



A 16-beam Non-Scanning Swath Mapping Laser Altimeter Instrument

**Anthony Yu, Michael Krainak, David Harding, James Abshire,
Xiaoli Sun, John Cavanaugh, Susan Valett, Luis Ramos-Izquierdo,
Pete Dogoda, Brian Kamamia**

**Paper 8599-25
03FEB2012**

Raytheon
Space and Airborne Systems





Instrument Incubator Program (IIP) Objectives and Approaches

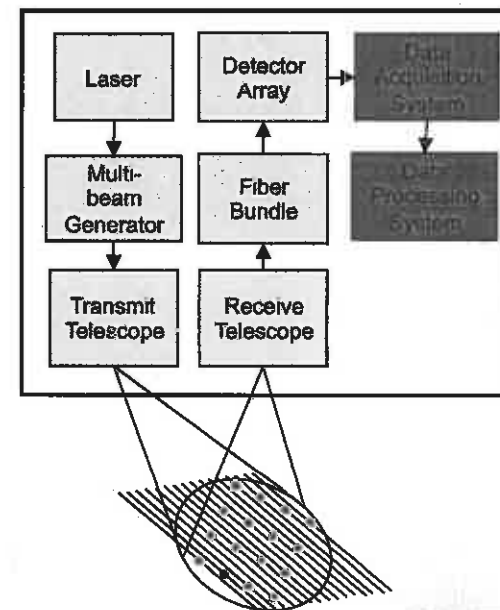


Objectives -

- Develop key technologies to meet the LIST mission requirements and provide scalability study for spaceborne mission.
- Advance TRL of critical subsystems (Laser & Detector) on airborne platform.
- Develop and demonstrate a >15% wall plug efficient laser system coupled with a highly sensitive detector array to realizing the global elevation mapping goals of the LIST mission.

Approaches -

- Develop and demonstrate a 16-channel airborne instrument - *Airborne Lidar Surface Topography Simulator (ALISTS)* to demonstrate key subsystems and measurement techniques in support of the LIST mission.
- Key subsystems being matured in this IIP - Laser, Detectors and Optical System.
- COTS - Data Acquisition and Processing Systems



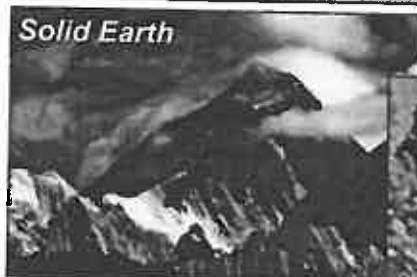


LIST Mission Objectives and Requirements

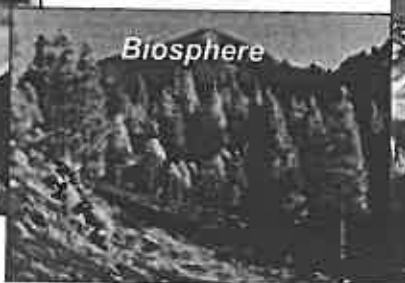


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The Lidar Surface Topography mission will serve a diverse array of science and applications objectives, providing foundation data on the Earth's topography, the height of overlying covers of vegetation, water, snow and ice, and their change.



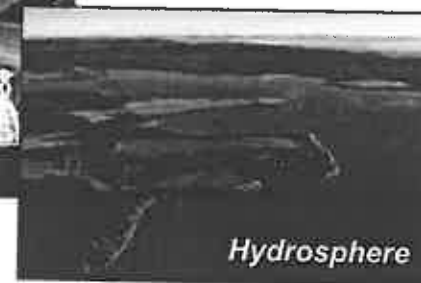
Solid Earth



Biosphere



Cryosphere



Hydrosphere



LIST Advanced Mission Concepts Study
David Harding, Study Scientist
Conducted in 2007 for NASA HQ

ground
topography

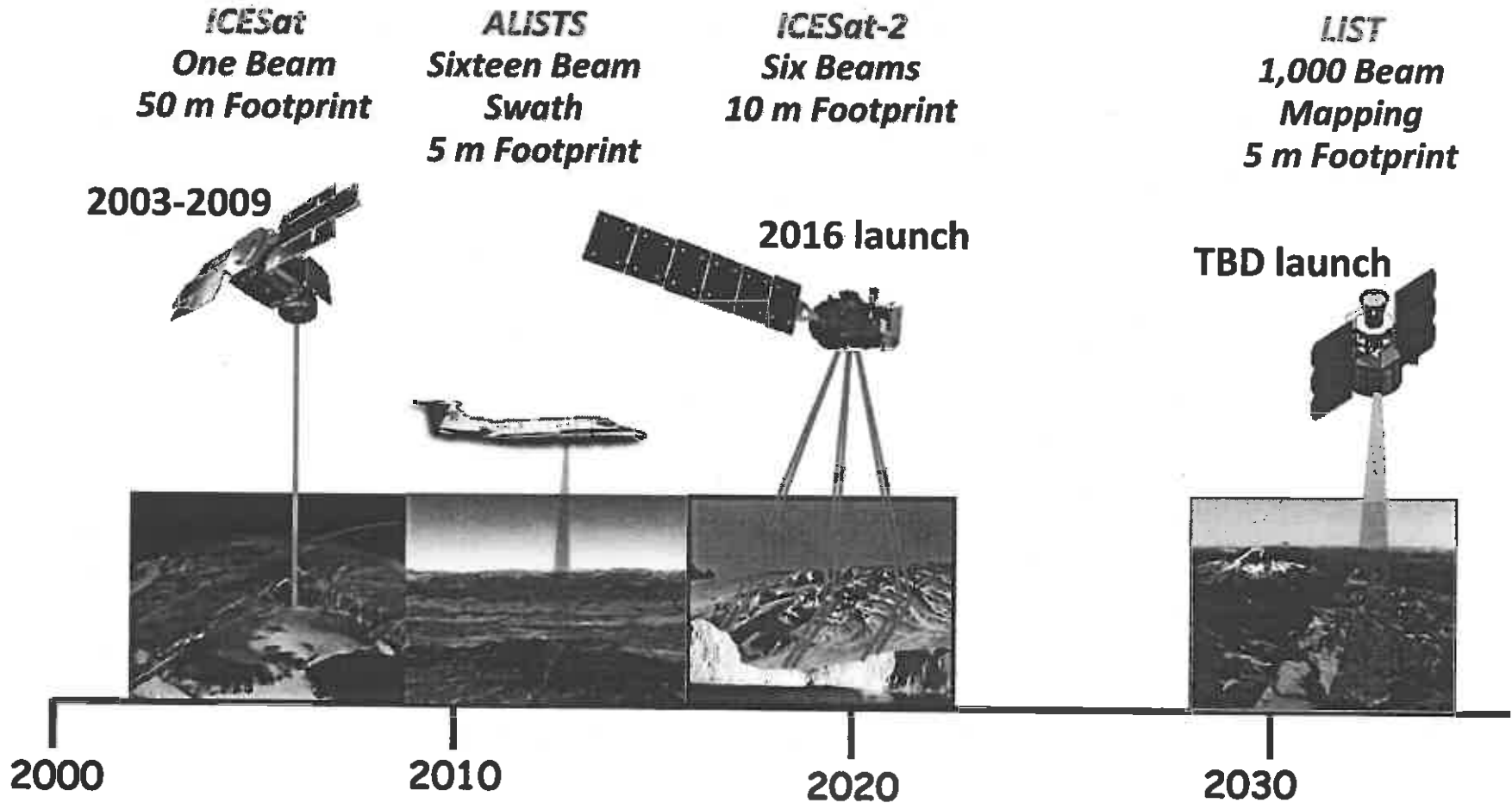
canopy
structure

- **Map land topography including where covered by dense vegetation**
 - 5 m spatial resolution
 - 10 cm vertical precision
 - 20 cm absolute elevation accuracy
- **Map vegetation height and vertical structure**
 - 1 m accuracy for 25 m x 25 m area
- **Complete global mapping in 3 years**
 - 5 km swath to build up coverage during clear sky conditions
 - Multi-beam "push-broom" approach: $5 \text{ km} / 5 \text{ m} = 1,000$ beams
 - **Requires highly efficient measurement approach**

ALISTS measurement approach developed to meet the demanding LIST requirements

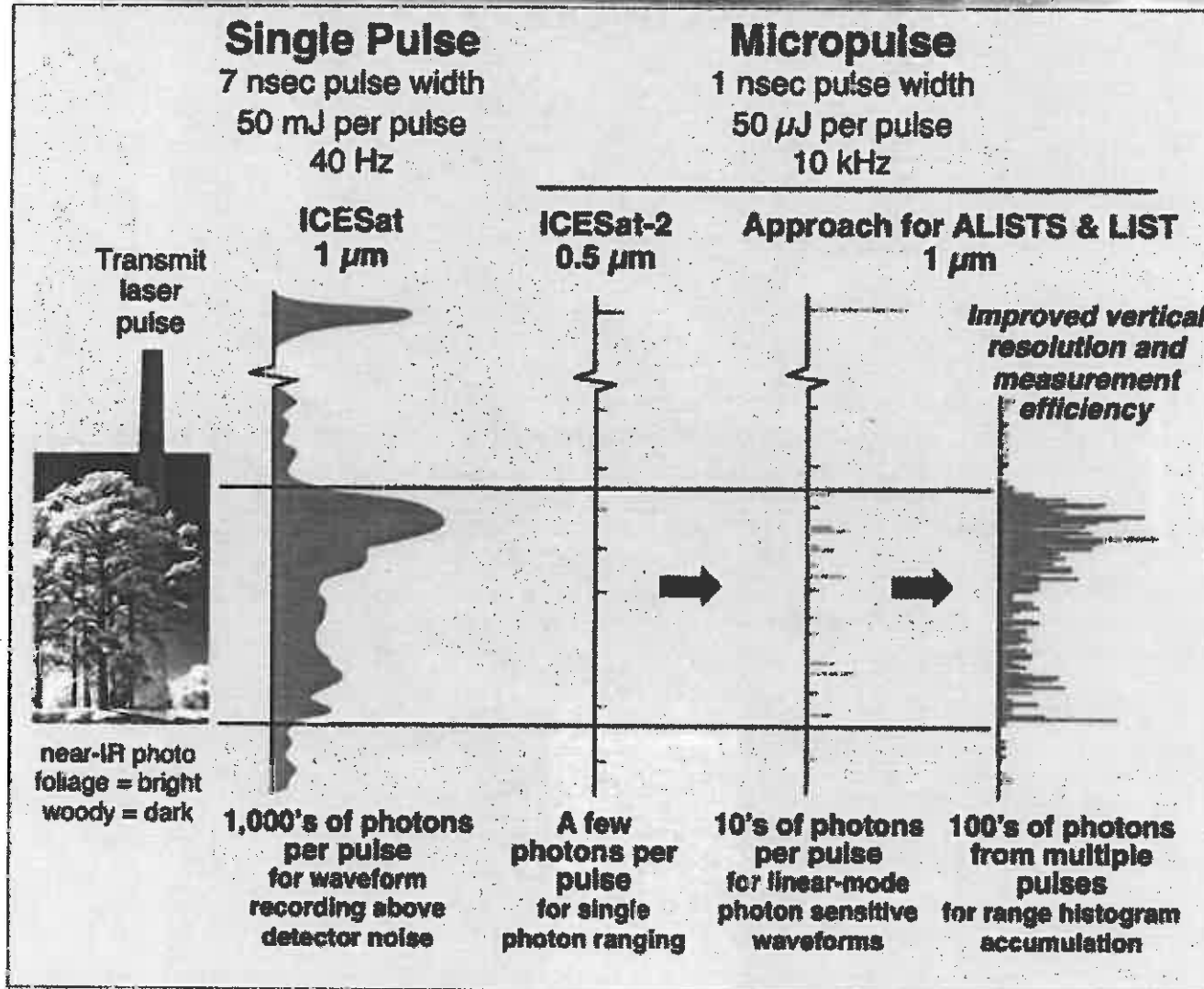


ALISTS Spaceflight LIDAR Mission Context





ALISTS and LIST: An Efficient Lidar Measurement Approach





Key differences between LIST lidar and earlier lidars



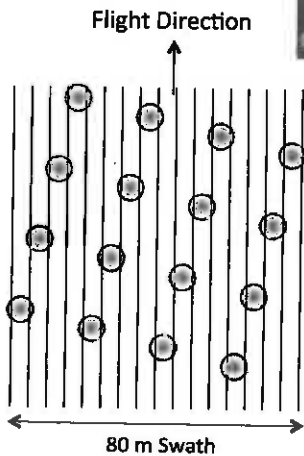
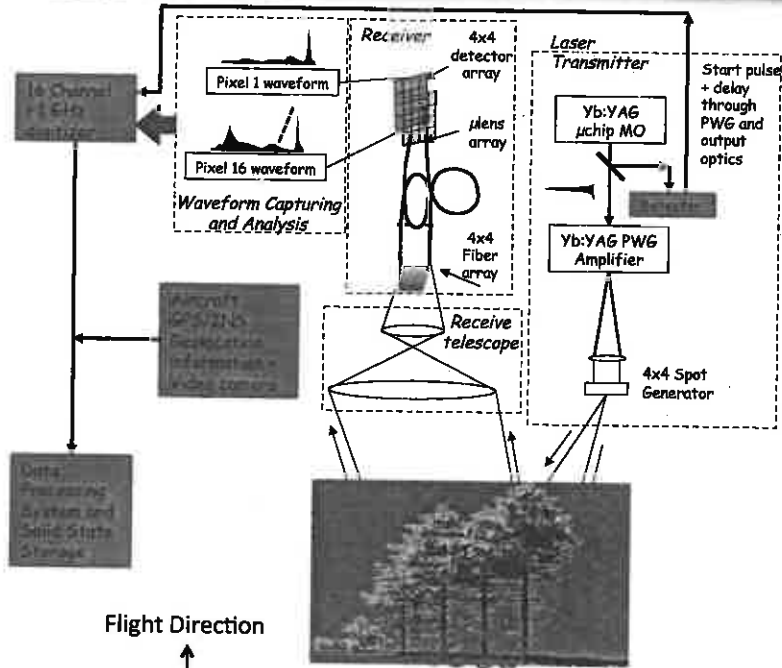
- **Laser Transmitters:**
 - Low to medium pulse energy and high pulse rate, similar to ICESat-2/ATLAS but at a near IR wavelength
 - Much higher electrical to optical conversion efficiency
- **Optics and Alignment**
 - Similar to previous lidars but with up to 1000 instantaneous field of view (IFOV), or pixels, and new challenges in alignment
- **Detectors:**
 - Infrared, single-photon-sensitivity, linear-mode analog output, and multiple element array
- **Signal Processing**
 - On board storage, filtering, and data volume reduction



IIP ALISTS Instrument Concept & Performance Prediction

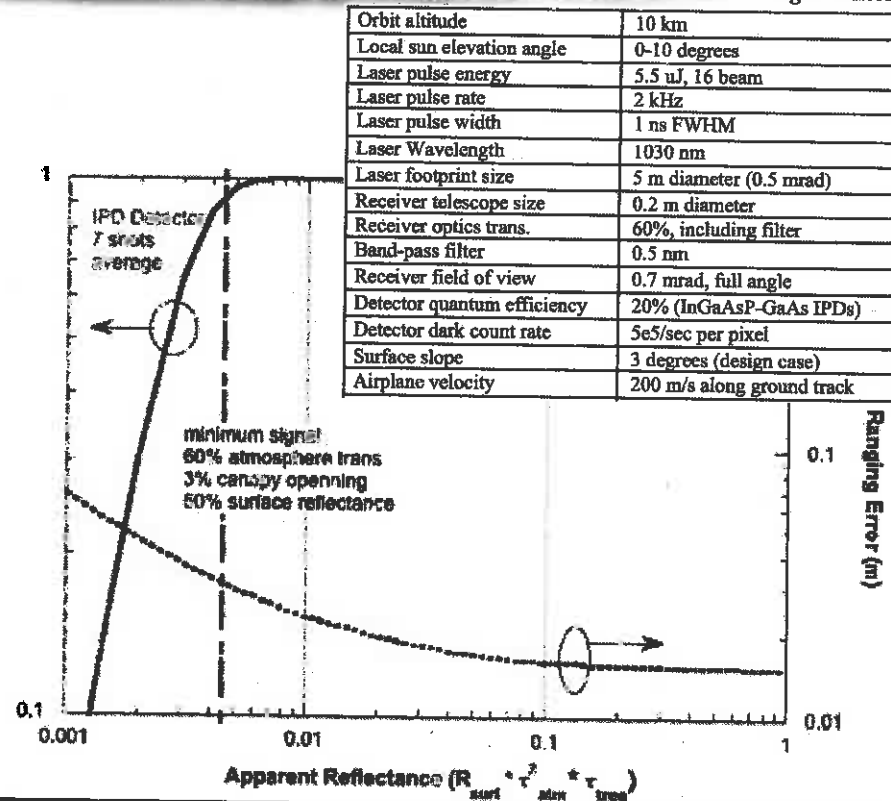


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Altitude = 10 km
 16 adjacent, parallel beams
 Detector FOV = 7 m (0.7 mrad);
 Laser Spot = 5 m (0.5 mrad);
 Spot Spacing = 20 m (2 mrad)

Probability of Detection



Orbit altitude	10 km
Local sun elevation angle	0-10 degrees
Laser pulse energy	5.5 μ J, 16 beam
Laser pulse rate	2 kHz
Laser pulse width	1 ns FWHM
Laser Wavelength	1030 nm
Laser footprint size	5 m diameter (0.5 mrad)
Receiver telescope size	0.2 m diameter
Receiver optics trans.	60%, including filter
Band-pass filter	0.5 nm
Receiver field of view	0.7 mrad, full angle
Detector quantum efficiency	20% (InGaAsP-GaAs IPDs)
Detector dark count rate	5e5/sec per pixel
Surface slope	3 degrees (design case)
Airplane velocity	200 m/s along ground track

- Same approach as for space, with:
 - Lower altitude: 10 vs 400 km
 - Smaller telescope: 0.2 vs 2 m
 - Lower laser energy: 5 vs 50 μ J
- Significant over sampling along track at lower aircraft velocity:
 - Allows optimization of measurement & signal processing techniques.



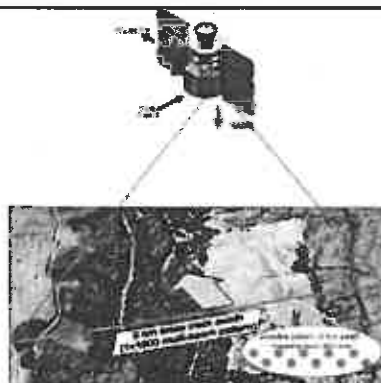
Spaceflight and Airborne Measurement Comparisons



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All use micropulse lidar with waveform capturing and analysis detection scheme

Parameters	Spaceborne Instrument	Airborne Instrument Engineering Flights	Airborne Instrument Science Demonstration Flights
Spatial Resolution	5 meter	5 meter	5 meter
Beam Divergence	12.5 μ rad	0.5 mrad	0.5 mrad
Altitude	400 km	32.8 kft / 10 km	~28 kft / ~8 km
Swath Width	5 km	80 m	80 m
Laser Energy	50 μ J/beam for 1000 beams @ 10 kHz*	~5 μ J/beam for 16 beams @ 2 kHz	~5 μ J/beam for 16 beam @ 10 kHz
Detector (> 1 GHz bandwidth/pixel)	1000 pixels	16 pixels	16 pixels
Platform Speed	7000 m/sec	200 m/sec	~170 m/sec
Number of footprints per 5-m along track	7	50	300



**assuming detector similar to Intevac IPD performance for spaceborne mission*



ALISTS Airborne Campaigns



Engineering Flights – Sept 2011

- Platform: Lear-25
- Location: NASA GRC
- Laser: Microchip Laser
- Detector: Intevac 16 element IPD
- Number of beams: 16
- Altitude: 10 km



Science Demonstration Flights – Aug 2012

- Platform: P-3B
- Location: NASA WFF
- Laser: Microchip Laser & MOPA Laser
- Detector: Intevac 16 element IPD
- Number of beams: 16
- Altitude: 1-2 km (due to SNR limitation)





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ALISTS Instrument Overview

JOHN CAVANAUGH

NASA GSFC CODE 554



Airborne Instrument Requirements



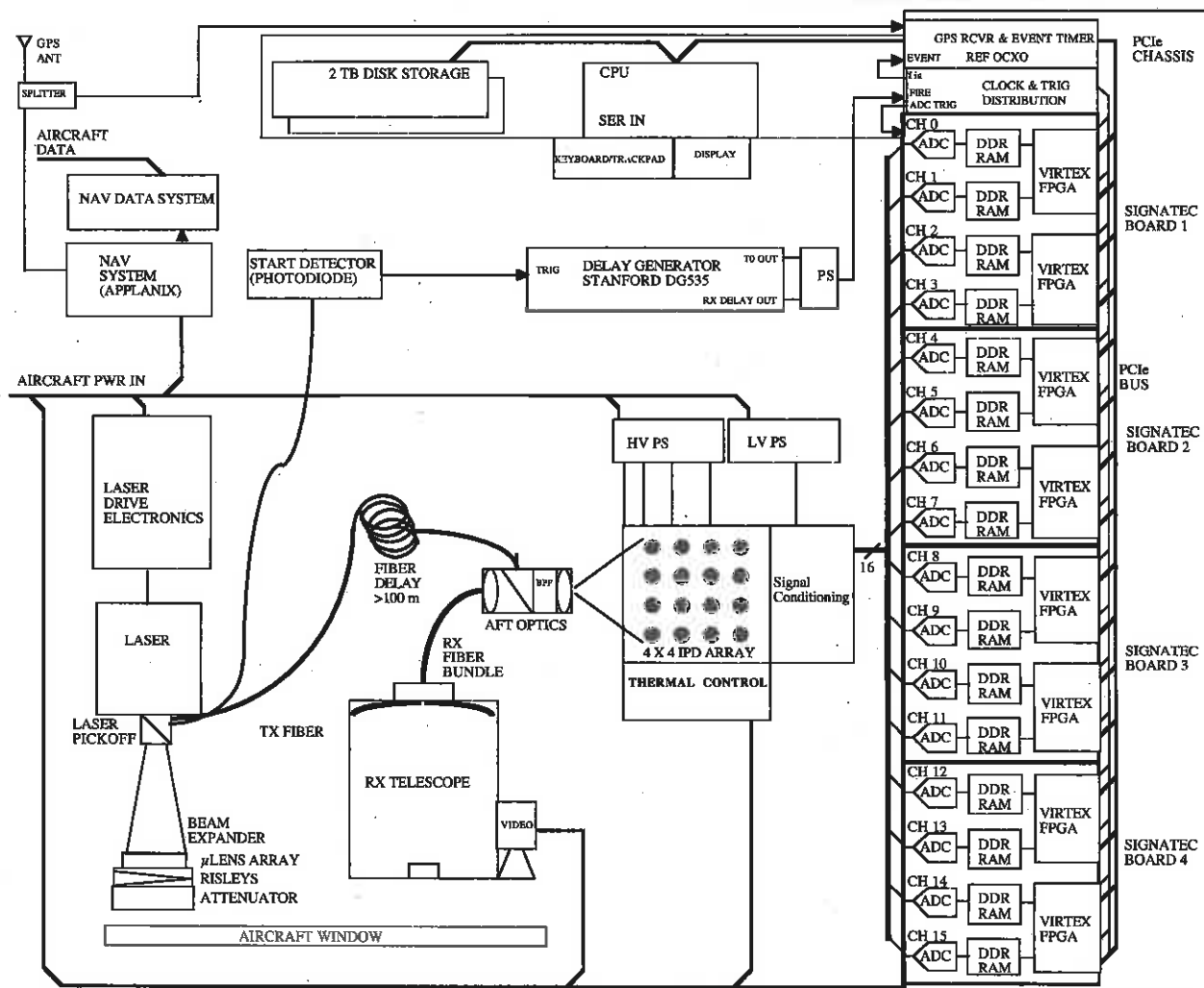
- **Measure pulse time of flight**
 - 0.1 m accuracy for 1° slopes
 - 0.5 m accuracy for 10° slopes
- **Signal Characteristics**
 - 10 kHz pulse repetition rate
 - 1 transmit pulse
 - 0.7 – 1.0 ns FWHM Gaussian
 - 16 received pulses
 - Signal spreading < 300 m (2 μ s max)
- **Detector Bandwidth**
 - Constant group-delay filter
 - 467 MHz -3 dB
 - 1 GHz -50 dB
- **Rx Tracking Requirement**
 - Track 2 μ s Rx signal window
 - Center sample window on signal
 - \pm 150 m window
 - Adjust at >2 Hz rate (5k shots)
- **Acquisition Requirements**
 - 8-bit quantization (ENOB > 6.5)
 - Sample rate > 1.5 GS/s
 - Data rate for 2 μ s Rx window @ 1.5 GS/s:
 - 3000 samples x 16 channels Rx
 - 100 samples Tx
 - > 500 MB/s continuous rate
- **Storage Requirement**
 - 1 Hour continuous -> 1.8 TB
- **Ancillary Data**
 - Aircraft Nav Data
 - GPS & Attitude (Applanix)
 - Nadir video stream



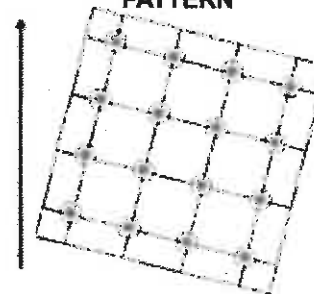
ALISTS Block Diagram & Measurement Pattern



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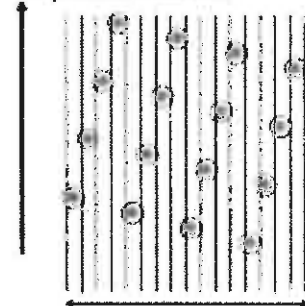
MEASUREMENT PATTERN



Swath Width

4 x 4 fiber-coupled detector array rotated 14.5°

Detector FOV's separated to prevent cross-talk

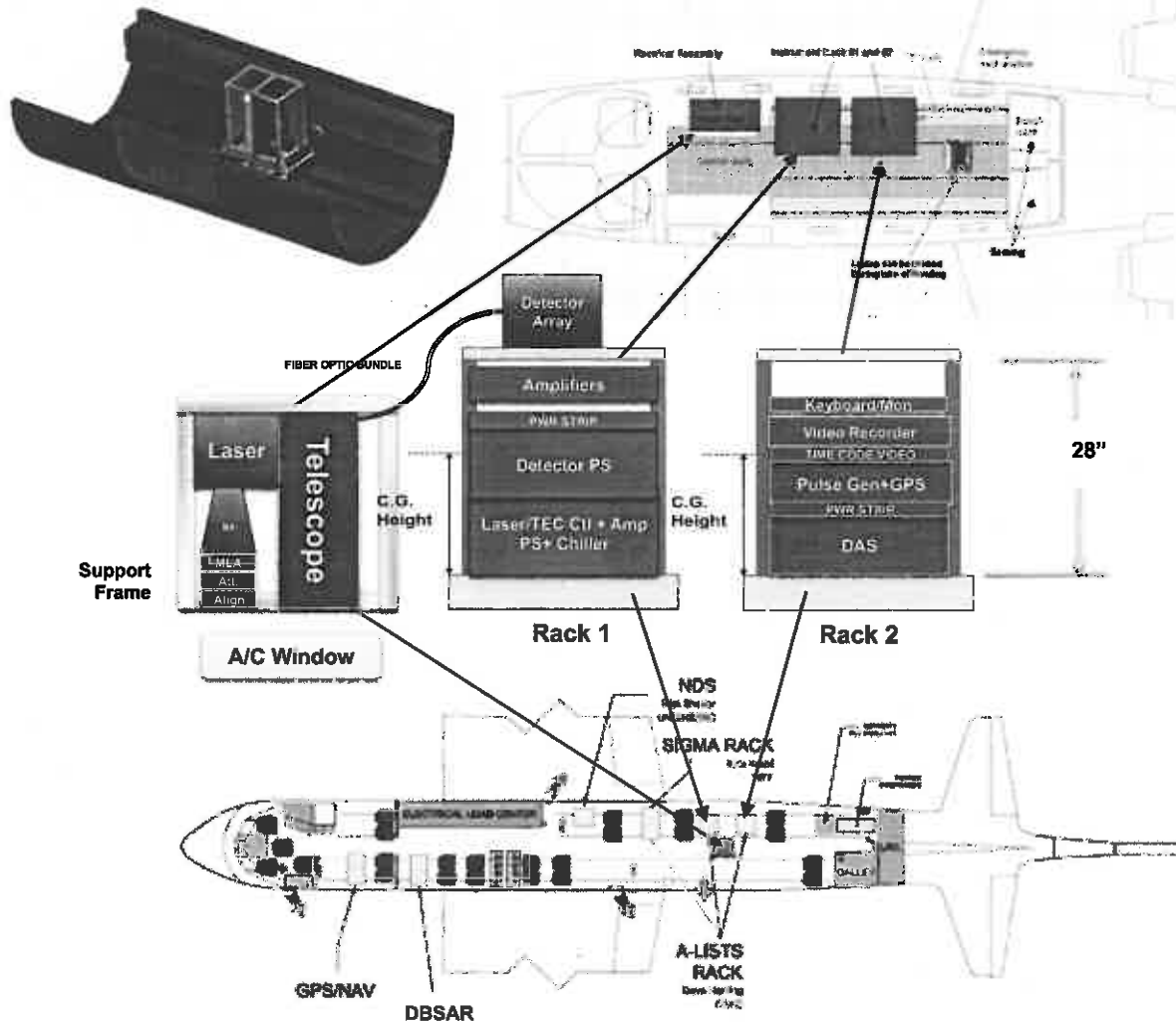


16 contiguous, cross-track, 5 m wide profiles in flight direction

At 10 kHz rep rate and 200 m/sec ground speed spots spaced 2 cm along track; 35x oversampling compared to LIST



ALISTS Transceiver and Racks for Lear-25 and P3 Flight Campaigns



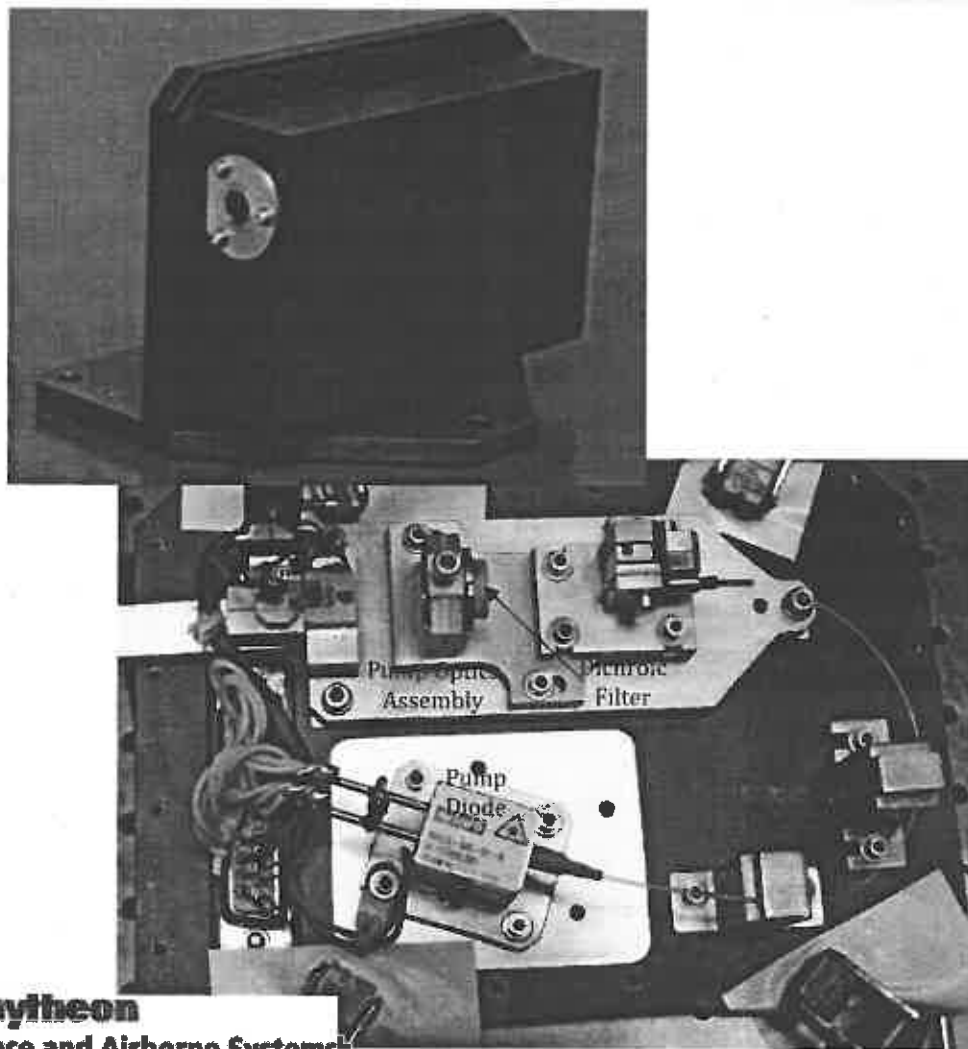
**GRC Lear-25
Engineering Flight
Configuration**

**WFF P-3B
Science Demonstration
Flight Configuration**



RAYTHEON PROPRIETARY

Yb:YAG Microchip Laser for ALISTS



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Space and Airborne Systems

Laser Output Beam Parameters

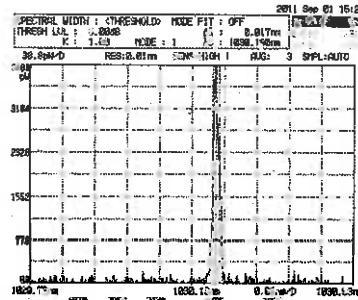
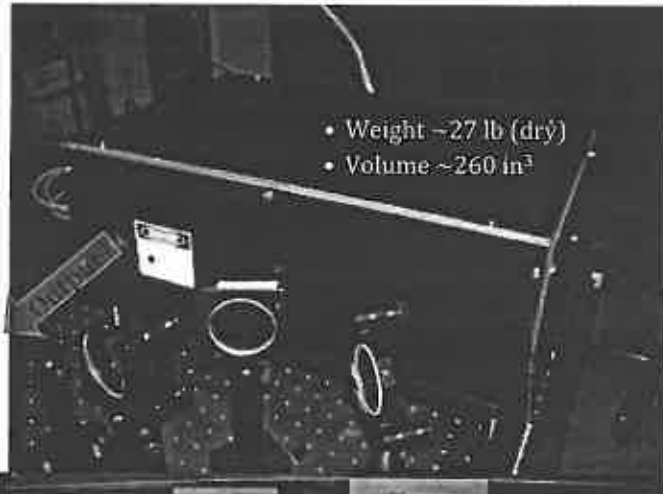
Pulse Energy:	0.1 mJ
Repetition Rate:	10 kHz
Wavelength:	1030.2 nm
Linewidth:	17 pm
Polarization Ext:	25 dB
Pulsewidth:	0.83 nsec
Beam Quality M2:	1.3
O-O Efficiency:	25%

Laser Operating point

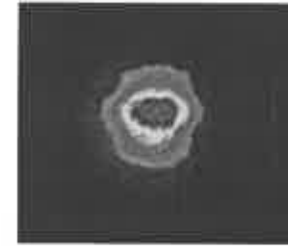
Diode Current:	4.5 A
Diode Output Power:	3.9 W
Chiller Temp:	29.8 °C
Diode Temp:	31 °C
μChip Temp:	17.8 °C
VBG Temp:	20 °C



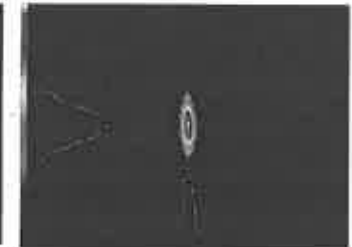
Packaged MOPA for Swath Mapper IIP – Power Scaling Demonstration



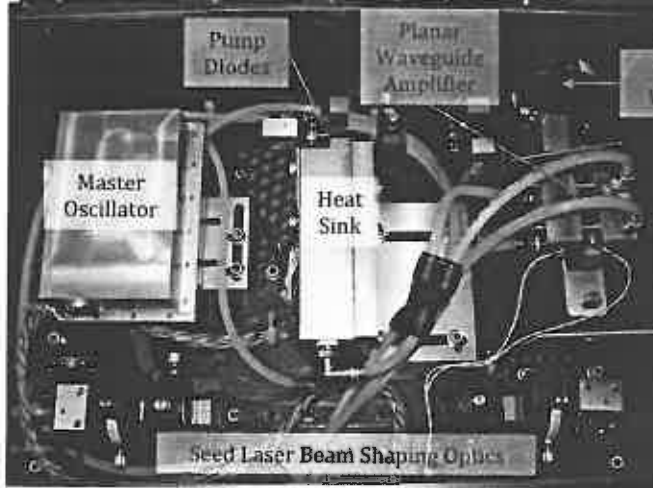
Wavelength ~1030.2 nm;
<20 pm spectral width



NF Image at ~84 cm from
MOPA Output
FW1/e² size: 2.6 mm x 3.3 mm



FF Image



Output Window

MO Nominal Operating Point

- Pulse Energy 0.1 mJ
- Repetition Rate 10 kHz
- Wavelength 1030.2 nm
- Linewidth 0.018 nm
- Polarization ER 25 dB
- Pulsewidth 0.8 nsec
- Beam Quality $M^2 \sim 1.3$
- Opt-Opt Efficiency 25.6%
- El-Opt Efficiency 12.8%

MOPA Nominal Operating Point

- Pulse Energy 2.2 mJ
- Repetition Rate 10 kHz
- Wavelength 1030.2 nm
- Linewidth 0.02 nm
- Polarization ER 18 dB
- Pulsewidth 0.8 nsec
- Beam Quality $M^2 \sim 1.1$
- Opt-Opt Efficiency 24%
- El-Opt Efficiency 11%

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Receiver for ALISTS

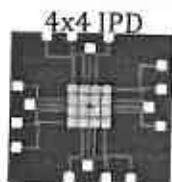


Selected the Intevac InGaAsP 4x4 intensified photodiode (IPD)

High performance, large active area (mm), high bandwidth (~1GHz), high gain (>10,000), high quantum efficiency (>20%)

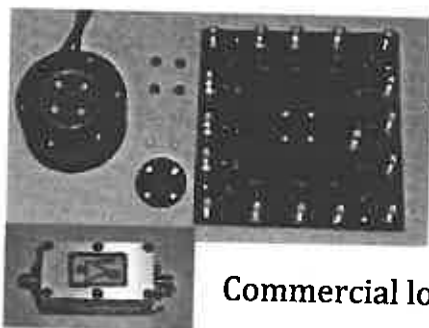


InGaAsP field assisted photocathode with QE up to 25% over 950-1300 nm



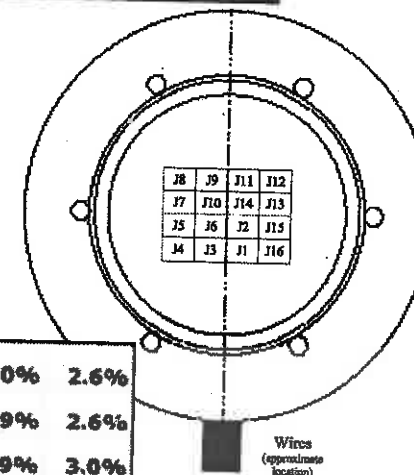
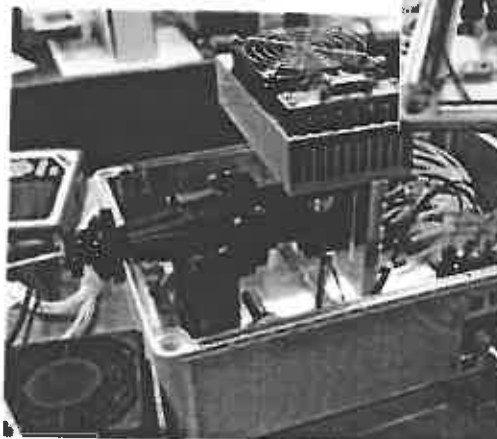
4x4 IPD

Segmented GaAs APD anodes to form a 4x4 array



4x4 fan-out at the back of the IPD

Commercial low noise amplifier



2.9%	2.6%	1.0%	2.6%
3.1%	3.0%	2.9%	2.6%
3.1%	3.2%	2.9%	3.0%
3.1%	3.2%	2.9%	2.9%

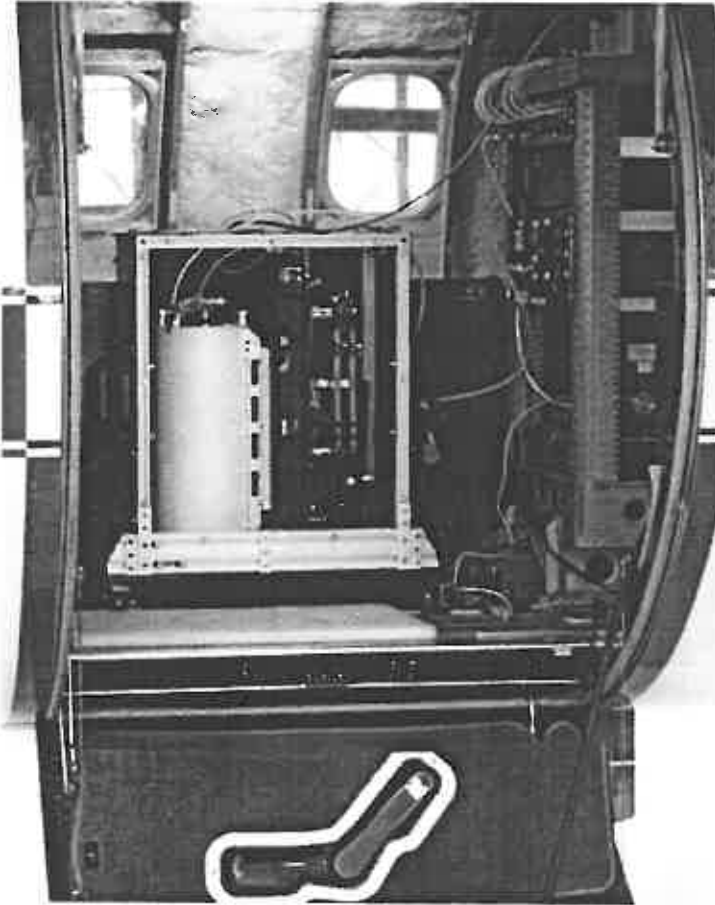
QE Map



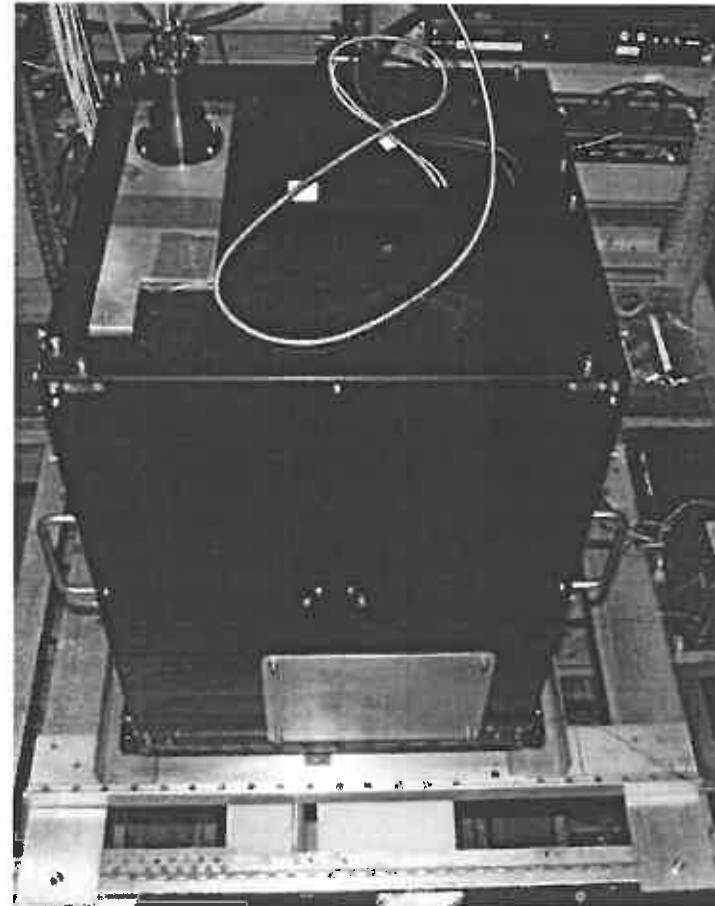
ALISTS on Airborne Platforms



**ALISTS on Lear-25 over Nadir Port
9/2011**



**ALISTS on P-3B over Nadir Port #2
8/2012**



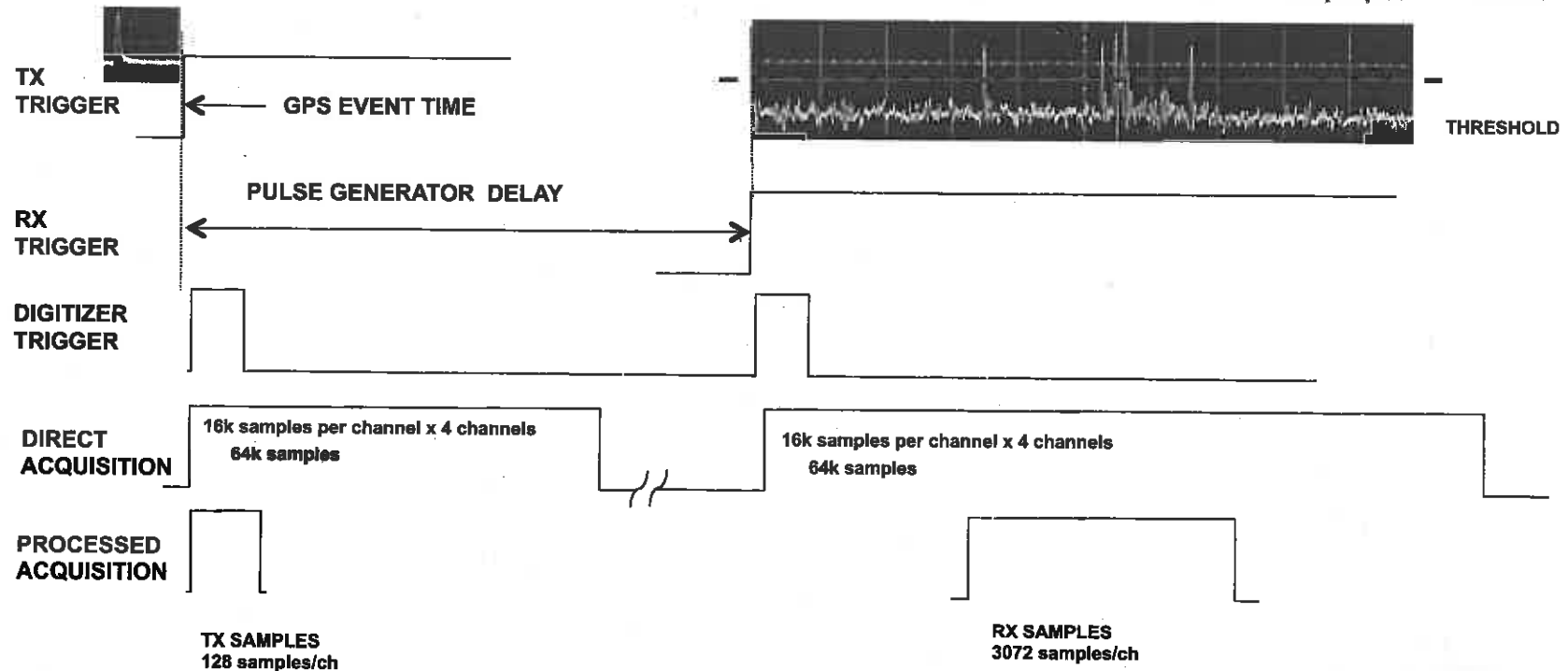


Signal Acquisition Cycle and Data Rates



- Two acquisition modes for August, 2012 flights:
 - Direct (raw): Rx only, 819 meter range gate, 5-kHz rate
 - Processed (FPGA): Tx+Rx, 1638-meter range gate, 10-kHz rate

Acquisition Scheme	Laser PRF	Sample rate	TX window samples	RX Window samples	meters	Sample size (bits)	Sample size (bytes)	Channels	Data rate (bytes/s)	2-hour storage
Direct Acquisition	5000	1.50E+09	0	8192	8.E+02	8	1	16	655,360,000	4.72E+12
Processed Acquisition	10000	1.50E+09	128	3072	3.E+02	8	1	16	512,000,000	1.02E+10





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Flight Data Collection, Analysis and Validation

DAVID HARDING AND SUSAN VALETT

NASA GSFC CODE 698 & 587



September, 2011 Engineering Flights



- ***Objectives***

- Implement measurement approach using master oscillator laser
- Acquire waveforms over a variety of land cover and terrain types
- Repeat at multiple altitudes up to 10 km to evaluate link margin model
- Develop data processing, visualization and analysis software



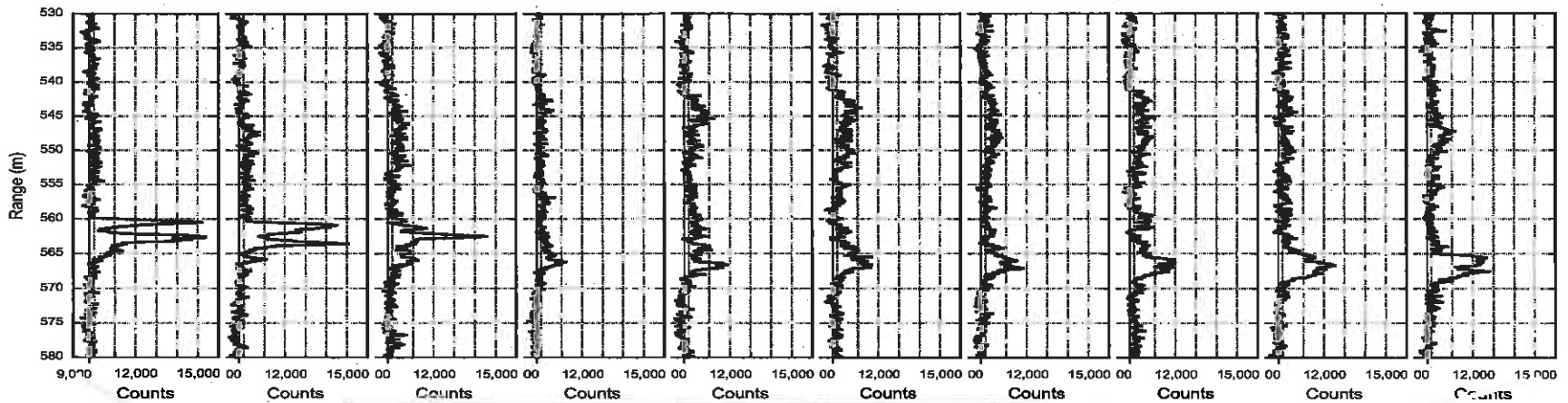
The majority of the objectives were met despite limited data collection opportunities, due to slow-moving east coast “frankenstorm” and laser failure due to over current.



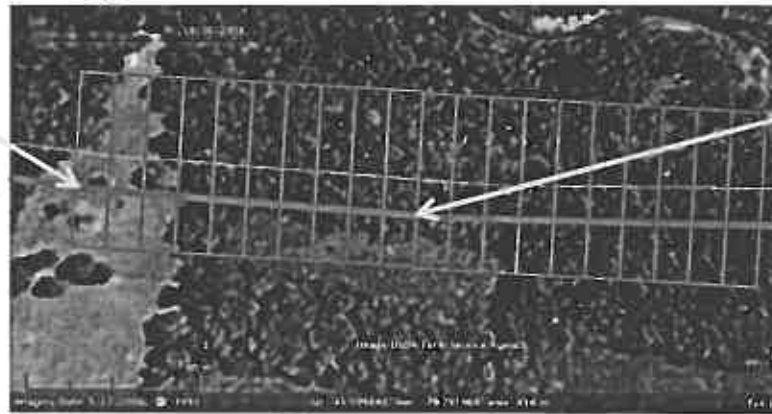
Land Cover Vertical Structure from ALISTS Waveforms



- Waveforms acquired from 10 km altitude
- 200 laser shot average over 20 m along-track distance
- Vertical structure is consistent with video-documented land cover



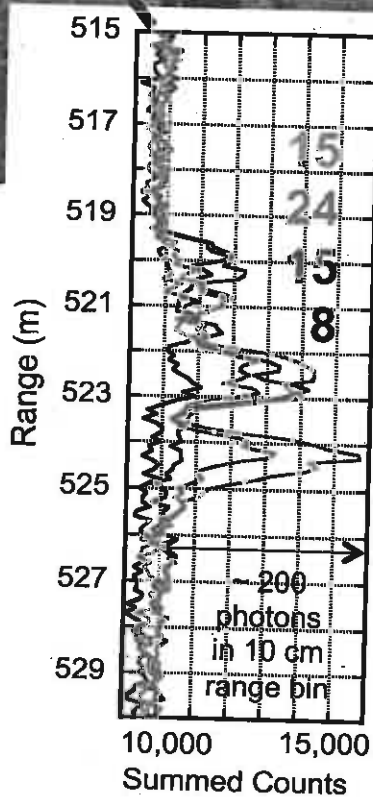
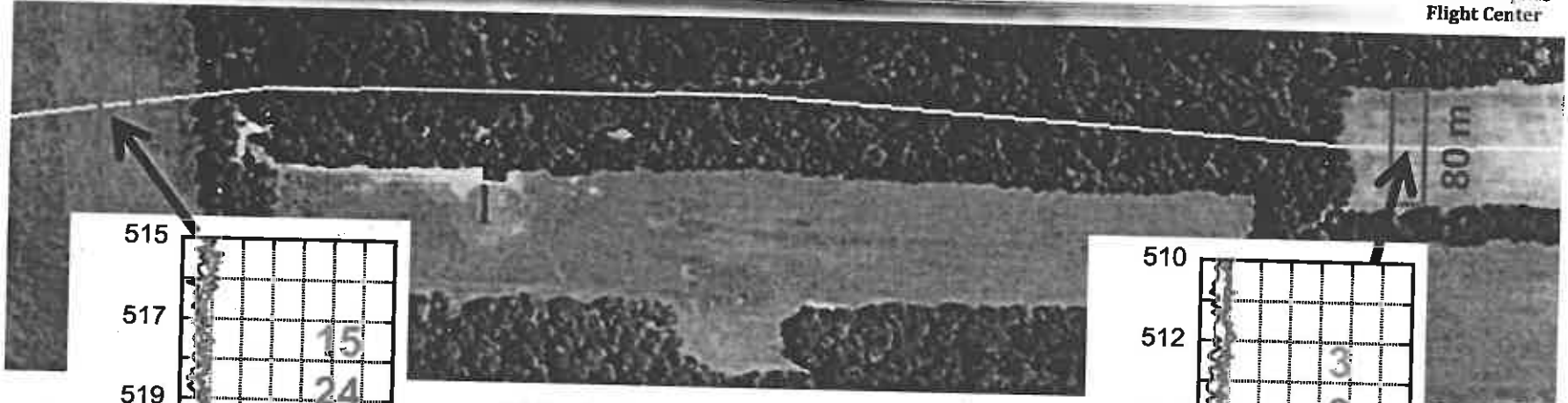
Single beam



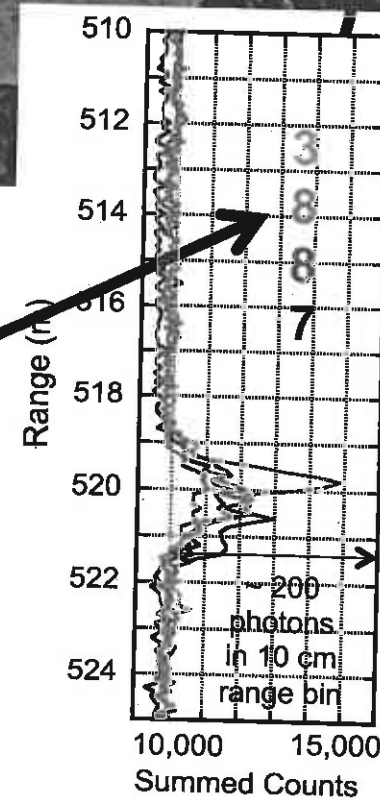
80 m swath



Evaluation of Signal Link Margin Model



200 shot aggregate waveforms
 ~ 30 digitizer counts = 1 photon
 Average number of photons per laser shot per beam
 Nominally 10 photons per shot
 ALISTS 3% QE detector
 = 1/5 LIST 15% QE goal
 10 photons x 5 x 7 shots/5 m pixel
 = 350 signal photons
 (~1.5x predicted LIST performance)





August, 2012 Science Demonstration Flights



- **Objectives**

- Acquire data at 10 km for several ecosystem research sites
- Validate measurement approach by comparison to independent data
- Utilize master oscillator power amplifier laser in-flight

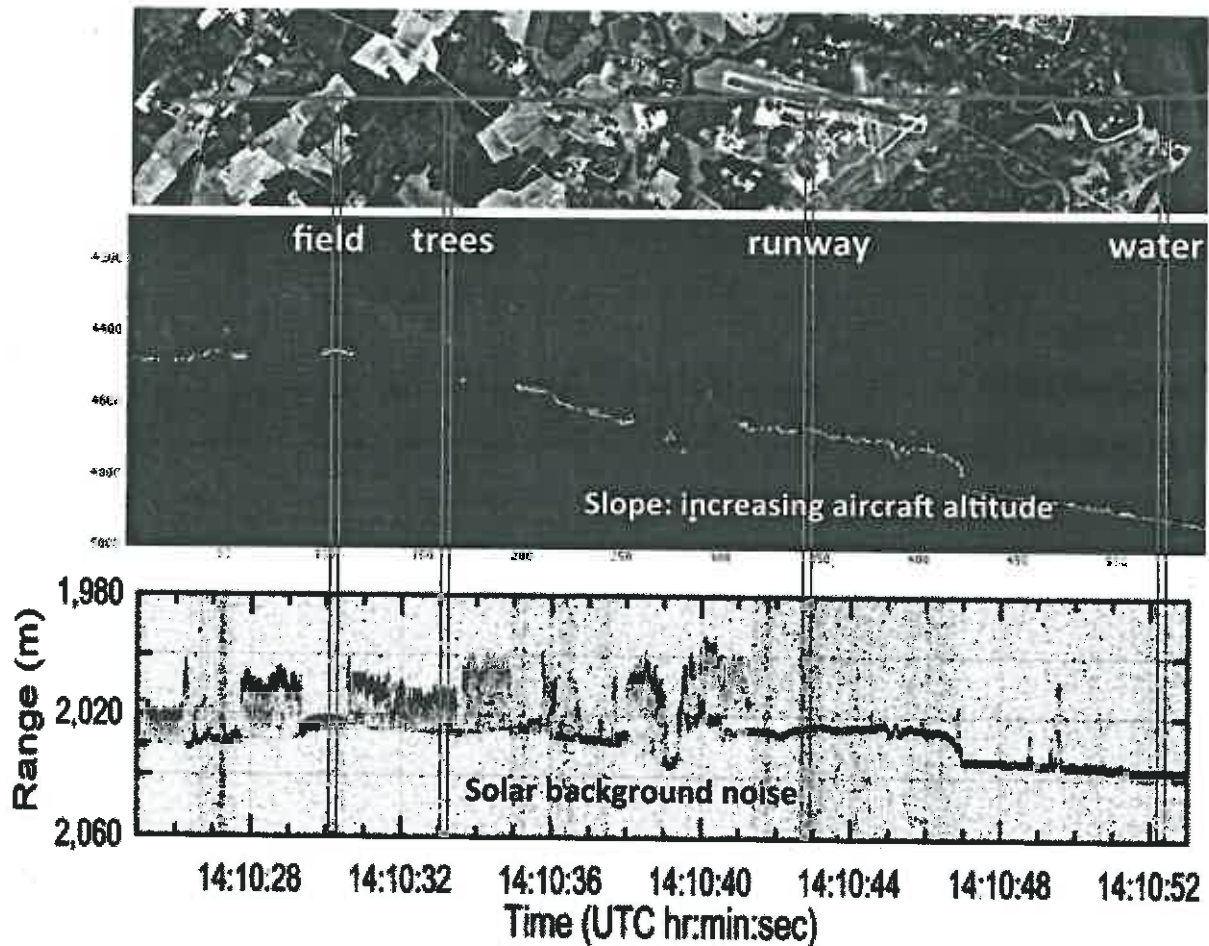


Validation accomplished although flights had to be conducted at 1.5 km to overcome signal loss due to instrument misalignment and low window transmission and wavefront distortion

ALISTS August, 2012 flight over Wallops Flight Facility
Repeated SIMPL August, 2011 lines: yellow
Crossed G-LiHT high-res lidar mapping: white outline
Targeted field stem map plots: red dots
ALISTS and SIMPL comparison: red line



ALISTS Waveforms and SIMPL Single Photons



ALISTS 8/29/12
and SIMPL 8/23/11
flight track (red)

ALISTS
Waveforms
1,000 shot averages
Color = amplitude

SIMPL
Single photons
High sampling density
provides validation data



Wallops Runway Results: Flat Surface Returns



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SIMPL Histogram

- One 532 nm beam of 4 0.2 footprints
- Single photon detection
- 10 cm range bins
- ~10,000 laser shots
- ~20% PD
- ~ 100 m along-track distance

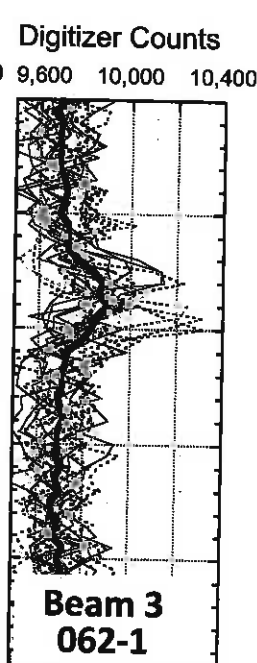
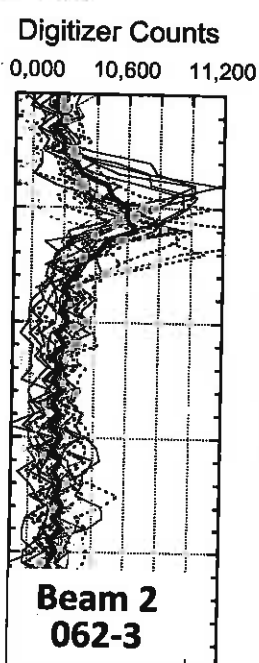
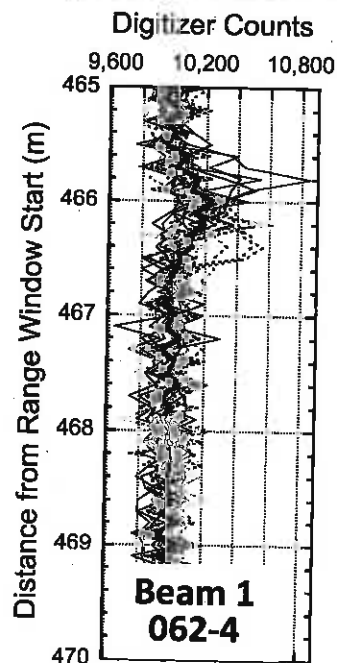
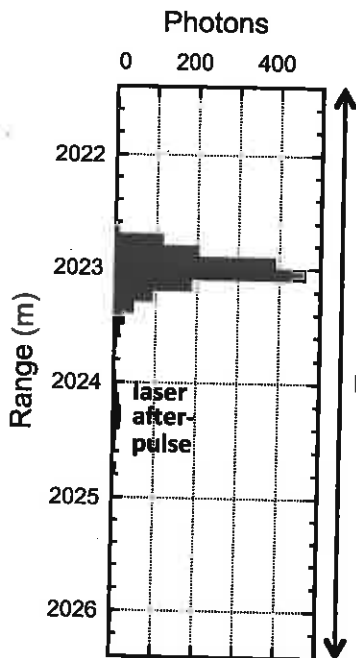


SIMPL & ALISTS narrow width returns

- Similar ~20 cm FWHM impulse responses
- Due to short pulses and high timing resolution

10 cm range precision

shown for ALISTS by within-beam range change of 5 m along-track waveforms across runway



ALISTS Waveforms

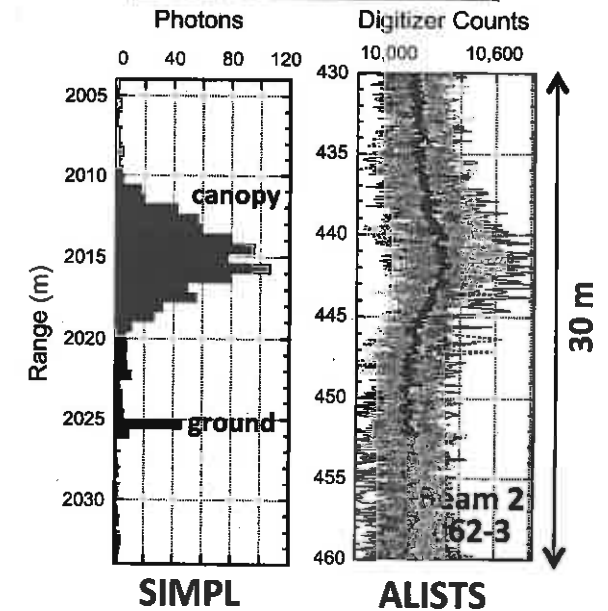
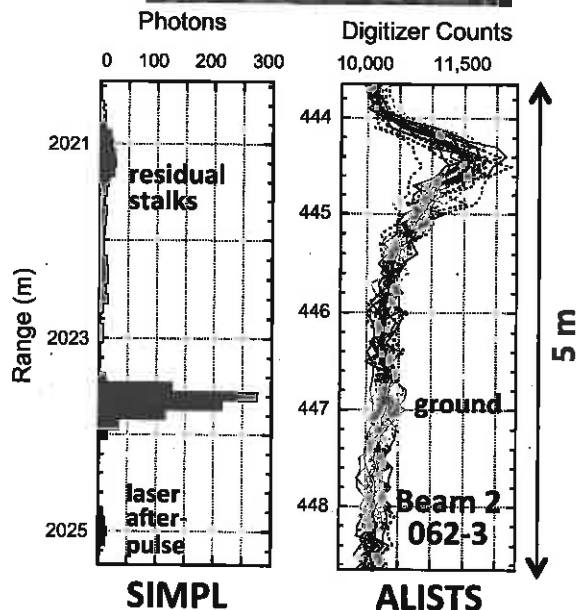
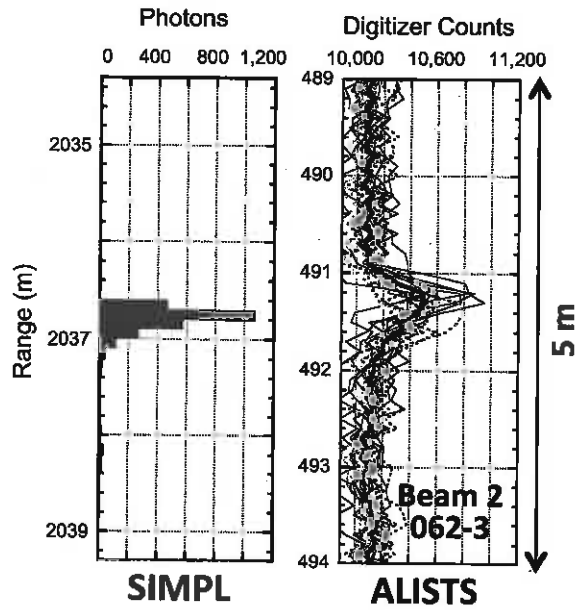
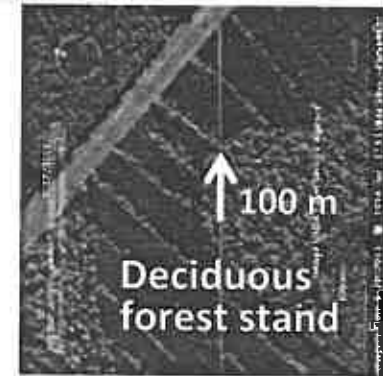
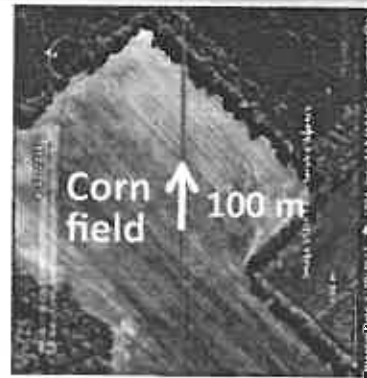
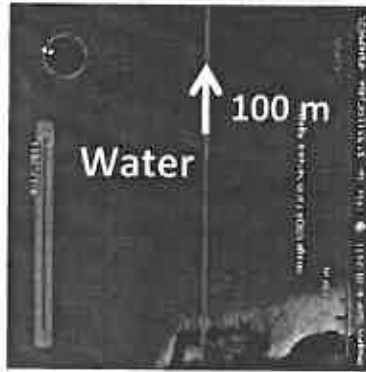
- Three 1064 nm beams of 16 0.7 m footprints
- Linear-mode photon detection
- 1.5 GHz digitization
- 10 cm range resolution
- 19 along track waveforms plotted
- Each combining 215 laser shots
- ~ 5 m along-track distance
- Average waveform (bold black)
- ~ 100 m along-track distance
- Waveform offsets between beams due to channel timing biases
- Low SNR due to receiver misalignment and low window transmission



Waveform Validation for Several Surface Types



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post-harvest pre-harvest
field conditions from in-flight nadir videos



Consistent Waveforms Across the 16 Beam Swath

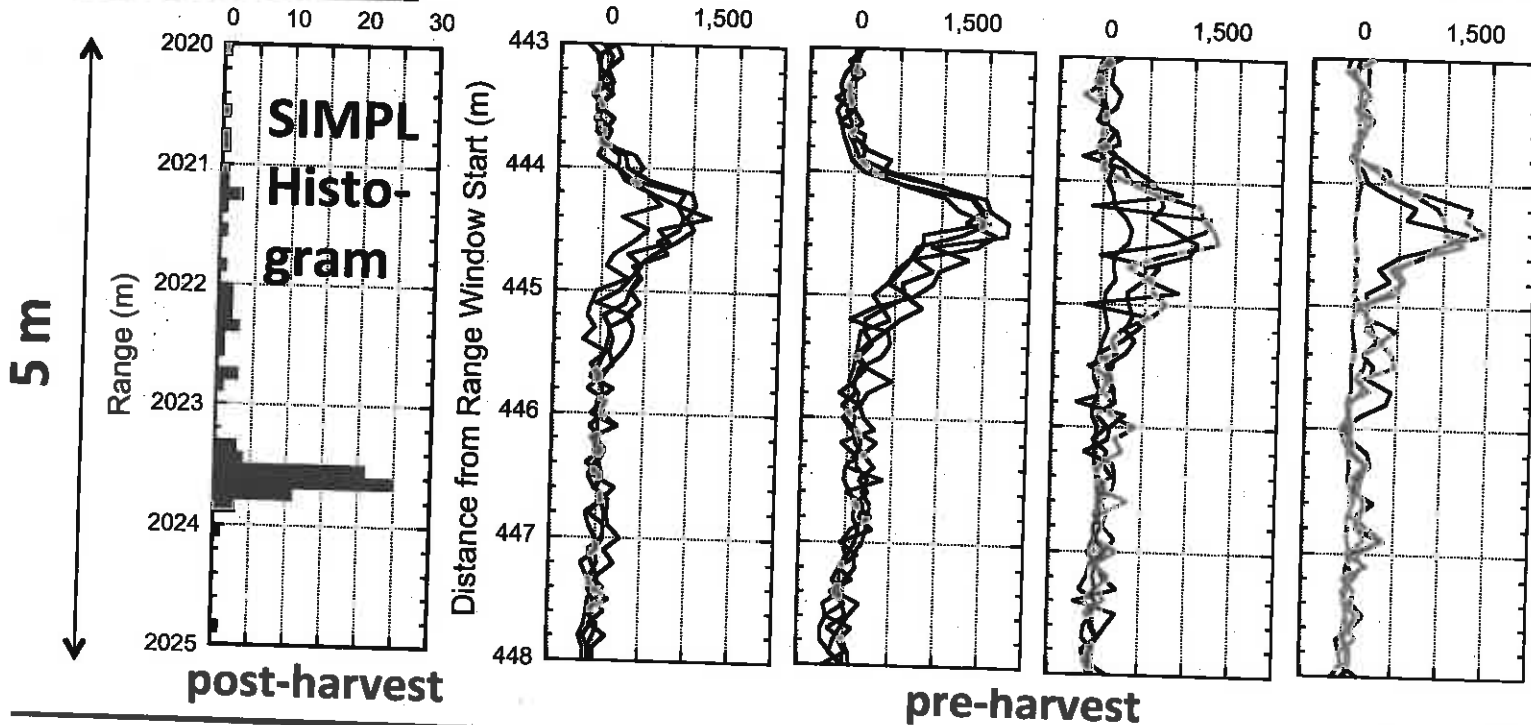


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ALISTS Waveforms

- Sixteen cross-track beams plotted in groups of 4 adjacent beams
- Each waveform combines 215 laser shots over ~5 m distance
- Noise floors and range biases removed
- Show systematically changing structure across the swath
- Indicates the absence of optical and electronic cross-talk



Card
062
117
140
195



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Conclusion

ANTHONY YU AND DAVID HARDING

NASA GSFC CODE 554 AND 698



IIP Accomplishments



- 1. Developed and demonstrated a highly efficient measurement approach that can meet the LIST mission requirements**
 - a. Micropulse, photon-sensitive waveform recording using multi-beam, swath-mapping;
 - b. Modeled performance to define instrument and sub-system requirements.
- 2. Working with vendor partners, advanced laser and detector technologies needed to achieve the performance requirements**
 - a. Short pulse (< 1 ns) multi-beam laser transmitters with >12% wall plug efficiency:
 - a. Master Oscillator used in airborne flights
 - b. Master Oscillator Power Amplifier demonstrating power scaling for spaceflight
 - b. High sensitivity, linear mode array detectors for photon sensitive waveform capturing;
 - c. Characterized performance of key new components/technologies in the lab and in flight.
- 3. Designed, assembled, flight tested, and evaluated the Airborne List Simulator, a prototype swath mapping instrument**
 - a. 4x4 laser array and 4x4 receiver array for a 16-channel LIST prototype;
 - b. Same spatial resolution (5-m spot diameters) as LIST;
 - c. Demonstrated and validated measurements over a variety of surface types, including those of vegetation canopy and underlying topography.
- 4. Advanced technical readiness of a scalable instrument architecture for LIST**

Accomplished goals: Developed and demonstrated a highly efficient measurement approach and worked with vendor partners to mature the needed laser and detector technologies.



Follow-on Science Plans



- **3 Year Space Geodesy ROSES-2010 Project**
 - “Algorithm Development and Observation Strategies for the LIST Geodetic Imaging Mission”
 - Acquire ALISTS data for a diverse range of ecology and geomorphology sites
 - Develop acquisition algorithms and enhanced science product generation

Using our new approach for lidar mapping we will advance readiness for the LIST mission by:

- *Acquiring data using A-LISTS*
- *Developing algorithms for on-orbit data acquisition and processing*
- *Establishing an efficient method for mapping the ground beneath dense canopies*
- *Validating our instrument performance model*

LIST

Airborne LIST Simulator



Conclusion



We successfully accomplished the goals of this IIP by:

Developing and demonstrating a highly efficient measurement approach that can meet the LIST mission requirements

Working with vendor partners, maturing laser and detector technologies needed to achieve the performance requirements

Designing, assembling, flight testing, and evaluating the Airborne List Simulator, a prototype swath mapping instrument

Advancing the technical readiness of a scalable instrument architecture for LIST



LIST



Airborne LIST Simulator