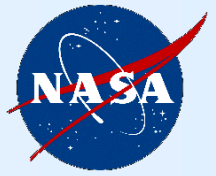
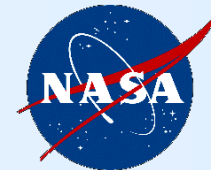

ACE Lidar Concept: $3\beta+2\alpha+2\delta$ HSRL & UV Laser Lifetime Study

Chris Hostetler, Johnathan Hair, Rich Ferrare,
Kathy Powell, John Yorks, Matt McGill, Dave
Whiteman, Floyd Hovis, Tim Shuman, and
many others



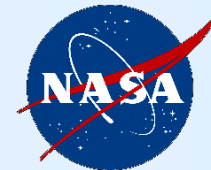
- What ACE science foci does the lidar address?
- What are the driving measurement requirements?
- How is the ACE lidar different from CALIPSO?
- Are airborne prototypes showing that we can make the required measurements?
- Are these lidars scalable to space?
- What is the Technology Readiness Level?
- Can the laser achieve the required lifetime?
- What investments should be made in technology development and retrieval development?
- Summary

Lidar Addresses “A”, “C”, and “E” of ACE



- Aerosol
 - Vertically resolved optical, macrophysical, and microphysical properties for aerosol direct forcing and indirect effects
 - Vertically resolved aerosol type and amount to assess/improve chemical transport models
 - Augments passive sensors for column AOD: capable of complex scenes and immune to cloud 3-D effects
- Cloud
 - Cloud top height
 - Tenuous cloud vertical structure and optical depth
 - Cloud phase
- Ocean Ecosystems
 - Aerosol correction for Ocean Color Radiometer
 - Aerosol measurements for ocean-aerosol science
 - Subsurface particulate backscatter for estimates of POC and NPP

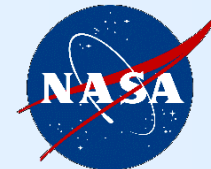
What are the driving measurement requirements?



Driving Requirements

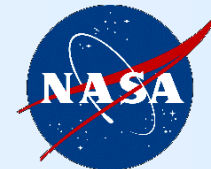
- Aerosol requirements explicitly drove the lidar architecture
 - Driving requirements are for vertically-resolved aerosol macrophysics and microphysics:
 - Aerosol size (DARF and ACI)
 - Index of refraction (DARF and ACI)
 - Single scatter albedo/absorption (DARF)
 - Concentration (ACI)
 - Lidar-only implementation to meet requirements is $3\beta + 2\alpha + 2\delta$ lidar
 - Simpler lidar+polarimeter combined retrieval to be studied.
- Cloud measurements require fewer channels but impact dynamic range of detectors
- Ocean subsurface measurements were first considered a “goal” but are listed in white paper as a requirement.
 - Drive detector requirements
 - Could drive laser requirements and receiver complexity/cost if compromises aren't negotiated.

DARF = Direct Radiative Forcing
ACI = Aerosol Cloud Interactions



Aerosol Requirements

- From Aerosol Chapter of Draft White Paper
 - Aerosol optical depth (AOD)
 - Vertical profile of aerosol extinction and backscatter
 - Vertical profile of aerosol nonsphericity (discrimination of spherical vs. nonspherical particles)
 - Vertical profile of aerosol type
 - Vertical profile of effective radius and width of size distribution
 - Vertical profile of refractive index
 - Vertical profile of single scatter albedo
 - Vertical profile of number concentration
 - Aerosol absorption optical depth in clear sky, and partitioned above and below cloud levels using cloud-free “holes” in partially cloudy fields



Ocean Ecosystem Requirements

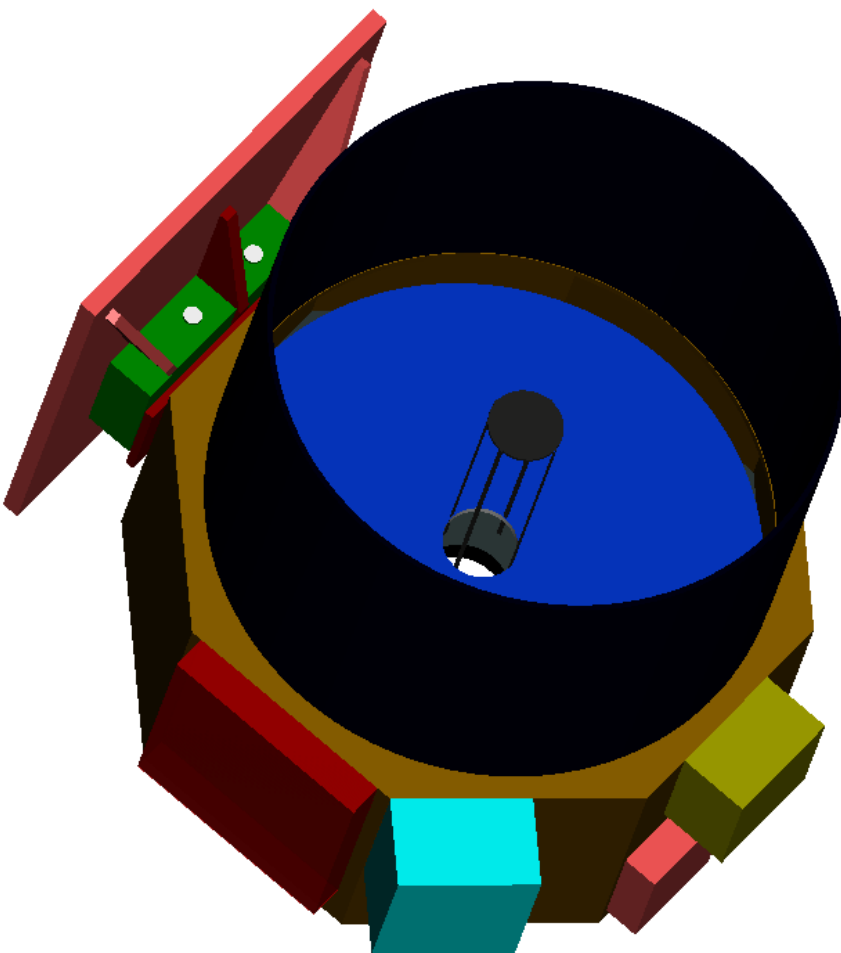
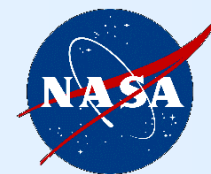
- From Ocean Ecosystems STM
 - 2-m sub-surface resolution
 - $< 0.3\%$ polarization misalignment
 - $0.1 \text{ Mm}^{-1}\text{sr}^{-1}$ aerosol backscatter sensitivity at 532 nm after averaging
 - Brillouin scattering capability (i.e. HSRL capability in water)
 - $< 4 \text{ ns}$ e-folding transient response
 - Receiver FOVs: 0-60 m; 0-120 m

**Drive receiver complexity and choice of laser/detectors →
Drive risk and cost**

- Recent conversations with oceanographers indicate that requirements can be relaxed
 - 5-m depth resolution ($\sim 25 \text{ ns}$ e-folding)
 - Single FOV

**How is the ACE lidar concept different
from CALIPSO?**

$3\beta+2\alpha+2\delta$ High Spectral Resolution Lidar (HSRL) Instrument Concept



■ Measurements

- Backscatter at 355, 532, 1064 nm (**3β**)
- Extinction 355 and 532 nm (**2α**)
- Depolarization at 2 wavelengths (**2δ**)
- Ocean surface/subsurface at 532 nm (backscatter and Brillouin scatter)

■ Products

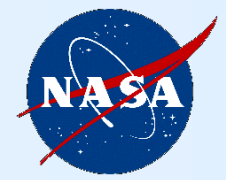
- Lidar-only retrieval of aerosol optical and microphysical properties, cloud optical properties, and aerosol/cloud vertical distribution
- Lidar + polarimeter retrievals of aerosol optical and microphysical parameters
- Lidar + radar cloud retrievals
- Lidar-only retrievals of ocean subsurface particulate backscatter

One of many possible realizations:

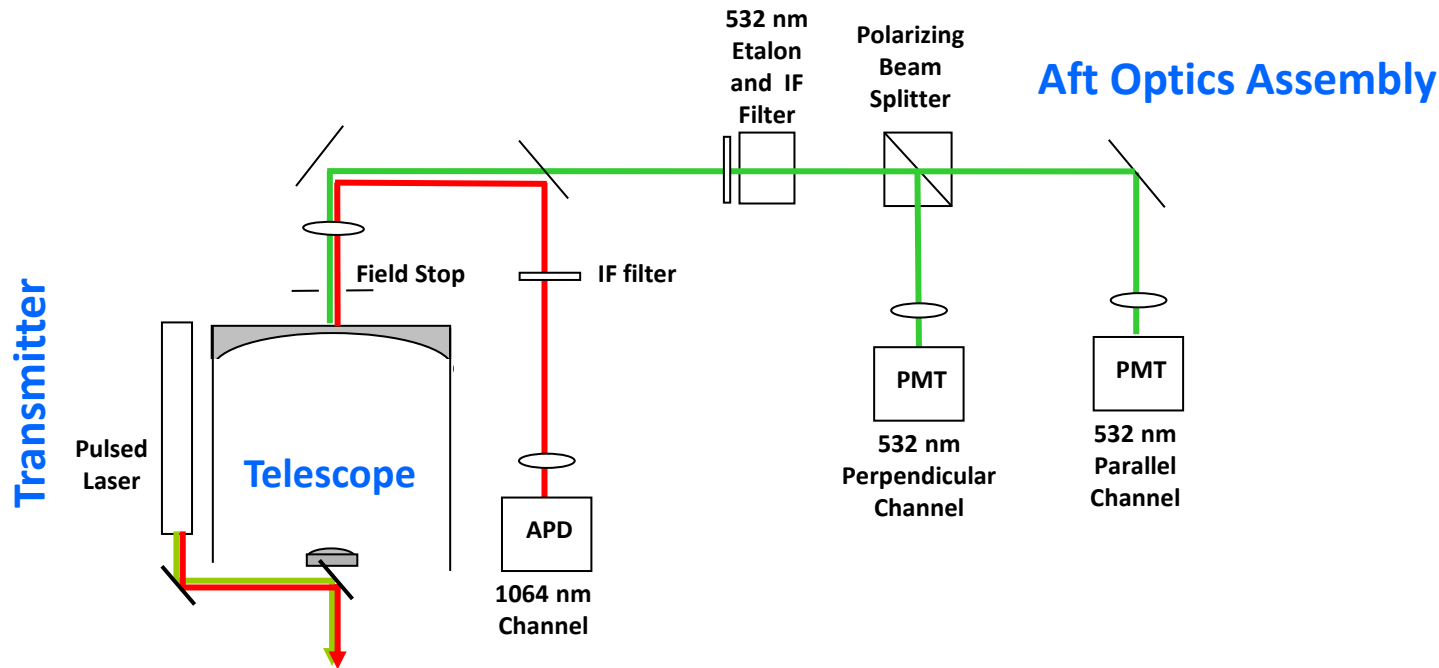
Transmitter: 25 W average power

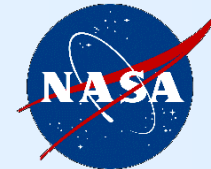
Telescope: 1.5-m diameter

CALIOP on CALIPSO: $2\beta+1\delta$



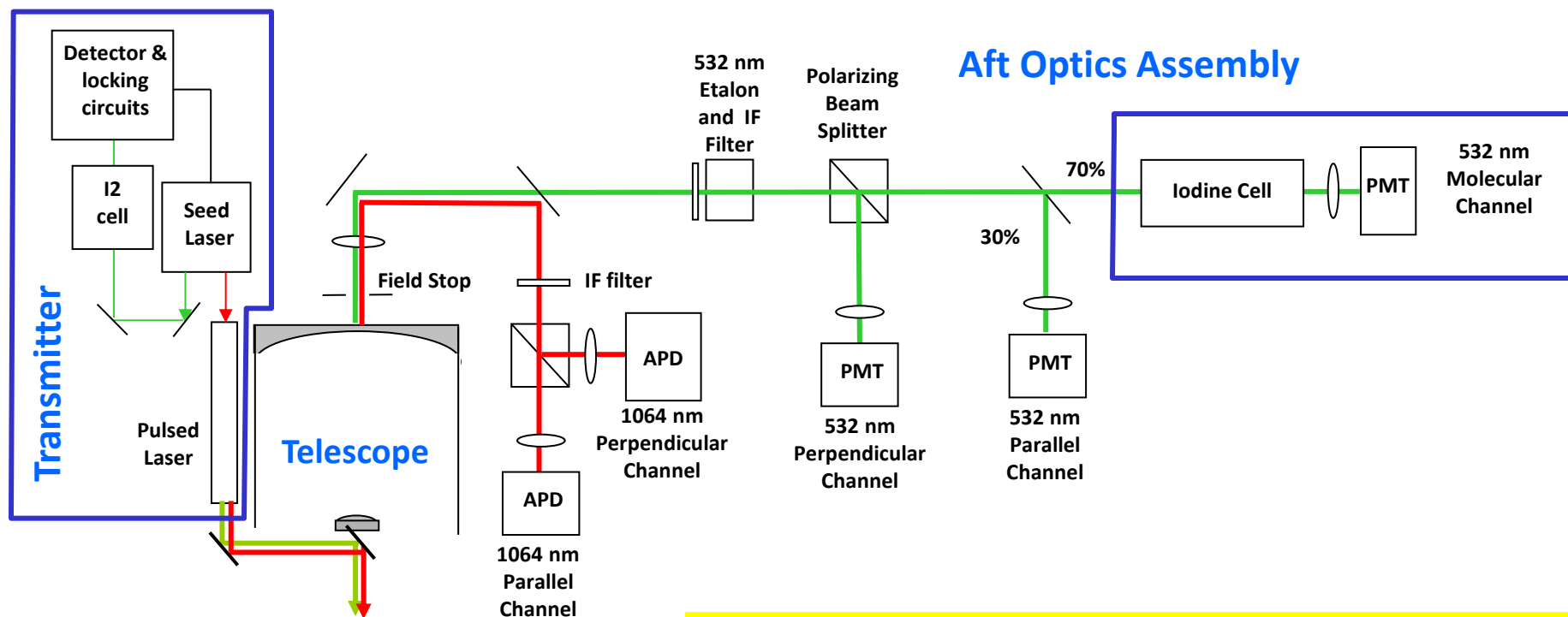
- Robust design
- 8 years near flawless operations!



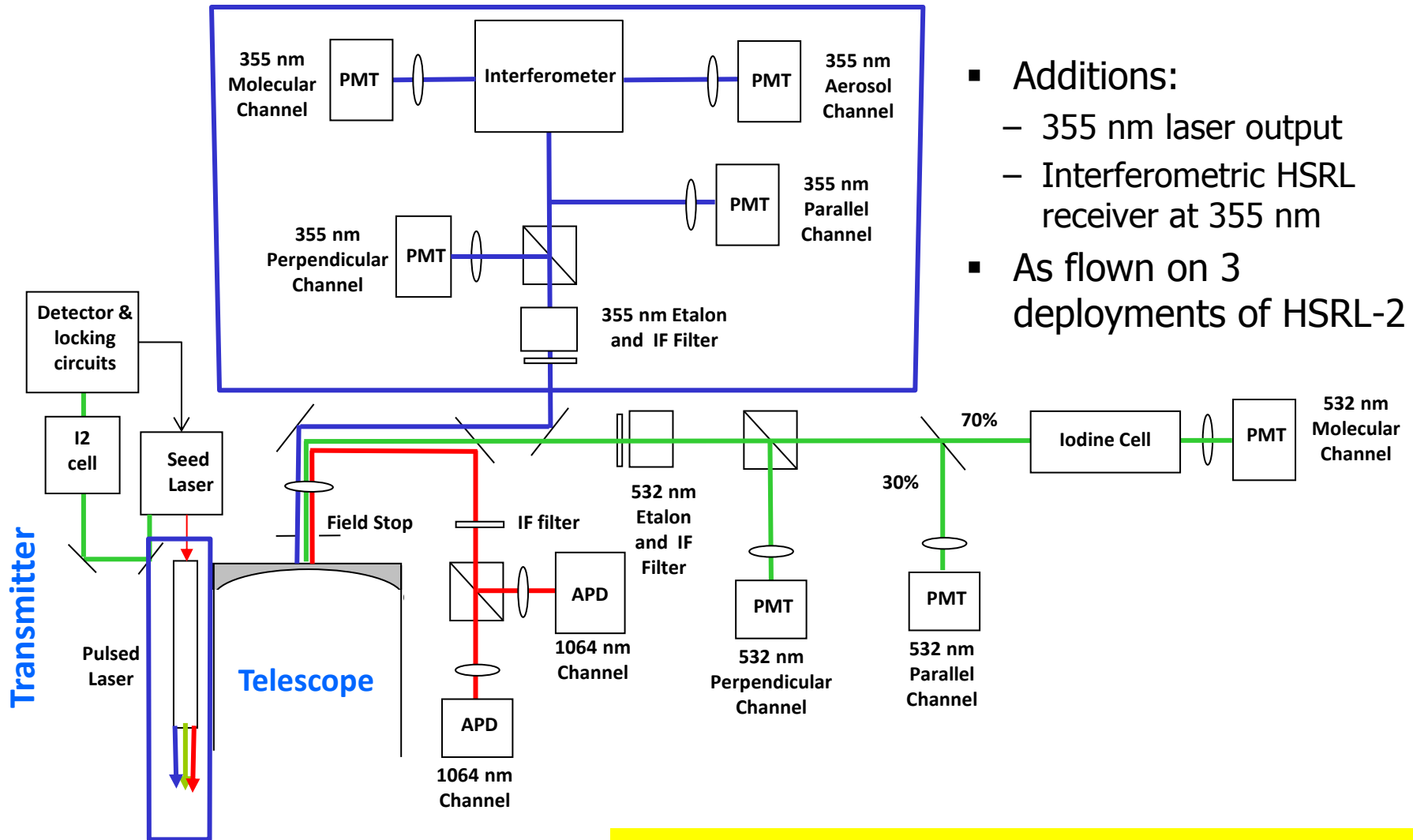


HSRL-1 Airborne Prototype: $2\beta+1a+2\delta$

- Additions:
 - Single-frequency laser with seed laser and frequency locking
 - Iodine cell and extra detector in receiver
- As flown on B200 for 10 years (>350 flights)



Alternate implementations are possible.
See Matt McGill's presentation on CATS.

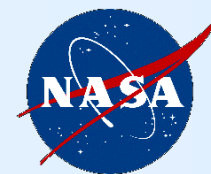


- Additions:
 - 355 nm laser output
 - Interferometric HSRL receiver at 355 nm
- As flown on 3 deployments of HSRL-2

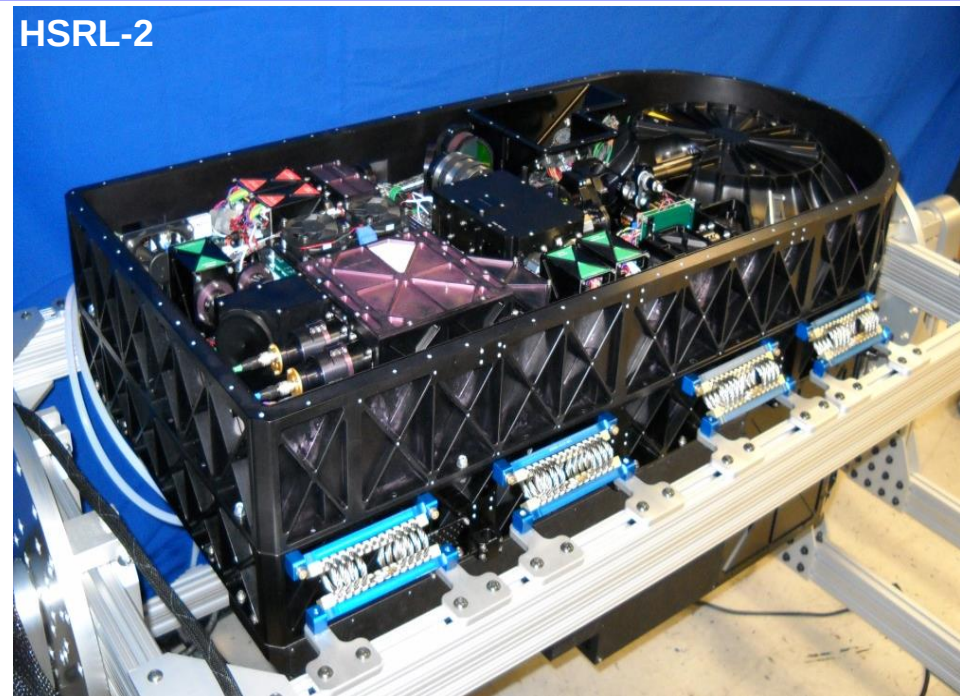
**Alternate implementations are possible.
See Matt McGill's presentation on CATS.**

**Are airborne prototypes showing that we
can make these measurements?**

HSRL-2: the ACE Lidar Simulator



HSRL-2



B200 King Air

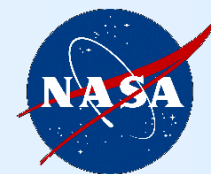


ER-2

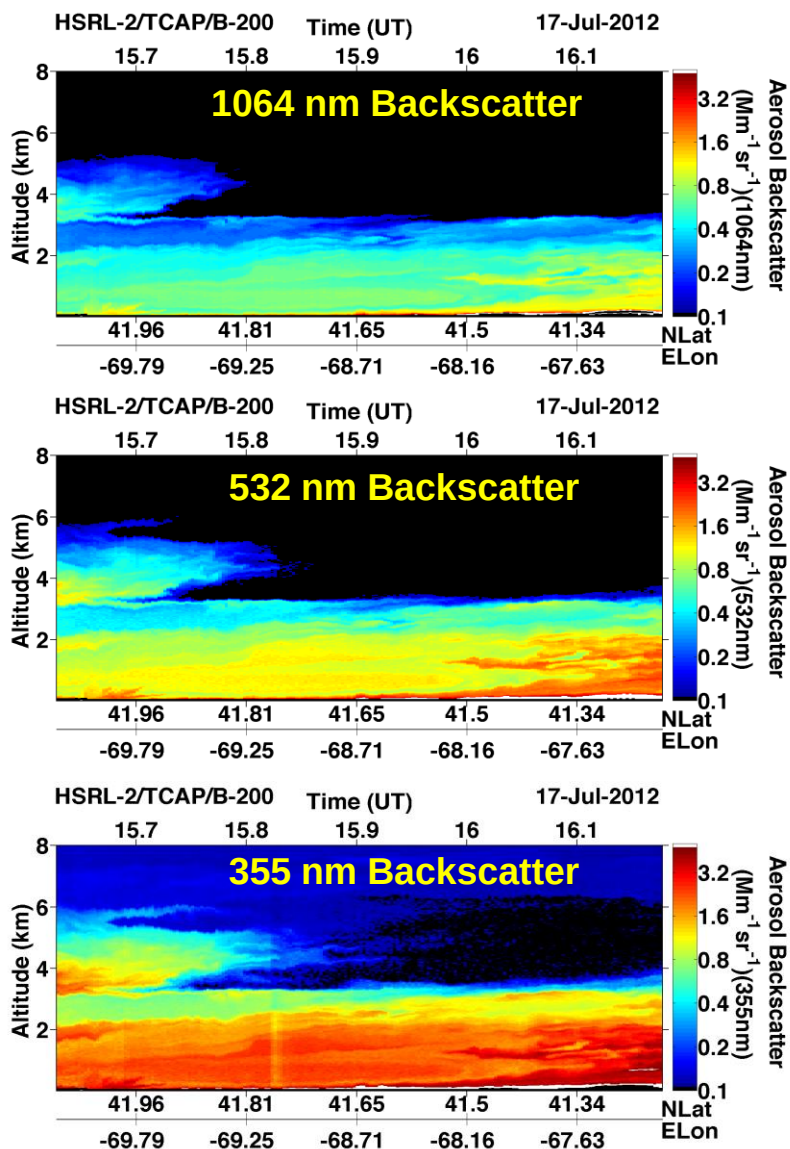


- Built for deployment on ER-2 and other aircraft
 - Not flown on ER-2. First flights on ER-2 in 2015
- Meets all ACE atmospheric measurement requirements
- Flown on 3 field missions, 4th starting July 2014
- Operational data processing code exists and demonstrated on field data

Airborne multi-wavelength "3 β +2 α " HSRL measurements from the TCAP field campaign



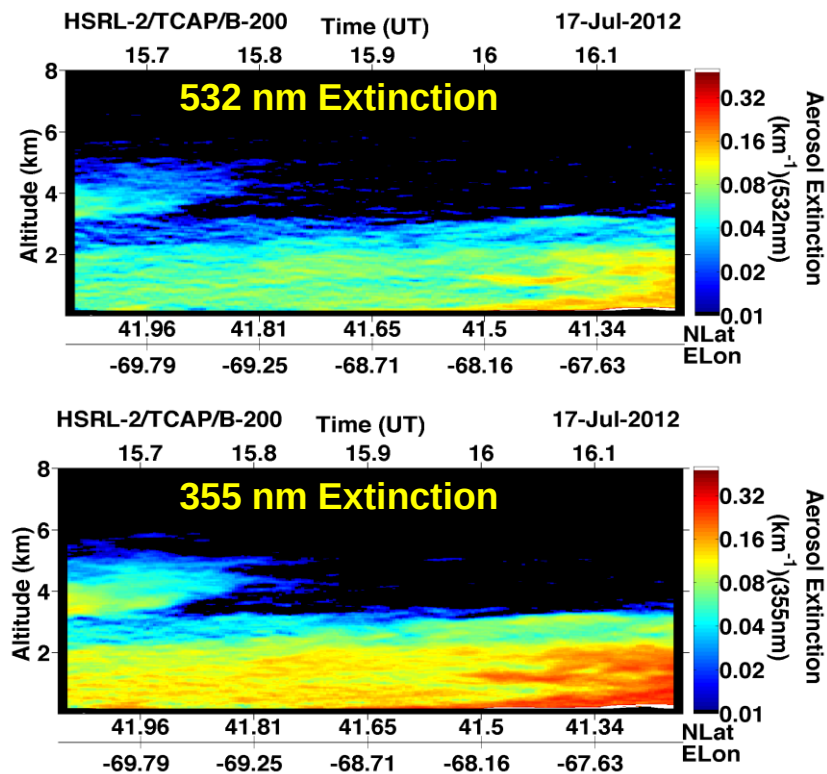
07/17/2012 TCAP flight on B200 aircraft

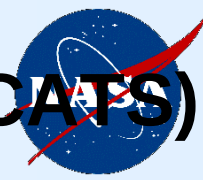


3 β

2 α

- 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

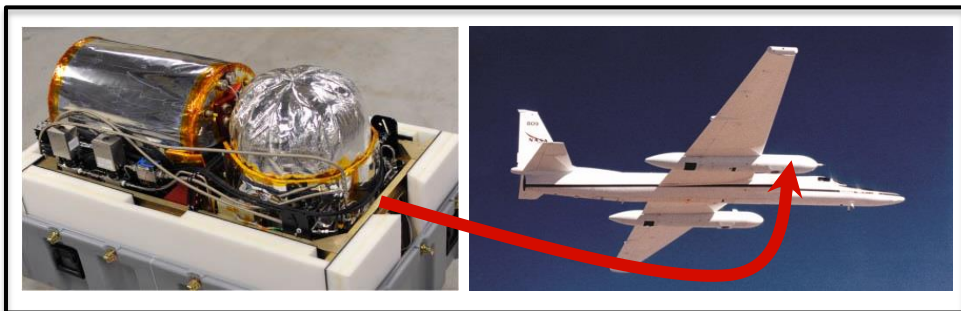




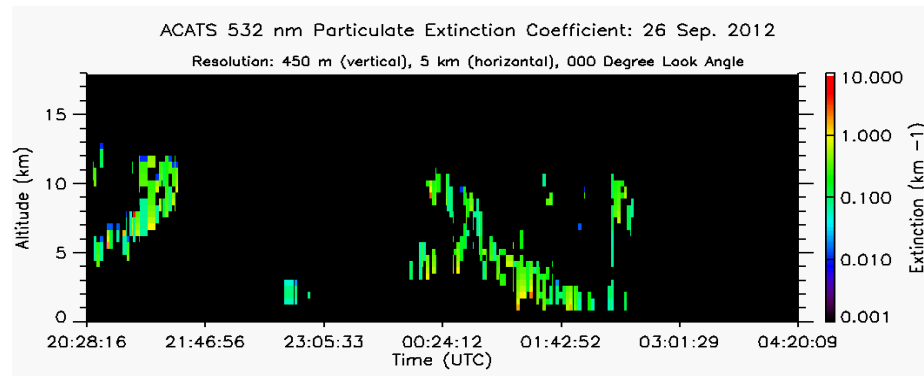
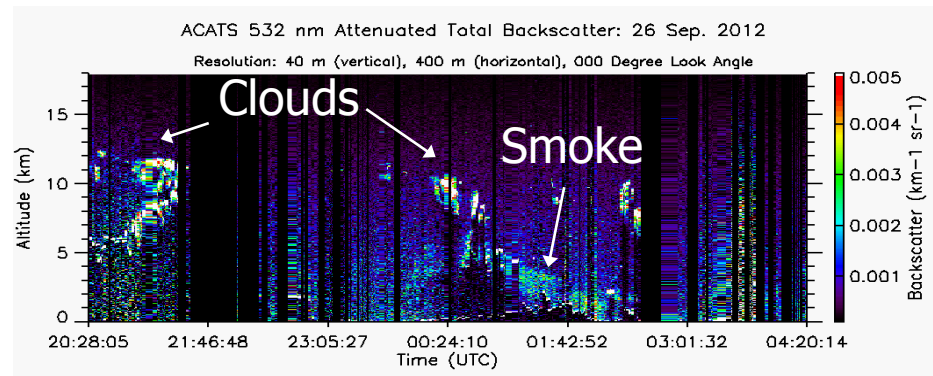
Airborne Cloud-Aerosol Transport System (ACATS)

Instrument Characteristics:

- Airborne HSRL and Doppler wind lidar developed at NASA GSFC
- Operates from high-altitude ER-2
- 532 nm operating wavelength
- Rotating telescope w/ 45 degree view angle for wind
- Etalon provides spectral resolution for HSRL retrievals
- Participated in flights out of Wallops Island, VA in Sept. 2012
- More info to come in Matt McGill's talk

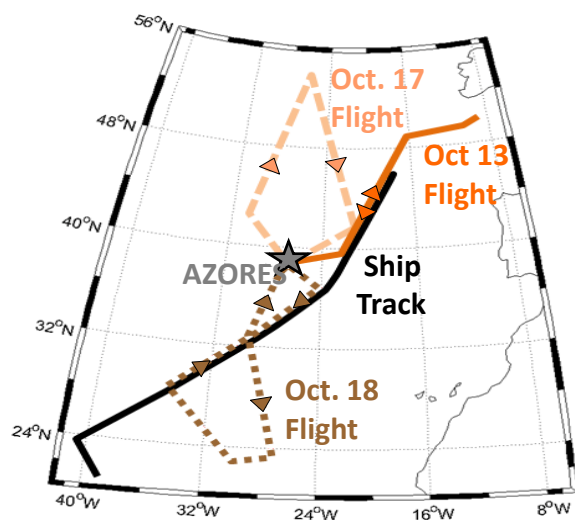


laser type	Nd: YAG, seeded
operating wavelength	532 nm
laser repetition rate	250 Hz
laser output energy	~10 mJ/pulse
telescope diameter	8 inches
viewing angle	45 degrees
Telescope FOV	350 microradians
etalon spacing	10 cm
etalon reflectivity	85%
orders imaged	1.2
detector channels	24

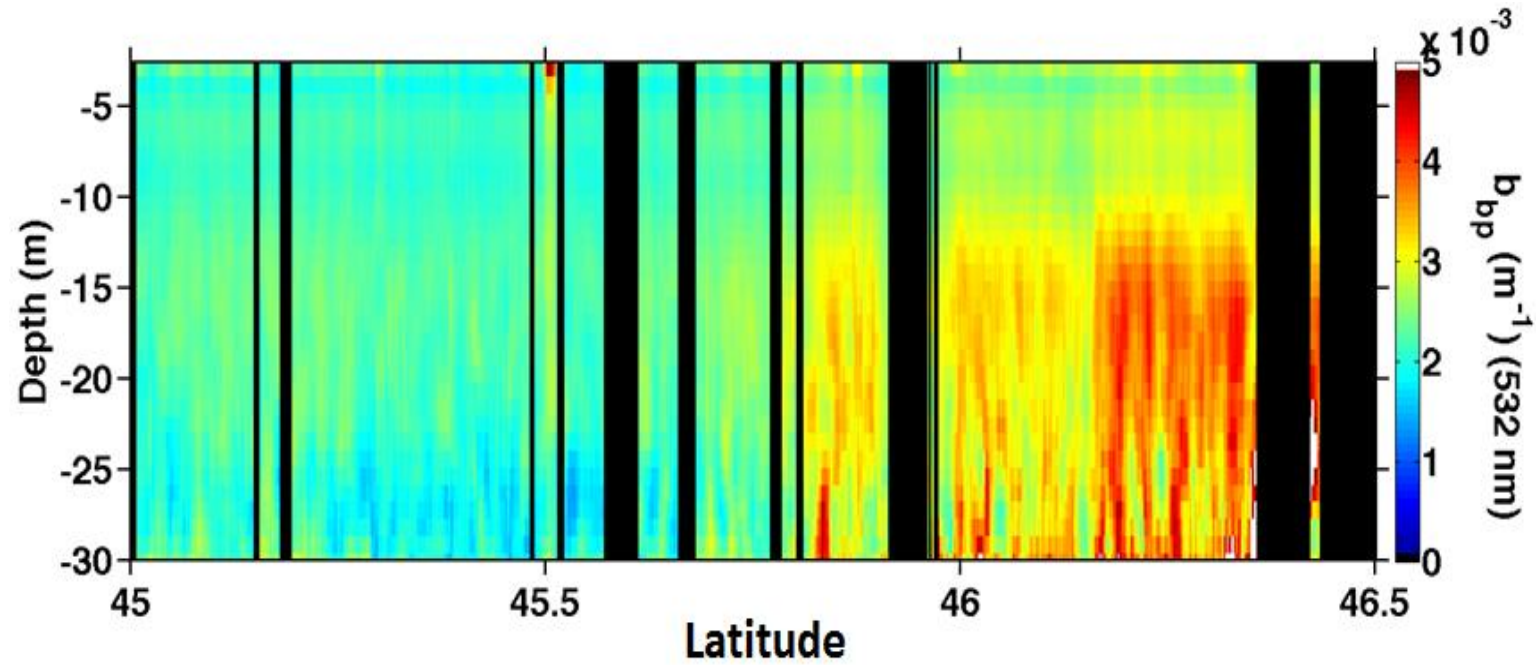
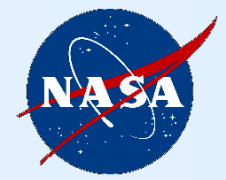


Ocean Profiling

- Ocean profiling has been demonstrated with the airborne HSRL-1 instrument
- HSRL-1 was modified under the AITT program for high vertical resolution (1-m) ocean subsurface profiling at 532 nm
- First airborne mission conducted Oct 2012 on NASA P3-B



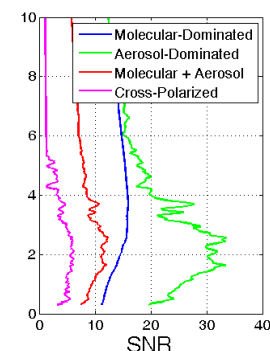
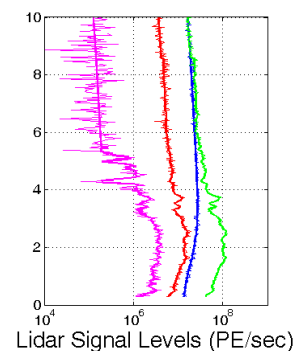
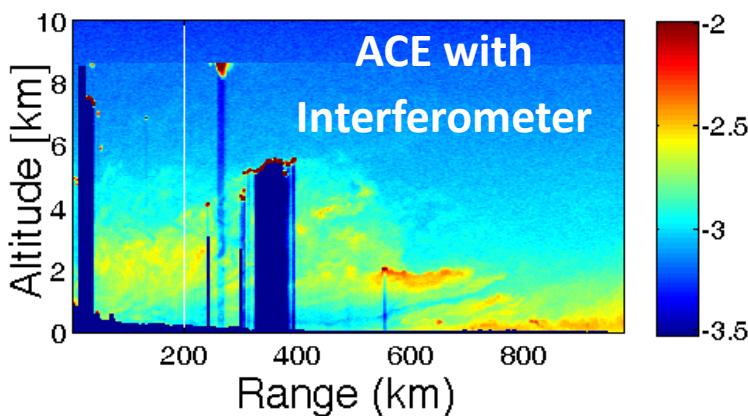
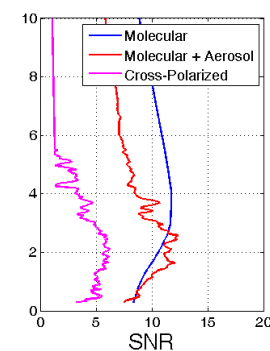
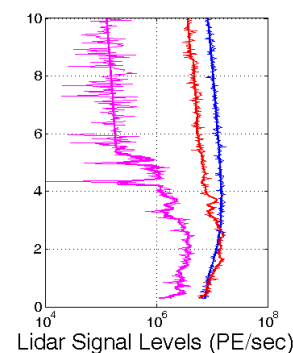
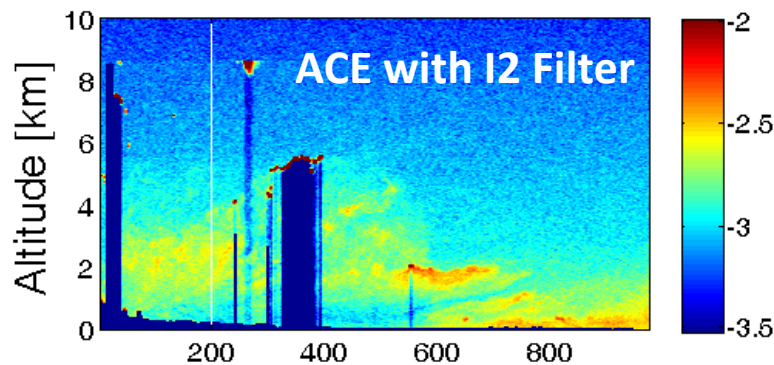
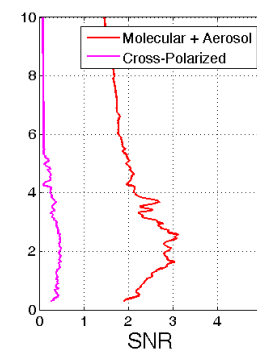
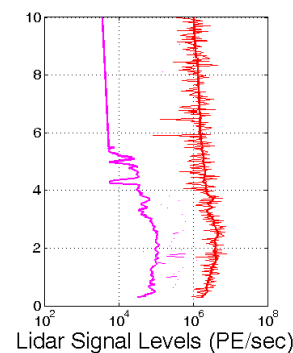
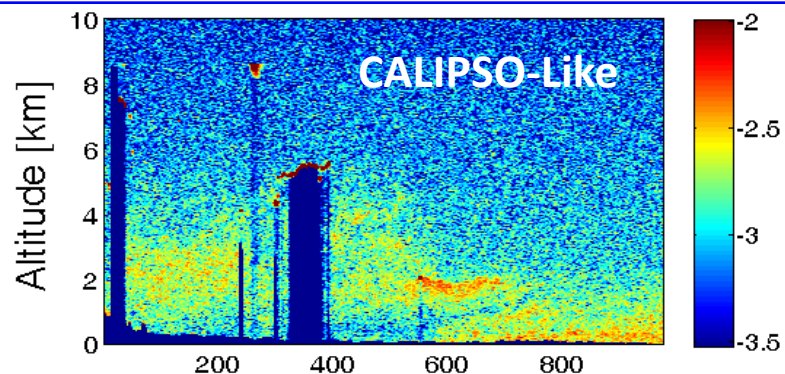
Ocean particulate backscatter retrieved with HSRL-1



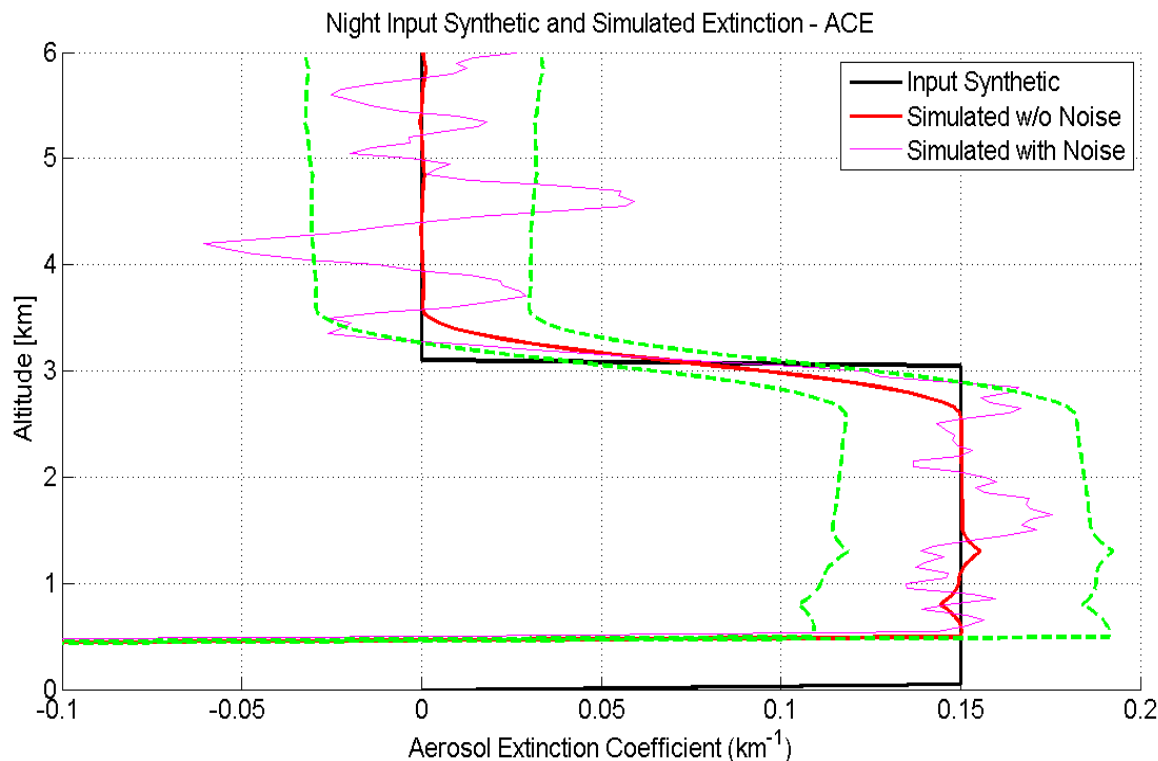
- Azores mission provided first-ever independent profiles of K_d and b_{bp} from lidar via the HSRL technique
- HSRL-1 has since been modified to improve the retrievals
- IIP just awarded to apply advances to HSRL-2, making it ocean capable at both 355 and 532 nm.

Are these systems scalable to space?

Comparison with CALIPSO

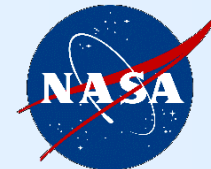


Simulated retrieval of extinction



- Random error in extinction drives power-aperture product of the lidar
- Case above: 500-m vertical resolution and 10-km horizontal resolution

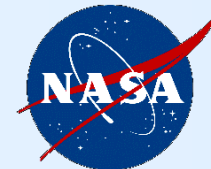
**What is the Technology Readiness Level
(TRL) of the ACE lidar?**



Technology Readiness Level

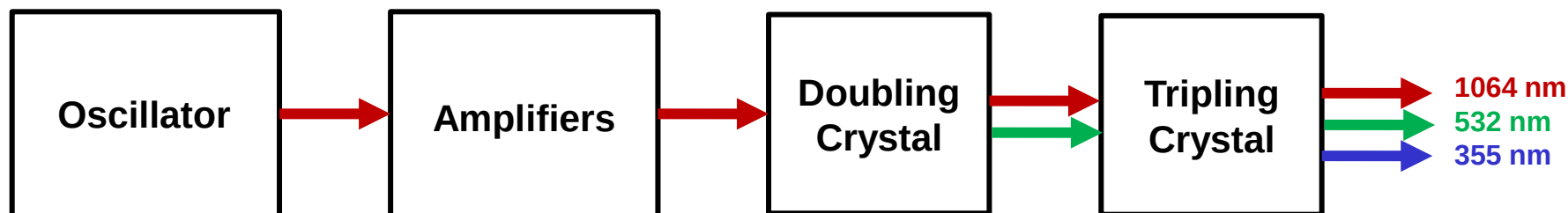
- Reviewed by the NASA Systems Engineering Working Group in 2013
- Design concept based on CALIPSO architecture with modifications required to implement a $3\beta+2\alpha+2\delta$ HSRL. Modifications:
 - Single mode transmitter with higher power and output at 355 nm
 - Iodine vapor filter HSRL implementation at 532 nm
 - Interferometric HSRL implementation at 355
 - 1.5-m diameter telescope
 - Detector changes at 532 (also used at 355)
 - Hybrid PMTs to achieve both atmosphere and ocean measurements
 - Electron-multiplying CCDs if ocean profiling is dropped
 - FPGA based data averaging to reduce downlink requirement
 - And a few other things a bit more esoteric
- Assessment: TRL-5
 - May be optimistic
 - Biggest concerns are detectors and laser lifetime
- Recommendation:
 - Investment in detector assessment and, potentially, development
 - Investment in laser lifetime studies

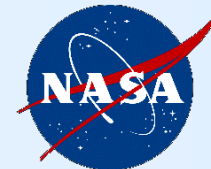
**Can the laser achieve the required
lifetime?**



What is the problem?

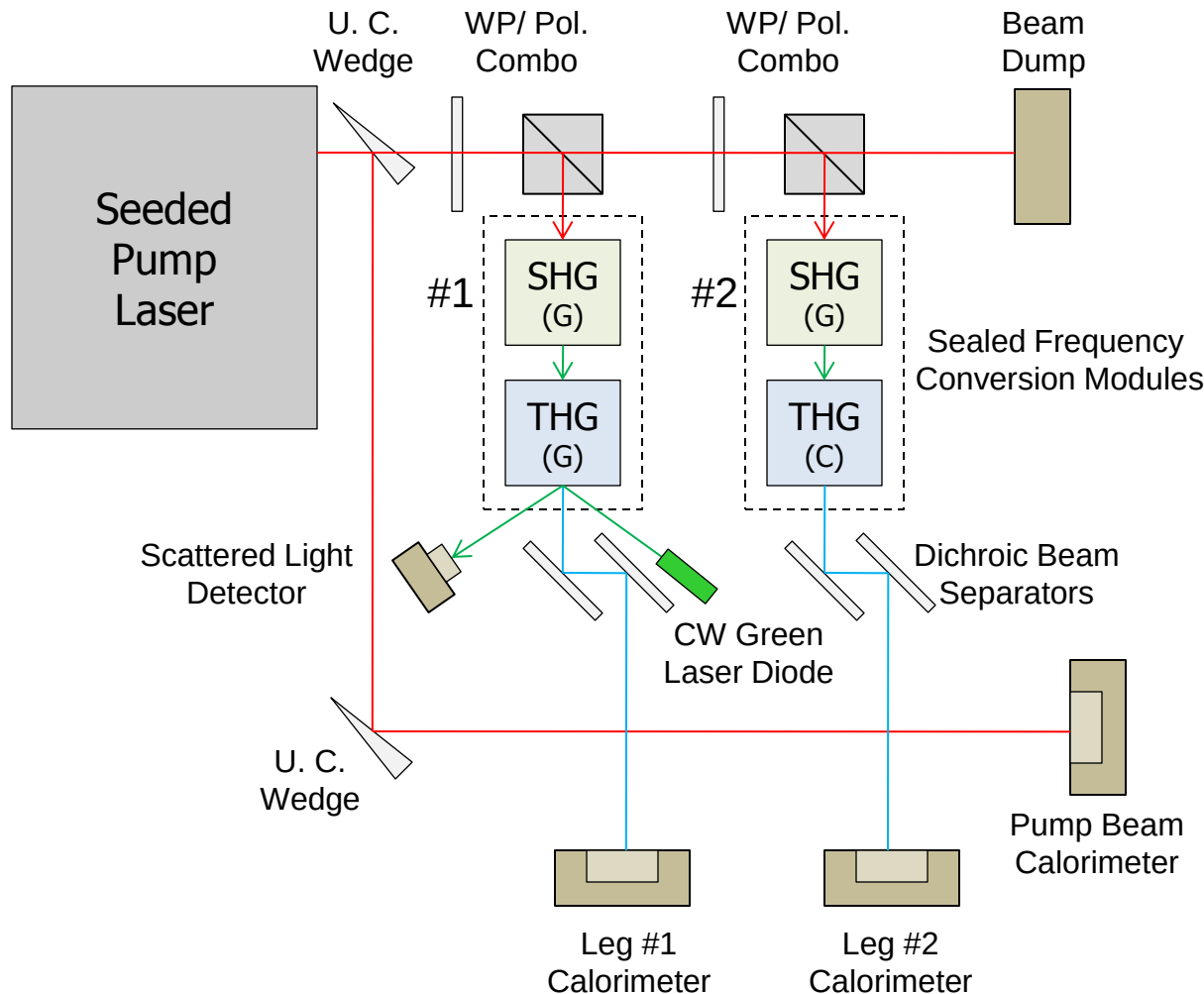
- High-fluence laser transmission at the 355 nm wavelength can damage optics in the transmitter
 - Was a problem for ESA's ADM-Aeolus wind lidar satellite mission
 - Anecdotal experience in US with fielded lasers indicated problems
- Highest risk area is the frequency tripling crystal
 - Laser beam entering and exiting crystal is made small to achieve high fluences for efficient tripling
 - Damage to coatings is most likely limit to laser life
 - Damage could result from contamination or problems intrinsic to specific coatings





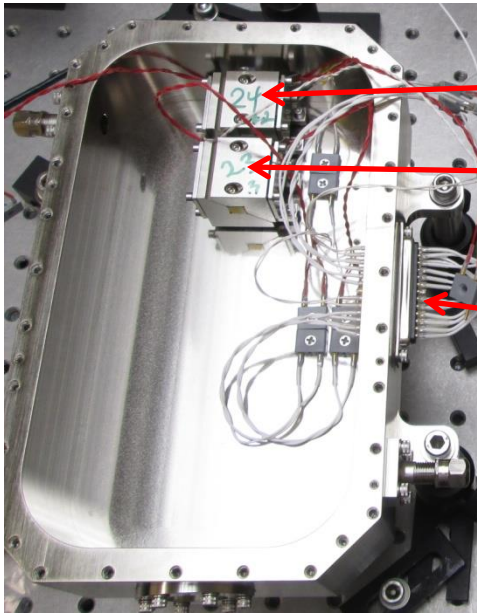
What has been done?

- Contract awarded to Fibertek
 - Built CALIPSO lasers which have achieved 8-year lifetime on orbit
 - Built of ICESat-2 lasers, CATS lasers, and several lasers which are the prototypes for the ACE $3\beta+2\alpha+2\delta$ laser
 - Have extensive experience in space laser development and laser contamination control and other issues affecting laser lifetime
- Objectives
 - Develop qualitative and quantitative understanding of UV-induced laser damage
 - Identify laser operational and crystal design changes that mitigate damage
 - Perform lifetime tests to validate identified changes.
- Work under contract
 - Assessed state-of-knowledge on UV damage issues
 - Assessed vendors and procured industry-best tripling crystals/coatings: two different vendors
 - Developed crystal housings/ovens using non-outgassing components and best practices for contamination control
 - Built test assembly with diagnostics
 - Conducted life tests starting 10/2012
 - Conducted post test diagnostics on crystals and coatings
 - Developed plan for improvement setup, alternate coatings, and further tests.



(G) – GAMDAN
(C) – Coherent

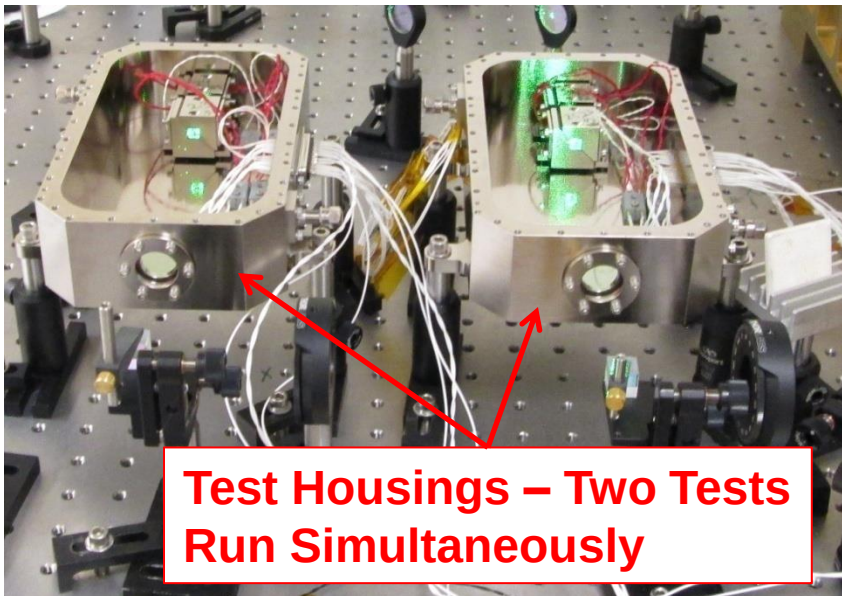
- Pump pulse energy to each module controlled with the WP/ Pol. Combo
 - Adjusted for ~120 mJ/ leg
- Frequency conversion modules are sealed
 - Purged with dry air
 - Minimal adhesives and electronic components (heaters) inside
- Dichroic separators filter out the fundamental and second harmonic wavelengths
- Scattered light from crystal surface
 - CW green laser and detector
 - Similar setup on Leg #2
- Near field images periodically acquired
 - Lens/ camera arrangement replaces each calorimeter
- Pump light far field characterized
 - Lens/ camera arrangement replaces beam dump
 - No reflective optics outside pump laser



Tripling Crystal

Doubling Crystal

Welded Electrical Connector

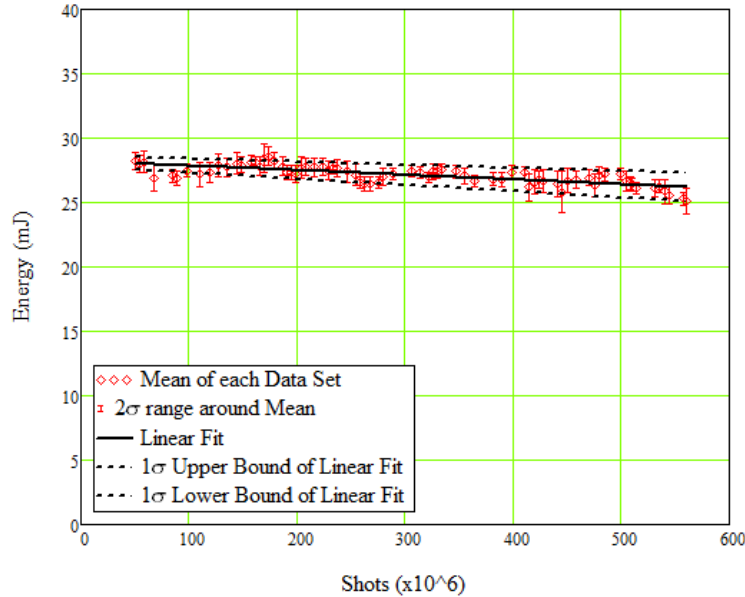


Test Housings – Two Tests
Run Simultaneously

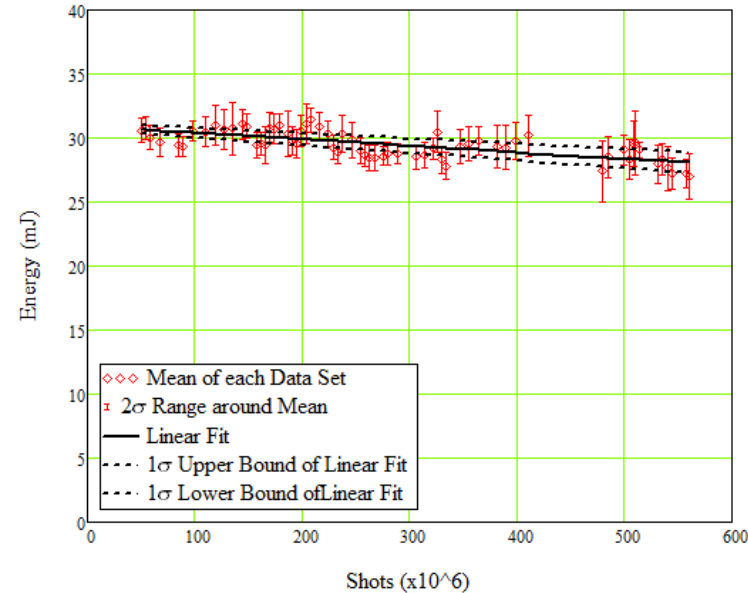


Two Test Legs at Full Power
Each Leg >30 mJ @ 355 nm

Leg #1 UV Ouput Pulse Energy



Leg #2 UV Ouput Pulse Energy

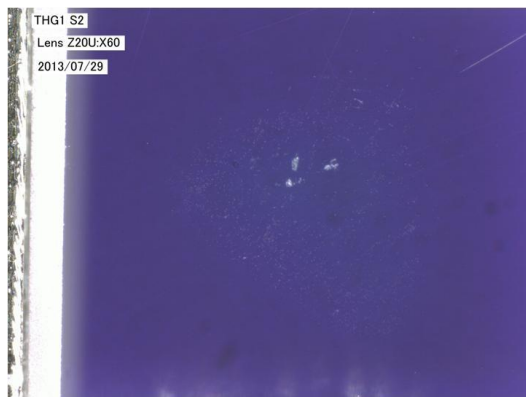


- Extrapolating results to 80% energy levels
 - 1.4 Billion shots
 - 6 month on orbit at 100 Hz
 - Not close to meeting ACE mission life
- End of the story? No

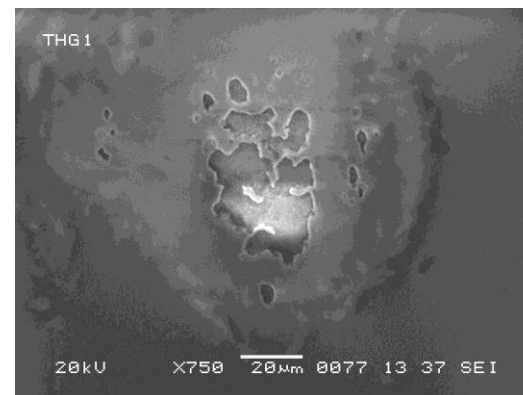
Post-test analysis

- 0.55 Billion shots on 2 triplers from different vendors
- Damage observed in both but different in nature

Crystal #1

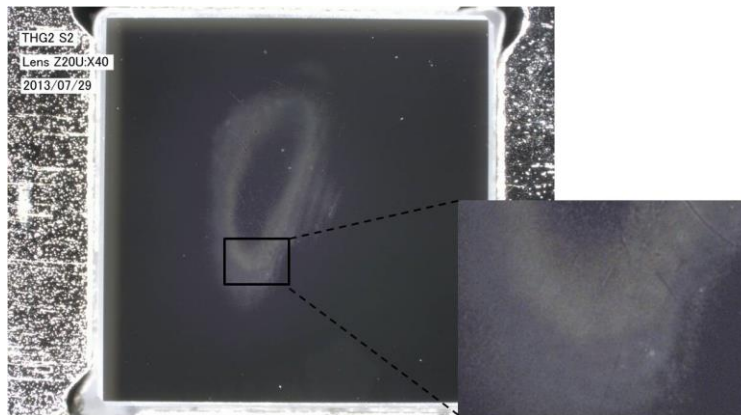


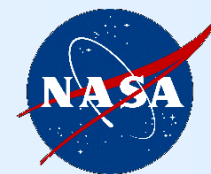
Optical Microscope Image



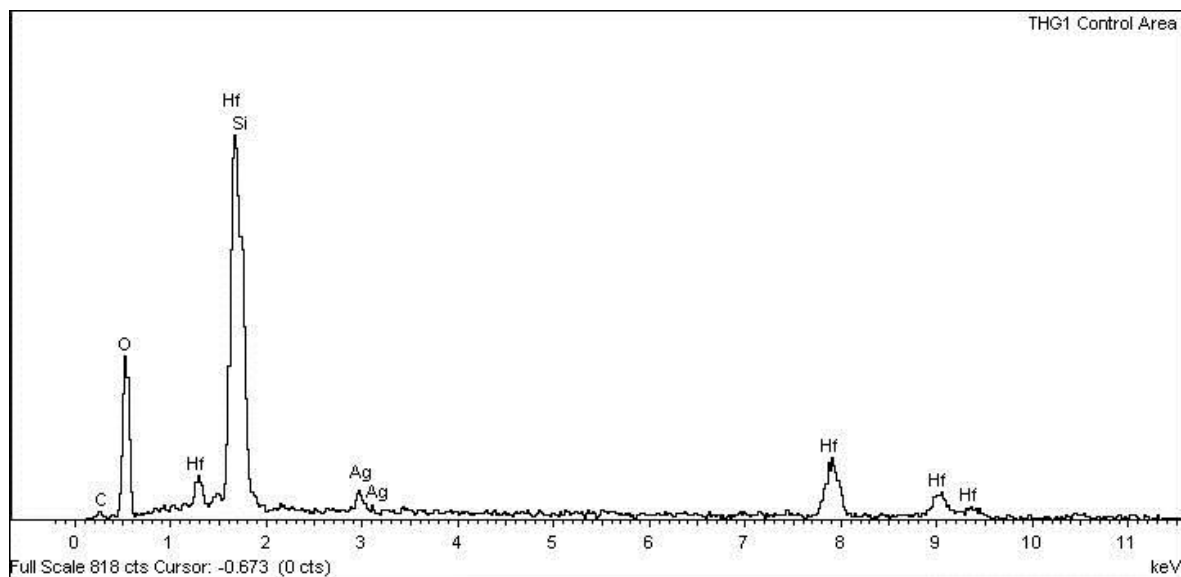
Scanning Electron Microscope
Image of a Damage Site

Crystal #2

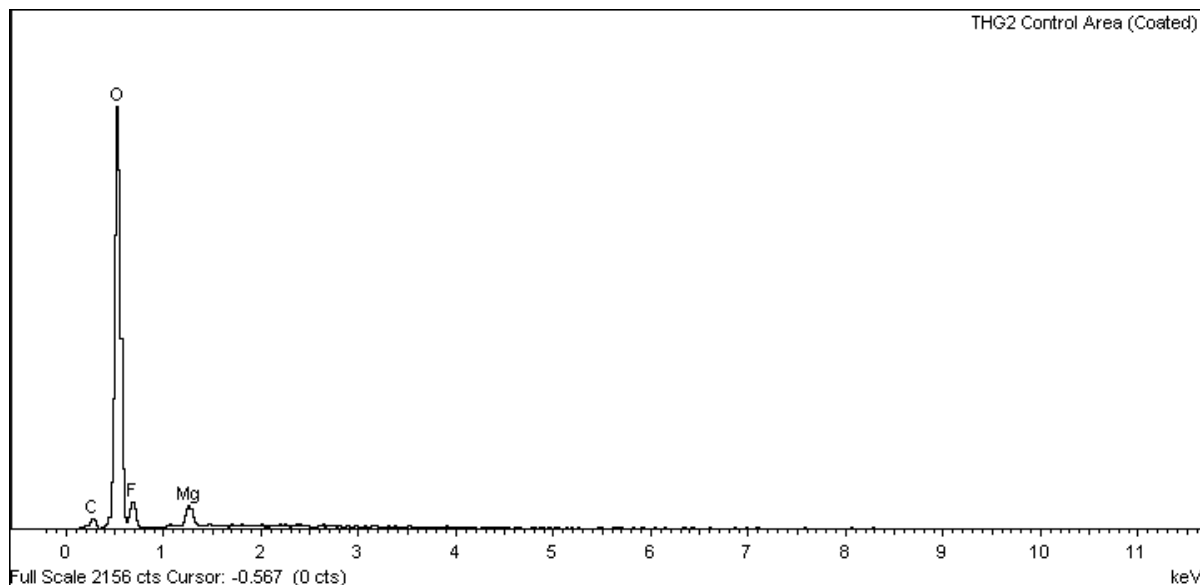




Energy Dispersive X-ray Spectroscopy



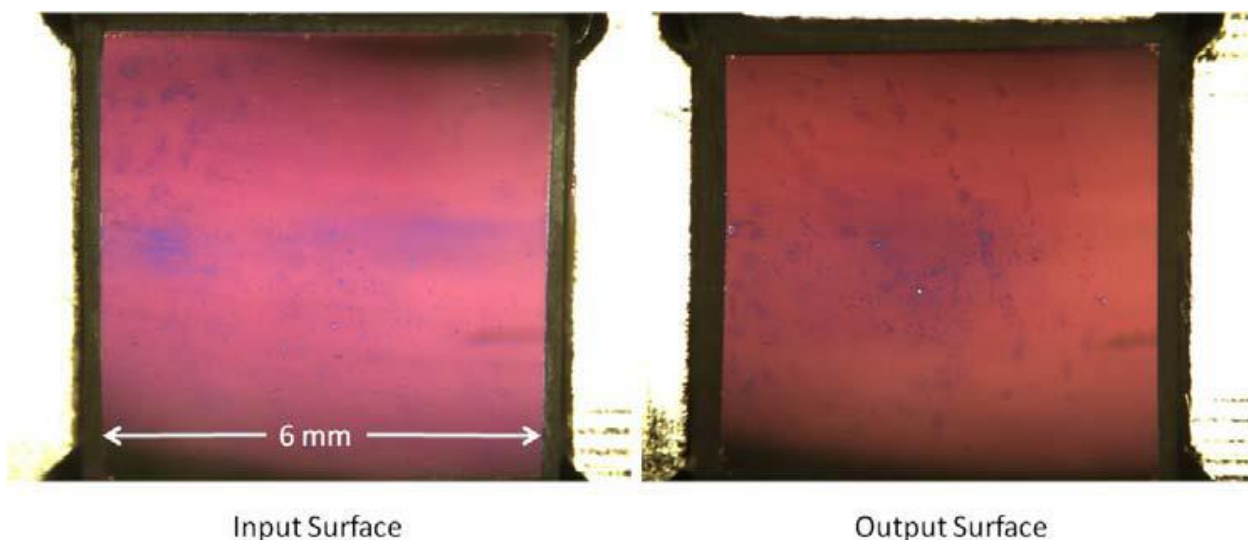
- Spectroscopic post-analysis provided insight on coating makeup



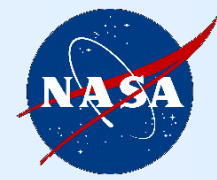
- No smoking gun here

Damage to doubling crystals

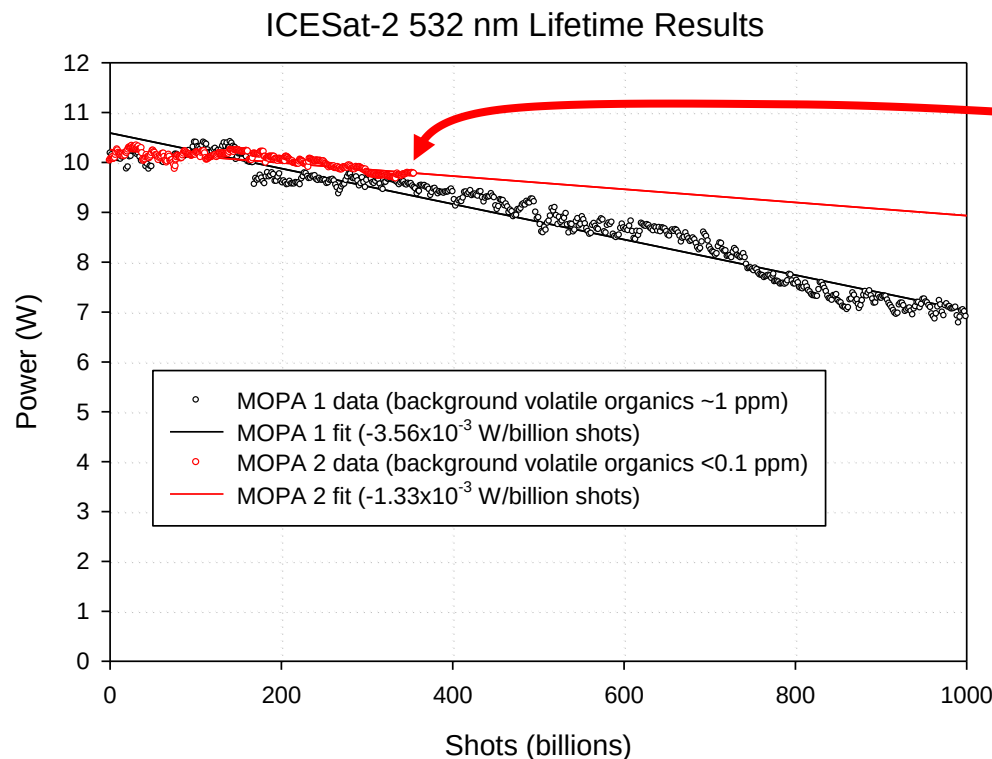
- Totally unexpected and inconsistent with experience
- Recent data from a test restart indicates defective crystal polish/finish was the key contributor to the SHG damage
 - Coater had been validated by extensive testing as part of the ICESat-2 qualification program
- Damage to tripling crystals most likely related to doubler damage



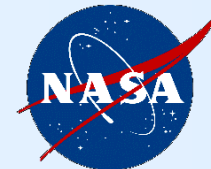
ICESat-2 Lifetime Testing Shows Importance of Contamination Control



- Trillion shot 532 nm lifetime demonstrated
 - Long term decay found to be due to slow contamination damage
- Reducing volatile organics from ~ 1 ppm to <0.1 ppm decreases long term contamination effects by 3X

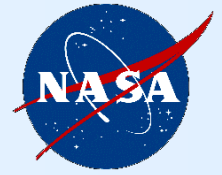


**1 year at 10 kHz
= 10 years of
ACE at 100 Hz !**



Summary of UV Damage Issues

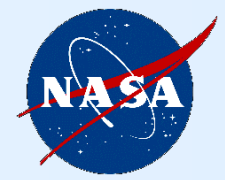
- Damage to tripling crystals most likely related to doubler damage
- Results are inconclusive
 - Projection of lifetime from time series energy data cannot be trusted
 - Many areas for improvement to tests
- Morphology of damage quite different for the two UV coatings tested
 - Different coatings respond differently
 - Need to assess more coatings and variations in coating processes



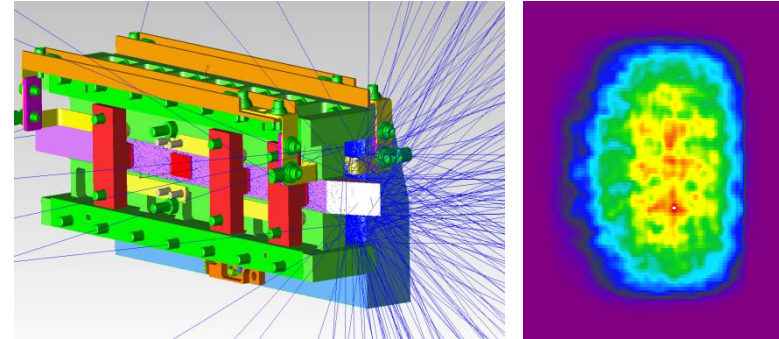
- Restart the 50 Hz, higher energy life test with fresh crystals (doubler and tripler) at higher fluence under Fibertek funding
 - Improved diagnostic setup
 - Less ambiguity in the pump energy at the crystal input
 - Fixed near field and far field imaging diagnostics for the pump
 - Near field imaging of the UV at the converter output
 - Doubler crystals are in the process of being pre-certified
- Continue to investigate UV optical coating performance issues through technical literature search and open dialog with candidate crystal and coating vendors
- Execute an accelerated UV lifetest funded under the High Efficiency UV Demonstrator (HEUVD) program
 - 10 kHz, 15 W ICESat-2 engineering laser to be used as the source
 - Achieves over 8 billion shots in 10 days
 - Use the improved HEUVD tripler box design as the test bed
 - Contains only the THG oven and an expansion scope
 - Only polymers are high purity fluorocarbon O-ring seals that will be processed to ICESat-2 cleanliness standards

High Efficiency UV Demonstrator

PI: Floyd Hovis, Fibertek



- Develop and demonstrate a highly efficient, ruggedized UltraViolet (UV) demonstrator laser with a lifetime in excess of a billion shots needed for many future space-based Earth Science active remote sensing measurements (ACE, 3D-WINDS, GACM).
- Function as a testbed for high energy UV conversion technologies and non-linear optical materials evaluation
- Advance the space flight readiness of UV laser technology



Conceptual laser head design with ray tracing of exiting pump rays, and modeled 1064 nm laser spot following amplification

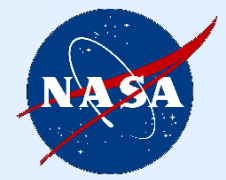
- Develop an improved 1064 nm final power amplifier that can achieve 750 mJ/pulse at 50 Hz repetition rate
- Develop a purely conductively cooled laser optics module design for packaging the 50 Hz, 750 mJ 1064 nm pump laser
- Develop a UV conversion module design with a lifetime of $>10^9$ shots that converts the 750 mJ pump to 350 mJ at 355 nm
- Build and test the pump laser and UV conversion modules
- Execute an 8 month life test of the pump laser and UV conversion

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|--|-------|
| • Conclude power amplifier conceptual study | 07/13 |
| • Conclude power amplifier modeling | 09/13 |
| • Complete UV conversion module design | 02/14 |
| • Conclude final power amplifier design and test | 04/14 |
| • Conclude pump laser opto-mechanical design | 06/14 |
| • Complete testing of electronics module | 10/14 |
| • Complete testing of laser module | 11/14 |
| • Complete system integration | 12/14 |
| • Conclude lifetest | 08/15 |

Co-Is/Partners: Mike Albert, Fibertek

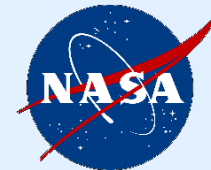
$TRL_{in} = 4$ $TRL_{current} = 4$

UV Laser Life Test Summary and Plan



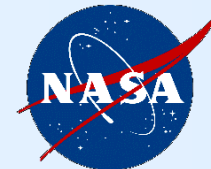
- Results so far are inconclusive
 - We have not yet determined the fundamental limit on UV laser lifetime
- Europeans believe they have solved this problem and are launching two UV lidars, ALADIN and ATLID, in the next few years. We will learn more about their approaches and follow their progress.
- Fibertek will
 - Continue with lifetests using two setups and different coatings
 - 50 Hz ACE-funded setup
 - 10 kHz accelerated test setup under HEUVD program
 - Incorporate lessons learned in the ESTO-funded HEUVD laser project, which will conduct further life tests with a full-up laser similar to that required for ACE
 - Publish results

Recommendation: fund coating vendors



- Applications like ACE requiring years of lifetime from coatings are rare
- Coating vendors are focused on coating recipes and processes to meet their high-volume customer base
- Funding 1 or 2 vendors to improve their coatings and processes may be required to get their full cooperation in reducing risk of long-term damage.

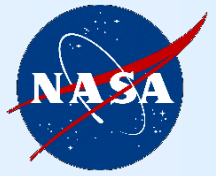
**What investments are needed in
technology and retrieval development?**



Suggestions for investment

- Lasers
 - Continue space qualification and life test of current designs
 - Develop higher efficiency lasers capable of sufficient pulse energies for ACE
 - Space qualify seed laser subsystems
 - Fund coating vendors to develop better coatings for UV applications
- Detectors
 - Conduct performance tests on various candidates
 - Space qualify candidate detectors
- Interferometer
 - Continue work improving design and reducing risk
- Develop detailed instrument concepts
 - Perform instrument trades based on recent developments
 - Refine estimates of performance, mass, power, volume, cost and risk
 - Develop more detailed radiometric math models of performance

Summary



- Outlook positive for developing a lidar generally meeting ACE requirements
 - Some requirements drive design in different directions. Need to work out best compromises. Need to work with teams on merit those requirements that drive cost.
- Airborne simulators are demonstrating both technologies and retrievals
- TRL $\sim$ 4-5
- Concerns
 - UV lifetime
 - Detectors

Backups