High-Altitude Lidar Mapping Concept: Local-State-Federal-Commercial Elevation for the Nation Partnership

National Lidar Initiative Meeting: Strategy Discussion for Elevation for the Nation

USGS HQ, Reston, VA

February 14-16, 2007

David J. Harding

NASA Goddard Space Flight Center

Science & Exploration Directorate

david.j.harding@nasa.gov

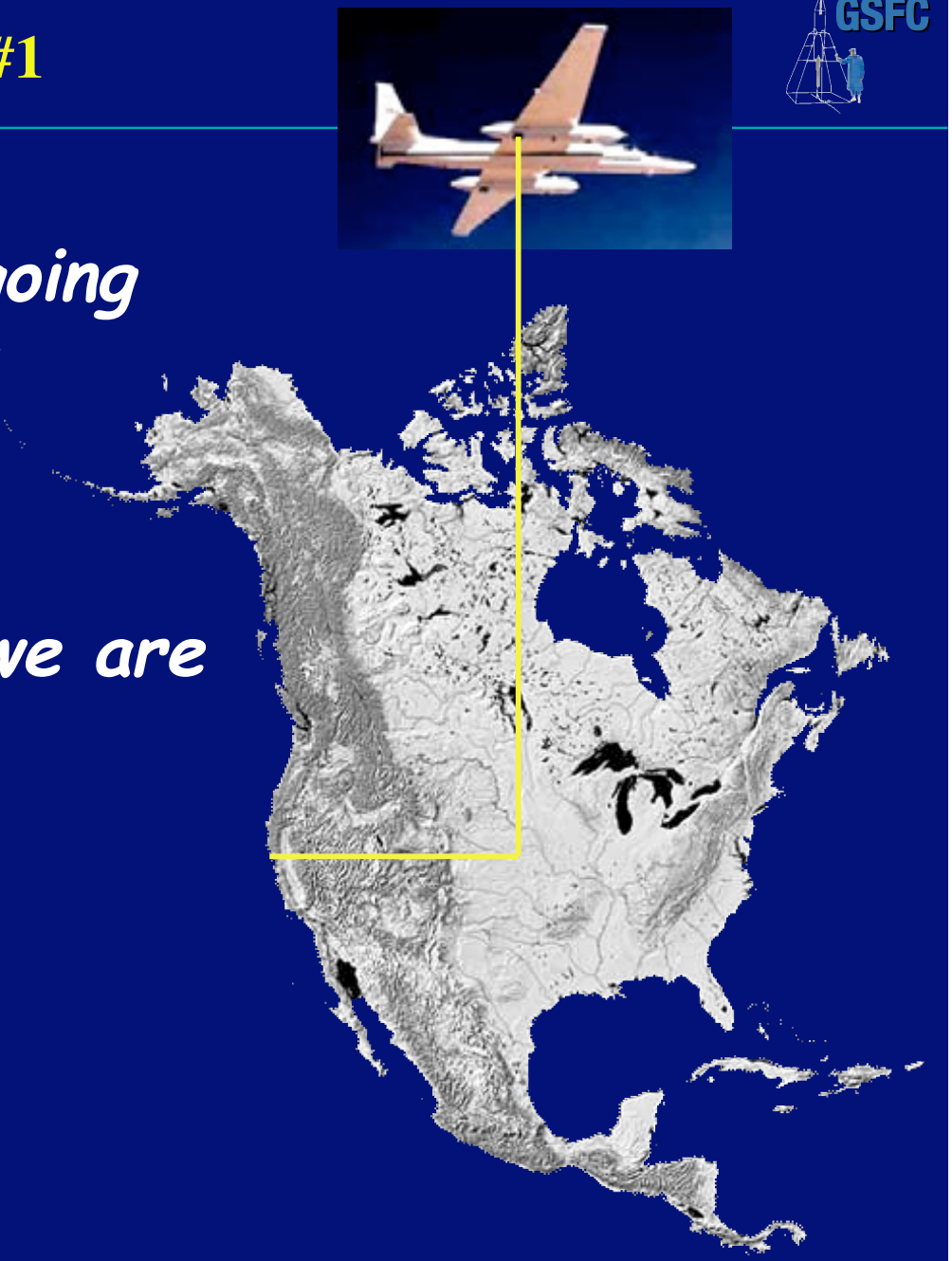
Take-away Message #1

To know where we are going

and how to get there,

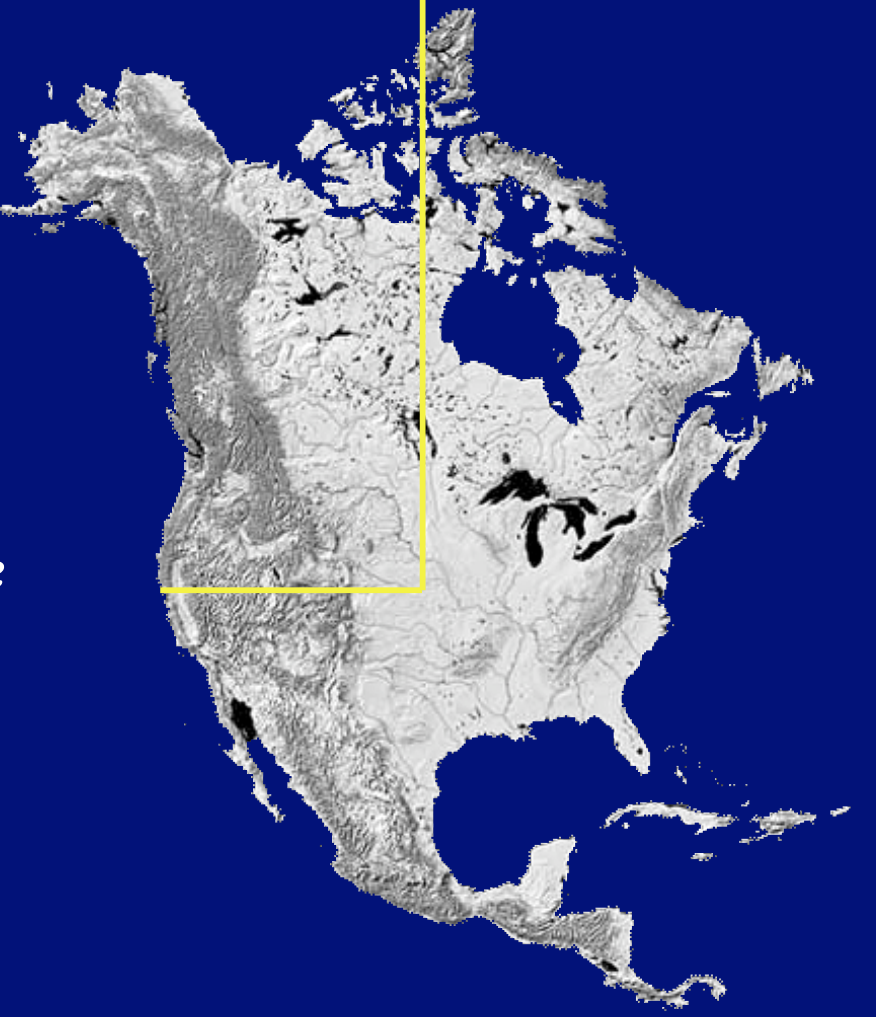
it helps to know where we are

and how we got here.



Take-away Message #2

- *The airborne lidar mapping industry was only in its infancy 10 years ago.*
- *Therefore, what will be achievable 10 years from now is not known but will assuredly be better than today.*
- *The National Lidar Mapping Initiative must have a structure that not only accommodates those improving cabilities, but should be a driving force for those improvements.*



Take-away Message #3

We are talking about a really, really big effort. Look at national and global scale data collection and distribution efforts for lessons learned, not only at existing airborne lidar surveys.

Land area of U.S. = 9,161,923 sq km
Assuming:
- *2 laser pulses per sq m*
- *an average of 1.5 returns per pulse*
- *35 data bytes per return*

= 1 x 10^{15} bytes of point cloud data
= 1 petabyte = 1,000 terrabytes

1 year of national NOAA Doppler radar data = 180 terrabytes
1 year of global NASA EOS Terra mission data = 310 terrabytes

Presentation Outline

NASA Topography Missions: Past, Present & Future

GSFC Laser Altimeter Systems

Laser Pulse Reflection & Feature Mapping

Swath Imaging Multi-polarization
Photon-counting Lidar (SIMPL)

National High-Altitude Mapping Concept

National High-Altitude Mapping Concept: Prior Presentations

America Association of State Geologists Delegation
NASA HQ, Washington, D.C.
March 21, 2006

USGS-NASA-NOAA-AASG Working Group
NASA HQ, Washington, D.C.
September 12, 2006

NRC Workshop on Floodplain Mapping Technologies
National Academy of Sciences, Washington, D.C.
October 18, 2006

MAPPS Fall Policy Conference
MAPPS/ASPRS Specialty Conference, San Antonio, TX
November 9, 2006

Coordinating with:
Dewayne Cecil, NASA Earth Science Applications Chief Scientist
John Labrecque, NASA Earth Surface and Interior Program Manager

National Academy of Sciences NRC Recommendations:
Earth Sciences Decadal Survey & Elevation for the Nation

Two Reports Issued in January, 2007

Committee on Earth Science and Applications from Space

Laser altimeter spaceflight missions:
ICESat-II for ice sheet height changes
DESDynI for vegetation canopy structure
LIST for global land surface topography

PREPUBLICATION COPY
Subject to Further Editorial Correction

Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond

Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future

Space Studies Board
Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL

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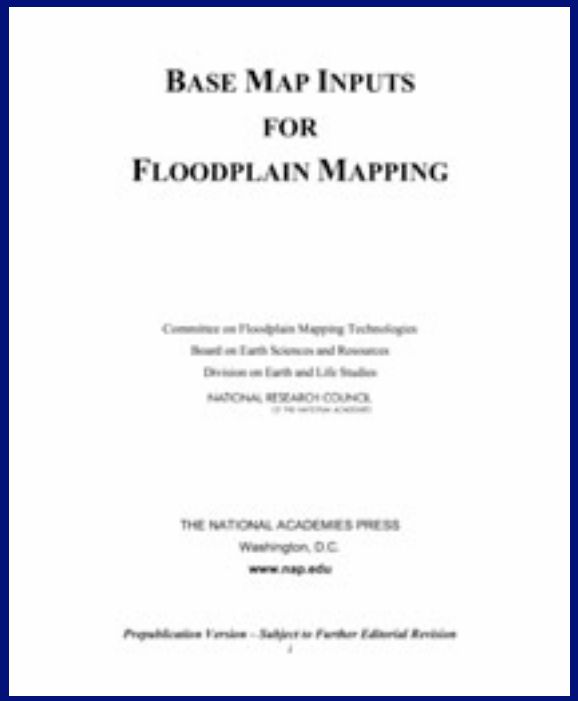
Committee on Floodplain Mapping Technologies

A seamless, public-domain, nationwide elevation data set created using airborne laser swath mapping


BASE MAP INPUTS
FOR
FLOODPLAIN MAPPING

Committee on Floodplain Mapping Technologies
Board on Earth Sciences and Resources
Division on Earth and Life Studies

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Prepublication Version – Subject to Further Editorial Revision

NASA Topography Missions & Objectives: Shuttle Radar Topography Mission (SRTM)

Global DEM to 60° N & S

C-band radar interferometry (InSAR)

U.S. grid posting: 1" (~30 m)

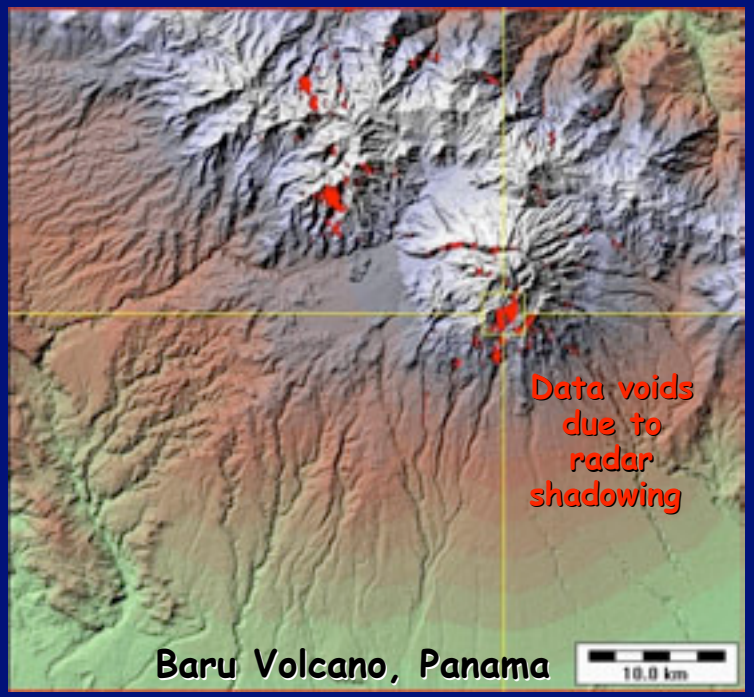
Non-U.S. grid posting: 3" (~90 m)

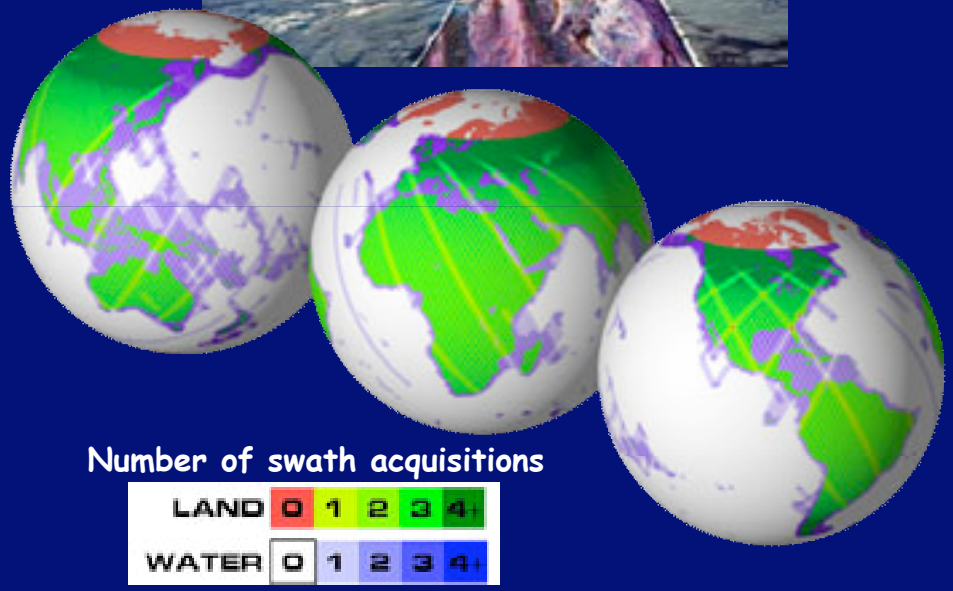
Elevation data: radar phase center

Phase center vertical accuracy: 3 m

Data acquired: Feb. 11-22, 2000

Organizations: NASA-JPL-NGA-EDC





NASA Topography Missions & Objectives: Ice, Cloud & land Elevation Satellite (ICESat)

Geoscience Laser Altimeter System (GLAS)

1064 nm: topography & vegetation height

532 nm: cloud & aerosol height distribution

Elevation data: laser backscatter waveform

Flight Altitude: 600 km

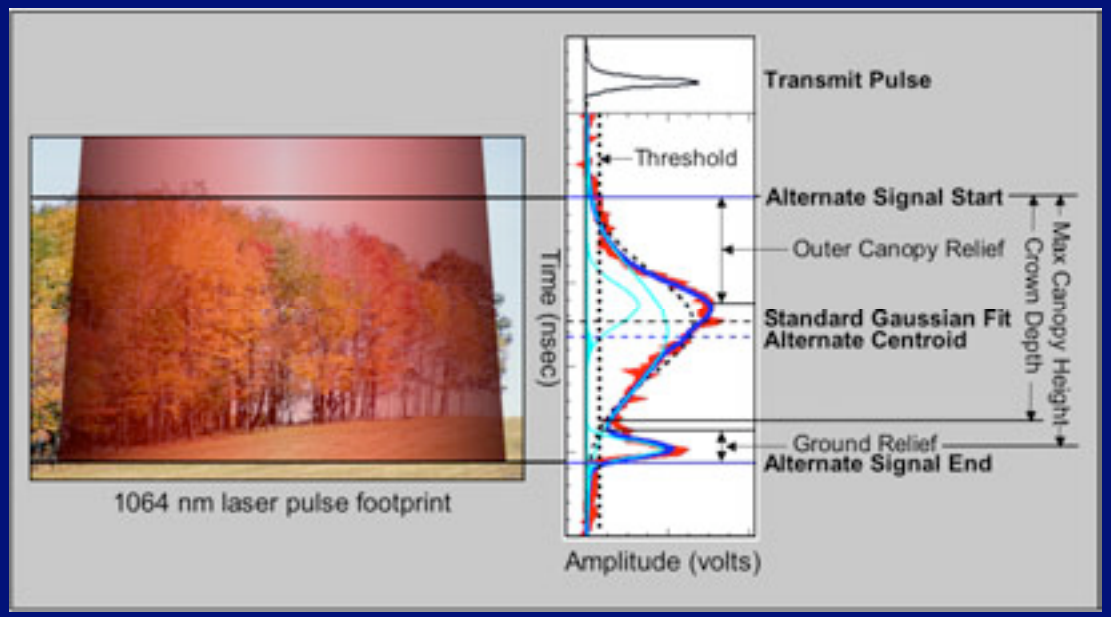
Vertical precision : 2 cm (flat surfaces)

Vertical absolute accuracy: 15 cm (flat surfaces)

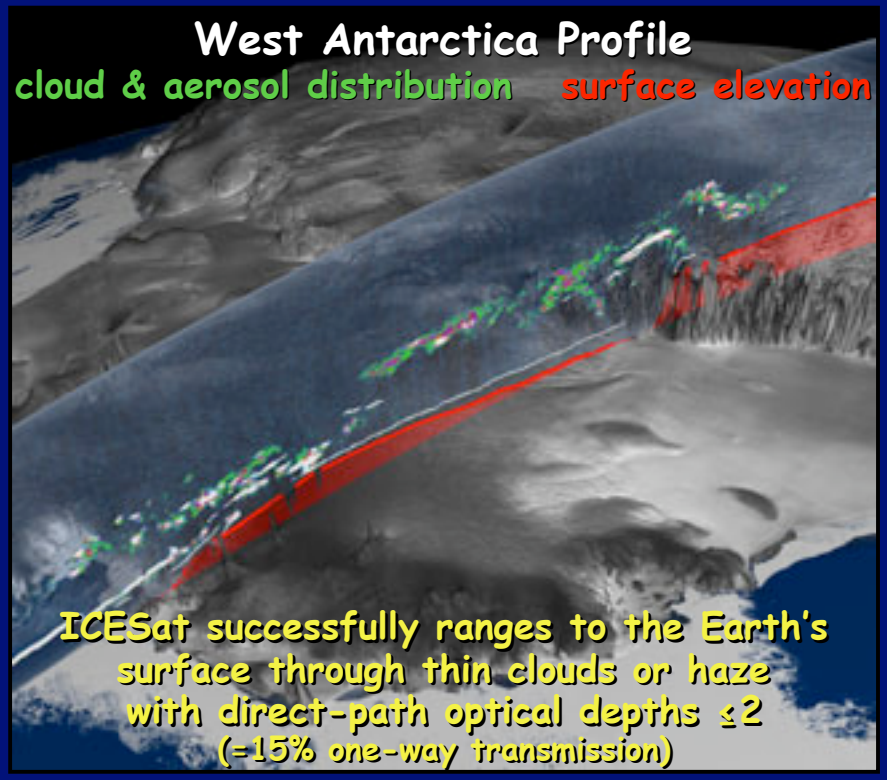
Horizontal absolute accuracy: 10 m

Data acquired: 2003 to current

Organizations: NASA-GSFC-Univ.TX-NSIDC



NASA Topography Missions & Objectives: Ice, Cloud & land Elevation Satellite (ICESat)



Primary Objective

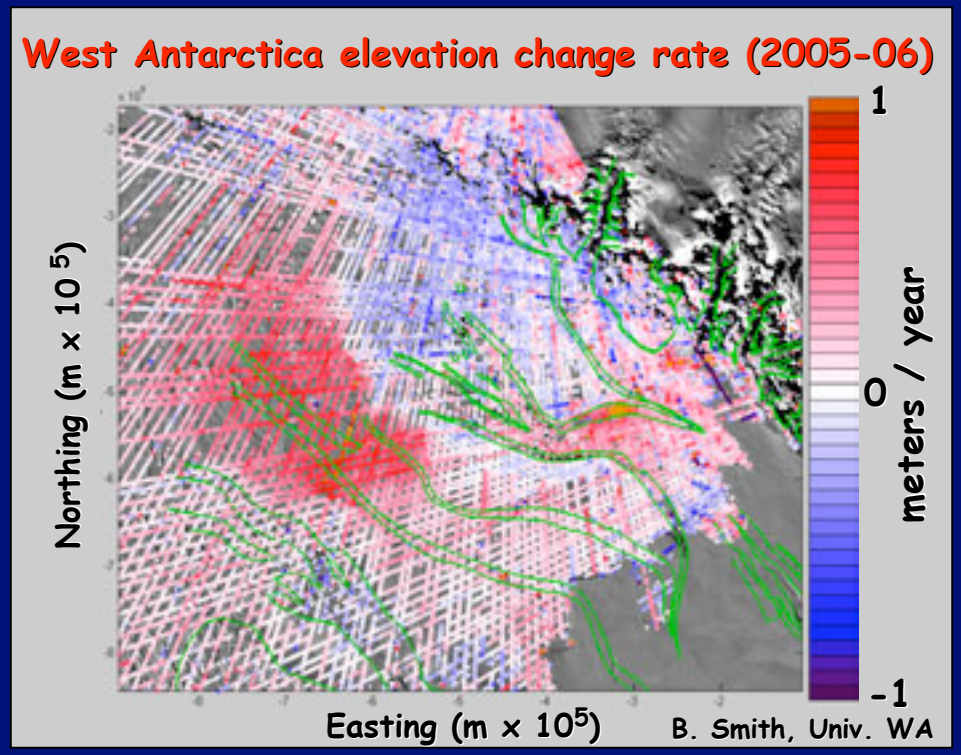
Greenland and Antarctica ice sheet elevation change & mass balance

Secondary Objectives

Sea ice extent and thickness
Cloud & aerosol heights
Geodetic land topography profiles
Forest canopy height sampling

Globally-distributed Repeated Profiles

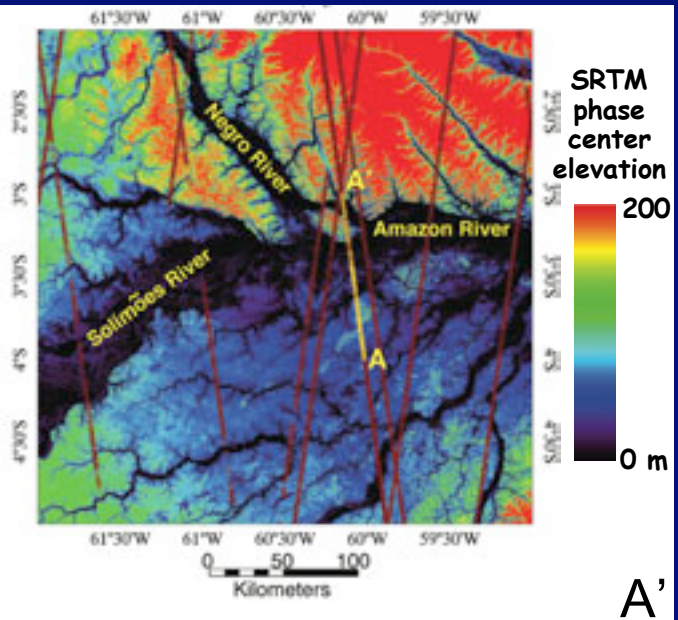
91-day exact repeat orbit
8-day and 33-day global sampling sub-cycles
Orbit position controlled to ±1 km
Laser profile location controlled to ±150 m by precise spacecraft pointing
Elevation change determined at cross-over locations and along precisely repeated profiles

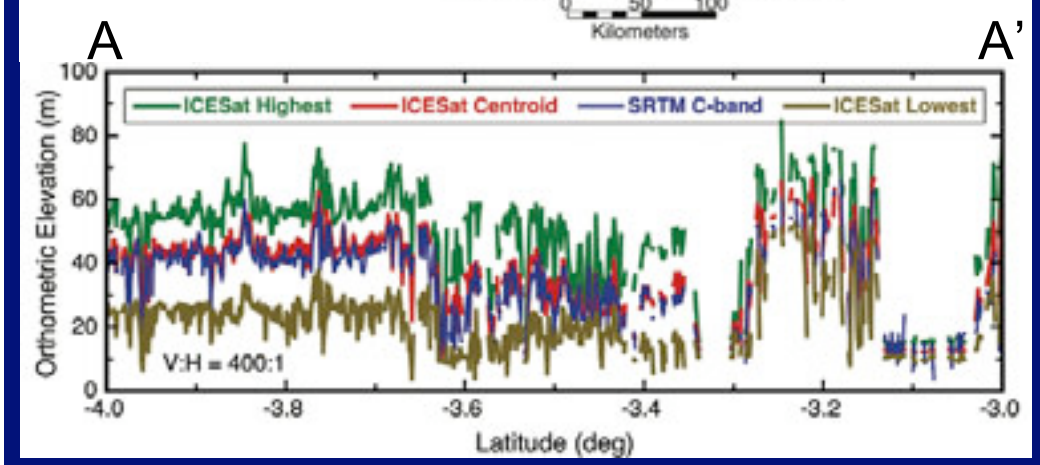


NASA Topography Missions & Objectives: SRTM & ICESat Integration

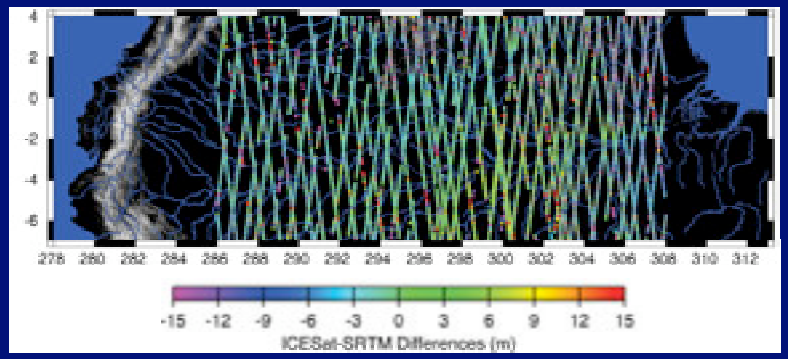
Central Amazon Basin

Oct-Nov, 2004 ICESat tracks on SRTM C-band 90 m DEM

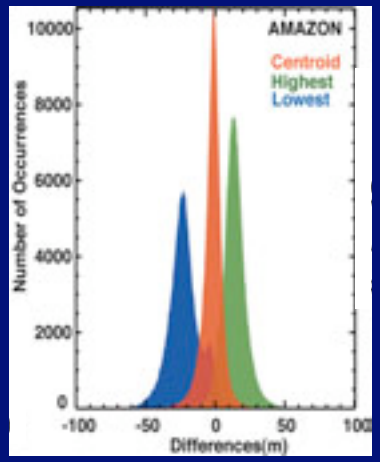




ICESAT — SRTM Elevation Differences



Region	ICESat Elevation	Mean (m)	Median (m)	STD (m)	90% (m)
Amazon N = 255646	Highest	14.46	13.89	10.01	24.46
	Centroid	-1.94	-1.43	7.30	11.45
	Lowest	-22.35	-22.81	11.79	35.99

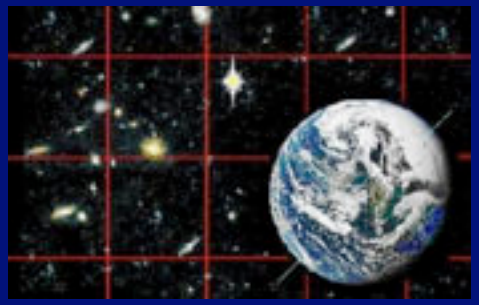


In vegetated areas, the SRTM radar phase center elevation is biased upward & closely corresponds to the ICESat waveform centroid (average height of optical backscatter).

NASA Topography Missions & Objectives: Enabling Geodesy Infrastructure

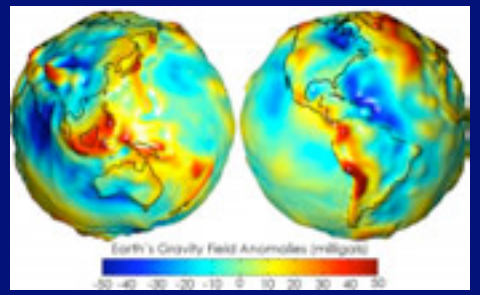
Earth Reference Frame

- *GSFC Very-long Baseline Interferometry*
- *JPL Global GPS Ground Station Network*



Global Geoid Modeling

- *GSFC Earth Geoid Model-96 for DoD NGA*
- *UT-JPL GRACE Time-varying Gravity Mission*



Precision Spacecraft Orbit & Attitude

- *GSFC Satellite Laser Ranging*
- *GSFC Geodyn POD and PAD*

Long-range Platform Trajectories

- *JPL Precision Point Positioning Global Differential GPS*

NASA Topography Missions & Objectives: Solid Earth Science Working Group (SESWG)

Chartered to recommend long-term vision and strategy for NASA Earth Surface & Interior Science Program

Report delivered to NASA in 2002

Scientific Challenges Identified

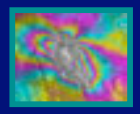
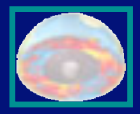


Plate Boundary Deformation:
What is the nature of deformation at plate boundaries and what are the implications for earthquake hazards?

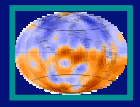
Tectonic-Climate Interactions:
How do tectonics and climate interact to shape the Earth's surface and create natural hazards?

Sea Level Change:
What are the interactions among ice masses, oceans, and the solid Earth and their implications for sea level change?

Volcanism:
How do magmatic systems evolve and under what conditions do volcanoes erupt?



Mantle & Crust Dynamics:
What are the dynamics of the mantle and crust and how does the Earth's surface respond?



Magnetic Field Dynamics:
What are the dynamics of the Earth's magnetic field and its interactions with the Earth system?

NASA Topography Missions & Objectives: Solid Earth Science Working Group (SESWG)

SESWG Recommendation in 2002 for High-Resolution Topography

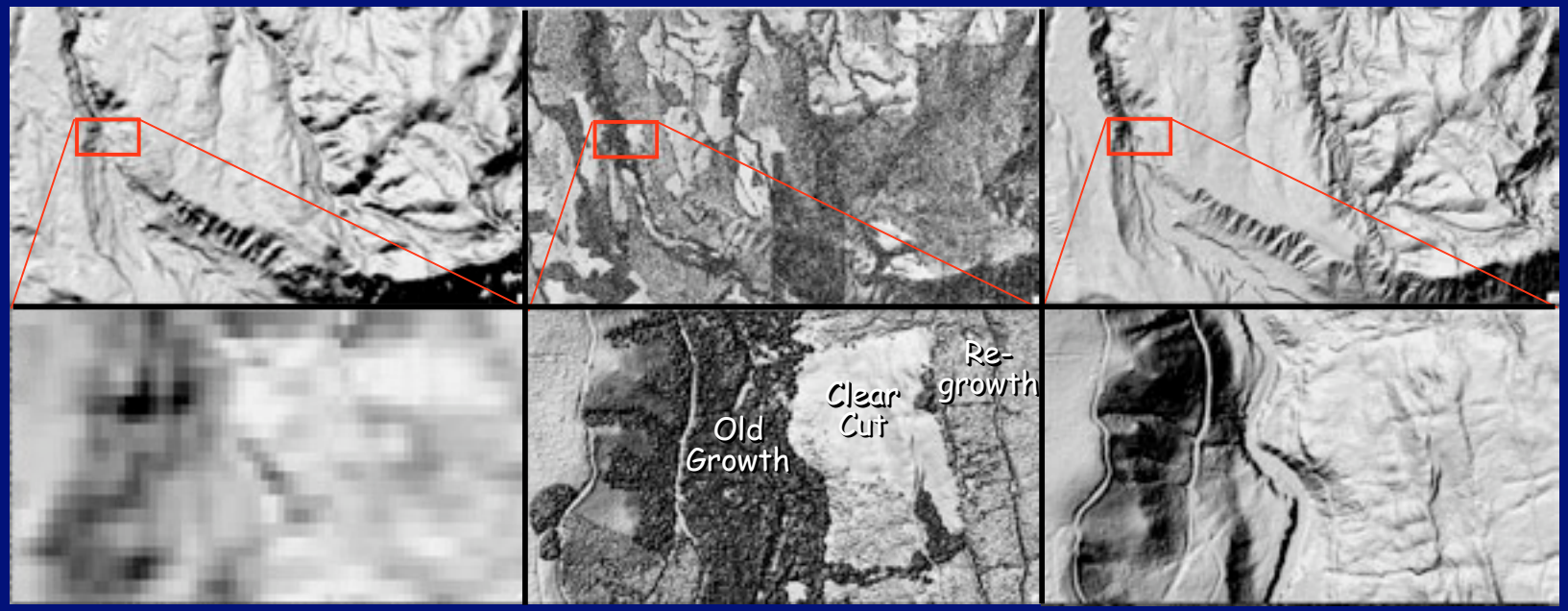
Near term (2007-2012):

Global mapping to supercede the SRTM data set

- One-time, non-repeated global mapping
- 2 to 5 m spatial resolution
- 0.5 m vertical accuracy for the ground surface

SRTM DEM
C-band Phase Center

Airborne Laser Swath Mapping (PSLC)
Highest Reflective Surface Bald Earth Topography



NASA Topography Missions & Objectives:
National Academy Study: Earth Science & Applications from Space

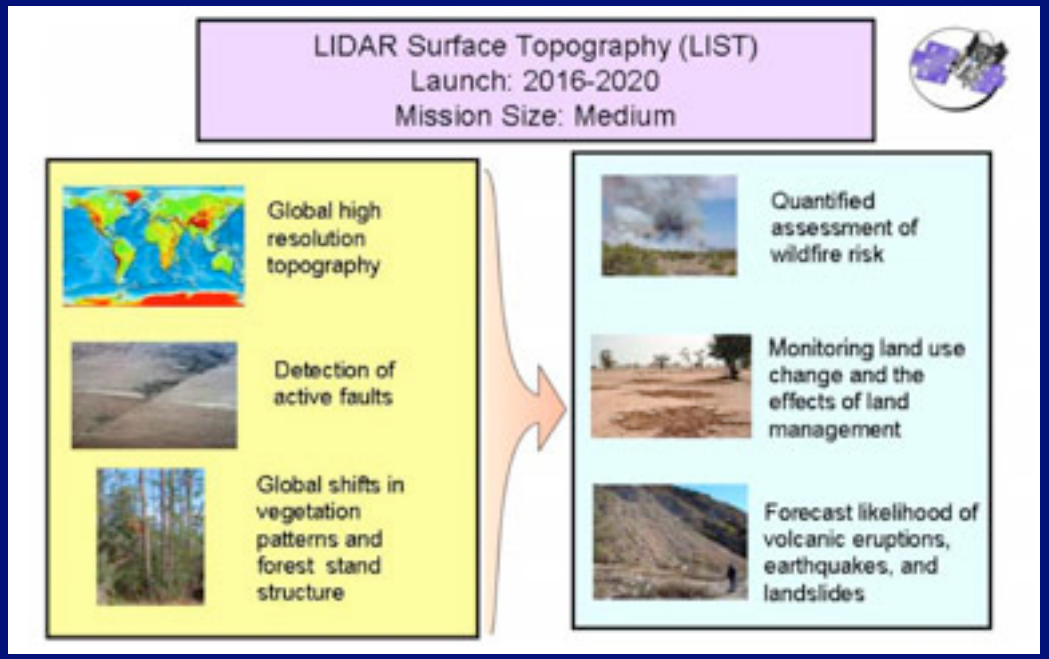
NAS Recommendation in 2007 for High-Resolution Topography

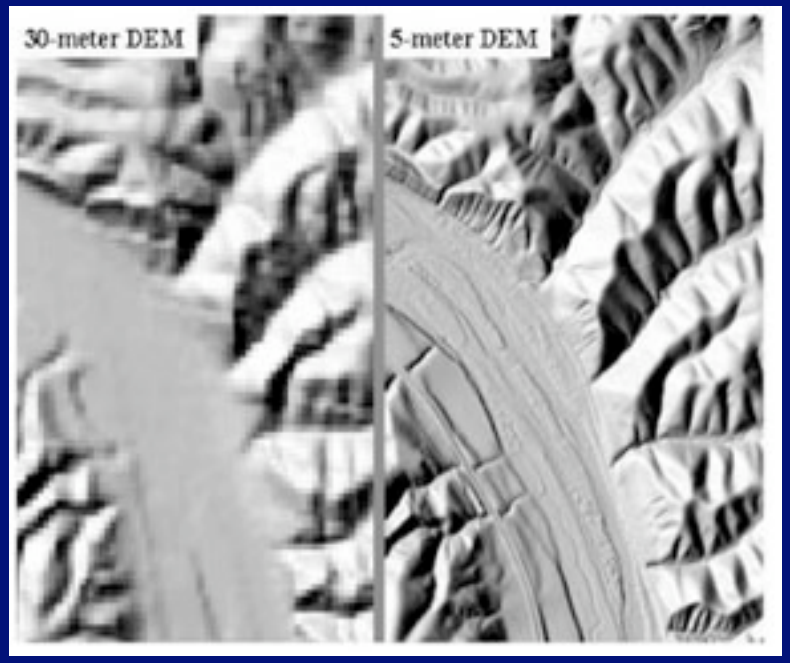
Time Frame (2016-2020):

Global mapping to supercede the SRTM data set

5 m spatial resolution

0.1 m vertical accuracy for the ground surface

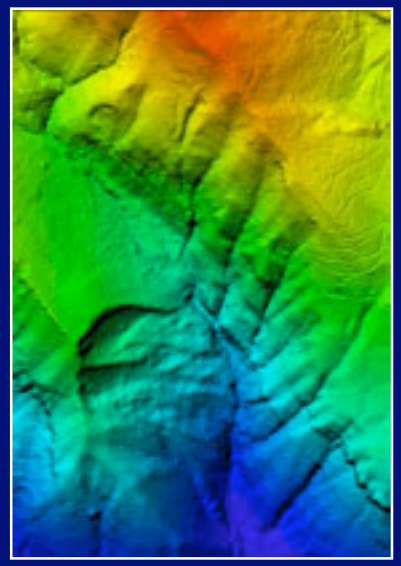


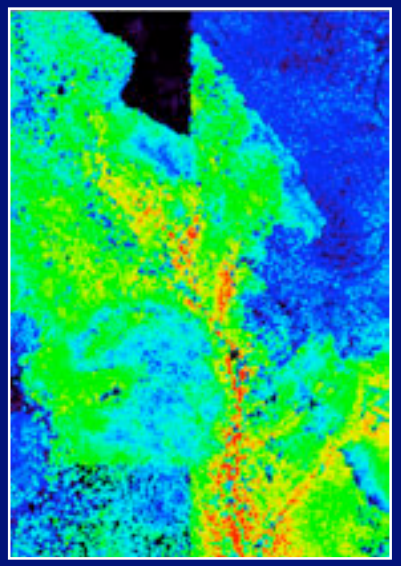


One of 15 Earth-orbiting spaceflight missions recommended for the next decade.

NASA Topography Missions & Objectives: Improved Ground Topography + Vegetation Structure & Biomass

Ground topography from last returns

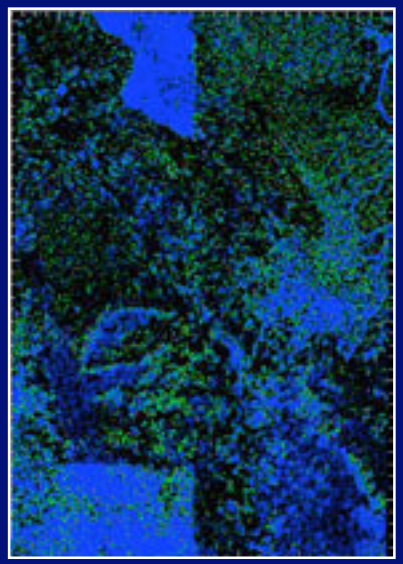




Canopy height = highest surface – ground

Outer canopy surface roughness from shaded relief image

0.5 km



Canopy closure from ground return density

Ground Return Number:
1st (78%)
2nd (20%)
3rd (2%)
7% of Total Laser Shots

Ground Topography and Especially Vegetation Structure: Depends on Instrumentation & Inter-Survey Consistency a Challenge

Ground & canopy classification depends on:

Surface properties

- vegetation height and density
- spatial and angular distribution of gaps
- reflectivity of the ground & canopy
- ground relief vs. understory cover

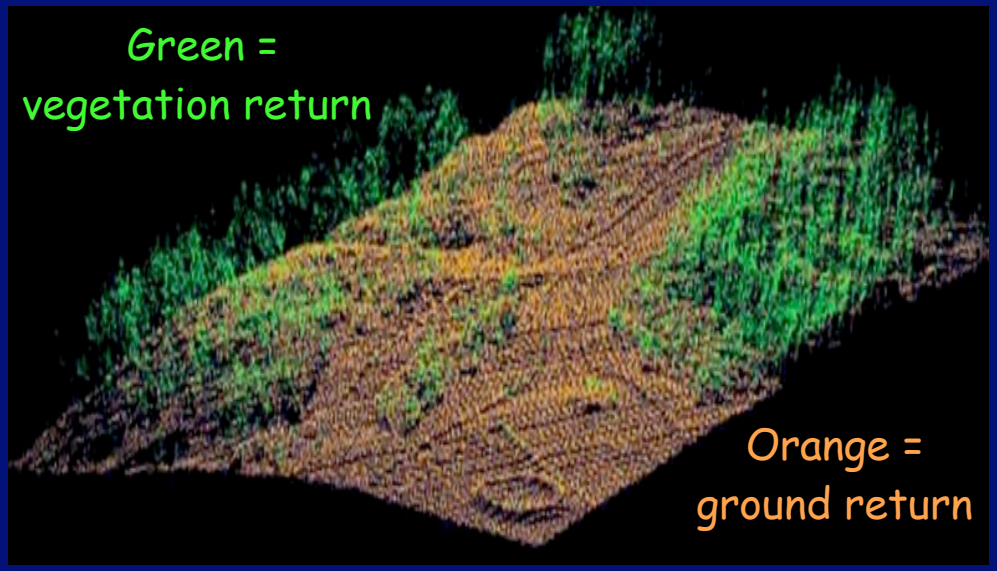
Altimeter properties

- off-nadir beam pointing
- density of laser footprints
- size of laser footprint
- laser pulse wavelength
- laser pulse width
- detector bandwidth
- signal-to-noise performance
- detection threshold level
- ranging electronics detection method

Data processing

- filtering & classification methodology

Returns classified by spatial structure (± intensity)



Laser Altimeter Journal Publications in the Earth Sciences
Web of Science Citation Search as of March, 2006

Waveforms

Full waveform recording or pulse width

Discipline	Papers	Times Cited
Techniques & Concepts	12	89
Biosphere	**36**	**495**
Cryosphere	11	18
Hydrosphere	3	11
Solid Earth	**11**	**67**
TOTAL	**73**	**680**

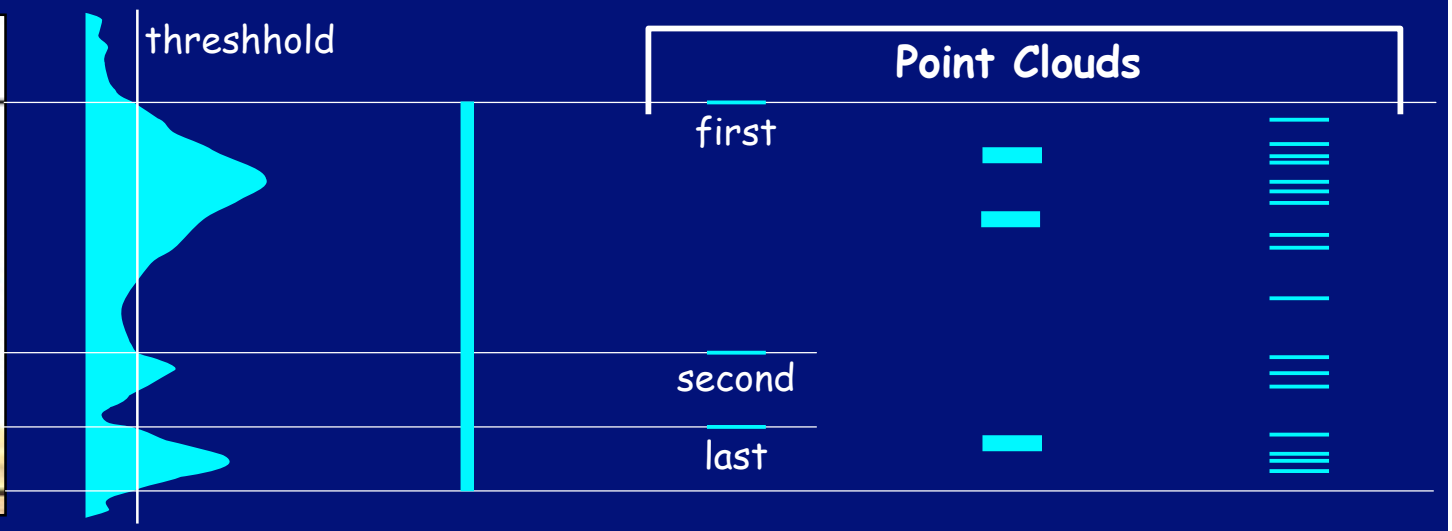
Point Clouds

Discrete returns or photon counting

Discipline	Papers	Times Cited
Techniques & Concepts	30	342
Biosphere	**68**	**701**
Cryosphere	15	178
Hydrosphere	13	64
Solid Earth	**50**	**230**
TOTAL	**176**	**1,515**

GSFC Laser Altimeter Systems: Laser Ranging Methods

Laser Pulse

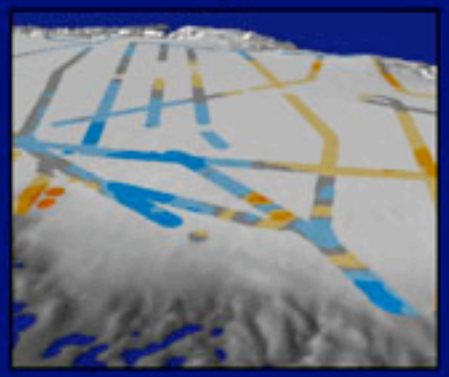


GSFC Laser Altimeters	Monopulse Waveform Digitization	Monopulse Pulse Width	Monopulse Discrete Return	Monopulse Single Photon	Micropulse Single Photon
	AOL SLICER LVIS EAARL SLA GLAS	MOLA MLA LOLA	AOL ATM	GLAS	MMLA SIMPL

Wavelength: green near-infrared Platform: *airborne* spaceflight

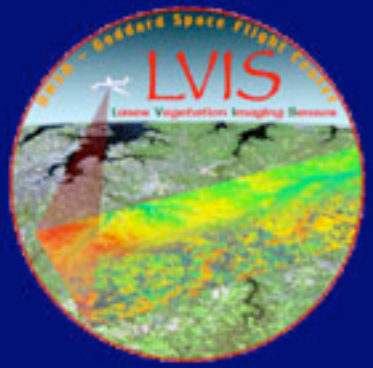
GSFC Laser Altimeter Systems: Technology R&D and Science Leadership

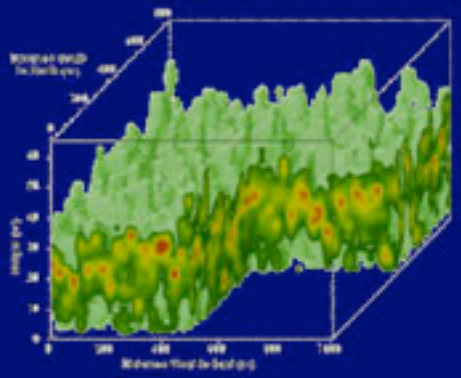
ATM
Airborne
Topographic Mapper
B. Krabill, PI



Geodetic Elevation Change
Swath Mapping
532 nm Discrete Returns

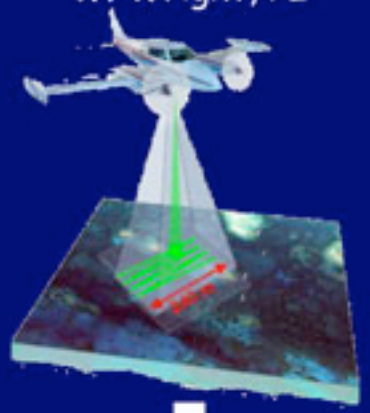
LVIS
Laser Vegetation
Imaging System
J.B. Blair, PI

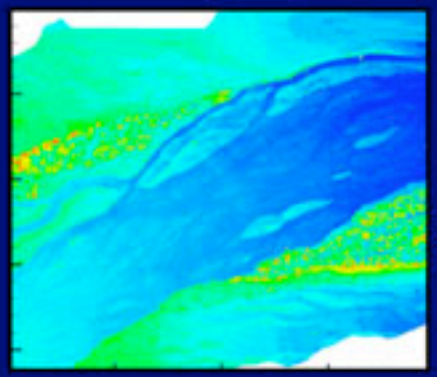




Forest Canopy
Volumetric Mapping
1064 nm Waveforms

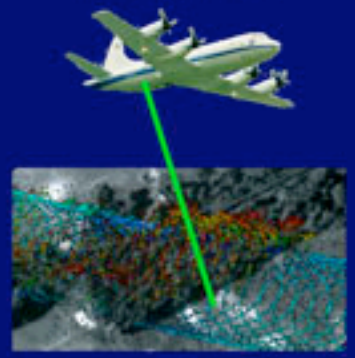
EAARL
Experimental Advanced
Airborne Research Lidar
W. Wright, PI

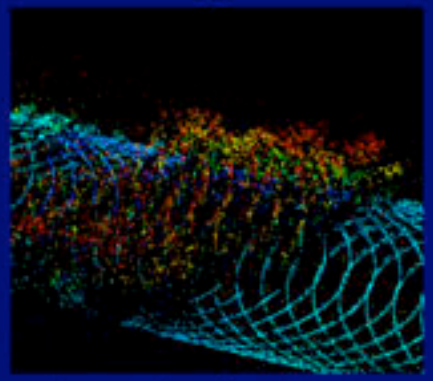




Simultaneous Bathymetry
& Topography Mapping
532 nm Waveforms

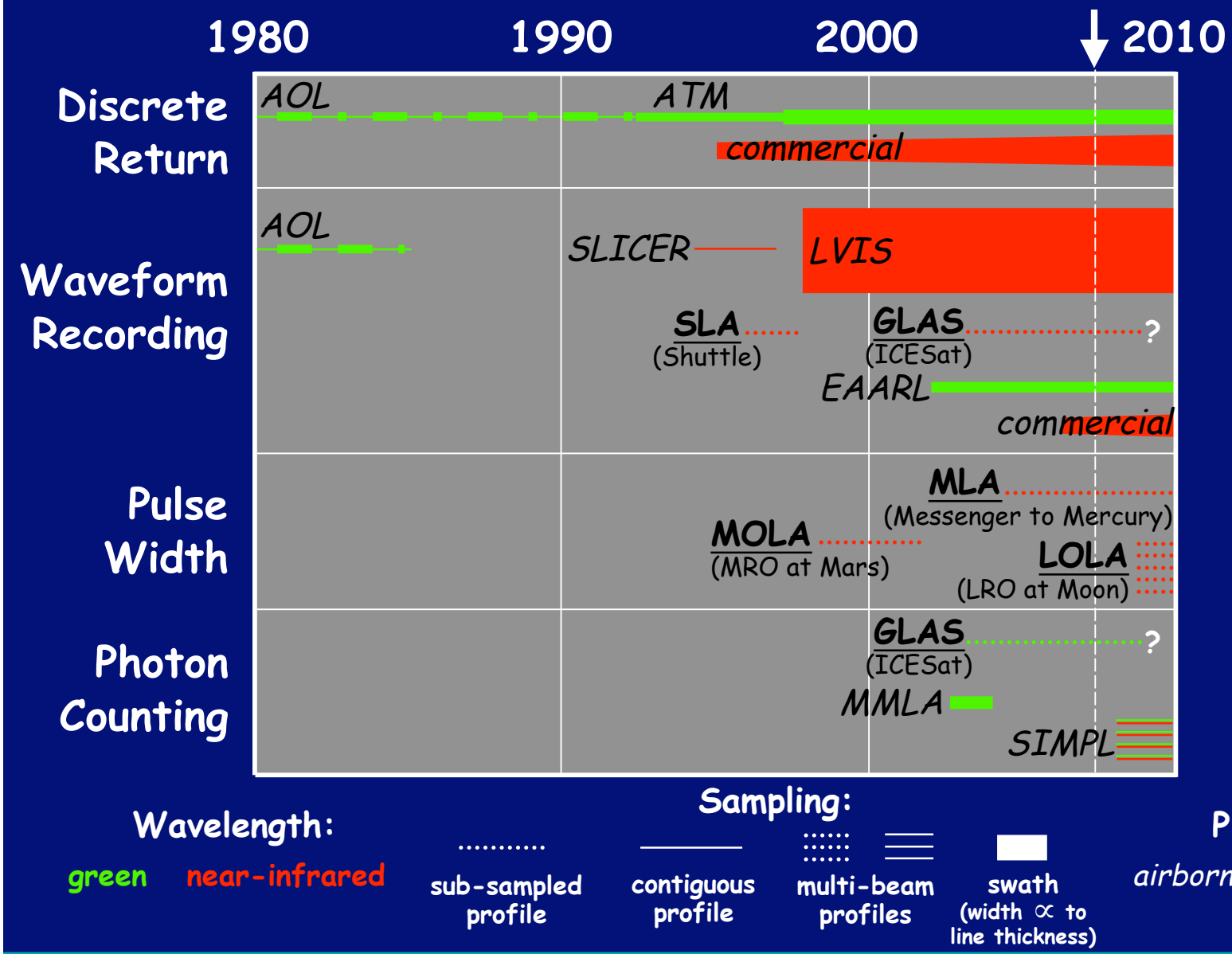
MMLA
Multikilohertz
Micro-Laser Altimeter
J. Degnan, PI



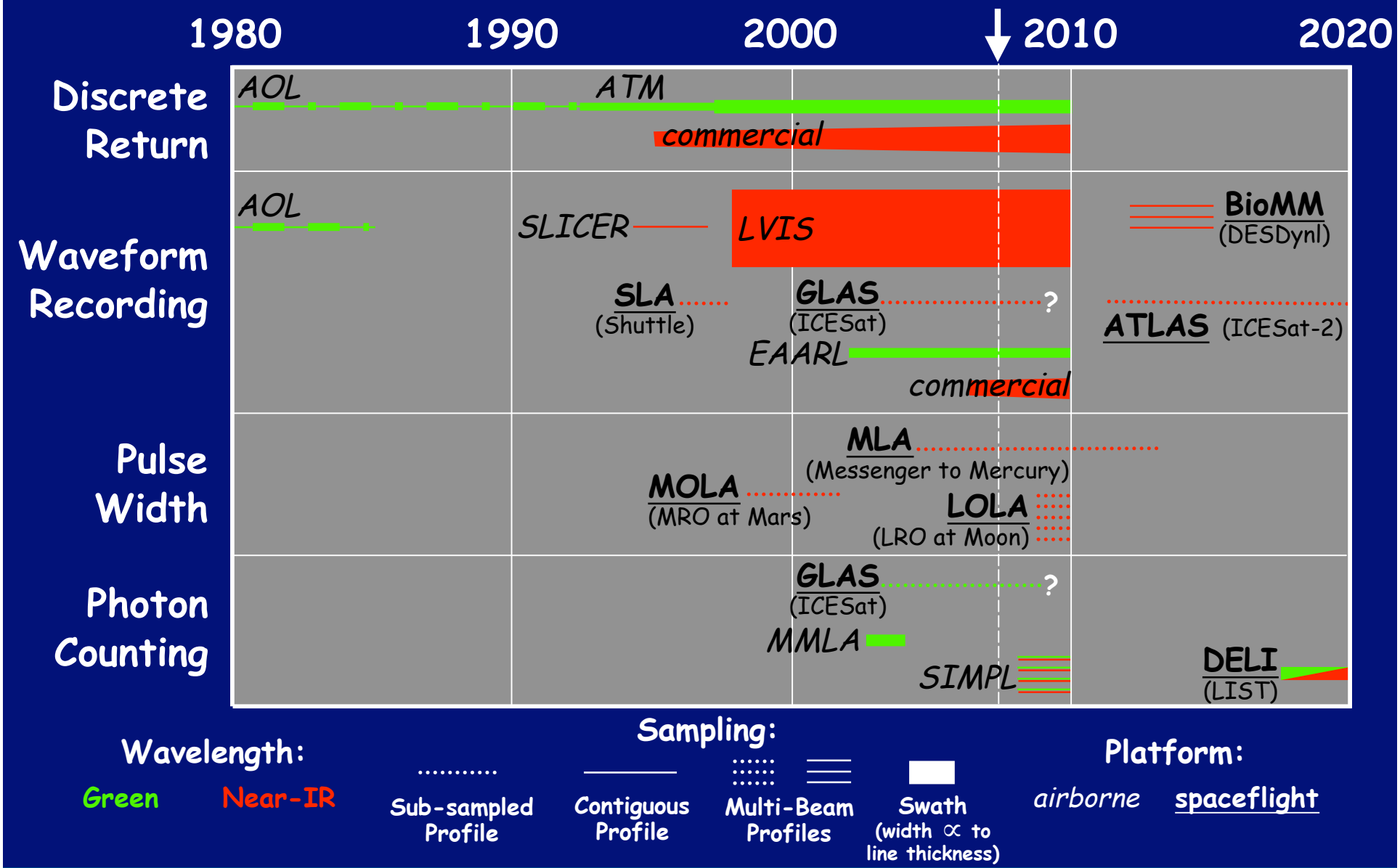


Low Signal-to-Noise
Point Clouds
532 nm Photon Counting

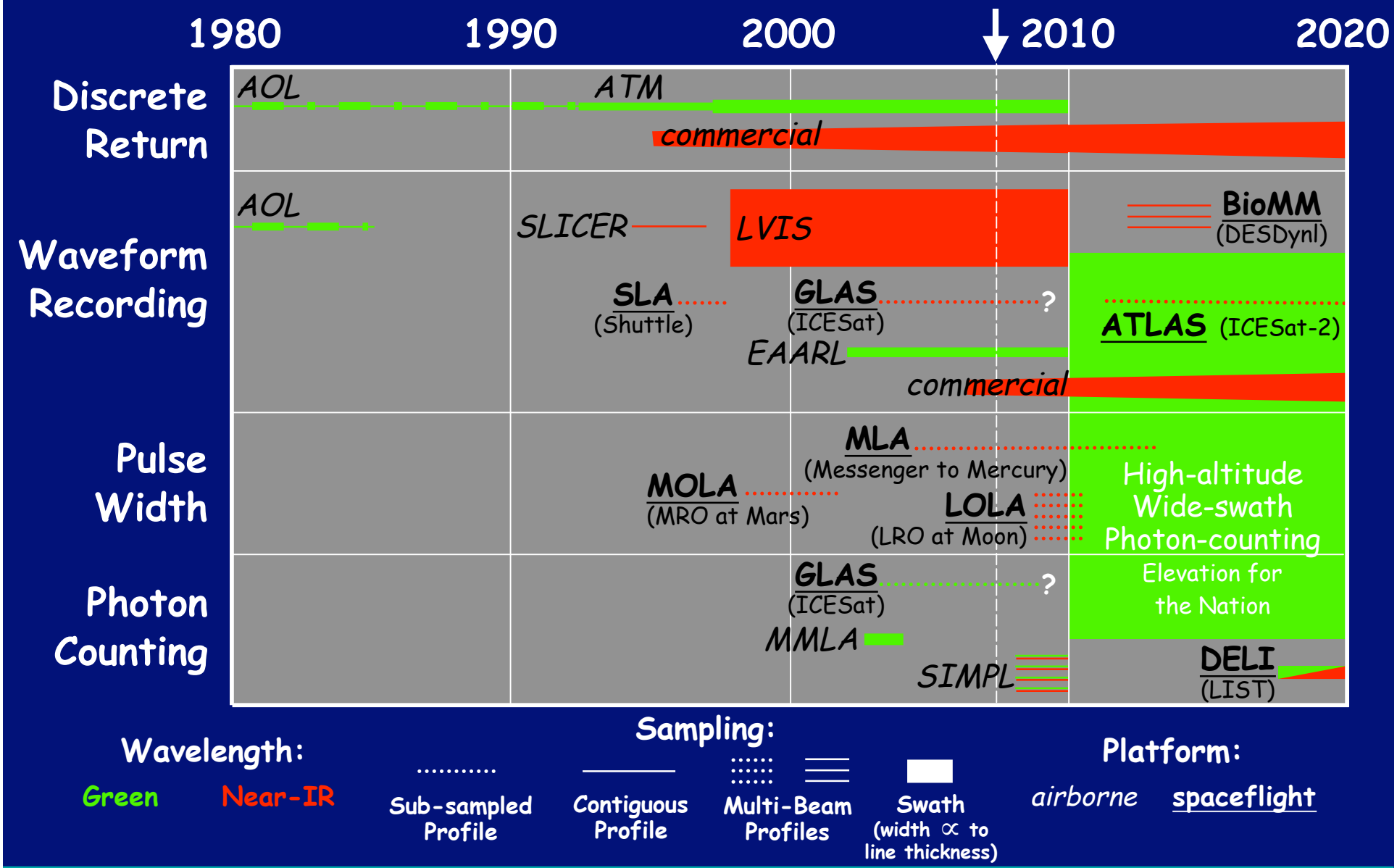
GSFC Laser Altimeter Systems: Development Timeline



GSFC Laser Altimeter Systems: Concepts to Implement NAS Decadal Survey



GSFC Laser Altimeter Systems:
Concepts to Implement NAS Decadal Survey & Elevation for the Nation



Feature Mapping Using Laser Backscatter Energy: Monochrome, Single-Band Reflectance Image at Laser Wavelength

Perspective View of Surface Elevation Draped with Laser Backscatter Intensity

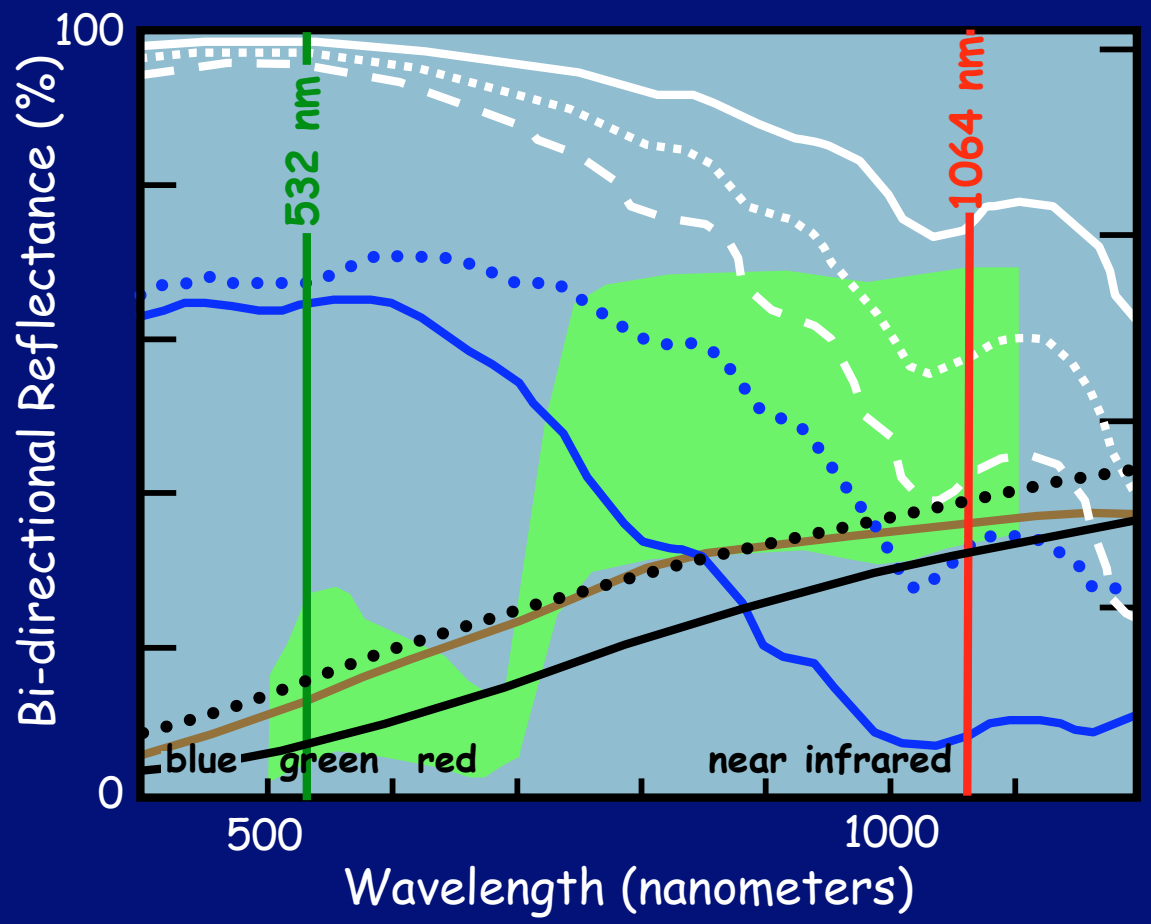
IKONOS 1m Images

Itaipu Dam, Brazil/Paraguay

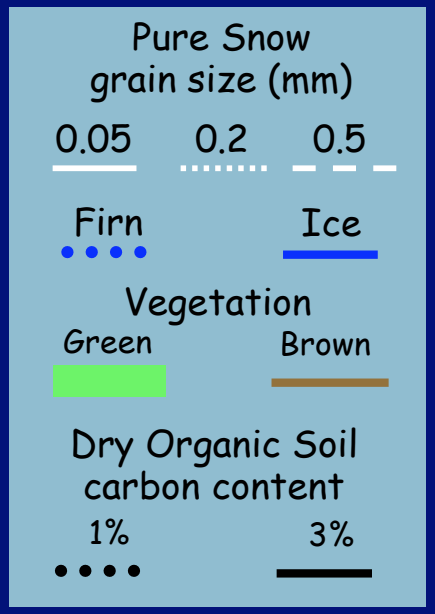
Single-wavelength laser backscatter intensity in combination with the elevation data improves feature mapping.

Can a laser altimeter provide additional feature information, such as is provided by multi-spectral imaging?

Feature Mapping Using Laser Backscatter Energy: 532 nm vs. 1064 nm



532 vs. 1064 nm contrast improves differentiation of surface types



Clear water bathymetry:

To 10's of meters: high transmittance at visible wavelengths

None: NIR absorbed in top few cm

Huygens-Fresnel equations:

For light intersecting water at angles of 20° or less, 98% of the energy is refracted into the water and 2% is reflected at an angle equal to the incidence angle (i.e., specular reflection).

Feature Mapping Using Laser Backscatter Energy: Opposition "Hot Spot" Retro-reflection

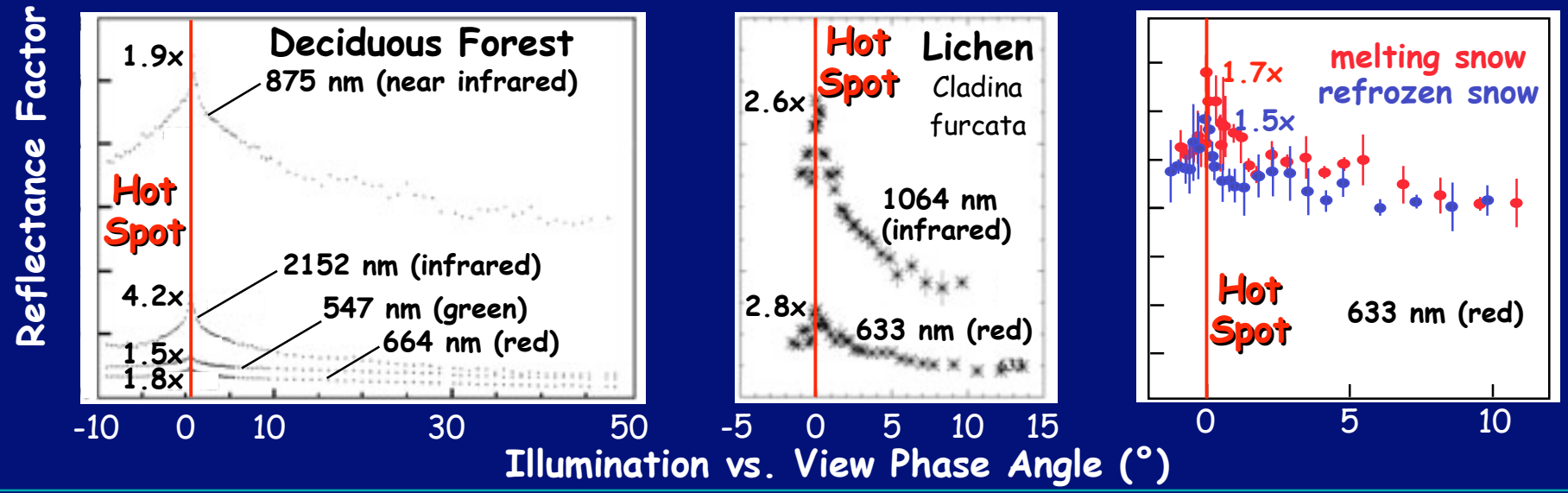
Opposition: illumination angle = view angle
- always the geometry for laser altimeters
- very rarely the geometry for passive imaging

Causes:
- absence of self shadowing
- single-scatter coherent phase amplification
- specular (fresnel) reflection, in some cases

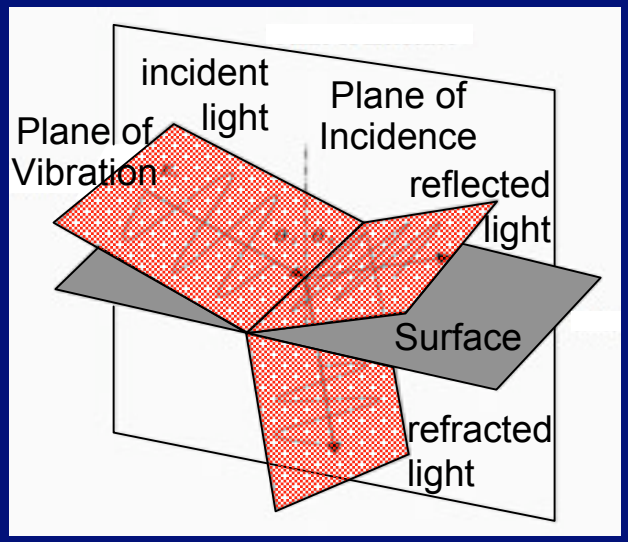
Function of:
- particle size
- surface composition and roughness
- laser wavelength & incidence angle
- transmitter & receiver polarization planes

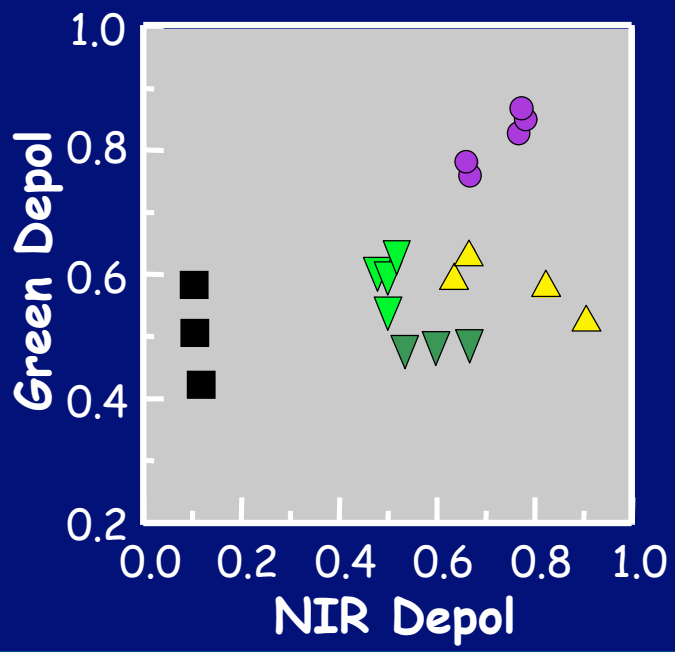
MODIS Airborne Simulator
http://cloud.ucsd.edu/dscovr/objectives/517

Laser Retro-reflection
Kaasalainen & Rautiainen, 2005, JGR
Kaasalainen et al., in review



Feature Mapping Using Laser Backscatter Energy: Depolarization Ratio





Unlike sunlight, emitted laser light is plane polarized (orientation of the vibration plane of the electric field wave remains constant).

Single-scattering reflection or refraction preserves the plane of polarization.

Multiple-scattering reflections cause depolarization (rotation of the plane of polarization).

The degree of depolarization is related to the proportion of single and multiple scattering from a surface or volume and is thus diagnostic of the reflecting target's scattering properties.

Snow
Ice
Broad-leaf Trees
Needle-leaf Trees
Salt, Sand, Gravel, Asphalt

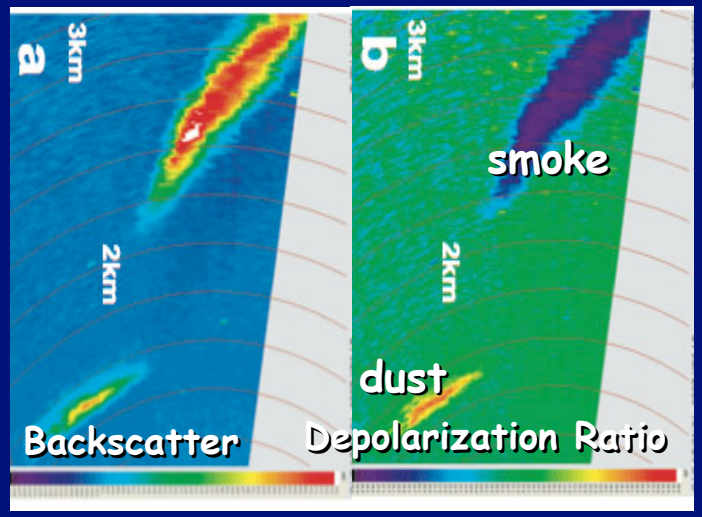
$$\text{Depolarization} = P_{\perp}/P_{//}$$

Atmospheric Lidar:
Heritage for Range-resolved Laser Depolarization

Laser backscatter depolarization is used to differentiate liquid water and frozen water (ice) in clouds, and aerosol type based on particle size

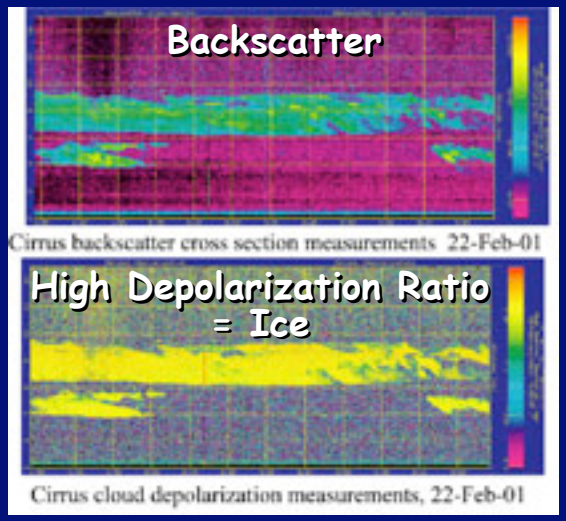
Ground-based Atmospheric Polarimetric Lidars

NCAR REAL



Aerosol Type

UW HSRL



Cloud Water State

Spaceflight Atmospheric Polarimetric Lidar

Primary Instrument:
Cloud-Aerosol Lidar with Orthogonal Polarization
3-channel lidar:
532 nm parallel PMT
532 nm perpendicular PMT
1064 nm APD

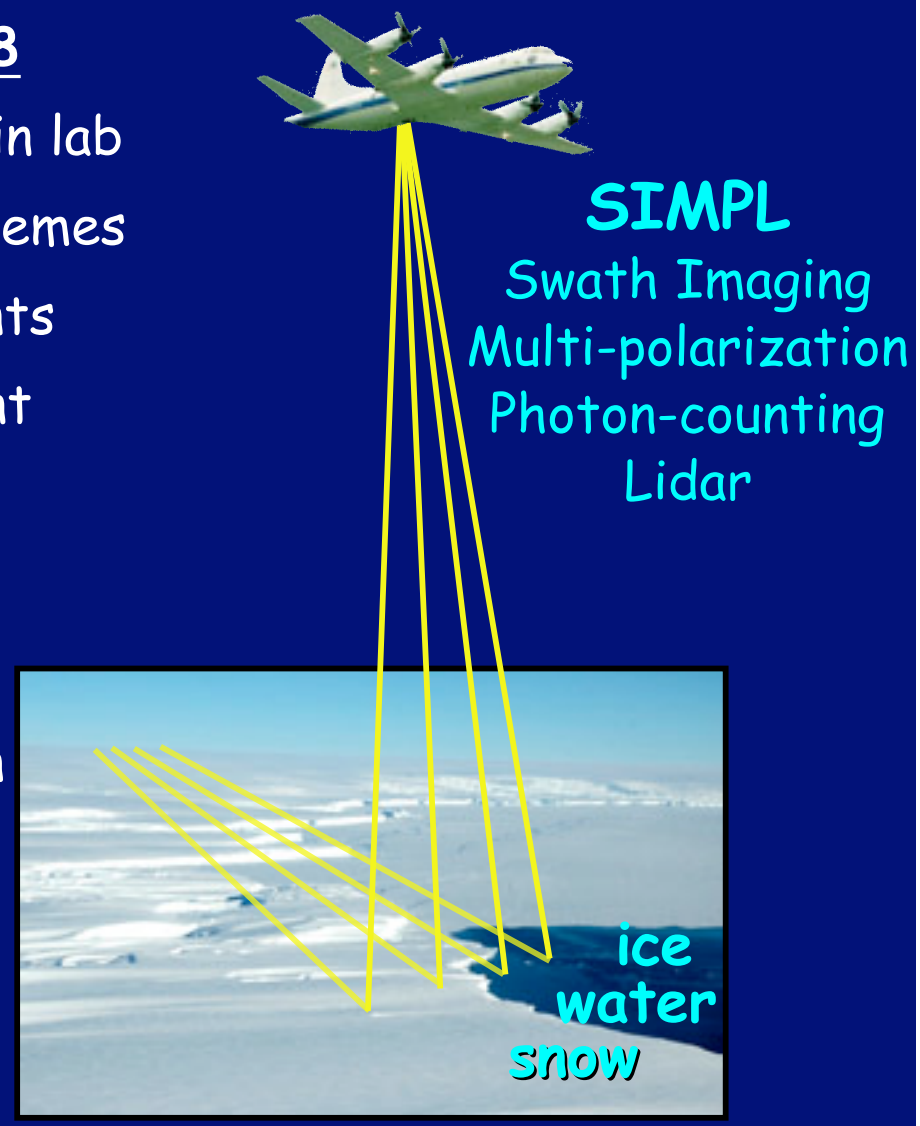
$$\text{Normalized Depolarization} = \frac{P_{//} - P_{\perp}}{P_{//} + P_{\perp}}$$

$P_{//}$ = return intensity parallel to transmit polarization

$P_{\perp}$ = return intensity perpendicular to transmit polarization

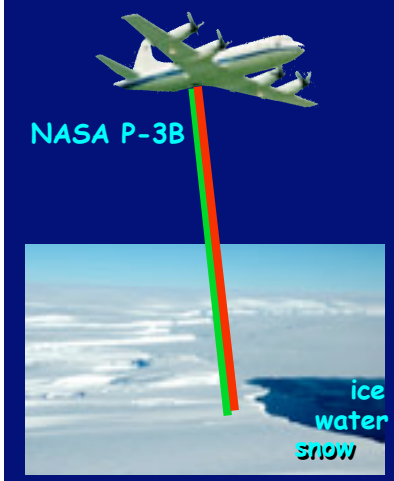
Three year effort: 2006 - 2008

- measure retro-reflection properties in lab
- evaluate alternative laser ranging schemes
- identify and test candidate components
- develop prototype airborne instrument
  - 1-beam profile in 2007
  - 4-beam bush-broom in 2008
  - 532 & 1064 nm wavelengths
  - parallel & perpendicular polarization
- collect and analyze airborne data as part of the International Polar Year
- define spaceflight instrument and mission implementation



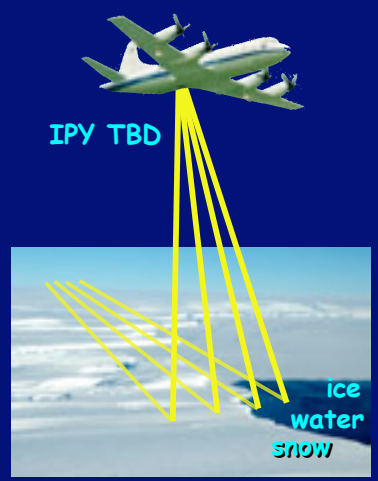
Lidar Swath Mapping Incremental Development Path to Space

SIMPL
COTS Components
Breadboard Design
2007



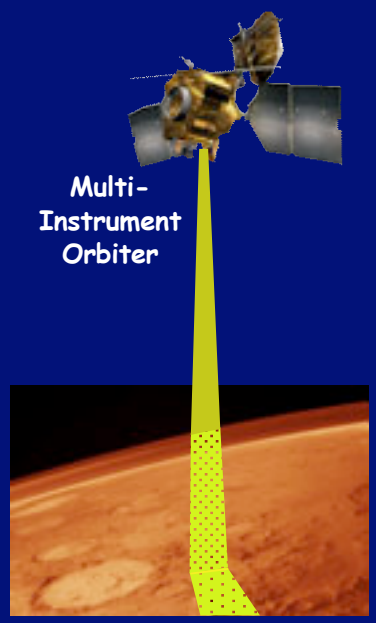
6 km flight altitude
single-beam profile

SIMPL
Space Prototype
Design & Components
2008



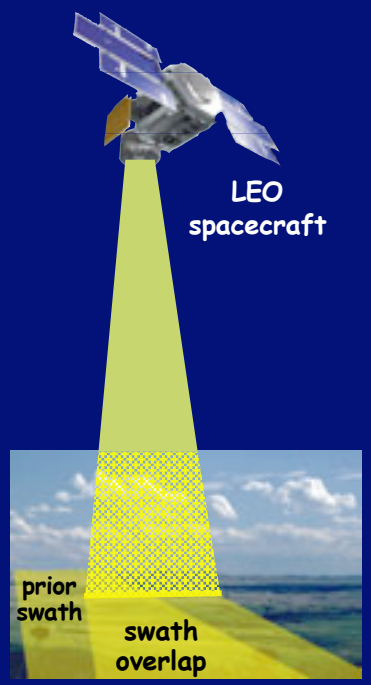
6 km flight altitude
multi-beam push-broom
50 m wide beam pattern

Mars &
Icy Moons
Missions



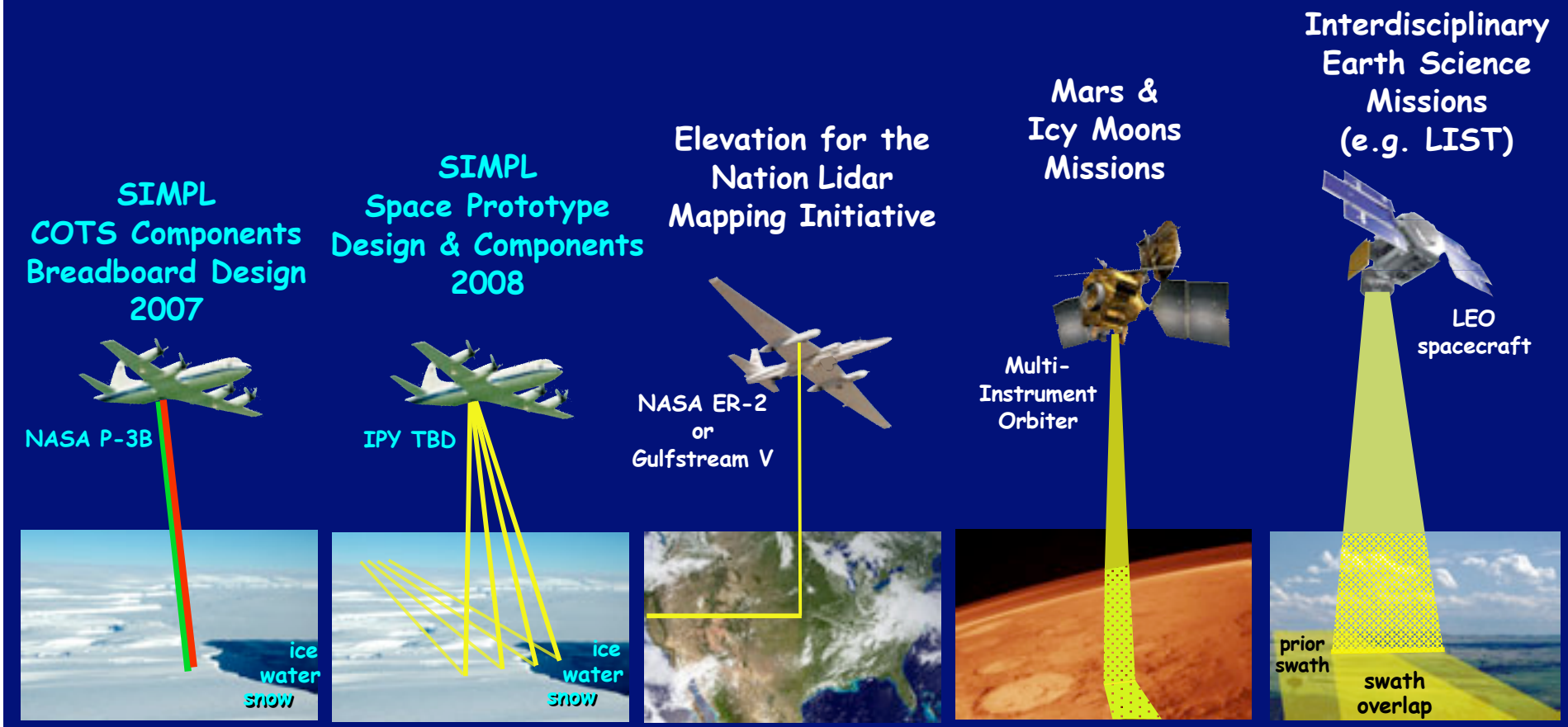
TBD flight altitude
along-track push-broom
TBD wide swath

Interdisciplinary
Earth Science
Missions
(e.g. LIST)



525 km flight altitude
along-track push-broom
300 m wide swath

Lidar Swath Mapping Incremental Development Path to Space



6 km flight altitude single-beam profile	6 km flight altitude multi-beam push-broom 50 m wide beam pattern	15 km flight altitude push-broom scanning 10 km wide swath	TBD flight altitude along-track push-broom TBD wide swath	525 km flight altitude along-track push-broom 300 m wide swath

National High-Altitude Mapping Concept: Implementation Approach

- **Long-duration, long-range aircraft (e.g., ER-2, Gulfstream V)**
  - ✓ high-altitude flights at 50,000 to 60,000 ft above commercial airspace
  - ✓ aircraft cruise speed = 200 m/sec (~ 800 km/hr)

- **Cross-track scanned bush-broom laser altimeter**
  - ✓ NASA-developed based on spaceflight approach
  - ✓ 10 km wide swath & products with 3 m grid posting
  - ✓ nationally uniform data acquisition and processing
  - ✓ technology transferred to commercial sector
- **Potential for complimentary instrumentation**
  - ✓ airborne gravity for improved geoid model
  - ✓ airborne magnetics for crustal structure
  - ✓ multi-spectral or hyper-spectral optical imaging
  - ✓ dual-wavelength SAR Interferometry
- **Fly to and map regionally cloud-free areas**
- **Continue low-altitude, higher-resolution (≤1m) commercial lidar mapping**
  - ✓ urban areas and other high-priority locations
  - ✓ cal/val of national mapping products in selected areas

National High-Altitude Mapping Concept: Laser Altimeter Instrumentation

- **Multiple-beam bush-broom scanned cross-track**
  - ✓ 36 beams x 3 m beam spacing = 108 m scan width
  - ✓ ±18° scan = 10 km wide along-track swath
  - ✓ 2 Hz scan rate = 8% along-track scan overlap
- **400 KHz fiber laser array transmitter**
  - ✓ 20 transmit pulses / cross-track meter / beam
  - ✓ short pulse-width (1 nsec), plane-polarized, 532 nm (± 1064 nm)
  - ✓ 40 pulses simultaneously in-flight per beam = 375 m range ambiguity for transmit & receive pairs
- **Photon counting receiver**
  - ✓ 4.3 million single photon surface ranges per second (@ nominal 30% probability of detection)
  - ✓ 6 detected photons / cross-track meter / beam = 2 detected photons / square meter
  - ✓ 18 detected photons per 3 m pixel
  - ✓ parallel & cross-polarized channels for surface type differentiation
  - ✓ narrow band-pass etalon filter for solar background rejection
- **High-precision, event-timing ranging electronics**
  - ✓ 10 cm range precision per detected photon

National High-Altitude Mapping Concept: Airborne High-Altitude Geolocation

- **Aircraft Trajectory**
  - ✓ Point positioning Global Differential GPS (GDGPS) RMS vertical accuracy ~ 10 cm

- **Optical Bench Attitude**
  - ✓ High-end gyros + star camera + GDGPS (e.g., ICESat)
  - ✓ Total-angle pointing knowledge:
    0.003° = 10 arc sec (3x WORSE than ICESat)
    = 10 cm flat-surface range error at scan mid-point (± 9°)
- **Geolocation of Photon Returns in Point Cloud**
  - ✓ Simultaneous solution of pointing, timing, and trajectory errors using GSFC Geodyn range-residual, least-squares method applied to along-track swath overlaps
- **Performance Analysis**
  - ✓ 10 cm range precision per single photon (due to short pulse & high precision timing)
  - ✓ sqrt (18 photons) per 3 m pixel = 2 cm range precision for flat, non-vegetated pixels
  - ✓ Elevation accuracy = RSS(2 cm + 10 cm + 10 cm) = 14 cm RMSE
    - at mid-points from nadir to swath edges
    - better at nadir but less good at swath edges

National High-Altitude Mapping Concept: JPL Real-time Global Differential GPS Trajectories

GDGPS Ground Station Network

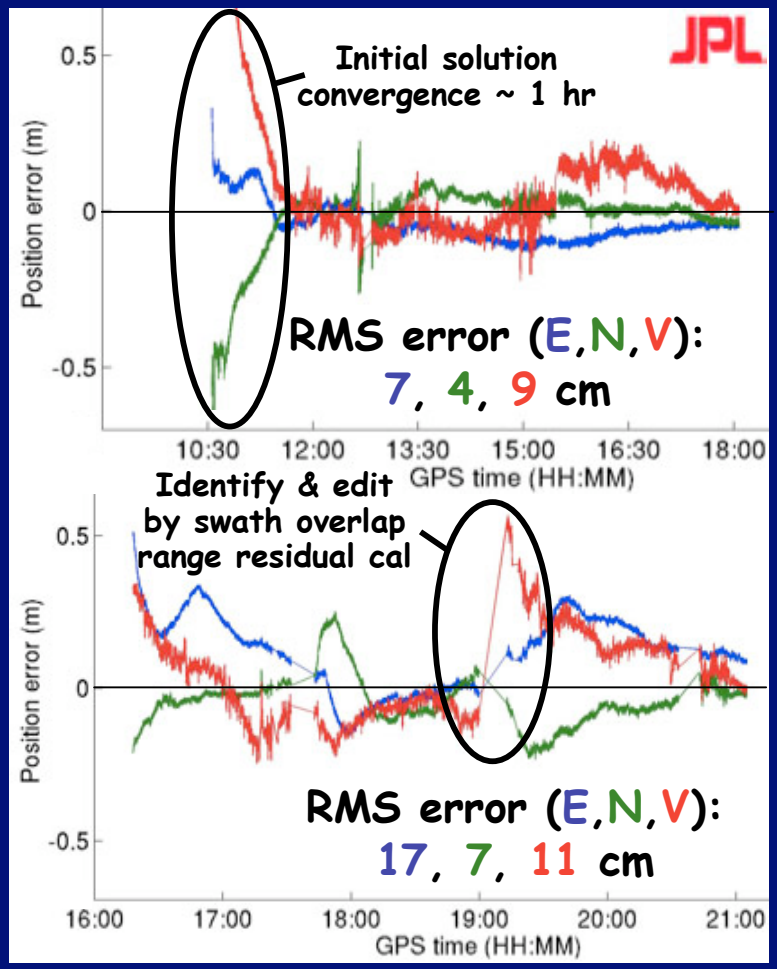
Network solution of GPS orbit and clock corrections broadcast globally in real-time

Accuracy (3D RMS) for Airborne Trajectory
dual-frequency, 1 Hz stand-alone, mobile receiver point positioning solution

Latency:	< 10 sec	1 day to 1 week	> 1 week
Accuracy:	< 25 cm	< 15 cm	< 10 cm

Available as commercial service globally in real-time via NAVCOM Starfire

GDGPS Trajectory Difference vs. Kinematic Short-baseline Solution
(Greenland 2002 ATM flights)

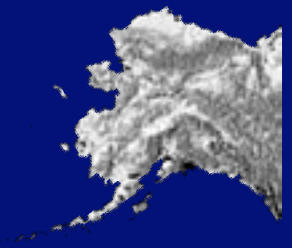


National High-Altitude Mapping Concept: Continental U.S. and Alaska Coverage

Complete Mapping Coverage ~ 2.5 years

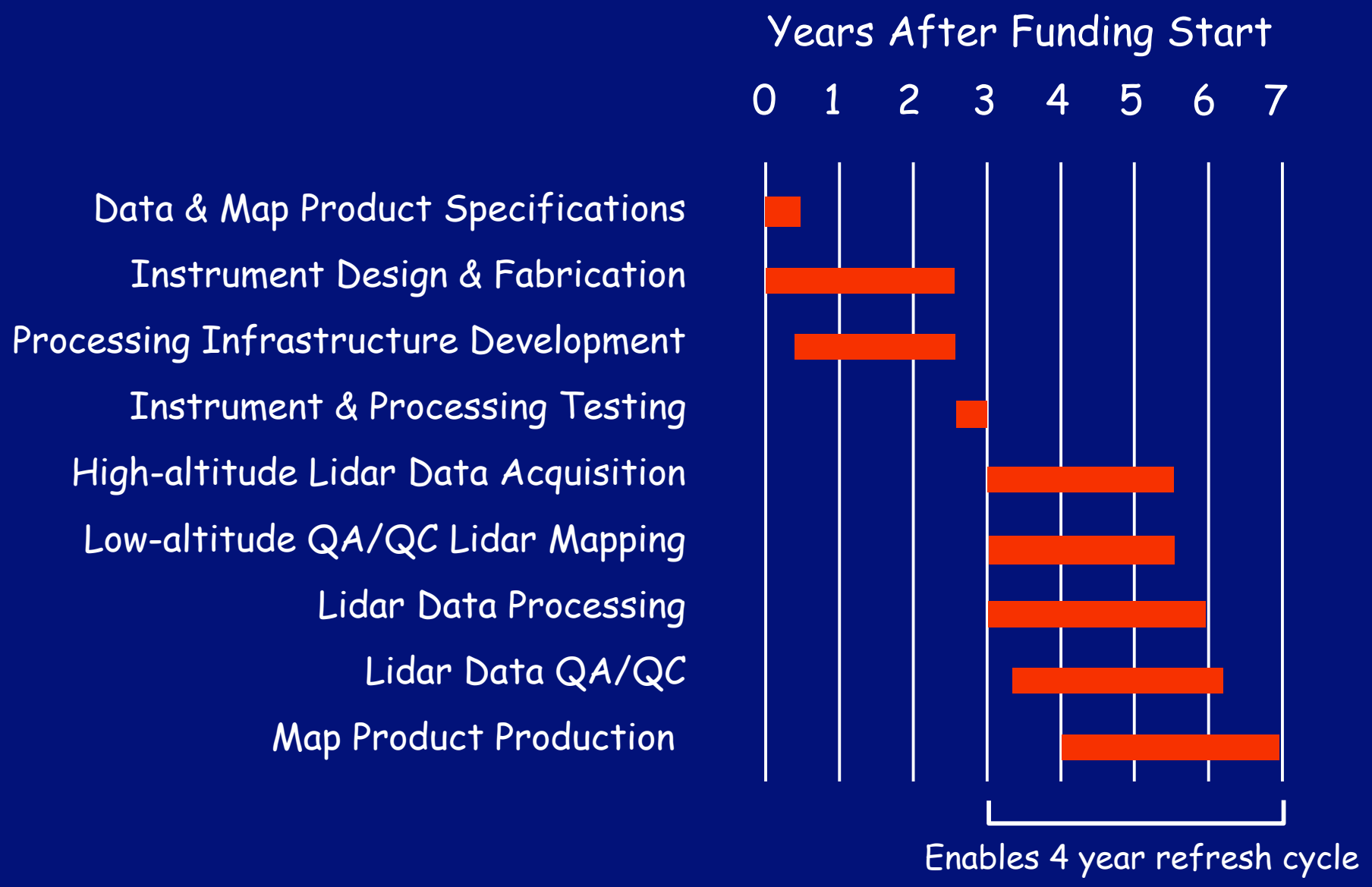
- 2 aircraft based on east & west coasts
  - Deploy to clear-sky areas
- 5 km flight line spacing = 50% swath sidelap
  - Doubles data density
  - Prevents gaps due to sparse dense clouds & instrument drop-outs
  - Combines near-nadir data with large scan-angle data
  - Adjacent flight lines flown in opposite directions
    - enables robust along-track bias calibration
  - Validation by swath differencing can be done everywhere
- Conterminous U.S. = 560 EW flight lines @ 5.3 hrs
- + Alaska = 260 EW flight lines @ 1.6 hrs
  - = 3400 data collection flight hours
  - x 1.5 (for transits & turns) = 5100 total flight hours
  - ÷ 6 hours/day ÷ 2 planes ÷ 50% flyable days
  - = 850 days ~ 2.5 years

Conterminous U.S.
+ Canadian & Mexican border areas:
25° NS x 50° EW (average)
= 2800 km x 4200 km

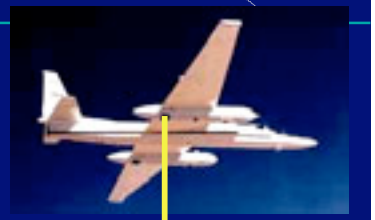


Alaska + Canadian border area:
12° NS x 28° EW (average)
= 1300 km x 1300 km

National High-Altitude Mapping Concept: Estimated Timeline for Project Completion



National High-Altitude Mapping Concept: Potential Partner Roles



USGS:

- project management

Local, state and federal agencies:

- requirements for national lidar data & products meeting their mandates

NASA:

- fabricate and test high-altitude airborne lidar instruments
- implement processing methods & infrastructure
- provide instrumentation and infrastructure to commercial sector

Commercial Sector:

- acquire and process high-altitude, nation-wide data
- acquire and process low-altitude, higher-resolution data for high-priority areas and for QC/QA
- apply point cloud classification & feature extraction
- generate TINs, DTMs and DSMs
- produce national lidar map products
- create and market value added products

Local, state and federal agencies:

- QA and utilize data and map products for their specific mandates

USGS:

- archive and distribute "raw" data, TINs, DTMs, DSMs and national map products