardened versions suitable both for LEO and high radiation planetary needs. The measurement technique has been verified by thousands of hours of data collection from 10 systems in commercial aircraft, 2 high-altitude military systems, and full flight qualification and characterization by NASA GSFC for the ATLAS instrument.

ACKNOWLEDGEMENTS

Sigma acknowledges partners at GSFC, JPL, and Langley for partnering on prior space missions, space technology development, and aircraft development efforts. These include Matt McGill, Stan Scott, Andrew Kupchock, Bruce Gentry, Anup Katake, Alejandro San Martin, Steven Jurczyk, Robert Hodson and Judd Welton.

References

1. Matthew McGill, Dennis Hlavka, William Hart, V. Stanley Scott, James Spinhirne, and Beat Schmid, 2002: Cloud Physics Lidar: Instrument Description and Initial Measurement Results, Applied Optics 41, 3725-3734
2. Bruce Gentry, Matthew McGill, Geary Schwemmer, Michael Hardesty, Alan Brewer, Thomas Wilkerson, Robert Atlas, Marcos Sirota, Scott Lindemann, Floyd Hovis, 2007: Development of an airborne molecular direct detection Doppler lidar for tropospheric wind profiling, Proc. SPIE 6681, Lidar Remote Sensing for Environmental Monitoring, San Diego, VIII, 66810B
3. Degnan, J., 2016: The Impact of Single Photon SLR Technology on Large Scale Topo-Bathymetric Mapping, International Workshop on Laser Ranging, Potsdam, Germany

NASA Technical Interchange Meeting on Active Optical Systems for Supporting Science, Exploration, and Aeronautics Measurements Needs

July 31-Aug 3, 2018
Location: Universities Space Research Association Headquarters, Columbia, MD

Single Photon Lidar Measurement Technologies

Roman Machan CTO Sigma Space, LLC



Two Distinct Active Optical Techniques For NASA Observables

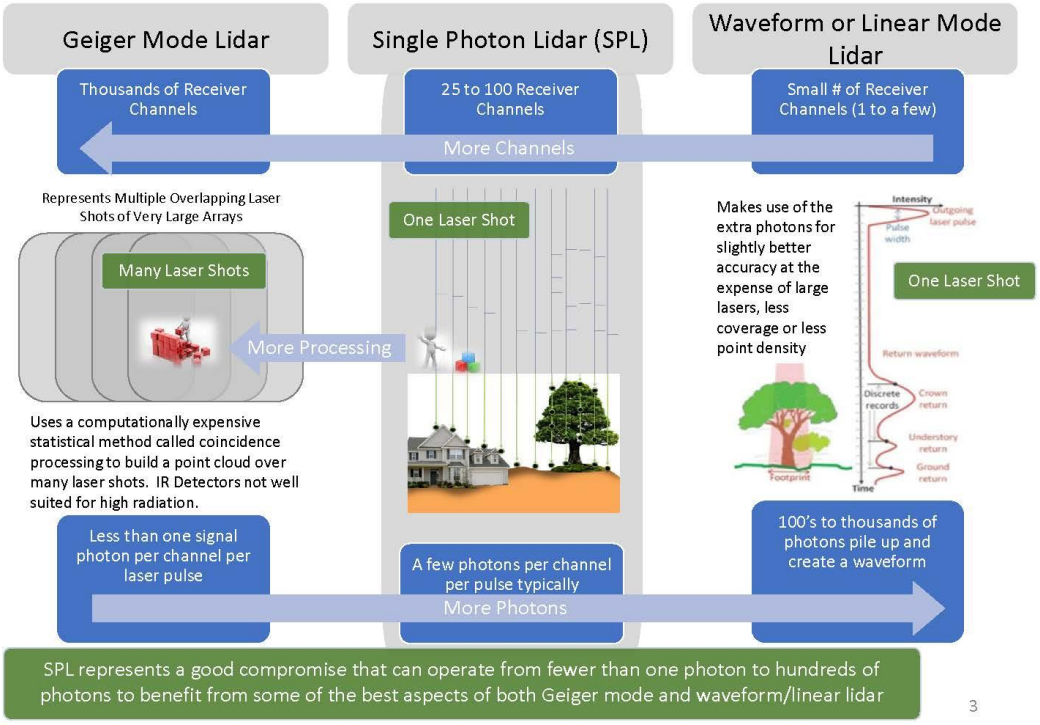
NASA Observables	Active Lidar Technique	Typical Timer Resolution
Ice Elevation; Snow Depth and Water Equivalent; Surface Topography, Vegetation, Landing	Single Photon Lidar • Fine Timing, Dual-Stage Timer • Precise Range Measurements • Multi-shot Timer • Each Laser Shot Returns Range Information for Continuous, Single Pass Mapping • 25 to 100 Detector Channels	7 – 70 ps (RMS) Note 1 1 – 10 mm Time "Tags"
Aerosols / Planetary Boundary Layer; Clouds; Winds	Photon Counting • Coarse Timing, Binning, Histogramming • High Speed Counter • Integrate Signal for 0.1 sec to 15 minutes for improved Signal-to-Noise ratio • 1 to 24 Channels	33 – 467 ns 5 – 70 m Note 2 Time "Bins"

Note 1: Full measurement is dominated by detector transit time jitter and laser pulse width error contributions.
Note 2: 2-way distance of light

Different science measurements use different techniques and different resolution

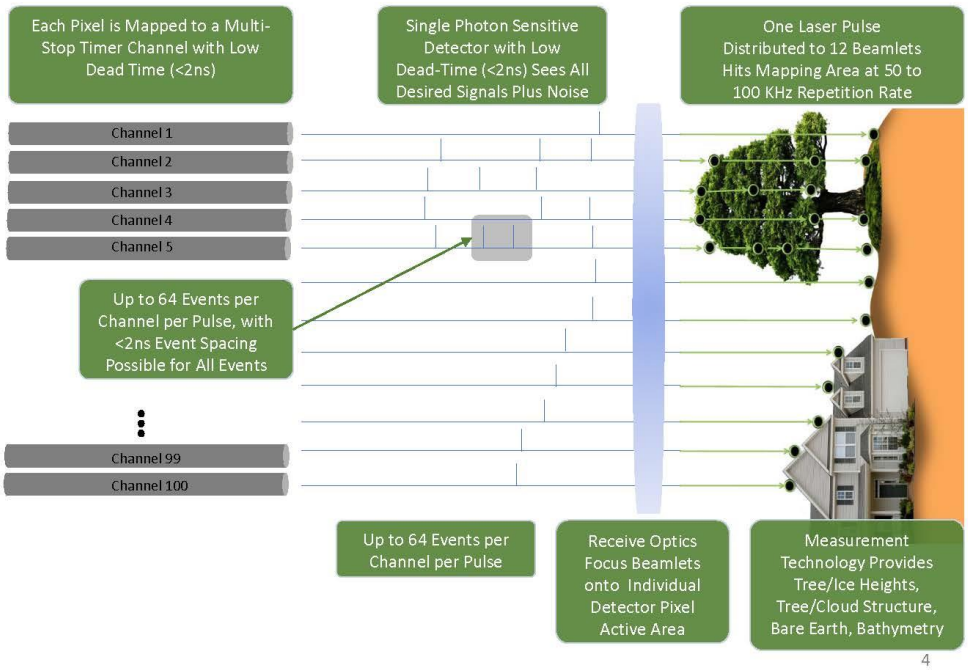
2

Other Approaches to SPL Techniques



3

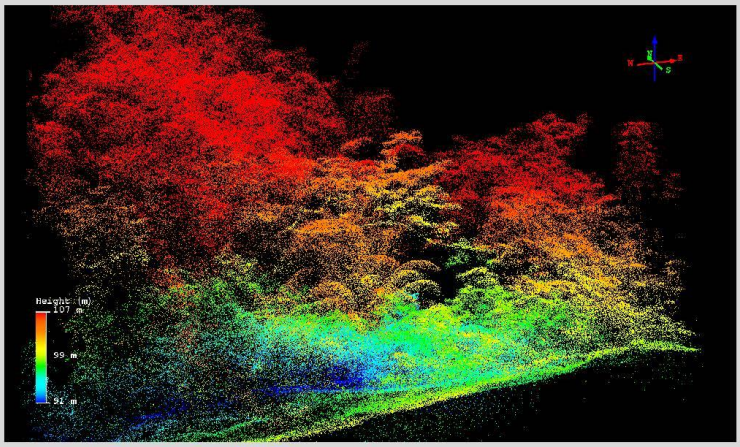
How Does the SPL Multi-Stop Timer and Detector with Low Dead-Time Benefit the Measurement?



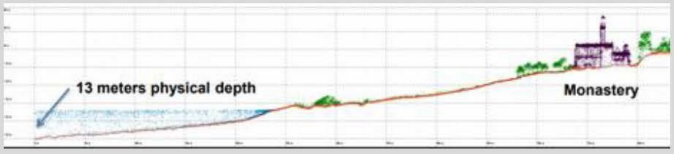
4

SPL Biomass, Tree Heights, and Water Penetration

Biomass & Tree Heights



Water and Ice Melt Penetration



- Data over Oahu, HI shows distinct layers of triple-canopy forest, ground below trees.
- We see 5 or 6 signal returns per channel per pulse in the data, demonstrating the SPL active lidar technique with low dead time and multi-stop timer is effective for biomass and tree height instruments.
- Excellent for bathymetry, ice melt ponds thin clouds, or other semi-porous obscurations.

5

Lidar Key Components and Desired Features

Laser, Scanner, Optics

Pulsed Laser
- Q-Switched, Solid State, Diode Pumped
- Often green (532nm) due to combined efficiency of available lasers and detectors
- Pulse Width <1ns FWHM
- Pulse repetition rates of 20 to 100KHz typical
- Micro joules per pixel per shot

Transmission Optics & Scanner
- Fast Steering Mirror or Dual Wedge Scanner
- Flexible Scan Patterns
- Low Loss Optics and coatings
- DOE for Multiple Beamlets

Gaussian-like Pulses (one or more in the air simultaneously)

Target



Clouds | Trees | Ice

Arrays (multiple channels) provide faster coverage or higher density information

Lidar Receiver

Receive Optics
- Low Losses
- Thermally Stable
- Robust Mounts
- Speed of Light Correction for long stand-off distances
- Tight Spectral Filter

Detector
- Single Photon Sensitive
- Low Transit Time Jitter
- High Efficiency
- Low Dead Time

Amp/Discriminator (Front End)
- High Bandwidth
- Compact
- Low Power
- Low Distortion
- Low Jitter

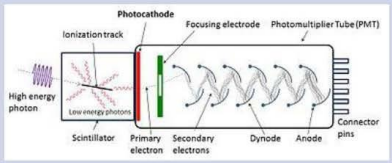
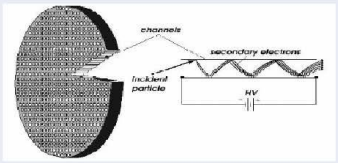
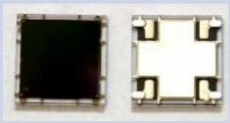
Timer
- Good Precision
- Long Distance Measurements
- Flexible Features
- Optimize for Mission
- Multi-Stop
- Many Channels

Processing
- Simple Processing Desired
- Capable of Real-Time Operation

6

Applicable Detector Technologies (<2ns Dead Time Including Timer Electronics)

Photo Multiplier Tubes Have the Best Radiation and Magnetic Field Immunity

Detector Technology	Architecture	Key Advantage
PMT Photomultiplier Tube with dynode chain electron multiplication		Proven for space applications, with correct window and cathode materials
MCP-PMT PMT with microchannel plate electron multiplication		Improved timing (low transit time spread)
SiPM / MPPC Silicon Photo Multiplier Mulitple SPADs per pixel (channel), Geiger mode		Low cost, uniformity, solid state, low voltage, robust, acceptable timing

Note: APDs are not single photon sensitive, and SPADs have long dead times.

7

Sources of Range Timing Error

Detector	Pulsed Laser	Timer & Front-End Electronics
		
•Multi-anode detectors available in SiPM for 532. Hundreds of microcells per pixel, low dead time •Tubes with microchannel plate gain have less time jitter, best for radiation, but high voltage and lifetime challenges •Detector often dominates the timing error	•Shorter pulse widths are preferred (6 ps to 500 ps FWHM) •Flight Lasers are often closer to 1ns FWHM pulse widths due to available lasers in the power and repetition rates needed.	•Relatively small timing errors (7 to 20 ps rms) is often achieved •100 or more channels in a single device •Discrete or ASIC solutions for Front-End Electronics have negligible contribution to error

Typically Decreasing Timing Error Contributions

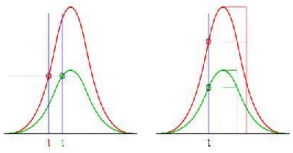
- Transit Time Spread (TTS) is the measure of detector error for timing applications.
- TTS represents the jitter of the leading edge of the lidar return, and varies with different MCP photocathode materials

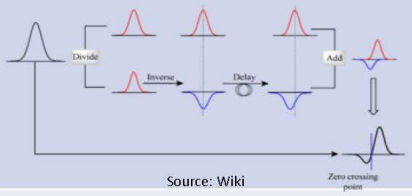
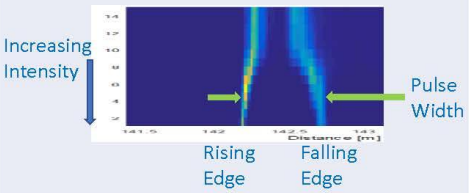
Detector Type	Photocathode Material	Transit Time Spread (FWHM) (single photon)	Quantum Efficiency (QE) @532 nm	Radiation Susceptibility
MCP PMT	Multialkali	70 ps	9%	Excellent
MCP PMT	GaAsP	100 ps	35%	Excellent
SiPM	Si	150 ps	25%	Poor
Dynode Chain PMT	Any	>370 ps	N/A	Excellent

8

Range Walk Corrections

- Range walk in single photon systems is a result of discriminating various pulse heights at a constant threshold value.



	Range Walk Correction Technique	Approach
Preferred for Small Number of Channels	**Constant Fraction Discriminator** • Move the zero crossing to align edges in time • Not a compact solution for a large number of channels	 Source: Wiki
Preferred for Large Number of Channels	**Time Over Threshold** • Pulse height is related to pulse width • Measure pulse width using same threshold • Adjust reported time (range) based on pulse width • Compact solution, also provides a measure of intensity on a per return, per shot basis	

9

Time Stability

- **Short Term Stability:** Shot-to-shot random jitter (select oscillator with good jitter cleaner - sub ps components are readily available)
- **Long Term Stability:** Two methods to provide reference clock stability
  1) Measure against GPS 1PPS
  2) Synchronize to highly stable oscillator
     - Ex. Stanford Research PRS10, 10 MHz Rubidium frequency standard
     - PLL locked to 10 MHz reference, spun up to desired timer reference frequency

10

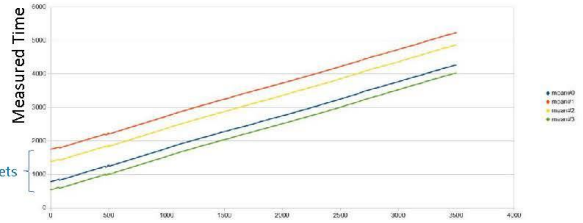
Timer Implementation Trades

- Custom ASICs vs. FPGAs
  - ASICs allow more choices of timer architectures, more flexible clocking, full control of routing, lowest power.
  - FPGAs offer flexibility, low development cost, and adequate performance. As transistors scale with Moore's law, you enjoy rapid upgrade paths to more logic & memory, faster speed, and lower power (core voltage) – often in the same PCB footprint. Care must be taken for optimum selection of timer architecture and use of limited global resources to accommodate large numbers of channels. FPGAs allow for design portability and customization for specific project needs, thereby allowing for much re-use over multiple projects.
- Analog vs. Digital timers
  - Smaller CMOS feature sizes make better timers than voltage resolution of analog signals.
  - Analog systems typically require more power, must be "tuned" and tend to drift significantly with temperature and voltage variations.
  - Digital can be re-scaled in post processing to remove temp/volt errors and be tied to a stable reference clock. Integral non-linearity can be removed through calibration.

SPL is a Fully Flight-Qualified Technique

Many Channels can be Built in a Single FPGA with Similar Linearity

Offset Delays are Calibrated Out at The System Level





Credit NASA GSFC

- The SPL measurement technique is fully qualified for flight on the ATLAS mission, due to launch Sept 2018.
- Separate test boards also characterized the timer techniques for stability over temperature, crosstalk, I/O and core voltage variations, and process variations.

State-of-The-Art and Gaps for Future

SPL Key Component	Current NASA State-of-the-Art (SOA)	TRL for (LEO)	Commercial / Military SOA	NASA Planned Developments	TRL of Planned Items	Gap for NASA Needs
Detector	Dynode Chain	8	Solid State SiPM and MCP PMT, 532 and 1064 nm wavelengths	256-Channel MCP PMT, Bialkali cathode, for high-radiation	4	Characterize MCP PMT noise for direct and secondary radiation effects
Front End Electronics	Discrete Analog	8	ASIC	ASIC, 64- Channels, High Radiation	4	Upgrade SEE characteristics, re-package to CGA for flight
# of Timer Channels	60	8	100	256 (one FPGA), high radiation	4	Scale VHDL to larger device
Processing	Compress and downlink time tags	8	On-board storage	Real Time Processing / hazard avoidance	4	Real time processing is required for landing applications
Laser	< 1.5 ns pulse width (FWHM)	8	200-700 ps FWHM	<1 ns FWHM Power is adequate	4	Validate laser for high-radiation environment (based on heritage design)
Scanner	Fast Steering Mirror (FSM)	9	Dual Wedge Scanners	Upgrade radiation specs	4	Validate FSM for high-radiation environment

Planned developments include rad hard detector, single chip timer and front-end electronics for 256 channels (4 chips) for NASA's most harsh radiation environments.

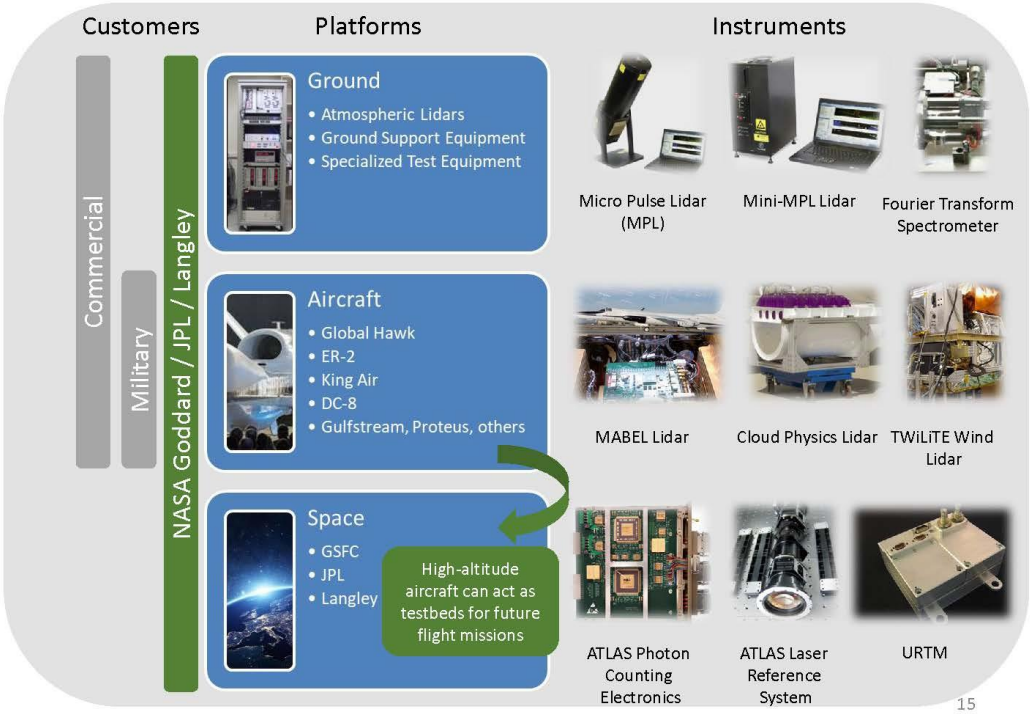
13

Why Single Photon Lidar for NASA Missions?

- **Optimally Efficient** – requires one detected photon for each range measurement
- SPL allows for **dense point collections**
- **SWAP** – Can use a smaller laser to get similar information. Lower power lasers are cheaper, more reliable, don't burn optical coatings. Smaller systems enable new missions (CubeSat, for example).
- **Highly compact** sensor, analog front-end and timer solution for high-radiation environments planned
- **Performance** – Using same sized laser, get higher spatial resolution, or greater area coverage, or higher operational altitudes, etc. For example, high radiation limits instrument survival for planetary mapping. Desire both a small laser (mass important for interplanetary), and fast coverage.
- **Penetration of Semi-porous obscurations** – thin clouds, ground fog, dust, vegetation, water columns
- **Bathymetry** – Can be collected simultaneously with topographic data. Requires suitable wavelengths [355 (blue) to 532 (green)], and benefit greatly from low dead time detectors coupled with a multi-stop timer

14

Sigma's Technology Development Benefits Multiple Customers



5 Session 5

Planetary Science was designed to examine issues related to making various scientific measurements outside the Earth environment. The Session Chair, Jonathan Rall, gave an overview presentation of the area to start the session. A total of three research presentations representing the work of researchers at GSFC and the University of Hawaii was received. Table 5-1 lists the four session papers. See Section 3 of the Assessment Report for observations and assessment comments.

Table 5-1. Session 5 Papers

Paper Number	Author	Title	Paper	Presentation
S5-1	Jonathan Rall	Overview		☑
S5-2	James B. Abshire[1], Graham R. Allan[2], X. Sun[1], Daniel Cremons[3], Scott D. Guzewich[1], Anthony Yu[1], Floyd Hovis[4], Michael D. Smith[1], H. Riris[1], Bruce M. Gentry[1] [1]NASA GSFC; [2]Sigma Space Corporation; [3]Universities Space Research Association; [4]Fibertek Inc.	MARLI: MARs Lidar for Global Wind and Aerosol Profiles from Orbit		☑
S5-3	Anupam K. Misra, Tayro E. Acosta-Maeda, John N. Porter, Shiv K. Sharma, Macey Sandford, Miles Egan, University of Hawai'i	Standoff, Active, Non-contact, Non-destructive "Search for Life" Systems with Fast Detection	☑	☑
S5-4	Barry Coyle, NASA GSFC	A Mission-enabling UV Laser for Mass Spectrometry (UVMS) with Continuously Selectable Output for in situ Planetary Exploration		☑

List of presentations

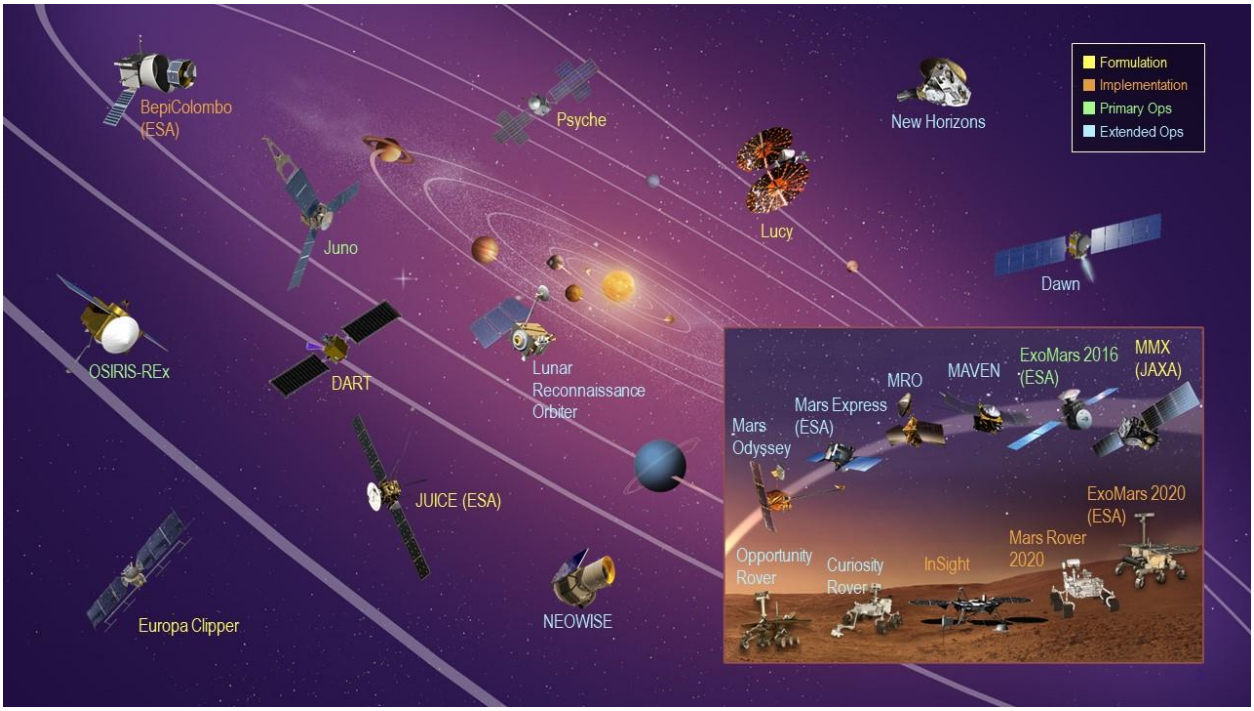
5.1 Planetary Science Division.....5-2
5.2 MARLI: MARs LIdar for Global Climate Measurements from Orbit.....5-33
5.3 Standoff, Active, Non-Contact, Non-Destructive "Search for Life" Systems with Fast Detection.....5-45
5.4 A Mission-Enabling UV Laser for Mass Spectrometry (UVMS) with Continuously Selectable Output for in situ Planetary Exploration.....5-64

5.1 PLANETARY SCIENCE DIVISION

Jonathan A. R. Rall

Planetary Research Director, Planetary Science Division, Science Mission Directorate, NASA Headquarters, Washington, D. C.





Planetary Science Budget

3

Planetary Science Program Content

	Actual FY 17	Enacted FY 18	Request FY 19	Notional FY 20	Notional FY 21	Notional FY 22	Notional FY 23
Science	5,762.2		5,895.0	5,859.9	5,841.1	5,822.4	5,803.6
Planetary Science	1,827.5		2,234.7	2,199.6	2,180.8	2,162.1	2,143.3
Planetary Science Research	230.1		258.0	247.6	247.6	247.6	247.6
Planetary Defense	60.0		150.0	150.0	150.0	150.0	150.0
Lunar Discovery and Exploration	19.0		218.0	218.0	218.0	218.0	218.0
Discovery	194.6		381.2	476.6	375.0	355.6	348.5
New Frontiers	134.0		130.2	163.7	245.0	327.6	388.4
Mars Exploration	647.0		601.5	529.7	371.9	290.8	215.3
Outer Planets and Ocean Worlds	359.5		285.6	213.8	373.3	372.5	375.5
Technology	183.3		210.2	200.2	200.0	200.0	200.0

4

Planetary Science Budget Features

What's Changed

- New Lunar Discovery and Exploration Program supports public-private partnerships and innovative approaches to achieving science and human exploration goals
- New Planetary Defense Program for near-Earth object detection and mitigation includes development of DART and studies a low-cost, space-based near-Earth object detection mission
- Supports trade studies and technology development for returning Mars samples cached by Mars 2020 rover
- Europa Clipper as early as FY25; proposes to fly Clipper on a commercial launch vehicle given cost savings

What's the Same

- Supports InSight, Psyche, Lucy, and next New Frontiers selection in FY19
- Funds all operating missions, and completes development of Mars 2020
- DoE production of radioisotope power generators and Pu-238 to fuel missions
- Healthy research program and SmallSat/CubeSat investments

5

Enhanced Planetary Defense

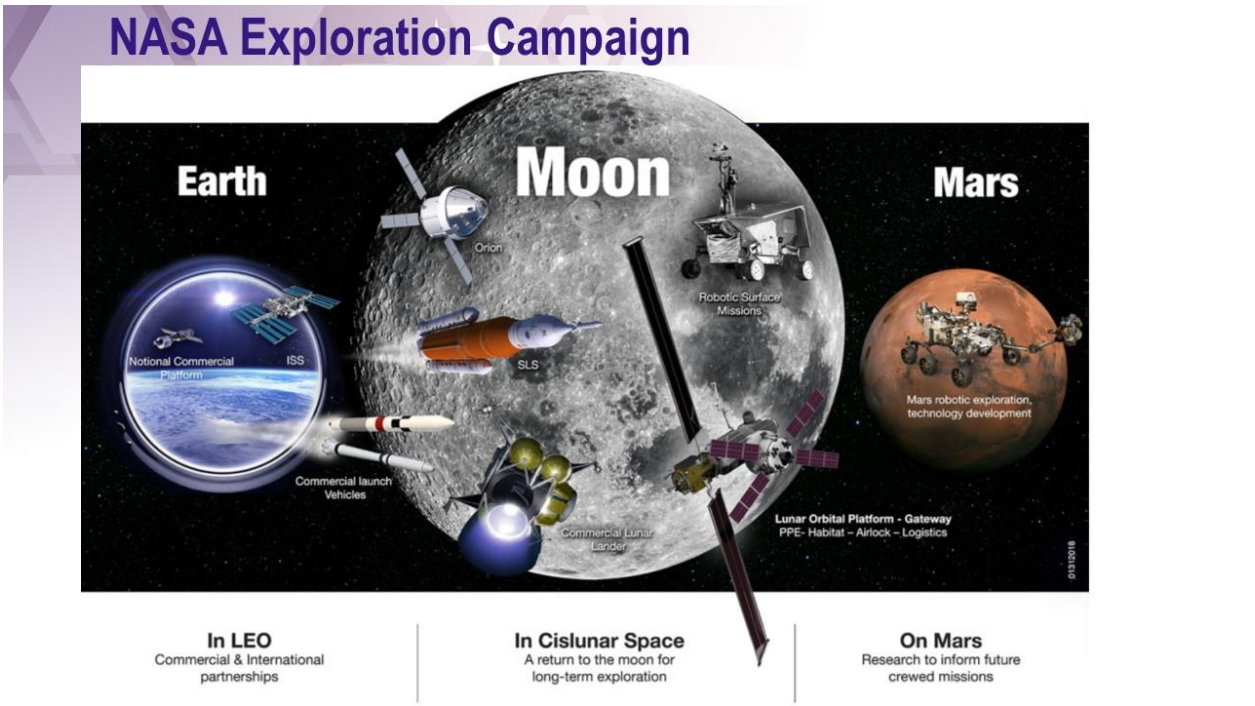
- FY19 budget request executes an enhanced Planetary Defense program for near-Earth object detection and mitigation
- This is a significant ramping up of our NEO-related activities!
- DART, w/CubeSat/SmallSat, is an innovative way to test deflection capability
  - Joint study with ASI for CubeSat
- Currently studying cost-effective space-based near-Earth object detection mission

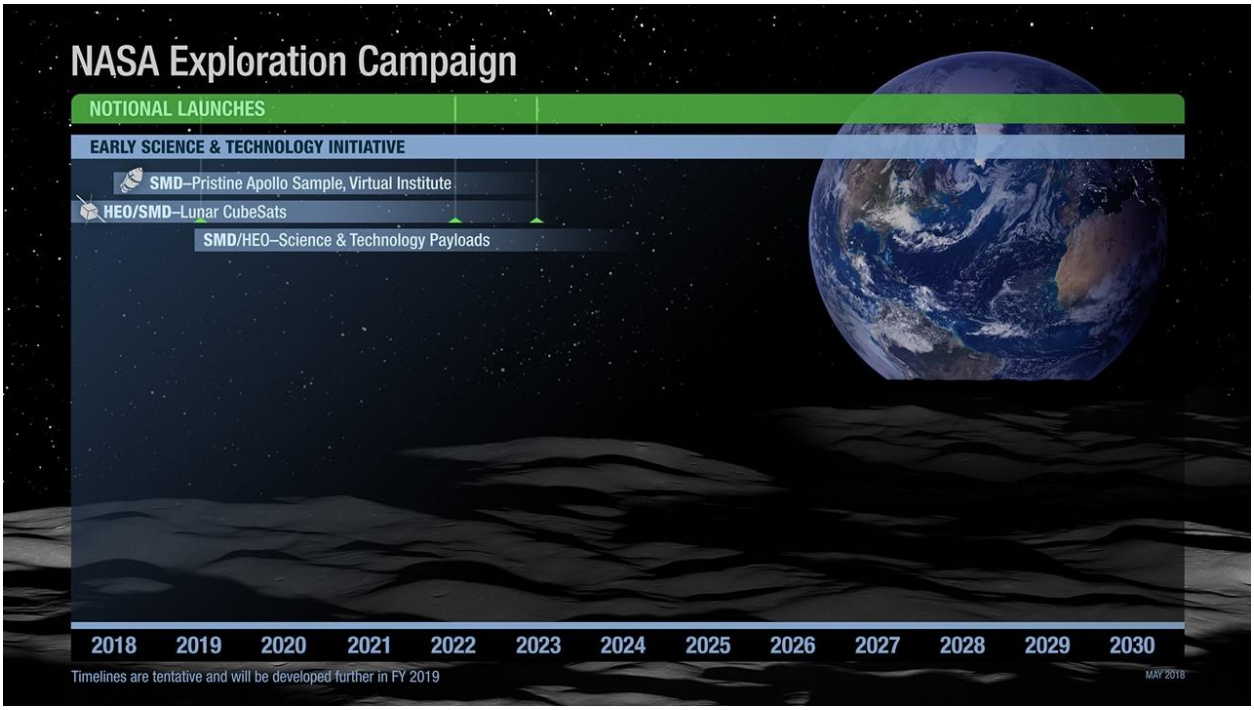
6

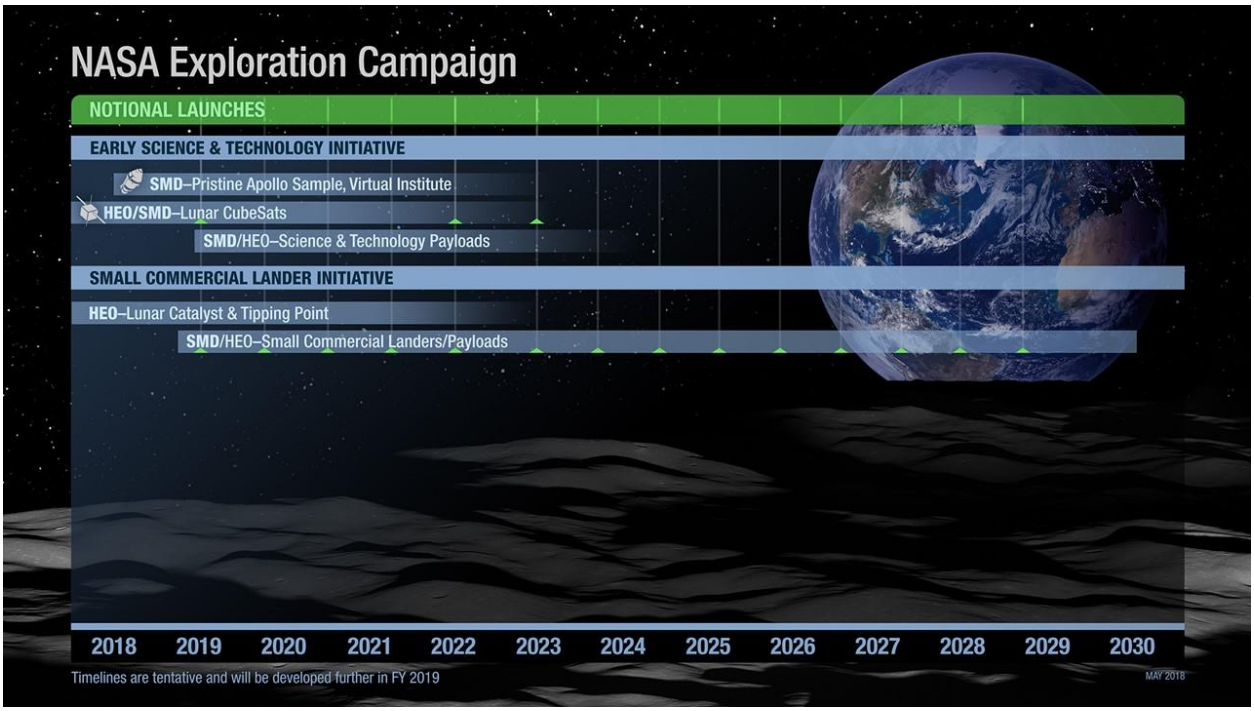
NASA Exploration Campaign

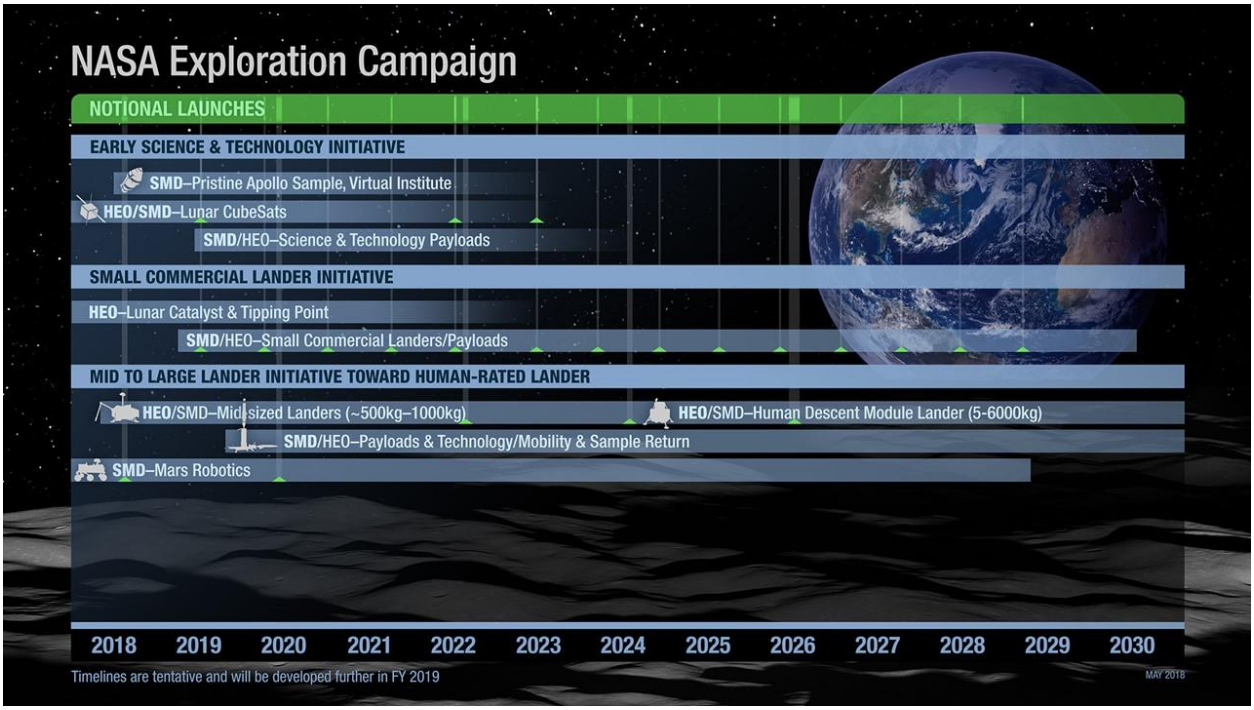
Space Policy Directive-1 (December 11, 2017) amends the National Space Policy to include the following paragraph:

"Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations;"


NASA Exploration Campaign
Earth
Moon
Mars
Orion
Robotic Surface Missions
Notional Commercial Platform
ISS
SLS
Mars robotic exploration, technology development
Commercial launch Vehicles
Commercial Lunar Lander
Lunar Orbital Platform - Gateway
PPE- Habitat – Airlock – Logistics
In LEO
Commercial & International partnerships
In Cislunar Space
A return to the moon for long-term exploration
On Mars
Research to inform future crewed missions


NASA Exploration Campaign
NOTIONAL LAUNCHES
EARLY SCIENCE & TECHNOLOGY INITIATIVE
SMD–Pristine Apollo Sample, Virtual Institute
HEO/SMD–Lunar CubeSats
SMD/HEO–Science & Technology Payloads
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
Timelines are tentative and will be developed further in FY 2019
MAY 2018


NASA Exploration Campaign
NOTIONAL LAUNCHES
EARLY SCIENCE & TECHNOLOGY INITIATIVE
SMD–Pristine Apollo Sample, Virtual Institute
HEO/SMD–Lunar CubeSats
SMD/HEO–Science & Technology Payloads
SMALL COMMERCIAL LANDER INITIATIVE
HEO–Lunar Catalyst & Tipping Point
SMD/HEO–Small Commercial Landers/Payloads
2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030
Timelines are tentative and will be developed further in FY 2019
MAY 2018


NASA Exploration Campaign
NOTIONAL LAUNCHES
EARLY SCIENCE & TECHNOLOGY INITIATIVE
SMD–Pristine Apollo Sample, Virtual Institute
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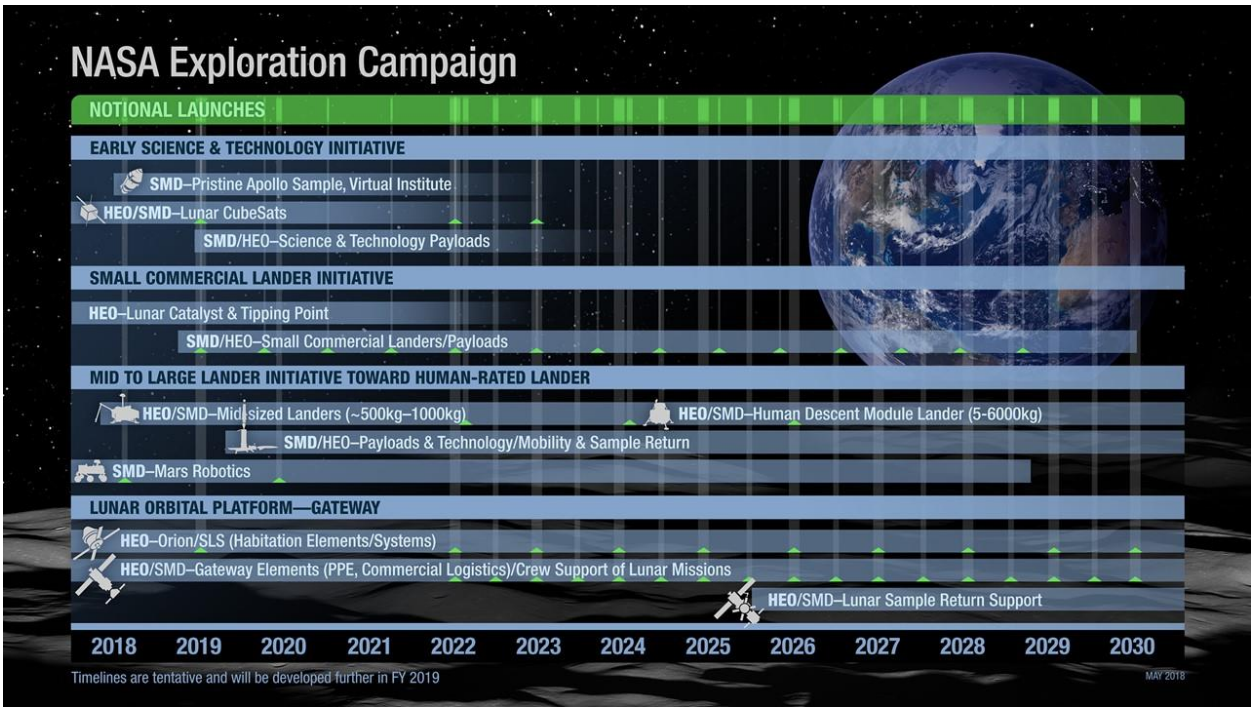
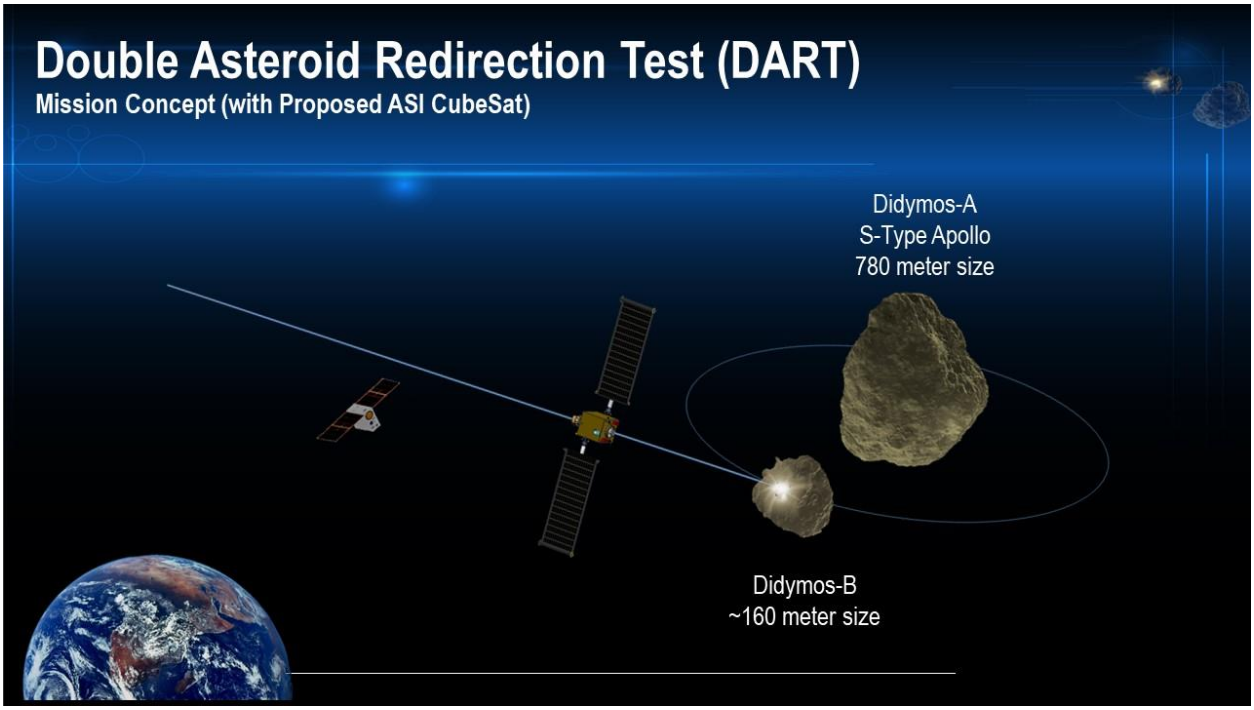
SMD/HEO–Science & Technology Payloads
SMALL COMMERCIAL LANDER INITIATIVE
HEO–Lunar Catalyst & Tipping Point
SMD/HEO–Small Commercial Landers/Payloads
MID TO LARGE LANDER INITIATIVE TOWARD HUMAN-RATED LANDER
HEO/SMD–Mid sized Landers (~500kg–1000kg)
HEO/SMD–Human Descent Module Lander (5-6000kg)
SMD/HEO–Payloads & Technology/Mobility & Sample Return
SMD–Mars Robotics
2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030
Timelines are tentative and will be developed further in FY 2019
MAY 2018



Planetary Defense

14


ASSESS
[CENTER FOR NEAR EARTH OBJECT STUDIES]
IAU
Minor Planet Center
SEARCH, DETECT & TRACK
[GROUND-BASED & SPACE-BASED OBSERVATIONS, IAWN]
PLANETARY DEFENSE
MITIGATE
[DART, FEMA EXERCISES]
CHARACTERIZE
[NEOWISE, GOLDSTONE, ARECIBO, IRTF]
PLAN & COORDINATE
[SMPAG, PIERWG, DAMIEN IWG]
15


Double Asteroid Redirection Test (DART)
Mission Concept (with Proposed ASI CubeSat)
Didymos-A
S-Type Apollo
780 meter size
Didymos-B
~160 meter size



ROSES 2018 - Program Name	Step-1 Due Date	Step-2 Due Date
Exobiology (EXOB)	***04/16/2018****	***05/24/2018***
Exoplanets (XRP)	***03/29/2018***	***05/30/2018***
Emerging Worlds (EW)	***03/29/2018***	***06/01/2018***
Development & Advance of Lunar Instruments (DALI)	***04/03/2018***	***06/05/2018***
Solar System Obs. (SSO)	***04/05/2018***	***06/07/2018***
MatISSE	***04/18/2018***	06/20/2018
Laboratory Analysis of Returned Sample (LARS)	***04/26/2018***	06/28/2018
Planetary Data Archiving, Restoration, Tools (PDART)	***05/10/2018***	07/12/2018
Planetary Major Equipment/Facilities (PME/F)	***TBD***	TBD
Cassini Data Analysis (CDAPS)	***06/01/2018***	08/01/2016
New Frontiers Data Analysis Program (NFDAP)	***06/12/2018***	08/23/2018
Planetary Sci./Tech. Through Analog Research (PSTAR)	07/25/2018	10/10/2018
Mars Data Analysis (MDAP)	08/23/2018	10/25/2018
Discovery Data Analysis (DDAP)	08/30/2018	11/01/2018
Rosetta Data Analysis Program (RDAP)	08/30/2018	11/01/2018
PICASSO	09/20/2018	11/20/2018
Habitable Worlds (HW)	11/15/2018	01/17/2019
Solar System Workings (SSW)	11/15/2018*	01/31/2019
Lunar Data Analysis (LDAP)	11/29/2018	02/28/2019

General R&A Updates

- ROSES 2018 released on Feb 14, 2018!!
- Facilities Update – New CAN for Facilities on hold:
  - NASA has requested a National Academies study; ad hoc committee is working: Sample Analysis Future Investment Strategy
- National Academies Study on R&A Restructuring
  - Report completed https://www.nap.edu/catalog/24759/review-of-the-restructured-research-and-analysis-programs-of-nasas-planetary-science-division
- Archiving manuscripts – new policy for all NASA funded work to be put into PubSpace (part of PubMed)
  https://www.nasa.gov/open/researchaccess/pubspace

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Small Innovative Missions For Planetary Exploration (SIMPLEx)

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SIMPLEx Spacecraft Type and Launch Opportunities

- SIMPLEx is soliciting small complete science missions based on small spacecraft (SmallSats) flying as secondary payloads
  - ESPA-class (180 kg) or smaller
    - Allowable configurations include CubeSats up to 12U, and ESPA-class
    - ESPA-Grande sized spacecraft allowed for some opportunities (still limited to 180 kg)
  - Total mission cost capped at $15M - $55M
  - NASA expects awards to span the full range cost cap range

- Proposed missions are limited to the launch opportunities listed in Appendix A of the PEA. Currently listed are:
  - SMD missions (Lucy, Psyche, and IMAP),
  - Commercial Lunar opportunities,
  - LEO/GTO opportunities, and
  - Exploration Mission "x" (EM-2 or beyond)

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SIMPLEx Selection Schedule

- July 24, 2018
  - Proposal due date for first round of evaluation/selections
  - Final Proposal due date for Lucy and Psyche
  - **NON-CONFLICTED VOLUNTEERS for Science Review Doris.Daou@nasa.gov**
- Proposal due date for second round of evaluations/selections will be announced well in advance of that deadline. This due date is likely to be no earlier than July, 2019.
- September, 2018
  - Science Review Panels
- October, 2018 – January, 2019
  - Technical Management Cost Review Panels
    - Only a subset of the proposals, based on their science review scores
- ~February, 2019 – Selection Announcements
- ~May – ~August, 2019 – Contract Awards
  - Contract award time based on dollar value of contract

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Discovery Program

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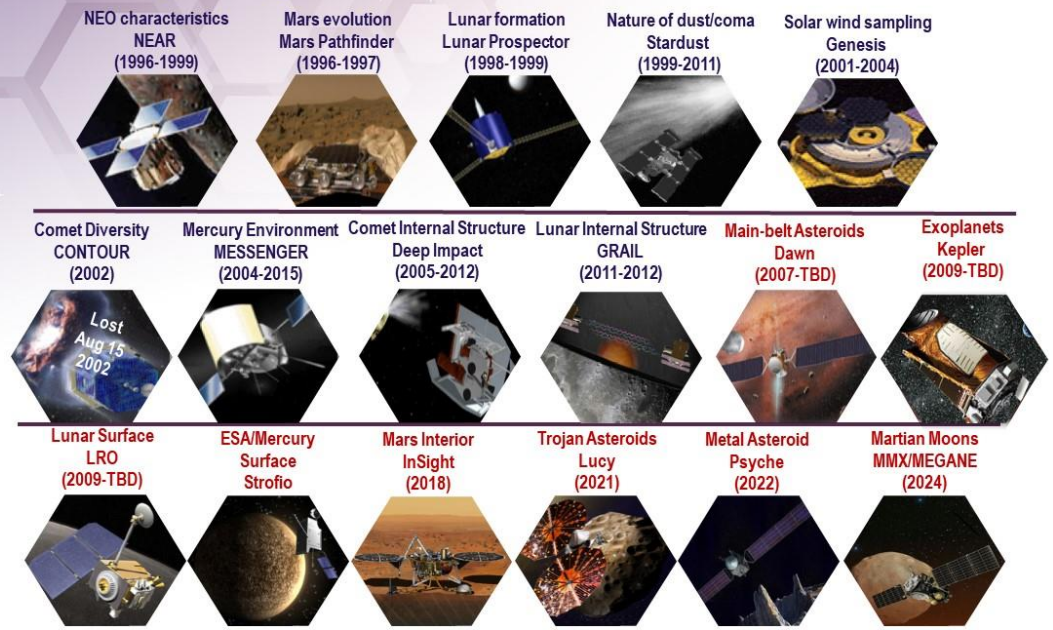
Discovery Program



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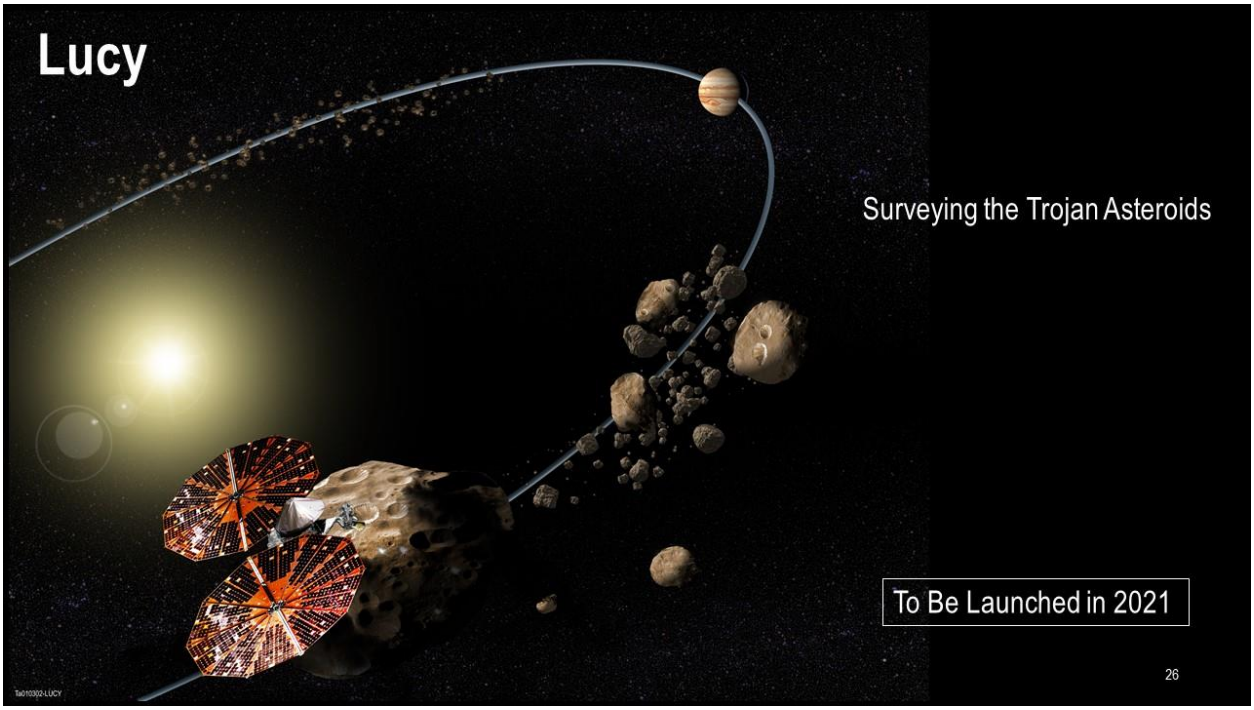
Psyche
Journey to a Metal World
Deep-Space Optical Comm (DSOC)
To Be Launched in 2022


Lucy
Surveying the Trojan Asteroids
To Be Launched in 2021
26

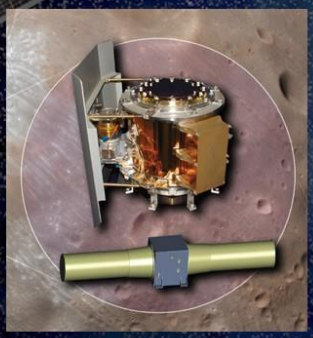
JAXA Martian Moons eXploration (MMX) Mission

Neutron & Gamma-Ray Spectrograph

- Solicited by NASA through the SALMON-3 AO
- Selection Announced Nov 16, 2017
  - MEGANE ("eyeglasses")
  - David Lawrence (JHU APL), PI

To Be Launched in 2024

- Cryocooled high-purity Germanium γ-ray detector (MESSENGER GRS heritage)
- ^{3}He proportional counter neutron detector (Lunar Prospector heritage)



Discovery Long-Range Planning

- Cost Cap $495M Phase A-D (FY19) excluding LV
- ~~May not propose the use of radio-isotope power systems (RPS)~~ – UPDATED
- May include radioisotope heater units (RHUs)

Release of draft AO	September 2018 (target)
Release of final AO	February 2019 (target)
Pre-proposal conference	~3 weeks after final AO release
Proposals due	90 days after AO release
Selection for competitive Phase A studies	December 2019 (target)
Concept study reports due	November 2020 (target)
Down-selection	June 2021 (target)
Launch readiness date	NLT December 31, 2026

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Reconsideration In the Use of RPS for Discovery

After analysis and consultation with the Department of Energy, NASA's Planetary Science Division is pleased to announce that the ban on the use of Radio-isotope Power Systems (RPS's) by proposers responding to the upcoming Discovery 2018 AO has been removed.

Proposer's will be able to include the use of up to two (2) Multi-mission Radio-Isotope Thermal Generators (MMRTG's) to enable or significantly enhance their mission concept.

Costs to be borne by proposers for the MMRTG's, the related environmental impact assessments, and the required Nuclear Launch Approval process will be announced once determined.

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New Frontiers Program

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New Frontiers Program

1st NF mission
New Horizons

Pluto-Kuiper Belt



Launched January 2006
Flyby July 14, 2015
PI: Alan Stern (SwRI-CO)

2nd NF mission
Juno

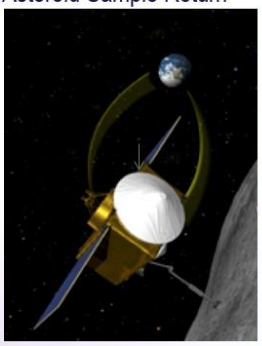
Jupiter Polar Orbiter



Launched August 2011
Arrived July 4, 2016
PI: Scott Bolton (SwRI-TX)

3rd NF mission
OSIRIS-REx

Asteroid Sample Return



Launched September 2016
PI: Dante Lauretta (UA)

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New Frontiers 4 AO

Investigations (listed without priority)

- Comet Surface Sample Return
- Lunar South Pole-Aitken Basin Sample Return
- Ocean Worlds (Titan, Enceladus)
- Saturn Probe
- Trojan Tour and Rendezvous
- Venus In Situ Explorer

12 Proposals received on ..... April 28, 2017

Step-1 Selections Announced (target)..... December 2017

Phase A Concept Study Reports due..... December 2018

Down selection for Flight (target)..... July 2019

Launch Readiness Date..... NLT December 31, 2025

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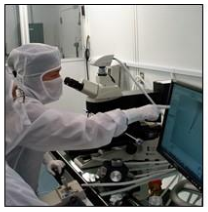
Comet Astrobiology Exploration Sample Return

- Comets record presolar history, the initial stages of planet formation, and the sources of prebiotic organics and volatiles available for the origin of life.
- Target comet is 67P/Churyumov-Gerasimenko.
- Mission and Sample Acquisition System (SAS) have been designed for the known properties of 67P.
- SAS collects at least 80 g of comet nucleus sample.
- As volatiles evolve from the sample they are transferred to a separate reservoir, preventing sample alteration. Both non-volatile and volatile materials are returned to Earth for analysis.
- Sample stored at -80° to -40° C through return cruise, and below 0° C through entry, descent, landing, and recovery.



PI: Steve Sqyres, Cornell University. CAESAR will return the first sample from the nucleus of a comet. Sample analysis in worldwide laboratories will address questions about Solar System starting materials, and how they came together to form planets and give rise to life.





33

A rotorcraft to explore prebiotic chemistry and habitability on the ocean world Titan

- Flight is highly efficient on Titan, enabling Dragonfly to sample materials in a variety of settings with its **science payload:**
  - Mass spectrometer
  - Gamma-ray and neutron spectrometer
  - Meteorology and seismic sensors
  - Camera suite

Science Objectives:

- Analyze chemical components and processes at work that produce biologically relevant compounds
- Measure atmospheric conditions, identify methane reservoirs, and determine transport rates
- Constrain processes that mix organics with past surface liquid water reservoirs and subsurface ocean
- Search for chemical evidence of water-based or hydrocarbon-based life

Aerial mobility provides access to Titan's diverse materials at a wide range of geologic settings at dozens of sites, 10s to 100s of kilometers apart



PI: Dr. Elizabeth Turtle at APL
Dragonfly would arrive at Titan in 2034 and explore for over 2 years, performing detailed chemical analyses, measuring the atmosphere and seismic activity, and imaging the surface.

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Planetary Defense Coordination Office

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Planetary Defense Coordination Office Status

- Over 18,000 near-Earth objects (NEOs) discovered and confirmed to date
  - Over 8,000 NEOs greater than 140 meters in size
  - Over 1,900 NEOs are Potentially Hazardous Asteroids
- White House National Near-Earth Object Preparedness Action Plan to be released late June 2018 by the Detecting and Mitigating the Impact of Earth-Bound Near-Earth Objects (DAMIEN) Interagency Working Group



- 2017 NEO Science Definition Team reassessed NEO search and characterization given current technology and understanding of the NEO population. Of the estimated 25,000 NEOs 140 meters or larger in size (that can cause regional damage), 1/3 have been found. Space-based assets will be needed to complete the catalog.

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NASA Planetary Science Studies

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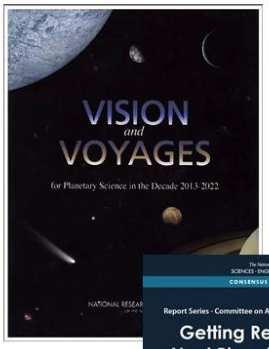
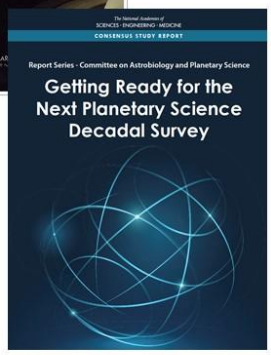
Timeline of Studies

- 1st Planetary decadal: 2002-2012
- 2nd Planetary decadal: 2013-2022
- CubeSat Review: Completed June 2016
- Extended Missions Review: Completed Sept 2016
- R&A Restructuring Review: Completed June 2017
- Searching For Life : Completed Sept 2017
- Large Strategic Science Missions: Completed Aug 2017
- Midterm evaluation:
  - Tasked August 26, 2016
  - Above NAS studies will be input
  - Expect report to NASA due ~June 2018
- Sample Analysis Investment Strategy
  - Started November 2017
- 3rd Planetary Decadal: 2023-2032
  - To be tasked *before* October 2019
  - Expect report to NASA due 1st quarter 2022
- CAPS reviewed completed studies and recommended several more to be completed





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Mission Studies Completed Thus Far

- Mars orbiter
  - 2015 MEPAG's Next Orbiter Science Analysis Group
- Uranus and Neptune (Ice Giants) system missions
  - 2017 NASA science definition team report
- Europa lander
  - 2017 NASA science definition team report
- Venus orbiter and lander (Venera-D)
  - 2017 joint U.S.-Russian science definition team report
- NEO Search and Characterization
  - 2017 NEO science definition team updated report

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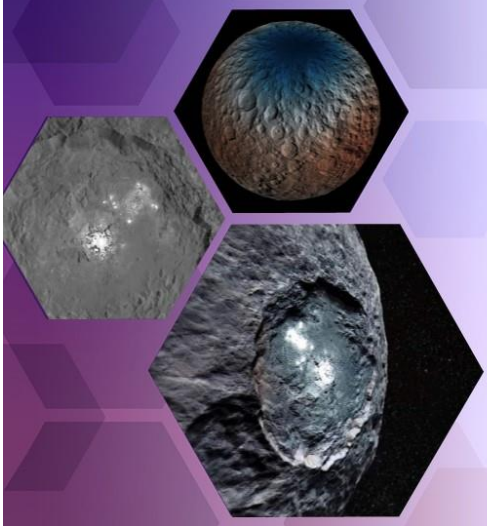
CAPS Priority Areas Candidates for Large or Medium Class Mission Studies (Unprioritized)

Venus exploration missions	Additional concepts beyond the Venera-D orbiter and lander
Lunar science missions	Understanding interior processes and polar volatiles (Volatiles SAT Team-2)
Mars sample-return next-step missions	Mission elements beyond Mars 2020 necessary for second and third phases of a Mars sample-return campaign
Mars medium-class missions	Multiple mobile explorers, polar explorers, & life-detection. Investigations responsive to new discoveries
Dwarf planet missions	Large- & medium-class mission concepts to Ceres, Pluto, Triton
Io science (NEW FRONTIERS FIVE)	Reexamine mission to Io
Saturn system missions	Affordable, large strategic missions that visit multiple targets
Dedicated space telescope for solar system science	Dynamic phenomena on planetary bodies

40



Ceres Pre-Decadal Study

- CAPS highlighted Ceres for pre-decadal study
- Dawn revealed Ceres to be an active dwarf planet; It is a solid body, but is it a relic ocean world?
- JPL to lead the Ceres study; Michael Kelley is the PSD POC
- Goals are to assess science priorities and examine trade space of mission concepts
  - Spectrum of alternatives, including New Frontiers and Large Strategic missions
  - Orbiting, landing, roving, sample return?
  - Launch dates between 2024 – 2037
  - PP to be noted, uncover technologies to be addressed
- Key dates:
  - SDT call for applications issued – team is being selected
  - Design study February – Late FY18
  - Engagement with AGs and workshops/conferences

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QUESTIONS ?

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NASA Exploration Campaign – BackUp

Benefits of Near-Term Lunar Missions

- Return Science
  - Reduce costs and risk for high priority science (Decadal Survey, SCEM, etc.) through regular mission cadence
  - Ensure the strength of the lunar science community
- Benefit Exploration
  - Volatiles may be key to future exploration architectures; characterizing volatiles entrainment in regolith is the first step
- Encourage Industry Participation
  - Expand the economic sphere to cis-lunar space
  - Foster initial R&D for resource acquisition and processing
  - Leverage investments in commercial landers
- Demonstrate Technologies
  - Precision Landing/Hazard Avoidance and Ascent
  - Improvements in power generation and storage
  - Extreme environment instruments/systems for day/night survival/operations - relevant to Icy Moons
- Advance planning for Mars and other destinations
  - Enables deep-space architectures
  - Reduces logistics chain from Earth
  - Flight qualifies critical technologies such as precision landing and ascent vehicles

Commercial Lunar Payload Services (CLPS)

- Draft RFP (SMD/HEOMD/STMD developed) for CLPS posted April 27
- Competition open to U.S. commercial providers of space transportation services, consistent with National Space Transportation Policy and Commercial Space Act
- Multi-vendor catalog, 10-year IDIQ contract, managed through task order competition for specific payload missions
- First vendor selection by Dec 31; future on-ramps as more capabilities are developed
- Structured for NASA as the marginal buyer of a commercial service
- Statement of work permits addition of more complex services as vendor capabilities grow such as providing surface mobility or sample return
- Based upon prior HEOMD investments through the Lunar CATALYST public-private partnerships with industry, we expect multiple vendors to bid

45

Payload Development

- Current Activities to develop payloads
  - CubeSats – SIMPLEx-2 SALMON-3 PEA AO
  - Instrument Development call – DALI
  - STMD technology interests
- What payloads are available now?
  - SALMON-3 PEA AO for payloads that are ready, or nearly ready, to fly
  - GSFC retroreflectors - quick and easy
  - Resource Prospector instruments

Small Innovative Missions for Planetary Exploration (SIMPLEx)

- SIMPLEx-2 AO is released; in addition to soliciting SmallSat proposals for all planetary destination, specific emphasis has been added for SmallSats to conduct lunar science or address exploration SKGs
- Available for potential delivery by commercial lander service provider
  - Ride along under CLPS; providing additional opportunities for commercial companies
- Science that would help us prepare for human exploration

DALI (Development and Advancement of Lunar Instrumentation)

- Step 1 proposals were due April 3, Step 2 were due June 5
- Lunar instruments that support NASA's broader lunar exploration goals, including human exploration and in situ resource utilization (ISRU), as well as lunar science.
- "Particularly interested" in instruments for small stationary landers, but call is open for any lunar instrumentation, including orbiters/rovers.
- "Most interested in" technologies that will reach at least TRL 6 by end of grant, flight hardware builds for landers with flight opportunities as early as ~2021.

DALI (Development and Advancement of Lunar Instrumentation)

- Received 47 Step 2 proposals
  - UV/Vis/IR/Thermal Spectrometers, Mass Spectrometers, Raman Spectrometers, Neutron/Gamma Ray Spectrometers
  - Dust/plasma/solar wind instruments,
  - Seismic instruments, heat flow probe
  - Lunar Laser Ranging
  - Magnetometers, RADAR
  - LIDAR, LIBS, XRD/XRF
  - Volatiles detection, Radiation detection

Scope of Science and Technology Payload SALMON PEA

- Payloads that are ready, or nearly ready, to fly
  - Engineering models
  - Student-built hardware
  - Modified off the shelf
- Cross-division/directorate call
  - Open to Planetary/Heliophysics/Astrophysics/Earth
  - HEOMD SKGs/ISRU
  - STMD goals ("technology", not just "instruments")
- Significant international participation will be permitted
  - but not international proposals, they will have to partner with US researchers
- 15 kg limit per instrument, but may combine multiple instruments for a single flight opportunity

2-Stage process

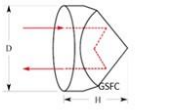
- Different from our usual 2-step downselects
- Phase 1 – "get your instrument ready to fly"
  - No guarantee you will fly
  - Expect to select on order of 8-12 instruments
  - Selections expected ~Summer 2019
- Phase 2 – integrate onto a specific flight opportunity
  - Additional funds for integrating, ops, and science
  - Internal process based on factors such as ease of accommodation, readiness timeline, and appropriateness for landing site for the science or technology proposed

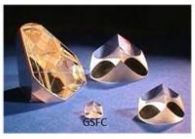
NASA GSFC/MIT Laser Retro-reflector Arrays (LRA) for Lunar Landers

Goddard SPACE FLIGHT CENTER

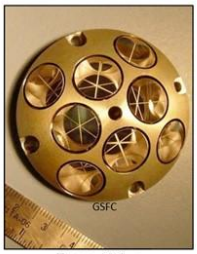
MIT

- **What they are:**
- Custom glass cube corner arrays that retro-reflect incoming laser beams over a wide incident angle.
- Light weight, rad-hard, and long lifetime
- Similar LRAs are carried by Earth-orbiting satellites for precision laser tracking from ground stations





- **Science applications**
- Lander position and movement determination (laser tracking from orbiting or descent LIDAR)
- Permanent fiducial markers on the Moon
  - Location of science measurements by on board instrument, e.g., seismometer
  - Landmarks for precision landing of future lunar craft
- Test of concept of LRA on Mars, asteroids, etc.



← 5 cm, 21 g →

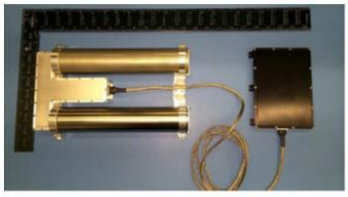
GSFC and MIT LRA team information – Contact Michael Amato, Dave Smith, Xiaoli Sun, for more information.

Resource Prospector Legacy Instruments

- NASA recently conducted an internal science and engineering assessment of RP instruments.
- Determined that all four RP instruments are at a high enough TRL and have ability to obtain useful science data on the Moon.
- As development continues, plan to integrate instruments into early CLPS missions.







Long-Lived Instruments, Landers and Small Rovers

- Initial landers delivered through the Commercial Lunar Payload Services (CLPS) are expected to last one lunar day (14 Earth days)
- NASA is planning investments to enable operations and mobility for long-lived instruments, stationary landers and small rovers
  - Power supplies, electronics, and mechanisms to survive and/or operate across the extreme temperatures of lunar day and night, despite lunar dust
  - Mobility systems or surface utility stations to enable small, long-lived rovers compatible with delivery to the lunar surface under CLPS capabilities
  - Radioisotopes for heat or power
  - An initial Long Duration Lunar Surface Operations workshop is planned for Fall 2018 co-sponsored by HEOMD, SMD, and STMD

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Planetary Defense Coordination Office BACKUP

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PDCO Mission Projects

NEOWISE

- Continues in extended NEO survey operations

NEOCam: Near-Earth Object Camera

- Infrared survey telescope optimized for meeting congressional mandate to find and characterize NEOs down to 140 meters in size
- Continues in extended Phase A
- Passed SRR/MDR on February 28, 2018

DART: Double Asteroid Redirection Test

- Demonstration of kinetic impactor mitigation technique
- Target - Moon of 65803 Didymos
- Launch period opens June 2021, impact October 2022
- Passed mission-level PDR on April 12, 2018
- KDP-C scheduled for June 22, 2018

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Mars – BackUp

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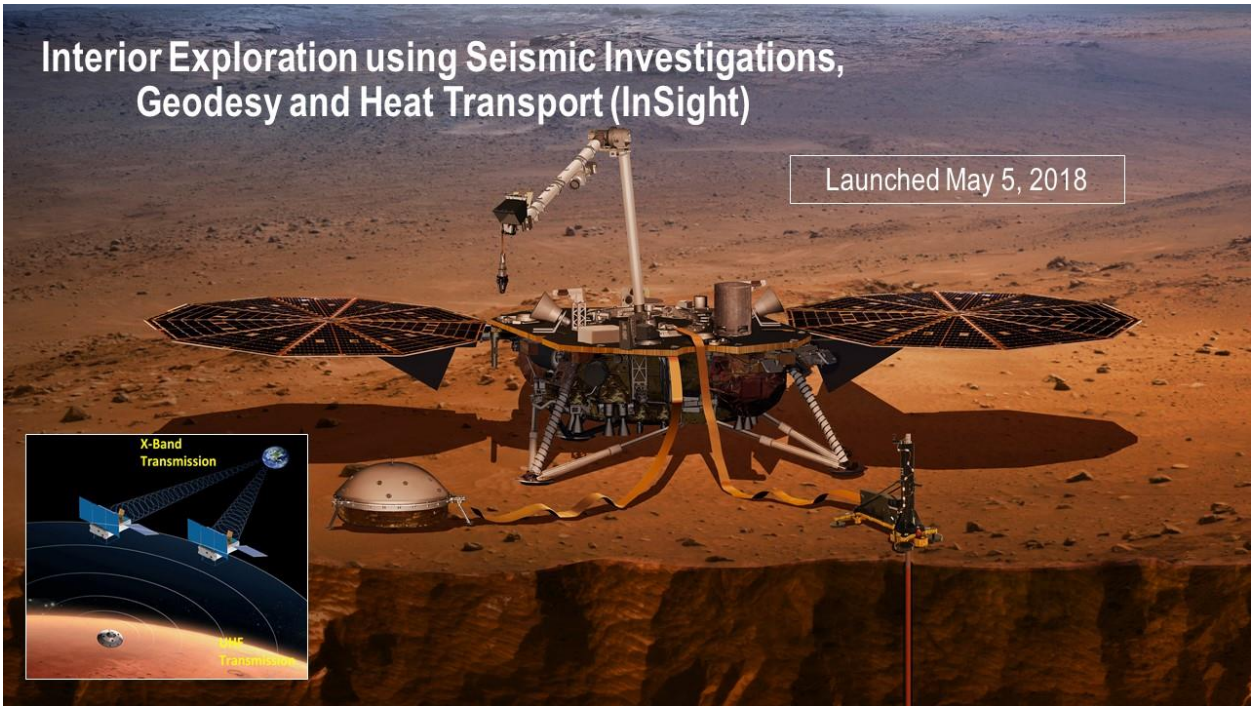
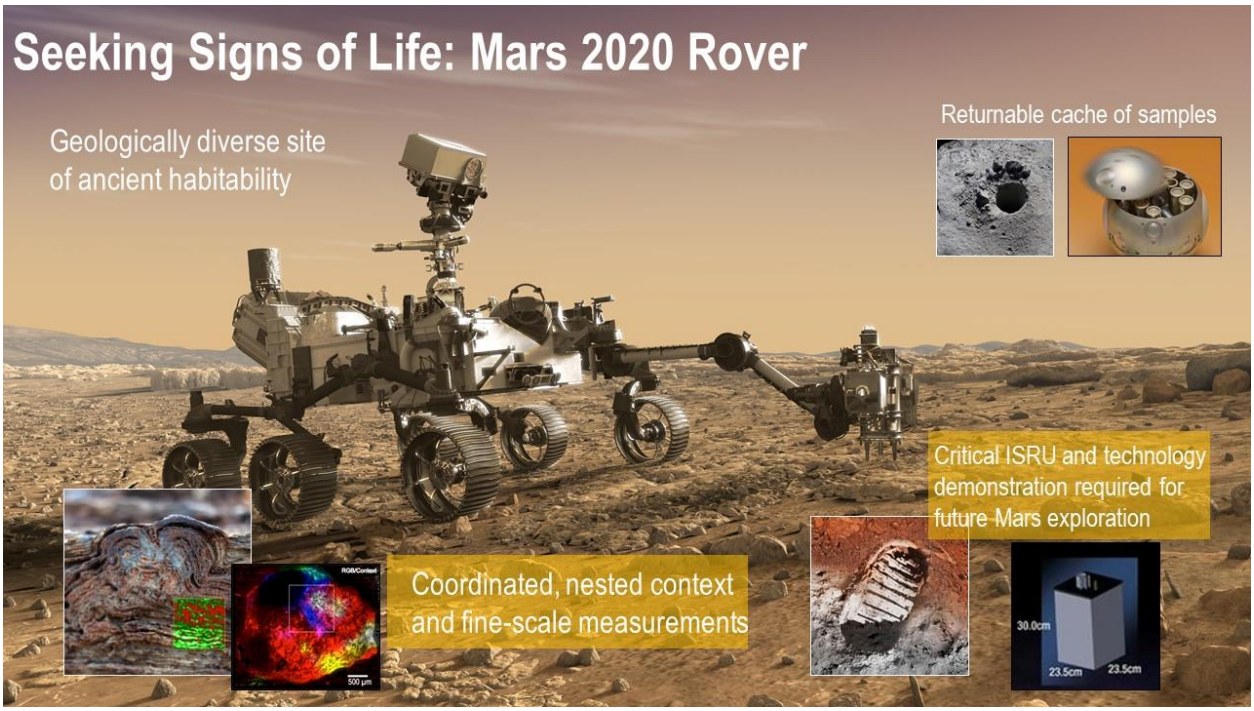
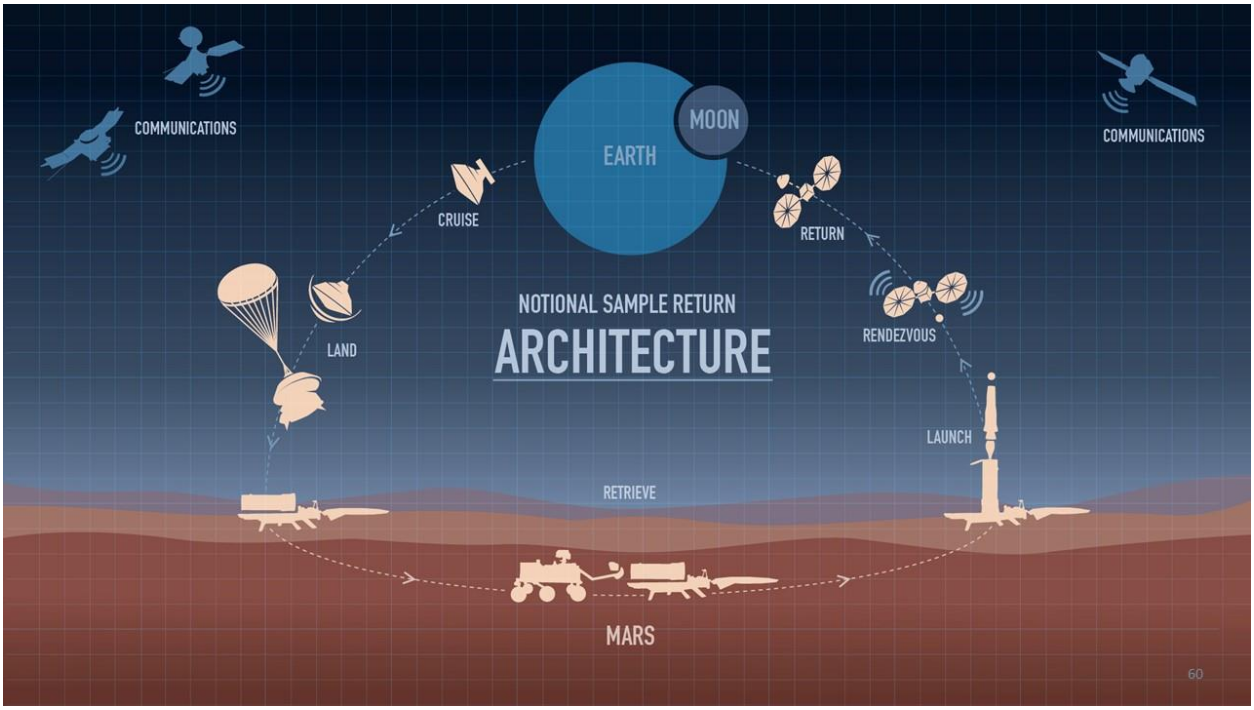



Seeking Signs of Life: Mars 2020 Rover
Geologically diverse site of ancient habitability
Returnable cache of samples
Critical ISRU and technology demonstration required for future Mars exploration
Coordinated, nested context and fine-scale measurements
30.0cm
23.5cm
23.5cm


COMMUNICATIONS
COMMUNICATIONS
MOON
EARTH
CRUISE
RETURN
NOTIONAL SAMPLE RETURN
ARCHITECTURE
LAND
RENDEZVOUS
LAUNCH
RETRIEVE
MARS
60

Oceans Worlds – BackUp

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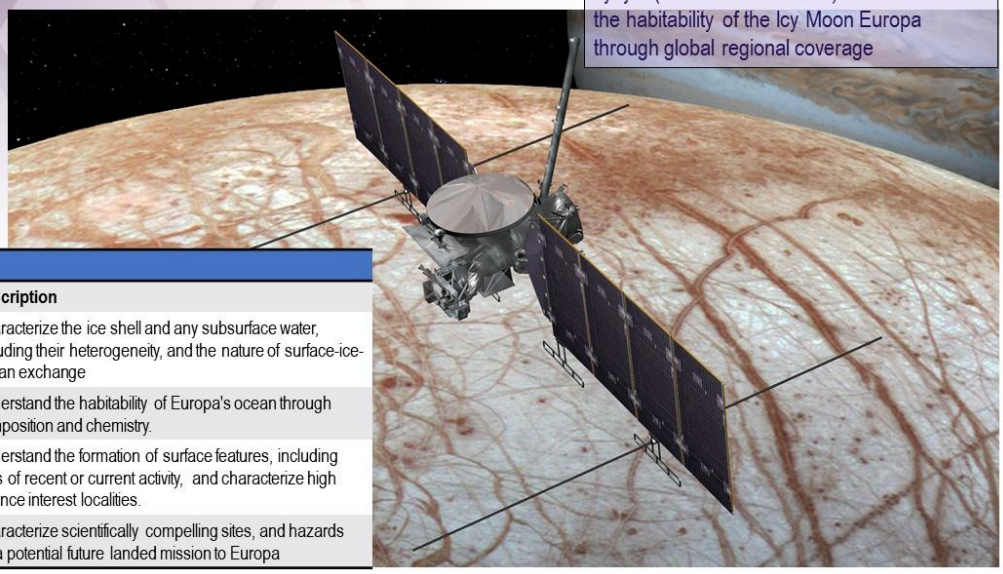
Europa Clipper Overview

Will conduct approximately 45 low altitude flybys (25 – 100 km altitude) to characterize the habitability of the Icy Moon Europa through global regional coverage



Science	
Objective	**Description**
Ice Shell & Ocean	Characterize the ice shell and any subsurface water, including their heterogeneity, and the nature of surface-ice-ocean exchange
Composition	Understand the habitability of Europa's ocean through composition and chemistry.
Geology	Understand the formation of surface features, including sites of recent or current activity, and characterize high science interest localities.
Recon	Characterize scientifically compelling sites, and hazards for a potential future landed mission to Europa

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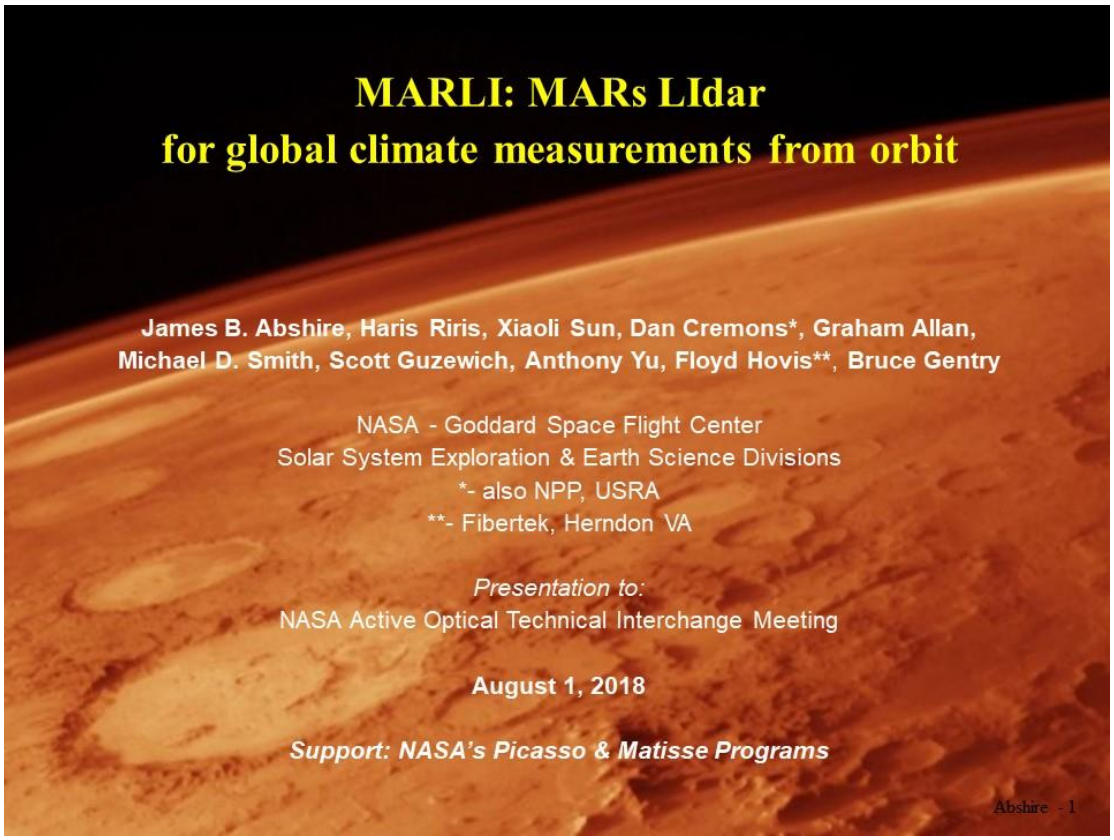
5.2 MARLI: MARs LIdar for Global Climate Measurements from Orbit

James B. Abshire, Haris Riris, Xiaoli Sun, Dan Cremons*, Graham Allan,
Michael D. Smith, Scott Guzewich, Anthony Yu, Floyd Hovis**, Bruce Gentry

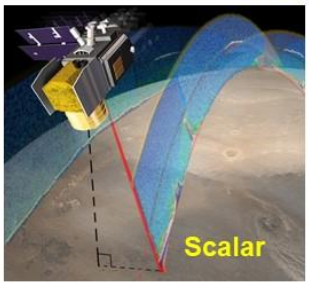
NASA Goddard Space Flight Center, Solar System Exploration & Earth Science Divisions, Greenbelt, Maryland

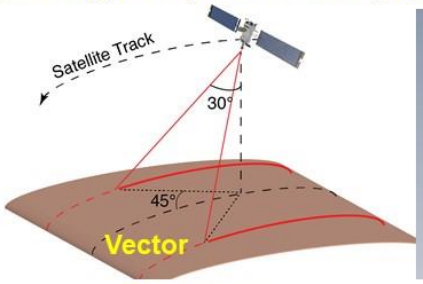
** NASA Postdoctoral Program, Universities Space Research Association*
*** Fibertek, Herndon, Virginia*

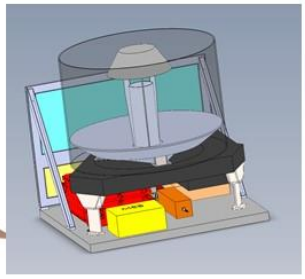


MARLI Lidar development

Development supported by NASA's Picasso program







Objectives:

• Design a lidar to measure atmospheric backscatter profiles, depolarization profiles, and wind profiles, from a Mars polar orbit.

Approach:

• Develop a flexible concept and measurement performance model
• Leverage key lidar technologies from ESTO and from previous GSFC lidar
• Advance readiness of key technologies (laser transmitter & wind receiver) to TRL 4
• Perform initial design of a space version
• Demonstrate a laboratory version & demonstrate atmospheric wind measurements

Status:

• Completed 3rd year of development under Picasso, started Matisse

Science - Why Global Wind Measurements ?

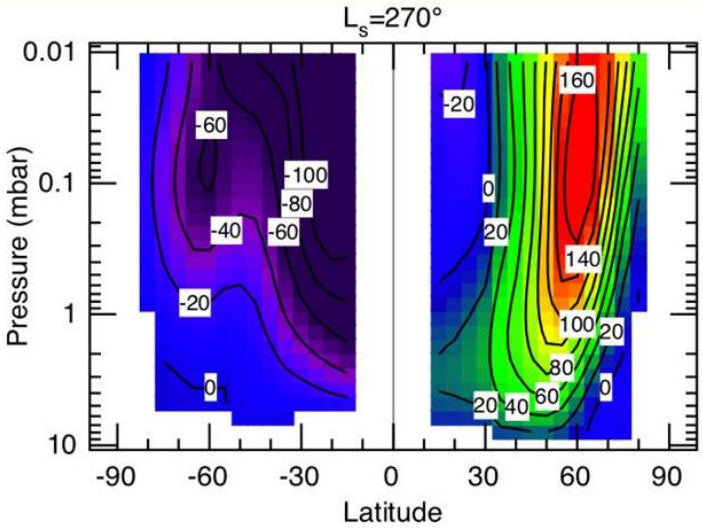
Wind profiles will provide crucial new information*

• Winds regulate the transfer of gases and heat throughout the atmosphere, raise dust at the surface, and are a primary player in all surface-atmosphere interactions

• Measured wind profiles provide sensitive input and needed validation for improving current GCM models

• Winds are of critical for the safety and precision of spacecraft entry, descent and landing (EDL) on Mars

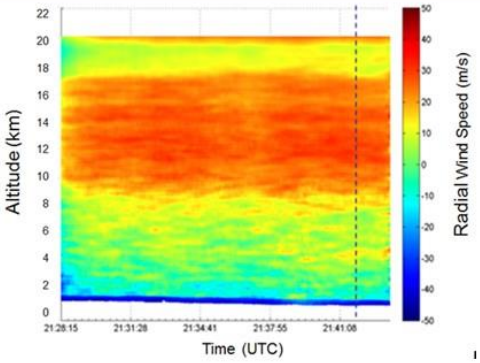
* - Recent summary: MEPAG NEX-SAG Report (2015), Report from the Next Orbiter Science Analysis Group



Calculated "gradient winds" (m/sec) for season Ls=270, inferred from latitude gradients of temperature. Presently, this is the best way to estimate global-scale winds from observations. They describe in a very broad sense the general modeled winds from GCMs. **Shortcoming are these require lots of assumptions, don't work near the equator, only give zonal (east-west) winds, don't include weather or any local phenomena, and are not very precise.**

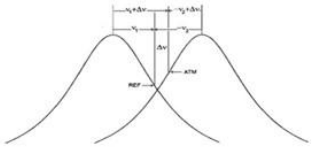
Heritage for Wind Measurements - Tropospheric Wind Lidar Technology Experiment -TWiLiTE - (Bruce Gentry)





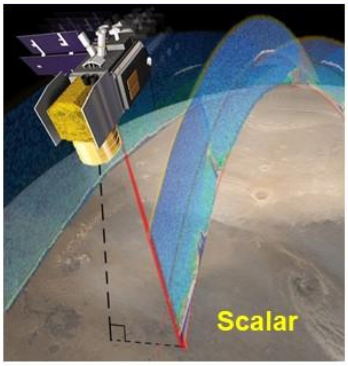
The TWiLiTE Airborne direct detection wind lidar, flown on the NASA ER-2 (http://twilite.gsfc.nasa.gov/)

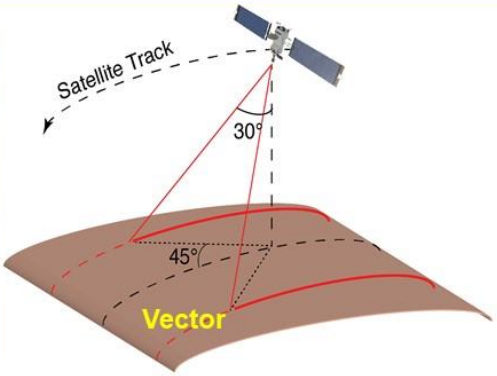
Radial wind speed data from an airborne campaign in February 2011.



Two offset etalons "double edge" used in the lidar receiver to resolve the Doppler shift of the laser backscatter

Measurement Concept – 1 of 2





Lidar measurement approach

Continuously measures:

- Aerosol backscatter profiles
- Range to the scattering surface
- Cross polarized (ice) backscatter profiles
- Doppler (wind) profiles

All measured together with same instrument
=> self consistent data set

Measurement orientation

- Ideally circular polar orbit, 400 km altitude

Implementation Options:

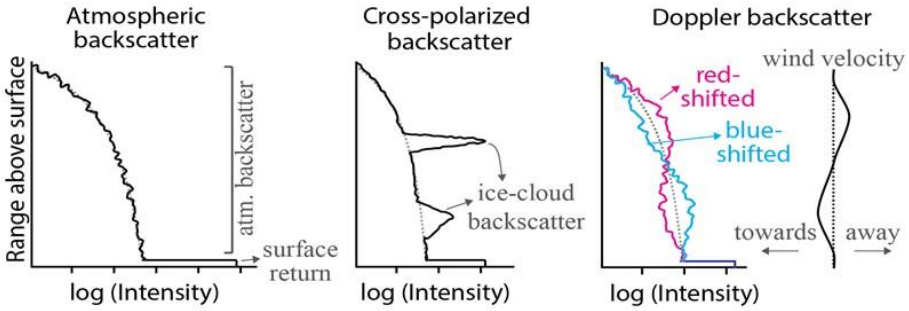
- ***Scalar:*** Allows measuring Doppler shift of wind in cross-track direction *(single line of sight)*
  Lidar is pointed cross-track 30 deg off nadir
- ***Vector:*** Simultaneous measurements along 2 lines of sight with lasers & receivers pointed at ~90 deg

Measurement Concept – 2 of 2

Range (height) resolved aerosol backscatter profiles.

Profiles of cross-polarized backscatter, caused by clouds with ice-crystals.

Horizontal wind profile - computed from scaled ratio (difference/sum) from detectors following the double-edge filter.

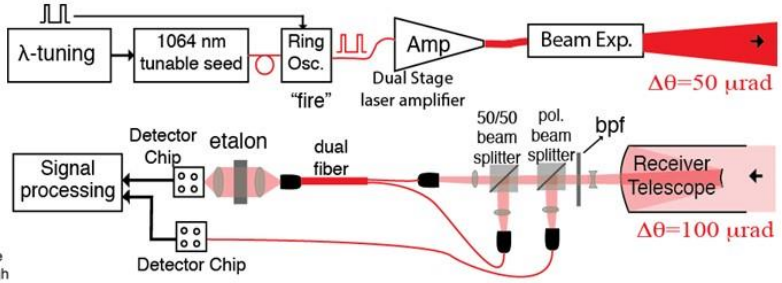


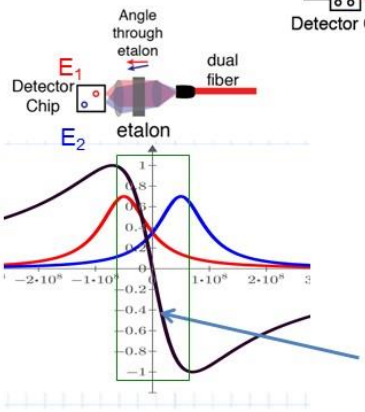
Height resolved Doppler (wind) backscatter profiles as seen by the two detectors after passing through the double-edge filter.

Lidar Vertical and Horizontal Resolution

- Lidar is being designed to return data with 150 m vertical resolution and at a 10 Hz rate
- Performance estimates depend on vertical bin depth and averaging time.
- Performance shown is based on averaging into 2 km bins vertically for 40 sec. along track (~ 2 deg latitude)

Lidar Approach





(Top) Block diagram for the single line-of-sight approach. The four independent photon sensitive detector elements are on the same HgCdTe APD detector chip.

(Top Left) Sketch showing dual fiber assembly illuminating etalon at two different angles, producing double-edge transmission response.

(Bottom Left) Transmission vs optical frequency for the double edge optical frequency discriminator.

Black curve = $(E_1 - E_2)/(E_1 + E_2)$

Doppler shift calculated from linear region (inside green box)

Progress under Picasso – Lidar Performance



Updated estimate – single beam
4 mJ laser, 60 cm telescope, updated detector parameters

Table1.1 Summary of the updated MARLI performance calculation

Parameter	*Surface*	*5 km*	*10 km*	*20 km*	*30 km*
Backscatter SNR	360	320	260	140	80
Wind horiz. velocity (m/sec)	0.3	0.4	1	2	3
Range to surface (m)	<1	<1	<1	<1	<1

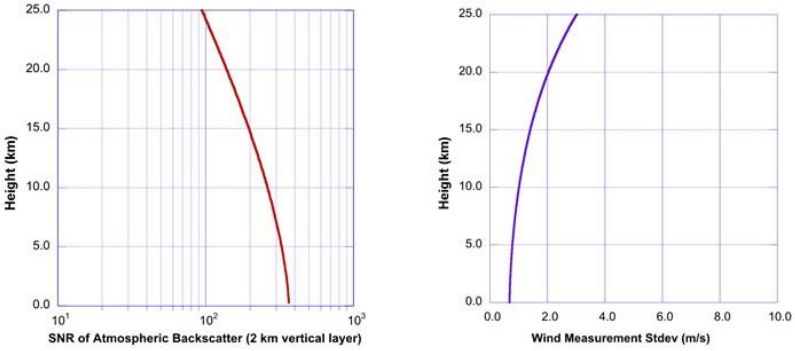
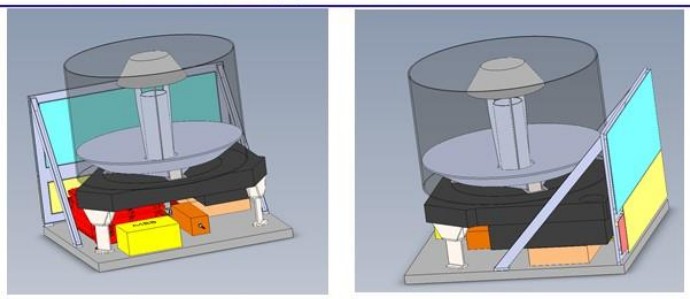


Figure 3.2. MARLI performance calculations, based on 4 mJ laser pulse energy, a 60 cm receiver telescope, updated detector parameters, 2 km vertical averaging, 40 second horizontal averaging.

Instrument Concept Drawings for Scalar Approach

GSFC

- Drawing of the single beam version.
- Receiver telescope diameter is now 50 cm

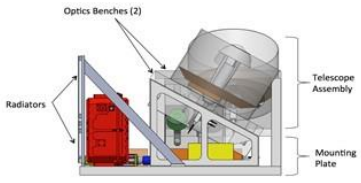


Also considered a dual beam (vector) wind measurement

- Same laser power is split between the 2 directions, receiver telescopes are 40 cm diameter

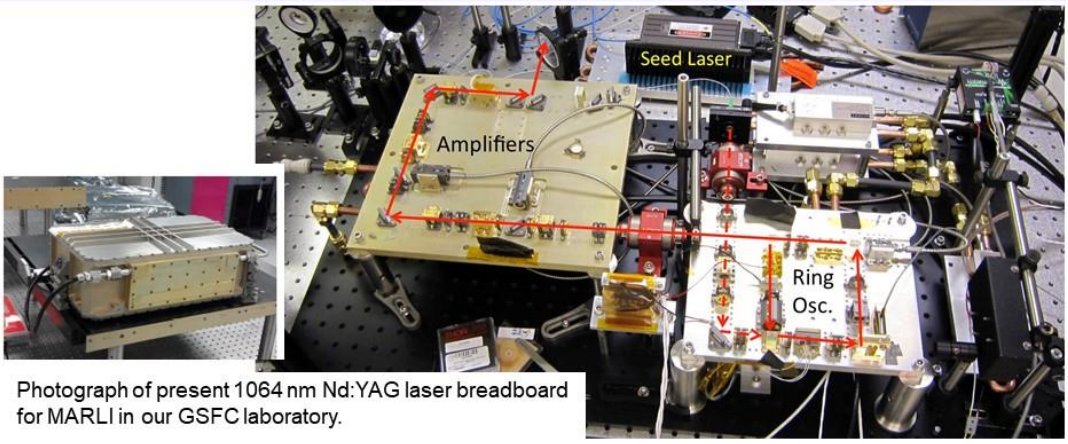
=> Larger measurement errors





Targeted lidar size: ~70 cm cube, similar to Mars Orbiter Laser Altimeter (MOLA).
Lidar mass is ~ fixed, but power is flexible. Errors scale as 1/root (P_{laser} * A_{tel})

Laser breadboard



Photograph of present 1064 nm Nd:YAG laser breadboard for MARLI in our GSFC laboratory.

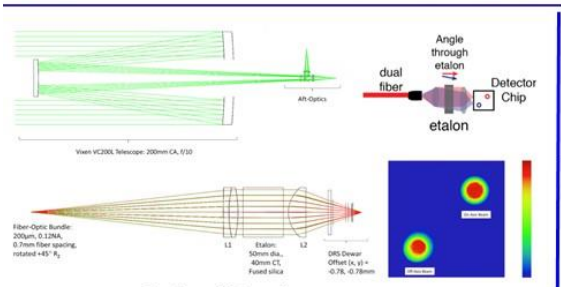
This laser was developed by Fibertek, based on their CATS laser, for the Picasso-supported work on MARLI.

The photo shows the seed laser, the ring oscillator stage, and the two power amplifier stages.

The laser breadboard meets all key MARLI performance specifications.

Laser Parameter	Goal	Demonstrated
Wavelength	1064 nm	1064 nm
Pulse energy	3 mJ	3.4 mJ
Repetition rate	1 kHz	4 kHz
Linewidth	< 30 MHz	25 MHz
Spectral Purity	> 2%	300:01:00
Pulse width	>20 nsec	28 nsec
Beam Quality	$M^2 < 2$	1.5
Polarization purity	> 30: 1	>100:1

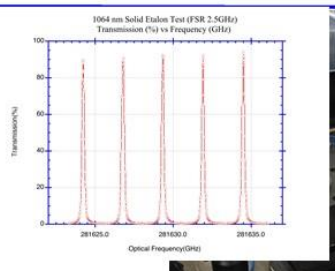
Receiver Breadboard Design & Components on hand



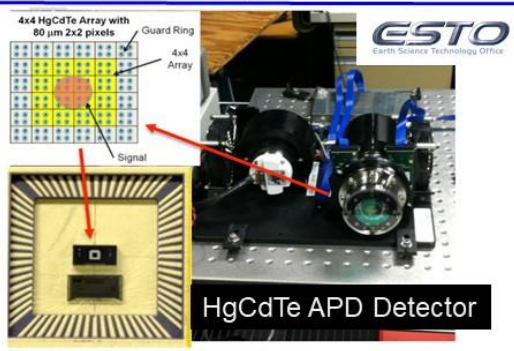
Optical Design



Receiver Telescope

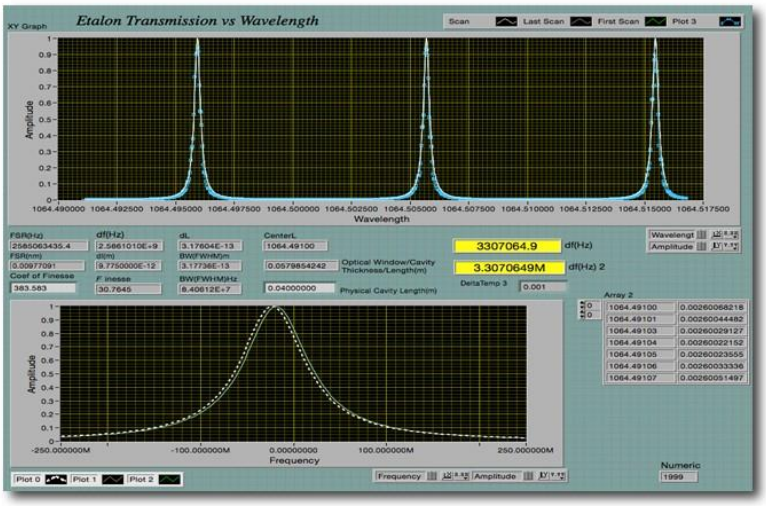


Solid Optical Etalon



HgCdTe APD Detector

Receiver Etalon Characterization & Modeling



(*Upper plot)* The measured free spectral range (FSR) blue squares and numerical fit to the solid etalon transmission (white solid line).
The bottom plot shows the model's prediction for a simulated etalon temperature change of 1mK. This temperature change produced a frequency shift of ~3MHz in the response.

Picasso – Doppler measurement demonstration (in the lab)

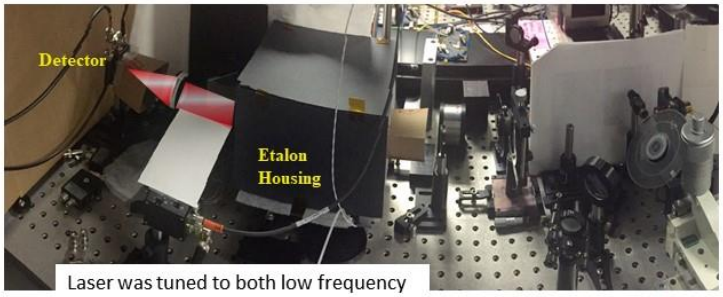
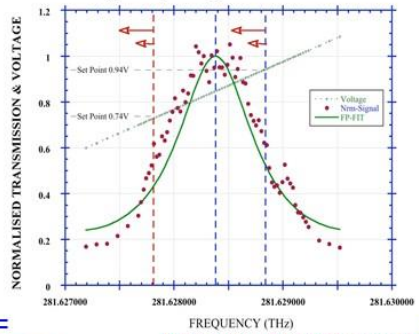
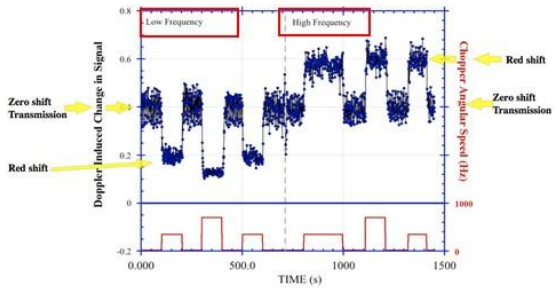


Figure 6.5 Photograph of the Doppler measurement setup where the doppler shift of the "wind" is simulated by the speed of a spinning disk (Chopper Wheel).

Laser was tuned to both low frequency & high frequency side of etalon



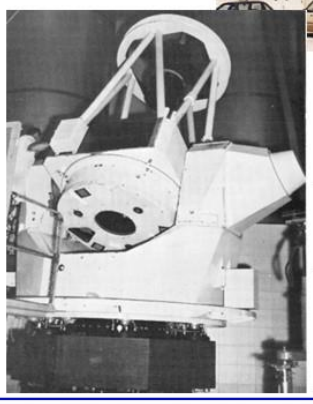
Measured Doppler Induced Change in Transmission

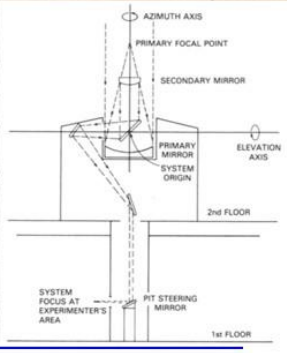


MARLI backscatter & wind measurement experiments at Goddard's 1.2 m Telescope

- Research facility for satellite laser ranging at GSFC
- Laser/tracking telescope used in many experiments in space laser ranging, 2-color SLR, Earth-Mars laser detection
- 1.2 m diameter primary mirror (only partially used here)
- 32 m effective focal length
- Elevation over azimuth gimbal system





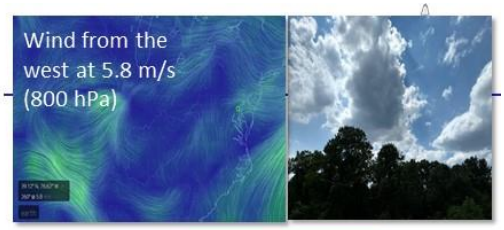


MARLI experiment:

- Integrate MARLI breadboard into system
- Demonstrate lidar backscatter profiles
- Demonstrate wind profiles measured at different fixed azimuth & elevation angles:

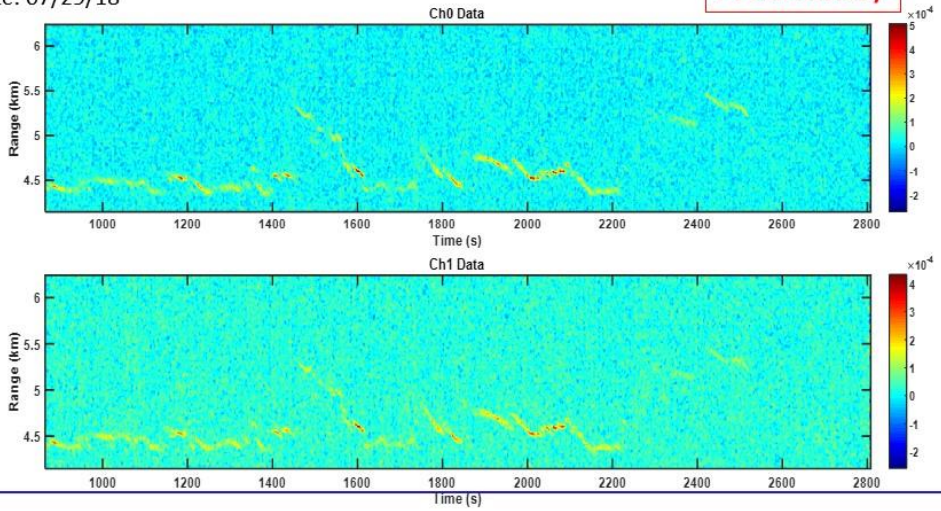
  Into, away90 deg. from wind
- Compare MARLI wind profiles to those from weather models

Initial Backscatter from Clouds at ~ 2 km altitude (Dan Cremons, Graham Allan)



Pulse Energy: 300 µJ, PRF: 4000 Hz
APD Gain: 12 V, 10-s windowed average
Telescope Azimuth: 270° (W),Telescope Elevation: 25°
Date: 07/29/18

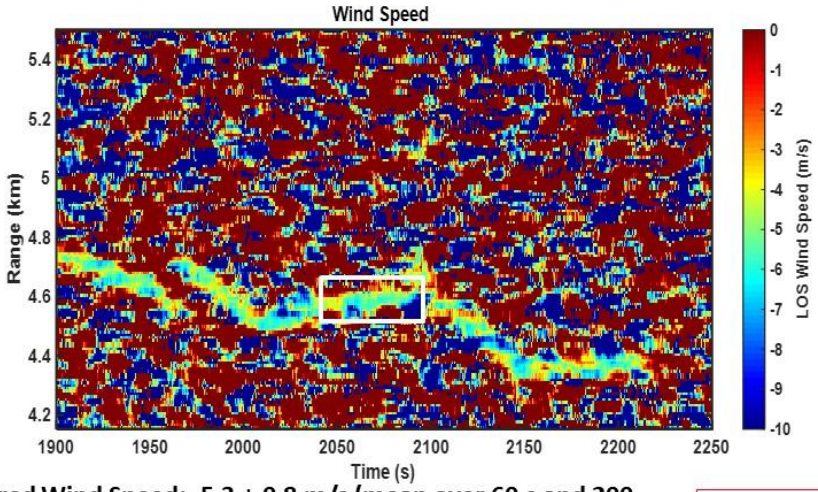
Preliminary



Some initial results- Doppler Velocity from Lidar profiles (Dan Cremons, Graham Allan)

GSFC

Pulse Energy: 300 µJ, PRF: 4000 Hz
APD Gain: 12 V, 10-s windowed average
Telescope Azimuth: 270° (W),Telescope Elevation: 25°
Date: 07/29/18

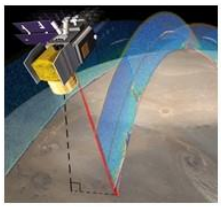


Measured Wind Speed: -5.3 ± 0.8 m/s (mean over 60 s and 200 m range)

Preliminary

MARLI - MatISSE Award (work is ongoing)







Primary Target:

- Mars atmosphere - from orbit

Science:

- Measure atmospheric backscatter profiles , dust vs ice profiles, & wind profiles, globally via a range-resolved lidar
- Addresses Mars global 3-D wind structure and how it changes with local time, location, and season.
- These are needed for improvement and validation of Global Circulation Models (GCMs)
- Knowledge of winds is critical for EDL.

- **Started November 2017**
- **24 month duration**

MatISSE Objectives:

- Mature designs of single and vector measurement versions of Mars atmospheric lidar
- Develop hardened versions of key laser, optics and detector assemblies
- Demonstrate wind measurements with brassboard
- Take to TRL6 via environmental tests
- Adapt approach to Titan atmosphere & demonstrate the key elements

MARLI Lidar - Development History

- Goddard IRAD: mid-2012 – October 2013
- Picasso Award: mid-2014 – November 2017
- Matisse Award: November 2017- October 2019

Collaborations; leveraged approaches & technologies:

- Strong & active Mars atmospheric science interest at Goddard
- Single frequency Nd:YAG laser – CATS Lidar (McGill) & Fibertek
- Receiver Telescope – Beryllium (from MOLA, GLAS, CATS, ATLAS lidar)
- Doppler discriminator – Double Edge approach (Korb & Gentry):
  - Here adapted to aerosol measurements & based on solid etalon
- Highly sensitive HgCdTe APD detector – from ESTO IIP (CO_2 Sounder) & ESTO Invest (packaging & environmental testing)

Lidar development process for Planetary Science (my views)

Similar to ones for CO_2 Sounder

- Competition isn't perfect, but is "least bad" approach:
  - Makes program responsive to technological changes
  - It keeps awardees focused & on their toes
  - Is incentive to be on lookout for partners & better technologies
- Whether to collaborate or not is best done at investigator level
- Opportunities for early (Picasso) and later phase (Matisse) developments is good
- Are plenty of conferences to learn of other activities/ technologies/ etc.

Challenges (similar to Earth Science):

- Continuity of effort
- Space demonstrations – are really compelling – how to do them ?
- NASA's competitive mission selection process -> many uncertainties:
  - which mission, & when ?

My recommendations for this meeting

Similar to ones for CO2 Sounder

- Increase support the laser/lidar development within the planetary program via the Picasso & Matisse programs
- ***Augment the programs:*** **bring in more $'s for laser & lidar development**
- *Use additional $'s to* ***increase the cadence*** for Picasso & Matisse solicitations

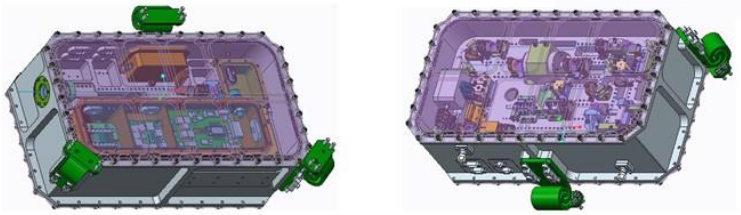
Backup

CATS vs MARLI Laser - Sizes

FIBERTEK, INC.

- CATS – 19”x11”x6.6” (5.9” without cover ribs)
- MARLI - 14.67”x8.12”x5.1”
  - 57% of CATS footprint
  - 44% of CATS volume





5.3 STANDOFF, ACTIVE, NON-CONTACT, NON-DESTRUCTIVE "SEARCH FOR LIFE" SYSTEMS WITH FAST DETECTION

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ABSTRACT

The University of Hawaii has developed two compact "Search for life" systems with active laser interrogation (a) the Standoff Color Biofinder and (b) Remote Search for Life System (RSLS). The Standoff Color Biofinder provides large area images of biological materials in a collection of rocks with fast detection time. The RSLS is a compact spectroscopy based system with remote Raman range tested up to 122 m and remote bio-fluorescence range up to 1690 m with 10-30 s integration time.

1 INTRODUCTION

The "Search for Life" is one of the important goals outlined in the NASA Decadal Survey. The detection of biological materials such as residues of fossils, amino acids and proteins would be evidence in support of life outside our planet and an important step towards meeting the "Search for Life" goal. Remote detection of biological materials is feasible using two active laser based techniques: (i) remote Raman and (ii) remote bio-fluorescence. Both technologies provide bio-detection at a range of several tens of meters with fast integration time of few seconds. Both techniques are non-destructive and work in daytime and nighttime conditions without any sample collection. Here, we will present two compact systems for standoff detection of biological materials: (i) Standoff Color Biofinder and (ii) RSLS. The Standoff Color Biofinder system is a large area imaging system capable of detection of ppm levels of biological materials from standoff distances of few meters with integration time of less than 1 s. The RSLS system is a compact spectroscopy based system which can quickly scan a geological site using fluorescence spectroscopy at long range and confirms the detection of organics using Raman spectroscopy at closer range of tens of meters.

2 METHODOLOGY

2.1 STANDOFF COLOR BIOFINDER

Most of the biogenic and organic materials give strong fluorescence signals when excited with UV and visible lasers. Microbes, such as photosynthetic and methanogenic microbes, produce unique biomolecular compounds that enable their detection via native fluorescence. Compounds such as chlorophyll and phycocyanins can be easily stimulated by blue light to provide red/yellow fluorescence features. Amino acids, nucleic acids, and lipids are major components of microbes. These components can be used as biomarkers during search-for-life missions. The decay time or lifetime of bio-fluorescence is much shorter (<1 to 100 ns) [1-3] than the phosphorescence decay time of metal ions (1 μs to several ms) in minerals [4]. The Standoff Biofinder exploits the short lifetime of bio-fluorescence to separate out biological materials from luminescent minerals.

The standoff biofinder instrumentation uses a nano-second pulse laser to illuminate distant target materials. The laser beam is expanded to illuminate a large sample region. A gated detector with a focusing lens is used to record time-resolved fluorescence images. The timing of the detector is synchronized with the pulse laser. A notch filter is used in front of the focusing lens to reject the laser wavelength.

2.2 STATE OF THE ART: STANDOFF COLOR BIOFINDER

Figure 1 shows the capability of the standoff biofinder system to successfully detect all biological materials in daylight from 3 m distance during an outdoor test on a sunny day in Hawaii. A 355 nm Nd-YAG pulsed laser (10 mJ/pulse, 20 Hz, 10 ns pulse width) was expanded to a diameter of 60 cm to illuminate an area with lava rocks and small plants. The close up image of the target area is shown in Figure 1, bottom image. The sample

set contains Hawaiian basaltic lava rocks, green leaf plants, soil, dry leaf, fallen seeds from tropical almond tree (Terminalia catappa), stones, etc. Presence of natural biological material such as microbes, algae on the lava rocks is not detectable with regular vision.



Figure 1: Outdoor testing of Standoff Biofinder on a sunny day in Hawaii. The bio-images were collected from a collection of lava rocks as seen towards the right of the system at 3 m distance (top image). Close up picture of 60- cm wide sample area (bottom image. Inset image: Schematic diagram.

The false-color bio-fluorescence image, Figure 2 (a), with red color indicating higher intensity, shows the location of all biological materials in the target area with 1 s integration time. It is shown that all lava rocks have significant amount of biological material on their surfaces.

Figure 2 (b) shows the color fluorescence image using Bayer RGB filters. One of the advantages of the color biofinder is the ability to differentiate multiple biological materials in a target area by providing their fluorophore colors, along with morphologies.

The compact version of standoff color biofinder uses a small color CMOS detector with 1" diameter camera lens. Figure 3 shows the white light and short-lived bio-fluorescence images of shrimp fossils from Green River formation, Wyoming, USA (Eocene, 56.0-33.9 Ma old) in their containing matrix.

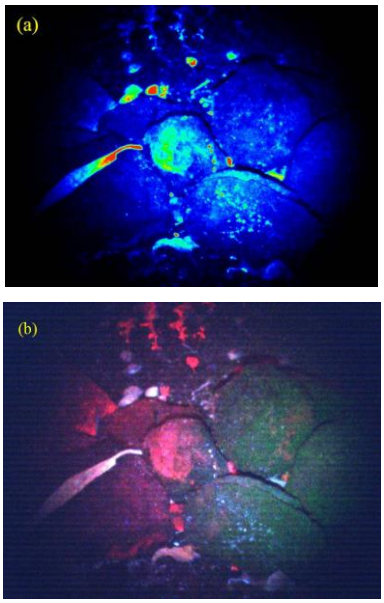

Figure 2: (a) False-color bio-fluorescence image of the target area using the Biofinder with 1 s integration time. (b) Color fluorescence image using RGB filters: Green leaf plants are seen as bright red due to intense chlorophyll fluorescence. Microbial diversity on the lava rocks are seen as various colors.

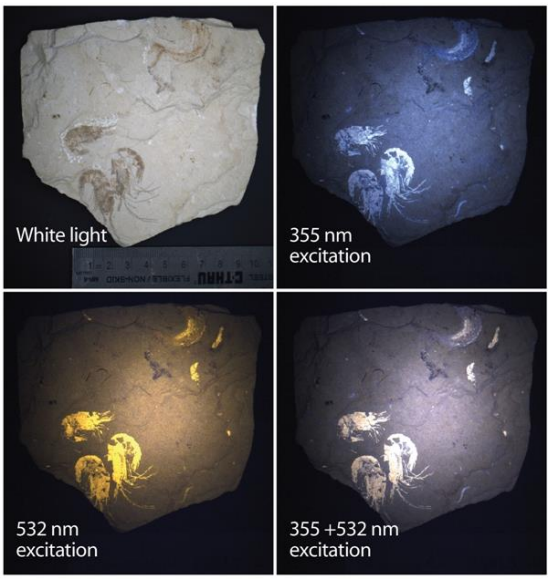

Figure 3: Shrimp fossils from the Green River formation, Colorado, Wyoming and Utah, USA. Clockwise from the top left: white light image; short lived fluorescence images excited with 355 , 355+532, and 532 nm laser light.

The images reported in Fig. 3 were obtained from a distance of 50 cm with combinations of 355 and 532 nm excitation pulses from a Nd-YAG laser. Samples were excited with total pulse energy of 5 mJ at 355 nm plus 4 mJ at 532 nm to illuminate a 20 cm wide area (single pulse excitation and detection).

2.3 RSLS

RSLS is a powerful system for astrobiology; RSLS can detect and characterize water, ice, bio-minerals, hydrous minerals, poly-aromatic hydrocarbons (PAH's), amino acids, fossils, clays, sedimentary rocks, plants, microbes, residues of biological materials, proteins, etc. from 100s of meters and few seconds integration time. The RSLS combines two active laser-induced remote sensing technologies into a single instrument: (i) bio-fluorescence spectroscopy and (ii) Raman spectroscopy. One of the advantages of the bio-fluorescence system is that it is highly sensitive and can detect very minute trace amount of biological materials below parts per billion levels. Raman spectroscopy is an ideal technique for identifying CHNOPS-bearing chemicals to a high degree of specificity, as well as other bio-signatures that could be critical to life including water and oxygen.

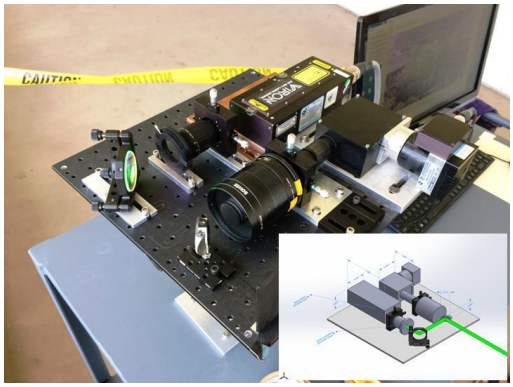

Figure 4: Compact RSLS system with remote Raman and fluorescence spectroscopy capabilities.

2.4 STATE OF THE ART: RSLS

Figure 4 shows the picture of RSLS instrument during an outdoor testing. RSLS uses a very compact spectrograph made from volume phase holographic gratings with high throughput and spectral resolution (0.2 nm). The size of the compact spectrograph is 10 x 8.2 x 5.2 cm3 (L x W x H) and it weighs 571 g. RSLS also uses a custom mini-ICCD as a detector and a small diode pumped Nd:YAG laser. Figure 5 shows the long range detection ability of RSLS to identify water, ice, and CO_2 ice (dry ice) and hydrous minerals $CaSO_4 \cdot 2H_2O$ (gypsum), $MgSO_4 \cdot 7H_2O$ (epsomite) from a distance of 122 m with 30 s integration time [5].

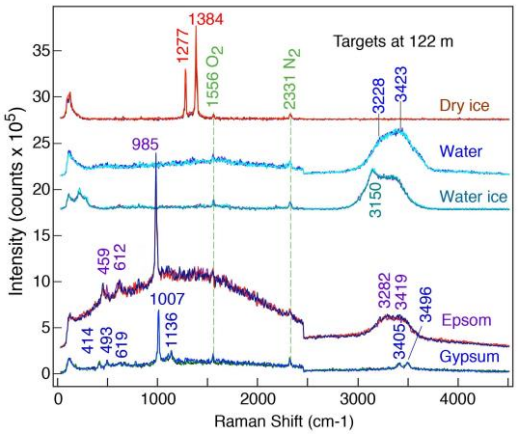

Figure 5: Remote Raman spectra of water, ice, dry ice and hydrous sulfate minerals from a distance of 122 m with a 30 s integration time. Three measurements for each chemical are shown.

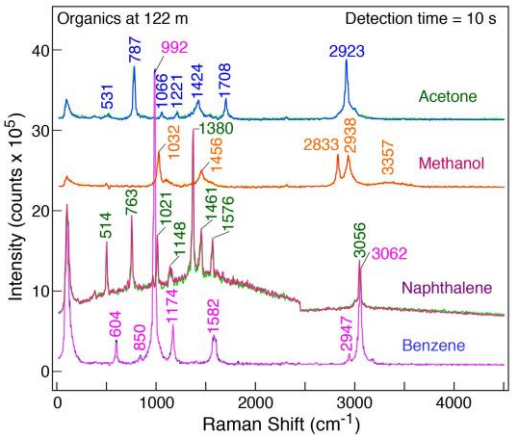

Figure 6: Remote Raman spectra of organics from a distance of 122 m with 10-s integration time. Two measurements for each chemical are shown.

Figure 6 shows the remote Raman detection of various organics with 10 s integration time from 122 m distance using RSLS. Figure 7 shows remote detection of bio-fluorescence signal during afternoon sunlight from trees at several hundred meters. With RSLS, fluorescence signal from trees

at 500 m could be easily detected with 1 s integration time. The ICCD image on the left shows the strong chlorophyll fluorescence signal from a tree at 726 m with 10 s integration time. The right image shows the fluorescence signal from bushes on the mountain at 1690 m.

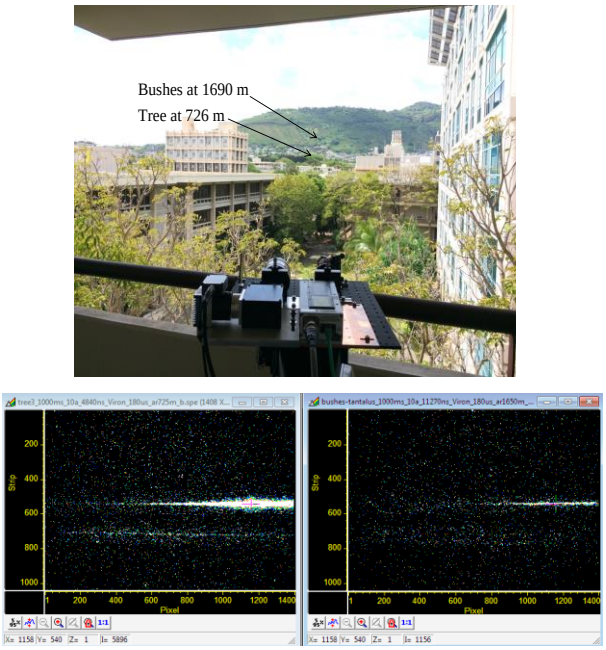

Figure 7: Detection of biomass at 726 and 1690 m distances. ICCD image showing biofluorescence signal during daylight from a tree at 726 m distance (left image) and the bushes on the mountain at 1690 m distance (right image) with 10 s integration time. Chlorophyll fluorescence band is observed on the top spectral image.

2.5 FUTURE TECHNOLOGY NEEDS

Both Raman and fluorescence techniques need a pulse laser and a gated detector. Since Raman signals are significantly weaker than fluorescence signals, the technology needs are more demanding for a remote Raman system. For Raman system one needs a compact, active Q-switched, nano-second pulse laser with high pulse energy, narrow line width and stable wavelength. The Raman system also needs a gated detector with high sensitivity. The requirements of narrow line width and stable laser wavelength are not critical for a biofinder system.

3 PROGRAMMATICS

The standoff color biofinder is currently funded under NASA PICASSO program (POC Dr. James Gaier) and has just finished the 1st year of a 3 year award. RSLS is not currently funded and we have submitted a Matisse proposal to further develop the system.

4 WIDER VISION

The standoff biofinder can be used by NASA's planetary protection division for evaluating cleanliness of space vehicles and rovers in order to avoid forward bio-contamination of planetary bodies. The instrument will be also useful for non-contact evaluation of materials from sample return missions.

5 CONCLUSIONS

We have developed two state of the art "Search for Life" systems. The standoff color biofinder system uses a new approach of fast fluorescence bio-imaging using diverging diffused laser beam illumination. It provides a large area color image showing locations and morphologies of various biological materials in a geological setting with fast detection time. The RSLS is a compact remote Raman and fluorescence system using a remote spectroscopy approach. This system has the advantage of long detection range of several hundred meters using a collimated laser beam excitation. Area chemical maps can be made by scanning and post processing the spectroscopy data using RSLS.

ACKNOWLEDGEMENTS

The RSLS was supported in the past by NASA EPSCoR program. The color biofinder system is currently supported by NASA PICASSO program (Program manager Dr. James Gaier)

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1. Misra, A. K., T. E. Acosta-Maeda, et. al, 2016 "Standoff Biofinder" for fast, non-contact, non-destructive, large area detection of biological materials for planetary exploration, *Astrobiology*, **16** (9), 715-729.
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3. D. M. Jameson (2014) “Introduction to Fluorescence”, CRC, NY, 295pp.
4. Gaft, M., Reisfeld, R., and Panczer, G. (2005) Luminescence Spectroscopy of Minerals and Materials. Springer-Verlag Berlin Heidelberg. Germany, 356pp.
5. Sandford, M., Misra, A. K., Acosta-Maeda, T. E., et. al., Detection of “search of life” elements using compact remote Raman system from 122 meters. 2018, 49th LPSC, abstract# 1695.

Standoff, active, non-contact, non-destructive "Search for Life" systems with fast detection

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Presented at NASA Technical Interchange Meeting, August 2018, Columbia, MD

Hawaii Institute of GeoPhysics & Planetology
University of Hawaii

Remote detection of biological materials is possible using:

(1) Raman signals

(2) Bio-fluorescence signals

Raman Spectroscopy

Very weak signal, Raman efficiency ~ 10^{-7}

↓

Vibrational modes of molecules $\omega = \sqrt{\frac{k}{\mu}}$

↓

Depends on atomic mass, bond lengths, bond strength, configuration, etc…

↓

Unique spectrum for each molecule

↓

Chemical detection with very high confidence level

Remote Raman system:

For 3" diameter telescope at 10 m range:
Collection efficiency ~ 3.5×10^{-6}

* Non-contact
* Non-destructive
* No sample preparation
* Daytime/nighttime detection
* Fast (0.1 -30 s)
* Detection of all phases (gas, liquid, solid)

Easy to detect:
Water, ice, dry ice, gas hydrates, atmospheric gases,…

Organics: benzene, nitro-benzene, methanol, acetone, naphthalene, cyclohexane, urea, plastics, paraffin, oil, etc…

Minerals: hydrous minerals, carbonates, sulfates, nitrates, phosphates, chlorates, oxides, sulfur, diamond,…

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Fluorescence Spectroscopy

* Non-contact
* Non-destructive
* No sample preparation
* Daytime/nighttime detection
* Fast

* **Extremely sensitive detection of bio-molecules**
* Can separate biological materials from mineral luminescence

* Very high quantum efficiency in comparison to Raman scattering
* Detection limits better than ppb levels

* Not very specific for identification.

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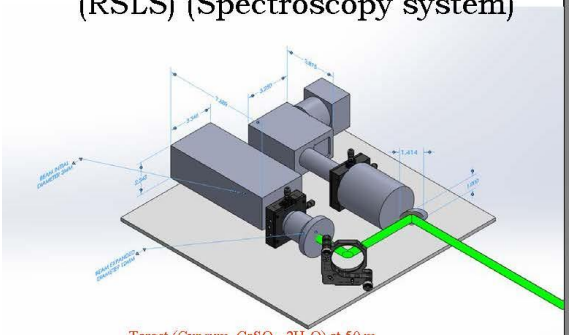
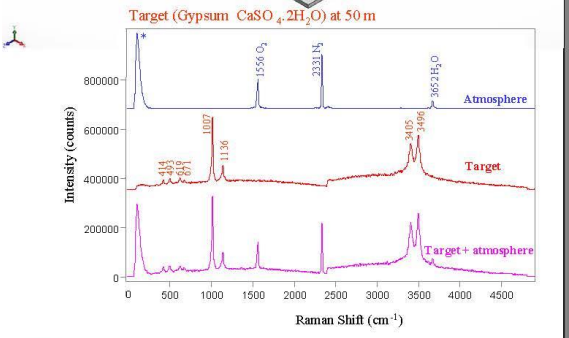
Remote Search for Life System

(RSLS) (Spectroscopy system)





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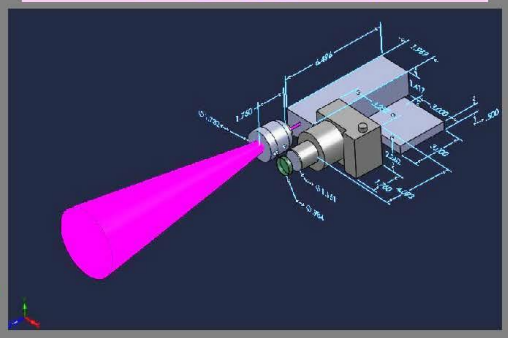
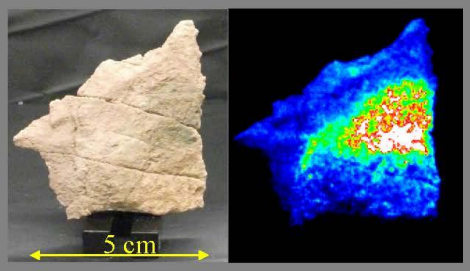
Standoff Color Biofinder

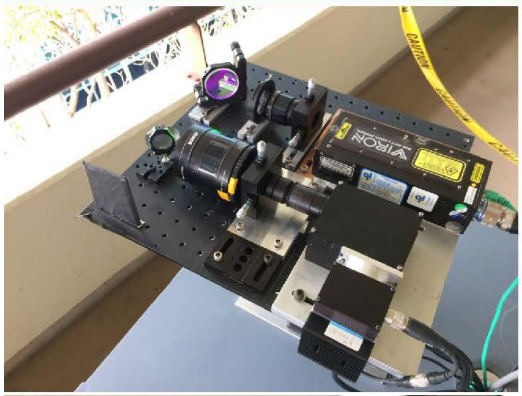
(Imaging system)





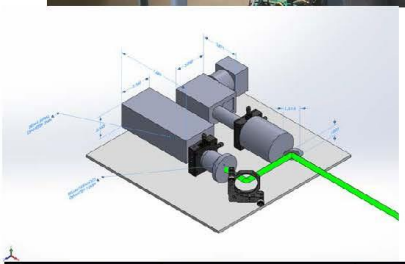
NASA

Remote Search for Life System (RSLS)



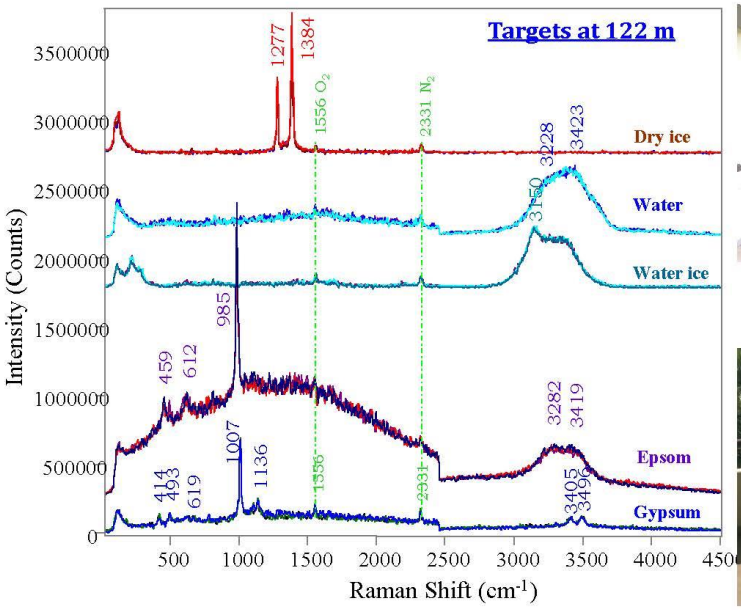






Component	Dimension (cm)	Weight (g)	Power (W)
1. Telescope	7.5 (outer dia.) x 10.0	314	
2. Spectrograph	10.0 x 8.2 x 5.2	571	
3. Mini-ICCD	7.7 x 6.0 x 8.4	620	3.5
4. Laser (Viron)	19.5 x 8.9 x 5.6	1700	240

Remote Raman detection of water & hydrous minerals from 122 m, 30 s.





* 3 measurements for each sample are shown

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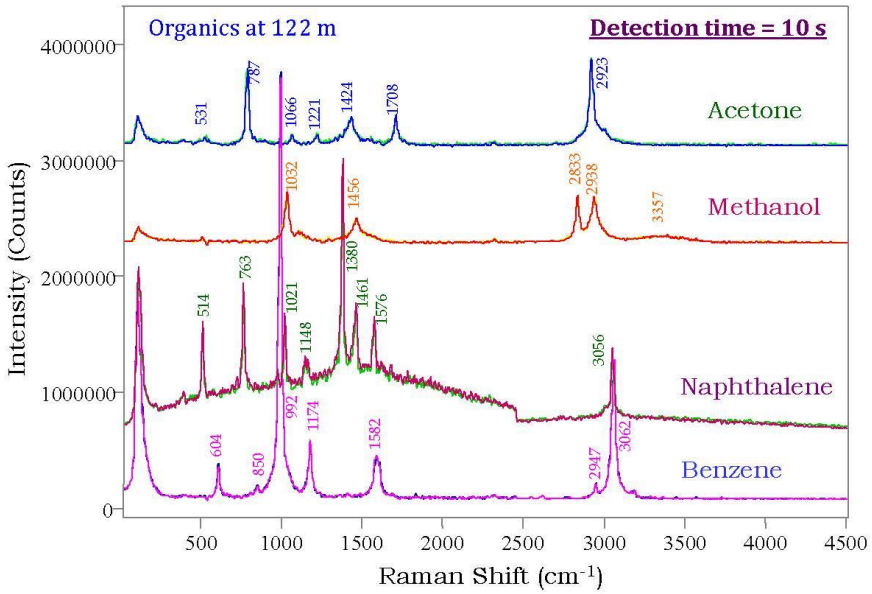
Laser 532 nm, 10 ns pulse width, 20 mJ/pulse, 20 Hz

Remote Raman detection of organics from 122 m, 10 s.



* 2 measurements for each sample are shown

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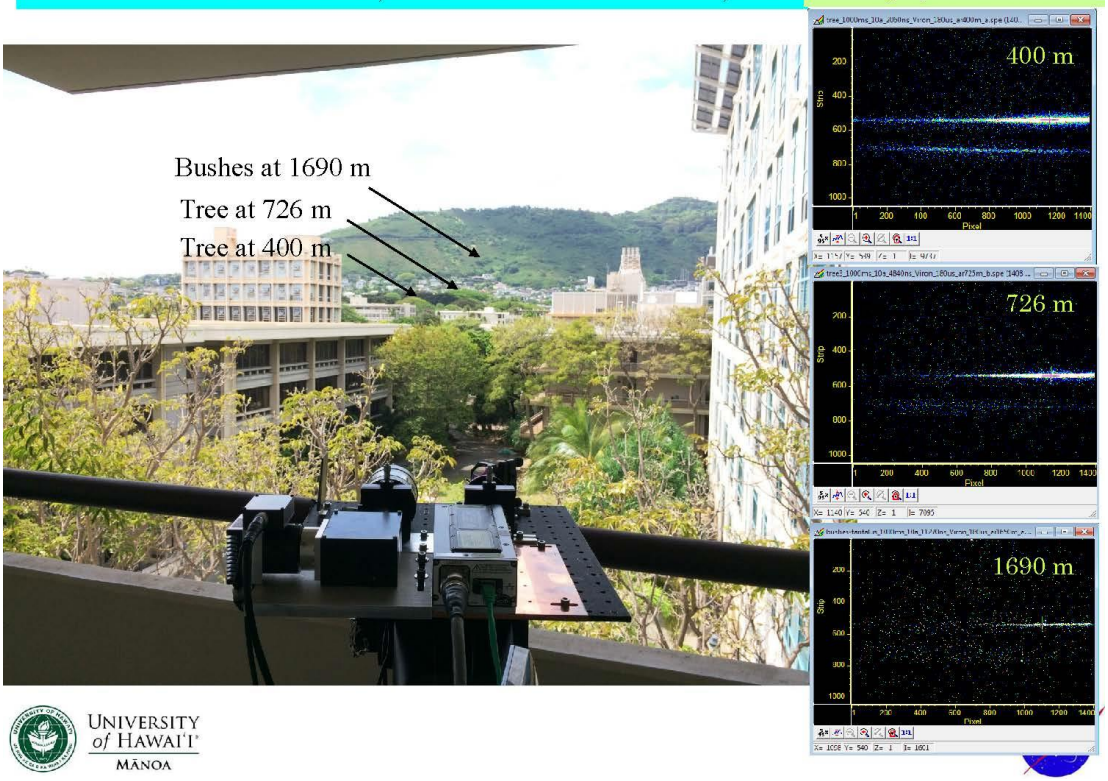
Detection of biomass at 400, 726 and 1690 m distances, 10 s

Chlorophyll fluorescence



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Issue: which rock holds bio-signature?



"Kimberley" formation on Mars, NASA's Curiosity rover, Sol 580

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NASA

Same issue on micro-scale: which grains are biogenic?

Mixed soil: Antarctic soil, Hawaiian basalt, Waikiki beach sand, salt, PAH etc…
US dime for scale (D = 17.9 mm), image from 50 cm distance.



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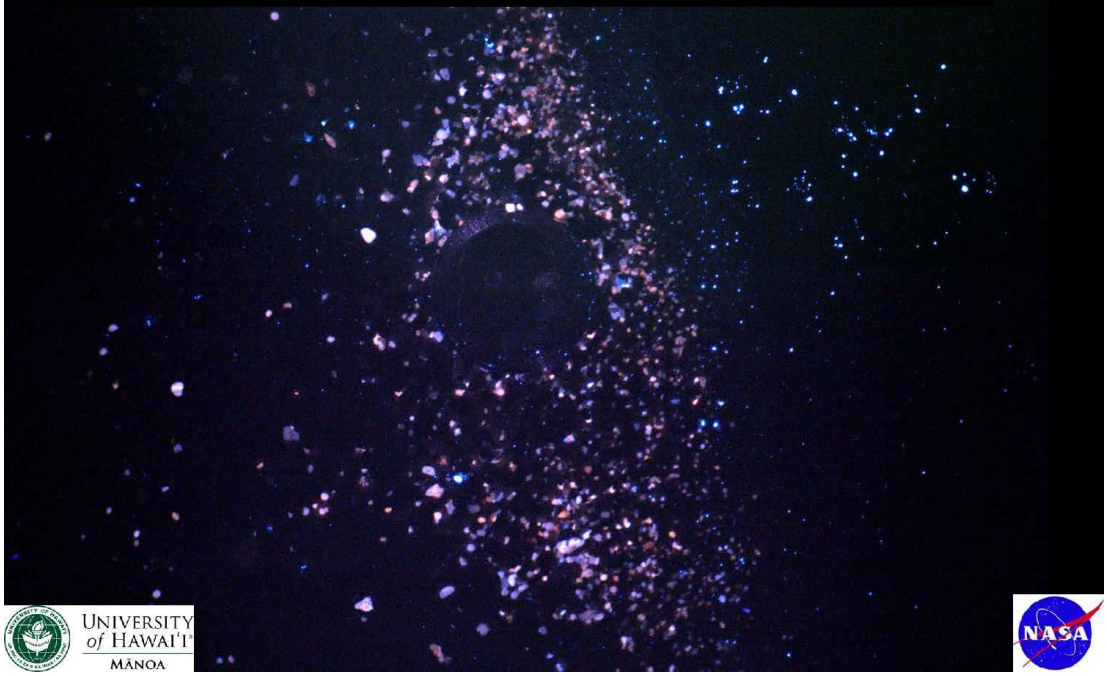
NASA

Standoff Color Bio-finder

Detects all biological and PAH materials
with just one laser pulse excitation/detection
Image from 50 cm distance



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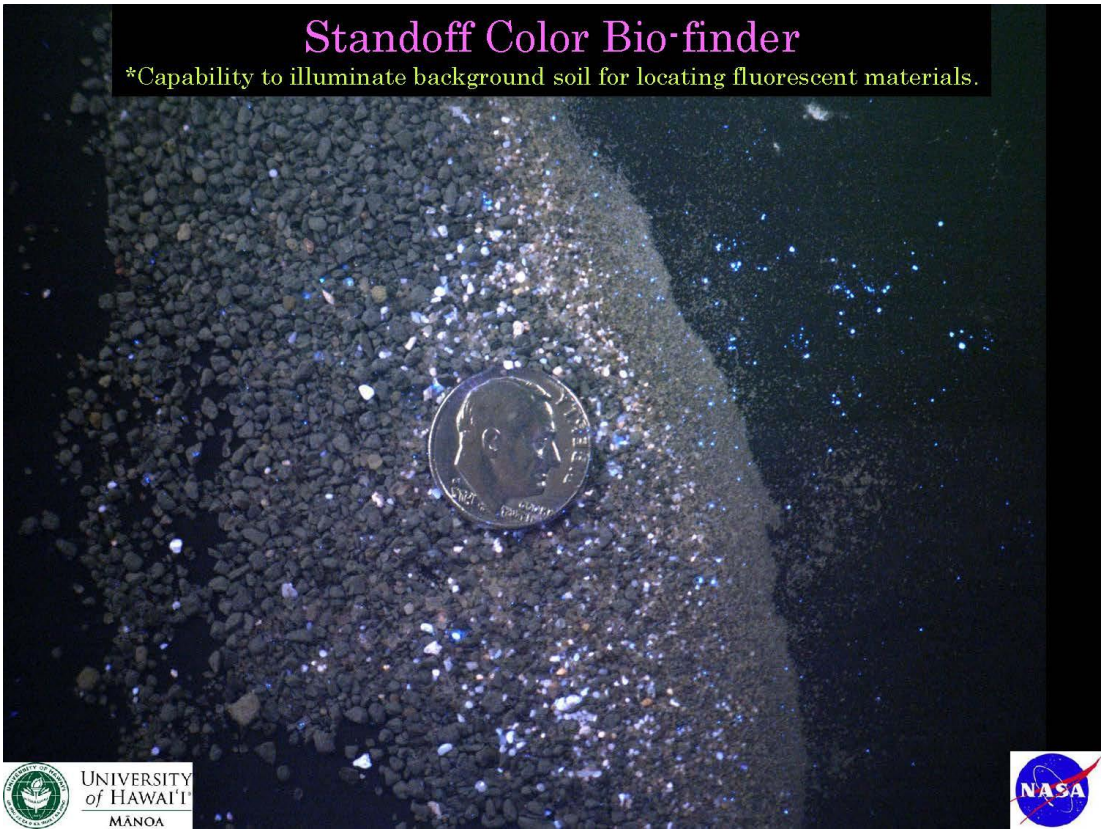

Standoff Bio-finder

2012 Concept & prototype system developed: Misra et al., LPSC abstract#1498



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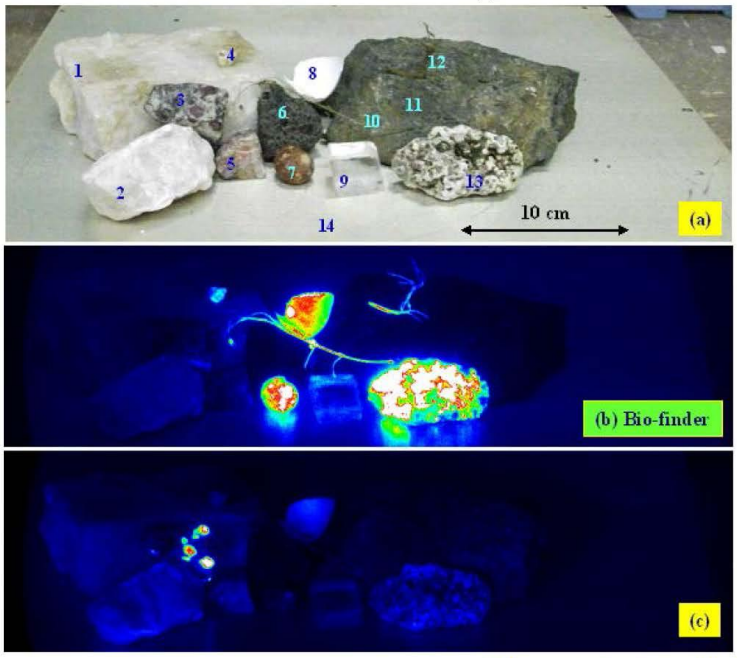
0.1 s detection, Laser 532 nm, 0.1 mJ/pulse, 10 kHz



(ICCD detector, False color images) Misra *et al.*, Astrobiology 2016.

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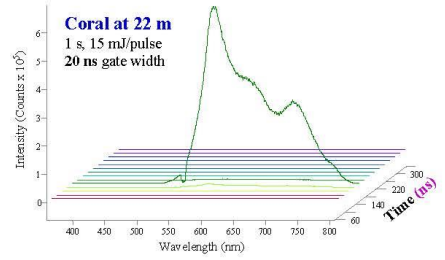
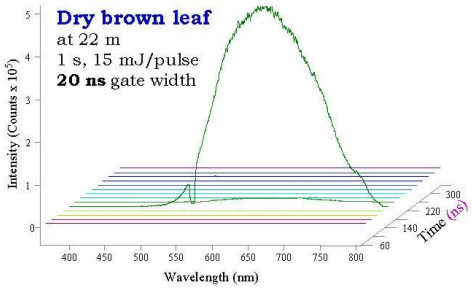
Working principle of Standoff Bio-finder:

* All biological materials give strong fluorescence signals with life time < 20 ns.





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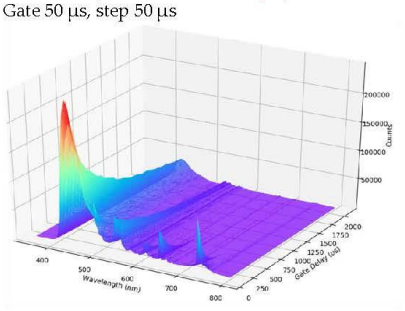
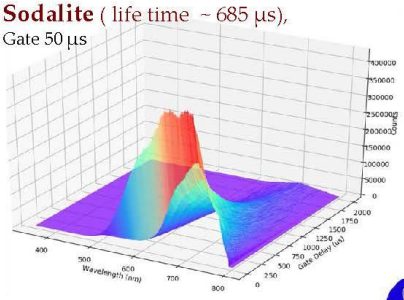
* Minerals phosphorescence long life time (>>μs)

Fluorite (life time ~ 1100 μs),
Gate 50 μs, step 50 μs



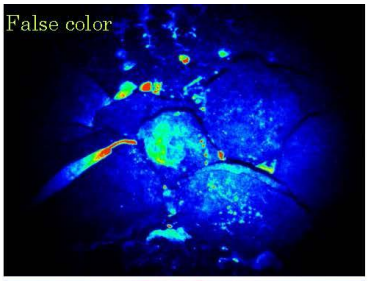
Sodalite (life time ~ 685 μs),
Gate 50 μs

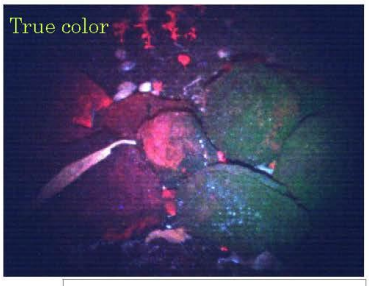


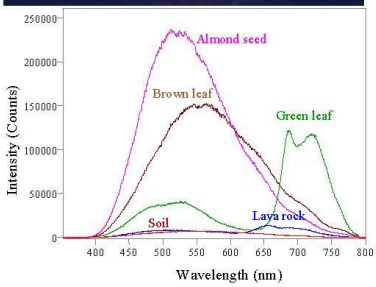
Daytime detection of microbes on lave rocks

From 3 m , 1s detection, 60 cm wide area, 355 nm









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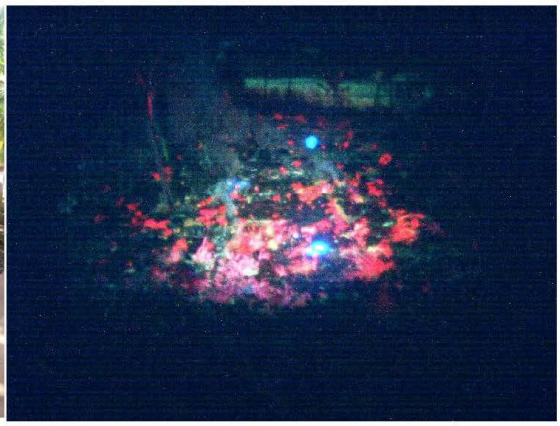
Large area biological detection during daylight

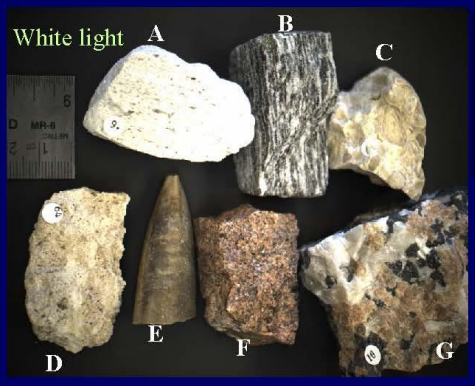
1 s integration, 50 ns gate, RGB, 355 nm excitation.



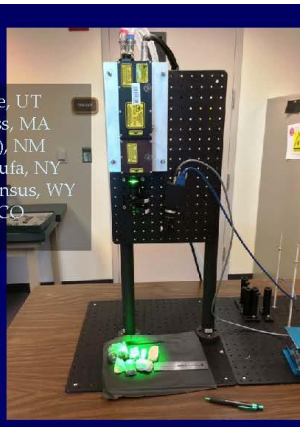


* Paper markers (seen as bright blue objects) are at 5 and 10 m distance

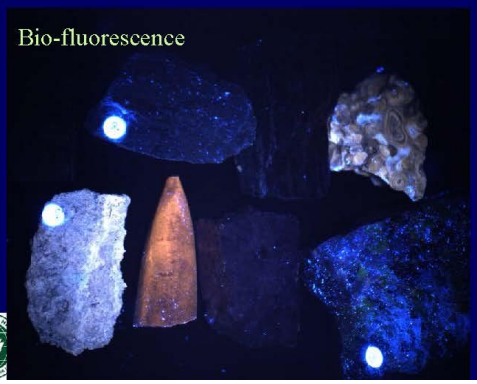
Color Biofinder (single pulse excitation/detection)



A: Igneous rock, Extrusive, Pumice, UT
B: Metamorphic rock, Biotite gneiss, MA
C: Fossil, Permian, Pisolites (algae), NM
D: Sedimentary rock, Calcareous tufa, NY
E: Fossil, Jurassic, Pachyteuthis densus, WY
F: Igneous rock, Intrusive, Aplite, CO
G: Willemite with Franklinite, NJ









Bio-detection through ocean water
(single pulse, ICCD)

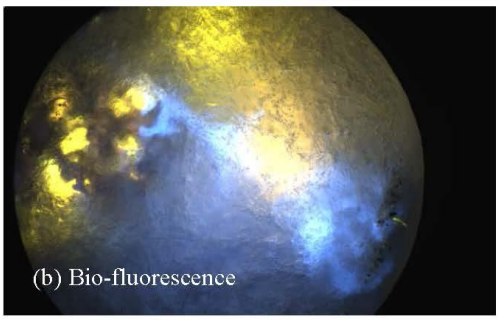




Sea floor depth ~ 3 m

Bio-detection through ice
(single pulse, CMOS)





Ice diameter = 12 cm

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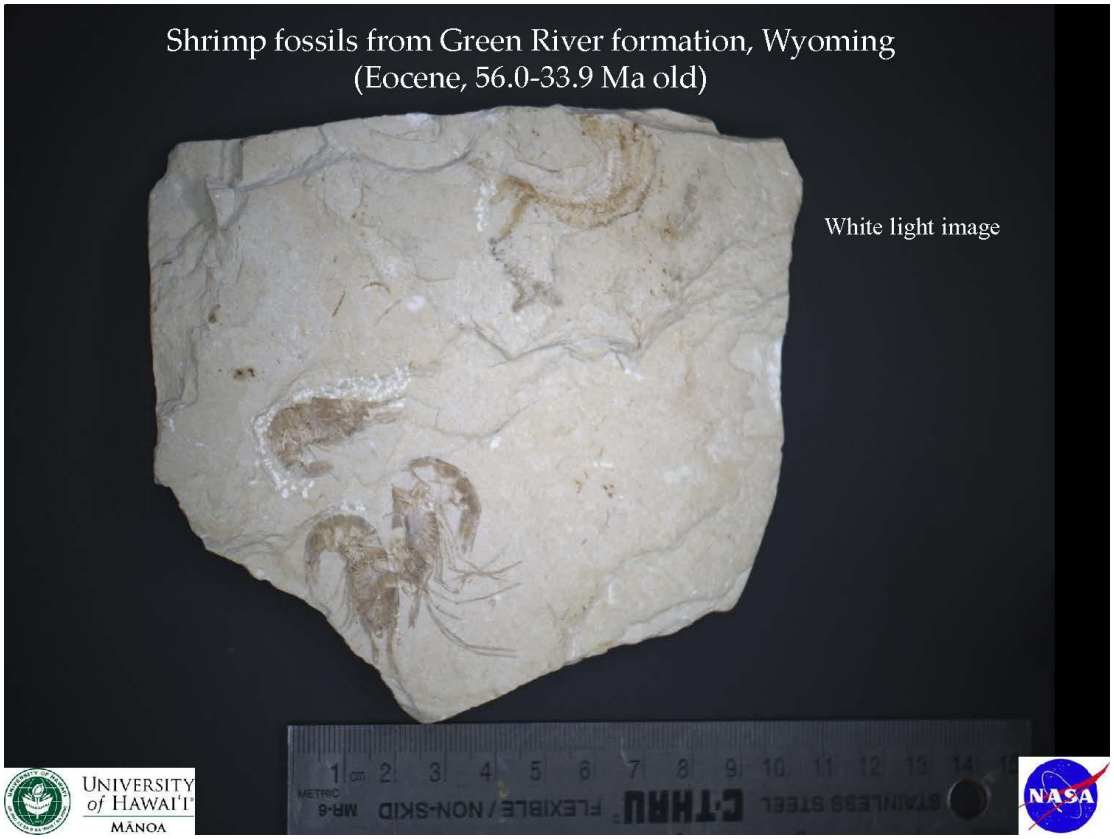
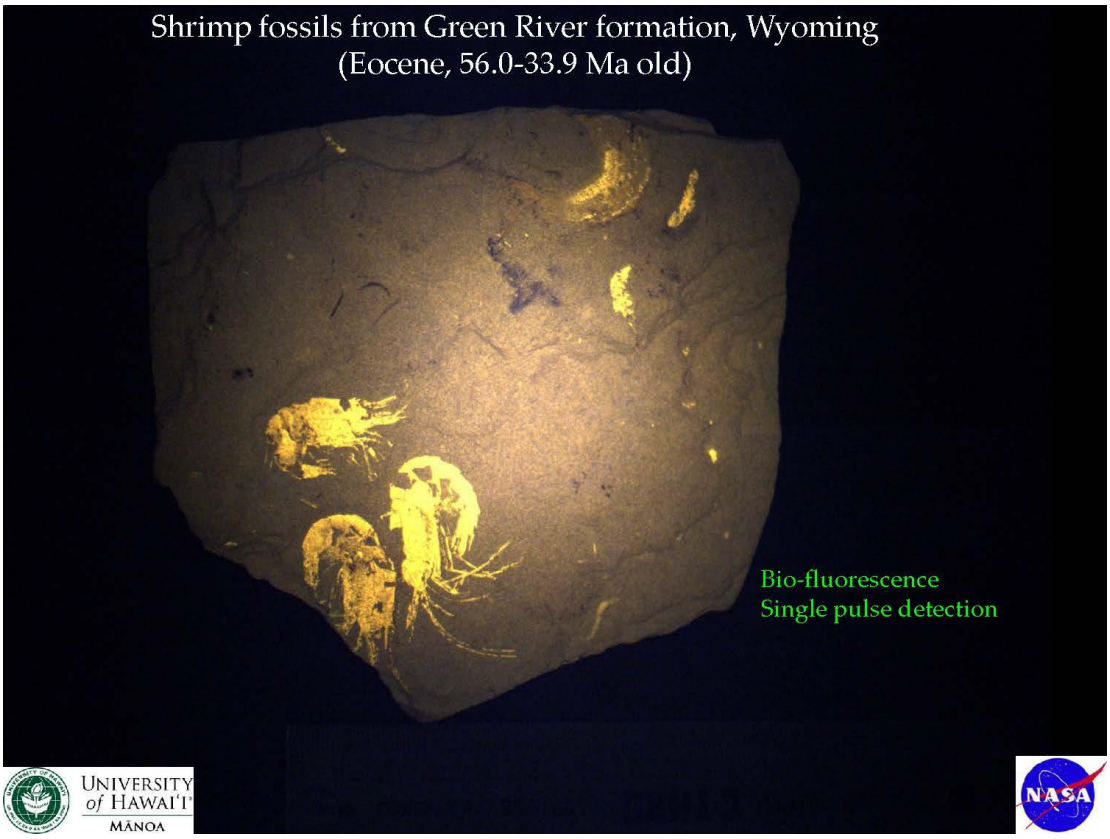
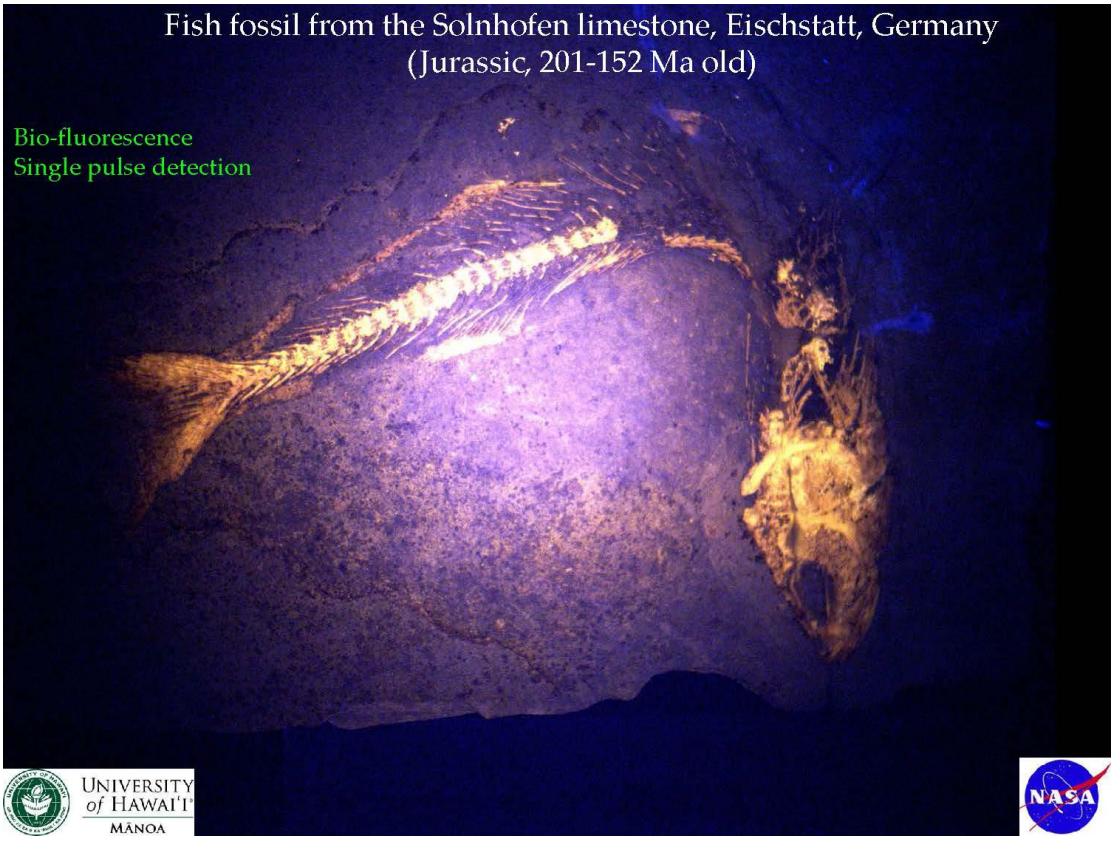

Shrimp fossils from Green River formation, Wyoming
(Eocene, 56.0-33.9 Ma old)
White light image
UNIVERSITY of HAWAI'I MĀNOA
NASA


Shrimp fossils from Green River formation, Wyoming
(Eocene, 56.0-33.9 Ma old)
Bio-fluorescence
Single pulse detection
UNIVERSITY of HAWAI'I MĀNOA
NASA


Fish fossil from the Solnhofen limestone, Eischstatt, Germany
(Jurassic, 201-152 Ma old)
White light image
UNIVERSITY of HAWAI'I MĀNOA
NASA


Fish fossil from the Solnhofen limestone, Eischstatt, Germany
(Jurassic, 201-152 Ma old)
Bio-fluorescence
Single pulse detection
UNIVERSITY of HAWAI'I MĀNOA
NASA





2 billion years old fossil is detectable

#	Species	Type	Stratigraphic unit, Location	Geologic period	Age (Ma)
1	*Collenia* species	Stromato-lites	Biwabik Iron fm. Michigan	Precambrian	2200-2400
2	*Elrathia kingi*	trilobite	Wheeler shale Utah	Middle-Cambrian	509-497
3	*Glyptorthis insculptus*	brachiopod	Richmond group Ohio	Ordovician	485-444
4	*Rynchotreta cuneata*	brachiopod	Waldron shale Indiana	Silurian	444-419
5	*Autocystis* species	coral	Silica shale Ohio	Devonian	419-359
6	*Neospirifer dunbari*	brachiopod	Des Moines stage Missouri	Pennsylva-nian	323-299
7	Pisolites	algae	Captain's Reef fm. New Mexico	Permian	299-252
8	*Pachyteu-this densus*	cephalopod	Sundance fm. Wyoming	Jurassic	201-152
9	*Oliva* species	gastropod	Caloosahatchee fm., Florida	Pliocene	5.3-2.6

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Technology needs:

* Compact laser with high pulse energy
* Compact sensitive detector

Raman laser:

* Narrow line width
* Stable wavelength
* High pulse energy
* Repetition rate (10-100 hz)
* Active Q-Switched

Bio-fluorescence laser or fast LED:

* ~~Narrow line width~~
* ~~Stable wavelength~~
* ~~High~~ pulse energy
* Repetition rate (10-100 hz)
* Synchronized pulsed illumination

Raman Detector

* Highly sensitive (ICCD)
* Compact
* Frame rate to match with laser
* Nano-second gate capability
* Wider chip

Bio-fluorescence Detector

* Sensitive color detector (CMOS)
* Compact
* Frame rate to match with laser/LED
* Timing capability, short exposure

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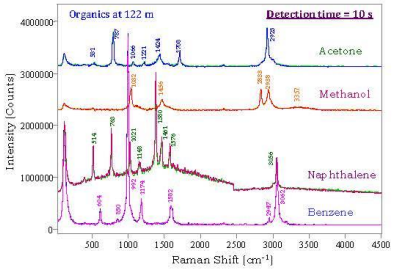
Summary: Two "Search for life" systems

* Active
* Non-destructive
* Standoff detection
* Fast response

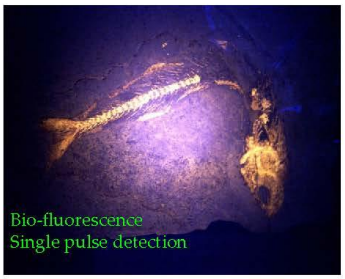


(1) Remote Search for Life System (RSLS)
(Spectroscopy system)

* Remote Raman capability: 122 m, 30s
* Remote Bio-fluorescence capability: 1690 m, 10s
* Chemical maps can be made by scanning.
* Also detects water, ice, organics, hydrous minerals, gases

(2) Standoff Color Biofinder (bio-imaging system)

* Large area detection
* Fast detection <1 s
* Provides morphologies and locations of biological materials
* Highly sensitive



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Thank you.

5.4 A MISSION-ENABLING UV LASER FOR MASS SPECTROMETRY (UVMS) WITH CONTINUOUSLY SELECTABLE OUTPUT FOR IN SITU PLANETARY EXPLORATION

D. Barry Coyle[a], Demetrios Poulios[b], Ricardo Arevalo[a], Matthew Mullen[b], Paul R. Stysley[a]

[a]NASA Goddard Space Flight Center, Lasers and Electro-Optics Branch, Greenbelt, Maryland 20771

[b]The American University, Dept. of Physics, 4400 Massachusetts Ave NW, Washington, D. C. 20016

A mission-enabling UV laser for mass spectrometry (UVMS) with continuously selectable output for in situ planetary exploration

NASA Technical Interchange Meeting on Active Optical Systems for Supporting Science, Exploration, and Aeronautics Measurements Needs

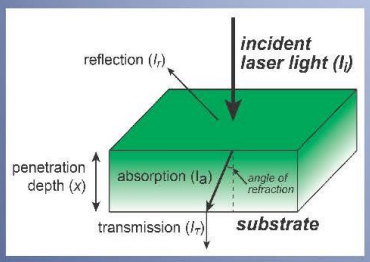
July 31 – August 3, 2018

D. Barry Coyle[a], Demetrios Poulios[b], Ricardo Arevalo[a], Matthew Mullen[b], Paul R. Stysley[a]

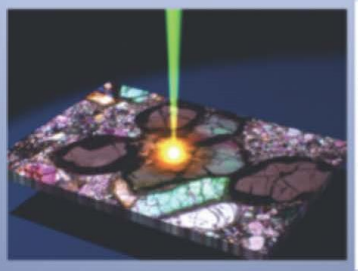
– [a]NASA Goddard Space Flight Center, Lasers and Electro-Optics Branch, Greenbelt, MD 20771

– [b]The American University, Dept. of Physics, 4400 Massachusetts Ave NW, Washington, DC 20016

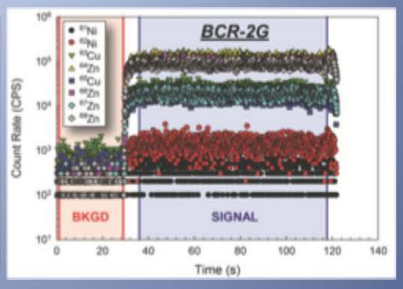
Laser desorption for ion production and the hunt for organics



Laser desorption fundamentals: incorporating reflection, scattering, and absorption of a geologic planetary sample.



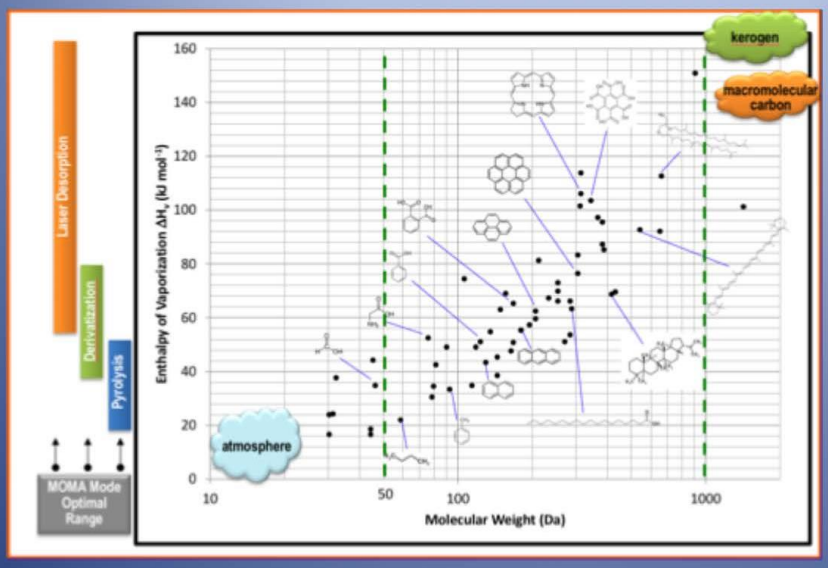
Artistic depiction of laser processing of a geological thin section, illustrating the spatial resolution provided by laser ablation and desorption techniques.



Real laser ablation spectrum (intensity, in counts per second, versus time, in seconds) derived from the analysis of first-row transition metals in the USGS basaltic glass standard, BCR-2G

(Geostandards and Analytical Research, Vol 35, No 2 Arevalo et al., 2011).

The Organic "Reach" of Laser Desorption



Derivatization employs a chemical reaction with the sample, where the products are studied in a MS.

Pyrolysis source thermally decomposes the sample for GC/MS.

*Laser Desorption produces free ions with minimal heating and no changes in chemical makeup, when done properly.

* With short UV laser pulses and precise intensity control.

Laser "desirements" for planetary laser desorptive ion production?

1. Pulses of 266 nm are better absorbed by most geological materials, particularly optically transparent minerals/phases. 266 nm is ideal for Mars, rocky satellites, asteroids, and comets.

2. 266 nm is also very effective at ionizing organics in the residues of sublimated ices, so in that case cryogenic environments are also accounted for.

3. Adjustable output energy can adjust for sample albedo, absorption, minimize heating pyrolysis effects.

4. Ability to "dial in" the incident fluence (ex: 1.2 – 1.3 J/cm^2 for Arevalo et al., 2011).

5. A 100 Hz rep rate burst is easier to maintain thermally without requiring TECs (some instruments cannot accommodate more than a single shot, like TOFMS and Orbitrap-based instruments)

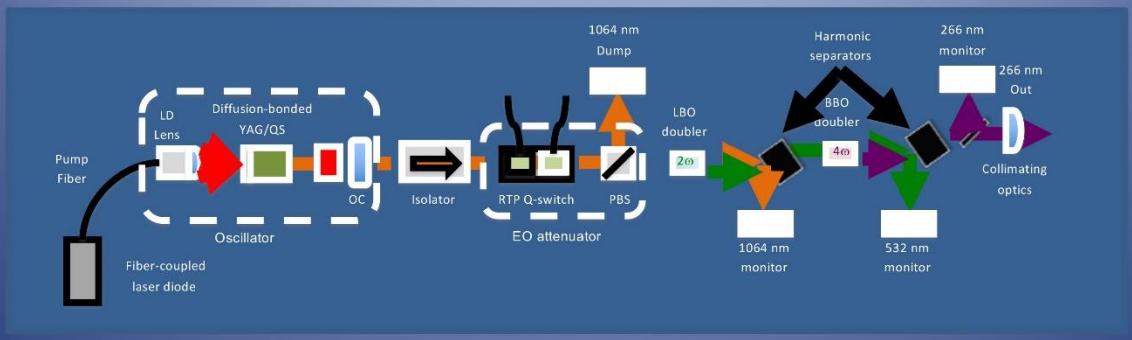
6. Generally, planetary payload instruments are buffered at -50C/+75C operational. (Low temp sensitivity.)

7. UV laser are best for rocky samples with or without organics, but longer wavelengths (3 micron ideally) are best for icy samples. Thus, 266 nm is ideal for Mars, rocky satellites, asteroids, and comets.

8. Super small and lightweight of course....

Breadboard UVMS Design

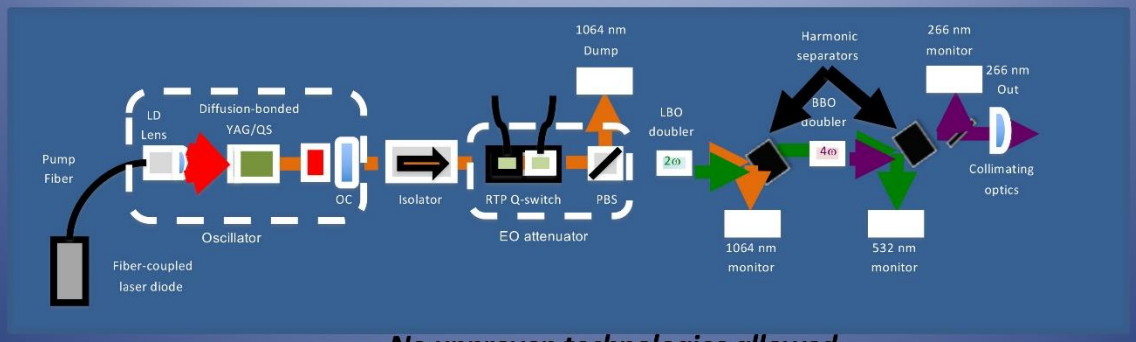
Pulse Energy:	**≥ 200 uJ**
Pulse Width:	**~ 2-3 ns**
Wavelength:	**266 nm**
Repetition Rate:	**100 Hz burst (50 shots)**
Lifetime:	**> 3 M**
Thermal:	**-30C to +25 C (operating)**
Duty Cycle:	**> 1%**
Notes:	**Pulse energy adjustable w/ ≥ 10 settings**



Breadboard must translate to high TRL components:

Item	TRL	Heritage
Fiber-coupled pump laser	6	ICESat-2
Mirrors, lenses, PBS	6+	GLAS, MLA, MOLA, GEDI, CALIPSO, GEDI
Nd:YAG crystal	6+	GLAS, LOLA, MOLA, MLA, GEDI, CALIPSO, GEDI

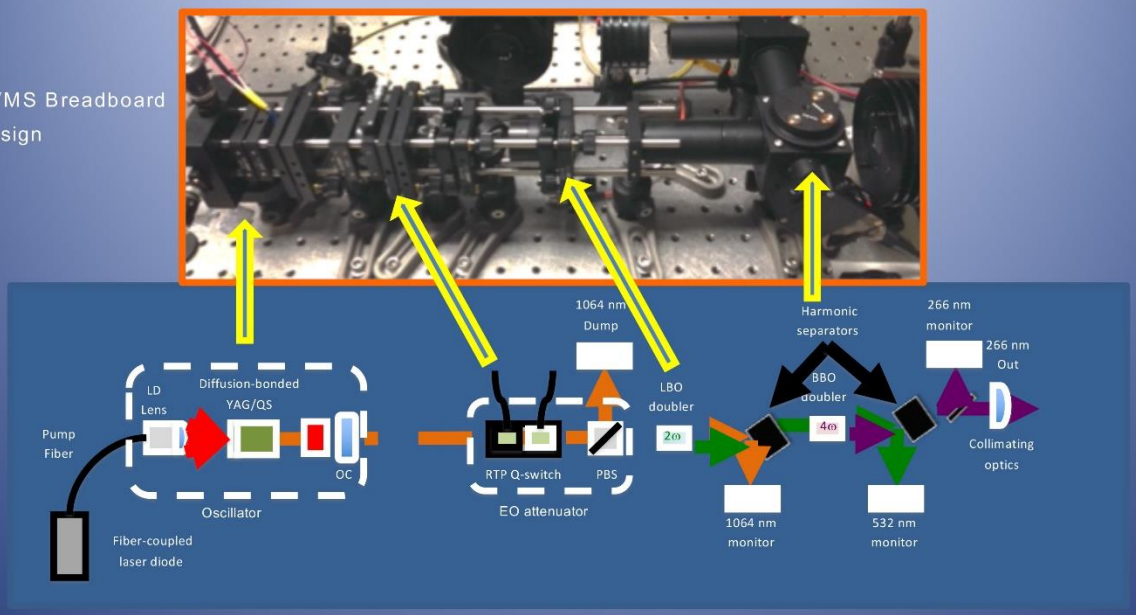
Item	TRL	Heritage
Cr^{+4}:YAG passive QS	6+	GLAS, LOLA, MOLA, MLA
RTP Pockels Cell	6	ICEsat-2, CHEMCAM
KTP SHG crystal	6+	GLAS, ICESat-2



- *No unproven technologies allowed.*

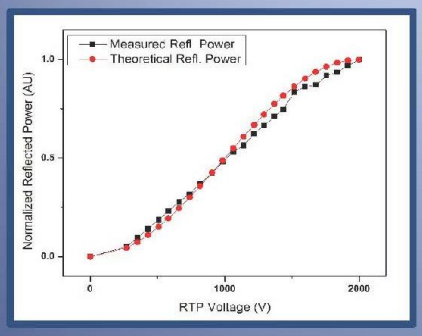
Full breadboard construction, and lifetest setup

UVMS Breadboard Design

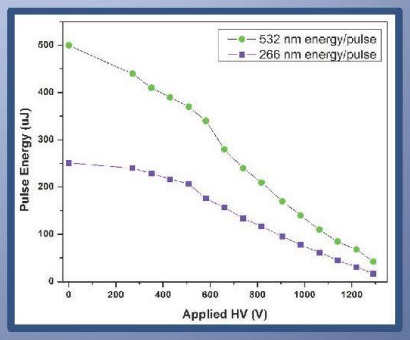


Full breadboard construction, and lifetest setup

Breadboard UVMS Laser



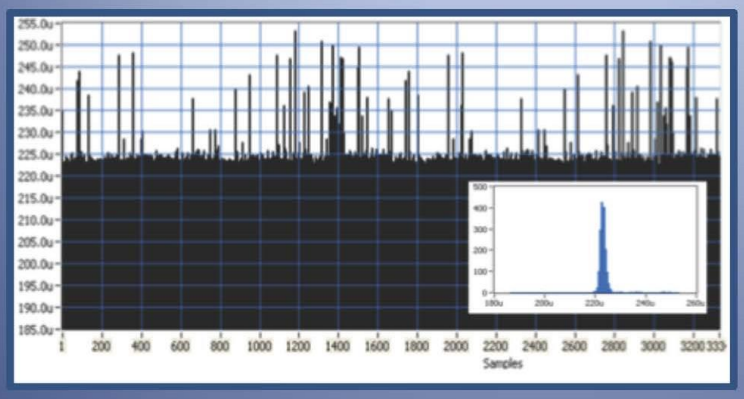
As we adjust the HV on the RTP device, the reflected (ejected) 1064 nm power (black curve) can be precision tuned, and thus control how much we send to the frequency conversion section.



The final 266 nm (violet) and 532 nm (green) pulse energies as function of applied RTP "attenuator" HV. UV energy can be tuned to virtually any value between 0-250 uJ for each specific pulse.

Full breadboard construction, and lifetest setup

Breadboard UVMS Laser



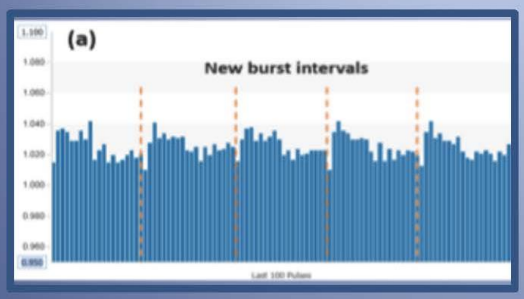
Short lifetest of 10 Million shots at 266 nm.

Typical planetary MS desorption laser requirement is ≤ 1 Million shots.

Small pitting was present on LBO doubler output face, but no degradation was witnessed.

Full breadboard construction, and lifetest setup

Breadboard UVMS Laser





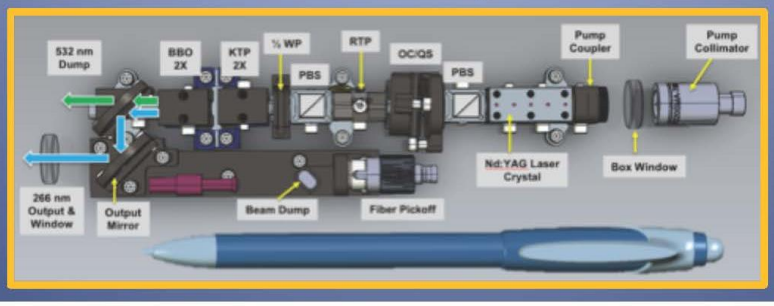
- Operated with bursts of 20 shots and 40 shots (left – right), each at 100 Hz rep rate, but at a burst interval of 1 Hz.
- The pulse to pulse deviation was < 5%.

Next generation UV packaged design factors:

Goals:

- Apply lessons learned from bread board.
  - Undoped pump cap on laser rod to reduce thermal effects.
  - No isolator needed.
  - Insert ½ wave plate for enhanced frequency conversion.
  - Move to KTP from LBO for 532nm and reduced damage risk.

- Shrink cavity as much as possible to minimize pulse width.
- Reduce footprint and mass for total package, ie…make attractive for future lander or rover mission.
- Minimize thermal sensitivity (*Titanium mounts and single Ti rail for optical bench.)



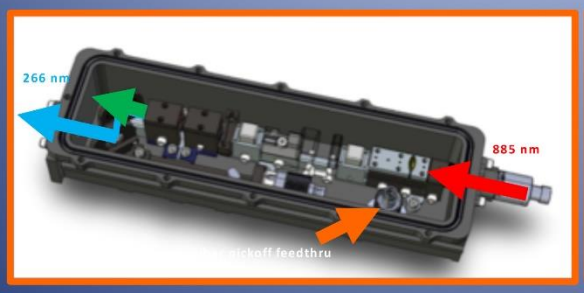
Flexure mirror mount attempted instead of risley prism pair.

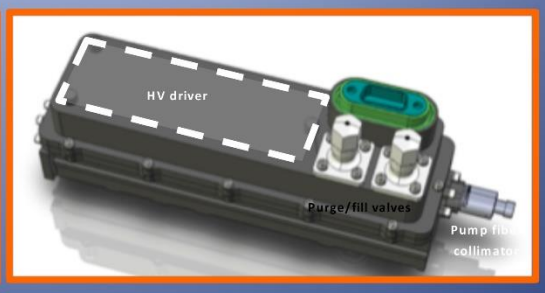
* Ti rail proved restrictive for rigid cavity opto-mechanics and assembly on our small budget.

Next generation UVMS packaging effort:

Design Goals:

- Fiber pickoff laser monitoring.
- Simple electrical control.
- Fiber Coupled pump (remote location).
- Small cavity w/ passive Q-switching.
- Minimize part count.
- Minimum thermal control.
- Hermetic, pressurized laser enclosure
- Temperature independent nonlinear optics
- Shot to shot pulse energy control
- High component TRL (flight heritage on everything)
- No excessive metal, exposed bonded optics should be adequate



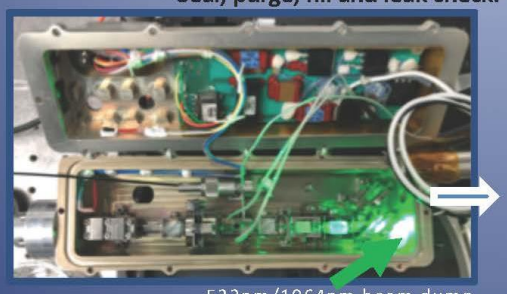


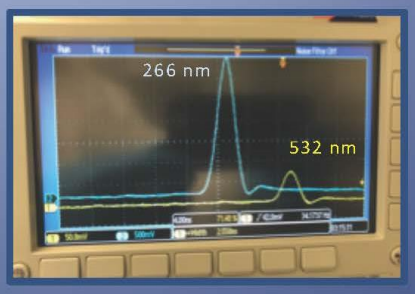
Next generation UV packaging effort, to do list:

Final Assembly Status:

UVMS has operated at or better than bread board specifications.
Currently undergoing final optics bonding (KTP and BBO) 4/13/18.
To Do:

- **Fully bonded functional test and characterization.**
- **Integrate with HV driver and characterize burst mode parameters.**
- **Mount in enclosure and install package pump optics.**
- **Functional and characterization tests, final bonding of output coupler.**
- **Seal, purge, fill and leak check.**

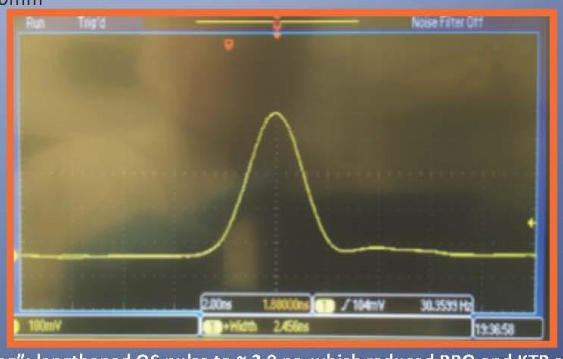




Next generation UV packaging effort, summary:

Pulse Energy:	1.1 mJ @ 1064 nm, 0.60 mJ @ 532, >0.15 mJ @ 266 nm*
Pulse Width:	~ 2.4 ns @ 1064 nm
Wavelength:	1064 nm, 532 nm, 266 nm
Repetition Rate:	100 Hz burst (50 shots) capable, 20 Hz for testing
Thermal Notes:	Pump Diode = 27 – 32 C, Laser Unit = 20 C (±TBD)
Pump Notes:	885 nm, 350 us @ 4 A = 60W pulses
Pump Notes:	400 um fiber, 2:1 double asphere coupler
Beam Quality:	TEM00
Cr^{4+}YAG QS OD:	0.85
YAG-ND:YAG Dim:	3 mm x 20mm





* Currently producing less energy due to cavity "stretching"; lengthened QS pulse to ~ 2.9 ns, which reduced BBO and KTP efficiency.

Final thoughts:

1. The LDMS fills a small niche in laser performance; 0.1 – 1 mJ, low rep rate, small footprint, low cost and simplicity.
   - YDFA is not cost effective
   - Small passive QS lasers are not out of the game, and still fill an important science need.
2. Taking an IRAD funded effort to an integrated field experiment MS late this summer.
   - Bit off more than we could chew wrt testing, homework, and packaging assumptions.
   - The laser's small size and simplicity reduces overhead, but does not justify shortcuts.
3. Continuous trade off with pump beam size, mode size, for best performance.
   - More work needed (ie: read more papers) on this method of optimization.
4. COTS available components and materials have opened up countless opportunities for further development in mini-DPSS laser source design and improvements.
5. IRAD budgets are (obviously) small, and "appear" to not follow the rising cost of doing laser cutting edge R&D over the past 2 decades.

DRAGONFLY

What's next? A rotorcraft lander to explore prebiotic chemistry and habitability on the ocean world Titan

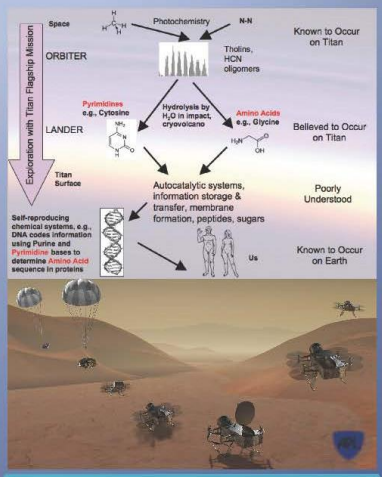
APL

- Titan is an ideal destination that brings together:

  Energy: sunlight, photochemistry

  Carbon: abundant complex organics

  Solvent(s): liquid H_2O, as well as CH_4
- Dragonfly takes advantage of Titan's unique organic laboratory to **investigate prebiotic chemistry** and to **search for biosignatures**
- Flight is highly efficient on Titan, enabling Dragonfly to sample materials in a variety of settings with its **science payload:**
  - **Ion Trap Mass spectrometer** with **laser-desorption capability**
  - Gamma-ray and neutron spectrometer
  - Meteorology, seismic sensors & Camera Suite
- Dragonfly mass spectrometer enables this search with analysis of mid- to low-volatility organics (laser-desorption mode)



How far has organic synthesis progressed in environments that provide key ingredients for life?

6 Session 6

Entry Descent and Landing Technologies was designed to examine issues related to supporting Entry Descent and Landing (EDL) applications. The Session Chair, Michelle Munk, gave an overview presentation of the area to start the session. A total of six research presentations representing the work of researchers at GSFC, LaRC, JPL, JSC and academia was received. Table 6-1 lists the seven session papers. See Section 3 of the Assessment Report for observations and assessment comments.

Table 6-1. Session 6 Papers

Paper Number	Author	Title	Paper	Presentation
S6-1	Michelle Munk, NASA LaRC	Overview		☑
S6-2	Carolina Restrepo JSC/GSFC	SPLICE	☑	☑
S6-3	Farzin Amzajerdian[1], Glenn D. Hines[1], Diego F. Pierrottet[2], Bruce W. Barnes[1], Aram Gragossian[2], Mitchell J. Davis[1], Tak-kwong Ng[1], Alexander D. Scammell[1], Adam Ben Shabat[1], Larry B. Petway[1], Jacob J. Follman[1], and John M. Carson III[3] [1]NASA LaRC; [2]Coherent Applications, Inc.; [3]NASA JSC	Navigation Doppler Lidar for Autonomous Precision Landing	☑	☑
S6-4	Manoranjan Majji Texas A&M University	Recent Advances in Relative Navigation of Aerospace Systems		☑
S6-5	Andrew Johnson, JPL	Terrain Relative Navigation: Mars 2020 and Future Systems	☑	☑
S6-6	A. Miguel San Martin, E. David Skulsky, Nikolas Trawny, and Anup Katake, JPL	A Hazard Detection Sensor for Landing on Europa	☑	☑
S6-7	Dominique Fourguette[1] and Volkan Ötügen[2] [1]Michigan Aerospace Corporation; [2]Southern Methodist University	Speed Sensor for Planetary EDL: "SPRY"	☑	☑

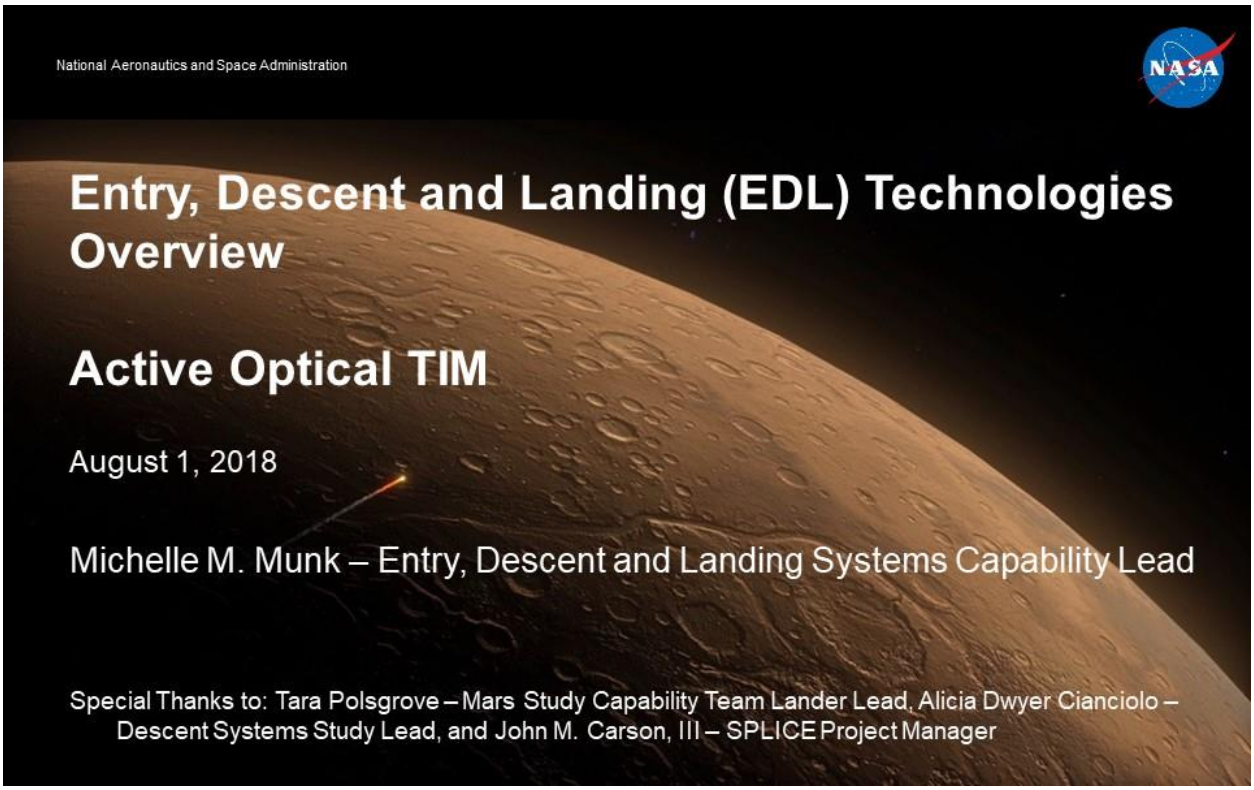
List of presentations

6.1 Entry, Descent and Landing (EDL) Technologies Overview....6-2
6.2 NASA SPLICE Project: Development and Testing of Precision Landing GN&C Technologies....6-12
6.3 Navigation Doppler Lidar for Autonomous Precision Landing....6-22
6.4 Recent Advances in Relative Navigation of Aerospace Systems....6-34
6.5 Terrain Relative Navigation: Mars 2020 And Potential Future Systems....6-48
6.6 A Hazard Detection Sensor for Landing on Europa....6-61
6.7 Speed Sensor for Planetary EDL "Spry"....6-76

6.1 ENTRY, DESCENT AND LANDING (EDL) TECHNOLOGIES OVERVIEW

Michelle M. Munk

Entry, Descent and Landing Systems Capability Lead, NASA Langley Research Center, Hampton, Virginia



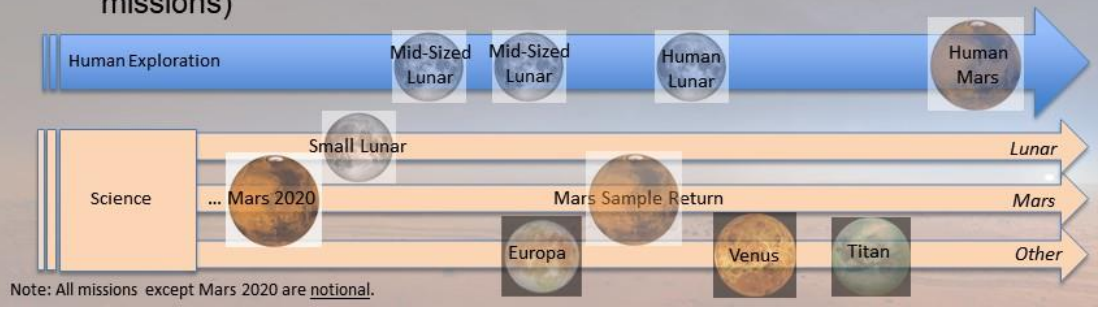
Introduction to the Entry, Descent and Landing Session

- Provide a context for technology needs in planetary EDL
- Identify challenges for future missions
- Summarize the results of current human Mars mission analysis that will influence future technology decisions
- Give a perspective on the current state of developments
- Set the stage for the session talks to follow

2

Upcoming Planetary EDL Missions

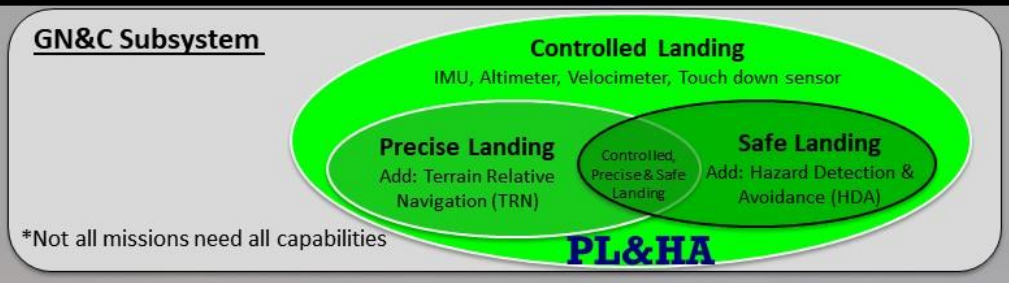
- **Many science and exploration missions can benefit from precision landing and/or hazard detection, for a variety of objectives:**
  - Enabling landing missions in treacherous terrains or those where our surface imagery is at a low resolution (such as Europa)
  - Reducing the risk of the landing (especially for smaller landers)
  - Reducing the operations time (and hence risk) of the mission (such as for a rover to drive to an interesting site)
  - Aggregating resources at one site (such as human lunar and Mars missions)



Note: All missions except Mars 2020 are notional.

3

Progression of GN&C Capabilities



Controlled Landing

- Minimize vertical descent rate and lateral velocity to ensure a soft (or controlled) touchdown
- No knowledge of global position – "blind" landing

Precise landing – Terrain Relative Navigation (TRN)

- Global navigation through onboard matching of real-time terrain sensing data with *a priori* reconnaissance data
- Enables efficient maneuvering to minimize landing error and avoid large hazards identified in *a priori* analyses

Safe Landing – Hazard Detection & Avoidance (HDA)

- Real-time terrain sensing to identify sites safe from lander-sized hazards that are undetectable in *a priori* data
- Enables a hazard avoidance maneuver to the identified safe site
- Can be leveraged for subsequent Hazard Relative Navigation (HRN) – similar to TRN

4

NASA's Current Approach for Human Mars Missions

- **Studies continue, to inform near-term investments in technology and capabilities**
- **Multiple four-person crews land at the same surface site.**
  - Allows for infrastructure build-up over several missions/crews.
  - Exploration opportunities (science, and technology testing) are significant enough to keep multiple crews actively engaged.
- **Cargo for each crew is delivered on multiple landers, so landing within close proximity is required.**
  - Atmospheric ISRU is assumed, to fuel the Mars Ascent Vehicle
  - Crew will interact with multiple assets, and resources will likely be shared (power, etc.)
  - Landing sites will be chosen based on resource availability, science interest, terrain risk, and other factors…

5

Example Mars Exploration Zone Containing Several Regions of Interest (ROI's)

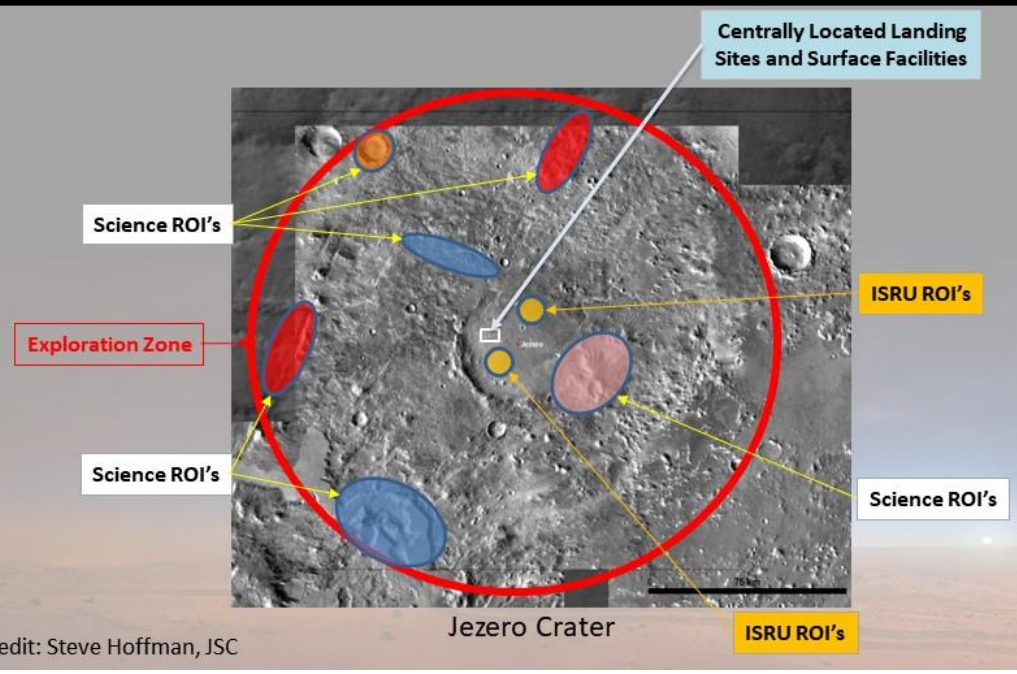
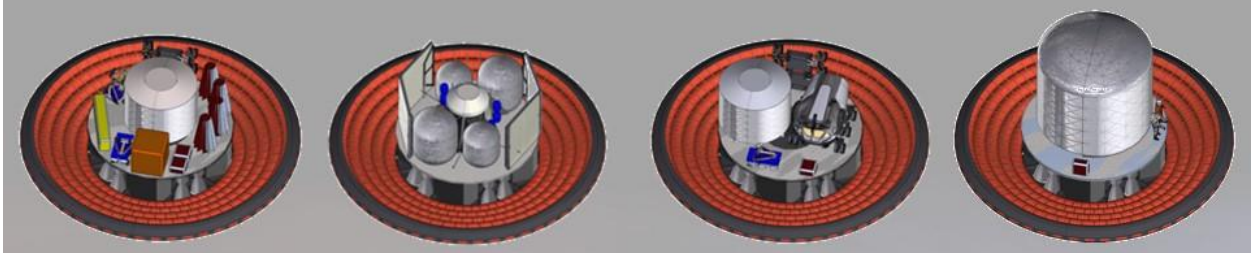


Chart Credit: Steve Hoffman, JSC

6

What We Need to Land:
Cargo Elements for Long Duration Surface Stay

10 m diameter SLS fairing | 300 day stay | Crew of 4 | Four 20 t payloads



Lander 1

- Surface Power Units
- Unpressurized Rovers
- Cargo Off-loading
- Logistics Module
- Science Payloads

Lander 2

- Mars Ascent Vehicle
- Atmosphere ISRU
- Crew Access Tunnel

Lander 3

- Pressurized Rover
- Logistics module
  - Crew consumables
  - Fixed system spares
  - Mobile system spares
  - EVA spares
- Surface Mobility

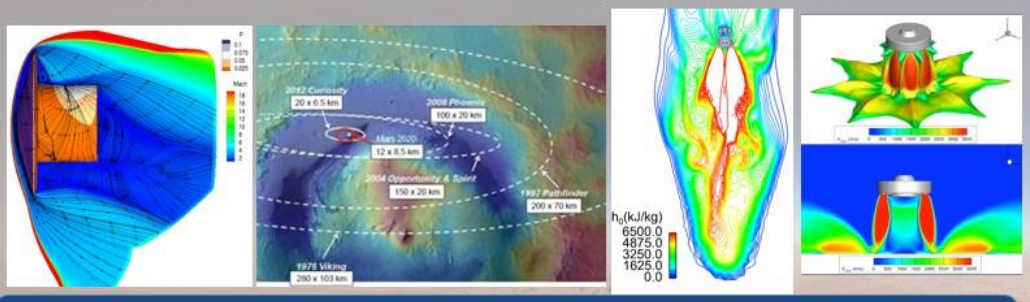
Lander 4

- Habitation
- Crew

7

Human Mars Lander Challenges

- 20x more payload to the surface
- 200x improvement in precision landing
- Dynamic atmosphere; poorly characterized
- New engines; performing Supersonic RetroPropulsion
- Terrain hazard detection - improving, but not perfect
- Surface plume interaction - debris ejecta could damage vehicles

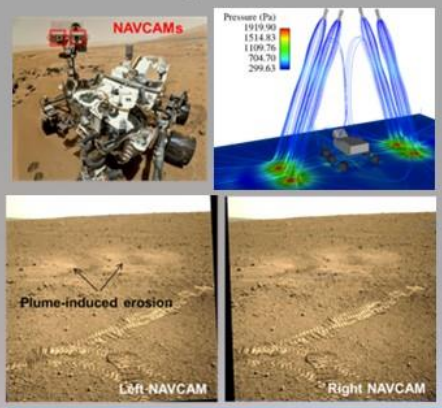


Landing is one of the most significant challenges of sending humans to Mars.

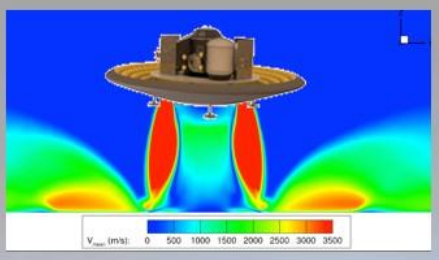
8

Surface Plume Interaction

Mars Science Laboratory
5,600 → 700 lbf of thrust, 60+ft from surface
Damaged instrument



Human Mars Lander
180,000 lbf → 36,000 lbf of thrust,
10+ft from surface
in proximity to other assets

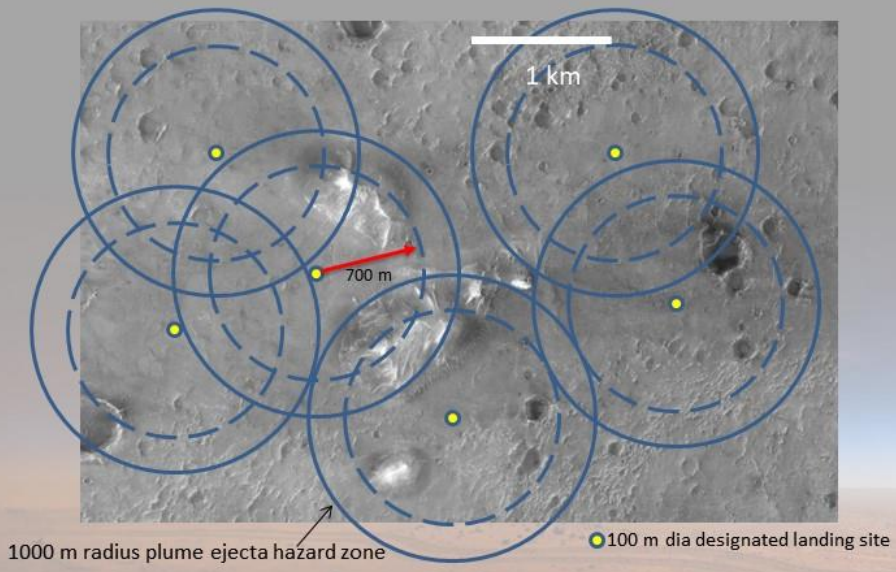


Plumes may be 10s of meters in front of the vehicle on approach. The total thrust at landing is 50 times more than Curiosity or InSight missions. Landing on bedrock is preferred, but even that may be altered.

9

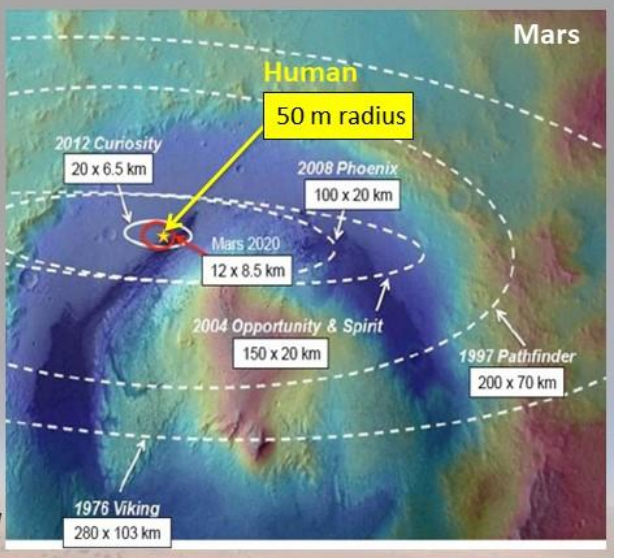
Human Mars Mission Landing Requirements

Potential outpost site landing locations (no plume impingement allowed for any hardware)



Mars Landing Precision

- **Landing precision is improving with each Mars mission**
- **To get to the current state of the art, system changes have been made, along the way:**
  - MSL had the first active hypersonic guidance
  - In addition, Mars 2020 employs a range trigger on the parachute, and uses Terrain Relative Navigation
- **Human missions will need integrated guidance, improved velocimetry, and hazard detection/ avoidance**



11

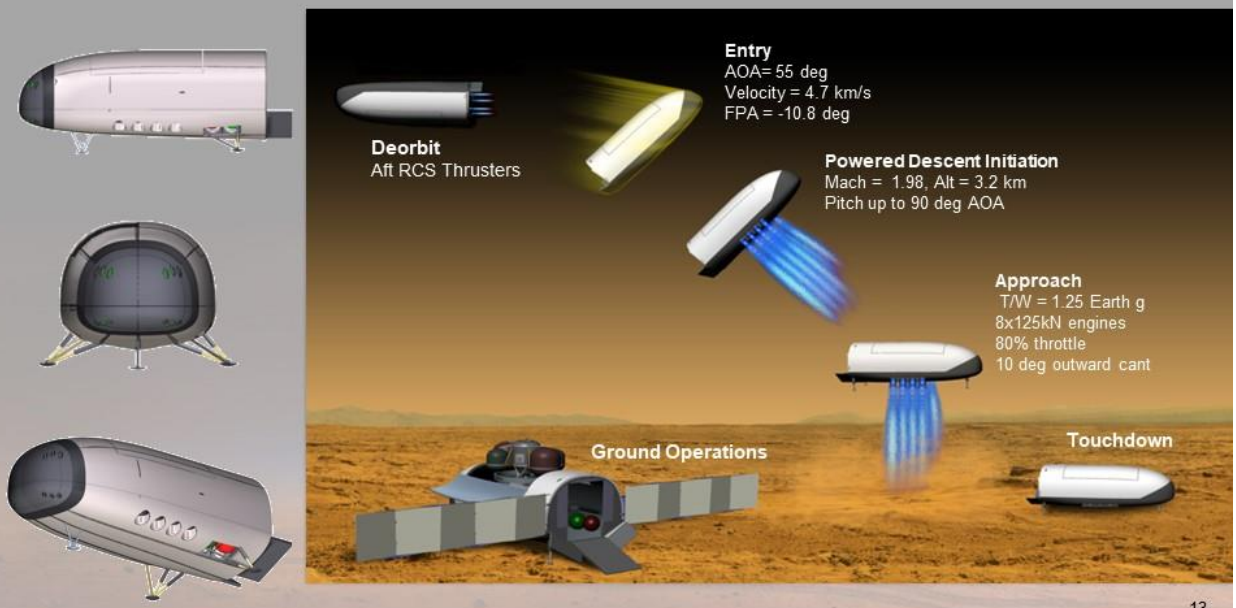
EDL Vehicle Designs: 20 t Payload Capability

Name	Shape	Vehicle Dimensions	Launch Mass	Entry Mass	Ballistic Number	L/D
Capsule		10 m (h) x 10 m (w)	68t	63t	500 kg/m^2	0.3
Mid L/D		22m (l) x 7.3m (h) x 8.8m (w)	66t	62t	380 kg/m^2	0.55
ADEPT		4.3m (h) x 18m diameter	60t	55t	155 kg/m^2	0.2
HIAD		4.3m (h) x 16m diameter	57t	49t	155 kg/m^2	0.2

ADEPT = Adaptable Deployable Entry & Placement Technology
HIAD = Hypersonic Inflatable Aerodynamic Decelerator
Mid-L/D = Has a lift-to-drag ratio (L/D) of about 0.55

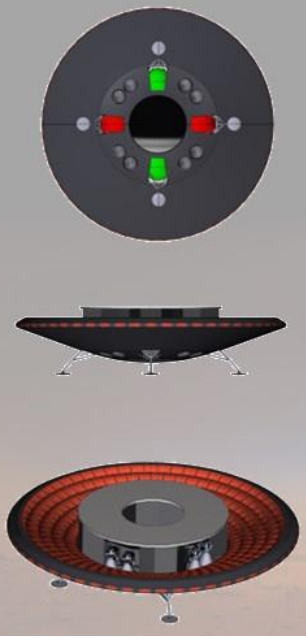
12

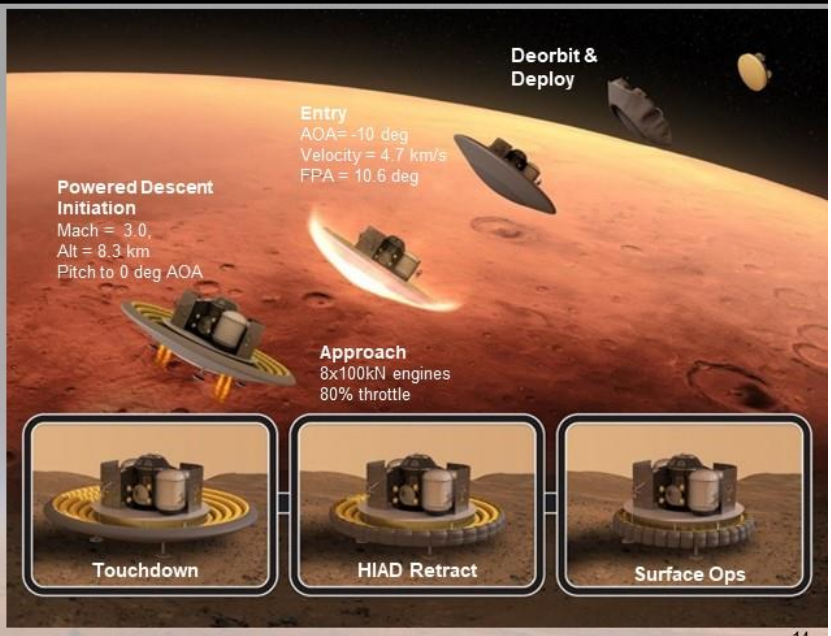
Mid L/D EDL Sequence



13

HIAD EDL Sequence





14

Current Landscape of the NASA PL&HA Domain

- **Agency development, testing and infusion of GN&C technologies for controlled, precise and safe landing**
- **Investments have come from multiple HQ Directorates (HEO, STMD, SMD) and included cross-center collaborations and many past & present projects:**
  - ALHAT (Autonomous precision Landing and Hazard Avoidance Technology)
  - LVS (Lander Vision System): Mars 2020 passive-optical TRN (Terrain Relative Navigation)
  - COBALT (CoOperative Blending of Autonomous Landing Technologies)
  - ILS (Intelligent Landing System): for Europa Lander concept
  - SPLICE (Safe & Precise Landing - Integrated Capabilities Evolution): multi-use
  - Lander Technologies (LT): support for COBALT, SPLICE and CATALYST-related PL&HA
  - ACSC (Advanced Cislunar and Surface Capabilities): Mid-Sized Lunar landers
- **Includes sensors, algorithms, avionics, software & techniques for missions (robotic or human) with various Concepts of Operation (ConOps) and various terrain illumination (light/shadow/dark)**

Johnson Space Center
Houston, Texas

Langley Research Center
Hampton, Virginia

Jet Propulsion Laboratory
California Institute of Technology

Marshall Spaceflight Center
Huntsville, Alabama

Goddard Spaceflight Center
Greenbelt, Maryland

Summary and Closing Remarks

- **We are on the cusp of making precision planetary landing commonplace, with Mars 2020 as the first step**
- **This capability is one of the most straightforward technologies to extend from the Moon to Mars; interest in landing close to interesting science, and aggregating resources, is common to both destinations**
- **The GN&C system is not "one size fits all;" analysis is being used to determine requirements for various future missions**
- **Multiple sensor technologies will be needed, as well as algorithm development and component/system testing in meaningful environments**
  - SPLICE forms the backbone of the investments, with mission-specific future spinoffs
  - Air, ground, and hardware-in-the-loop testing platforms
  - Several commercial entities have capabilities but NASA is leading, in GPS-deprived environments
  - Industrial and academic partners will be key to rapid, robust development

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Session Line-Up

1:50PM	S6-1	C	20	EDL Technologies	Michelle Munk	Michelle Munk, NASA LaRC	Overview
2:10PM	S6-2	C	20	EDL Technologies	Michelle Munk	Carolina Restrepo	SPLICE
2:30PM	S6-3	C	20	EDL Technologies	Michelle Munk	Farzin Amzajerdian[1], Glenn D. Hines[1], Diego F. Pierrottet[2], Bruce W. Barnes[1], Aram Gragossian[2], Mitchell J. Davis[1], Tak-kwong Ng[1], Alexander D. Scammell[1], Adam Ben Shabat[1], Larry B. Petway[1], Jacob J. Foliman[1], and John M. Carson III[3] [1]NASA LaRC; [2]Coherent Applications, Inc.; [3]NASA JSC	Navigation Doppler Lidar for Autonomous Precision Landing
2:50PM	S6-4	C	20	EDL Technologies	Michelle Munk	Manoranjan Majji	Recent Advances in Relative Navigation of Aerospace Systems
3:10PM	COFFEE	CB	20				
3:30PM	S6-5	C	20	EDL Technologies	Michelle Munk	Andrew Johnson, NASA JPL	Terrain Relative Navigation: Mars 2020 and Future Systems
3:50PM	S6-6	C	20	EDL Technologies	Michelle Munk	A. Miguel San Martin, E. David Skulsky, Nikolas Trawny, and Anup Katake, NASA JPL	A Hazard Detection Sensor for Landing on Europa
4:10PM	S6-7	C	20	EDL Technologies	Michelle Munk	Dominique Fourguette[1] and Volkan Ötügen[2] [1]Michigan Aerospace Corporation; [2]Southern Methodist University	Speed Sensor for Planetary EDL: "SPRY"
4:30PM	S6-Panel	C	20	EDL Technologies	Michelle Munk	All Paper Presenters	
4:50PM	END	E	0				

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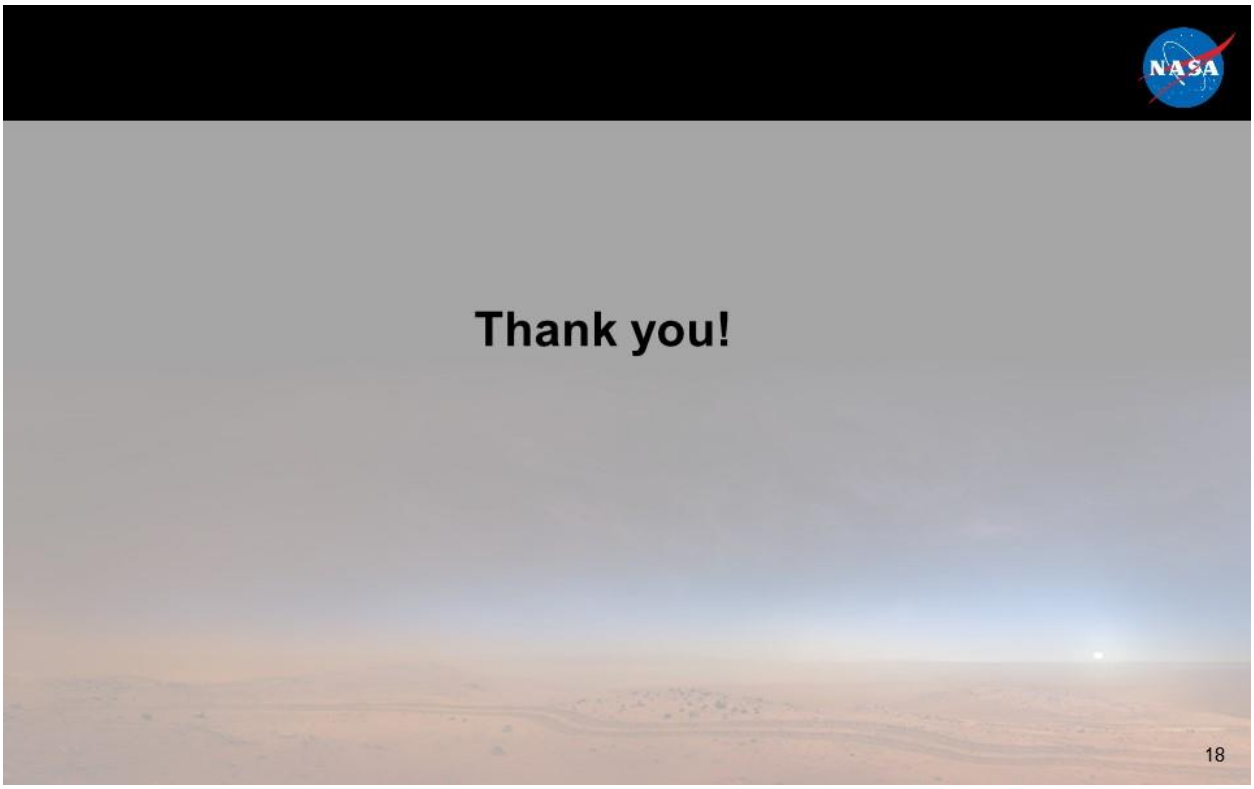

Thank you!
18

6.2 NASA SPLICE PROJECT: DEVELOPMENT AND TESTING OF PRECISION LANDING GN&C TECHNOLOGIES

John M. Carson III,[1] Ronald Sostaric,[1] Carolina Restrepo,[1] and Michelle Munk[2]
NASA Johnson Space Center, Houston, Texas[1]
NASA Langley Research Center, Hampton, Virginia[2]

1 Introduction

NASA's technology advancement needs for entry, descent, and landing call for high-precision, high-rate sensors that can improve navigation accuracy and vehicle control performance. Higher landing accuracy is required for any future human lander missions, and likely, for most robotic missions.[1,2] Sensors and algorithms that significantly reduce navigation errors and can image the local terrain will enable landing at locations of high scientific interest that would otherwise pose significant risk to the vehicle.

The Safe and Precise Landing—Integrated Capabilities Evolution project, or SPLICE, is developing precision landing and hazard avoidance (PL&HA) technologies for NASA and for potential commercial space flight missions. SPLICE technologies include sensors, algorithms, advanced space flight computing capabilities, and simulation tools used to integrate and study guidance, navigation, and control (GN&C) system performance. SPLICE efforts include hardware-in-the-loop (HWIL) simulation testing, ground testing, and flight testing, including reuse of hardware from the CoOperative Blending of Autonomous Landing Technologies (COBALT) suborbital flight-test payload.[3,4]

Two of the precise navigation sensors that are being developed and matured within SPLICE are LiDARs. Since 2006, NASA Langley has been developing a Navigation Doppler LiDAR (NDL) for precise velocity measurements, and SPLICE is building an NDL engineering test unit (ETU) that will be brought up to TRL 6 following environmental and high-speed[1,2] testing. NASA Goddard is developing a Hazard Detection LiDAR (HD LiDAR) engineering development unit (EDU) for SPLICE that has relevance to future human and robotic lander missions. The HD LiDAR will be flight test and matured to TRL 5.

2 Navigation Doppler Lidar

The SPLICE project will implement the NDL ETU with space flight qualifiable parts and evolve the third-generation NDL design from the former COBALT project.[5] The NDL provides both velocity and range measurements. The sensor hardware consists of a custom optical head and electronics box, as shown in Figure 1. The electronics include a seed laser, fiber amplifier, synthesizer, wideband receiver and a NASA-developed command and data handling (C&DH) board. The NDL ETU is targeting infusion into near-term space flight missions including prospective public-private lunar lander partnerships in the early 2020s and future New Frontiers, Discovery or other robotic-science or technology demonstration missions for the moon, Mars and elsewhere.



Figure 1. Navigation Doppler LiDAR.

3 Hazard Detection Lidar

The SPLICE project HD LiDAR EDU will be designed, implemented and tested to performance specifications relevant to robotic lunar lander concepts and other relevant NASA robotic missions. The HD LiDAR EDU will be capable of generating a real-time, three-dimensional terrain map within seconds and

from a slant range of at least 500 meters, similar to what is shown in Figure 2. Figure 2 shows the DEM from a square hazard field at the Kennedy Space Center that was designed to test the ALHAT Hazard Detection System[6]. The HD LiDAR will generate a circular DEM instead. The map resolution will be sufficient to identify lander-sized hazards and safe landing sites. The HD LiDAR map generation will be tested on an airborne vehicle, and hazard detection algorithm performance will be analyzed within the SPLICE HWIL simulation.

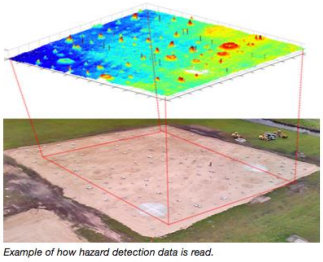


Figure 2. Hazard field map.

4 Descent and Landing Computer

The SPLICE descent and landing computer (DLC) EDU leverages a commercial surrogate processor for the in-development, NASA High Performance Spaceflight Computing (HPSC) processor. The HPSC is a joint investment between NASA and the Department of Defense. The HPSC surrogate within the DLC is a commercially available board with an ARM (Advanced RISC Machine) A53-processor and other components in common with the NASA HPSC architecture. The DLC EDU will be ground tested within the SPLICE HWIL simulation and flight tested onboard a revised COBALT payload. The DLC EDU jointly benefits the PL&HA and HPSC communities and can provide use cases for the accelerated development and spaceflight infusion of SPLICE and HPSC technologies.

5 Simulation and HWIL Testing

SPLICE is developing a HWIL simulation test bed for implementing, maturing and validating PL&HA and GN&C algorithms, avionics, sensors, and flight software. The flight software is being implemented within NASA's core Flight System (cFS) framework to ensure a path to spaceflight infusion. The HWIL test bed leverages the NASA "Trick Simulation Toolkit" framework and the "iPAS" (integrated Power, Avionics and Software) environment, which allows assessment of GN&C technologies within a space mission context. This combined infrastructure provides capabilities for dynamic simulations integrated with the DLC EDU and GN&C/PL&HA hardware. The HWIL test bed also provides a low-cost method for GN&C subsystem development and validation prior to higher-cost suborbital flight testing and follow-on integration and flight onboard space flight missions.

6 Flight Testing

Flight tests of SPLICE technologies will be planned and conducted on multiple terrestrial test platforms to obtain data to validate SPLICE sensor (NDL ETU and HD LiDAR EDU) and flight software performance. A high-speed test (aircraft, rocket sled, or other platform) of the NDL ETU is planned to validate NDL velocity performance. An airborne vehicle test of the HD LiDAR EDU is planned to collect data from a terrestrial, lunar-like terrain field for evaluation of HD LiDAR map generation. A closed-loop flight test of the revised COBALT payload, incorporating the DLC and NDL, is planned to validate integrated PL&HA sensors and flight software. Figure 3 shows a photo of the first generation COBALT[3,4] payload onboard the Masten Space Systems Xodiac rocket during a flight test in the spring of 2017.



Figure 3. COBALT flight test.

7 Infusion of Technologies and Future Work

The NASA PL&HA domain includes a diverse suite of GN&C technologies for precise and safe landing. These technologies will enable new mission concepts by enlarging the trade space of feasible landing sites for surface exploration both for humans and robots. Many of these technologies are approaching readiness for infusion into near-term robotic science missions in the early 2020s. The SPLICE project aims to maintain a knowledge base of all relevant technologies that will aid in any future lander missions and actively work towards making these technologies adaptable and available to future lander missions.

References

1. Steering Committee for NASA Technology Roadmaps; National Research Council of the National Academies, NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space, The National Academies Press, 2012.
2. Office of the Chief Technologist, 2015 NASA Technology Roadmaps, NASA, 2015.
3. Carson III, J. M., Restrepo, C. I., Seubert, C. R., Amzajerdian, F., Pierrottet, D. F., Collins, S. M., O'Neal, T., and Stelling, R., "Open-Loop Flight Testing of COBALT Navigation and Sensor Technologies for Precise Soft Landing," Proc. AIAA SPACE 2017 Conference & Exposition, Orlando, FL, September 2017.
4. Restrepo, C., Carson, J.M., Amzajerdian, F., Seubert, C.R., Lovelace, R., McCarthy, M., Tse, T., Stelling, R., Collins, S., "Open-Loop Performance of COBALT Precision Landing Payload on a Commercial Sub-Orbital Rocket", Proc. AIAA Scitech GN&C 2018 Conference, Kissimmee, FL, January 2018
5. Pierrottet, D., Hines, G., Barnes, B. Amzajerdian, F., Petaway, L., Carson, J.M., "Navigation Doppler Lidar Integrated Testing Aboard Autonomous Rocket Powered Vehicles", Proc. AIAA Scitech GN&C 2018 Conference, Kissimmee, FL, January 2018
6. Epp, C., Robertson, E., Rutishauser, D., "Helicopter Field Testing of NASA's Autonomous Landing and Hazard Avoidance Technology (ALHAT) System fully integrated with the Morpheus Vertical Test Bed Avionics ", Proc. AIAA Space 2013 Conference, San Diego, CA, September 2013

PL&HA
Precision Landing and Hazard Avoidance



NASA SPLICE Project: Development and Testing of Precision Landing GN&C Technologies

Dr. Carolina Restrepo
Hazard Detection Lead for NASA SPLICE Project

Dr. John M. Carson III
Project Manager for NASA SPLICE Project

Michelle M. Munk
NASA EDL System Capabilities Leadership Team (SCLT) Lead
STMD EDL Principal Technologist

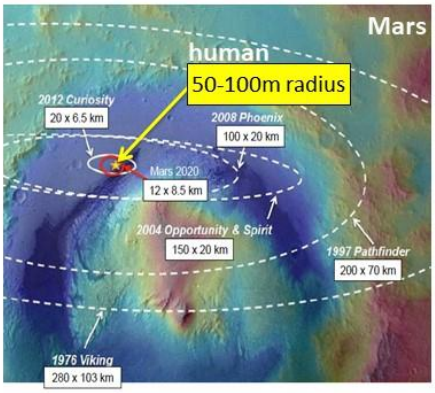
August 1, 2018

Cleared for External Release
Charts herein include content provided by multiple NASA centers and supporting institutions.

PL&HA

The Motivation for PL&HA Technology

- Enable landing at locations that pose significant risk to vehicle touchdown or payload deployment (including near pre-positioned surface assets)
- Technology has been deemed critical in NASA and NRC Space Technology Roadmaps and architecture studies for future robotic and human missions
  - Required for future human landings on Mars
  - Enabler for robotic exploration of new destinations









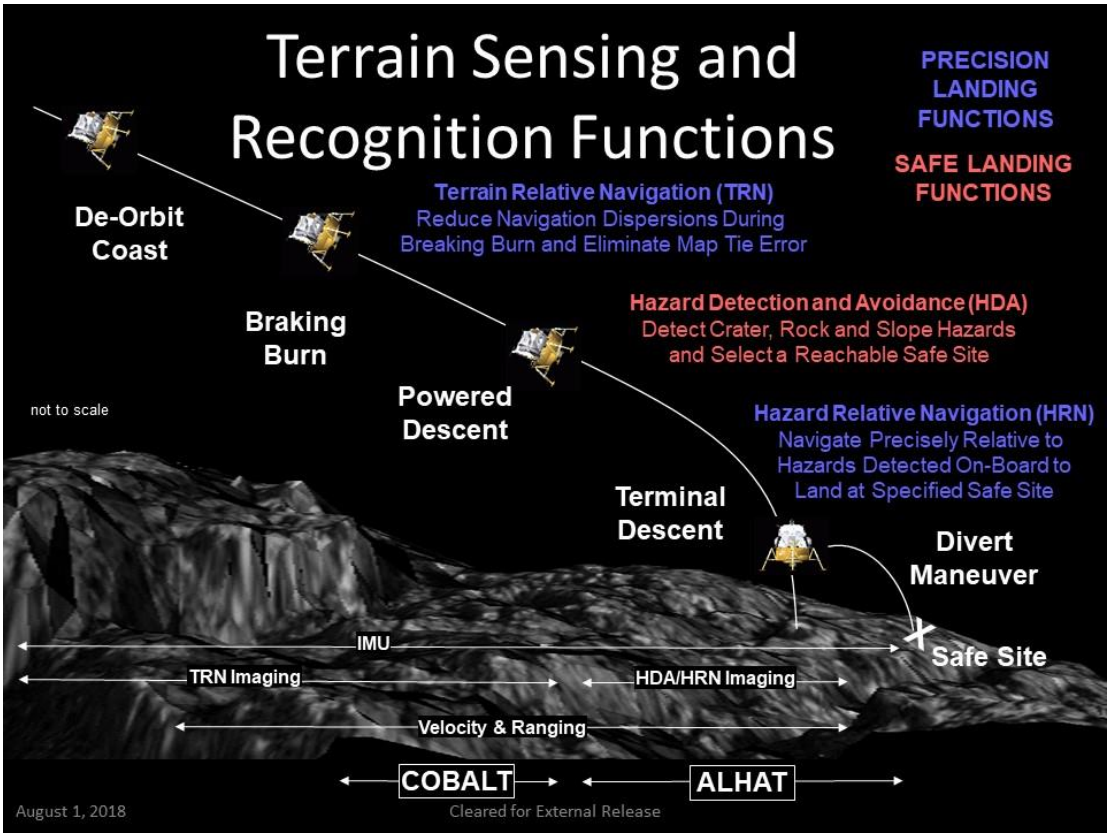




What is the NASA PL&HA domain?

- **NASA development, testing and infusion of GN&C technologies for controlled, precise and safe landing**
- Investments have come through **multiple HQ Directorates** (STMD, SMD, HEO) and have included **multi-center collaboration** in past & present projects:
  - ALHAT (Autonomous precision Landing and Hazard Avoidance Technology)
  - LVS (Lander Vision System)
  - COBALT (CoOperative Blending of Autonomous Landing Technologies)
  - Lander Technologies (LT)
  - ILS (Intelligent Landing System)
  - SPLICE (Safe & Precise Landing – Integrated Capabilities Evolution)
- Domain includes technologies for sensors, algorithms, avionics, software & techniques for missions (**robotic or human**) having various Concepts of Operation (ConOps) and various terrain illuminations (light/shadow/dark)

Johnson Space Center, Houston, Texas
Jet Propulsion Laboratory, California Institute of Technology
Langley Research Center, Hampton, Virginia
Goddard Spaceflight Center, Greenbelt, Maryland
Marshall Spaceflight Center, Huntsville, Alabama



ALHAT Overview

PL&HA

Autonomous precision **L**anding
Hazard **A**voidance **T**echnology

- ALHAT combined autonomous guidance, navigation and control algorithms capable of characterizing the landing surface while identifying and avoiding lander-sized hazards in real time
- ALHAT flew on JSC's Morpheus Lander as a self-contained payload with the goal of prototyping future hazard avoidance & hazard relative navigation systems for future robotic or human landers

Video

Johnson Space Center
Houston, Texas

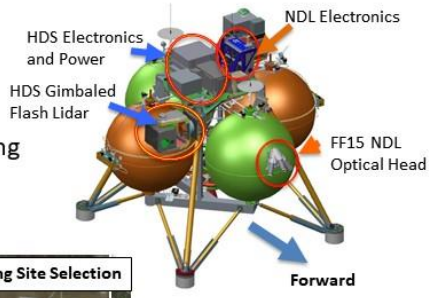
Langley Research Center
Hampton, Virginia

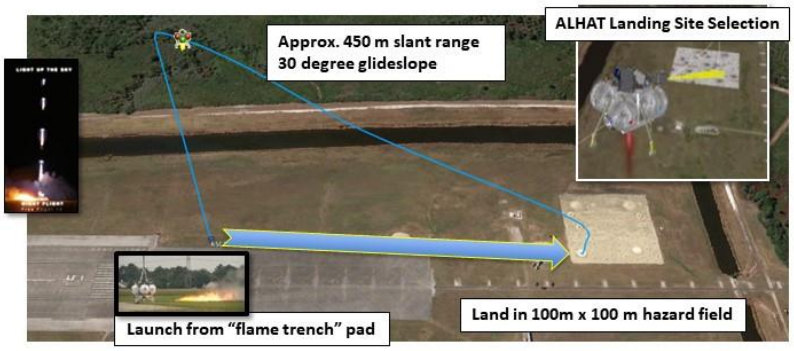
Jet Propulsion Laboratory
California Institute of Technology

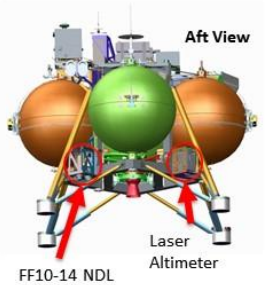
2014 ALHAT on Morpheus 1.5B

PL&HA

- Six flights: three open-loop & three closed-loop
- Tested safe and precise landing technologies
  - NDL (Gen-2), HDS (Gen-1), Laser Altimeter
  - TRN was not a part of the Morpheus tests
- Successfully demonstrated integration and flight testing of ALHAT capabilities and techniques
- Performed one flight test in darkness







COBALT Overview



Co-**O**perative **B**lending of
Autonomous **L**anding **T**echnologies

- A platform to mature TRL and reduce risk for spaceflight infusion of GN&C PL&HA technologies into near-term robotic and future human missions
- Self contained and could be modified to test different GN&C technologies on different host vehicles

Video

Johnson Space Center
Houston, Texas

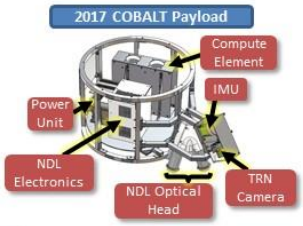
Langley Research Center
Hampton, Virginia

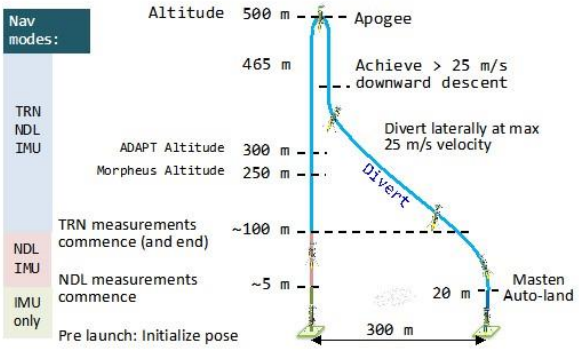
Jet Propulsion Laboratory
California Institute of Technology

2017 COBALT Flights on Masten Xodiac



- COBALT: CoOperative Blending of Autonomous Landing Technologies
- Platform to mature TRL and reduce risk for spaceflight infusion of GN&C PL&HA technologies
- Multi-center collaboration: JSC, Langley, JPL
- Multi-directorate partnership: STMD & HEOMD









Portfolio of Current PL&HA Technologies

Controlled (Soft) Landing
Velocity and/or Range Sensing

HEO/STMD/SMD



Navigation Doppler Lidar (NDL) TRL 5+ (6 in FY19)
Line-of-site velocity of 200 m/s (±1.7-cm/sec, 1σ)
Line-of-site range of 4+ km (±2.2m, 1σ)
dev & test in ALHAT/Morpheus, COBALT, & SPLICE

HEO/STMD



Long-range Laser Altimeter (LAlt) TRL 4
Range in vacuum, 50+ km (5 cm, 1σ)
dev & tested in ALHAT/Morpheus

SMD/other

Optical Velocimetry (many in development) TRL 3+
Estimates from image-based feature tracking and optical flow

Precise Landing
Terrain Relative Navigation (TRN)

SMD/STMD/other

Passive-Optical/Camera-Based
(requires illuminated terrain: applicable to most missions)
- **JPL Lander Vision System** (LVS): camera + IMU + dedicated computing **to be TRL 9 with Mars2020**
- **TRN solutions also available from APL, Draper & elsewhere** in dev for multiple mission concepts
- **JPL Intelligent Lander System** (ILS) in dev for Europa Lander concept

HEO/STMD



Active/Lidar-based TRL 3-4
(dark/shadowed or illuminated terrain)
dev & tested in ALHAT

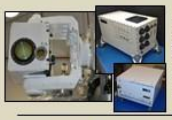
PL&HA Computing

STMD

Descent & Landing Computer (DLC)
HPSC (High Performance Spaceflight Computing) multicore A53 (extendable) + FPGAs (extendable) + PL&HA sensor interfaces
(in dev & test within SPLICE) TRL 3 (5 in FY2020)

Safe Landing
Hazard Detection (HD) and Hazard Relative Nav (HRN)

HEO/STMD



Hazard Detection System (HDS) prototype TRL 4
flash lidar + gimbal + dedicated IMU + dedicated computing
Range, 1 km (±8cm, 1σ). Generates 100mX100m map & safe landing sites within 10-12 sec dev & tested in ALHAT/Morpheus

STMD/SMD

Hazard Detection Lidar (HDL) in dev & test within SPLICE TRL 4 (5 in FY2020) uses many flight heritage parts
Scan array lidar + FPGA. Provides long-range altimetry and rapid medium- & short-range high-resolution terrain maps

SMD

JPL Intelligent Lander System (ILS) in dev for Europa Lander concept

Overview of NASA SPLICE Project
(FY2018-FY2020)

- NASA Centers
  - JSC, LaRC, GSFC, AFRC, MSFC, JPL, KSC (FY19-20)
- Project Components (Elements)
  - NDL: Implement an **NDL (Navigation Doppler Lidar) Engineering Test Unit (ETU) & Achieve TRL6** in FY2019
  - ConOps: Develop a **multi-mission PL&HA requirements matrix** for relevant robotic science & human exploration destinations (to drive PL&HA infusion & investment)
  - Avionics: Develop an **HPSC-surrogate DLC (Descent & Landing Computer) to TRL 5** for future COBALT tests and spaceflight infusion missions
  - HWIL Sim/SW: Evolve **HWIL sim/test capabilities and PL&HA flight software** to foster PL&HA infusion into NASA & US commercial missions
  - Field Test: conduct NDL environmental tests, validate NDL & HDL performance on airborne vehicles, and lead **closed-loop COBALT flight tests** on the Xodiac suborbital rocket
  - HD: Design, develop, and test a **multi-mission HDL (Hazard Detection Lidar) to TRL 5** with relevance to future robotic & human missions

GSFC Hazard Detection Lidar Summary

- GSFC HDL Design Approach
  - Multi-purpose design/capability - usable for potential HEO (Lunar , small body) and SMD targets (Europa, Enceladus, etc)
  - Heritage GSFC hardware designs, algorithms, data analysis and performance simulations/models which allow rapid maturation of design and results prediction (GEDI, LOLA, etc...)
  - Leverages previous GSFC flight lidar builds and Europa lander work to create a high performance, large environment range, lander descent lidar which also has a reasonable flight maturation path.
- Performance Requirements and Goals
  - Candidate lidar to be at matured to TRL-6, earth flight tested with EDU, and flight tested
  - Surface Imaging and DEMS with centimeter precision
  - Rapid 3-D landing site imaging start at 500 m altitude till the lander touch down]
    - The lidar imager operates during the PDV descent at ~30 m/s – robust to motion and attitude changes during imaging
    - Imaging works from longer range with lower resolution
    - Frame rate or Range samples per second : 8 M ranges/s
  - 2000x2000 pixels over 100x100 m area at 5-cm spatial resolution at ~1 frame/s (8 M pixels/sec).
  - The data from the lidar will be altimetry and a gridded 3-D map of surface elevation, i.e. DEM in x,y,z for GNC ingest
  - Additional high altitude altimetry channel: Single beam altimetry starting at 10 km altitude with < 10 cm range precision. Longer ranges possible as are better resolutions based on application and available mass
  - Power goal less than 50W, Mass goal less than ~12 Kg, high radiation tolerant.
- GSFC HDL Prototype in development, subsystems demonstrated, detailed brassboard design underway with prototypes and flight-like test models to follow.
- Contacts: Bryan Blair, Michael Amato

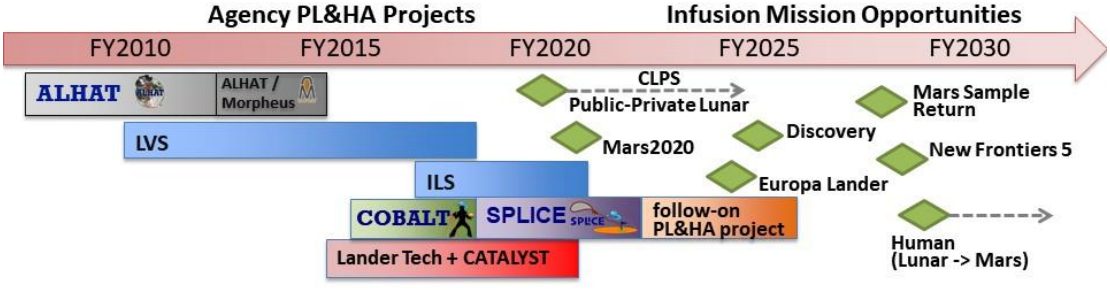
PL&HA Development & Infusion Strategy

Goal

- Develop multi-mission technologies that become part of the standard suite of GN&C capabilities
- Develop technologies for robotic missions that also feed forward into future human missions

Approach

- Develop and maintain a PL&HA knowledge base that captures robotic and human mission needs
- Prioritize technologies that promote multiple robotic missions and align to human mission needs
- Form a cross-directorate strategy and leverage multi-center/multi-project partnerships



Closing Remarks

- The NASA PL&HA domain includes a diverse suite of GN&C technologies for precise and safe landing
- Many of these PL&HA technologies are approaching readiness for infusion into near-term robotic science missions
- PL&HA capabilities enable new mission concepts by enlarging the trade space of feasible landing sites for surface exploration
- Development of PL&HA technologies for robotic missions also benefits future human missions

6.3 NAVIGATION DOPPLER LIDAR FOR AUTONOMOUS PRECISION LANDING

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Coherent Applications, Inc., Hampton, Virginia 23693, USA
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ABSTRACT

A coherent Doppler lidar has been developed to address NASA's need for a high-performance, compact, and cost-effective velocity and altitude sensor onboard its landing vehicles. Future robotic and manned missions to solar system bodies require precise ground-relative velocity vector and altitude data to execute complex descent and soft landing maneuvers. This lidar sensor meets the required performance of landing missions while complying with vehicle size, mass, and power constraints.

1 INTRODUCTION

Global Positioning System (GPS) is commonly used in terrestrial navigation for vehicle position and velocity knowledge. In the absence of a GPS signal, past landing missions to planetary bodies primarily relied on radar to provide the necessary data to execute descent and landing maneuvers.[1-3] The Navigation Doppler Lidar (NDL) offers several critical advantages compared to radar, including significantly higher precision with reduced size, weight, and power. In addition, the laser-based NDL sensor does not suffer from measurement perturbation from terrain features or signal ambiguity from transmitted side lobes, and is far less susceptible to signal clutter, such as returns from the lander structure or jettisoned vehicle components such as heatshields. The higher quality data provided by the NDL will enable both a more precise navigation towards the designated landing site and a well-controlled touchdown (with greater stability and lower impact loads). This translates into lower fuel reserve and smaller leg span requirements for a landing vehicle which thus further reduces vehicle mass, therefore the NDL can potentially reduce the overall cost and risk of landing missions and enable new capabilities for planetary exploration missions including missions to the Moon, Mars, asteroids, and planetary moons.

2 NDL SYSTEM DESCRIPTION

The NDL uses a frequency modulated continuous wave (FMCW) technique to simultaneously measure velocity and range to the ground. The principle of the NDL operation is illustrated in Fig. 1 which shows the modulation waveform consisting of three segments: up-ramp chirp, constant frequency, and down-ramp chirp. The resultant returned waveform from the target is delayed by td, the light round trip time. When the target or the lidar platform is not stationary during the beam round trip time, the signal frequency will be also shifted up or down, depending on the velocity direction, due to the Doppler effect. When mixing the two waveforms at the detector, an interference signal is generated whose frequency is equal to the difference between the transmitted and received frequencies. In the absence of velocity along the laser beam, the signal frequency during the "up-ramp" and "down-ramp" periods are equal and their magnitude is directly proportional to the distance to the target. When the vehicle is moving, the up-ramp and down-ramp frequencies will not be equal and their difference is related to the Doppler velocity. The target range and magnitude of the velocity component along the laser beam are determined through the following simple equations:

$$R = \left(\frac{TC}{2B}\right)\left(\frac{f_{IF}^{+} - f_{IF}^{-}}{2}\right)$$

$$V = \left(\frac{\lambda}{2}\right)\left(\frac{f_{IF}^{+} + f_{IF}^{-}}{2}\right)$$

where f_{IF}^{+} and f_{IF}^{-} are the intermediate up-ramp and down-ramp frequencies, B is the modulation bandwidth, T is the waveform period, C is the speed of light, and λ is the laser wavelength. The constant frequency segment also produces a Doppler velocity that can be used for eliminating data dropouts when either up-ramp or down-ramp frequency is very close to zero, and allows for

eliminating the measurement ambiguities that may arise in certain scenarios.

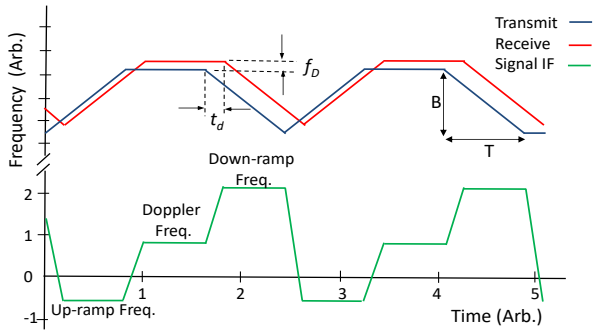

Figure 1. Linearly frequency modulated transmitted beam and returned signal, and the resulting intermediate frequency (IF) of the homodyne signal.

The NDL transmits three laser beams at different pointing angles toward the ground to measure the velocity and range along each beam. The three line-of-sight measurements are then combined in order to determine the three components of the vehicle velocity vector and its altitude relative to the ground without attitude data from an external sensor.

Figure 2 shows the NDL prototype system developed for a series of flight tests to demonstrate its capabilities and viability for future landing missions to planetary bodies. The prototype consists of an electronic chassis and an optical head. All the lidar components including the transmitter laser, receivers, and signal processor are housed in the electronic chassis. The optical head consists of three transmit/receive lenses connected to the chassis via a fiber optic cable.



Figure 2. Prototype NDL.

3 PERFORMANCE MEASUREMENTS AND ANALYSIS

The NDL performance was characterized over different phases of its development through ground tests, helicopter flight tests, and onboard autonomous rocket-powered test vehicles while operating in open and closed-loop with a guidance, navigation, and control (GN&C) system.[3-5] The results of these tests helped optimize the NDL design leading to the development of a compact and robust prototype unit shown in Fig. 2.

The NDL meets the performance requirements of almost all planetary landing missions being considered for launch over the next decade. The velocity precision and accuracy demonstrated in the flight tests are about an order of magnitude better than those required for well-controlled soft landing. The resolutions of line-of-sight (LOS) velocity and range measurements are 0.2 cm/sec and 25 cm, respectively, limited by the FFT processing algorithm. The NDL measurement precision, defined as random noise about its mean, was determined experimentally using flight test data. The LOS velocity and range precisions are about 1.7 cm/sec and 2.2 m, which were predominantly due to vehicle vibration and rapid angular motions. The NDL can measure velocities up to 200 m/sec along the LOS of its beams. The actual vehicle velocity can be significantly higher than 200 m/sec since there will always be an angular separation between the laser beams and the vehicle flight path. As a result, the NDL can measure vehicle velocities of well over 1000 km/hr.

The maximum operational range of the NDL is harder to define since it is highly dependent on the atmospheric environment and the surface albedo. To better assess the NDL performance in different terrestrial and planetary environments, a set of operational range measurements were performed on the Langley Air Force Base runway which provides a relatively long path length. For these tests, the NDL was placed at one end of the runway pointing one of its beams toward a calibrated target on the back of a moving box-car truck.[5] The targets used for these measurements have a diffuse Lambertian surface and were placed nearly orthogonal to the NDL beam's optical axis. Range, velocity, and return signal magnitude data were

collected continuously as the truck travelled from 250 meters range to 3.8 km.

Fig. 5 shows the lidar equation fit to measured data indicating a terrestrial maximum operational range of over 4 km in most atmospheric conditions and terrains. This is a conservative estimate considering that the measurements were performed over a horizontal path of approximately 1.5 m above the runway's concrete surface and in 70 % humidity thus causing significant signal power degradation due to atmospheric turbulence, absorption, and scattering. Using these results, the projected maximum LOS operational range on the Moon and Mars, under nominal atmospheric and surface albedo, were estimated to be 7.5 km and 5.7 km, respectively.

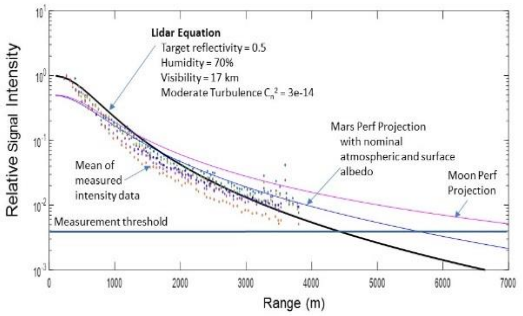

Figure 4. Estimated maximum operational range for operation on Earth, Moon, and Mars.



Figure 5. NDL Engineering Test Unit.

4 DEVELOPMENT OF SPACEFLIGHT UNITS

The prototype lidar described above was designed with the vision of its eventual integration and operation from a planetary landing vehicle. The design of the prototype unit considered size and mass constraints of landing vehicles and the harsh thermal and vacuum environments of space while meeting the performance requirements for a wide range of landing scenarios. This prototype unit is now serving as a testbed for the development of a spaceflight Engineering Test Unit (ETU) of the NDL intended to reduce the risk and cost of building spaceflight units. The ETU is being designed (see Fig. 5) to meet the thermal, vacuum, and radiation environments of space and to be able to tolerate launch vibration loads. Efforts are underway to build the components of the ETU using space-grade or spaceflight-qualifiable parts and validating their functionality, robustness, and reliability for operation in space. Once the ETU is fully assembled, it will be subjected to extensive spaceflight-qualification tests. The ETU assembly and test are expected to be completed by July 2019. The ETU will be then integrated with other landing vehicle avionics for a series of flight tests onboard aircraft and/or a rocket-powered free-flyer test vehicle prior to building the spaceflight units.

5 POTENTIAL PARTNERING FOR CONTINUED NDL TECHNOLOGY ADVANCEMENTS

There are several areas of possible collaboration with industry, academia, and other government organizations for utilization of the NDL for expanding the capabilities of the NDL to other space applications, such as automatic rendezvous and capture, and terrestrial applications such as manned and unmanned aircraft. Conventional aircraft Guidance, Navigation, and Control (GN&C) systems combine the Inertial Measurement Unit (IMU) data with the signals from a Global Positioning System (GPS) to determine the vehicle position and velocity vector. An IMU has an excellent response to rapid motion but suffers from an accumulated error over time (drift) while GPS can provide accurate long-term data. However, the GPS signal can be blocked or jammed by intentional or unintentional interference causing significant deviation in the navigation solution.[6] Also, GPS position (altitude) data is referenced to sea-level and is of limited value when landing on a moving platform or in limited visibility conditions, or when autonomous navigation and landing is required.

A modification of the NDL can also make a dramatic impact to the ongoing efforts for achieving safe and efficient autonomous ground vehicles. By scanning its laser beam, the NDL can

provide 3-D images of the surrounding area plus the velocity of moving objects within its field of regard. Fully autonomous cars can only become feasible when the onboard sensors can replace all the required sensing functions of a human driver.[7] This includes distance, and relative speed and direction of other cars and people. The driverless car demonstration tests to date have been based on using a laser sensor with a scanning mirror to provide a static 3-D view in the vicinity of the car. However, such sensors cannot directly or accurately provide the critical speed and direction of moving targets. On the other hand, the NDL can provide both 3-D range and Doppler (velocity) images of surroundings. The areas that we are seeking collaboration for further advancing the NDL technology for both space and terrestrial applications are listed below.

- Spaceflight-qualified photonic/fiber optic components
- Integrated Photonics to significantly reduce size, mass, and cost
- Non-Mechanical Beam Steering for generating range and Doppler images
- Advanced/Composite materials for light weighting chassis and optical head
- Highly efficient signal processing algorithm to improve effective SNR and reduce computation loads

ACKNOWLEDGMENTS

The authors would like to acknowledge the continued support from multiple NASA program offices including the Space Technology Mission Directorate (STMD)-Game Changing Development (GCD) Office, the Human Exploration and Operations Mission Directorate (HEOMD)-Advanced Exploration Systems (AES) Division, the STMD-Flight Opportunities (FO) Program, and the Science Mission Directorate (SMD)-New Frontiers (NF) Program. The authors are particularly grateful to Michelle M. Munk, NASA EDL System Capability Lead, for her support and guidance.

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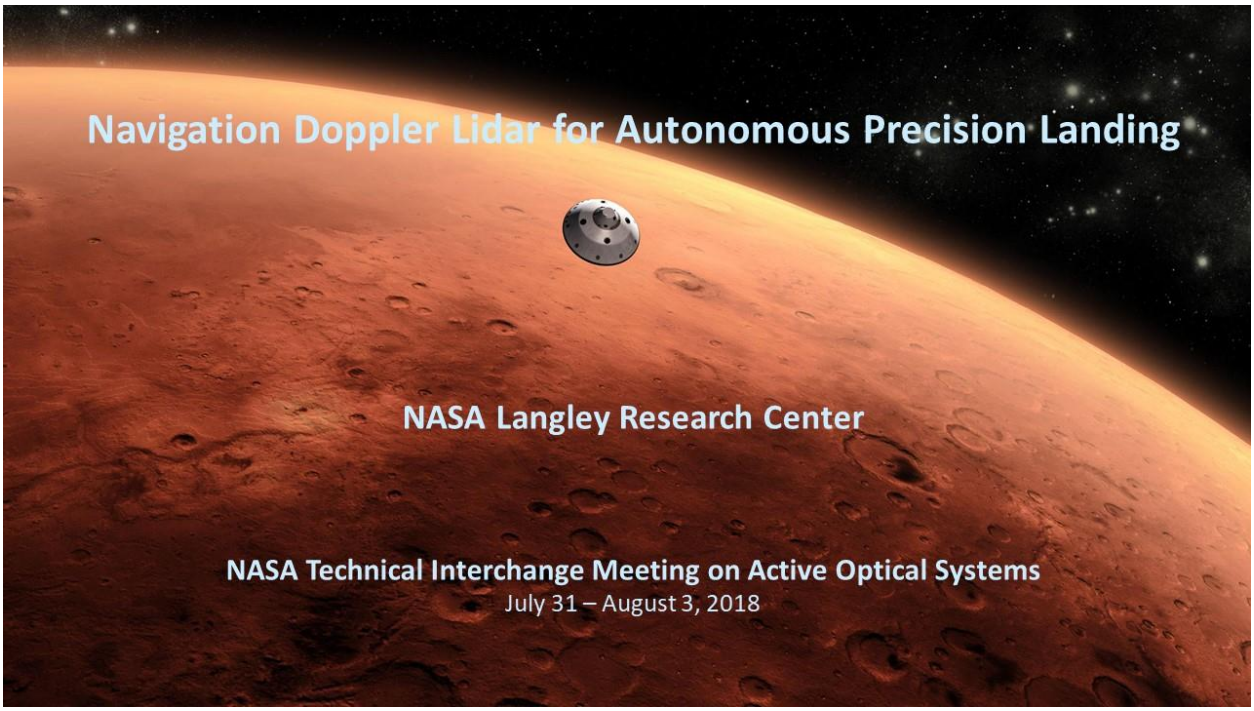
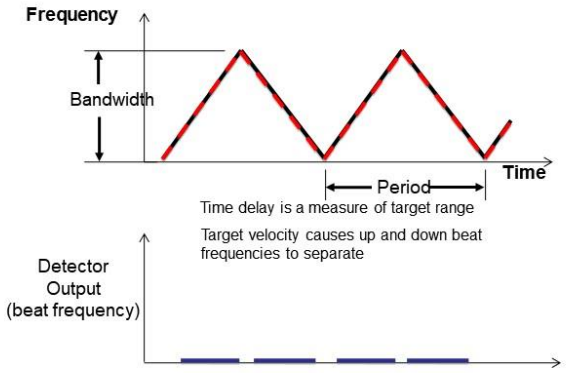


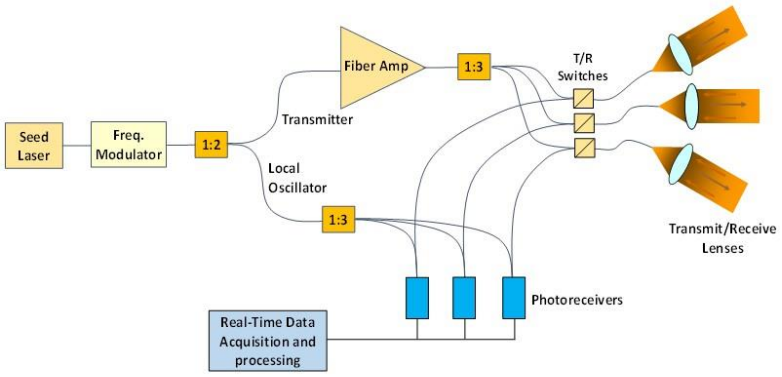
Principle of Navigation Doppler Lidar

Frequency Modulated, Continuous Wave (FMCW) Technique



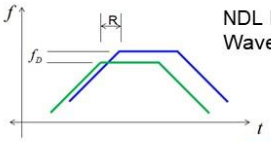
Navigation Doppler Lidar (NDL)

- NDL Measures velocity and range along three different laser beams
- Simultaneous line-of-sight measurements are used to estimate:
  - Velocity Vector (V)
  - Altitude relative to local ground (No IMU data required)

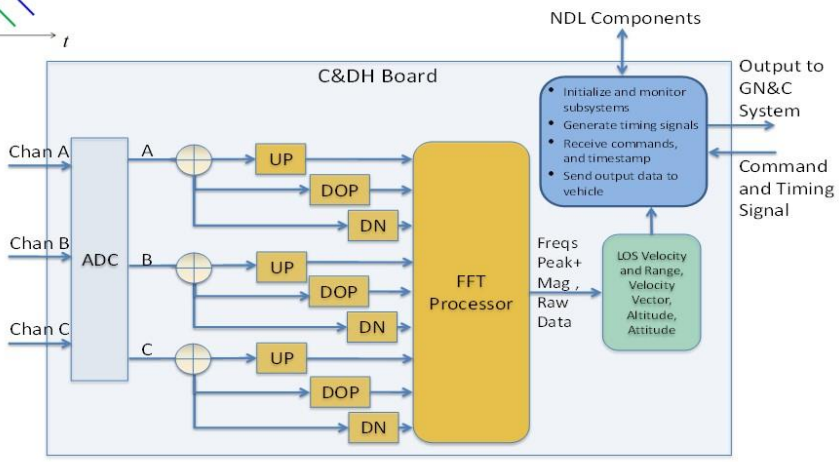


3

NDL Real-Time Processor & System Controller

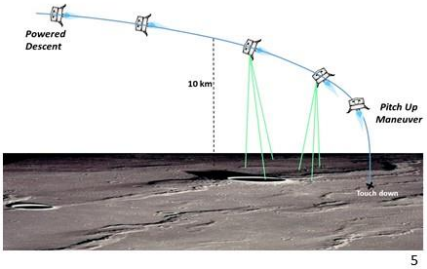


NDL Modulation Waveform



NDL Replaces Radars on Space Vehicles

- Past landing missions used radars for vehicle position and velocity data in absence of GPS
- NDL offers an order of magnitude higher precision and much higher data quality (low false alarms) while reducing required size, mass, and power
- NDL enables "***precision navigation***" to the designated landing location
- NDL enables "***well-controlled***" descent, landing, and ascent maneuvers to within a few cm/sec
  - Reduced touchdown impact loads ⟹ ***lower lander mass***
  - Optimized fuel consumption ⟹ ***lower mass and risk***



5

NDL development from breadboard to fully-autonomous prototype



2008



2010



2012

rocket-powered free-flyer vehicles



2014



2017

Breadboard without real-time processing

~200 kg

GEN 1: ~ 60 kg



GEN 2: 28 kg



GEN 2.1: 17 kg

Fully-Autonomous Prototype



GEN 3: 10 kg

6

GEN 3 NDL

- **Fully-autonomous operation**
- **Integrated real-time processors**
- **Robust operation onboard different terrestrial vehicles**

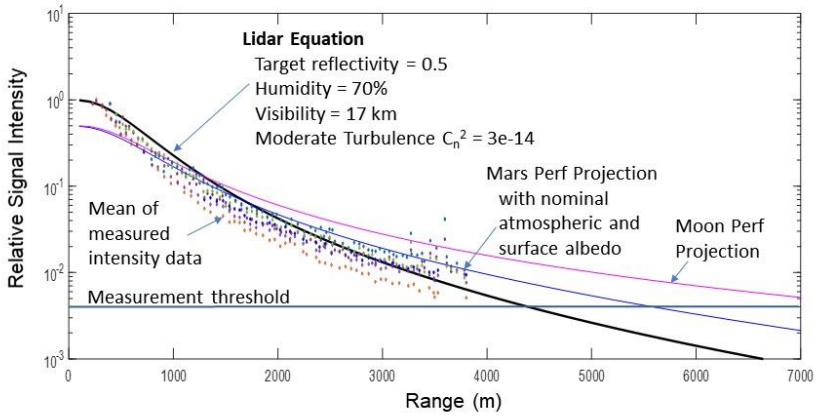


Chassis 11”x9”x8”
Optical Head 2” lenses

7

Maximum Operational Range Predications

- Maximum operational ranges in Mars and Moon extrapolated from measured data
  - Mars 5.7 km
  - Moon 7.5 km



GEN 3 NDL Performance

Maximum LOS Range[a]		> 4500 m
Maximum LOS Velocity		200 m/sec
LOS Velocity Error[b]		0.2 cm/sec
LOS Range Error[b]		25 cm
Data Rate		20 Hz
Dimensions	Electronic Chassis	28 x 22 x 20 cm
	Optical Head	34 x 33 x 21 cm
Mass	Electronic Chassis[C]	8.7 kg
	Optical Head	5 kg
Power (28 VDC) [C]		80 W

a. Dependent on atmosphere and surface albedo

b. Errors dominated by the vehicle's vibration and angular motions (1.7 cm/sec and 2.2 m in flight tests)

c. Heatsink and fans module for terrestrial operation adds 1.5 kg and 10 W





$$\text{Max Vehicle Velocity} = \frac{\text{Max LOS Velocity}}{\cos\alpha}$$

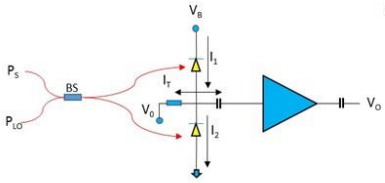
$$\sim 300 \text{ m/s } (700 \text{ miles/hr or } 1100 \text{ km/hr})$$

Key NDL Features

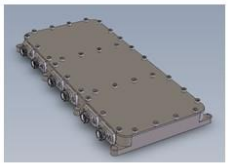
- Stable, Narrow Linewidth, Low Noise Laser
- Stable and Low Noise Fiber Amp
- Highly Linear Modulation Waveform
- Low Noise, Flat Response, and Well-Balanced Receiver
- High Resolution FFT Processor
- Robust Signal Processing Algorithm
- Compact Chassis
  - Efficient Thermal Design
  - Mechanically Robust

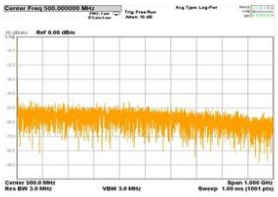
In-house built C&DH board
20 layers and thousands traces





3-channel Dual-Balanced Receiver





Spaceflight Engineering Test Unit (ETU)

- Spaceflight Engineering Test Unit (ETU) will be completed and tested by mid 2019
  - Comparable in size and mass with NDL-3
  - Use "*space-qualified*" or "*space-qualifiable*" parts
  - Conduct radiation and thermal/vacuum tests at component/subsystem level
  - Efficient heat conduction to host vehicle
  - Robust structure
  - EMI resistance

NDL-3



ETU



Future Work

- Complete and test Spaceflight Engineering Test Unit (ETU) by mid 2019
  - Flight tests onboard a high speed aircraft and a rocket-powered vehicle in summer 2019
- Continue study and field testing for terrestrial applications
  - Autonomous ground and aerial vehicles
  - Helicopter landing in degraded visual environments (DVEs)
  - Other proprietary applications
- Continue technology advancement
  - Miniaturization
  - Expand NDL capabilities for other space and terrestrial applications

Potential Areas of Collaboration and Partnership

- Integrated Photonics to significantly reduce size, mass, and cost
- Non-Mechanical Beam Steering to reduce the number of lenses to one
- Advanced/Composite materials for light weighting the chassis and improving heat transfer
- Advanced/Composite materials for light weighting fiber-coupled transmit/receive lens and extending its operational temperature range
- Spaceflight-qualified photonic/fiber optic components
- Optimized signal processing algorithm to improve effective SNR and reduce computation loads

Backup

NDL Characterization

Gantry Tests





NDL
Optical Head

Operational Range Measurements at Langley AFB Runway



NDL Setup





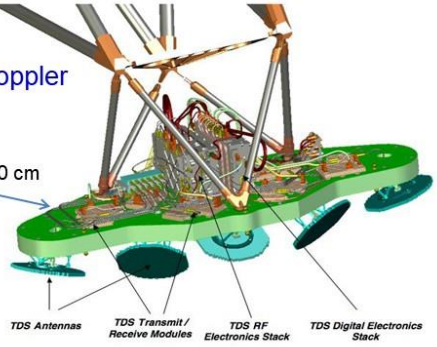
Calibrated Target on back of a truck driven on the runway

15

Comparison of NDL and MSL Radar

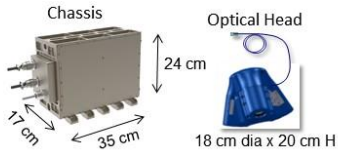
MSL Doppler Radar

130 cm x 50 cm x 40 cm



6 antennas each 22 cm diameter, 4 cm thick

Navigational Doppler Lidar



	MSL Radar	NDL
Mass (kg)	26	13
Power (W)	120	80

- 30X higher velocity and altitude precision
- 3 orders of magnitude tighter beams
- 40% reduction in power, 50% in mass, and 60% in size

16

6.4 RECENT ADVANCES IN RELATIVE NAVIGATION OF AEROSPACE SYSTEMS

Manoranjan Majji

Director, Land, Air and Space Robotics Laboratory, Texas A&M University, College Station, Texas

AEROSPACE ENGINEERING
TEXAS A&M UNIVERSITY
Land Air & Space Robotics Laboratory

Recent Advances in Relative Navigation of Aerospace Systems

Manoranjan Majji, Director,
Land, Air and Space Robotics Laboratory,
Texas A&M University

Warm acknowledgements to my colleagues: John Junkins and Robert Skelton

AEROSPACE ENGINEERING
TEXAS A&M UNIVERSITY
Land Air & Space Robotics Laboratory

Research Vision

- Proximity operations research
  - Land based
  - Seaboard
  - Airborne and
  - Space
- Technology expertise
  - Structural Systems
  - Dynamics and Control
  - Sensors and Computational Vision
- Current projects
  - Space habitat systems and tensegrity robotics
  - Satellite servicing (DARPA)
  - UAS sensor research with CANVASS (aerial refueling, carrier landing, etc.)



AEROSPACE ENGINEERING
TEXAS A&M UNIVERSITY
Land Air & Space Robotics Laboratory

Land Air and Space Robotics

Sensing Systems

iGPS
Localization System

Vicon
Motion Capture System

Phase Space
Motion Capture System



Computational Vision

3D Imaging/Sensing

Ground-Based Robotics

Quad-Rotor Aerial Robotics

LASR developed during FY2006-2011 via AF, NASA, TAMU & IC Investments

Robotics Lab Facility Specs:

- **3** Independent Metrology Systems
- Mm Precision Navigation (100HZ)
- **2000** sq. ft. Flat Floor
- Real Time Information Fusion & Control
- Reconfigurable Wireless Comm.

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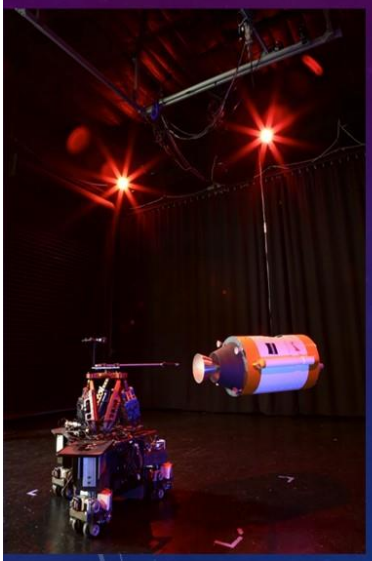

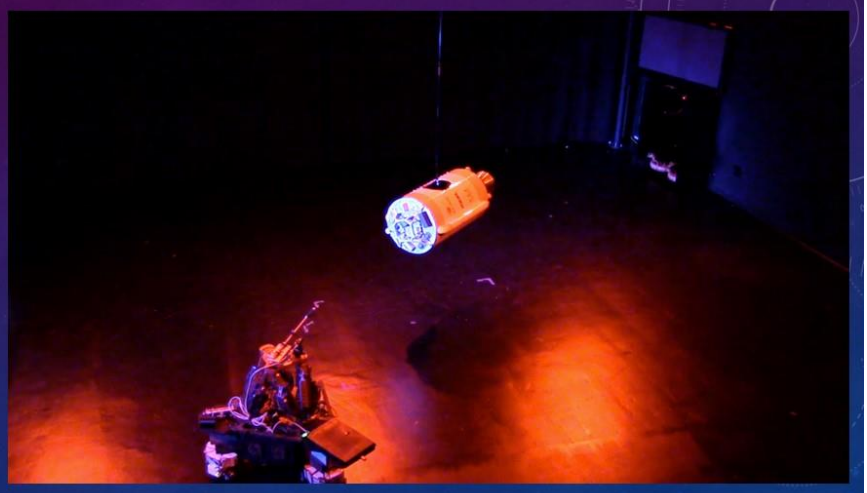

Separate presentations available for more details


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Separate presentations for more details


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Engineering grand challenge in aerospace systems
DARPA Orbital Express Video – Nav. Solution + 3D Geometry
Images
3D Model
Feature-based Navigation (~ 40% outliers)
Team's Past Experience
DARPA Spacecraft Servicing Challenge



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Engineer's Talk Du Jour …

My uncertainty is worse than yours!

- **Image operations**
  - Image formation
  - Feature extraction (complex PAMI algorithms)
  - Feature tracking
- **Unique challenges**
  - Discretization (pixels) – random variables of high dimensions
  - Underlying physical process is continuous…

How to derive uncertainty from the Data?
How to navigate in an uncertain environment?

Features, features everywhere!

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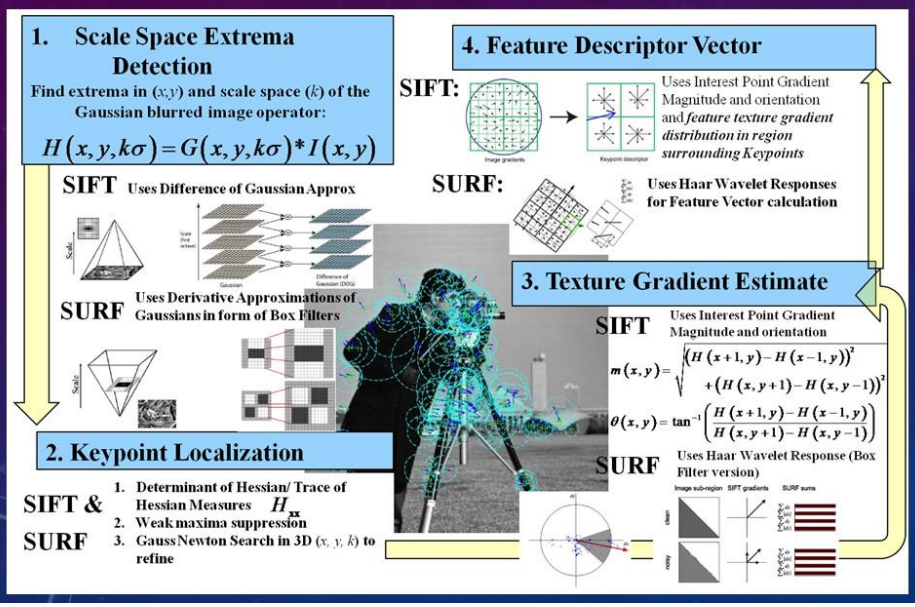

Scale space paradigm merges frequency and spatial domain considerations for extrema detection

Descriptor is a local identification tag to make subsequent identification possible.

Uncertainty Analysis of the KLT Tracker

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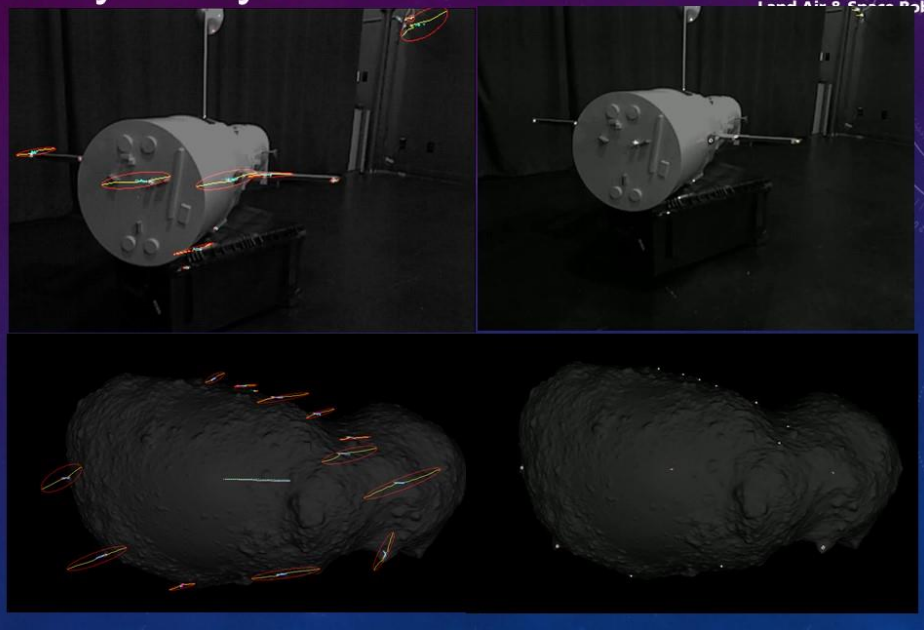

Uncertainty Analysis of KLT Tracker

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Uncertainty Analysis of KLT

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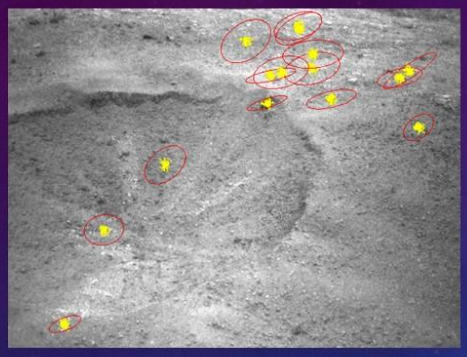



Key Observations

1. When track uncertainty balloons => highly likely we will lose it.
2. Large motion problems => our constant shift model doesn't capture effectively, so UQ is optimistic in that case.

Extended Kalman Filter Implementations

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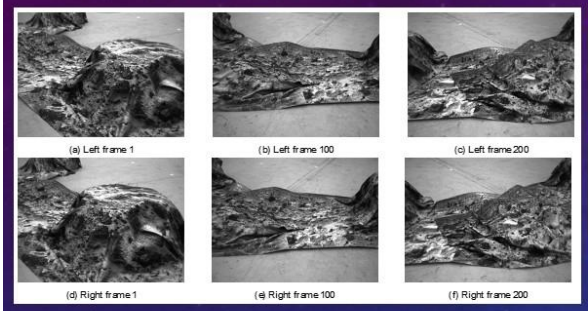
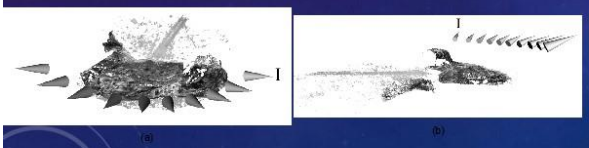
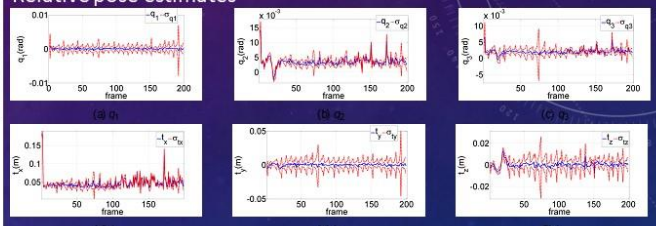
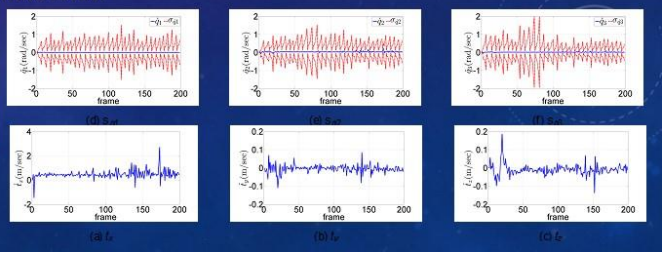




Relative pose estimates



Pose rates:



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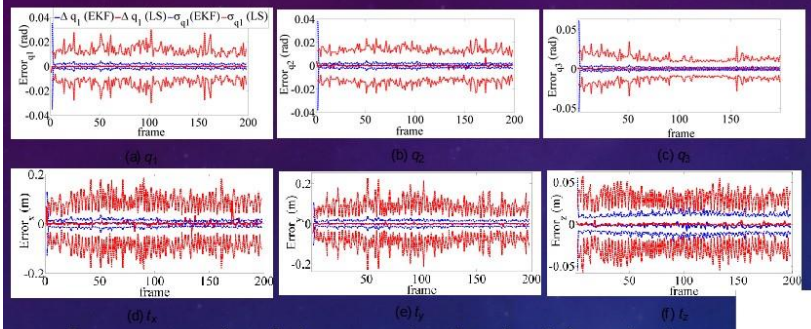
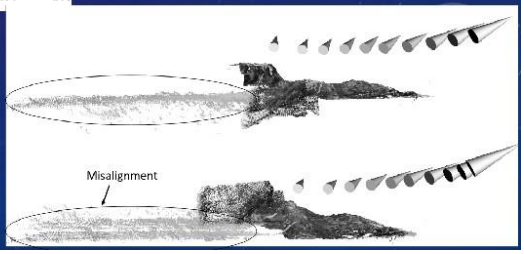
Extended Kalman Filter Implementations



- Iterative EKF implementation based upon solution to linear algebra problem
- Covariance improves in state space
- Alignment improves by dynamical system constraints
- Weights of both problems depend on motion model fidelity

- Degenerates to the relative pose estimation when information is insufficient
- We have implementations that adapt and provide appropriate rate information dependent on information density

Smoother estimates used as the de-facto ground truth



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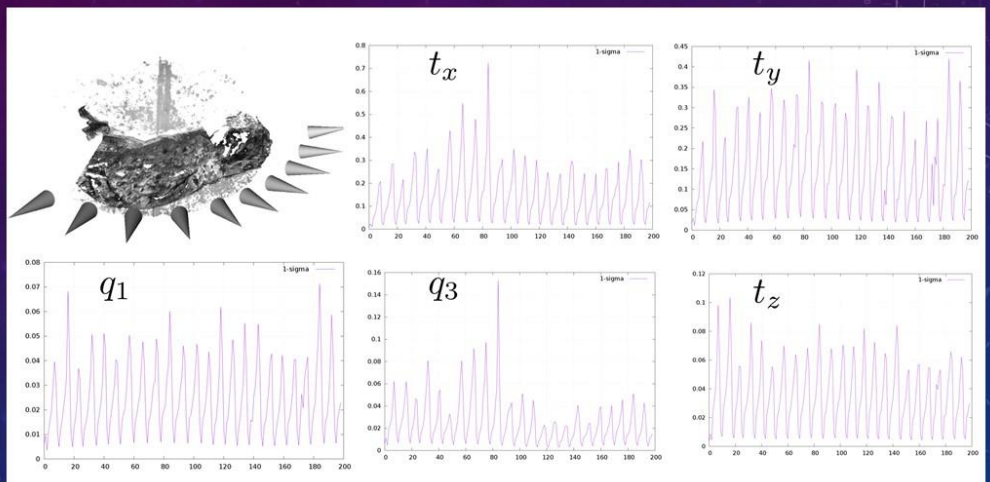
Error Growth



Rates, error covariances are also similar calculated.

ICP and Other Things!

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Valedyne LADAR data on a city block survey

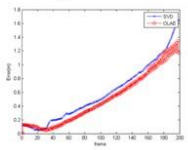


Figure 4: Comparison of trajectory error

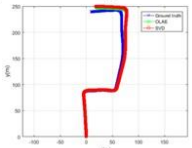


(a)

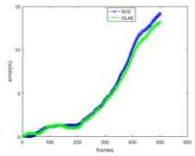


(b)

Figure 5: "LIDAR 3D map reconstructed by (a)OLAE ICP (b) SVD ICP"



(a)

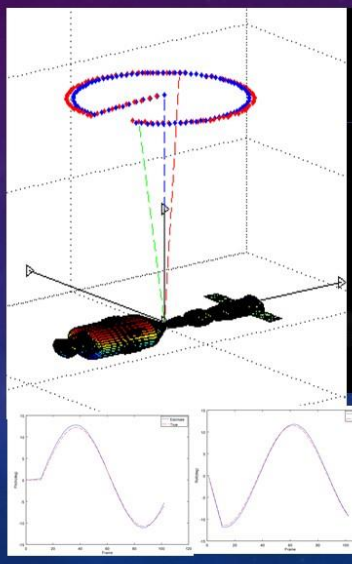


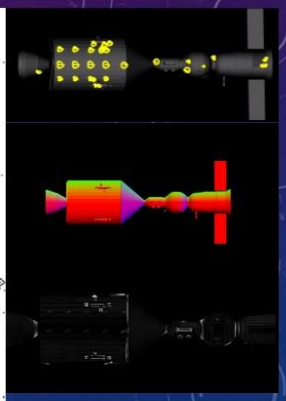
(b)

Figure 6: "Comparison of ICP estimated (a)trajectory (b) position error

case	OLAE ICP	Arun ICP
total (500 frames)	54.604 sec	1 min 32 sec
1 frame (~ 8e3 Pts.)	0.1092 sec	0.1840 sec

OLAE ICP => OCVP
(without image features)





Reprojection based navigation approaches

Emulation Environments for TRN

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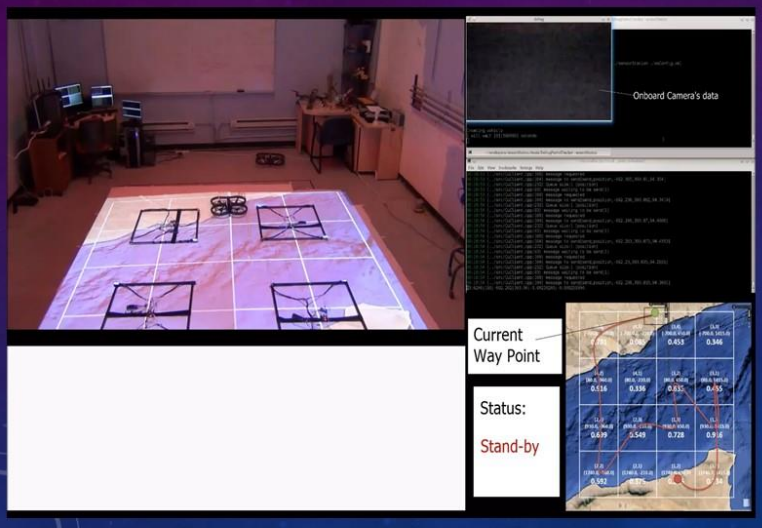

- Planetary reentry
- Precision and pinpoint landing
- Hazard navigation
- UAS routing and path planning

High Definition Imaging in 6D (HD6D)

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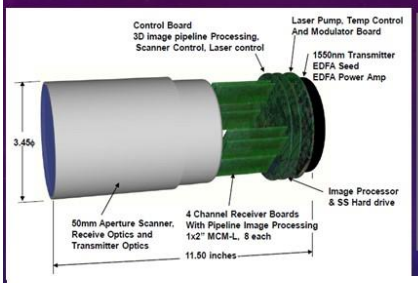
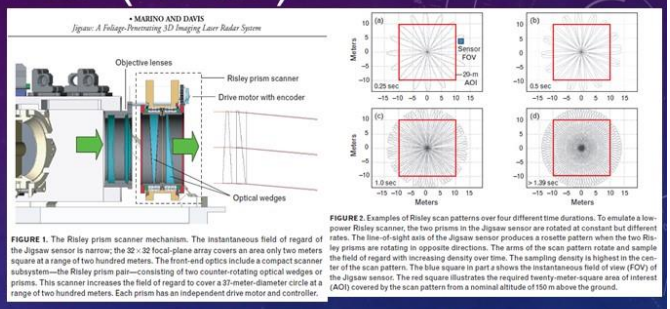
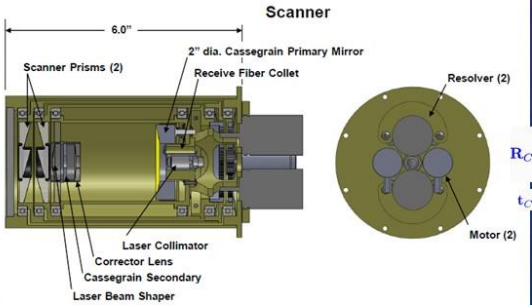


SWAP Requirements:
- < 2kg
- < 30 w
- < 4"x4"x12"
- Eye Safe
- 1550nm

1st Prototype Tested: 10/31/2011



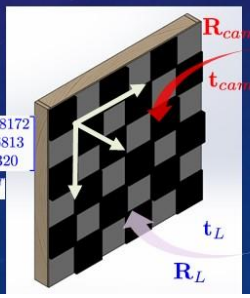


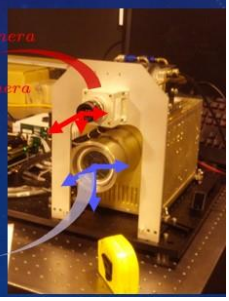
Calibration Results

$$\mathbf{R}_{C/L} = \begin{bmatrix} 0.9997 & -0.02388 & 0.0028172 \\ 0.0194 & 0.7317 & -0.6813 \\ 0.01421 & 0.6812 & 0.7320 \end{bmatrix}$$

$$\mathbf{t}_{C/L} = \begin{bmatrix} -1.5601 & 8.2926 & -10.4723 \end{bmatrix}^T$$

Position error standard deviation: **2 in**





HD6D Version 2.0

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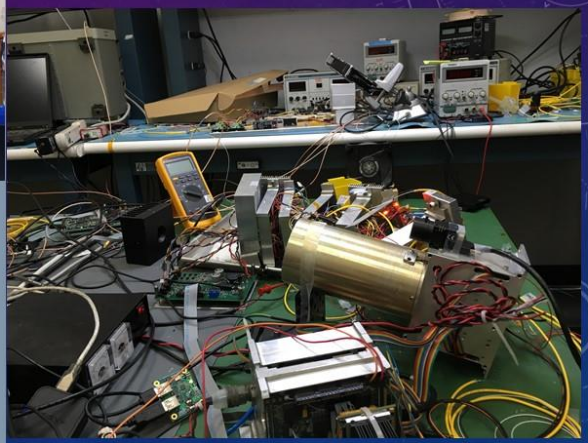

HD6D Version 2.0

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Calibration Targets, 318K points, Raw Point Cloud Image



3 Calibration Targets, Accumulated Image, 29K points, X / Y point grid on 1/8 inch centers

HD6D Version 2.0

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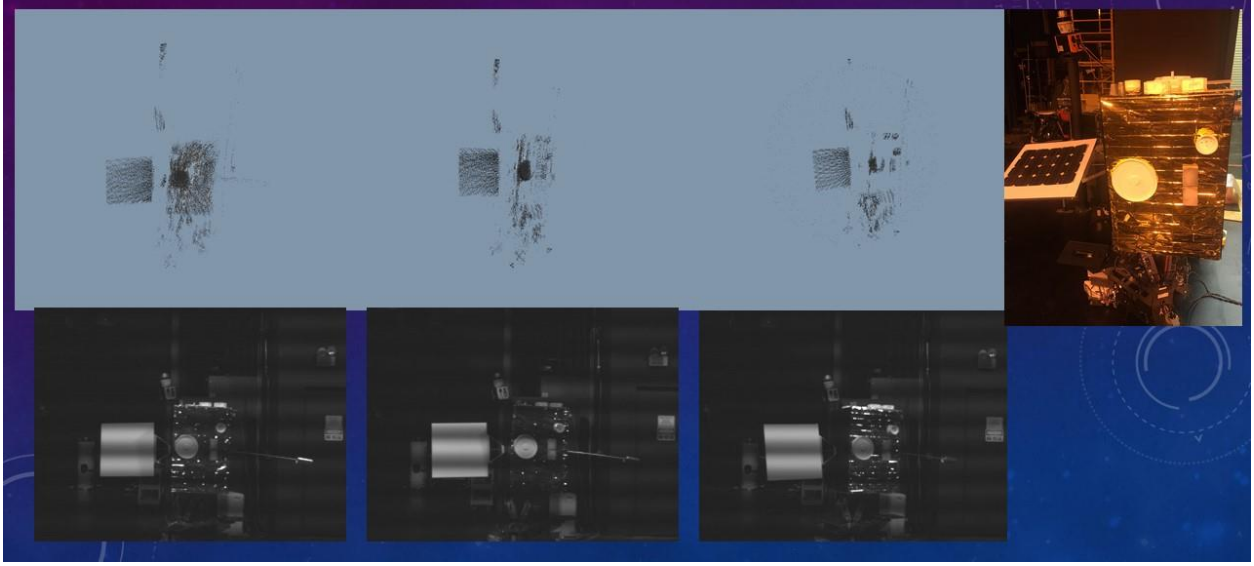

UAV Flight System for Aeromagnetic Survey

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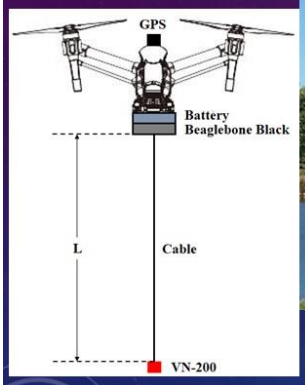
Land Air & Space Robotics Laboratory

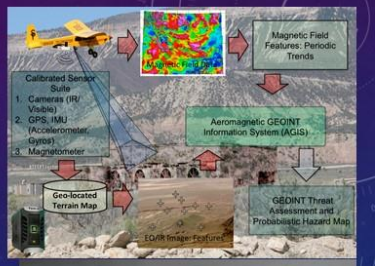






- UAV system with a low-cost magnetometer (IMU) for aeromagnetic surveys
- Data-driven modeling methods for processing surveyed data and anomaly detection

Industrial Partner:
Vector Nav







Aeromagnetic Survey with a Low Cost Magnetometer

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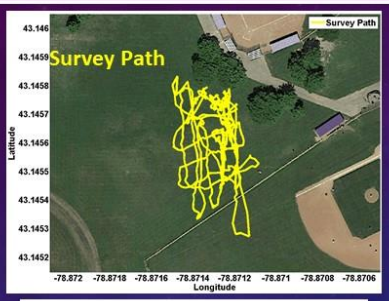
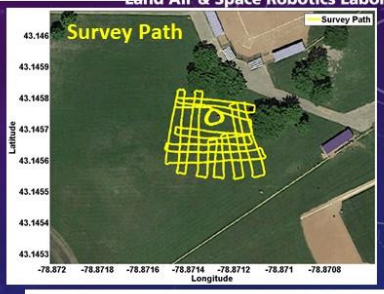
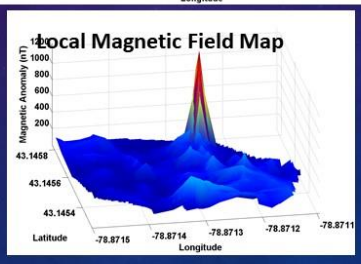
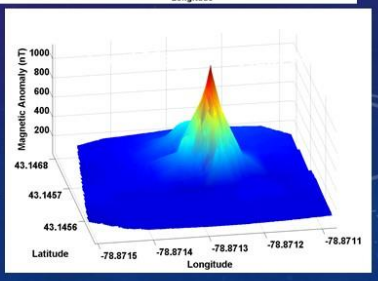
Waypoints (Autopilot)











Moving towards GPS Denied Navigation Using Magnetic Fields!

Valedyne

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Valedyne LADAR data on a city block survey

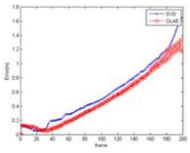


Figure 4: Comparison of trajectory error

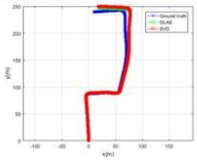


(a)

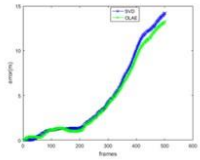


(b)

Figure 5: "LIDAR 3D map reconstructed by (a)OLAE ICP (b) SVD ICP"



(a)



(b)

Figure 6: "Comparison of ICP estimated (a)trajectory (b) position error

case	OLAE ICP	Arun ICP
total (500 frames)	54.604 sec	1 min 32 sec
1 frame (~ 8e3 Pts.)	0.1092 sec	0.1840 sec

OLAE ICP => OCVP
(without image features)

- Application of computational vision pipeline on standard datasets provided good results.
- Current work includes the use of computational vision pipeline with Valedyne and TI LADAR systems.
- HD6D point cloud fusion experiments are planned in the future.

Interferometric VisNav System

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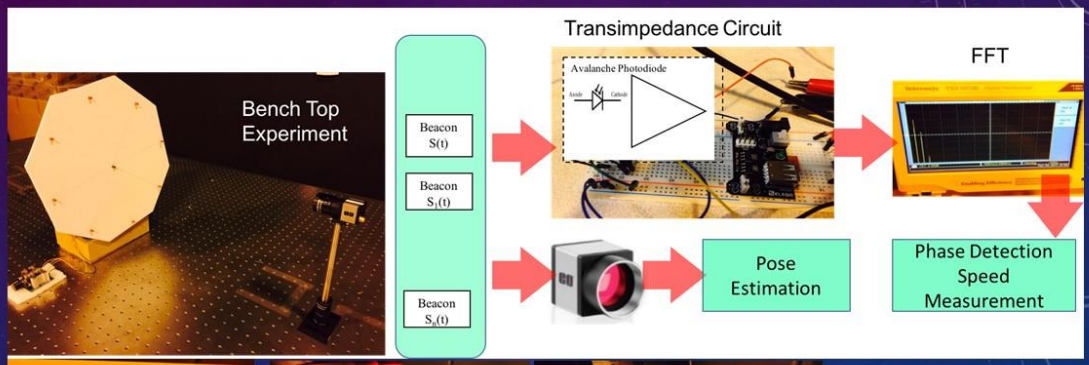

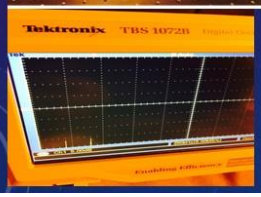





- Technical details available upon request
- Stay tuned for more publications on this

Tensegrity Systems: Space Habitat

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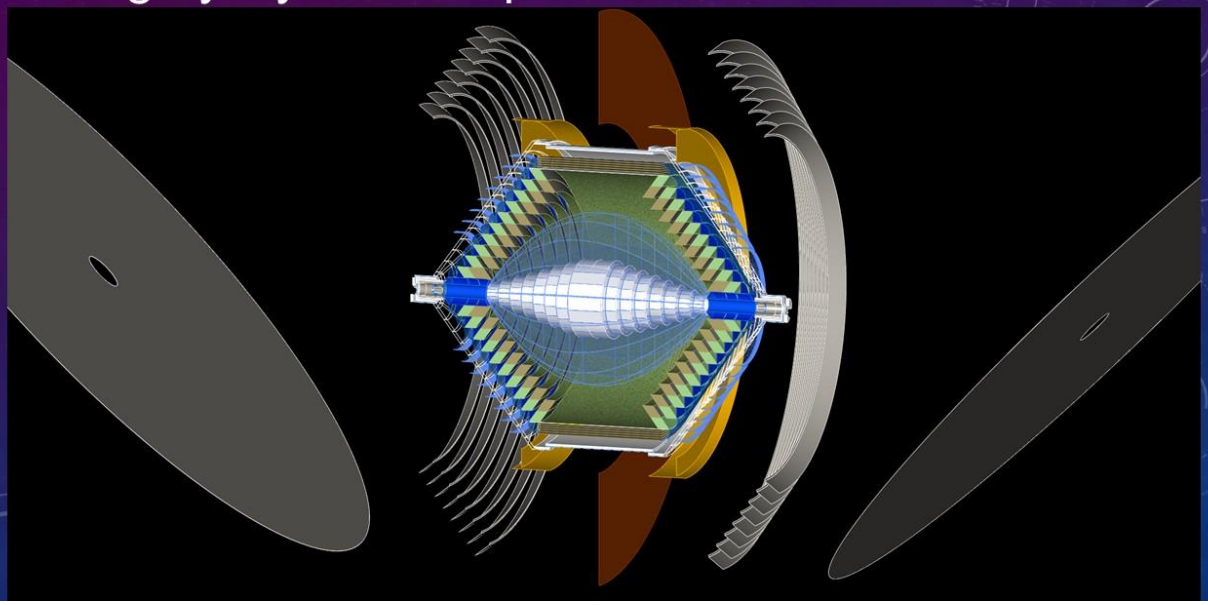

Tensegrity Systems

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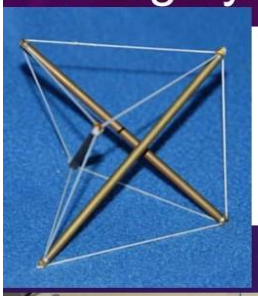


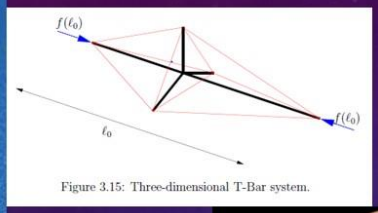
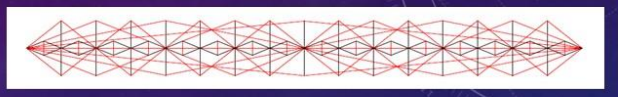
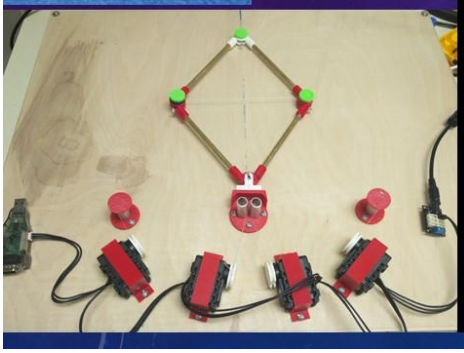
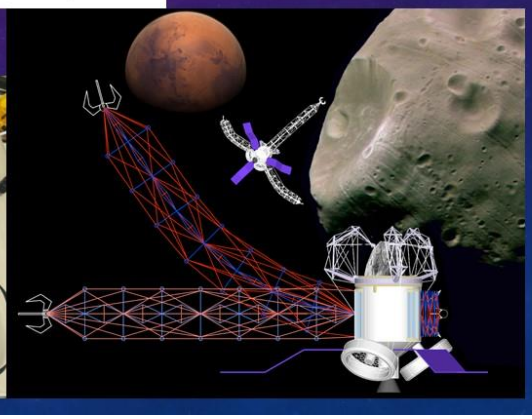


Figure 3.15: Three-dimensional T-Bar system.

Key Result
Minimal mass compressive, tensile, torsional and bending structures are tensegrity!







Topology optimization
Sensing
Actuation
Modeling
Information architecture
Structural system design
Mechanisms
Robotics

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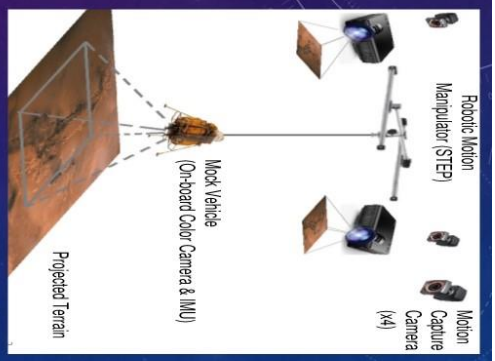
Looking into the future …

- Sensor technologies
  - Continuing the crusade on HD6D sensor fusion
  - Applications to terrain relative navigation systems
  - Plans are in place to build emulation testbeds at LASR lab.
  - Next gen vision systems. Recent invention – interferometric VisNav (iVisNav)



6.5 TERRAIN RELATIVE NAVIGATION: MARS 2020 AND POTENTIAL FUTURE SYSTEMS[1]

Andrew E. Johnson

Jet Propulsion Laboratory, California Institute of Technology, USA aej@jpl.nasa.gov

ABSTRACT

During the Apollo moon landings, astronauts sighted landmarks for precision landing and looked out the window during final descent to avoid craters and boulder fields in order to land safely. Since then, technology has advanced to the point where this human capability can be replaced by sensors, algorithms and on-board computing. To this end, Mars 2020 is developing a Terrain Relative Navigation (TRN) system that identifies landmarks and matches them to a map generated from orbital imagery. The Mars 2020 TRN system is dependent on camera images so it is limited to daytime operations and it is sensitive to excessive atmospheric dust. An alternative form of TRN that circumvents these problems by using lidar altimetry has been demonstrated, but currently there is no space-qualified lidar that can be used for this purpose. The Mars Helicopter demonstration on Mars 2020 also uses a laser altimeter and combines it with imagery, for navigation, but these are terrestrial COTS sensors that could not fly on missions requiring high reliability. These applications point out that the lack of space-qualified lidar altimeters is a gap in active optical sensing that needs to be filled for planetary landing missions.

1 INTRODUCTION

By matching on-board sensor data to a map of the landing area, Terrain Relative Navigation (TRN) provides a map relative position fix that can be used to accurately target specific landing points on the surface. Almost all future NASA science mission concepts that would land on planetary bodies will benefit from this capability. Europa and Enceladus have small fissures to target where material from subsurface oceans could be present.

Comets and asteroids have rough terrain requiring careful targeting to safely acquire a sample. The moon has permanently lit terrain at the poles that is hard to target but provides a thermally stable location with near constant solar energy. TRN was added to the Mars 2020 mission to mitigate landing hazards present in the regions with the greatest geological diversity for sample collection. A potential follow-on mission would also require TRN to avoid the same hazards and also land near the cache of samples for return to earth.

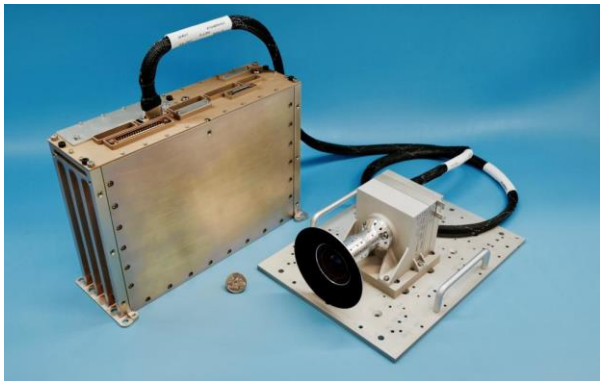


Figure 1 Lander Vision System EM

Mars 2020 is using the Mars Science Laboratory (MSL) Entry, Descent and Landing (EDL) system. This system generates an inertial position by propagating an IMU from the ground navigation position fix prior to entry; the error on this position can be as large as 3.2km. The Lander Vision System is being added to Mars 2020 to decrease this position error down to 40m relative to a map of the landing site. Using this position, the guidance system selects a landing point that is reachable given the fuel onboard and that also avoids hazards identified a-priori in the map. With this approach, sites that were previously considered too hazardous for landing, but very desirable scientifically, are now viable candidates for Mars 2020 and future missions.

The Lander Vision System (LVS) has been in development for many years, starting with initial proof of concept algorithms and culminating with a closed loop pin-point landing demo on a

[1] The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. © 2018. California Institute of Technology. Government sponsorship acknowledged.

terrestrial vertical take-off and landing rocket [1][2][3][4][5] Mars 2020 picked up the technology in January 2016 after it achieved Technology Readiness Level 6. Mars 2020 TRN required the development of algorithms for landmark matching, state estimation and safe site selection, a high-performance compute element and software, a high frame rate camera and high precision mapping techniques. The development of the TRN system is nearly complete and will be delivered to spacecraft assembly in the Fall of 2018 [6].

2 METHODOLOGY

The LVS is the state of the art within NASA for TRN, but it has some limitations: namely, it requires solar illumination and is sensitive to atmospheric dust. A less mature lidar-based approach could mitigate these issues for some missions.

2.1 STATE OF THE ART

The sole purpose of the LVS is to estimate position relative to map during Mars EDL. The LVS needs to reduce an initial 3.2km position error down to 40m and do this in 10 seconds. Processing hundreds of landmarks in less than 10 seconds cannot be done on a standard flight processor, so the LVS has a dedicated Vision Compute Element (VCE). The VCE contains a flight processor card, a power condition card and a Computer Vision Accelerator Card (CVAC). The LVS Camera (LCAM) takes images at 1Hz, but must transfer them to the VCE in less than 100ms, it also needs a wide field of view (90˚) and fast exposure times (<1ms) to deal with the large attitude swings during imaging on the parachute. Finally, it needed to be small and self-contained given the limited space on the rover for accommodation. An engineering model version of the VCE and LCAM are shown in Figure 1. The VCE also interfaces to the existing Descent Inertial Measurement Unit which provides inertial data for position and attitude propagation between images.

The LVS matches landmarks from 4200m to 2000m altitude. The computationally expensive image processing for landmark matching occurs on the CVAC in two phases as shown in figure 2. First a coarse phase with 5 landmarks per image reduces the initial 3.2km position error to something on-order 100m. Then a fine phase happens with many more landmarks to reduce the error down to 40m. Typically 3 coarse images and 3 fine images are processed in the 10 second processing requirement window.

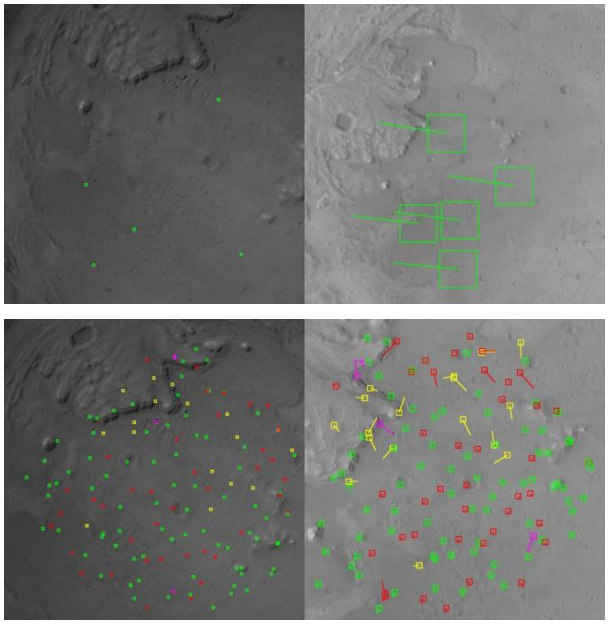


Figure 2 Coarse (top) and fine (bottom) landmark matches between the LCAM image (left) and the map (right) from the an LVS simulation run at the potential Mars 2020 Jezero Crater landing site

As demonstrated in field testing and simulation, the LVS works well across the entire Mars 2020 operational envelope. However, because it relies on passive visible imagery, it may have issues for other potential missions. The first issue is that the LVS requires daytime solar illumination. It can work close to dawn and dusk, but there is nothing that can be done about nighttime. Visible imagery is also sensitive to atmospheric dust. The Mars 2020 landing opportunity occurs at a very low dust time of year, but other missions may land when the possibility of a dust storm is more likely. LVS can work to a dust tau of 1.5, which is its requirement, but not much above that. Dust can also be kicked up from the lunar and other planetary surfaces by rocket engines during landing. Studies of the Apollo missions showed that this will start below 100m altitude, which is below TRN altitudes but could affect final descent and landing.

2.2 NEW APPROACHES

Under the Autonomous Landing and Hazard Avoidance Technology (ALHAT) project, JPL developed a lidar-based terrain relative navigation

algorithm. Unlike the LVS, this is an active range sensing approach that can operate under any illumination conditions and can enable landing anywhere on the moon at any time of day. This TRN approach is intended for use during the braking burn phase of a lander, after it de-orbits. During this phase, the lander travels a significant distance downrange at a shallow path angle; thus, the cumulative lidar data forms a long contour. After collection, the lidar data is projected into a digital elevation map (DEM) using the most current position estimate for the lander. To obtain a position correction, this "lidar DEM" is correlated with a "reference DEM" constructed from a-priori reconnaissance, such as the Lunar Reconnaissance Orbiter data. This approach was designed for lunar landing but can be applied to other landing approaches that have a long horizontal phase with a clear view of the surface. Potential missions including icy moon landers and large Mars landers that utilize supersonic retro-propulsion.

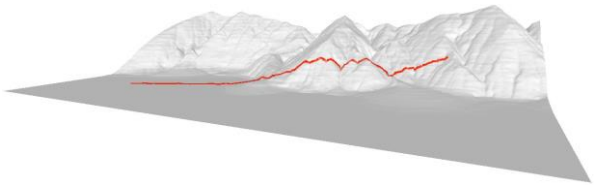


Figure 3: A lidar contour matched to an elevation map for lidar altimeter based TRN.

In 2009, ALHAT conducted a lidar TRN field test using a fixed wing aircraft. The plane flew a nadir-pointed laser altimeter and a flash lidar with a focused beam. Both lidars were developed by NASA Langley Research Center (LaRC). The plane flew at altitudes ranging from 8km to 4km over Nevada Test Site and Death Valley National Park. The lidar data from both instruments was post-processed through the lidar TRN algorithm and position errors typically less than 90m were obtained when terrain relief along the contour exceeded 25m [7]. This agreed well with performance studies done in simulation [8].

The computer vision techniques utilized in LVS require a range measurement to determine absolute scale. On Mars 2020, this is provided by the landing radar, but in future missions this could be provided by a laser altimeter. Case in point, back in 2001, JPL demonstrated real-time motion estimation, terrain map generation and safe landing site identification using a camera, laser altimeter and IMU only [9]. Figure 4 shows one of the results generated in real-time on an autonomous helicopter test platform. Today the Mars Helicopter, flying as a technology demonstration on Mars 2020, will use these same types of sensors (camera, IMU, laser altimeter) to estimate the vehicle motion while flying. This suite of sensors was chosen because they enable accurate mapping and navigation with a very small size weight and power.

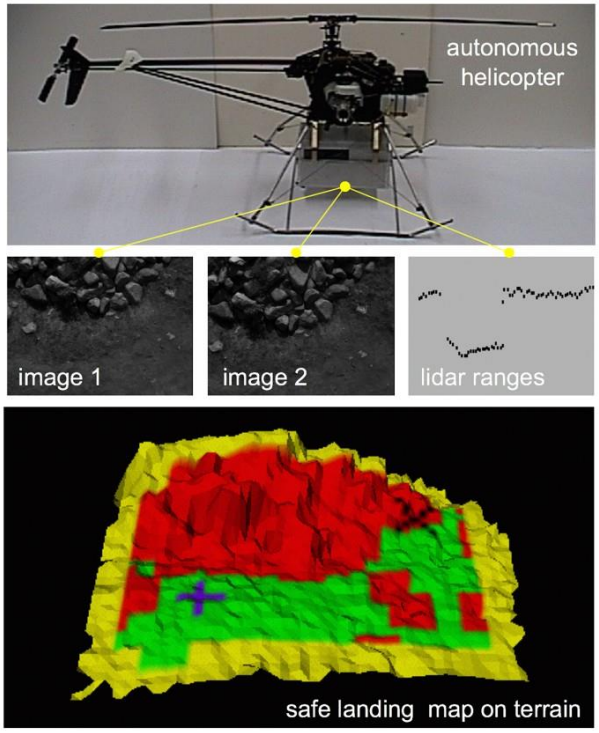


Figure 4: Terrain maps can be generated from a single camera and laser altimeter on a platform moving horizontally.

2.3 POTENTIAL FUTURE STATE

There are multiple benefits from Lidar TRN

- If a commercial or government outpost is going to be built on the moon, then many landings near to each other would be required. Lidar TRN enables accurate landing in the dark, which doubles the possible landing opportunities.
- To ease requirements on thermal and power systems (and cost), many lunar science mission concepts seek to complete their objectives in a single lunar day (14 Earth days). With lidar TRN, accurate landing can

occur just before lunar dawn and yield the entire lunar day for a surface science mission.

- Lidar TRN also enables landing at the lunar poles where illuminated terrain for visible image TRN is scarce. The lunar poles contain permanently dark craters that could contain volatiles for in-situ resource utilization. Lidar TRN would enable landing in these craters and close to or on the volatiles.
- Unlike the LVS, Lidar TRN is not limited by the available solar illumination. It brings its own light source, which can be designed to have sufficient power to penetrate through potential dust conditions.

An EDL terrain sensor system composed of a laser altimeter and camera is quite powerful and broadly applicable with potentially a low size weight and power.

- A camera alone cannot determine the scale of the scene being imaged. A laser altimeter solves this problem by providing a range to the surface. From the combination of these two sensors, the surface relative position, velocity and attitude can be estimated. With sufficient horizontal motion, these sensors can generate a digital elevation map of the imaged scene, which can be used for picking a safe spot to land. A shown by the LVS, absolute position relative to a map can also be generated.
- The LVS is less than 6kg. Orbital laser altimeters can be tens of kilograms, while the Mars Helicopter altimeter is less than 100g. Potentially, by reducing the required range, a lower mass and power laser altimeter can be generated. If so, when combined with the LVS this low SWAP sensor suite will be quite attractive to planetary EDL mission concepts.
- Helicopter and small primitive body explorers would obtain all their terrain relative sensing needs from this sensor suite. Other planetary EDL missions could use it as well (Europa, Enceladus, the moon). Potentially it could also be used for rendezvous and docking.

2.4 RISKS AND REWARDS

As described previously, laser altimeters have multiple engineering uses; however, flight projects cannot buy off the shelf laser altimeters for their mission. Table 1 shows driving requirements for three different laser altimeters that NASA could begin work on for future missions. The Basic Altimeter requirements are for a lander mission that simply needs an altitude measurement albeit all the way to touchdown. The TRN Altimeter requirements are for a mission just using the lidar for TRN; if the altimeter is also needed for touchdown then the Basic and TRN requirements should be combined. Finally, the requirements for a low SWAP helicopter lidar are proposed; these would enable motion estimation and terrain mapping over a broader range that the Mars Helicopter. In all cases, these lidars should be developed to be high reliability, work at night and during the day and also penetrate the atmospheric dust at Mars (could be up to tau 5.0).

Table 1: Proposal Lidar Altimeter Requirements

	Basic Altimeter	TRN Altimeter	Helicopter Altimeter
Operating Ranges	20km to 1m	20km to 100m	<100m
Sample Rate	10Hz	1000Hz	100Hz
Range Accuracy	0.1m	0.1m	0.01m
Mass	~5 kg	~5 kg	100 g
Power	10s of W	10s of W	<1W

3 PROGRAMMATICS

The purpose of this paper is to state the need for lidar altimeters but not specify how they should be developed. LaRC, NASA Goddard Space Flight Center (GSFC), and industry are well positioned to develop the lidar altimeters in Table 1. JPL and GSFC are users of these sensors so they can specify high level requirements on the developers.

The Basic and TRN Altimeters are well within the reach of current technology. An organization needs to build a high-reliability laser altimeter than could be used by multiple mission customers. Ideally industry would do this, potentially with funding from NASA. Because of the low SWaP and the high reliability, the Helicopter Altimeter

will be a challenging development. A NASA center could lead the development of initial prototype and then spin it off to industry.

All of these altimeters are at the entrance to the "valley of death" in technology development. What is needed to pass through it is sufficient funding from NASA with a clear tie into program offices for infusion.

4 CONCLUSIONS

Terrain relative navigation enhances the safety and science return of planetary EDL missions. The LVS is a very effective TRN system that should work well for Mars 2020. However, it cannot work at night or in extreme dust conditions. Lidar altimeter-based TRN does not have these disadvantages, but a suitable lidar does not exist. The Mars Helicopter uses a terrestrial COTS camera and lidar altimeter for navigation due to their low SWaP. These specific sensors, when combined, provide a lot of navigation and mapping functionality, but they cannot be used for most follow-on mission concepts due to their low reliability. NASA should encourage the development of a suite of EDL laser altimeters for future planetary mission concepts.

ACKNOWLEDGEMENTS

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California Institute of Technology

Terrain Relative Navigation: Mars 2020 and Potential Future Systems

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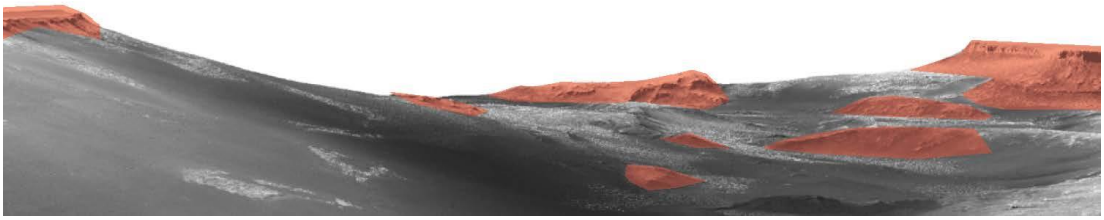

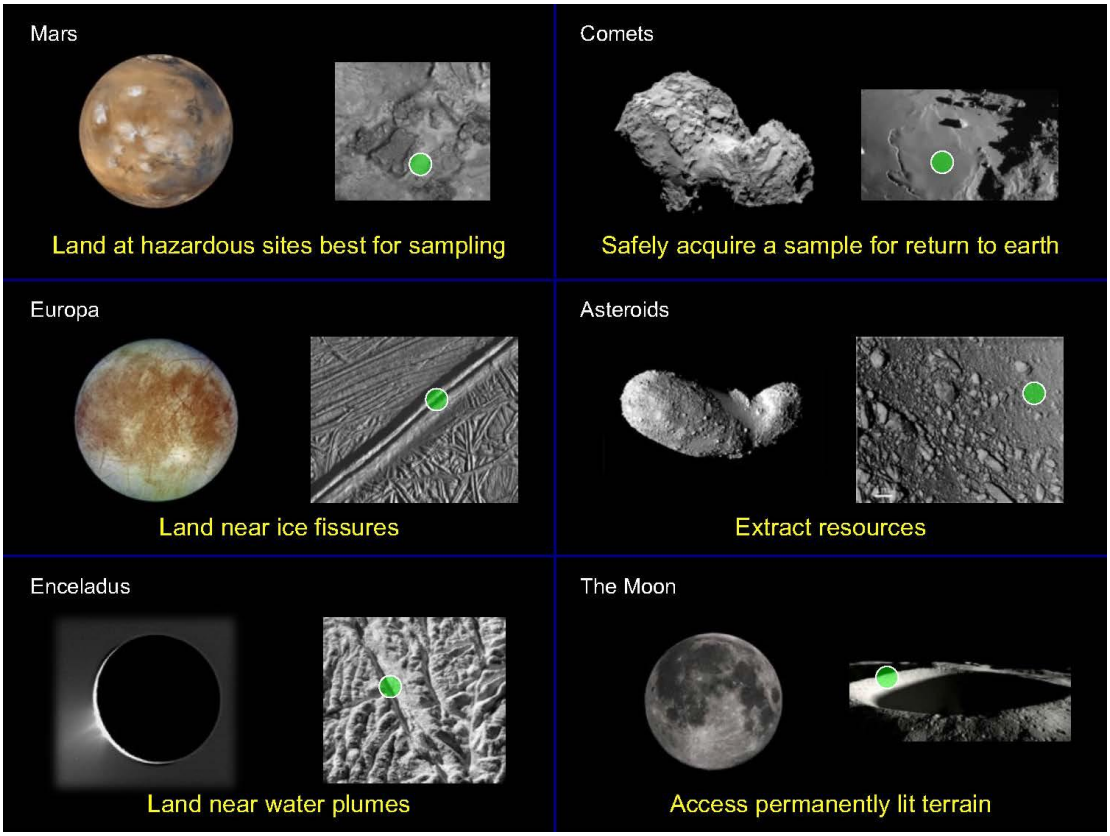

Application of Terrain Relative Navigation on Mars 2020

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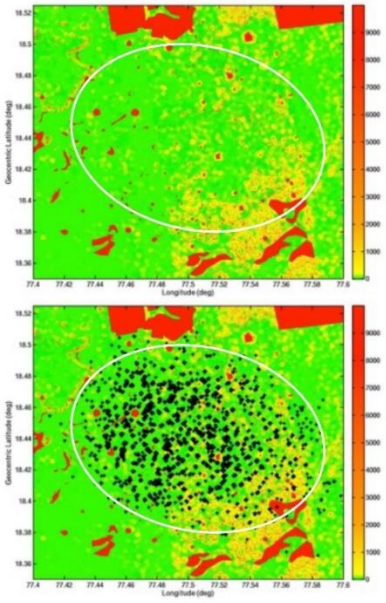
California Institute of Technology

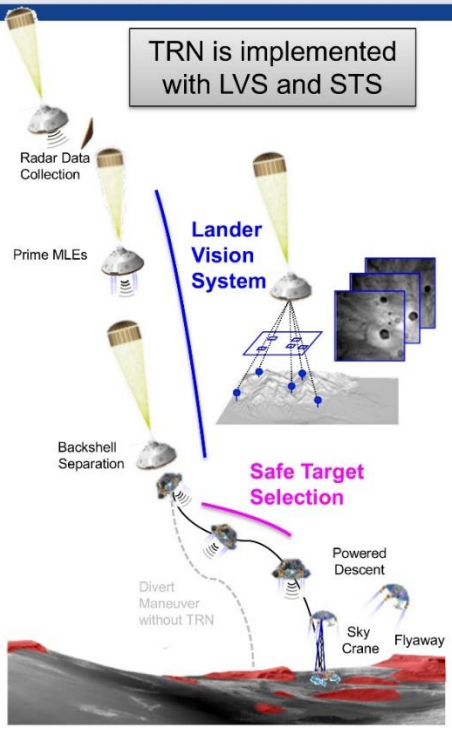
TRN enables access to hazardous landing sites



Mars 2020 landing ellipse can contain numerous hazards

TRN augments MSL EDL to avoid hazards and land safely

TRN is implemented with LVS and STS



LVS Problem Statement

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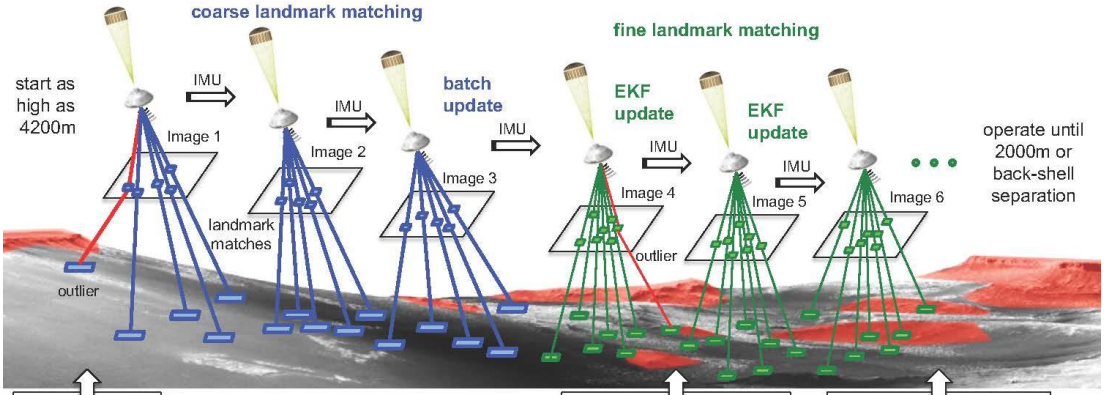
LVS estimates position during parachute descent.

sun elevation between 38° & 49°
sun azimuth between 256° & 292°
+/-15° elevation and +/-35° azimuth
difference between map and landing

off nadir angle < 45° & angular rates < 50°/s
horizontal velocity < 70 m/s & vertical velocity between 60 and 115 m/s



Remove Initial Position Error of 3.2km

slope < 15°
terrain relief < 150m
appearance entropy > 4

Reduced Position Error 40m 99%tile 95% of the time at 6 seconds

Nominal Position Error 40m 99%tile 99% of the time at 10 seconds

4

Various LVS Results

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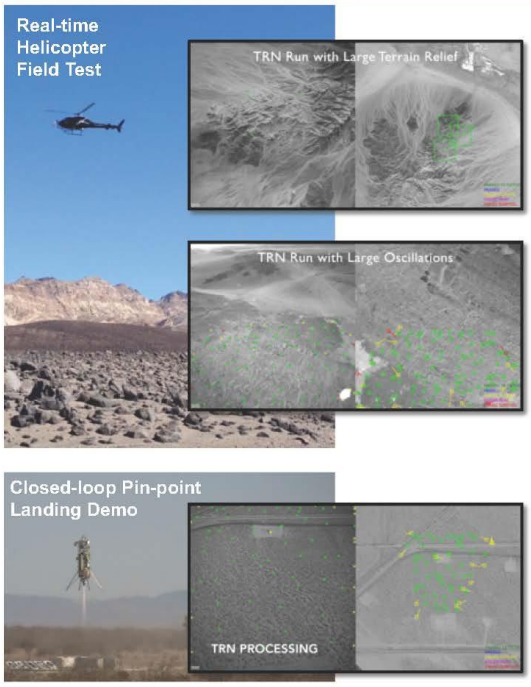
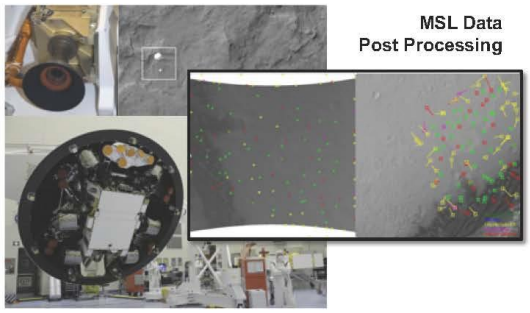
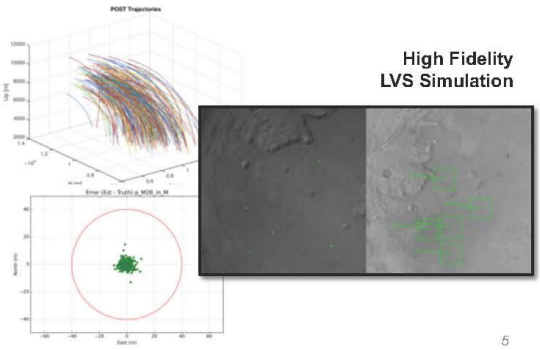
California Institute of Technology







5

LVS Flight Status

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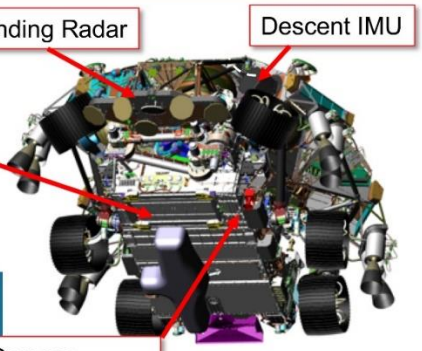
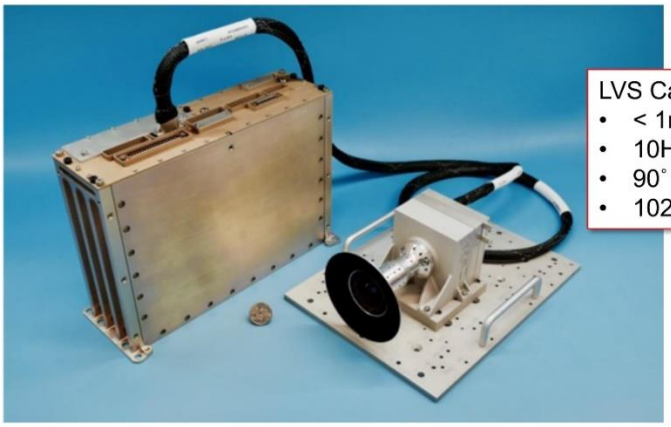
LVS Vision Compute Element (3 slot, 6U)
- RAD750 flight processor
- Power Conditioning Card
- Computer Vision Accelerator Card
  - Virtex5 FPGA for image processing
  - RTAX 2000 FPGA for housekeeping





LVS Camera
- < 1ms exposure
- 10Hz frame rate
- 90˚ FOV
- 1024x1024

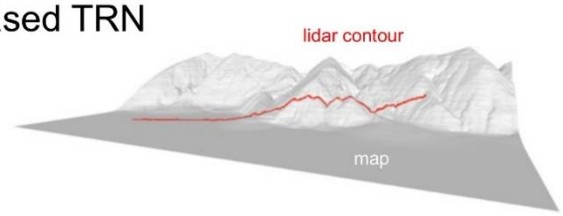
Schedule
- EM fabricated and tested (shown)
- FM delivered in 12/2018
- Field Test in 2/2019
- Landing 7/2021

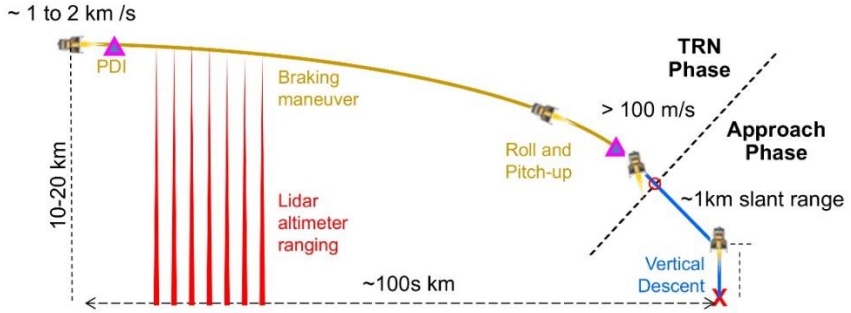
6

Lidar Terrain Relative Navigation

Jet Propulsion Laboratory
California Institute of Technology

- Disadvantages of vision based TRN
  - Daytime operation only
  - Sensitive to dust
- Advantages of Lidar TRN
  - Any time day or night
  - Dust can be mitigated with laser power





7

Lidar TRN Results: ALHAT Field Test 3

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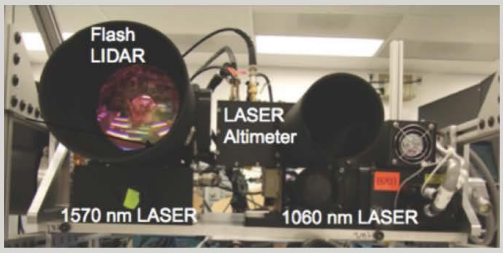

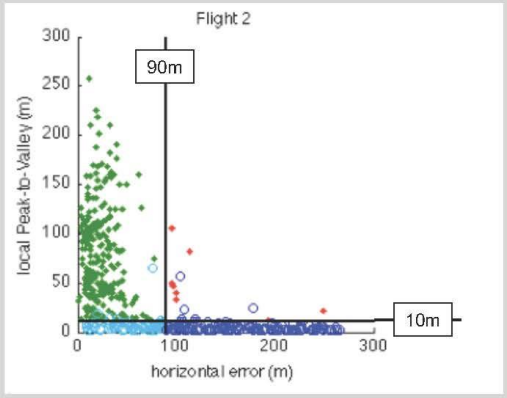

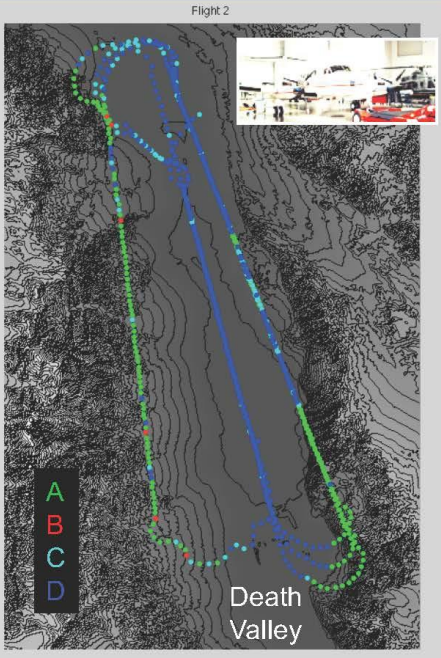

Camera and Lidar for Near Surface Navigation (helicopter or primitive body)

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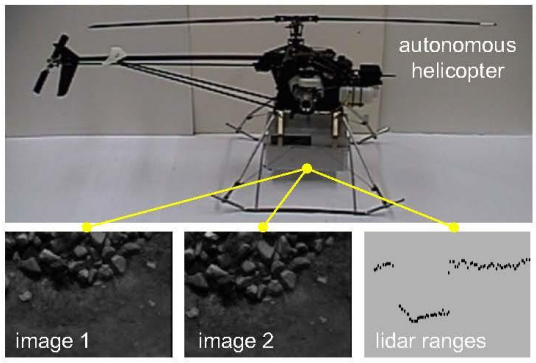
- A camera and lidar altimeter can be combined to estimate position and velocity and build terrain maps for safe landing
- Future helicopters and primitive body landers and hoppers are ideal for this sensor combination
  - Navigation close to surface
  - Low mass and power



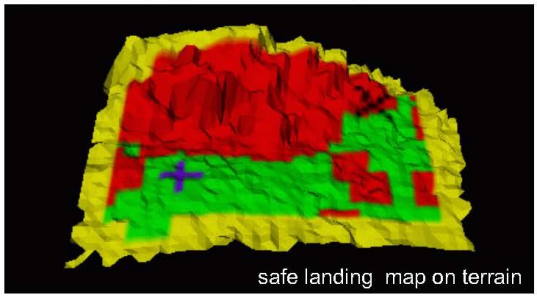
structure from motion from images

set scale with lidar

dense motion stereo

slope and roughness

safe sites election



9

Mars Helicopter

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The mars helicopter sensors are all COTS but with testing to show that environmental requirements can be met

Camera
- 640x480 pixels
- 133˚x100˚ field of view
- 30 frames per second
- power < 150mW
- mass < 1g

Lidar Altimeter
- **40m max range to 70% reflective**
- **2.5-10cm range accuracy**
- **650Hz**
- **power < 750mW**
- **mass < 25g**

IMU
- high rate motion

Inclinometer
- calibrates IMU

10

Potential Lidar Altimeter Requirements for EDL

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California Institute of Technology

	Basic Altimeter	TRN Altimeter	Helicopter Altimeter
Operating Ranges	20km to 1m	20km to 100m	< 100m
Sample Rate	10Hz	1000Hz	100Hz
Range Accuracy	0.1m	0.1m	0.01m
Mass	~5 kg	~5 kg	100 g
Power	10s of W	10s of W	< 1W

Requirements for all lidars

- High reliability
- Full sun and night operation
- Penetrate dust
  - tau from 1.5 up to 5.0 for Mars
  - Dust within 100m for Moon

Acknowledgement

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BACKUP

Thoughts on Development

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- Lidar altimeters have multiple engineering uses
- Flight projects cannot buy off the shelf lidar altimeters
- The requirements on lidar altimeters for TRN are not that challenging
  - Can industry be encourage to develop this capability from NASA requirements?
  - Or given the small market should a NASA center produce these as a commodity?
- Follow on helicopter science mission concepts need high reliability sensors
- The mass and power combined with high reliability make the helicopter lidar very challenging to develop
  - NASA could lead and prototype the first of these sensors and then spin off to industry

Applicable Priority Topics



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- *Lunar Exploration* including **landing navigation and hazard avoidance, and surface exploration and characterization**
- *Jovian Moons* including **surface features and characterization** ***(for navigation)***, and tidal signatures
- *Mars Exploration* including atmospheric winds, density, and dust profiling, surface topography, **surface exploration and characterization**, search for organic signatures, moisture distribution, and cloud characterization
- *Martian Mission Support* including **precision landing, navigation, and hazard avoidance,** sample return rendezvous and capture, atmospheric characterization to support entry, descent, and landing
- *Titan and Venus* including **balloon-borne active optical instrumentation** ***(for navigation)***

6.6 A HAZARD DETECTION SENSOR FOR LANDING ON EUROPA

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ABSTRACT

Based on the limited imagery available, the surface topography of Jupiter's icy moon Europa is expected to be hazardous for robotic landers. The Europa Lander Concept Pre-Project Team has therefore concluded that onboard hazard detection (and avoidance) using an imaging light detection and ranging (lidar) system is an enabling technology. In this paper we describe the challenges, requirements, technical solution space, and our maturation strategy to advance lidar technology for a Europa Lander mission concept to TRL 6 by 2021. JPL is confident that the resulting technology will be of value to a wide range of lunar and planetary landing missions.

1 INTRODUCTION

The Jet Propulsion Laboratory is currently investigating a Europa Lander mission concept that would search for evidence of life, assess its habitability via in situ techniques, and characterize the surface and subsurface to enable future robotic exploration [1]. However, autonomous safe and precise landing on Europa poses unique challenges.

The currently available surface imagery from the Voyager and Galileo spacecraft is limited in resolution. Roughly 10% of Europa's surface is imaged at scales of ≤ 250 m/pixel, while the rest is imaged at scales upwards of 1 km/pixel [2]. The highest resolution images (6-12 m/pixel) cover only 0.0001% of the surface. From the available data, it is theorized that meter-scale landing hazards, such as such as blocks, pits, domes, cracks, ridges, penitentes, icebergs or rafts are plausible [1]. The Europa Clipper mission is planning to image at least forty sites, ≥ 2 km × 4 km in area, at ≤ 1 m/pixel spatial resolution, thus vastly improving the ability to pre-select a safe landing site [1]. However, even this scale is insufficient to reliably detect all terrain features hazardous to a small robotic lander, motivating the need for an onboard active hazard detection sensor [5].

High-energy electrons and protons trapped by Jupiter's magnetic field result in an extremely intense ionizing radiation environment, which substantially affects sensor performance, possible modes of operation, sensor component selection, and flight qualification. Based on the current mission design trajectories and the GIRE-2p Jovian radiation model, the Lander is expected to experience a total ionizing dose (TID) of ~1.7 Mrad, primarily from electrons, behind 100 mil of aluminum (Si equivalent). Most Lander electronics will likely be housed in a radiation vault similar to that used on Juno, which would decrease the expected TID to 150 krad (Si) or less. All electronics within the vault would need to be rated to 300 krad to maintain a radiation design factor of two (RDF = 2) [4].

Europa Lander would have to comply with NASA planetary protection procedural requirements [3] and, as an anticipated Category IV mission, the probability of contamination (defined as the introduction of a single viable terrestrial microorganism) must be less than 10^{-4}. The implication of these requirements on Lander hardware, including the hazard detection sensor, is that it must be sterile before it reaches the surface. The planetary protection strategy would likely consist of several sterilization techniques including cleaning and dry-heat microbial reduction (DHMR). For components which can be neither cleaned nor heated, the project would consider incineration devices onboard the vehicle to destroy any residual biological material.

Finally, the launch mass to landed mass ratio for a Europa lander is approximately 50-to-1 (i.e., for every kilogram delivered to the surface of Europa, approximately 50 kg of launch mass is required). This results in the need to minimize size, weight, and power (SWaP) through optimized sensor design, packaging, and shielding.

2 METHODOLOGY

The Europa Lander Deorbit, Descent, and Landing Concept of Operations is illustrated in Figure 1.

The sequence starts with a Deorbit Burn that uses a solid rocket motor (SRM) to reduce the velocity from ~1900 m/sec to ~70 m/sec. At burnout, the vehicle is at an altitude of 5 km. After jettisoning the SRM, the spacecraft turns to nadir to perform Terrain Relative Navigation (TRN). The TRN function uses a passive imager, a laser altimeter, a dedicated vision compute element, and an on-board map to compute the absolute location of the vehicle in a Europa fixed frame and its 3-axis velocity relative to the ground. This information is then used to clean the trajectory delivery errors by performing a precision landing maneuver that delivers the vehicle to a 100 m radius ellipse centered around the targeted landing site and at 1 km altitude. The vehicle then starts a vertical descent trajectory until it reaches 500 m altitude where the Hazard Detection and Avoidance phase begins.

During the Hazard Detection and Avoidance phase the 3D lidar first scans an area of 100 m × 100 m, and creates a digital elevation map (DEM) with a 5 cm (3σ) voxel resolution in one second. The following second is then used to compute hazards over the 1.5 m radius lander footprint and select a landing site that avoids them. The third second is margin. The landing sequence continues by performing a trajectory maneuver that brings the lander over the safe landing zone, followed by precision velocimetry and altimetry starting at 100 m, and finally, by landing using the same SkyCrane technique employed in the Mars Science Laboratory.

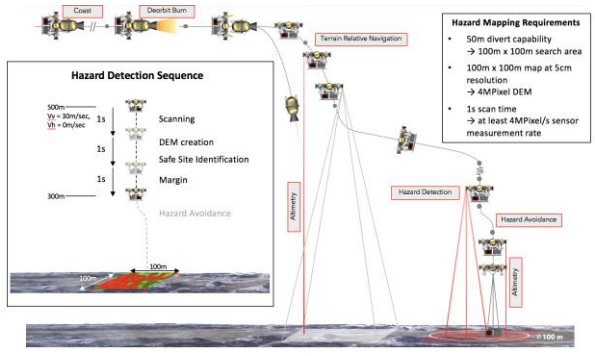

Figure 1 Deorbit, Descent, and Landing ConOps

During the 3D lidar image acquisition period the vehicle is descending at a nominal 30 m/sec vertical velocity and zero horizontal velocity with variations of up to 0.7 m/sec. The nominal attitude is with the sensor boresight pointing along the vertical with variations of up to 0.1 deg. The attitude knowledge can be assumed to be perfect but the 3-axis velocity knowledge can have an error of up to 0.6 m/sec that remains constant during the entire frame acquisition.

The SWaP requirements are: mass including radiation shielding < 7 kg, power < 50 W, volume < 25 cm x 25 cm x 25 cm (optical head and lidar signal processor, each).

The purpose of the Europa Lander lidar development is to field a sensor that fulfills the combined altimetry and hazard detection functions described above.

2.1 State of the Art

The driving requirement for the sensor is the measurement rate of 4 million range measurements per second from an altitude of 500 m (Figure 2). The state-of-the-art in planetary missions is represented by the OSIRIS-Rex Laser Altimeter (OLA) [6], with a measurement rate of 10,000 range measurements per second from up to 1 km altitude. While there are terrestrial sensors that can achieve higher range measurement rates from higher altitudes, none meets the Europa Lander SWaP, DEM generation time, and radiation requirements.

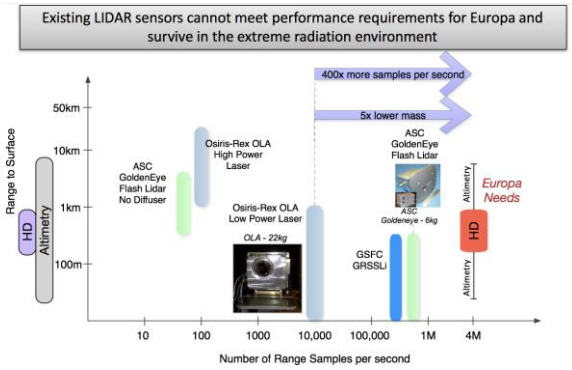

Figure 2 3D-Lidar State of the Art

2.2 New Approach

In order to meet these sensor development challenges, the Europa Lander team performed several technology surveys, including an RFI and an RFP, of the technology and industry capability around the world. The following is a brief summary of the technologies we surveyed.

Detection:

The detection technique drives the number of photons required to achieve a certain probability of detection and meet the range accuracy requirements, which have a large impact on sensor SWaP. It also drives the amount of processing required to produce a valid measurement as well as robustness to background noise. The different detection techniques can also present different degrees of challenges when it comes to constructing large sensor arrays. Finally, the intense radiation environment imposes strong requirements on the detector materials which can impact the detection technique.

The choices of detection techniques include Coherent vs. Incoherent Detection, and Continuous Wave (CW) vs. Pulsed Time-of-Flight (TOF). The Pulsed TOF detection options are Geiger Mode, Single Photon, and Linear Detection. The result of the technology survey narrowed the options to these three Pulsed TOF techniques.

Frame Acquisition:

Frame acquisition refers to how the range measurements are collected over the map area. There are three approaches: 1) scanning a single range detector in two axes over the area to be mapped, 2) flashing a detector array over the entire mapping area (i.e., no scanning is required), and 3) a hybrid approach in which an array of detectors is scanned in one or two axes. The first approach places challenging requirements on the scanning mechanism while the second approach is a challenge for the detector array and required laser power. The hybrid approach is a compromise which was embraced by most of the proposers and is the only one being pursued by Europa Lander at this time.

It is important to note that in any sensor concept which requires scanning—including the hybrid approach—the motion of the vehicle and the velocity and attitude knowledge errors during frame acquisition can result in map artifacts which are indistinguishable from real hazards (e.g., holes and seams). This is a critical consideration when selecting the size and shape of the detector array and the scan pattern and speed.

The FOV size (18° × 18°) of the sensor for this application opens up a large option space for scanning mechanisms: fine steering mirrors (FSM), rotating polygonal mirrors, galvo mirrors, and Risley prisms. Solid state scanning and MEMS mechanisms are not currently under consideration because of TRL, development risk, concerns about radiation, and/or incompatibility with the application.

Overall Architecture:

The other architectural choices that are being explored and that are unique to the Europa Lander application are: separate altimeter vs. common laser/detector for both functions, single box vs. separate optics and electronic boxes. We are also exploring several sensor output options like a single fully-registered DEM at the end of the scan vs. continuous registered maplets during the scan.

2.3 DESCRIBE THE FUTURE STATE

This development effort is already bearing fruit by defining a clear use case for hazard detection for planetary landings, including requirements and constraints, which is relevant to many missions, pushes the state-of-the-art in a realistic way, and provides focus to industry and government R&D efforts (e.g. SBIR's, internal R&D, etc.).

2.4 RISKS AND REWARDS

Radiation is the dominant risk followed by development risks (cost and schedule). As described in the following sections, these risks are mitigated by following a gradual and disciplined development strategy that retires risks through early testing and by avoiding premature selection of technologies and teams.

If successful, the 3D lidar sensor developed through this effort not only will enable the Europa Lander mission but will also have major uses in other lander applications: Mars, Moon, Comets, or Asteroids.

3 PROGRAMMATICS

The Europa Lander study team, including upper management, decided early that hazard detection and avoidance was an enabling capability for that mission and, as a result, started generating a plan to develop a hazard detection sensor. This decision was informed by prior hazard detection work conducted by JPL as part of the Autonomous

Landing and Hazard Avoidance Technology (ALHAT) program [7], ongoing SBIR work on lidar for hazard detection, and a general survey of the commercial technology that indicated that hazard detection sensing technology was at the right development level to be infused into Europa Lander.

3.1 STRATEGIC APPROACH

The Europa Lander 3D lidar requirements were derived by adapting the ALHAT concept of operations to the Europa Lander concept of operations and adjusting the DEM accuracy requirements to the physical characteristics of the lander.

It was recognized early on that to achieve the required high measurement rate the sensor architecture would have to employ an array of multiple detectors and an effort was started to study the maturity and radiation susceptibility of such detector arrays. For this purpose, funding from STMD Ocean Worlds was used to issue several study contracts to companies and academia with expertise in the field; these were small studies with a duration of three months. The conclusion from these studies was that there were multiple detector array approaches which could support the required measurement rates and survive/perform in the harsh radiation environment.

The next step was to issue an RFI for a full sensor concept. The responses to the RFI allowed us to gauge the interest in the private sector for participating in the sensor development and to survey once again the technologies that could be employed in such a sensor.

At this point a sensor development strategy was formulated to try to avoid the shortcomings in previous efforts where the technology and the developing organization were down-selected too early in the process. The resulting strategy is centered on bringing two sensor concepts to TRL-6 by Europa Lander PDR in 2021, each concept developed by independent teams and, desirably, using competing technologies. The plan is also for both efforts to produce a fieldable sensor breadboard for performance testing in a relevant flight envelope by JPL. In addition, the two teams must show that the sensor concept can be built into flight units that meet SWaP requirements and that it can be flight qualified to survive and perform in the expected space environment (vibration, shock, thermal, radiation). Radiation is of particular concern and each team is expected to provide and execute a plan that includes the proper combination of parts analysis and, for key components in the sensor architecture, radiation tests.

The development effort is divided into three phases with two gates between them for down-selection or termination. During the first phase the requirements are finalized, the concept and technology refined, and the plan for dealing with radiation developed. The second phase is a detailed design phase, continuation of component radiation testing and other risk mitigation efforts. During the third phase, the component radiation testing is finalized and the fabrication and assembly of the breadboard is completed. It is also expected that during the third phase a proposal to develop the flight instrument will be generated by each team.

We have selected three teams for the first phase of the effort to be selected down to two at the end of the phase.

One of these three teams is a commercial company, Sigma Space LLC., which was selected through a rigorous competitive process by issuing an RFP and selecting a winner. The second team is MIT/Lincoln Laboratory (MIT-LL), a federally funded research and development center (FFRDC) with expertise in Geiger Mode lidar. The third team is NASA Goddard Space Flight Center (GSFC) with expertise in lidar for space applications.

After all contracts are completed and after the tests of the breadboards and evaluation of the proposals are finished, the Europa Lander team will decide on the strategy for the development of the flight units. Among the possible strategies, and depending on the results of the ongoing effort, the project may elect to pursue a single source award to implement one of the concepts developed by the current effort or to open the competition to other teams and technologies by issuing an RFP. The second scenario might include an important relaxation of requirements based on what we would have learned so far.

3.2 DEVELOPMENT PLANS AND MILESTONES

The current effort must achieve TRL-6 by Europa Lander PDR in 2021. The six-month long Phase 1

development is currently near completion. Phase 2 is also planned for a six-month duration and Phase 3 for 18 months.

3.3 PARTNERING

Building on more than 10 years of partnering with NASA Johnson Spaceflight Center (JSC), Langley Research Center (LaRC), and Marshall Space Flight Center (MSFC) in ALHAT and SPLICE in hazard detection, JPL has engaged ALHAT leadership to support the Source Evaluation Team for the Europa Lander Hazard Detection lidar.

The teams that have been selected for Phase 1 include a NASA center, GSFC, an FFRDC, MIT-LL, and a commercial company, Sigma Space LLC.

JPL continues to engage the commercial sector and academia through SBIRs and other study contracts.

3.4 OVERCOMING THE VALLEY OF DEATH

The Europa Lander mission concept study has determined that hazard detection and avoidance is a mission enabling technology and has recommended that the project funds the development of the sensor.

4 WIDER VISION

The Europa Lander mission concept study had to consider technologies that could achieve TRL-6 by 2021. Among the technologies that were left out and that should be pursued by NASA with separate funding are: Coherent detection for combined Doppler velocimetry including optical microchips, different detector materials for lower noise (e.g. MerCadTel), continuous wave (CW) concepts that leverage image sensors, solid state beam steering approaches, and improved linear mode detector arrays.

In addition, NASA should consider leveraging the large developments and advances being pursued by the auto industry.

5 CONCLUSIONS

The Europa Lander mission concept study is currently engaged in the development of a high-performance 3D-lidar for hazard detection that must survive and perform in the harsh radiation environment of Europa.

The sensor development approach leverages the best technology and expertise provided by government agencies and the private sector.

If successful, the 3D-lidar sensor developed by this effort not only will enable the Europa Lander mission but it will also have major utility for other lander applications: Mars, Moon, Comets, Asteroids.

ACKNOWLEDGEMENTS

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NASA Active Optical TIM
Columbia, Maryland
July 31, 2018

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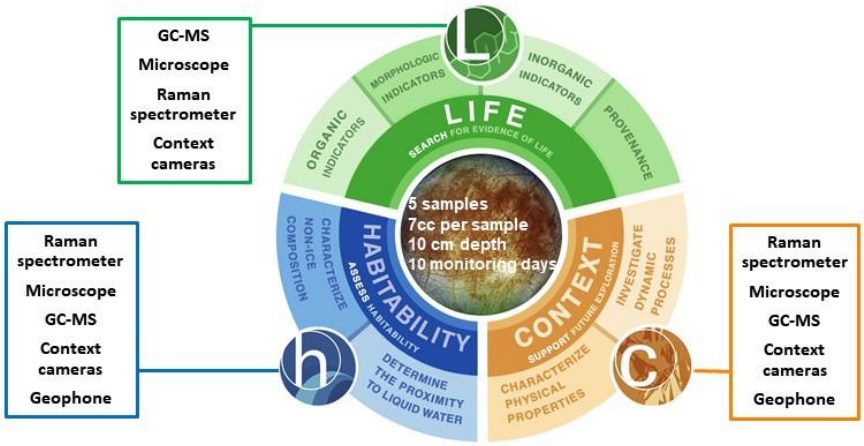
Science Definition Team Recommendations

A connected set of goals and objectives addressed with a focused model payload



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Scientifically interesting Locations on Europa are Likely to Have More Challenging Topography



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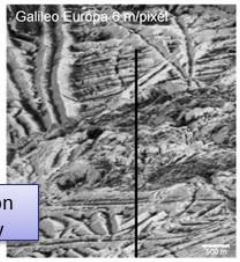
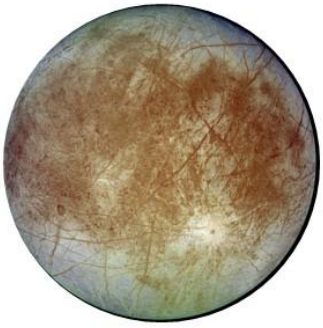
Challenges of Landing in Europa

Current Lack of High-res Recon Maps

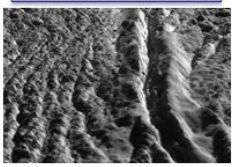


Highest Resolution Europa image currently available

Illumination Variability



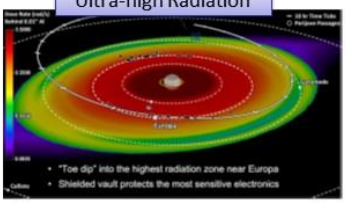
Highly Hazardous & Unknown Terrain





Limited Lander SWAP Resources

Ultra-high Radiation





Large Propulsive Delta-V

Less than 10^{-4} probability of introducing a single "Viable Organism" to any Europa habitable zones

Planetary Protection

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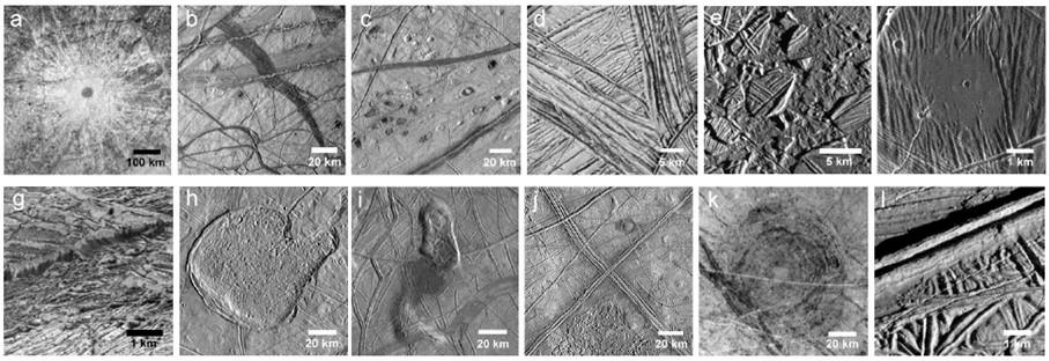
Galileo Images Show Europa Having Rugged, Unusual Terrain



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Penitentes







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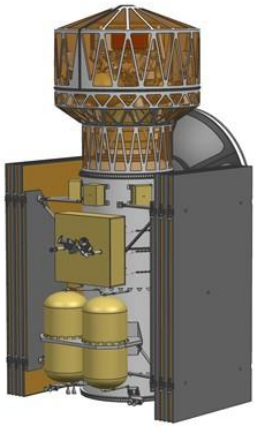
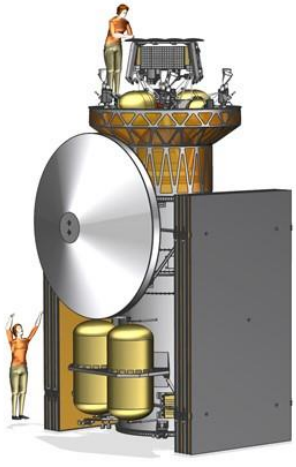
Launch Stack Is About Three Stories Tall





Artist's concept

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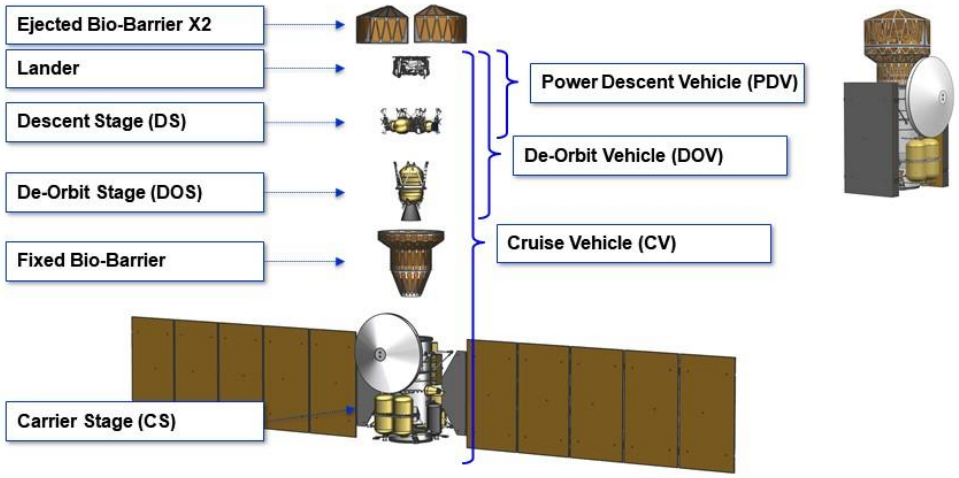
Flight System Launch Assembly & Nomenclature



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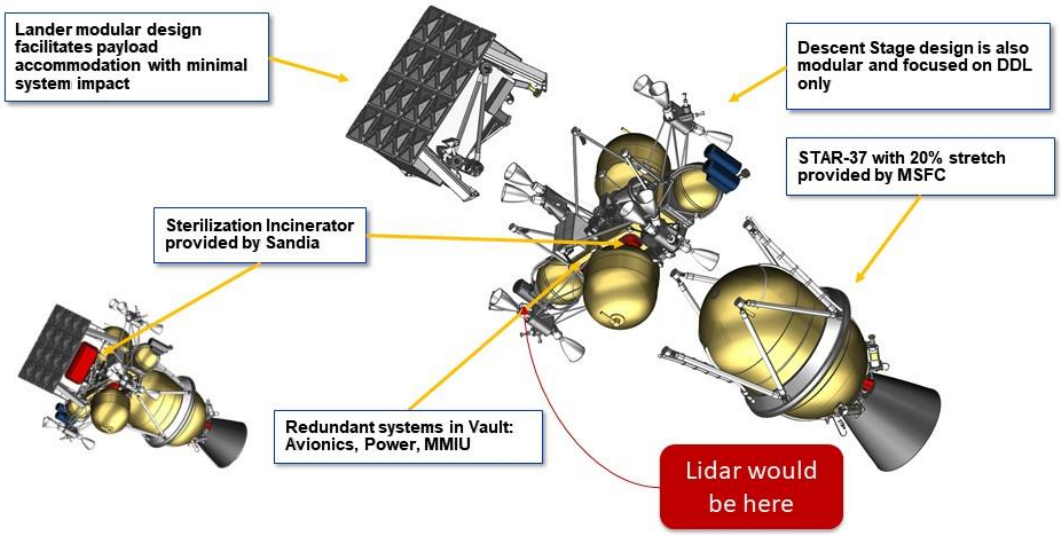
De-Orbit Vehicle Has a Modular Concept



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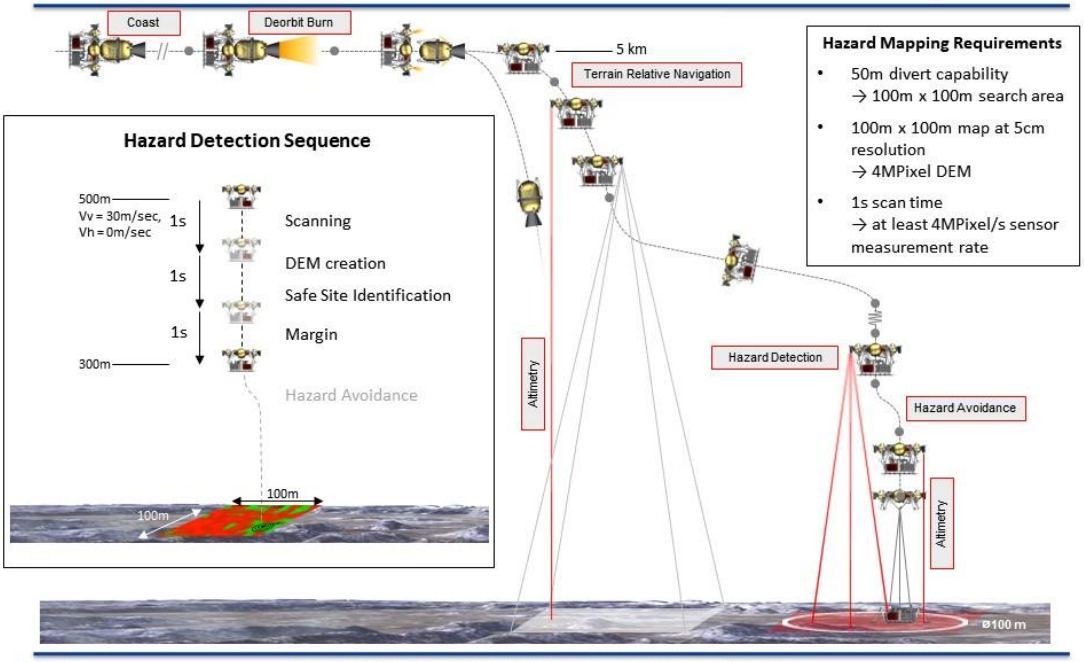
DDL ConOps





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LIDAR Requirements

- DEM Generation
  - 100m x 100m
  - 5cm grid spacing
  - 5cm (3 sigma) elevation error
  - < 2 sec data acquisition and DEM generation time
- True Trajectory
  - Altitude = [400-500]m
  - Constant vertical velocity V_v = 30 m/s, +/- [0.4-0.7] m/s
  - Zero horizontal velocity V_h = 0 m/s, +/- [0.4-0.7] m/s
  - Nadir-pointed attitude, +/- 0.1 deg change over 2 s
- Estimated Trajectory
  - Velocity knowledge error = [0.3-0.6] m/s (3 sigma) per axis, constant through acquisition
- Mass (including shielding) < 7kg
- Power < 50w
- Volume < 25cm x 25cm x 25cm (optical head, electronics box, each)
- Radiation TID
  - 1.7Mrad (Si) behind 100mil of aluminum
  - 300 Krad (Si) inside electronic vault (RDF = 2)

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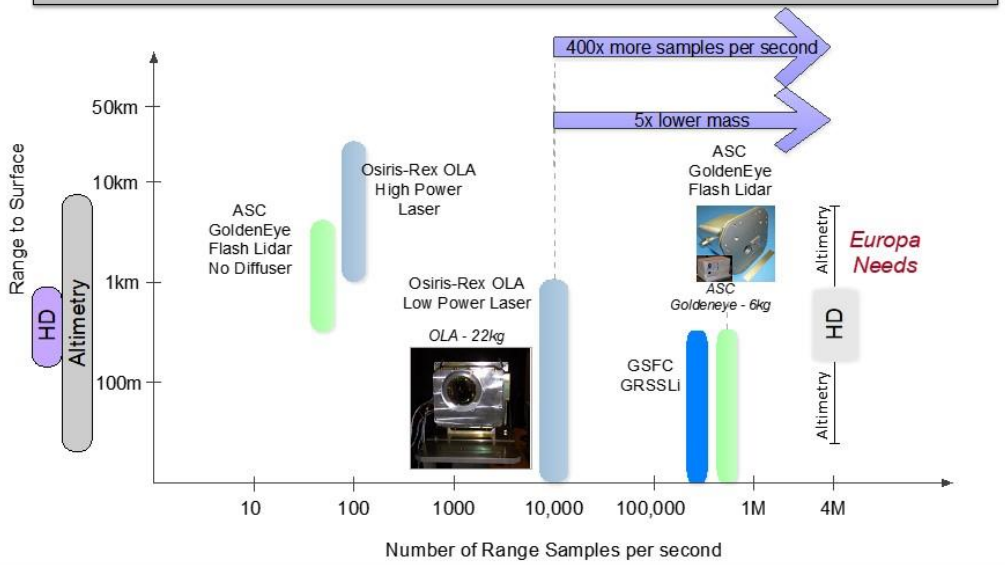
Comparisons with State-of-the-Art

Existing LIDAR sensors cannot meet performance requirements for Europa and survive in the extreme radiation environment



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Preliminary Studies and Background

- ConOps and LIDAR requirements developed based on ALHAT experience
- Technical management of SBIR's for space HD applications
- Issued Europa Lander detector array study contracts
  - Feasibility
  - Radiation susceptibility
  - Detector architecture
  - LIDAR architecture
- Issued Sensor RFI
- Issued RFP

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Trade Space

- Detection
  - Coherent vs. incoherent
  - CW vs. Pulsed
  - Linear Mode
  - Single Photo Detection
  - Geiger Mode
- Frame Acquisition
  - Flash LIDAR
  - Scanning single detector
  - Scanning array of detectors
    - Size and shape of detector array
- Scanning approach
  - Galvo mirrors
  - Polygonal mirrors
  - Fast Steering Mirrors
  - Risley prisms
  - Solid state
  - MEMS
- Overall Architecture
  - Separate altimeter vs. combined altimeter/HD
  - Separate optical head vs. single integrated box

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Sensor Development Approach (part 1)

- Objective: TRL 6 by Europa Lander PDR (2021)
  - Prove that the Design meets performance requirement in the relevant flight-envelope (altitude, velocity, angular rates, terrain, etc.)
    - Field Tests with Brass-board
  - Prove that the Design can be space qualified
    - Parts lists analysis
    - Component radiation testing
    - Radiation Test Unit for testing by JPL
  - Prove that the resulting Flight Model will meet SWaP requirements
    - Preliminary detailed design for EM and FU
  - Prove that the Flight Unit can be developed within project costs and schedule constraints
    - Development team including partners and component vendors
    - Preliminary cost and schedule plans

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Sensor Development Approach (part 2)

- Approach:
  - Select two teams to develop two TRL-6 designs with the following deliverables
    - Detailed design description and performance analysis
    - Fieldable Brass-board
    - Radiation Test Unit
    - Parts analysis and selection
    - Radiation testing of critical components
    - Preliminary detailed design for EM and FU
    - Preliminary cost and schedule for EM and FU
  - 3-Phase development with 2 gates for down-selection and/or termination
    - Phase 1: Systems Engineering & Trade Studies
    - Phase 2: Detailed Design
    - Phase 3: Build & Test Brass-board

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Sensor Development Approach (part 2)

- Status:
  - Three vendors selected for Phase 1
    - Sigma Space
      - Commercial vendor with experience in aerial terrain mapping and LIDAR for space, selected competitively after issuing RFP
    - MIT Lincoln Labs
      - FFRDC specialized in Geiger Mode LIDAR
    - Goddard Space Flight Center (GSFC)
      - NASA center with experience in altimetry for space applications (MOLA, LOLA, etc.)
  - Phase 1 almost complete

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Conclusions

- The Europa Lander Study is developing a Hazard Detection LIDAR sensor that represents a significant jump in sensor performance and SWaP while meeting the harsh radiation European environment
- A careful sensor development strategy was developed based on previous experiences
- Three vendors have been selected with designs that span a large architectural space

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Pre-Decisional Information — For Planning and Discussion Purposes Only.

6.7 SPEED SENSOR FOR PLANETARY EDL "SPRY"

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ABSTRACT

A compact optical speed sensor for planetary EDL is presented. The Doppler shift of the back scattered light from particulates and gas molecules is detected by observing the whispering gallery mode shifts of a micro-resonator. The resonator replaces the typical Fabry-Perot interferometer, miniaturizing the detection system. The current effort opens the path to extremely compact optical air data systems for NASA's efforts in the development of manned aircraft and UAVs, atmospheric entry, and hypersonic platforms.

1 INTRODUCTION

The main motivation of the present effort is the need for accurate speed measurements during atmospheric entry of spacecraft. During the entry, descent, and landing (EDL) phase of planetary missions, accurate information on vehicle velocity, altitude, and attitude are critical for success of the EDL operation. While fully integrated and tested devices for direct optical measurement of airspeed are commercially available, many are too bulky and far too heavy to be feasible for planetary exploration and other high-speed applications.

The measurement principle of a WGM based micro-resonator is similar to that of a Fabry-Perot interferometer, with a few, mainly geometric, exceptions. The most significant difference is the cavity shape. The WGM based micro-resonators are spherical (rather than linear or confocal as for most FP interferometers), but may also be cylindrical, disk, racetrack or toroidal in shape. The optical path must remain close to tangential in order to ensure that light in the cavity experiences total internal reflection and remains trapped inside the sphere.

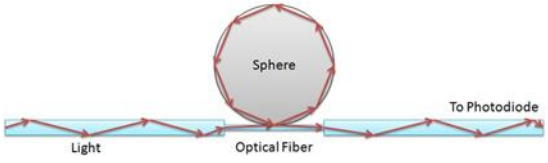

Figure 1. Fiber Coupled WGM Micro-resonator

Figure 1 shows, schematically, a typical fiber coupled WGM micro-resonator configuration. Laser light is coupled into the sphere through the optical fiber (or another type of waveguide) at grazing angle. When the light returns to its entry point exactly in phase, an optical resonance is observed. We can estimate the optical resonance condition to be

$$2\pi r n0 = l\lambda \quad (1)$$

Where r and n_0 are the resonator radius and refractive index, λ is the vacuum wavelength of the interrogating laser and l is an integer representing the circumferential optical mode. Equation (1) holds for $r >> \lambda$. When the light from the laser is tuned across a narrow range, the optical WGM resonances are excited each time the condition of Equation (1) is met. The WGM are observed as sharp dips in the transmission spectrum by a photodetector placed on the other end of the fiber. Each dip in the transmission spectra corresponds to a different integer value of l.

The fact that light is coupled into the WGM micro-resonator tangentially and remains in the resonator via total internal reflection, rather than just the high reflectivity and/or anti-reflective coatings of FP interferometer components, means that the resonator itself has very low optical loss. The losses in a given resonator are described in terms of, Q, the optical quality factor, which is the ratio of energy stored to energy lost. The linewidth of the observed resonances, $\delta\lambda$, which directly impacts the measurement resolution, is related to Q as

$$Q = \lambda/\delta\lambda \quad (2)$$

The reason WGM micro-resonators in this configuration show so much promise for planetary exploration and high velocity flow applications is the unusually high Q they demonstrate with a remarkably small physical size and mass. We routinely achieve values in excess of 10^7 in our lab and values greater than 10^9 have been demonstrated by researchers elsewhere.

High optical quality factor dielectric microspheres have received significant attention for their potential application in a wide range of fields. WGM applications have been explored in communication (switching, filtering, and multiplexing) and sensor technologies [1]. Sensors utilizing the whispering gallery mode (WGM) shifts of microspheres have been proposed for impurity detection in liquids [2], mechanical sensing, including force [3] pressure [4] temperature [5] and wall shear stress for aerodynamic applications [6, and references therein].

In the present application, we shine a narrow line-width tunable laser at a target, collect scattered light, and couple it into a micro-resonator. The collected light is first coupled into a single mode fiber and then side–coupled into the micro-resonator in a similar fashion to that depicted in Figure 1. The only difference is that light scattered from a target travels through the fiber rather than the laser light itself. We observe the WGM as a series of troughs through the transmission spectra (photodiode output) as we tune the narrow-line interrogation laser. The WGM shifts in the spectra, relative to a reference spectrum taken while the target is stationary, are proportional to the Doppler shift of the scattered light from the target. In the atmospheric application, the scattering is expected to be a combination of Mie (scattering from particulates in the atmosphere) and Rayleigh (molecular scattering from small particulates and gas molecules). In the present phase of the study, as a first order proof of concept, we measure the rotational speed of a disk using a low power, narrow line, tunable Littman-Metcalf cavity diode laser as the light source [10]. The scattered light from the target location is collected and fed (via side coupling) into the micro-resonator. As the laser frequency is tuned over a narrow range, the optical modes (WGM) of the resonator are excited by the surface-scattered light. The fiber serves as an input-output device, and is connected to a free space to fiber coupler on one end and a photodiode on the other. The experimental setup is shown schematically in Figure 2.

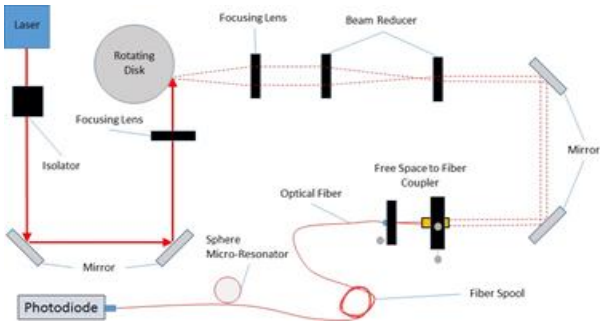

Figure 2. Experimental Setup

Using the setup described above, we performed a set of experiments with different disk rotational speeds. A summary of these preliminary results is presented in Figures 3 and 4.

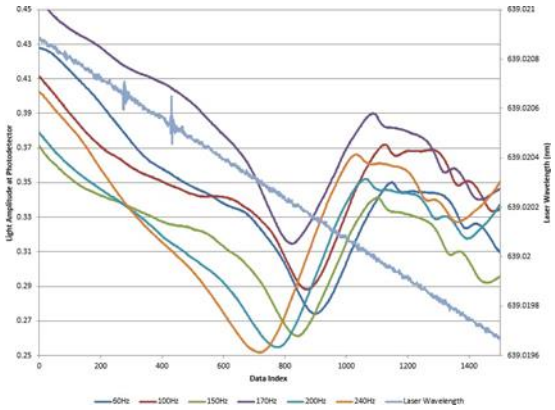

Figure 3. Transmission Spectrum

The laser was scanned at a rate of 700 Hz using triangle waveform. Across each scan of the laser, 6000 digitized data points were recorded to form the transmission spectra. Figure 3 shows a subrange in the transmission spectra that captures a single WGM at various disk frequencies, along with the corresponding laser. As the disk's rotational frequency increases, the WGM moves to the left (longer wavelengths) due to Doppler shift. The curve for each disk frequency shown in the figure is an ensemble average of approximately 600 successive scans of the laser. Ensemble averaged transmission spectra are used to determine the WGM and the Doppler shifts. The total duration for each measurement is on the order of a second.

Figure 4 shows WGM shifts (corresponding to the Doppler shifts) of the data of Figure 3. This figure presents three different approaches of determining dip location, along with the least squares

regressions for each resonance shift detection method.

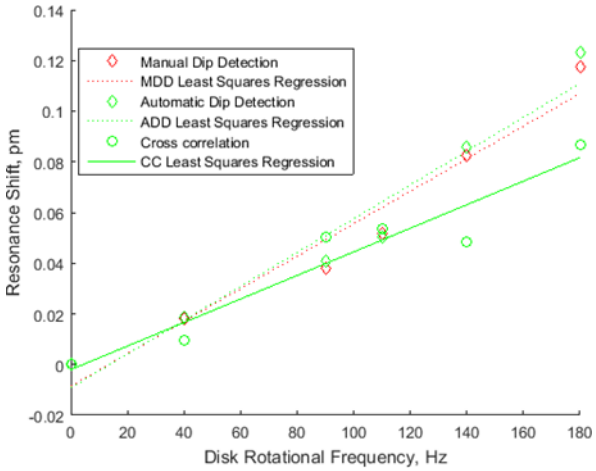

Figure 4. WGM Shift vs Disk Rotational Frequency

In the manual dip detection (MDD) method, WGM shifts are determined visually by selecting the location of the minimum value of each dip. The automatic dip detection (ADD) method uses software to choose the absolute minimum value in each data vector (ensemble averaged scan), which is much faster than MDD, but may be challenged by noisy data. In the last method, cross–correlation (CC) is performed between each data vector and a reference data vector. There is good agreement between MDD and ADD results. The CC results show slightly lower Doppler shifts and have a larger scatter, which perhaps indicates that further signal processing and/or an increased number of resonance features are required to allow a more robust cross–correlation approach. Cross–correlation approach generally is preferable to the ADD method, given that it is less susceptible to noisy data, and can be computationally less demanding.

2 METHODOLOGY

2.1 STATE OF THE ART

Current state of the art to measure molecular Doppler shifted light relies generally on Fabry-Perot interferometers (in the absence of aerosols). While the technique has yielded reliable results, the hardware is bulky and extremely sensitive to the environment. The current NASA TRL for the project is 5.

Figure 5 displays the laboratory setup. The backscattered light is collected using a receiver. Two options are being investigated, the first is to couple light from the receiver into a multimode fiber, to then couple light into a single mode fiber with a coupler, or couple light directly into a single mode fiber using a parabolic mirror. The collected light is passed through the resonator into a detector.

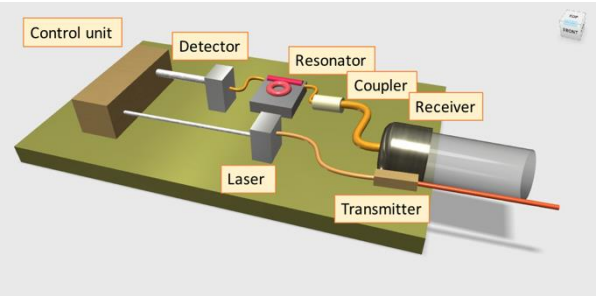

Figure 5 SPRY experimental setup

The project includes the following technical demonstration:

- Light coupling efficiency from the collection optics: The collection optics need to be able to collect sufficient amount of light into a single mode fiber. As an alternative solution, light could be coupled into the resonator using free space optics. The current effort is investigating free space optics coupling.
- Light coupling efficiency into the resonator from waveguide.
- Resonator temperature stability: stabilization of the resonator assembly (1 mm x 1 mm) requires low power.
- Signal Processing: cross correlation has shown to be a simple yet accurate approach to determine the Doppler shift in laser scans. This approach allows the use of FPGA for signal processing, a low power convenient approach.

2.2 NEW APPROACH

The current development path includes a technology demonstration in the laboratory using a controlled jet flow. The flow will be seeded to provide aerosol (narrow line) backscattered light. Subsequently, the setup will be tested using molecular scattering (temperature-broadened signal). The laboratory demonstration will bring the instrumentation to TRL 5. Subsequently, the air data sensor will be packaged for planetary applications and on-board speed sensing.

2.3 RISKS AND REWARDS

At this time, there is no air data sensing capability for high-speed vehicles. We anticipate that this technology will be used to instrument hypersonic vehicles. Moreover, as optical air data sensing develops to provide an alternative to Pitot tubes, this technology affords a very compact, low power approach.

3 PROGRAMMATICS

The first project milestone will be the completion of the NASA SBIR Phase II. At the Phase II completion, the sensor principle will have been demonstrated and the sensor performance established. The second milestone will be to identify a partner in the development of a commercial product.

3.1 PARTNERING

Partnering with industry for a commercial sensor development will be the preferred approach. Honeywell is already involved in the project as the manufacturer of the resonators.

3.2 OVERCOMING THE VALLEY OF DEATH

If successful, this sensor potentially addresses a growing need in molecular air data sensing. The risk will be mitigated through partnership with industry.

4 WIDER VISION

Whispering gallery mode technology has already been demonstrated in other applications, such as seismometer development [7]. The technology developed during this effort contributes to other areas of applications.

5 CONCLUSIONS

The preliminary results are encouraging. For example, the current preliminary results indicate that, for a back-scatter LIDAR system using a side-coupled WGM resonator, a velocity resolution of 2.4 m/s is possible. Signal processing that selects scans with variances over a certain threshold value can at least partially mitigate the signal dropout effects when using fiber-coupled approach. Another possible approach to mitigate signal dropout due to beam steering may be direct (free space) coupling of scattered light into the optical resonator and observing the WGMs in the light scattered from the resonator. If successful, this technology will lead to compact, and low power approach to optical air data sensing for commercial and R&D applications.

ACKNOWLEDGMENTS

We gratefully acknowledge the support of NASA through SBIR Phase I and II contracts, No.: NNX17CL10C, with Dr. Farzin Amzajerdian as Program Manager.

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SPEED SENSOR FOR PLENATARY EDL "SPRY"

Dominique Fourguette and Volkan Ötügen

NASA TIM AOS Meeting, Columbia, MA

*Supported by NASA through SBIR Phase I and II programs with Dr. F. Amzajerdian as Program Manager

Outline

- Project Motivation
- Measurement Principle
- Proof of Concept
- Applications
- Conclusion and Questions

MICHIGAN AEROSPACE

Planetary EDL

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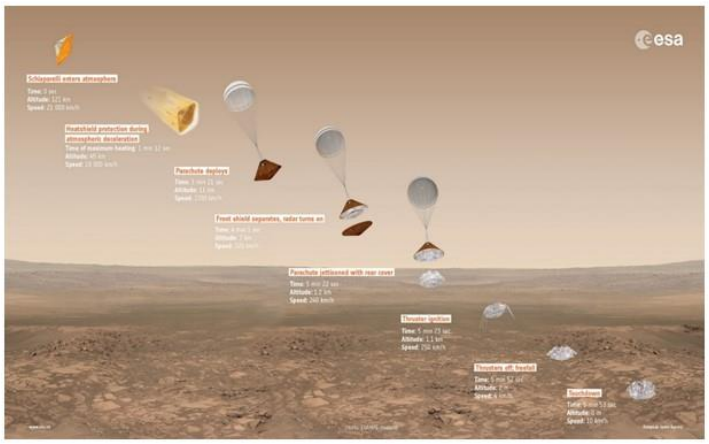


Need for lightweight, compact, rugged and reliable speed sensors for EDL

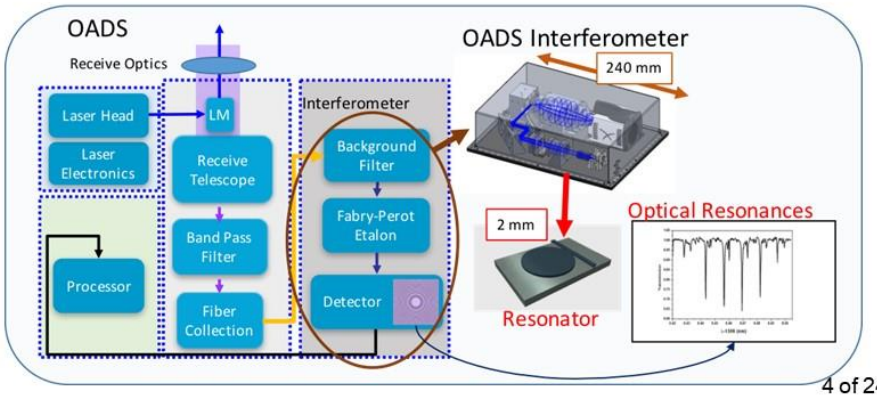
Other possible OADS applications: Aircraft & hypersonic platforms

MICHIGAN AEROSPACE

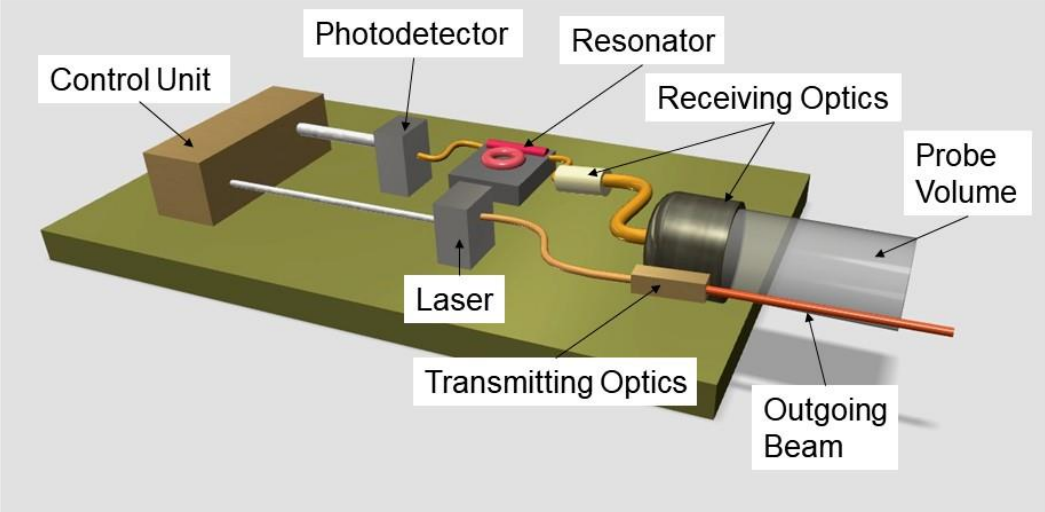
Optical Air Data Sensing

SMU

- Direct detection of Doppler shift in backscattered light utilizes a Fabry-Perot interferometer
- This effort aims to replace the interferometer with a micro-resonator



Schematic



Whispering Gallery Modes

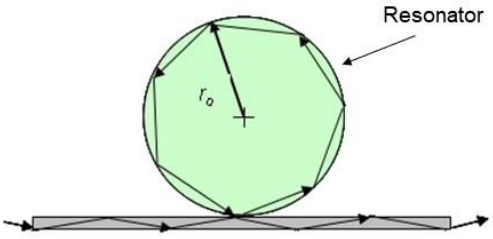
Optical resonance condition:

$$2\pi r n \approx \ell \lambda$$

Any perturbation in resonator refractive index or radius will lead to:

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta\nu}{\nu} = \frac{\Delta n}{n} + \frac{\Delta r}{r}$$

Quality factor $Q = \dfrac{\lambda}{\delta\lambda}$



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Resonances

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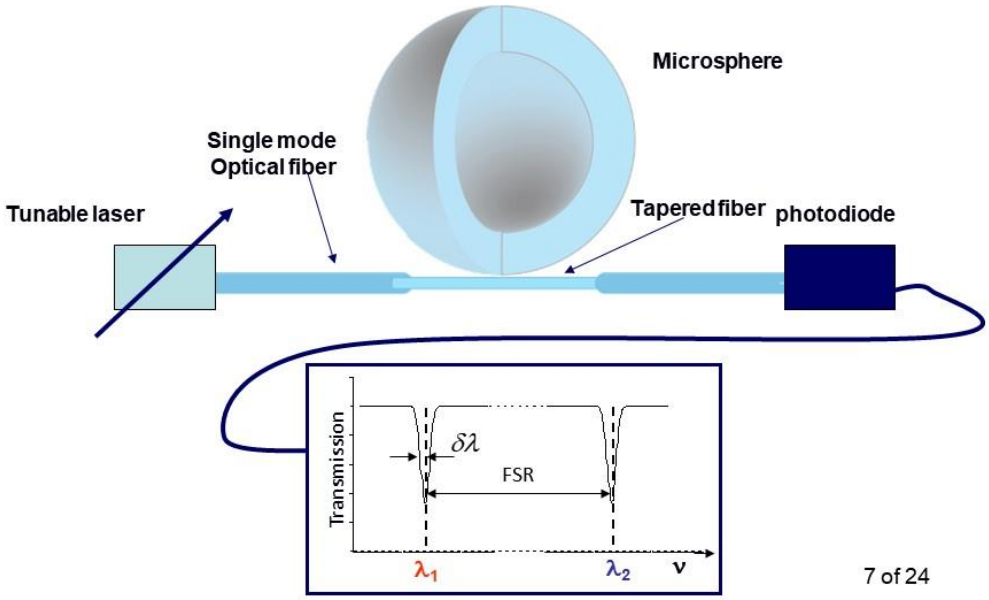

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Proof of Concept

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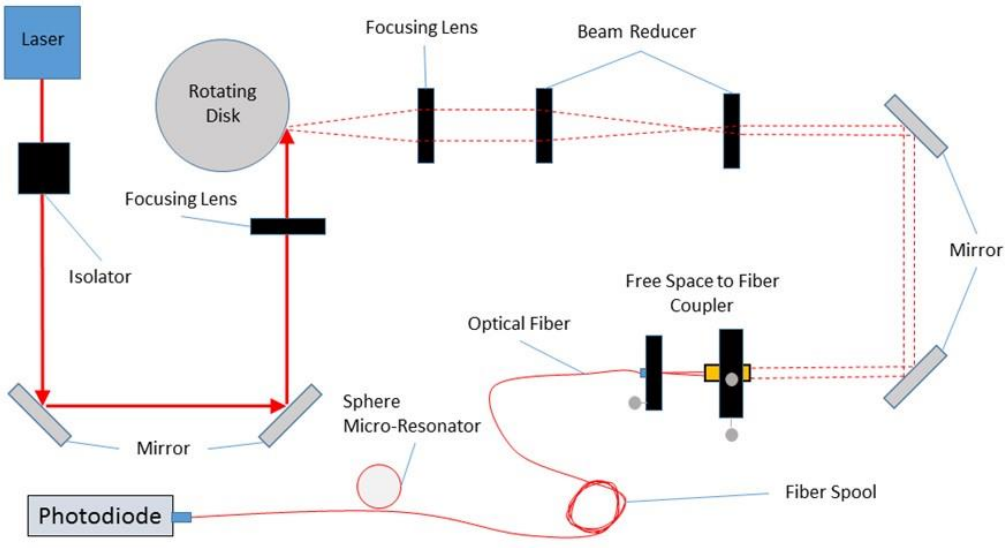

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Experimental Setup

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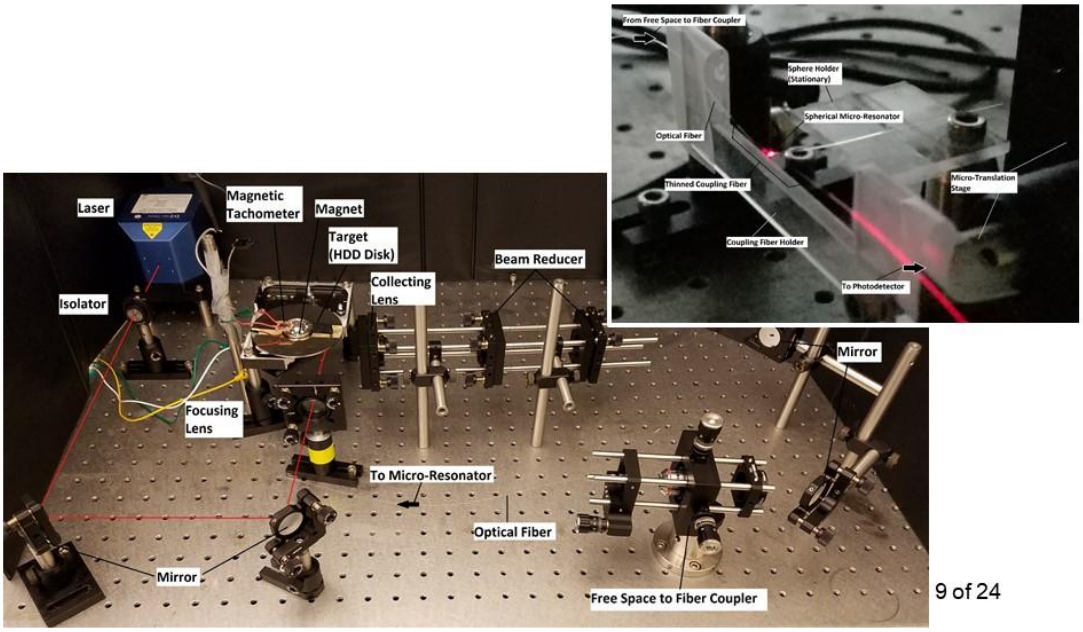

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Resonances

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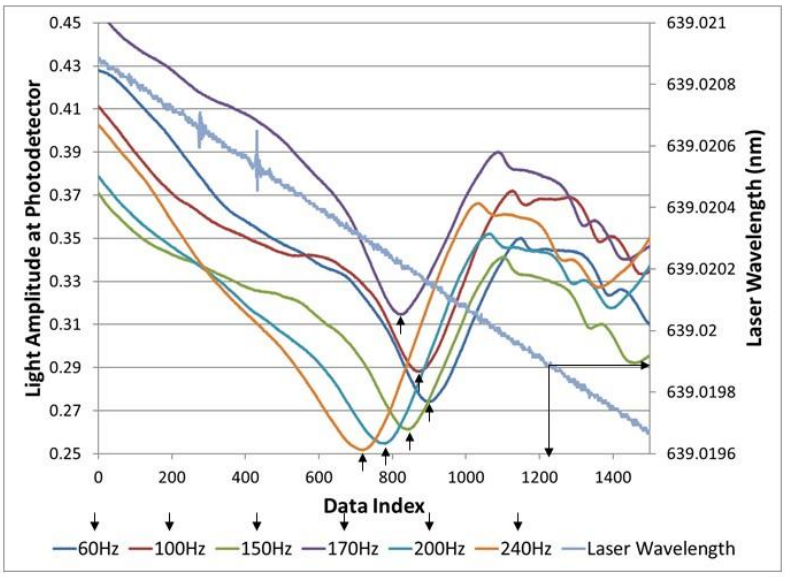

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Velocity Calculations

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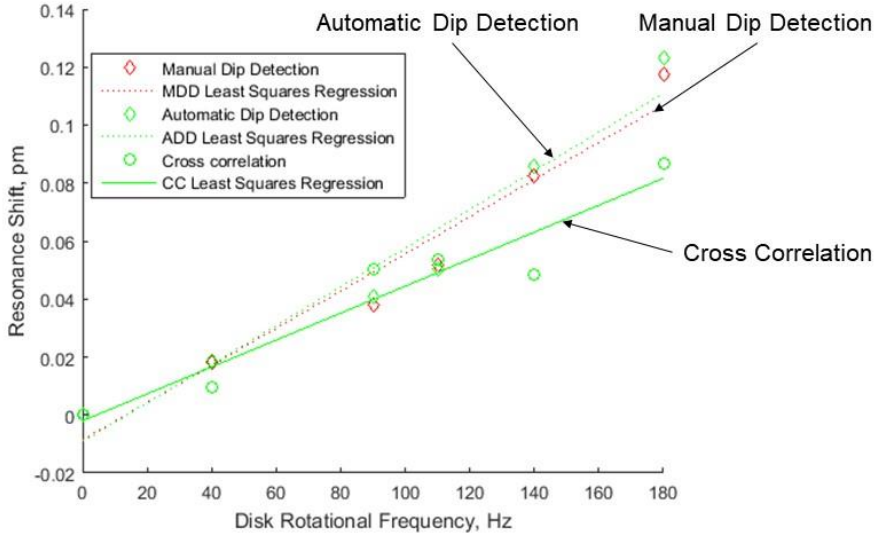

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SIGNAL PROCESSING

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Typical Signal

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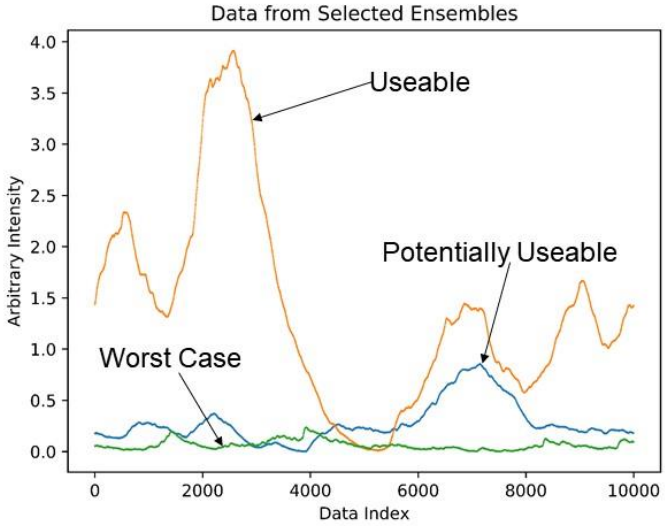

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Filtering

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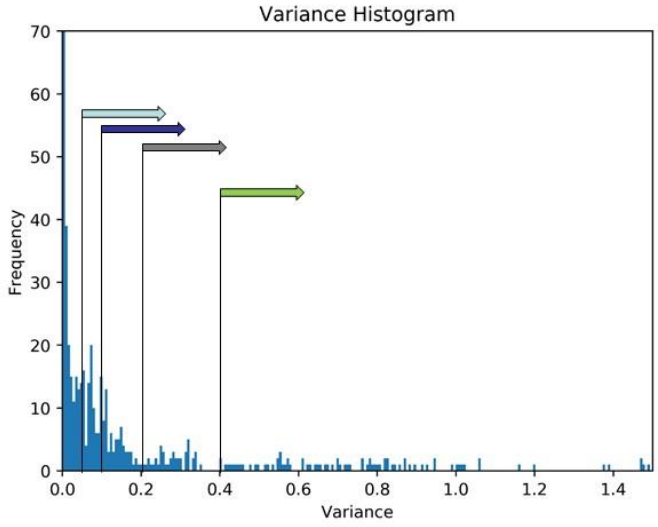
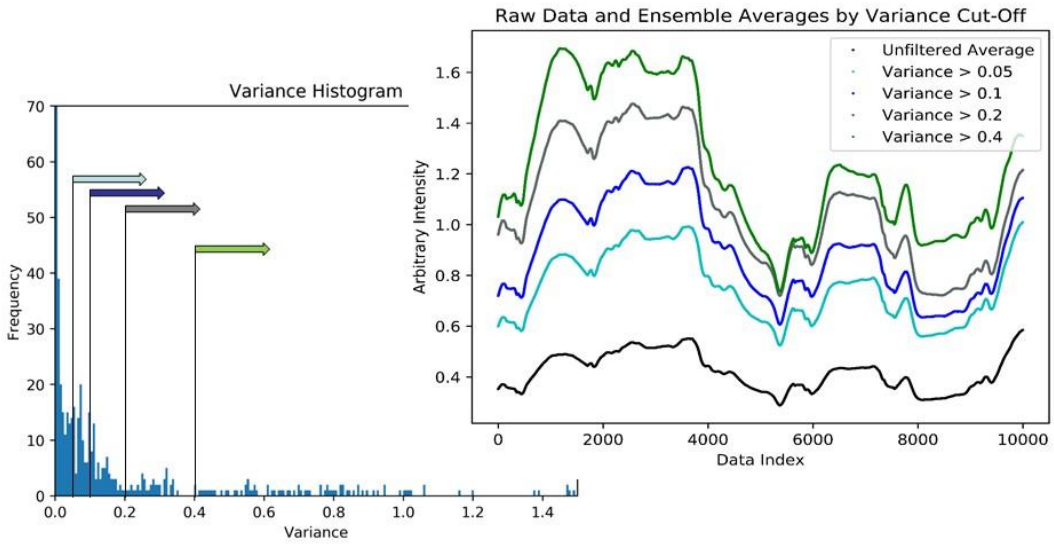


Variance Filtered Resonances



Challenges

- Backscattered light:
  - Signal level: coupling in SM fiber
  - Proof of concept was achieved using a rotating disk to generate Doppler shifted light
  - Current effort will demonstrate the concept with a jet flow.
    - Flow will first be seeded with particulates to test the concept without molecular broadening.
    - Purely molecular scattering with pressure broadening will then be tested
- Stability:
  - Resonator is small, straightforward to stabilize

Programatics (SBIR Phase II)

- The first project milestone will be the completion of the NASA SBIR Phase II. At the Phase II completion, the sensor principle will have been demonstrated and the sensor performance established.
- The second project milestone will be to identify a partner in the development of a commercial product.

Future Development

- Partnering with industry for a commercial sensor development will be the preferred approach.
- Honeywell is already involved in the project as the manufacturer of the resonators.
- Development of a flight worthy instrument and packaging will be the goal of the next development phase.

Conclusions

- Conclusions
  - Demonstrated measurement of Doppler-shifts of laser light scattered from a moving target
  - Due to high resonator Q-factors, very small changes in the velocity can be determined
    - Current results indicate a 2.4 m/s velocity resolution
  - Demonstrated a signal processing approach that may mitigate the effect of signal dropout
  - Demonstrated a direct (free-space) coupling approach to further mitigate effect of signal dropout

BACKUP MATERIAL

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A Microresonator Based Laser Velocity Sensor

SMU

FREE SPACE COUPLING

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A Microresonator Based Laser Velocity Sensor

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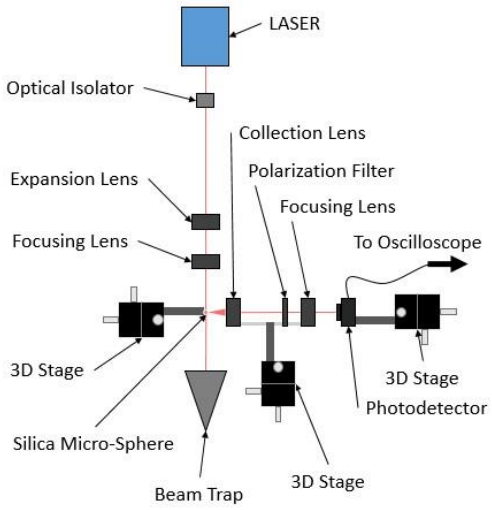
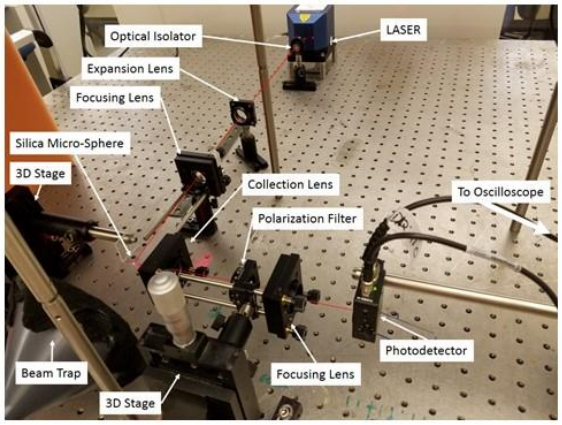
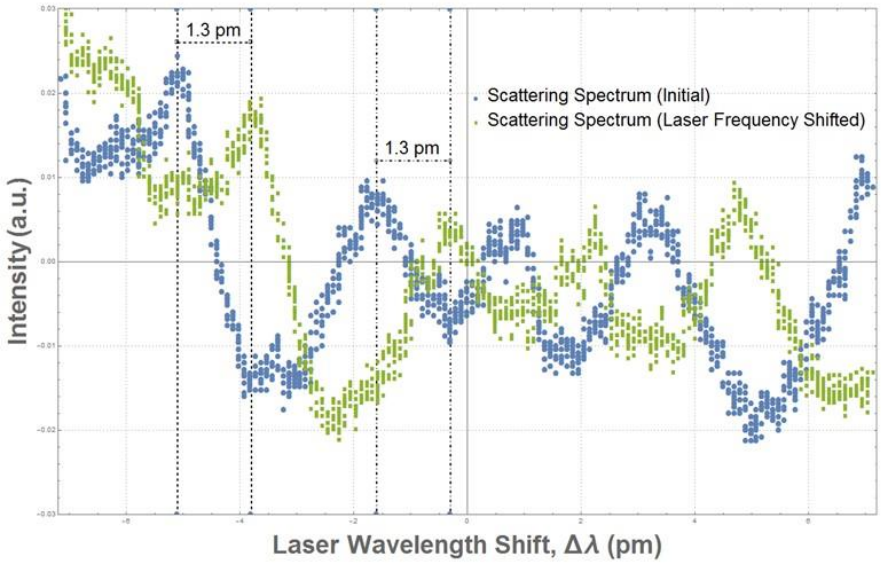




A Microresonator Based Laser Velocity Sensor



7 Session 7

Exploration was designed to examine issues related to supporting the overall exploration architecture. The Session Chair, Chris Moore, gave an overview presentation of the area to start the session. A total of five research presentations representing the work of researchers at GSFC, LaRC, JPL, JSC and SCaN was received. Table 7-1 lists the six session papers. See Section 3 of the Assessment Report for observations and assessment comments.

Table 7-1. Session 7 Papers

Paper Number	Author	Title	Paper	Presentation
S7-1	Chris Moore	Overview		☑
S7-2	Don Cornwell, NASA SCaN	NASA's Optical Communications Program for 2018 and Beyond	☑	☑
S7-3	Antonios Seas[1], Bryan Robinson[2], Tina Shih[2], Farzana Khatri[2], and Mark Brumfield[1] [1]NASA GSFC; [2]MIT Lincoln Laboratory	Optical Communication Activities through the Laser-Enhanced Mission Communications Navigation and Operational Services (LEMNOS) Office		☑
S7-4	Abhijit Biswas, JPL	Deep Space Optical Communications (DSOC)	☑	☑
S7-5	Bo Naasz[1], Neil Dennehy[2], Scott Cryan[3], Nathaniel Gill[3] [1]GSFC, [2]NESC, [3]JSC	Active Sensors for NASA Rendezvous and Capture Missions	☑	☑
S7-6	Farzin Amzajerdian, Paul F. Brewster, Vincent E. Roback, and Glenn Hines, NASA LaRC	3-D Imaging Flash Lidar for Autonomous Safe Landing and Spacecraft Proximity Operation	☑	☑

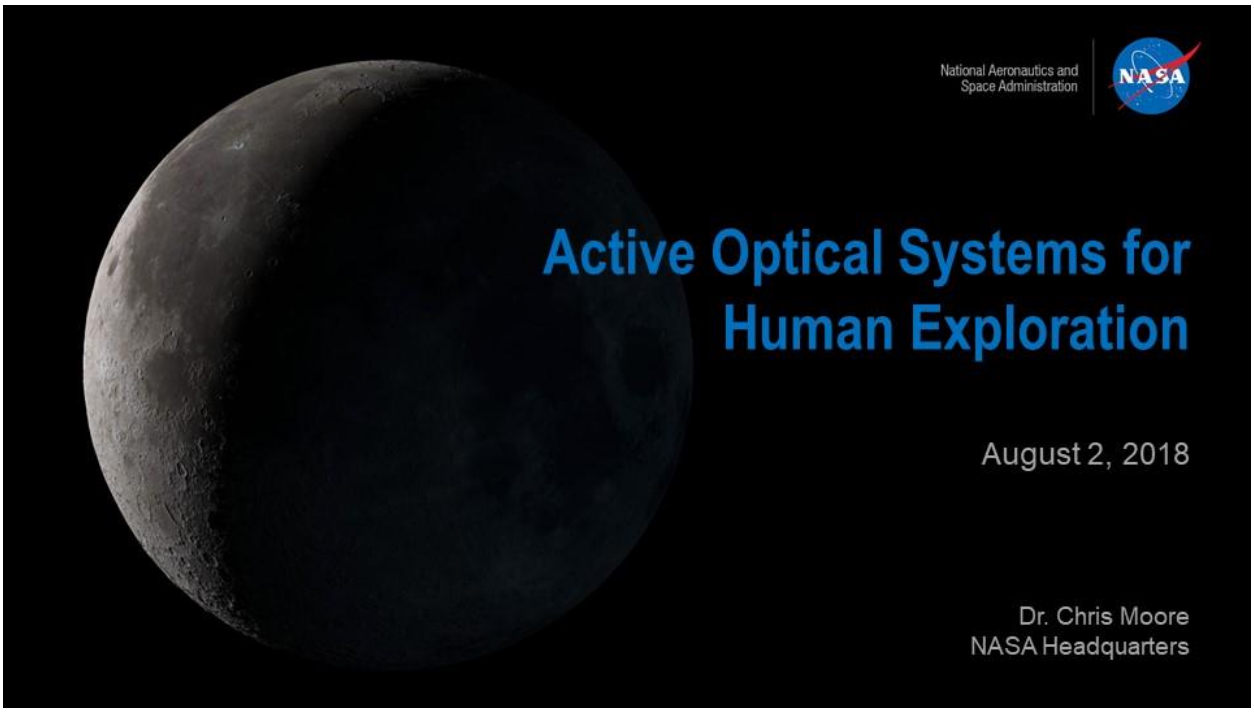
List of presentations

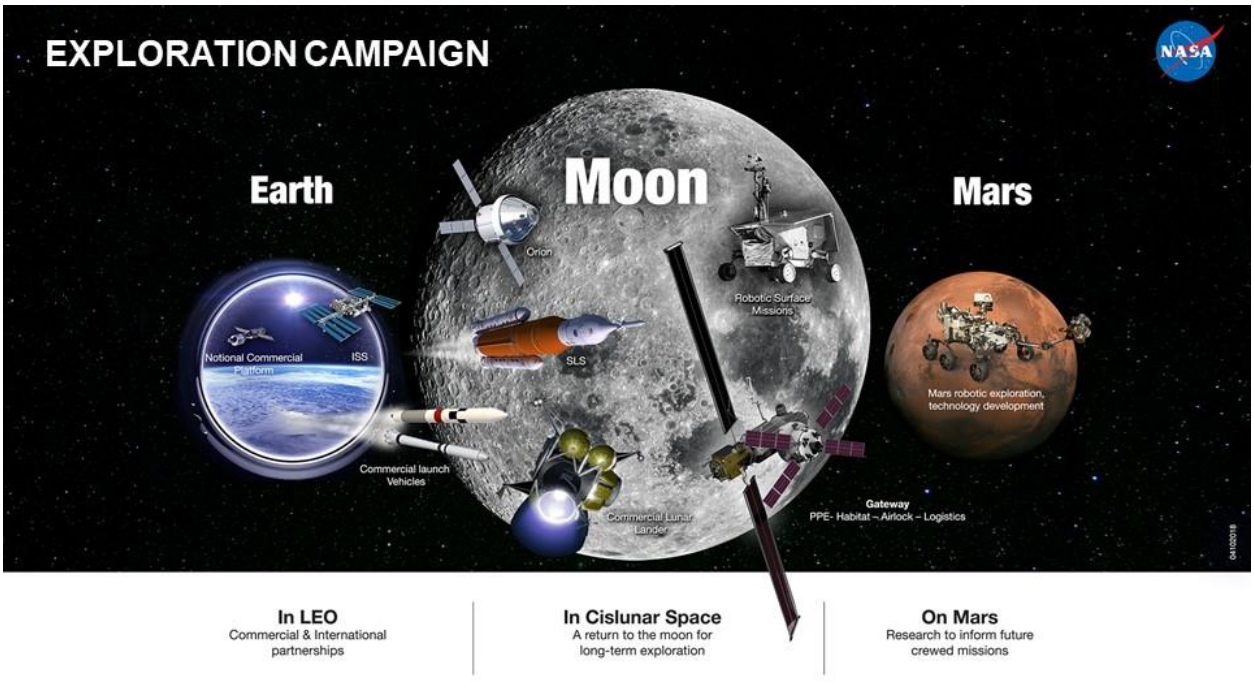
7.1 Active Optical Systems for Human Exploration 7-2
7.2 NASA's Optical Communications Program for 2018 and Beyond 7-7
7.3 Optical Communication Activities Through the Laser-Enhanced Mission Communications Navigation and Operational Services (LEMNOS) Office 7-25
7.4 Deep Space Optical Communications (DSOC) 7-39
7.5 Active Sensors for Nasa Rendezvous and Capture Missions 7-51
7.6 3-D Imaging Flash Lidar for Autonomous Safe Landing and Spacecraft Proximity Operation 7-65

7.1 ACTIVE OPTICAL SYSTEMS FOR HUMAN EXPLORATION

Chris Moore

NASA Headquarters, Washington, D. C.



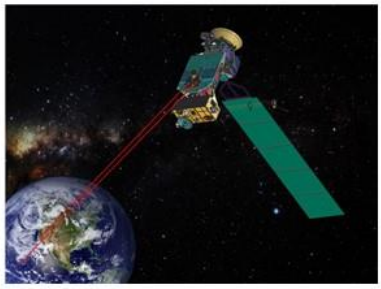


Optical Communications

- High data rate optical communications will be a key element of the in-space infrastructure needed to support human exploration and commercial missions in cislunar space and on Mars.
- The Lunar Laser Communications Demonstration (LLCD) in 2013 transmitted 622 Mbps from the Moon to the Earth.
- The Laser Communications Relay Demonstration (LCRD) in 2019 will demonstrate 1.244 Gbps communications relay between GEO and two ground stations.
- Deep Space Optical Communications will be used on the mission to asteroid Psyche in 2022. Data rate will be 264 Mbps.



LLCD



LCRD

3

Autonomous Precision Landing

Navigation Doppler Lidar (NDL)

- NDL is used for measuring lander's descent velocity and altitude.
- NDL flew on Masten Space Systems lander in 2017.

Flash Lidar

- Flash Lidar is used to acquire 3D images of rocks and craters in the landing zone for hazard avoidance.
- Autonomous Landing and Hazard Avoidance Technology (ALHAT) Flash Lidar flew on the Morpheus lander in 2014.



Navigation Doppler Lidar

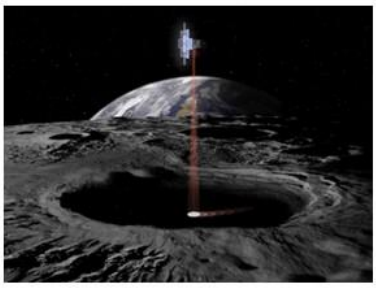


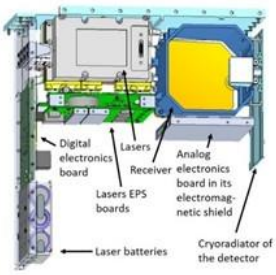
Flash Lidar

4

Lunar Flashlight: Laser Reflectance Spectrometry

- Lunar Flashlight is a 6U CubeSat that will launched on the first mission of SLS.
- Lunar Flashlight uses four lasers at different frequencies in the 1 to 2-micron band to illuminate the floors of permanently shadowed craters.
- The reflected laser light is collected by a spectrometer on the spacecraft to detect water ice in the lunar regolith.
- The lasers transmit 72 Watts of power, and the spatial resolution of the spectrometer is about one kilometer.





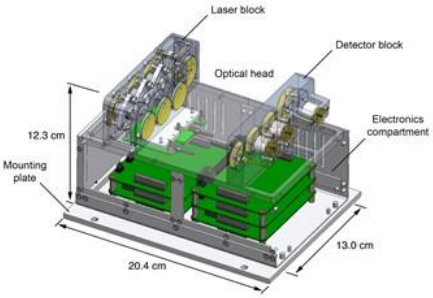
5

Laser Sensors for Environmental Monitoring

- Laser sensors are needed for a variety of environmental monitoring applications.
- **Spacesuits**
  - Multi-gas sensor monitors CO_2 and water vapor concentrations in spacesuit Portable Life Support System.
- **Contaminants Monitoring**
  - Laser sensors will be flown on Orion EM-2 to monitor contaminants in cabin air.
- **Fire Safety**
  - 6-channel laser spectrometer measures toxic combustion products from spacecraft fires.
  - Combustion Products Monitors will fly on the next 3 Saffire fire safety flight experiments.



Multi-gas sensor for spacesuits

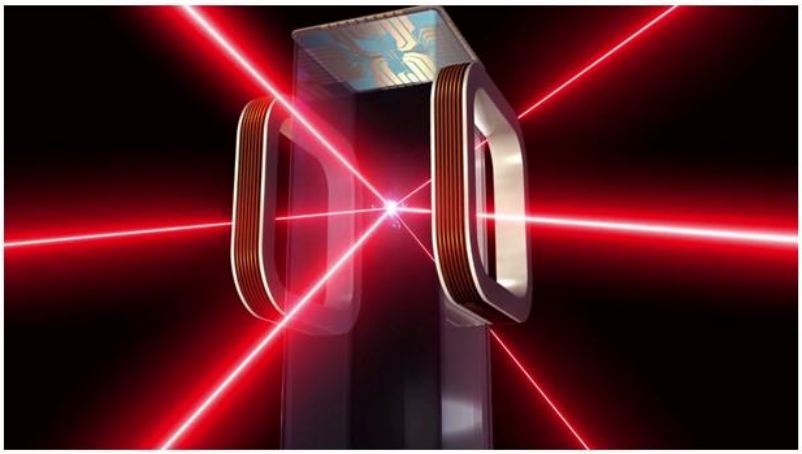


Combustion Products Monitor

6

Cold Atom Lab

- The Cold Atom Lab is a payload on the ISS that uses lasers to cool a cloud of atoms to less than 100 pico-Kelvin to form a Bose-Einstein Condensate. The experiment will investigate the quantum mechanical behavior of matter at ultra-cold temperatures.



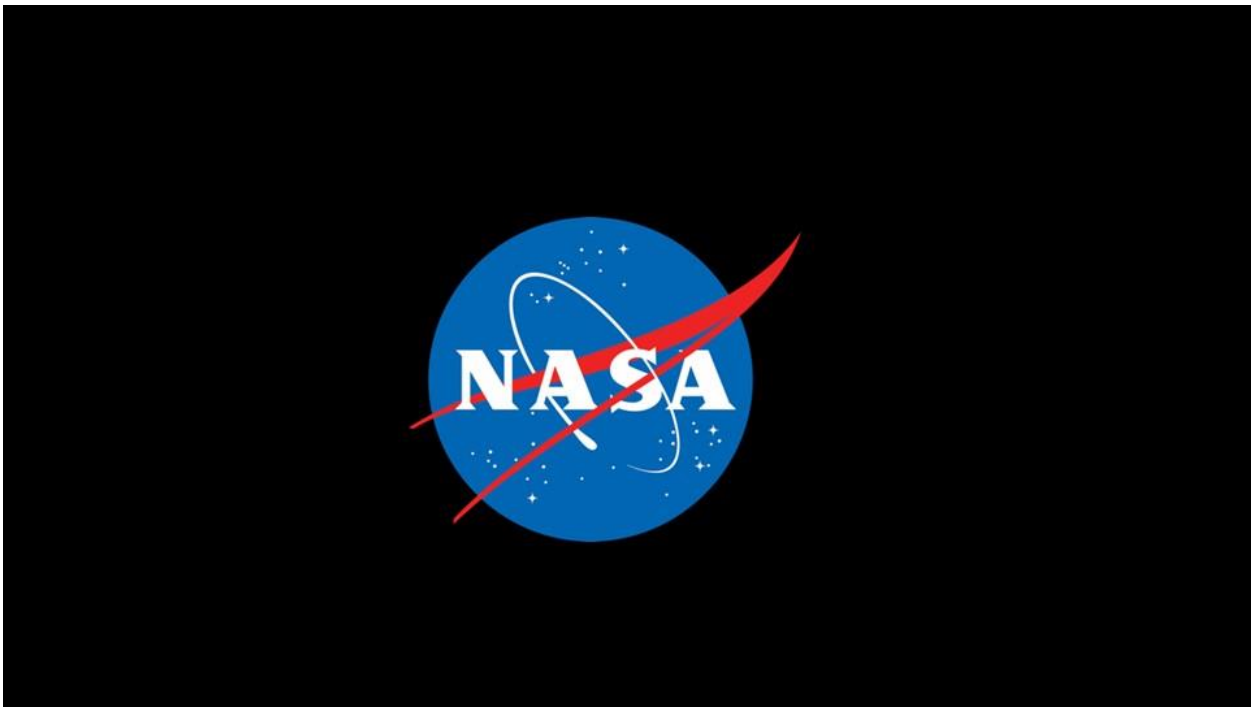
7

Potential Future Needs for Laser Systems

- Lidars for profiling Mars winds and aerosols to inform Entry, Descent, and Landing systems of atmospheric conditions.
- Laser power beaming to enable lunar surface systems to operate in permanently shadowed craters.
- Beamed energy propulsion.



8


NASA

7.2 NASA'S OPTICAL COMMUNICATIONS PROGRAM FOR 2018 AND BEYOND

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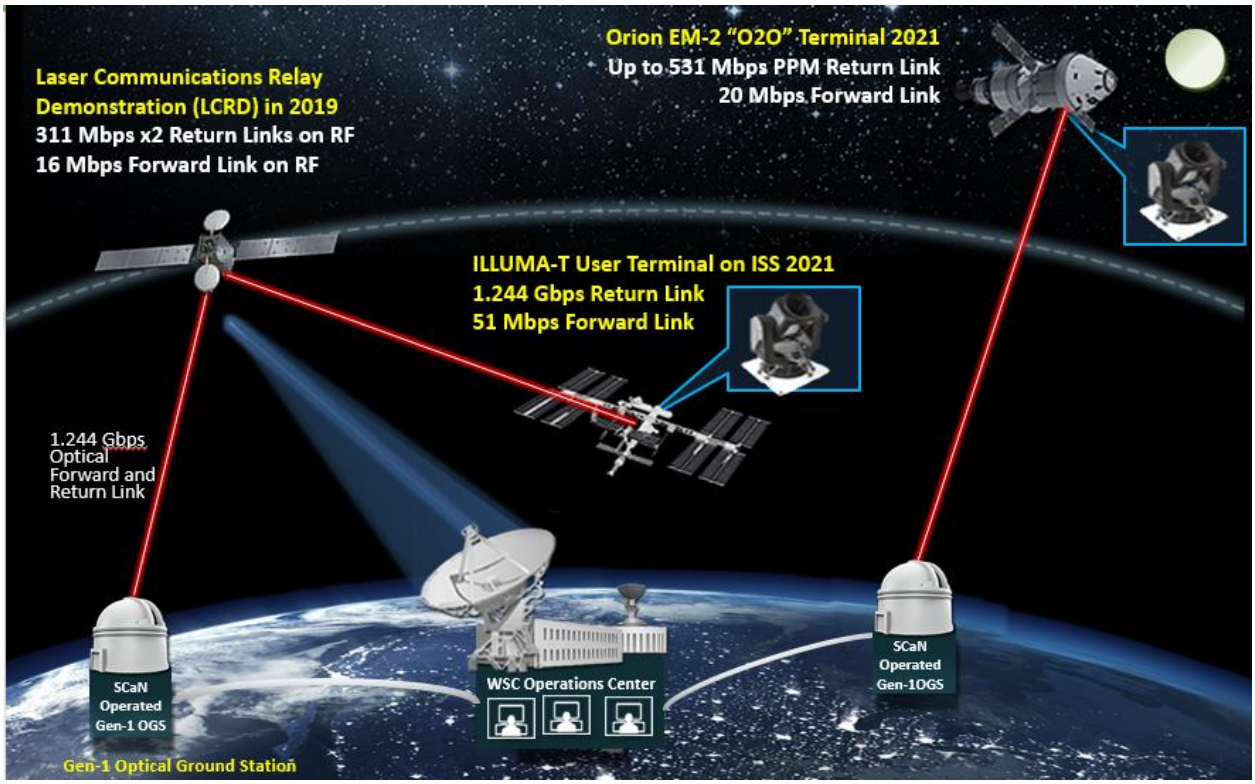

Fig. 1 NASA's near-term missions for near-Earth optical communications 2019-2021.

ABSTRACT

NASA's Space Communications and Navigation (SCaN) Program at NASA Headquarters is pursuing a vibrant and wide-ranging optical communications program for future near-Earth missions such as the Laser Communications Relay Demonstration and the Orion Exploration Mission-2 (EM-2) lunar mission, and planetary missions such as the Deep Space Optical Communications system on the Discovery mission to the asteroid Psyche. This presentation will also address NASA's plans to infuse this new technology into NASA's existing communications networks.

Keywords— free space optical communications, laser communications, relay, high-bandwidth, deep space

1 2019: The Laser Commnuications Relay Demonstration

NASA has continued and expanded its optical communications program since the success of the Lunar Laser Communications Demonstration (LLCD) in 2013 [1]. NASA's next related mission is the Laser Communications Relay Demonstration (LCRD) [2], which will be a hosted payload on the US Air Force Research Lab (AFRL) Space Test Program's STPSat-6, is scheduled to launch to geostationary orbit (GEO) in June 2019. LCRD is designed to complement and possibly supersede RF single access (SA) service at Ka-band on the

next generation of NASA's near-Earth relays, providing higher-bandwidth duplex data links to ground or low-Earth orbit (LEO) users of up to 2.88 Gbps uncoded or 1.244 Gbps with ½ rate DVB-S2-based forward error correction (FEC). The LCRD payload includes two independent Optical Space Terminals (OSTs), which communicate via bi-directional optical links with the LCRD optical ground stations at Table Mountain, CA [3] and Maui, HI. Each OST consists of an Optical Module (OM) and Controller Electronics (CE) module that are both based on the successful LLCD design. However, LCRD includes a new differential-phase key shifting (DPSK) modem, the Multi-Rate Modem (MRM), with 2x the available user bandwidth of the LLCD modem [4]. LCRD also includes a Space Switching Unit (SSU), which is a Commercial Off-The-Shelf (COTS) space-qualified FPGA-based frame-layer switch that connects to the two OSTs and also to two recently-added onboard Ka-band RF transceivers (up to 311 Mbps user rate each) that can route the OSTs signals through clouds to the STPSat-6 ground system at White Sands, NM. The SSU can switch, broadcast, and even loop back between the multiple communications ports and will be NASA's first communications switch and processor in space, noting that all of our current Tracking and Data Relay Satellites (TDRS) have essentially been "bent pipe", analog relays. It is also very important to note that NASA's Space Network (SN), the current operator of the Tracking and Data Relay Satellite (TDRS) constellation in GEO, will also be operating the STPSat-6 bus for AFRL and is developing the Ka-band ground station to support the RF downlinks [5].

As of this writing, all of the modules for LCRD have been assembled and all but the MRM 2 have been environmentally tested, passed, and delivered for payload integration and test, with final shipment of the complete LCRD payload for spacecraft integration in May 2018. Photos of the OM and MRM in environmental testing are shown in Fig. 2.

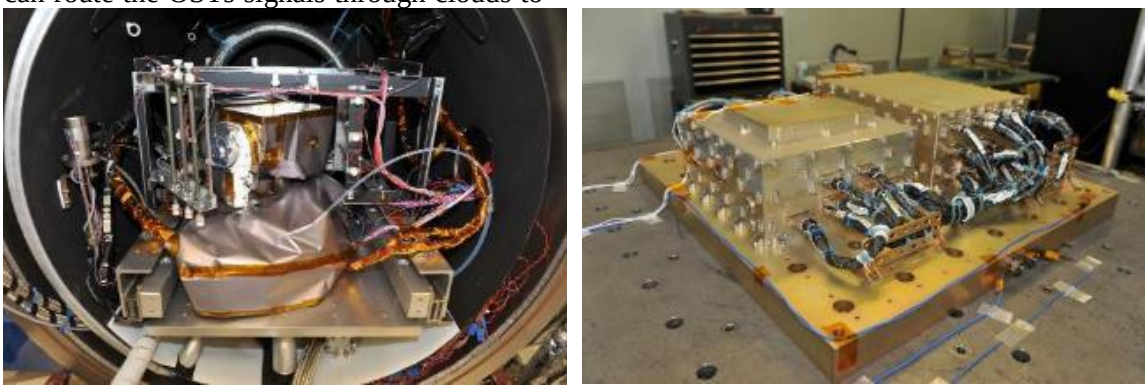

Fig 2. CRD Optical Module in TVAC testing (left) and LCRD Modem (MRM) vibration testing (right).

2 2021: ILLUMA-T USER TERMINAL FOR THE ISS AND ORION EM-2 MISSIONS

NASA's current TDRS constellation is used to provide relay services from NASA users in LEO through GEO to the ground stations in White Sands, NM. For LCRD to provide similar services, a user terminal is required to close LEO-GEO links of 40,000 km or longer. NASA SCaN is developing the Integrated Lasercomm LEO User Modem Amplifier – Terminal (ILLUMA-T) for such users, with an initial demonstration from the International Space Station (ISS) in early 2021. Fig. 3 shows the ILLUMA-T configuration, which is based on a new 10 cm optical module known as the Next Gen Terminal (NGT) [6], which will again be controlled by a variant of the LCRD-based COTS Controller Electronics (CE). ILLUMA-T also includes a new, commercially-available 2.88 Gbps DPSK modem, which includes an erbium-doped high-power optical amplifier (HPOA) which can transmit up to 3 W at 1550 nm both as a beacon and for communications. The NGT uses a 2-axis gimbal but unlike the OM for LCRD, it can articulate over a large field-of-regard (360° azimuthal x 270° elevation) to allow for communications independent of the spacecraft bus orientation. It is also designed to provide fine pointing and tracking at the high gimbal slew rates

required for LEO-GEO or even LEO-GND tracking.

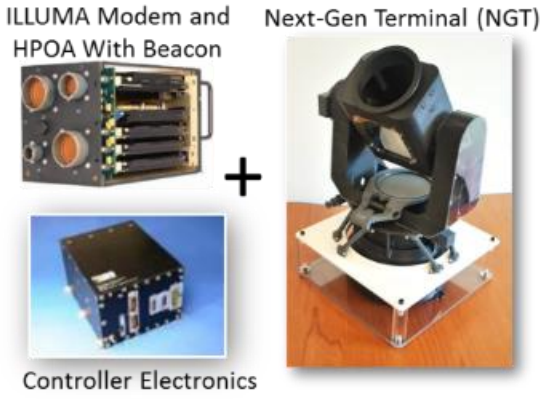

Fig. 3 ILLUMA-T User terminal with Modem, CE, and 10 cm Next Gen Terminal (NGT).

A variant of the ILLUMA-T, using a pulse-position modulation (PPM) modem, will be used to support the Orion EM-2 mission to the Moon later in 2021. MIT Lincoln Laboratory is designing, integrating, and testing both the ILLUMA-T and Orion terminals; however, the primary components of the system are being designed and procured in US industry, with a commercially-procured flight-like Engineering Development Unit (EDU) of the NGT currently in the lab under test. Commercialization of the hardware is critical since the overall viability of this technology will require a vendor base that can supply both Government and commercial sources with the necessary hardware and software. NASA is also encouraging the use of commercial practices (rather than NASA-dictated manufacturing standards, for example) to lower costs and widen the potential industrial base.

It is noted that NASA missions are generally very conservative and will therefore consider the use of this technology with some hesitation. In order to foster the transition from RF to optical systems, NASA's SCaN program has secured funding to procure five copies of a second iteration of the ILLUMA-T terminal that can be provided for free to NASA missions as technology demonstrations. The key to success for this technology will be in keeping the cost and user burden (size, mass, power) of the system comparable to RF systems (specifically Ka-band). In fact, leveraging the massive investments from the fiber telecommunications market may enable optical communications technology implementations to achieve significantly lower cost and user burden than RF systems.

3 2019: 100 Gbps Space and Ground Terminals for LEO Direct-to-Earth

The short distance and corresponding range loss of a LEO link direct-to-Earth (DTE) offers an opportunity to provide extremely high bandwidth downlinks at very low cost, size, weight, and power (SWaP) [7]. Under NASA SCaN support, MIT Lincoln Laboratory is developing such a terminal that can deliver 200 Gbps downlink using only 1.9U x 1U x 1U volume (1U=10 cm). The baseline 100 Gbps modems are variants of a COTS design and current efforts are now focused on the satellite 2.5 TB memory and controller which must be read at similar data rates. A demonstration flight is planned on the NASA Space Technology Mission Directorate (STMD) Pathfinder 3 CubeSat in mid-2019 and it is expected to demonstrate downloads of the entire data buffer on a single pass. While the initial demonstration may use existing NASA optical ground stations, there are also plans to develop low-cost optical ground stations to support such rates to be specifically co-located at mission data storage facilities or even commercial data centers to reduce the recurring monthly charges for ground-based fiber backhaul. The ground system can be built at low cost because it leverages COTS components, not only for the astronomical telescope and dome but also for the pre-amplified receiver and modem. However, because it is low-cost, it is important to point out that it is not designed to support pulse-position-modulated (PPM) signals from deep space missions beyond GEO (such as Orion at the Moon) since it will not deploy a cryogenically-cooled (~ 1 K) photon-counting receiver, which is generally required for such distances.

4 Beyond LCRD: NASA'S Next Generation Relay and USer Terminals for 2024

LCRD will be NASA's pathfinder for integrating laser communications into our current operational Space Network over the course of several years. NASA will use this experience to design and refine our plans for the Next Generation Relay (NGR) system, first to complement our current TDRS services in 2025 and then replace them as we

transition NASA high-rate data services in the optical regime.

The proposed NGR constellation in GEO is shown in Fig. 4 and initially will consist of two spacecraft nodes with 10 Gbps user service links and 100 Gbps downlinks and crosslinks, which leverage the 100G technologies demonstrated in NASA's 2019 CubeSat mission. One node will fly over the continental US (CONUS) while the other will be stationed outside of CONUS, which will provide constant, low-latency, near-global contact for NASA missions in LEO. Like the current TDRS system, it will primarily be a "hub-and-spoke" architecture where the local node or hub provides up to 10 Gbps services to many users (or "spokes") within its field of view. Unlike the current TDRS, which acts as a pure "bent pipe" relay that amplifies and redirects analog RF user waveforms to the ground, NGR will be a purely digital relay with onboard frame-layer switching and multiplexing so that user traffic will be digitally multiplexed onto 100 Gbps Space-to-Ground Links (SGLs) or crosslinks, leveraging NASA's HIDRA architecture [8]. The high-bandwidth crosslinks will eliminate the need for high-bandwidth ground stations outside of the US, allowing all OCONUS traffic to be backhauled to an optical station over CONUS. Like the current TDRS, the primary user cases focus on high-bandwidth data return links with much lower data rate forward links (<10 Gbps) to minimize decoding in space. The NGR HIDRA switch will also support the DTN store-and-forward function with a large integrated solid state recorder (SSR), and port-to-port routing leveraging an Ethernet frame switch.

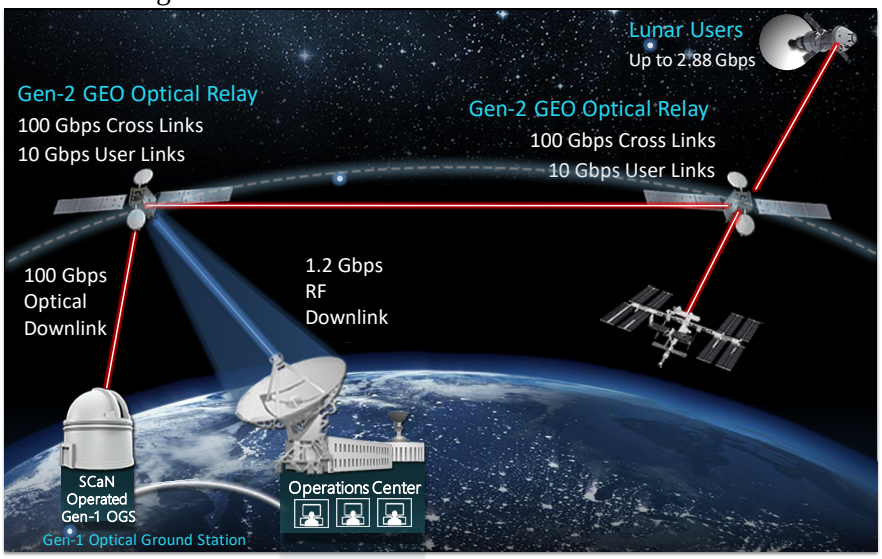

Fig. 4 NASA's planned Next Generation Relay constellation in GEO in 2025.

The NGR 10G user service will be compliant with the new CCSDS standard being developed with CNES, JAXA, and NICT, but will also maintain backward compatibility with the current LCRD modulation, coding and synchronization format (which supports user links down to 2 Mbps) via a software-defined modem. The new GEO relay terminal is based on a larger 20 cm optical module (Fig. 5) that gracefully scales from the current modular 10 cm NGT design of the ILLUMA-T user terminal; the 6 dB increase in aperture gain, in combination with a 20 W space-qualified HPOA, is required to support the 100 Gbps downlinks and crosslinks and also the 10 Gbps links to 10 cm ILLUMA-T users in LEO and below. The 20 cm NGT on the NGR could also support 2.88 Gbps links from the Moon using a similar terminal.

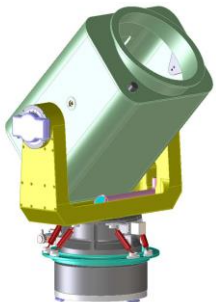

Fig. 5: Modular 20 cm Optical Terminal for NASA's Next Gen Relay leveraging ILLUMA NGT design.

5 NASA'S Deep Space Optical Communications Project

NASA's Jet Propulsion Laboratory (JPL) continues development of the Deep Space Optical Communications (DSOC) system, which is now manifested to fly as a demonstration on NASA's Discovery mission to the asteroid Psyche in 2022 as illustrated in Fig. 6 [9]. NASA's Space Technology Mission Directorate (STMD) and Science Mission Directorate (SMD) are supporting the development and flight accommodation of the DSOC space terminal while the author's Space Communication and Navigation (SCaN) is supporting development and operation of the DSOC ground terminal.

The body-pointed 22 cm DSOC space terminal will implement the newly-developed CCSDS High Photon Efficiency standard for pulse-position modulation (PPM) [10] to deliver 125 Mbps at 40 Mkm while demonstrating new technologies such as kilowatt-class uplink beams (serving both as a beacon and low-rate communications link) from the ground, a photon-counting detector array on the spacecraft to centroid and lock on to that uplink beam for pointing, and inertially-stabilized platforms that provide an order-of-magnitude improvement in stable beam pointing (as compared to LLCD and LCRD) with similarly larger point-ahead angles for the downlink beam.

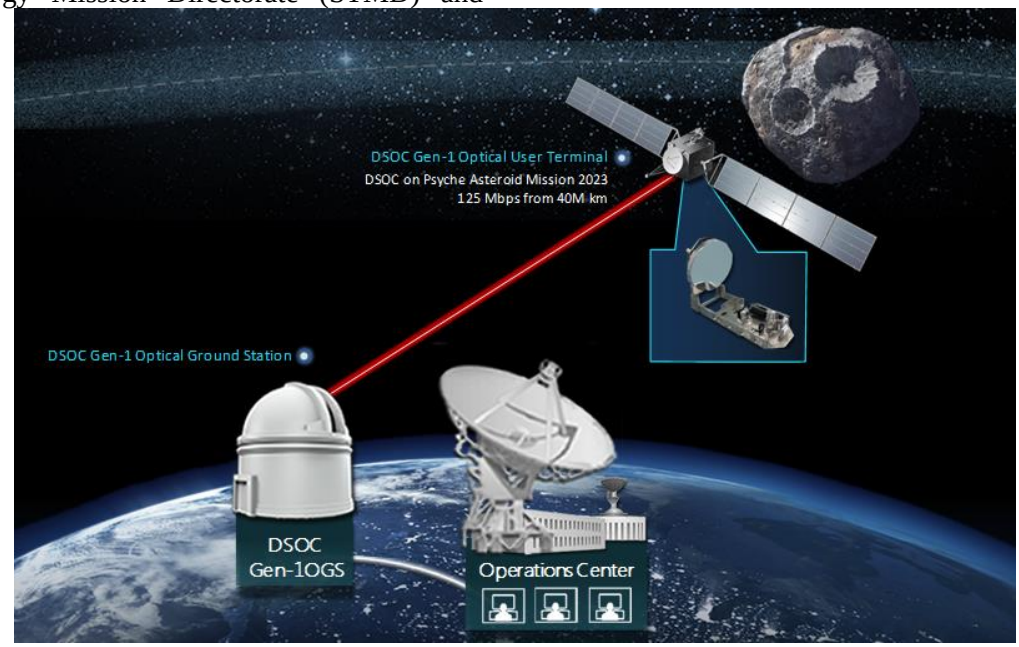

Fig. 6: NASA's Deep Space Optical Communications system on Discovery Psyche 2022.

The baseline plan for the Optical Ground Station (OGS) is to use the 5 meter diameter Hale telescope on Mount Palomar near San Diego, CA with a 320 micron diameter Superconducting Nanowire Detector Array (SNDA) newly developed by JPL [11]. However, JPL is also investigating an RF/optical "hybrid" solution where spherical optical mirrors would be arrayed within the inner diameter of a Deep Space Network (DSN) 34 meter diameter RF antenna [12]. Each mirror would be co-aligned to incoherently add their collected signal on the focal plane optics and receiver that is mounted to the RF secondary reflector structure. Initial experiments have been

very promising and demonstrate both the exquisite blind pointing capability and stability of the underlying 34 m antenna mount [13]. NASA SCaN is now considering an array of such mirrors with the effective collecting aperture equivalent to an 8 meter diameter single mirror; such a large aperture could support 125 Mbps downlinks from Mars at opposition (64 Mkm).

6 CONCLUSION

NASA continues to provide strong support to the Space Communications and Navigation (SCaN) Program's optical communications efforts in both the near-Earth and deep space regimes. NASA Headquarters and the executing centers at GSFC, JPL, and MIT-LL continue to work together and with US industry and international partners to develop the technologies and commercial ecosystem required to make free-space optical communications both complementary and competitive with the current operational communications solutions both in RF and also terrestrial and undersea fiber telecommunications.

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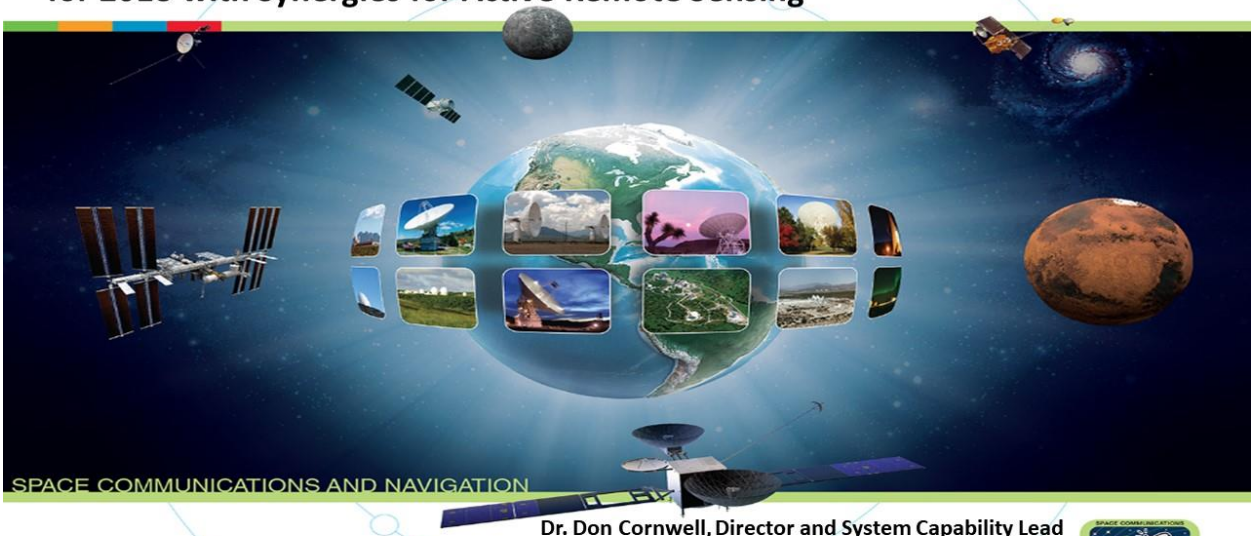
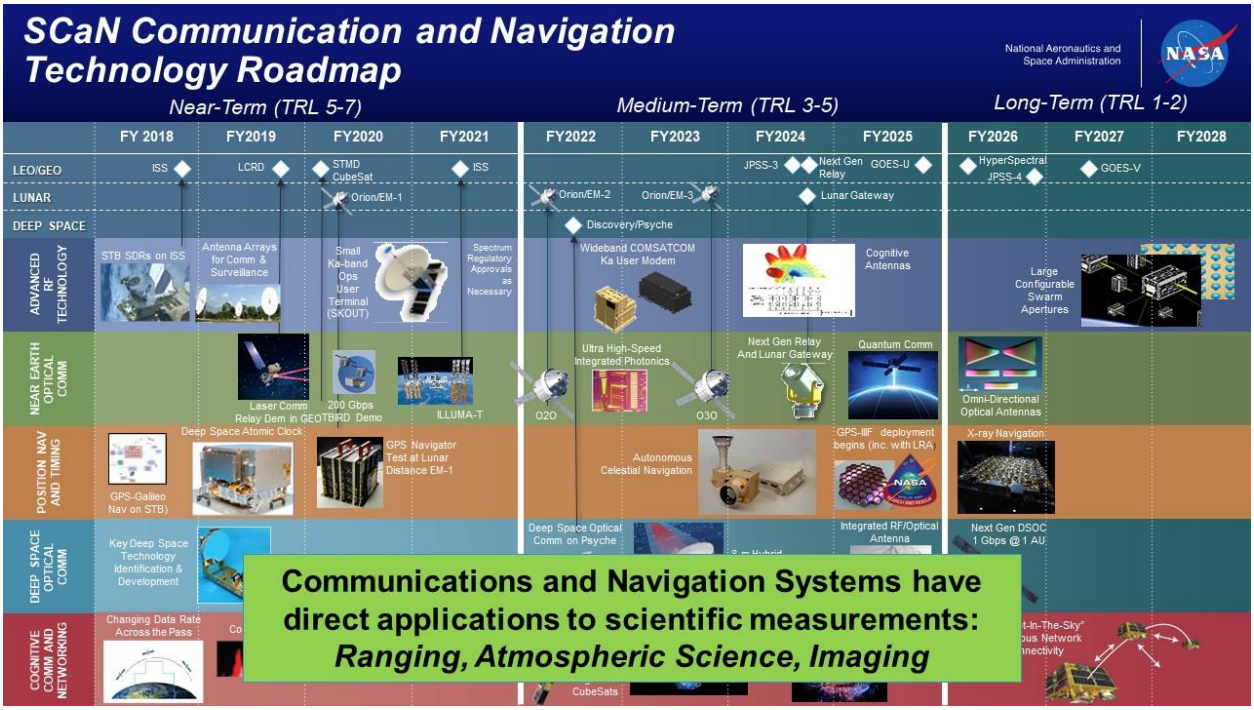
NASA's Optical Communications Program for 2018 with Synergies for Active Remote Sensing



Dr. Don Cornwell, Director and System Capability Lead
Advanced Communications and Navigation Division
SCaN Program, NASA HQ

www.nasa.gov

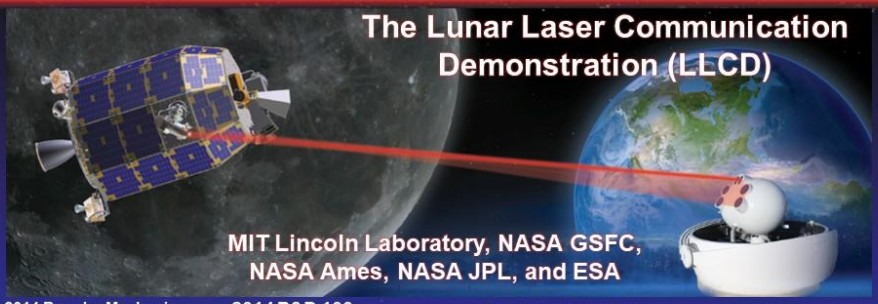
SCaN Communication and Navigation Technology Roadmap



Communications and Navigation Systems have direct applications to scientific measurements:
Ranging, Atmospheric Science, Imaging

3

2013: NASA's First, Historic Lasercom Mission



2014 Popular Mechanics Breakthrough Award for Leadership and Innovation for LADEE

2014 R&D 100 Winning Technology in Communications category

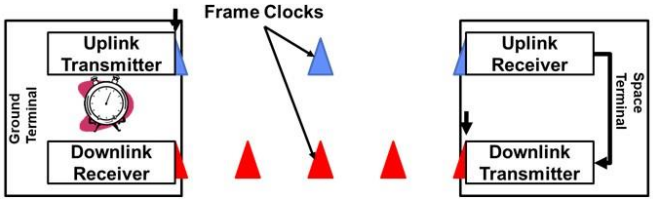
Nominated for the National Aeronautic Association's Robert J. Collier Trophy

Winner of the National Space Club's Nelson P. Jackson Award for 2015

LLCD returned data by laser to Earth at a record 622 Megabits per second (Mbps) = *streaming 30+ HDTV channels simultaneously!*

LLCD's Time of Flight System

- Uplink and downlink clocks locked together allow high-accuracy measurement of up/down time of flight based on signal framing structures and 311 MHz clock



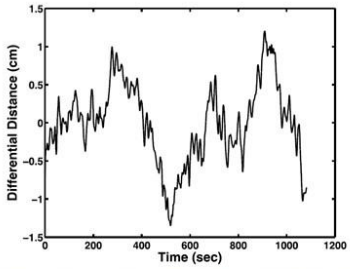


Figure 10. Low-frequency variations observed in a differential measurement following the removal of the linear slope components and the application of a 0.2-Hz temporal filter.

- The LLCD TOF system made real-time phase comparisons of the uplink and recovered downlink signals, and yielded a precision in relative one-way distance measurements typically better than 1 cm RMS with real-time samples at 20 kS/s and 200 Hz filtering over 400,000 km
- Additional filtering could be applied to yield millimeter precision

Stevens, M. L., R. R. Parenti, M. M. Willis, J. A. Greco, F. I. Khatri, B. S. Robinson, and D. M. Boroson. "The lunar laser communication demonstration time-of-flight measurement system: overview, on-orbit performance, and ranging analysis." In *Free-Space Laser Communication and Atmospheric Propagation XXVIII*, vol. 9739, p. 973908. International Society for Optics and Photonics, 2016.

NASA's Optical Program of Record: Deep Space Optical Communications (DSOC in 2022)



5

Laser Communications Relay Demonstration (LCRD)

Scheduled launch: 2019

Mission duration:
Two year ops demo
Six years ops

Hosted payload: US Air Force's Space Test Program Satellite – 6 (STPSat-6)

Partnership:
STMD/Technology Demonstration Missions and SCaN

Gro
and

Gue

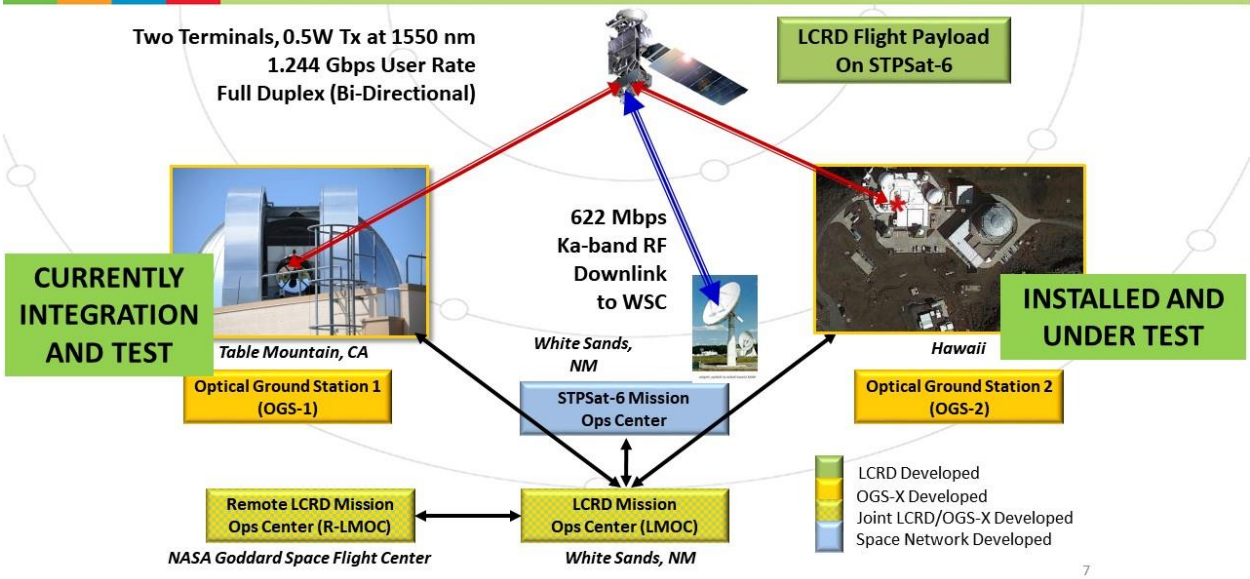
Flight payload:

- **Two LLCD-heritage Optical Modules and Controller Electronics Modules**
- **Two software-defined DPSK Modems with 2.88 Gbps data rate (1.244 Gbps user rate)**
- **622 Mbps Ka-band RF downlink**
- **New High Speed Switching Unit to interconnect the three terminals**

Ranging to be added during 2-year demo period
Program is open to scientific proposals as Guest Investigators

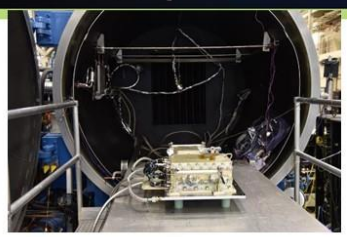
6

LCRD Mission Architecture with SCaN-Provided Ground System Directly Integrated into NASA's Space Network



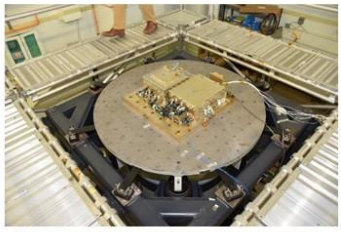
LCRD Payload in Integration and Test for July 2018 Delivery to Spacecraft

All HW Now Space-Qualified (TRL 6) at the Module Level





Flight Modem #1
Attaching Thermistors to Intermediate Plate





LCRD PAYLOAD READY TO SHIP TO S/C

2
ariable
Measurements of Quad Cell Noise

NASA's Open Call for Commercial Collaboration in Laser Communications

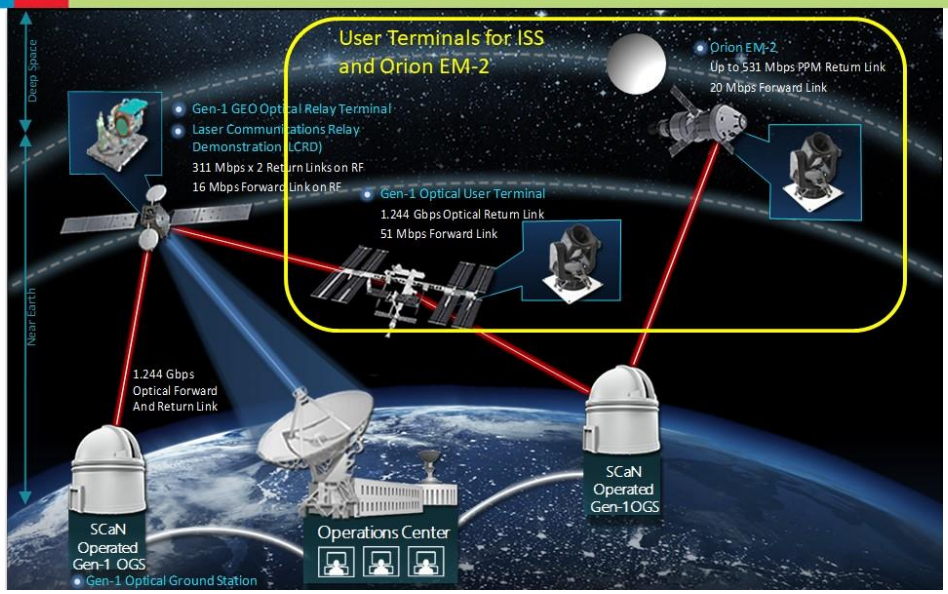


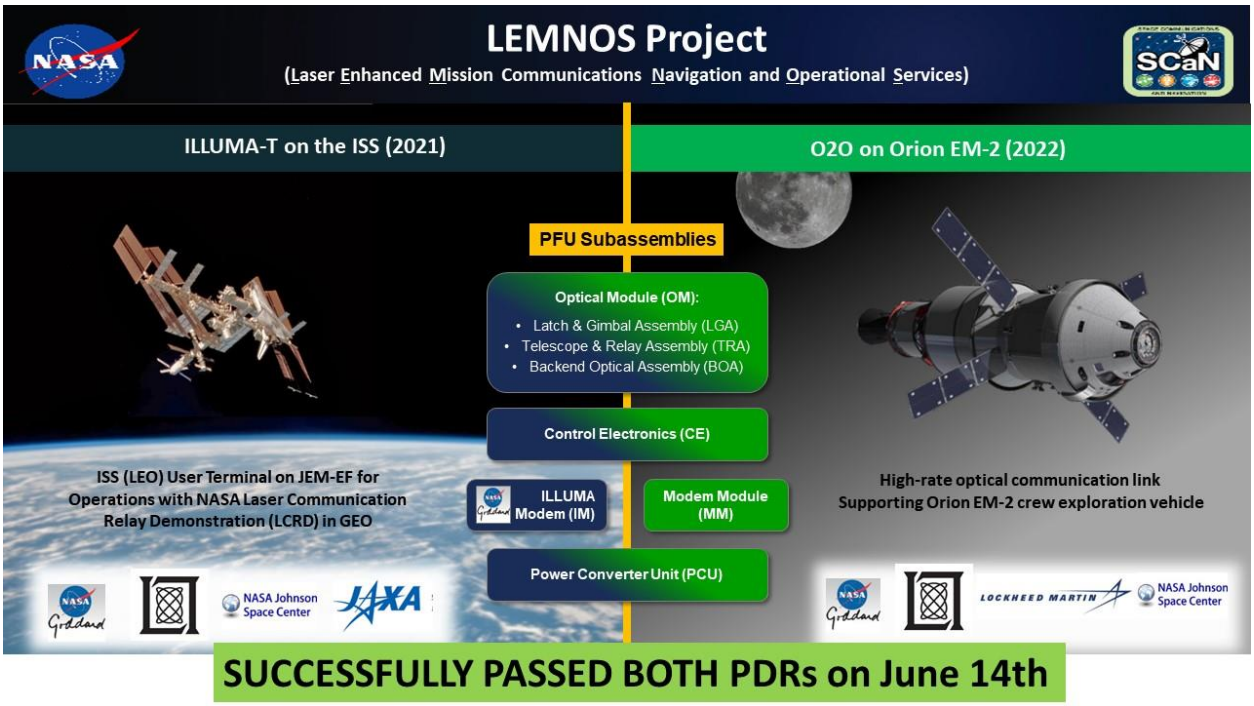
"NASA is soliciting proposals from all interested U.S. private sector enterprises that wish to enter into partnerships through Reimbursable Space Act Agreements to develop a Partnership for Commercial Optical Communication Systems (PCOCS)."

- **Possible Collaborations:**
  - LCRD Guest Investigator Program
  - Collaborative technology development and flight demonstrations
  - Access to NASA's resources including technical expertise, assessments, lessons learned

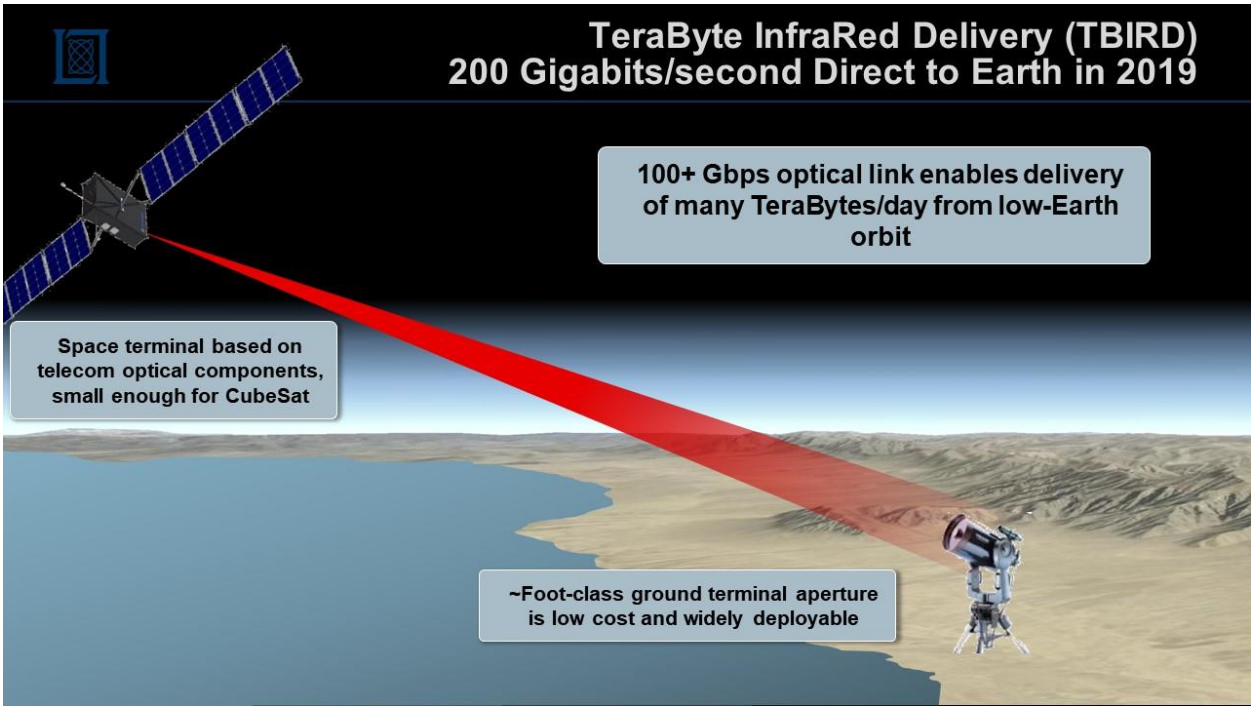
NASA and BridgeSat have signed a Reimbursable Space Act Agreement in March 2018

NASA's Optical Plan Forward: User Terminals for LEO and the Moon





SUCCESSFULLY PASSED BOTH PDRs on June 14th



TBIRD Space Segment: 200 Gigabit per second CubeSat Demonstration

- Highly-integrated COTS components enable small, low-power space terminal designs
- Low-cost demonstration on CubeSat
  - Targeting 2019 demo on NASA Pathfinder 6U CubeSat
- Space terminal specs
  - 200 Gbps
  - ~3 kg
  - ~2U volume
  - Spacecraft pointed w/ tracking sensor
  - 150 W (< 1 nJ / transmitted bit!)
    - 2W, 200 Mbit/s X-band link = 10 nJ/bit
- Engineering challenges associated with CubeSat
  - Power (peak current)
  - Thermal



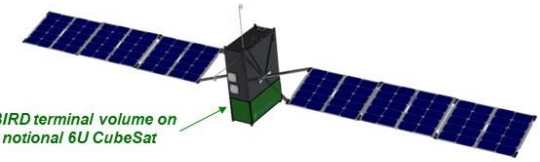
500-GB Solid State Drives



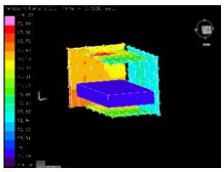
100-Gb/s Optical Transceiver



1-W Optical Amplifier



TBIRD terminal volume on notional 6U CubeSat

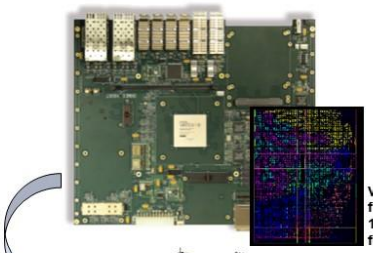


Preliminary thermal analysis for operations in ISS orbit

TBIRD 200G Space Terminal

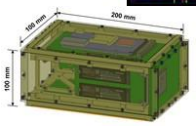
Recent Accomplishments

- **High rate digital processor and buffer development**
  - Custom board designs
  - Firmware for buffer with high-rate read-out and ARQ
- **Payload based on preliminary STMD Pathfinder ICD**
- **Uplink design to provide simultaneous spatial acquisition and communications for reliable data delivery**
- **Proton radiation testing of key components PASSED**
- **Testing of next-generation commercial transceivers**
  - Up to 200 Gbps per transceiver
  - 50% reduction in volume AND power
  - Improved receiver sensitivity



Current COTS breadboard electronics prototype

Virtex 6 floorplan 100 Gbps for ARQ

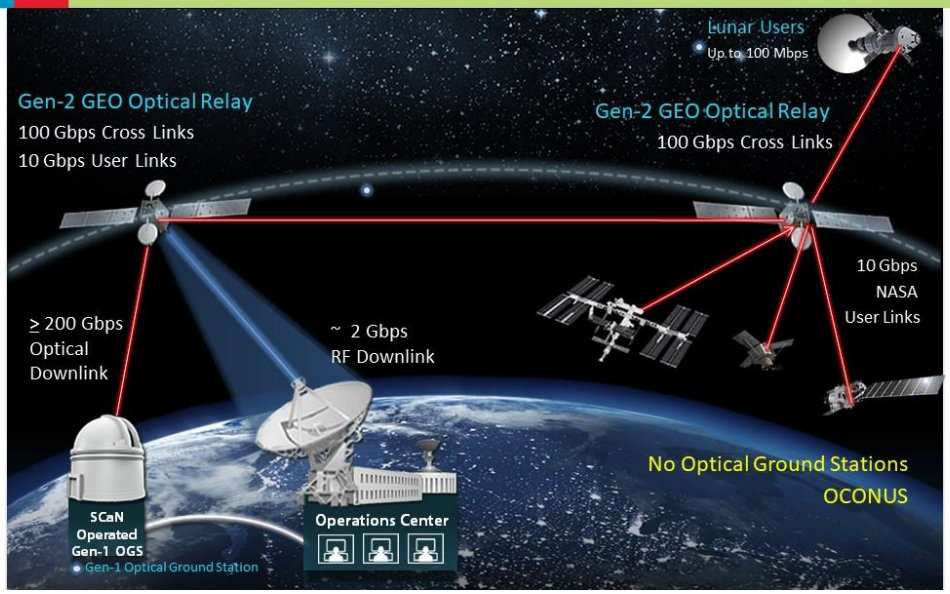


Custom payload electronics design and packaging



Concept for TBIRD Payload in 6U STMD pathfinder CubeSat

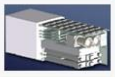
NASA's Next Gen Relay (2024) with 10G Users and 100G Crosslinks

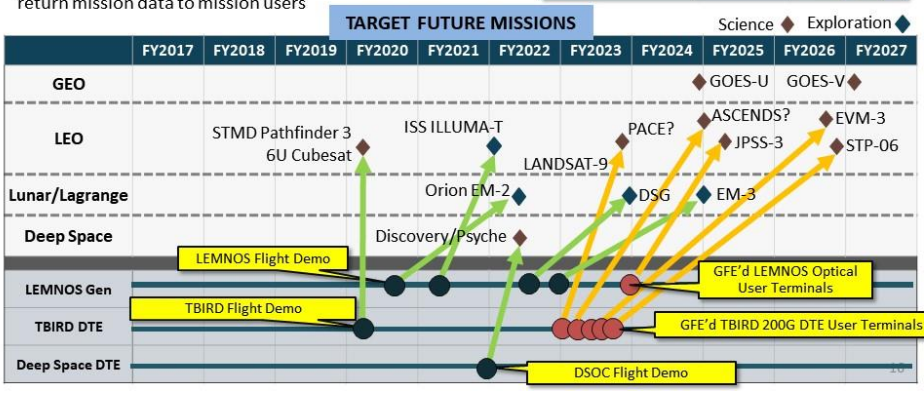


SCaN's Plan for Optical Infusion: ...to "GFE" User Terminals to Missions

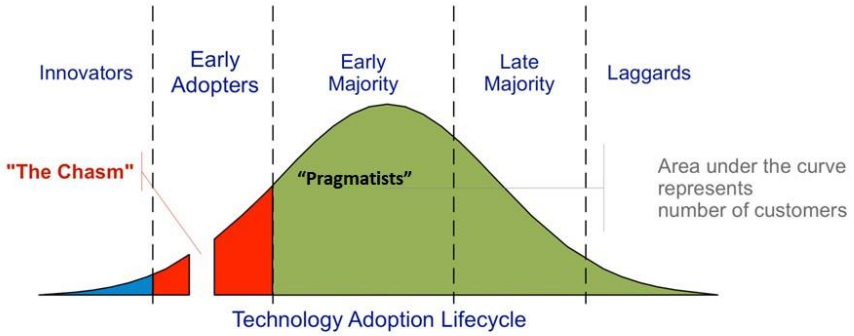
THE PLAN

- Apply STMD & SCaN optical communication technology investment to Science & Exploration missions to transition optical communications to operations
- SCaN provides GFE terminals to NASA missions for direct or relayed services
- STMD & SCaN provide optical relay & ground stations to return mission data to mission users

TBIRD 200G DTE User Terminal Build Quantity: 5	**GFE starting in 2021** 
Gen-1 Optical User Terminal Build Quantity: 5	**GFE starting in 2023** 



G. Moore's "Crossing the Chasm" Model for Technology Acceptance in High-Tech Markets



Each group has different expectations for a new, <u>disruptive</u> product:

- ***Innovators see a competitive advantage to allow them to leapfrog their competition…***
- ***…While Pragmatists want a COMPLETE SOLUTION to a business problem (the Whole Product Model)***

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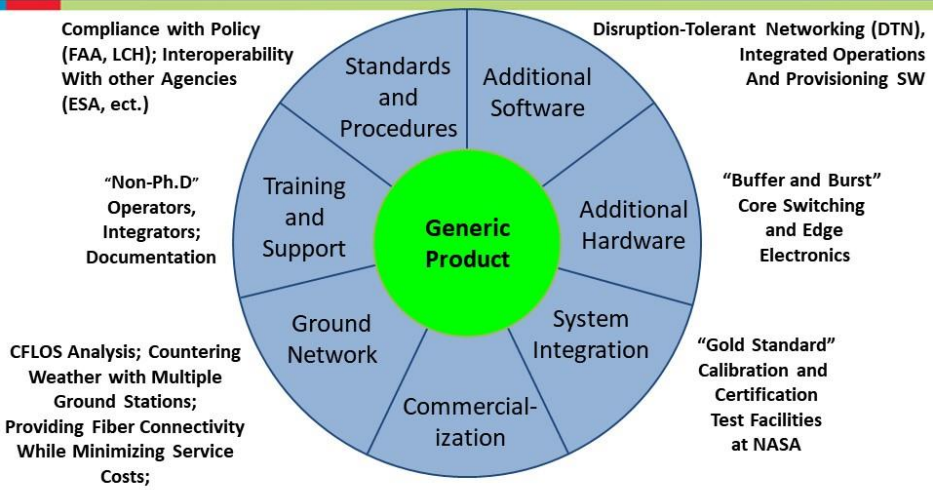
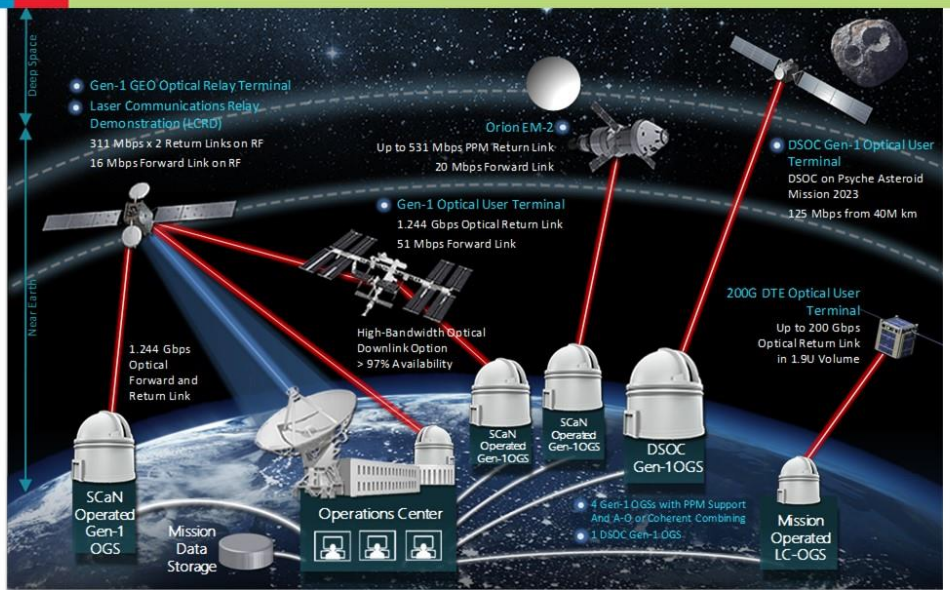
The Whole Product Model for Infusing Optical Comm into NASA Missions



Summary:
NASA's Future Space Optical Network



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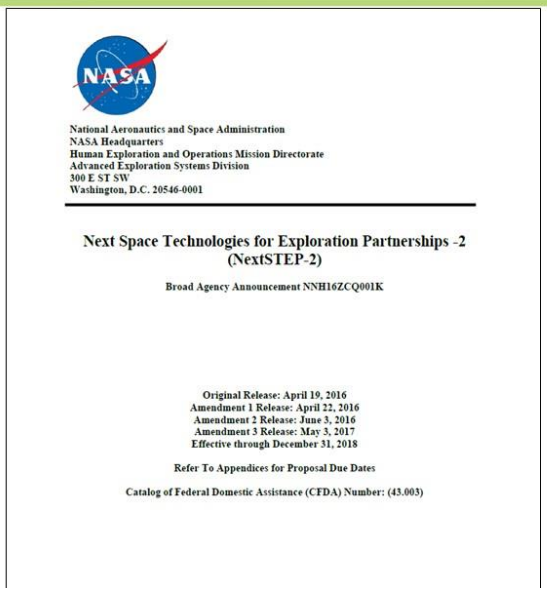
Questions?

Please feel free to contact me at:

Dr. Don Cornwell
NASA Headquarters SCaN Program
Donald.M.Cornwell@NASA.gov
202-358-0570
410-336-2473 (cell)

NASA has pioneered competitive procurements which also include commercial partner contributions

- NASA OGC recommends using procurements with specified amounts of partner contributions (usually minimum 30%)
- This has been used to great success by HEO's Advanced Exploration Systems (AES) "NextSTEP" procurement program
- May be less complex than Space Act Agreements



National Aeronautics and Space Administration
NASA Headquarters
Human Exploration and Operations Mission Directorate
Advanced Exploration Systems Division
300 E ST SW
Washington, D.C. 20546-0001

Next Space Technologies for Exploration Partnerships -2 (NextSTEP-2)

Broad Agency Announcement NNH16ZCQ001K

Original Release: April 19, 2016
Amendment 1 Release: April 22, 2016
Amendment 2 Release: June 3, 2016
Amendment 3 Release: May 3, 2017
Effective through December 31, 2018

Refer To Appendices for Proposal Due Dates

Catalog of Federal Domestic Assistance (CFDA) Number: (43.003)

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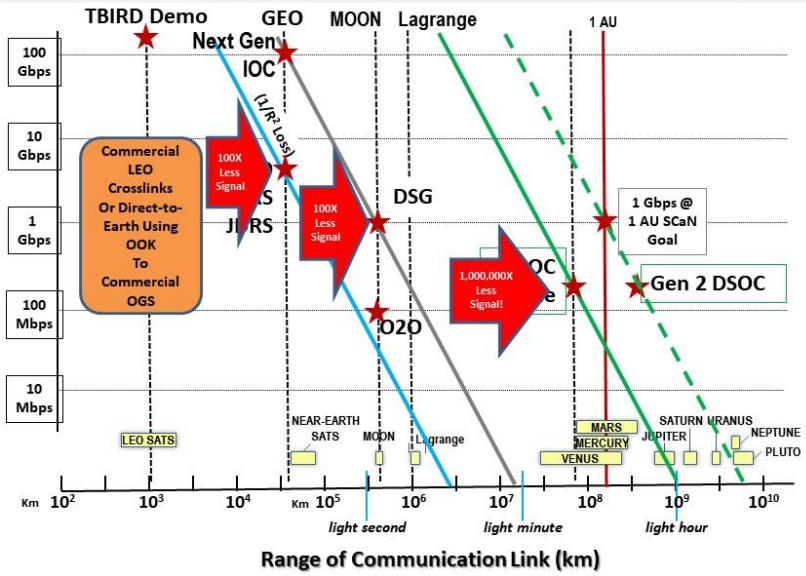
NASA and Commercial Optical Communication Systems: Different Designs for Different Scenarios



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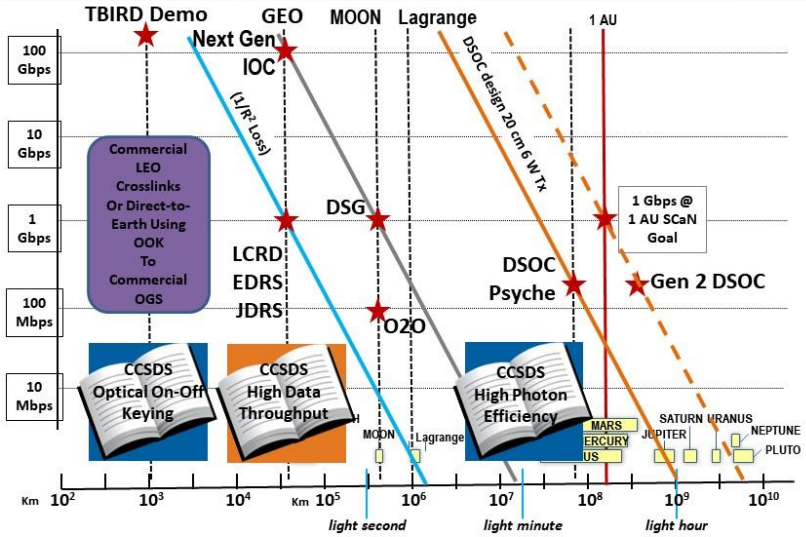
NASA and Commercial Optical Communication Systems: CCSDS International Standards in Development



NASA's Optical Plan Forward: Commercial Optical Ground Station Expansion

OVERVIEW

- Initially two SCaN-managed facilities at TMF and HI for Gen-1 GEO relay demo in June 2019 (LCRD)
- Slew at LEO rates with Adaptive Optic (AO) correction for single-mode fiber coupling; initially deployed with LCRD-compatible modem
- OGS-1A (TMF 2), OGS-3 (WSC) and OGS-4 (Livermore) baselined as 60 cm "Hawaii" design with CCSDS HPE support

PROGRAM STATUS AND NEXT STEPS

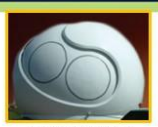
- OGS-1 and OGS-2 in final development for site I&T in 2018 to support flight demo in 2019

COMMERCIALIZATION

- Work through RSAAs with commercial OGS providers to provide additional stations for >99% availability

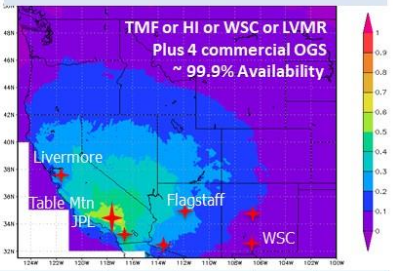


OGS-1 TMF in CA



OGS-2 in Hawaii

Cloud-Free Correlation of New Sites to OGS-1 Table Mtn



	Segment	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
NEAR EARTH RELAY	SPACE	Gen-1 GEO Optical Relay Terminal					Gen-1 Optical User Terminal				
	GROUND				Gen-1 OGS						
Orion EM-2	---------						Orion EM-2				

7.3 Optical Communication Activities Through the Laser-Enhanced Mission Communications Navigation and Operational Services (LEMNOS) Office

Antonios Seas[1], Bryan Robinson[2], Tina Shih[2], Farzana Khatri[2], and Mark Brumfield[1]

[1]NASA Goddard Space Flight Center, Greenbelt, Maryland

[2]MIT Lincoln Laboratory, Lexington, Massachusetts



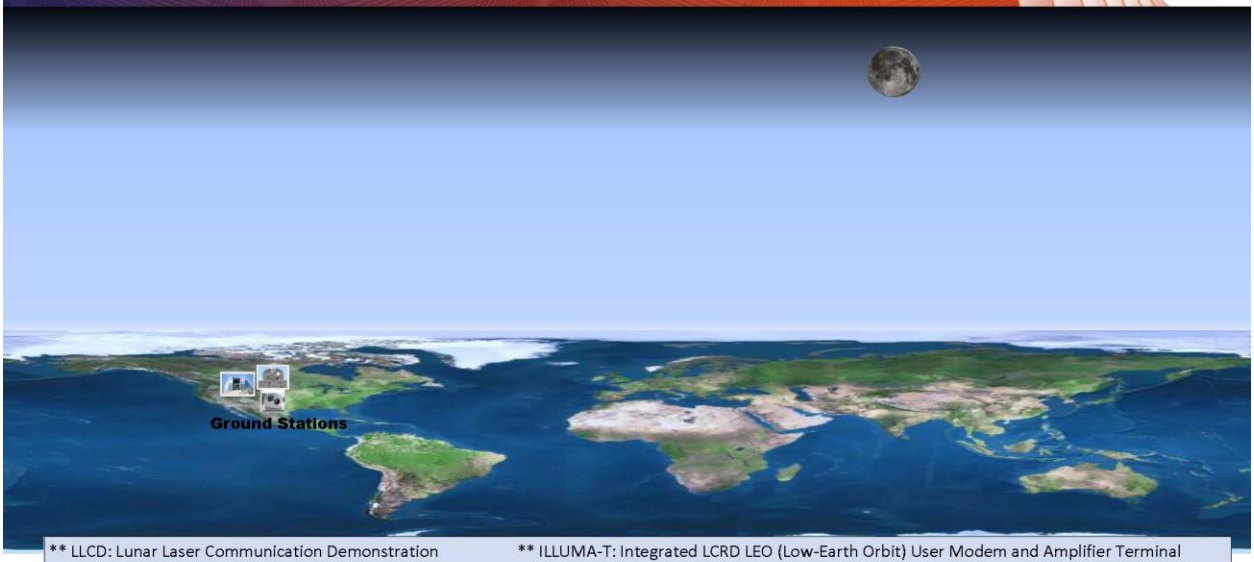


- Introduction
- Objectives & L1 Requirements
- High Level System Architecture/Operational Characteristics
- Modular, Agile, Scalable Optical Terminal (MAScOT)
- Conclusion

Laser-Enhanced Mission Communications Navigation and Operational Services (LEMNOS)

2

LEMNOS Introduction



** LLCD: Lunar Laser Communication Demonstration
** LCRD: Laser Communication Relay Demonstration
** O2O: Orion EM2 Optical Communications Terminal
** ILLUMA-T: Integrated LCRD LEO (Low-Earth Orbit) User Modem and Amplifier Terminal
** LEMNOS: Laser-Enhanced Mission Communications Navigation and Operational Services

3

LEMNOS Introduction

- *Space-based Optical Comm demonstrated on LADEE LLCD*



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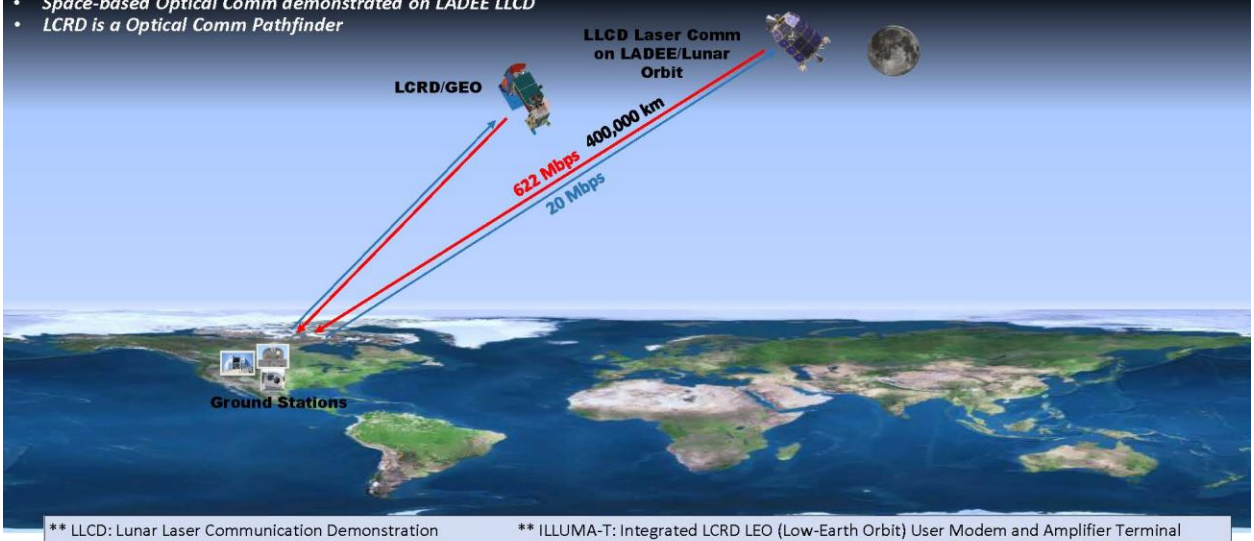
4

LEMNOS Introduction

- *Space-based Optical Comm demonstrated on LADEE LLCD*
- *LCRD is a Optical Comm Pathfinder*



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** LEMNOS: Laser-Enhanced Mission Communications Navigation and Operational Services

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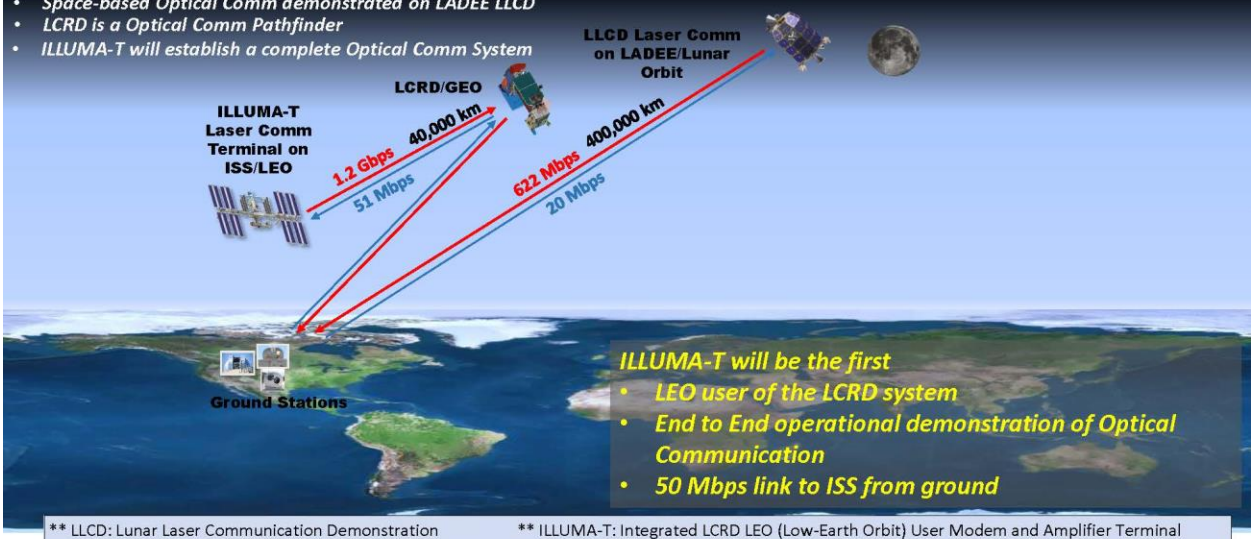
LEMNOS Introduction

- *Space-based Optical Comm demonstrated on LADEE LLCD*
- *LCRD is a Optical Comm Pathfinder*
- *ILLUMA-T will establish a complete Optical Comm System*



ILLUMA-T will be the first
- *LEO user of the LCRD system*
- *End to End operational demonstration of Optical Communication*
- *50 Mbps link to ISS from ground*

** LLCD: Lunar Laser Communication Demonstration
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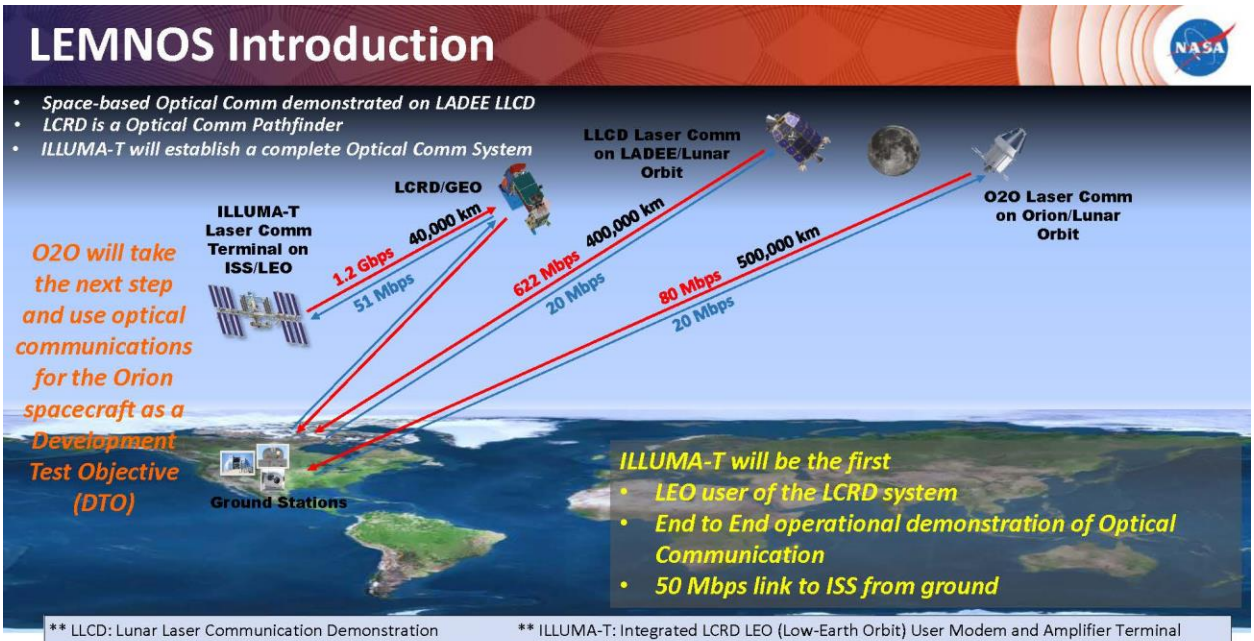
6

LEMNOS Introduction



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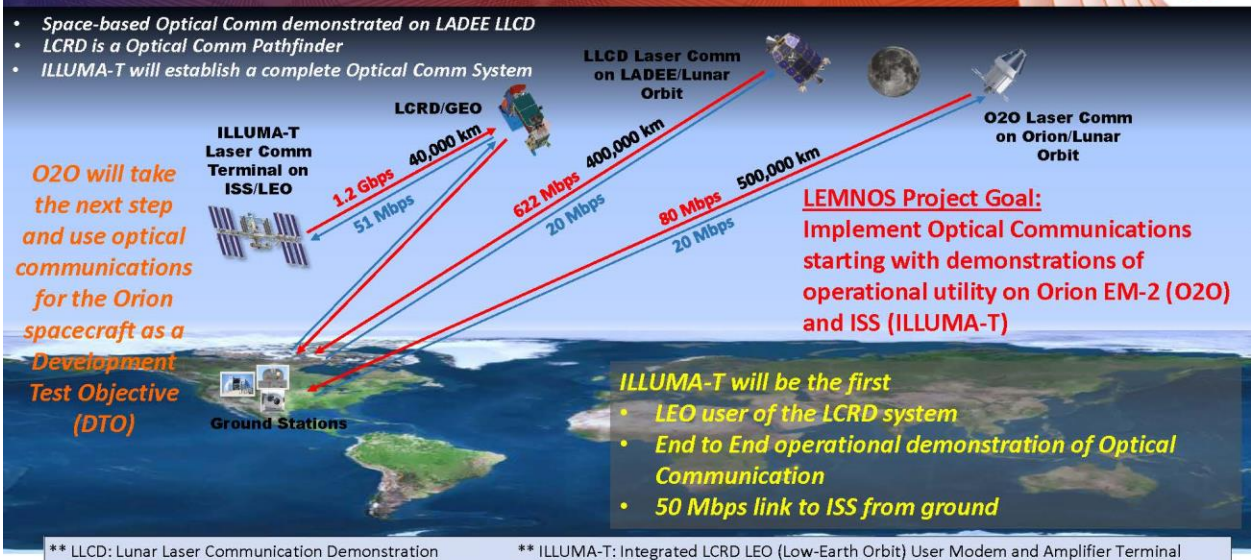
7

LEMNOS Introduction



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LEMNOS Projects



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O2O Objective and L1 Requirements

Objective: Implement optical communications capability for Orion series of spacecraft, starting with a demonstration of operational utility on EM-2	
1.0	Develop an Optical Comm System to plan and demonstrate an operational optical comm link for Orion EM-2
2.0	Maintain a development path to a fully operational Optical Comm System
3.0	Flow data from Orion through the Optical Comm Fight Terminal to the Optical Comm Ground Terminal
4.0	Flow data from Optical Comm Ground Terminal to Optical Comm Fight Terminal and forward to Orion
5.0	Distribute data to/from Orion MOCC real time or store and distribute later
6.0	Flight terminal conforms to the Orion accommodations, mission objectives, and environments
7.0	Ground terminal and data system developed with operational interfaces

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ILLUMA-T Objective and L1 Requirements

Objective: The ILLUMA-T project shall develop an optical communications user terminal to demonstrate data transfer between low Earth orbit and the ground through a geosynchronous relay	
1.1	The ILLUMA-T project shall demonstrate a duplex optical communications link from the ILLUMA-T terminal located on the ISS to a ground station via the LCRD satellite
1.2	The ILLUMA-T user terminal shall operate up to 1.244 Gbit/s on the return link (ISS to Ground) and up to 51 Mbps on the forward link (Ground to ISS)
1.3	The ILLUMA-T protoflight terminal shall be developed using an approach that includes participation of commercial companies and enables the transfer of optical communications technology to industry
1.4	The ILLUMA-T terminal orientation shall support line of sight to a ground station
1.5	The ILLUMA-T terminal shall support a bi-directional data connection of at least 1.0 Gbit/s (i.e. 100/1000 Mbps Ethernet connection)

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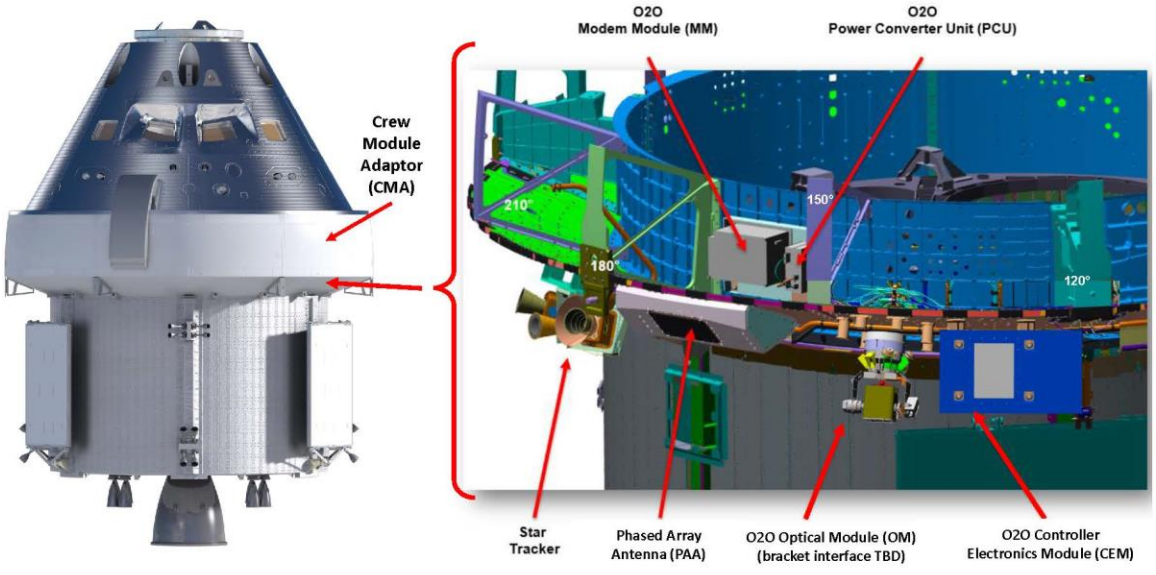
O2O Implementation



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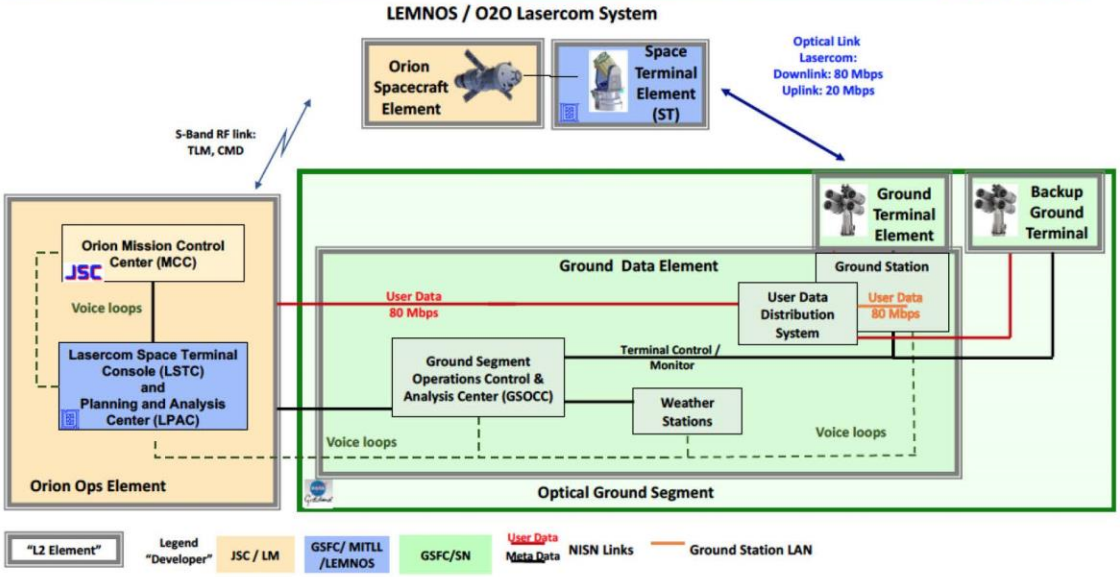
O2O Architecture



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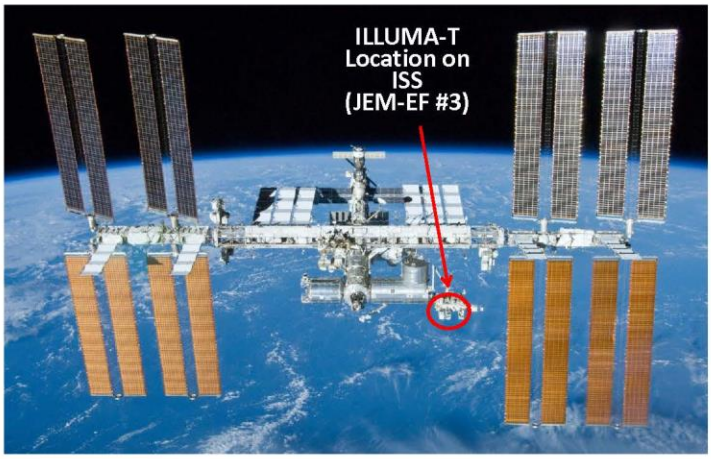
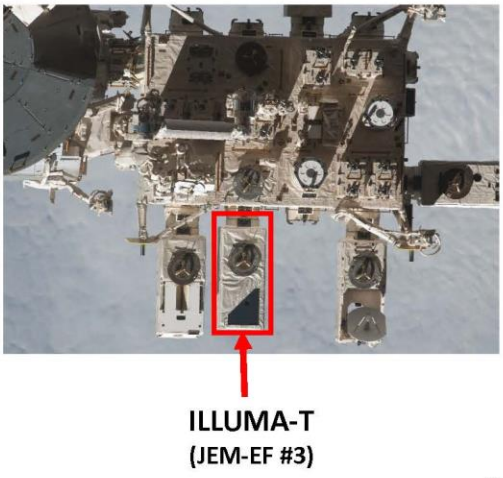
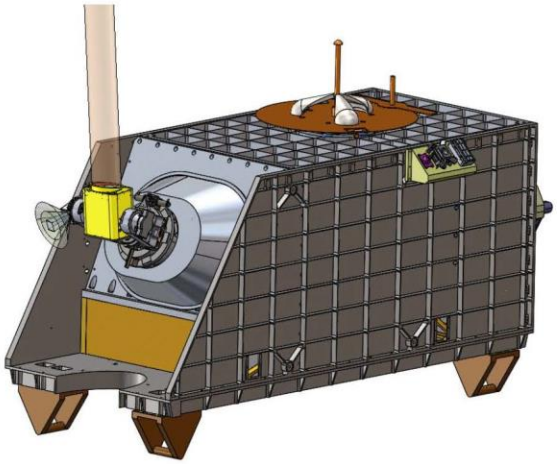
ILLUMA-T Implementation





16

ILLUMA-T Payload





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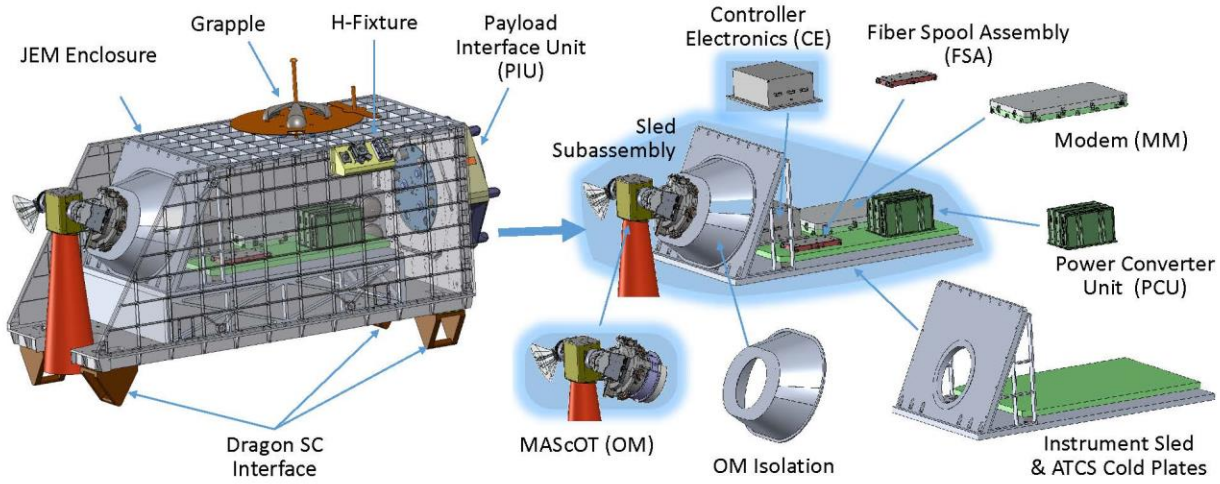
ILLUMA-T Space Terminal Elements



MITLL Responsible for procurement of OM & CE and I&T of Sled Subassembly

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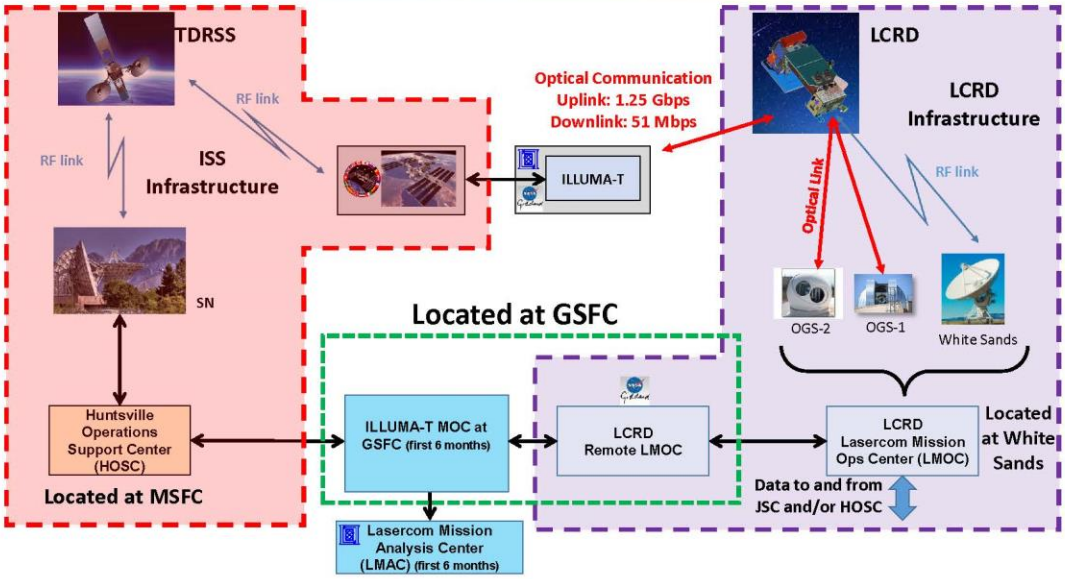
ILLUMA-T Architecture



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Lasercom Terminal Evolution



LLCD Optical Module on LADEE

2009-2014

NASA/MITLL developed and demonstrated during Lunar Laser Comm Demo (LLCD)

*T. Shih, et al, "A Modular, Agile, Scalable Optical Terminal Architecture for Space Communications", ICSOS 2017.

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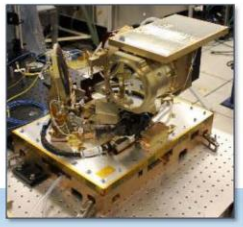

LCRD Optical Module

2011-Present

Industry "build to print" of LLCD-based terminal; to be used for Laser Comm Relay Demo (LCRD)

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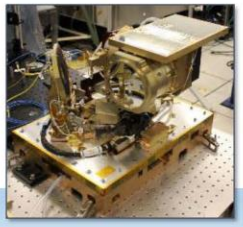


LCRD Optical Module

2011-Present

Industry "build to print" of LLCD-based terminal; to be used for Laser Comm Relay Demo (LCRD)





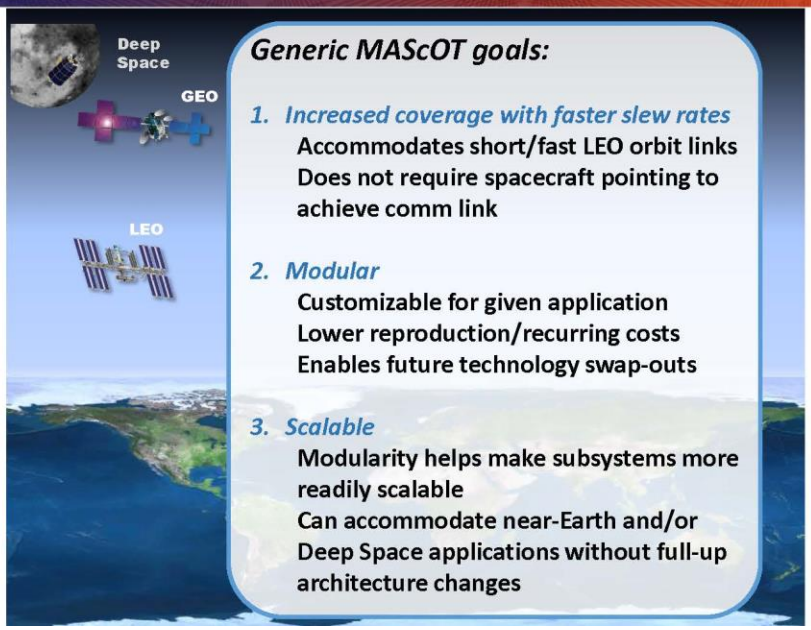
Modular, Agile, Scalable Optical Terminal (MAScOT)*

2013-Present

NASA/MITLL concept, industry-built; to be used in new programs with ISS and Orion; incorporates lessons learned from LLCD/LCRD

*T. Shih, et al, "A Modular, Agile, Scalable Optical Terminal Architecture for Space Communications", ICSOS 2017.

Modular, Agile, Scalable Optical Terminal(MAScOT)



Generic MAScOT goals:

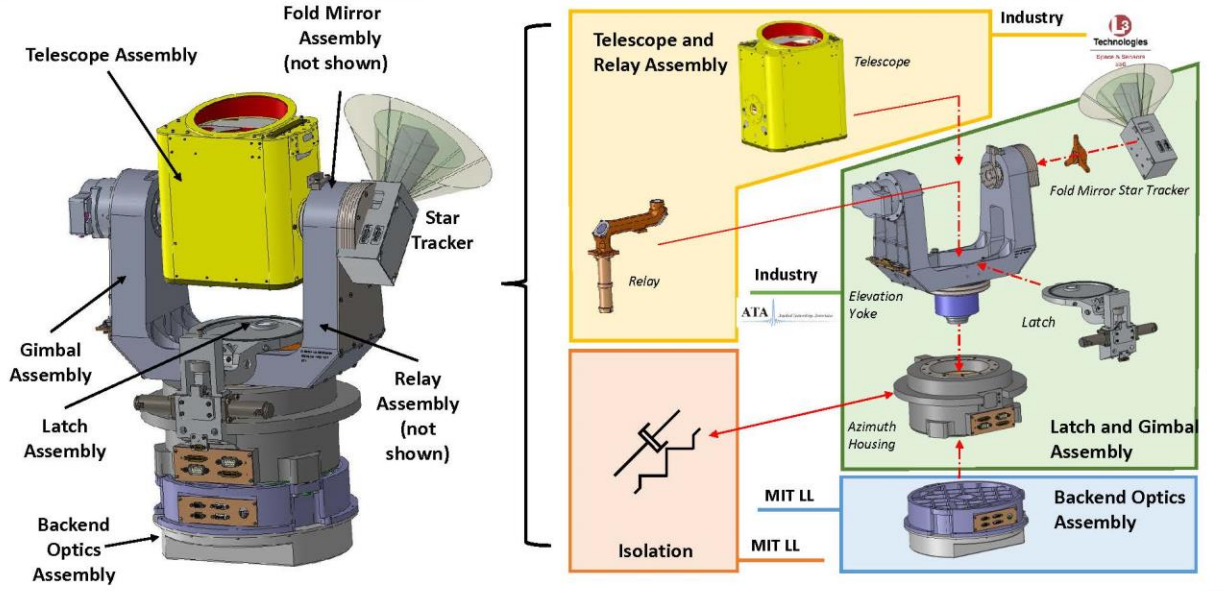
1. *Increased coverage with faster slew rates*
   - Accommodates short/fast LEO orbit links
   - Does not require spacecraft pointing to achieve comm link
2. *Modular*
   - Customizable for given application
   - Lower reproduction/recurring costs
   - Enables future technology swap-outs
3. *Scalable*
   - Modularity helps make subsystems more readily scalable
   - Can accommodate near-Earth and/or Deep Space applications without full-up architecture changes



Modular, Agile, Scalable Optical Terminal (MAScOT)

10-cm Terminal Architecture

OM Subassembly Breakdown



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Conclusion

- The LEMNOS team represents a world recognized group aiming to advancing the use of optical communications system for space communications
- LEMNOS projects embody important opportunities to demonstrate key characteristics of optical communications based systems and are natural precursors to planned deployment of the next generation communications relay system (Optical TDRS) and deep space optical communications
- By 2022 the LEMNOS project will deliver two optical communications terminals demonstrating operational utility of laser communications in both relay and direct to earth scenarios

GO LEMNOS!

BACKUP SLIDES

7.4 DEEP SPACE OPTICAL COMMUNICATIONS (DSOC)

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ABSTRACT

NASA's future deep space science and exploration missions will require enhanced communications and navigation services. Laser communications offers expanded bandwidth and the potential for satisfying this need, with comparable mass and power as state of the art telecommunication systems. Consequently, NASA is planning a Deep Space Optical Communications (DSOC) technology demonstration, to retire the risk for future enhanced optical communication services. NASA's upcoming Psyche Mission scheduled to launch in August of 2022 plans to host a DSOC flight laser transceiver (FLT) for demonstrating optical links from deep-space to earth. Existing ground assets retrofitted with laser transmitters and photon-counting receivers will be used for the technology demonstration. Advancing optical technology from near-Earth ranges to deep space (> 0.01 astronomical units or AU) involves orders of magnitude increased link difficulty (defined as data-rate × squared distance). The plan to bridge the difficulty gap implements new technologies developed over the past two decades. These technologies emphasize high photon efficiency (HPE) with the use of high-peak-to-average power laser transmitters in space, and single photon-counting sensitivity detectors, that together support signaling schemes for achieving approximately 2-3 information bits per detected photon. Implementing HPE schemes relies on accurate and stable pointing of narrow laser beams from space platforms using active control. Key developments needed for future technology infusion, following a successful DSOC technology demonstration, include, cost-effective ground infrastructure, long term reliability of space lasers and detection systems, and solutions for high precision laser ranging. The current status of the DSOC Project and plans for future development will be discussed in this paper.

1 INTRODUCTION

NASA's future missions will require returning larger data volumes, faster, from deep space missions. Both higher resolution science instruments and human exploration will be enabled by this capability. Optical communications offers these capabilities for approximately similar mass and power burden used by state of art telecommunications systems. With this in mind JPL has been pursuing a technology demonstration of deep space optical communications. Following nearly four years of technology development and maturation under the NASA's Space Technology Mission Directorate (STMD) Game Changing Development Program (GCDP) and the Human Exploration and Operations Mission Directorate (HEOMD) Space Communication and Navigation (SCaN) Program, the JPL DSOC Project [1] is planning a technology demonstration (TD). The TD is funded jointly by the STMD/Technology Demonstration Missions (TDM) Program and HEOMD/SCaN Program. Figure 1 illustrates the TD system architecture. The Psyche Mission [2] spacecraft, scheduled to launch in August 2022,

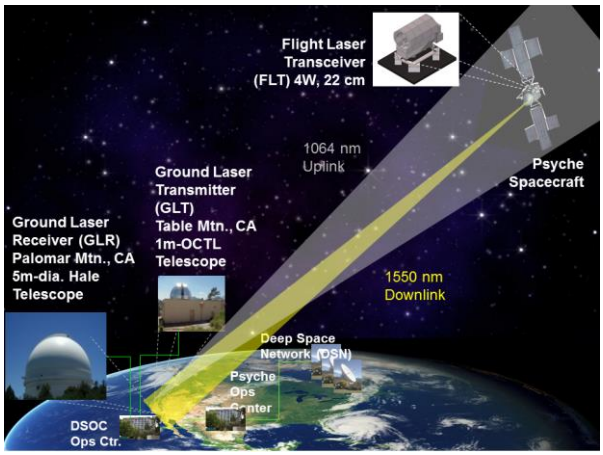

Figure 4 DSOC Operational Architecture

is planning to accommodate the Flight Laser Transceiver (FLT) being developed by the DSOC Project,. The DSOC TD opportunity was incentivized by the NASA Discovery Program announcement of opportunity through which Psyche was selected. The DSOC TD will transmit laser beacon transmitted from the ground to the FLT on-board the Psyche spacecraft. The FLT will acquire and track the beacon assisted by the Psyche spacecraft coarse pointing and on-board attitude

knowledge. The acquired beacon will serve as a pointing reference for returning the downlink laser to earth. The DSOC Ground Laser Transmitter (GLT) will use the Optical Communication Telescope Laboratory (OCTL), 1 m diameter telescope, located at Table Mountain, CA. OCTL will be retrofitted with a high power (5 kW average) laser transmitter. The Ground Laser Receiver (GLR) requiring a large aperture will use the 5m diameter Hale telescope at Palomar Mountain, CA. The angular separation between the GLT and GLR is less than the downlink laser beam width (8-μrad) from a distance of ~ 0.2 AU. Data-rates ranging from 0.2 Mb/s to > 200 Mb/s well be demonstrated over the 0.2-2.7 AU link range. A photon-counting optical receiver integrated to the Hale telescope will perform optoelectronic conversion and subsequent signal processing for extracting the information.

The uplink (beacon) and downlink laser wavelengths are 1064 nm and 1550 nm. The choice of wavelengths is driven largely by fiber laser and amplifier technology and the communications requirements. Deep space optical communications involves a huge increase in distance, relative to near earth applications. Defining link difficulty as data-rate × squared distance indicates a 60 dB increase in difficulty for returning the same data-rate from Mars versus the Moon. Merely scaling of power and aperture does not provide a viable solution.

DSOC has developed technologies to overcome the difficulty gap. High photon-efficiency communications, requiring high peak to average power laser transmitters and single photon sensitive detectors, will allow demonstrating communications with 2-3 information bits per detected photon. The faint downlink signal will be transmitted using spatially narrow beam-width lasers, thereby introducing a pointing challenge. Given typical spacecraft platform stability, active control will be required to achieve accurate pointing. Ground laser beacon acquisition by the FLT uses a 256 μrad field-of-view detector and a +/- 4 mrad field of regard realized using active struts for stabilizing the line-of-sight in the presence of spacecraft platform disturbance and attitude. Downlink pointing to the ground receiver, with appropriate point-ahead angle, will use the beacon as a pointing reference. The beacon signal delivered to the FLT is dim, requiring a photon counting camera (PCC) for sensing. The dim beacon will support low bandwidth pointing control and low rate (1.6 kb/s) uplink data-rates at a distance ofg 1 AU.

DSOC technologies include a 1550 nm, 4 W average power flight laser with a peak-to-average ratio of 160, and a variable repetition frequencies of 100's of MHz. The laser operates with sub-nanosecond pulse-widths with < 0.1 nm spectral linewidths. The 22 cm diameter off-axis flight transceiver receives the 1064 nm beacon laser signal using the PCC. The flight transceiver includes active isolation pointing assembly struts (IPA-S) for vibration isolation and low bandwidth closed loop control.

On the ground tungsten silicide (WSi) superconducting nanowire single photon detector (SNSPD) array forms the front end of the photon counting receiver to be integrated to the Hale telescope.

The DSOC Project is integrating and implementing the technologies so that the flight transceiver can be hosted by the Psyche spacecraft in time for launch in August 2022.

2 METHODOLOGY

Deep space communications has and will continue to be mission enabling. Historically the frequency and performance have been increasing [3].

2.1 STATE OF THE ART

Today deep space communication and navigation typically carries a high gain X-band or Ka-band system. These systems provide excellent mission support for returning science and telemetry. Projecting into the future scaling to higher power transmitters and larger antennae to satisfy future demand translates into increased mass and power. RF systems are also constrained by bandwidth regulations

2.2 NEW APPROACH

Optical services, if they could be implemented, would result in a significant augmentation of the current radio frequency capability. For near-earth missions optical has matured beyond technology demonstrations and transitioning into operational status.

An order of magnitude improved downlink deep space data-rate performance with comparable mass and power as state-of-art telecommunication systems is the goal to pursue.

To accomplish this goal driving requirements are, firstly, a technology demonstration from deep space, secondly, an earth receiving infrastructure for operational use, and finally improved reliability and scaling for operationally robust and redundant systems.

The DSOC Project TD will address the first of by validating: (i) acquisition, tracking and pointing of narrow lasers to and from deep space; and (ii) signaling performance that supports deep-space links.

2.3 FUTURE DSOC USE CASES

An orbiting telecommunication infrastructure around Mars that includes optical services [4] is an achievable by the end of the next decade. For human landing and operations safety, the required high resolution mapping and high rate communication can be significantly augmented with optical communications. Streaming multiple channels of high definition imagery supporting human exploration will be enabled. Higher uplink data-rates will also be supported within the constraints of atmospheric turbulence induced earth to deep space laser propagation effects.

2.4 CHALLENGES AND REWARDS

Key challenges in this development approach are (i) timely deployment of ground infrastructure to support flight operations (ii) validating the long term operational reliability, primarily of flight lasers and detectors and (iii) scaling flight transceiver performance to satisfy the future performance demands.

A key operational challenge is optical link availability. Atmospheric disturbances and signal blockage by clouds will reduce the optical link single path availability. Active mirror optics to mitigate atmospheric distortion and an increase in the number of geographically dispersed ground stations provides multiple paths for the optical signal to raise the link availability.

Models addressing the effects of thermal cycles, radiation induced damage and darkening of detectors, optics and fibers need validation.

Scaling of flight transceivers to larger diameter and higher power lasers will be introduce additional pointing difficulty and engineering of laser components to withstand higher peak power.

Overcoming these challenges will provide NASA with robust, reliable, lower size weight and power communication systems that can augment performance significantly.

3 PROGRAMMATICS

The first step, a technology demonstration of deep space optical communications is currently funded and in Phase B progressing toward preliminary design review in 2018.

Studies for the development of cost-effective large ground apertures that can support daytime operations are also currently funded by HEOMD/SCaN..

Through HEOMD/ScaN Planning, Programming, Budgeting and Execution (PPBE) process future studies for the next generation DSOC have been proposed with a planned start dates of FY 2020. The proposed studies include developing and implementing ground detectors and receivers for larger aperture collectors. Studies for atmospheric mitigation, especially for reducing the penalty for daytime performance are included. For flight systems the development of higher emitted isotropic radiated power (EIRP) flight transceivers is planned.

3.1 DEVELOPMENT PLANS

Studies for realizing cost-effective larger operational ground apertures to support deep-space optical communications with possible development of a pathfinder capability [1, 5] in the middle of the next decade are underway. The use of existing RF antennae to provide mirrored surfaces without significantly impacting RF performance is being studied. This approach would result in 8-11 m class optical apertures that operate to within < 10° of the sun with 30-40% efficiency. Successfully implementing such a capability at a single site, such as Goldstone, CA, by the end of the next decade would support operational demonstrations advancing both space and ground systems, while augmenting existing deep space communications services. Success with this approach will result in additional ground assets for implementing site diversity.

The costs for both developing the next generation DSOC that includes, ground receivers for larger aperture collectors along with atmospheric mitigation and scaled up flight transceivers are in planning and review

3.2 DEVELOPMENT MILESTONES AND DATES

The key development milestones for deep space optical communications are:

10. Perform a successful TD in the 2022-2024 time frame
11. Develop a single ground based large aperture collector equipped with photon counting receivers for daytime link operations in the 2025-2030 time frame
12. Advance reliable higher EIRP optical transceivers. This will require lightweight large (50 cm class) transceivers and higher average power (20 W class) laser transmitters. Deploy a Mars orbiting optical transceiver in the 2028 time frame returning at least 75 Mb/s from Mars farthest range. Target a 75 kg mass and < 250 W power.

3.3 PARTNERING

Partnering with other NASA centers FFRDC's such as MIT-Lincoln Laboratory is underway. Industry is also involved in providing advanced lasers, actuators and detectors.

Partnering with international space agencies for site diversity of ground sites will also prove cost effective. Involving astronomy, solar astronomy and Cerenkov radiation community on implementing large apertures will be instructive.

4 WIDER VISION

Laser ranging measurements over the laser link in support of navigation is an expected extension of the technology. A number of light science applications akin to radio science performed by telecommunications systems today but with higher resolution and at optical frequencies will follow.

5 CONCLUSIONS

Deep space optical communications is on the verge of an important TD milestone that will qualify flight hardware, demonstrate key flight and ground technologies and link processes setting optical communication for prime flight support uses.. Having a successful TD will result in a demand for operational ground infrastructure, longer time reliability of flight lasers, sensors and actuators. Some work toward these goals is underway but unless a commitment is made an opportunity will be lost. Once the capability is infused further enhancements such as high precision ranging and light science will follow.

ACKNOWLEDGEMENTS

Ongoing discussions, review and support by Steven Townes, David Bell, Don Cornwell and William Klipstein are acknowledged. The work described here was performed at the Jet Propulsion Laboratory (JPL), California Institute of Technology under contract with the National Aeronautics and Space Administration.

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Deep Space Optical Communications (DSOC)

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Aug. 2, 2018 NASA Technical Interchange Meeting on Active Optical Systems for supporting Science, Exploration and Aeronautics Needs,
Pre-Decisional Information -- For Planning and Discussion Purposes Only

Outline

- **Deep Space Optical Communications (DSOC) Architecture**
- **Technology Development**
- **DSOC Technology Demonstration**
- **Concept of Operations**
- **Flight Laser Transceiver**
- **Ground Data System**
- **Link Performance Summary**
- **Future Developments**
- **Summary**

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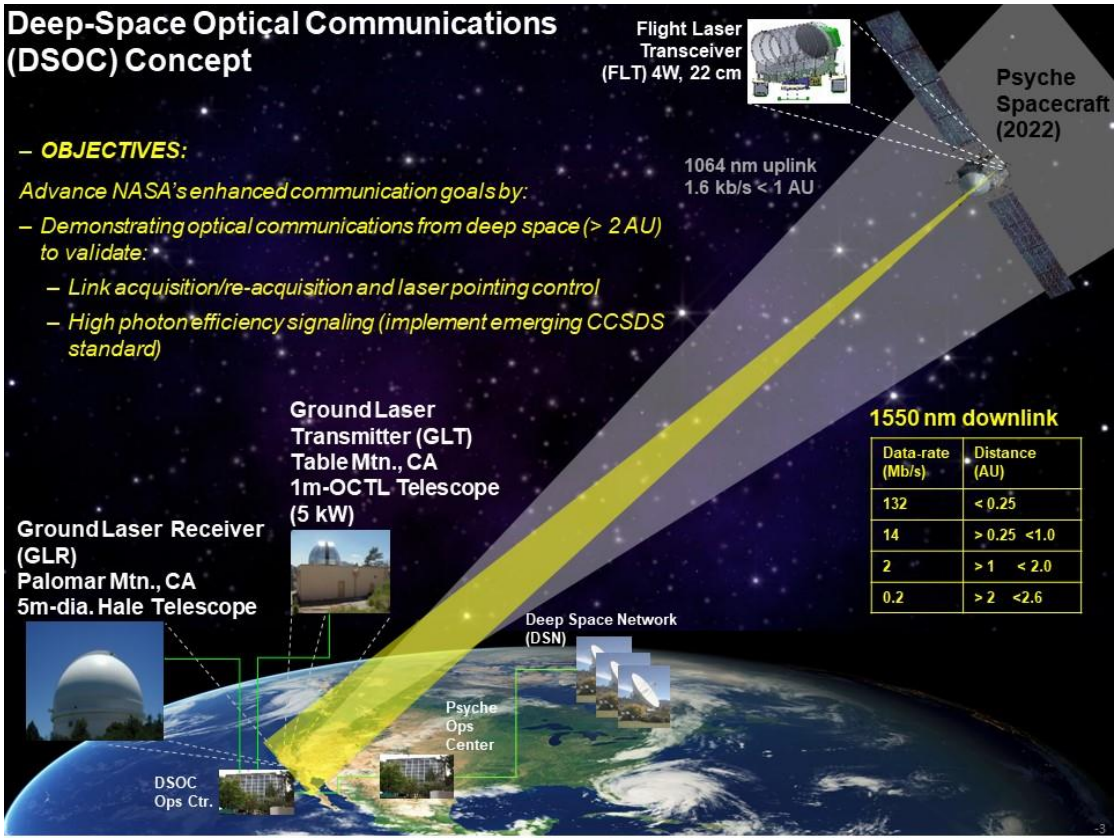


DSOC Project Technology Development

- **Technology development under the NASA/STMD Game Changing Program and HEOMD/SCaN**
  - Preceded and enabled the planned Deep Space Optical Communications Technology Demonstration
  - 2014 to 2016



Electron microscope detail of 320-μm active area tungsten silicide (WSi) superconducting nanowire single photon detector (SNSPD) array

Packaged Nanowire Array

Ground Technology

- Downlink high photon efficiency (HPE) signal processing algorithms and simulations
- An emerging CCSDS Modulation/Coding standard



Aluminum Optical Transceiver Assembly

Flight Technology

Point-Ahead Mirror



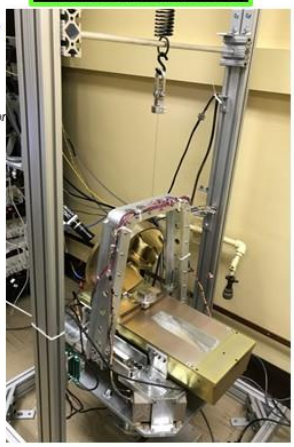


Laser Transmitter (Avg. Pwr 4 W, Pk-to-Avg ratio 660)



Flight like electronics

Acquisition trackin Pointing Testbed



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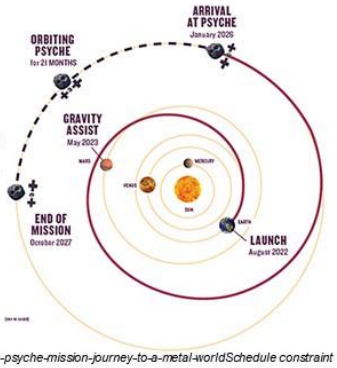
DSOC Technology Demonstration

- **The DSOC Project at JPL is jointly funded by:**
  - NASA/STMD/TDM Program
    - Flight Laser Transceiver
  - HEOMD/SCaN Program
    - Ground Data System
  - SMD/Discovery
    - Accommodation on Psyche Spacecraft



- **DSOC tech demo planned to be hosted by Psyche Mission**
  - Selected by NASA/Discovery Program to explore the asteroid Psyche-16
  - Primary science objective is to determine whether Psyche-16 is a core or if it is un-melted material
  - Psyche scheduled for launch in summer of 2022 with a 21-day launch window
    - Trajectory uses a Mars Gravity Assist
    - 21-day launch window around August 2022



https://medium.com/the-nasa-psyche-mission-journey-to-a-metal-worldSchedule constraint

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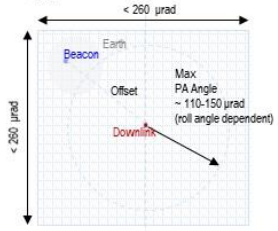
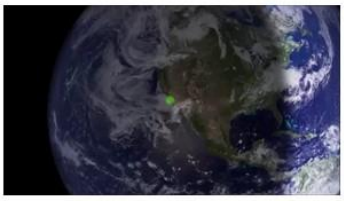
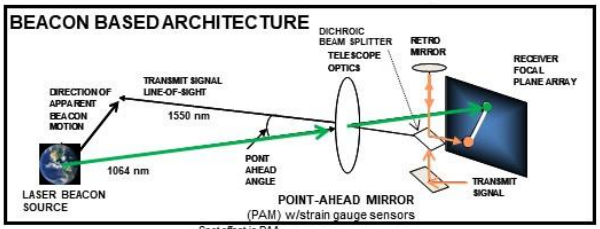
Concept of Operations

- **DSOC tech demo operations concept is under formulation**
  - Following commissioning and calibration a typical day-in-the life will involve: A
    - Transmit ground laser beacon using predicts while Psyche powers FLT and "**coarse poi**nts" to Earth
    - DSOC searches out beacon in s/c pointing uncertainty space
    - FLT stabilizes line-of-sight to Earth with beacon assisted closed-loop control
    - Points downlink to Earth while Ground Receiver is pointing to Psyche using predicts
    - Receive and store downlink
  - Telemetry gathered and stored at FLT for post pass transmission to ground
  - Limited "real time" telemetry during pass may be available









Spot offset is PAA
(For PAA > FOV
– PAM strain gauge tracks PAA
– Strain gauge calibrated with Tx spot

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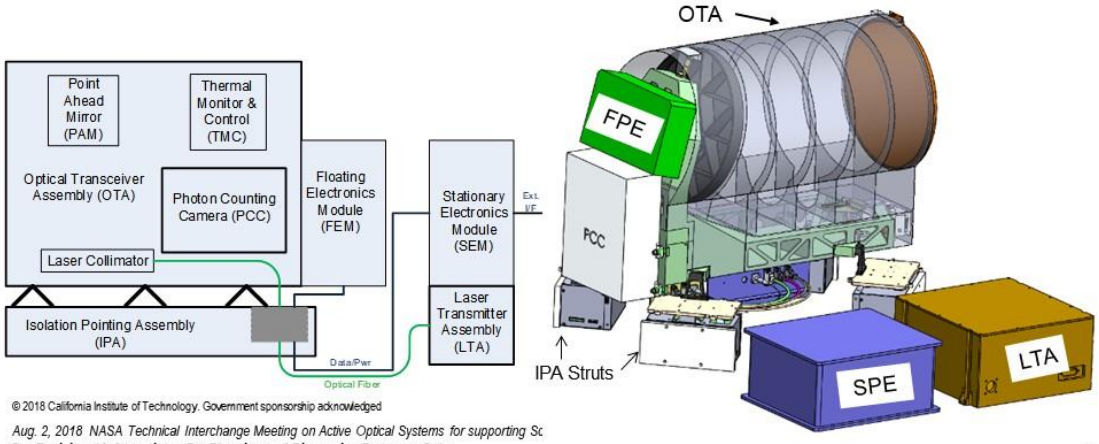
DSOC Flight Laser Transceiver (FLT)

- **The Flight Laser Transceiver (FLT) makes up the flight subsystem**
  - **Silicon carbide (SiC)** Optical Telescope Assembly (OTA) receives beacon and transmits downlink
  - **Photon Counting Camera (PCC)** detects "dim" 1064 nm laser beacon transmitted from Earth
  - **Isolation Pointing Assembly (IPA)** "floats" OTA to stabilize and steer OTA line-of-sight
  - **Laser Transmitter Assembly (LTA)** delivers high peak power pulse train modulated by downlink data
  - **Electronics** – firmware/software platforms, power and clock distribution for "floating" and stationary parts, power and data interface to spacecraft



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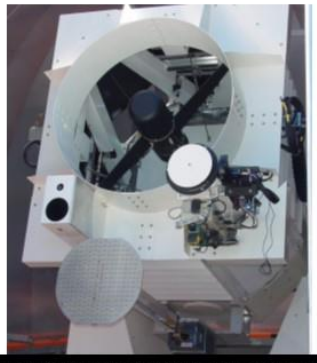
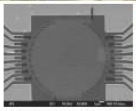
DSOC Ground Data System (GDS)

- **DSOC technology demonstration would utilize**
  - Ground Laser Transmitter at OCTL telescope near Wrightwood, CA
    - Retrofit high power (5 kW) laser transmitter @ 1064 nm
  - Ground Laser Receiver at Hale telescope at Palomar Mountain, CA
    - Tungsten silicide (WSi) superconducting nanowire single-photon detector (SNSPD) array w/signal processing electronics
  - Mission ops center for coordinating ops (not shown)



Optical Communication Telescope Laboratory (OCTL) 1m aperture Az/El Drive





SNSPD array (~ 320 μm dia.)

Ground Laser Receiver(GLR)
- Photon-counting ground detectors
- 50% Eff. WSi nanowire arrays

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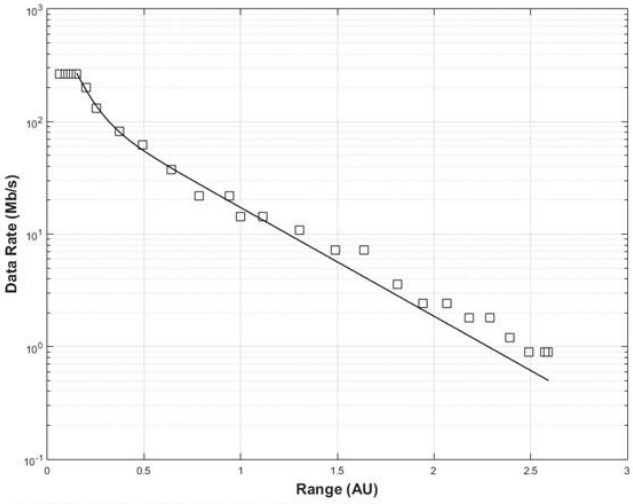
Predicted Nominal Link Performance

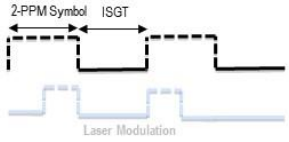
- 4 W average power laser with 22 cm diameter FLT
- Received with 5m diameter Hale Telescope and SNSPD based

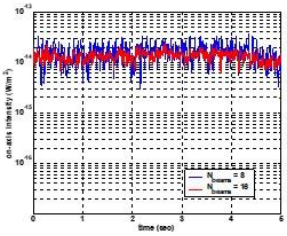
Predicted Nominal Downlink Performance



Uplink

- **1.6 kb/s @ 1 AU**
- **~ 4 pW/m² irradiance at FLT aperture**





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Future Systems

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Gaps after DSOC Technology Demonstration

- **What will it take to infuse optical communications in NASA's communications tool box following a successful DSOC TD?**

- **Implement an operational ground infrastructure**
  - Provide large aperture 5-11 m diameter
  - Support daytime operations < 10° sun-earth-probe (SEP) angles
  - Provide site diversity for increased link availability

- **Emphasize long term reliability of communications lasers and detectors**
  - Validate radiation darkening/damage of fibers, optical components and detectors
  - Reliability of optical communications flight sub-systems to thermal cycling
  - Effects of long term exposure to outgassing

- **Scale flight transceivers for increased emitted isotropic radiated power (EIRP)**
  - 50 cm optical transceivers
    - Introduces tighter pointing requirements
  - > 20W laser transmitters
    - Designs withstand higher peak powers without parasitic non-linear optical effects

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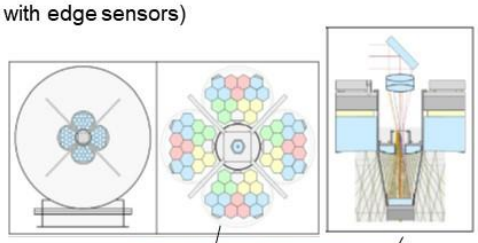
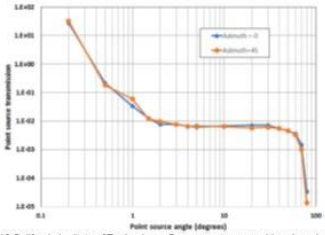
Future Ground Assets

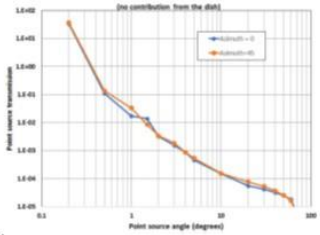
- **Ground infrastructure for deep space optical communications is lacking**
  - Need large aperture optical collectors that can operate in daytime while pointing within 10-15° of sun
  - Develop appropriate detectors and receivers for larger apertures
  - Atmospheric mitigation to improve daytime performance
- **JPL funded to study adding mirrors to existing 34 m RF antennae**
  - ~ 8 m aperture with spherical figure (actively maintained with edge sensors)
  - 30-40% optical efficiency
  - Recently completed Stray light analysis
    - Surfaces in vicinity of mirror pods contribute worst stray light
    - Eliminating this surface provides acceptable stray light
  - Possible solution is use of a specially designed Lyot stop
    - 75% reduction in effective aperture from practical implementation constraints
    - Reduced aperture of ~ 6 m at shallow sun-earth-probe (SEP) angles of TBD –to-10 degrees





DSN 34-m antenna





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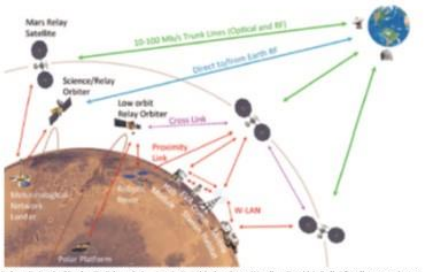
Future Deep-Space Flight Transceivers (FLT)

- **Scale FLT emitted isotropic radiated power (EIRP) and provide long term operational reliability**
  - Mars telecommunication orbiter likely near-term Infusion
  - Target > 75 Mb/s from Mars far range
    - Link analysis predicts the need for
      - 50 cm diameter FLT with 20 W laser transmitter
      - Higher effective laser power achieved by wavelength multiplexing
      - Pointing and thermal challenges of operating while pointing close to sun
      - Validate laser and detector lifetime models in deep space
        - Thermal cycles, radiation damage, cumulative contamination from outgassing



Robert E. Lock, Charles D. Edwards Jr., Austin K. Nicholas, Ryan Woolley, David J. Bell, "Small Areostationary Telecommunications Orbiter Concepts for Mars in the 2020s," IEEE Aerospace Conference, 1-12, 2016.

- **Implementing robust and reliable future FLT's will enable other applications**
  - High precision laser ranging laser applications to support navigation and science
  - Extending the range to the outer planets
    - Explore strategies for using celestial sources as beacon reference for active pointing control
  - Similar to radio science done with SOA telecommunications, light science will be enabled
    - Active probing of planetary atmospheres and solar corona using the FLT advanced pointing control

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Near Term Rewards

- **Planned developments can provide improvements summarized below**
  - Assume that the RF-Optical hybrid aperture can be implemented
    - 8m effective aperture diameter that is reduced to 6m when operating at smaller SEP angles
    - Atmospheric conditions are similar to Goldstone, CA
    - Nearby laser beacon trnamsitter (e.g. OCTL) is available
  - 20-40 W laser transmitters are ready for flight
  - Implement 50 cm flight transceivers
  - Appropriately sized photon-counting detectors are developed
    - Double the WSi SNSPD from 320 μm to 640 μm

Data-rate/Link Margin summary

	Mars Near Range (0.415 AU)			Mars Far Range (2.62 AU)		
	Best	Nom	Worst	Best	Nom	Worst
DSOC Flight Laser Transceiver (22 cm dia. Aperture, 4 W Avg. Pwr. @ 1550 nm)	132/3.6	100/3.8	66/3.6	1.8/3.3	1.2/4	0.25/3
Future Transceiver (50 cm dia. Aperture, 20-40 W Avg. Pwr. @ 1550 nm)	528/7.4*	528/6.6*	528/4.3*	75/5.3**	75/5**	75/1.5**

← Ground aperture only

← Ground aperture and scaling of flight transceiver

* 20 W laser; ** 40 W laser

- **Not assuming any active atmospheric turbulence mitigation – further (as yet unquantified) improvements possible**

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Summary

- **DSOC Architecture**
- **Technologies, technology demonstration and concept of operations**
- **System Description and TD Performance Summary**
  - Flight Laser Transceiver description
  - Ground Data System
- **Future Developments**
  - Ground Infrastructure
  - Scaling Fight Transceivers
  - Enhanced Reliability for robust operational systems
- Partnering with NASA Centers and FFRDC's already underway
- Involving astronomy, solar astronomy and Cerenkov radiation studies community

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7.5 ACTIVE SENSORS FOR NASA RENDEZVOUS AND CAPTURE MISSIONS

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ABSTRACT

This paper presents an overview of NASA's active sensing development and flight activities in the Rendezvous and Capture area, and provides an overview of the performance requirements for active sensors.

1 INTRODUCTION

Active sensors are a critical part of several NASA missions, including currently active and near-term missions using relative navigation sensors to enable rendezvous, proximity operations, and in some cases capture or contact with other space vehicles or solar system small bodies (comets and asteroids.) Figure 1 shows several recent, near term, and future missions utilizing rendezvous and capture, or similar system capabilities.

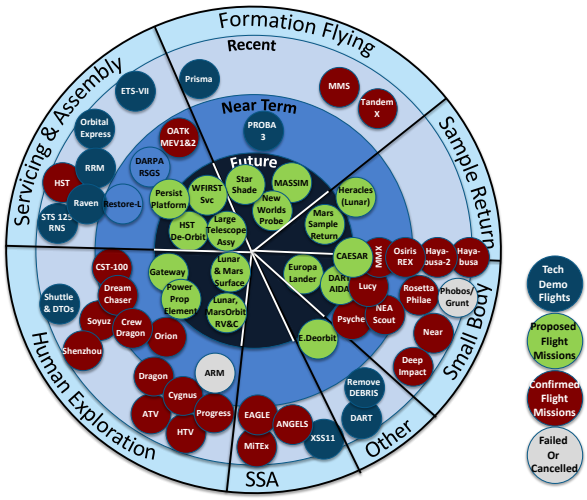


Figure 1 - Missions requiring rendezvous and capture or similar capabilities

Current operational missions include several International Space Station (ISS) cargo vehicles, the RAVEN experiment on ISS, and OSIRIS-Rex. Future missions at various points in the mission life cycle include ISS crewed vehicles, the Restore-L satellite servicing mission, Orion and various Lunar Gateway vehicles, Mars Sample Return, and various other servicing, assembly, and small bodies missions in early study and proposal phases.

Active sensors for Rendezvous and Capture (R&C) missions provide system capabilities as shown in Table 1.

Table 1 – Relevant R&C System Capabilities

	Coop	Non-Coop	Small Body
Direct Range Monitoring	X	X	X
Relative Position Estimation (3-DOF)	X	X	X
Descent Corridor Monitoring			X
Cooperative 6DOF pose	X		
Non-Coop. 6DOF pose	X	X	
Terrain-Relative 6DOF pose			X
Relative Position & Attitude Est. (6-DOF)	X	X	X
Robotic Grapple Visual Servoeing	X	X	X

Direct ranging to a client vehicle or surface, and *descent corridor monitoring* serve fault management functions to keep the relative motion safe and trigger aborts of the approach sequence if necessary.

Three-degree-of-freedom (3-DOF) relative position estimation fuses range and bearing measurement information from an active sensor with other available sensors to provide navigation during long range rendezvous maneuvering (distances from 100s of meters to 10s of km.) These measurements are usually based on a computed point cloud centroid from a Light Detection and Ranging (LIDAR), or a filtered range measurement from a Laser Range Finder (LRF), with sensor boresite tied to inertial space using spacecraft inertial attitude estimation to provide an inertial bearing measurement.

6-DOF relative position and attitude estimation serves a similar purpose at closer ranges (100s of m to 10s of cm) where proximity operation GNC closed-loop control requires full relative state knowledge. Here LIDAR point clouds are matched to internal models of the client or small body (ie using an iterative closest point or similar

algorithm) to return a relative attitude and position measurement.

We consider *cooperative* and *non-cooperative vehicle-relative navigation*, as well as *terrain-relative navigation*. For the purposes of active sensing, *cooperative* refers to the presence of reflective elements such as corner cubes to augment sensor performance. *Non-cooperative* refers to *legacy vehicles* not specifically designed with rendezvous and capture in mind.

An area of future growth for active sensing is in sensing for Robotic Grapple Visual Servoeing. Here, sensors mounted to the end of a robot arm are used in the robot control loop to allow precision placement of a grapple tool over a grapple feature to affect capture. Current state of the art uses monocular or stereo visible wavelength cameras, perhaps with a structured light source, to perform this task. As LIDARs continue to decrease in size, power, and reliability, this type of sensing could provide significant benefit to the autonomous capture scenarios we face.

2 METHODOLOGY

NASA's Rendezvous and Capture System Capability Leadership Team (R&C SCLT) [1] consists of practitioners across the Agency working to provide stewardship of NASA's critical capabilities in R&C to meet current and future mission needs. The team collaborates on sensor specification, development, and procurement and test activities in an effort to improve performance and efficiency across multiple NASA's missions.

In 2015 the R&C SCLT developed a Common Sensor Specification enveloping the performance requirements of various relative navigation sensor types for multiple missions, including LEO legacy-vehicle (non-cooperative) servicing, cis-lunar human exploration (cooperative), and deep space asteroid sample return (small body) missions [2]. Table 2 shows select driving requirements for active sensors for these missions.

Table 2 - Key Requirements by R&C Mission Type

Spec	**Coop**	**Non-Coop**	**Small Body**
Target Specification	1" corner cubes	1.2x2.3m Gold MLI	Asteroid surface
Target reflectance %	>95%	varies*	<6%
Max Range (km)	2.5	1.2	2
Min Range (m)	0.5	1.5	5
Imaging Field of View/ Regard (°)	±10°	±20°	±20°
Instantaneous Field of View (mrad)	1.5	3-6	4-8
Long Range Field of View/Regard (°)	N/A	1.4	N/A
Range Accuracy/ Precision (1σ)	Larger of 2cm or 0.1% of range		
Imaging Frame Rate	10 Hz	5 Hz	1 Hz
Design Life (years)	10	1	5
Mission Duration (days)	231	N/A	N/A
Duty Cycle	15-20 hrs	10%	5%
Eye Safe	Yes	No	No
Mass (kg)	14	17	17
Power (W)	30	70	70

* - Surface reflectance varies greatly due to surface texture, view angles, and the specular nature of the material. Worst case values could be less than 1%

Recently, members of the R&C SCLT have lead various procurement, development, and ground and flight test efforts to insure the availability and performance of active relative navigation sensors for NASA's missions. Examples of test activities include Raven, SOSC, and IDA testing.

Raven, shown in Figure 2, is a relative navigation sensor and algorithm testbed on the International Space Station (ISS) [3]. It uses visible, infrared, and flash LIDAR sensors mounted on a two-axis gimbal to image ISS visiting vehicles. It also processes those images on a space qualified processor, measuring the visiting vehicle pose (relative translation and attitude) in real time, feeding those measurements into a relative navigation filter, and using the resulting solution to point the package at the approaching vehicle.

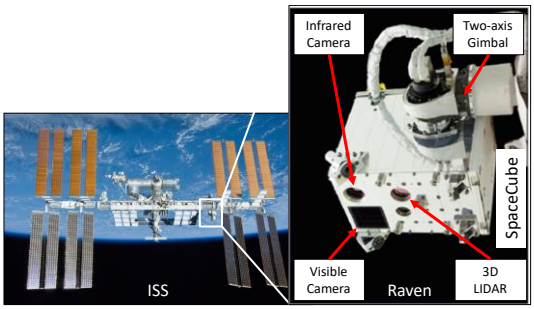


Figure 2 - Raven testbed on ISS

The International Docking Adaptor (IDA), that has been installed on the International Space Station's (ISS) docking ports, was available for sensor testing at NASA-KSC's Space Station Processing Facility (SSPF) prior to launch and deployment. Various organizations took the opportunity to test the IDA with their LIDARs and cameras. The testing spanned a test range from 120 m to 1m. The IDA was in its flight configuration including the perimeter reflector targets (retroreflector assemblies), peripheral docking target and centerline docking target as shown in Figure 3.

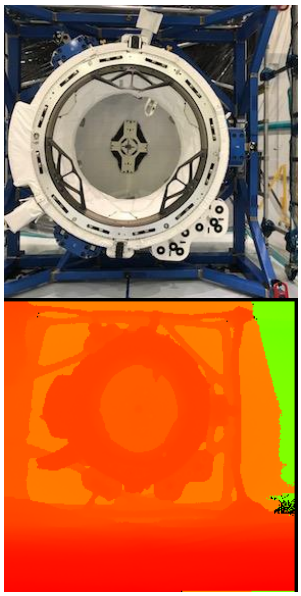


Figure 3 - International Docking Adaptor at SSPF (left) with range image output from NASA LIDAR (right)

The objective of the IDA testing was to provide each organization an opportunity to characterize the IDA with their sensors. JAXA, ESA, Boeing, SpaceX and NASA all participated in tests with the IDA. Each of these tests featured LIDAR as the core sensor under investigation.

Lockheed Martin's Space Operations and Simulation Center (SOSC) has hosted numerous testing campaigns for various programs: Orion, Raven, Restore-L, and Osiris-Rex are three recent test activities led by NASA. The SOSC is a large facility that enables relative 6 degree of freedom (6-DOF) testing over a range of 50 m. Real-time control and feedback of the platforms enables high-fidelity testbed testing to mimic the close-range relative kinematics associated with proximity operations and docking. The facility has been instrumental in refining sensor testing and operation onboard their host spacecraft.

2.1 STATE OF THE ART

Active sensors for R&C missions (laser range finders and LIDARs) typically balance range measurement accuracy and precision vs frame rate, reliability, and SWaP. Flash LIDARs for example are adept at collecting high frame rate data without the liability of moving parts, whereas mechanical scanning LIDARs excel at measurement quality at lower overall frame rates. Newer generation imaging LIDARs, such as Kodiak under development by the Restore-L mission, aim to blend the measurement quality of traditional scanners and frame rate of flash LIDARs while limiting moving parts only to fast and highly reliable MEMS mirrors.

Figure 4 shows example sensor suites for a selection of R&C missions. The current state of the art for active sensors supports the functionality shown in the figure, with performance as described in Table 2.

2.2 NEW APPROACH

The R&C SCLT is tasked with developing a NASA-wide, cross-program strategy for the discipline. The approach is to facilitate collaboration across Programs and Projects to make best use of available resources.

2.3 DESCRIBE THE FUTURE STATE

Our goal for the future state of active sensors for R&C is to have a consistent supply of sensors to support NASA missions. R&C priorities for future enhancements to these three sensor types include:

For flash LIDARs: 1) improve range measurement accuracy and precision; 2) calibrated point cloud output; 3) reduce per unit costs.

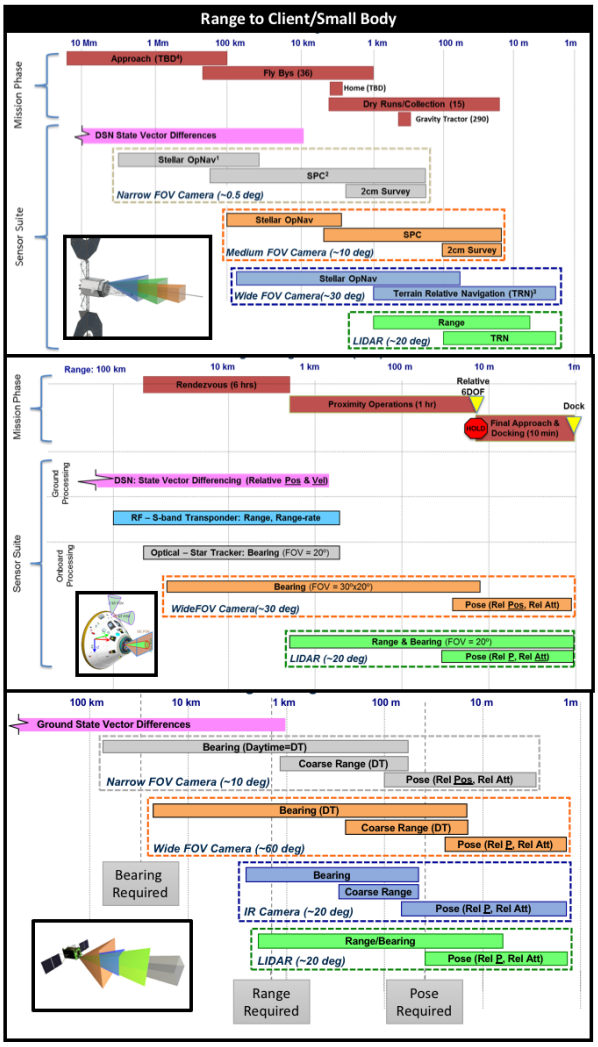


Figure 4 - Notional Relative Navigation Sensor suites for selected missions: Asteroid Redirect Robotic Mission (top); Orion (middle); Restore-L (bottom)

For Mechanical scanning LIDARs: 1) reduce SWaP; 2) improve overall frame rate; 3) demonstrate long term (~10 year) reliability; 4) reduce per unit costs

For MEMS scanning LIDARs: 1) reduce SWaP; 2) increase range; 3) reduce per unit costs.

Other future improvements include: 1) development of LIDAR Photon Counting and PN Code Modulation modes into active sensors to decrease SWAP and increase range performance; and 2) incorporation of centroiding and pose computing into the sensor.

2.4 RISKS AND REWARDS

Advancement will require significant Multi-Program/Multi-Project NRE for relative navigation sensor technology development. NRE investments can be mitigated with common sensor approach across multiple Programs/projects.

3 PROGRAMMATICS

3.1 STRATEGIC APPROACH

The R&C SCLT priorities map directly to the NASA Mission Directorates Program and project needs. HEOMD's existing Orion Program and the emerging Gateway Program are prime examples. Likewise, SMD's Mars Sample Return (MSR) is a driver for the R&C SCLT as are the multiple asteroid encounter and sampling missions emerging from the Decadal Survey. On a similar note the most important missions addressing primitive body community goals in the coming decade are, in priority order, the Comet Surface Sample Return (CSSR) mission and the Trojan Asteroid Tour and Rendezvous mission [4]. Challenging missions such as these will require R&C technology development, initiated years in advance.

The R&C SCLT will be considering a *"Lead - Leverage – Collaborate"* approach for the necessary technology development. This approach would identify where industry-developed technology solutions are most appropriate, either in the form of direct procurements (e.g., a 6-DOF capable spacecraft bus) or through strategic partnerships/collaborations where there is shared technology development risks and rewards. Application of this *"Lead - Leverage – Collaborate"* paradigm would also identify those specific high-risk R&C technology development areas where NASA must take the leadership role.

3.2 PARTNERING

NASA's R&C SCLT currently includes participation from practitioners across the Agency, who interact directly with other government agencies, industry, academia, and international partners.

4 WIDER VISION

The R&C SCLT is in the process of formulating a "Strategic Vector" for the next 10-20 years for this system capability area.

5 CONCLUSIONS

Active relative navigation sensors currently play an essential role in NASA's missions that require the functions of rendezvous, proximity operations, and capture. Looking to the future, the need for advanced active relative navigation sensors will be a technology driver for the Agency given the increasing number of new missions, programs, projects being formulated by NASA's HEOMD and SMD Mission Directorates. These missions include, for example, the Gateway, Mars Sample Return, and multiple projects to encounter solar system small bodies such as asteroids and comets.

Senior NASA management, in order to ensure the most effective use of the scarce active relative navigation sensor technology development resources, has given the R&C SCLT the challenging task of developing an integrated NASA-wide, cross-program strategy. The team's first step is to take an Agency-wide view of active sensor needs across the multiple Programs and Projects that require R&C functions. To make best use of available resources the R&C SCLT members collaborate on active sensor specification, development, and procurement and test activities in an effort to improve performance and efficiency across these multiple NASA's missions.

The R&C SCLT will be implementing a "Lead - Leverage – Collaborate" approach for the necessary active sensor technology development. This approach will identify where industry-developed technology solutions are most appropriate, either in the form of direct procurements or through strategic partnerships where there is shared technology development risks and rewards. Application of this "Lead - Leverage – Collaborate" paradigm would also identify those few specific high-risk R&C active sensor technology development areas where NASA itself must take the leadership role.

The ultimate goal for the future state of active sensors for R&C is to have a consistent supply of reliable, robust, and affordable sensors in the supply chain to support NASA missions currently in formulation. There will be a critical need to have active sensors that envelope the range of relative navigation performance requirements for multiple missions, including LEO legacy-vehicle (non-cooperative) servicing, cis-lunar human exploration (cooperative), and deep space asteroid/comet (small body) sample return.

ACKNOWLEDGEMENTS

This effort is made possible by participation of NASA's Rendezvous and Capture System Capability Team.

References

1. "Capability Leadership", NASA website (last visited July 26, 2018) : https://www.nasa.gov/offices/oce/functions/cap_ldshp.html
2. Hinkel, H., Strube, M., Zipay, J., Cryan, S.: Technology Development of Automated Rendezvous and Docking/Capture Sensors and Docking Mechanism for the Asteroid Redirect Crewed Mission, *2016 IEEE Aerospace Conference*, Big Sky, MT, 2016, pp. 1-8.
3. Strube, M., et al: Raven: An On-Orbit Relative Navigation Demonstration Using International Space Station Visiting Vehicles, AAS GN&C Conference; 30 Jan. - 4 Feb. 2015; Breckenridge, CO.
4. "Vision and Voyages for Planetary Science in the Decade 2013-2022", National Research Council, Washington, D. C.: The National Academies Press.

ACTIVE SENSORS FOR NASA RENDEZVOUS AND CAPTURE MISSIONS

NASA Technical Interchange Meeting on Active Optical Systems for Supporting Science, Exploration, and Aeronautics Measurements Needs

2 August 2018

Bo Naasz (NASA, R&C SCLT Leader)
Neil Dennehy (NASA, GN&C CLT Leader)
Scott Cryan (NASA/JSC, Gateway GN&C-RPOD Lead)
Nathaniel Gill (NASA/GSFC, SSPD/Restore-L Lidar Pose System Engineer)

NASA Pre-decisional: Internal Use Only

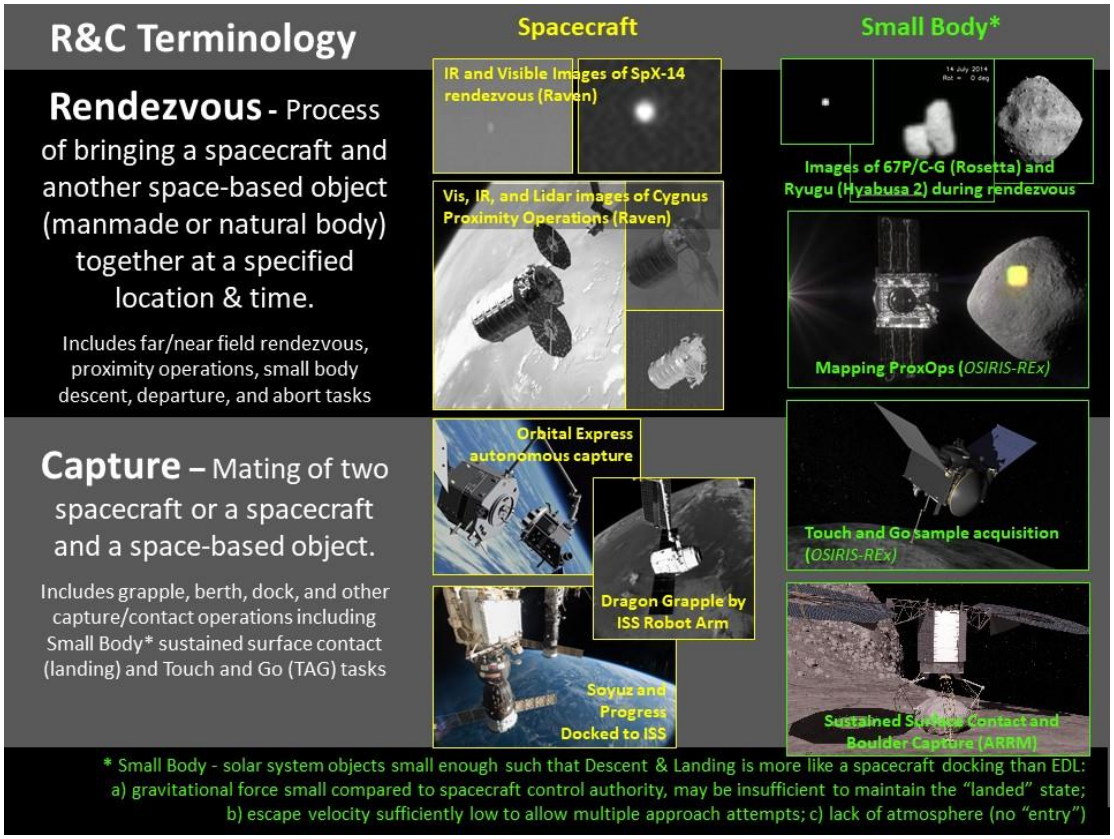
NASA's Rendezvous & Capture (R&C) System Capability Leadership Team (SCLT)

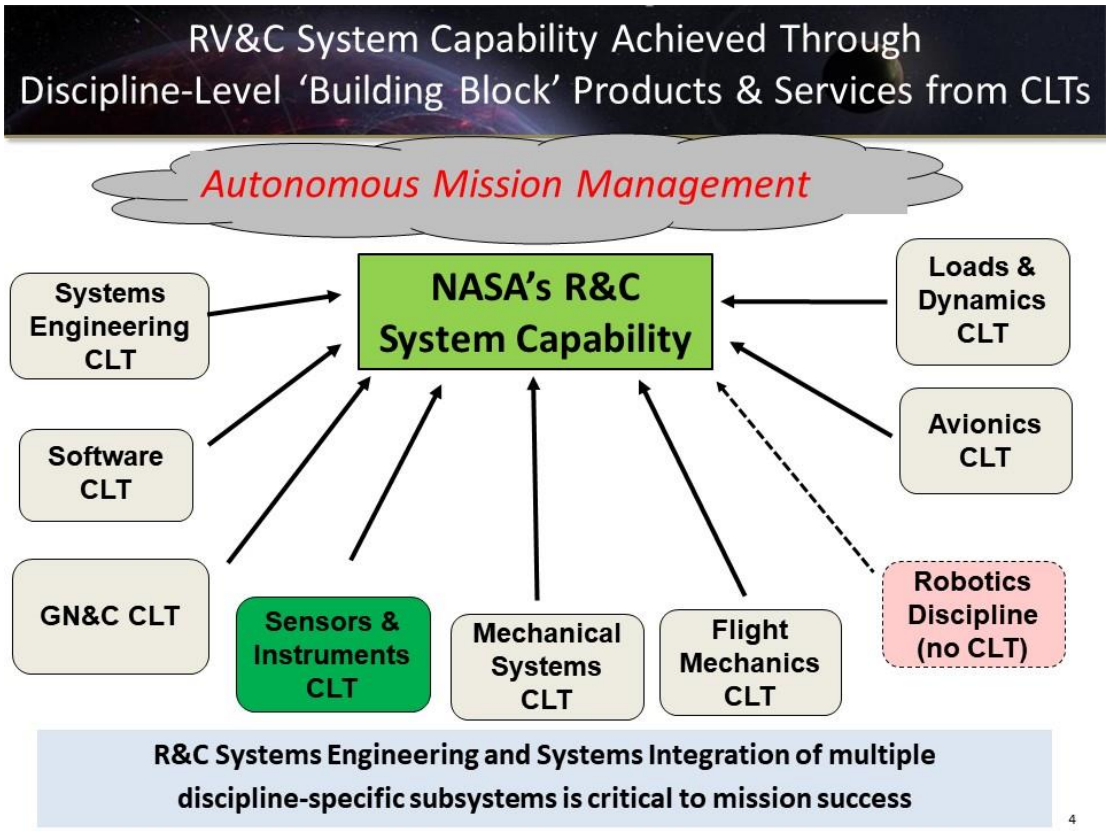
- The R&C SCLT is an advisory team to senior NASA management with:
  - Practitioners actively working on the current set of NASA's R&C missions
  - Subject matter experts thinking strategically at the R&C *system-level*
  - Technologists with experience in sensors, algorithms and mechanisms
  - Representatives from the relevant 'building block' discipline CLTs, and
  - Representatives from the mission directorates with responsibly for the systems/missions

- The R&C SCLT looks across the multiple R&C related operational and development activities currently on-going at NASA to create synergies and make efficient Agency-wide use of the scarce resources available
  - Also monitors and leverages the R&C developments by OGAs/Commercial sector

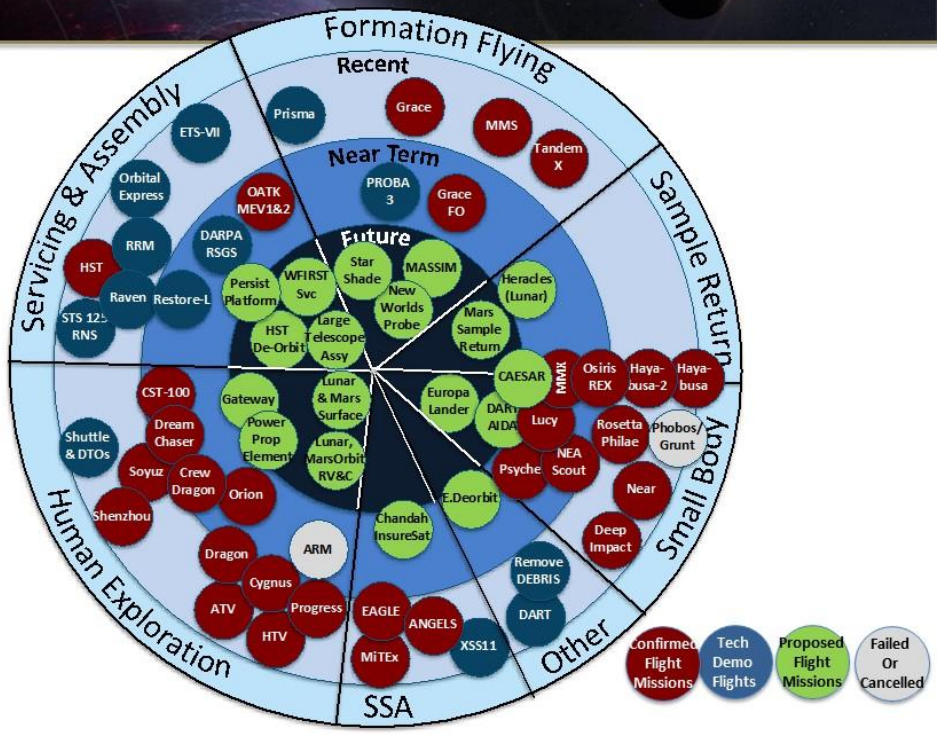
- The current primary R&C SCLT's focus area is formulating and implementing a Strategic Vector for this system capability
  - Long-term goal is creating an integrated plan that identifies time phased investment priorities (for technology, workforce, test facilities) for R&C system advancement.

The R&C SCLT is formulating the strategic view for NASA to sustain and advance the Rendezvous & Capture system capability

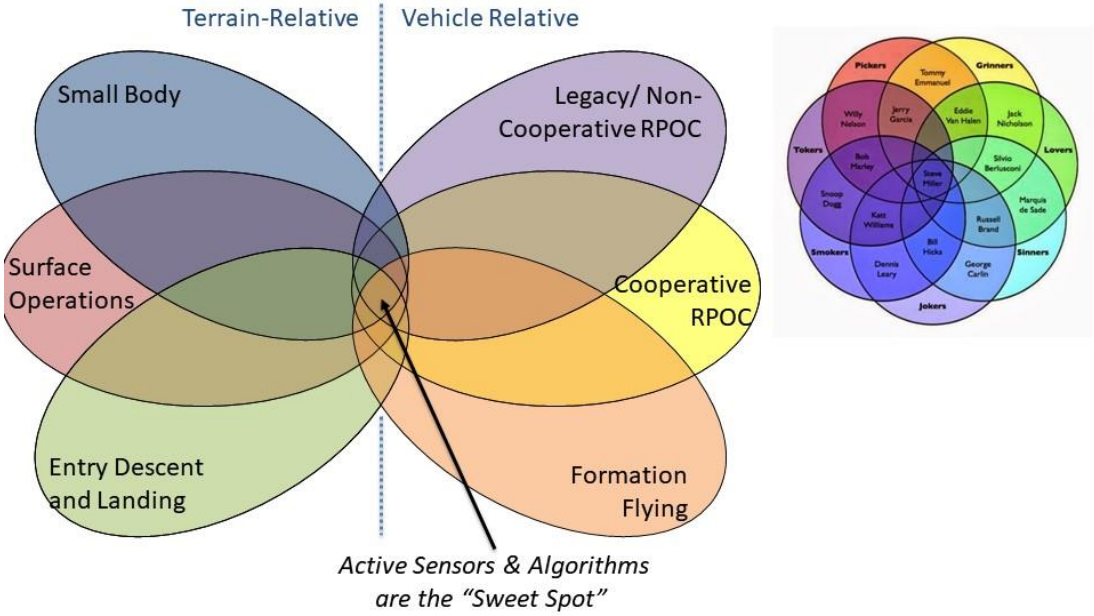

R&C Terminology
Spacecraft
Small Body*
Rendezvous - Process of bringing a spacecraft and another space-based object (manmade or natural body) together at a specified location & time.
Includes far/near field rendezvous, proximity operations, small body descent, departure, and abort tasks
IR and Visible Images of SpX-14 rendezvous (Raven)
Vis, IR, and Lidar images of Cygnus Proximity Operations (Raven)
Images of 67P/C-G (Rosetta) and Ryugu (Hyabusa 2) during rendezvous
Mapping ProxOps (OSIRIS-REx)
Capture – Mating of two spacecraft or a spacecraft and a space-based object.
Includes grapple, berth, dock, and other capture/contact operations including Small Body* sustained surface contact (landing) and Touch and Go (TAG) tasks
Orbital Express autonomous capture
Dragon Grapple by ISS Robot Arm
Soyuz and Progress Docked to ISS
Touch and Go sample acquisition (OSIRIS-REx)
Sustained Surface Contact and Boulder Capture (ARRM)
* Small Body - solar system objects small enough such that Descent & Landing is more like a spacecraft docking than EDL: a) gravitational force small compared to spacecraft control authority, may be insufficient to maintain the "landed" state; b) escape velocity sufficiently low to allow multiple approach attempts; c) lack of atmosphere (no "entry")


RV&C System Capability Achieved Through Discipline-Level 'Building Block' Products & Services from CLTs
Autonomous Mission Management
NASA's R&C System Capability
Systems Engineering CLT
Software CLT
GN&C CLT
Sensors & Instruments CLT
Mechanical Systems CLT
Flight Mechanics CLT
Loads & Dynamics CLT
Avionics CLT
Robotics Discipline (no CLT)
R&C Systems Engineering and Systems Integration of multiple discipline-specific subsystems is critical to mission success
4

Missions Requiring R&C or Similar Functionality

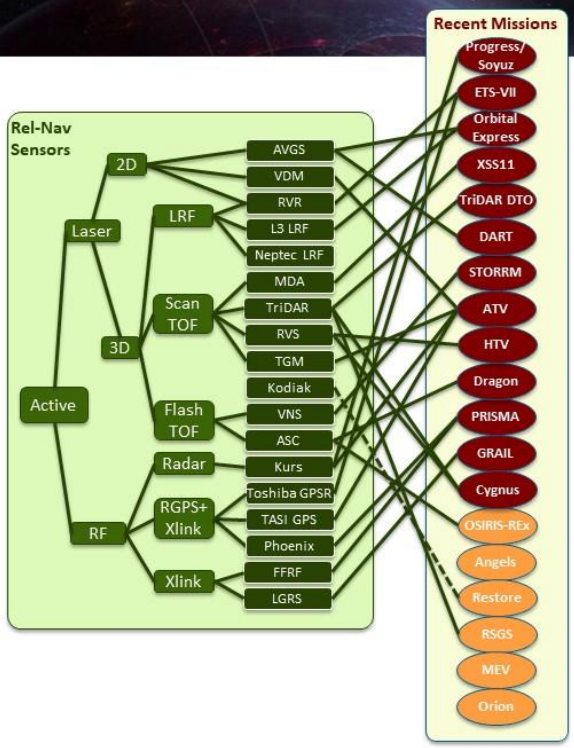


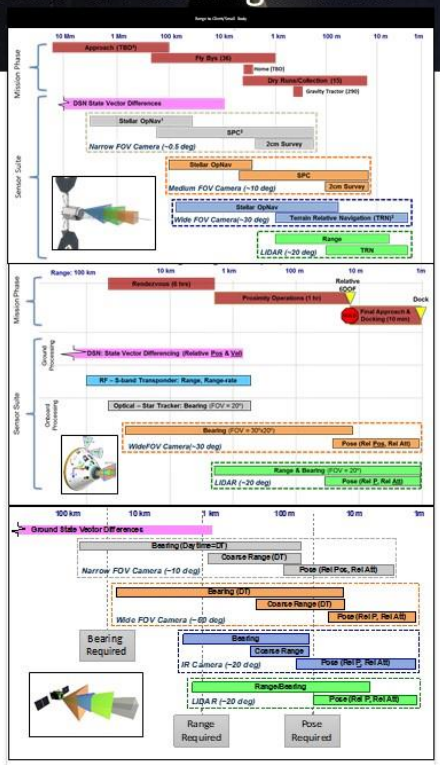
Active Relative Navigation Sensors are Required for Several NASA Mission Types



6

Active Relative Navigation Sensors & Pose Algorithms





Key Requirements by R&C Mission Type

Specification	Coop	Non-Coop	Small Body
Target Specification	1" corner cubes	1.2x2.3m Gold MLI	Asteroid surface
Target reflectance %	>95%	varies*	<10%
Max Range (km)	2.5	1.2	2
Min Range (m)	0.5	1.5	5
Imaging Field of View/ Regard (°)	±10°	±20°	±20°
Instantaneous Field of View (mrad)	1.5	3-6	4-8
Long Range Field of View/Regard (°)	N/A	1.4	N/A
Range Accuracy/ Precision (1σ)	Larger of 2cm or 0.1% of range		
Imaging Frame Rate	10 Hz	5 Hz	1 Hz
Design Life (years)	10	1	5
Mission Duration (days)	231	N/A	N/A
Duty Cycle	15-20 hrs	10%	5%
Eye Safe	Yes	No	No
Mass (kg)	14	17	17
Power (W)	30	70	70
* - Surface reflectance varies greatly due to surface texture, view angles, and the specular nature of the material. Worst case values could be less than 1%			

8

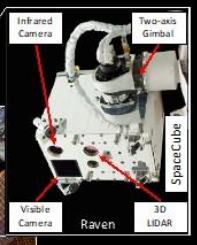
2017-2018 Key R&C System Capability Activities:

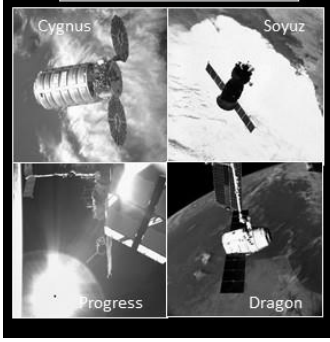
- **Sensors**
  - **Sensors status**
  - **Raven Testing on ISS**
  - **Common sensor specification**
  - **Lidar Testing (Orion)**
  - **Kodiak Lidar/LRF Development (Restore-L)**
- Cooperative RV&C
  - ISS Crew, Cargo
  - Orion
  - Gateway
  - Human Rated Docking Mechanisms
  - Mars Sample Return
- Non-cooperative (legacy) RV&C –
  - Restore-L
  - CubeSat and SmallSat Rendezvous and Capture
  - Non-NASA: RSGS, Commercial Servicers (MEV, MEV-2, SSL RSGS)
- Small Bodies Missions
  - Osiris Rex
  - Hyabusa 2/MASCOT
  - Lucy
  - Psyche
  - CEASAR
  - DART
- Standards

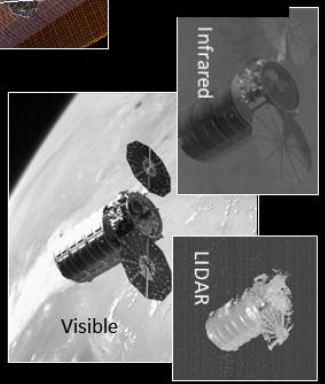
Raven

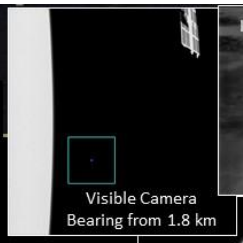
- An on-orbit testbed to mature relative navigation sensors & algorithm technologies
- Raven tracks incoming visiting vehicles to the International Space Station (ISS)
- Launched on a Space-XDragon in February, 2017

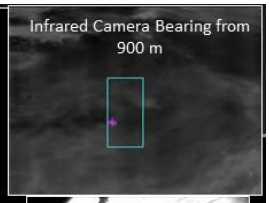












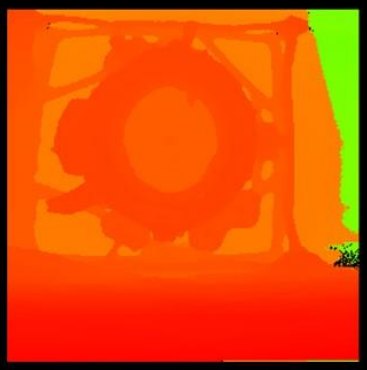




LIDAR Testing with International Docking Adaptor (IDA) at NASA/KSC



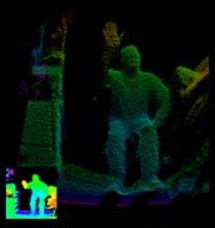




Kodiak Lidar/LRF Development (GSFC)

GRSSLi EDU

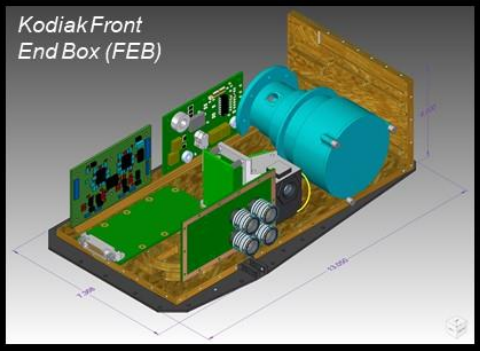


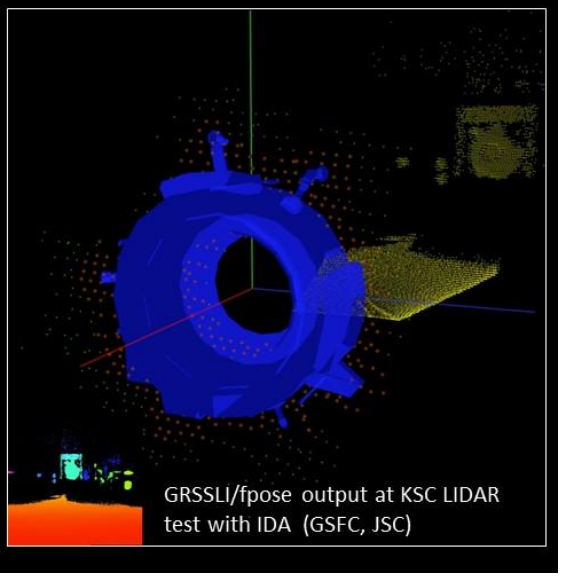


300ms Scan

Kodiak will be at TRL 6 by Dec 2018
Full box-level qualification (ETU test) planned for Dec 2018

Kodiak Front End Box (FEB)

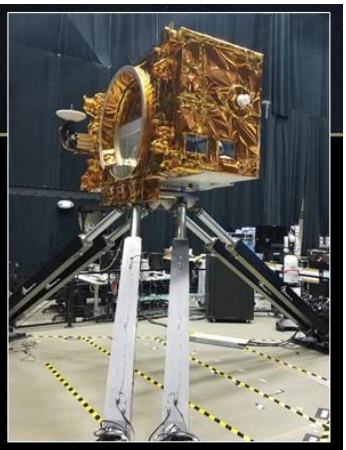




GRSSLI/fpose output at KSC LIDAR test with IDA (GSFC, JSC)

Non-Cooperative (Legacy) R&C – Restore-L Autonomous Capture Testing (GSFC)







Small Bodies Activities

Active Missions	Small Body	Launch Date	Arrival	Mission Phase	Note
Hayabusa 2	Ryugu	2014	2018	E	JAXA
MASCOT	Ryugu	2014	2018	E	DLR/CNES
Rover 1A	Ryugu	2014	2018	E	JAXA, University of Aizu
Rover 1B	Ryugu	2014	2018	E	JAXA, University of Aizu
Rover 2	Ryugu	2014	2018	E	Tohoku University
OSIRIS REx	Bennu	2016	2019	E	NASA (GSFC), UofA, LMSS
NEA Scout	1991VG	2019	2022	D?	NASA (JPL/MSFC), CubeSat
Lucy	Trojans	2021	2027	A	NASA (GSFC), SwRI, LMSS
Psyche	16 Psyche	2022	2026	A	NASA (JPL), ASU, SSL
MMX	Phobos, Deimos	2024	2025		JAXA
Ceasar	67P/CG	TBD	TBD	Pre-A	NASA (GSFC), Cornell, OATK
DART	Didymos	2020	2022	Pre-A	NASA, APL

OSIRIS-REx

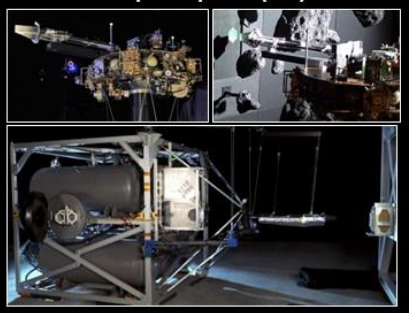


Hyabusa 2



Asteroid Ryugu seen from a distance of around 40km

Proximity Operation and Comet Sample Capture (JPL)



R&C SCLT "Future State" Goals for Active Relative Navigation Sensors

- Maintain a consistent supply of reliable, robust, and affordable sensors to support NASA missions
- Priorities for future enhancements:

➢ **Flash LIDARs:**

1) improve range measurement accuracy and precision
2) calibrated point cloud output
3) reduce per unit costs

➢ **Mechanical scanning LIDARs:**

1) reduce SWaP;
2) improve overall frame rate;
3) demonstrate long term (~10 year) reliability;
4) reduce per unit costs

➢ **MEMS scanning LIDARs:**

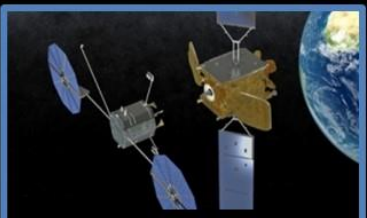
1) reduce SWaP
2) increase range
3) reduce per unit costs.

➢ **Other improvements:**

1) development of LIDAR Photon Counting and PN Code Modulation modes into active sensors to decrease SWAP and increase range performance
2) incorporation of centroiding and pose computing into the sensor

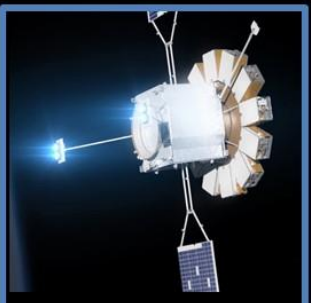
15

Commercial Servicers are Coming



"Orbital ATK signs Intelsat as first satellite servicing customer", Jeff Foust , SpaceNews, April 12, 2016

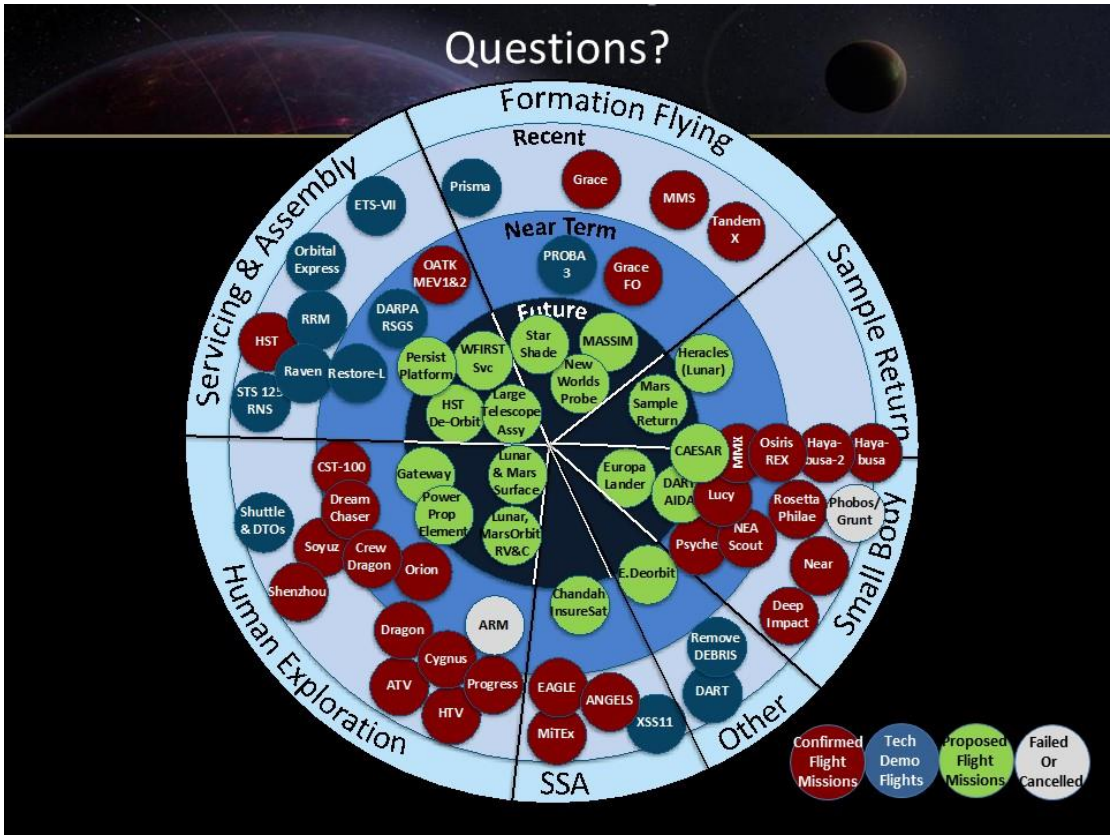
"Orbital ATK Receives Order for Second In-Orbit Satellite Servicing Vehicle" Orbital ATK Press Release, January 4, 2018



OATK Space Logistics Mission Robotic Vehicle (MRV)™, Satellite 2018 Presentation, March 2018



"SES and MDA Announce First Satellite Life Extension Agreement", 28 Jun 2017, www.ses.com


Questions?
Formation Flying
Recent
Near Term
Future
Servicing & Assembly
Sample Return
Small Body
Human Exploration
SSA
Other
Prisma
Grace
MMS
Tandem X
ETS-VII
Orbital Express
OATK MEV1&2
PROBA 3
Grace FO
DARPA RSGS
RRM
HST
Raven
Restore-L
STS 125 RNS
Persist Platform
WFIRST Svc
Star Shade
MASSIM
New Worlds Probe
Heracles (Lunar)
HST De-Orbit
Large Telescope Assy
Mars Sample Return
CAESAR
Osiris REX
Haya-busa-2
Haya-busa
CST-100
Gateway
Lunar & Mars Surface
Europa Lander
Lucy
Rosetta Philae
Phobos/ Grunt
Dream Chaser
Power Prop Element
Shuttle & DTOs
Lunar, MarsOrbit RV&C
NEA Scout
Psyche
Soyuz
Crew Dragon
Orion
E.Deorbit
Near
Shenzhou
Chandah InsureSat
Deep Impact
Dragon
ARM
Remove DEBRIS
Cygnus
ATV
Progress
EAGLE
ANGELS
DART
HTV
MiTEx
XSS11
Confirmed Flight Missions
Tech Demo Flights
Proposed Flight Missions
Failed Or Cancelled

7.6 3-D IMAGING FLASH LIDAR FOR AUTONOMOUS SAFE LANDING AND SPACECRAFT PROXIMITY OPERATION

Farzin Amzajerdian*, Paul F. Brewster, Vincent E. Roback, and Glenn Hines

*NASA Langley Research Center, Hampton, Virginia 23693, USA, *f.amzajerdian@nasa.gov*

ABSTRACT

NASA perceives 3-D imaging flash lidar technology as an important technology due to its significant potential in enabling onboard hazard avoidance capability for future challenging landing missions to various destinations, and for providing critical distance and bearing data as an autonomous rendezvous and docking/capture sensor.

1 INTRODUCTION

The 3-D imaging flash lidar technology is of importance to NASA as it can provide precision and hazard avoidance capabilities for landing missions to planetary bodies[1-3] and enable spacecraft autonomous rendezvous and docking with satellites or asteroids.[4-6] When used as a landing sensor, the flash lidar can generate 3-D maps of the terrain during the descent phase at several kilometers altitude. By comparing the 3-D maps with onboard terrain maps, the lander's position error is significantly reduced and a divert trajectory towards an alternate pre-designated landing site can be determine.[2] Once within about a kilometer of the landing site, the high resolution 3-D images of the flash lidar can be used to identify hazardous terrain features and the safest landing location at the site.[3] During final approach, the flash lidar can track terrain features and guide the vehicle to a safe landing location. Flash lidar is a solution for future robotic missions to the Moon and Mars that require landing at pre-designated sites of high scientific value, while avoiding hazardous terrain features, such as escarpments, craters, slopes, and rocks. Future missions planned to pave the path to colonization and mining of the Moon and human landing on Mars will need onboard hazard detection and precision navigation to ensure safe landing near previously deployed assets.

As an autonomous rendezvous proximity and docking or capture sensor, flash lidar can identify the rendezvous target and provide distance and bearing as the vehicle approaches the target satellite or station. The range images of flash lidar will enable new capabilities for resupply missions to the International Space Station, servicing satellites, and space debris identification and removal. Flash lidar is also viewed as a critical technology for asteroid mission concepts requiring precision rendezvous, identification of landing or sampling site location, and precision navigation to highly dynamic objects that may be tumbling in space.[5]

NASA's interest in flash lidar technology stems from its ability to record full 3-D images with a single laser pulse, freezing the scene on every frame by removing all motion of the transmitter/receiver platform. Unlike earlier topographic imaging lidar systems that generated 3-D images by scanning the laser beam across the scene and measuring the time of arrival for each returned laser pulse, the flash lidar records a full 3-D image frame by illuminating the scene with a single laser pulse and imaging the scene onto one focal plane array (FPA). Each pixel in the FPA takes independent measurements of the lidar pulse time of flight to the target. Therefore, the flash lidar permits much higher frame rates without any blurring or inaccuracies due to platform motion.

The capabilities of flash lidar for landing application were demonstrated by the Autonomous Landing and Hazard Avoidance Technology (ALHAT) project.[7] The flash lidar used within the project was demonstrated onboard a rocket-propelled Vertical Testbed (VTB) referred to as Morpheus.[8] The demonstration flights were conducted at a hazard field specifically constructed for this purpose near the north end of the Shuttle Landing Facility (SLF) runway at NASA Kennedy Space Center. The hazard field is a 100 m x 100 m area simulating a challenging lunar terrain and consists of realistic hazard features (rock piles and craters) and designated landing areas. Operating in closed-loop with the ALHAT avionics, the flash lidar data was used to select the best safe location within the hazard field and helped the vehicle to execute a divert maneuver towards the designated site.[9-11]

The effectiveness of flash lidar for autonomous rendezvous proximity and docking applications was tested on three Space Shuttle flights before it retired. These demonstration flight projects to the International Space Station (ISS) were the SpaceX DragonEye in 2009 and 2011 (STS-127 and 133), and the Sensor Test for Orion Rel-Nav Risk Mitigation (STORRM) in 2011 (STS-134).[12-14] In these flights, the ability of the flash lidar to provide relative range and bearing information to the spacecraft was demonstrated. The Raven instrument suite[15], currently operating on the ISS, will further validate the capabilities of flash lidar technology for on-orbit proximity maneuvers. Raven uses a flash lidar similar to the one used for STORRM.

The flash lidar performance requirements for most operational scenarios being considered for both landing and rendezvous proximity and docking applications are quite similar as described in fthe ollowing sections. This raises the possibility of developing a common flash lidar sensor that can be modified to the specific objectives and accommodation constraints of each mission. However, achieving this vision requires further technology advancement in order to enhance the flash lidar performance beyond the current state of the technology including improving its efficiency, reducing its size and mass, and addressing its reliable operation in a space environment.

2 FLASH LIDAR SENSOR DESCRIPTION

The principal of a flash lidar sensor system is illustrated in Fig. 1. The flash lidar uses a two-dimensional detector array to detect a laser pulse return from the target. The detector's Readout Integrate Circuit (ROIC) measures the laser pulse time of arrival of each individual pixel simultaneously, thus each flash of the laser generates a 3-D image of the target illuminated by the laser beam. In older, more conventional imaging lidar systems, the laser beam is scanned over the targeted area in a raster pattern and a single detector is used to detect consecutive pulses. Thus many laser pulses are required to cover the target area and generate a multi-pixel image with sufficient resolution. For example, generating a 3-D map of a 100 m X 100 m area with 10 cm resolution (1M pixels) using a typical 10 kHz laser repetition rate will take 100 seconds which is not practical for a landing scenario. Another major challenge of a scanning system is controlling the laser beam pointing from a moving platform and then estimating the laser spot position in the target area for each transmitted pulse. By recording a full 3-D image with a single laser pulse, the flash lidar provides a much higher image frame rate, eliminating the need for a fast laser beam scanning mechanism, and mitigates the effects of platform motion.

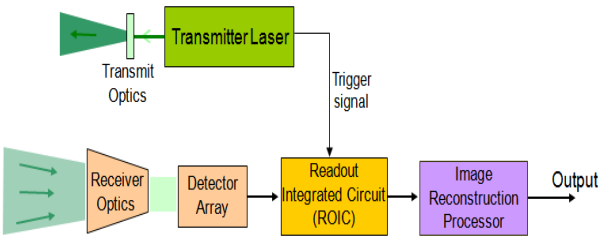


Figure 1. Schematic of Flash Lidar

3 LANDING OPERATIONAL CONCEPTS AND REQUIREMENTS

As a landing sensor, flash lidar can perform four essential functions during the descent and landing phases: Altimetry, Terrain Relative Navigation (TRN), Hazard Detection and Avoidance (HDA), and Hazard Relative Navigation (HRN).[1-3] Figure 2 illustrates flash lidar operation in the context of a lunar landing. The lidar begins its operation at about 20 km above the ground after thruster rocket firing is initiated. At this stage, the lidar transmitter beam is focused to illuminate only a few pixels in the center of the detector array to measure range to the ground. Reducing the divergence of the lidar transmitter beam to a fraction of its receiver field of view increases its operational slant range to well over 20 km from a nominal 2 km. The ground-relative altitude measurements provided by the flash lidar reduce the vehicle position error significantly since the Inertial Measurement Unit (IMU) suffers from drastic drift over the travel time from the Earth. The IMU drift error can be over 1 km for a Moon-bound vehicle and over 10 km for Mars. Accurate altitude data reduces position error to a few hundred meters. When the altitude drops to about 15 km, the lidar beam is expanded to illuminate approximately a thousand detector pixels. In this phase of its operation, the flash lidar generates relatively low-resolution elevation data of the terrain below which are subsequently compared with stored maps having

known surface features such as large craters. This process, referred to as Terrain Relative Navigation, further reduces the vehicle's relative position error from hundreds of meters to tens of meters. From about 1 km to 0.5 km altitude, the flash lidar operates with its full field of view, generating a high resolution elevation map of the landing area while identifying hazardous features such as rocks, craters, and slopes. This elevation map is then processed, performing the HAD function, to determine the most suitable landing location. The flash lidar then continues to update the map in order to establish a trajectory toward the selected landing location. This phase of flash lidar operation is referred to as Hazard Relative Navigation. The flash lidar operation terminates at approximately 100 m above the ground before the vehicle thrusters create a dust plume.

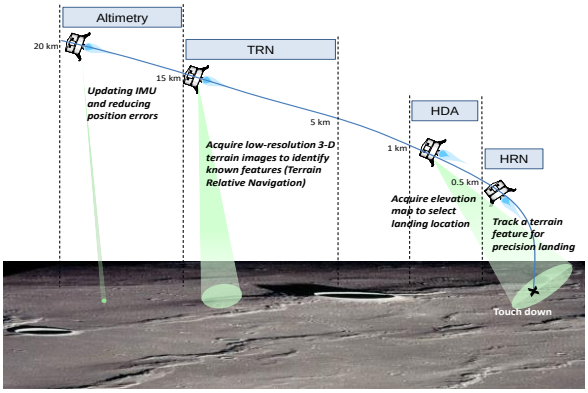


Figure 2. Flash lidar landing operational concept.

In order to perform the HDA function at 1 km altitude, the lidar must have a maximum operational range of 1.4 km assuming a 45 degree trajectory angle. Considering that the intensity of the reflected laser light decreases with the incident angle relative to the surface, the maximum operational range of the same lidar at normal incident will be 2 km. Therefore, in the landing scenarios where the trajectory is nearly vertical, such as past Mars landings, the lidar transmitted pulse energy or its receiver aperture can be reduced. In the case of a Mars landing, the altimetry and TRN functions may also be initiated at a lower altitude of about 10 km when the vehicle velocity is reduced to well below hypersonic speeds by parachutes or deployable decelerators and the heat shield is released.

4 RENDEZVOUS PROXIMITY OPERATIONS AND DOCKING

NASA is interested in developing a common capability for a wide range of missions requiring autonomous Rendezvous Proximity Operations and Docking (RPOD). These missions include human landing on the Moon and Mars, lunar mining, crew and supply transportation to and from the International Space Station, satellite servicing, space debris removal, and asteroid sample return and redirect (Fig. 3). Common capability implies that the system must be: 1) fully autonomous, meaning RPOD can be executed onboard without ground support; and 2) fully operational with both cooperative and non-cooperative targets. Non-cooperative targets means no RF transmitters, optical reflectors, or pre-installed distinguishing markings are on the targeted body.[5,6]

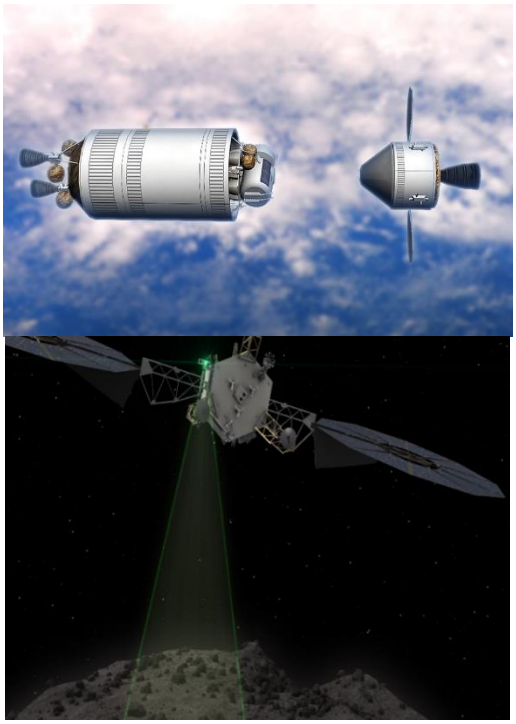


Figure 3. Orion vehicle docking with an Earth Departure Stage (up); Lidar sensor characterizing an asteroid surface before terminal approach for collecting samples or capturing a boulder (bottom).

A flash lidar based solution will be a major component of the autonomous RPOD system due to its ability to identify a docking location on the targeted body (either on man-made platforms or planetary bodies) and to provide the necessary

bearing, range, and relative attitude data for executing the rendezvous and docking maneuver.[7] The flash lidar operational scenario for RPOD is similar to that of a landing application. The main difference is the size of the target body, which may be smaller than the lidar field of regard for the RPOD application. The flash lidar starts its operation from tens of kilometers away using a few of its pixels to determine the distance to the target. The flash lidar will then operate in full field of view from 2 km to 3 km distance to characterize the target surface and identify the docking location. Below 1 km, the flash lidar provides relative range and velocity measurements, along with 3-D range images that are used to compute the vehicle relative pose for use by the navigation filter.

5 FLASH LIDAR TECHNOLOGY ADVANCEMENTS

The Morpheus flights proved to be an excellent demonstration of the flash lidar capabilities for future landing missions.[9-11] However, further technology advancement is required for the development of a multi-purpose flash lidar that can fully meet the needs of a wide range of landing missions as well as the rendezvous and capture missions. Such a common multi-purpose 3-D imaging sensor will present a significant cost saving and risk reduction for a number of missions such as robotic landings on the Moon, Venus, and Saturn moons, human precursor missions to Mars, asteroid redirect and sample return, transport missions to the international space station, and satellite servicing missions. The flash lidar technology advancement and maturation includes performance enhancement, design optimization for size and power reduction, and improved robustness and space qualification considerations. Table 1 lists the ALHAT flash lidar specifications and the desired parameters of a multi-purpose sensor instrument. A major driver in establishing the flash lidar advancement path is the need to map a 100 m x 100 m area with 10 cm resolution (GSD) that is a 1 M pixel digital elevation map (DEM), but a flash lidar with a 1 M pixel detector array may be impractical for the foreseeable future. This type of high-resolution sensor will require significant advancements in Avalanche Photodetector (APD) arrays and the associated Readout Integrated Circuit (ROIC) chips. In addition to almost two orders of magnitude more pixels, the hybridized detector array and ROIC must achieve a considerably smaller pitch size and much lower noise and higher gain than the current state of technology in order to allow for a reasonable laser pulse energy and receiver aperture size. A near-term compromise could be a 100k-class detector array and use of multiple image frames to construct a 1 M pixel DEM. There are two possible approaches for generating a DEM larger than the individual flash lidar images. The first approach is scanning the lidar field of view (FOV) over the target area to generate a mosaic of image frames that can be stitched together to produce a 1 M pixel DEM. This approach was successfully implemented and demonstrated by ALHAT in Morpheus flight tests using the current 16 K pixel lidar. The second approach is a Super-Resolution (SR) technique for which the lidar FOV is enlarged to cover the whole area and then a sequence of image frames of the same scene are blended to achieve the desired resolution.[16] Compared with mosaicking, the SR technique has the advantage of requiring a smaller gimbal (since it's only used for pointing), improved DEM quality (lower noise and eliminated bad pixels), and reduced acquisition time (fewer image frames). In addition, the SR algorithm provides independent relative position and orientation data that may help with precision navigation during the final approach phase of landing and RPOD maneuvers. We have successfully demonstrated the SR technique through moving truck and helicopter flight tests achieving 16X image resolution enhancement.[17] Analytical models indicate that 64X or even higher image magnification is quite feasible using the SR algorithm.

Table 1. Flash lidar specifications satisfying both landing and RPOD applications compared with ALHAT instrument.

Parameter	**ALHAT Flash Lidar**	**Next Generation Lidar**
Detector Array Size	16K	> 65k
Range Precision within a frame (1-σ)	7 cm	3 cm
Map Resolution (no. of pixels)	360 k	1.0 M
DEM Acquisition Time	6 sec	1 sec
Max Operational Range	1800 m	2000 m
Weight	60 kg	8 kg
Power	460 W	70 W

6 CONCLUSION

Over the past decade, NASA has been actively advancing and testing 3-D flash lidar technology for two distinct applications: autonomous, safe landing on solar system bodies and for autonomous Rendezvous Proximity Operations and Docking. Flash lidar can play a key role in enabling future ambitious robotic and manned missions (Moon, Mars, Jupiter and Saturn moons, etc.) requiring precision landing and onboard hazard avoidance capabilities. Flash lidar is also an important technology for safe and reliable proximity operation, capture, and docking necessary for asteroid sample return and redirect missions, spacecraft docking, satellite servicing, and space debris removal. The ALHAT project developed and demonstrated a flash lidar sensor system for landing applications through the closed-loop Morpheus flight test campaign. The autonomous rendezvous and docking application of flash lidar was previously assessed by three Space Shuttle missions to the International Space Station. These programs revealed the impact of flash lidar technology on NASA's operation in earth orbit and exploration missions beyond earth orbit. However, the flash lidar in its current state does not fully meet the desired performance specifications for either landing or rendezvous proximity operations and docking applications. A set of common specifications has been defined to direct the flash lidar technology advancement toward a single sensor that satisfies a wide spectrum of landing missions, and for missions requiring autonomous rendezvous and docking capabilities. Such a flash lidar sensor can be developed in the near-term by a combination of an incrementally larger focal plane array on the order of 100 k pixels and a super-resolution algorithm to produce sufficiently large digital elevation maps with 1 M to 6 M pixels in less than one second from a range on the order of 2 km. Performance of the super-resolution technique and its real-time implementation have been demonstrated through analytical models and simulations and experimental data from a helicopter flight test.

ACKNOWLEDGMENTS

The authors are grateful to Christopher Moore and NASA's Advanced Exploration Systems (AES) office for their continued support.

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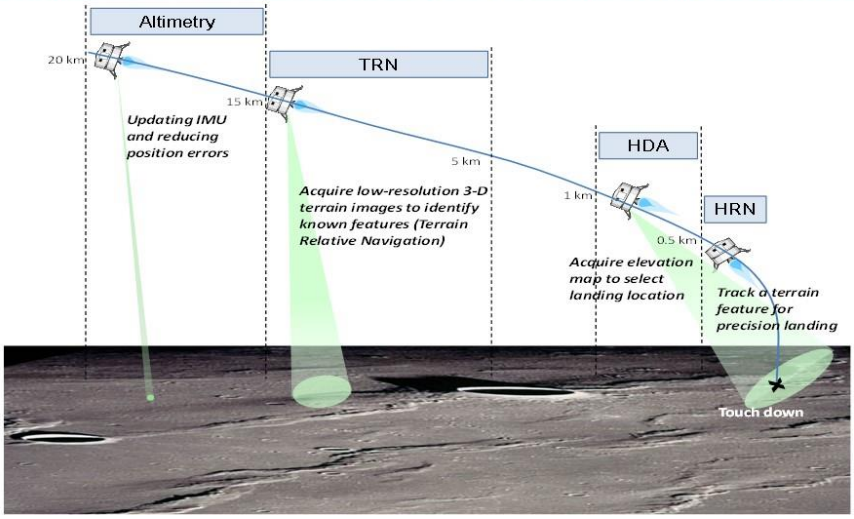
Flash Lidar can play a key role in future NASA missions

- Many future missions to the Moon, Mars, and other solar system bodies will require hazard detection and avoidance capability
  - Scientific and resource utilization missions – often require landing near escarpments, craters, slopes and rocks
  - Moon colonization and human Mars missions must land near pre-deployed assets
- Efficient and safe operation in space requires Autonomous Rendezvous and Docking (AR&D) capability
  - Satellite servicing, space debris removal, docking with International Space Station
  - Asteroid sample return, capture, and redirect missions
  - Crew or robotic vehicle docking with Earth departure stage

Flash Lidar Operation for Landing Application

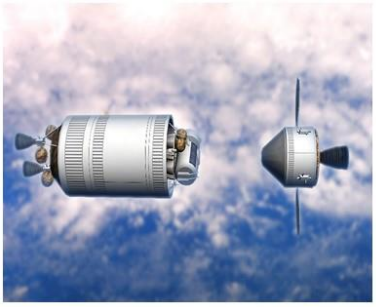
Terrain Relative Navigation (TRN) helps the landing vehicle to get to the desired site and Hazard Detection and Avoidance (HDA) allows it to safely and precisely land at the designated location



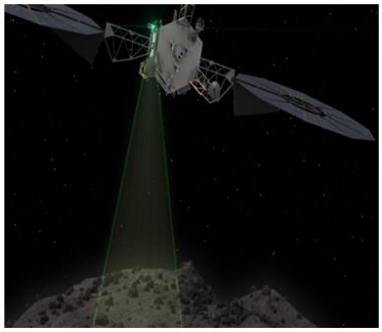
Flash Lidar Operation for Autonomous Rendezvous and Docking (AR&D) Application

Flash lidar can identify/characterize the docking location and provide distance and bearing data as the vehicle approaches the target

Orion crew vehicle docking with an Earth Departure Stage



Lidar sensor characterizing an asteroid surface before terminal approach for collecting samples or capturing a boulder

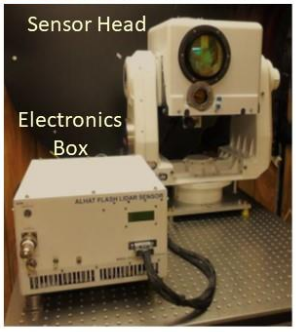


- Flash lidar was evaluated through 3 space shuttle flights in 2009 and 2011, and RAVEN on ISS in 2017-2018

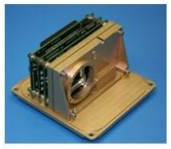
Flash Lidar built and demonstrated under Autonomous Landing and Hazard Avoidance (ALHAT) project

Parameter		Value
Max operational range		1800 m
Array size		16.4k
Range precision		7 cm
Frame Rate		20 Hz
Dimensions	Sensor Head	28x34x33 cm
	Electronics	24x36x33 cm
Weight	Sensor Head	16 kg
	Electronics	16 kg
Power (28 VDC)		450 W

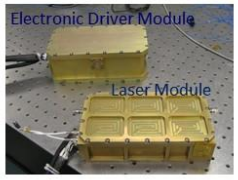
Much of SWaP was used for removing heat and controlling sensor engine and laser temperatures



Sensor Engine: ASC TigerEye



Transmitter Laser: custom-built by Fibertek



Sensor Controller/Processor:
PC104 stack with Intel Atom processor



Vertex 5 FPGA for SR



5

Field Tests:

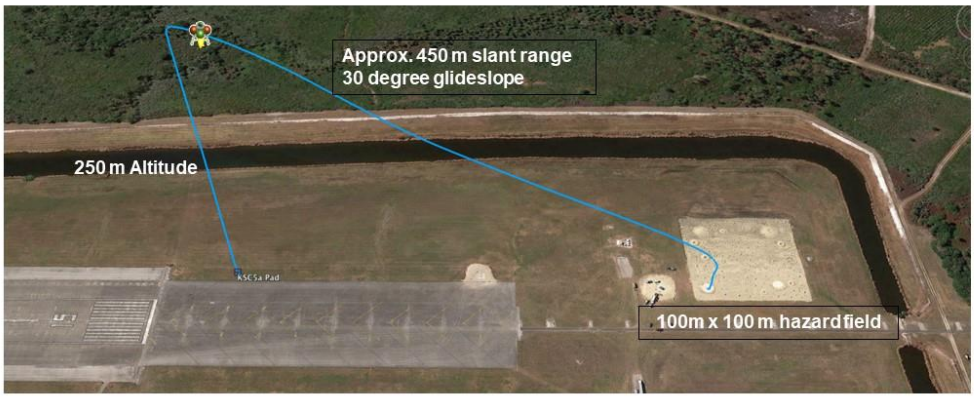
Lidar development from breadboard to fully-autonomous prototype units



6

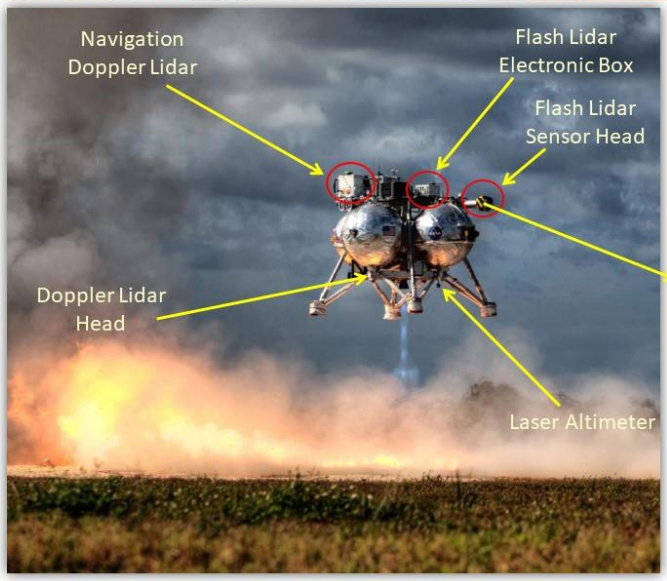
Morpheus Closed-Loop Demonstration at NASA-KSC

- 3-D Flash Lidar mapped the terrain for real-time hazard detection and avoidance
- NDL provided data for precision navigation and soft landing at the selected site
- 3 open loop flights (April 2014)
- 3 closed loop flights (two in May 2014 and one in December 2014)



7

ALHAT Prototype Lidar Sensors Integrated with Morpheus Vehicle





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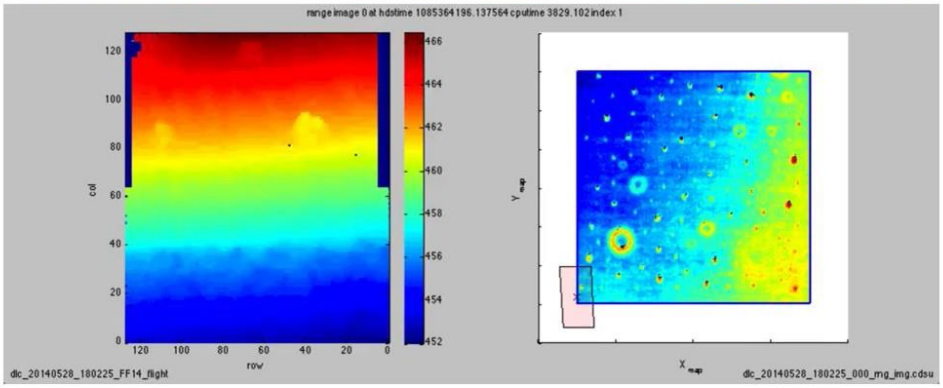
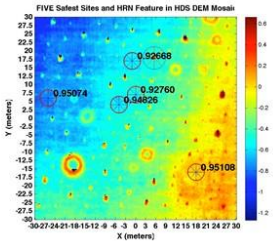
Morpheus Flight: Flash Lidar Data
Hazard Detection and Hazard Relative Navigation Operation

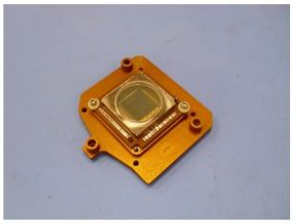




Flash Lidar Technology Advancement

- Current Flash Lidar technology does not meet NASA's performance requirements
- A common sensor is envisioned to satisfy both landing and AR&D needs:
  - **1 M pixel DEM in less than 1 sec from > 2 km slant range**
  - **Less than 8 kg and 70 W**
- Initiated the development of component technologies:
  - Focal Plane Array - 4X larger array (66k pixels) and ~10X higher sensitivity
  - Super-Resolution Algorithm (increase DEM resolution to 66k X 16 = 1M pixels)
  - Highly efficient and compact laser

ALHAT Focal Plane Array developed by Raytheon: 256x256 Integrated Detector and ROIC in a sealed Dewer



10

Potential Synergies

- Autonomous cars: substantial investments in 3-D lidars including flash lidar technologies
- Aircraft navigation in degraded visual environment (DVE), e.g. helicopter brownout
  - *DARPA* - Sandblaster
  - *ONR* - HELO
  - *AFRL* - PhLASH program
  - *Army* - DVE Mitigation program
- Identification of targets concealed by foliage or camouflage
  - *DARPA* - Jigsaw program
- Autonomous Aerial Vehicles
  - *ONR* - Autonomous Aerial Cargo/Utility System (AACUS)
- NASA – Autonomy and Robotic projects





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Potential Areas for Collaboration and Partnership

- Large format, low-noise, focal plane arrays
- Compact laser
- Variable zoom transmitter optics
- Non-mechanical beam steering
- Image processing and video navigation algorithms
- Simulation facilities
- Flight testing onboard helicopter, fixed-wing aircraft, and free-flyer vehicles

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SUMMARY



- Developed a fully-autonomous, highly reliable, prototype unit
- Demonstrated the capabilities of Flash Lidar through 3 helicopter and 1 fixed-wing aircraft flight test campaigns
- Conducted 6 flights onboard rocket-propelled Morpheus vehicle (3 open-loop and 3 closed-loop)
- AR&D application of flash lidar evaluated through 3 space shuttle flights and an ISS mission
- A common landing and AR&D sensor requires further technology advancements:
  - Increase number of image pixels from 16k to >1M
  - Reduce range noise from 7 cm to 3 cm
  - Increase maximum operational range from 1.8 km to > 2.0 km
  - Reduce SWaP by > 4X



Backup

Flash Lidar Super-Resolution Algorithm

- Super-Resolution (SR) technique uses a set of consecutive frames, from slightly different positions and angles (resulting from platform motion), to generate a high resolution DEM
- Demonstrated 16X resolution enhancement using 20 frames with ALHAT lidar (7 cm noise)
- 64X enhancement is feasible with a lower noise lidar (< 5 cm noise)
- SR also provides vehicle surface-relative 6-DOF state vector (position and attitude) that can be used for video navigation

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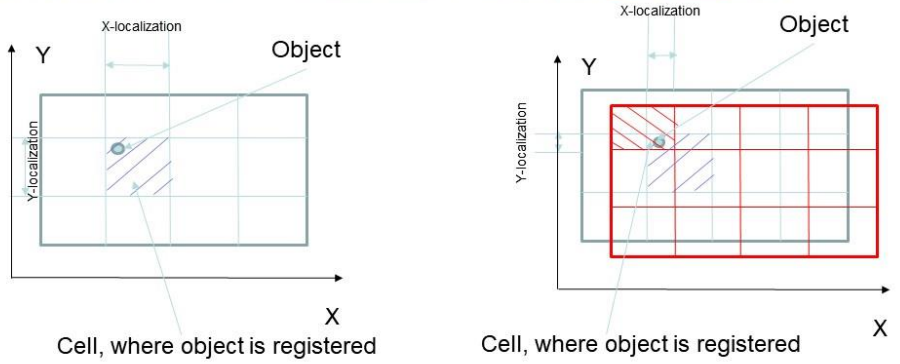
Flash Lidar Super-Resolution Algorithm



1. Using low resolution grid, it is possible to localize the object location only inside of the cell.
2. Using two shifted grids, it is possible to improve the object localization because it belongs to two cells at the same time.

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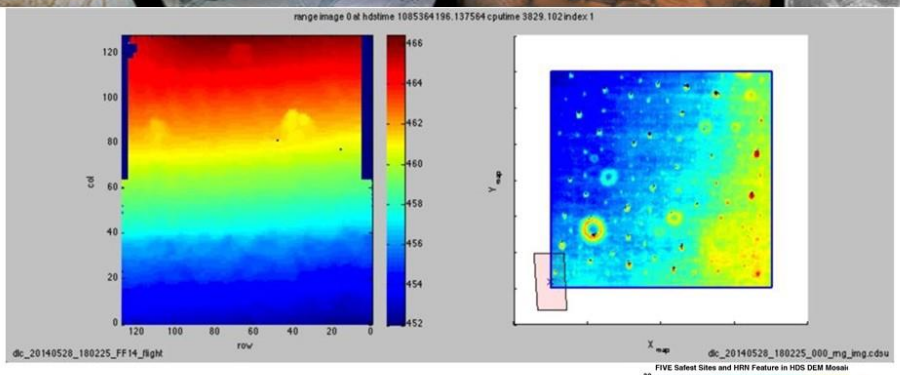
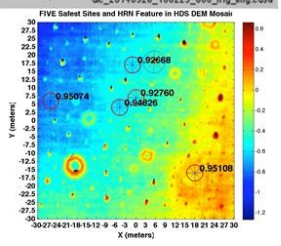
Morpheus Flight: Flash Lidar Data

Hazard Detection and Hazard Relative Navigation Operation





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Next Generation Flash Lidar

Parameter		Current Sensor	Next Generation	Upgrades
Array size		16.4k	65.6k	New FPA
Frame Rate		20 Hz	20 Hz	-
Max operational range		1800 m	2000 m	-
Resolution (no. of pixels)		16.4k	1.05M	Super-Resolution algorithm
Range precision		7 cm	3 cm	
Position precision		-	20 cm	
Attitude angles precision		-	0.05 deg	
Dimensions	Sensor Head	28x34x33 cm	20x30x17 cm	New Laser, New Optics New thermal and package designs
	Electronics	24x36x33 cm	15x25x25 cm	
Weight	Sensor Head	16 kg	4.0 kg	
	Electronics	16 kg	4.0 kg	
Power (28 VDC)		450 W	70 W	New thermal and power unit designs

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8 Session 8

Aeronautics was designed to discuss issues related to aeronautics applications. The Session Chairs, Paul Danehy and Greg Adamovsky, gave an overview presentation of the area to start the session. A total of six research presentations representing the work of researchers at GRC, LaRC, and Iowa State University was received. Table 8-1 lists the seven session papers. See Section 3 of the Assessment Report for observations and assessment comments.

Table 8-1. Session 8 Papers

Paper Number	Author	Title	Paper	Presentation
S8-1	Paul Danehy, LaRC Greg Adamovsky, GRC	Overview		☑
S8-2	Hyun Jung Kim[1] and Thomas Jones[2] [1]National Institute of Aerospace; [2]NASA LaRC	Unique Capabilities within the Advanced Measurement and Data Systems Branch at NASA LaRC	☑	☑
S8-3	Paul Danehy, LaRC	Active Optical Sensing for Flow Quantification in Wind Tunnels in Support of Aeronautics, Science and Exploration	☑	☑
S8-4	Ivan Clark, NASA LaRC	Active Optical Systems for Aeronautics	☑	☑
S8-5	Richard J. Schwartz[1], Carey F. Scott[1], Meaghan L. McCleary[2] [1]AMA Inc; [2]Iowa State University	SAMI, the SCIFLI Airborne Multispectral Imager: An Airborne Platform to Support Development and Testing of Active Optical Components and Sensors	☑	☑
S8-6	Grady Koch, Ivan Clark, Fred Proctor, and Narasimha Prasad, NASA LaRC	Wind Lidar for Aviation Safety and Enhanced Efficiency	☑	☑
S8-7	Mark R. Woike, NASA GRC	Advanced Optical Instrumentation for the NASA Glenn Research Center's Aeronautical Test Facilities		☑

List of presentations

8.1 Active Optical Sensing for Aeronautics 8-2
8.2 Active Optic Component Development: Unique Capabilities Within the Advanced Measurement and Data Systems Branch (AMDSB) at Nasa LaRC 8-8
8.3 Active Optical Sensing for Flow Quantification in Wind Tunnels in Support of Aeronautics, Science and Exploration 8-17
8.4 Active Optical Systems for Aeronautics 8-40
8.5 SAMI, the SCIFLI Airborne Multispectral Imager: An Airborne Platform to Support Development and Testing of Active Optical Components and Sensors 8-57
8.6 Wind Lidar for Aviation Safety and Enhanced Efficiency 8-67
8.7 Advanced Optical Instrumentation for the NASA Glenn Research Center's Aeronautical Test Facilities 8-77

8.1 ACTIVE OPTICAL SENSING FOR AERONAUTICS

Paul M. Danehy[1] and Grigory Adamovsky[2]

[1]NASA Langley Research Center, Hampton, Virginia

[2]NASA Glenn Research Center, Cleveland Ohio

Active Optical Sensing for Aeronautics

Paul M. Danehy
NASA Langley Research Center
Hampton, Virginia

Grigory Adamovsky
NASA Glenn Research Center
Cleveland Ohio



NASA TIM on Active Optical Systems for Supporting Science, Exploration, and Aeronautics Measurements Needs, Aug, 2018

Role of Active Optical Measurement Techniques in Aerospace Vehicle Development



Evaluate new concepts: Tailcone Thruster

Flight Test (X-planes)



Planned X-plane: QueSST

Ground Test of Components and Vehicles

Design based on Computational Fluid Dynamics (CFD)

Measurement Needs:

- Force + Moment
- Surface:
  - Pressure
  - Temperature
  - Shape, Deflection
  - Shear Stress
- Off-body (gas)
  - Flow visualization
  - Velocity
  - Density
  - Pressure
  - Temperature
  - Concentration

- Computational methods often cannot reproduce ground test results (wind tunnel)
  - Could be inflow conditions!
- Many of the models in these codes have not been validated at relevant conditions
  - Flow/Surface data needed
- In some cases, detailed flow data are needed for physics based modelling:

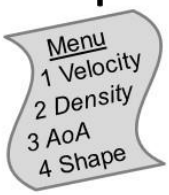
$$\rho u'v', \quad T'\chi_i'$$

- Requirements drive spatial, temporal resolution, multi-parameter measurement

Computational Methods predict:

- Cruise at Mach 0.85
- Turbulence
- Flow separation
- Boundary layer (BL) transition
- Shock BL Interaction
- Aeroelasticity
- Plumes / Jet flows
- Fuel-air mixing
- Combustion

Measurement Needs Template "The Menu"



Paul Danehy

TTT Innovative Measurements (IM)

Working with Tom Jones, IM Lead

Please contact Paul.M.Danehy@nasa.gov or 757-862-4737 for assistance and to submit completed surveys.

Measurement Needs Survey

- Need your help in planning developing instrumentation strategy for Agency WT Diagnostics
- Want to capture/quantify technology pull:
  - Identify what experimentalists and CFD'ers Need/Want from wind tunnel data:
    - Need ≡ can't accomplish goals of test without this data
    - Want ≡ would augment value of data but not critical (wish list)
- Survey focus: advanced measurement techniques.
  - Should assume standard force/moment balances, pitot rakes are available but if new please note that.
- 2-page template to be filled out by hand.
  - Instructions and completed example provided.
- Some things you want may not exist yet: We will try to develop it! (This will inform SBIRs, NRA's etc.)

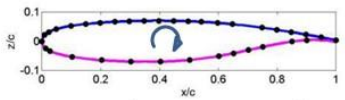
Measurement Needs Survey — TDT Aeroelasticity — **Measurement Needs/Want** — EXAMPLE — v2

POC: Jen Heeg (Langley Research Center)

Overview

- Problem description: Use time-resolved surface and flow measurement techniques to correlate fluid structure interactions for validation of aeroelasticity simulation codes
- Timing of test: ☐ past ☐ currently ongoing ☒ planned (for FY 18) ☐ long term vision
- Program that supported/will support test: TTT / RCA Probability of occurring: high
- Information about you (check all that apply): ☐ Program manager ☐ Experimentalist ☐ CFD'er
- Mach number or range: 0·1-0·9 Type of problem: aeroelasticity Facility TDT Type heavy gas
- Why important? As vehicles get lighter, thinner to improve efficiency they become more flexible but there is limited data to validate prediction tools· Need quantitative data·
- Impact if progress made? Will provide unique data to validate aeroelasticity models used in CFD which will lead to improved designs and performance·
- Primary use of data? (e.g. Code validation?) Code validation; understand flow physics
- Customers / Program for this data/knowledge? ARMD/TACP/TTT

Experimental Configuration



The Benchmark Supercritical Wing (BSCW) Rigid model allowed to oscillate at ~6 Hz Typical Conditions: Mach 0·85, α = 5°, dynamic pressure of 200 psf, Re_c=4·5 x10⁶

Draw a schematic and sketch a typical desired result.

Measurement Needs (5,4) / Wants (3,2,1) or Not (0): "The Menu"

Criticality Scale:
5 = absolutely critical top priority
4 = critical
3 = significantly enhancing
2 = enhancing
1 = nice to have
0 = not important at all

Criticality	Parameter	Spat. Domain	Spat. Resol. (mm)	Time Res. (μs)	Rep rate	Accuracy	Precision	Freestream (fs) value	Other
INFLOW									
5 n/a			0.1 1 (10) mm	(avg) 1 10 100	n/a Hz	2 % fs	n/a % fs	500 m/s	1 2 (3) components
n/a			0.1 1 10 mm	avg 1 10 100	Hz	% fs	% fs	Pa	
3 n/a			0.1 1 (10) mm	(avg) 1 10 100	Hz	% fs	% fs		
NEAR W									
4 n/a			0.1 (1) 10 mm	avg (1) 10 100	20 Hz	2 % fs	% fs	500 m/s	1 (2) 3 components
2 n/a	Density	0D 1D 2D 3D	0.1 1 10 mm	avg 1 10 100	Hz	% fs	% fs	kg/m³	
(n/a)	Temperature	0D 1D 2D 3D	0.1 1 10 mm	avg 1 10 100	Hz	% fs	% fs	K	
(n/a)	Pressure	0D 1D 2D 3D	0.1 1 10 mm	avg 1 10 100	Hz	% fs	% fs	Pa	
4 (n/a)	Deformation	0D 1D 2D 3D	0.1 1 10 mm	avg 1 10 100	Hz	% fs	% fs	mm	rigid but moving
4 n/a	AoA	0D (1D) 2D 3D	0.1 1 10 mm	avg 1 10 (100)	50 Hz	% fs	% fs	deg.	photogrammetry
5 n/a	Surf. Press.	0D 1D (2D) 3D	0.1 (1) 10 mm	avg 1 10 (100)	50 Hz	% fs	% fs	Pa	best effort accuracy
(n/a)	Shear stress	0D 1D 2D 3D	0.1 1 10 mm	avg 1 10 100	Hz	% fs	% fs	Pa/m²	
(n/a)	Surf. Temp.	0D 1D 2D 3D	0.1 1 10 mm	avg 1 10 100	Hz	% fs	% fs	K	
n/a		0D 1D 2D 3D	0.1 1 10 mm	avg 1 10 100	Hz	% fs	% fs		
WAKE FLOW									
(n/a)	Velocity	0D 1D 2D 3D	0.1 1 10 mm	avg 1 10 100	Hz	% fs	% fs	m/s	1 2 3 components
(n/a)		0D 1D 2D 3D	0.1 1 10 mm	avg 1 10 100	Hz	% fs	% fs		

Note: Not all capabilities are available in every facility; many techniques are under development. This survey will help prioritize development work.

Proposed Experiment

TDT Aeroelasticity

POC: Jen Heeg (Langley Research Center)

Measurement Needs/Want EXAMPLE

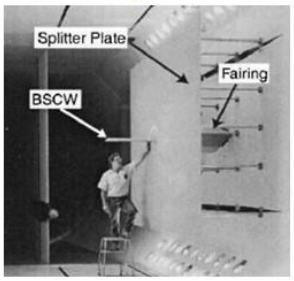
Additional Requirements & Experimental Details

- When is the data needed? (real time? Next day? Months ok?)
  Not specified
- Do any measurements need to be acquired simultaneously?
  Surface shape (AoA), surface pressure, near model velocity.
- Can seed particles be added to the flow or facility? If so, what type
  Yes, fog and possibly others
- Can inert gases (e.g. Krypton) be added to the flow or facility?
  Yes
- Can toxic gases (e.g. nitric oxide) be added to the flow or facility?
  Probably no.
- Are gases other than air naturally produced in the facility or by the flow (e.g. OH or NO or atomic species) If so, which?
  No.
- How critical is measurement of shape of facility inner wall for inlet and test section? *somewhat critical to CFD validation*
- How critical is model shape, roughness?
  In general very important for flexible models but this is rigid
- Is data in this survey proprietary? Y(N) Can it be published? (Y) N
- Additional Issues / Difficulties in doing measurements:
  Tunnel uses heavy gas (R134 with traces of 1-5% air) and has limited optical access but optical access is planned to be improved. Test section is large (16' square). Sub 1 atm. Can currently measure plunge and AoA but want improved method

Contact Information

- Email address: *Jennifer.Heeg@nasa.gov*
- Phone number: *757.864.2795*
- Branch Name/Code: *Aeroelasticity Branch / LaRC D308*
- Primary project supporting this work: *ARMD/TTT*
- Secondary project supporting this work: *AETC*

Additional Experimental Details



Location:

- NASA Langley Research Center, Hampton VA

Facility Type:

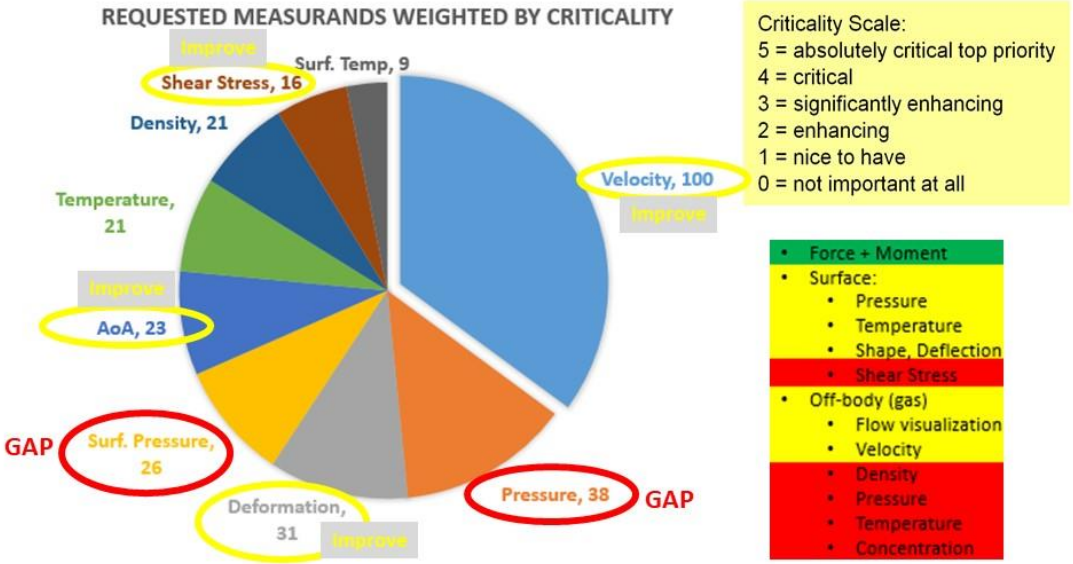
- Transonic Heavy Gas Tunnel (Unique in USA)
- This closed-circuit, continuous flow facility can be operated in air or heavy gas to simulate

Flow conditions:

- Test medium: Air or R134a (with 1-5% air)
- Mach #: up to 1.2; Reynolds #: 3 - 10x10^6 / ft
- Static Pressure: 0.03-1 atm (0.5 – 14.7 psia)
- Velocity: up to 500 m/s (1640 fps; 1118 mph)
- Static Temp.: ~Ambient, depends on Mach

Show additional details and/or schematics or computational results you would like validated

Survey Results: What needs measuring?



Criticality Scale:
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4 = critical
3 = significantly enhancing
2 = enhancing
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- Force + Moment
- Surface:
  - Pressure
  - Temperature
  - Shape, Deflection
  - Shear Stress
- Off-body (gas)
  - Flow visualization
  - Velocity
  - Density
  - Pressure
  - Temperature
  - Concentration

- Survey by PMD of 12 planned or ongoing NASA Wind Tunnel tests
  - NASA Glenn, NASA Langley and NASA Ames
  - Subsonic (3), Transonic (4), Supersonic (4), and Hypersonic (1)

7

Specific Gap Areas 1

1. Measurement of surface skin friction on wind tunnel models, particularly two-dimensional measurement over large surface areas in all speed regimes including in transonic cryogenic tunnels (TCTs) where oil flow does not work.
2. Measurement of surface pressure in flows that do not contain oxygen (for example, pure nitrogen flows such as TCTs).
3. Measurement of flowfield pressure, temperature and velocity:
   (i) in transonic wind tunnels for aerodynamics studies,
   (ii) in supersonic wind tunnels in support of sonic boom reduction research,
   (iii) in supersonic isolator experiments related to scramjet powered flight,
   (iv) in supersonic transition experiments where particles cannot be seeded into the flow, and (v) high-speed measurement for studying launch vehicle buffet occurring at rates of 10's of kHz.
4. Time resolved, simultaneous measurement of flowfield velocity, surface pressure, and model deformation in aeroelastic flowfields. Currently particle based measurements interfere with pressure sensitive paints used.

8

Specific Gap Areas 2

5. Visualization and quantification of unseeded RCS jets and other plumes in supersonic and hypersonic flows. In many facilities the plumes cannot be seeded as was done to produce the data in Fig. 3 above.
6. To determine accurate boundary conditions for computational methods, the inflow conditions of the wind tunnels need to be fully characterized. These include static and stagnation pressures and temperatures as well as velocity fields. Of particular interest is the flow angularity which is required with an accuracy of a fraction of a degree.
7. Measurement of combustion reactants, products and intermediates simultaneously with temperature and velocity in subsonic and hypersonic combustion flows, for CFD code turbulence-chemistry model development and validation.
8. Improved methods of measuring emissivity and temperature of hypersonic materials under test. Further quantification of material properties such as thermal conductivity obtained in situ during testing would also be useful.
9. Temporally and spatially resolved measurements in short duration environments like shock tubes and shock tunnels (much more than 1 image per 50 msec run).

9

Measurement Challenge Example: Aeronautics

Subsonic-Transonic Wind Tunnel

- National Transonic Facility
- High Reynolds Number Testing

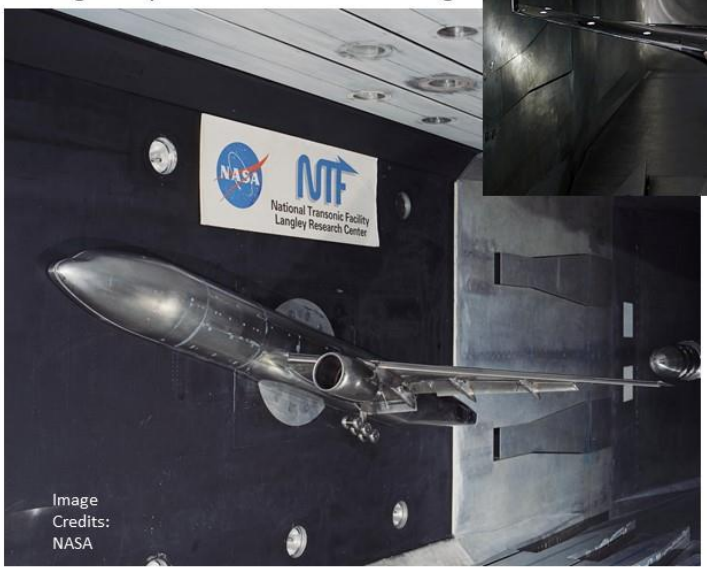

Image Credits: NASA



- Large scale (8 foot =2.4 m)
- High pressure (10 atm) plenum
- Low temperature cryogenic gaseous N_2 (100 K): frost
- High density: refraction
- No external optical access; limited internal access
- Remote operation required
- Expensive operation and expensive models
- No H_2O or particle seeds

Todays talks

- Intro presentation only focused on Active Optical Measurements for Wind Tunnel Instrumentation
  - Field is much wider than that… hear some of that today:

11:20AM	S8-1	C	20	Aeronautics	Greg Adamovsky/Paul Danehy	Session Chairs	Overview
11:40AM	S8-2	C	20	Aeronautics	Greg Adamovsky/Paul Danehy	Hyun Jung Kim[1] and Thomas Jones[2] [1]National Institute of Aerospace; [2]NASA LaRC	Unique Capabilities within the Advanced Measurement and Data Systems Branch at NASA LaRC
12:00PM	LUNCH	LB	60				
1:00PM	S8-3	C	20	Aeronautics	Greg Adamovsky/Paul Danehy	Paul Danehy	Active Optical Sensing for Flow Quantification in Wind Tunnels in support of Aeronautics, Science and Exploration
1:20PM	S8-4	C	20	Aeronautics	Greg Adamovsky/Paul Danehy	Ivan Clark, NASA LaRC	Active Optical Systems for Aeronautics
1:40PM	S8-5	C	20	Aeronautics	Greg Adamovsky/Paul Danehy	Richard J. Schwartz[1], Carey F. Scott[1], Meaghan L. McCleary[2] [1]AMA Inc; [2]Iowa State University	SAMI, the SCIFLI Airborne Multispectral Imager: An Airborne Platform to Support Development and Testing of Active Optical Components and Sensors
2:00PM	S8-6	C	20	Aeronautics	Greg Adamovsky/Paul Danehy	Grady Koch, Ivan Clark, Fred Proctor, and Narasimha Prasad, NASA LaRC	Wind Lidar for Aviation Safety and Enhanced Efficiency
2:20PM	S8-7	C	20	Aeronautics	Greg Adamovsky/Paul Danehy	Mark R. Woike, NASA GRC	Advanced Optical Instrumentation for the NASA Glenn Research Center's Aeronautical Test Facilities
2:40PM	S8-Panel	I	30	Aeronautics	Greg Adamovsky/Paul Danehy	All Paper Presenters	

8.2 ACTIVE OPTIC COMPONENT DEVELOPMENT: UNIQUE CAPABILITIES WITHIN THE ADVANCED MEASUREMENT AND DATA SYSTEMS BRANCH (AMDSB) AT NASA LARC

Hyun Jung Kim[1]*& Thomas Jones[2]

*[1]National Institute of Aerospace, USA, *hyunjung.kim@nasa.gov*
[2]AMDSB, NASA Langley Research Center, USA

ABSTRACT

This paper highlights the material science knowledge and NASA in-house production capability in the Advanced Measurement and Data Systems Branch at NASA Langley Research Center. The ISO5 optical cleanroom facility in the Branch is well suited for prototyping and developing low-quantity, high-quality output for highly specific research needs. Several components have been developed or proposed to support a variety of NASA missions, including: (1) a photon sieve telescope lens for LIDAR applications, (2) an optical vortex plate employed for atmospheric sensing, and (3) a tunable mid-wave infrared filter for remote sensing.

1 INTRODUCTION

AMDSB has invested in a state of the art (SOA) ISO5 optical cleanroom for research, development, and characterization of optical components. The cleanroom is an environmentally controlled facility. Environmental factors that are controlled include contamination, pressure, temperature, humidity, and static charge. As a class 100 cleanroom, contamination levels are fewer than one hundred particles per cubic foot. This level of control is required for the fabrication and testing of delicate components with demanding fabrication tolerances such as optical components, energy devices and semiconductor devices.



Figure 1. Photo of the ISO5 optical cleanroom at NASA Langley Research Center

Capabilities afforded with the cleanroom include thin film coating, laser-lithography, wet / dry etching, polymer casting, and characterization of microfabrication for quality control. The facility is well suited for prototyping and developing low-quantity, high-quality output for highly specific research needs. Components fabricated in the cleanroom can range from Technology Readiness Level (TRL) 1 through TRL 9.

Table 1-1 – Current cleanroom instrumentation and fabrication hardware inventory

Categories	Instrument	Manufacture
Patterning	Laser lithography writer	Heidelberg instrument
Patterning	Mask aligner	ABM
Characterization	Optical microscopes	Signatone Co
Characterization	Profilometer	Ambios
Post-process	Vacuum oven	VWR
Post-process	Furnace	LAB-LINE Instruments
Film deposition	RF / DC Sputter	Infovion, Inc
Film deposition	RF / DC Sputter	Nano-Master, Inc
Etching	Wet process benches	
Etching	Relative Ion Etcher	Technics
Packaging	Glue dispenser	Asymtec
Pre-process	Spin coater	Laurell
Pre-process	Ozone UV cleaner	Jelight Co, Inc
Pre-process	Ultra-sonic bath	Branson
Polymer casting	Doctor blade (printing / coating)	Pacific scientific
Storage	Chemical refrigerator	Lab-Line instruments Inc.
Post-process	Fluid dispensing system	Asymtek Nordson Co.
Pre-process	Balance	Mettler Toledo
Pre-process	Hot plate	Fairweather
Pre/ Post	Chemical Hood	ASTEC

2 METHODOLOGY

The goal is to exploit the existing NASA investment in knowledge and facilities to advance

the SOA of active optics through support of research and development of prototype components. In order to meet the scientific goals of the customer, it is necessary to understand the requirements, performance goals of the proposed component, the available budget, and the time to complete the project. The cleanroom employs researchers and engineers in the facility who have knowledge to fabricate and test the active optics in a prototype phase. Additionally, the facility can be used to conduct research on optical materials and procedures to achieve the required component.

To date, projects undertaken in the ISO cleanroom include: (1) a Photon Sieve (PS) telescope lens for ultra-lite weight space-based Light Detection and Ranging (LIDAR) for atmospheric sensing, (2) an optical vortex plate employed to discriminate the LIDAR signal and noise, and (3) a tunable mid-wave infrared (MWIR) filter to identify the spectral fingerprint of many chemical species. These have applications in remote sensing, radiant thermal signatures, astronomical and military imaging systems.

Figure 2 shows the operational process concept utilized in the cleanroom.

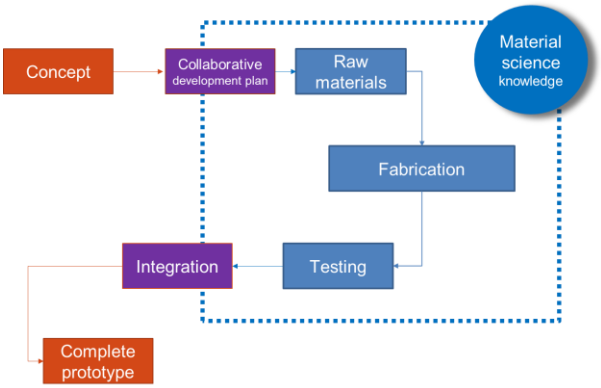

Figure 2. Operational Concept

When an active optical component or **concept** is required by a customer, cleanroom researchers and engineers set up **a collaborative development plan**. Based on their material science expertise, the cleanroom operators select the appropriate **raw materials**, **fabricate** the proposed device, and **test** the optical component. Support and feedback during **integration** of the device into the proposed system provides valuable insight for advancing the design. Finally, once the component is successfully integrated, the team can come together to **complete the design prototype.**

(1) Photon Sieve Project

One example of the cleanroom concept of operation in practice is the photon sieve project [1-4].

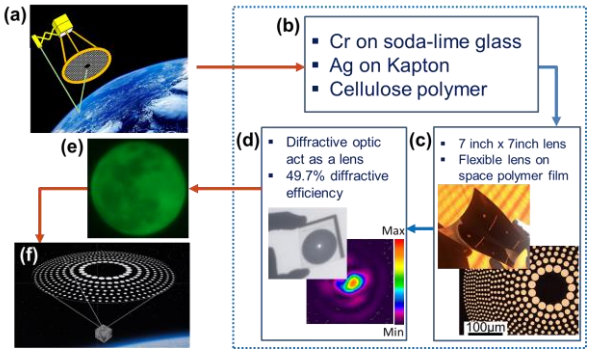

Figure 3. Operational Concept of the Photon Sieve project

Initially, a **concept** was proposed to utilize flexible diffractive optics called photon sieves to replace expensive, heavy collection optics in space-based LIDAR systems. In order to prove the concept, a **collaborative plan** was set up to decide the process flow of the photon sieve technology development, as seen in box (a) of Figure 3. This allowed the team to move from simple devices to more complicated ones, and eventually to develop a totally novel photon sieve design. The project began with basic raw materials, as seen in box (b) and moved forward towards developing a new class of cellulose active polymer materials in order to support the next generation of photon sieves. In box (c), examples are shown of **fabrication**, where the sieves in box (b) are brought into fruition using the cleanroom resources. Next, **testing** was conducted in the cleanroom on the fabricated photon sieves. Sieve efficiency has been shown to reach as high as 50% with high focal point quality. Once samples were successfully fabricated and tested, they were **integrated** into a telescope system and used to image the moon in order to demonstrate proof of concept. Lasty, in (f), a rendition of the proposed completed prototype is shown, namely a photon sieve deployed in orbit via CubeSat.

(2) Optical Vortex Plate (OVP) Project

In order to discriminate between noise and signals in a photon sieve-based LIDAR system, an optical vortex plate can be used. Essentially, it is a layer of material of precisely varying thickness with azimuth angle. By introducing a constant phase shift, the light beam becomes out of phase with itself at the center, producing total destructive interference and generating a donut-shaped beam. Fabrication of an OVP in the cleanroom is straightforward. A thick photo-resist (PR) is deposited on a substrate using the spin coater, chemical bench, and hot plate. Then, the laser lithography writer is used to generate a 3D pattern. Once exposure is completed, the PR is developed at the chemical bench, and the final structure is examined using optical microscopy and profilometry to confirm the geometry.

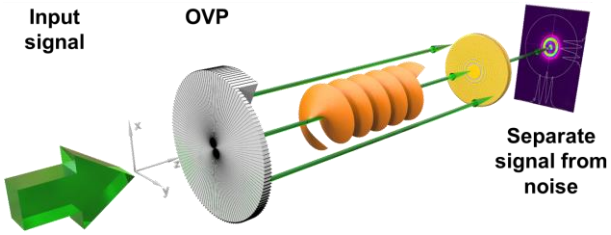

Figure 4. Operational Concept of the Optical Vortex Plate project

(3) Tunable Mid-Wave Infrared (MWIR) Filter Project

The tunable mid-wave infrared (MWIR) filter is a proposed project to research the optimal materials and processes to develop a unique optical component. The filter will employ phase-change materials (PCMs) to create a device that can be tuned as a narrow band resonance filter. This will allow for continuous tuning across the entire MWIR spectrum, while the filter geometry allows for very narrow bandwidth transmission (< 1 nm) with flat side lobes.

The fabrication process involves: (1) optimum film deposition procedures (magnetron sputtering to deposit PCMs and dielectric thin films used for resonance tuning), (2) characterization of optical properties of the films via ellipsometry and UV-Vis spectrometer (3) laser lithography to generate the grating patterns of the filter, (4) sputtering of additional top layer thin films required to achieve high background reflection, and (5) characterization of the tunability of the MWIR filter.

3 A PARTNERING APPROACH

The capabilities and expertise that exist in the AMDSB ISO5 optical cleanroom are available for collaborative efforts for in-house development of customized prototypes of active optical components. As has been shown here, the facility is well suited for the development and testing of unique, high quality prototype components without the need to commit to a large production run. In addition, expertise in the science of the wide array of materials that may be considered is readily available. As a NASA facility, NASA intellectual property rights are secure and easily managed.

There are a diverse number of activities that are supported by the cleanroom. As a government asset the overhead to operate the facility is amortized over a number of different sources. Thus, the overall overhead cost to any particular project is low, making the cleanroom both technically and financially attractive. Of primary importance is the feedback received from the partners. This will help set the direction of future acquisitions and research directions.

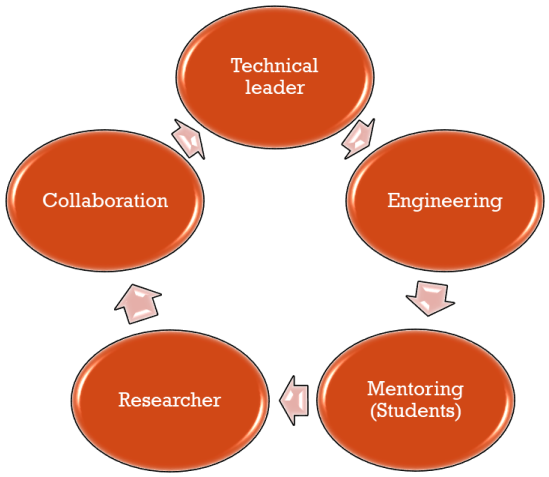

Figure 5. Model for cleanroom operations in which a diverse number of participants may contrinute

4 FUTURE PLANS

In the last several years the cleanroom has established state of the art capabilities in fabrication and testing of optical components. The goal now is to expand the capabilities and combine the material science expertise with the cutting edge

needs of the research community. This may be obtained in the following ways:

- Extend collaboration both within NASA and with industry and universities,
- Expand the knowledge base to allow for the development of novel and state of art concepts,
- Obtain new commercially available or in-house developed fabrication and characterization hardware,
- Gain additional stakeholders, and
- Support a wide range of science, aeronautics, and space projects.

5 CONCLUSIONS

Researchers can take advantage of the existing material science capability and SOA facilities at NASA LaRC to research and develop prototype components for active optical devices. The ISO5 optical cleanroom is designed for high quality device prototyping and material development at any TRL level, and has a proven track record of supporting existing NASA projects: (1) Photon Sieve telescope lens for LIDAR, (2) an optical vortex plate employed for atmospheric sensing, and (3) a tunable mid-wave infrared filter for remote sensing. Through a cooperative process involving collaboration between customers and cleanroom scientists, the facility provides excellent capabilities for in-house development of highly specific and advanced optical components to fit the unique applications required by NASA missions. In the future, the goal of the cleanroom will be to expand the breadth of the facility to address the ever-increasing needs of the research community, and create a facility that is considered a key Agency resource.

ACKNOWLEDGEMENTS

The authors appreciate Scott Bartram in the Langley Research Directorate (RD) and David Macdonnell in the Langley Science Directorate (SD) for their assistance and support of the optical cleanroom and Photon Sieve project. The authors also thank the PS team, OVP team, MWIR team, Richard Schwartz, Richard Wheless, William Lipford, and William Humphreys for their help, fruitful discussion, and support during the work.

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Active Optic Component Development

Unique capabilities within the Advanced Measurement and Data Systems Branch at NASA LaRC



Hyun Jung Kim[1] and Thomas Jones[2]

1. National Institute of Aerospace, supporting AMDSB at NASA Langley Research Center (LaRC)
2. AMDSB, NASA LaRC, Hampton, VA 23681-2199

Introduction

- The objective of this presentation is to highlight *NASA in-house production capability* and the *material science knowledge* in AMDSB at NASA LaRC for designing, prototyping, manufacturing, and characterizing *advanced active optics*

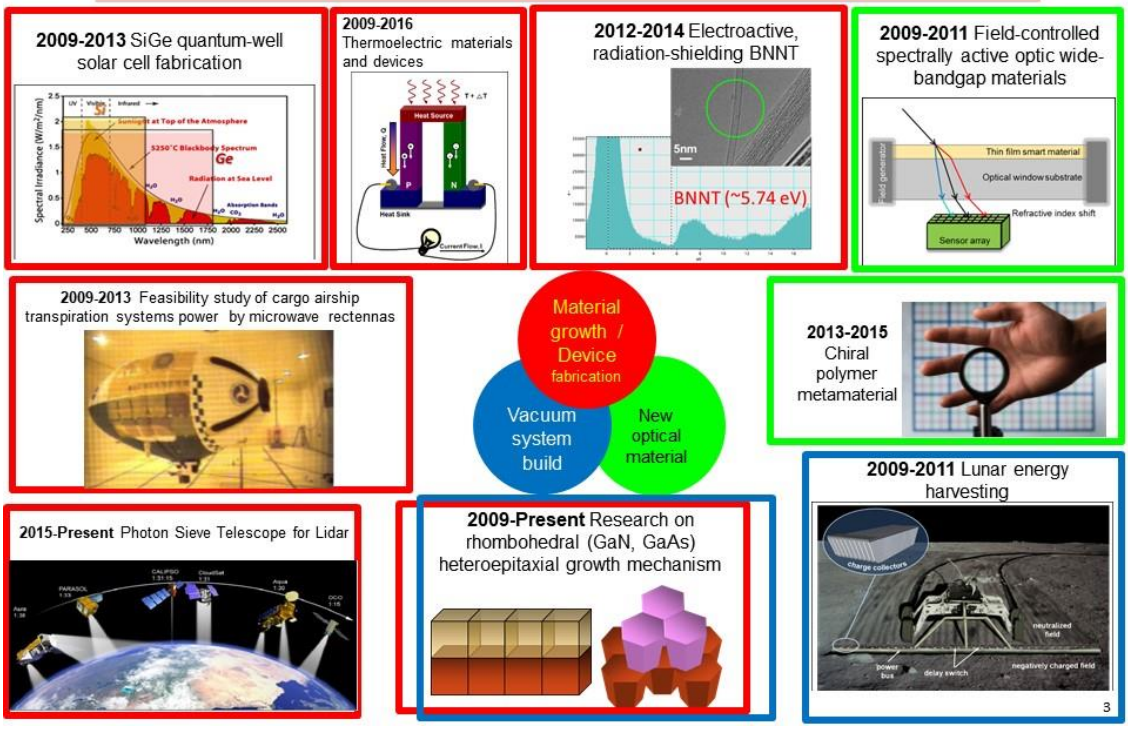
- **The AMDSB cleanroom facility is well suited for prototyping and developing;**
  - ✓ Low-quantity, high-quality output for highly specific research needs
  - ✓ Components for ground-based, airborne, and space-based applications

- The following components have been developed or proposed to support NASA missions;
  - ✓ **Photon Sieve (PS) telescope lens** for LIDAR applications. (funded)
  - ✓ **Optical vortex plate** employed for atmospheric sensing. (funded)
  - ✓ **Tunable mid-wave infrared (MWIR) filter** for remote sensing. (proposed)

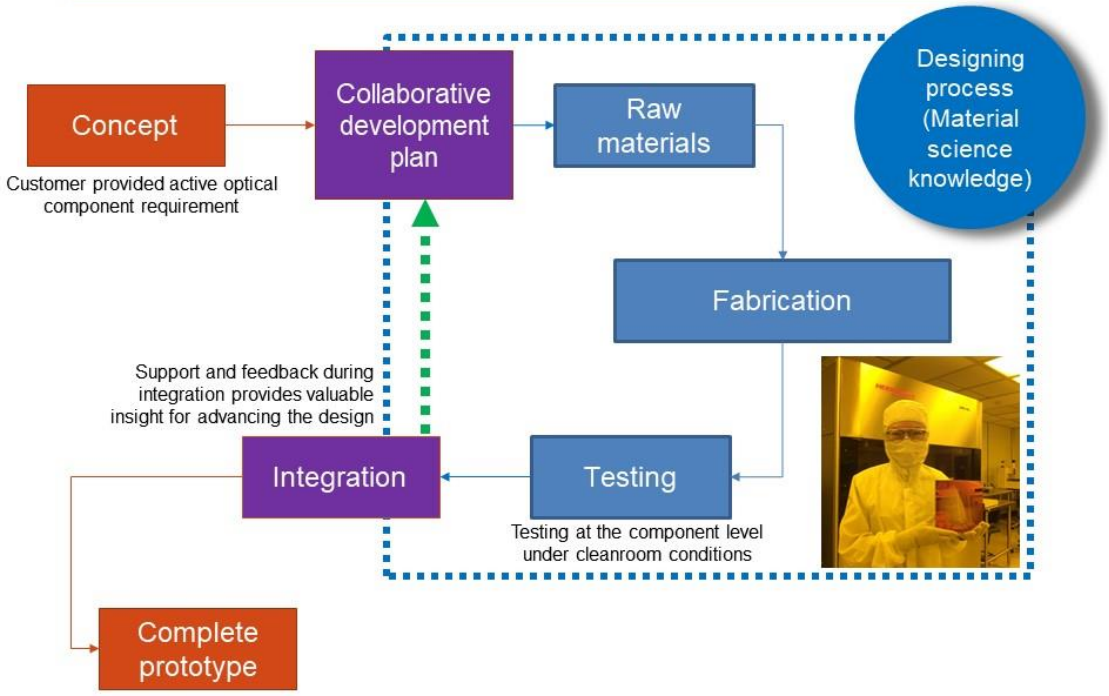


Background & Personal Experience

Materials Design and Manufacturing



Operational Concept

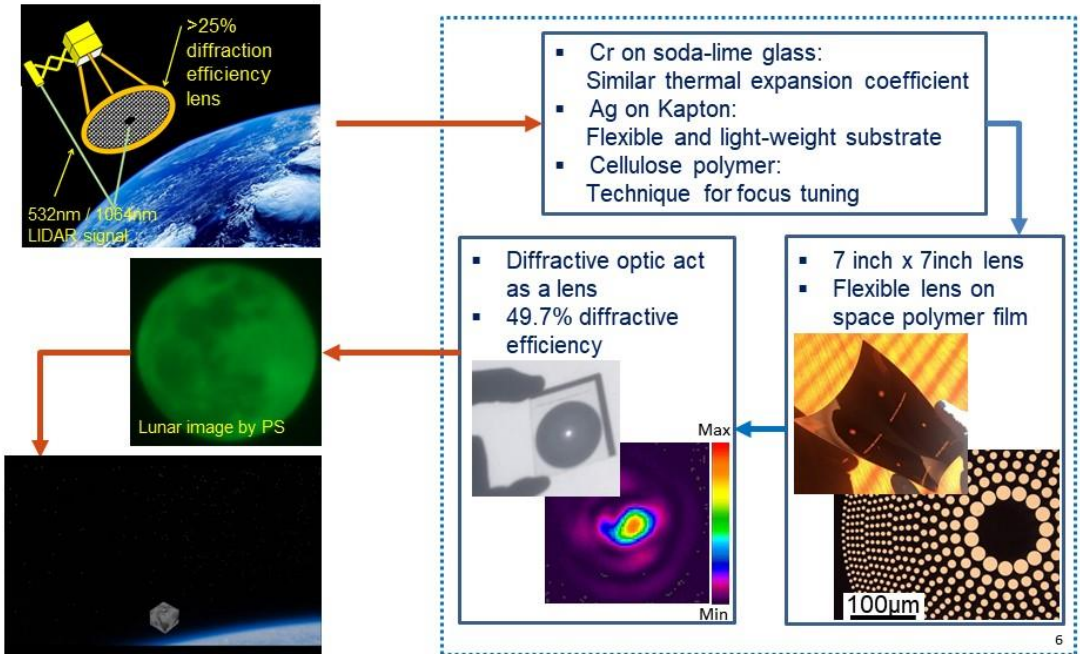


5

Photon Sieve Project

Funding from NASA with Collaborators SD + RD + ED

A photon sieve telescope lens for ultra-lite weight space-based LIDAR applications

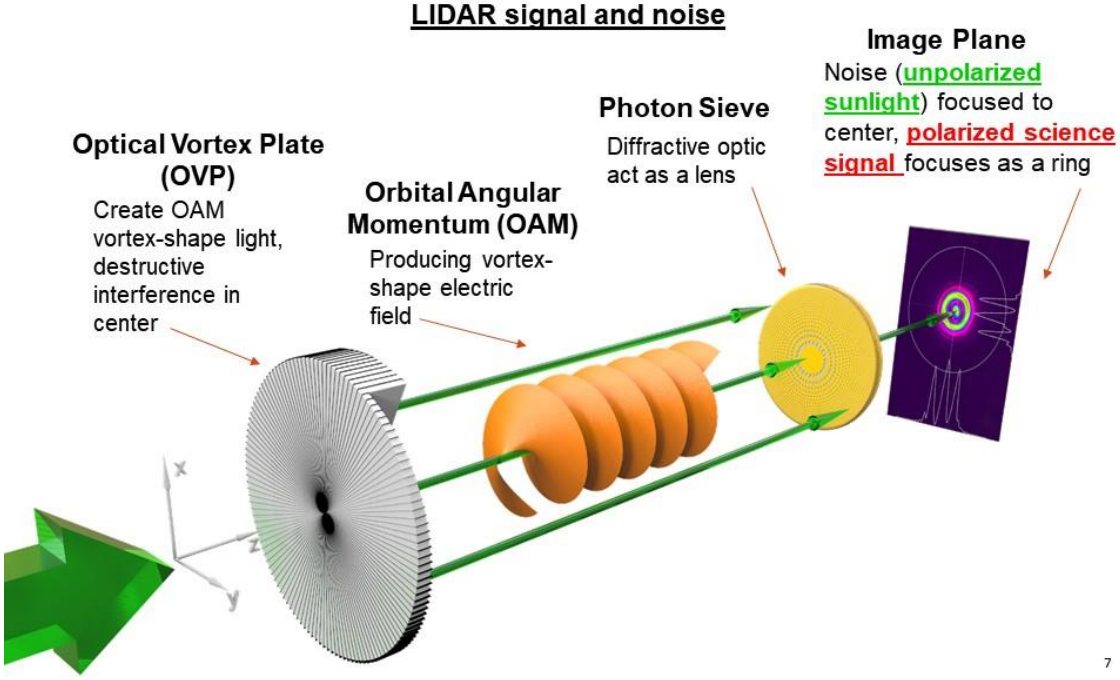


6

Optical Vortex Plate (OVP) Project

Funding from U.S. Army Research Office and Collaborators SD + RD + Mississippi State University

An optical vortex plate employed for atmospheric sensing to discriminate LIDAR signal and noise



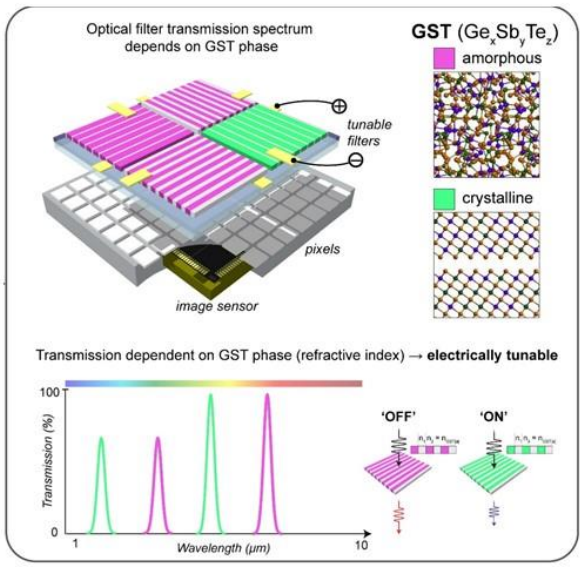
7

Tunable Mid-Wave Infrared Filter

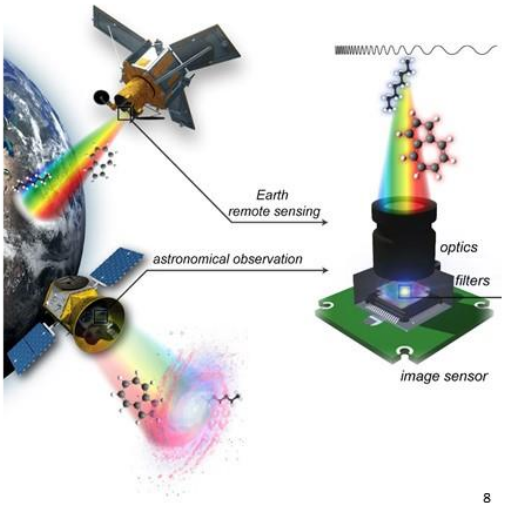
Funding from NASA LaRC and Collaborators SD + RD + U. of Cambridge

A tunable mid-wave infrared (MWIR) filter to detect the spectral fingerprint of many chemical species, with applications in remote sensing, radiant thermal signatures, astronomical and military imaging systems

(a) Tunable guided mode resonance (GMR) GST-based filters



(b) Example: Imaging spectroscopy



8

Future Development

Priorities

- Utilize cleanroom to expand production of active optics
- Use customer feedback for enhancing capabilities to create world class facility

Risks

- Limitations of fabrication equipment
- Limitations of material science knowledge

Payoff

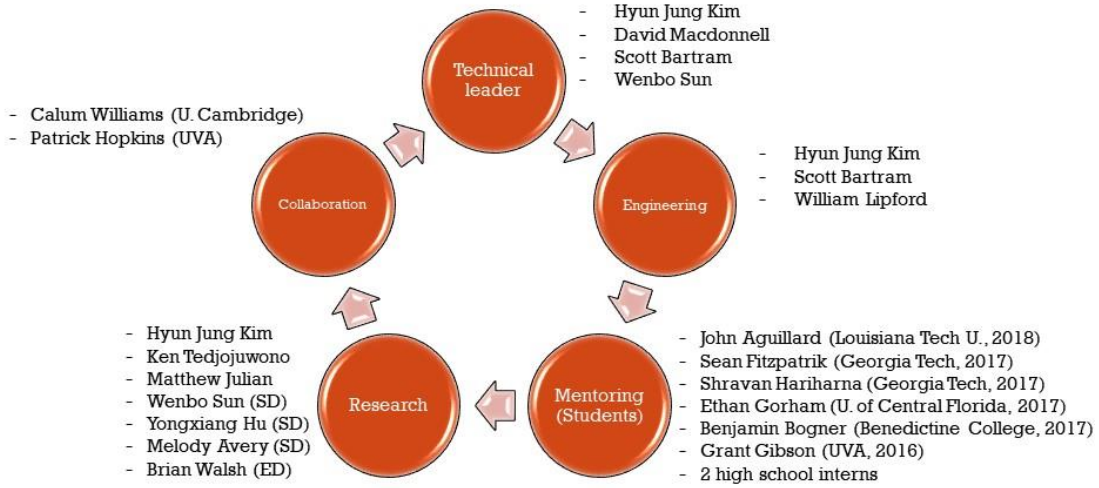
- Cost effective
- Develop in-house product
- Protect intellectual property
- Ability to create unique prototype
- Work closely with researchers / engineers to meet their needs

My big dream

- **People + $ + Instruments**
- New fabrication / characterization instruments: commercially available and developed in-house
- Extend collaboration both in-house and with outside partners
- Multiple stakeholders
- Support science, aeronautics, and space projects
- Model development / new concept investigation

Conclusion

Researchers can take advantage of the existing material science capability and state of the art facilities at NASA LaRC to research and develop prototype components for active optical devices



In the last 2 years:

9 papers, 4 conference, 11 NASA invention disclosures & patents, 7 proposal submission, 8 students mentoring

8.3 ACTIVE OPTICAL SENSING FOR FLOW QUANTIFICATION IN WIND TUNNELS IN SUPPORT OF AERONAUTICS, SCIENCE AND EXPLORATION

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ABSTRACT

Active optical sensing techniques are developed and applied to perform qualitative flow visualizations and quantitative measurements in wind tunnel testing of NASA flight vehicles and vehicle components. Measurement techniques have been developed and implemented to support Aeronautics, Science and Exploration missions at NASA. Examples of projects that used active optical sensing are included for each of these three areas. Enhancements to these and related technologies are discussed. Also the results of a recent measurement needs survey which identified gap areas are described.

1 INTRODUCTION

When developing new Aeronautics, Exploration or Science flight vehicles or vehicle sub-systems, a combination of wind tunnel testing and computational fluid dynamics (CFD) simulations are used to invent new concepts, improve existing designs and to assure vehicle safety. Obtaining qualitative and quantitative data during the wind tunnel tests is critical both for inventing new concepts, for validating CFD, and in some cases for populating aero- or aero-thermal databases used for vehicle design and operation.

1.1 MISSION DIRECTORATE APPLICATIONS

The Aeronautics Research Mission Directorate has been developing and wind tunnel testing new vehicles and vehicle technologies. These include subsonic and near transonic blended wing body vehicles and electric powered aircraft (Maxwell, X-57 and an electrically-driven "tail cone thruster" concept as examples), supersonic Quiet Ultra-Efficient Supersonic Transport (QueSST, X-59) as well as hypersonic vehicle technologies. NASA's Science Mission Directorate uses wind tunnel testing for developing and testing its various entry, descent and landing (EDL) technologies for planetary entry and sample-return missions. A recent example is the Mars Science Laboratory (MSL) entry capsule that delivered the Curiosity rover to Mars. Finally NASA's Human Exploration and Operations Mission Directorate uses wind tunnel tests for development of both the launch vehicle technology (Space Launch System, SLS) and the return capsule (Orion). These are some of the major NASA missions that are driving the need for improved instrumentation in NASA's wind tunnels through the full speed regime from subsonic to hypersonic.

1.2 KEY MEASUREMENTS REQUIRED BY MISSIONS

Key data needed in most wind tunnel tests includes measurement of force and moment on the vehicles. Sometimes pressure distributions and thermal loads on the vehicles are needed. The detection of transition from laminar to turbulent flow is often needed because of the implications for heat transfer and vehicle aerodynamics. In all speed regimes, flow separation is difficult for CFD to predict accurately and quantitative surface and flowfield data (for example, skin friction and velocity, respectively) are highly sought after. Reducing the intensity of sonic boom is an active area of research in supersonic flight, so pressure measurement in that speed regime is highly important, as is velocity measurement. In both supersonic and hypersonic speed regimes, aero-propulsion interactions are very challenging to predict. Examples include both launch and entry vehicles, the latter of which use reaction control systems (RCS) that flow jets of gas out of the vehicle interacting with the oncoming flow. In hypersonic flows, so called "real gas effects" such as ionization, dissociation and rotational-vibrational nonequilibrium and further effects such as surface catalysis, material oxidation, nitridation, ablation, and radiation are difficult to predict and need quantitative data to validate computational models. Finally in combustion flows associated with aircraft propulsion (typically subsonic) and scramjet engines (typically supersonic or mixed subsonic-supersonic) additional parameters are needed to validate reacting computations such as species concentrations, temperature (including nonequilibrium), and velocity. While the above list

of measurement needs is not exhaustive, it describes some typical measurement needs in NASA's wind tunnel tests. In summary, *flowfield measurements* of velocity, pressure, density, temperature, and species concentration are required and *surface measurements* of pressure, temperature, skin friction, angle of attack and surface shape and deformation are required by aeronautics, science, and exploration researchers. Using active optical methods to measure these properties is preferable to using conventional probes (for example thermocouples, hotwires and pressure probes) because optical methods don't perturb the flow and are not damaged by harsh environments.

1.3 SPECIFIC EXAMPLES OF WIND TUNNEL MEASUREMENTS

Below, a few examples of recent active optical measurements produced by the author's research group are described. One example each is given for aeronautics, science and exploration.

1.3.1 Aeronautics: FLEET in Transonic Cryogenic Tunnels

Practical considerations prevent the use of particle based measurement methods in NASA's transonic cryogenic wind tunnels. Instead, molecular techniques are being developed. One such method, the femtosecond laser electronic excitation and tagging (FLEET) technique,[1] excites fluorescence along a line or at a point using a nonlinear, nonresonant excitation process in nitrogen gas, which actually creates a weak plasma along the laser focus. A femtosecond laser is used in this instance to achieve the high peak laser powers. The slow recombination of this plasma and the resulting visible fluorescence can be monitored for tens of microseconds. By imaging this fluorescence as a function of time using multiple exposures with a gated camera the velocity of the gas can be measured. An example sequence of images is shown in Fig. 1 where an 800 nm femtosecond laser focused to a point about 1 mm in size excites fluorescence of N_2 in a transonic, cryogenic wind tunnel. By processing the images the movement of the spot can be accurately determined. The velocity can then be determined from the displacement divided by the time delay between the images. Acceleration can also be measured.

The FLEET method uses a single, visible wavelength, turn-key laser and can acquire 2 components of velocity with a single camera or 3 components of velocity with two camera views. FLEET uses ambient nitrogen present in air or N_2 flows. In general, FLEET is relatively easier to set up and perform compared to competing velocimetry methods and it is straightforward to measure both velocity and acceleration at 1 kHz repetition rates.

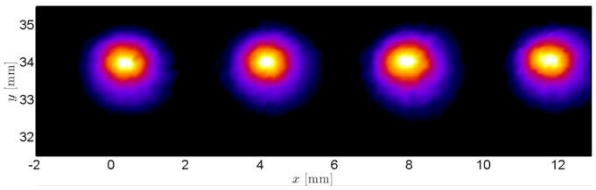

Fig. 1. Example FLEET signal images. This figure shows a superposition of four images of the FLEET signal obtained with a time separation of 15 μs between images. Each image is normalized to its maximum value. Flow is from left to right at about 250 m/s.

Figure 2 shows velocity profiles from a FLEET measurement in a transonic cryogenic wind tunnel. In the figure, flow is left to right over an airfoil mounted to the opposite tunnel wall. The laser passes nearly parallel to the surface of the wing exciting a spot which is then imaged as it convects around the wing. The measurement point is scanned to measure velocity profiles as shown.

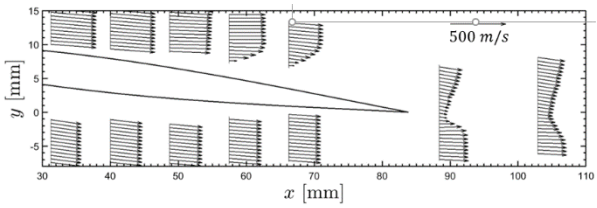

Fig. 2. FLEET velocity measurements near an airfoil at a 7 degree angle of attack at Mach 0.85.[2]

1.3.2 Science: NO PLIF on the Mars Science Laboratory (MSL) Capsule

The planar laser induced fluorescence (PLIF) method was used to excite nitric oxide (NO) seeded into reaction control system (RCS) jets in a Mach 10 flowfield in support of the Mars Science Laboratory (MSL) capsule. A 226 nm laser with a 10 ns duration is formed into a sheet. The laser is tuned to an absorption line of NO which fluoresces and is then detected by an intensified CCD camera.

The laser sheet is swept spatially through the flowfield to visualize and measure the three dimensional shape of the jet. This was done for both Orion[3] and MSL[4] vehicles, though only the MSL results are shown here.

Figure 3 shows a comparison between experimental NO PLIF measurements of the shape of an MSL RCS jet with a computation performed using NASA's OVERFLOW computational fluid dynamics (CFD) code.[5] The CFD code was used to predict the PLIF signal intensity using a spectroscopic model for the PLIF process and then iso-contours of both computed PLIF and measured PLIF are shown. We term this method of computing the PLIF images from CFD computational flow imaging (CFI). Both measurements and computations shows the complex three dimensional flowfield of the jet. The computations and the experiment are remarkably similar. Similarly, multi-jet flowfield measurements agreed with computations. This gave the MSL program confidence that the computational codes were reliably predicting this complex flow and provided evidence to improve confidence in the aerodynamic database that the computations predicted.[3] Ultimately, the MSL vehicle successfully delivered the Curiosity rover to Mars in August 2012.

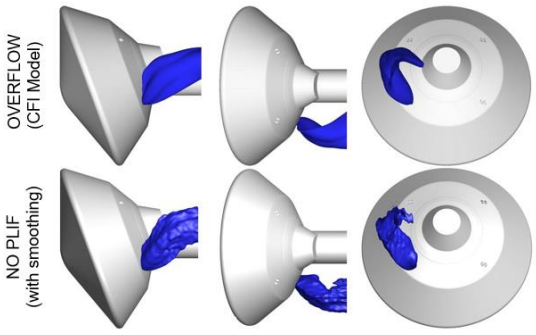

Fig. 3. Mars Science Laboratory entry vehicle PLIF results at Mach 10 (bottom) in comparison with computations (top).[3]

1.3.3. Hydroxyl radical (OH) PLIF on the Space Launch System (SLS)

In support of the NASA SLS, we used the PLIF technique to probe OH that has been produced naturally as a result of H_2/O_2 combustion in a rocket engine simulating the NASA SLS at CUBRC in Buffalo, N.Y.[6] The OH expands out of the engines and is present in the entire wake flowfield.

A laser was tuned to near 283 nm to excite OH fluorescence. This laser light was formed into a sheet oriented perpendicular to the base heat shield which was passed along the model centerline between the four engines. The laser excited the naturally-occurring OH, allowing the flowfield features to be visualized. Of highest interest was a shock wave forming parallel to the base heat shield, confirming that a reverse flow (flow towards the heat shield) had been established. This result confirmed CFD predictions. The location of the shock wave also agreed with CFD. Prior Schlieren and infrared imaging measurements were not sensitive enough to visualize this shock wave so the PLIF data provided important evidence to substantiate the CFD. This shock wave is clearly visible in the thermometry data shown in Fig. 4 and detailed next.

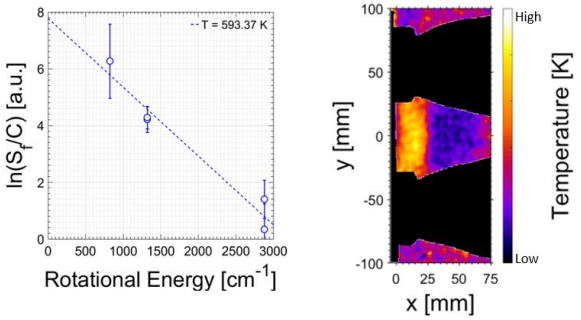

Fig. 4. Boltzmann plot (left) used to determine temperature and resulting temperature map (right) on SLS base heatshield. [6]

By acquiring images at different laser wavelengths, quantitative temperature images could be obtained. The different states probed have different populations depending on the temperature. By measuring three different transitions and assuming that the temperature field is repeatable, the data could be graphed on a so called "Boltzmann plot" which plots the logarithm of the signal intensity on the vertical axis and energy of the probed state on the horizontal axis. The slope of a best-fit line between these data points indicates the temperature. Figure 4 shows a representative Boltzmann plot on the left and the resulting temperature map on the right. The black areas indicate the location of the engine nozzles. The expected strong jump in temperature across the shock wave is clearly shown. Very close to the

heatshield the temperature decreases as heat is transferred to the vehicle. CFD predicts the same trends.

2 METHODOLOGY

2.1 STATE OF THE ART

Regarding the state of the art, a wide variety of instrumentation is available to NASA researchers when performing ground-testing of subsonic, transonic, supersonic or hypersonic flight vehicles. Several conventional techniques are in use, including force and moment measurement using strain-gauge-based balances, surface pressure measurement using pressure taps including time-averaged or time-resolved measurements, surface heating using thin-film gauges or thermocouples, angle-of-attack measurement using accelerometers, and flow visualization using the Schlieren or shadowgraph methods. More recently, surface pressures and temperatures have been measured using pressure sensitive paint (PSP), temperature sensitive paint (TSP) or phosphor thermography. Whereas pressure measurements describe forces on the model, surface temperature measurements indicate heat transfer to the model as well as areas where flow is transitioning from laminar to turbulent flow, indicating areas of increased drag. Surface shape or deformation is sometimes measured using photogrammetry. Oil flow and discrete gauges can be used for shear stress detection and surface flow visualization.

Complementing these surface measurements, off-body measurements in the flowfield are used for validation of computational codes as well as improved understanding of the flow physics. Off-body measurements are frequently acquired using lasers which allow high spatial (<1 mm) and temporal (<1 μsec) resolution with planar or even volumetric measurement. Such measurements fall into two classes: particle-based and molecular-based measurements. For particle-based measurements like laser Doppler velocimetry (LDV), particle image velocimetry (PIV), and Doppler global velocimetry (DGV), some type of particle must be seeded into the flowfield. However, especially in high-speed flows the particles may not always follow the flow or could even influence the flow. Thus, molecular-based techniques are preferable in many applications.

The level of technical maturity of these methods varies technique to technique and cannot be assessed in this report.

2.2 MEASUREMENT NEEDS AND GAPS

The author has recently been conducting a survey and analysis for advanced optical measurement systems for wind tunnels where various capabilities, needs, gaps and opportunities for NASA researchers have been identified. A preliminary result summarizing the measurement needs is shown in Figure 5 below. For this survey, 12 different planned research projects were surveyed (3 subsonic, 4 transonic, 4 supersonic and 1 hypersonic). The measurement needs were weighted by how critically they were needed by the program (5 was most critical, 0 was not at all critical). A project could request measurements for inflow, near-model or outflow, or for all three.

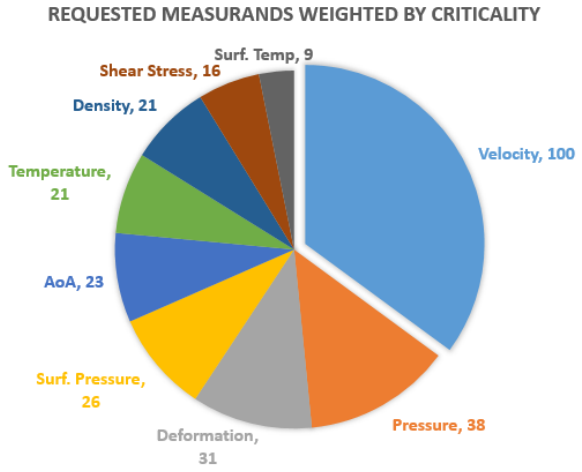

Fig. 5. Measurement needs determined by surveying researchers planning 12 different NASA wind tunnel tests (preliminary result).

The survey indicates that velocity measurement is clearly the most requested, followed by flowfield pressure. Note that this graph describes needs and not gaps. In many of the cases, for example surface pressure, AoA or even velocity, suitable measurement techniques are available to meet many of these needs.

Regarding gaps in the state of the art, many have been identified during this survey. While not an exhaustive list, some of these gaps are:

1) Measurement of surface skin friction on wind tunnel models, particularly two-dimensional measurement over large

surface areas in all speed regimes including in transonic cryogenic tunnels (TCTs) where oil flow does not work.

2) Measurement of surface pressure in flows that do not contain oxygen (for example, pure nitrogen flows such as TCTs).

3) Measurement of flowfield pressure, temperature and velocity: (i) in transonic wind tunnels for aerodynamics studies, (ii) in supersonic wind tunnels in support of sonic boom reduction research, (iii) in supersonic isolator experiments related to scramjet powered flight, (iv) in supersonic transition experiments where particles cannot be seeded into the flow, and (v) high-speed measurement for studying launch vehicle buffet occurring at rates of 10's of kHz.

4) Time resolved, simultaneous measurement of flowfield velocity, surface pressure, and model deformation in aeroelastic flowfields. Currently particle based measurements interfere with pressure sensitive paints used.

5) Visualization and quantification of unseeded RCS jets and other plumes in supersonic and hypersonic flows. In many facilities the plumes cannot be seeded as was done to produce the data in Fig. 3 above.

6) To determine accurate boundary conditions for computational methods, the inflow conditions of the wind tunnels need to be fully characterized. These include static and stagnation pressures and temperatures as well as velocity fields. Of particular interest is the flow angularity which is required with an accuracy of a fraction of a degree. Such a measurement is challenging and time consuming to measure with probes though it is very important for accurate determination of vehicle lift and drag.

7) Measurement of combustion reactants, products and intermediates simultaneously with temperature and velocity in subsonic and hypersonic combustion flows, for CFD code turbulence-chemistry model development and validation.

8) Improved methods of measuring emissivity and temperature of hypersonic materials under test. Further quantification of material properties such as thermal conductivity obtained in situ during testing would also be useful.

9) Temporally and spatially resolved measurements in short duration environments like shock tubes and shock tunnels (much more than 1 image per 50 msec run).

2.3 NEW APPROACH: PULSE BURST LASER

The length of the present paper prevents proposing solutions to all of the gaps identified above. Instead this section will focus on a single technology that shows potential for filling some of these gaps, notably 3)-7) and 9) noted above. This technology involves using a new capability obtained by NASA. It is a high-repetition-rate Nd:YAG laser amplifier technology, called a "pulse burst laser" developed by an SBIR partner, Spectral Energies LLC in Dayton OH. Whereas the current SOA technology uses a 10 Hz laser for wind tunnel measurements (e.g. shown in figures 3 and 4 above) the new technology can make measurements at rates of between 10 kHz and 1000 kHz. The higher repetition rate obviously allows time dynamics of fluid flows to be studied but it also allows data to be taken more quickly which is critical in short-duration wind tunnel facilities like shock tubes and shock tunnels used by NASA. Furthermore this technology also lends itself to innovative wavelength tuning strategies potentially leading to new measurement capabilities. The technology is versatile and can be used for a variety of measurement types such as:

- Rayleigh scattering for molecular based (unseeded) measurement of velocity, temperature and pressure (or density) in any gaseous fluid provided the composition is known. This includes transonic cryogenic tunnels and plumes. Challenges associated with this method are rejecting scattering from particles and walls since the detected light is very close to the laser's wavelength. Also, in low density flows the Rayleigh scattering signal can be weak and difficult to detect.

- The same laser and measurement approach can as used for Rayleigh can be used to scatter light from naturally occurring fog present in some facilities. This approach can be used for velocimetry only. This technique is known as Doppler Global Velocimetry (DGV). If larger particles are present the same laser can be used for particle image velocimetry (PIV).
- Raman scattering which can be used for major species detection in combustion applications and which can be performed simultaneously with Rayleigh scattering if additional temperature and velocity data are desired.
- If the pulse burst laser is used to pump an optical parametric amplifier (OPA) and if that light is frequency mixed to the UV, then the types of experiments shown in Figs 3 and 4 could be performed at high repetition rates allowing time-resolved statistics of the flow to be acquired even in short-duration facilities like shock tunnels.

A key programmatic and practical advantage of this technology is that the measurement system can be swapped back and forth from particle-based measurement (PIV) to fog-based DGV to Rayleigh scattering by reconfiguring all the same laser and camera hardware. This means that the same equipment and research team could use multiple velocity measurement techniques to study the same flow with each technique using different operating principles, thereby increasing confidence in the final results.

2.4 DESCRIBE THE FUTURE STATE

This laser system was just delivered in February, 2018. Personnel are learning to operate the system and additional required supporting equipment such as high speed cameras, is being procured. The system will be used in a series of demonstration tests in the laboratory and then will be brought to different wind tunnel facilities for demonstration experiments. A key initial facility where tests will occur is the 0.3 meter transonic cryogenic wind tunnel at NASA Langley. It is relatively low cost but has many of the features of NASA's flagship National Transonic Facility which needs temperature, pressure, and velocity measurement capability. Another logical demonstration experiment would occur in NASA Langley's 4 foot Unitary plan wind tunnel where unseeded velocity measurements are desired. Still, implementation of this measurement system in NASA's wind tunnels will be a significant effort that will require partnering with our small business and university partners.

2.5 RISKS AND REWARDS

Several risks have been identified with this technology.

- The Rayleigh scattering is susceptible to interference from particle scattering in dirty, dusty flows and susceptible to interference reflections and scattering off walls and model surfaces as alluded to previously. Strategies are being developed to overcome these challenges.
- In lower pressure flows the signal intensities may be too low to obtain high enough signal to noise ratio to yield sufficient accuracy and precision to meet customer needs.
- The laser is a one-of-a-kind technology and it, or some component within it could fail, leading to loss of use during a critical test.

Despite these risks, the pulse burst laser technology has potential for greatly expanding the use of flowfield pressure, temperature and velocity measurement capabilities in a variety of NASA's wind tunnels, particularly in the transonic and supersonic regimes.

3 PROGRAMMATICS

3.1 DEVELOPMENT PLANS

At the present time only a rough development plan to implement this technology has been completed. Currently the development of pulse-burst laser instrumentation is being supported at a low level by the Aeronautics Research Mission Directorate's Transformational Tools and Technologies (TTT) Project, which fosters and develops low-TRL technologies. The project title is "*High Speed Velocimetry*." Current support is for about 0.1 FTE and 0.5 WYE on this project with an equipment budget of just a few thousand dollars per year. Ideally 0.5 FTE and 1 WYE would be devoted to the project with additional resources provided if the system would be used in extensive production testing. The required equipment budget would depend strongly on how many measurement setups would be required. As a baseline, a procurement budget of $50k would be satisfactory.

If the pulse burst OPA technology described in section 2.3 was to be developed and implemented, additional resources (at least $200k, but preferably Phase 1&2 SBIRs to further develop and mature the OPA technology and its integration at NASA) would be required. This information is captured in the table below. In this plan, the increased FTE, WYE and procurement as well as augmented funding for the OPA development would both start in FY19.

Table 8-1 -- Development Budget Profile

High Speed Velocimetry	**FY 18** baseline	**FY 19** proposed	**FY 20** proposed	**FY 21** proposed	**TTL** prop.
Budget ($M)	0.100	0.475	0.475	0.475	1.425
FTE	0.1	0.5	0.5	0.5	1.5
WYE	0.5	1.0	1.0	1.0	3
Procurement	0.010	0.250	0.250	0.250	0.75

(Note: $150k / FTE and $150k / WYE was assumed. These amounts are included in Budget but not Procurement.)

3.2 Development Milestones and Dates

Again, a full plan has not been established but a notional plan follows:

- FY19: Laboratory development of Rayleigh Scattering pressure, temperature velocity (P, T, V) measurement.
- FY20: Demonstration of P, T, V measurement in a small facility such as the 0.3 meter TCT.
- FY20: Laboratory demonstration of a near-turn-key OPA system for performing NO and OH PLIF (with SBIR partner)
- FY21: Demonstration of P, T, V measurement in a large scale facility such as the Unitary Plan Wind tunnel and/or the NTF at NASA Langley.
- FY21: Demonstration of OPA system for PLIF measurement in a shock tunnel facility, for example at CUBRC in Buffalo, NY.
- FY22: Routine use of P, T, V measurement in large scale NASA wind tunnels including OPA use for fluorescence imaging.
- FY23: Develop and demonstrate high speed P, T, V measurement at rates up and possibly faster than 100 kHz.

3.3 Partnering

NASA would be a leading organization in this research project with other key partners including Spectral Energies LLC or possibly other industrial partners who may be able to contribute key technologies. Also at least two universities have contributed to developing this technology and it is expected that collaborations with those universities and possibly others would continue.

3.4 Overcoming the Valley of Death

For this technology the valley of death would be for the program to end once the low-TRL funding ends. The key way we anticipate avoiding the valley of death is by providing value to various NASA programs testing in wind tunnels while still receiving low-TRL funding. If the programs see value they will continue requesting our services even after low-TRL funding ends. Still, we need to keep an eye on costs to prevent our services from becoming too expensive and thus limiting use of this technology.

4 CONCLUSIONS

In summary, numerous gap areas in the area of wind tunnel instrumentation have been identified. The scope of the introduction and discussion through the section on gaps is very general and focuses on a wide range of needs in the area of active optical measurements for wind tunnels in support of Aeronautics, Science and Exploration. Starting in section 2.3, the report focuses on development of one specific technology, the pulse burst laser, which can be used for numerous measurements and to address many of the gaps identified in the previous section. This technology has the potential to provide some key measurements that are not currently possible at NASA.

ACKNOWLEDGEMENTS

I acknowledge the support of the ARMD TTT project under the leadership of Mike Rogers and also Tom Jones, the lead for Innovative Measurements. Also James Bell from the Aeronautics Evaluation and Test Capabilities (AETC) Portfolio, and Eric Walker, Luther Jenkins and Chris Rumsey from NASA Langley have been helpful in developing the survey and contributing to the gaps identified in this report.

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2. R. A. Burns, P. M. Danehy “Unseeded Velocity Measurements Around a Transonic Airfoil Using Femtosecond-Laser Tagging,” AIAA Journal Vol. 55, No. 12, December 2017
3. J. A. Inman, P. M. Danehy, D. W. Alderfer, and G. M. Buck, and A. McCrea, "Planar Fluorescence Imaging and Three Dimensional Reconstructions of Capsule Reaction-Control-System Jets", AIAA Journal Vol. 47, No. 4, April (2009).
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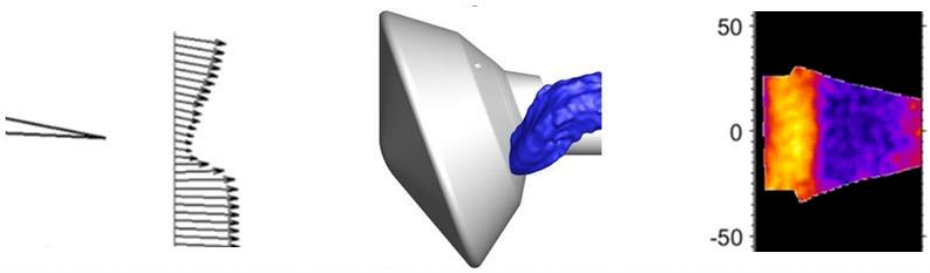
5. C.T. Johansen, P.M. Danehy, S.W. Ashcraft, B. Bathel, J.A. Inman, S.B. Jones, “Planar Laser-Induced Fluorescence of Mars Science Laboratory Reaction Control System Jets” Journal of Spacecraft and Rockets, Vol. 50, No. 4, pp. 781-792, 2013
6. R. A. Burns, P. M. Danehy, J. A. Inman, M. Mehta, R. A. Parker, A. T. Dufrene, J. Weisberger “Quantitative, Multi-line, OH-PLIF Thermometry to Examine Base Heating in the Space Launch System Core and EUS”, JANNAF Joint Subcommittee Meeting, Newport News, VA, 4-7 Dec 2017



Active Optical Sensing for Flow Quantification in Wind Tunnels in support of Aeronautics, Science and Exploration

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Advanced Meas. and Data Systems Branch
NASA Langley Research Center
Hampton, Virginia, USA

NASA TIM on Active Optical Systems for Supporting Science, Exploration, and Aeronautics Measurements Needs, Aug, 2018

Outline

- Recent Examples of Active Optical Measurements
  - Aeronautics
  - Exploration
  - Science
- Future Capability: Pulse Burst Laser Technology







Aeronautics Application:

Femtosecond Laser Electronic Excitation Tagging (FLEET)
Molecular Tagging Velocimetry in Transonic Cryogenic Tunnels

What is FLEET?

- Femtosecond Laser Electronic Excitation and Tagging (Princeton)



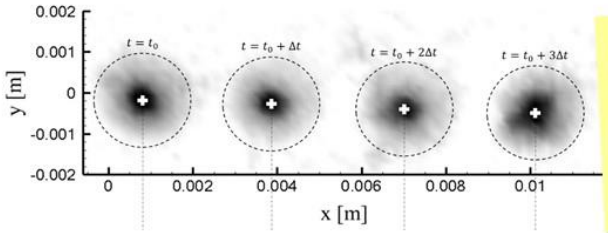
- 70 fs laser focused down excites N_2 which fluoresces for 10's of μs
  - Acquire image pairs or sequences and determine velocity from displacement (Δt = 1 μs, 5 μs, … 50 μs)
  - Can perform precise velocity measurements in air and N_2 flows

Laser (1 kHz)
-1 ms = 1000 usec between pulses
Camera (200 kHz)
-5 usec between images



FLEET Raw Data obtained in 0.3 m transonic cryogenic tunnel at NASA Langley (use slideshow mode)

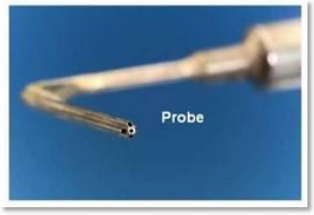
$V = \Delta x/\Delta t$

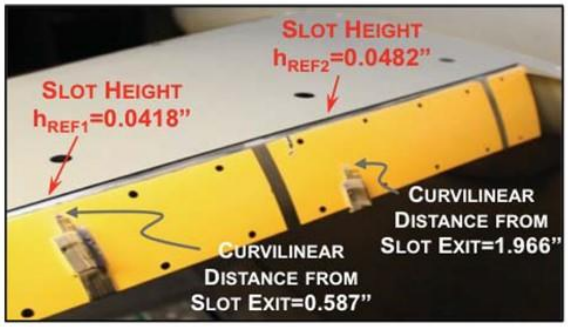


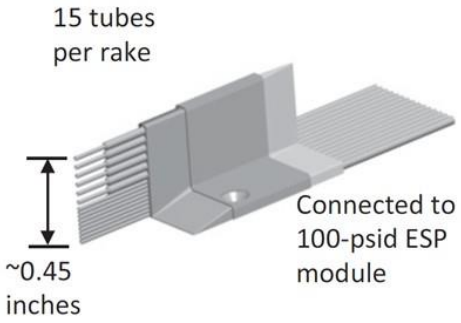
- Single, robust laser
- Single camera, 200 kHz
- 800 nm laser, 1 kHz
- Visible fluorescence
- Multi-exposure
- No seeded gas

Current Flow Measurement in TCTs

- *What are they doing now in TCTs?*
  - Physical probes (hotwire; pitot-static)
    - bulky, slow, perturb the flow.
    - Typically mount on main sting or model.
    - Not always available in National Transonic Fac. (NTF)
- Current flow measurement approach in NTF uses rakes attached to model:



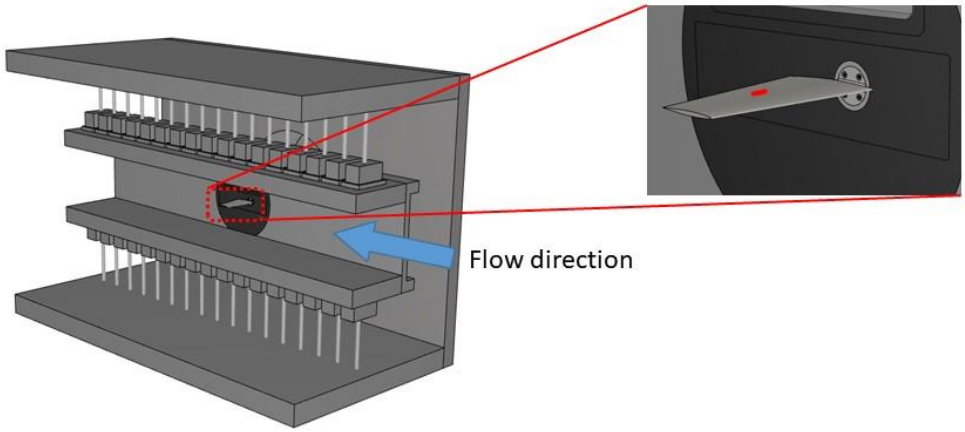




Milholen, Jones, et al, 2013

FLEET Velocimetry on an airfoil

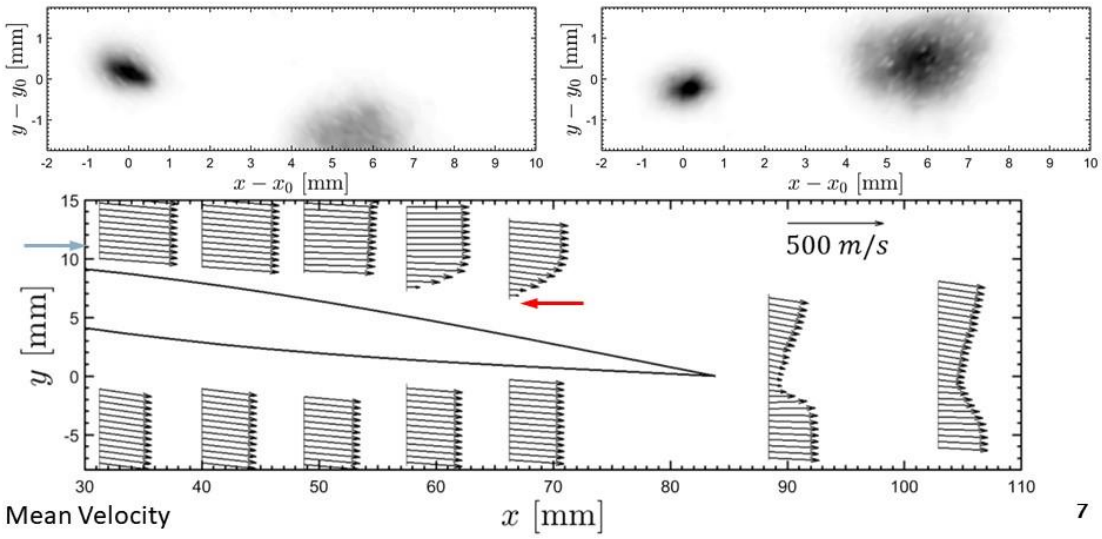
Test Model – Transonic airfoil
- Symmetric
- Semi-span, tapered
- Wall-mounted



FLEET Velocimetry on an airfoil

Had previously deployed FLEET in 0.3-m TCT facility several times ~1% accuracy

- Assessed practical performance of FLEET velocimetry
  - Made mean and fluctuating velocity measurements in wake and on surfaces of a transonic airfoil at different Mach numbers and angles of attack



Mean Velocity

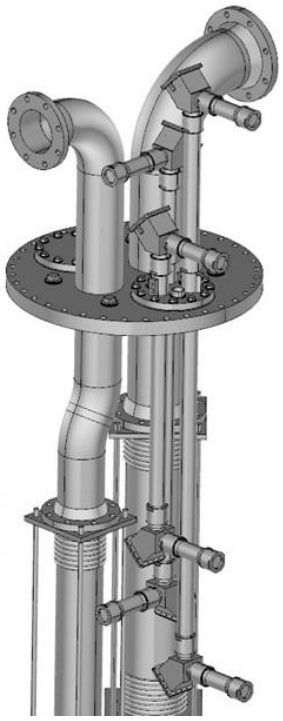
7

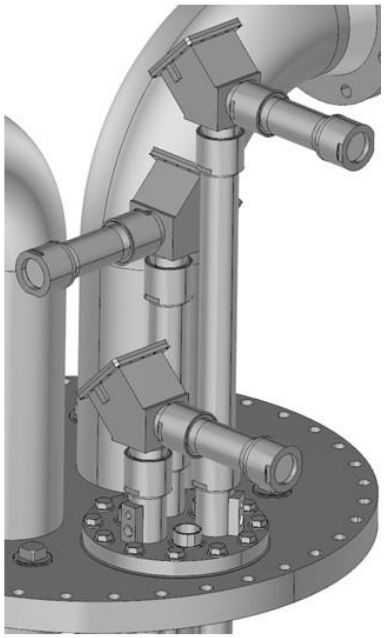
Use laser-based methods in NTF: Beam Tubes

- National Transonic Facility
  - High pressure cryo facilit
  - Unique National asses
  - High Reynolds number testing



- Designed and procured a beam transmitting system
  - Evacuated beam path
  - Articulating mirrors



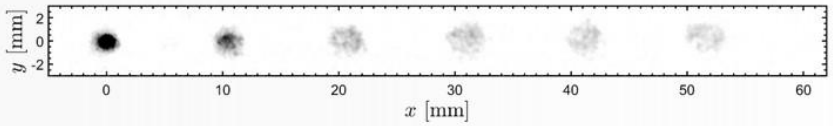


8

Higher Speed (100 kHz) Measurements: PLEET

Deployment of a high-repetition rate PLEET (picosecond-LEET) system

- Make similar velocity measurements at up to 100 kHz using pulse burst laser



MST Manuscript (under review): Burns, Danehy, Jiang, Slipchenko, Felver, Roy, "High-Speed, Unseeded Velocimetry for Transonic Cryogenic Tunnels Using Pulse-Burst PLEET."

QuasiModo 1000

Burst-mode Nd:YAG laser



PLEET Experiment performed at 0.3 m TCT in collaboration with Spectral Energies LLC

Pulse Burst Laser:
>500 mJ/pulse at 10 kHz for 10 msec pulse burst every 12 seconds

CAN BE USED FOR MOLECULAR RAYLEIGH SCATTERING TOO!!!

9

OH PLIF Visualization and Thermometry for NASA Space Launch System (SLS) Base Flow Heating

Exploration Application

Optical Diagnostic Imaging of Multi-Rocket Plume-Induced Base Flow Environments

Manish Mehta[1] and Darrell E. Gaddy[2]
NASA Marshall Space Flight Center, Huntsville, Alabama, 35812

Paul M. Danehy[3], and Jennifer A. Inman[4]
NASA Langley Research Center, Hampton, Virginia, 23666

and

Ron Parker[5] and Aaron T. Dufrene[6]
CUBRC Inc., Buffalo, New York, 14225

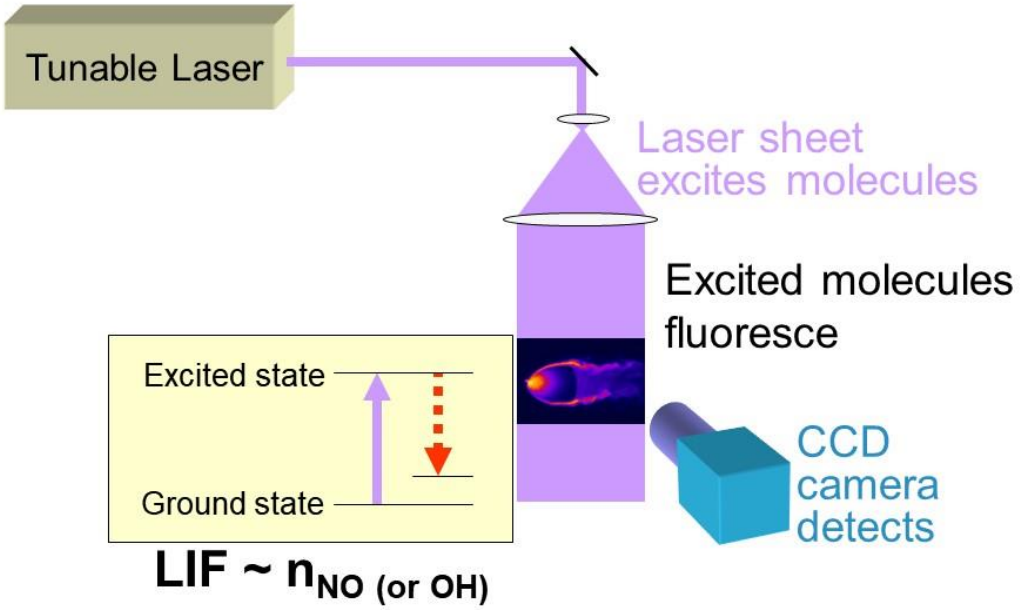


Measurements at CUBRC in Buffalo
Using NASA Mobile PLIF system

AIAA AVIATION Forum
5-9 June 2017, Denver, Colorado
47th AIAA Fluid Dynamics Conference
JANNAF Conference, Newport News, Dec 2018

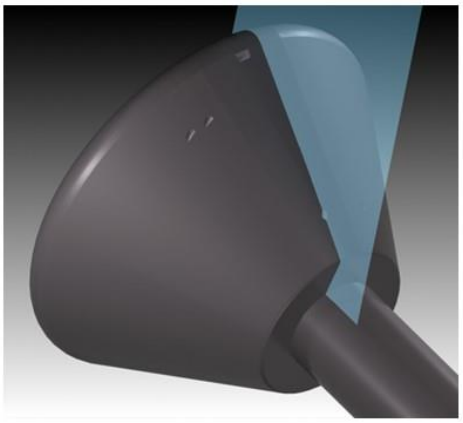
10

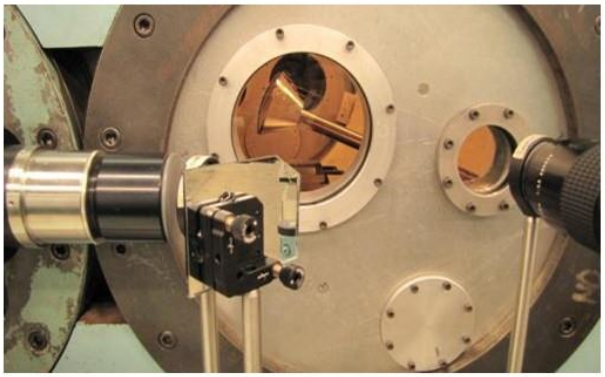
What is Planar Laser-Induced Fluorescence (PLIF)?



PLIF Imaging in CUBRC Lens-1 Facility

- Optics direct laser sheet directed into flow
- Imaged by cameras

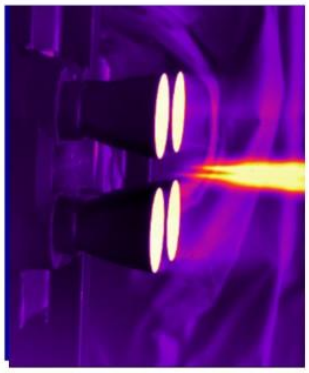


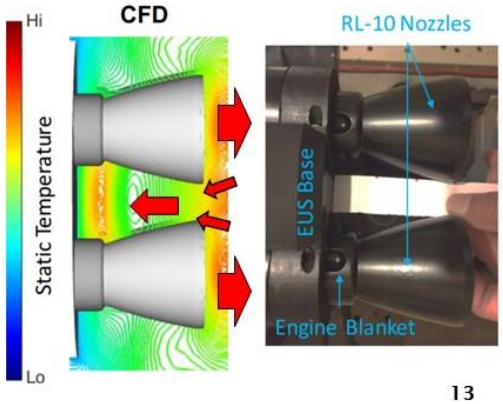


OH PLIF Visualization and Thermometry for NASA Space Launch System (SLS) Plume Induced Base Heating

- At high altitudes, flow leaving engines impinges on base
- Prior to PLIF: no direct experimental evidence of shock formation
- Wind tunnel tests: Use OH Planar Laser-Induced Fluorescence (PLIF)
  - Naturally-occurring OH present in plume and plume-induced base flow
- OH PLIF flow visualization clearly showed stagnation shock.
  - Neither Schlieren nor IR showed base flow structures
- Position of shock agreed with CFD, increasing confidence in CFD.

Mid-IR

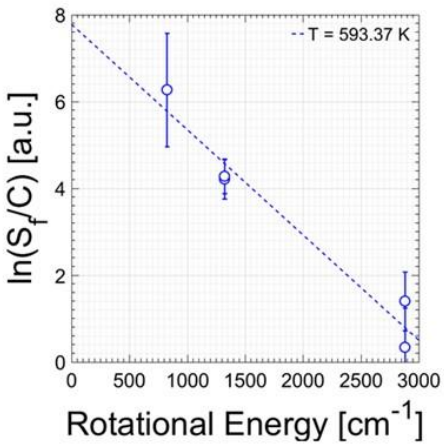


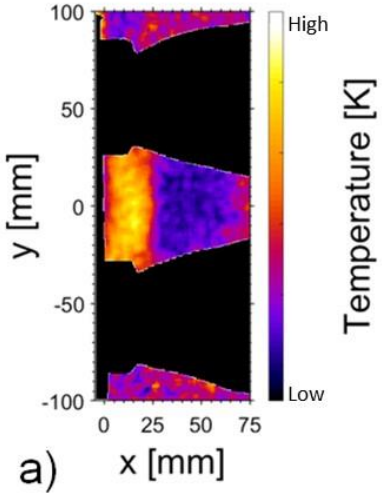


13

OH PLIF Thermometry of SLS Base Flow

- Probe different ground state transitions: measure rotational temperature





- "Recovery temperature" measurement is needed to determine flight-scaled convective heat transfer coefficient
- Quantity critical in determining flight-scaled heat transfer rates
  - Previously used a few thermocouples protruding into flow: 50-80% uncertainty
  - Using PLIF for the first time, measured with uncertainty of 10-30% with only 5 images
- Used to design base thermal protection system (TPS) thickness

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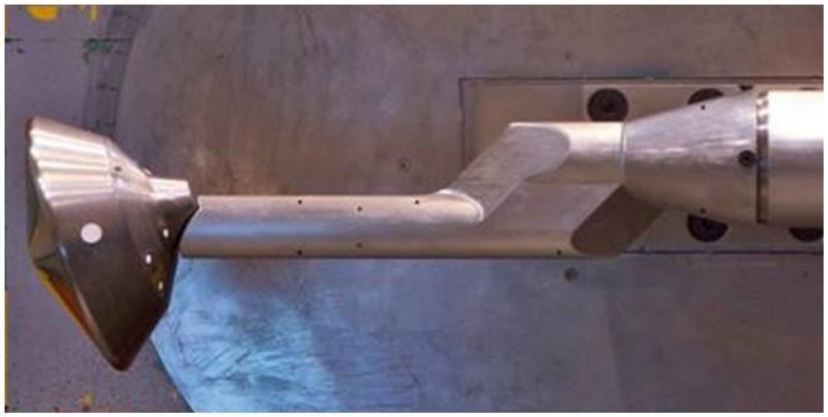
Mars Science Laboratory Reaction Control System Jet Computations with Visualization and Velocimetry

Science Application

C. T. Johansen, L. Novak, B. F. Bathel, S. W. Ashcraft, and P. M. Danehy, *Journal of Spacecraft and Rockets*, (2013)

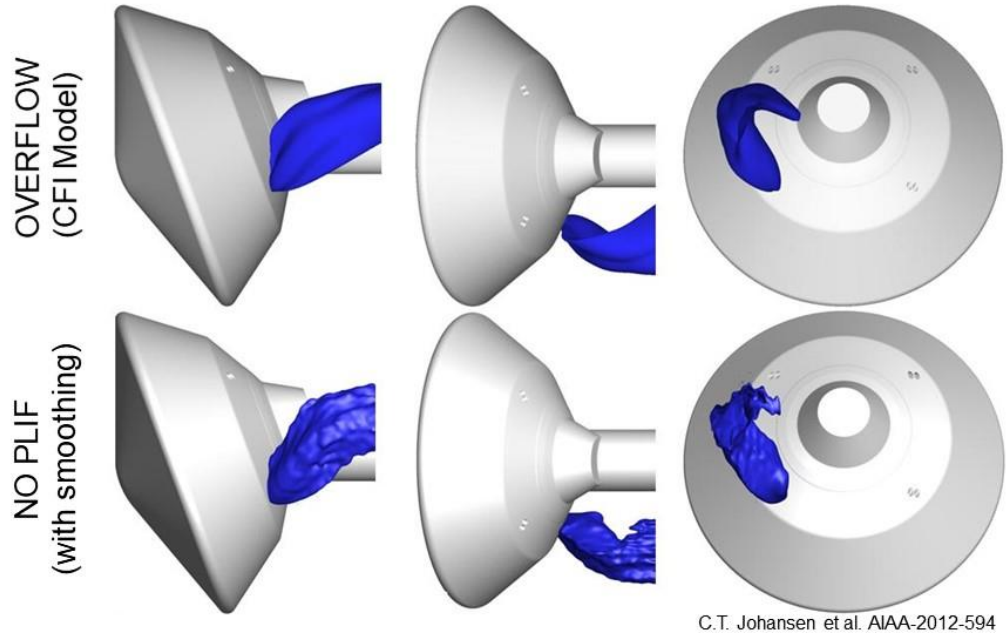


Measurements at NASA Langley Mach 10
Using NASA Mobile PLIF system

15

MSL NO PLIF vs CFD (CFI), Mach 10

- Mars Science Lab (MSL) vehicle delivered Curiosity:
  - Do we understand RCS jet wake flow and interactions? Predict?



C.T. Johansen et al. AIAA-2012-594

Future Work: High Speed Velocimetry and more

Specific Gap Areas 1

1. Measurement of surface skin friction on wind tunnel models, particularly two-dimensional measurement over large surface areas in all speed regimes including in transonic cryogenic tunnels (TCTs) where oil flow does not work.
2. Measurement of surface pressure in flows that do not contain oxygen for implosive nitrogen flows such as Titan.
3. Measurement of flowfield pressure, temperature and velocity:
   (i) in transonic wind tunnels for aerodynamics studies,
   (ii) in supersonic wind tunnels in support of sonic boom reduction research,
   (iii) in supersonic isolator experiments related to scramjet powered flight,
   (iv) in supersonic transition experiments where particles cannot be seeded into the flow, and (v) high-speed measurement for studying launch vehicle buffet occurring at rates of 10's of kHz.
4. Time resolved, simultaneous measurement of flowfield velocity, surface pressure, and model deformation in aeroelastic flowfields. Currently particle based measurements interfere with pressure sensitive paints used.

Specific Gap Areas 2

5. Visualization and quantification of unseeded RCS jets and other plumes in supersonic and hypersonic flows. In many facilities the plumes cannot be seeded as was done to produce the data in Fig. 3 above.
6. To determine accurate boundary conditions for computational methods, the inflow conditions of the wind tunnels need to be fully characterized. These include static and stagnation pressures and temperatures as well as velocity fields. Of particular interest is the flow angularity which is required with an accuracy of a fraction of a degree.
7. Measurement of combustion reactants, products and intermediates simultaneously with temperature and velocity in subsonic and hypersonic combustion flows, for CFD code turbulence-chemistry model development and validation.
8. Improved methods of measuring emissivity and temperature of hypersonic materials under test. Further quantification of material properties such as thermal conductivity obtained in situ during testing would also be useful.
9. Temporally and spatially resolved measurements in short duration environments like shock tubes and shock tunnels (much more than 1 image per 50 msec run).

9

QuasiModo 1000

Burst-mode Nd:YAG laser



Pulse Burst Laser:
>500 mJ/pulse at 10 kHz for 10 msec pulse burst every 12 seconds

Time resolved measurements using:
- Molecular Rayleigh Scattering
- High Speed PIV (up to 2 MHz)
- Doppler Global Velocimetry
- Planar Laser Induced Fluorescence (potentially)

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Summary

- Significant progress has been made to apply active optical measurement techniques to study wind tunnel flows for aeronautics, exploration and science.
- Survey of NASA wind tunnel measurement needs and capabilities is nearing completion.
- Gaps identified and are being used for NRA, SBIR calls for proposal and also for determining direction of NASA internal work.
- Some (not all) of these gaps are being addressed by ARMD TTT program.
- Pulse burst laser technology can address some of these gaps.

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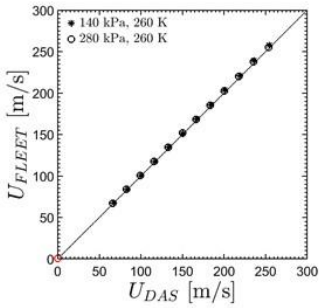
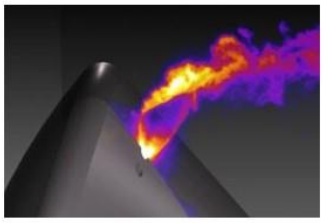
Thanks for your attention!

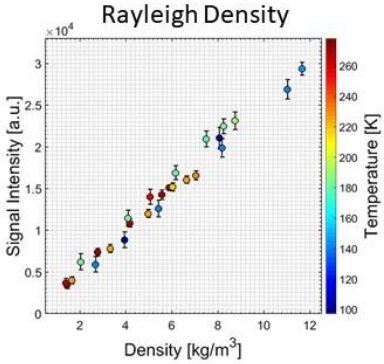
FLEET Velocity Accuracy



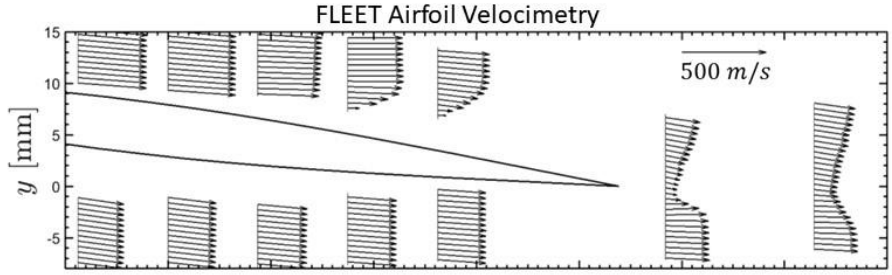
PLIF Flow Visualization



Rayleigh Density



FLEET Airfoil Velocimetry



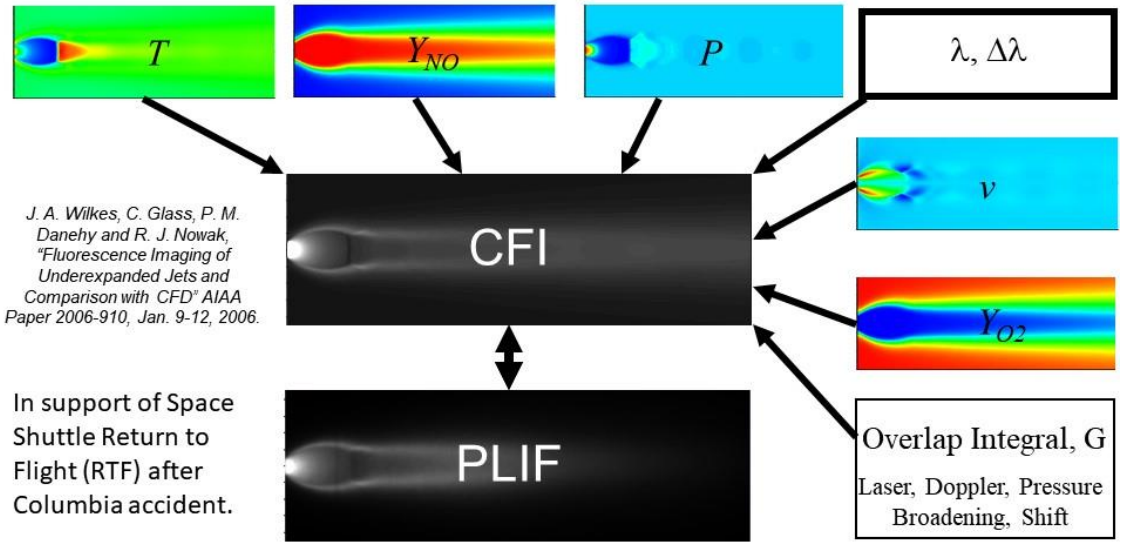
19

Backup

20

Computational Flow Imaging (CFI)

- Compute PLIF Images based on CFD and spectroscopic data (broadening, shift, quenching)
  - More direct comparison between PLIF and CFD



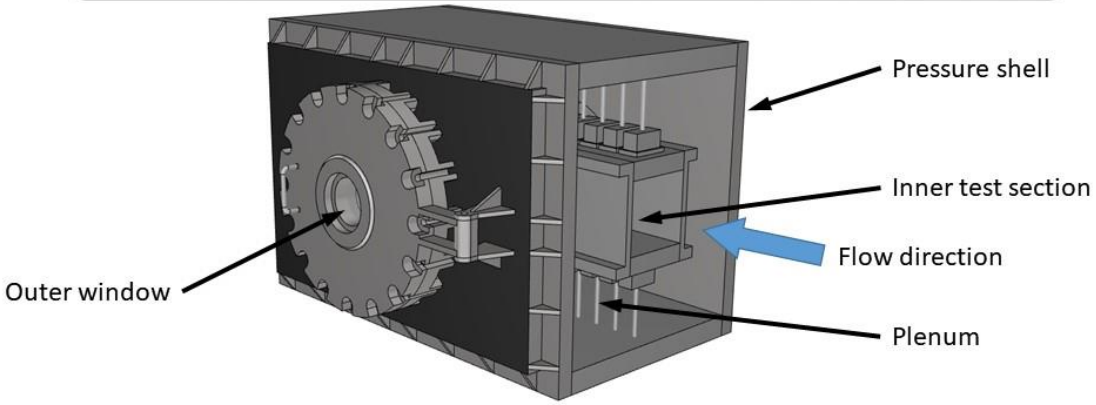
J. A. Wilkes, C. Glass, P. M. Danehy and R. J. Nowak, "Fluorescence Imaging of Underexpanded Jets and Comparison with CFD" AIAA Paper 2006-910, Jan. 9-12, 2006.

In support of Space Shuttle Return to Flight (RTF) after Columbia accident.

Transonic Cryogenic Wind Tunnel

Flow Facility – NASA Langley 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT)

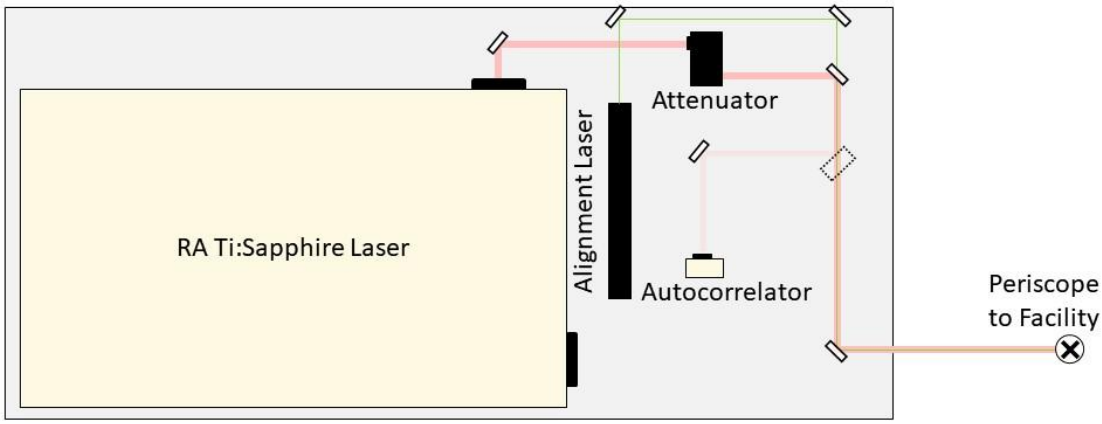
- Continuous, closed-circuit wind tunnel operating with air or N_2
- Mach number range: 0.2 to 0.9
- Total pressure range: 100 kPa to 500 kPa
- Total temperature range: 95 K to 320 K
- Reynolds number range: 4×10^6 1/m to 300×10^6 1/m
- Double-shelled construction
- Optical access: outer pressure shell window + two windows in turntable



22

Optical Setup

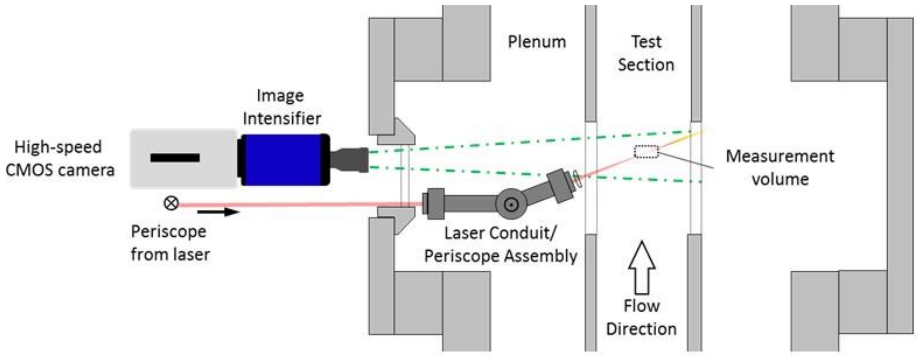
Optical Systems – Femtosecond Laser
- Regeneratively-amplified Ti:Sapphire laser
- Output wavelength: 800 nm
- Output bandwidth: 20 nm
- Pulse duration: 70 fs
- Pulse energy: 1 mJ (0.5-0.7 mJ at measurement location)



23

Optical Setup

- Within plenum, laser passed through an evacuated conduit/periscope to alleviate wavefront distortion caused by density fluctuations
- Beam focused at center of test section with f = + 200 mm PCX lens
- High-speed intensifier lens-coupled to CMOS camera
- Quasi-boresight imaging perspective
- Acquisition rate: 200 kHz in bursts of 15 frames (100 bursts/s)



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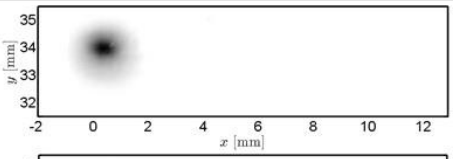
Characterization of FLEET velocimetry

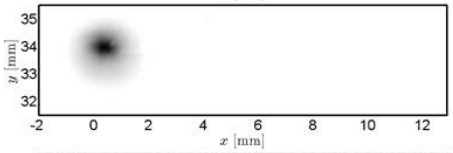
Data Sample

- FLEET signal takes on a nearly-circular intensity distribution due to boresight imaging
- Burst imaging allows the simultaneous measurement of signal position and intensity as a function of time
  - Immunity to vibration-based errors in velocity calculations
  - Signal intensity- /lifetime-based measurements

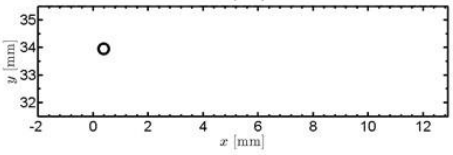
Raw data



Scaled data



Centroid data (processed)

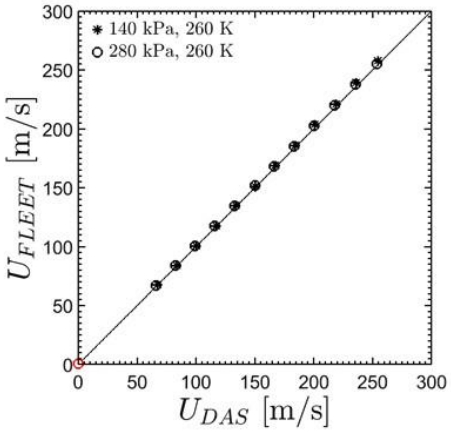


25

Characterization of FLEET velocimetry

Measurement Accuracy

- Accuracy assessed by comparing FLEET velocity measurements to those calculated by the 0.3-m TCT data acquisition system (DAS)
- Standard error found to lie between 0.5% and 1.5% of measured velocity



- Burns, Danehy, Halls, Jiang, "Application of FLEET Velocimetry in the NASA Langley 0.3-m Transonic Cryogenic Tunnel," Aviation 2015, AIAA-2015-2566.
- Burns, Danehy, Halls, Jiang, "Femtosecond Laser Electronic Excitation Tagging Velocimetry in a Transonic, Cryogenic Wind Tunnel," AIAA Journal, 2016.

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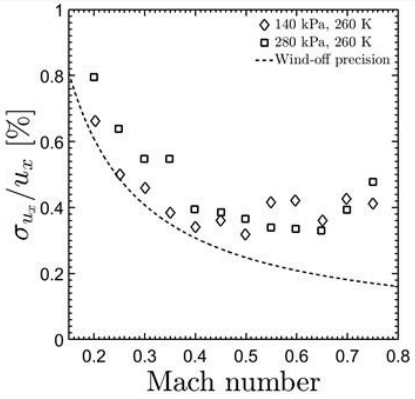
Characterization of FLEET velocimetry

Measurement Precision

- Zero-velocity precision measured by taking velocity measurements in quiescent N_2 and calculating the standard deviation of the measured velocities
  - Wind-off precision: $\geq$ **0.4 m/s**
- Standard deviation of velocity measurements compared to wind-off values
  - Measurement precision consistently less than 1% of measured velocities

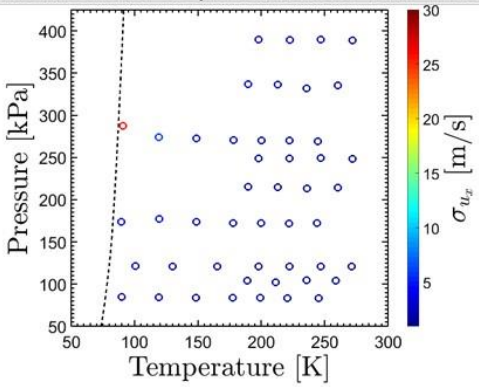


27

Characterization of FLEET velocimetry

Measurement Precision

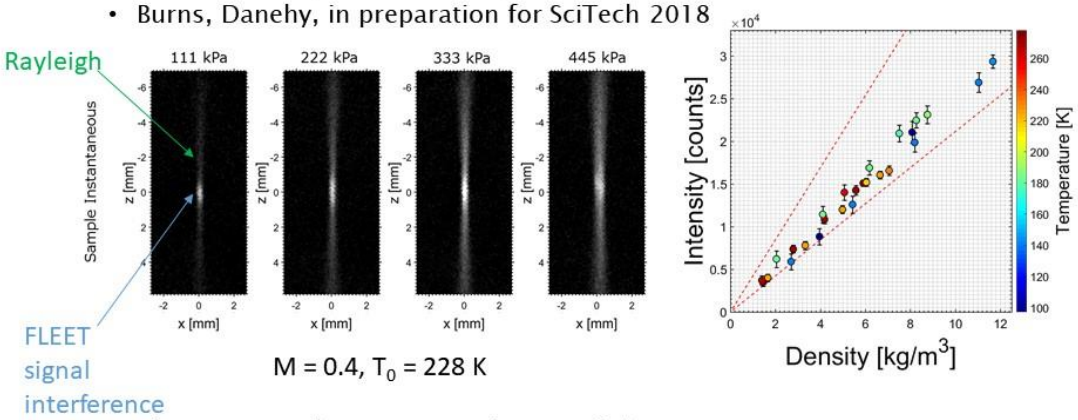
- Zero-velocity precision measured by taking velocity measurements in quiescent N_2 and calculating the standard deviation of the measured velocities
  - Wind-off precision: $\geq$ **0.4 m/s**
- Standard deviation of velocity measurements compared to wind-off values
  - Measurement precision consistently less than 1% of measured velocities
- Precision is maintained throughout facility operational envelope *except* when tunnel conditions approach the gas-vapor saturation point
  - N_2 condensation/residual droplets interfere with FLEET signal formation



28

Multi-parameter measurement: Density from Rayleigh scattering

- Using just 1 mJ/pulse at 800 nm we obtained instantaneous Rayleigh scattering line density measurements in 0.3 m TCT (EMCCD camera)
  - Simultaneous with FLEET velocimetry
  - Single-shot images over the full operational envelope of the facility
  - Measurement precision of ~6 percent
  - Burns, Danehy, in preparation for SciTech 2018



- Also see particle scattering when not fully on point: PIV?

8.4 ACTIVE OPTICAL SYSTEMS FOR AERONAUTICS

Ivan O. Clark, PhD

NASA Langley Research Center, USA, ivan.o.clark@nasa.gov

ABSTRACT

The use of active optical systems for various aspects of aeronautical research and of situation awareness has been included in many of the NASA and National Advisory Committee for Aeronautics (NACA) Aeronautics programs. A brief historical overview of these efforts highlight the subject matter expertise and other resources available to support on-going research and development as well as supporting the certification processes for incorporating these technologies in the National Air Space.

1 HISTORICAL BACKGROUND

The use of active optical systems for aeronautics began at the National Advisory Committee for Aeronautics Langley Memorial Aeronautical Laboratory in 1934 in the form of Schlieren imaging [1]. The system allowed the study of compressible flows through the transonic region [2]. This usage continued in NACA and NASA wind tunnels until it was superseded by newer point and planar flow measurement techniques. Development of Laser Doppler Velocimetry (LDV) began at multiple NASA centers in 1971. LDV measures 1, 2, or 3 component of air velocity at a point. By the mid-1980's, LDV techniques had evolved sufficiently to provide the basis for a successful proposal to a Commercialization of Space Announcement of Opportunity. The Chemical Vapor Deposition Facility for Reactor Characterization (CVDF) had the goal of developing a prototype facility for characterizing reactive flows in chemical vapor deposition (CVD) reactors under the reduced gravitational levels of the International Space Station (ISS). This represented a technology transfer from NASA's aeronautics area to space applications. It was soon found that the point measurement nature of LDV resulted in flow field measurement times that would be too long for ISS application. As a result, CVDF contributed to the start-up funding of Doppler Global Velocimetry (DGV), Particle Imaging Velocimetry (PIV), Laser Induced Fluorescence (LIF), and Holographic Inverse Lens (HIL). DGV measured 3 components of velocity in a plane, but the relatively slow flows of the CVDF were below the speed threshold for the technique. Early PIV measured 2 components of velocity in a plane. It successfully made flow measurements in a reactor in CVDF but the geometries and the hand-welded optics of the chamber limited the velocity planes that could be developed. Early LIF research did not identify a gas and laser combination appropriate for CVDF measurements. HIL attempted to develop holographic optics that could transform optical paths to effectively remove the glass walls of the CVDF reactors. The complexity of the CVD reactors was beyond the range of application for HIL at the time. DGV, PIV, and LIF all continue to find applications in NASA wind tunnels.

More recent Aeronautics programs applying active optics have included: Airborne Windshear Program, Aviation Safety Program (ASP) Weather Accident Prevention Project, ASP Integrated Intelligent Flight Deck Project, ASP Atmospheric Environment Safety Technologies Project, and Wake Vortex Field Measurement Program. Infrared coherent Doppler wind lidar has been investigated for microburst detection, wake vortex detection and assessment, turbulence detection and mitigation, flight path optimization, gust alleviation, and airport area winds measurements (including early info of wind shifts affecting runway selection). Ultraviolet direct Doppler lidars have been implemented as forward-looking Optical Air Data Systems for turbulence detection and mitigation, icing condition detection, and as an icing-tolerant alternative to the vanes and pitot tubes of the standard Air Data Systems. Hard target lidars have been evaluated as laser altimeters and for collision avoidance during ground operations. Flash lidar and active imaging systems have been investigated to enable visual-equivalent operations through obscurants and non-cooperative vehicle detection both in flight and on the ground. Multi-color lidar systems have been studied for volcanic ash detection, runway state detection, and detecting the boundary between visual meteorological conditions (VMC) and instrument meteorological conditions (IMC).

The Airborne Windshear Program, Aviation Safety Programs, and Wake Vortex Field Measurement Program sought to evolve and validate active optical systems in both active imaging and lidars to meet national needs for safe, efficient operations in the National Air Space (NAS). NASA Aeronautics has long had very limited resources to meet broad national needs. With the close out of the Aviation Programs and the Wake Vortex Program in 2015, these resources shifted away from in-flight and airdrome measurement capabilities to focus on other research areas.

Looking to future needs, the development of some active optical measurement capabilities have been fostered under the Small Business Innovative Research (SBIR) program. The size, weight, and power (SWAP), and cost of measurement systems are critical for successful commercialization of aeronautics applications and their implementation in the NAS. Active imaging work has included Laser Imaging Through Obscurants (LITO) that demonstrated the capability of enabling visual equivalent operations in white-out and in brown-out conditions. Lidar efforts have included: (1) the development of wind lidar prototypes as small as a Pringles can for real-time flight path optimization, (2) Optical Air Data Systems (OADS) the provide forward-looking 3D winds, temperature, and pressure, (3) flash lidars for near-field situation awareness, and (4) multi-frequency lidars for runway state and for boundary identification between Visual Meteorological Conditions and Instrument Meteorological Conditions.

2 RECENT AND CURRENT EFFORTS

At the conclusion of the Wake Vortex Field Measurement Program in Memphis, a coherent Doppler wind lidar and an instrumented meteorological tower became available for in-house research. At the same time a test range for Unmanned Airborne Vehicles (UAV) was established at LaRC. A concept referenced as Lidar Canopy began as an attempt to apply the former wake vortex systems to characterize the wind fields in the airdrome that includes the UAV test range. This would provide a similar level of quantitative flight tests as provided to researchers in the NASA wind tunnels. This concept has now been generalized as developing performance requirements for virtual meteorological towers for airdromes for Urban Air Mobility (UAM) operations.

Current and planned NAS operations are dependent upon the radio-frequency-based the Automatic Dependent Surveillance—Broadcast (ADS–B) system for maintaining separation between cooperative aircraft. The ADS-B system is subject to problems with increasing latency as aircraft densities become high. With the projected addition of tens of thousands of UAV to the NAS, the latency may rise to the point that the ADS-B system becomes inoperative. IRAD funding allowed an initial analysis of an optical beacon based system for optical communication between cooperative aircraft with validation of range and relative bearing.

As part of the Airborne Windshear Program, Aviation Safety Program (ASP) Weather Accident Prevention Project's Turbulence Detection and Warning effort, it was found that safety could be significantly improved by decreasing the effect of turbulence on transport aircraft by a factor of 2. At that point, people and carts would not become airborne in the cabin. It was found that modern transport aircraft had sufficient control authority to meet that factor of 2 reduction through active turbulence mitigation if the winds ahead could be accurately measured. Both Boeing and Airbus marketed their latest generation of aircraft with this turbulence mitigation capability. Unfortunately, the lack of a forward-looking wind measurement system has prevented the use of turbulence mitigation. At the request of industry, the RTCA SC-230 Airborne Weather Detection Systems has formed a new Working Group for "LIDAR Clear Air Turbulence detection and hazard estimation." This working group will seek to establish the Minimum Operating Performance Standards (MOPS) to enable active flight control for turbulence mitigation. LaRC is expecting to provide the working group's government technical representative

3 PROGRAMMATICS

With the reduction of in-house development of airborne measurement systems and their certification, has resulted in dwindling personnel resources due to non-replacement of researchers lost to attrition. Significant subject matter expert

resources still exist, but they are all at or nearing retirement eligibility.

4 PARTNERING

The LaRC Electromagnetics and Sensors Branch is actively seeking research partners through in-house collaborations such as CAS and through Space Act Agreements. Current external partnerships include the Federal Aviation Administration (FAA), the Department of Transportation (DoT) Virginia Tech Transportation Institute (VTTI), and the US Army.

5 CONCLUSIONS

NASA, NASA LaRC, and the Electromagnetics and Sensors Branch (ESB) have significant experience with active optical systems, ground-based and airborne testing, and certification processes. The limited resources available to the NASA Aeronautics area contributed to the phasing out of both the Aviation Safety Programs and the Wake Vortex Programs and the de-emphasis of research for airborne situation awareness. ESB is reaching out to establish new partnerships both internal and external to NASA.

References

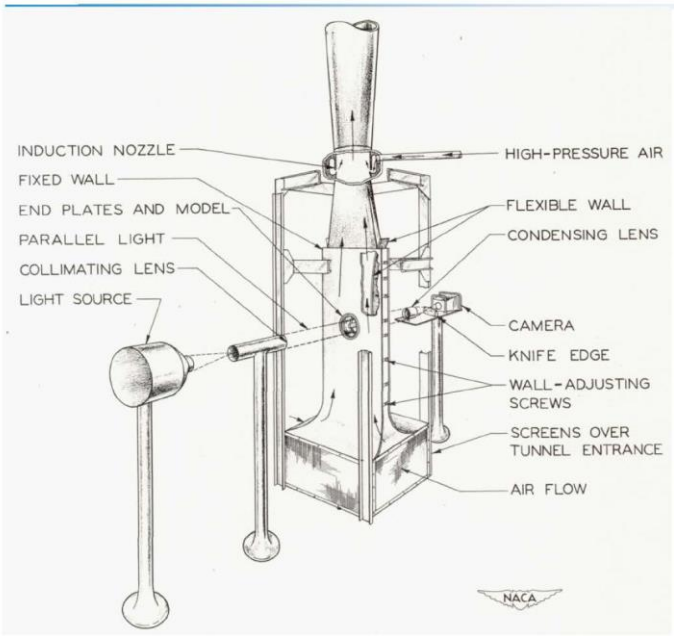
1. John D. Anderson, Jr., The Airplane: A History of Its Technology (Library of Flight), AIAA, 2003.
2. Bernard N. Daley and Milton D. Humphreys, Effects of Compressibility on the Flow Past Thick Airfoil Sections, NACA TN-1657, July 1948.

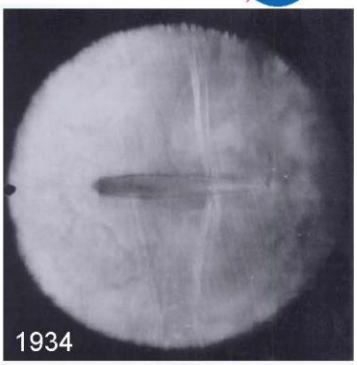
Active Optical Systems for Aeronautics

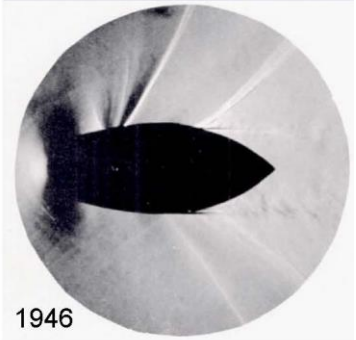
Ivan O Clark, PhD
NASA Langley Research Center, Hampton, VA



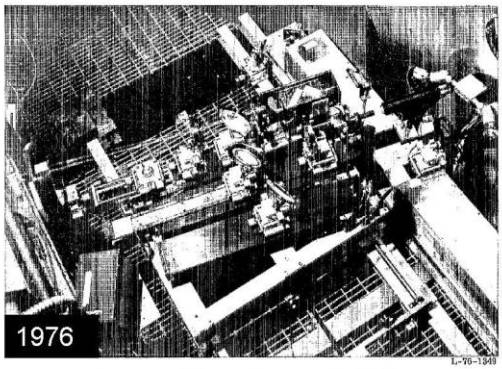
Early Active Optical Systems: Schlieren



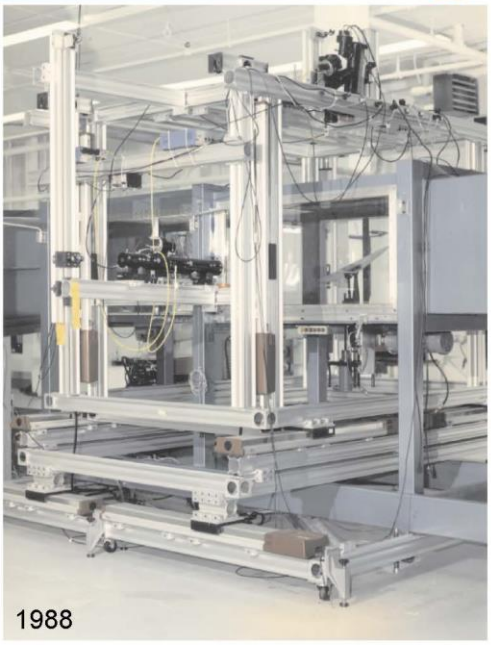




Early Active Optical Systems: Laser Doppler Velocimetry (LDV)



Laser Doppler Velocimetry (LDV)
- R&D initiated 1971
- Jointly demonstrated with Raman spectroscopy 1973
- Lasers also used for flow visualization



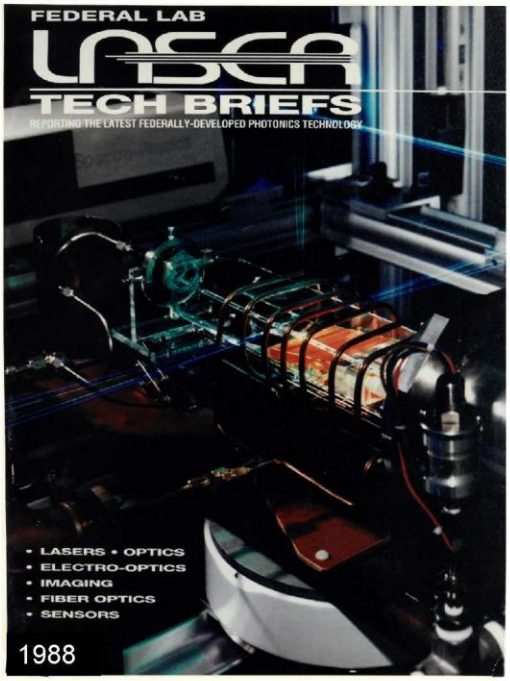
Early Active Optical Systems: Commercialization of Space

Chemical Vapor Deposition for Reactor Characterization (CVDF) selected for funding under Commercialization of Space Announcement of Opportunity

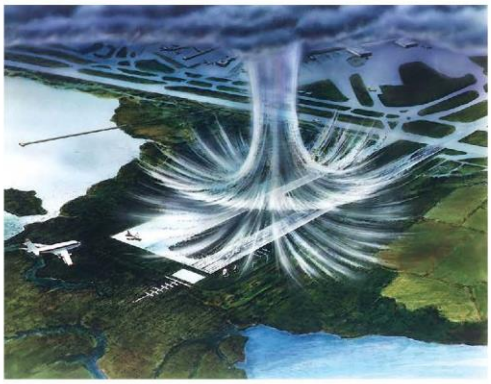
LDV-based prototype facility to measure reactive flow dynamics on International Space Station (ISS)

Technology transfer from Aero to Space

To overcome measurement challenges contributed to early development of:
- Doppler Global Velocimetry (DGV)
- Particle Imaging Velocimetry (PIV)
- Laser Imaging Fluorescence (LIF)
- Holographic inverse lensing



NASA/FAA Airborne Windshear Program 1986-92





NASA B-737 used for flight test validation 1991-1992
- Coherent lidar (2micron)
- Microwave radar (3cm, X-band)

X-band Doppler Weather Radar successfully validated for wet microbursts and mandated as equipage for transport-class aircraft

Coherent lidar encountered equipment problems and could not be validated
- No current detection-and-warning systems for dry microbursts

NASA Aviation Safety Programs 1998 - 2015

- **Weather Accident Prevention**
  - 1998 - 2004
  - Turbulence Detection
- **Integrated Intelligent Flight Deck**
  - 2005 - 2010
  - Lidar & Electro-Optics
- **Atmospheric Environment Safety Technologies**
  - 2010 - 2015
  - Lidar & Electro-Optics

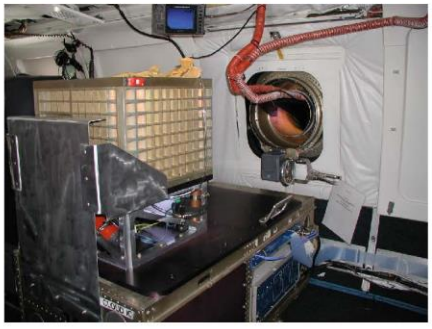
Aviation Safety Turbulence Detection
NASA DC-8 with Lidar Periscope

1998 – 2004 Turbulence Detection
Coherent 2um Lidar - 3 flight campaigns



Aviation Safety Turbulence Detection
ACLAIM 2um Coherent Lidar Installation



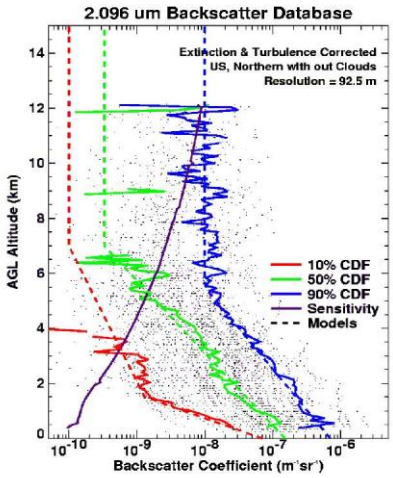


- 163 Flight Hours
  - CAMEX-4 piggy-back
  - Cold Land Processes Experiment (CLPX) piggy-back
  - Large Coastal Eddies piggy-back
  - ACLAIM dedicated flight (CA mountains)
- Demonstrated Clear Air Turbulence (CAT) Detection
- Provided Clear Air Backscatter Measurements at Altitude

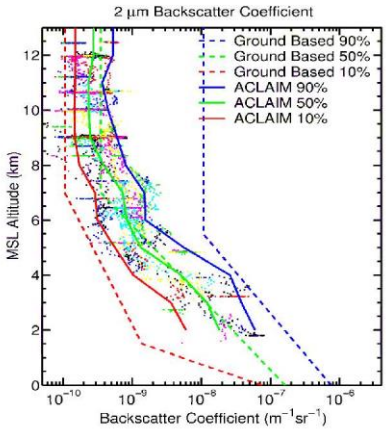
Atmospheric Aerosol Backscatter for Clear Air: Previous Database and CAMEX ACLAIM

Aviation Safety Program

- Ground database collected 1995-96 in continental US
- High altitude 50% profile derived from 1.06m GLOBE measurements

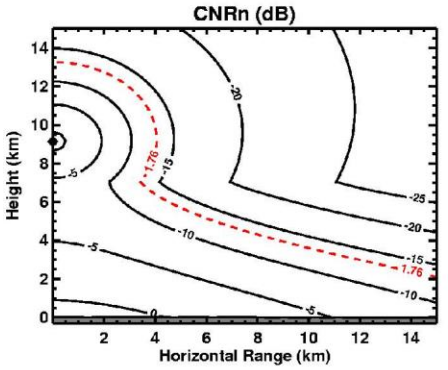


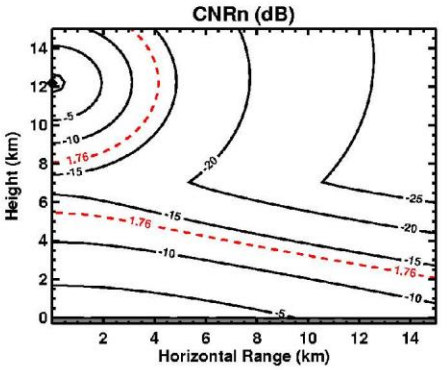
- CAMEX-4 ACLAIM database
- Forward-looking, clear-air only
- 3600 discrete samples of 5 seconds each
- Consistent with ground-based measurements



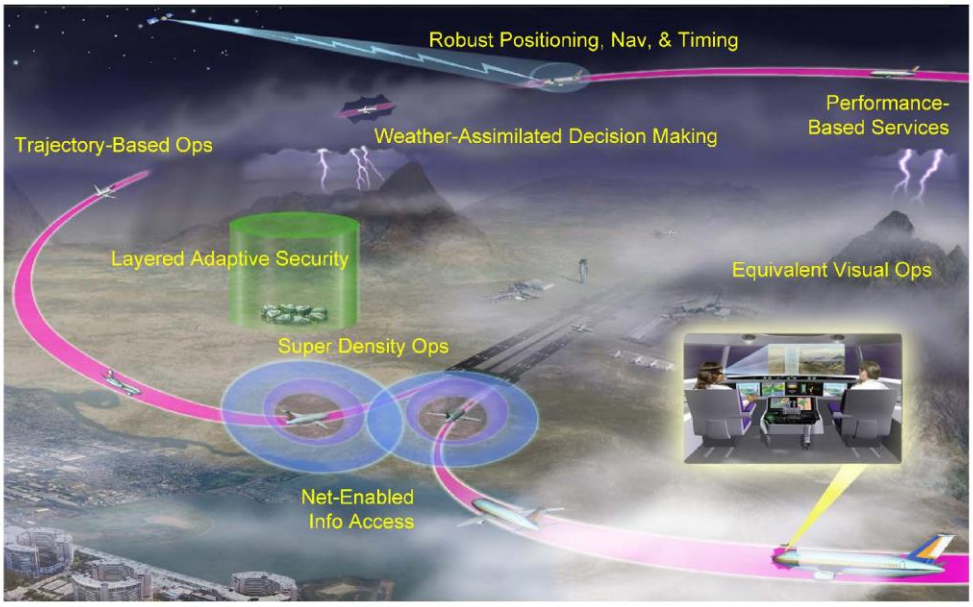
Range vs. Altitude Performance Predictions: Low (Eye-Safe) Laser Power - 1000 Pulse Averaging

CNR and maximum range (FOM = $\sqrt{N}CNRn$ = 1.76 dB) for 1000 pulse averages at a 30 kft platform (left) and 40 kft platform (right)





NASA Aviation Safety Programs 2005 - 2015
Application Domain – NextGen



NextGen's Key Capabilities, from "Operational Concept for the Next Generation Air Transportation System (NextGen)," Version 2.0, JPDO, June 13, 2007



Aviation Safety Program 2005 - 2015
Lidar & Electro-Optics (LEO) Element Purpose

Improve Aviation Safety Through Enhanced Situation Awareness

- **Preventing or Mitigating Loss of Situation Awareness**
  - Low visibility conditions
  - Icing
- **Providing New or Enhanced Situation Awareness**
  - Kinetic air hazards
    - wake vortices
    - turbulence
    - mountain rotors
    - microbursts / windshear
  - Geospatial location
    - CFIT avoidance
    - validation of on-board geospatial databases
  - Volcanic ash
- **Address the Needs of the Next Generation Airspace Transportation System**
  - Air transport class aircraft
  - Business jet class aircraft

LEO Approach

- **Apply evolving technologies to address prioritized aviation hazards**
  - Evaluate state of sensor technology versus aviation hazards
  - Down select a Hazard-Sensor matrix for further effort based on:
    - hazard priority
    - sensor suitability (including probable airworthiness)
    - budget constraints
- **Current efforts include:**
  - Passive imaging for:
    - kinetic air hazards (multi- & hyper-spectral)
    - surface runway state (hyper-spectral)
    - reduced visibility operation (hyper-spectral)
  - Active imaging for:
    - reduced visibility operation
  - Lidar for:
    - kinetic air hazards
    - optical air data systems
    - volcanic ash

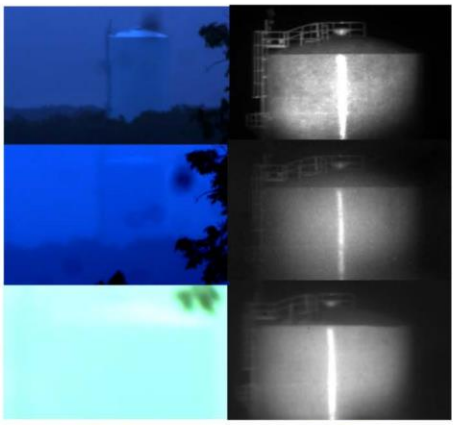
	HAZARDS								
Sensors	A	B	C	D	E	F	G	H	I
Passive Imaging	■			■			■		
Active Imaging			■				■		
LIDAR		■				■			
Other					■			■	■

Goal:
compact, low power consumption, multi-function sensor capability for enhanced situation awareness and hazard mitigation

Active Imaging for Visual-Equivalent Operations

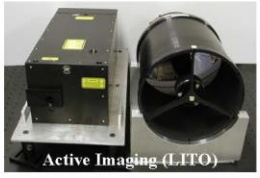
Laser Imaging Through Obscurants (LITO)

- Reduced Visibility Operations
  - Fog
  - Rain
  - Snow
  - Brown-Out
- Icing
  - Obscurant Identification
- Volcanic Ash
  - Obscurant Identification
- Experimental validation and numerical modeling
  - RL Associates, Inc. (SBIR Phase 3)



Imaging Through fog at the Army's Precision Armaments Lab





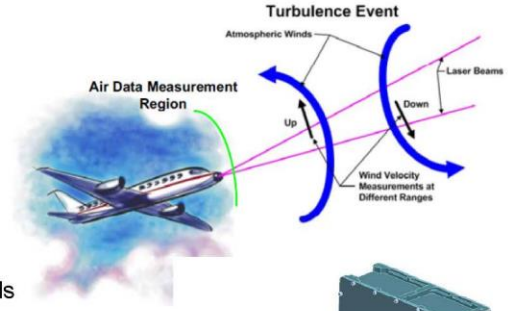
Doppler LIDAR for Aviation Safety

Hazards

- Kinetic Air Hazards
  - Turbulence (mitigation (M))
  - Wake Vortices
    - Terminal Area (avoidance (A))
    - En Route (A, M, utilization (U))
  - Dry Wind Shear (A, M)
- Icing (A, M)

Efforts

- Fiber Laser Coherent Doppler for Kinetic Air
  - Fibertech, Inc (SBIR Phase 3)
- Low-Cost Lidar for Wake-Vortex & Other Hazards
  - Q-Peak, Inc (SBIR Phase 2)
- High Energy Fiber Amplifier for Coherent Doppler for Turb
  - Sibell Optics (SBIR Phase 1)
- OADS & Kinetic Air by Direct Doppler
  - Ophir Corporation (SBIR Phase 2)
- OADS & CAT Sensor by Direct Doppler
  - Michigan Aerospace Corporation (SBIR Phase 2)
- OADS & Icing
  - Michigan Aerospace Corporation (SBIR Phase 1)
- Numerical Modeling
  - Aerospace Innovations (Wake Vortex NRA)
  - In-House
- Ground and Flight Validation of Doppler Lidar for Kinetic Air
  - In-House





Fiber-optic Coherent Lidar sub-systems

Fiber Laser Coherent (FILCO) Lidar Hardware



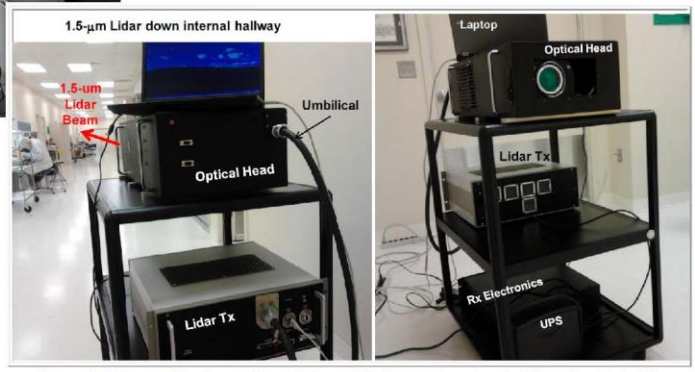


Figure 1. Coherent Fiber-Laser Lidar at 1.5-μm (*left*) showing the set-up for lidar calibration inside Fibertek's lab hallway, and (*right*) lidar operator view of the instrument.

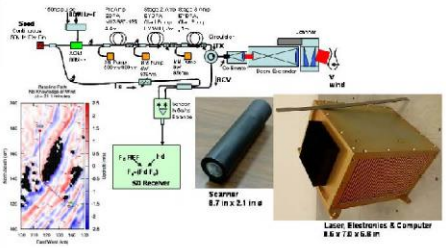
NASA SBIR/STTR Technologies

S3.04-9526 - Miniature UAV Wind LIDAR & Flight Extension System

PI: Bradley Sallee
Systems & Processes Engineering Corp - Austin, TX

Identification and Significance of Innovation

Systems & Processes Engineering Corporation and Texas A&M University propose a Wind Measurement LIDAR System for extending the flight duration or decreasing fuel consumption on UAVs and light aircraft. The system uses a fiber optic based, eye-safe wind LIDAR from another NASA effort, combined with previous software studies on an Army program to yield a system capable of increasing fuel economy by up to 20% by optimally moving control surfaces in response to thermals and wind gusts, seen by the wind LIDAR. The system also plots the optimum course through thermals and wind gust for maximum dwell time or fuel economy. The sensor assembly is composed of a wind LIDAR using fiber optic transceiver operating at eye-safe1550nm. This LIDAR allows air current Doppler detection beyond 3km and fine range resolution by using pulse compression. The LIDAR was sized to detect energy sources, vertical uplifts, wind direction, wind gradients and transient gusts, for energy conservation in UAVs.



Estimated TRL at beginning and end of contract: (Begin: 4 End: 5)

Technical Objectives and Work Plan

The principal objectives of the Phase I work are: to collect the detailed system requirements for the Wind Measurement LIDAR System for fuel saving, loiter and soaring applications. System level performance analysis in all weather conditions with the scenarios of interest will be performed for the LIDAR. Doppler image processing algorithms. A coherent laser transceiver assembly with Doppler capability will and computational capability for flight path optimization software will demonstrate wind current Doppler capability. Flight path optimization algorithms will be further refined and coded for real time application. The LIDAR capability demonstration and algorithm demonstration will prove feasibility of the concept needed for further investment.

NASA Applications

The wind measurements LIDAR System can be used for optimal flight path for energy conservation, soaring and extended dwell time for UAVs. Itcan be used for measurement systems on a variety of unmanned aircraft. It can be used in programs like 3D-WINDS. The system is small enough so that with radiation hardening, it can be used in various planetary missions

Non-NASA Applications

Commercial applications include air turbulence sensing for commercial aircraft. Other applications, studied in past programs, are using the wind LIDAR to determine an optimal path for maximum fuel economy and/or station keeping for UAVs and aircraft.

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FAX: (512) 494-0756

NON-PROPRIETARY DATA

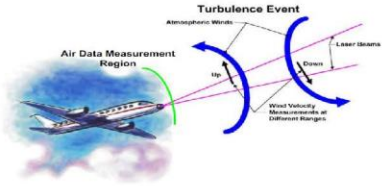
NASA SBIR/STTR Technologies

A1.04-9528 - Multifunction Lidar for Air Data and Kinetic Air Hazard Measurement

PI: Loren Caldwell
Ophir Corp - Littleton, CO

Identification and Significance of Innovation

The significance of this proposed work is the capability to provide a single sensor that has multiple use functionality including air data measurement, turbulence and wind hazard detection and ride comfort enhancement, all in a lightweight, low cost lidar. Conventional air data systems provide critical information to the aircraft for safe flight. However, there are vulnerabilities to the conventional Pilot-static systems, as evidenced by the recent Air France catastrophe. A more robust air data system for flight controls on aircraft is needed, particularly to measure airspeed in icing and hazardous weather conditions. The proposed lidar system also measures airspeed ahead of the aircraft in order to measure kinetic wind hazards such as turbulence and wind shear. Range-resolved wind measurements provided by the lidar hardware can be used to enhance aircraft ride stability, improving passenger comfort and reducing stresses on the airframe.



Estimated TRL at beginning and end of contract: (Begin: 3 End: 5)

Technical Objectives and Work Plan

The Technical Objectives of this proposed project include: to design, assemble and test a multifunction lidar capable of providing atmospheric measurement of temperature, pressure and velocity, and the 3D wind fields ahead of the aircraft; to complete a Proof-of-Capability test to demonstrate lidar air data measurement capabilities in a controlled environment; and to perform Proof-of-Functionality testing of a multifunction lidar from a flight test platform.

The Work Plan consists of the following tasks:

Task 1: Finalize the Phase II prototype multifunction lidar design.
Task 2: Assemble, laboratory test and calibrate the prototype lidar.
Task 3: Proof-of-Capability lab testing.
Task 4: Algorithm development for velocity retrievals.
Task 5: Phase II prototype flight packaging.
Task 6: TRL 5 multifunction lidar prototype flight demonstration.
Task 7: Final report and data analysis.

NASA Applications

Airspace transformation to NextGen may be significantly safer by providing additional information for supplemental air data measurement and kinetic air hazard detection. NASA has pioneered many innovations and improvements for wind hazard detection, warning and forecasting (TPAWS, AWIN). This innovation provides wind hazard measurement resulting in real-time information for air traffic operations and a redundant air data capability for increased, in-flight safety.

Non-NASA Applications

The markets addressed by this multifunction sensor development are the unmanned and manned military and commercial aircraft markets. This sensor may also be used by the regional jet market and by the Air Force for new aircraft flight testing and calibration.

Firm Contacts Loren Caldwell
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10184 West Belleview Avenue, Suite 200
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FAX: (303) 933-1430

NON-PROPRIETARY DATA

NASA SBIR/STTR Technologies

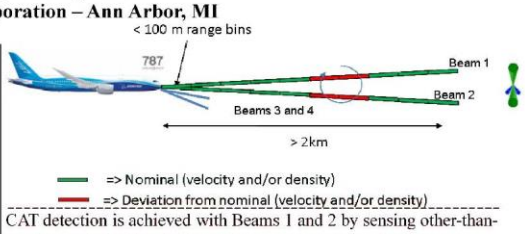
09-2 A1.04-9447 – Molecular Air Data Clear Air Turbulence Sensor: MADCAT
Phase 1 Contract #NNX10CE68P

PI: Dr. Dominique Fourguette
Michigan Aerospace Corporation – Ann Arbor, MI

Identification and Significance of Innovation:

- Clear Air Turbulence (CAT) is a significant air safety and passenger comfort issue.
- MADCAT will extend an existing optical air data system design to sense CAT for warning purposes.
- Michigan Aerospace uses direct-detection ultraviolet Doppler LIDAR that works in clear air using molecular backscatter and is eye safe.

Expected TRL Range at the end of Contract (1-9): 5



CAT detection is achieved with Beams 1 and 2 by sensing other-than-nominal velocity/density in some range bins compared to the rest. Beams 3 and 4 provide air data.

Technical Objectives and Work Plan

Technical Objectives:

1. Establish final MADCAT technical specifications.
2. Fabricate and test an engineering model of MADCAT.
3. Recommend a final design for testing on an airborne platform.

Work Plan tasks:

1. Finalize MADCAT design specifications.
2. Design and fabricate a MADCAT engineering model.
3. Further develop algorithms necessary to process MADCAT data.
4. Design engineering model test program.
5. Run engineering model tests.
6. Draw up recommendations for MADCAT prototype design suitable for airborne testing.

NASA and Non-NASA Applications

NASA: Turbulence detection for both warning and research purposes, with optical air data system capability.

Non-NASA: Commercial and military aircraft turbulence warning with optical air data system capability. Technology can be applied to turbulence warning and wind mapping for ground applications, such as for wind farms and military artillery and other fire-control activities.

Contacts:

Technical: Dr. Dominique Fourguette
(734) 975-8777 x114; dfourguette@michaero.com
Administrative: Dr. Robert Sampson, CEO
(734) 975-8777 x115; rsampson@michaero.com

NON-PROPRIETARY DATA

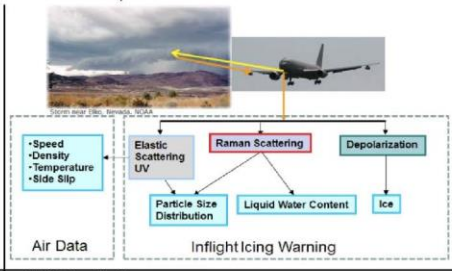
NASA SBIR/STTR Technologies

A1.01-9814 - RIDES: Raman Icing Detection System

PI: Charles Richey
Michigan Aerospace Corporation - Ann Arbor, MI

Identification and Significance of Innovation

Michigan Aerospace Corporation proposes to develop an integrated LIDAR instrument capable of identifying icing conditions while also providing air data sensing capabilities. The resulting Raman Icing Detection System (RIDES) will be an integrated air data sensing and icing condition detection instrument, providing a backup to the Pitot tubes potentially affected by icing, thus providing redundancy for critical information. The proposed solution will operate without protrusions into the flow, behind a flush mounted window on the skin of the aircraft, mitigating the risk of ice build-up during operation.



Estimated TRL at beginning and end of contract: (Begin: 3 End: 4)

Technical Objectives and Work Plan

Technical Objectives:
--1. Determine the operational envelope of the sensor and the resulting requirements.
--2. Perform trade studies and photon budgets using models to determine the design parameters of the instrument.
--3. Design the instrument for fabrication in Phase II.
--4. Algorithm development for droplet size distribution.

Work Plan:
--Task 1: Requirements Analysis
--Task 2: Sensor Performance Trades and Modeling
--Task 3: Instrument Design
--Task 4: Sensing Algorithm Work
--Task 5: Demonstration Plan for Phase II
--Task 6 (ongoing): Management (Reporting and risk assessment)

NASA Applications

The system resulting from this effort will allow better studies of icing by giving clearer indications of the actual conditions outside a test aircraft in real time, providing safer and more accurate means of studying icing conditions.

Non-NASA Applications

Military and civil aviation is often affected by icing, sometimes severely, and the ability to detect these conditions so as to avoid or at least account for them (activating de-icing systems, etc.) would be of tremendous safety value. Combining the system with an optical turbulence detection and air-data system would result in a robust optical-based sensor suite for modern aircraft.

Firm Contacts

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FAX: (734) 975-0239

NON-PROPRIETARY DATA

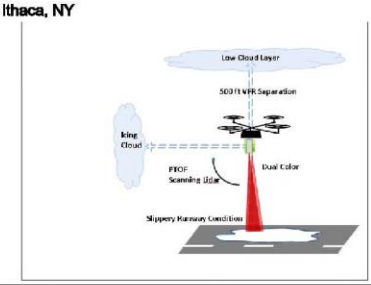
NASA SBIR/STTR Technologies

A3.02-8717 - Aircraft Weather Hazard Management LIDAR for Take-off and Landing Safety

PI: Joseph Gerardi
Innovative Dynamics, Inc. - Ithaca, NY

Identification and Significance of Innovation

There is a need for technologies focused on increasing the efficiency and safety of UAV operations for the first and last 50 feet, and under diverse weather conditions. Small UAV's and rotorcraft are not typically equipped for icing avoidance or all-weather operation. Current aircraft weather radar that operate at X-band (8-12 GHz) have limited ability to help pilots detect and quantify icing potential. Use of LIDAR technology for ice/snow avoidance could significantly expand the mission envelope of aircraft during cold weather operations.IDI is proposing development of a multi-channel 3D LIDAR that will identify both cloud layers and surface hazard information for UAV's. Key to the innovation is incorporation of water absorption wavelengths chosen to identify both cloud layer properties and runway surface contaminates - up to a 1 mile radius from the aircraft. Also significant is the capability for an unmanned aircraft to identify its surroundings both on the ground and in the air for snow and icing hazards prior to take off that's typically done visually by pilots in the cockpit.



Estimated TRL at beginning and end of contract: (Begin: 4 End: 5)

Technical Objectives and Work Plan

The overall objective is to develop a low cost miniaturize LIDAR for determination of short range weather related hazards that occur during aircraft takeoff and landing segments posed by ice, water, slush and low altitude icing cloud layers. Incorporation of key water absorption laser wavelengths and polarization signal processing with PTOF LIDAR electronics allow for this innovation. The LIDAR would be integrated with existing UAV's to allow a 360 degree scanning configuration with the capability to detect local icing cloud layers and runway surface hazards, as well as normal obstacles. The proposed system will provide the UAV capability to identify weather related hazards in its immediate surroundings.Test objectives include collecting representative environmental data with a LIDAR prototype unit to measure FAA Appendix C cloud liquid water content, as well as runway surface contaminates using the same LIDAR hardware. Specific Phase I objectives include:

- Develop Requirements for a miniature Optical LIDAR Sensor to identifyweather related hazards in the immediate vicinity of the aircraft.
- Build/Package miniaturized LIDAR hardware prototype.
- Development of data accquisition software and LabView simulation tools tostore and process laser backscatter measurements from the LIDAR.
- Proof of Concept testing of prototype LIDAR hardware in a laboratory cloud chamber

NASA Applications

The proposed 3D LIDAR sensor will provide icing cloud imaging and ranging information for NASA's all weather UAV operations both in-flight and during take-off and landings. The LIDAR will identify cloud layer location at night to allow safe separation distances from icing clouds and identify clearings for safe decent and landing. The LIDAR also has the capability for ground obstacle avoidance and detecting hazardous surface conditions such as black ice that require increased stopping distance.

Non-NASA Applications

The proposed compact LIDAR instrument will have widespread application to aircraft that do not currently have certified on-board ice protection equipment, such as police, air ambulance, and search and rescue helicopters. The proposed LIDAR will augment standard cockpit radars and provide a new capability to locate hazardous icing cloud layers that are currently invisible to weather Radar.

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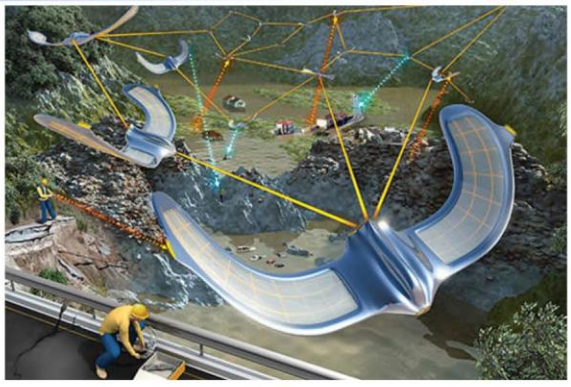
FAX: (607) 257-0516

NON-PROPRIETARY DATA

Optical Beacons for Communications & Cooperative Range & Bearing





2017 IRAD Time-Synchronized Beacons for Relative UAV Position Determination

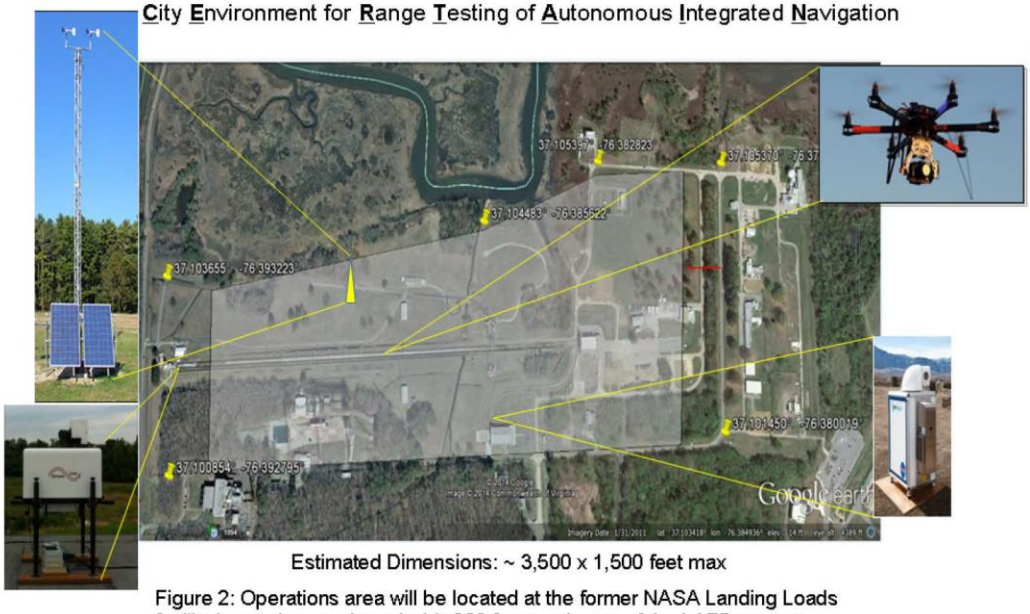
- Optical communications implementation of ADS-B
- Imaging provides relative bearings
- Time synchronization of beacons provides ranging

Memphis Wake Vortex Field Experiment – 2013 - 2015



Lidar Canopy – Airdrome Winds Characterization

City Environment for Range Testing of Autonomous Integrated Navigation



Estimated Dimensions: ~ 3,500 x 1,500 feet max

Figure 2: Operations area will be located at the former NASA Landing Loads facility located approximately 11, 000 feet northwest of the LAFB runway.

FAA Certification Support

- RTCA SC-230 Airborne Weather Detection Systems
- New Working Group forming:
  - LIDAR Clear Air Turbulence detection and hazard estimation
  - Seeks to enable active flight control for turbulence mitigation
  - LaRC providing government technical representative



Closing Remarks

- NASA Langley Research Center has broad experience in airborne and ground-based applications of active optical systems for airspace applications
- With end of Aviation Safety Programs, in-house efforts for aeronautics sensors has been de-emphasized
- NASA Aeronautics a very small portion of NASA budget
- Civil service expertise in active optical systems lost to attrition is not being replaced
- Seeking partners for collaborative efforts

Questions



8.5 SAMI, THE SCIFLI AIRBORNE MULTISPECTRAL IMAGER: AN AIRBORNE PLATFORM TO SUPPORT DEVELOPMENT AND TESTING OF ACTIVE OPTICAL COMPONENTS AND SENSORS

Richard J. Schwartz[1], Carey F. Scott[2], Meaghan L. McCleary[3]

[1]AMA Inc, Hampton VA, richard.j.schwartz@NASA.gov,
[2]AMA Inc, Hampton VA, [3]Iowa State University

ABSTRACT

Advanced active optical components under development will require testing and validation prior to becoming operational elements in future adaptive sensors. The Scientifically Calibrated In-Flight Imagery (SCIFLI) team is developing SAMI, the SCIFLI Airborne Multispectral Imager, a platform to provide capabilities beyond heritage remote airborne observations of flight-test vehicles. As such, SAMI can act as a highly flexible test bed for advanced active optical components or complete sensor packages slated for airborne or space applications.

1 INTRODUCTION

The Scientifically Calibrated In- Flight Imagery (SCIFLI) team is developing SAMI, the SCIFLI Airborne Multispectral Imager to be an airborne optical platform capable of obtaining calibrated thermal, visual, and spectral data. A Phase II-X SBIR (Small Business Innovation Research) to OKSI Inc. in Los Angeles, CA, funds this effort. While the platform can be placed in a variety of aircraft, it is being designed for the NASA LaRC C-20 (Gulfstream III). The Research Support Directorate (RSD) at LaRC will bring this aircraft on line in 2018. SAMI is an outgrowth of a joint NASA / DoD effort to develop an automated airborne optical platform for use on the NASA Global Hawk aircraft. While SAMI is being designed for human-in-the-loop operation on crewed aircraft, it will contain similar state-of-the-art optics, tracking software, and a modular design that will allow researchers to quickly and easily change out optical components to meet mission requirements. As such, SAMI will be able to acquire multiple channels of data from different sensors simultaneously along multiple optical paths originating from the telescope. Each of those optical paths may be configured uniquely, providing a flexible platform for testing prototype optical components. This can include adaptive or actively actuated elements. While SAMI's primary role will be to provide an operational capability for airborne observations of flight tests, typically the schedule and frequency of such flight-testing would allow time for the system to be utilized as a testbed for a variety of different optical components and cameras. In this role, SAMI should prove to be valuable for testing prototype components in flight in a shirtsleeve environment, where the flight profile can be tailored to meet the needs of the sensor.

2 RATIONALE FOR SAMI

Traditionally, the SCIFLI team has conducted airborne and ground based observations of flight test vehicles through the use of contracted optical platforms. These have included the US Navy P-3 Cast Glance, the high altitude NASA WB-57 (Figure 1), and ground based systems from MARS Scientific. Each of these asset providers have a long and successful record in obtaining high resolution calibrated thermal and visual imagery for SCIFLI (and its predecessor, HYTHIRM)[1]. However, the airborne platforms have historically been expensive to deploy, and given the dynamic scheduling that arises with flight-testing and spaceflight, there have been challenges in ensuring the asset's availability. Also, each platform possesses attributes that are critical to some, but not all, missions. In the case of the P-3, the aircraft has a long range and up to 11 hours of endurance, while the WB-57 can attain altitudes in excess of 50K feet.



a. *b.*

Figure 1. a - US Navy Cast Glance, b- NASA WB-57 aircraft

The observations conducted by these platforms have delivered calibrated thermal and visual data dating back to the Space Shuttle (Figure 2) and EFT-1 missions [2]. SCIFLI is now focusing on future observations of the NASA Space Launch System (SLS), Orion Multi-Purpose Crew Vehicle, and emerging commercial and DOD vehicles.

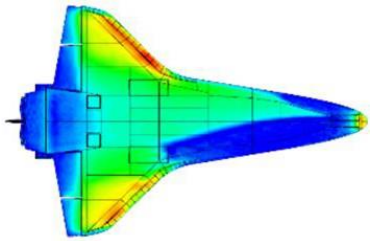


Figure 2. Calibrated thermal imagery acquired during the Space Shuttle Program from the US Navy Cast Glance aircraft mapped to a Computational Fluid Dynamics mesh.

The SCIFLI team has found that while these platforms fill unique niches and will remain highly valuable assets, a lower cost, smaller airborne platform based on the recently acquired NASA LaRC C-20 (Gulfstream III) can provide a capable, more economical, and easier to schedule platform. NASA will bring the aircraft on line as a research platform in 2018. SAMI is scheduled to be ready to fly by late 2019.

3 SAMI DESIGN CONCEPT

The SAMI design is currently in its early phases and is evolving to meet the mission demands, cost constraints, and physical limitations imposed by the aircraft. There are currently two competing concepts for the design of the telescope.

3.1 STEERING MIRROR

This design would place all of the optics on a fixed optical bench solidly mounted to the aircraft (Figure 3). A steering mirror would control the pointing of the telescope. The steering mirror is a large, highly precise element that can pan and tilt to direct the incoming photons to the telescope. This type of design has been successfully implemented for telescopes used on airborne platforms such as the US Navy Cast Glance and the L-3 HALO (High Altitude Observatory) aircraft. Key aspects include:

- Mostly off-the-shelf components (can use existing controls from CDI or SRI)
- Very robust concept (same as HALO-I and Cast Glance)
- Steering mirror cost may be prohibitive (8" may be the cost limit for SAMI)

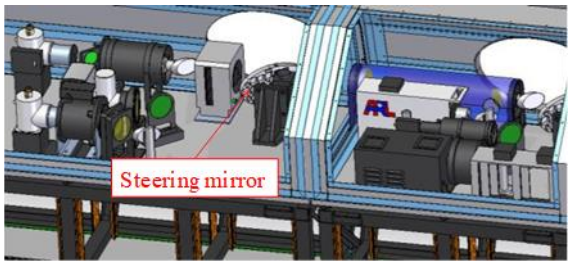


Figure 3. Layout of steering mirror telescope design

3.2 CENTER PIVOT GIMBAL (CPG)

The second concept for SAMI is to use a CPG mount. The CPG is a pedestal that can rotate and pivot to point the entire optical bench at the target (Figure 4).



Figure 4. Layout of telescope and optical bench on the Center Pivot Gimbal system, shown from an earlier concept on aircraft with smaller round windows.

Using the CPG has the advantage of having a larger aperture without the need for an expensive steering mirror and obtaining more stable, high-quality imagery. The CPG mount is a proven off-the-shelf component that has been used in programs such as the OH-58 (Figure 5).



Figure 5. Application of CPG mount above rotor on OH-58 helicopter

To expand the field of regard and take full advantage of the oval shaped C-20 window, the CPG would need to be placed on a horizontally translating sliding stage, which would make the system unique. Key aspects of this system include:

- Numerous off the shelf components
- Avoids expensive steering mirror, as the cost grows exponentially with steering mirror diameter
- Will require a translating base to achieve FOR and aperture requirements (cost goes up, elegance goes down)
- Would be a system with unique design and capabilities, but at some elevated risk level.

3.3 SAMI TRACKING SYSTEM

As mentioned in the introduction, SAMI is being developed as an offshoot of work for the DoD on an autonomous telescope system to be placed in the NASA Global Hawk aircraft. Under that program, a robust, fully autonomous tracking system is under development. This will allow the imaging platform to acquire a target at long range using a Wide Field Of View (WFOV) infrared sensor which will then point a Narrow Field of View (NFOV) calibrated science sensor to obtain the high-resolution imagery or spectral data.

SAMI will use a variant of this software which will provide autonomous tracking, but also allow the operator on the aircraft to have manual override should the tracking software require adjustment during the observation. Features such as automatic exposure control are envisioned to be part of the software.

3.4 CURRENTLY PROPOSED SAMI SENSORS

The following table lists proposed sensors that will meet immediate SCIFLI mission requirements. Additional sensors may be added based on future mission needs.

Table 3-1. Potential sensors for SAMI.

Channel	Camera	X Pixels	Y Pixels	FOV, deg
UV-Vis	Color	1900	1200	0.319
NIR	Near	1900	1200	0.319
SWIR	Shortwave	1280	1024	0.367
MWIR	Midwave	1280	1024	0.440
MWIR	Wide field	1280	1024	2.934
NIR	Near infrared	3200	2400	0.413
NIR	Wide field	1920	1200	1.595
UV-Vis	Spectrometer	30	30	0.172

3.5 APPLICATIONS AS A TESTBED FOR ACTIVE OPTICS

As envisioned SAMI could be a robust flying test platform for a variety of different active optical components. Multispectral filters, focus correcting adaptive optics, sensors with unique material properties, and more can be tested in a flight environment observing real-world targets.

As the SAMI design evolves, the SCIFLI team is looking for feedback on features that would make SAMI attractive as a testbed for active optics. It is obvious that the final platform will need to be highly configurable. It may need to provide power, light blocks, cooling, or other elements to support active optics. By gaining an understanding of what the user community requires early in the process, consideration can be given to incorporating these features in the system before the need for costly changes develops.

4 NASA LaRC C-20 AIRCRAFT

NASA LaRC has recently acquired a former USAF C-20 aircraft, a military personnel transport derived from the Gulfstream III business jet. The aircraft interior passenger compartment will have most accoutrements removed to serve as a research platform.

Aircraft performance characteristics are:
- Speed: 576 mph
- Range: 4,250 miles
- Ceiling: 45,000 ft
- Nominal Load: 12 passengers



Figure 6. NASA LaRC C-20 aircraft

The SCIFLI team has been able to obtain a sapphire window large enough to fit the entire C-20 oval shaped window portal. NASA Armstrong Flight Research Center (AFRC) has developed a window frame for scientific grade windows for the C-20. SCIFLI will be able to leverage off this design work.



Figure 6. a – CAD representation of window frame for scientific grade glazing, b – installed configuration on AFRC C-20

5 FUTURE DIRECTIONS FOR SAMI

The baseline SAMI system will meet the immediate needs of the SCIFLI team as a cost-efficient platform to gather calibrated thermal, spectral, and visual data of flight test vehicles. However, it is envisioned that SAMI will continue to evolve to maintain its status as a state- of-the-art airborne platform.Future enhancements may include the use of active optics for enhanced image clarity and resolution. Additionally, payload directed flight will allow SAMI's tracking computer to communicate with the aircraft autopilot. Algorithms will determine the optimum aircraft orientation during an observation. As sensors continue to improve they will be evaluated for incorporation into the suite of components available. It is also possible that some of the tested active optical components will become part of the standard suite of SAMI components if they support the primary role as on observation platform. In addition, while not directly tied to SAMI, it is desirable to look for an airborne upward looking LIDAR system to be able to take atmospheric measurements while simultaneously conducting the optical observation. One such system under development is HALAS by Michigan Aerospace.

6 A HOLISTIC ENVIRONMENT

NASA LaRC maintains a suite of facilities and capabilities that can serve researchers. A holistic approach to develop active optics can include the support of the Advanced Measurement and Data Systems Branch (AMDSB) for material science expertise, clean room fabrication, and element testing. The SCIFLI team can provide an operational airborne platform for mounting complete prototype components, and the Research Sciences Directorate can provide the airborne platform, such as the C-20 or potentially other NASA aircraft.

7 CONCLUSIONS

SAMI is slated to become an operational capability at NASA LaRC in late 2019. The baseline telescope will provide a new, in-house NASA capability for airborne observation of flight test vehicles. It will do so with state-of-the-art optical components, and will be from ¼ to ½ the cost of specialized aircraft from other organizations. With an eye toward expanding SAMI's return on investment and providing a new capability to the Agency, it is envisioned that SAMI could be a testbed for a variety of different advanced active optical components. SAMI may also be able to take advantage of some of this technology. The SCIFLI team is looking for feedback from the community to understand what requirements are desired for such a flying testbed in order to incorporate those into the early design of the system.

ACKNOWLEDGEMENTS

Many thanks go to the members of the immediate and extended HYTHIRM / SCIFLI team, OKSI Inc, and the US Navy Cast Glance, VX-30, and NASA WB-57 organizations.

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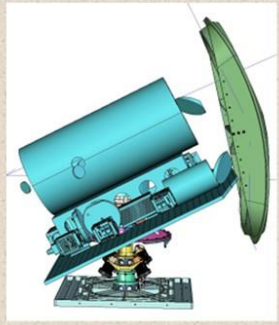
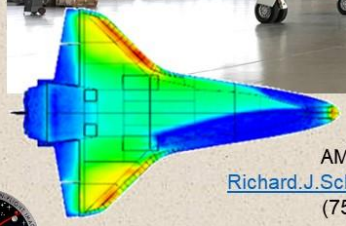
SAMI, the SCIFLI Airborne Multispectral Imager: An Airborne Platform to Support Development and Testing of Active Optical Components and Sensors







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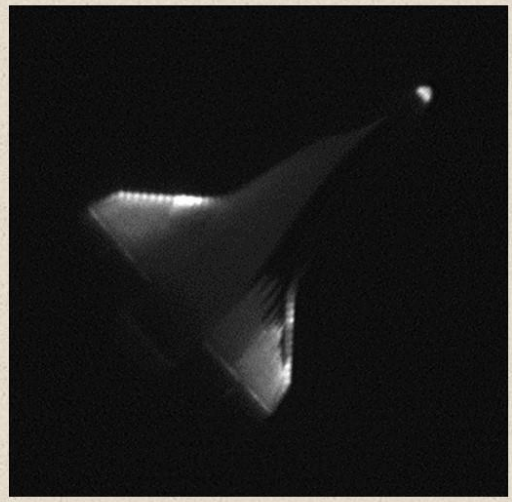
Introduction

1. What is SCIFLI and SAMI
2. Rationale for developing SAMI
3. SAMI design concept
4. NASA C-20 aircraft
5. SAMI as a flying testbed
6. Future directions



Near Infrared image of STS-134 at about Mach 6 displaying development of boundary layer transition, unprocessed data image.

SCIFLI

A short and somewhat incomplete pictorial history of SCIFLI



Mission	Date	ELT FE	Imaging Assets	Mach Observations	Waveoffs	Comments	Data Sampling
IF 5-119	3-26-2009	Yes	CG MARS	8.5 N/A	1 orbit	MARS in Florida had bad weather	
IF 5-128	5-14-2009	No	CG	14.5	Two 1-day delays, 1 orbit	Landed EDW after two 24 hour waveoffs and a 1 orbit waveoff to KSC	
IF 5-129	9-11-2009	Yes	CG	15.0	1-day delay, 1 orbit	Landed EDW after one 24 hour delay and a 1 orbit waveoff to KSC	
IF 5-131	4-20-2010	Yes	MARS 1 MARS 2	15.0	1-day delay, 1 orbit	Descending node, landed KSC after 24 hour delay and 1 orbit waveoff	
IF 5-132	5-26-2010	No	CG	12.5	None	Science goal Mach 19, bad weather led to reposition at Mach 12.5. Allowed turbulent flow from damage to be seen	
SpaceX C1	12-08-2010	NA	CG Telemetry P3	17 21	None	Supported by NASA COTS Office, two Navy P-3s deployed, one for imaging, one for telemetry	
IF 5-135	3-9-2011	Yes	CG MARS 1 MARS 2	18.0 N/A	None	MARS systems were unable to acquire due to weather	
IF 5-134	5-15-2011	Yes	CG CG MARS	16.5 NA 6.0	None	Ground based system obtained very high resolution data	

Mission	Date	Imaging Assets	Imaging Goal	Comments	Data Sampling
MLAS	7-6-2009	MARS	Capsule sep / chute deploy	Obtained ultra high resolution imagery	
SpaceX C2	5-22-2012	CG	Early ascent, Dragon sep and solar deploy	Sea based imaging clouded over, land based obtained ultra high resolution early ascent	
SpaceX CRS-3	9-11-2009	CG	First stage supersonic retro propulsion	Thunderstorms and icing grounded observation aircraft	
SpaceX Orbcomm1	7-14-2014	NASA WB-57	First stage supersonic retro propulsion	First SCIFLI WB-57 deployment, lost tracking prior to SRP maneuver	
SpaceX CRS-4	9-21-2014	CG NASA WB-57	First stage supersonic retro propulsion	P-3 and WB-57 each obtained complete data set from shortly after launch to shortly before water impact	
EFT-1	12-05-2014	CG Coordinated 2nd CG and Ikhana	Orion heat shield peak heating thermal measurements	Weather forced P-3 to move down trajectory, measurements made in Mach 9 region of reentry	
EM-1	2018	TBD	Orion heat shield peak heating thermal measurements	Looking for spatial and spectral measurements, exploring ascent imaging possibilities	
AA-2	2019	TBD	Thermal imaging of separation sequence	Obtain unique views and thermal imagery	

The Evolution of SAMI





Legacy airborne platforms, will continue to support SCIFLI Missions

HAARTS telescope to be deployed on NASA Global Hawk, first flight 2019









SAMI will use HAARTS technology in a human-in –the –loop version on the NASA C-20. Funded by a $750K Phase IIX SBIR First flight 2019

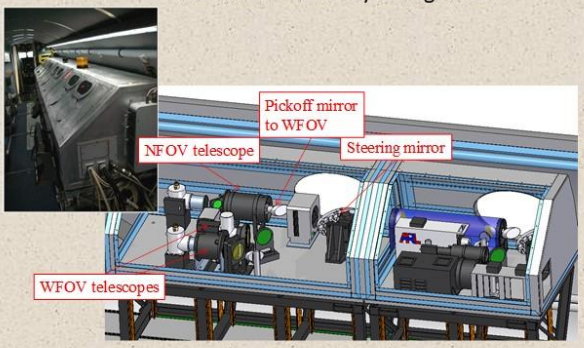
SAMI

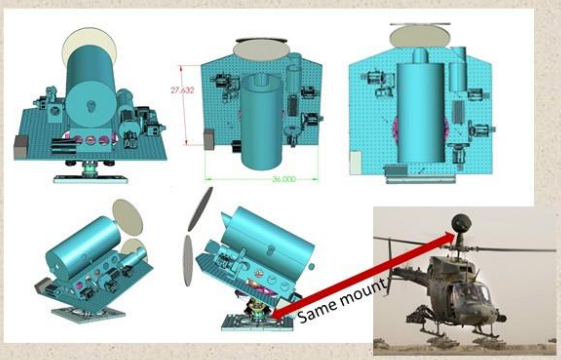
SAMI is in the early design stage. It will take on one of two forms currently being discussed.

Steering Mirror option, design shown is based on the L-3 HALO I airborne observatory configuration

OR

Center Pivot Gimbal mount, with the entire optical bench placed on a platform that can pan and tilt





Each configuration will allow multiple optical paths for independent sensors to simultaneously acquire data, and each design will be modularized such that a variety of optical components may be placed in the various optical paths.

SAMI

Potential sensor suite for SAMI

Channel	Camera	X Pixels	Y Pixels	FOV, deg
UV-Vis	Color	1900	1200	0.319
NIR	Near Infrared	1900	1200	0.319
SWIR	Shortwave	1280	1024	0.367
MWIR	Midwave	1280	1024	0.440
MWIR	Wide field	1280	1024	2.934
NIR	Near infrared	3200	2400	0.413
NIR	Wide field	1920	1200	1.595
UV-Vis	Spectrometer	30	30	0.172

Vendors and final specs are yet to be determined



Aircraft performance characteristics:

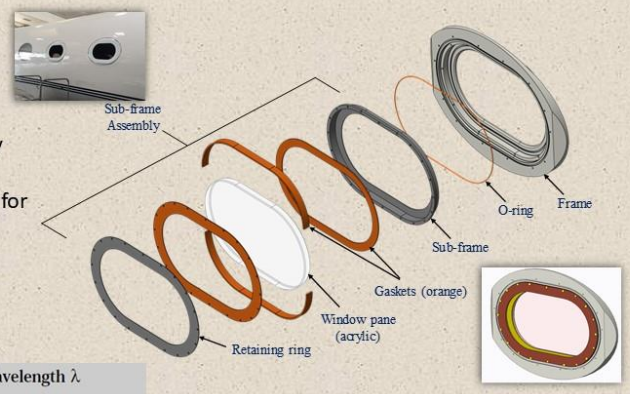
- Speed: 576 mph
- Range: 4,250 miles
- Ceiling: 45,000 ft
- Nominal Load: 12 passengers

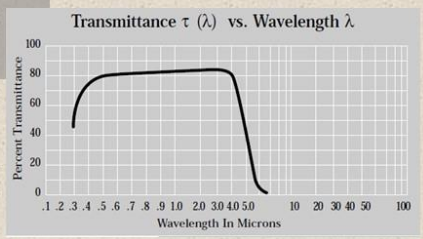
Internal space and power can support lasers adjacent to the SAMI in the aircraft.

Existing C-20 Window Design

The Armstrong Flight Research Center has developed, built and flown a window frame for scientific grade glazing for the C-20 aircraft. SCIFLI will leverage this effort to create the window frame for a sapphire insert.

Multiple frames may support different windows, optimized for laser transitions





Other window materials may be substituted for sapphire if required.

General transmittance plot for sapphire – well suited for Near and Midwave IR

SAMI As An Optical Component Testbed

The desire is to make SAMI available to the research community as a flying testbed for components that require testing or flight certification.

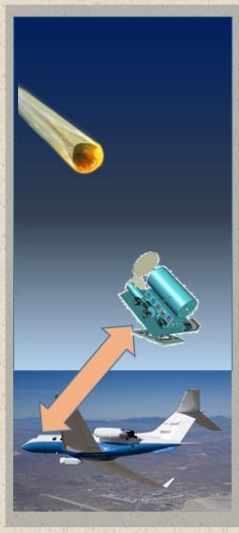
SAMI can provide:

1. Vibration isolated, stable tracking mount
2. Wide to narrow field of view of objects of interest on the ground, in the air or in space (orbital or astronomical)
3. Up to six hours or more endurance at high altitude
4. Ability to go above 40K feet if desired, eliminates most weather concerns
5. Shirtsleeve environment for researchers, customized workstations may be place on aircraft.
6. Potential to piggy-back with other missions to amortize cost over multiple projects.
7. NASA in-house resource, minimize concerns over unauthorized access to intellectual property
8. C-20 will provide a cost effective platform for observations

Open for business mid to late 2019



Future Development



Payload directed flight, where the telescope tracking system is tied into the aircraft autopilot to optimize the flight path for the observation.



Provide a holistic development environment including the NASA LaRC ISO5 cleanroom for elemental component design, fabrication and testing, leading to integration with SAMI and flight testing.

Enhance SAMI with advanced active and adaptive optical components to attain the highest quality imaging available from an airborne platform.



SCIFLI is slated to image SLS ascent on EM-1 and EM-2

Summary

- The NASA SCIFLI Team is developing a capability available to the Agency to fill a need for affordable, high quality airborne imaging
- SAMI will be coming on line in late 2019 to support airborne imaging missions
- SAMI can be utilized as an affordable, NASA in-house testbed for optical components
- We are seeking a continuous process of improvements to the system that will potential include active and adaptive optics.

8.6 WIND LIDAR FOR AVIATION SAFETY AND ENHANCED EFFICIENCY

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ABSTRACT

Several aspects of aviation safety and efficiency would benefit from a coherent Doppler lidar that can measure wind and turbulence features ahead of aircraft. Wind features can be encountered in flight that can present a hazard including clear air turbulence, wind shear, gusts, and wake vortices generated by preceding aircraft. A lidar sensor could measure these wind features and be of substantial benefit if installed in commercial and passenger aircraft, similar to Doppler weather radar currently in common use. By detecting potentially hazardous wind and/or turbulence features ahead of the aircraft with sufficient warning time, steps could be taken by the pilot or autopilot to protect passengers and the aircraft. Also, mild wind and turbulence features could be taken into account to dynamically adjust wing control surfaces to provide better fuel efficiency. However, current Doppler lidar technology is lacking in several requirements to realize a cost-effective sensor solution. In particular, lasers are needed at eye-safe wavelengths with high pulse energy (> 10 mJ), high pulse repetition rate (> 500 Hz), suitable pulse width (100 to 500-ns), diffraction limited beam quality, and single-frequency spectrum. In addition, the lidar system must be of a rugged design of limited size, weight, and power suitable for installation in aircraft. Possible technology solutions are described in this paper.

1 INTRODUCTION

The wind lidar proposed here addresses goals of NASA's Aeronautics Research Mission Directorate (ARMD) to improve aircraft performance. One ongoing NASA program of applicability is the Advanced Air Vehicle Program with a goal to "enable new aircraft to fly safer, faster, cleaner, quieter and use fuel more efficiently."[1] Predictive knowledge of wind dynamics addresses this call for improving safety, speed, and fuel efficiency. A second NASA program of note is Advanced Air Transport Technology, with a goal to provide "revolutionary energy efficiency and environmental compatibility."[2] The proposed wind sensor, along with a control system of wing surfaces, would advance toward the goal of improving energy efficiency. Development of a wind lidar could be implemented into the ARMD Strategic Implementation Plan via two thrusts. Specifically, lidar development aligns with Thrust 1: Safe Efficient Growth in Global Operations with a call for "technologies for safe global operations with all-weather capability, multi-domain situational awareness and prognostic safety awareness, prediction, and alerting."[3] Also, the lidar's role in improving fuel efficiency aligns with Thrust 3A: Ultra-Efficient Commercial Vehicles Subsonic Transport with a goal of "1.5-2% fuel burn reduction per year."[3]

NASA has previously investigated airborne wind lidar in the 1990s, including a clear air turbulence sensor and a wind-shear detection sensor.[4,5] While these programs demonstrated the utility of wind lidar, adoption of the technique did not come to fruition due to limited range capability, high cost, and complexity. Example data is shown in Figure 1. However, new advances in laser technology address the limitations previously found, warranting a re-evaluation of airborne wind lidar for aviation. Furthermore, studies have progressed showing that measurements from a lidar could be used to good effect considering that modern aircraft have sufficient control authority to significantly mitigate the effects of turbulence on aircraft and their passengers and crew.[6]

Based on performance of prior flight tests in the 1990s and on downward-looking airborne wind lidar developed more recently, the requirements for an aviation wind lidar can be set.[7] These requirements are summarized in Table 1. Of note in deriving requirements is the level of aerosol backscatter at cruise altitude in the upper troposphere and of a need to provide adequate warning time for corrective action.

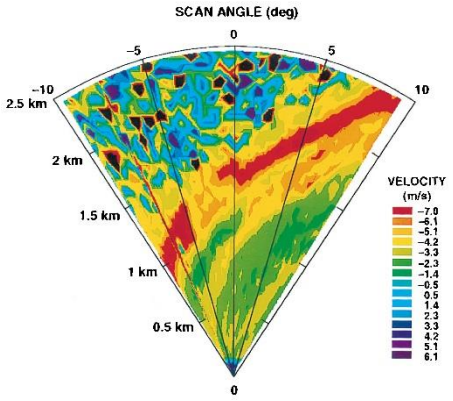

Figure 5: Example horizontal scan from 1990s NASA flight test of airborne Doppler wind lidar for detecting aviation hazards.[4] Advances in technology since the 1990s warrant a re-evaluation of the technology for aviation applications.

Table 1 Requirements for aviation wind lidar

parameter	value	comments
wavelength	between 1530 to 1675-nm	needed for eye-safety, off of absorption line, and matching C, L, or U telecom bands
pulse energy	> 10 mJ	needed for range capability
pulse width	100-500 ns	involves trade-off of range/velocity resolution
beam quality	diffraction limited	
pulse repetition rate	> 500 Hz	needed for fast update rate
spectrum	single frequency	
telescope aperture	> 15-cm	needed for range capability
scanning	forward-looking, conical	

2 METHODOLOGY

The promise of a cost-effective long-range wind lidar centers on advances in lasers and optical components in the 1.5-µm wavelength regime. With this wavelength being used extensively for fiber optic telecommunications, a wide range of technologies have spun off that can be used for lidar such as photoreceivers, modulators, tunable single-frequency diode lasers, and fiber amplifiers. Commercial interests have used this 1.5-µm technology to foster widespread adoption of ground-based wind lidar, albeit from low-energy laser transmitters suitable only for atmospheric conditions of strong aerosol backscatter such as within the atmospheric boundary layer. Based on this approach of leveraging telecommunications technology, a technology push from NASA could increase laser transmitter energy to establish wind lidar for lower aerosol backscatter conditions, such as those encountered at aircraft cruise altitude.

2.1 STATE OF THE ART

The gap in realizing a wind lidar for long-range low-backscatter conditions is moving from current low-energy (< 1 mJ) to high-energy (> 10 mJ) lasers. The current state of the art in pulsed laser lidar transmitters of single-frequency spectrum in the telecommunications band is the use of continuous-wave diode or fiber lasers, modulated to generate a pulse, then amplified by erbium doped fiber amplifiers. This approach has a limit in pulse energy to less than 1-mJ by the onset of stimulated Brillouin scattering or optically induced damage. Technology based on 2-µm wavelength holmium or thulium solid-state lasers could possibly reach the laser transmitter pulse output requirements, but not within a suitable size, weight, power, or cost. 2-µm lasers for wind lidar require excessively long laser cavity lengths (> 2-m) that drive a need for large and heavy packaging to maintain alignment stability. Furthermore, many receiver components do not exist at 2-µm wavelength or require cost-prohibitive custom procurement of exotic semiconductor materials and specialized optical coatings. Leveraging components and miniaturization of the developed 1.5-µm telecommunications band is key to developing a cost-effective aviation wind lidar.

2.2 NEW APPROACH

A new approach is needed for a high-energy pulsed lidar transmitter that matches telecommunications wavelengths. Two options are possible and proposed to be investigated in parallel to a brassboard implementation suitable for vibration testing. The design found to be better would then

be combined with a receiver to build a flight-ready lidar prototype. The two technology possibilities are:

- Solid-state amplification of a diode laser with fiber pre-amplifier. This approach adds an erbium solid-state amplifier to the current commercial ground-based transmitter architecture. Promising solid-state erbium amplifier designs have shown gain needed to amplify sub-millijoule input pulse energy to greater than 10-mJ output.[8] Pulse length, spectrum, and beam quality are theoretically maintained in this amplification, but experimental validation is needed. This approach combines the best features of various laser gain implementations: diode lasers for single-frequency spectrum in a tiny package, fiber amplifiers for alignment-free pre-amplification, and solid-state amplifiers for handling high pulse energy.
- Erbium solid-state laser injection seeded by a diode laser. Erbium solid-state lasers have been the basis for wind lidars used in commercial high-performance ground-based wind lidar that could possibly be improved for pulse energy from their current levels of a few millijoules. [9, 10] In particular, the recent availability of in-band pump sources merits evaluation. A development effort would need to show a size and weight feasibility from this design—generating the needed long pulse length from a short laser cavity (< 1-m) is a challenge.

2.3 Describe the Future State

The future state of the proposed technology is a wind sensor of a performance and cost that can find widespread use in commercial aviation. Detection and mitigation of aviation hazards could be installed on passenger aircraft to reduce accidents, increase fuel efficiency, and improve passenger comfort.

2.4 Risks and Rewards

The primary risk in this development is that the laser transmitter pulse energy or average power can't be realized in a rugged package. Hence, a development plan is proposed to evaluate this critical laser step prior to building a lidar system. The reward of successful development would be making airborne lidar a common sensor for improving aviation safety and performance, much like airborne weather radar now in use.

3 PROGRAMMATICS

3.1 Development Plans

The Development Plan includes three phases of technology development to bring an aviation wind lidar to a point where adoption of the technology is favorable for commercial aviation:

- In the 1st Phase, an investigation is performed of the best approach for a high-energy (> 10 mJ) laser transmitter. The two approaches described above will work toward a brassboard implementation for vibration testing. This development is expected to require two years in development and an additional 6 months for environmental testing. The better performing design would move to Phase 2.
- In the 2nd Phase, a prototype wind lidar will be built that is suitable for flight testing. The lidar will be based on the transmitter technology developed from Phase 2, along with the incorporation of an optical receiver, control electronics, data acquisition, and signal processing. Phase 2 is expected to require 3 years of activity.
- In the 3rd Phase, the aviation wind lidar will be tested onboard an aircraft. Two flight test campaigns are proposed, with a year between the two tests to address problems that may arise from the first flight test. A duration of 18 months is envisioned for Phase 3.

Table 2 -- Development Budget Profile

<Project>	**Phase1**	**Phase2**	**Phase3**	**TTL**
Budget ($M)	2.5	4	1.5	**8**
FTE	3	4	3	**10**
WYE	2	3	2	**7**
Procurement	1.5	2.5	.5	**4.5**
Duration (year)	2.5	3	1.5	**7**

3.2 DEVELOPMENT MILESTONES AND DATES

The profile of progress is summarized in Table 2. Milestones and decision points are built in between phases of development:

- At the end of Phase 1, a down-select will take place to proceed with the better laser design.
- Phase 2 ends with delivery of a lidar sensor ready for flight testing. Meeting performance requirements will indicate readiness for flight testing.

3.3 PARTNERING

Laser and lidar system development would be a combination of NASA and industry. Several small business have capabilities in the laser development and could be engaged by the SBIR program. NASA would oversee technology requirements, down-selection of designs, system design, and flight testing.

3.4 OVERCOMING THE VALLEY OF DEATH

The key transition to development is from technology demonstration to adoption by the aviation industry. Engagement of end users can bridge this gap with the involvement of the Federal Aviation Administration and RTCA industry group.

4 WIDER VISION

Cross-cutting benefits include application of the wind lidar to weather and Earth science applications. Hurricane studies would find benefit in a rugged lidar system for installation on the Government's fleet of hurricane hunting aircraft. Several defense applications are also of note for an airborne lidar including parachute drops and aircraft carrier operations.

5 CONCLUSIONS

Wind measurements by Doppler lidar are showing widespread use in ground-based applications. Airborne use would have substantial benefits and commercial applications, but a technology push by NASA is needed to realize these benefits.

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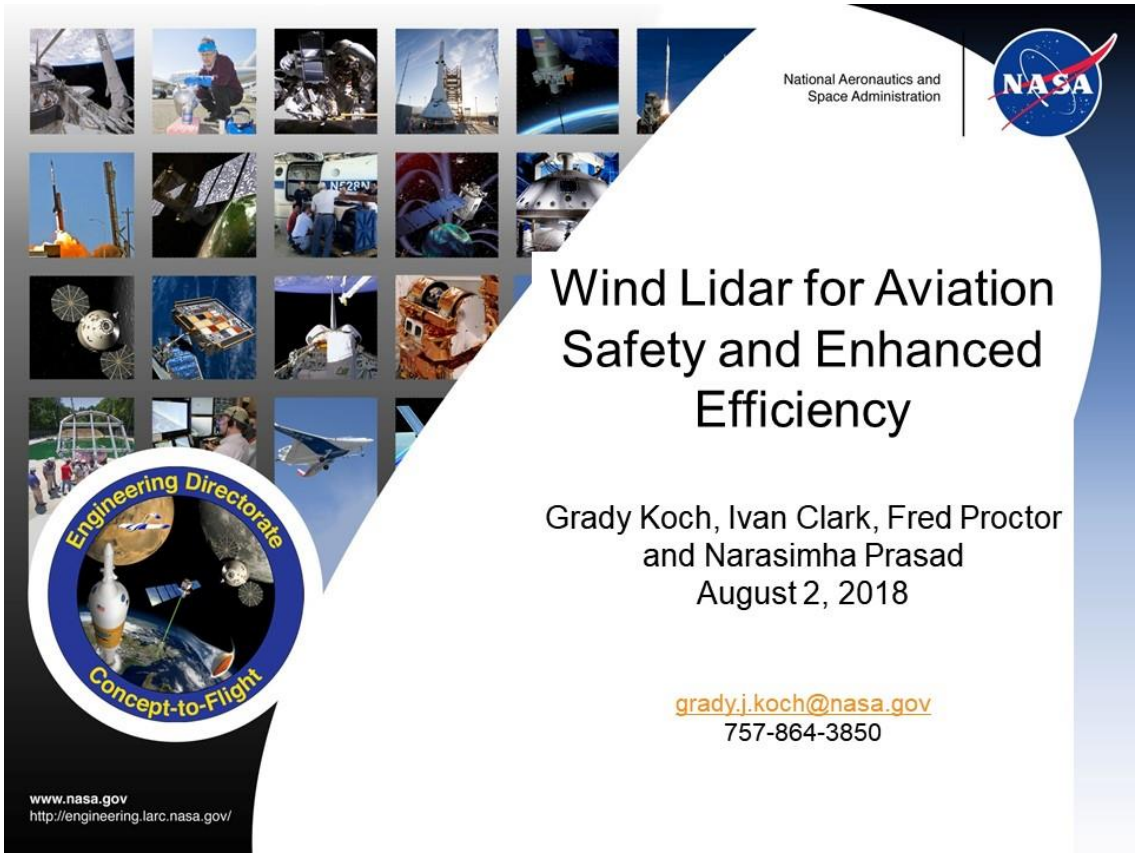

National Aeronautics and Space Administration

Wind Lidar for Aviation Safety and Enhanced Efficiency

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August 2, 2018

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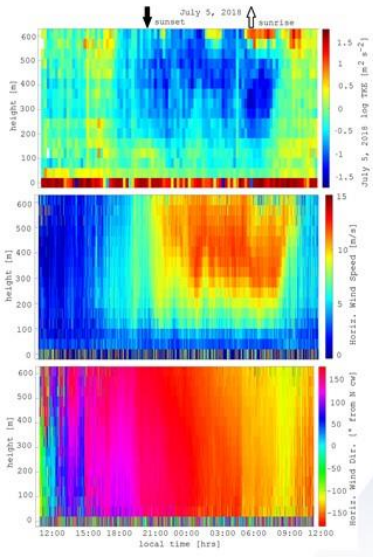
Proliferation of Wind Lidar (Ground-Based)

- **Wind lidar (ground-based) has become a common meteorological tool.**
  - For example, student interns are running lidar measurements at NASA LaRC.
- **Why don't we see airborne wind lidar in common use?**



STEM-Takes-Flight intern Clayton Gilkeson is using dual-Doppler techniques for measuring wind flow around structures.



Undergrad intern William Krier developed custom algorithms for wind and turbulence profiling over a UAV test site.

2

Wind-Related Clear-Air Aviation Incidents

- **Clear air turbulence:**
  - NTSB records show 563 serious injuries from 2002-2016 from in-flight clear-air turbulence.
- **Wake vortex encounters:**
  - In 2001, an A306 aircraft over New York crashed with 265 fatalities after a series of events triggered by a wake vortex encounter.
  - In 2008, an A319 aircraft over Oroville, WA underwent a sudden 55-degree roll and descent of 1400-ft from a wake vortex generated by aircraft 11-nm ahead. 11 serious injuries after persons and cabin service carts hit ceiling.
- **Wind shear:**
  - In 2006, a B732 aircraft over Abuja, Nigeria crashed with 96 fatalities from wind shear encountered after take-off.

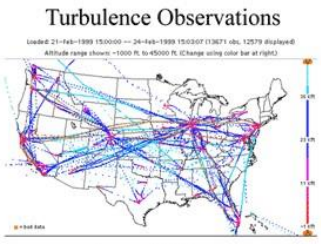


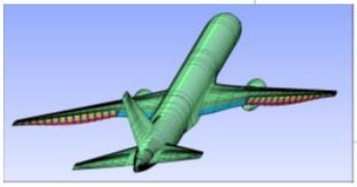
image credit: NASA

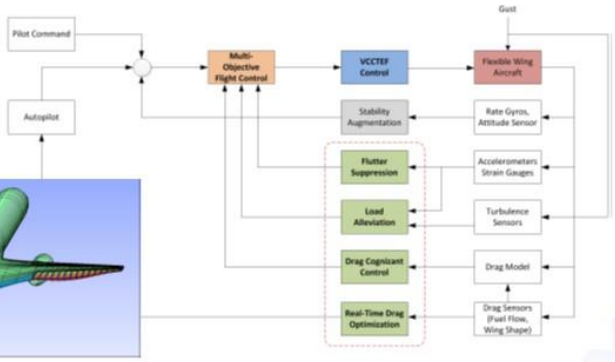

image credit: NASA


image credit: NASA

Active System for Gust Load Alleviation

- Wind measurement ahead of an aircraft could feed information into a control system to reduce gust loading on wings.
- A means to reduce loading on the wings allows for weight reduction in the design of the aircraft.
  - **Aircraft can be made lighter and more fuel efficient.**
- The most relevant wind information is variation of the vertical wind component.
  - A wind lidar must therefore be scanned in viewing angle.



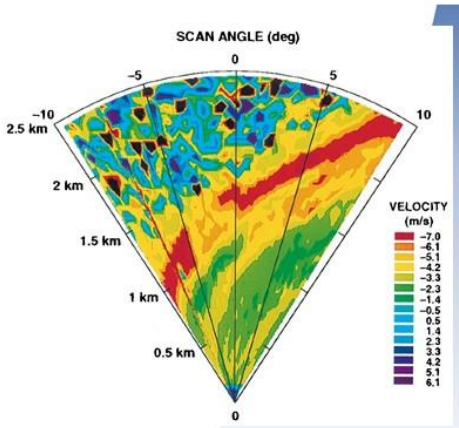


Example of load alleviation study at NASA Ames: "NASA Demo of Multi-Object Flight Control for Drag Minimization and Gust Alleviation," Nhan Nguyen, 2016.

Prior Work on Aviation Wind Lidar: Wind Shear Detection

- CLASS: Coherent Lidar Airborne Shear Sensor.
  - Flight tested both 2-µm and 10-µm wavelength lidar.
  - Flown on NASA B737 (1994)



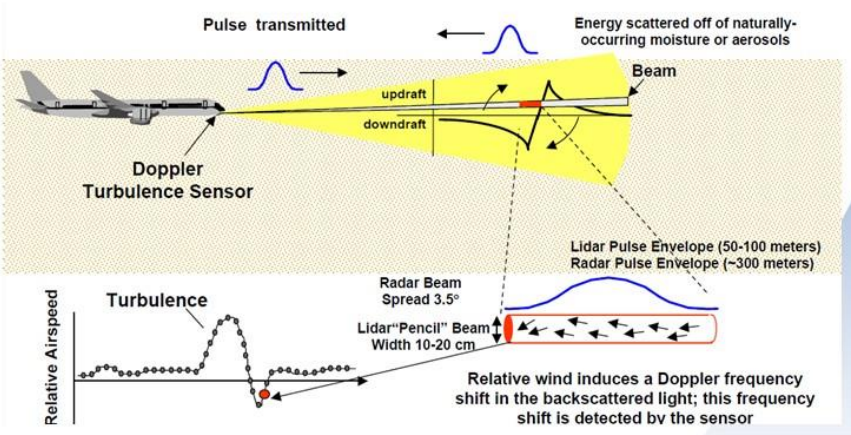


from R. Targ et al, "Coherent lidar airborne wind sensor II: flight test results at 2 and 10-µm ," Applied Optics 35, 1996.

5

Prior Work on Aviation Wind Lidar: Clear Air Turbulence

- ACLAIM: Airborne Coherent Lidar for Advanced In-flight Measurements
  - Flight tested a 2-µm wavelength lidar.
  - Flown on both NCAR Electra (1998) and NASA DC8 (2001, 2003) aircraft.
  - Successfully measured turbulence several miles ahead of aircraft.



from R. Bogue, "A Status Report on Turbulence Warning Technology," International Aircraft Fire and Cabin Safety Research Conference, 2001

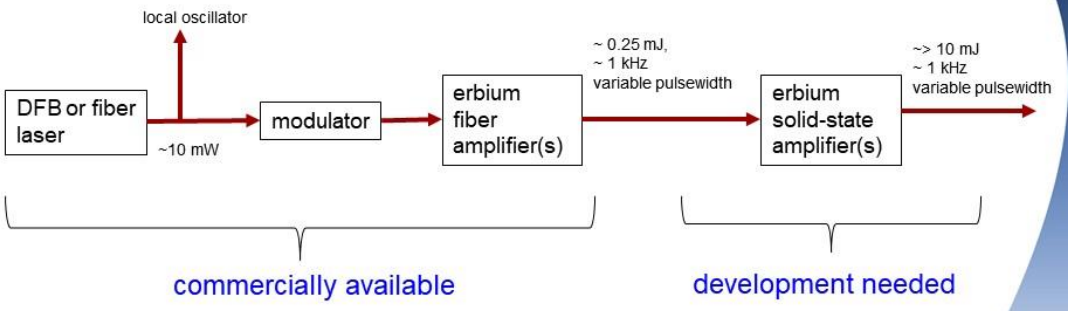
6

Aviation Wind Lidar

- **Flight tests showed aviation wind lidar works, but:**
  - it's too expensive.
  - it doesn't quite reach ahead far enough.
  - it doesn't quite have enough warning time for turbulence events.
  - it's too bulky.
  - it's too complex.
- **However, laser and optical technology has improved in the past 20 years.**
  - Follow a path taken by commercial ground-based wind lidar.
    - Leverage telecom technology around 1.5-μm.
    - All the component exist, except for pulse energy > 10-mJ.
      - Such pulse energies have become within reach.

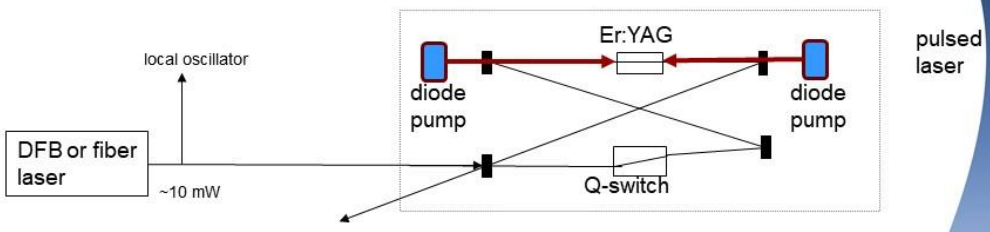
7

Transmitter Architecture, Option 1



- The diode/fiber-amplifier components are well established technologies.
- However, fiber amplifiers are limited in output pulse energy to < 1-mJ.
- Hence, a solid-state amplifier is used for high gain.
  - For example, J. Vetrovec et al, "Erbium-based edge-pumped disk laser," Proc. SPIE 8599, Solid State Lasers XXII, 2013.
- Strong advantage: no long laser cavity to maintain in alignment.

Transmitter Architecture, Option 2



- Some wind lidar designs are based on similar idea of erbium solid-state laser, injection seeded by single-frequency continuous-wave laser.
- However, advances in past few years suggest a higher pulse energy can be achieved.
  - In-band pump sources are now available.
  - Progress can be seen in, for example:
    - M. Wang et al, "In-band pumped polarized, narrow-linewidth Er:YAG laser at 1645-nm," Applied Optics 53, 2014.
    - S. Wang et al, "1645-nm single-frequency injection-seeded Q-switched Er:YAG master oscillator and power amplifier," Optical Engineering 57, 2018.

9

Follow Path of Doppler Weather Radar

- **Build for similar size, weight, power, and cost as Doppler weather radar.**
- **Engage industry (such as through RTCA) and regulatory requirements (Federal Aviation Administration) to encourage technology adoption.**
  - Requirements and standards will need to be developed.



image credit: NASA

10

Proposed Development Plan

- **Phase 1: Determine best means to generate high-energy (> 10-mJ) pulses.**
  - Other transmitter requirements are listed in 4-page paper.
  - Multiple design architectures should be tested.
  - Build brassboard versions suitable for environmental testing.
  - Down-select best performing design.
  - Likely a 2.5 year effort.
- **Phase 2: Build complete wind lidar system.**
  - Build to flight-ready design for cargo-bay type of environment
  - Likely a 3 year effort.
- **Phase 3: Flight Tests**
  - Conduct series of flight tests to demonstrate turbulence detection.
  - Likely a 1.5 year effort.

8.7 ADVANCED OPTICAL INSTRUMENTATION FOR THE NASA GLENN RESEARCH CENTER'S AERONAUTICAL TEST FACILITIES

Mark R. Woike and Grigory Adamovsky

NASA Glenn Research Center, Cleveland, Ohio

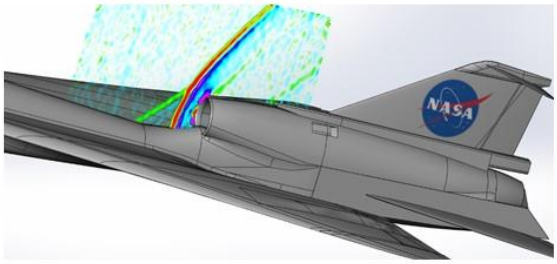


Advanced Optical Instrumentation for the NASA Glenn Research Center's Aeronautical Test Facilities

NASA Technical Interchange Meeting on Active Optical Systems for Supporting Science, Exploration, and Aeronautics Measurements Needs

Columbia, MD
July 31 – Aug 3, 2018

Mark R. Woike/LCP
Grigory Adamovsky/LCS
NASA Glenn Research Center



NASA Glenn Research Center

National Aeronautics and Space Administration

- 1 of 10 NASA field centers located across the US.



2

NASA Glenn Campuses



Lewis Field (Cleveland)

- **350 acres**
- **~1561 civil servants and ~1476 contractors**



Plum Brook Station (Sandusky)

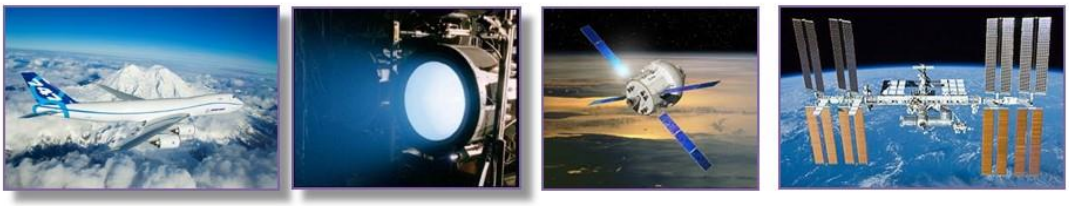
- **6500 acres**
- **~18 civil servants and ~89 contractors**

3

NASA Glenn Missions

Glenn's Mission:

We drive research, technology, and systems to advance aviation, enable exploration of the universe, and improve life on Earth.



Glenn's Core Competencies:

1. Air-Breathing Propulsion
2. In-Space Propulsion and Cryogenic Fluids Management
3. Physical Sciences and Biomedical Technologies in Space
4. Communication Technology and Development
5. Power, Energy Storage and Conversion
6. Material and Structures for Extreme Environments

4

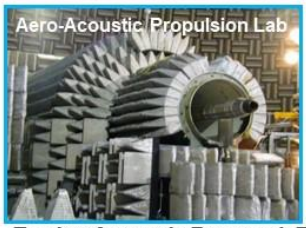
NASA Glenn Unique Aeronautics Test Facilities



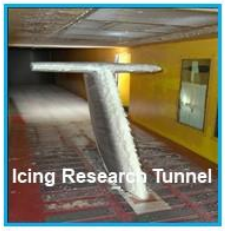
Subsonic Propulsion Wind Tunnel
- Noise suppression
- Inlet/Airframe integration
- STOVL hot gas ingestion



Transonic and Supersonic Propulsion Wind Tunnels
- Advanced propulsion concepts
- Inlet/Airframe Integration
- Internal/external aerodynamics



Engine Acoustic Research Facility
- Fan/nozzle acoustics research
- Simulate hot engine nozzles in flight
- Aerodynamic and Aeroacoustic measurements capabilities



Largest Icing Tunnel in US
- Aircraft icing certification
- Ice protection systems development
- Icing prediction/code validation



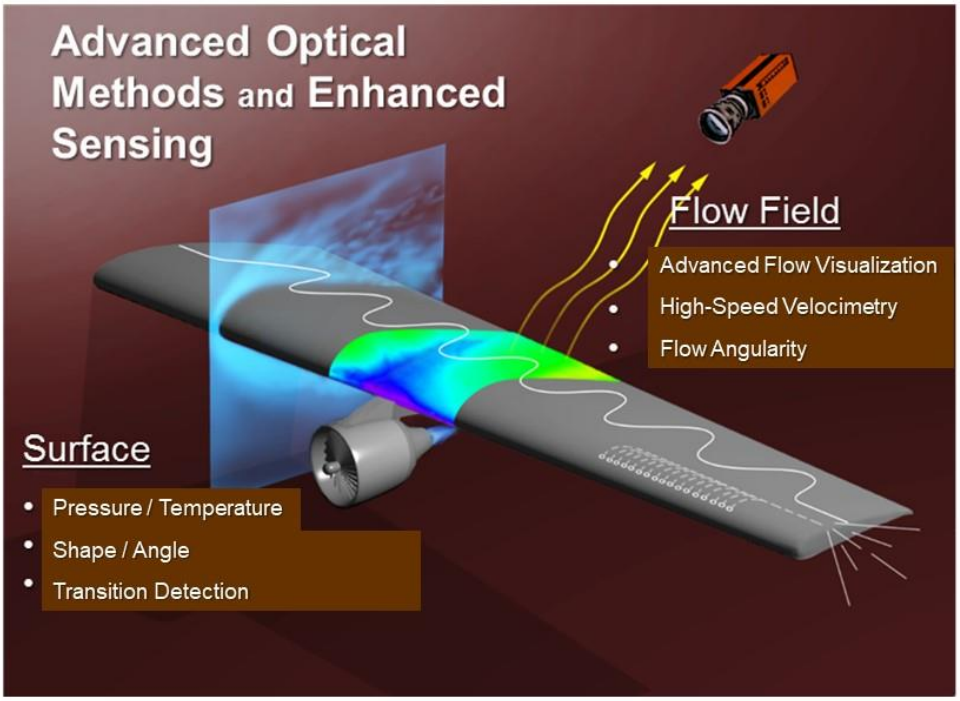
NASA's only altitude full-scale engine facility
- Jet Engine Icing Research
- Engine operability/performance
- Nozzle-engine integration



Over 50 Versatile Engine Component Facilities
- Combustor and Heat Transfer
- Compressor and Turbine
- Inlets and Nozzles

5

Optical Instrumentation for Flow Field & Surface Measurements



6

ARMD Projects for Instrumentation Development

- **The Transformational Tools and Technologies (T3) Project , Innovative Measurements (IM) Discipline**

  emerging Technical Challenge (eTC)

  – "Develop new and improved non-intrusive measurement technologies to support and validate flow field and structural measurements of velocity, temperature, density, pressure, and deflection. Demonstrate new or fivefold improvement in existing techniques in terms of accuracy, precision, efficiency, bandwidth, spatial resolution, or temporal resolution over the current state-of-the-art** supporting planned ARMD unsteady flow field validation experiments."

- **The Aerosciences Evaluation and Test Capability (AETC) Portfolio, Test Technology (TT) Subproject**

  Capability Challenge CC-TT-01 - Optical Instrumentation

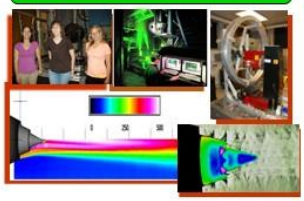
  – "Provide initial deployment of advanced optical instrumentation in AETC facilities to support CFD validation, wind tunnel characterization, flow diagnostics, and assessment of wind tunnel model performance. Enable acquisition of next generation aerodynamic test data required by researchers and modelers to further develop CFD tools. Improve measurement capabilities (pressure, force, flow, and temperature), test techniques and processes, and develop technologies critical to meeting NASA research needs and applicable to a multitude of facilities."

7

Optics and Photonics Branch (LCP)

http://www.grc.nasa.gov/WWW/Optinstr/

Optical Instrumentation



- Our data and instrumentation help designers understand the fundamental physics of new systems, validate aeronautics computational and life models, and improve space optical communications for human and robotic explorations.
- Our data leads to improved designs, validation and verification of systems' performances, increased communications, safety and security and reduced design cycle times for many of the core technologies developed at Glenn and across NASA.

Photonics and Health Monitoring



Flow/Noise/Combustion Diagnostics
- Particle imaging Velocimetry (PIV)
- Background Oriented Schlieren
- Rayleigh Scattering
- PIV Tomography
- Raman Diagnostics (Species, T)
- Plasma generation

Surface Diagnostics
- Temperature Sensitive Paint
- Pressure Sensitive Paint
- Stress Sensitive Film

Engine Icing
- Light Extinction Tomography
- Light Extinction Probes
- Raman Spectroscopy
- Impedance Sensor

Optical Communications



Free Space Optical Communications
- Optical Teletennas
- Beaconless Pointing Systems
- High Data Rate for Deep Space & Near Earth

Secure Quantum Optical Communications
- Quantum Entanglement
- Pulsed photon Pairs
- Quantum Illumination
- Quantum Key Distributions

Mobile and Remote Sensing
- On-Orbit Solar Cell Characterization MISSE 5-8; TACSAT- 4;
- Hyperspectral Imaging
- Mobile Sensing Platforms

Communications
- Communications over power lines
- Communications Interface Boards
- High Data Rate

Propulsion Health Monitoring
- Advanced Blade Tip Clearance
- Self diagnostic Accelerometer
- Fiber optics sensors
- Morphology dependent resonance
- Phosphor Thermography
- Wireless and wired techniques
- Light driven actuators

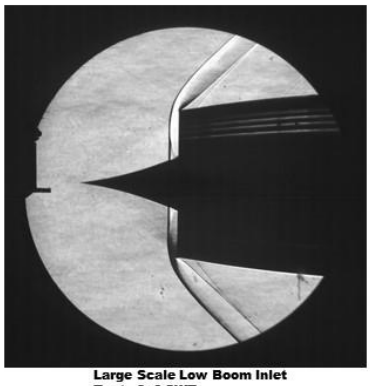
8

Flow Field Diagnostics

9

Schlieren Flow Visualization Technology

- "Conventional" Schlieren
  - Upgrade technique to utilize new LED lighting and high speed camera technologies.
- New Advanced Techniques in development (more robust, more portable, greater viewing capability)
  - Background Oriented Schlieren (BOS)
  - Focusing Schlieren



Large Scale Low Boom Inlet Test - 8x6 SWT



Jet Surface Interaction Tests – Engine Research Bldg

- Overall Goal
  - Transition schlieren from a flow visualization to a quantitative flow measurement tool
  - Allow better simulation, measurement and validation of conditions that a "vehicle" is experiencing in our test facilities

POC: Mark Woike (GRC) 10

Background Oriented Schlieren (BOS)

- BOS is a more recent development of the schlieren and shadowgraph techniques.
- Based on an apparent movement of the background when imaged through a density field onto a detector plane.
- BOS captures the density field but only requires a CCD camera, light source, and a high-contrast "speckled" background

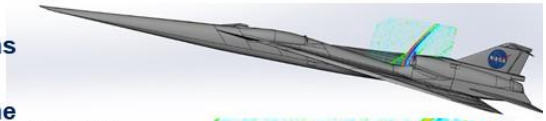


BOS installed in 8x6 SWT for QueSST

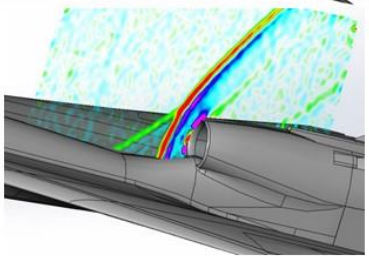
- More portable than traditional systems
- Can use it to view a wider range of locations on a test article
- Can be used to calculate the density of the flow field

Camera and light box setup for QueSST





Flow images produced from data taken during QueSST testing. Shown imposed over CFD surface model.

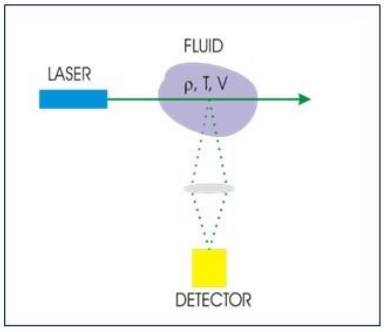


POC: Jonathon Ponder (GRC) 11

Rayleigh Scattering

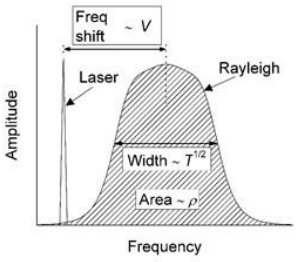
Rayleigh scattering as a flow diagnostic:

- Uses spectral characteristics of laser light elastically scattered from gas molecules to extract velocity, temperature, and density information.



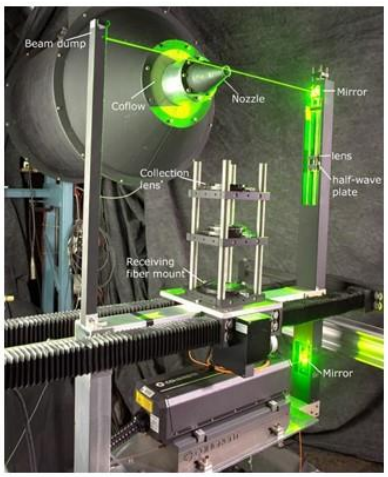
Methodology:

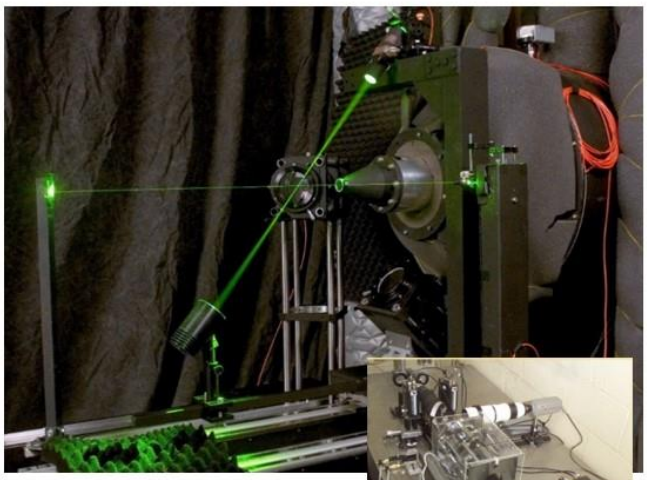
- Total signal strength is proportional to number density directly ($I \propto \rho$)
- Scattered signal is not species specific, therefore cannot be used to determine individual species concentrations
- Frequency shift between laser and Rayleigh spectral peaks yields one component of gas velocity ($\Delta f \propto V$)
- Thermal motion of the molecules causes spectral line broadening that is proportional to the speed of sound in the gas, and hence a measure of temperature (linewidth $\propto \sqrt{T}$)



POC: Amy Fagan (GRC)

Rayleigh Scattering





Rayleigh Scattering in Free Jets (CW-17)



Typical Setup for Analysis and Detection of Rayleigh Signals

POC: Amy Fagan (GRC)

TomoPIV

PROBLEM
Classic Stereo particle imaging velocimetry (PIV) measurements are limited to 3-component velocity measurements across a single plane. Development of a Tomographic PIV technique which can provide high spatial resolution, 3-component velocity measurements across a volume is needed.

ACCOMPLISHMENT
This is the first application of tomoPIV in supersonic jet flows, and represents one of the highest resolution tomoPIV reconstructions ever performed.

The data were compared against 2-component PIV and Stereo PIV measurements in the same facility. tomoPIV data were concentrated around a shock cell in the underexpanded flow enabling full 3-component, 3D reconstruction of the Mach disk in the flow.

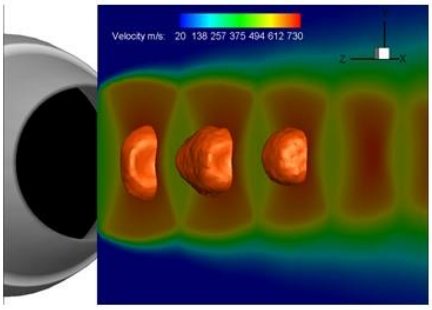
SIGNIFICANCE
Tomographic PIV can provide velocity measurements across a volume – yielding previously unavailable flow properties such as all three components of shear stress and vorticity.

MILESTONES
Successful TomoPIV demonstration in Large Scale Facility CST Level II Milestone:
Completed

4-camera TomoPIV installation in the acoustic dome



TomoPIV data from a Mach 1.4 supersonic jet, showing the 3D reconstruction of the Mach disk.

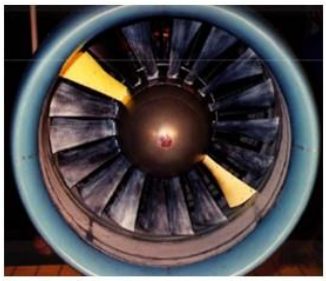


POC: Mark Wernet (GRC)

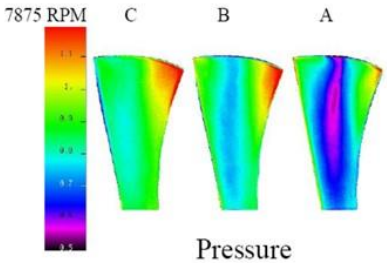
Surface Diagnostics

Pressure Sensitive Paint (PSP) Measurement Technique

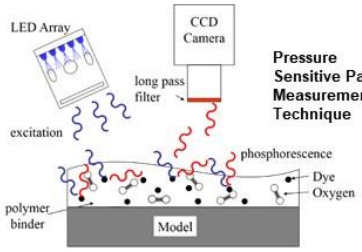
- Motivation: To achieve non-intrusive global pressure measurements on an aerodynamic surface
  - Image based technique
  - O2 sensitive fluorescent dye in a O2 permeable (polymer) binder
    - When a dye molecule is excited, it recovers to a ground state by emitting a photon of longer wavelength
    - In some materials, O2 interacts with molecule causing a non-radiative transition (O2 quenching).
    - Higher pressure = Higher O2 = Higher quenching = Lower intensity of returned light
- Acquisition is accomplished by coating surface, illuminating it with the proper excitation light, and imaging it with a filter to separate the luminescent signal from the excitation light



Painted Blades for pressure measurements



Blade pressure profiles for 3 different test conditions

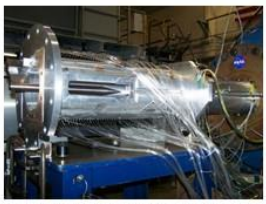


Pressure Sensitive Paint Measurement Technique

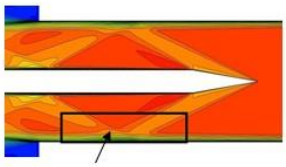
POC: Mark Woike / Jonathon Ponder / Tim Bencic (GRC)

Pressure Sensitive Paint (PSP) - Examples

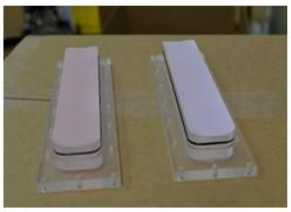
Shockwave Boundary Layer Interaction Experiment



Axisymmetric test section with shock generator installed

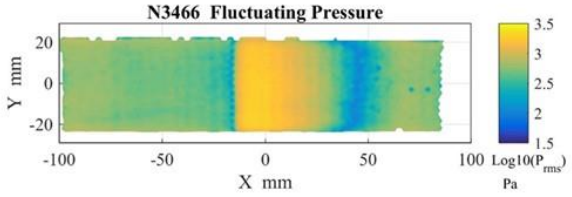


Shock wave boundary layer interaction area of interest



Fast PSP Windows

- The goal of this validation experiment was to better characterize the shock wave boundary layer interaction region with more refined and detailed measurements for CFD validation
- PSP was applied to the inner flow surface side of specially made windows and imaged from the backside looking through the window to make unsteady pressure measurements (intensity based technique)



Mach 2.5 with 13.5 deg. shock generator at Reynolds numbers of 5E6:

POC: Mark Woike / Jonathon Ponder (GRC)

Luminescence-Based TBC Diagnostics

PROBLEM

Thermal barrier coatings (TBCs) lack robust non-intrusive diagnostics for coating performance and temperature monitoring below TBC is nonexistent.

OBJECTIVE

Develop luminescence-based mapping of temperature both above and below thermal environmental barrier coatings (TBCs) used to protect turbine engine components.

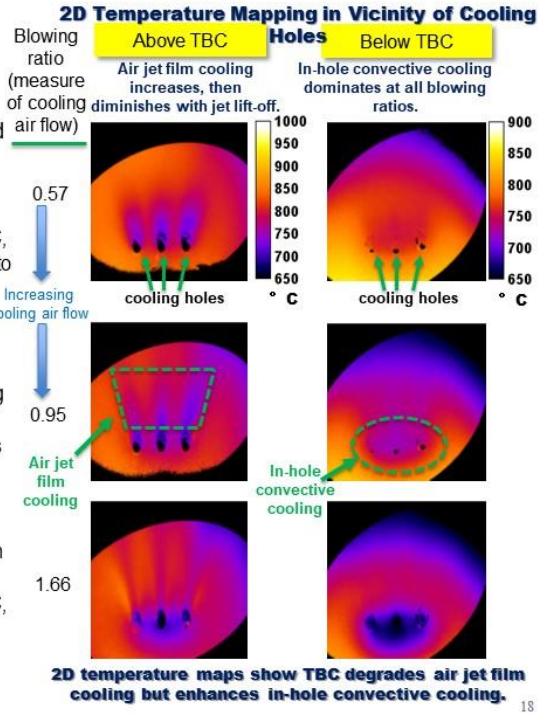
APPROACH

Develop 2D full-field temperature mapping both above and below TBC, using luminescence lifetime imaging from sensing layers integrated into TBC. Demonstrate ability to map temperature gradients produced by air film cooling in combustion environments.

Progress

- Developed custom thermographic phosphors for nonintrusive integration of sensing layers into TBCs for temperature mapping using luminescence lifetime imaging.
- Successfully demonstrated 2D temperature and cooling effectiveness mapping above and below TBC with high temperature and spatial resolution in presence of strong background radiation associated with combustor burner flame.
- First ever temperature mapping below TBC, where thermal protection needs to be monitored.
- Data revealed that air film cooling was severely degraded below TBC, while in-hole convective cooling was significantly enhanced.
- Important implications for cooling hole design for TBC-coated components.

POC: Jeff Eldridge (GRC)



18

Icing Diagnostics

19

Light Extinction Tomography

- New measurement technique developed to measure the uniformity and density of the Icing Clouds used in the GRC Icing Test Facilities
  - Propulsion Systems Laboratory (PSL) – Icing effects on engines
  - Icing Research Tunnel (IRT) – Icing effects on wings, tails, aero surfaces, etc.



Ice Accretion Testing – Icing Research Tunnel

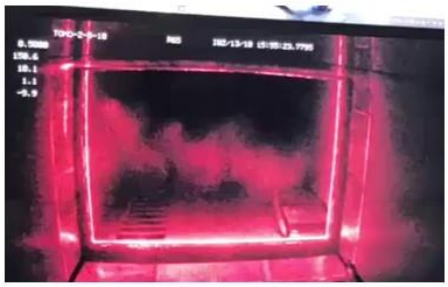


Engine Icing - Propulsion Systems Laboratory

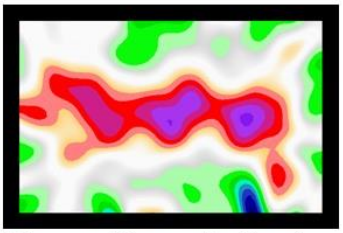
POC: Mark Woike / Jonathon Ponder / Tim Bencic (GRC) 20

IRT Icing Tomography System

- IRT Prototype Tomography System
  - 6' x 9' Square geometry
  - 60 light sources and 120 detectors
- Light extinction tomography
  - One light source fires, many detectors measure light extinction due to cloud/particles in the optical path from the lasers to the detectors
  - Sequential firing of light sources located around the periphery yields a 2D reconstruction of the cloud
  - Utilizes tomographic reconstruction techniques



Video of a typical icing cloud spray



2D tomographic reconstruction of icing cloud spray



From development in the lab to implementation in the test facility

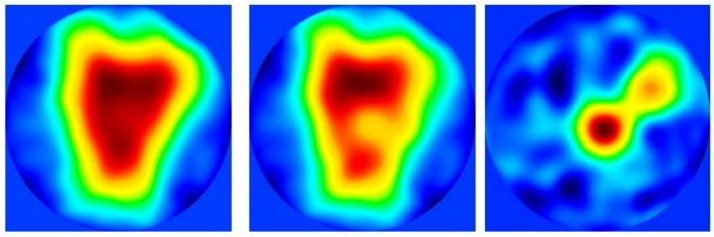
POC: Mark Woike / Jonathon Ponder / Tim Bencic (GRC) 21

PSL Light Extinction Tomography Results



PSL Icing Tomography System

Icing spray nozzle diagnostic monitoring capability

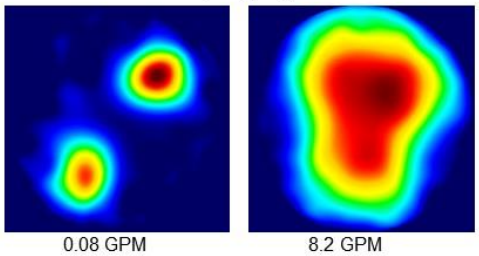


30 Nozzles | 28 Nozzles | Difference



PSL Icing Tomography System

Extremes of spray system water flow



0.08 GPM | 8.2 GPM

POC: Tim Bencic (GRC)

Other Areas of Instrumentation Development for the Test Facilities

- High Temperature Sensors
- Model Attitude Sensors
- Force Measurement Technology
- Wind Tunnel Characterization Instrumentation



- Questions?

Thank you!

9 Session 9

Innovations was designed to bring in more non-traditional applications than the typical science measurement. In many cases, the practitioners use technologies that are similar to the science applications, but with a different spin on the technology. The Session Chair, Mike Seablom, gave an overview presentation of the area to start the session. Table 9-1 lists the seven session papers. See Section 3 of the Assessment Report for observations and assessment comments.

Table 9-1. Session 9 Papers

Paper Number	Author	Title	Paper	Presentation
S9-1	Mike Seablom	Overview		☑
S9-2	Nan Yu, JPL	Laser and Optical Systems for Atomic Clocks, Sensors, and Quantum Applications in Space		☑
S9-3	Paul Suni, Lockheed Martin Space	Photonic Integrated Circuits for Active Optical Sensing in Space	☑	☑
S9-4	Kenji Numata, Anthony Yu, Hua Jiao, Scott Merritt, Frankie Micalizzi, Molly Fahey, Jordan Camp, and Michael Krainak NASA GSFC	Laser System for the Laser Interferometer Space Antenna (LISA)	☑	☑
S9-5	Abigail Licht, MIT Lincoln Laborarory	Geiger Mode Avalanche Photodiode Development at MIT Lincoln Laboratory		☑
S9-6	David D. Smith and Andrew Keys, NASA MSFC	Prospects for the Development of Fast-Light Inertial Sensors	☑	☑
S9-7	Jennifer Inman, NASA LaRC and Ian Miller, N&R Engineering	Ocular Hazard Risk Management for Airborne and Spaceborne Active Optical Systems	☑	☑

List of presentations

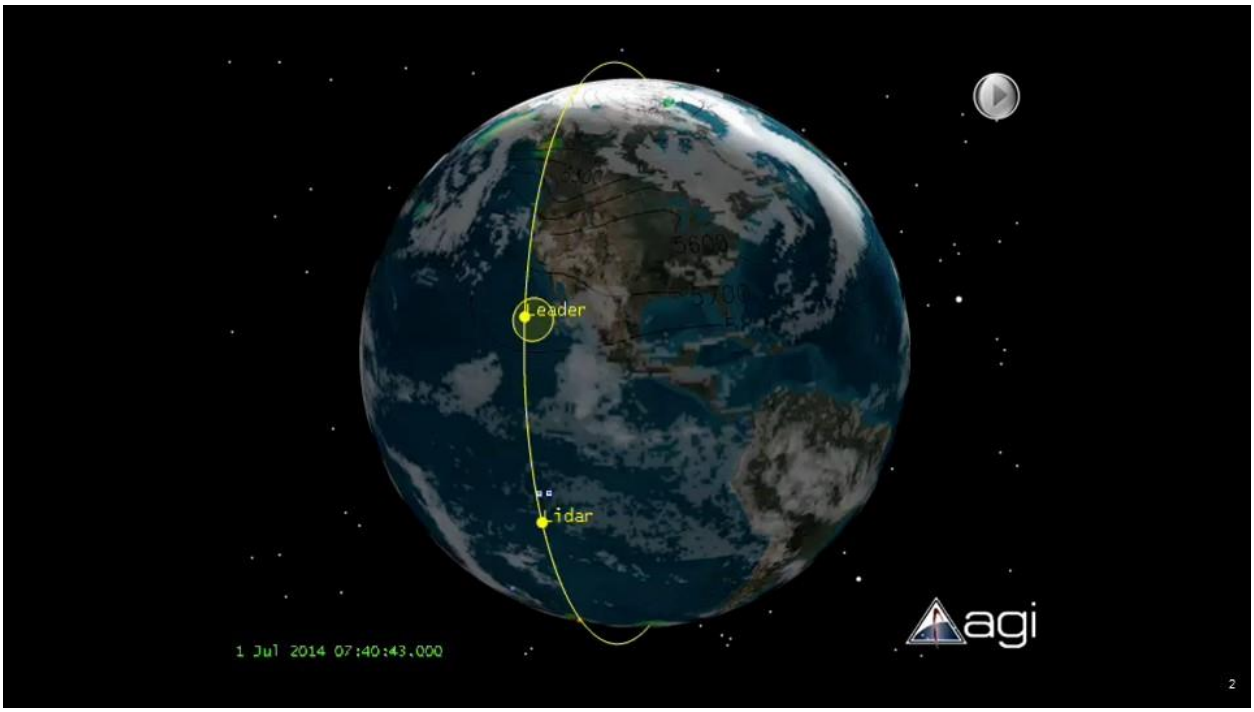
9.1 A Proposed Strategy for SMD Technology....9-2
9.2 Laser and Optical Systems for Atomic Clocks, Sensors, and Quantum Applications in Space....9-10
9.3 Photonic Integrated Circuits for Active Optical Systems in Space....9-19
9.4 Laser System for the Laser Interferometer Space Antenna (LISA)....9-30
9.5 Geiger-mode Avalanche Photodetector Development at MITLL....9-46
9.6 Prospects for the Development of Fast-Light Inertial Sensors....9-58
9.7 Ocular Hazard Risk Management for Airborne and Spaceborne Active Optical Systems....9-72

9.1 A PROPOSED STRATEGY FOR SMD TECHNOLOGY

Michael Seablom

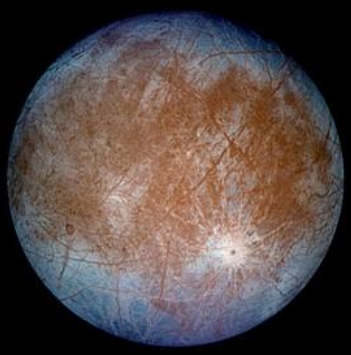
Chief Technologist, Science Mission Directorate, NASA Headquarters, Washington, D. C.





SMD Philosophy

- Technology and continued technological progress is critical for the future of SMD and its future missions
- Technology investments are pathways to flight as strategic elements of SMD programs
- SMD is actively developing flight opportunities for new technologies as part of AOs.
  - Based on our experiences, performance metrics and feedback, we will continually adjust.



3

Vision for SMD Technology

SMD's technology investments will enable the Agency to achieve its science goals. A balanced portfolio of highly innovative projects will produce breakthrough science missions that are affordable and achievable.

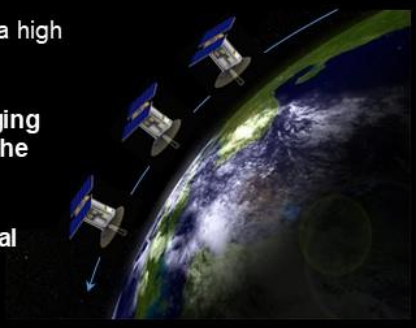


4

Strategic Objectives

1. Raise the bar on scientific discovery by increasing the number of technology infusions into SMD missions.

- The nurturing and infusion of small satellite technologies is a high priority.



2. Enhance the value of technology investments by leveraging capabilities, technologies, and lessons learned from all of the research divisions.

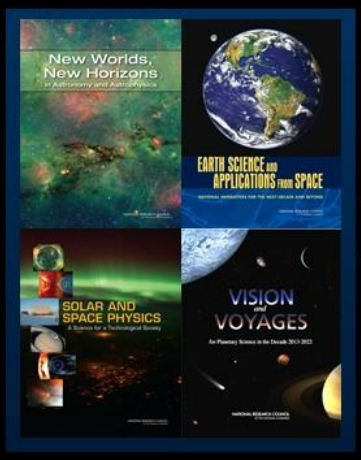
3. Maximize the contributions to our programs from external organizations, including OGAs, industry, and academia.

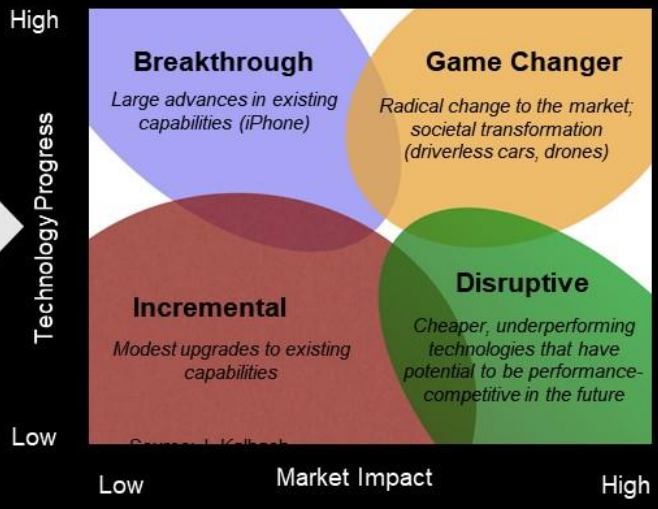
4. Continuously strive for excellence.

- Establish comprehensive metrics and clear objectives for defining organizational and cultural flexibility and efficiency.

5

Role of Technological Innovation



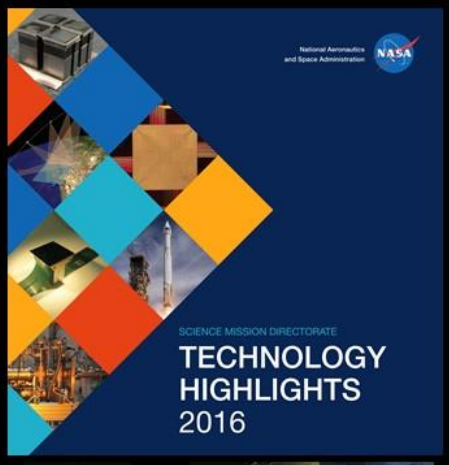


6

The SMD Technology Portfolio

Over $250 million supporting a dozen programs and nearly 250 projects per year across Astrophysics, Earth Science, Heliophysics, and Planetary Science

An additional 12 projects partnered with the Space Technology Mission Directorate (STMD) , which also supports crosscutting platform technologies across the Agency





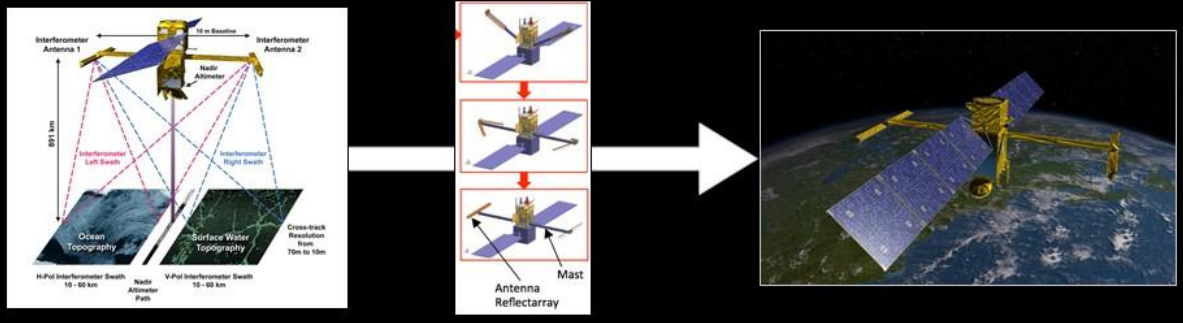




7

Examples of “Breakthrough” Innovations

Surface Water and Ocean Topography (SWOT) Mission



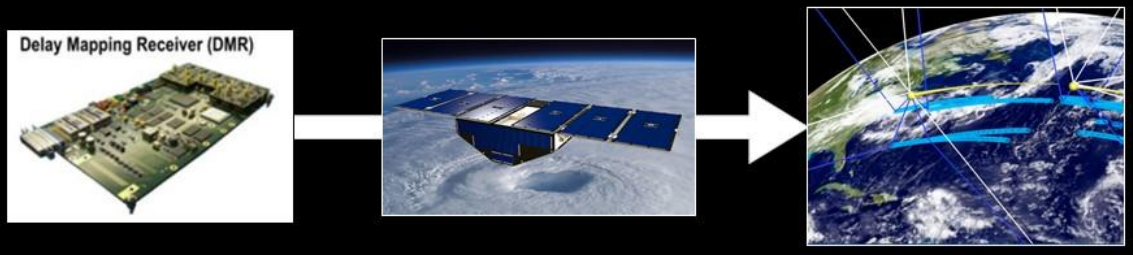
Enabling Technology: Investments in Ka-band interferometer and precision antenna mast

Result: Unprecedented swath measurements of terrestrial water heights and sea surface heights (SWOT to launch in 2020)

8

Example of "Disruptive" Innovation

Cyclone Global Navigation Satellite System (CYGNSS)



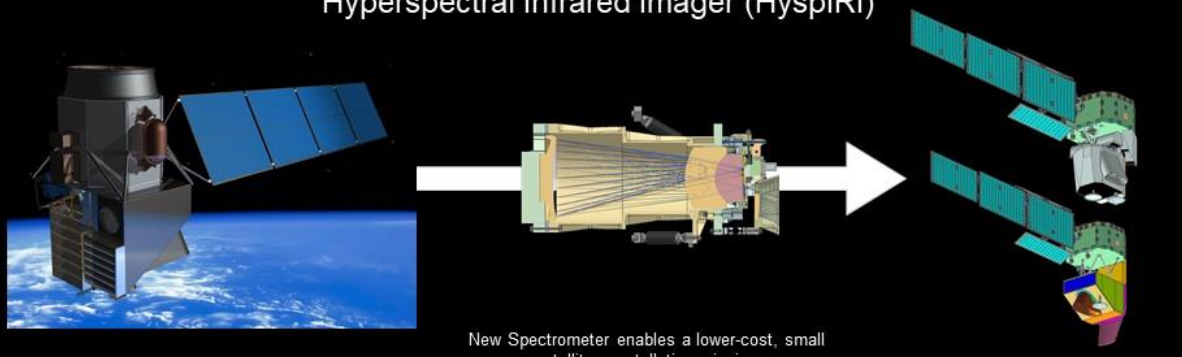
Enabling Technology: Existing technology (delay mapping receiver) deployed in an unique constellation of 8 LEO spacecraft.

Result: Frequent and accurate measurement of ocean surface winds will improve tropical cyclone forecasting

9

Example of "Game Changing" Innovation

Hyperspectral Infrared Imager (HysplRI)



High mass (700kg), high power (700W)

New Spectrometer enables a lower-cost, small satellite constellation mission

Low mass (155kg), high power (380W)

Enabling Technology: Investment in new spectrometer (Dyson replaces Offner)

Result: Small satellite constellations are the new paradigm for future hyper spectral imaging missions

10

SMD Technology: Current State

STRENGTHS

- Innovative workforce which can build a diverse set of space-borne scientific sensors that push the state-of-the-art
- World-class research scientists and analysts who understand the capabilities needed for our future missions
- Highly capable facilities, tools, and institutional resources to conduct science research and to validate technology

CHALLENGES

- Risk-averse management culture creates barriers to infusing new technologies
- Institutional obstacles that inhibit exploiting new and disruptive capabilities (e.g., small satellites)
- Insufficient coordination both within the agency and with industry, OGAs, and academia
- Lack of formal assessments of successes and failures of technology programs

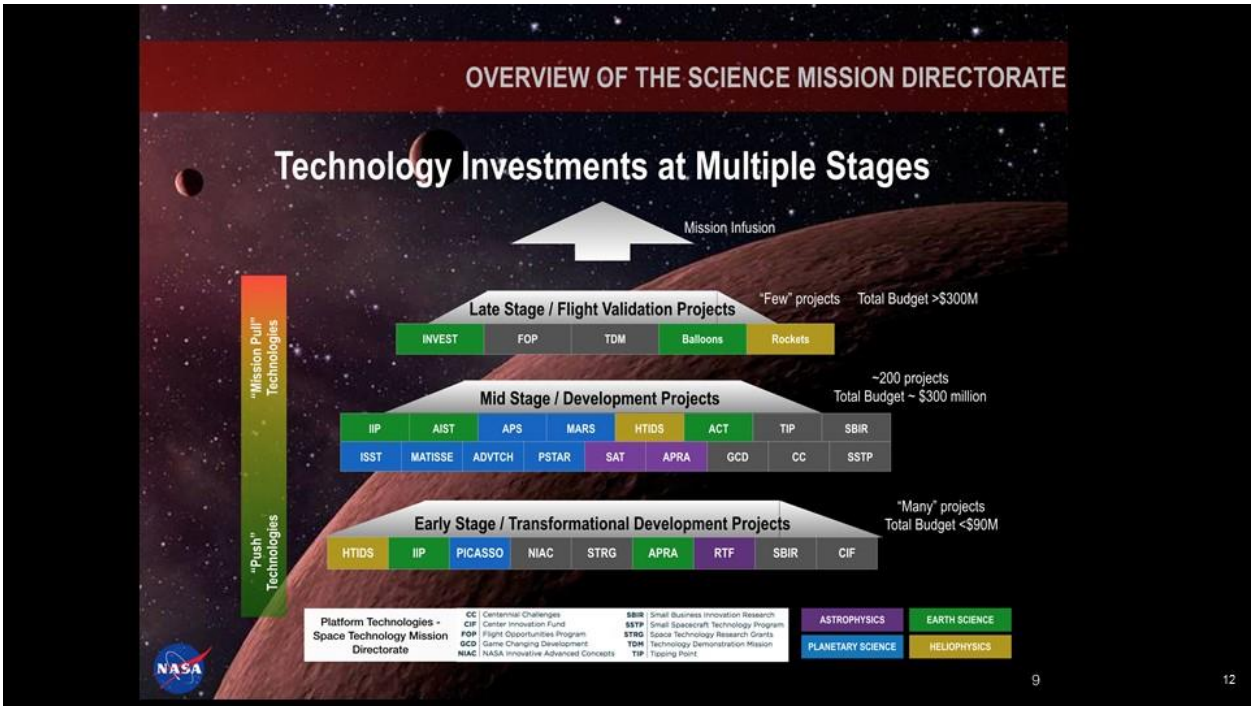
OPPORTUNITIES

- Anticipated breakthroughs in the miniaturization of instruments can enable new, affordable science missions
- Industry, academia, and OGAs are investing in technologies needed by SMD, particularly in the areas of small satellites, autonomy, and information systems
- Lower cost access to space, rideshare opportunities enable additional missions

THREATS

- Recent, rapid growth in capabilities in scientific sensors and platform technologies from Europe, China could threaten US science and technology leadership
- Attrition of workforce in critical skill areas is occurring across the Agency and could result in fewer, more expensive missions
- Re-vectoring of current science activities due to reprioritization or budget cuts could disrupt current technology investment strategies

11





13

Direction of SMD Technology Related Emphases

- Utilize AOs and SMD missions proactively for technology infusion and flight.
- Prioritize technologies of high impact for the SMD portfolio.
- Measure needs, impact and effectiveness of our technology investments and pivot, where needed.

14

Tech Infusion: Status Quo



SMD Technology Programs

TRL 3-5

Suborbital & In-Space Validation

Ground Validation

TRL 5-8

Announcements of Opportunity

Discovery, New Frontiers, Explorers Earth Venture

TRL 6-9

15

Enhanced Tech Infusion, Coordinated With STMD



SMD Technology Programs

+ New coordination with STMD Game-Changing Development (GCD) Program

TRL 3-5

Suborbital & In-Space Validation

Ground Validation

+ New coordination with STMD Technology Demonstration Mission (TDM) Program

TRL 5-8

Discovery, New Frontiers, Explorers Earth Venture

Announcements of Opportunity

+ Expanded technology demonstrations, infusions; expanded Rideshare opportunities

TRL 6-9

16

9.2 LASER AND OPTICAL SYSTEMS FOR ATOMIC CLOCKS, SENSORS, AND QUANTUM APPLICATIONS IN SPACE

Nan Yu

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California



Jet Propulsion Laboratory
California Institute of Technology
National Aeronautics and Space Administration

LASER AND OPTICAL SYSTEMS FOR ATOMIC CLOCKS, SENSORS, AND QUANTUM APPLICATIONS IN SPACE

Nan Yu

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California Institute of Technology

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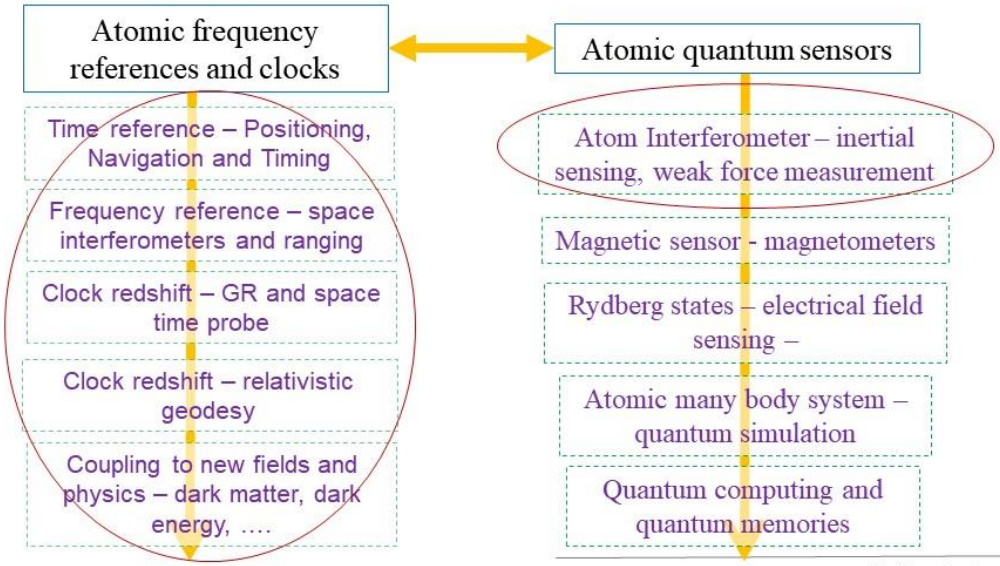
Outline

- Atomic and quantum sensor systems
- Laser roles and requirements
- Current implementation in CAL
- Challenges, development and investment needs

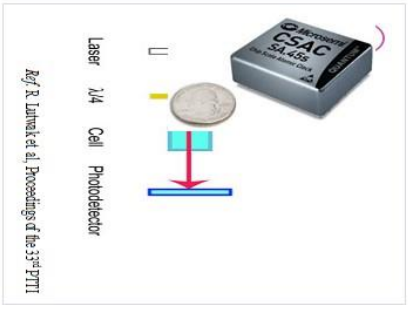
Atomic Quantum System

Salient properties of atomic system:
Constant/stable, Shielded/long coherence, Internal structure/highly controllable, Light/relativistic, and Intrinsically quantum mechanical

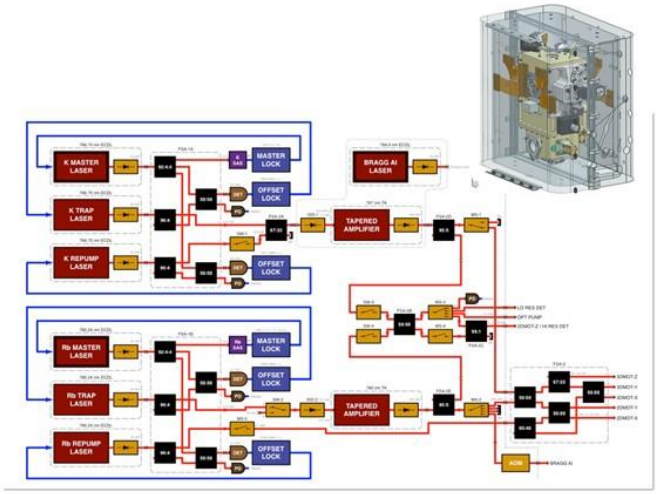


Roles of Laser and Optical System (LOS)

The link between atoms in a quantum system to the rest of the world (devices and instrument) through atom-light interactions

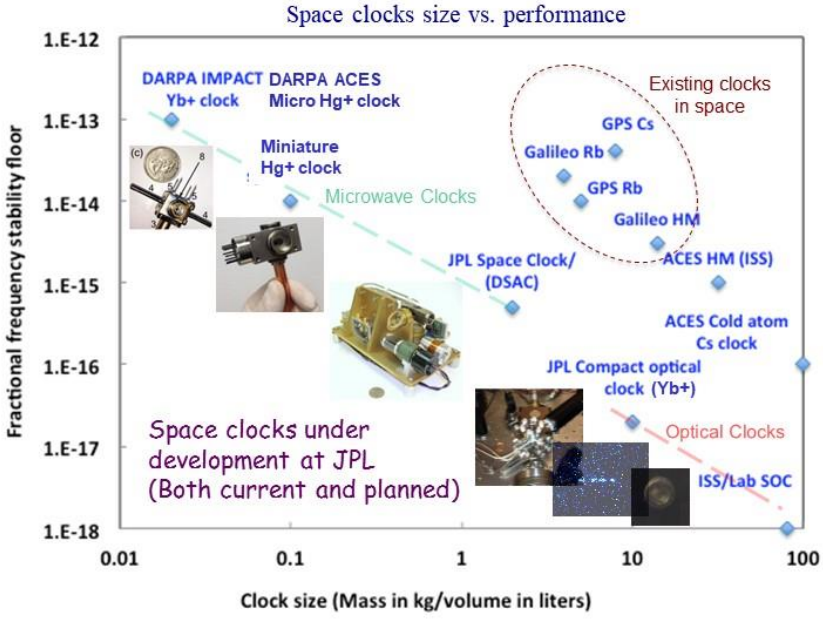


Chip-sized atomic clock



LOS for Cold Atom Laboratory (CAL) on ISS

JPL Space Clock Development



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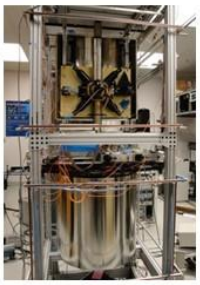
California Institute of Technology
National Aeronautics and Space Administration

Cold Atoms and Quantum Sensors at JPL

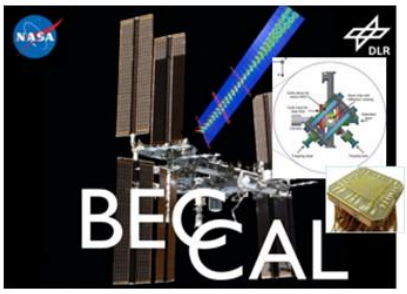




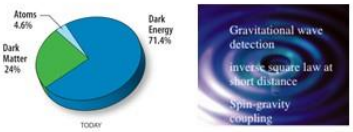
Gravity gradiometer



Compact orbiter accelerometer prototype







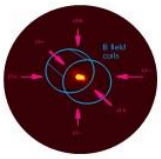
Direct detection of dark energy scaler fields, gravitational waves

Quantum Test of Equivalence and SpaceTime (QTEST)

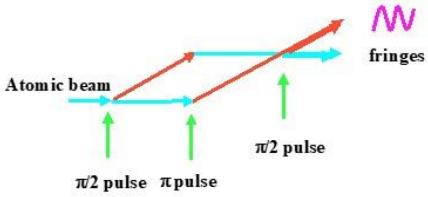
Jet Propulsion Laboratory
California Institute of Technology
National Aeronautics and Space Administration

Atomic Freefall Test Mass in Space

Freefall test mass + ***Displacement Detection*** + ***Atomic system stability***



Laser-cooled Cs atom cloud at μK



atom-wave interferometer (laser-based atom optics)

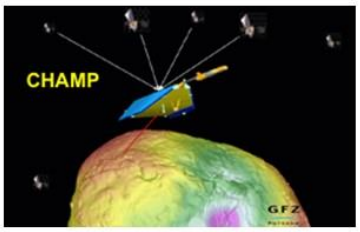


Atoms are stable clocks

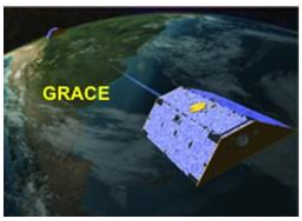
- Use totally freefall atomic particles as ideal test masses
  identical atomic particles are collected, cooled, and set in free fall in vacuum with no external perturbation other than gravity/inertial forces; laser-cooling and trapping are used to produce the atomic test masses at μK and nK; no cryogenics and no mechanical moving parts.
- Matter-wave interference for displacement measurements
  displacement measurements trough interaction of lasers and atoms, pm/Hz$^{1/2}$ when in space; laser control and manipulation of atoms with opto-atomic optics.
- Intrinsic high stability of atomic system
  use the very same atoms and measurement schemes as those for the most precise atomic clocks, allowing high measurement stabilities.
- Enable orders of magnitude sensitivity gain when in space
  microgravity environment in space offers long interrogation times with atoms, resulting orders of magnitude higher sensitivity compared terrestrial operations.

Atomic Sensors for Earth Science

GPS-CHAMP high-low satellite-to-satellite and ground based laser tracking

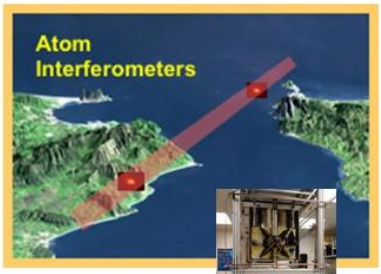


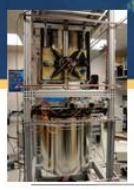
Low-low satellite-to-satellite microwave tracking and ranging (for long wavelength i.e. 500 km and time variation)





GOCE satellite gradiometry using 3-axis accelerometers (for high resolution ,i.e. 100 km)





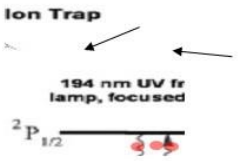
Quantum gravity gradiometer using cold atoms as truly drag-free test masses (high spatial resolution + high stability for time variation)

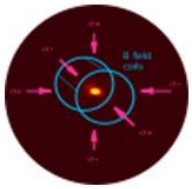
Major Functions and Requirements

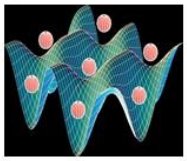
Lasers are to induce transitions between atomic level states- very wavelength specific on atomic species, spectroscopy qualities

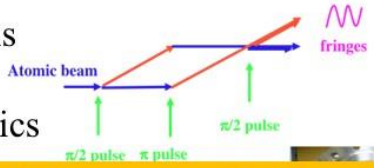
Major functions:

- Induce optical pumping
- Create velocity and spatial dependent forces
- Form optical potentials
- Act as atom-wave optics









LOS requirements: specific wavelength, linewidth, stability, tunability, frequency and phase control, intensity control, high extinction ratio, and polarization control.

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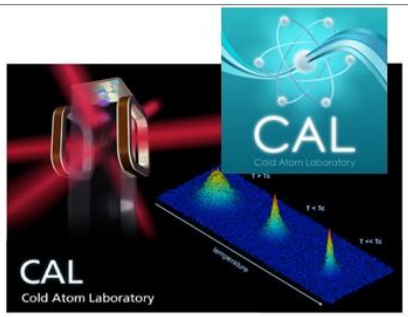
National Aeronautics and Space Administration

Efforts to Bring Atomic Systems to Space



ESA ACES mission





NASA/JPL Cold Atom Laboratory



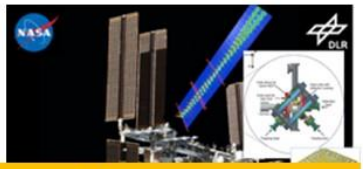
DLR drop tower
Micro gravity

BEC

QUANTUS







There is a distinctive lack of NASA investment in space qualifying the laser and optical systems for atomic systems and quantum sensors.

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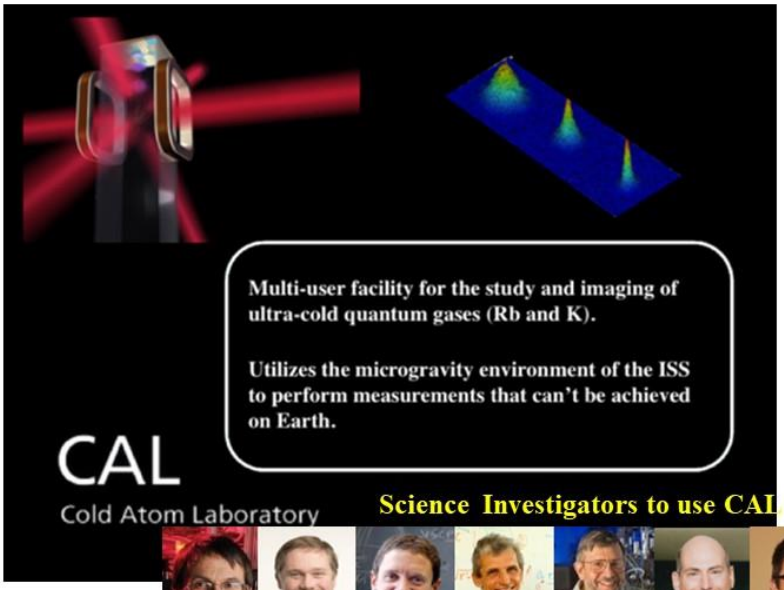
National Aeronautics and Space Administration

Cold Atom Laboratory

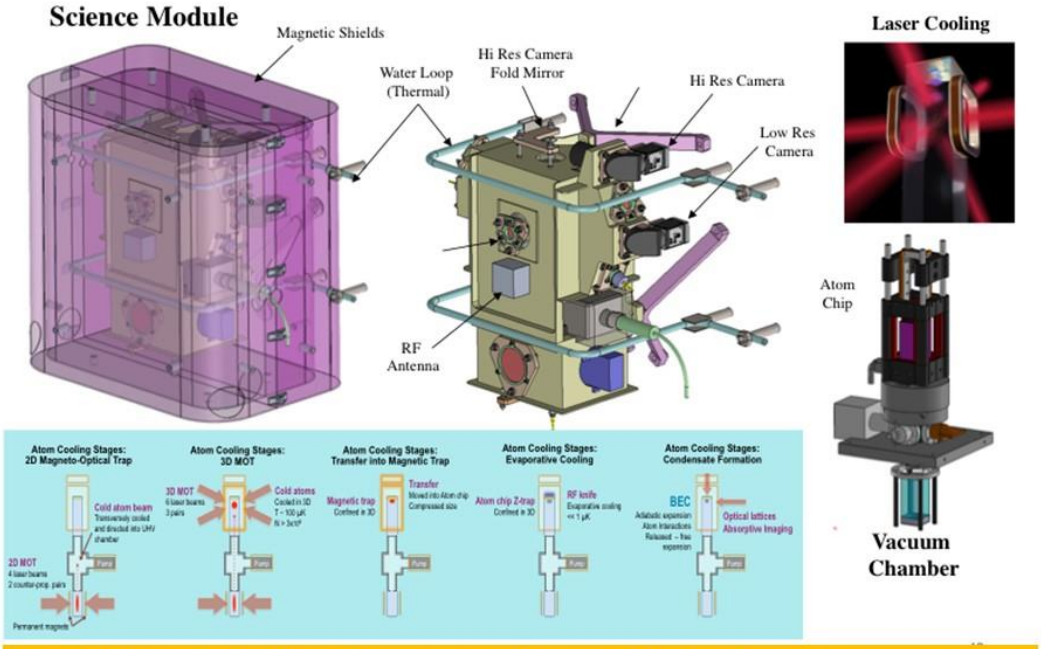


Science Investigators to use CAL



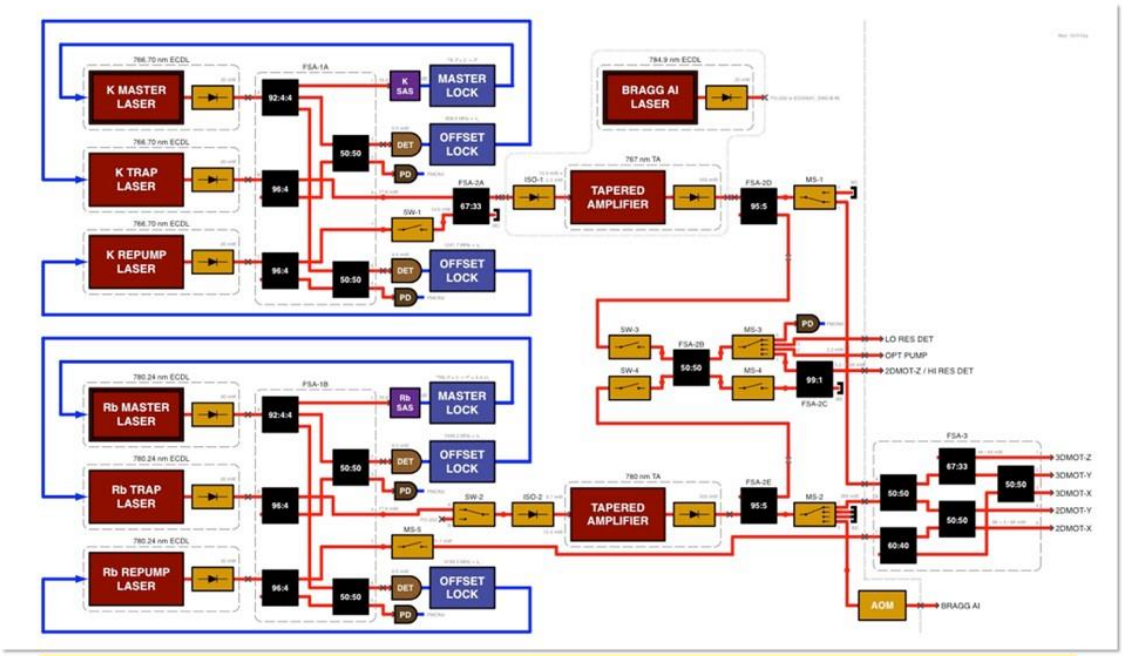
E. Cornell N. Lundblad N. Bigelow W. Ketterle W. Phillips J. Williams C. Sackett G. Raithel D. Stamper-Kurn

CAL Science Module



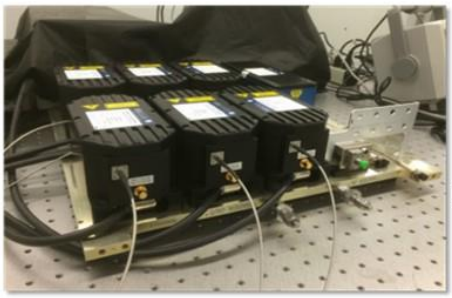
Exquisite control of laser frequency, phase, and intensity are necessary

CAL Laser and Optical System



Possibly the most involved laser and optical system ever flown in space

CAL Laser and Optical System

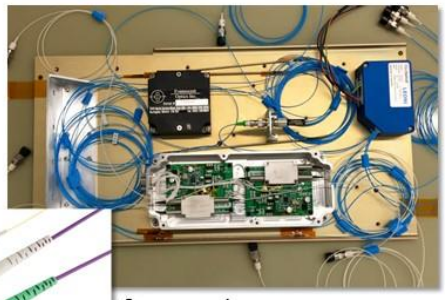


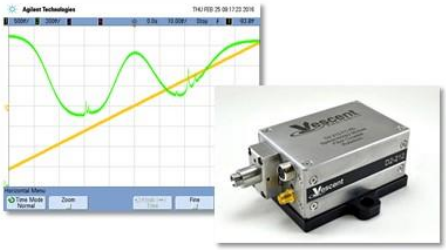




MEMS Fiber Switch (*left*) and integrated Fiber Splitter (*right*).

Flight Lasers and Tapered Amplifier on Heat Exchanger 2





Spectroscopy Module



Space-grade
fiber connectors

Detection Subassembly containing Electro-Optical Fiber Switches, Integrated Fiber Splitter/Combiners, and MEMS Fiber Switches.

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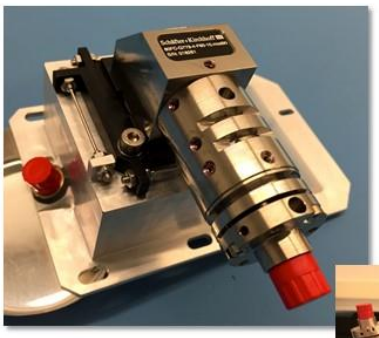
National Aeronautics and Space Administration

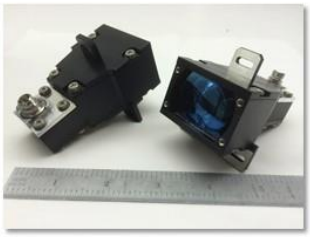
CAL Laser and Optical System



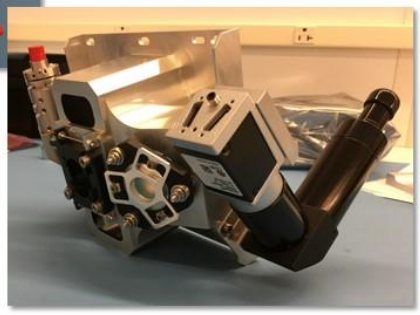
3D-MOT Collimator



Optical Module containing 3D-MOT collimator and Optical Pumping Fixture.



2D-MOT Collimators



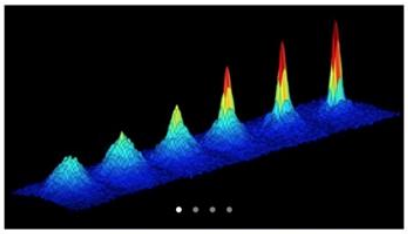
Optical Module containing 3D-MOT Optics and High-Resolution Imaging Subsystem.

Jet Propulsion Laboratory
California Institute of Technology
National Aeronautics and Space Administration

Coolest Spot in the Universe

NEWS | JULY 27, 2018

Space Station Experiment Reaches Ultracold Milestone



This series of graphs show the changing density of a cloud of atoms as it is cooled to lower and lower temperatures (going from left to right) approaching absolute zero. The emergence of a sharp peak in the later graphs confirms the formation of a Bose-Einstein condensate -- a fifth state of matter -- occurring here at a temperature of 130

The International Space Station is officially home to the coolest experiment in space.

NASA's Cold Atom Laboratory (CAL) was installed in the station's U.S. science lab in late May and is now producing clouds of ultracold atoms known as Bose-Einstein condensates. These "BECs" reach temperatures just above absolute zero, the point at which atoms should theoretically stop moving entirely. This is the first time BECs have ever been produced in orbit.



NASA's Cold Atom Lab will produce clouds of ultra-cold atoms aboard the International Space Station to perform quantum physics experiments in microgravity. Atoms are chilled to about one 10 billionth of a degree above Absolute Zero, or about 10 billion times colder than the average temperature of deep space. At those temperatures, atoms

Summary

- **Cold Atom Laboratory signifies the beginning of the era for cold atom fundamental physics in sustained microgravity environment and a giant step towards using atomic quantum systems in space applications.**
- **Atomic quantum sensors are powerful tools for precision measurements for exploring fundamental physics and space science including astrophysics, planetary science and Earth science, as well as deep space operations.**
- **Laser and optical system is a critical part of an atomic quantum system. They are complex, unique, and diverse, and require substantial investments and significant focused efforts to bring the technologies to the maturity necessary for space missions.**

9.3 PHOTONIC INTEGRATED CIRCUITS FOR ACTIVE OPTICAL SYSTEMS IN SPACE

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ABSTRACT

Photonic integrated circuit technology is advancing rapidly in terms of novel components, as well as integration into complex optical systems. PIC technology offers low size, weight, and power (SWaP) and the opportunity to build on-the-fly reconfigurable systems. These developments point to PIC technology integration into a broad set of space-based systems, either as complete systems or as key subsystems. Applications include mapping lidar, differential absorption lidar (DIAL), metrology sensors, and relative navigation sensors.

1 INTRODUCTION

A generation ago integrated optics generally referred to single functional elements, such as a modulator, that had to be combined with other elements by hand by the end user. It is now possible to put hundreds or thousands of elements on single chips. Figure 1 shows examples of parts fabricated under the MOABB program for us by UC Santa Barbara and UC Davis. These are sophisticated circuits with hundreds of elements that implement an optical phased array (OPA) for a miniaturized lidar. The rapid development of PIC technology parallels the development of electronic integrated circuits over time, with a roughly 40 years' time lag.

These commercial applications have also driven R&D efforts in academia and industry aimed at developing a broad set of components that enable construction of complex and sophisticated optical systems on a chip.

PICs provide size and weight advantages not possible with bulk optics and the increasing evolution of functional elements now makes it possible to fabricate complex systems, including optical sensors, at the chip level. DARPA has funded multiple PIC programs in this area in recent years. It is currently funding Modular Optical Aperture Building Blocks (MOABB) aimed at building chip-level coherent lidar systems. Lockheed Martin (LM) participated in Phase 1 of MOABB and is building capabilities to extend that work into a broad range of PIC-based subsystems and systems for a host of applications related to sensing and metrology.

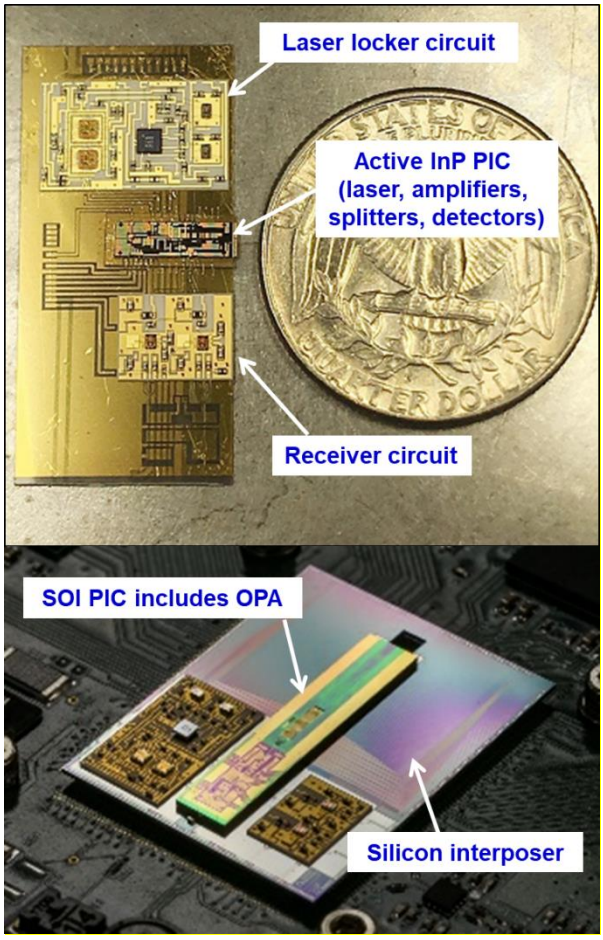

Figure 1 Top: Active/passive-component transceiver PIC. Bottom: Silicon-on-insulator (SOI) PIC incorporating optical phased array (OPA)

2 METHODOLOGY

2.1 STATE OF THE ART

Today a broad range of active and passive component designs are available for fabrication.

Active components include tunable lasers, optical amplifiers, detectors, and modulators. Passive components include waveguides for routing, multiple types of splitters, components for coupling light in and out of chips to free space or optical fibers, and even optical isolators.

TRL is highly variable depending on component types. Many parts are still at low TRL and designed on an *ad hoc* basis to meet specific needs. Other parts and subsystems, such as datacom transceivers and tunable lasers, are at TRL 9 and sold commercially.

There are substantial efforts underway in industry as well as in consortia like AIM Photonics (http://www.aimphotonics.com/) to develop process development kits (PDKs) that contains libraries of standard components, similar to what has existed in the electronics industry for several decades. Further development in this area is needed to "get the Ph.D.s out of the design cycle."

Limitations on current PIC technology that need to be addressed in coming years include loss reductions and extension of spectral ranges. Individual PIC components can incur losses at the 1 dB or higher level and cascading many functional elements can lead to very high aggregate insertion losses. High losses are frequently problematic with active optical systems and are particularly challenging with lidar systems where you see losses both in transmission and reception.

Because datacom/telecom has driven the explosion of interest in PICs much of the development has concentrated in the 1.5 µm spectral region. Silicon is transparent to ~12 µm so it can form the basis for wavelength extensions into the infrared. However, silicon by itself is insufficient and much further materials and component work is needed to provide a component ecosystem like that currently available in the telecom bands. Efforts are underway to address the infrared bands [1].

For space deployment radiation effects are also important. It is currently an area of relative immaturity compared with electronics. Radiation effects impact PIC components in different ways. Detectors and lasers are subject to increases in noise and threshold currents etc. Passive components can be impacted by small changes in refractive indices. For example, evanescent wave couplers and narrow micro-ring filters that rely on stable mode sizes or fixed optical pathlengths may see changes in coupling ratios or resonance frequencies over time. As an example, Figure 2 illustrates use of a ring filter to measure resonance frequency shifts due to gamma radiation [2].

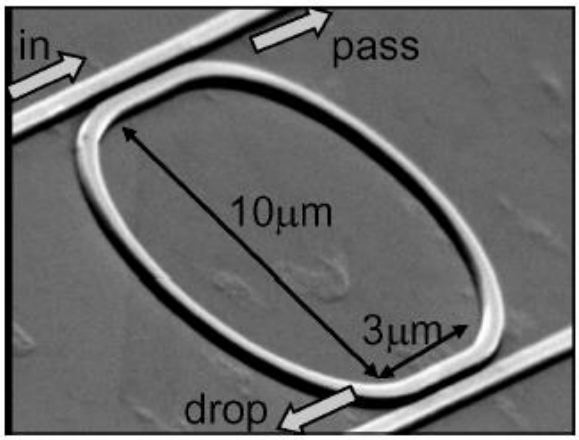

Figure 2. Laser frequency sweep can be used to measure refractive index changes due to radiation by measuring shifts in resonance frequencies [2].

2.2 NEW APPROACH

The new approach described here relates to a paradigm shift in designing and building instruments for space missions, rather than a specific instrument or sensor. As an example of such a shift we note that Lockheed Martin is currently developing PIC-based telescopes that capture light at the pupil plane, rather than at an image plane, and reconstruct images computationally [3]. This enables collapsing the thickness of the instrument to almost arbitrarily small dimensions, in the process reducing SWaP by 1-2 orders of magnitude. While a telescope does not in conventional form represent an active optical system, the thought process behind these revolutionary imagers is representative of what can be done when these new PIC tools are available. Figure 3 illustrates the operating principle of the telescope and Figure 4 shows an image from a first-generation demo system.

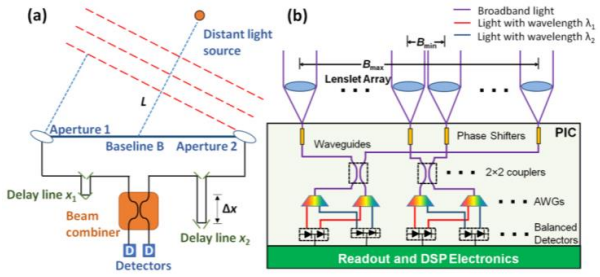

Figure 3. (a) A two-aperture interferometry system. (b) Working principle of the interferometer PIC

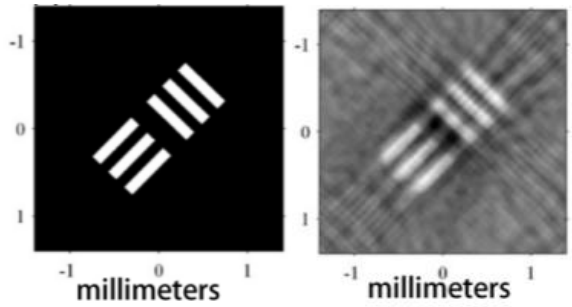

Figure 4. USAF bar chart test target used for SPIDER imaging demo: left - test target and right - laboratory image reconstruction.

2.3 DESCRIBE THE FUTURE STATE

We envision a future state like that of electronic integrated circuits (ICs), where:

- Stable processes to produce low loss parts are available from multiple foundries
- Rich component libraries exist to enable selection of parts for a broad range of systems and applications
- Simulation and design tools are simple enough that they can be used by relatively inexperienced engineers
- Packaging is matured and, to the extent possible, standardized
- Radiation effects are known well enough that parts can be confidently designed for the space environment
- Optical and electronic part are embedded in the same chips through 3D integration techniques currently in development

Maturation to this future state will enable rapid fabrication of subsystems and systems for a host of applications, including: range finding, imaging and differential absorption (DIAL) lidar; metrology; relative navigation; free-space optical communication (FSOC); imaging telescopes; and others. The small form factors enabled by PIC implementations will enable hosting on smallsats and cubesats, where SWaP is currently prohibiting deployment of many types of instruments.

To play an important part in future instrumentation PICs do not have to constitute the entirety of the system but may be used to form critical subsystems. An example would be as agile and small form-factor seed lasers for lidar systems. Because of the ease of fabricating small structures, one option may be to replicate multiple units on a single chip with switches used to enable/disable individual units under detected failure conditions.

2.4 RISKS AND REWARDS

The payoff associated with development of space-based PIC systems are clear: low SWaP, stable fabrication processes, low fabrication cost once non-recurring engineering cost are met. Rapid re-configuration, for example by building multiple on-the-fly switchable systems with different functionality on a single substrate, is another potentially high payoff area.

Risks that could endanger rapid future development include technical issues noted above (e.g. reducing losses, developing infrared parts). It is also critical that technology and infrastructure development is funded at a sufficient level to enable the continued growth of PIC technology. Active collaborations between universities, small and large businesses, as well as government organizations are essential to drive development forward.

3 PROGRAMMATICS

3.1 DEVELOPMENT PLANS

We do not at this time have a specific program in mind, but propose, based on the above comments, that there are two broad areas that could be considered for funding:

- Perform a comprehensive assessment of potential application areas of interest to NASA, where PIC technology could provide clear advantages over current bulk technology
- Perform a comprehensive assessment, supplemented by testing, of radiation effects on PIC components

Execution of these tasks would deliver reports on the state of the art and recommendations for future actions. Assessments should include a broad range of experts drawn from government, industry, and academia.

3.2 DEVELOPMENT MILESTONES AND DATES

Upon request LM would be pleased to develop a program plan with milestones and schedules to execute the proposed tasks. At this point we estimate that the noted assessment/parts testing tasks could likely be completed in 6-12 months.

3.3 PARTNERING

NASA centers, including GSFC and LARC, as well as related organizations, particularly JPL, could play an important role in the proposed work. This applies to both the assessment of PIC applicability to future instruments and the radiation effects assessments. Many universities and small businesses active in PIC development could also play important partnering roles.

3.4 OVERCOMING THE VALLEY OF DEATH

At LM many PIC-based systems are currently developed to the functional demonstration level in a laboratory environment. The "valley of death" relates largely to packaging and qualification of devices for the space environment. We are addressing these issues internally but would benefit from the establishment and adoption of best practices and standardization of packaging approaches.

4 WIDER VISION

PIC technology is generic in the same sense as electronic ICs. Developments in one area, such as lidar, will have cross-cutting benefits for other areas. FSOC and computational imaging systems have been mentioned. Others include spectroscopy and RF photonics.

5 CONCLUSIONS

PIC technology continues to be developed at a rapid pace and may one day be as commonplace as electronic ICs. Continued investments are needed to maintain development of parts and infrastructure. For space applications radiation effects is an incompletely characterized area that would benefit from in-depth assessment.

ACKNOWLEDGEMENTS

The author acknowledges support from many individuals for the DARPA MOABB portion of this work. These include: Jim Colosimo, Cale Gentry, and Greg Whaley at Lockheed Martin; John Bowers, Larry Coldren, Jonathan Klamkin, and Tin Komljenovic at UC Santa Barbara; and S.J. Ben Yoo and Yu Zhang at UC Davis.

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Numbered in the order they appear in the text, with brackets. Example of references:

1. http://www.aimphotonics.com/news-release/ucsbled-team-selected-for-demonstration-of-a-novel-waveguide-platform/
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3. Su, T, et al., 2018: Interferometric imaging using Si3N4 photonic integrated circuits for a SPIDER imager, *Optics Express* **26** (10), pp. 12801

PHOTONIC INTEGRATED CIRCUITS AT LOCKHEED MARTIN SPACE

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This research was developed in part with funding from the Defense Advanced Research Projects Agency (DARPA). The views, opinions and/or findings expressed are those of the authors and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.
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Outline

- History
- Example: DARPA MOABB Coherent Lidar
- The Bigger Picture
- Risks
- Future State Vision
- Conclusions and Path Forward

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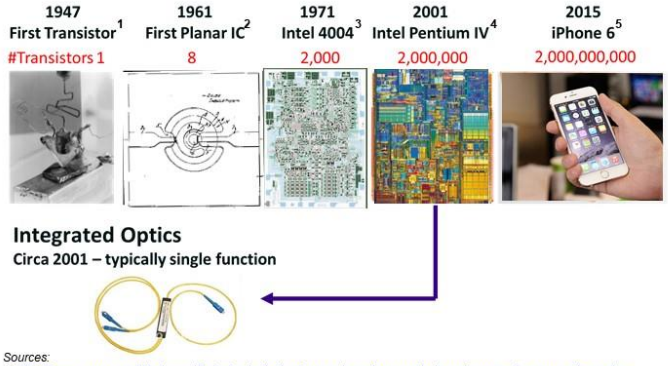
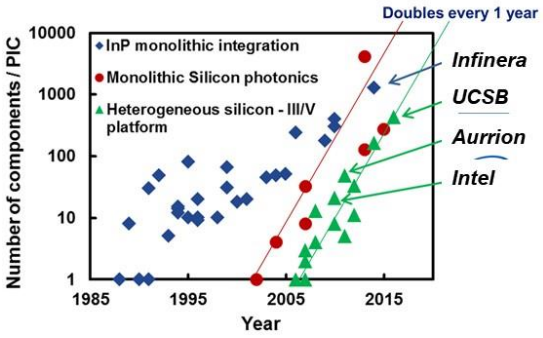
Electronics vs. Photonics History

Electronics



Photonics



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2. US Patent 2981877A
3. www.4004.com, licensed under CC BY-NC-SA 3.0
4. http://www.activewin.com/reviews/hardware/processors/intel/p4253ghz/cpuarch.shtml, © 1997-2012 The Active Network, Inc. Unless Otherwise Noted. All rights reserved.
5. https://www.tomsguide.com/us/apple-iphone-6,review-2390.html Credit: Jeremy Lips/Tom's Guide

Photonics lags electronics by ~40 years

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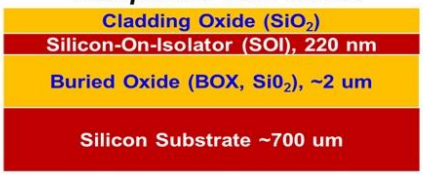
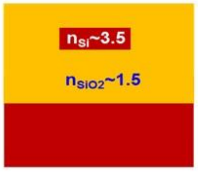
Key Enabler: Silicon Photonics

Compatible With CMOS

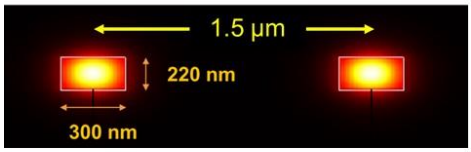


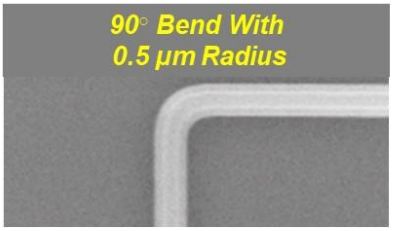
"Strip Waveguide"

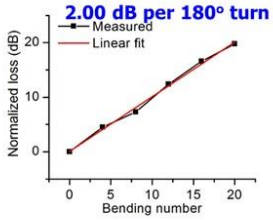


Huge Δn (3.5-1.5 = 2)

- → *Extremely tight mode confinement*
- → *High packing density w/ low cross-talk*
- → *Very tight bend radii*







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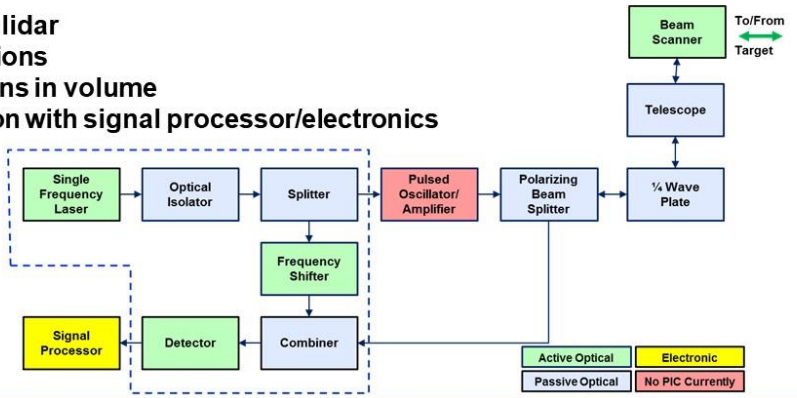
Coherent Lidar in a PIC?

Except for high peak power source coherent systems can be built with PICs
- **Peak power limited to ~100 mW in single Si waveguides, ~1 W in silicon nitride (SiN)**

Benefits of chip-scale lidar
- **Large SWaP reductions**
- **Large cost reductions in volume**
- **Future 3D integration with signal processor/electronics**



DARPA MOABB challenge: do this with increased aperture by phase

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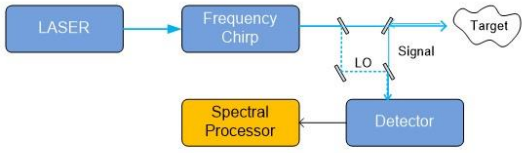
FMCW Lidar

- **Frequency-modulated continuous wave (FMCW) uses low power**
- **Coherent detection → single photon sensitivity**
- **Range resolution = $c/2B_{opt}$**
  - ***2 cm resolution → B_{opt} = 8 GHz***
- **Mix down B_{opt} to RF domain**
  - **Reduces electronics bandwidth B_{RF}**
  - **Typically need B_{RF} < 1 GHz**
- **Velocity for free from up-down chirp**

MOABB goal
Build single point scanned system
Incorporate non-mechanical beam steering



Time delay τ between LO and return signal produces intermediate frequency proportional to range R = ct_o/2. Velocity adds fixed frequency Doppler offset f_D*

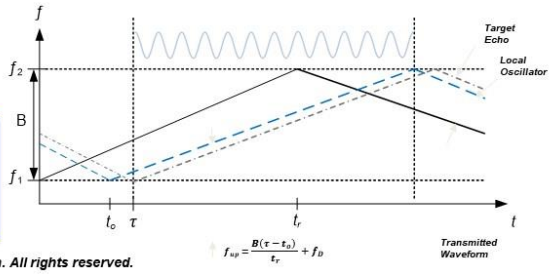
During up-chirp detector signal is proportional to where B = ramp bandwidth, t_r = ramp duration

$$\cos\left[2\pi\left[\frac{B(\tau - t_o)}{t_r} + f_D\right]t\right]$$

During down-chirp detector signal is similar with sign switch

$$\cos\left[2\pi\left[-\frac{B(\tau - t_o)}{t_r} + f_D\right]t\right]$$

Sum and difference of two measured frequencies extracts range and velocity



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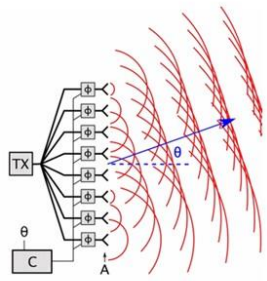
UC Santa Barbara Beam Steering

Key program goal: Incorporate non-mechanical beam steering

2D steering demonstrated under DARPA SWEEPER program

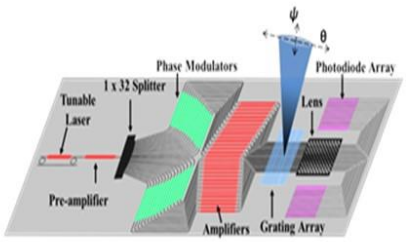
- Tunable laser + grating steers in one dimension
- Transverse phase gradient steers in other dimension (optical phased array - OPA)

Phased Array



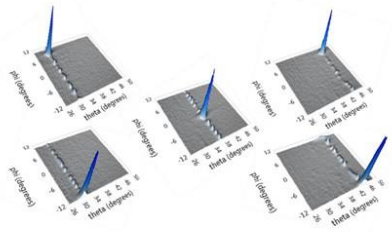
Source:https://en.wikipedia.org/wiki/Phased_array

UCSB Functional Layout



Source: J.C. Hulme et al., SPIE Photonics West [8989-6] (2014)

~24 x 12 Degree Steering Demonstration (using 16 channel test chip)



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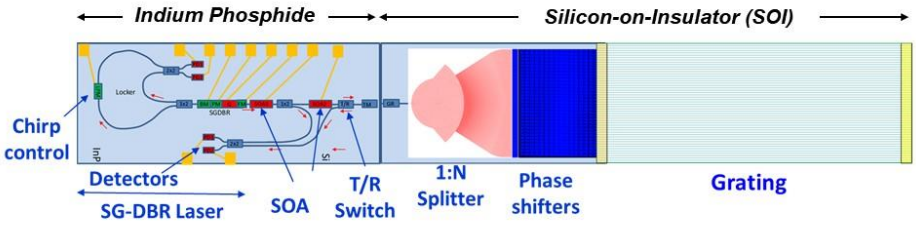
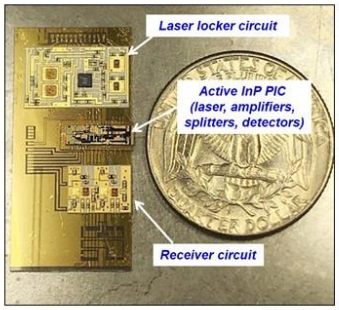
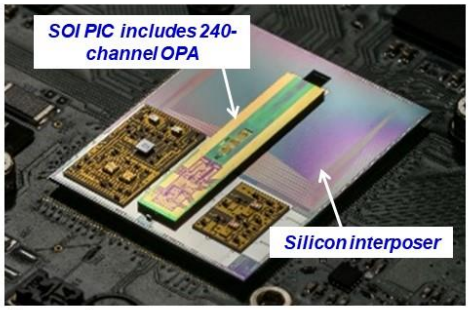
MOABB PIC Subsystems

Functional Architecture







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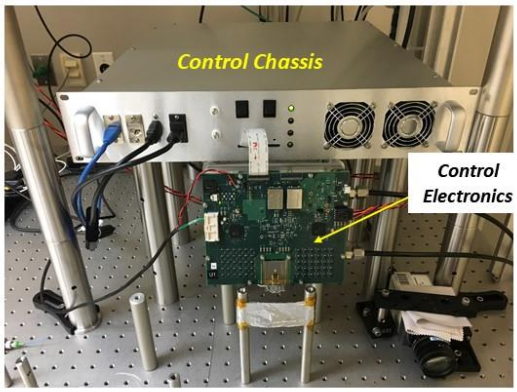
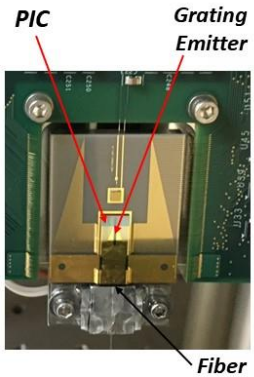
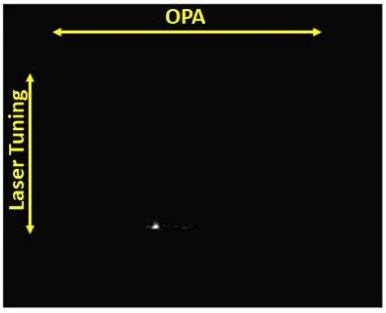
Non-Mechanical Beam Steering Demo

- **Uses 120 channel PIC from UC Davis with thermal phase shifters**
- **External tunable laser from Freedom Photonics**





Beam Steering Demo



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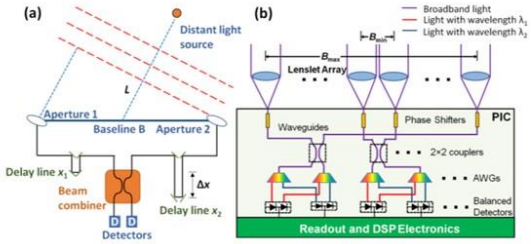
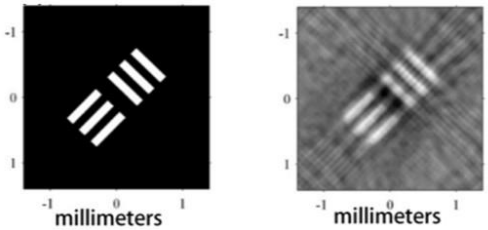
The Bigger Picture - PIC Applications

- **Metrology**
  - Nanometer-class position sensors
  - Benefit: Small, thermally stable
- **DIAL Lidar**
  - Tunable IR lasers, wavemeters
  - Benefit: Minimal SWaP
- **Communications**
  - Coherent comms terminals
  - Benefit: Minimal SWaP
- **Computational Imaging**
  - SPIDER interferometric imaging
  - Benefit: 10-100x SWaP reductions

SPIDER Imaging System





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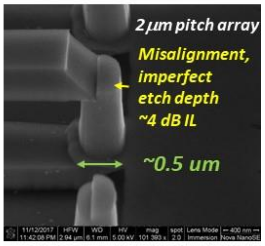
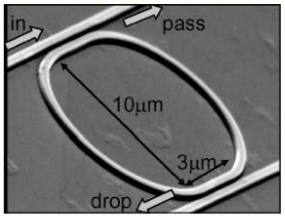
Rewards and Risks

- **Rewards**
  - Low SWaP (low power at system level)
  - Low cost after NRE
  - Rapid re-configuration
    - Multiple switchable different functionalities on a single substrate
    - Redundant switchable systems on single substrate
  - 3D integration of photonics
  - 3D photonic/electronic co-integration
- **Risks**
  - PIC components can have high insertion loss
    - Cascading many elements
    - In lidar systems losses hit in both Tx and Rx
  - Extending spectral range from telecom to infrared bands
  - Radiation effects far less well characterized than for electronics
    - Small refractive index changes can have big performance impact
  - Maintaining high technology and infrastructure development funding
    - Need continued active collaborations between universities, small and large businesses, as well as government organizations.

Sub-um fold mirrors transfer light between PIC layers (UC Davis)



*Example ring structure used to characterize radiation effects**



** Source: Dumon, P. et al., 2005: Measured radiation sensitivity of Silica-on-Silicon and Silicon-on-insulator micro-photonic devices for potential space application", Proc. SPIE 5897, pp. 58970D-1 (2005)*

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Future State Vision

- **Stable processes @ multiple foundries**
  - AIM Photonics flourishing
- **Rich component libraries**
  - Enables quick development of low risk parts
- **Simple simulation and design tools**
  - "Get the Ph.D.s out of the design cycle"
- **Mature/standardized packaging**
  - Currently ad hoc
  - AIM Photonics Testing And Packaging (TAP) facility
- **Well understood radiation effects**
  - Far less work done than for electronics
- **Co-integration of optical and electronic parts**
  - The same CMOS processes can do both for some parts

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Conclusions and Path Forward

- **PIC technology is advancing rapidly**
  - May be as common as electronic ICs in the future
  - Replace bulk optics
  - Enable new types of optical systems or subsystems
  - Enables deployment on new platforms e.g. cubesats
- **Space applications assessment**
  - Consider performing comprehensive assessment of potential application areas of interest to NASA, where PIC technology could provide clear advantages over current bulk technology
- **Radiation assessment**
  - Perform comprehensive assessment, supplemented by testing, of radiation effects on PIC components

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Thank You!

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9.4 LASER SYSTEM FOR THE LASER INTERFEROMETER SPACE ANTENNA (LISA)

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ABSTRACT

NASA Goddard Space Flight Center is developing a master oscillator power amplifier (MOPA) laser transmitter for the ESA-led Laser Interferometer Space Antenna (LISA) mission [1], which is designed to detect gravitational waves from various astronomical sources. The laser system is one of the candidate component contributions from the US. The LISA laser system has two unique requirements, ultra-low phase noise and long lifetime, in order to perform picometer-level interferometry in space. We will overview the current status of the LISA laser development, describing potential risks. We will also address synergistic opportunities that are expected to arise from the LISA laser development.

1 INTRODUCTION

The gravitational wave space mission LISA has been accepted for the European Space Agency (ESA) L3 launch opportunity (~2034 launch), and NASA intends to contribute instruments to the mission. LISA's eventual flight will open a spectacular new window on the universe, using gravitational waves to reveal the physics and astronomy associated with the merger of massive black hole systems. The primary scientific goal of LISA is to detect and observe gravitational waves from astronomical sources such as massive black holes (MBHs) and galactic binaries in a frequency range of 10^{-4} to 10^{-1} Hz. LISA is now under Phase A in ESA, and the ESA has expressed interest in the laser system as a possible contribution from NASA.

The LISA observatory is comprised of three spacecraft, free flying and arranged in an approximately equilateral triangle, each spacecraft exchanging laser signals through its telescopes with the two adjacent spacecraft (Figure 1). The separation between any two spacecraft in the constellation is 2.5 Million-km. Inside the spacecraft, there is an accelerometer system which monitors a 1 kg proof mass which acts as the end mirror in the interferometer arm. The relative motion of the proof mass, which represents the passage of gravitational waves, is monitored by heterodyne interferometers. The backbone of LISA is a highly stable laser with ~2 W power, which enables the picometer interferometry necessary to record the passage of a gravitational wave at shot-noise-limited performance. The requirements for the LISA laser system is summarized in Table 1.

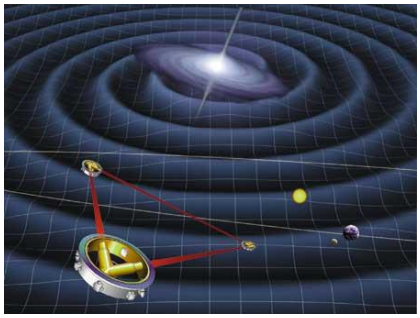

Figure 1, Conceptual figure of the LISA mission

Table 1, LISA laser requirement

Wavelength	1064nm	Lifetime	16 years (10 years in space)
Operating mode	CW	Frequency noise	<300Hz/rtHz@~10mHz (after prestabilization)
Output power	>2W	Intensity noise	$<10^{-4}$/rtHz@~10mHz <10-8/rtHz@~10MHz
Polarization	Linear	RF phase noise	<400 urad/rtHz@~10mHz
Spatial mode	TEM_{00}	Frequency repeatability	<50MHz
Phase modulation	~2.4GHz	Frequency tuning	>2GHz

Recently, there were three notable events that accelerated technology development efforts for LISA. The first event is the direct detection of gravitational waves by a terrestrial gravitational wave detector, the LIGO (Laser Interferometer Gravitational-wave Observatory), [2] in 2015. Three LIGO scientists received the Nobel Prize in Physics 2017 "for decisive contributions to the LIGO detector and the observation of gravitational

waves". The LIGO not only proved the existence of the gravitational wave, but also opened up a multi-messenger astronomy [3]. The second event is the successful operation and completion of the LISA Pathfinder (LPF) mission [4] in 2016-2017 [5]. The LISA Pathfinder mission was a proof-of-concept mission to test and prove the technology needed for LISA's success. The LPF tested several key LISA technologies, such as drag-free control, micro-Newton thrusters, and heterodyne interferometry in space. The performance of the LPF provided an experimental benchmark demonstrating the ability to realize the low-frequency science potential of the LISA mission. The third event is the successful operation of the laser ranging instrument (LRI) of the GRACE-FO (Gravity Recovery and Climate Experiment Follow-On) mission [6] in June 2018. The twin satellites follow each other in orbit around the Earth, separated by about 220 km. The separation of the satellites is monitored to map out the Earth's gravity field. The LRI has many common technologies to LISA, such as optical phase locking, precision phasemeter, and laser frequency stabilization. Therefore, the key technologies needed for LISA has been already demonstrated by the two related missions.

However, there are several areas, which still need careful development and evaluations for the laser system for LISA. They include the low-noise fiber amplifier, more compact master oscillator, and highly reliable components for the required long lifetime. We are working to demonstrate a TRL 6 laser system, which is an essential step toward qualifying lasers for space applications, by 2021, addressing these issues.

2 METHODOLOGY

2.1 STATE OF THE ART

Figure 2 shows the MOPA system for LISA. Our research effort has included both master oscillator (MO) and power amplifier (PA) developments, and their environmental testing and reliability for space flight. In addition to the standard requirements for size, weight and power (SWaP), radiation hardness requirements as a space laser, the most challenging requirements are set by 1) the low frequency noise, 2) the low intensity noise, and 3) the long lifetime (~16 years including integration, test, cruise phases and science operations). Our current baseline for the MO is a low-mass, compact mNPRO (micro non-planar ring oscillator) laser at 1064 nm. The fiber amplifier is forward-pumped by 976-nm multimode laser diodes, which are coupled to a tapered fiber bundle (TFB) to allow redundant power input to pump a double-clad, large-mode-area (LMA) ytterbium (Yb) gain fiber. We have performed laser system noise tests by amplitude- and frequency-stabilizing the PA output. At a breadboard level, the system has met the stringent noise requirements for LISA. The TRL of the NASA's laser system for LISA is 3-4 at the time of this writing.

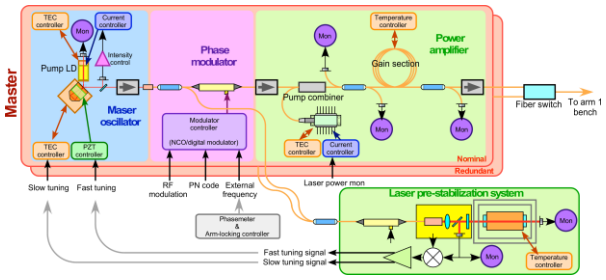

Figure 2, LISA laser optical system diagram

Another candidate component for LISA from NASA is a telescope to expand and to receive laser beams. Since the telescope is in the measurement path of the LISA's long arm, picometer level mechanical stability is required in order not to obscure the tiny displacement signal caused by the gravitational waves. Also, the scattered light must be small enough compared to the low laser power received from the far spacecraft (~300 pW). A 4-mirror off-axis telescope has been designed to minimize the effect of the scattered light. The TRL of the NASA's telescope system for LISA is also 3-4 at the time of this writing.

2.2 NEW APPROACH

As a backup plan and a new approach, we are working with commercial partners, both for the MO and PA. For the MO, we have initiated discussions with conventional NPRO vendors. For the PA, we are selecting potential PA builder(s) using the standard two-step selection method. The selected vendors have slightly different fiber amp technologies. We are also working on a crystalline fiber amplifier, which is expected to reduce the length, non-linear effect, and thus differential phase noise. Since the projected launch of LISA is 2034, it is not a trivial problem to identify laser

(parts) vendors that will be able to provide continuous production and support before and after the launch.

Having multiple MO and PA designs is programmatically advantageous for the long-term mission. It is also technically advantageous since the latest technologies (such as mNPRO and crystalline fiber amplifier) can be developed with reduced risks. We are putting our development priority to our in-house MO and PA efforts, since we have direct insights into all technical details and have achieved the key noise requirements with them.

2.3 DESCRIBE THE FUTURE STATE

Precision heterodyne interferometry in space is opening up new fields. As the GRACE-FO's LRI has demonstrated, it will be used to map gravity field of the earth and other planetary bodies. If SWaP is further improved, such compact laser terminal can be put on a smaller platform, such as CubeSats. The new concept would enable measurements between multiple spacecraft, and would also dramatically improve the measurement accuracy.

Follow-on missions to LISA are also conceived, for example, as the Big Bang Observer (BBO) [7]. It is assumed to use higher output power lasers (~100 W) with frequency conversions. This concept would enable observation of stochastic gravitational-wave background generated in the very early universe right after the Big Bang. Our low-noise, high-power continuous-wave laser development effort is paving the way for observing the early universe that cannot be accessed by any other electro-magnetic wavelengths.

2.4 RISKS AND REWARDS

The primary technical risk of the LISA laser is the lifetime issue of the laser system. It is practically impossible to test a laser system in space-like environment over 10 years (LISA's operation duration). In order to achieve the unprecedented lifetime in space, we have paid special attention to parts selection, testing, failure analysis, system design, and modeling. We work closely as possible with parts providers, especially with pump laser diode manufacturers. This experience benefits all other future space laser missions.

3 PROGRAMMATICS

3.1 DEVELOPMENT PLANS

Our development plan is driven by the funding profile from FY16-FY24 and we are prioritizing different efforts discussed in this paper accordingly. Our current target dates for the laser development path are breadboard demonstration targeting end of 2018, engineering model by October 2019 and the TRL 6 laser transmitter with laser electronics and pre-stabilization by July 2021.

3.2 DEVELOPMENT MILESTONES AND DATES

Our development milestones are aligned with the ESA's schedule. We are planning to deliver TRL 4/5 laser system engineering model (EM) to ESA by October 2019, before the end of Phase A, which will be on November or December of 2019. This TRL 4/5 system will not include the frequency pre-stabilization reference cavity. We will internally select laser architectures before then, primarily based on noise performance. We then will deliver TRL 6 laser system engineering test unit (ETU) with the reference cavity by July 2021, so that ESA can finish unit-level TRL 5/6 demonstration by the end of 2021. ESA will down-select a LISA laser system around this time out of some European laser groups and NASA.

3.3 PARTNERING

Due to market demands, the laser industry is mostly interested in high-power, pulsed laser applications. Watt-level, low-noise CW laser has much smaller markets. Our laser design and performance are in part limited by the available commercial products. For example, high power (>1W), single-mode 885-nm pump diode, which doesn't exist commercially, is expected to improve the mNPRO performance. Partnering with pump diode manufacturers would benefit this kind of applications based on low-noise lasers.

For the frequency stabilization cavity and its internal phasemeter, we'll work with JPL and Ball Aerospace, who built the GRACE-FO cavity.

3.4 OVERCOMING THE VALLEY OF DEATH

Parts reliability and availability are our major concerns and could be the "Valley of Death" for our development approach. We are 16 years from the tentative launch date. Qualification of parts and

reliability testing need to be coordinated with vendors to ensure they will be available at the time when the flight lasers are in production. Our mitigation plans to over the Valley of Death are: (a) for vendors and parts availability - we plan to, for any particular parts, have a prime and at least one backup vendor so that we are not relying on a unique product line, and (b) for parts reliability - we are working on significant de-rating and build-in redundancy to meet the long lifetime requirement.

Partnering with other vendors and/or research groups would also help to overcome these problems.

4 WIDER VISION

The LISA laser technology has already been applied to map the Earth's gravity field. Heterodyne interferometry with a stable laser will find other applications, such as the metrology laser source for deployable telescopes, precision formation flying, and coherent laser communication with precision ranging capability. The compact MO (mNPRO) will find its applications as a seed laser, for example, for trace gas sensing lidar for earth science, sodium lidar for heliophysics, and wind lidar for earth and planetary sciences.

5 CONCLUSIONS

The laser system is one of the candidate component contributions from NASA to the ESA-led LISA mission. The LISA laser system has two unique requirements, ultra-low phase noise and long lifetime, in order to perform picometer-level interferometry in space.

Key technologies for LISA has been demonstrated in space in pathfinder missions, and they can be directly applicable to earth science and astrophysics missions. We are developing the MOPA laser system for LISA and prioritizing our efforts with continue updates to our plans and concepts during this development period. Once the laser design is complete and TRL6 advancement has been demonstrated, we will work on transferring this design to the industry. We will be partnering with industry and other institutions in anticipation of the flight and flight spare laser build in mid-2020's for the 2034 launch of the LISA mission.

ACKNOWLEDGEMENTS

We thank the Physics of the Cosmos (PCOS) office for their funding support for the NASA/L3 LISA study activities.

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Laser System for the Laser Interferometer Space Antenna (LISA)

Kenji Numata, Anthony Yu, Hua Jiao, Scott Merritt, Frankie Micalizzi, Molly Fahey, Jordan Camp, Michael Krainak

NASA Goddard Space Flight Center

8/2/2018

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- 1. Introduction
  - Gravitational Waves (GW)
  - Brief history of GW projects
- 2. Measurement principles
  - Heterodyne interferometer
  - Laser requirements for LISA
- 3. Laser activities for LISA
  - LISA laser architecture
  - Master oscillator
  - Power amplifier
- 4. Summary

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1. INTRODUCTION

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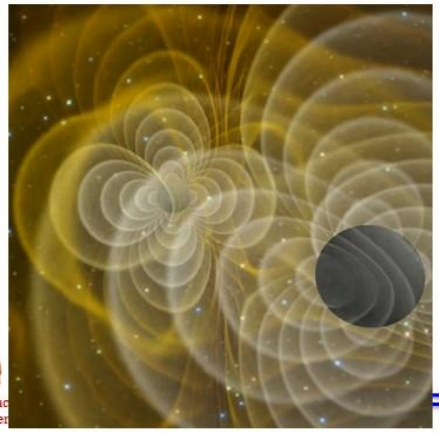
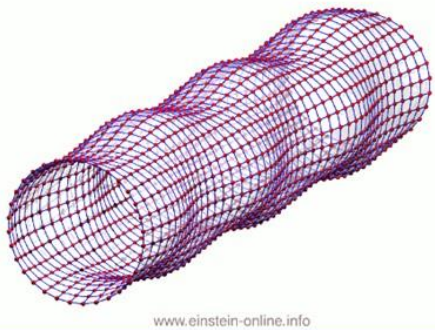
Gravitational waves

- **Emitted from super-massive objects**
  - New way to observe universe
    - E.g. Black hole (BH) – BH binary (GW150914)
  - Causes distance change between free masses (objects)
    - Detection by laser interferometer
    - Differential strain between two orthogonal directions





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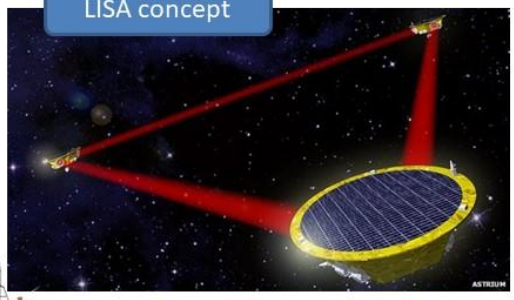
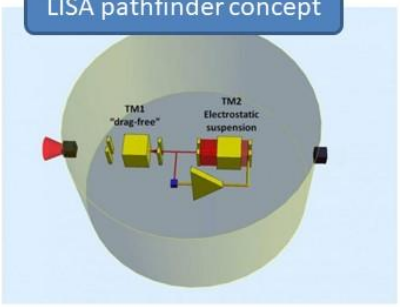
Gravitational wave detection

- **Size of strain**
  - h~10^{-21} for typical GW source
    - L=10^6km (LISA): L* h ~ 1 pm
      - C.f. Bohr radius (size of Hydrogen atom): 53pm
- **Displacement measurement between "free" masses**
  - Floating mirror (drag free)

LISA concept



LISA pathfinder concept



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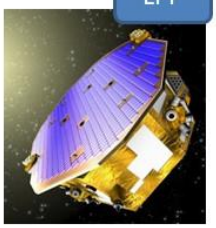
Brief history of GW projects

- 1916 Einstein Predicted the existence of GWs
- ~1960 Interferometric GW detector concept established
- ~1980 NSF Funded LIGO prototype
- ~1990 LISA Concept established, first proposed to ESA
- 1994 Initial LIGO Started
- 1997 LISA Pitched as a joint mission between ESA and NASA
- 2000 LISA Identified as a 'L1' mission candidate in ESA
- 2008 Advanced LIGO Funded by NSF
- 2011 NASA Exited LISA partnership with ESA
- 2012 ESA Established eLISA (Evolved LISA) concept
- 2013 eLISA Put in ESA's L3 slot (2034 launch)
- **2015 Advanced LIGO Detected the first GW**
- **2017 LISA pathfinder (LPF) Successfully completed**
- **2018 GRACD-FO Operating successfully**

LIGO



LPF



- **Laser is one of the candidate component contributions to the ESA-led LISA mission from NASA**

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6

2. MEASUREMENT PRINCIPLES

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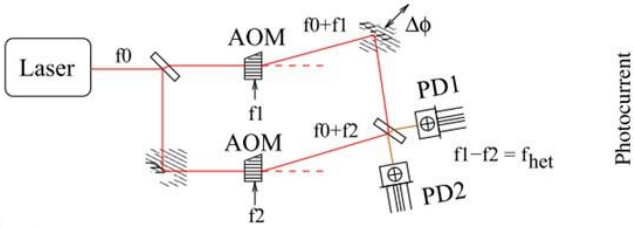
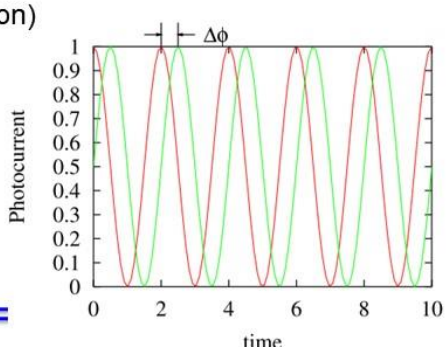
LISA pathfinder (LPF)

- **Heterodyne Mach-Zehnder interferometer**
  - Don't stay on dark fringe and/or resonance
    - Large dynamic range
  - Use of phasemeter
    - Measure phase change by comparing beatnote to ultra-stable oscillator (USO)
    - Typical noise: µcycle/√Hz ~ 1pm/√Hz
    - Frequency offset ~kHz
    - No phase locker (easy implementation)





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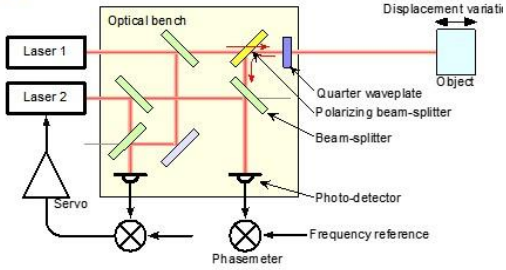
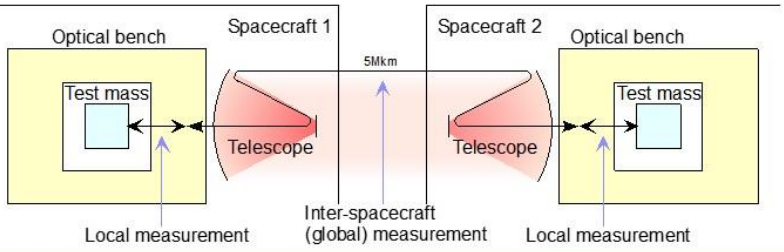
LISA

- **Similar heterodyne interferometer**
  - Two phase-locked lasers
    - "Amplifying mirror"
      - Changing Doppler shift
    - Phasemeter with internal PLL
    - Phase locker with ~μcycle accuracy
      - Shot noise limited (~30pW)
  - Split interferometry
    - 3 interferometers to measure 1 DoF





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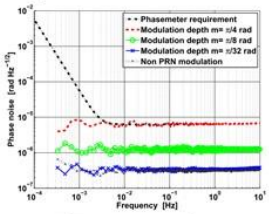
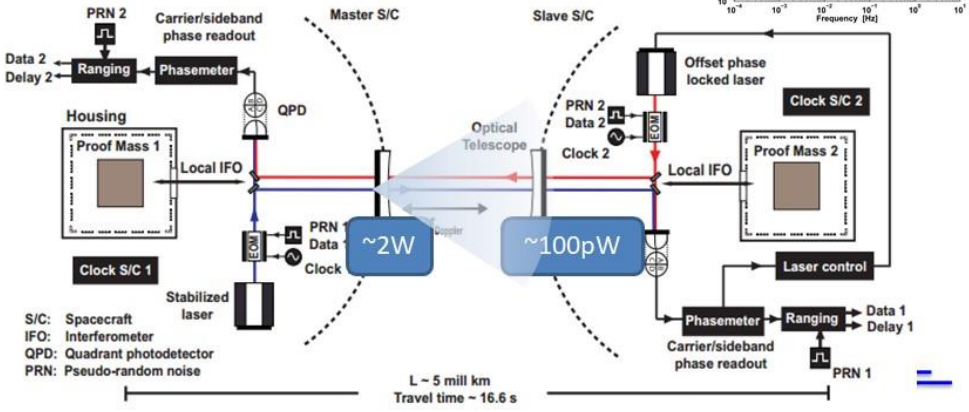
Amplifying mirror

- **Measurement principle requires "optical phase cloning"**
  - Except for GW signal, Doppler, & intentional frequency offset
    - Absolute ranging accuracy: sub meter
    - Relative measurement accuracy: picometer
      - Weak light phase locking





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Laser requirements for LISA

- **High level LISA laser requirements**
  - Wavelength & power
    - Wavelength:1064.49nm, >2W CW, single mode/frequency
  - Size & mass
    - 200 x 200 x 200mm (incl. electronics), 10kg per laser head (LH)
  - Lifetime
    - **>16 years** (including ground testing, cruise, normal and extended science ops)
  - Noise requirements
    - Frequency, intensity, RF phase noise
  - Other requirements
    - Dissipated power <50W
    - OP temperature 20±10°C
    - NOP temperature -20°C to +50°C
    - Few mW pick-off for Laser Pre-stabilization System (LPS)
    - Linear polarization

3. LASER ACTIVITIES FOR LISA

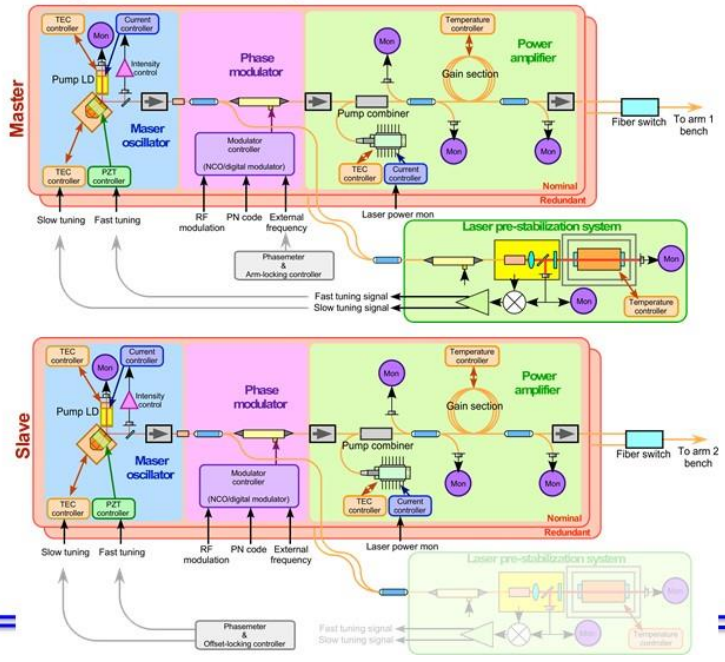
LISA Laser Architecture

- **Master oscillator power amplifier (MOPA)**
  - A MOPA architecture separates the problem
    - Low noise, high power, and GHz phase modulation
  - The MO dominates the frequency noise.
    - Low power, low noise MO, followed by a fiber-coupled phase modulator
  - The PA dominates the RIN and RF phase noise.
    - Low noise power amplifier for power scaling of the modulated MO output.

	Master oscillator (MO)	Power amplifier (PA)
GSFC in-house	micro-NPRO (AVO)	LMA Yb fiber amp. (LGS) Nd:YAG crystal fiber
External vendor	Conventional NPRO	Yb fiber amps (Fibretek, Advalue, vendor #3)

Laser Optical Module (LOM)

- **Not including redundancy within LH**



NASA Laser Activities

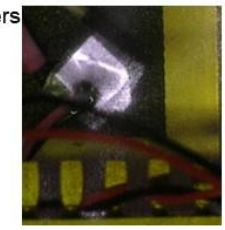
- **To develop and improve the technology readiness level (TRL) to 6:**

Tasks	GSFC Milestones	ESA Milestones and Need Dates
TRL4/5 Laser System Engineering Model (EM) (no-Prestabilization) Delivery	10/2019	MFR (End Phase A): November/December 2019
TRL6 Laser System Engineering Test Unit (ETU) with Pre-stabilization Delivery	7/2021	Unit-Level TRL 5/6 for Payload Demonstrator items: end 2021
TRL6 Laser System ETU Lifetest	implement at various development stages	"integrated-level" TRL 6 for adoption: end 2023

- **Significance of Work:**
  - Develop enabling technology for the LISA mission
  - US contribution to the LISA mission led by ESA
- **Approach:**
  - MOPA laser architecture that is consistent with the ESA approach for LISA
  - Develop two MO approaches for risk mitigation
  - Similar parallel approach for the PA development
  - Integrate MO and PA to demonstrate MOPA performance meeting LISA's requirement.
  - Develop and implement reliability test plan on critical components and systems.

MO approach 1 – GSFC micro NPRO

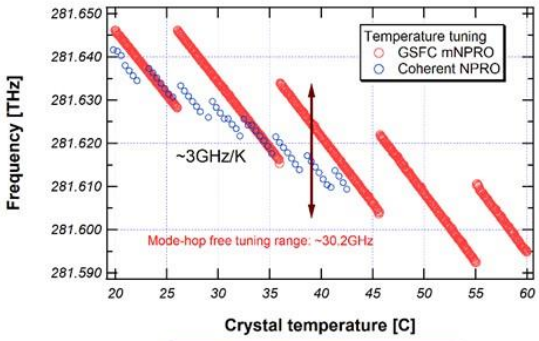
- **Conducted intensive research on different MO types**
  - Dropped fiber/semiconductor lasers because of their high intensity/phase noise
  - Realized a smaller NPRO (non planar ring oscillator) crystal is more advantageous for LISA
- **micro-NPRO features**
  - Larger free spectral range (FSR)
    - Less chance of mode-hop, easier frequency overlapping between 6 lasers
  - Better spatial overlap between pump and signal
    - Minimized un-pumped region and optical loss
    - Single spatial mode pumping for lowest phase noise
  - Smaller package
    - Use of telecom / semiconductor laser packaging technology
    - Can fit more MOs into the allocated volume



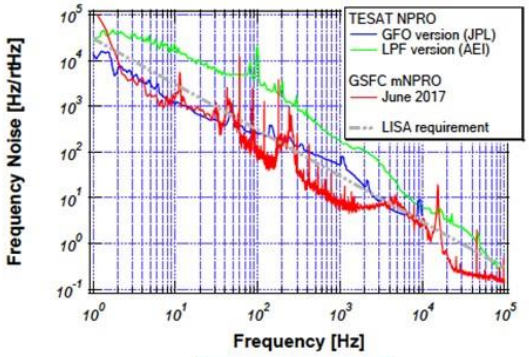
- **Redesigned small, alignment-tolerant crystal**
  - 3mm width, ~300mW output max (in free-space, high enough for PA seeding)

▪ **Goals are to reduce size and weight with improved performance, and to add extra redundancies and robustness.**

mNPRO breadboard performance



Thermal frequency tuning



Frequency noise

- **Thermal frequency tuning coefficient**
  - **Basically independent of crystal size**
  - **If only linear thermal expansion α is considered:**
    - $\frac{\Delta v}{v} \approx \frac{\Delta L}{L} \approx \frac{\alpha L \Delta T}{L} = \alpha \Delta T$
    - **Therefore,** $\frac{\Delta v}{\Delta T} = \alpha \times v \approx \left(6.1 \times 10^{-6} \frac{1}{\mathrm{K}}\right) \times (281\mathrm{THz}) \approx 1.7\ \mathrm{GHz/K}$

Goddard Space Flight Center

▪ mNPRO is NOT more temperature-sensitive than conventional NPRO.

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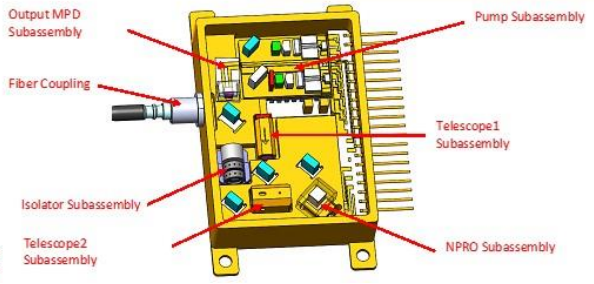
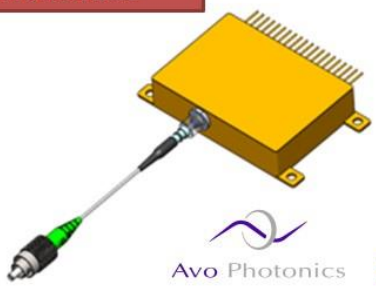
m-NPRO packaging

- **Completed Pre-Design Review (PDR) - 3/2018**
- **1st package delivery: 8/2018**
- **A mechanical model has been developed in accordance with optical design and required optical alignment tolerances.**
- **The design allows for minimal mechanical changes to move from prototype versions where epoxy is predominantly used to hold/align optics to production where epoxy is eliminated in favor or welded or soldered components.**
- **The design has been developed to be modular in nature such that key subassemblies may be assembled, characterized, and qualified outside the overall system.**

All materials and processes are under control of NASA. Looking for flight opportunities before LISA.



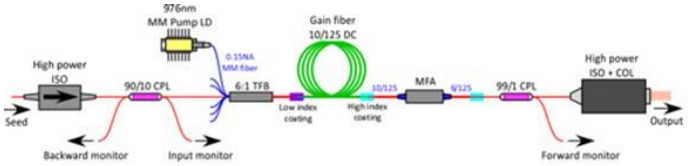


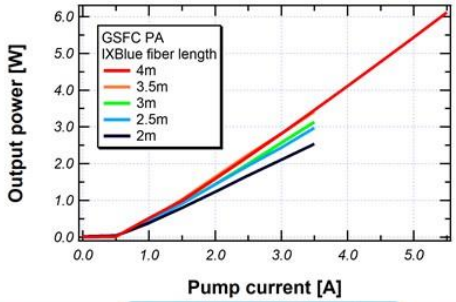
Avo Photonics

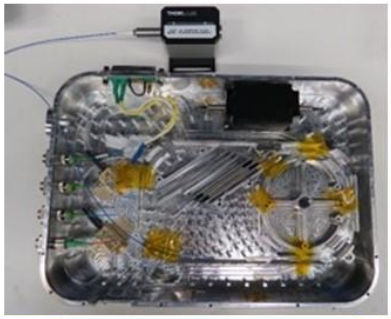
18

PA approach 1 - GSFC power amplifier

- **All-fiber configuration, based on LGS study**
  - >2W, continuous-wave output
    - Double-clad large mode area (LMA) fiber
    - Forward pumping for safety & lower SBS noise





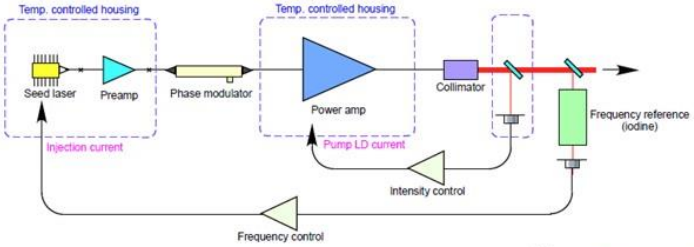


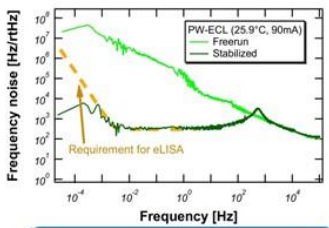
GSFC PA output power changing gain fiber length

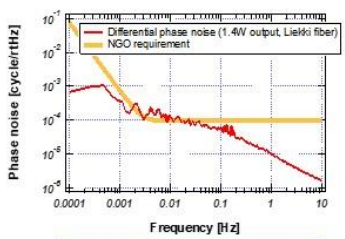
GSFC PA package (brassboard version)

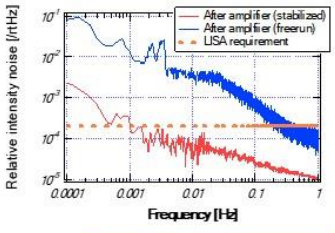
MO + PA system noise

- **System noise demonstrated to satisfy LISA requirements**
  - Master oscillator + power amplifier
    - Will be revisited with packaged m-NPRO, new PAs, and cavities.









Stabilized frequency noise of PW-ECL + GSFC PA

Differential phase noise of GSFC PA

Stabilized intensity noise of GSFC PA

4. SUMMARY



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4. Summary

- Technology needs
  - Ultra-low noise, single-frequency, single-mode, CW laser (>2W output)
  - Long lifetime in space
  - Frequency stabilized laser with world's best level stability
  - High optical power handling optical switches
- Current limitations
  - No long-lifetime CW laser at Watt level demonstrated in space
  - No high-power (>1W) single-mode pump laser at 808nm or 885nm with wavelength stabilization
  - No high-power (~30W) multi-mode pump laser at 975nm with wavelength stabilization and hermetic package
  - No high-power optical isolator at 1064nm with weak (or no) leakage magnetic field
  - No ~GHz low-loss phase modulator with >2Watt handling power
- Current measurement state of the art
  - Picometer-level displacement measurement at low-frequency (over ~30cm to ~100km)
  - Micro-cycle level optical phase locking at low-frequency
  - Ultrastable, compact seed laser technology
  - Frequency stabilization in space with high-finesse optical cavity



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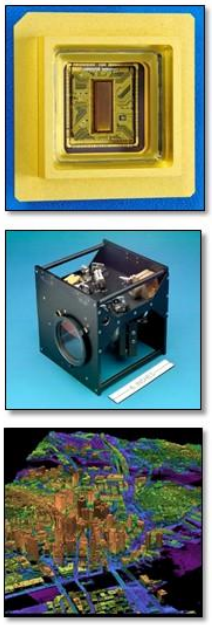
Summary (contd.)

- Desired future measurement needs
  - Higher power, lower noise laser for follow-on missions to LISA
  - More compact system for future gravity mapping missions for Earth and other planetary bodies
- Critical gaps in raising the TRL
  - Pump diode reliability for long lifetime in space
  - TRL 3~4: Low-noise fiber amp, micro NPRO package
- How will NASA "lead, leverage, or collaborate" between Centers, OGAs, FFRDC, academia, and industry to achieve the TRL necessary for the measurements?
  - Early decision to contribute to the LISA laser
  - Support related SBIR and R&D work
  - Help transfer technology from NASA to industry
- Cross-cutting or synergistic opportunities that are expected to arise from this technology advancement
  - Precision ranging (e.g. gravity-field mapping, formation flying, coherent ranging)
  - Coherent communication
  - Wind lidar
  - Metrology system (e.g. for deployable telescope)

9.5 GEIGER-MODE AVALANCHE PHOTODETECTOR DEVELOPMENT AT MITLL

Abigail S. Licht, Jon Frechette, Mohamed Diagne, Alex McIntosh, Brian Aull, and Erik Duerr

MIT Lincoln Laboratory, Lexington, Massachusetts



Geiger-mode Avalanche Photodetector Development at MITLL

Abigail S. Licht, Jon Frechette, Mohamed Diagne, Alex McIntosh, Brian Aull, Erik Duerr

NASA Technical Interchange Meeting on Active Optical Systems for Supporting Science, Exploration, and Aeronautics Measurement Needs, August 2018

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Outline

- MITLL Geiger mode Avalanche Photodetector (GmAPD) Applications
- GmAPDs
  - Principles of operation
  - Silicon and compound GmAPDs
  - Imaging systems and readouts
- Areas of Development
  - Crosstalk mitigation
  - Radiation testing
- Summary

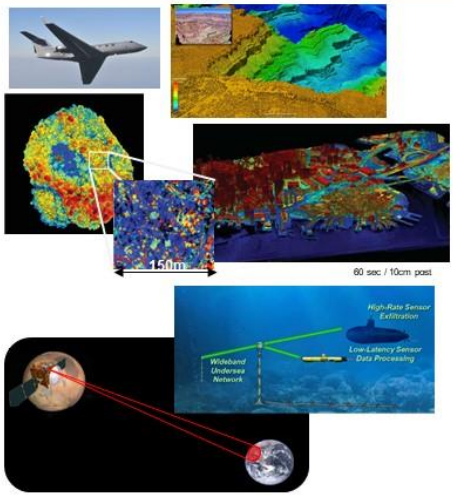
MIT Lincoln Laboratory Infrared GmAPD Applications

Ladar

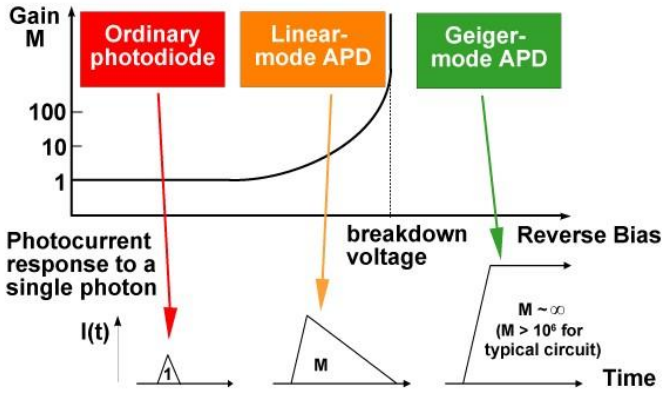
- Airborne Laser Radar Testbed
  - Wide-area mapping
- MACHETE Foliage Penetrating Ladar
  - Object identification under obscurants

Communication Systems

- Demonstrations of lasercom technology in high loss environments
  - Deep space
  - Underwater
- GmAPD detectors studied and developed as the basis for low SWAP optical receivers



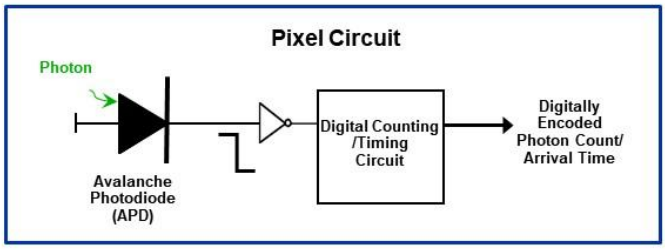
What is Geiger-mode?



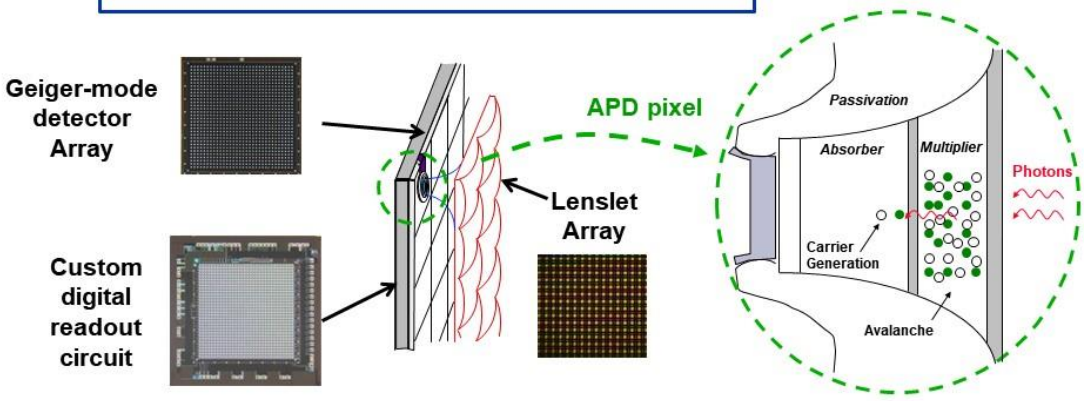
- Unity-gain photodiodes unsuitable for single-photon detection
- Linear-gain-mode APDs require high-gain and low-noise amplifiers for single-photon detection
- Geiger-mode APDs provide nearly infinite gain and allow for in pixel digitization, eliminating read out noise

Key Enabling Technology

Geiger-mode Imager: Photon-to-Digital Conversion

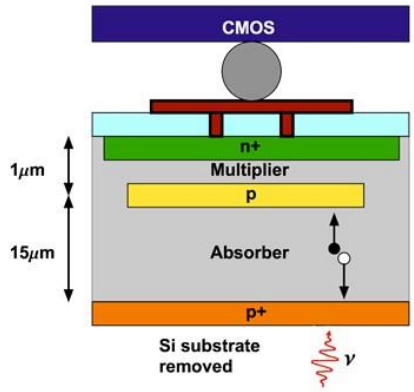


Geiger mode enables:
- **In-pixel digitization**
- **Noiseless readout**
- **Sub-ns timing**

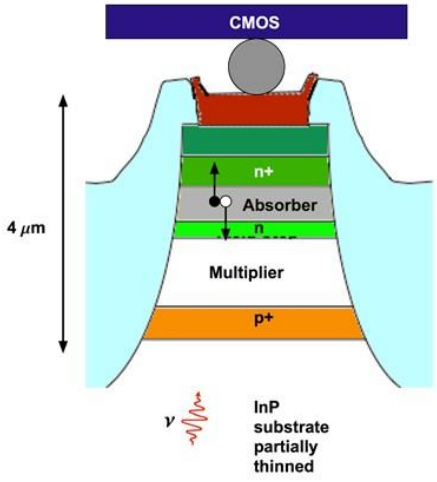


Silicon and InP-based GmAPDs

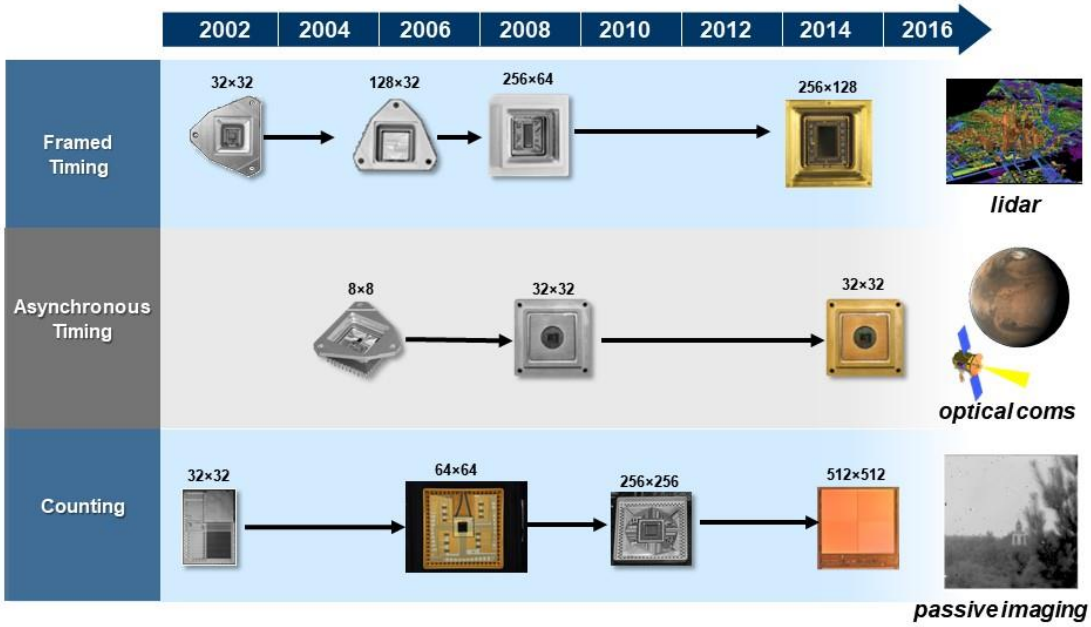
Silicon
λ < 900 nm



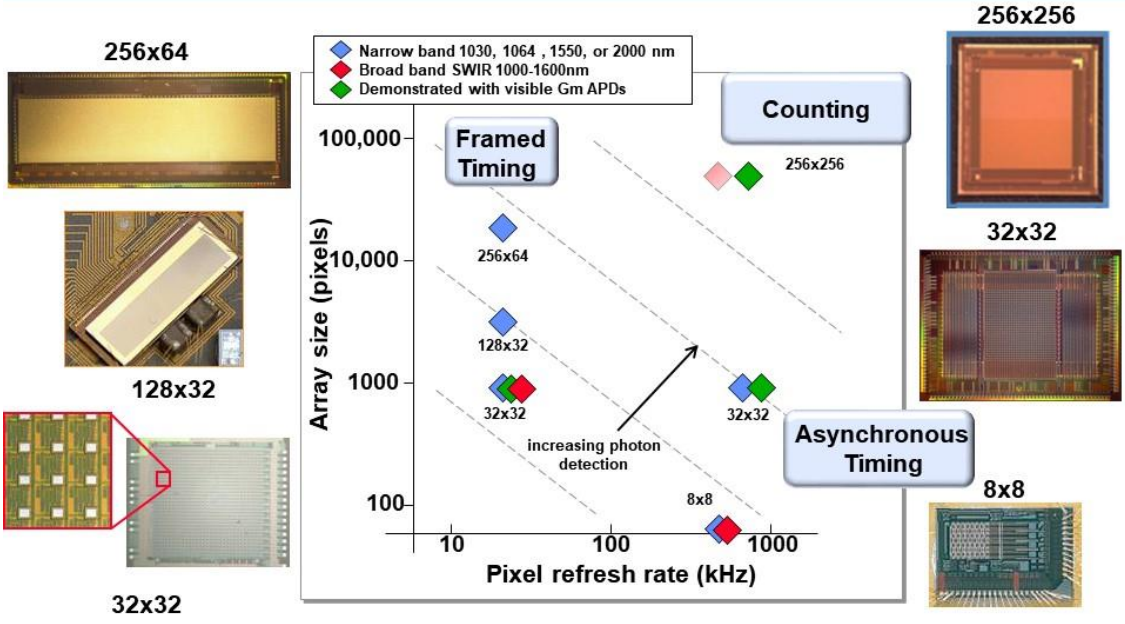
InP-based
λ < 1550 nm



Development Paths of GmAPDs at Lincoln Laboratory



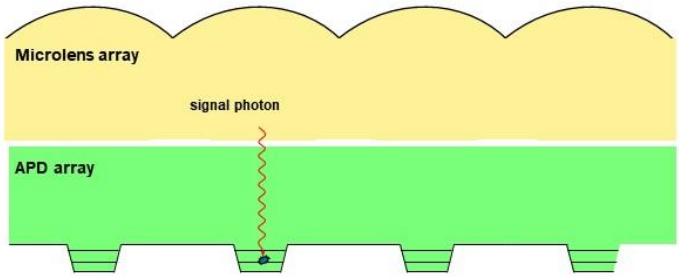
Detector Trade Space



Outline

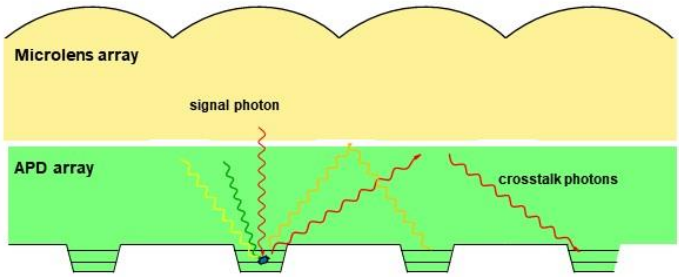
- MITLL Geiger mode Avalanche Photodetector (GmAPD) Applications
- GmAPDs
  - Principles of operation
  - Silicon and compound GmAPDs
  - Imaging systems and readouts
- **Areas of Development**
  - **Crosstalk mitigation**
  - **Radiation testing**
- Summary

Crosstalk Mechanism



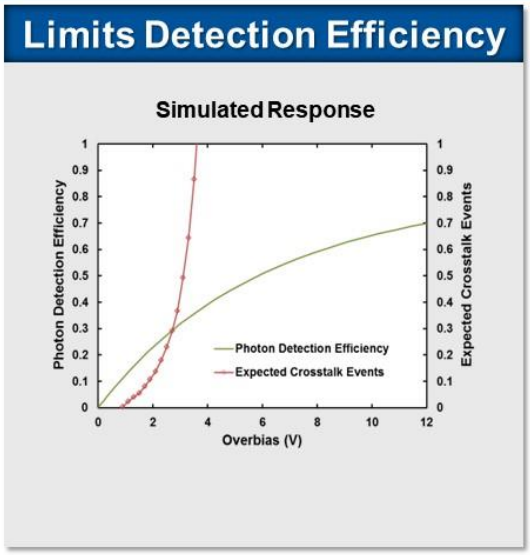
- Avalanche generates broadband light
- Light can couple to nearby APDs, generating false detections
- In extreme cases, creates cascades, swamping the array

Crosstalk Mechanism



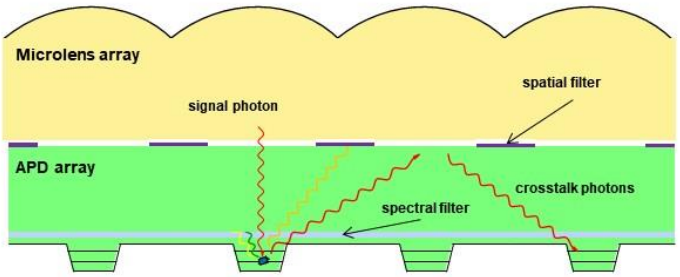
- Avalanche generates broadband light
- Light can couple to nearby APDs, generating false detections
- In extreme cases, creates cascades, swamping the array

Crosstalk effects on GmAPD arrays



- Exponential increase of crosstalk vs overbias
- Limited photon detection efficiency

Cross-Talk Mitigation in First Generation Design for InP GmAPDs

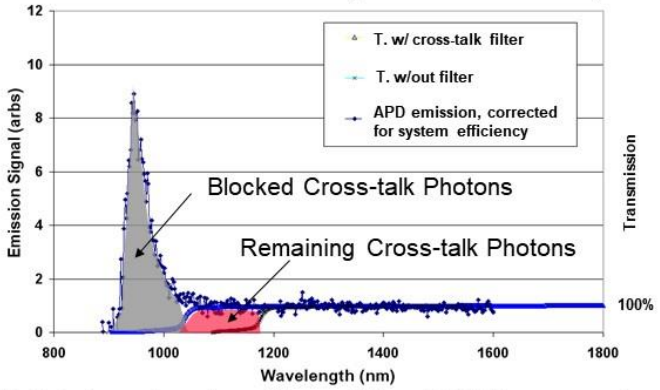


Combination of spectral and spatial filtering

Effect of Cross-Talk Filtering on Avalanche Emission Spectrum of InP GmAPD

Measured Avalanche Emission Spectrum

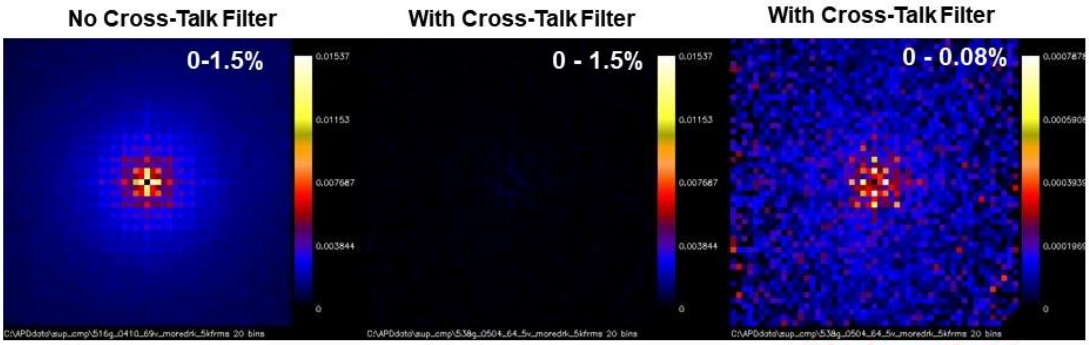
APD breakdown emission overlayed with transmission spectrum



- Spectrum of emitted photons shows broad thermal (T_{BB} ~ 3000K) component
- Epitaxial InGaAsP layer grown under APD structure acts as long-pass filter
  - Transparent at transmitter wavelength and highly absorbing at shorter wavelengths
  - Eliminates near-gap peak in cross-talk emission
  - Most useful for communications or laser radar type applications where narrow spectral response band is utilized

Cross-Talk Reduction in First Generation Design

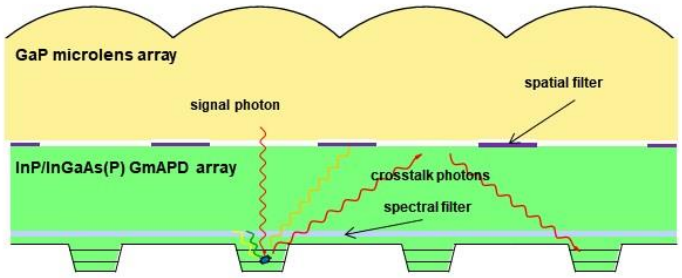
Cross-Talk in Gate, Spatial Dependence



(All at 2.4V Over-Bias)

- Detailed structure of cross-talk pattern due to internal reflections within APD array chip
- Cross-talk reduced >10x, but still present and still a problem at higher over-bias

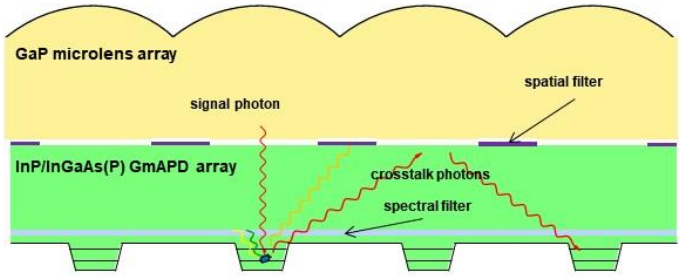
Challenges and Tradeoffs for Initial Design



Challenges:

- **Spatial filter loses effectiveness as pitch is reduced**
- **Spectral filter is temperature dependent and prevents broadband absorption**

Challenges and Tradeoffs for Initial Design



Challenges:

- **Spatial filter loses effectiveness as pitch is reduced**
- **Spectral filter is temperature dependent and prevents broadband absorption**

Solution: complete pixel isolation via substrate removal

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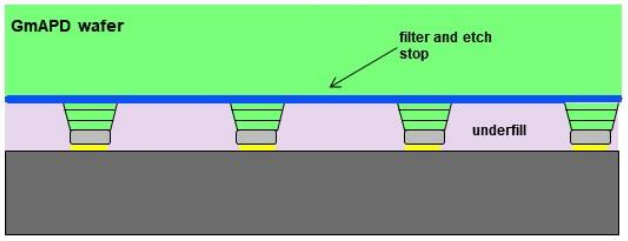
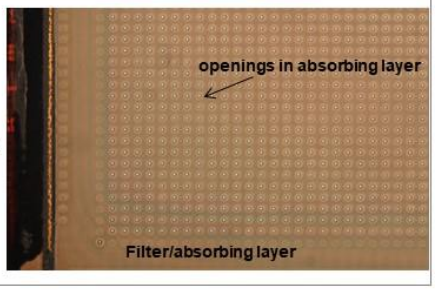
Fab of Next Generation Cross-talk Filter

Fabrication

Schematic Cross-section



Top View Photograph

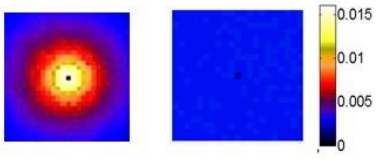


- **Demonstrate pixel isolation concept using fab technique on single hybridized die and wafer scale**
- **Pixel isolation achieved on legacy (50-μm-pitch) 256x64 FPAs**
  - **FPAs bonded to ROICs and underfilled**
  - **~2-μm-thick membrane (absorbing layer) electrically connects pixels**
- **Complete pixel isolation requires frontside and backside isolation**

Pixel Isolation and Spectral Response

Optical Crosstalk

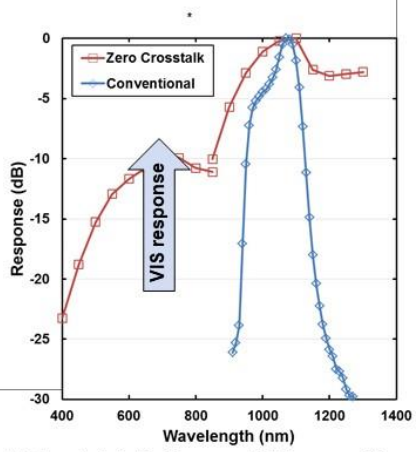
Measured crosstalk: Displayed as point spread functions



no mitigation | complete pixel isolation

- **In FY17, crosstalk reduced at least 150x from state-of-the-art (into noise floor)**
- **VIS response demonstrated in un-optimized APD**

VIS-SWIR Spectrum



* Detector not optimized for VIS response. 5-8 dB increase possible.

Path to megapixel-class VIS-SWIR multi-mode photon-counting imagers

Outline

- MITLL Geiger mode Avalanche Photodetector (GmAPD) Applications
- GmAPDs
  - Principles of operation
  - Silicon and Compound GmAPDs
  - Imaging Systems and Readouts
- Areas of Development
  - Crosstalk Mitigation
  - **Radiation Testing**
- Summary

Radiation Testing

- **Massachusetts General Hospital Francis H. Burr Therapy Center**
  - **Local state-of-the-art proton beam therapy laboratory**
  - **Test devices at various levels: individual component testing (e.g. ROIC, detector material, etc.) to small subassembly testing (e.g. sensor package)**
- **Umass Lowell Gamma Ray Facility**
- **MIT-LL X-Ray Testing**
- **Heavy Ion Testing at Brookhaven Relativistic Heavy Ion Collider, Texas Cyclotron Institute, and Lawrence Berkeley 88-inch Cyclotron**



MGH Francis H. Burr Therapy Center

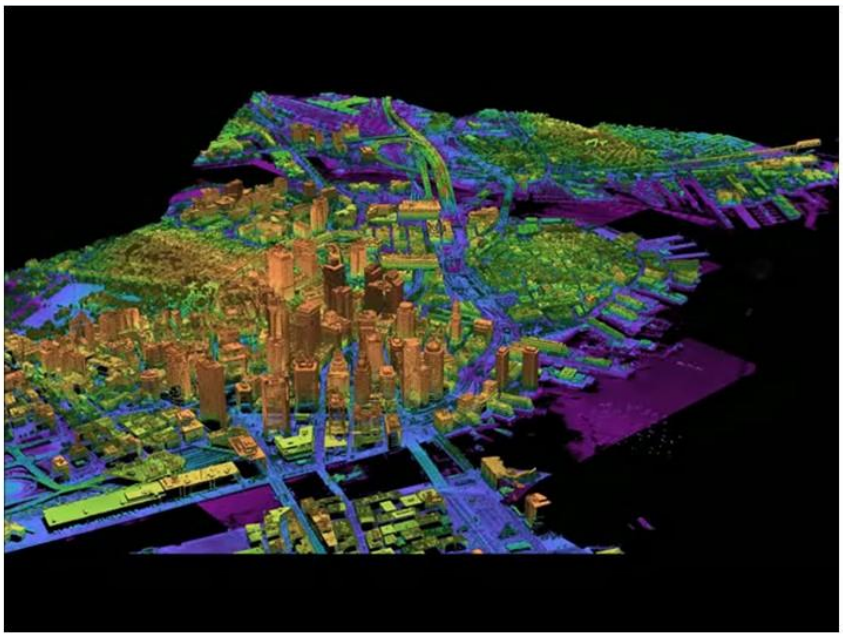


Brookhaven Relativistic Heavy Ion Collider

Summary

- Over the past 20 years, MITLL has developed customized GmAPD arrays and CMOS readout circuits for both photon timing and photon counting applications
- Both silicon and phosphide-based detectors have been developed to cover a range of wavelengths
- Large format arrays, 256x256 and counting
- Present research thrusts include:
  - Developing zero-crosstalk devices
  - Radiation analysis of devices under different environments

Example 3D Imagery with GmAPD Ladar



9.6 PROSPECTS FOR THE DEVELOPMENT OF FAST-LIGHT INERTIAL SENSORS

David D. Smith[1]* and Andrew Keys[1]

*[1]NASA Marshall Space Flight Center, USA, *david.d.smith@nasa.gov*

ABSTRACT

We discuss the prospects for the development of a new class of gyroscopes and accelerometers based on anomalous dispersion or "fast-light" media. In recent experiments, fast light has been shown to dramatically increase the sensitivity of optical cavities to changes in optical path length. The boost in sensitivity may enable more rapid and precise inertial measurements, with smaller gyros, translating to greater spacecraft autonomy, provided the challenges presented herein can be addressed.

1 INTRODUCTION

Next generation space missions are constrained by existing spacecraft navigation systems which are not fully autonomous. These systems suffer from accumulated dead-reckoning errors and must therefore rely on periodic updates provided by supplementary technologies that depend on line-of-sight signals from Earth, satellites, or other celestial bodies (e.g., GPS, star-trackers) for absolute attitude and position determination, which can be spoofed, incorrectly identified, occluded, obscured, attenuated, or insufficiently available. These dead-reckoning errors originate in the accelerometers and ring laser gyros (RLGs) themselves, which constitute inertial measurement units (IMUs). Commercially-available RLGs, for example, are typically limited to an angular random walk (ARW) of 0.0005 deg/hr$^{1/2}$.

Increasing the time for standalone spacecraft navigation therefore requires fundamental improvements in the precision of inertial sensors. The conventional method of increasing the precision of an optical gyro is to increase its size, but this is problematic in spaceflight where size and weight are at a premium. One promising solution to enhance gyro precision without increasing size is to place an anomalous dispersion or fast-light (FL) material inside the gyro cavity. The fast light essentially provides a positive feedback to the gyro response, resulting in a larger measured beat frequency for a given rotation rate as shown in Fig. 1.

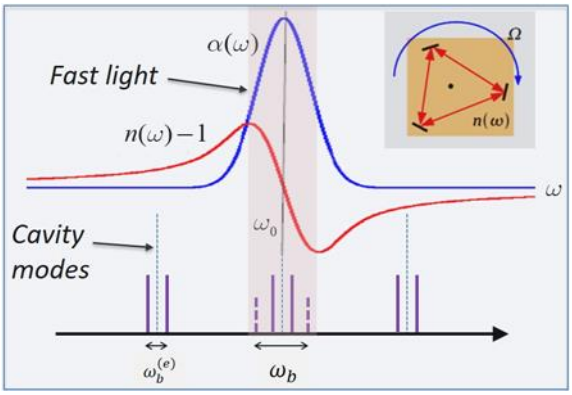


Figure 1. Illustration of how the response of a gyroscope is enhanced by FL. Each cavity mode is split by the rotation of the gyro. In the FL region the refractive index n decreases with frequency ω, which further separates the modes. The beat frequency ω_b is thus larger than that for the empty gyroscope cavity, $\omega_b^{(e)}$.

Another conventional method to increase precision is to increase measurement integration time. However, this method is problematic in situations where rapid accelerations are required. Under these circumstances a more accurate attitude or position determination is often obtained by taking many quick inertial measurements at a lower precision rather than a few longer ones at a higher precision. Investments in navigation technologies that rely on celestial landmarks are unlikely to fill this role because they are inherently limited by factors such as large lag times that increase with distance (attitude and position determinations will be in the past) and/or low photon flux (long integrations times are required so attitude and position determinations will not be instantaneous). In addition, for sufficiently long integration times, higher-order noise sources (such as bias instability, rate random walk, and rate drift) become dominant and can actually reduce precision. Therefore, there is an upper limit to the approach of increasing the measurement time. On the other hand, it is precisely under these rapid acceleration conditions, where the noise is dominated by angular random walk (ARW), that we expect FL inertial sensors to have their greatest impact. This is because FL is predicted to reduce ARW, potentially by many

orders of magnitude (an upper limit has been estimated to be ~10^6 [1]). In contrast the effects of FL on higher-order noise sources is less well understood.

To summarize, the benefit is that a measurement made at a particular measurement rate for a particular size gyro will be more precise. And, one can trade off this enhanced precision for faster measurements or for smaller gyros, i.e., faster, more precise measurements can be made, with smaller gyros. We therefore expect the greatest benefits in situations requiring rapid changes in attitude or position, or where knowledge of the environment is limited or obscured, for example by dust. Such scenarios include entry, descent, and landing (EDL), surface operations with rovers, formation flying or automated rendezvous and docking, and missions to small bodies including sample return and kinetic impactor missions. Recently JPL researchers concluded that, for kinetic impactors, spacecraft attitude knowledge is the single biggest factor in determining impact success, and that even the best currently-available IMUs resulted in a significant probability of mission failure [2].

With sufficient advancement in TRL, FL IMUs could work in conjunction with terrain-relative navigation technologies such as NASA Langley's Doppler LIDAR and JPL's Lander Vision System to provide an overall solution for precision EDL, potentially even in conditions that obscure these other methods. FL IMUs would also be markedly faster than these other technologies, providing enhanced compensation for last-minute motions, e.g., wind gusts that might occur during landing. The increased precision translates to reduced error ellipses enabling pinpoint landings for improved access to engineering needs and science targets.

FL IMUs could therefore have cross-cutting benefits that span a range of applications from Flagship missions such as Europa Lander and Mars Sample Return to crewed missions to NEAs, the moons and surface of Mars (DRM 6-9), and Flexible Lunar Explorers (FLEx) for the moon, to New Frontiers missions such as CAESAR, whose robotic arm would momentarily contact the surface of a comet, and international collaborations such as the Double Asteroid Redirection Test (DART).

2 METHODOLOGY

2.1 STATE OF THE ART

There are two types of FL cavities that could be used in inertial sensors: passive (probed by an external laser) and active (the laser gain medium is intracavity). Recent work on active cavities [3] has estimated a scale-factor sensitivity enhancement as large as $S = 190$, but this value is inferred from spectra of the gain profile. Experiments at NASA Marshall on passive fast-light cavities [4,5], on the other hand, have obtained values as large as $S = 363$ by taking the more direct approach of varying the optical path length (OPL) and monitoring the change in the cavity mode frequencies. In addition, sensitivity enhancement of passive FL cavities operating in a closed-loop configuration has recently been demonstrated at Marshall [6], enabling rapid measurements.

A sensitivity enhancement, by itself, is not sufficient to enhance precision, however. Precision is enhanced when the sensitivity increases without a concomitant increase in measurement uncertainty. Numerical calculations for passive cavities have shown that under near-ideal (high-signal-to-noise and quantum-noise-limited) conditions the increase in uncertainty is not as large as that in sensitivity, so an overall enhancement in precision can occur as a result of FL. An important and substantial advantage, however, may exist for active cavities. Recent work has predicted that the linewidth of active cavities is unaffected by FL [7], which implies that the enhancement in precision in active cavities is larger than in corresponding passive cavities, being close to that of the enhancement in sensitivity itself.

A number of approaches to active FL gyros rely on the use of nonlinear optical processes generated by added pump beams [3], which create a number of challenges such as difficulty of miniaturization, necessity for careful control of cavity and laser parameters via sophisticated control schemes, as well as added sensitivity to environmental effects. These nonlinear effects can be deleterious even when they are not used to generate the dispersion. In both passive and active FL cavities employing atomic vapors, for example, saturation and optical pumping can alter the resonance lineshape, couple the counterpropagating beams, and limit the

achievable intensity and signal to noise. Even when nonlinear effects are avoided entirely, reliance on discrete material transitions can have additional drawbacks. Transitions in atomic-vapor FL media, for example, are highly temperature dependent, requiring state-of-the-art temperature stabilization techniques to minimize the resultant noise. More significantly, use of these transitions limits the wavelength of operation, which could inhibit wide adoption. RLG manufacturers are generally resistant to changing to a different operating wavelength, having spent many years perfecting their performance at He-Ne wavelengths. In addition, experiments to date have not matured enough to reveal the predicted increase in measurement precision, in either passive or active FL cavities, in large part because this observation itself requires fresh development of a high-quality RLG at a new wavelength, dictated by the discrete transitions of the FL medium.

A solution to these problems might be found in FL gyros based on coupled resonators [8]. These systems do not use a medium at all, and are therefore not constrained in wavelength nor do they suffer from the inherent problems described above. Typically, one of the resonators has net gain and the other has net loss. When the loss in one resonator is equal to the gain in the other, the system is characterized as "PT-symmetric" owing to its invariance under a reversal of parity (P) and time (T). Recently, investigators have proposed coupled-resonator PT-symmetric gyros [9] that would, in theory, display the same increase in sensitivity as active FL gyros based on atomic media, but are far simpler, and can be microfabricated onto integrated optical chips. The enhancement is maximized near a singularity known as an exceptional point (EP) where the system eigenvalues coalesce. In practice, however, PT-symmetric gyros haven't shown any definitive boost in sensitivity because they rely on generating two modes for each counterpropagating gyro output direction. At small rotation rates these two modes are not distinguishable, so no beat signal is obtained. Additionally, PT-symmetric gyros are not common path, and therefore do not possess the same level of common-mode noise rejection as typical RLGs or FL gyros based on atomic media.

2.2 NEW APPROACH

The approach taken has been to develop passive FL cavities and gyros in-house at NASA Marshall, while leveraging SBIR/STTR and STMD programs to seed and mature a number of the most promising approaches for active FL gyros. The passive approach is less costly and complex to undertake, and preliminary results are thus easier to acquire. This approach has enabled Marshall to achieve a number of firsts in the field, some of which we described above [4–6, 8]. A direct demonstration of the increase in scale-factor sensitivity to rotation (rather than to length changes), as well as a definitive demonstration of the enhancement in precision are still needed. The former is a relatively straightforward extension of experiments that Marshall has already performed [6]5 and can likely be accomplished with existing hardware. The latter goal may also be within reach (the most recent experiments at Marshall on closed-loop cavities attained a relative enhancement of 0.66 using only COTS components), but will likely require the development of a more robust optical cavity with reduced noise, as well as a modification of the closed-loop frequency-locking scheme [6].

While the passive approach is promising for proof of concept, it seems unlikely that the ultimate FL gyro that is developed will be a passive one, for some of the reasons explained above. Therefore, an important part of the approach has been to leverage other NASA programs (such as SBIR/STTR) for external development of some of the more complex technologies required for active FL inertial sensors, in particular to solve the challenges we've described above, i.e., to find approaches that are common path, are not limited in signal to noise, do not require frequency locking, permit operation at any wavelength, are not affected by environmental effects such as temperature and acceleration levels, and can be easily miniaturized or microfabricated.

3 CONCLUSIONS

Ultraprecise compact FL IMUs could reduce mission risk, cost, and propellant, providing cross-cutting benefits in a number of mission scenarios, in particular those requiring rapid accelerations or tight controls on attitude or position such as formation flying and automated docking, precision

EDL, and missions to small bodies (kinetic impactors, sample return). We have discussed the prospects of this technology, the advantages and disadvantages of different approaches, and the outstanding challenges to be addressed for its implementation.

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Prospects for the Development of Fast-Light Inertial Sensors

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NASA MSFC, Optics and Imaging Branch,
Space Systems Department

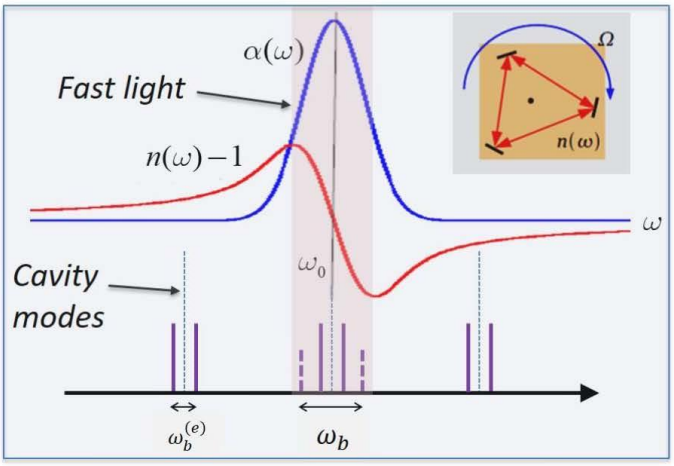


- Critical Need: ***"NASA's future missions show a diverse set of navigational challenges that cannot be supported with current methods. Onboard autonomous navigation and maneuvering (OANM) techniques are critical."*** Addresses TA-05 for minimization of mass, power and volume while increasing performance, avoiding navigation from becoming a constraint, and eliminating Earth from the real-time decision loop.
- Problem: Current inertial sensors limited in precision and require periodic attitude or position updates (e.g. using GPS or Star-trackers).
- Conventional means of increasing precision:
  1) Increase gyro size → problematic in spaceflight
  2) Increase measurement integration time → upper limit due to higher-order noise. Not useful for rapid accelerations.
- Technologies relying on external signals (GPS, DSN, Star-trackers, XNAV, etc.) limited by large lag times (measurements in the past) and/or low flux (long integration times). They can be spoofed, incorrectly identified, occluded, obscured, delayed, attenuated, or insufficiently available.
- **Fundamental improvements needed in precision of inertial sensors!**

The Problem – The Solution

Problem: Best gyros limited in precision, resulting in errors that require periodic correction. ***Fundamental improvements needed in gyro technologies!***

Solution: Develop ultrasensitive superluminal (or fast-light) gyros ⇒ more rapid and precise measurements with smaller gyros.



Scale Factors:

$$s^{(e)} = \frac{d\omega_b^{(e)}}{d\Omega} \propto Area$$

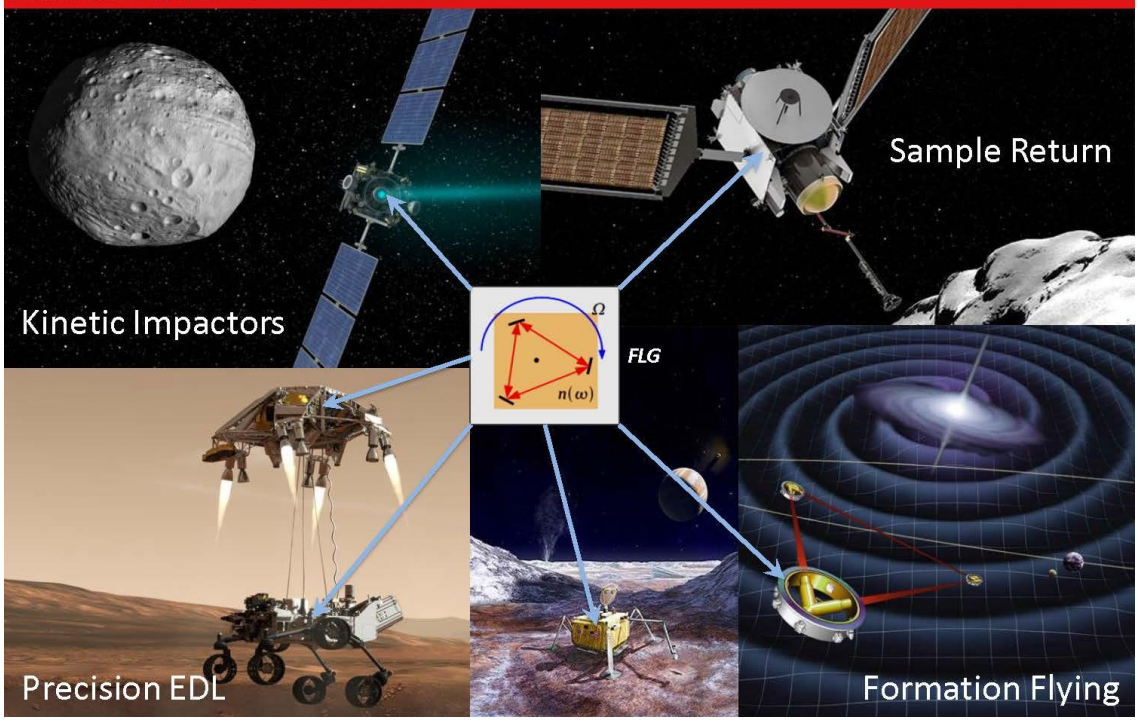
$$s = \frac{d\omega_b}{d\Omega}$$

Scale Factor Enhancement (w/o increasing Area):

$$S = \frac{s}{s^{(e)}} = \frac{d\omega_b}{d\omega_b^{(e)}} > 1$$

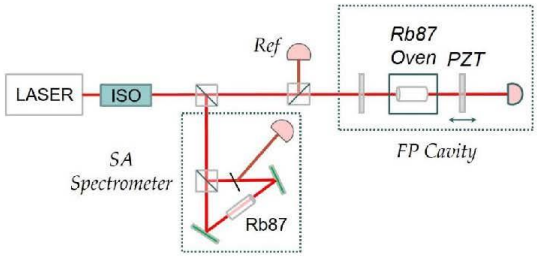
Increase in Error: $\varepsilon = \dfrac{\sigma}{\sigma^{(e)}}$ ⇒ *Enhancement in Precision when:* $\zeta = \dfrac{S}{\varepsilon} > 1$

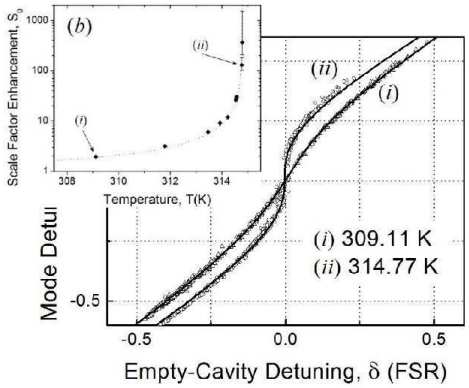
Potential Applications

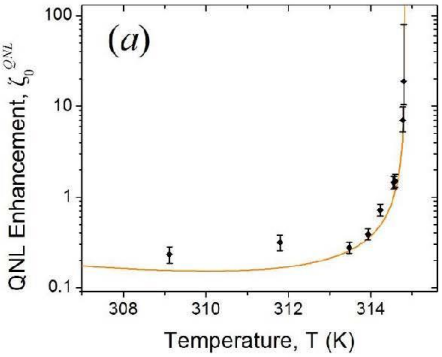


Passive FL Cavity

- First achievement of enhanced scale factor sensitivity (*S*) to OPL changes (*S* = 363).
- Tuning of *S* by temperature and by optical pumping







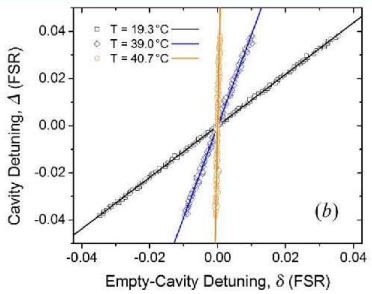
D. D. Smith et al., *Phys. Rev. A* 94, 023828, (2016).

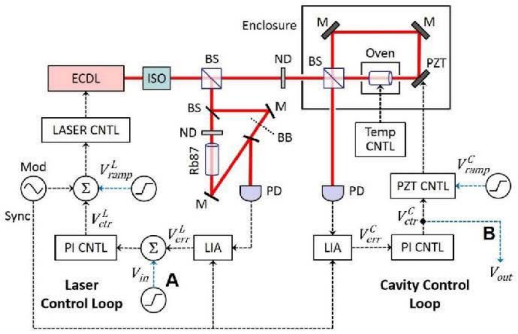
Limitations of Prior Experiments

- Cavity detunings Δ and δ not measured directly in real time in an operating device. Instead *S* and ε are deduced, after the fact, from the spectra
  - → Slow (5 mins vs. <1 sec. for closed-loop). Large amount of unnecessary data recorded.
  - → No real experimental evidence of enhancement. ζ inferred for ideal (QNL & high-SNR) conditions only.
- Instability due to mode pushing → data scarce near resonance. Large uncertainty in *S*. Stabilization needed.

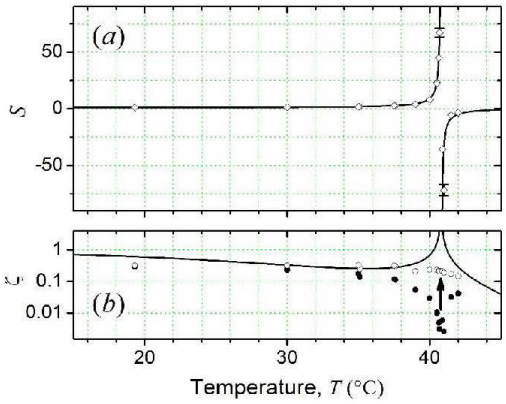
Closed-Loop Passive FL Cavity

- First direct measurement of boost in scale-factor sensitivity (S) in a ***closed-loop device*** using FL. ⇒ Paves way for passive FL gyro.
- Cavity remained locked through critical temperature. Both positive and negative values of S observed.
- Increase in ζ not yet observed due to classical noise. ⇒ Gyro geometry needed.





D. D. Smith et al., *Opt. Expr.* 26, 14905, (2018).

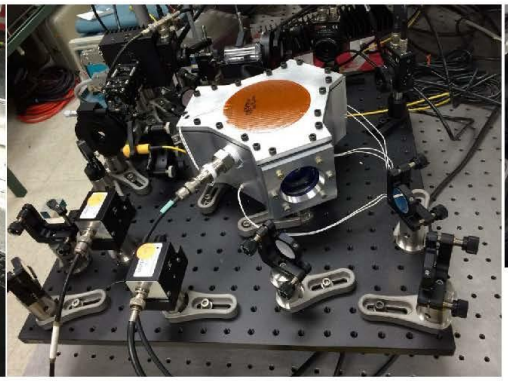


Passive FL Gyro

- Objective: Scale-factor enhancement for rotation has never been demonstrated in any experiment.



Table Shaker



Laser and Cavity on Rotation Stage



Passive Cavity

- Monolithic, vacuum-enclosed, magnetically-shielded, and temperature-stabilized to reduce noise.

Advantages / Limitations of Passive FLGs

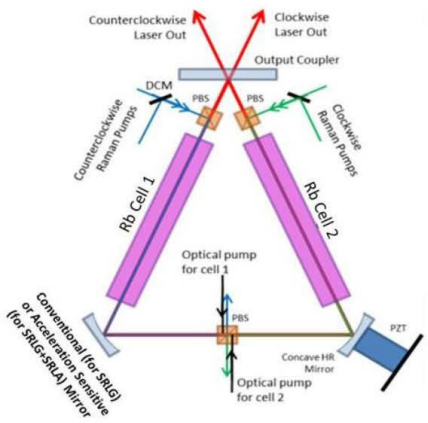
Advantages

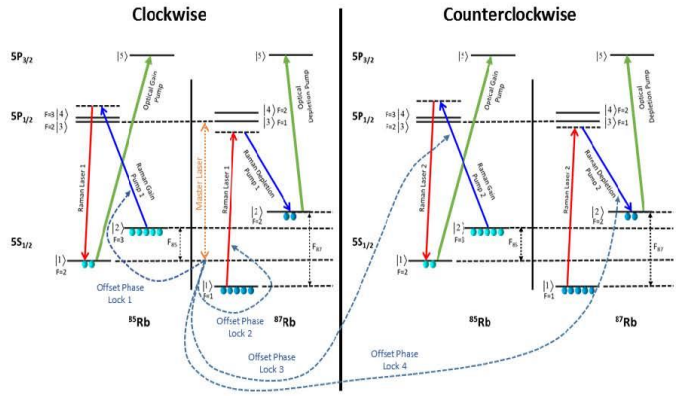
- Simpler and less costly to obtain preliminary data
- Avoids nonlinear dynamics from gain medium
- Only system so far to have shown boost in *S* to OPL changes.

Challenges / Limitations

- Sensitive to relative motion of components external to cavity
- Cavity modes attenuated by absorption. Reduced signal to noise.
- Saturation alters lineshape, couples counterpropagating beams, and limits achievable signal to noise.
- Require complicated closed-loop locking schemes
- Cavity linewidth also broadens. Not necessarily true for active cavities. **Active FL gyros may have higher enhancement in precision!**

Scheme for Active FLG Using Rb



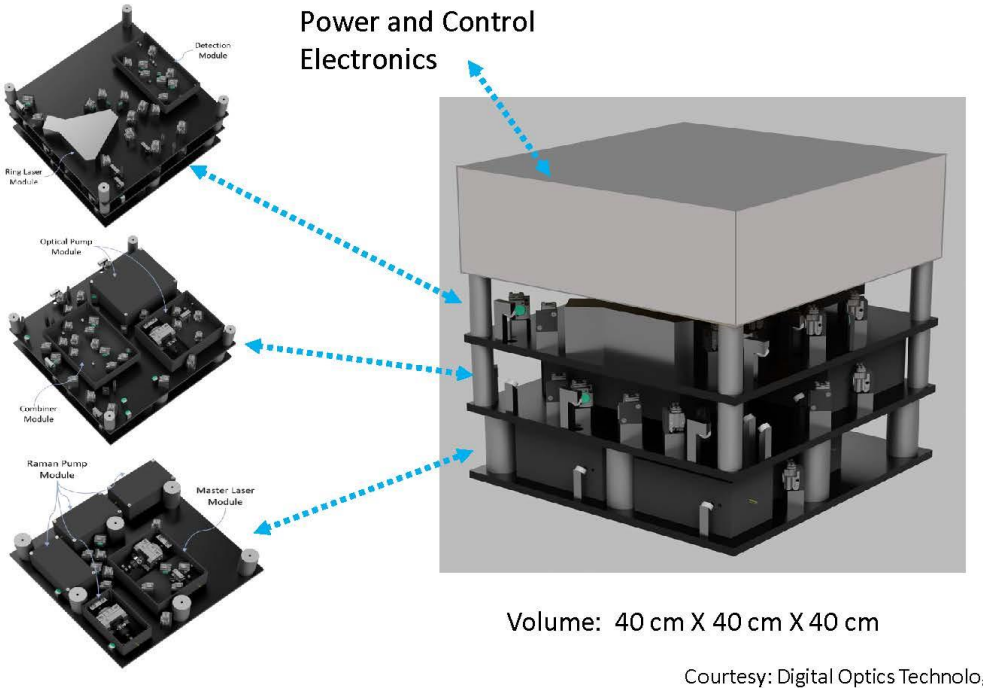


Quadruple Offset Phase Locking

- Two Raman lasers using dual-isotope vapor cells. Use different optical and Raman pumps for each isotope to produce a narrow dip in the gain. Apply Raman pumps for the two cells at different detunings resulting in a bias.
- Common path, bidirectional, self-biased FL gyro ⇒ Bias eliminates dead-band and direction ambiguity. Improved common-mode rejection. Lower power.

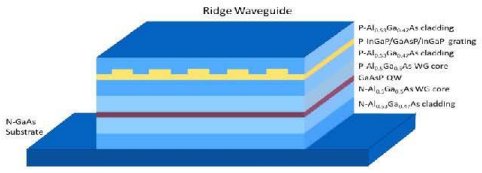
Courtesy: Digital Optics Technologies

Portable Active FLG in Development

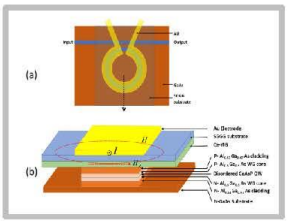


Courtesy: Digital Optics Technologies

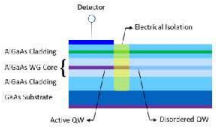
Future: Active FLG on a Chip



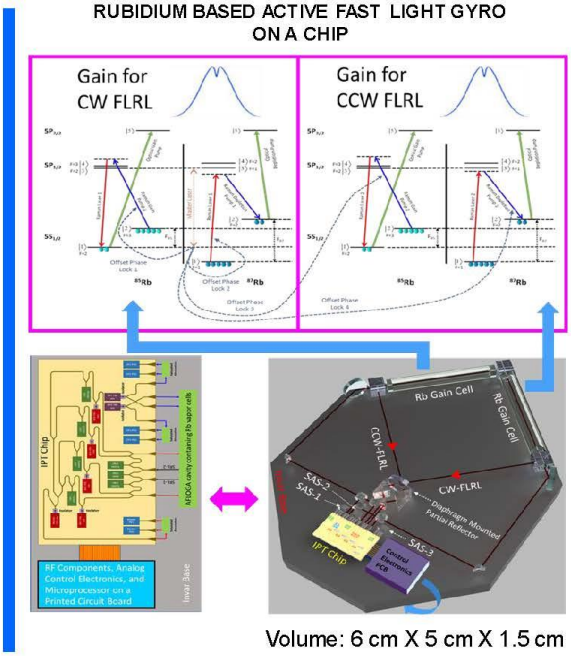
DFB LASER



MAGNETO-OPTIC ISOLATOR



DETECTOR

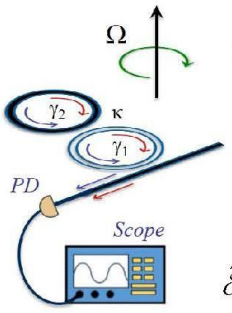


Courtesy: Digital Optics Technologies

Challenges for Active FL Gyros

- Dynamics of gain medium may cancel enhancement to some degree.
- No known composition of gases that eliminate gain competition for the two directions ⇒ unidirectional lasing
- Current approaches significantly more complex requiring multiple lasers. Rely on NLO processes generated by added pump beams
  - → **Difficult to miniaturize**
  - → Careful control of cavity and pump parameters
  - → Sophisticated control schemes required
  - → Added sensitivity to environmental effects
- Enhancement in *S* still not demonstrated directly, only inferred.
- Reliance on discrete material transitions (applies for passive as well)
  - → Transitions are inherently temperature dependent, requiring SOA stabilization techniques to minimize the resultant noise.
  - → **Limited operation wavelength inhibits wide adoption. RLG manufacturers want to stick with He-Ne wavelengths.**

Coupled Resonator (CR) Gyros



$$\gamma = \gamma_1 - \gamma_2 \neq 0$$

→ **Non-Hermitian**

$$\gamma_2 = -\gamma_1$$

→ **PT-Symmetric**

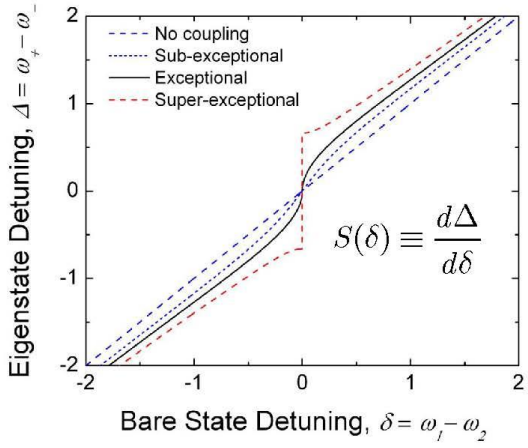
$$\tilde{\delta} = \delta - i\frac{\gamma}{2}$$ *Complex detuning*

Complex Eigenvalues:

$$\tilde{\omega}_{\pm} = \tilde{\omega}_{\text{avg}} \pm \frac{\tilde{\Omega}}{2} \qquad \tilde{\Omega} = \left[\tilde{\delta}^2 + \kappa^2\right]^{1/2}$$

$$\kappa = |\gamma / 2|$$

Exceptional point! Degenerate Eigenvalues.



$$S(\delta) \equiv \frac{d\Delta}{d\delta}$$

$$S(0) = \left[1 - (2\kappa / \gamma)^2\right]^{-1/2} \rightarrow \infty$$

Exceptional Point (EP) Coupling = Critical Anomalous Dispersion!



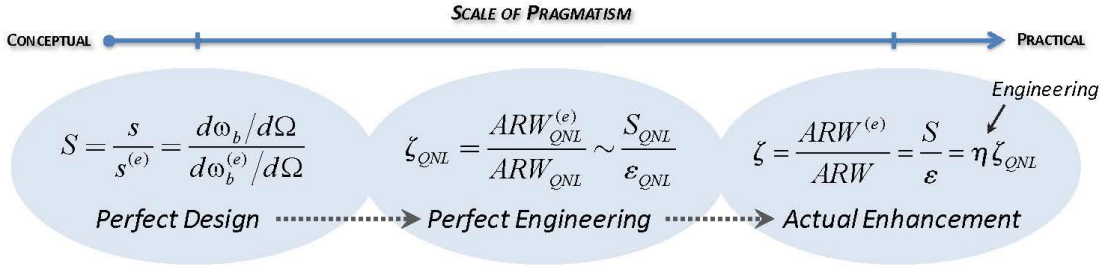
Advantages

- Easy to miniaturize via microfabrication
- Entirely linear effect, no saturation ⇒ higher signal-to-noise
- Eliminates temperature dependence of atomic absorption ⇒ potential for better scale-factor stability.
- Not limited to operation at atomic resonance frequencies. **Any wavelength possible, including He-Ne.**

Challenges / Limitations

- **PT-symmetric gyros not common path.** Resonators suffer from independent amounts of noise and drift. ⇒ Reduced common-mode noise rejection.
- **PT-symmetric gyros haven't shown any definitive boost in sensitivity**, b/c at small rotation rates the two modes (at each gyro output direction) are not distinguishable.

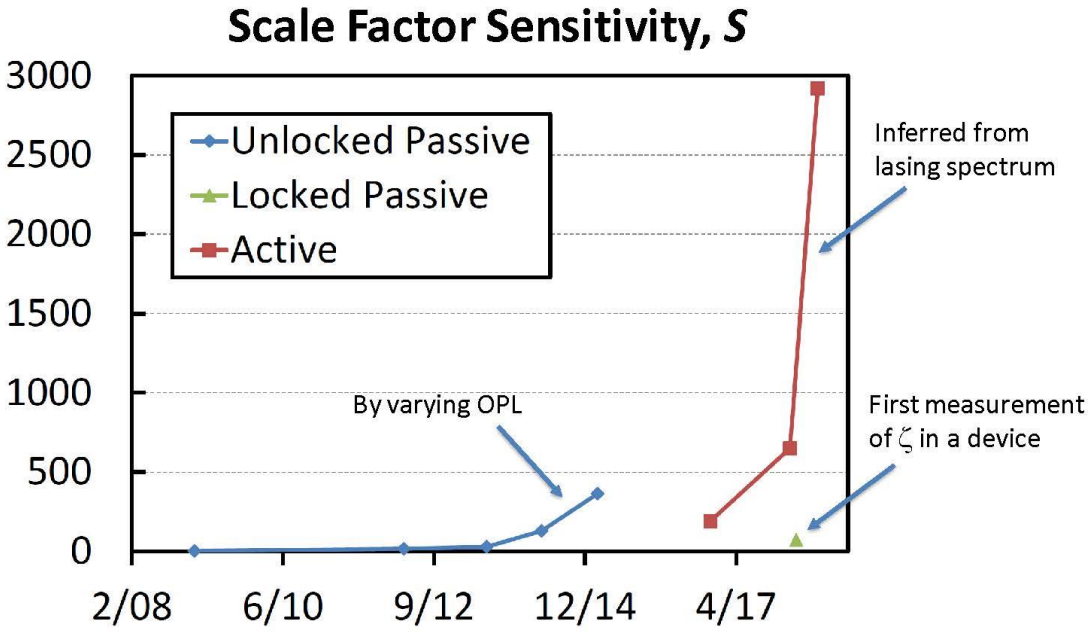




		Passive FL Cavity			Active FL Cavity
Parameter	Symbol	Atomic Vapor	Closed-Loop Atomic	Polarization Mode Coupling	Dual-isotope Atomic Vapor
Scale factor enhancement	S	363	67.1	28.3	2920 *
Ideal QNL Increase in Error	ε_{QNL}	19.4		4.7	
Actual Increase in Error	ε		101.5		
Ideal QNL Sensitivity Enhancement	ζ_{QNL}	18.8		6.0	
Actual Sensitivity Enhancement	ζ		0.66		
Angular Random Walk, °/h$^{1/2}$	ARW				
Bias Instability, °/h	B				

* Inferred Value

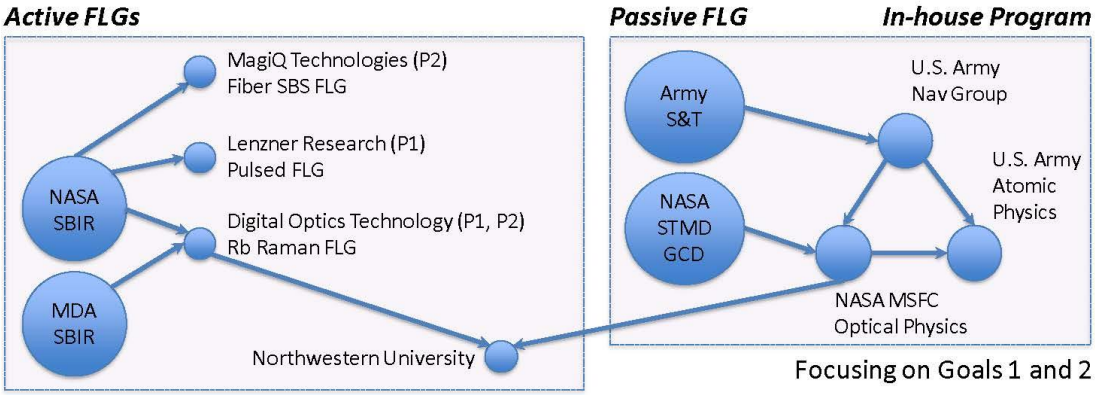
Increase in SOA over Time



What is still needed

1) Demonstrate scale-factor enhancement, *S*, to rotation.
2) Demonstrate enhancement in precision, ζ.
3) FL gyros that:
   - → Are common path
   - → Are not limited in signal to noise
   - → Do not require frequency locking
   - → Permit operation at any wavelength
   - → Can be easily miniaturized
   - → Are relatively insensitive to environmental (e.g. temperature) variations
   - → Can operate in varying G-conditions

Development Plan



Other Past & Present: Torch Technologies, Triad Technology, Aegis Technology, Honeywell, Los Gatos Research, Photodigm, Vescent Technologies, Freedom Photonics, Rochester Scientific, College of William and Mary.

International Efforts: Tel Aviv Univ. (Israel), National Univ. of Defense Technology (China), Harbin Institute of Technology (China), Thales Aerospace (France).

Valley of Death: To accomplish goal 2 may require development of a high-quality gyro. Sufficient funding for such development less likely until goal 2 met.

Future State: IMUs incorporating FL gyros/accelerometers with orders-of-magnitude (10^6 upper limit) reduced ARW.

9.7 OCULAR HAZARD RISK MANAGEMENT FOR AIRBORNE AND SPACEBORNE ACTIVE OPTICAL SYSTEMS

Jennifer Inman[1]*, Ian Miller[2], Vinod Nagpal[2], and Kim Merritt[3]

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[2]N&R Engineering: Cleveland, OH
[3]Mission Technologies, Inc.: Hampton, VA

ABSTRACT

Consideration of risks posed to the general public is an integral part of active optical system design. Without a common framework for risk evaluation and acceptance, individual programs must subjectively determine what constitutes an acceptable risk posture. We propose the adoption of a common risk criterion, against which future active optical systems can be evaluated, and we provide a methodology for evaluating the ocular hazard risk of pulsed laser systems operating from aircraft and/or satellite platforms.

1 INTRODUCTION

This effort is applicable to all Decadal Survey targeted observables that use lasers capable of causing ocular damage. NASA conducts atmospheric measurements which include airborne and spaceborne laser operations. Figures 1 and 2 schematically illustrate scenarios that need to be prevented, namely, exposing pilots and telescope operators to harmful doses of laser energy.

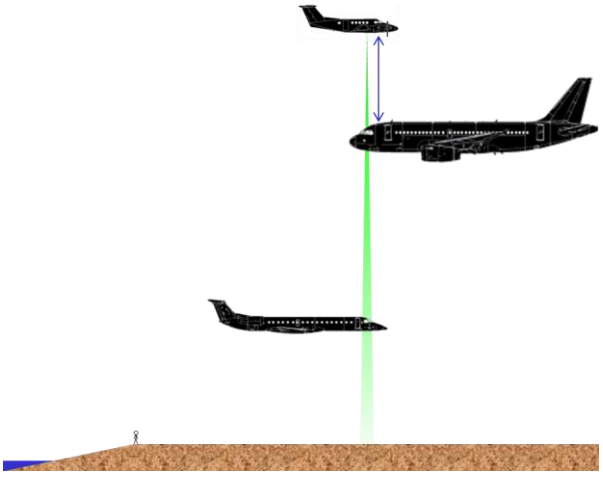

Figure 1 Exposure route for uninvolved pilots

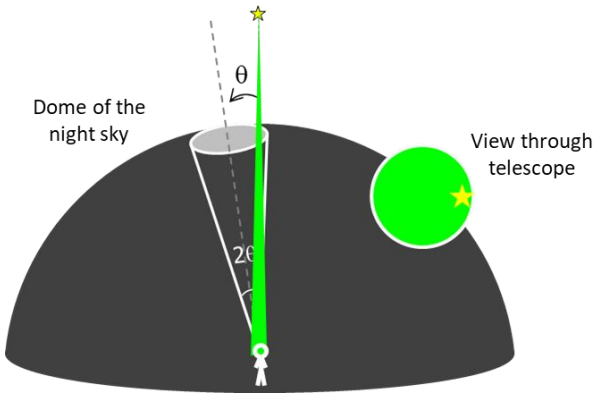

Figure 2 Exposure route for telescope operators

NASA voluntarily adheres to the American National Standards Institute (ANSI) Standards for Safe Use of Lasers [1] and Safe Use of Lasers Outdoors [2]. These standards state that people should not be exposed to laser radiation above the Maximum Permissible Exposure (MPE) under "reasonably foreseeable conditions of operation." In addition, these ANSI Standards define restrictions on laser energy densities that may be transmitted in proximity to airports during nighttime operations.

There is currently no common framework across NASA centers, programs, or projects for assessing ocular hazards—other than ensuring that lasers are eye safe for unaided viewing at ground level and comply with the limitations near airports—nor is there a common criteria for stake holders to use for determining what constitutes an acceptable risk.

2 METHODOLOGY

In order to quantify and evaluate the relative risk that such operations pose to uninvolved airborne or ground-based observers, a probabilistic risk assessment (PRA) was commissioned and funded by the Science Directorate at NASA Langley. The proposed MESCAL (Monitoring the Evolving State of Clouds and Aerosol Layers) satellite mission and HSRL2 (High-Spectral Resolution

Lidar 2) airborne instrument were used as test cases in defining the PRA parameters.

2.1 STATE OF THE ART

Eye safety calculations are currently handled independently by each NASA program. This results in different approaches with different levels of fidelity and entails different opinions on what constitutes a maximum tolerable level of risk. Handling by external entities, including review boards and the Federal Aviation Administration (FAA), is inconsistent and subjective to some degree. Months of effort are expended per mission which leads to uncertainty and programmatic risk.

Additionally, it is standard procedure to obtain a letter of non-objection from the FAA prior to an airborne mission, and to submit a Notice to Airmen (NOTAM) regarding the planned laser operations. NOTAMs must be submitted sufficiently far in advance of a flight (e.g. 72 hours) so as to require the notices to be overly broad in the times and locations that are specified. And because they contain no practical means for uninvolved pilots to avoid the advertised risk, NOTAMs do nothing to increase actual safety. However, NOTAMs do sometimes create burdensome workloads for air traffic controllers (ATC), who may elect to clear airspace in proximity to the research aircraft out of fear of (and unfamiliarity with) the perceived hazard posed by the laser(s). This has sometimes negatively impacted research operations when controller workloads prevented ATC from providing special handling to the research aircraft, which was instead ordered to remain clear of the busy controller's airspace.

2.2 NEW APPROACH

Establishing a consistent guideline across all NASA airborne and spaceborne lidar systems will reduce the time and effort expended by individual projects in debating whether the operations are sufficiently safe. Such a guideline will provide a rationale that is consistent with other NASA policies on risk management, for example, the NASA Technical Standard on the Process for Limiting Orbital Debris [3] and the Common Risk Criteria Standards for National Test Ranges [4].

Additionally, a software program is being developed to provide one practical means of demonstrating compliance with this standard, and enabling a project to assess potential ocular hazard risks in a matter of days or hours instead of weeks or months. The Software for Hazard Identification and Evaluation of Lidar Deployments (SHIELD) has two modules—AirSHIELD and SpaceSHIELD—which handle simulations for aircraft- and satellite-based lidar systems, respectively. These software packages provide an implementation of the probabilistic risk assessment using Monte Carlo methodology coded in the Python programming language.

Computing the expected number of injuries due to an airborne or spaceborne lidar system has been broken down into three basic steps for both (a) AirSHIELD and (b) SpaceSHIELD:

- Calculate the number of (a) aircraft or (b) people illuminated by each laser pulse. For (a), this requires modeling the distribution of other aircraft in the vicinity of the intended flight and accounting for things like the altitude of the research aircraft, the time of day, and the time of year. Scaling factors indicating the relative average aircraft density versus time of day and time of year are shown in Figure 3 (where UTC indicates universal time, EST is Eastern Standard Time and EDT is Eastern Daylight Time). For (b), this requires modeling the distribution of the Earth's population relative to the ground track of the orbiting satellite.

			Date/Time Scaling Factors												
			Standard Time			Daylight Savings Time								Standard Time	
UTC	UTC	Eastern Time	January	February	March (EST)	March (EDT)	April	May	June	July	August	September	October	November	December
5:00	4:00	0:00	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
6:00	5:00	1:00	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
7:00	6:00	2:00	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
8:00	7:00	3:00	0.1	0.2	0.2	0.1	0.2	0.1	0.2	0.2	0.2	0.1	0.1	0.1	0.2
9:00	8:00	4:00	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
10:00	9:00	5:00	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.3	0.3
11:00	10:00	6:00	0.6	0.6	0.7	0.7	0.7	0.6	0.7	0.7	0.7	0.6	0.6	0.7	0.7
12:00	11:00	7:00	1.0	1.0	1.1	1.0	1.0	1.0	1.1	1.1	1.1	1.0	1.0	1.1	1.0
13:00	12:00	8:00	1.2	1.3	1.4	1.3	1.3	1.3	1.4	1.4	1.3	1.3	1.3	1.4	1.3
14:00	13:00	9:00	1.4	1.4	1.5	1.4	1.4	1.4	1.5	1.5	1.5	1.4	1.5	1.5	1.5
15:00	14:00	10:00	1.5	1.5	1.6	1.5	1.5	1.5	1.6	1.6	1.6	1.6	1.7	1.7	1.6
16:00	15:00	11:00	1.4	1.4	1.5	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.6	1.6	1.6
17:00	16:00	12:00	1.4	1.4	1.5	1.5	1.4	1.5	1.5	1.5	1.5	1.5	1.6	1.6	1.6
18:00	17:00	13:00	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.6	1.6	1.6
19:00	18:00	14:00	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.6	1.7	1.7	1.6
20:00	19:00	15:00	1.5	1.5	1.5	1.6	1.5	1.5	1.6	1.5	1.5	1.5	1.7	1.7	1.6
21:00	20:00	16:00	1.5	1.5	1.5	1.6	1.5	1.5	1.6	1.5	1.6	1.6	1.7	1.7	1.6
22:00	21:00	17:00	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.6	1.6	1.5
23:00	22:00	18:00	1.3	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.5	1.4	1.4
0:00	23:00	19:00	1.2	1.2	1.3	1.2	1.2	1.2	1.3	1.3	1.3	1.2	1.3	1.3	1.3
1:00	0:00	20:00	1.1	1.1	1.2	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.2
2:00	1:00	21:00	0.9	0.9	0.9	0.9	0.9	0.8	0.9	1.0	0.9	0.9	0.9	0.9	0.9
3:00	2:00	22:00	0.7	0.8	0.8	0.8	0.8	0.7	0.8	0.8	0.8	0.7	0.8	0.8	0.8
4:00	3:00	23:00	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.5	0.4	0.5	0.5	0.5

Figure 3 Aircraft Density Date/Time Scaling Factors

- Multiply by the probability that (a) the pilot of the illuminated aircraft is viewing the laser or (b) the illuminated people are viewing the laser through a telescope. For (a), this requires modeling the distribution of aircraft geometries that permit pilot exposure, along with the probability that a pilot would be looking in a

direction where exposure was possible. For (b), this requires modeling the distribution of telescope operators relative to the overall population, along with a model for the size distribution of telescopes and certain aspects of observation behaviors (e.g. time of observations versus time of satellite overflight, telescope field of view, digital observations versus ocular observations, etc.). Figure 4 shows the relative prevalence of telescopes by entrance aperture, as determined from responses to a survey we conducted within the active astronomer community.

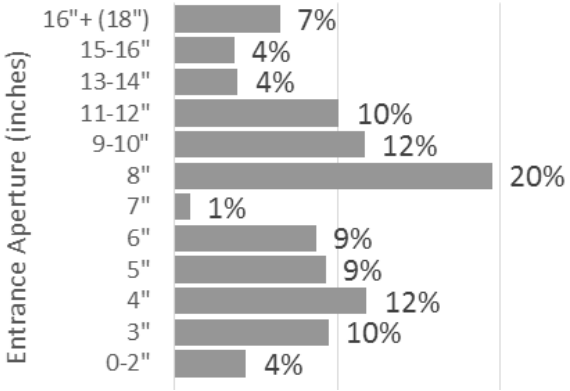

Figure 4 Telescope Prevalence by Entrance Aperture

- Calculate the delivered dosage and multiply by the probability of causing harm. The delivered dosage is a function of the laser divergence versus distance to the observer, in addition to mitigating factors like windshield transmission [5][6] or eyepiece magnification. The probability of causing harm is calculated using (1), which is based on the dosage response curves found in [7] and [8] and shown in Figure 5.

$$Odds\ of\ Ocular\ Damage = \frac{1}{1+\left(\frac{10}{MPE\ Ratio}\right)^{1.6}} \quad (1)$$

In regards to interfacing with the FAA, we are suggesting that a sensible path forward would be a paradigm wherein NASA agrees to comply with the common risk criterion for all flights within controlled airspace. Compliance with the standard would then obviate the need for issuing NOTAMs and for special handling by air traffic control (ATC). If and when a mission is proposed that exceeds the common risk criterion, then NASA would request special handling by ATC (e.g. clearing airspace below the research aircraft) and would issue a NOTAM regarding the activity.

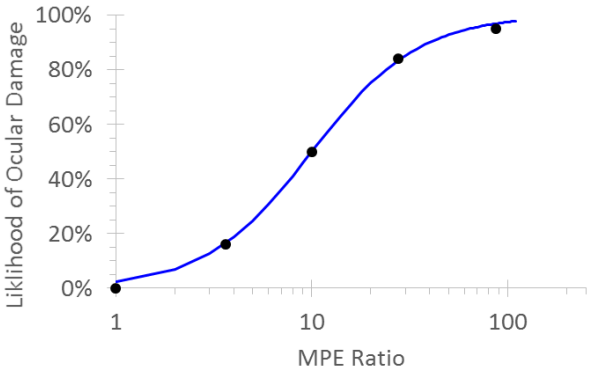

Figure 5 Odds of Ocular Damage vs. Dosage

2.3 Describe the Future State

With a common risk criterion in place, projects will have a sense, early in the design phase, of whether their approach is a safe one. The software tools, AirSHIELD and SpaceSHIELD, will allow relative hazards to be compared when weighing the tradeoffs between various candidate technical approaches. For example, it is not immediately obvious whether a high-repetition rate / low-pulse-energy laser system—which has a higher probability of exposure but a lower probability of injury per exposure—presents a lower risk of ocular injury than a higher-energy/lower-repetition rate system. Likewise, flying at higher altitudes (for airborne missions) reduces the laser energy density at a given altitude below the research aircraft, but also potentially exposes a larger number of aircraft than operating at a lower altitude. The software tools allow such relative hazards to be compared readily.

Under the proposed new paradigm, airborne missions will be able to interface smoothly and effectively with the FAA, without the current barriers which require extensive time and effort but do little, if anything, to enhance safety.

2.4 Risks and Rewards

Garnering consensus across diverse programs and projects and implementing new policy is an inherently political endeavor, which involves people from diverse backgrounds, organizations, and perspectives. The principal people supporting this effort are scientists and engineers, unskilled in the way of politics. Furthermore, the people who

fill the key roles at the FAA change on a fairly frequent basis, making it difficult to build the relationships and trust that will be necessary for changing the way NASA interfaces with the FAA.

3 PROGRAMMATICS

To date, the majority of the cost of this effort has been split between FTE (full-time equivalent, i.e. civil servant labor hours) and contractor (procurement) costs. In addition, an air traffic density dataset was purchased from a third party vendor with procurement dollars. Going forward, additional hours, travel funds, and procurement dollars are needed to facilitate meetings with decision makers, finalize drafts of the proposed criterion policy, incorporate a more detailed air traffic model into the software, create graphical user interfaces (GUIs) for both software tools, and to work through the software release process.

3.1 DEVELOPMENT PLANS

Currently, we are drafting a document which would define a common risk criterion. We envision this document being adopted by the Laser Safety Review Board (LSRB) as the standard against which future lidar missions will be evaluated. When reviewing a proposed operating plan for an outdoor laser operation involving an aircraft or satellite platform, the LSRB would ask the program or project to affirm that their mission presented an ocular hazard risk no greater than the common risk criterion.

3.2 DEVELOPMENT MILESTONES AND DATES

We are working towards having a solid draft of the policy document in the review process by the end of FY18 (Fiscal Year 2018), along with a draft of a memorandum of understanding (MOU) between NASA and the FAA. Likewise, working drafts of the GUIs for the software should be operational by the end of FY18. It is anticipated that the software release process will be completed by mid FY19.

3.3 PARTNERING

We want this effort to be enabling to NASA active optical sensing missions by providing clarity on the required level of safety that must be attained to meet our ethical requirement to protect the general public. To that end, we want to enlist the participation of other lidar projects to ensure that the computational tools we are developing are flexible enough to encompass the specific parameters of their mission. We would request that projects willing to partner with us contact the lead author and supply the following parameters for their system:

- Wavelength(s)
- Exit diameter
- Beam divergence
- Pulse repetition frequency
- Pulse width
- Nominal Ocular Hazard Distance (NOHD)
- Operational altitude (or altitude range)
- Type of orbit (for satellite platforms)
- Pointing angle

3.4 OVERCOMING THE VALLEY OF DEATH

The “valley of death” for this work is the bureaucratic path of policy. Namely, we must get documents reviewed and approved by the appropriate people at NASA. Figuring out who those people are is one hurdle. Figuring out how to craft a software management plan that makes sense while also conforming to procedural requirements is another hurdle. Moving to a new paradigm of cooperation with the FAA is a particularly large hurdle, partly because the personnel in the relevant roles change frequently at the FAA. The principal investigator (PI) for this effort is taking a detail assignment next fiscal year (FY19) and so the project could benefit from an interested party who would be willing to shepherd the proposed policies through their various approval processes. We could use a software manager who could oversee future patches and updates to the code for AirSHIELD and SpaceSHIELD. We could use funding support from other projects who stand to benefit from both the new risk criterion policy and from the software tools under development.

4 WIDER VISION

Risk is inherent to any research endeavor. Programs stand to benefit and the safety of the general public stands to be enhanced by tackling the issues of risk assessment and mitigation within a risk management approach. While most people would agree that risks should be minimized where possible, a pragmatic approach recognizes that risk cannot be eliminated entirely, and that some mitigation strategies are more effective than others. We hope that this effort will aid future programs and projects that include active sensing

systems to move beyond the paralysis that can result from a disproportionate aversion to risk and into an ethically sound approach to risk management.

5 CONCLUSIONS

The lack of a NASA-wide criterion on ocular hazard risks of lidar systems flown on satellites aircraft has the potential to inhibit NASA's ability to make needed scientific measurements. To that end, this effort has endeavored to establish an ethically-based risk criterion for future missions incorporating laser-based active optical systems, and to develop software tools capable of providing a conservative estimate of the level of risk posed by such systems.

ACKNOWLEDGEMENTS

We wish to acknowledge the guidance and support of the Science Directorate at NASA Langley Research Center, and specifically the MESCAL and HSRL2 teams, including Marie Ivanco, Chip Trepte, Chris Hostetler, John Hair, and Beth Brumbaugh, as well as our partners at the Centre national d'études spatiales (CNES).

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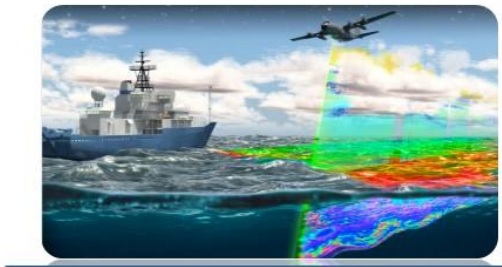
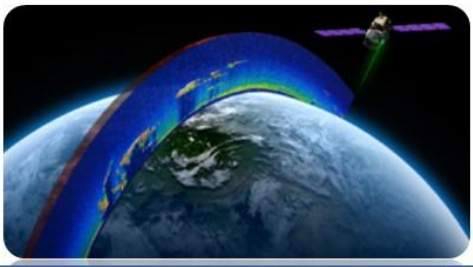




Ocular Hazard Risk Management for Airborne & Spaceborne Active Optical Systems

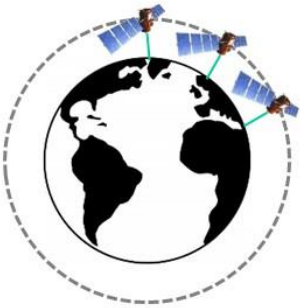
Jennifer Inman and Kim Merritt
NASA Langley Research Center

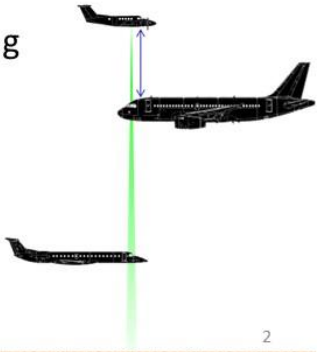
Ian Miller and Vinod Nagpal
N&R Engineering

2018 Technical Interchange Meeting on Active Optical Systems for Supporting Science, Exploration, & Aeronautics Measurements Needs, 30 July – 2 August 2018, Columbia, Maryland

Outline

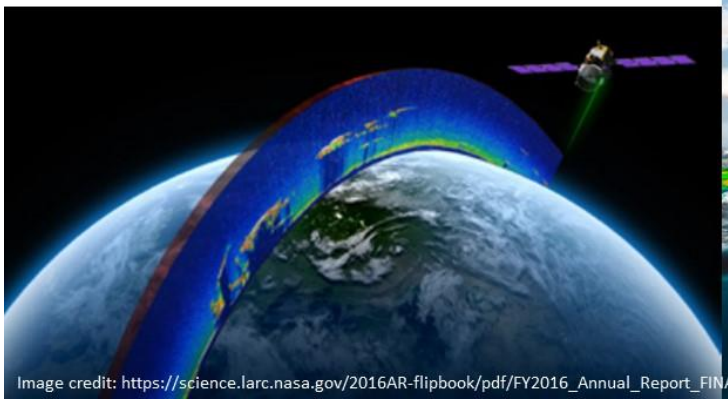
- Background
- The problem
- The path forward
  - NASA Common Risk Criterion
  - SpaceSHIELD overview
  - AirSHIELD overview
  - FAA/NASA Memorandum of Understanding
- Happy Thoughts
- Backup slides





Background

- NASA operates lasers from satellites and airplanes
- Below maximum permissible exposure (MPE) along Earth's surface
- What risk is posed to: Telescope operators? Other aircraft?
- Uncertainty has threatened viability of Science Directorate missions
  - Monitoring the Evolving State of Clouds and Aerosols Layers (MESCAL)
  - High Spectral Resolution Lidar (HSRL2)
- My background: physics, astronomy, laser work, Non-Ionizing Radiation Committee Chair, aviation



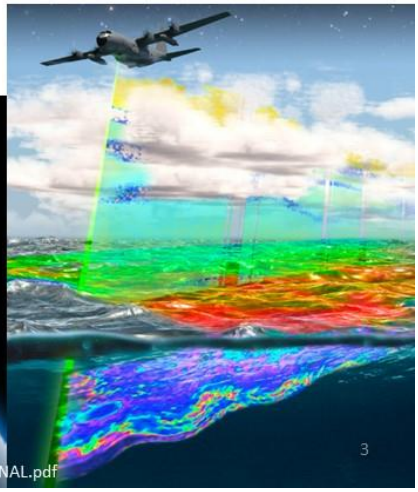


Image credit: https://science.larc.nasa.gov/2016AR-flipbook/pdf/FY2016_Annual_Report_FINAL.pdf

3

The Problem

- Science objectives must be weighed against the potential for causing injury to the public
- No common framework for risk assessment / acceptance
  - Eye safety calculations are handled independently by each program
    - Different approaches
    - Different opinions on maximum tolerable risk
  - Handling by external entities is inconsistent and subjective
    - Aviation Saftey Review Board—by NASA Center
    - Federal Aviation Administration—by Region
    - Air Traffic Control—by individual controller / workload
  - Months of effort are expended *per mission*
  - Leads to uncertainty, programmatic risk
    - Centre national d'études spatiales (CNES) involvement with MESCAL
    - HSRL2 grounded by unique "eye-safe below 18,000 ft" requirement

The Path Forward

- NASA and its partners must first decide on what level of risk is considered to be acceptable…

  …agree on how to calculate the risk…

  …quantify the effectiveness of mitigation strategies and decide which ones are warranted

- Probabilistic Risk Assessment (PRA)
  - Start with low-fidelity, conservative analysis
  - Monte Carlo sampler code
    - Written in Python under contract with N&R Engineering
    - Inputs can be either deterministic or distributions (with uncertainties)
    - Currently, two test cases: MESCAL (spaceborne) and HSRL2 (airborne)
    - Code still being developed as fidelity of analysis increases
    - Graphical user interface planned once methodology has been vetted

Space SHIELD Version 1.0 — Air SHIELD Version 1.0

SHIELD: Software for Hazard Identification and Evaluation of Lidar Deployments

The Path Forward

- NASA and its partners must first decide on what level of risk is considered to be acceptable…

  …agree on how to calculate the risk…

- Probabilistic Risk Assessment (PRA)

Example: NASA-STD-8719.14A
Process for Limiting Orbital Debris

NASA TECHNICAL STANDARD | NASA-STD-8719.14A (with Change 1)
National Aeronautics and Space Administration, Washington, DC 20546
Approved: 2011-12-08
Change 1 approved: 2012-05-25

…cess for Limiting Orbital Debris

…Measurement System Identification: Metric

4.7.2 Requirements for the Area

NASA space progr… structures need to l… on the surface of th…

4.7.2.1 *Requireme…* is assumed for any…

a. For uncontrolle… 0.0001 (1:10,000)…

b. For controlled reentry, the selected trajectory shall ensure that no surviving debris impact with a kinetic energy greater than 15 joules is closer than 370 km from foreign landmasses, or is within 50 km from the continental U.S., territories of the U.S., and the permanent ice pack of Antarctica (Requirement 56627).

c. For controlled reentries, the product of the probability of failure of the reentry burn (from Requirement 4.6-4.b) and the risk of human casualty assuming uncontrolled reentry shall not exceed 0.0001 (1:10,000) (Requirement 56628).

Requirement 4.7-1: Limit the risk of human casualty
"[T]he risk of human casualty from surviving debris shall not exceed 0.0001"
1 in 10,000 per mission

…vetted

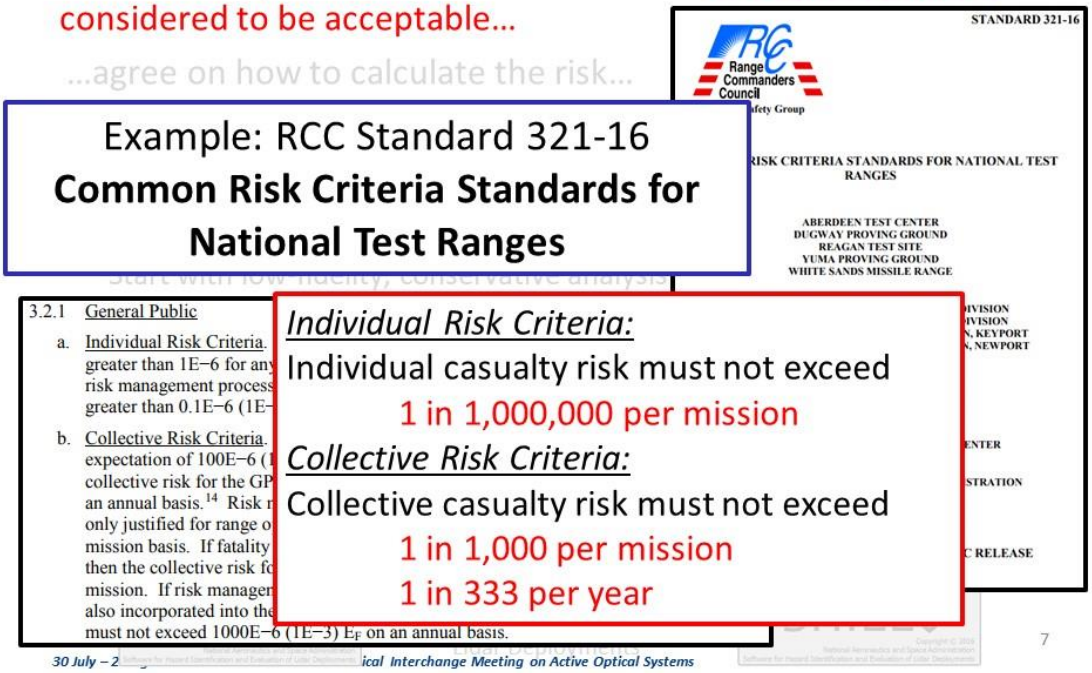
Air SHIELD

The Path Forward

- NASA and its partners must first decide on what level of risk is considered to be acceptable…

…agree on how to calculate the risk…

Example: RCC Standard 321-16
Common Risk Criteria Standards for National Test Ranges


STANDARD 321-16

Range Commanders Council

RISK CRITERIA STANDARDS FOR NATIONAL TEST RANGES

ABERDEEN TEST CENTER
DUGWAY PROVING GROUND
REAGAN TEST SITE
YUMA PROVING GROUND
WHITE SANDS MISSILE RANGE

3.2.1 General Public

a. Individual Risk Criteria. greater than 1E−6 for any risk management process greater than 0.1E−6 (1E−

b. Collective Risk Criteria. expectation of 100E−6 (collective risk for the GP an annual basis.[14] Risk r only justified for range o mission basis. If fatality then the collective risk fo mission. If risk manager also incorporated into the must not exceed 1000E−6 (1E−3) E_F on an annual basis.

Individual Risk Criteria:
Individual casualty risk must not exceed
1 in 1,000,000 per mission
Collective Risk Criteria:
Collective casualty risk must not exceed
1 in 1,000 per mission
1 in 333 per year

The Path Forward

- NASA and its partners must first decide on what level of risk is considered to be acceptable…

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…quantify the effectiveness of mitigation strategies and and decide which ones are warranted

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  - Start with low-fidelity, conservative analysis
  - Monte Carlo sampler code
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SHIELD: Software for Hazard Identification and Evaluation of Lidar Deployments

Air SHIELD Version 1.0 — Copyright © 2016 National Aeronautics and Space Administration — Software for Hazard Identification and Evaluation of Lidar Deployments

SPACEBORNE

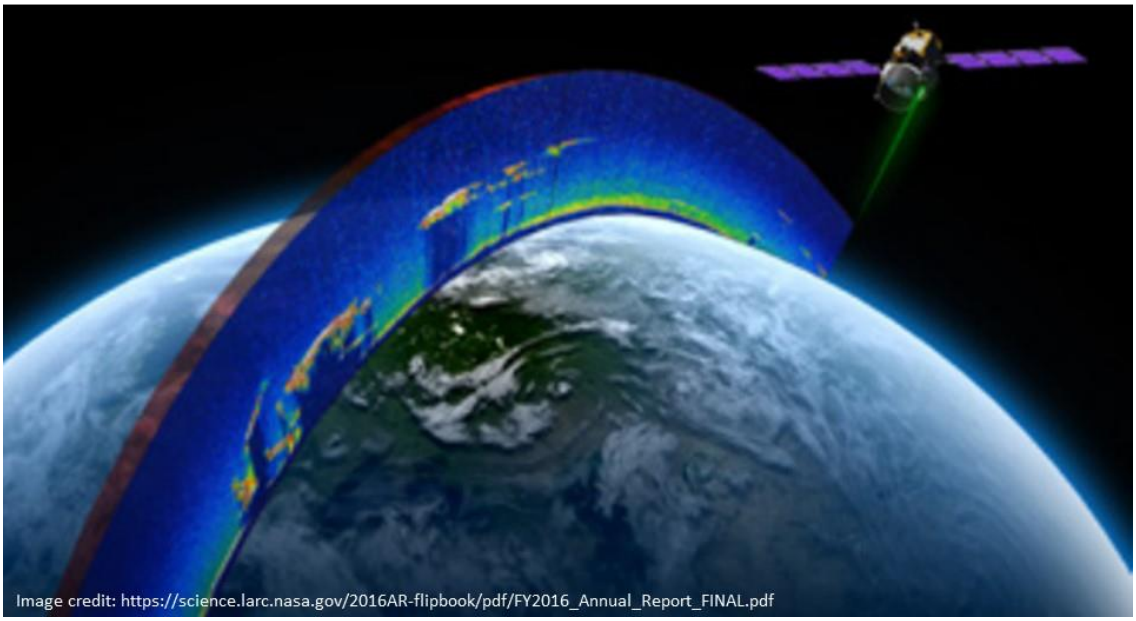
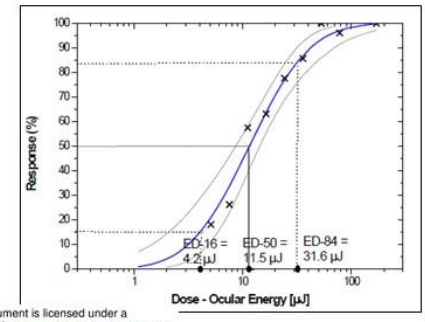


Image credit: https://science.larc.nasa.gov/2016AR-flipbook/pdf/FY2016_Annual_Report_FINAL.pdf

Overview: SpaceSHIELD

1. Calculate the number of people illuminated by each laser pulse.
2. Multiply by the probability that those people are viewing the laser through a telescope.
3. Calculate the delivered dosage and multiply by the probability of causing harm.


Data source: http://sedac.ciesin.columbia.edu/data/collection/grump-v1
Compiled by Bill Rankin, www.radicalcartography.net



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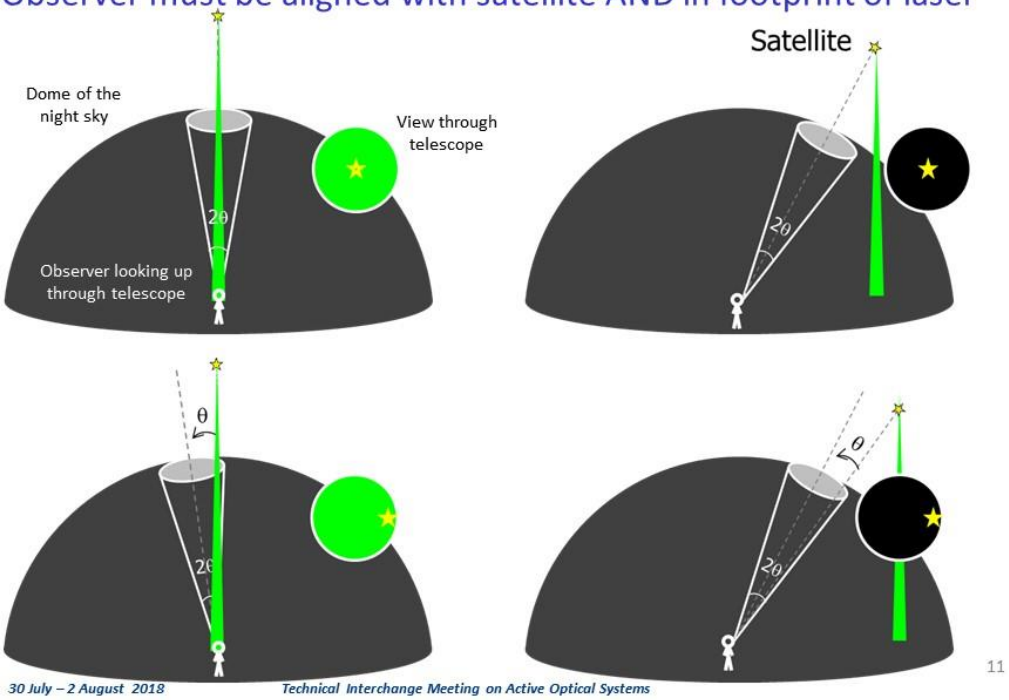
Aligning Telescope with Laser

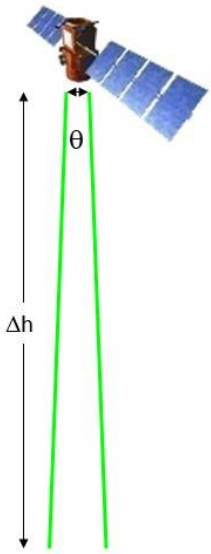
Observer must be aligned with satellite AND in footprint of laser



Diameter of Laser Footprint

$$D = h\theta$$

The diameter of the laser spot is a product of the divergence and the distance plus the exit diameter (which is negligible relative to the beam diameter at these distances).



Parameter		Input units	Units for Calculations
Altitude	h	km	m
Divergence	θ	mrad	radians
Exit Diameter	D_{exit}	cm	m

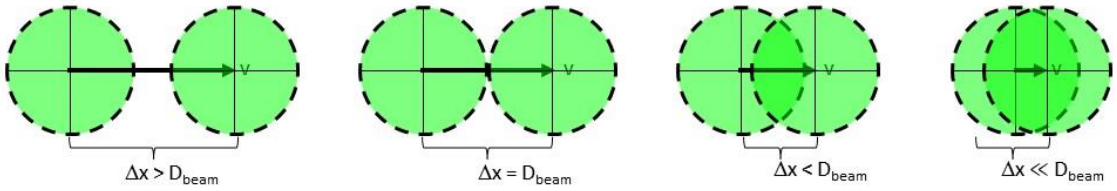
From geometry, we have $D = D_{exit} + h\sin\theta$
Use small angle approximation: $\sin\theta \cong \theta$

If $h\theta/D_{exit} \geq 100$,
$D = h\theta$
else $D = D_{exit} + h\theta$

Do pulses overlap?

The time between pulses, Δt, is the inverse of the pulse repetition frequency, PRF. The distance between pulses, Δx, is the ground speed times Δt. The pulses overlap if Δx is less than the diameter of the beam on the ground, D.

If $\Delta x < D$, then pulses will overlap



Constants

$G = 6.674 \times 10^{-11} N \cdot m^2\ kg^2$

$M_\oplus = 5.972 \times 10^{24} kg$

$\mu = GM_\oplus = 3.986 \times 10^{14} m^3 s^{-2}$

$R_\oplus = 6.37 \times 10^6 m$

$C_\oplus = 2\pi R_\oplus = 4.01 \times 10^7 m$

Formulas

$\tau = \frac{2\pi}{\sqrt{\mu}}\left(R_\oplus + h\right)^{3/2}$

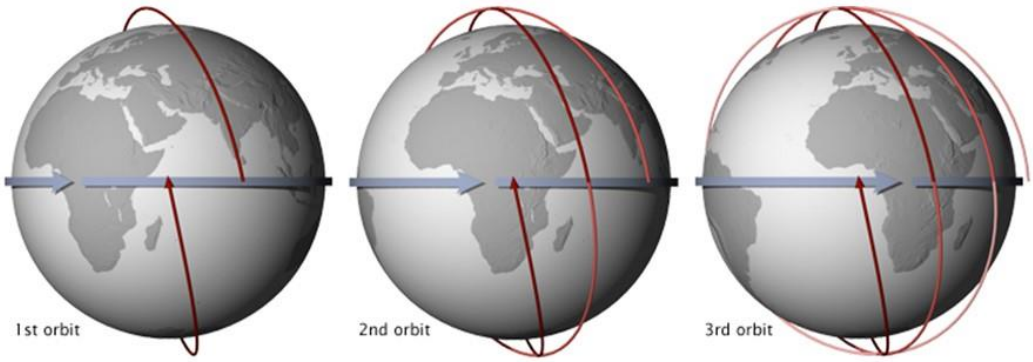
$v = C_\oplus / \tau$

$\Delta x = v \cdot \Delta t$

$\Delta t = 1/PRF$

$D = h\theta$

Orbital Parameters

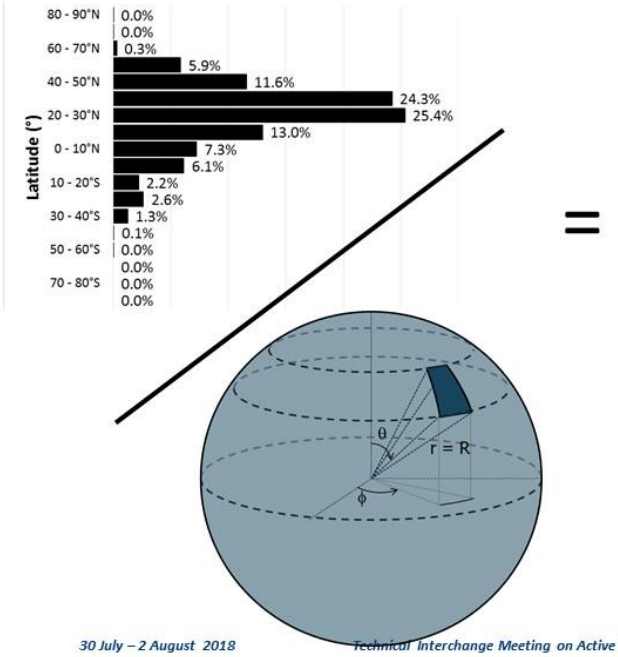


- Solar-synchronous
- Overflight at approximately same time of day/night
- Nearly uniform longitudinal coverage
- Over-sampling at poles/under-sampling at equator

NASA illustration by Robert Simmon: https://earthobservatory.nasa.gov/Features/OrbitsCatalog/page2.php

Population Density: people/km²

Population / surface area = population density

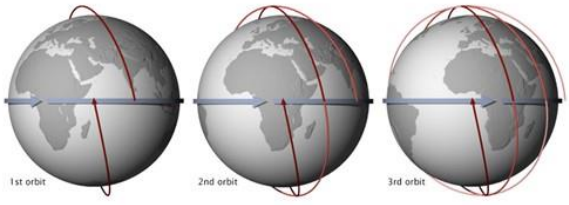


$$\rho_i = \frac{N_i}{A_i}$$

Latitude	$N_i/N^{\ddagger\S}$	A_i km^2	ρ_i People/km²
60-90°N	0.3%	34,167,841	0.66
50-60°N	5.9%	25,498,368	17.04
40-50°N	11.6%	31,434,466	27.31
30-40°N	24.3%	36,415,443	49.35
20-30°N	25.4%	40,289,956	46.62
10-20°N	13.0%	42,940,279	22.40
0-10°N	7.3%	44,285,883	12.14
0-10°S	6.1%	44,285,883	10.25
10-20°S	2.2%	42,940,279	3.81
20-30°S	2.6%	40,289,956	4.81
30-40°S	1.3%	36,415,443	2.56
40-90°S	0.1%	31,434,466	0.15

Some Parameters from Survey Responses

- Average number of nights per year that survey respondents observe: **57** (15.6% of nights).
  - Equivalently, 15.6% of active observers are observing on a given night.
- Respondents that never observe visually at 2am: **46%**
- Fraction of 2am observations that are visual: **18%**
- Average % of observations that are visual and 2am: **9.8%**
- Fraction of time spent looking through eyepiece: **13%**



NASA illustration by Robert Simmon: https://earthobservatory.nasa.gov/Features/OrbitsCatalog/page2.php

Current Results of Analysis

Interval	Expected Casualties
Per year	5.51E-5
Per 3-yr mission	1.65E-5
Per 5-yr mission	2.75E-5

Interval	Probability of Casualty
Per year	1 in 181,000
Per 3-yr mission	1 in 60,000
Per 5-yr mission	1 in 36,000

These numbers are injury expectation values showing collective risk to the general public (i.e. the odds that someone gets hurt).

Individual risk—the odds that a *specific* person gets hurt—is orders of magnitude lower.

RCC Standard 321-16
Collective Risk Criteria:
1 in 333 per year
1 in 1,000 per mission

AIRBORNE

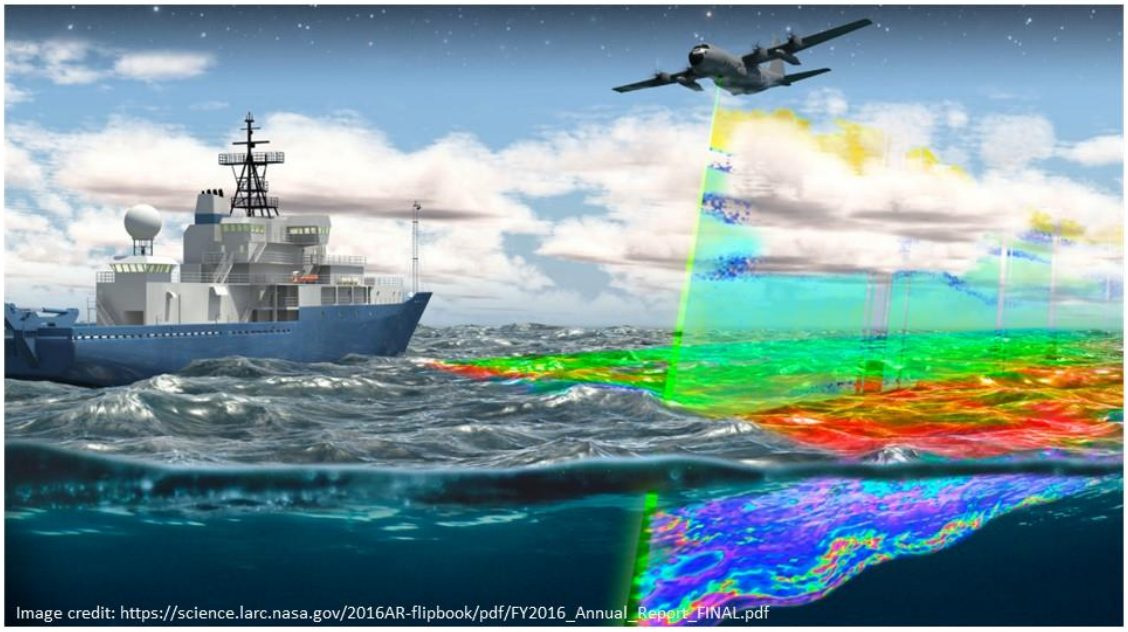


Image credit: https://science.larc.nasa.gov/2016AR-flipbook/pdf/FY2016_Annual_Report_FINAL.pdf

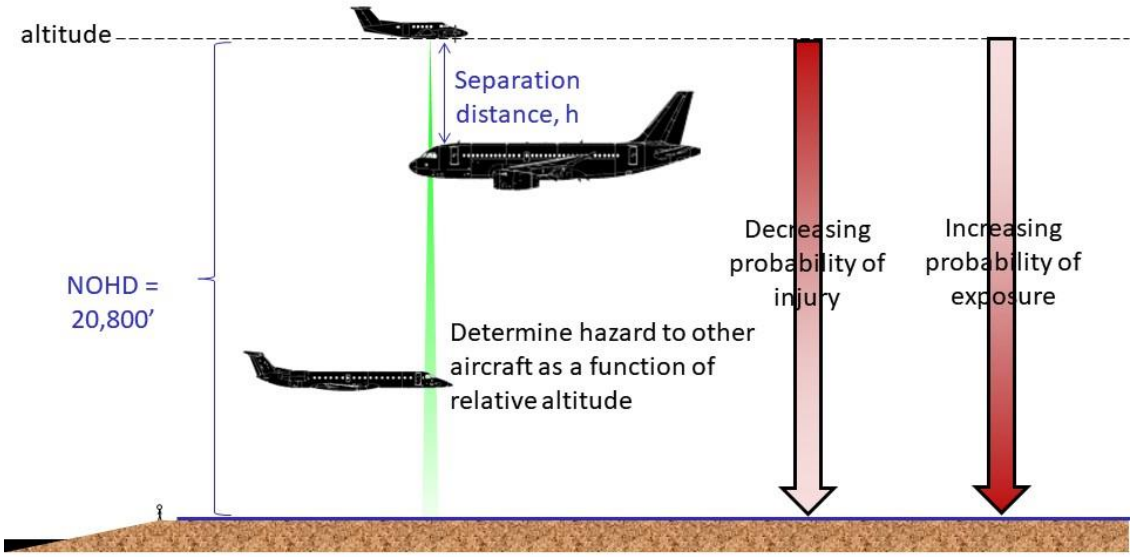
Overview: AirSHIELD

1. Calculate the number of aircraft illuminated by each laser pulse.
2. Multiply by the probability that pilot is viewing laser.
3. Calculate the delivered dosage and multiply by the probability of causing harm.

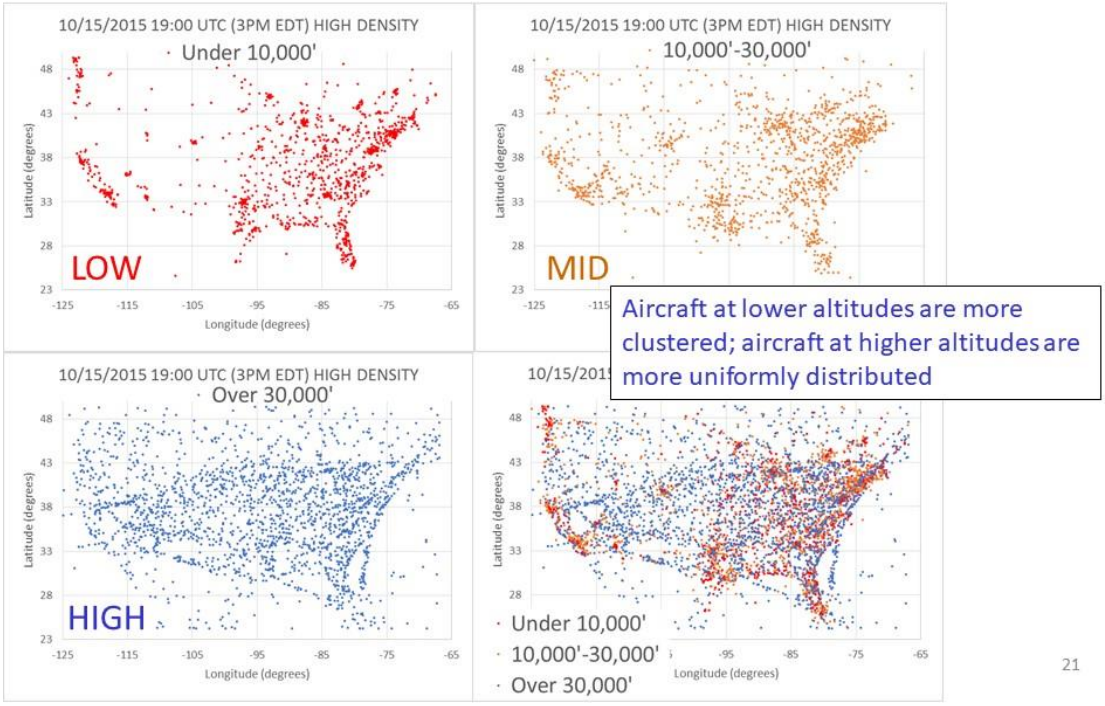


Exposure of Other Pilots

Observer must be directly beneath the laser AND looking up into the beam



Aircraft Density Drives Exposure Risk



Aircraft at lower altitudes are more clustered; aircraft at higher altitudes are more uniformly distributed

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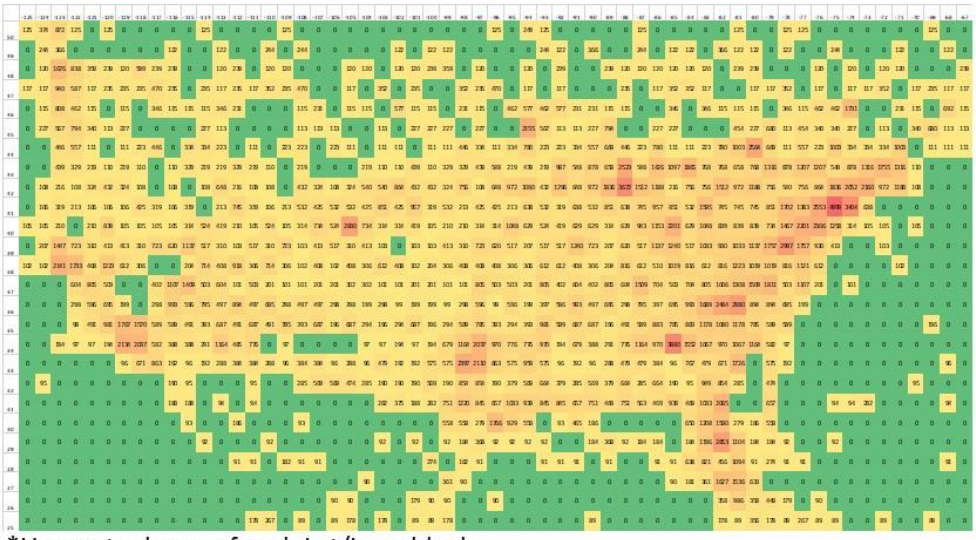
Number of aircraft per million km^2



*Uses actual area of each Lat/Long block

Data for HIGH density day (15 October 2015 19:00 UTC)

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Time of Year and Time of Day

Multiply the average CONUS air traffic density by the value in this table corresponding to the time and date of the mission:

			Date/Time Scaling Factors											
			Standard Time			Daylight Savings Time							Standard Time	
UTC	UTC	Eastern Time	January	February	March (EST)	March (EDT)	April	May	June	July	August	September	October	November	December
5:00	4:00	0:00	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
6:00	5:00	1:00	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
7:00	6:00	2:00	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
8:00	7:00	3:00	0.1	0.2	0.2	0.1	0.2	0.1	0.2	0.2	0.2	0.1	0.1	0.1	0.2
9:00	8:00	4:00	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
10:00	9:00	5:00	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.3	0.3
11:00	10:00	6:00	0.6	0.6	0.7	0.7	0.7	0.6	0.7	0.7	0.7	0.6	0.6	0.7	0.7
12:00	11:00	7:00	1.0	1.0	1.1	1.0	1.0	1.0	1.1	1.1	1.1	1.0	1.0	1.1	1.0
13:00	12:00	8:00	1.2	1.3	1.4	1.3	1.3	1.3	1.4	1.4	1.3	1.3	1.3	1.4	1.3
14:00	13:00	9:00	1.4	1.4	1.5	1.4	1.4	1.4	1.5	1.5	1.5	1.4	1.5	1.5	1.5
15:00	14:00	10:00	1.5	1.5	1.6	1.5	1.5	1.5	1.6	1.6	1.6	1.6	1.7	1.7	1.6
16:00	15:00	11:00	1.4	1.4	1.5	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.6	1.6	1.6
17:00	16:00	12:00	1.4	1.4	1.5	1.5	1.4	1.5	1.5	1.5	1.5	1.5	1.6	1.6	1.6
18:00	17:00	13:00	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.6	1.6	1.6
19:00	18:00	14:00	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.6	1.7	1.7	1.6
20:00	19:00	15:00	1.5	1.5	1.5	1.6	1.5	1.5	1.6	1.5	1.5	1.5	1.7	1.7	1.6
21:00	20:00	16:00	1.5	1.5	1.5	1.6	1.5	1.5	1.6	1.5	1.6	1.6	1.7	1.7	1.6
22:00	21:00	17:00	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.6	1.6	1.5
23:00	22:00	18:00	1.3	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.5	1.4	1.4
0:00	23:00	19:00	1.2	1.2	1.3	1.2	1.2	1.2	1.3	1.3	1.3	1.2	1.3	1.3	1.3
1:00	0:00	20:00	1.1	1.1	1.2	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.2
2:00	1:00	21:00	0.9	0.9	0.9	0.9	0.9	0.8	0.9	1.0	0.9	0.9	0.9	0.9	0.9
3:00	2:00	22:00	0.7	0.8	0.8	0.8	0.8	0.7	0.8	0.8	0.8	0.7	0.8	0.8	0.8
4:00	3:00	23:00	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.5	0.4	0.5	0.5	0.5

Current non-Monte Carlo Results*

*Preliminary and unverified. These are the first results attempting to incorporate a volumetric altitude-dependent air traffic density model (aircraft per cubic kilometer) using bulk average midday CONUS air traffic density. Software could distinguish between flight hours over Class B and/or Class C airspace.

Expected Injuries	No Mitigation	TCAS-only	TCAS+Other
Per flight hour	1.5E-5	9.9E-5	1.3E-09
Per 5-hr mission	7.4E-5	5.0E-5	6.2E-09

Collective Odds of Injury	No Mitigation	TCAS-only	TCAS+Other
Per flight hour	1 in 68,000	1 in 100,000	1 in 800,000,000
Per 5-hr mission	1 in 13,000	1 in 20,000	1 in 160,000,000

"Other" indicates the effect of the following mitigating assumptions:

- Aircraft geometry (1% transponding; 25% non-transponding)[~2 orders of magnitude]
- Pilot looking up 1% of the time [2 orders of magnitude]
- Windshield (85% transmission + 45° angle of incidence) [<1 order of magnitude]

The risk numbers shown would be expected to increase when flying missions in high-density areas and to decrease when flying early morning / late night.

Comparison with Cassini Mission

Cassini: Potential Events with Plutonium Dioxide Release	Probability	Estimated Fatalities	Risk Factor
Inadvertent Earth Swingby Reentry	1 in 1 million	120	0.00010
Early Launch Accident	1 in 1,400	0.1	0.00007
Late Launch or Reentry from Earth Orbit Accident	1 in 476	0.04	0.00008

Lidar Missions	Probability	Estimated Casualties	Risk Factor
MESCAL (5-yr mission)	1 in 36,000	1	0.00003
HSRL2 (5-hr mission, no mitigation)	1 in 13,000	1	0.00008

*Fatality risks are generally required to be 2 orders of magnitude lower than casualty risks.

National Aeronautics and Space Administration (NASA) Draft Supplemental Environmental Impact Statement for the Cassini Mission. Washington, D.C., April 1997.

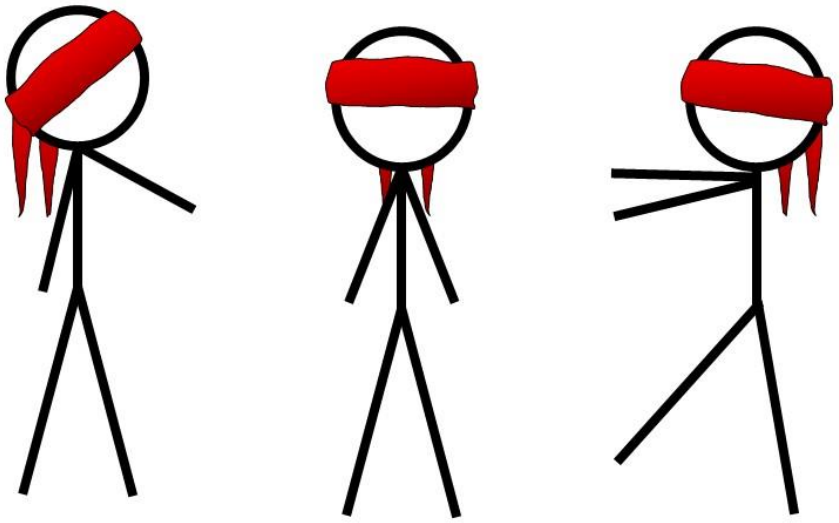
Happy Thoughts…

Diameter of Asteroid Hitting the Earth	Annual Probability	Estimated Fatalities	Risk Factor
10 km (6 mi)	1 in 100 million	5 billion	50
1.5 km (1 mi)	1 in 500,000	1.5 billion	3,000
50-300 m (150-1000 ft)	1 in 250	5,000	20

Clark R. Chapman and David Morrison, "Impacts on the Earth by Asteroids and Comets: Assessing the Hazard," Nature, Volume 367, 6 January 1994.

BACKUP

MITIGATION STRATEGIES



Happy Thoughts

Comparative Risks: Asteroid Impacts (annual)

Table 1

Potential Event	Probability	Estimated Fatalities	Risk Factor
10 Kilometer (6 Mile) Diameter, or greater, Asteroid Hitting the Earth	1 in 100 million	5 billion	50
1.5 Kilometer (1 Mile) Diameter Asteroid Hitting the Earth	2 in 1 million	1.5 billion	3,000
50-300 Meter (150-1000 Feet) Diameter Asteroid Hitting the Earth	1 in 250	5,000	20
Cassini Inadvertent Earth Swingby Reentry with Plutonium Dioxide Release	1 in 1 million	120	0.0001
Cassini Early Launch Accident with	1 in 1,400	0.1	0.00007
Cassini Late Launch or Reentry from Earth Orbit Accident with Plutonium Dioxide Release	1 in 476	0.04	0.00008

References

National Aeronautics and Space Administration (NASA). 1997. Draft Supplemental Environmental Impact Statement for the Cassini Mission. Washington, D.C., April 1997.

Clark R. Chapman and David Morrison. 1994. "Impacts on the Earth by Asteroids and Comets: Assessing the Hazard" in Nature, January 6, 1994 (Volume 367).

Mitigation Strategies

Spaceborne

- Offset in public ground track
- Educational outreach to astronomer communities

Airborne

- TCAS (Traffic Collision Avoidance System)
- Manual Shutter

Both

- Beam divergence
- Repetition rate / Pulse energy tradeoffs

Next Steps



- NASA Technical Standard
  - Buy-in from other NASA Centers
  - Need involvement from new Laser Safety Review Board (LSRB)
  - Cooperation and coordination with FAA
- Software development
  - Code rewrite is underway to incorporate higher-fidelity modeling of several parameters and incorporation of mitigation strategies
  - Graphical User Interface is under development
  - Software classification (preliminary classification complete based on internal use; will change when software is regularly used to make safety decisions)
  - Software development plan needs to be drafted
- Survey of astronomers
  - Currently analyzing and incorporating responses
- CONUS (continental United States) air traffic data
  - Density data being analyzed
  - Line-of-sight analysis needs to be done



BACKUP: SPACEBORNE

MESCAL Proposed Orbit & Laser Parameters

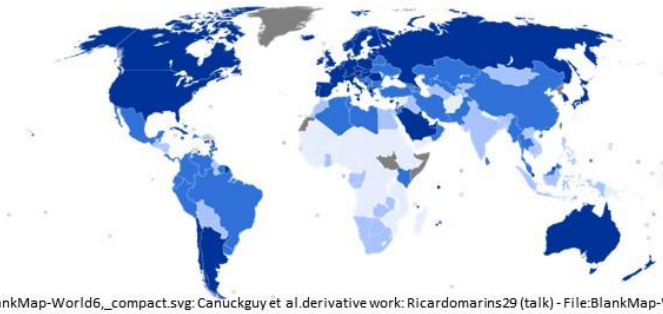
- Solar-synchronous orbit
  - Altitude: 450 km or 833 km
  - Random coverage, neglecting gap at extreme latitudes
  - The specific repeating 233 ground tracks are not considered
- Pulse repetition frequency: **150 Hz**
- Pulse width: **14 ns**
- Pulse energy
  - 1064 nm: 75 mJ
  - 532 nm: **100 mJ**
  - 355 nm: 75 mJ
- Beam diameter
  - 1064 nm: 5 cm
  - 532 nm: **5 cm**
  - 355 nm: 2.5 cm
- Beam divergence

  450 km
  - 1064 nm: 0.206 mrad
  - 532 nm: **0.206 mrad**
  - 355 nm: 0.206 mrad

  833 km
  - 1064 nm: 0.130 mrad
  - 532 nm: **0.11 mrad**
  - 355 nm: 0.11 mrad

Vulnerable Population

- "Astronomers"
  - People with an interest in astronomy + access to telescope
  - Percentage of population is different for "more developed" vs. "developing" populations
- Active Observers
  - People who use a telescope at least once per year
  - 5-10% of "astronomers" are "active observers" based on feedback from several astronomy organizations



"More Developed"
- 1.26 billion

"Developing"
- 6.24 billion

By BlankMap-World6,_compact.svg: Canuckguy et al.derivative work: Ricardomarins29 (talk) - File:BlankMap-World6.svg, http://hdr.undp.org/en/2016-report, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=57722223

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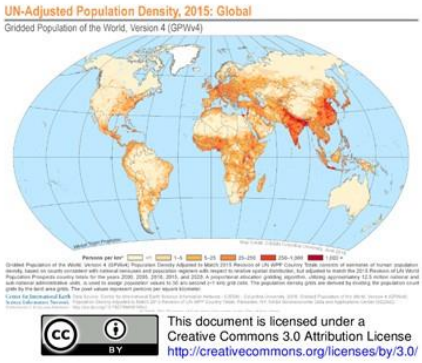
Population (by latitude): % total people

$$\rho_i = \frac{N_i}{A_i}$$

Latitude	$N_i/N^{\ddagger\S}$
60-90°N	0.3%
50-60°N	5.9%
40-50°N	11.6%
30-40°N	24.3%
20-30°N	25.4%
10-20°N	13.0%
0-10°N	7.3%
0-10°S	6.1%
10-20°S	2.2%
20-30°S	2.6%
30-40°S	1.3%
40-90°S	0.1%

We know what percentage of the world's population lives in each of these latitude bands.

What is the relative surface area of each band?



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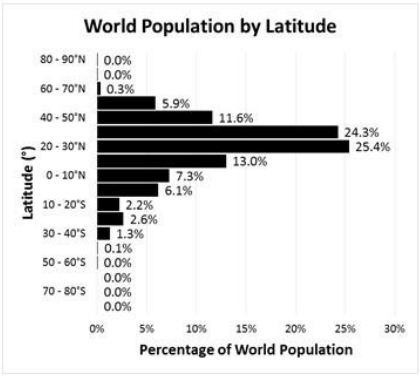


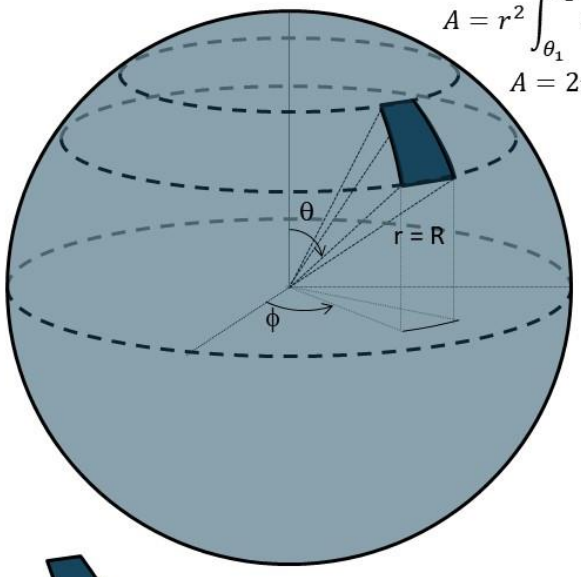
* http://nssdc.gsfc.nasa.gov/planetary/factsheet/earthfact.html
† https://www.cia.gov/library/publications/the-world-factbook/geos/xx.html
‡ http://www.census.gov/popclock/ (On 10/04/2016: 7.343564 billion)
§ http://dx.doi.org/10.7927/H4D50JX4 Accessed 04 October 2016

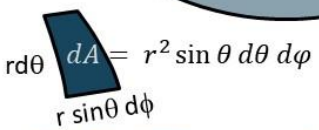
Data source: http://sedac.ciesin.columbia.edu/data/collection/grump-v1
Compiled by Bill Rankin, www.radicalcartography.net

Earth: Surface Area between Latitudes

$$A = r^2 \int_{\theta_1}^{\theta_2} \sin\theta \, d\theta \int_0^{2\pi} d\varphi$$

$$A = 2\pi R^2(\cos\theta_1 - \cos\theta_2)$$



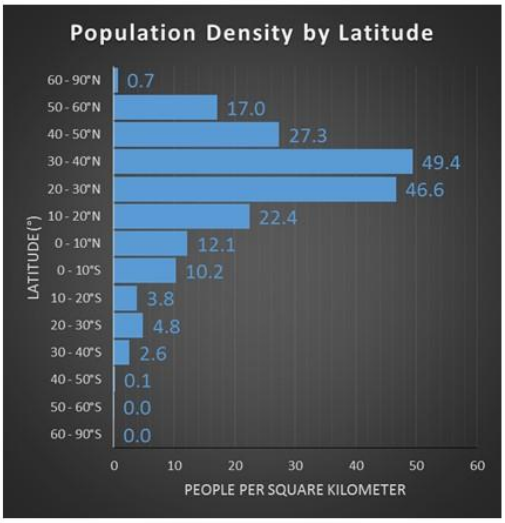


$$dA = r^2 \sin\theta \, d\theta \, d\varphi$$

θ_1	θ_2	A_i km^2
0°	30°	34,167,841
30°	40°	25,498,368
40°	50°	31,434,466
50°	60°	36,415,443
60°	70°	40,289,956
70°	80°	42,940,279
80°	90°	44,285,883
90°	100°	44,285,883
100°	110°	42,940,279
110°	120°	40,289,956
120°	130°	36,415,443
130°	140°	31,434,466
140°	150°	25,498,368
150°	180°	34,167,841

Time-Weighted Avg Population Density

$$\rho_{TWA} = 11.02\ people/km^2$$



Using data from http://www.radicalcartography.net/index.html?histland

If we weight the density in each band by the percentage of the time that the satellites spends there, we get an time-weighted average population density of 11.02 people per square kilometer.

This is somewhat less than the world's average population density of 14.51 people per square kilometer.

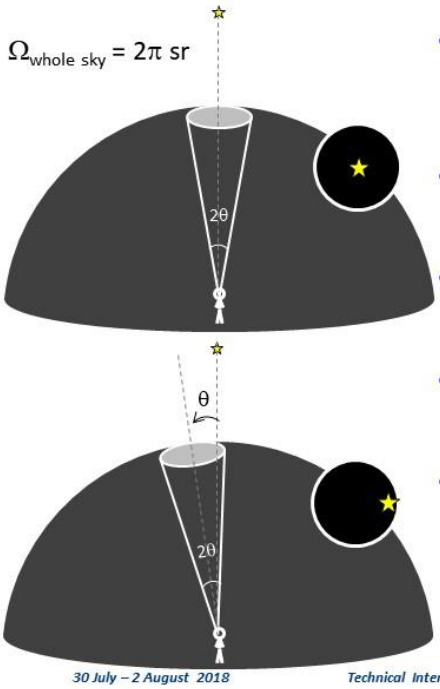
This is because the satellite spends 1/3 of its time illuminating latitudes greater than ±60° (the sparsely-populated high latitudes), another 5/18 of its time illuminating areas with population densities of less than 5 people per square kilometer, and only 7/18 of its time illuminating the high-population-density latitudes.

Overview: SpaceSHIELD

1. Calculate the number of people illuminated by each laser pulse.
2. Multiply by the probability that those people are viewing the laser through a telescope.
3. Calculate the delivered dosage and multiply by the probability of causing harm.

Aligning Telescope with Laser

Solid angle captured by telescope (steradians): $\Omega = 2\pi\ (1\text{-}\cos\theta)$



- Odds of randomly aligning a telescope vertically = $\Omega / \Omega_{whole\ sky} = 1\text{-}\cos\theta$
- For a large (5°) true field of view, the odds come out to 1 in 1,050.
- For a more typical field of view (0.5°), the odds come out to 1 in 105,000
- θ is the angular radius of a given telescope's field of view.
- The laser flash will only be visible if the telescope is pointed directly up (vertical) plus or minus the angular radius of its field of view (i.e. ±θ) in both axes.

5° FOV centered on full Moon

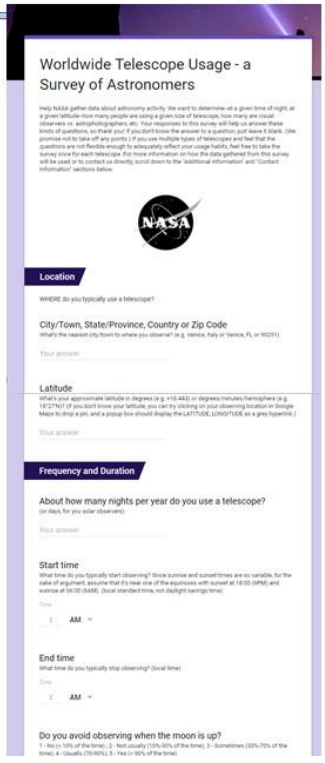


0.5° FOV centered on full Moon



Survey of Astronomers

- When and where
  - Location / latitude
  - Nights per year, date range
  - Time of day / night (2 am?)
- Entrance aperture
- Eyepiece focal length / power
- Astrophotography vs. visual observing
  - Time spent looking through eyepiece
- Focal ratio (f-number)
- True field of view
- Filters (moon, polarizing, spectral/color)
- Type of telescope
  - Refractor (lenses/dioptrics; e.g. Galilean, Keplerian)
  - Reflector (mirrors/catoptrics; e.g. Dobsonian)
  - Catadioptric (mirrors and lenses; e.g. Schmidt-Cassegrain)
- Observing targets
- GoTo capability, slew rate
- Zenith viewing limitations, telescopic mount type
- Club / organizational membership


Worldwide Telescope Usage - a Survey of Astronomers

Location

WHERE do you typically use a telescope?

City/Town, State/Province, Country or Zip Code

Latitude

Frequency and Duration

About how many nights per year do you use a telescope?

Start time

End time

Do you avoid observing when the moon is up?

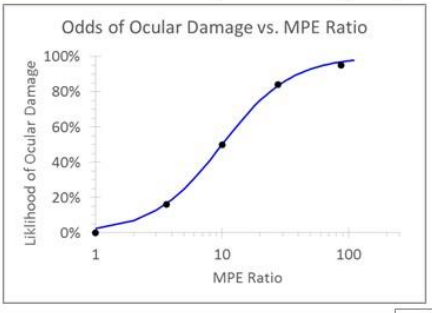
Overview: SpaceSHIELD

1. Calculate the number of people illuminated by each laser pulse.
2. Multiply by the probability that those people are viewing the laser through a telescope.
3. Calculate the delivered dosage and multiply by the probability of causing harm.

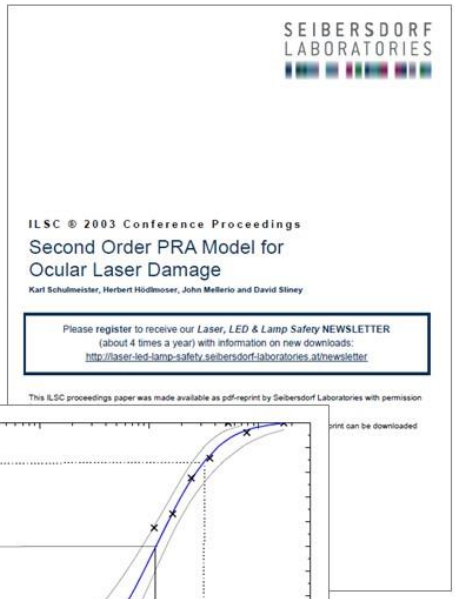
Odds of Ocular Damage

$$Odds\ of\ Ocular\ Damage = \frac{1}{1 + \left(\frac{10}{MPE\ Ratio}\right)^{1.6}}$$

MPE Ratio	Odds of Ocular Damage
1	2%
1.5	5%
2.5	10%
4.2	20%
5.9	30%
7.8	40%
10	50%
13	60%
17	70%
24	80%
40	90%
150	99%



We fit the data from this study with an equation relating MPE ratio to Odds of Ocular Damage.


SEIBERSDORF LABORATORIES

ILSC © 2003 Conference Proceedings

Second Order PRA Model for Ocular Laser Damage

Karl Schulmeister, Herbert Hödlmoser, John Mellerio and David Sliney

Please register to receive our *Laser, LED & Lamp Safety* NEWSLETTER (about 4 times a year) with information on new downloads: http://laser-led-lamp-safety.seibersdorf-laboratories.at/newsletter

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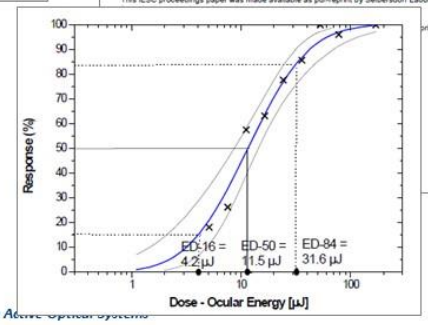
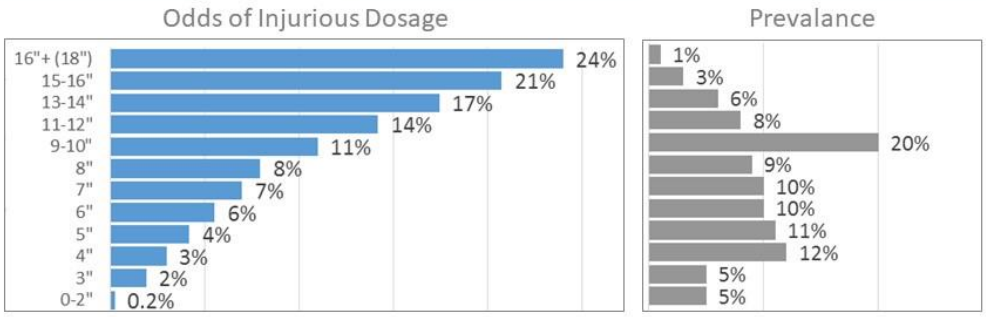
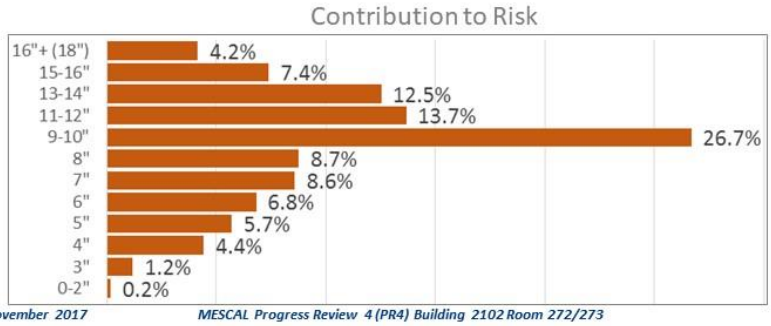
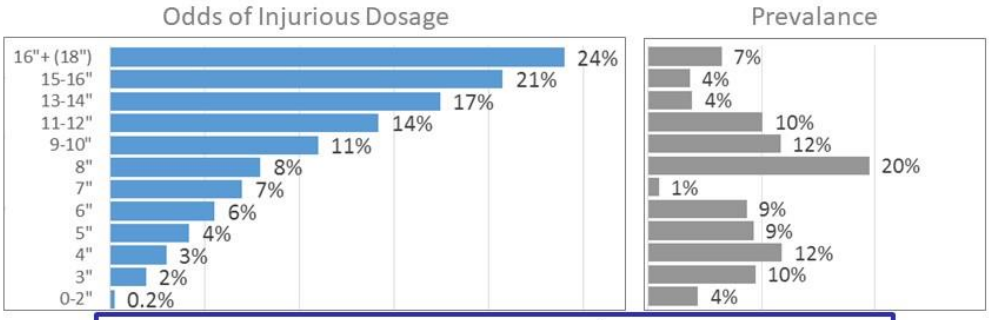


Entrance Aperture: Pre-Survey

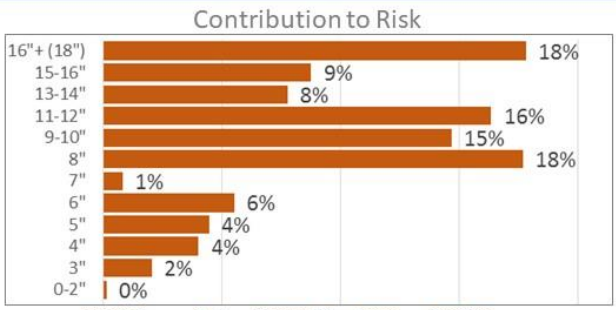




Entrance Aperture: Post-Survey



Have not yet accounted for eyepiece size / magnification, effect of filter usage, sample biases, or behavioral differences by aperture



Annual Collective Risk



"Collective risk for the GP [General Public] must not exceed a casualty expectation of 100E-6 (1E-4) for any single mission. If annual risk is measured, collective risk for the GP should not exceed a casualty expectation of 3000E-6 (3E-3) on an annual basis. Risk management using only an annual measure of collective risk is only justified for range operations that occur frequently and pose a low risk on a per-mission basis."

per-laser pulse per-orbit

"Individuals must not be exposed to a probability of casualty greater than 1E-6 for any single mission."

Current Results of Analysis



Probability:	1 year	3 year	5 year
	5.51E-06	**1.65E-05**	**2.75E-05**

1 in ___odds:	1 year	3 year	5 year
	181,632	**60,544**	**36,326**

These numbers are injury expectation values showing collective risk to the general public (i.e. the odds that *someone* gets hurt).

RCC Standard 321-16
Collective Risk Criteria:
1 in 333 per year
1 in 1,000 per mission

Individual risk—the odds that a *specific* person gets hurt—is orders of magnitude lower.



Comparison with Cassini Mission

Cassini: Potential Events with Plutonium Dioxide Release	Probability	Estimated Fatalities	Risk Factor
Inadvertent Earth Swingby Reentry	1 in 1 million	120	0.0001
Early Launch Accident	1 in 1,400	0.1	0.00007
Late Launch or Reentry from Earth Orbit Accident	1 in 476	0.04	0.00008

*Fatality risks are generally required to be 2 orders of magnitude lower than casualty risks. The current 5-yr numbers for MESCAL would give a Risk Factor of 0.00003, if casualties are treated as fatalities.

Diameter of Asteroid Hitting the Earth	Annual Probability	Estimated Fatalities	Risk Factor
10 km (6 mi)	1 in 100 million	5 billion	50
1.5 km (1 mi)	1 in 500,000	1.5 billion	3,000
50-300 m (150-1000 ft)	1 in 250	5,000	20

National Aeronautics and Space Administration (NASA) Draft Supplemental Environmental Impact Statement for the Cassini Mission. Washington, D.C., April 1997.
Clark R. Chapman and David Morrison, "Impacts on the Earth by Asteroids and Comets: Assessing the Hazard," Nature, Volume 367, 6 January 1994.

Comparison with Cassini Mission

Cassini: Potential Events with Plutonium Dioxide Release	Probability	Estimated Fatalities	Risk Factor
Inadvertent Earth Swingby Reentry	1 in 1 million	120	0.00010
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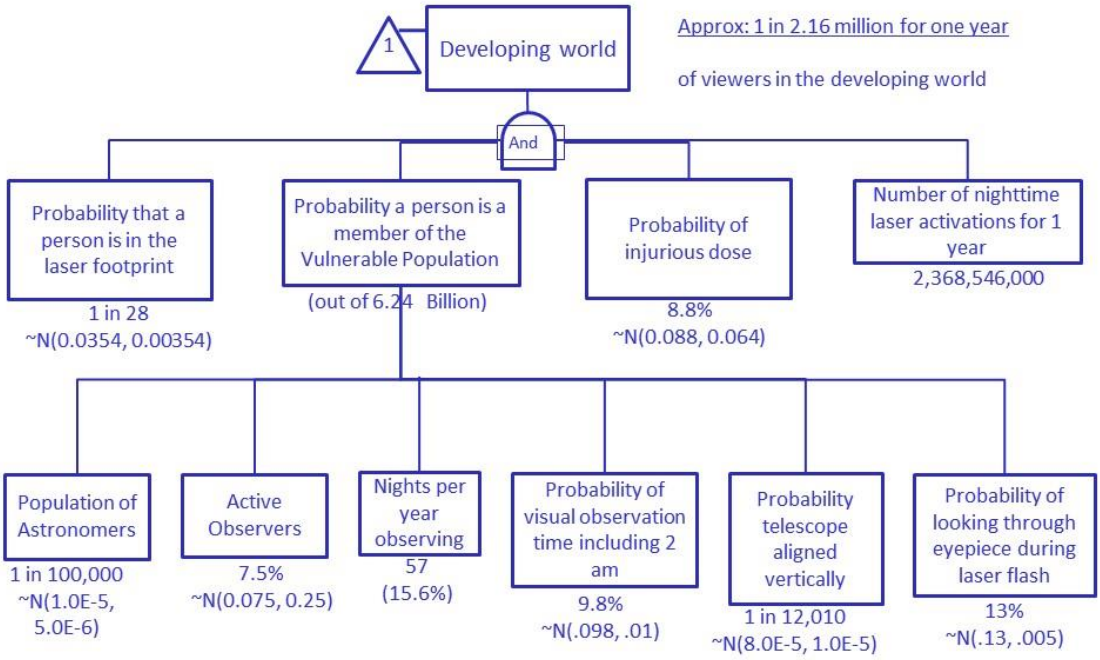
Late Launch or Reentry from Earth Orbit Accident	1 in 476	0.04	0.00008

*Fatality risks are generally required to be 2 orders of magnitude lower than casualty risks.

But if we treat ocular casualties as fatalities, the current 5-yr-mission numbers for MESCAL would give a Risk Factor of 0.00003, and the current 5-hr-mission number for HSRL2 would give a risk factor of 0.00007.

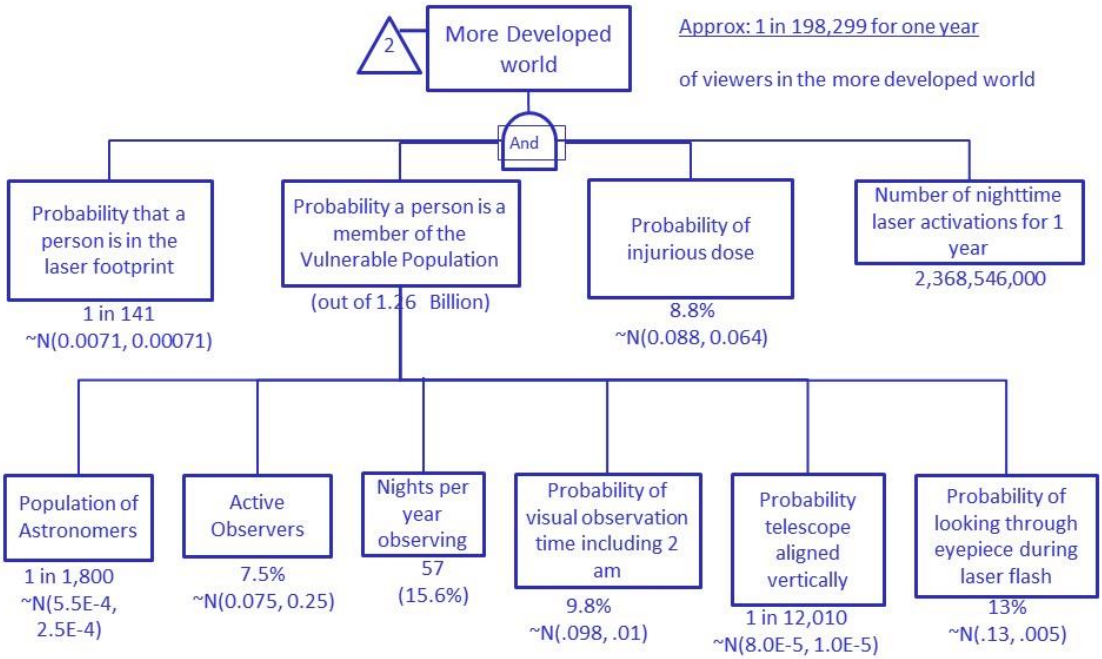
National Aeronautics and Space Administration (NASA) Draft Supplemental Environmental Impact Statement for the Cassini Mission. Washington, D.C., April 1997.
Clark R. Chapman and David Morrison, "Impacts on the Earth by Asteroids and Comets: Assessing the Hazard," Nature, Volume 367, 6 January 1994.

Fault Tree for developing world



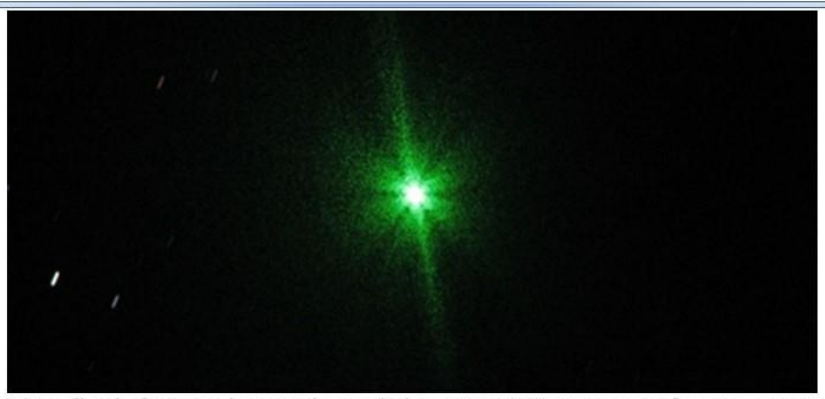
~N(μ,σ) means a normal distribution with a mean of μ and a standard deviation of σ

Fault Tree for more developed world



~N(μ,σ) means a normal distribution with a mean of μ and a standard deviation of σ

Determined Viewers (2007)



- The fleeting flash from a laser aboard the CALIPSO spacecraft was captured in this image by satellite tracker Gregg Hendry of Ball Aerospace on January 22, 2007
- To record this 20-nanosecond flash, Hendry positioned himself under the satellite's path near Nederland, Colorado; aimed his digital camera straight up; and took a time exposure. CALIPSO was launched aboard a Delta II rocket from Vandenberg AFB in 2006.

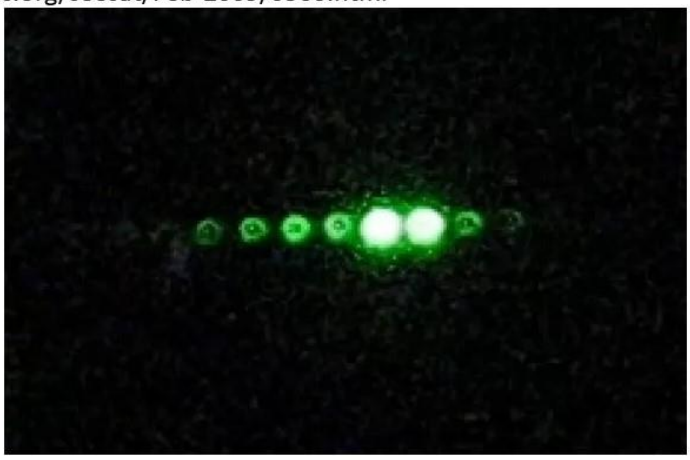
Copyright 2007, Gregg Hendry. Used with Permission.

http://www.spacearchive.info/news-2007-archive.htm

Determined Viewers (2008)

http://www.spacearchive.info/news-2007-archive.htm

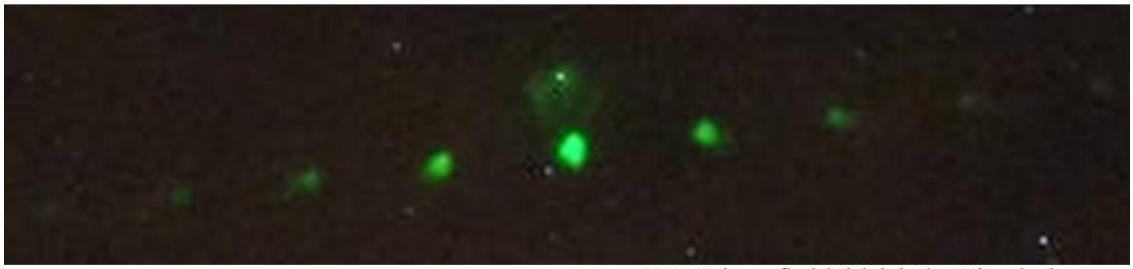
http://www.satobs.org/seesat/Feb-2009/0560.html

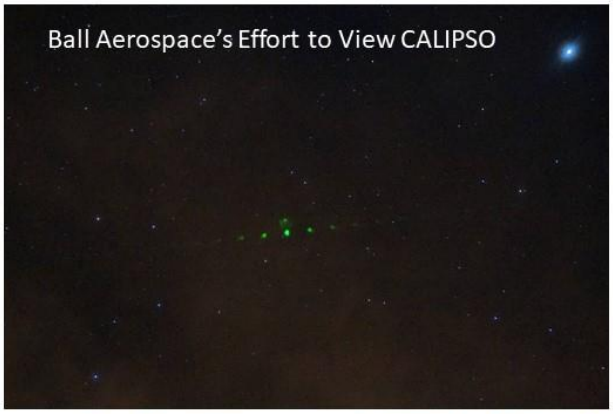


http://www.universetoday.com/103382/how-to-spot-and-track-satellites/

A CALIPSO LiDAR pass imaged by Gregg Hendry in 2008. Hendry mentions that, "The hollow nature of the spots is likely due to some spherical aberration in the camera lens coupled with imperfect focus, and is not representative of the laser beam's optical quality." (Credit: Gregg Hendry, used with permission).

Determined Viewers (2015)





CALIPSO lasers flash brightly in the Colorado sky on January 27, 2015.

CALIPSO -- NASA's Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation satellite -- sends out 20 laser pulses every second, and each is only 20 billionths of a second long. The satellite uses lidar -- light detection and ranging -- that is similar to radar but employs light instead of microwave energy.

Note: do not look at CALIPSO laser pulses with anything stronger than binoculars. The data from CALIPSO helps to answer questions about Earth's warming and cooling patterns as they are affected by clouds and aerosols.

Credit: Gregg Hendry/Ball Aerospace.
Used with permission

BACKUP: AIRBORNE

Quick Review of Laser Eye Safety Study

- NASA and its partners must first decide on what level of risk is considered to be acceptable…

  …agree on how to calculate the risk…

  …quantify the effectiveness of mitigation strategies and and decide which ones are warranted

- Probabilistic Risk Assessment (PRA)
  - Start with low-fidelity, conservative analysis
  - Monte Carlo sampler code
    - Written in Python under contract with N&R Engineering
    - Inputs can be either deterministic or distributions (with uncertainties)
    - Currently, two test cases: MESCAL (spaceborne) and HSRL2 (airborne)
    - Code still being developed as fidelity of analysis increases
    - Graphical user interface planned once methodology has been vetted



SHIELD: Software for Hazard Identification and Evaluation of Lidar Deployments



Acronymns

CNES: Centre National d'Études Spatiales

CONUS: Continental United States

HSRL2: High Spectral Resolution Lidar 2. Current altitude restrictions have grounded this system from operating on LaRC's King Air.

LSRB: Laser Safety Review Board

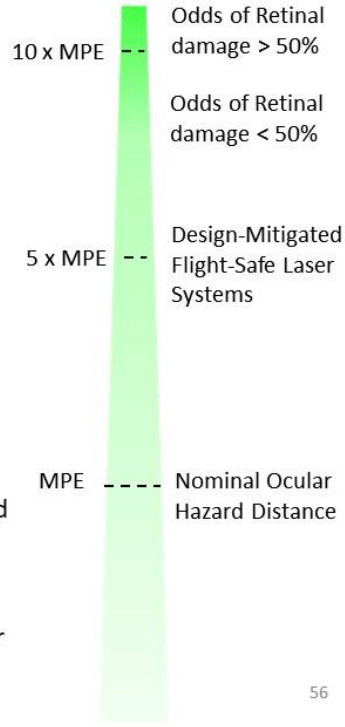
MESCAL: Monitoring the Evolving State of Clouds and Aerosols Layers. In the planning stages. Potential to be cancelled by safety reviewers from CNES.

MPE: Maximum Permissible Exposure
1/10th the energy density that has been shown to cause visible retinal lesions 50% of the time.

NOHD: Nominal Ocular Hazard Distance. Distance beyond which laser energy density is below the MPE and is therefore considered eye safe.

PRA: Probabilistic Risk Assessment

SHIELD: Software for Hazard Identification and Evaluation of Lidar Deployments



Visual Interference Limits: Calculations

MESCAL is 8 to 9 times less than FAA limit for Laser Free Zones

MESCAL Calculated Irradiance (nW/cm²)	833 km	450 km
At sea level:	5.60	5.48
Mt. Everest (9 km):	5.73	5.70
Highest Aircraft (30 km):	6.03	6.29

Visual Interference Limits

Laser Free Zone: 50 nW/cm²

Critical Flight Zone: 5 µW/cm²

Sensitive Flight Zone: 100 µW/cm²

Normal Flight Zone: 2.5 mW/cm²

$$Irradiance = V(\lambda)\frac{4}{\pi(D_{exit} + h\theta)^2}\frac{E}{T_{exp}}$$

Input Parameters

$V(\lambda)_{ANSI\ Z136.1\text{-}2014} = 0.9149$ (newer value)

$V(\lambda{=}532nm)_{ANSI\ Z136.6\text{-}2005} = 0.9250$ (more-conservative value)

$T_{exp} = 0.25$ s

$E_{532nm} = 0.100$ J/pulse (or 75 mJ/pulse)

$D_{exit} = 5.0 \times 10^{-2}$ m

$h = 8.33 \times 10^{5}$ m (or 4.50×10^{5} m)

$\theta_{532\ nm} = 1.10 \times 10^{-4}$ rad (or 2.06×10^{-4} rad)

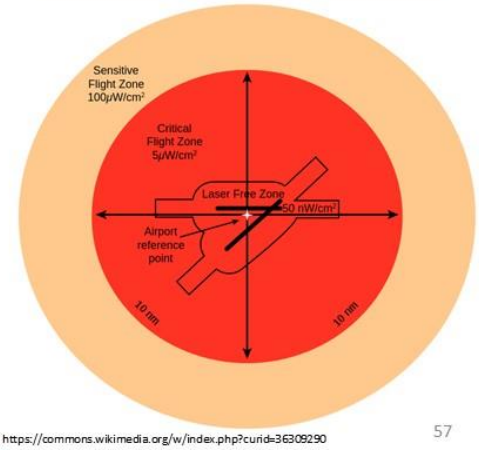
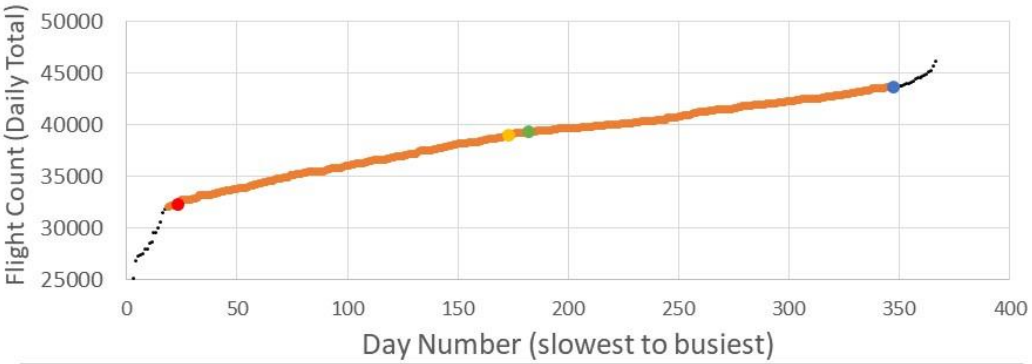


Image credit: Fred the Oysteri, created with Adobe Illustrator. - and FAA Advisory Circular 70-2, page 22, Public Domain, https://commons.wikimedia.org/w/index.php?curid=36309290

Air Traffic Density

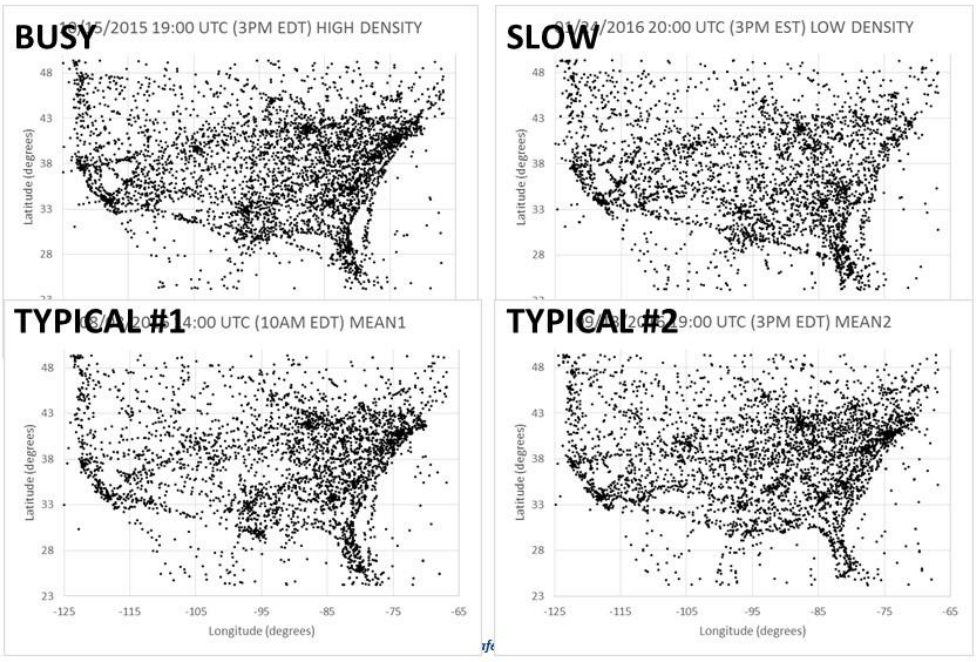
- NASA has access to air traffic data, but learning how to access it requires a large time investment
- Decided to purchase a limited dataset from a third party (FlightAware)
- Budget allowed selection of 4 snapshots in time of the following parameters:
  - Latitude
  - Longitude
  - Altitude
  - ICAO Aircraft Type
- Decided to select 2 typical days, 1 busy day and 1 slow day.
- Looked for days with no major weather events which would disrupt normal traffic patterns
- Chose near-busiest time on each day to maximize statistical dataset

Identify Busy/Typical/Slow Days



TRAFFIC	FLIGHT COUNT	# AIRCRAFT	DATE	TIME (EASTERN)
BUSY	45,799	4,616	15 OCTOBER 2015	3:00 PM
SLOW	25,217	3,473	24 JANUARY 2016	3:00 PM
TYPICAL #1	39,051	3,565	8 AUGUST 2016	10:00 AM
TYPICAL #2	39,363	3,945	13 SEPTEMBER 2016	3:00 PM

Latitude/Longitude Plots



Previous Results

These results used a 2D air traffic density model (aircraft per square kilometer) over a high-density area (NY3), with a simple above/below criteria for altitude dependence. These results do not include any mitigating effects of using TCAS.

Expected Injuries	With Mitigating Assumptions
Per flight hour	5.4E-06
Per 5-hr mission	2.7E-06

Collective Odds of Injury	With Mitigating Assumptions
Per flight hour	1 in 187,000
Per 5-hr mission	1 in 37,400

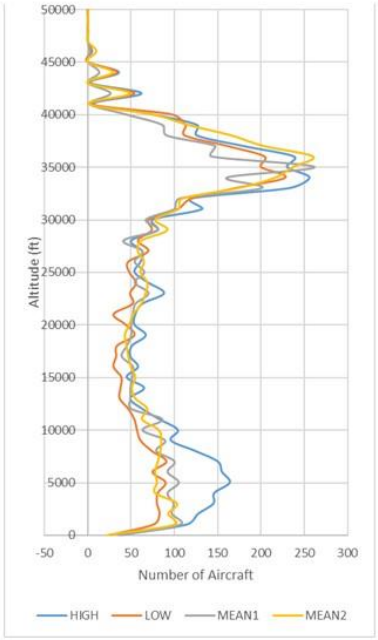
"Mitigating Assumptions" indicates the effect of the following:

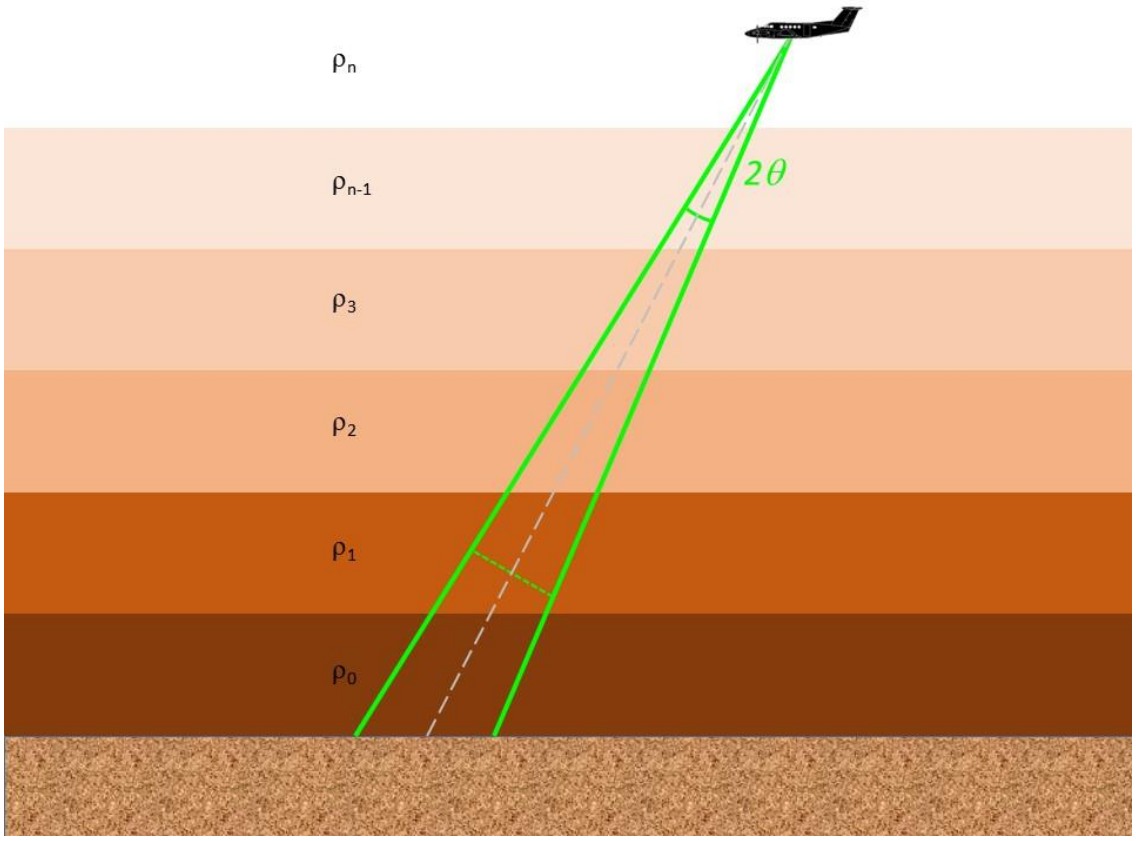
- Aircraft geometry (1% transponding; 10% non-transponding)[~2 orders of magnitude]
- Pilot looking up 10% of the time [1 order of magnitude]
- Windshield (85% transmission) [<1 order of magnitude]

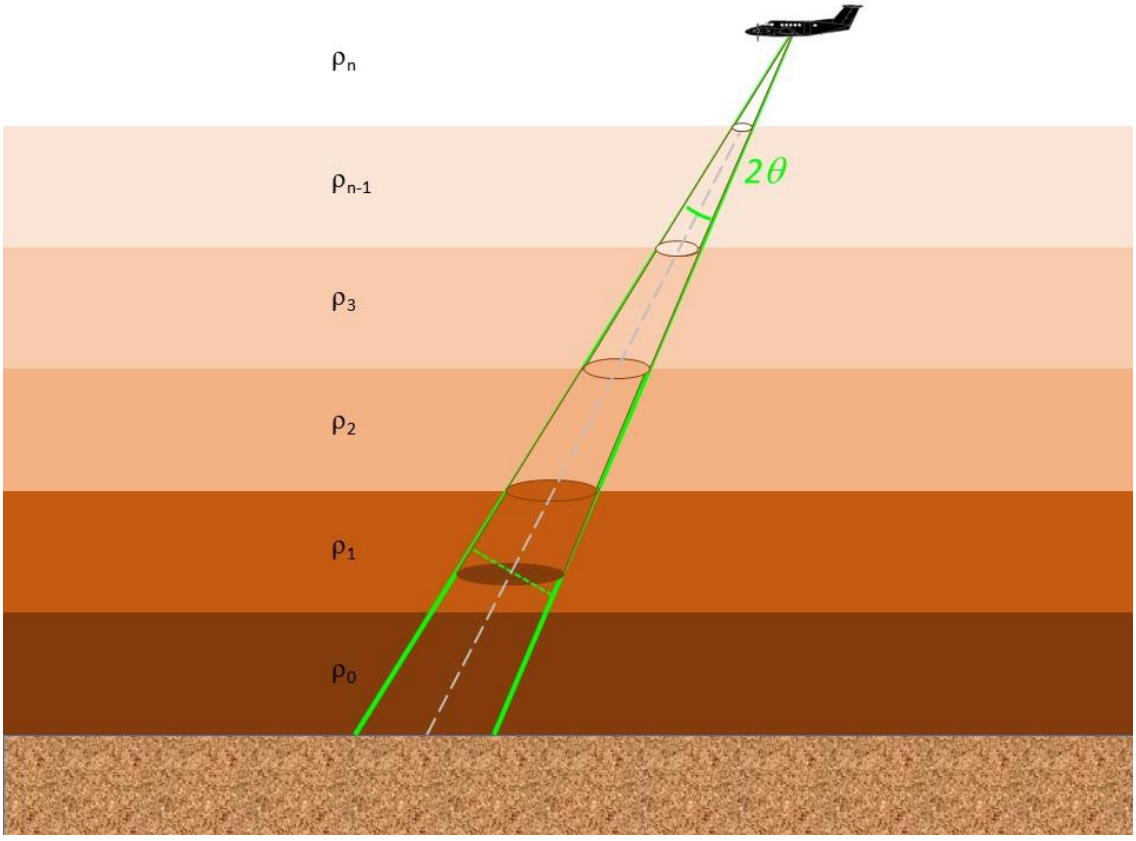
The risk numbers shown would be expected to decrease when flying missions in low-density areas and / or when flying early morning/ late night.

Volumetric Density (aircraft per km^3)

- Divide airspace into 1,000 ft layers and calculate volumetric density of aircraft
- Conduct piecewise integral along laser propagation axis
- Calculate energy density and associated ocular hazard at distance to each layer
- Calculate illuminated volume by layer




ρn
ρn-1
ρ3
ρ2
ρ1
ρ0
2θ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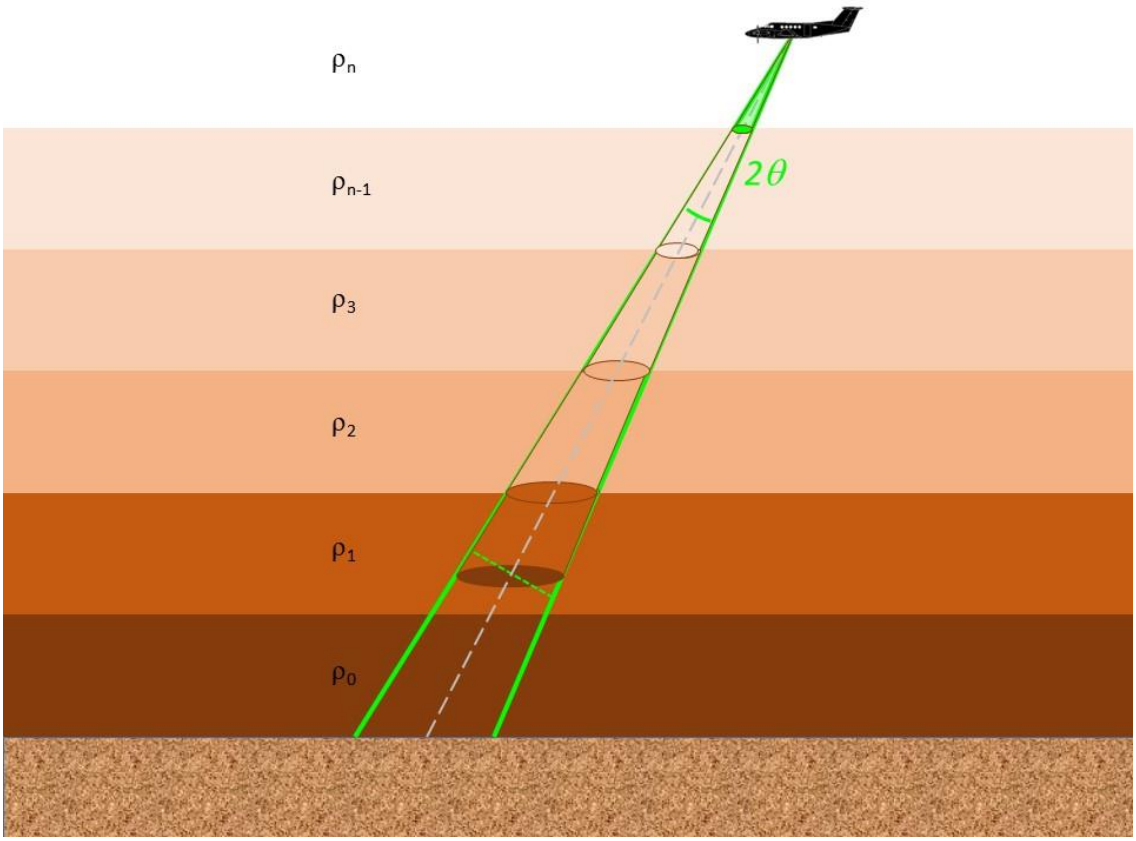
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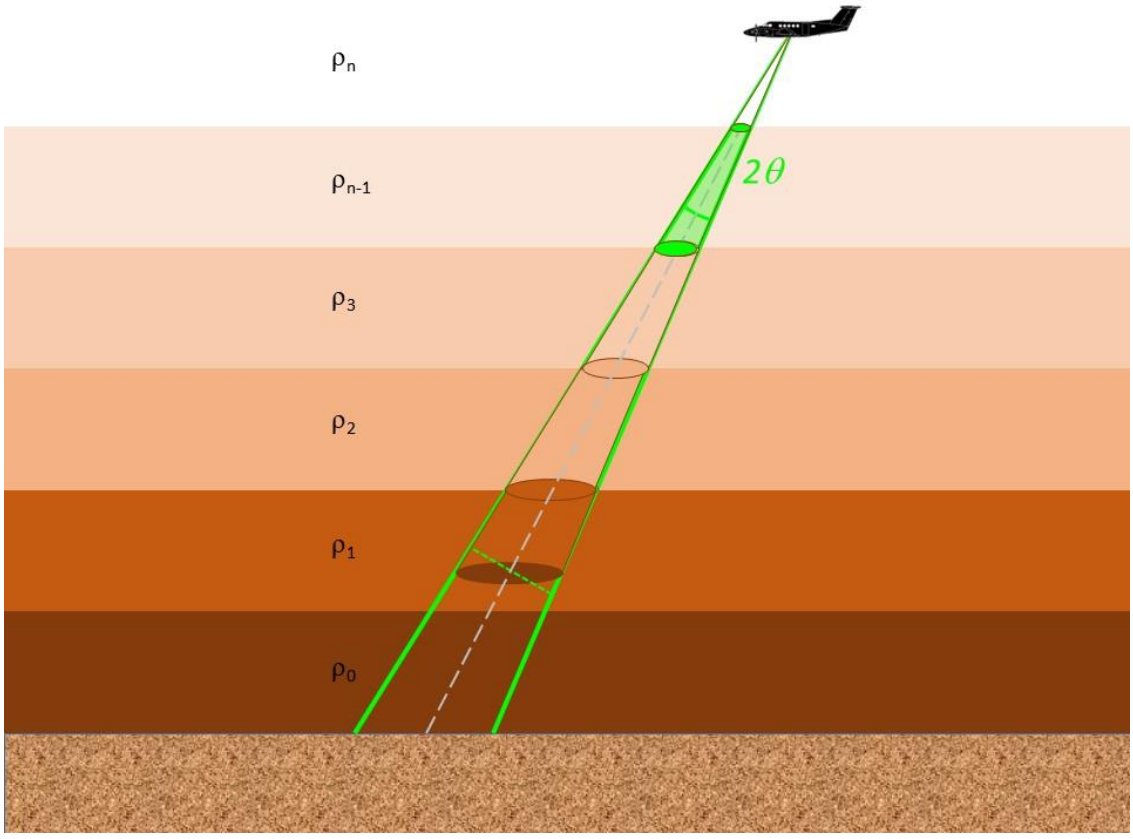
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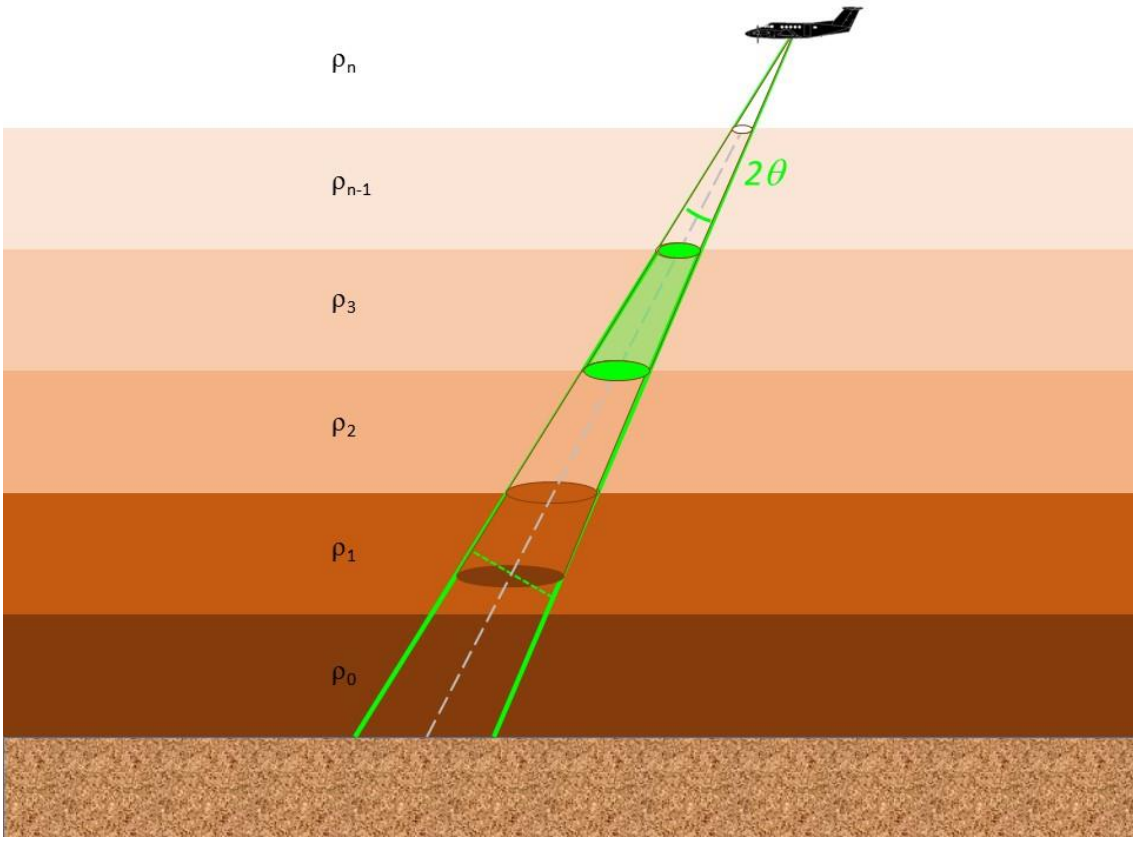
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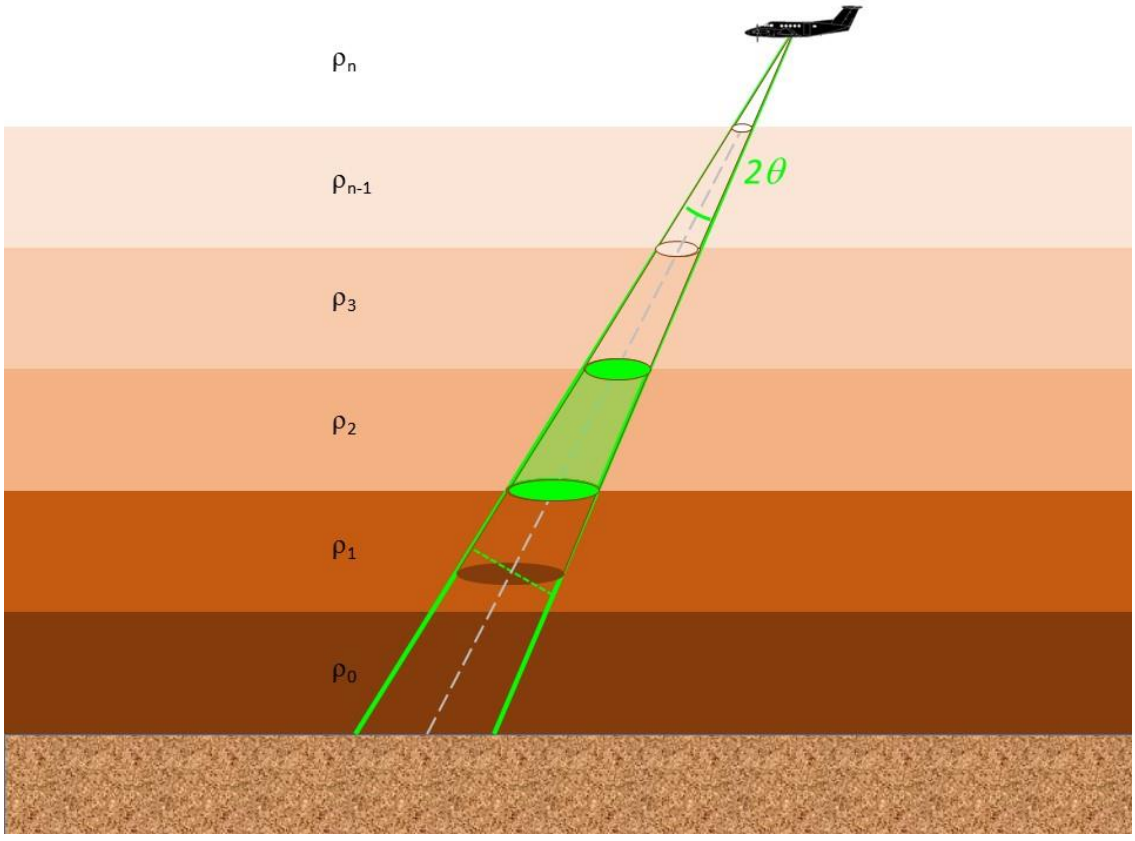
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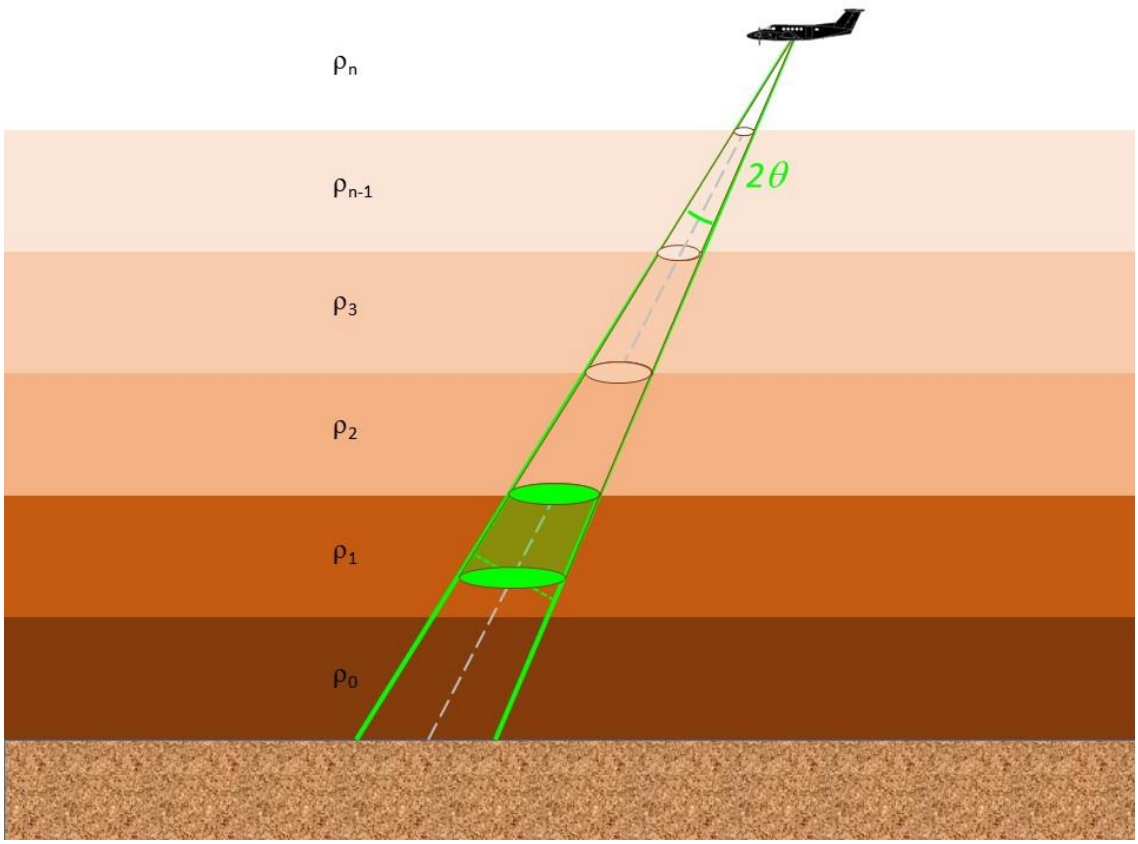


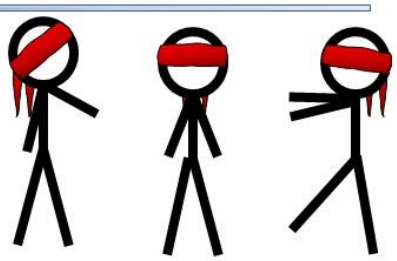
Current Inputs

- Repetition rate: 200 Hz (720,000 pulses per hour)
- Full-angle divergence: 0.00049 radians (0.028°)
- Pointing angle: 85° (5° off-nadir)
- Mission duration: 5 flight hours
- Flight altitude: 25,100 ft
- Total NOHD: 21,200 ft
  - 532nm: 11 mJ/pulse
  - 1064 nm: 34 mJ/pulse
  - 355 nm: 11 mJ/pulse
- Bulk average CONUS air traffic density for a given altitude (110% below 10,000 ft to account for non-transponding aircraft)
  - 19:00 UTC (3PM EDT) 15 October 2015 [HIGH]
  - 20:00 UTC (3PM EST) 24 January 2016 [LOW]
  - 14:00 UTC (10AM EDT) 08 August 2016 [MEAN1]
  - 19:00 UTC (3PM EDT) 13 September 2016 [MEAN2]

Previous Inputs

- Repetition rate: 200 Hz (720,000 pulses per hour)
- Full-angle divergence: 0.00049 radians (0.028°)
- Pointing angle: 90° (nadir)
- Mission duration: 5 flight hours
- Flight altitude: 26,000 ft
- Total NOHD: 20,800 ft
  - 532nm: 11 mJ/pulse
  - 1064 nm: 34 mJ/pulse
  - 355 nm: 11 mJ/pulse
- Average New York 3 air traffic density for IFR traffic
- Modeled air traffic density for VFR traffic

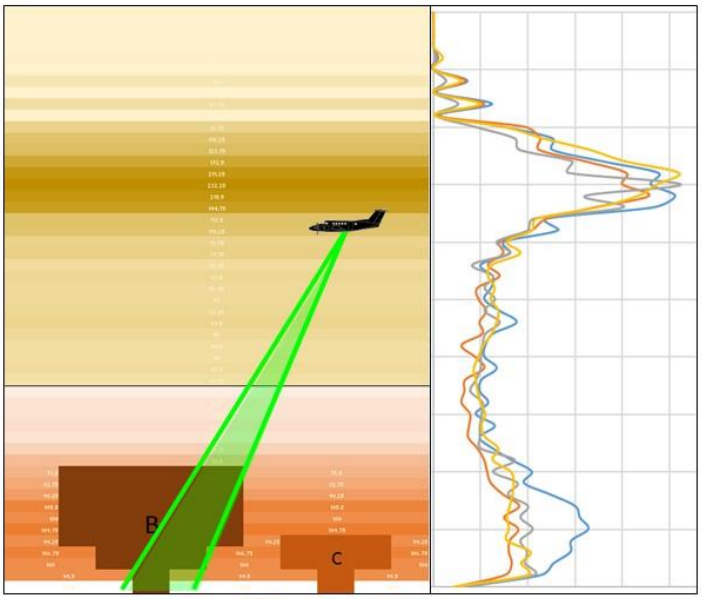
Mitigation Assumptions



- TCAS effectiveness
  - 95% up to 9,900 ft
  - 0% beyond 9,900 ft
- 1,000' vertical separation
- Pilot looking up 1% of the time
- Aircraft has vulnerable line-of-sight?
  - 25% of non-transponding aircraft
  - 1% of transponding aircraft
- Windshield of vulnerable aircraft
  - 85% transmission
  - 45° angle of incidence (4% reduction in dosage)

What's Next?

Software could account for flights over Class B / Class C airspace vs. flights *not over* Class B / Class C. Forward pointing?



LSRB - Common Risk Criteria Standard



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

COMMON RISK CRITERIA STANDARDS FOR LASER OPERATIONS [ACTIVE OPTICAL SYSTEMS?] FROM [ON?] AIRCRAFT AND SATELLITES

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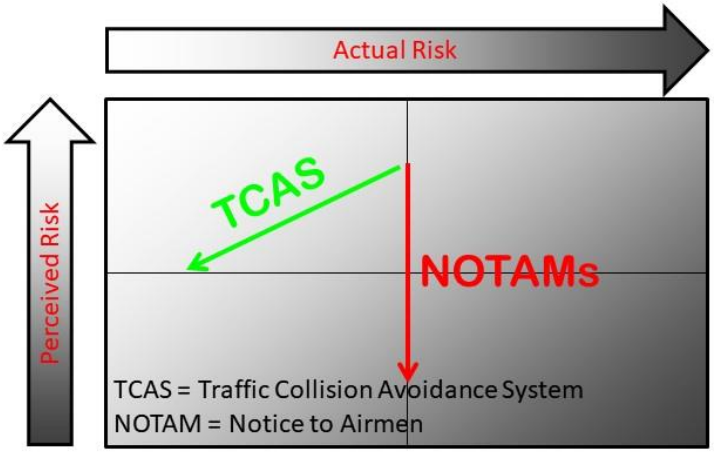
- Working on draft of document modeled after Range Commanders Council's Range Safety Group's Common Risk Criteria for National Test Ranges
- Guidance from Frank Groen of the Office of Safety and Mission Assurance at Headquarters indicates that the authority for this type of review now lies with the Laser Safety Review Board (LSRB)
- How can we change our paradigm for interfacing with the FAA?
  - Elimination of NOTAM requirement for risk-compliant operations
  - Coordination when air traffic management is needed to meet risk criteria
  - Memorandum of Understanding covering risk-compliant operations

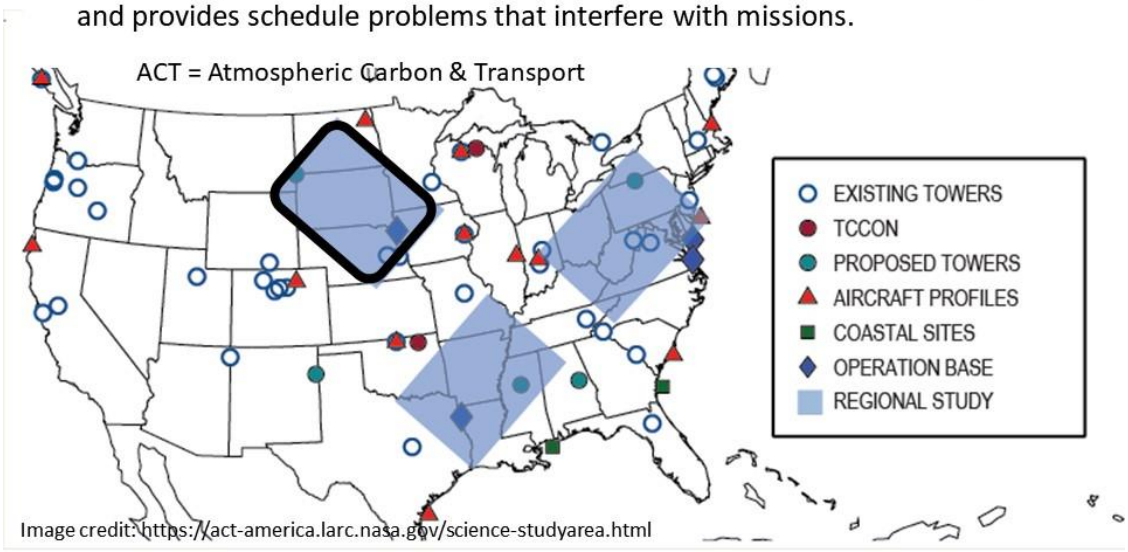
Interfacing with the FAA

- Policies which decrease *perceived* risk—without decreasing *actual* risk—make operations less safe



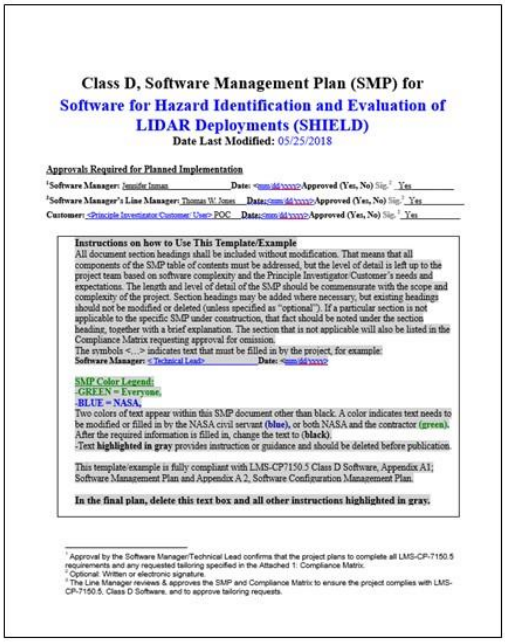
Interfacing with the FAA

- NOTAMs provide negligible value to other pilots because they provide no guidance on resolution / avoidance of hazard
- ACT America may follow atmospheric phenomena (e.g. smoke plumes, frontal boundaries). Don't know route ahead of time. This makes NOTAMS very broad and provides schedule problems that interfere with missions.



Software Management & Release Plan

- SHIELD is currently classified as Class E
- Working on Software Management Plan
- Graphical User Interface under development
- Classification could potentially increase to Class D if used by external entities



Class D, Software Management Plan (SMP) for
Software for Hazard Identification and Evaluation of LIDAR Deployments (SHIELD)
Date Last Modified: 05/25/2018

Approvals Required for Planned Implementation

[1]**Software Manager:** Jennifer Inman **Date:** <mm/dd/yyyy>**Approved (Yes, No)** Sig.[2] Yes
[1]**Software Manager's Line Manager:** Thomas W. Jones **Date:**<mm/dd/yyyy>**Approved (Yes, No)** Sig.[2] Yes
Customer: <Principle Investigator/Customer User> POC **Date:**<mm/dd/yyyy>**Approved (Yes, No)** Sig.[2] Yes

Instructions on how to Use This Template/Example
All document section headings shall be included without modification. That means that all components of the SMP table of contents must be addressed, but the level of detail is left up to the project team based on software complexity and the Principle Investigator/Customer's needs and expectations. The length and level of detail of the SMP should be commensurate with the scope and complexity of the project. Section headings may be added where necessary, but existing headings should not be modified or deleted (unless specified as "optional"). If a particular section is not applicable to the specific SMP under construction, that fact should be noted under the section heading, together with a brief explanation. The section that is not applicable will also be listed in the Compliance Matrix requesting approval for omission.
The symbols <…> indicates text that must be filled in by the project, for example:
Software Manager: <Technical Lead> **Date:** <mm/dd/yyyy>

SMP Color Legend:
-GREEN = Everyone,
-BLUE = NASA;
Two colors of text appear within this SMP document other than black: A color indicates text needs to be modified or filled in by the NASA civil servant **(blue),** or both NASA and the contractor **(green).** After the required information is filled in, change the text to **(black).**
-Text **highlighted in gray** provides instruction or guidance and should be deleted before publication.

This template/example is fully compliant with LMS-CP7150.5 Class D Software, Appendix A1; Software Management Plan and Appendix A 2, Software Configuration Management Plan.

In the final plan, delete this text box and all other instructions highlighted in gray.

[1] Approval by the Software Manager/Technical Lead confirms that the project plans to complete all LMS-CP-7150.5 requirements and any requested tailoring specified in the Attached 1: Compliance Matrix.
[2] Optional: Written or electronic signature.
[3] The Line Manager reviews & approves the SMP and Compliance Matrix to ensure the project complies with LMS-CP-7150.5, Class D Software, and to approve tailoring requests.

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A Technical Interchange Meeting (TIM) was organized and held July 31 through August 3, 2018 in Columbia, Maryland. This TIM consisted of over 80 technical presentations that provided a wide-ranging coverage of NASA Active Optical (AO) developments and current activities. It served as the kickoff for the Active Optical Assessment and Recommendation Team (AOART) assessment activities, and its session organization offered a template for categorizing the NASA AO activities and goals. This document contains the papers and presentations given at the TIM.

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