Push-broom Laser Altimeter for Space-based Swath Mapping of Cryospheric and Topographic and Surfaces

Presentation to:

ICESat Science Team meeting

October 5, 2006

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Support by:
NASA ESTO Instrument Incubator Program

Leveraging support:

MMLA IIP Project (2000-2003)
GSFC DDF program (2003 - 2005)
GSFC IRAD program (2006-2007)
NASA Earth Surface & Interior Focus Area (2004-2005)
ICESat Project and Science Team (1998 - 2008)

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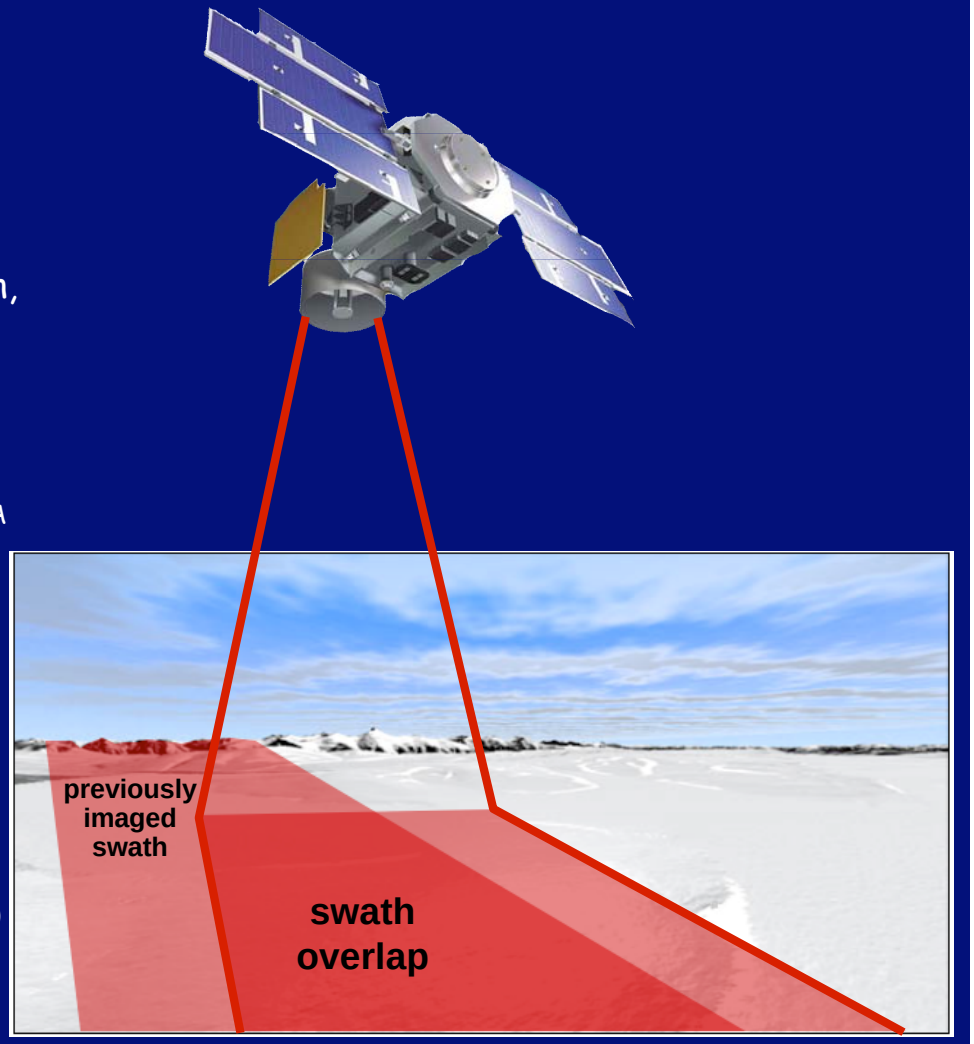
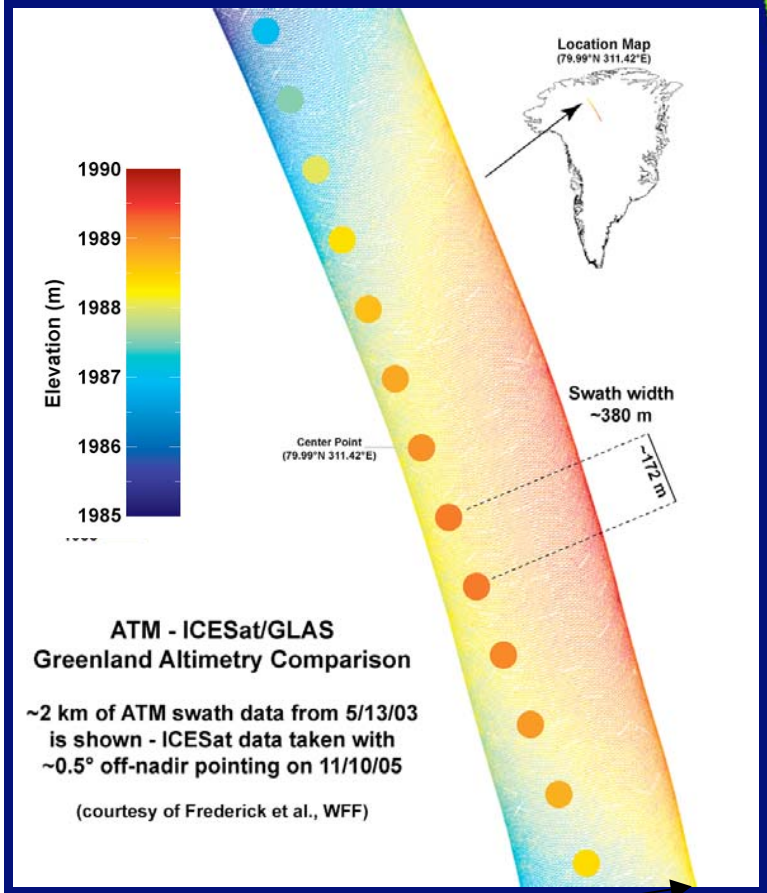


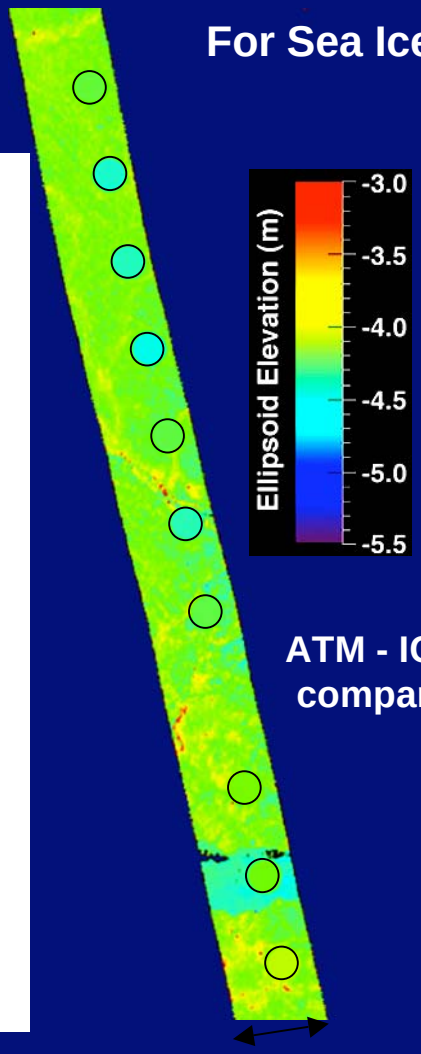
Swath Mapping Laser Altimetry - Science Benefits

For Ice Sheets



380 m

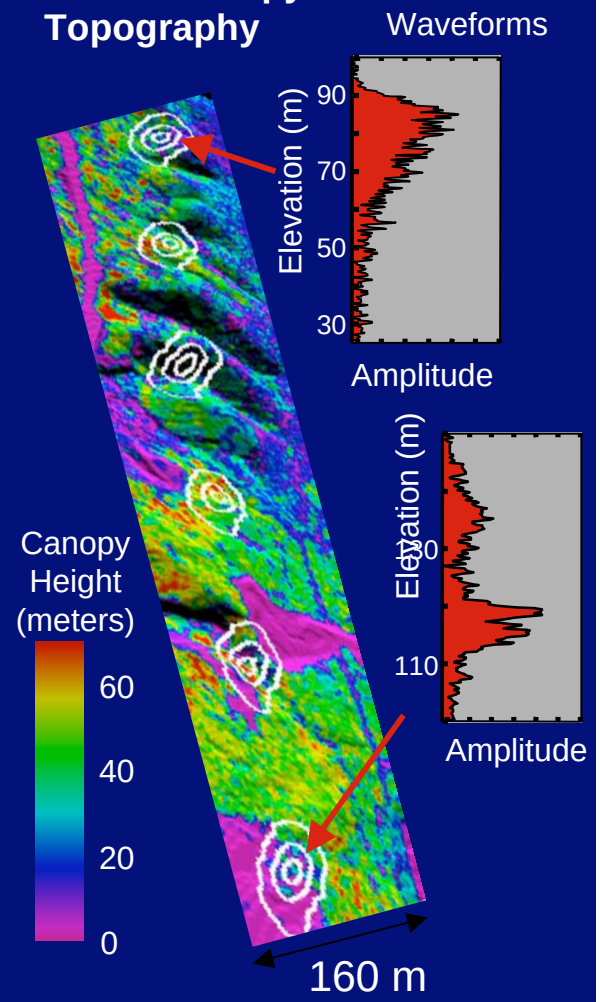
For Sea Ice



ATM - ICESat comparison

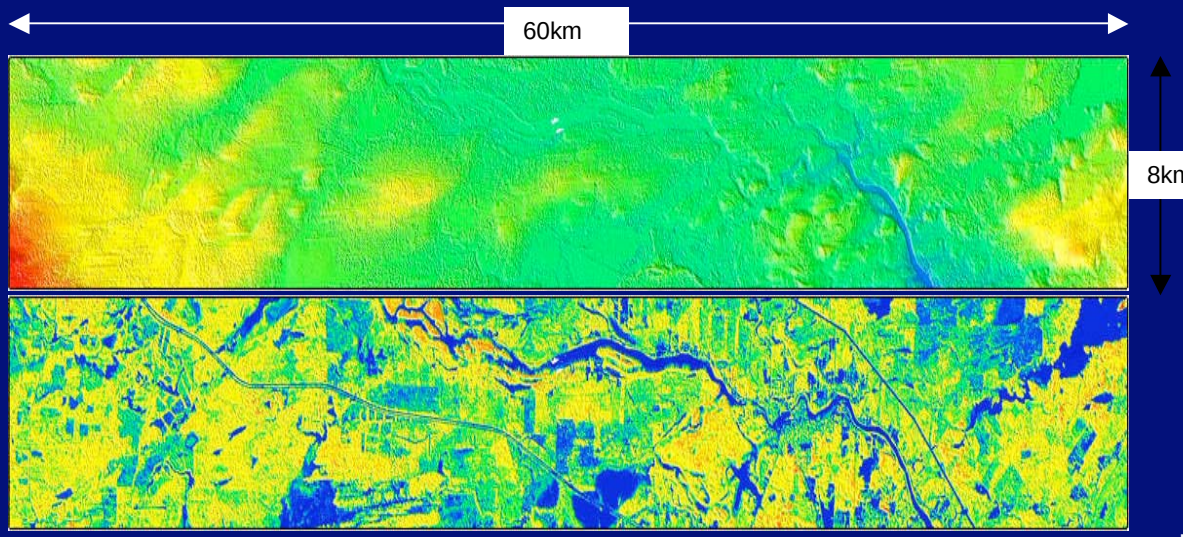
200 m

For Forest Canopy & Topography

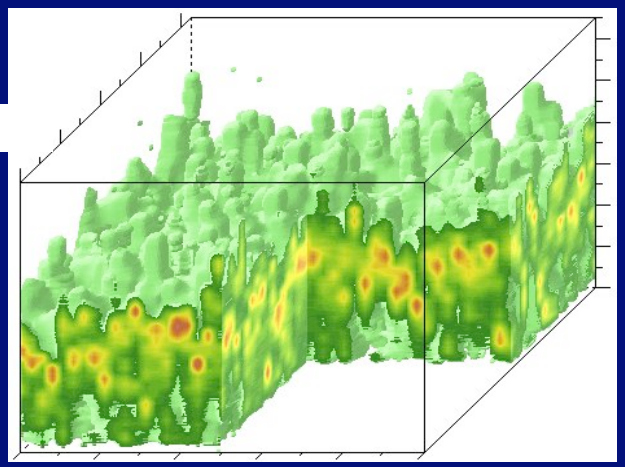


Airborne Laser Swath Mapping
perspective view with
shading = topography, color = vegetation height
white = GLAS footprint energy contours

Airborne Laser Mapping of the Earth Surface



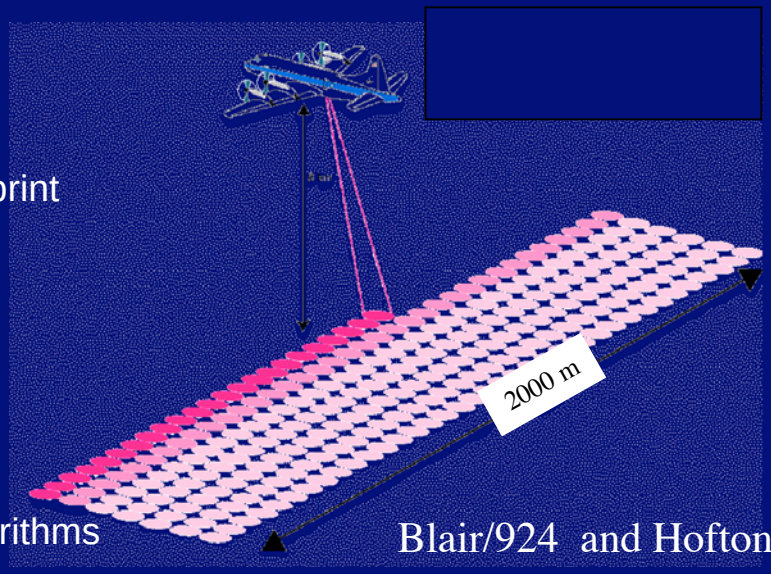
Images of sub-canopy topography (top) and canopy height (bottom) of the Howland and Penobscot Forests, ME, mapped using LVIS



LVIS 3-D surface structure of a 1 km^2 area in Costa Rica

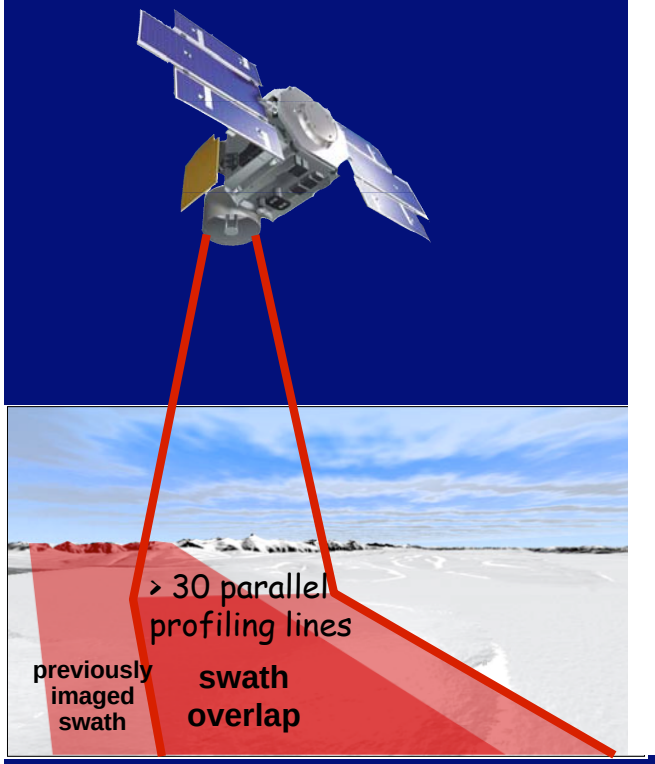
Airborne Precursor Demonstrations (LVIS):

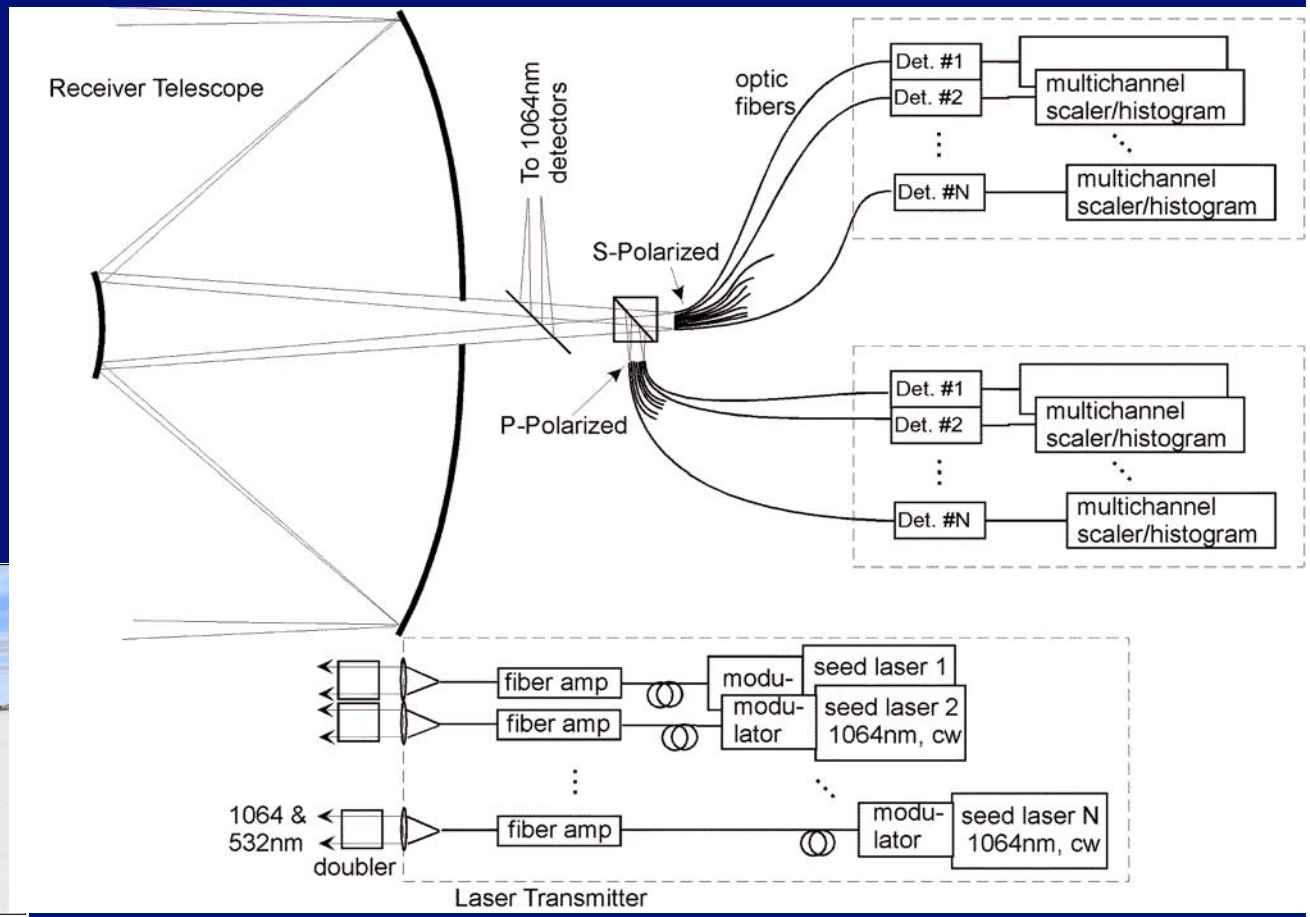
- Waveform profiling mapping laser altimeter
- Nominal operating mode: 2 km-wide swath, 5-20 m-wide footprint
- Generates 3-D image of surface structure
  - measures surface topography (inc. sub-canopy)
  - vegetation canopy height
- Penetrates vegetation in dense forests
- Science use: estimate above-ground biomass and other parameters, surface change detection
- Prototype for space imaging lidar, science applications & algorithms



Blair/924 and Hofton

Push-broom Laser Altimeter Configuration



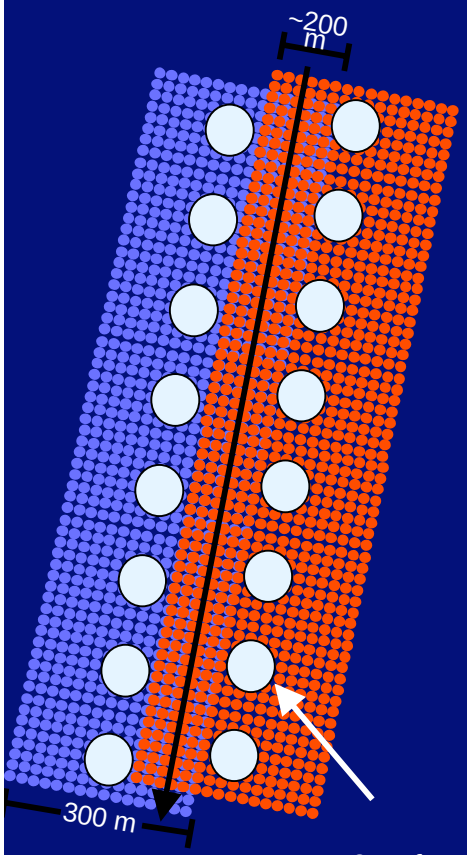


Nominal:
10 m spots, ~30 spots cross track
700 spots/sec in line
> 21K measurements/sec => Need Efficiency !!

Candidate wavelengths
(based on laser avail & detector sensitivity):
532 nm (now), 1064 nm (later)

Surface Sampling Pattern & Performance

Ground track:
Two swaths
overlapped by ≥ 200m

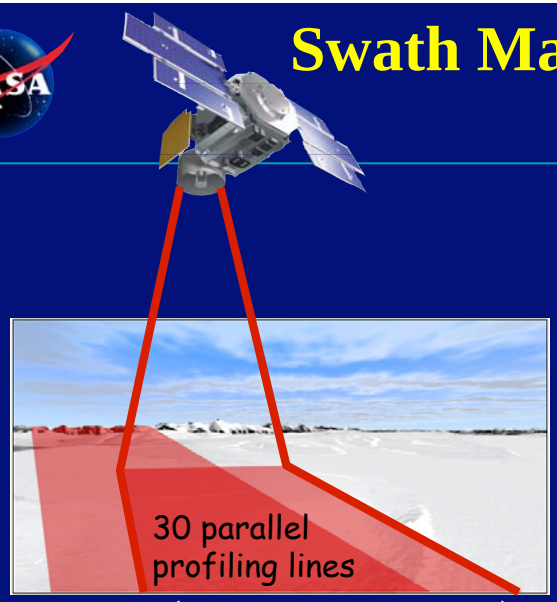


ICESat/GLAS
70 m footprints with 175 m spacing
(for comparison)

	GLAS	Pushbroom Altimeter
Surface Altimetry Wavelengths	1064 nm	532 nm (now) 1064 nm
Surface Altimetry & Atmospheric Profiling Polarization for diffuse vs. specular reflectance, liquid water vs. ice	n.a.	parallel & crossed
Resolution (footprint or pixel)	~ 70 m	10 m
Number of Adjacent Profiling Lines	1	≥ 32
Swath Width	~70 m	≥ 320 m
Pulse Rate Along Each Profile	40 Hz	~100 KHz
Laser Footprint Spacing Along Track	170 m	0.07 m
Probability of Detection per Laser Pulse	>> 1	~ 0.2 - 0.5
Detected Photon Spacing @ probability of detection for ice sheet reflectance	n.a.	.35 to 0.14 m
Detected Ice Sheet Photons per Footprint or Pixel	1,000's	~ 30 to 70
Laser Pulse Width FWHM	6 nsec	≤ 1 nsec
Time-of-Flight Resolution	1 nsec	< 0.2 nsec
Ice Sheet Range Precision per Footprint or 10 m Pixel	2.5 cm	~ 1.5 cm

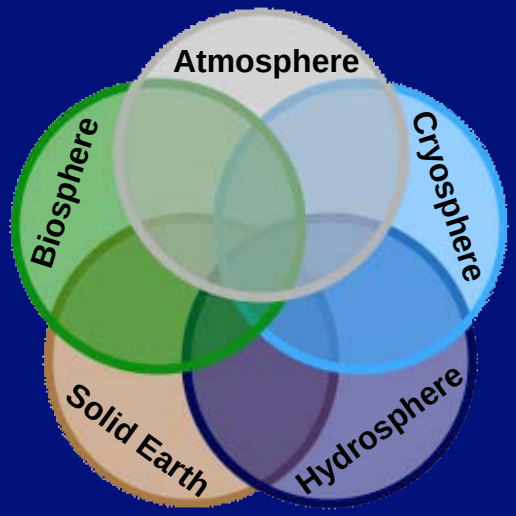
Swath Mapping Laser Altimeter Mission* Concept

(*Dynamic Elevation LIdar - DELI)



~ 300 m wide swath

Overlapping swaths by
precise cross-track pointing for
direct along-track change detection



Cryosphere:

- Ice sheet mass balance
- Glacier and ice stream dynamics
- Sea ice thickness and extent

Biosphere:

- Global biomass inventory
- Canopy 3-D structure
- Vegetation impact of and response to disturbance

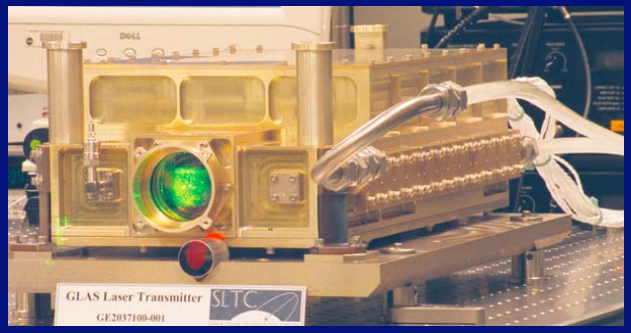
Hydrosphere:

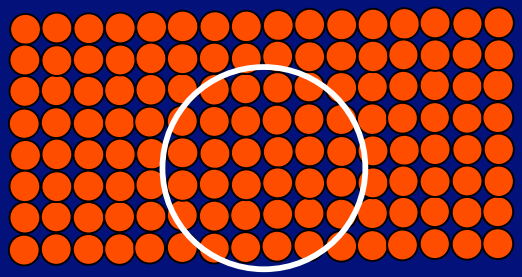
- River, lake & wetland water storage & discharge
- Snow depth and extent

Solid Earth:

- Geodetic ground topography mapping
- Natural hazard monitoring and change detection

Opportunities for improvement





60 m circle superimposed on
10 m swath mapping segment

3.1. Ice Sheet Altimetry

[10] The ICESat ice sheet altimetry measurements have dramatically improved the accuracy of elevation measurements of the Antarctica and Greenland continents (C. A. Shuman et al., Ice sheets from ICESat: Summary, submitted to *Geophysical Research Letters*, 2005, hereinafter

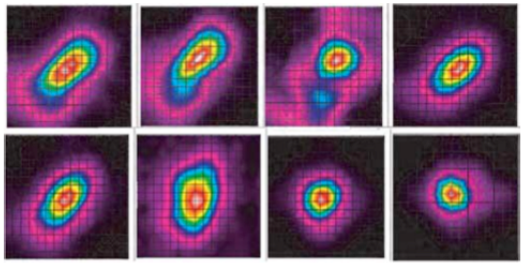


Figure 2. Sample GLAS images of the laser far field patterns measured during different campaigns. (top) Laser 1 (2/20/03), Laser 1 (3/4/03), Laser 1 (3/26/03), Laser 2a (9/26/03). (bottom) Laser 2b (2/18/04), Laser 2c (5/18/04), Laser 3a (10/4/04), and Laser 3b (2/18/05).

Swath Mapping laser approach

- Uses many small lasers
- Beams from single mode fibers
- inherently stable & isolated
- Uniform stable beam pattern
- Many Isolated pumps & lasers: Laser degradation & failure modes don't cascade

2 of 4

L21S02 ABSHIRE ET AL.: GEOSCIENCE LASER ALTIMETER SYSTEM (GLAS) L21S02

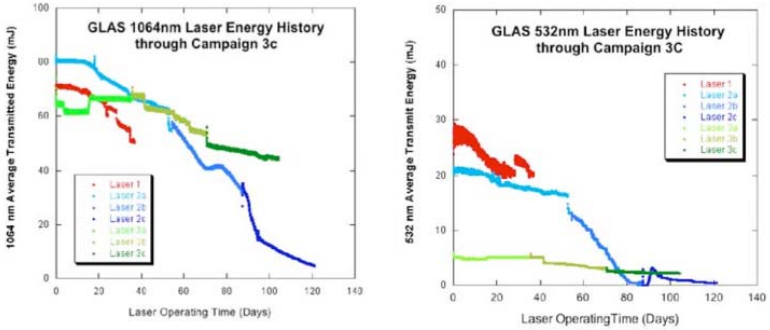
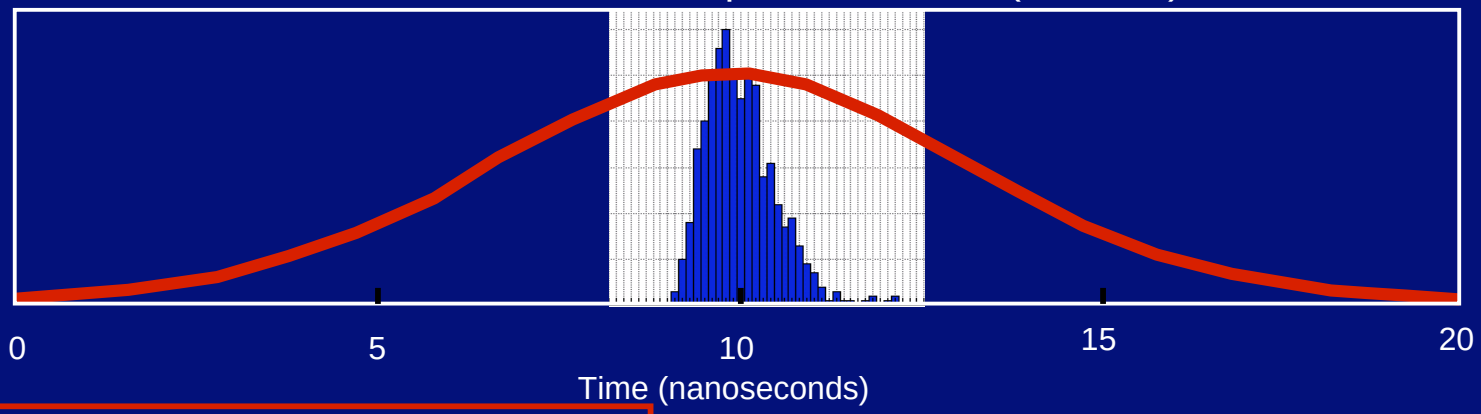


Figure 1. GLAS laser pulse energy history for all operating periods to date at (a) 1064 nm and (b) 532 nm. Laser 3 was powered off at the end of Laser 3c, and Lasers 2 and 3 are still operational. Some of the changes in laser energy were caused by commanded changes in laser temperature.

GLAS laser pulse vs (Short pulse & photon counting)

Echo Pulses from Flat, planar surface (to scale)



ICESat Waveform:

6 nsec FWHM pulse width GLAS laser

1064 nm

Si:APD analog detector

1 nsec (15 cm) timing resolution

3 **cm range precision requires**

2800 photons onto detector

Micropulse - Photon Counting Histogram:

0.5 nsec pulse width laser; 532 nm

SPCM photon counting detector

0.1 nsec (1.5 cm) timing resolution

0.2 ave. detected photons per pulse

3 cm range precision requires

5 photons onto detector

Summary:

Short pulse photon counting requires x560 fewer photons to receiver

Why ?

X100 gain from timing shorter pulse,

~ x5 from more sensitive detector

Energy needed from spacecraft/measurement:

Taking into account:

Laser photon generation efficiency

Cover equal surface area (need more small spots):

Net benefit : ~ x20-x100 less energy

A candidate Laser (Microchip)

Parameter		
Wavelength (nm)	1064	532
Energy/Pulse (μJ)	> 4	> 1.5
Pulse width (FWHM, ns)	<1	<0.6
Repetition rate (kHz)	10 to 13	10 to 13
Power Stability over 6 hrs	< ± 3 %	< ± 3 %
Beam Divergence (full angle at 1/e2, mrad)	Horiz.: 11 ± 2 Vert.: 13 ± 2	Horiz.: 8 ± 2 Vert.: 8 ± 2
Beam Profile	Gaussian	Gaussian
Polarization ratio	> 100:1	> 100:1
Base plate operating temperature range (°C)	0 to 50	0 to 50

teem photonics™

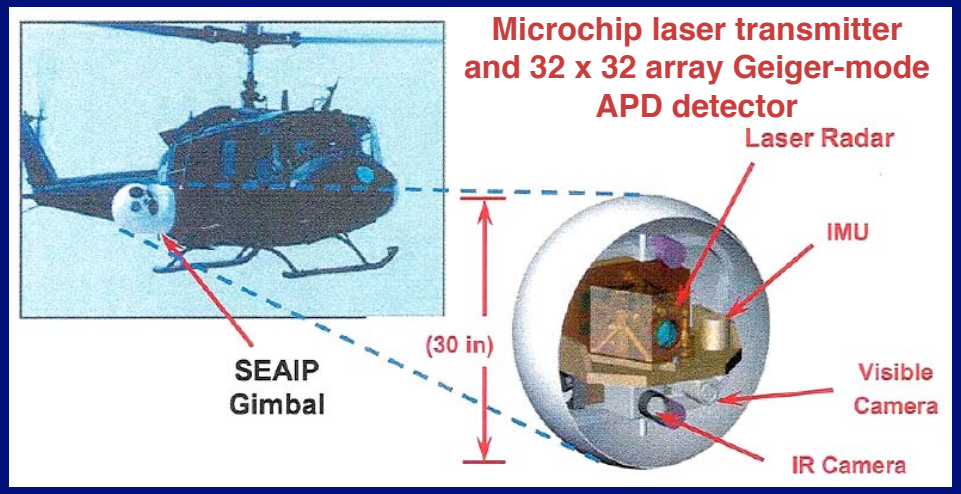
High Peak Power High Repetition Rate Sealed Q-switched 1064 & 532nm Microchip Laser

SNP/SNG series

Compared to fiber lasers: slower pulse rate & less reliable pump diodes

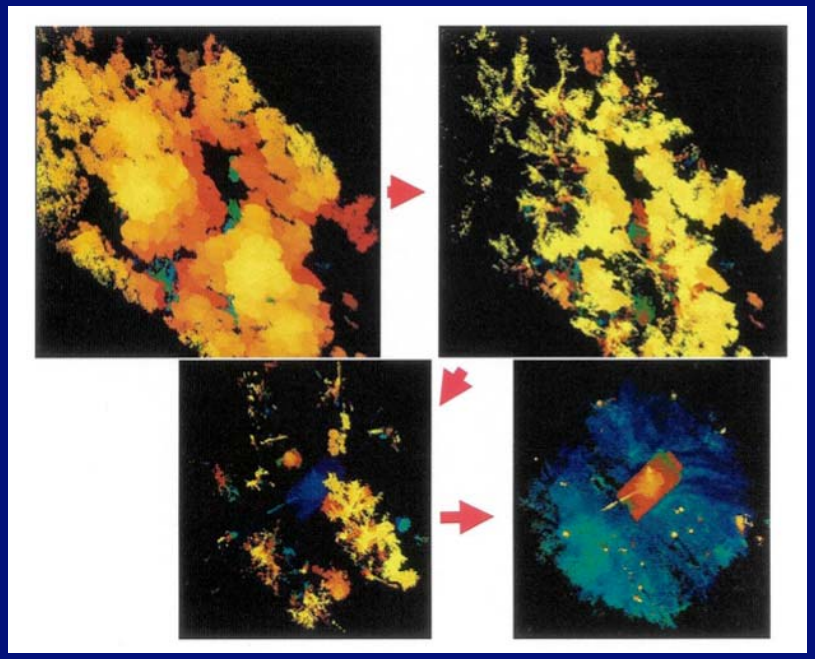
Airborne Range Imaging via Photon Counting (MIT/LL)

MIT Lincoln Labs Photon Detection Range Imaging

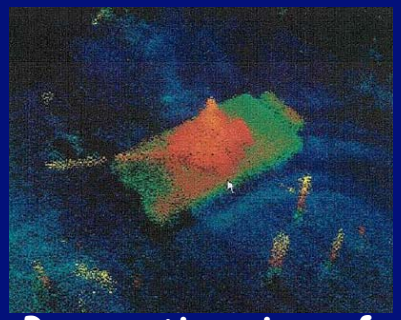


UH-1 platform, SEAIP gimbal, and Jigsaw sensor

Sequence of nadir-viewed images colored by height and with narrowing range window, revealing target beneath tree canopy.



Canopy Cover



Perspective view of target colored by height

Marino, R.M., et al., 2005, **High-resolution 3D Imaging Laser Radar Flight Test Experiments**, Laser Radar Technology and Applications, G.W. Kamerman, ed., Proc. of SPIE Vol. 5791, SPIE, Bellingham, WA, 2005.

Single Profile Micropulse Altimetry Airborne Demonstration with Prob (det) = 0.9 & PMT detector

PHOTON-COUNTING 3D IMAGING LIDARS

John J. Degnan
Sigma Space Corporation
Lanham, MD 20706

PhAST 2005 Conference
May 23-26, 2005, Baltimore, MD

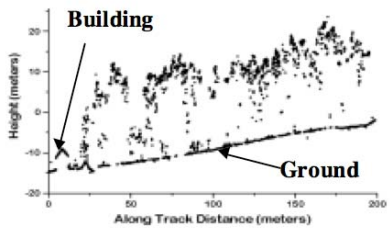
Our approach:

- Uses x10 higher pulse rate fiber laser
- Lower Pd = 0.2-.5
- Solid state detector
- => higher accuracy measurements not influenced by detector dead-time

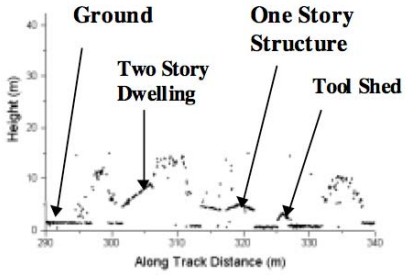
IIP Airborne Multi-kHz Microlaser Altimeter

Sample Profiling Data From 1st Engineering Flight, Jan 4, 2001

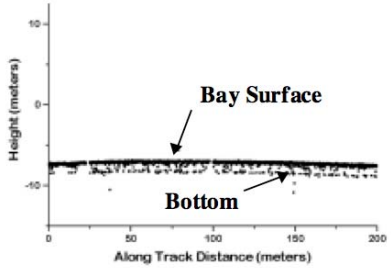
- **Engineering Flight Parameters**
  - NASA P-3 Aircraft, Wallops Flight Center
  - Locale: Chincoteague, VA & Chesapeake Bay
  - Flight Altitudes: 3.5 to 6.7 km (11,000 to 22,000 ft)
  - Early afternoon (maximum solar background)
  - Laser Energy: < 2 μJ @ 532 nm
  - Laser Repetition Rate: 3.8 kHz
  - Laser Power: ~7 mW
  - Effective Telescope Diameter: 14 cm
  - Mean Signal Strength per Laser Fire: ~ 0.88 pe



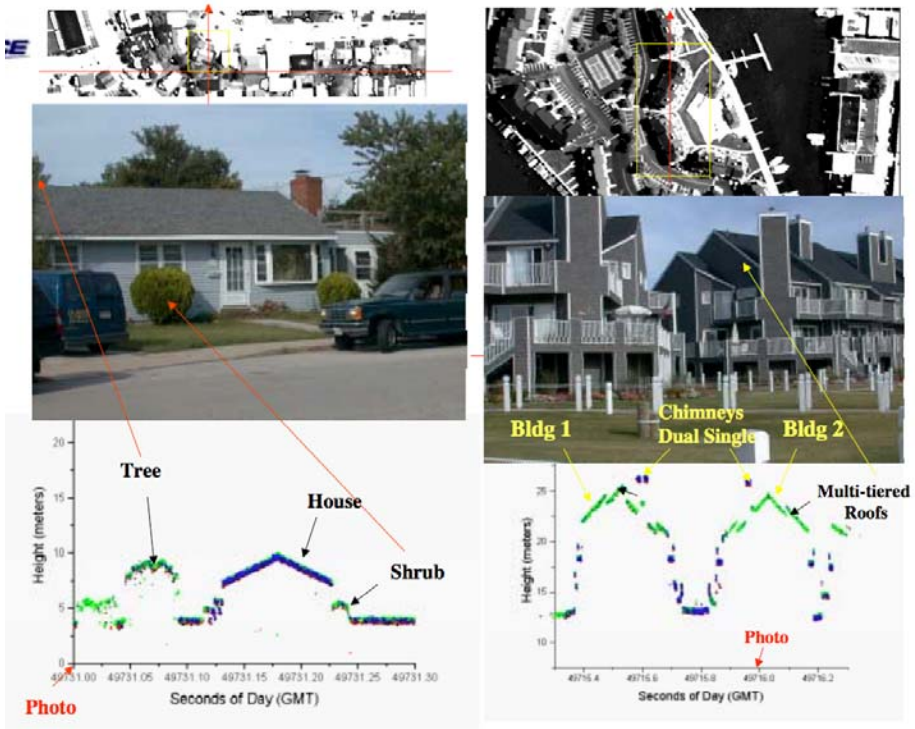
Tree Canopy Heights



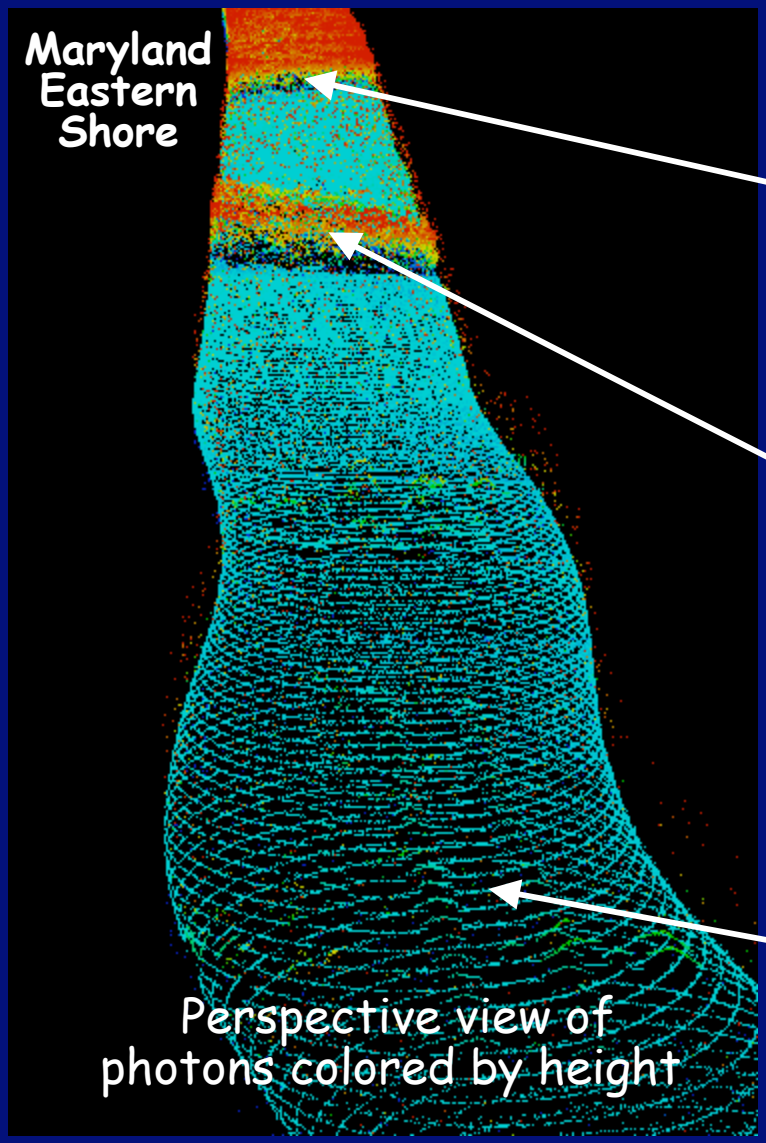
Buildings and Trees

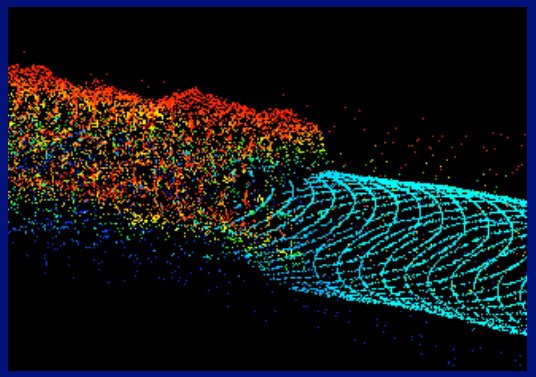


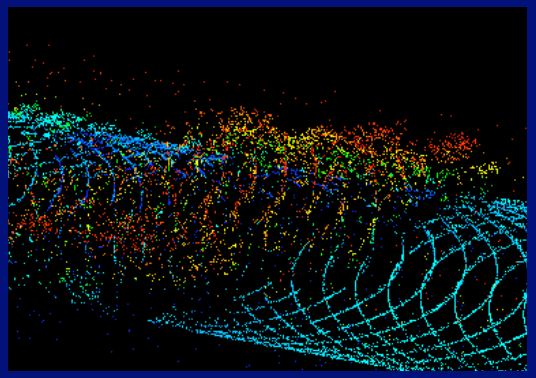
Shallow Water Bathymetry

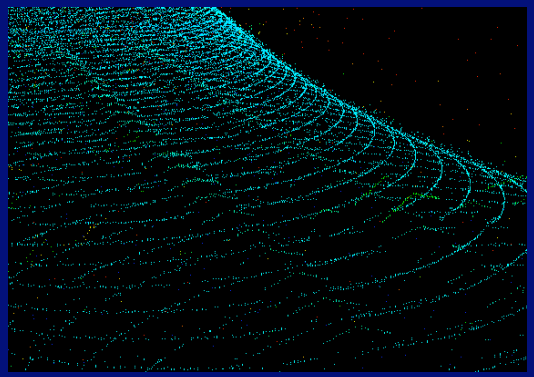


Scanning Airborne Photon Counting Laser Altimeter Measurements by MMLA Instrument









Measurement Tradeoffs Being Addressed
(and some Laser & Detector Examples)

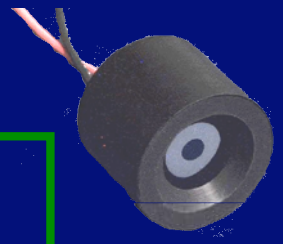
- Approach :
  - Heritage
  - Measurement performance (errors)
  - Measurement Efficiency (laser energy needed)
- Technology - Lasers & detectors:
  - Availability
  - Maturity
  - R&D direction (expanding is better)
  - Efficiency
  - Complexity
  - Size, Mass, Power
  - Lifetime
- Net Electrical Efficiency
  (Joules from spacecraft/measurement)

Candidate Detectors

Perkin Elmer SPCM

Micron Photon Devices SPCM

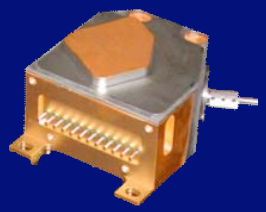
Present approach



InteVac HPMT

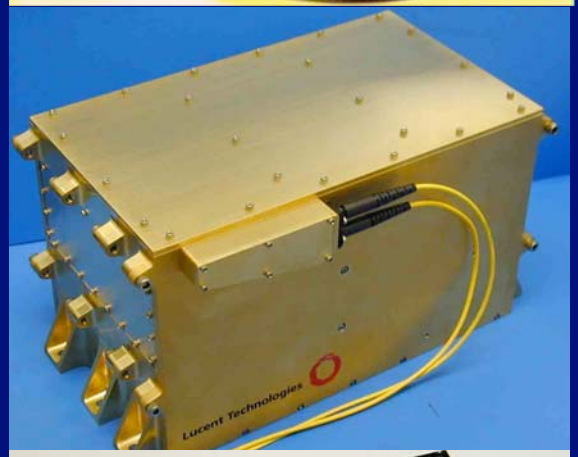
Yb & Er Fiber Lasers

Candidate Transmitters



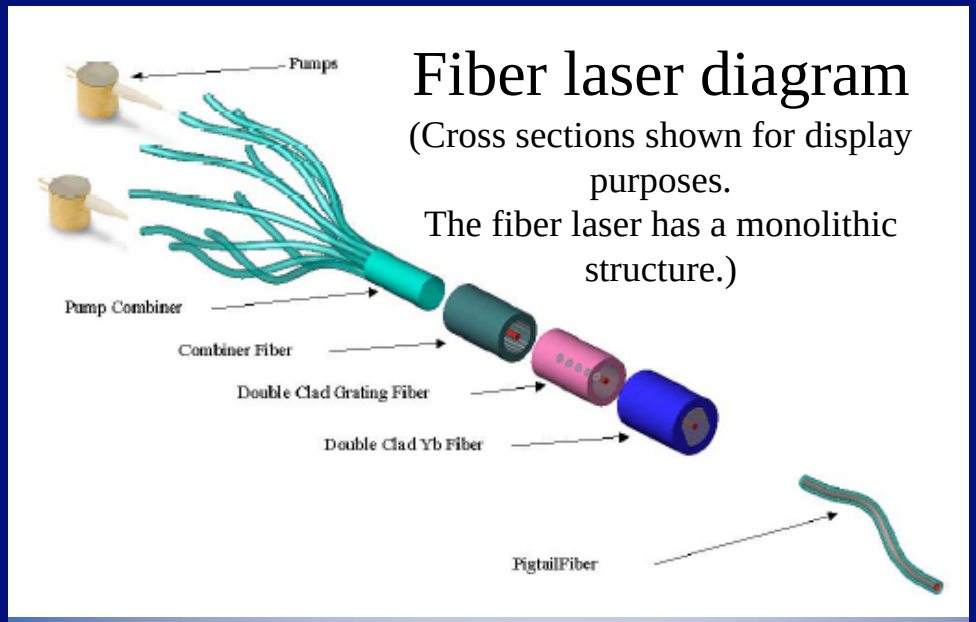
Tesat Microchip Laser

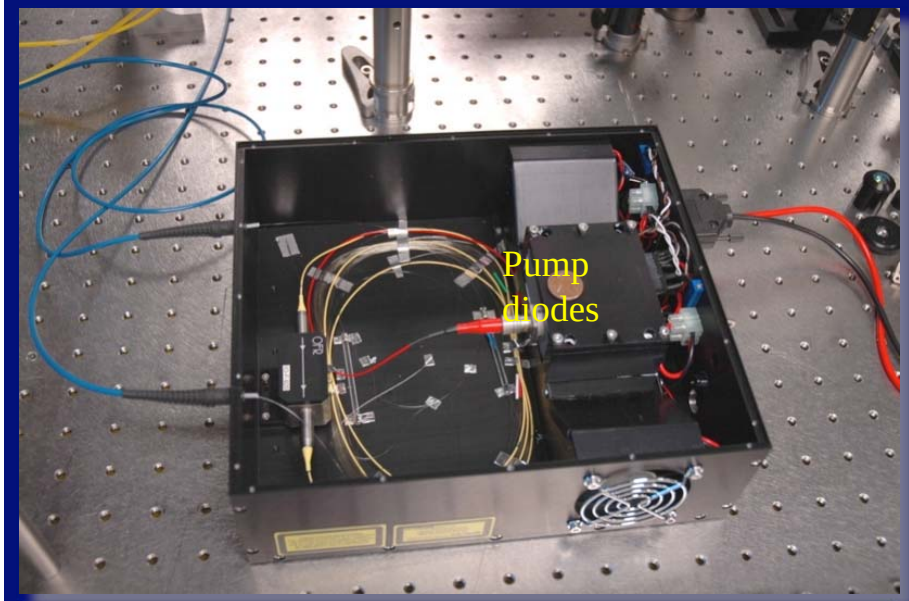
Fiber Laser Characteristics

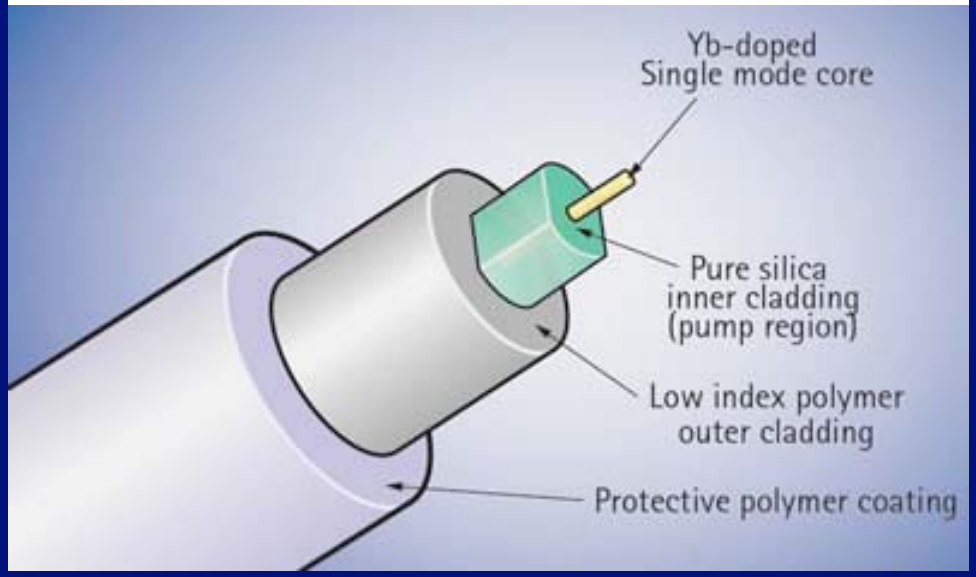


- Light stays in waveguides:
  - Rugged
  - Minimal optical mounts and alignment
- Distributed thermal load
- Lower parts count
- Wide wavelength range available
- Single frequency laser diode seed sources available
- Avail with > KW peak powers
- Compatible with micropulse modulation
- High wall-plug efficiency, > 15% (Yb)
- Significant leverage & "spin in"
  - In production by a growing industrial base
  - Very reliable pump laser diodes; several suppliers
- **Most reliable lasers yet developed**
  - **> 15 year lifetime for undersea repeaters**
- Actively supported by DOD

Fiber lasers







Key features:

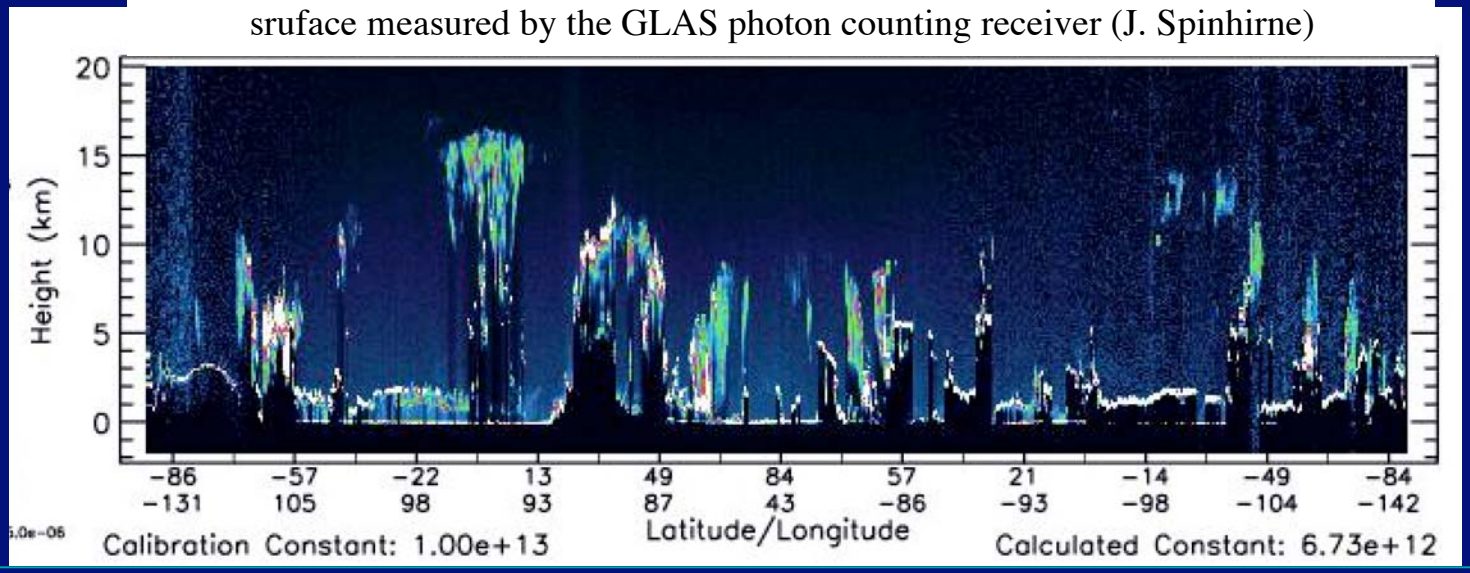
- Closed cavity - no contamination
- Fiber architecture - no misalignment
- Diode pumping technology is more reliable
- Distributed thermal load
- High electrical efficiency
- Leverages Billions of $ of investment from industry
- Components built to Telcordia standards (can be even more stringent than space flight)
- Availability of parts
- Wavelength flexibility

Long Lifetime Efficient Photon Counting Detectors in use on ICESat/GLAS

Narrowband tunable
Etalon filter on ICESat/GLAS

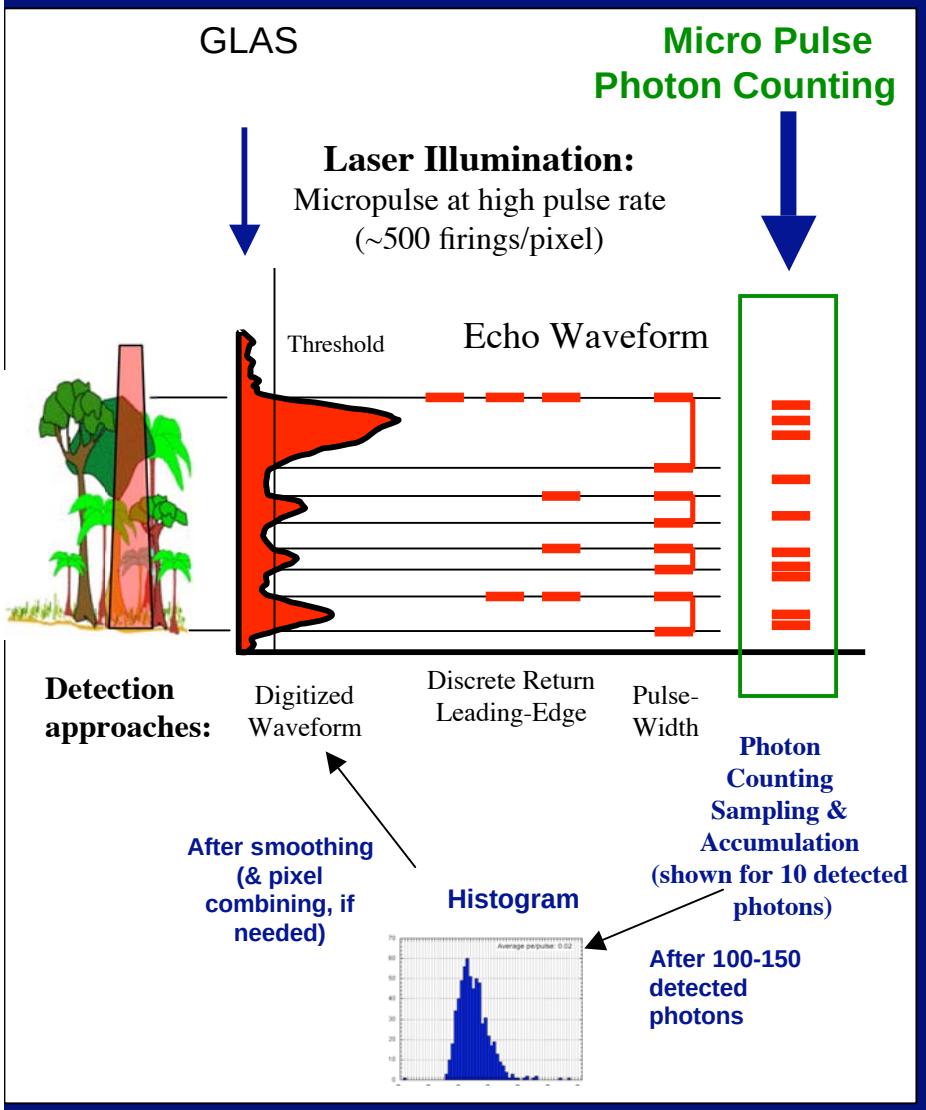
SPCM detector:
8 flown on ICESat/GLAS

One orbit sample of photon counting measurements of atmospheric backscatter & sruface measured by the GLAS photon counting receiver (J. Spinhirne)



Micropulse Approach at 532 nm is practical today

Approx. Performance

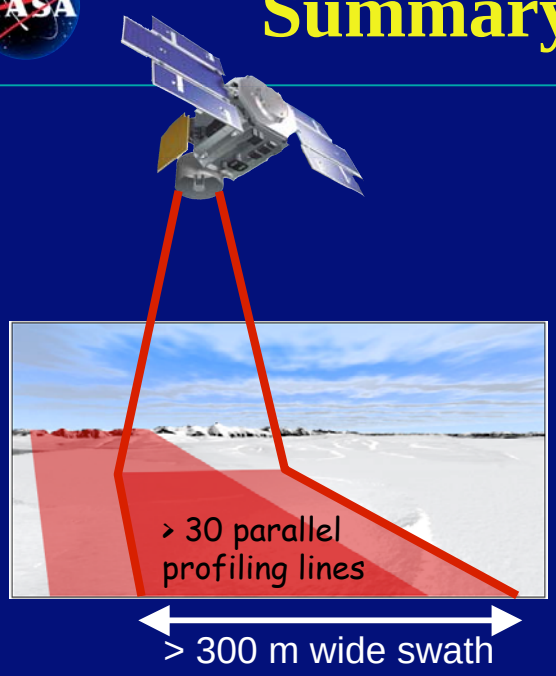


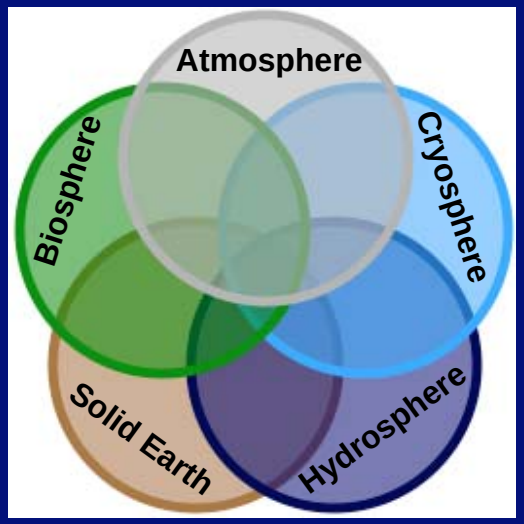
Swath Mapping Measurement Capability & Quality

100 KHz pulse rate, Pd = 0.2, 532 nm

Parameter	Capability			Comments
Beam Angle (PAD)	<1m spatial	1 urad (0.2 arcsec)		via Star timing sensors
Ground pixel resolution	*10 m spots 1 pixel*	*20 m spots 4 pixels*	*60 m spots 27 pixels*	*Selectable in ground processing*
# of detected photons ice	100-150	400-600	2700-4000	
Vert precision ice (uniform 3 deg slope)	2- 1.5 cm	1 to 0.75 cm	<0.75 cm	Glas high SNR limit ~5 cm
Vert precision ice (uniform 1 deg slope)	1.5- 1 cm	0.75 to 1 cm	<0.5 cm	Glas High SNR limit was ~2.6 cm (limited by laser pulsewidth)
2-way Atmospheric attn factor for 2 pe detection	x50	x200	x1000	GLAS with new lasers ~ x200
# of detected photons vegetation	30-50	133-200	900-1330	
# of detected photons from ground surface though 98% closed canopy	0.6 to 1	2.6 to 4	18 to 26	

Summary - Swath Mapping Laser Altimeter





- A space lidar for elevation swath mapping
- Overlapping repeat swaths allow direct along-track change detection in > 200m wide band
- Pushbroom configuration-multiple lasers & detectors
- Leverages very long lifetime laser technology
- Scalable, highly-redundant laser architecture
- 1 nsec laser pulse & detection probability < 1
- 1.5 cm-precision ranging, 10 m spots at ~ 20KHz rate
- High spatial resolution & measurement aggregation
- Depolarization ratio for solid/liquid surface discr.
- An "ATM instrument capability in Space"

Reporting & Proposals based on work

Conference Presentations:

J. Abshire, D. Harding, C. Shuman, X Sun, P. Dabney, M. .Krainak, T. Scambos, "Space - based Swath Imaging Laser Altimeter for Cryospheric Topographic and Surface Property Mapping", *Spring AGU 2005*, Paper C43B-04, May 2005.

J. B. Abshire, X. Sun, M. A. Krainak, "Laser Altimetry using Pseudo-Noise Code Modulated Fiber Lasers and Photon Counting Detectors," *Conference on Lasers and Electro-optics (CLEO'05)*, Paper JThI4, Optical Society of America, May 2005.

James B. Abshire, David J. Harding, Xiaoli Sun, Michael A. Krainak, Chris Shuman, Phil Dabney, "Space-based Swath-Imaging Laser Altimeter for Cryospheric and Topographic Mapping", *Fall AGU 2005*, San Francisco CA, Paper G21C-1288, December 2005.

RTOP Proposal funded:

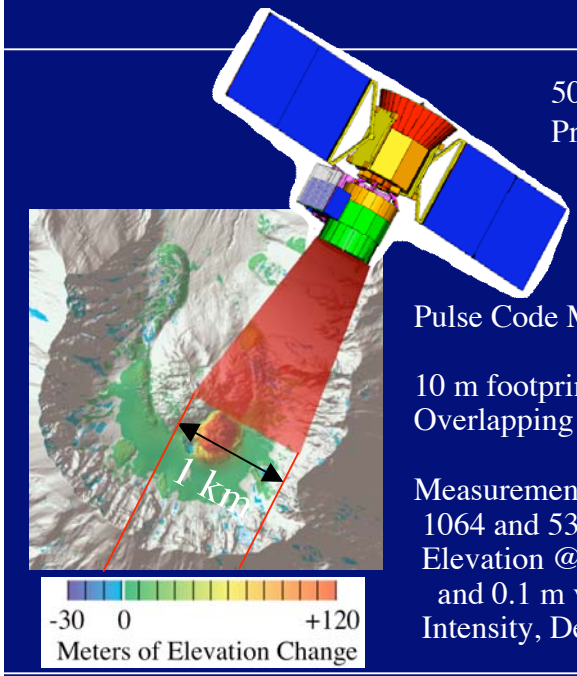
David Harding, James B. Abshire,Xiaoli Sun, Christopher Shuman, Theodore Scambos, Phillip Dabney, "Push-broom Laser Altimeter Demonstration for Space-based Cryospheric Topographic and Surface Property Mapping", funded under NASA 2005 Earth Science Instrument Incubator Program.

Proposal submitted:

"Swath mapping altimeter for Planetary Applications", selected by GSFC 2007 IRAD program

Push-broom Laser Altimeter Demonstration for Space-based Cryospheric Topographic and Surface Property Mapping

NASA Earth Science and Technology Office Instrument Incubator Program, D. Harding NASA/GSFC - PI



500 km polar orbit
Precision spacecraft pointing

Pulse Code Modulation Laser Altimetry

10 m footprints x 100 = 1 km swath
Overlapping repeat observations

Measurements:
1064 and 532 nm dual wavelength
Elevation @ 10 m spatial resolution and 0.1 m vertical accuracy
Intensity, Depolarization, & Penetration

Description and Objectives:

Next-generation satellite laser altimeter for targeted ice sheet, sea ice, and glacier mapping and change detection
Our development of an airborne laser instrument & mission design will provide:

- Scalable, efficient, inherently redundant solution for change detection laser altimetry from low Earth orbit
- Flexible modulation scheme that can be reconfigured in flight as a function of terrain type
- Simultaneous acquisition of high-resolution topography and surface property data in an image swath
- Personnel experienced in advanced laser altimeter techniques, instrument design, and science applications

Approach:

- Pulse code modulation, photon counting, and correlation ranging
- Scalable for swath imaging of topography and snow, ice, and water distribution and physical properties
- Leverage highly-reliable, well-funded (DOD, telecom), fiber laser and detector technology
- Experienced team of instrumentalists, engineers, and scientists
- Laboratory characterization of snow, ice, and melt water backscatter optical properties
- Breadboard and airborne prototype development

Co-I's/Partners:

NASA/GSFC: J. Abshire, P. Dabney, J. McGarry, C. Shuman, X. Sun
Aerospace Corporation: R. Fields, T. Rose
University of Colorado: T. Scambos

Schedule and Deliverables:

2006: Laboratory measurements of optical properties and one-channel breadboard evaluation of components and algorithms
2007: Assembly and test of four-channel prototype
2008: Airborne data acquisition/analysis and definition of spaceflight implementation

Applications/Missions:

- Continuation of ice mass balance satellite observations
- Assess glacier, ice sheet and sea ice response to climatic forcings
- Topographic change detection associated with natural hazards
- Vegetation height an biomass response to disturbance
- Surface water storage and discharge changes for global water cycle