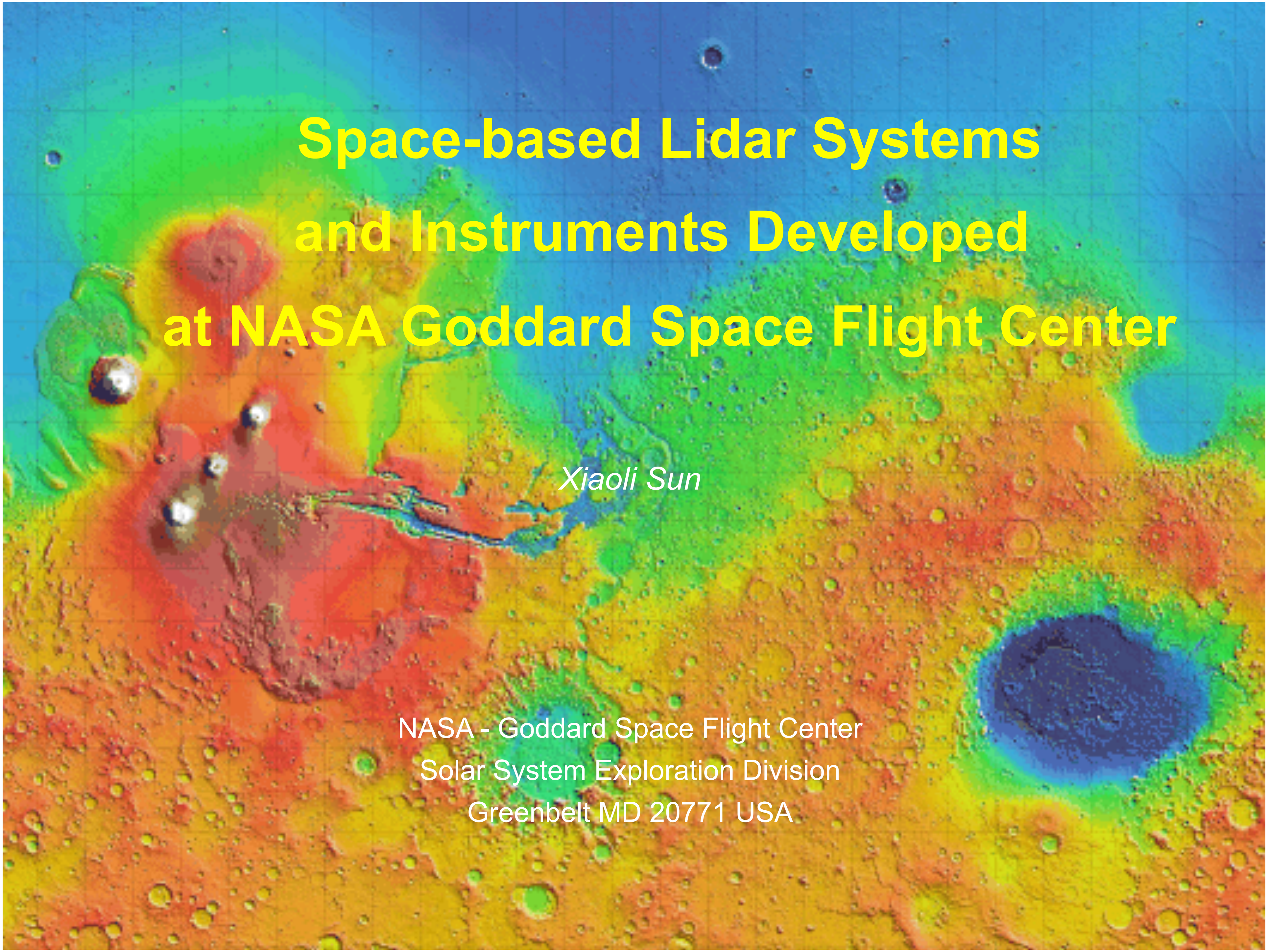


Space-based Lidar Systems and Instruments Developed at NASA Goddard Space Flight Center

Xiaoli Sun

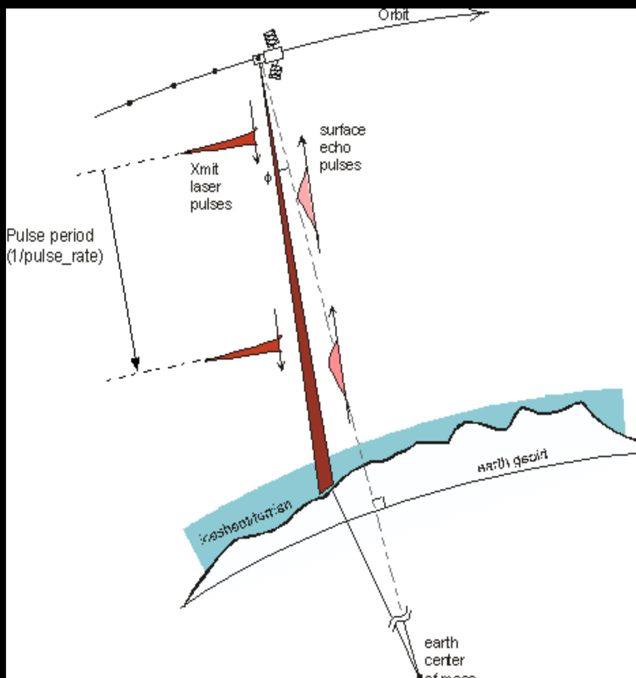
NASA - Goddard Space Flight Center
Solar System Exploration Division
Greenbelt MD 20771 USA

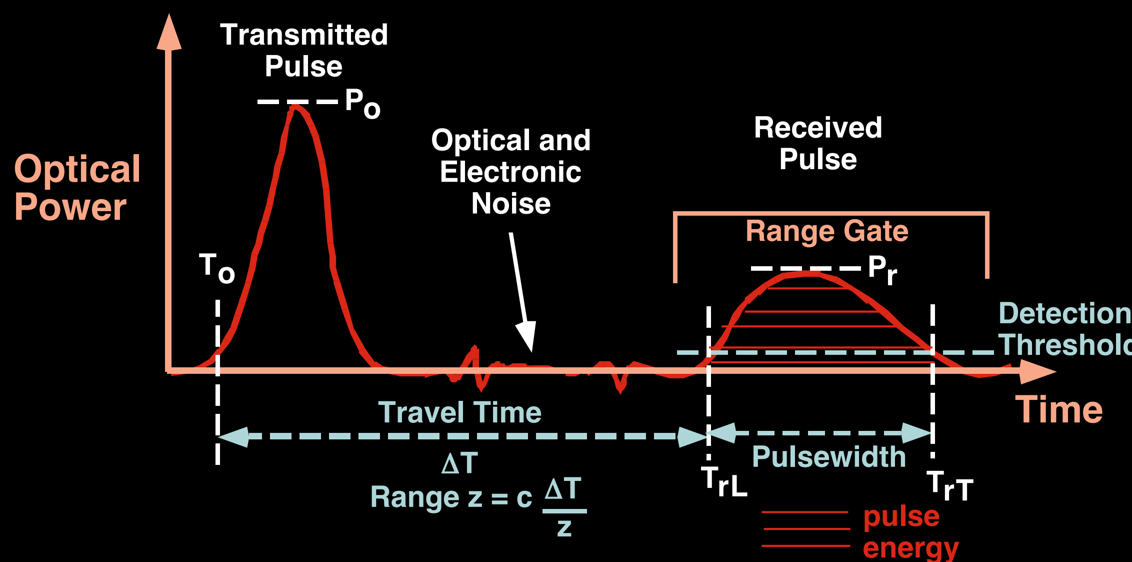
Outline:

- Introduction
- Early planetary lidar systems:
  - APOLLO 15, 16, 17
  - MOLA-1, NLR, LITE, SLA, and MOLA-2
- Recent space lidar missions:
  - GLAS, CALIPSO
  - HAYABUSA lidar, PHOENIX Lidar
  - MLA, LALT, LAM, LLRI, LOLA
- Observing laser light from space lidars
- Future lidar missions

Lidar: LIght Detection And Ranging

(Laser + Photonics + Light Scattering + Space Geodecy)



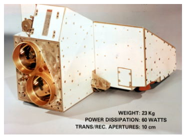


Range -> Elevation
Pulsewidth -> Surface roughness
Received/Transmitted Pulse Energy ->Surface reflectivity

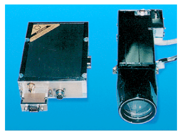
Lidar can also be used to measure atmosphere backscattering and absorption.

Space Lidar Systems to Date
(not including Space Shuttle Missions)

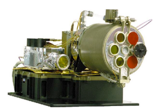
Apollo, - moon
NASA (1971-1972)



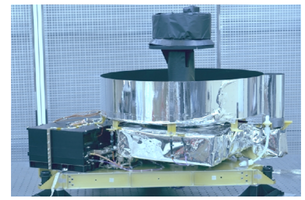
Clementine - moon
LLNL/NRL (1994)



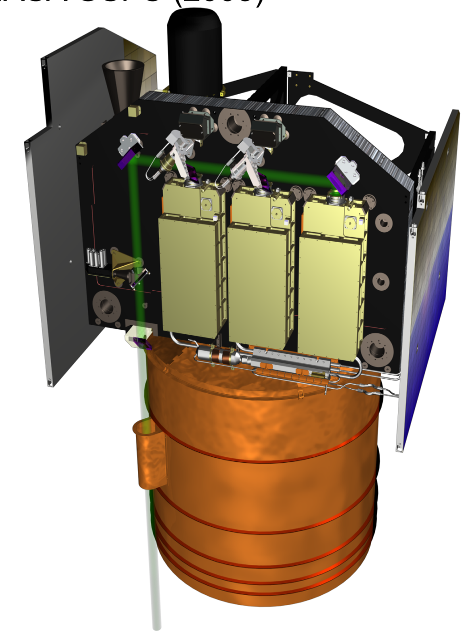
NEAR/NLR - Eros
JHU/APL (1996)



MGS/MOLA - Mars
NASA GSFC (1996)

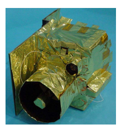


ICESat/GLAS - Earth
NASA GSFC (2003)

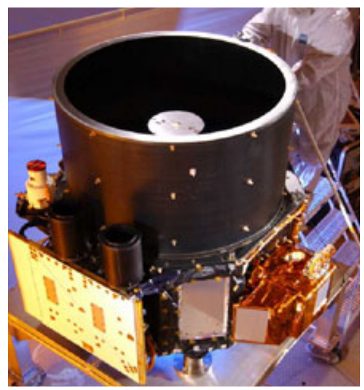


MESSENGER/MLA
- Mercury
NASA GSFC
(2004, still operating)

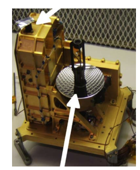
Hayabusa Lidar
- Itokawa
JAXA
(2004)



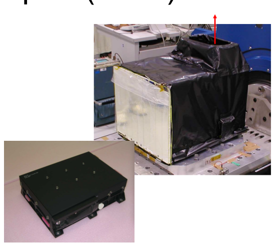
CALIOP/CALIPSO - Earth
NASA LaRC
(2006, still operating)



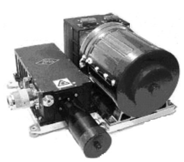
Phoenix Lidar
- Mars
CSA
(2008)



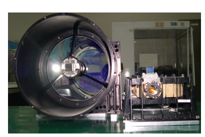
SELENE/LALT - moon
Japan (2007)



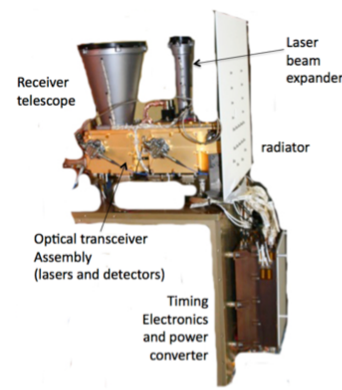
Chang'E - moon
China (2007)



Candrayaan/LLRI
- moon
India (2008)



LRO/LOLA - moon
NASA GSFC
(2009, still operating)

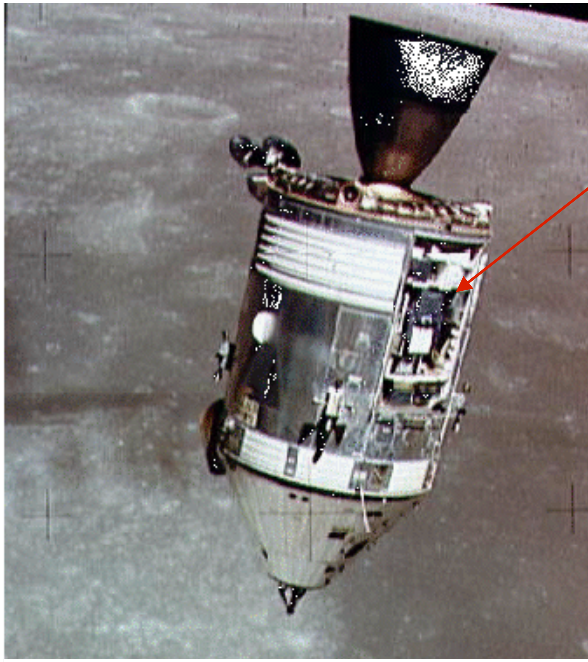


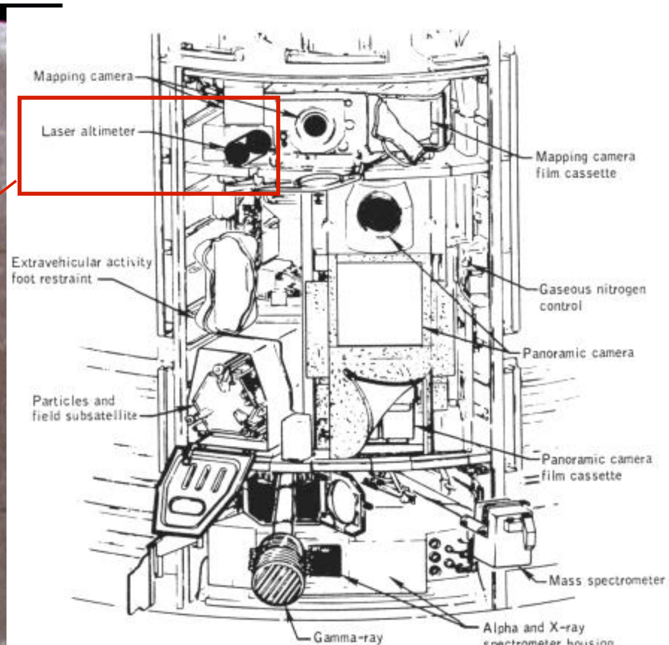
Comparison of Earth & planetary Lidar Systems

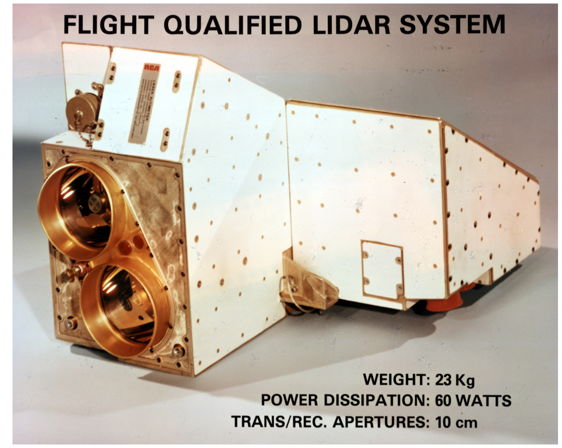
Missions	Instrument	Launch Date	Laser Energy	Pulse Rate	Precision	Mass/Power	Number of Altimetric Measurements
Clementine	LIDAR	25 Jan 1994	170 mJ	0.6, 8 Hz (burst)	40 m	2.4 kg, 6.8 W	72,000
NEAR	NLR	17 Feb 1996	15 mJ	1/8, 1, 2, 8 Hz	0.3 m	5 kg,17 W	11 million
MGS	MOLA	7 Nov 1996	50 mJ	10 Hz	0.4 m	26 kg, 34W	670 million
ICESat	GLAS	12 Jan 2003	75mJ/35 mJ*	40 Hz	0.1 m	330 kg, 300 W	3 billion
HAYABUSA	LIDAR	9 May 2003	10 mJ	1 Hz	1-10 m	3.6 kg, 17 W	4.1 million
MESSENGER	MLA	3 Aug 2004	20 mJ	8 Hz	0.15 m	7.4 kg, 25 W	11 million and counting
CALIPSO	CALIPO	28 Apr 2006	110mJ/110 mJ*	20 Hz	-	170 kg, 200 W	2 billion and counting
SELENE	LALT	14 Sep 2007	100 mJ	0.5, 1 Hz	5 m	19 kg, -	13 million
Chang'E-1	LAM	24 Oct 2007	150 mJ	1 Hz	5 m	16 kg, 25 W	8 million
Phoenix	LIDAR	4 Aug. 2008	0.3mJ/0.4mJ	100 Hz	-	6 kg, 30 W	65 million
Chandrayaan	LLRI	22 Oct 2008	13 mJ	10 Hz	1 m	10 kg, 15 W	millions
LRO	LOLA	18 Jun 2009	3 mJ/5	28 Hz x 5	0.15 m	13 kg, 34 W	5 billion and counting

Early Planetary Lidar
1970 -2000

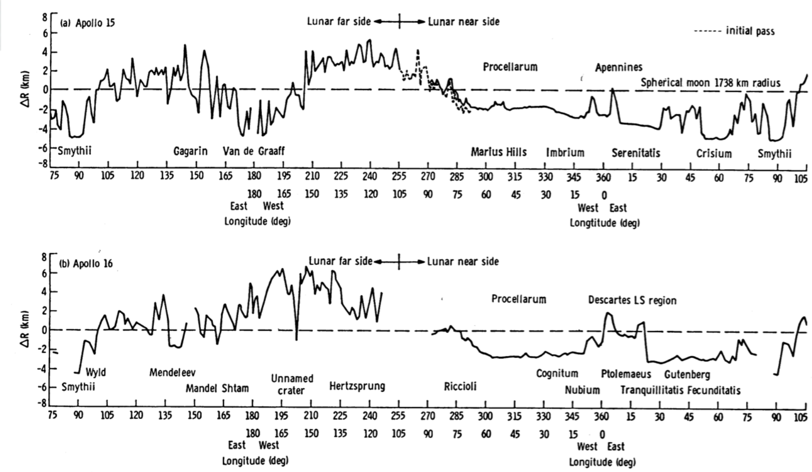
First Lidar in Space (1971) Apollo Laser Altimeters (Lunar orbit)

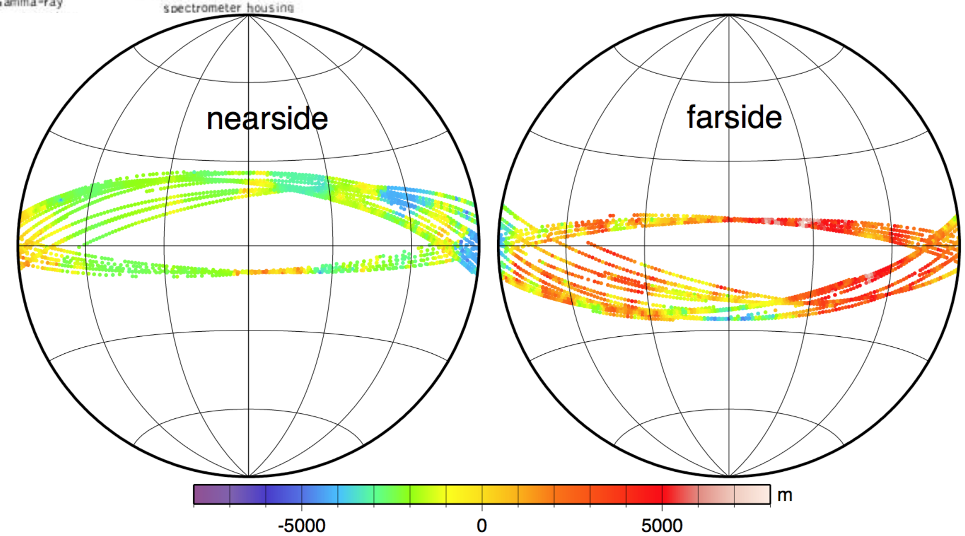




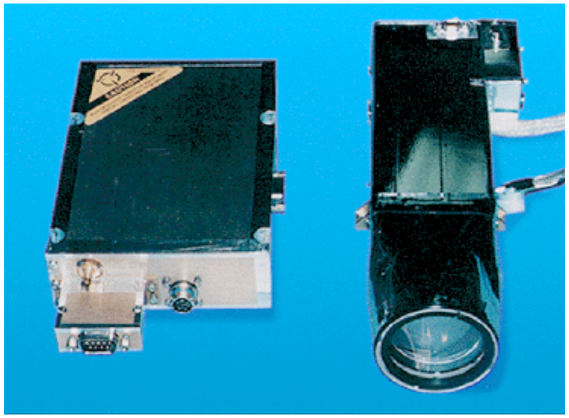


RCA Aerospace built flash lamp pumped, mechanically Q-switched ruby lasers for Apollos 15, 16 & 17
0.05 Hz

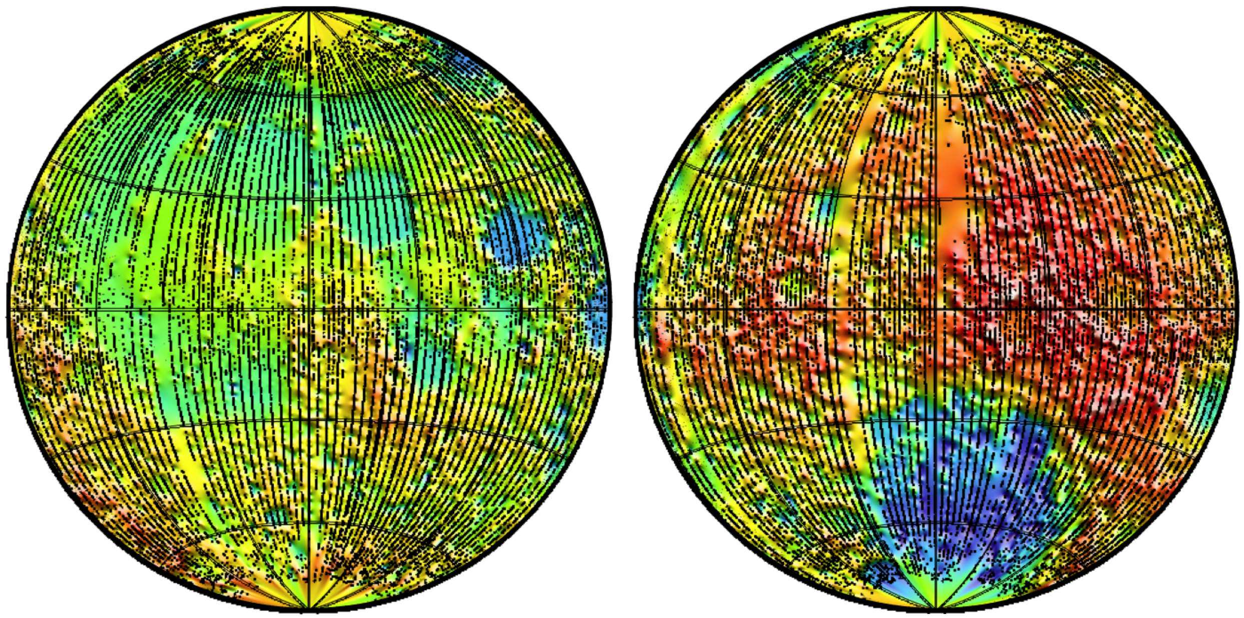




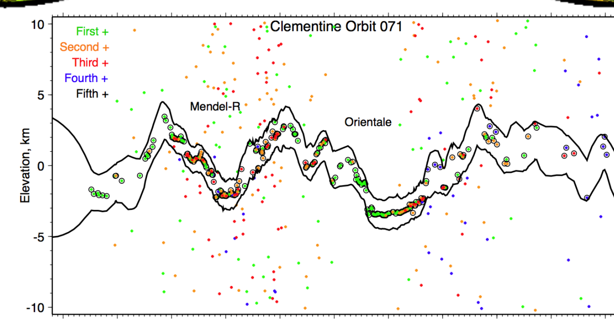
Clementine (1994, LLNL/NRL)



- 72,534 shots - 22x22 km “average” pixel size
- Cross-track spacing limits resolution to 80 km (deg. 66)
- 100 m vertical accuracy in COM coordinate system
- Resolves S. Polar basin; 16 km dynamic range



Diode pumped Nd:YAG laser
1064 nm, 170 mJ/pulse,
0.6Hz and 8Hz
10 cm telescope diameter
Si APD photodetector
2.4 kg, 6.8W



Near Laser Rangefinder (1998, APL)

GSFC

The Shape of 433 Eros from the NEAR-Shoemaker Laser Rangefinder

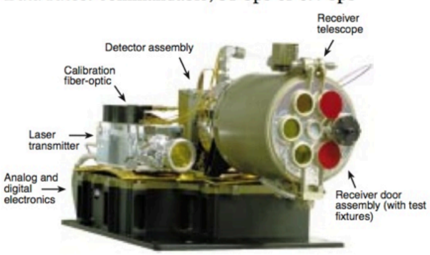
Maria T. Zuber,[1,2]* David E. Smith,[2] Andrew F. Cheng,[3] James B. Garvin,[2] Oded Aharonson,[1] Timothy D. Cole,[3] Peter J. Dunn,[4] Yanping Guo,[3] Frank G. Lemoine,[2] Gregory A. Neumann,[1,2] David D. Rowlands,[2] Mark H. Torrence[4]

oid (Fig. 1) (*15*). From these data we hav constructed a topographic model of Er (Fig. 2) with a spatial resolution of 960 m ar a radial accuracy of ~30 m (*16*) with respe to the asteroid's center of mass (*17*).

Eros has a mean radius of 7311 ± 10 (Table 1) and exhibits excursions in the equ torial plane that range from ~3500 m to ov 17,500 m. The maximum chord is 32.697 k (oriented along 3.96°N, 185.47°E to 0.31° 18.69°E), consistent with an orbital value

Specifications

General	Technical
Mass: 5 kg	**Laser wavelength:** 1.064 μm
Power: 20.7 W peak, 16.5 W average	**Range accuracy requirement:** 6 m
Volume: overall TX/RX assembly 37.5 cm (deep) × 21.6 cm (high) × 22.9 cm (wide) inclusive of overhangs; 10.9 × 15.2 × 3.8 cm laser power supply; 7.6 × 2.5 × 14 cm medium voltage power supply	**Range requirement:** 50 km
Data rates: commandable, 51 bps or 6.4 bps	**Inflight range calibration capability**
	Pulse repetition rate: commandable among 1/8, 1, 2, and 8 Hz
	Pulse energy: 15 mJ
	Pulse divergence: 235 μrad
	Pulse duration: 12 ns
	Range gates: two, commandable
	Detector threshold: commandable, eight values
	Receiver aperture: 7.6 cm (effective)
	Range quantization level: 31 cm
	Predicted range at asteroid acquisition: 150 km



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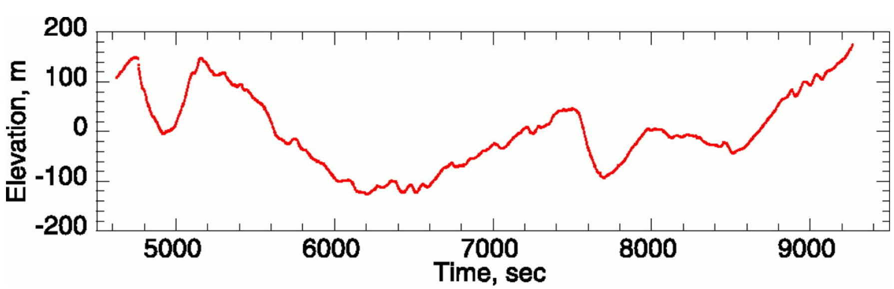


poorly constrained because the structure is situated within a regional low. Even given the depth uncertainty, Psyche is deeper relative to its size than simple (bowl-shaped) craters on the terrestrial planets, consistent with its formation in a low-gravity and perhaps a low-velocity regime.

A second, larger concavity, provisionally named Himeros, is centered at 0°N, 75°E. This structure spans a distance on the surface of slightly greater than Eros's mean radius and displays a saddle shape (Fig. 3), with the symmetry axis of its broad inflection in curvature [Web fig. 2 (*23*)] oriented approximately longitudinally. The structure also exhibits complex short-wavelength curvature variations to the east and west of the structure that trend approximately latitudinally. Himeros lacks topographic characteristics that are commonly associated with an impact origin such as a closed depression, rim, and ejecta blanket (*20, 30, 31*). If Himeros's present morphology was preserved since its time of formation, then this feature likely formed as a consequence of collision, i.e., contact between two bodies of roughly similar sizes. However, at the current resolution of the topographic model we cannot rule out the possibility that this structure formed as a result of impact when Eros was part of a larger parent body, or during the process of the asteroid's breakaway into a separate entity. In either of these scenarios, the morphology of an originally impact-generated Himeros would have been modified from its original configuration. We see no geophysical evidence that would suggest that Eros attained its present shape by accumulation or reaccumulation of smaller asteroidal bodies.

A mesh view of the shape of Eros (Fig. 4A) in the vicinity of Himeros includes superposed vectors of gravitational acceleration (*32*) that indicate directions of downslope movement. The highest slopes on the asteroid cluster to the southwest and northwest of Himeros, which are regions that have lower than average crater density (*18*), and collectively suggest that these are regions where regolith has been transported downward (with respect to the gravitational potential) by mass wasting.

The histogram in Fig. 4B shows that the average slope on a surface baseline of ~3° is about 10°, substantially higher than that on a comparable spatial scale on the terrestrial plan-

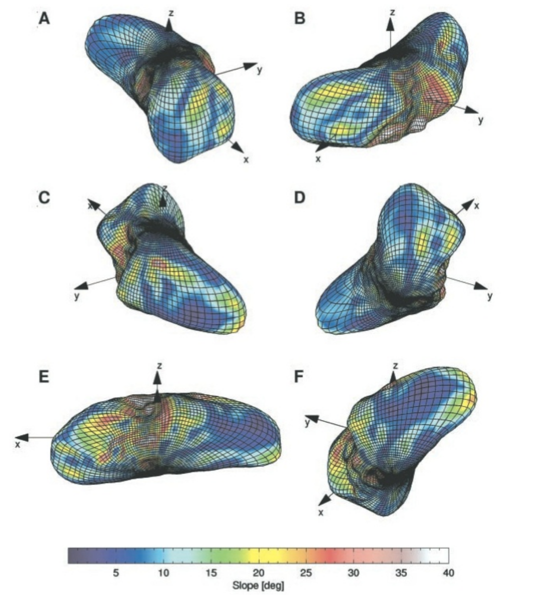


Fig. 3. Six perspective views of a three-dimensional shape model of 433 Eros from the NLR plotted to spherical harmonic degree and order 24. The mesh represents the scaled shape, and the surface facets are color-coded according to the surface slope with respect to a constant-density gravity field derived from the shape model (*32*). The asteroid is viewed at the following (elevation, azimuth) pairs: (**A**) 30°N, 60°E; (**B**) 30°N, 120°E; (**C**) 30°N, 0°E; (**D**) 30°S, 60°E; (**E**) 30°S, 300°E; and (**F**) 30°S, 0°E.

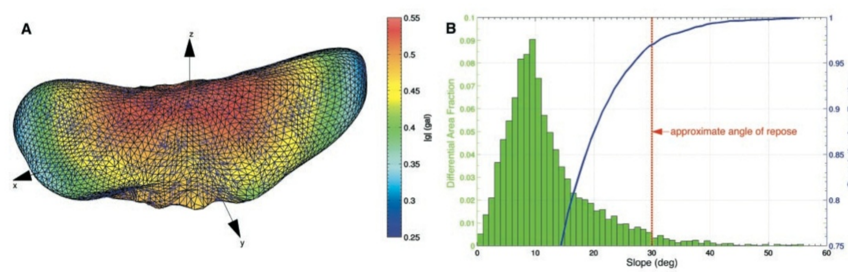
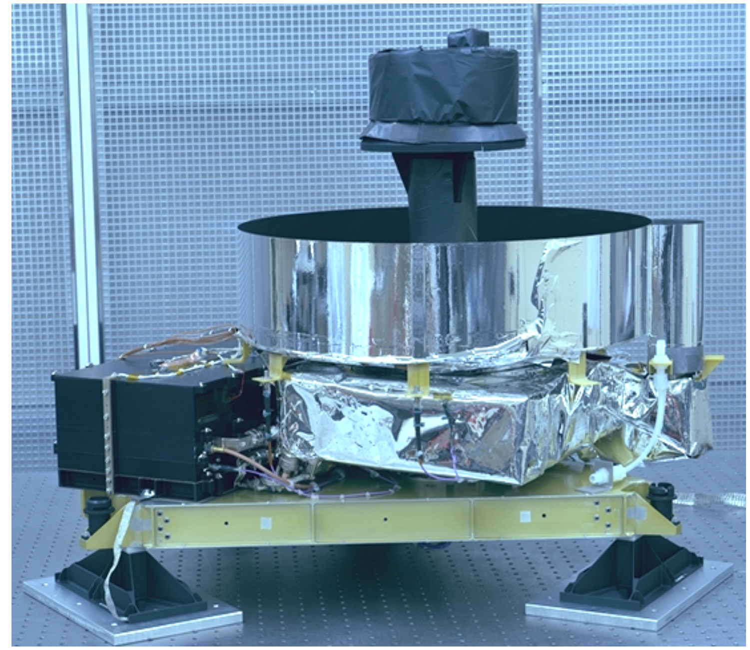


Fig. 4. (**A**) Vectors showing directions of gravitational acceleration ($\vec{g}$). Units are Gals, where 1 Gal = 1 cm s^{-2}. The asteroid is viewed from 30°N, 60°E. Colors represent the magnitude of $\vec{g}$ and arrows indicate the direction. (**B**) Histogram and cumulative frequency distribution of 3°-baseline surface slopes (*32*).

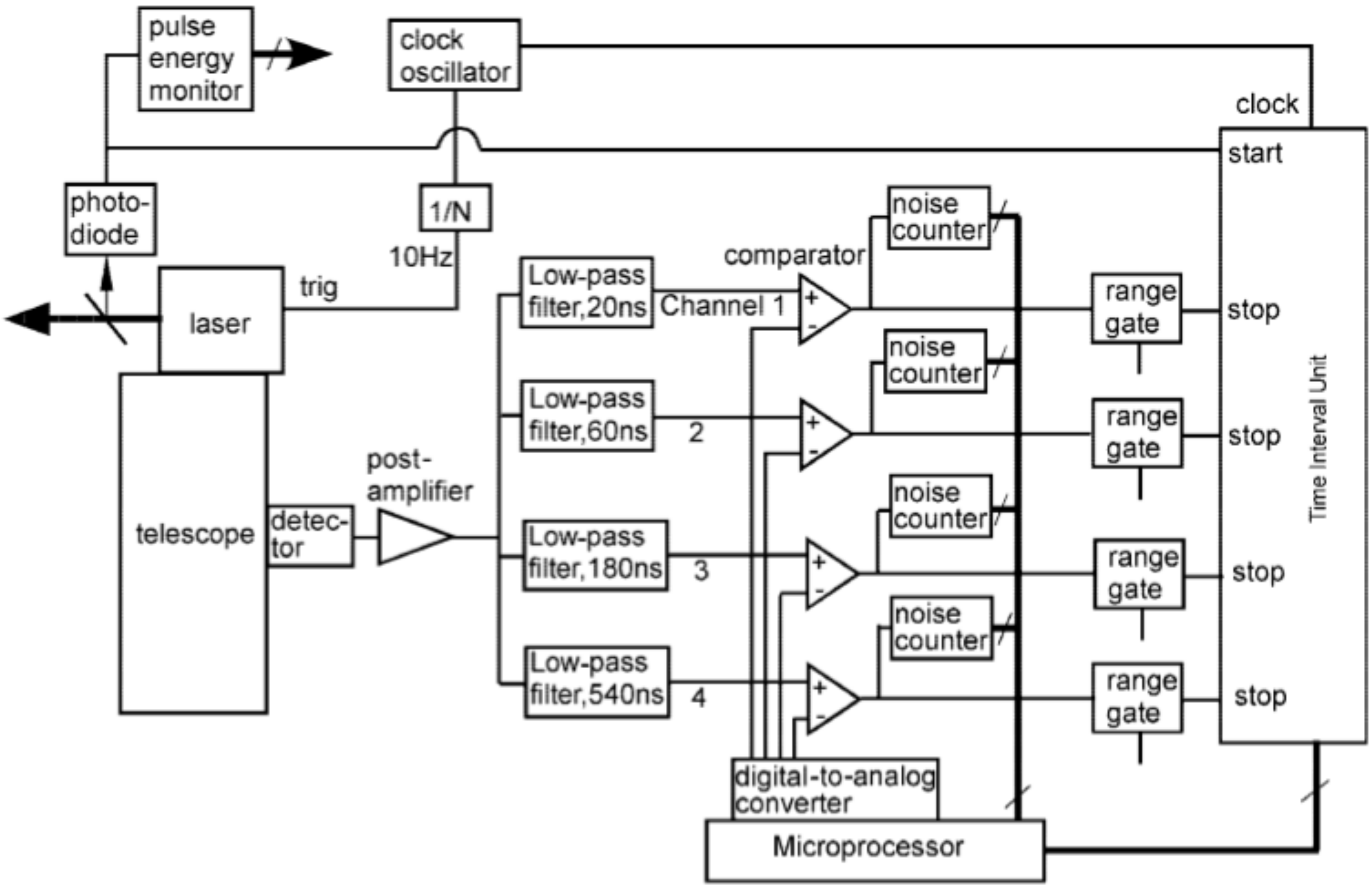
Mars Orbiter Laser Altimeter (1996, GSFC)

(initially on Mars Observer Mission, launched Sept., 1992)

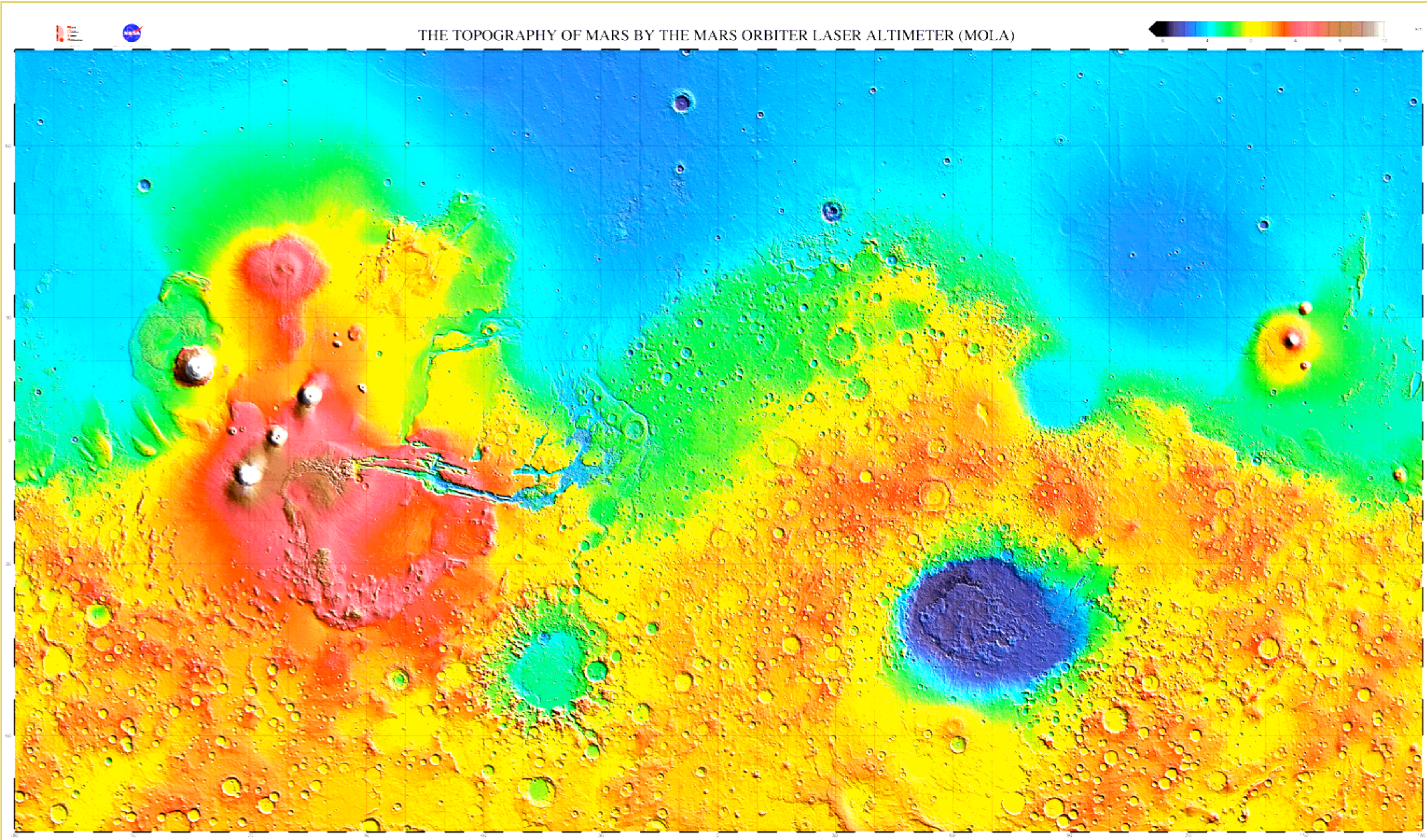


- Laser Wavelength: 1064 ± 0.2 nm
- Laser Pulsewidth: 8 nsec
- Pulse energy (start of mapping): 48 mJ
- Pulse repetition frequency: 10 Hz
- Range resolution: 38 cm
- Return pulses detected: ~99%
- Maximum range (hardware limit): 786 km
- Surface spot size in mapping orbit: ~168 m
- Along-track shot spacing: ~330 m
- Vertical accuracy (radial orbit error): <1 m
- Number of laser firings: 671,121,600
- Operated in lidar & radiometer modes

MOLA System Block Diagram

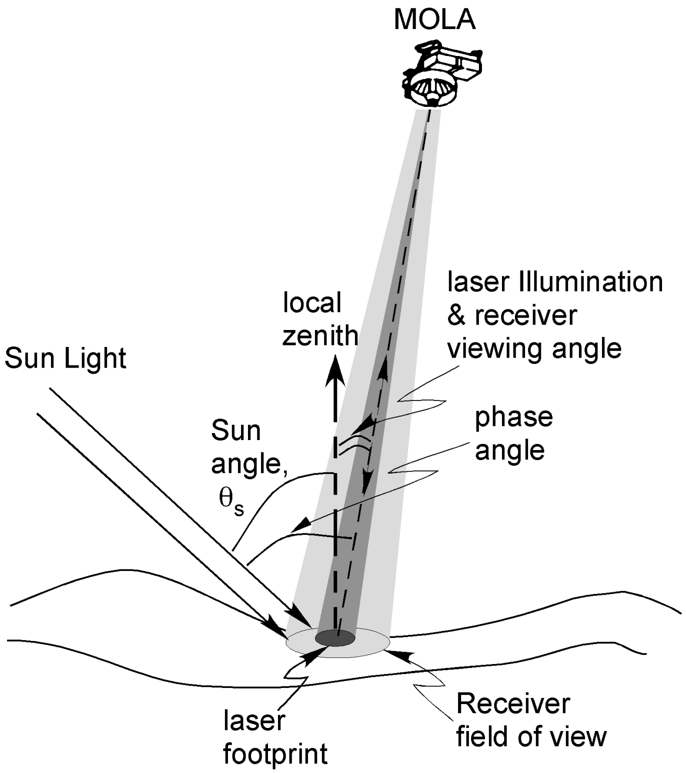


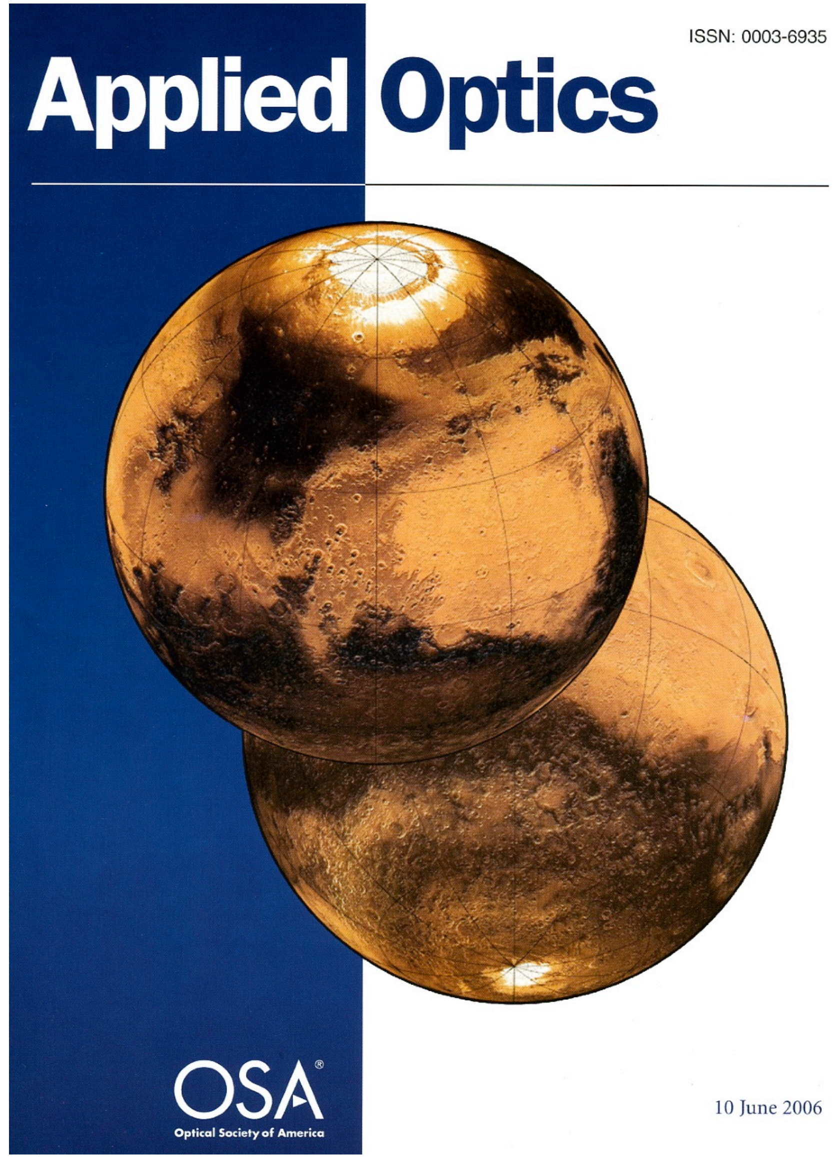
Topography of Mars from MOLA



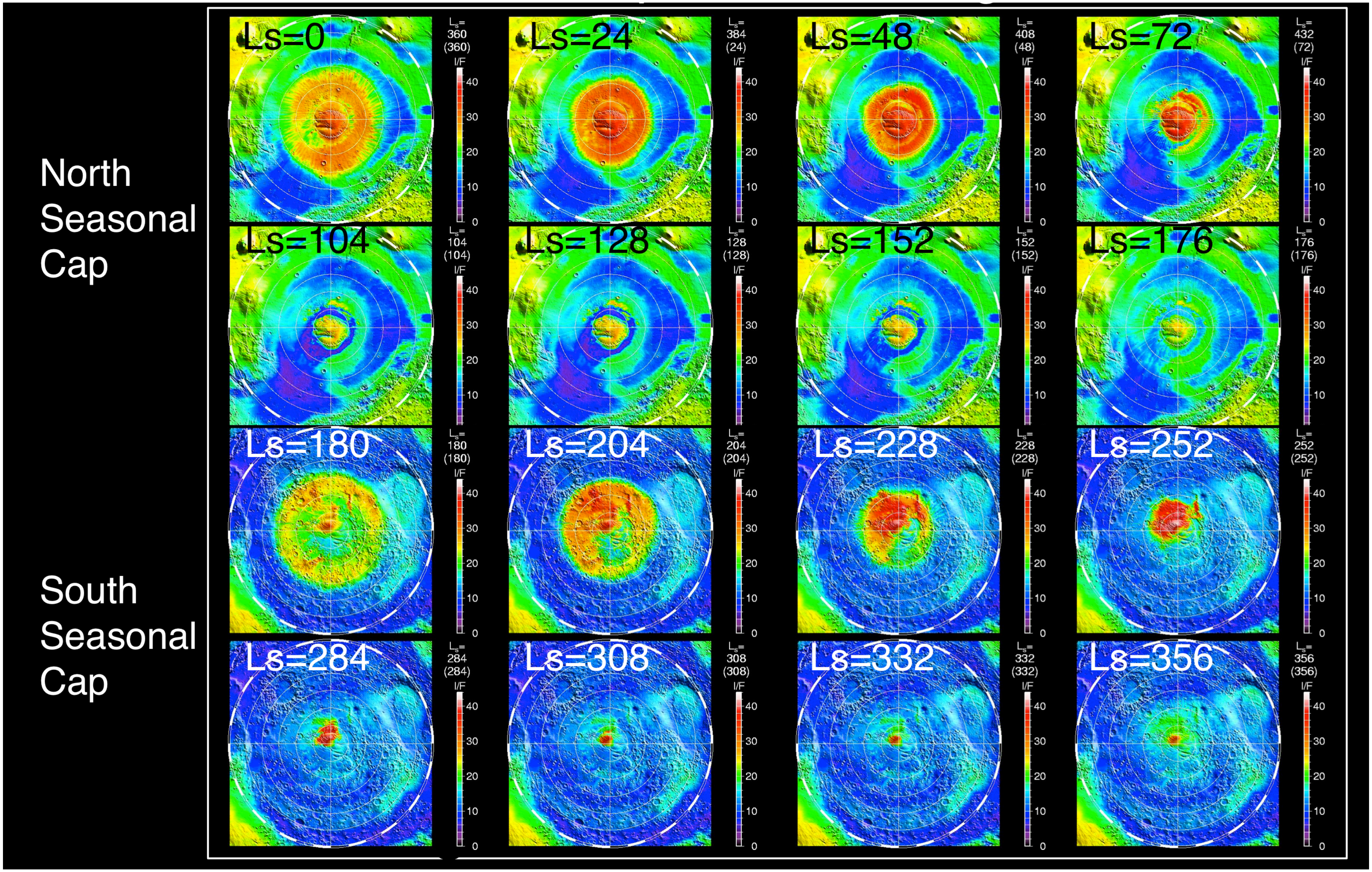
671 million altimeter measurements, <1 m topographic accuracy

MOLA 'Noise Map' of Mars



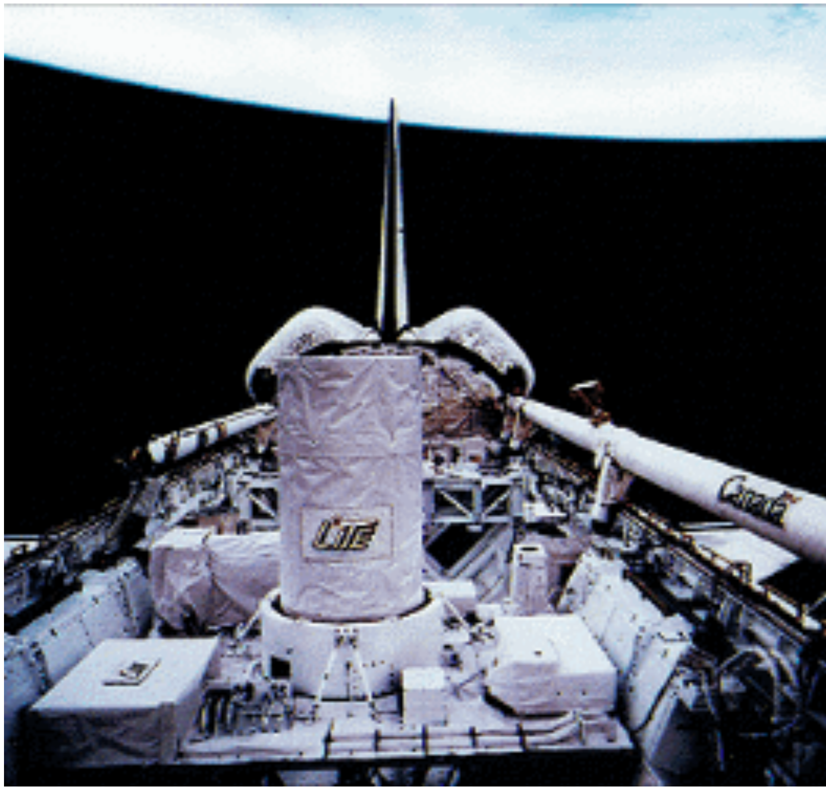


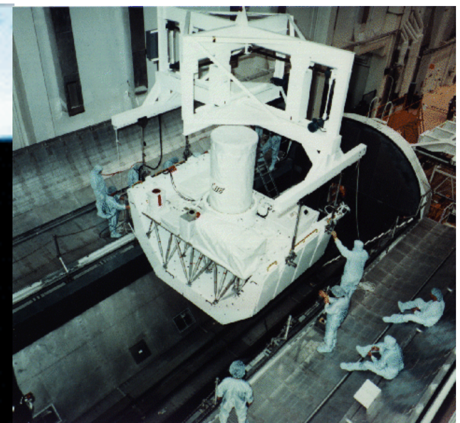
Mars Surface Reflectance to Sunlight from MOLA



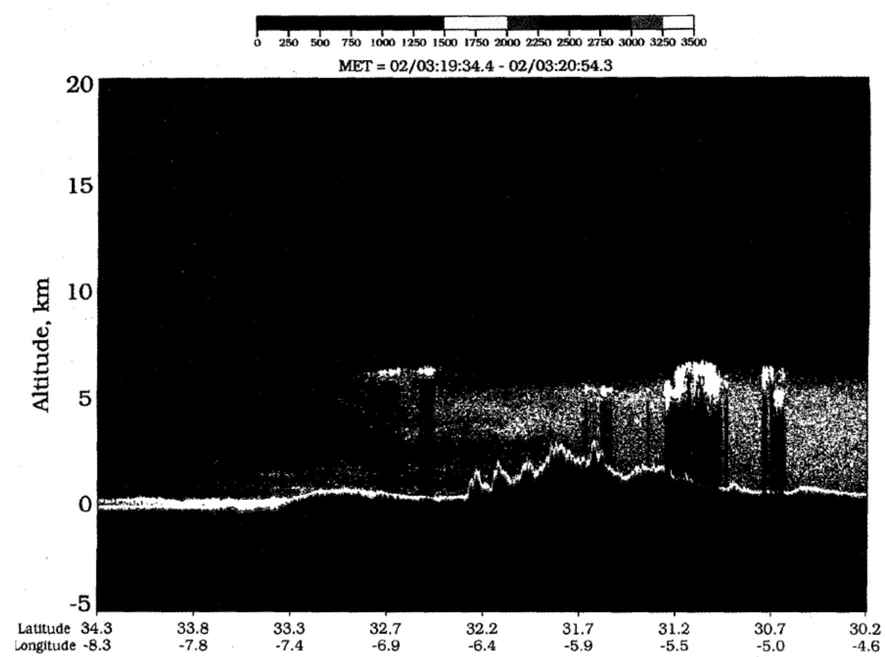
Earth Orbiting Lidars

LITE Experiment on Space Shuttle (1994, LaRC)





Flashlamp-pumped
Water-cooled
Pressurized canister

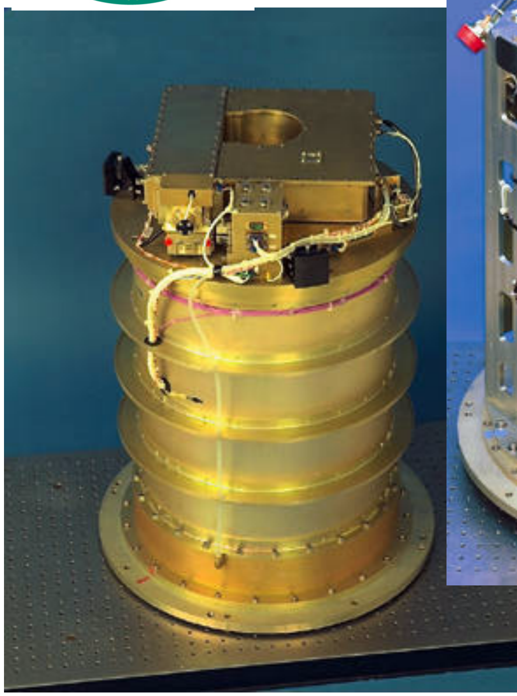


3. Offset-subtracted LITE return signal at 532 nm showing aerosol structure in the vicinity Atlas Mountains and the Atlantic coast of Morocco.

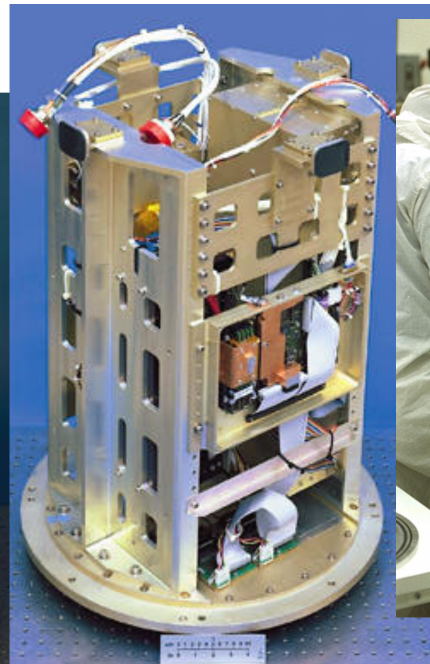
- The LITE instrument was flown aboard Space Shuttle Discovery on mission STS-64 in September 1994.
- Three measurement wavelengths: 355, 532, and 1064 nm.
- During its 11-day operation LITE accumulated 53 h of 10-sec averaged backscatter profiles within a few degrees of nadir
- **First lidar profiles of the Earth's atmosphere from space !**

Shuttle Laser Altimeter (SLA-1 & SLA-2)
GSFC Shuttle Hitchhiker Experiments

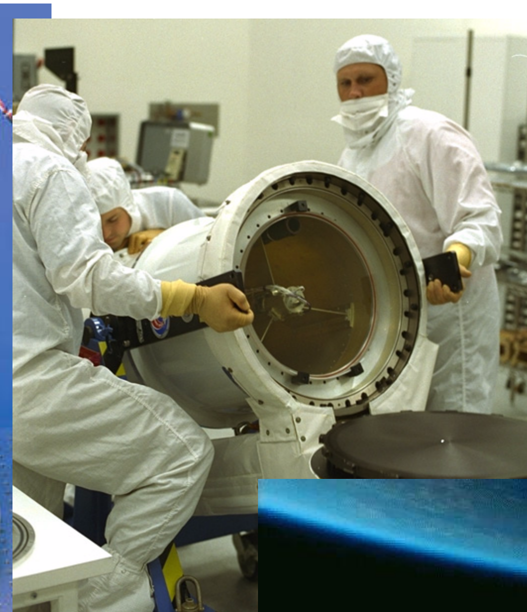
Jack Bufton, Jim Garvin, Bryan Blair, David Harding and others …



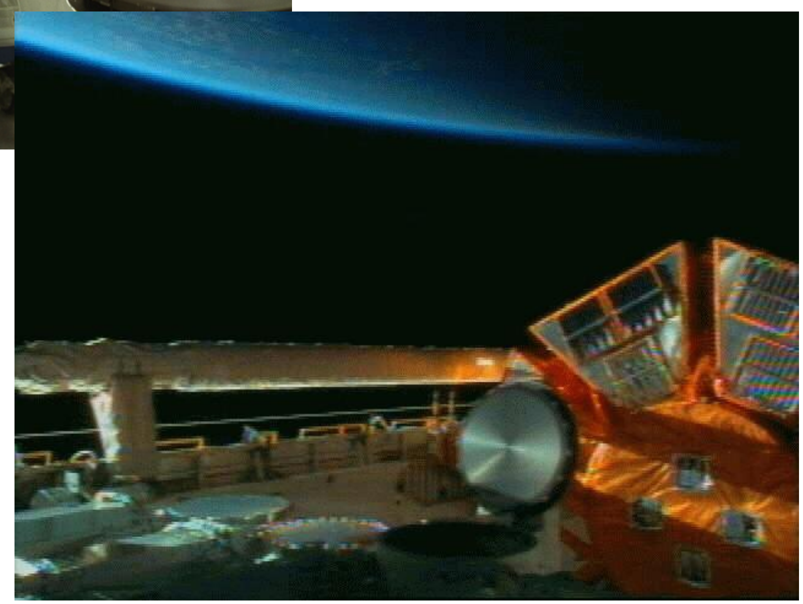
Laser Altimeter Canister



Altimeter Support Canister

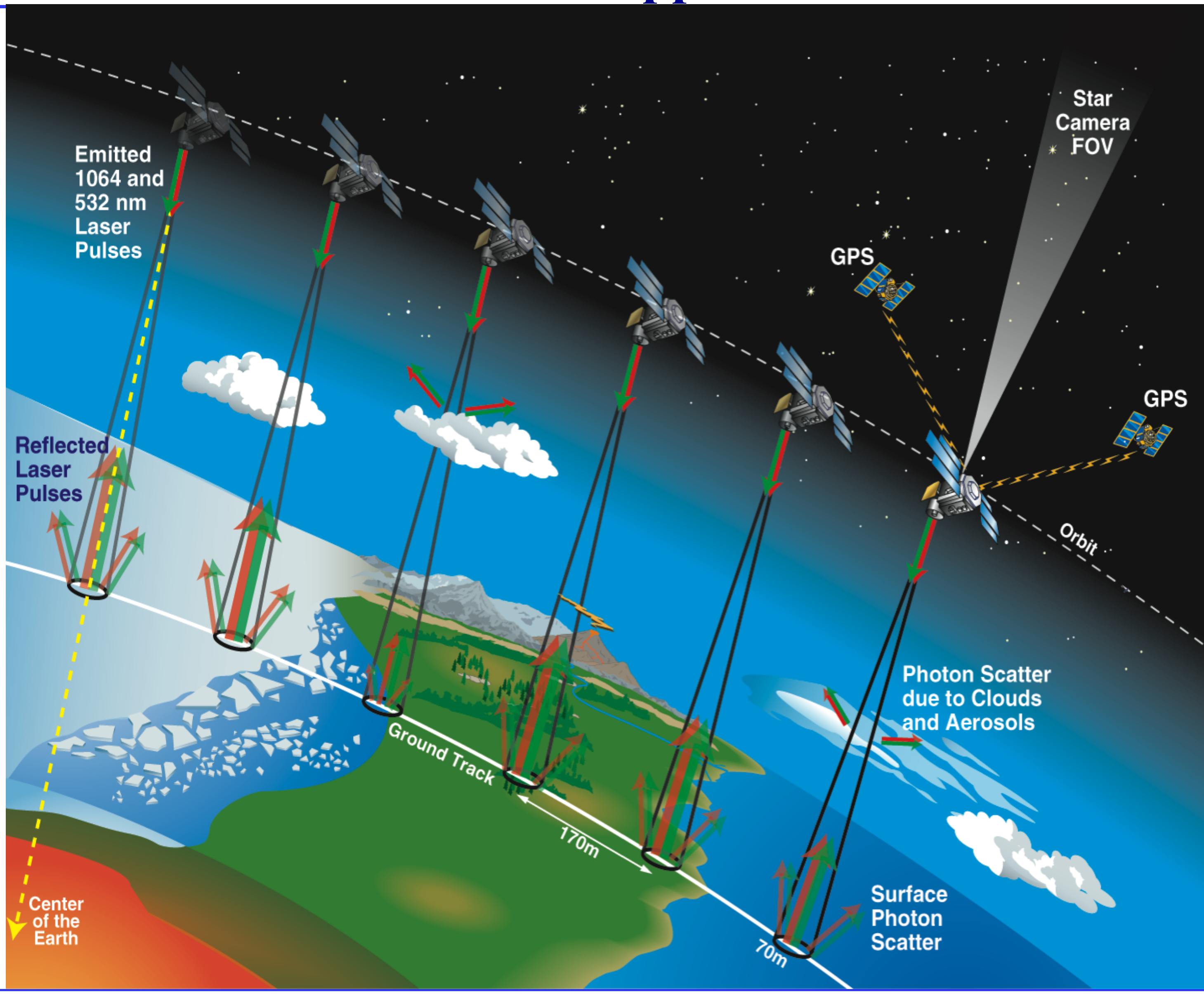


Laser Altimeter Canister integration into HH canister prior to SLA-01 Mission



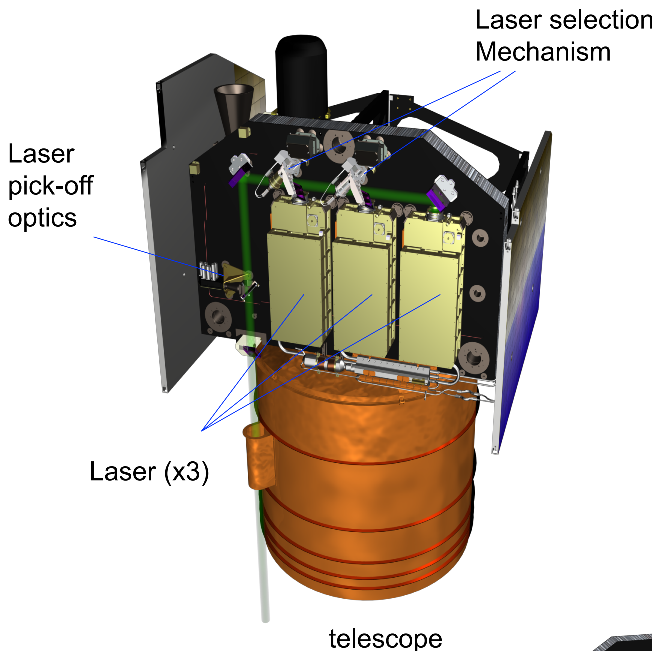
- SLA-01: Jan. 1996 flight, ± 28.5° orbit inclination, 80 hours operation
- SLA-02: August 1997 flight, ± 57° orbit inclination, 80 hours operation

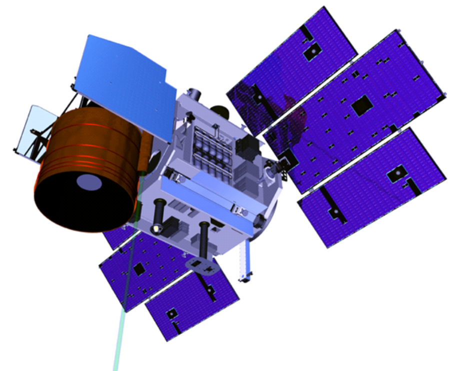
ICESat/GLAS - Launch Feb 2003
Measurement Approach

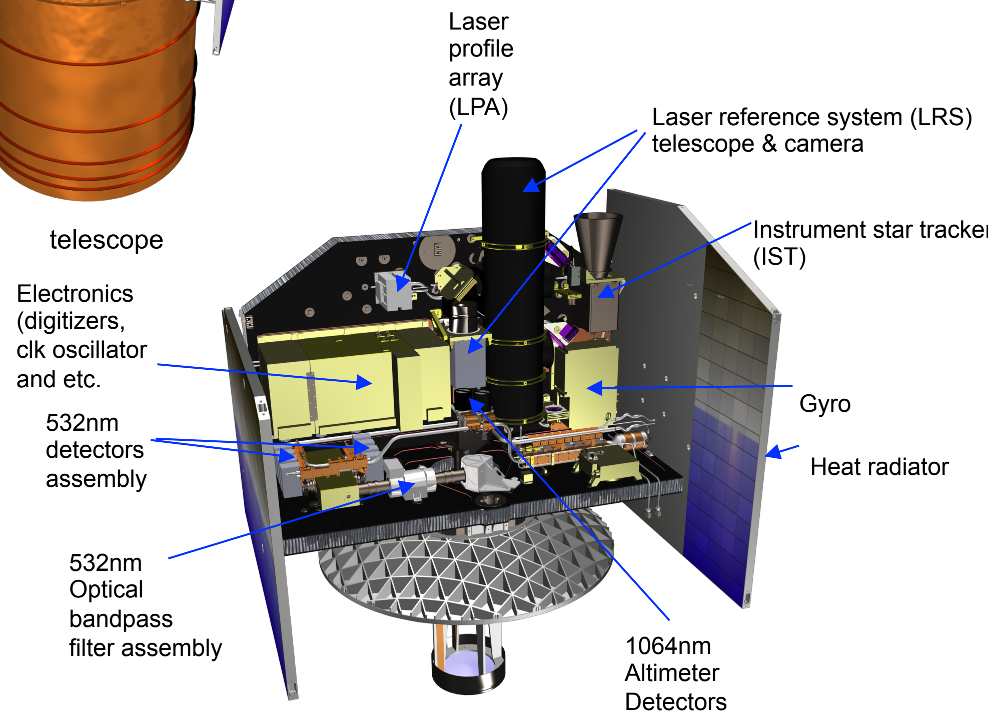


ICESat and GLAS

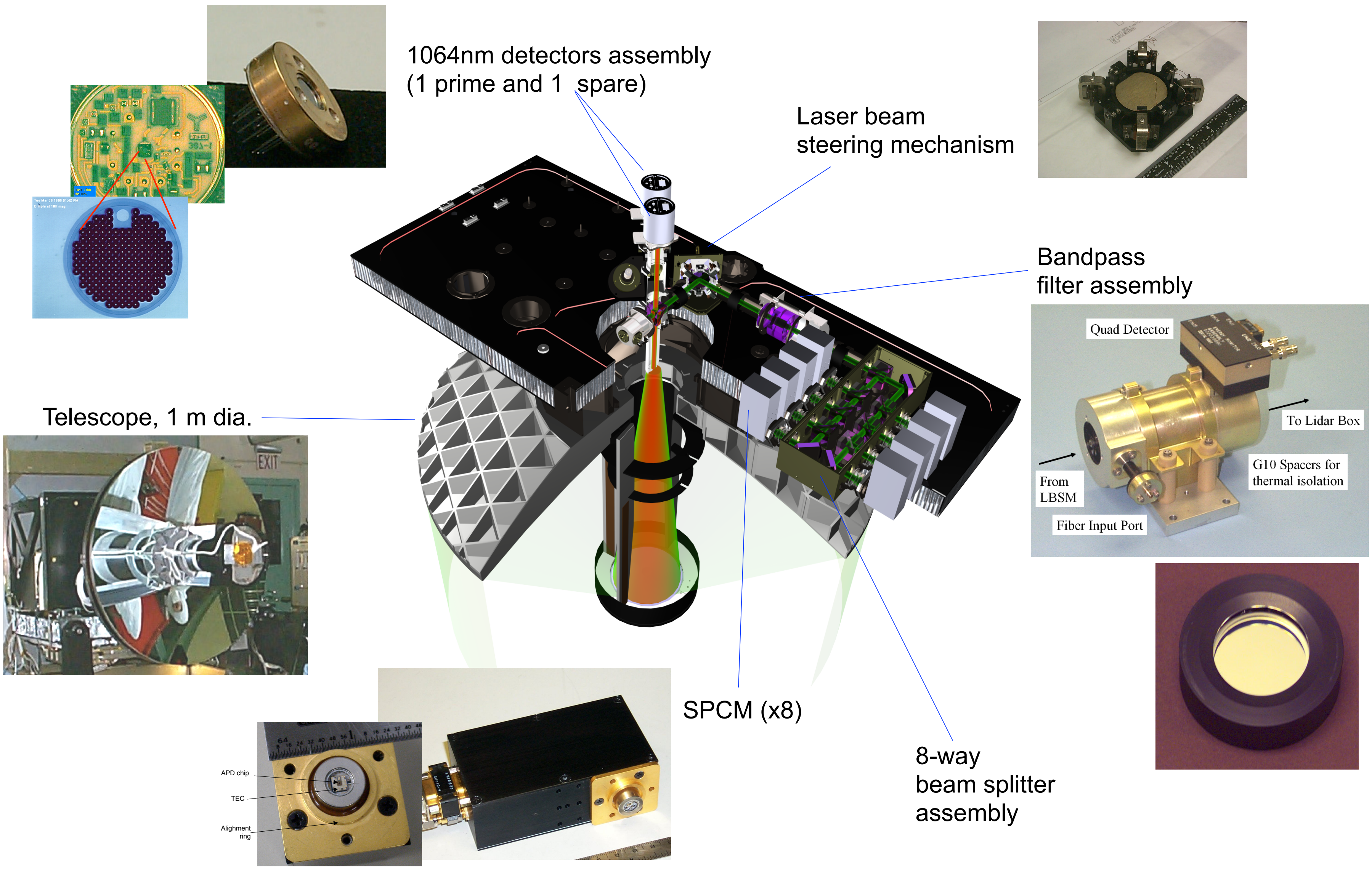
GLAS being integrated onto the spacecraft at the Ball Aerospace in 2002



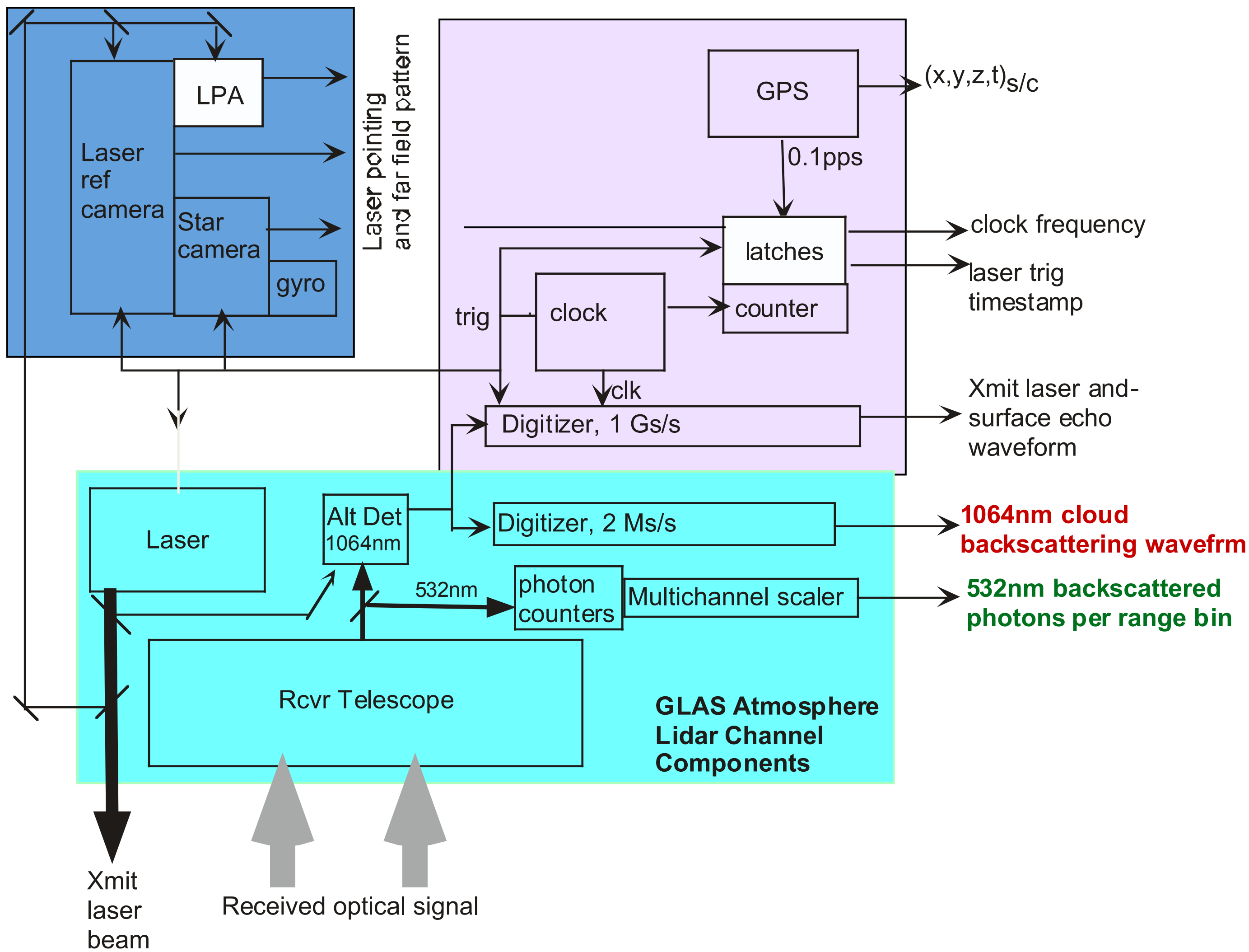




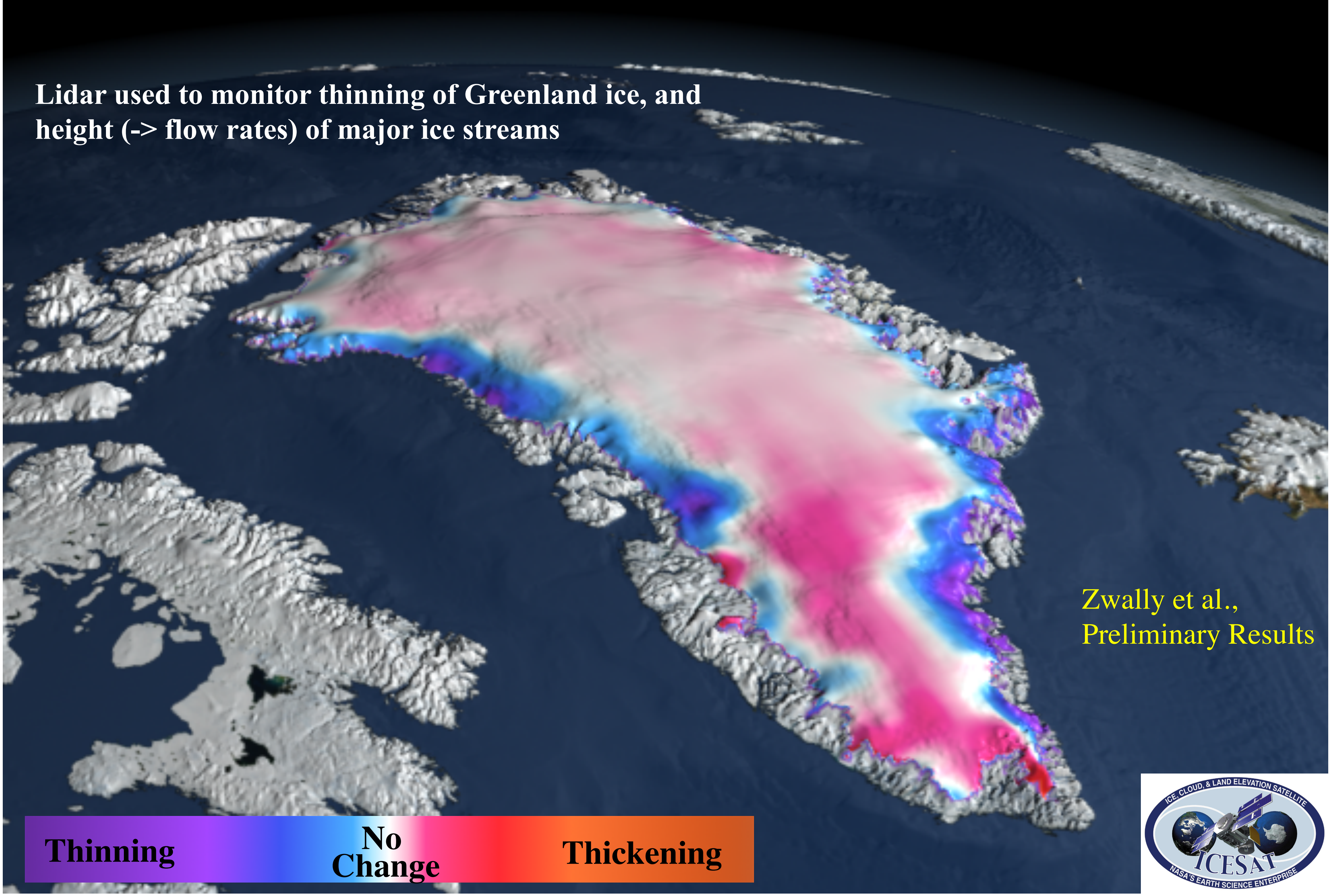
GLAS Receivers and Key Components



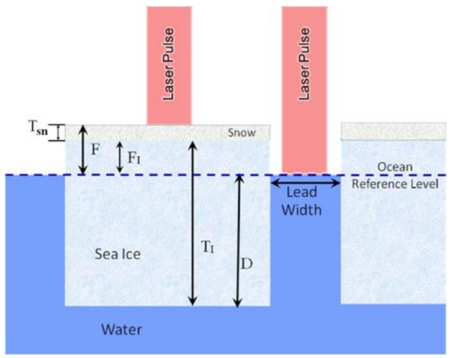
GLAS Function Block Diagram

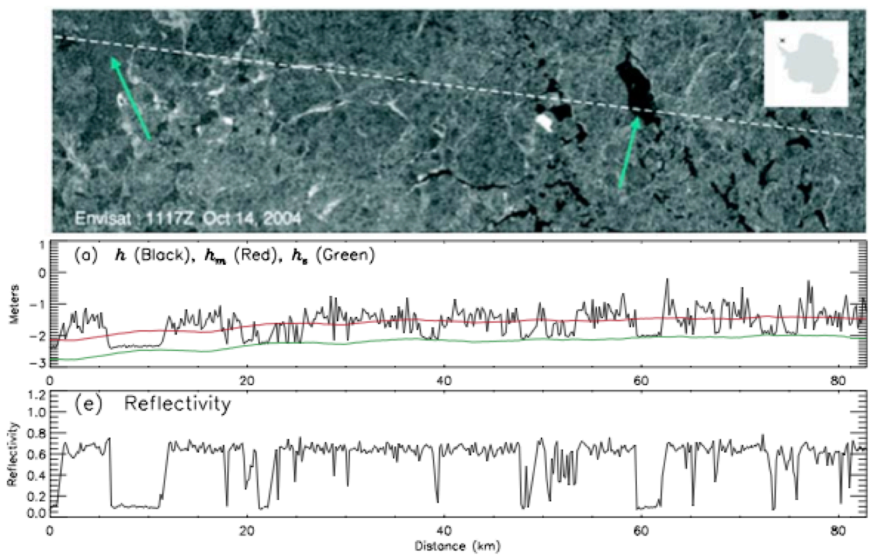


Greenland Elevation Changes Since 2003



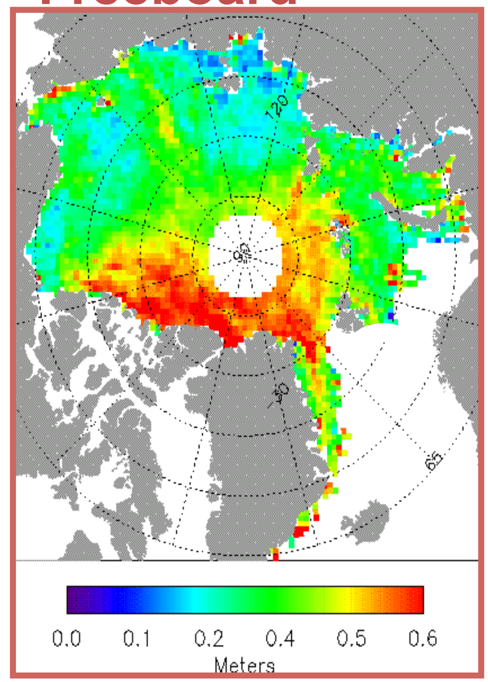
ICESat Sea Ice Measurements



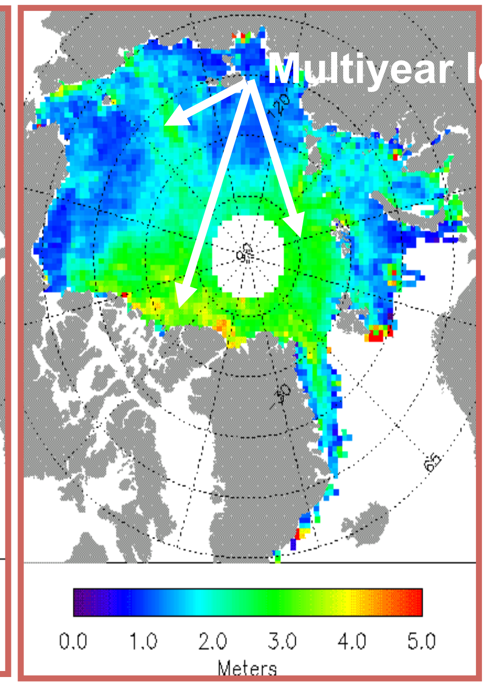


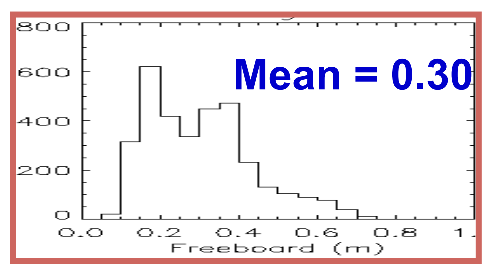
Feb 20-Mar 29, 2003

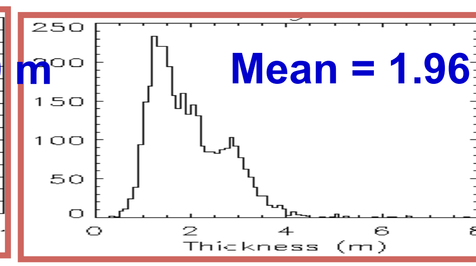
Freeboard



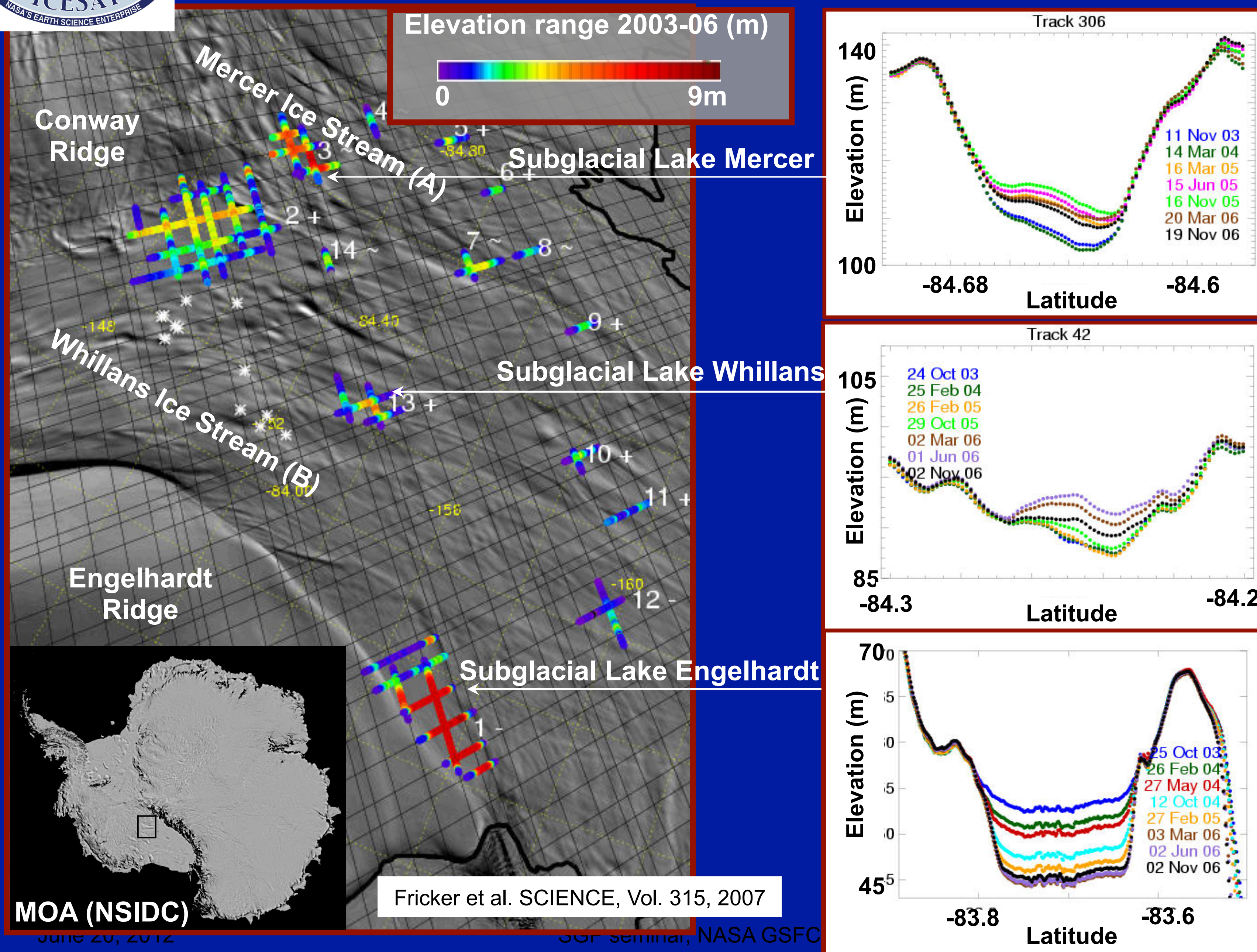
Thickness





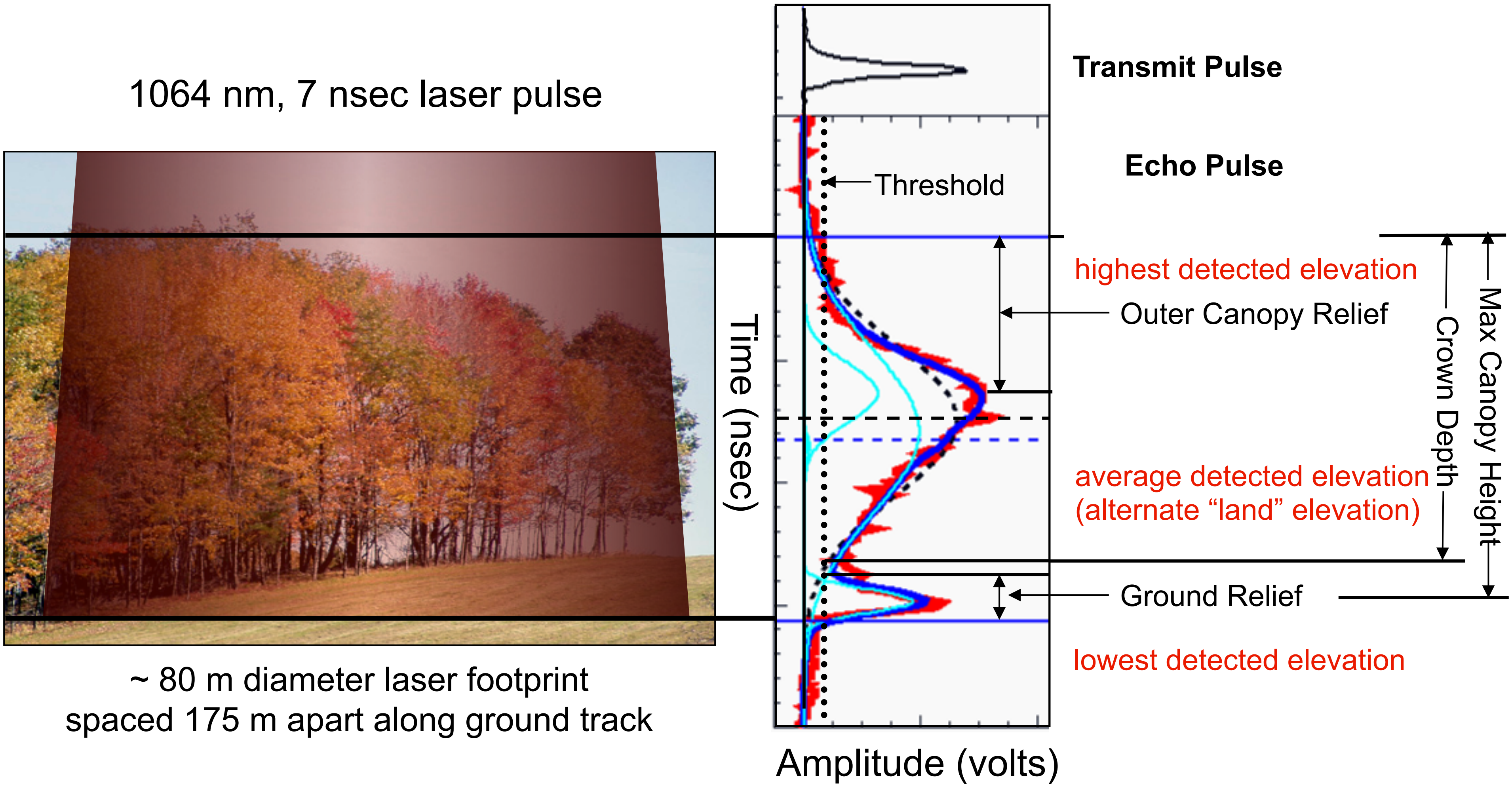


Active lakes under ice streams



GLAS Measurement of Echo pulse from Trees

1064 nm, 7 nsec laser pulse

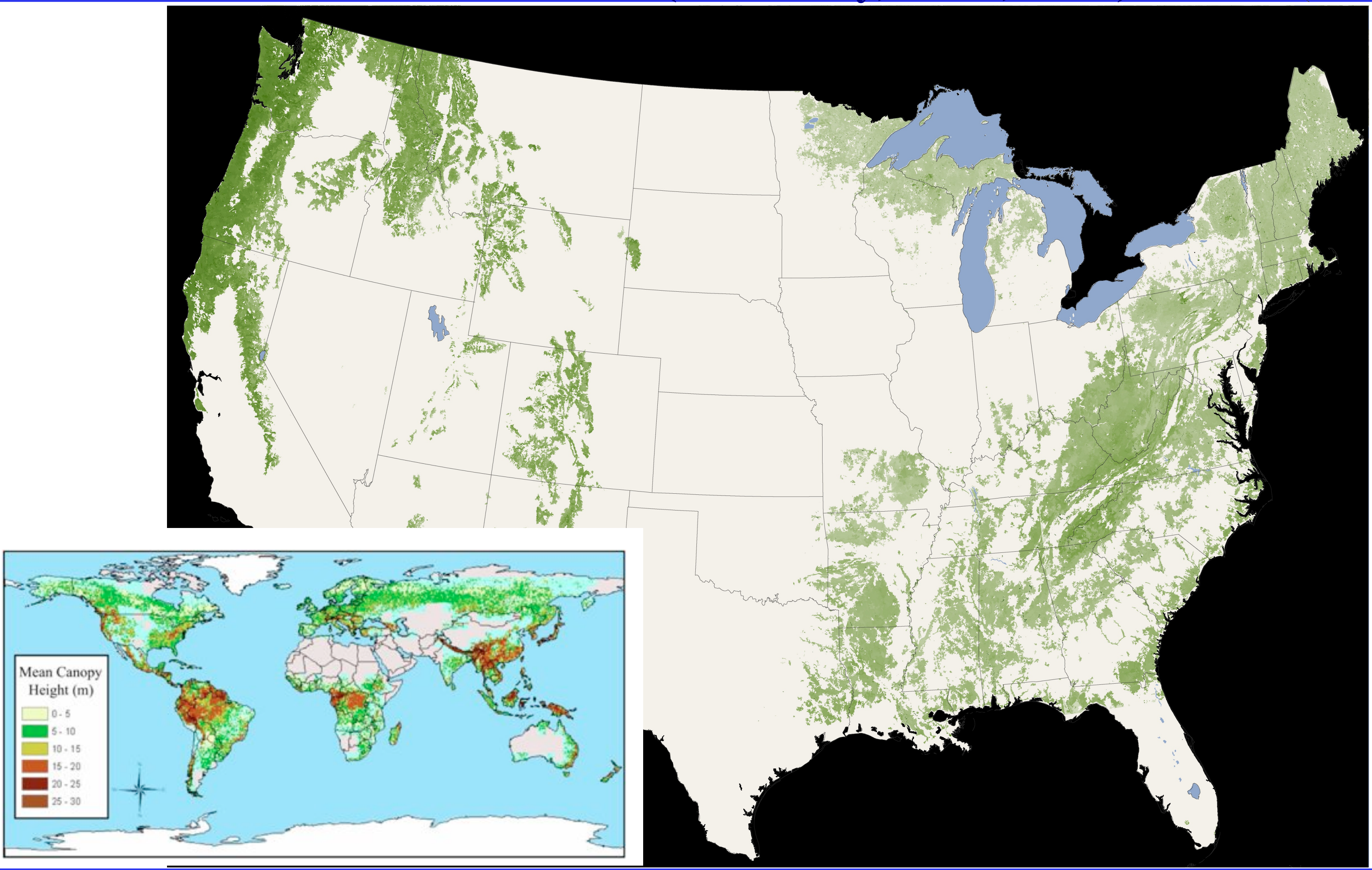


~ 80 m diameter laser footprint
spaced 175 m apart along ground track

Height Distribution of Reflected Laser power with 15 cm Vertical Sampling

Harding/NASA- GSFC

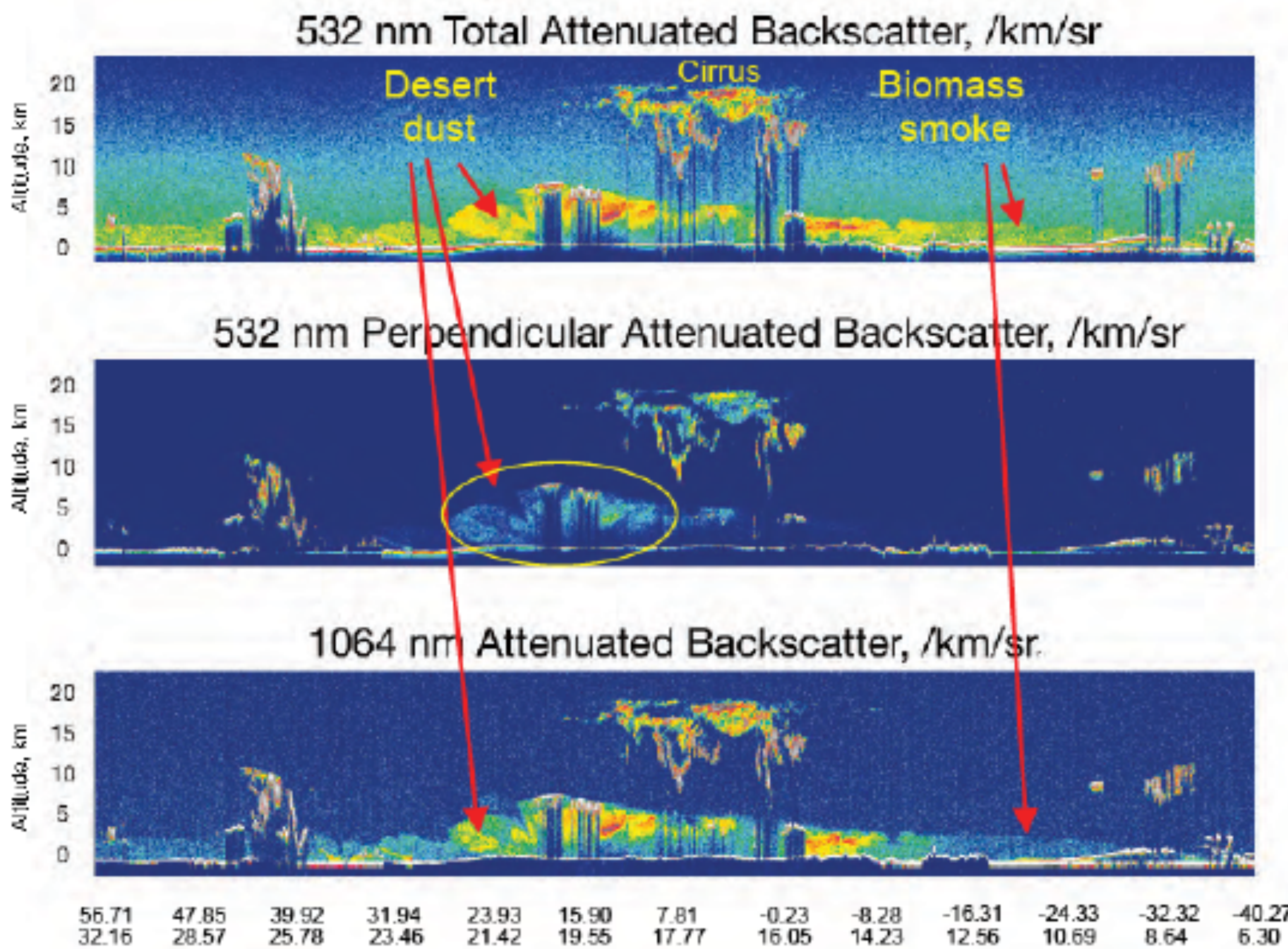
Global Forest Canopy Height Map from ICESat/GLAS (M. Lefsky, GRL, 2010)

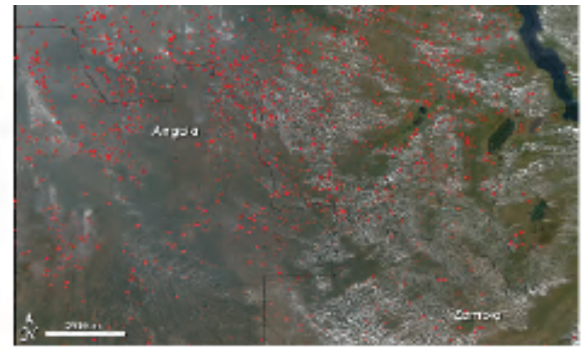


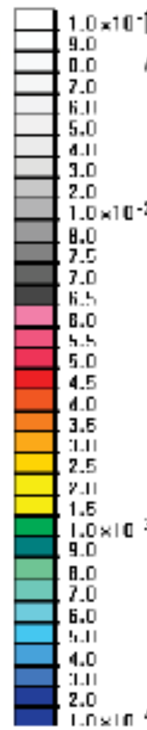

CALIPSO Mission
Earth Orbit, Atmospheric Structure
NASA LaRC
Sun-synchronous orbit
Three co-aligned instruments:
CALIOP: polarization lidar
- 70-meter footprint
- 1/3 km footprint spacing
IIR: Imaging IR radiometer
WFC: Wide-Field Camera
Dave Winker *et. al.*
NASA Langley, Hampton, VA
Calipso First light: 7 June 2006

CALIOP First Light Observations
(all 3 channels)

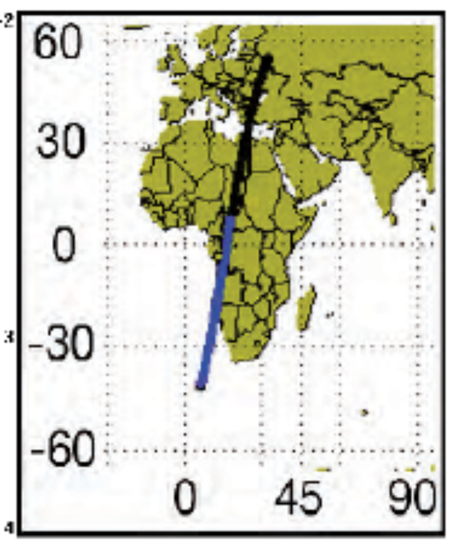
June 9, 2006







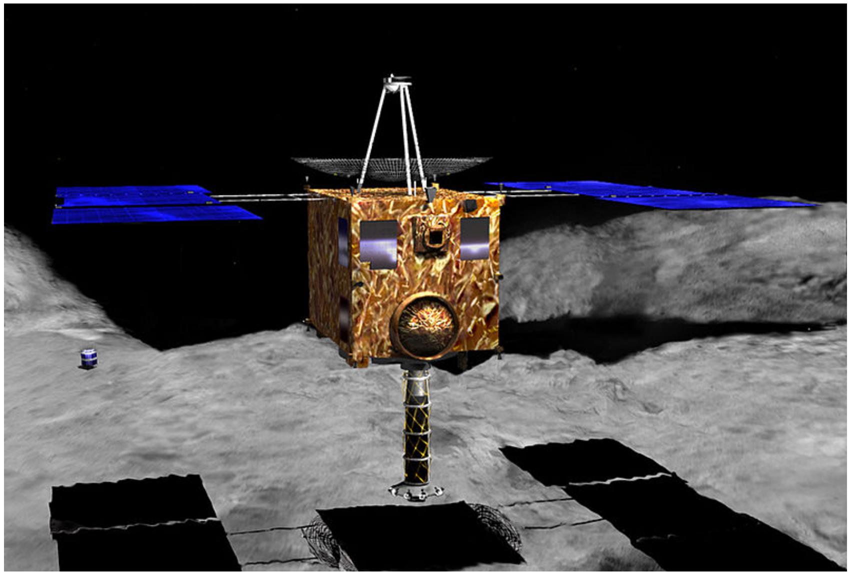
Fire locations in southern Africa from MODIS, 6/10/06



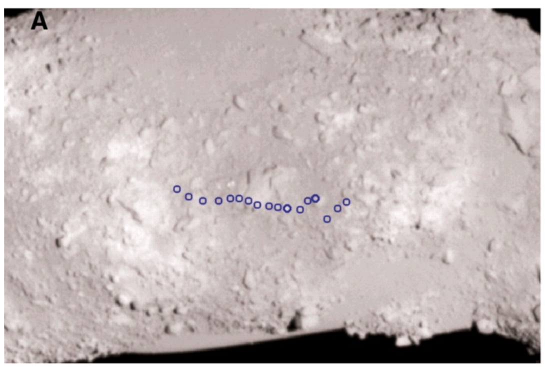
Three-channel profiles provide insight into aerosol type and mixing

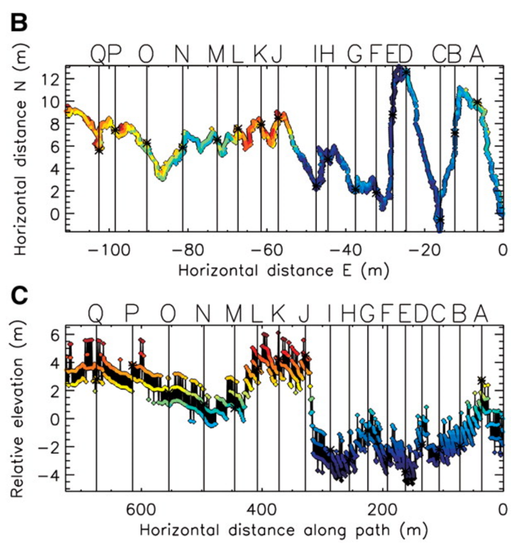
Recent Planetary Lidars (2000-present)

Hayabusa Lidar (2003-2005)
(JAXA/NEC/TOSHIBA, Asteroid Itokawa landing lidar)



Items	Specification
Range	50m～50km
Accuracy	±1m(@50m)
Repetition Rate	1Hz
Laser	Q-SW, Nd:Cr:YAG
Wave length	1064 nm
Output Power	8 mJ
Pulse Width	14 nsec
TX Beam Width	ϕ 1.7 mrad (1/e^2)
RX FOV	ϕ 1 mrad
RX Optics	Casegren ϕ 126 mm、SiC
Weight	3.7kg Include: DC/DC, Radiator
Power	17.0W (+LD Heater max5W)
Size	240mm×228mm×250mm Radiator: 240mm×300mm

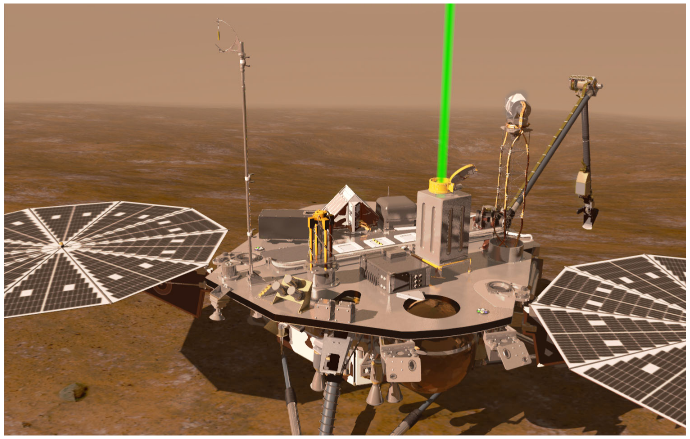




Examples of Hayabusa Lidar measurements
(*Science*, June 2006)

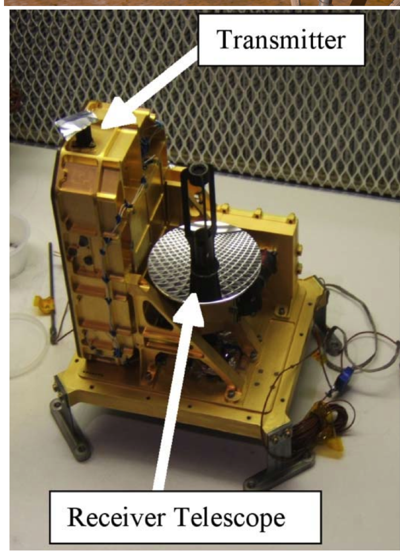
- Diode pumped Nd:YAG laser
- Operated from 50 km to 30 m
- 4.1 million laser shot measurements
- Hayabusa also had a four-beam laser rangefinder to measure altitude and slope from 100 to 7m

Phoenix Lander Lidar (2007-2008)
(Canadian Space Agency, Mar Atmosphere Backscattering Profile)

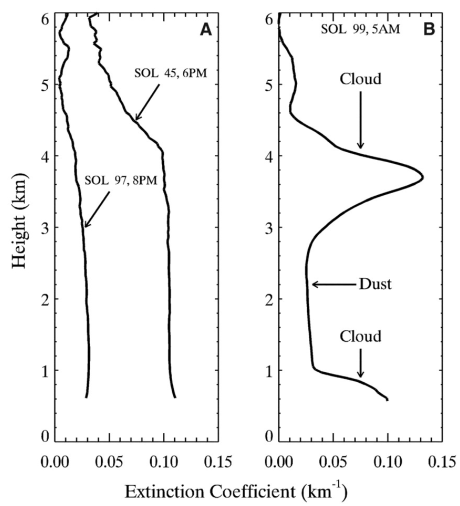


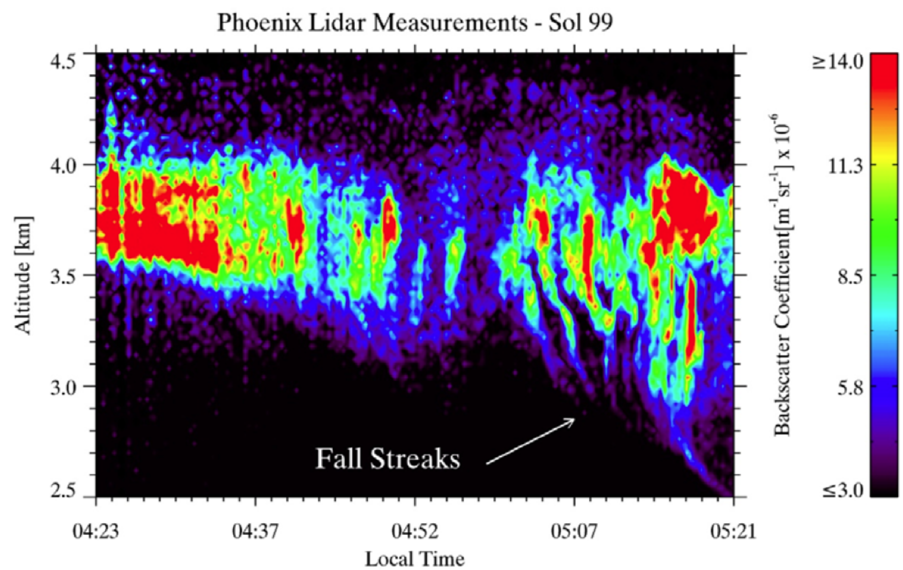
	1064 nm	532 nm
Transmitter		
Laser	Nd: YAG Diode pumped	
Wavelengths	1064 nm	532 nm
Pulse repetition rate	100 Hz	100 Hz
Pulse energy	0.3 mJ	0.4 mJ
Divergence	0.25 mrad	0.25 mrad
Emitted line width	0.25 nm	0.25 nm
Receiver		
Telescope	10 cm diameter	
Field of View	2 mrad	1.5 mrad
Spectral width	2 nm	1 nm
Detector	Silicon APD	PMT
Signal recording	Analog:14 bit ADC	Analog: 14 bit ADC + Photon Counting
Sampling frequency	30 MHz (5 m)	30 MHz (5 m)
Total mass	6 kg	
Maximum power	30 W	

Whiteway *et. al., JGR* 2008



Operated at Mars
~1 hour/day for ~6 months

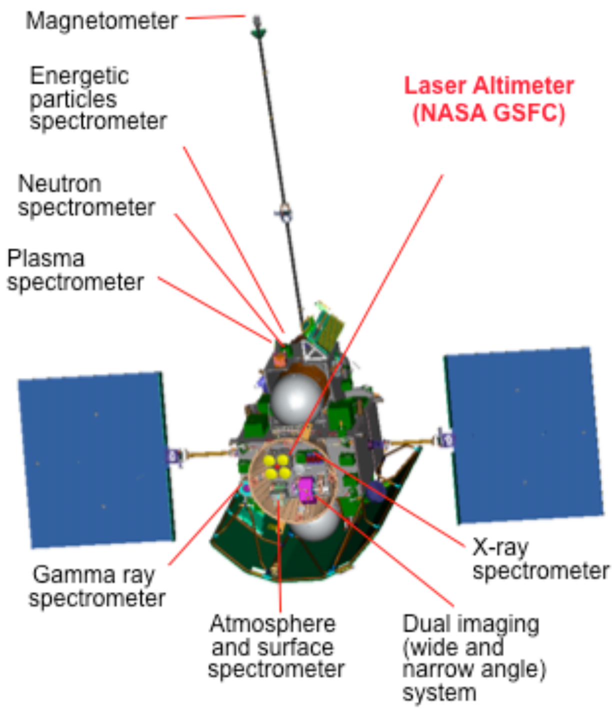


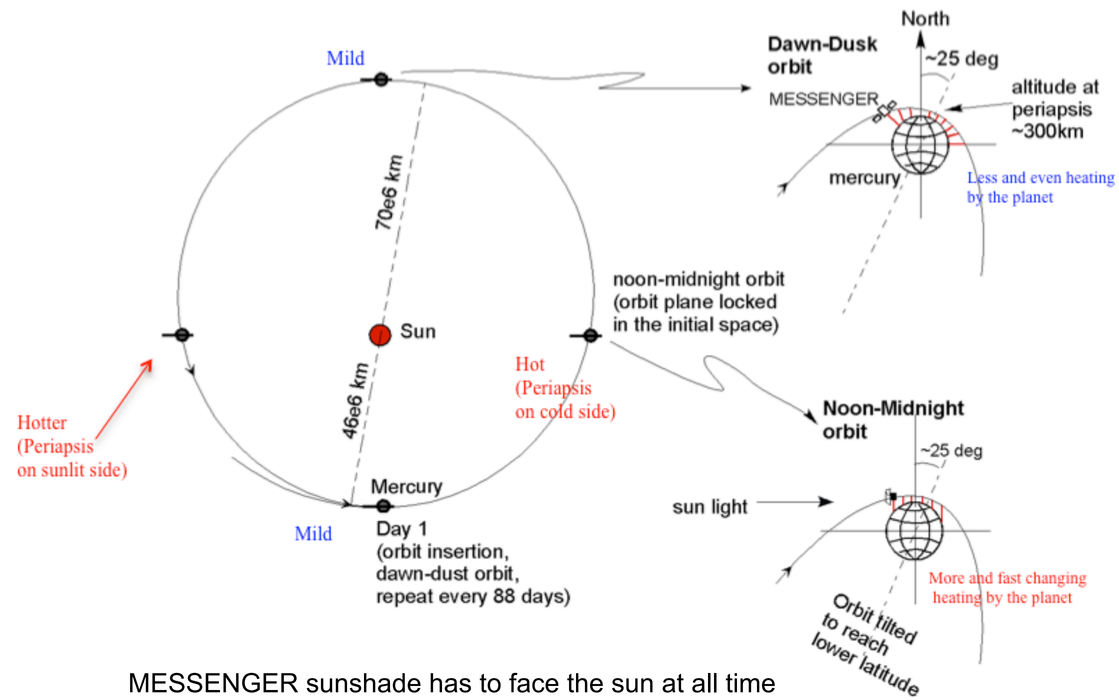


From Whiteway *et. al.*, *Science*, July 2009

MESSENGER Spacecraft & Science Payloads (JHU/APL, Mercury Orbit, 2004 to present)

MESSENGER - MErcury Surface, Space ENvironment, GEochemestry, and Ranging
MLA – Mercury Laser Altimeter





MESSENGER sunshade has to face the sun at all time and MLA has to range in non-nadir direction most of the time.

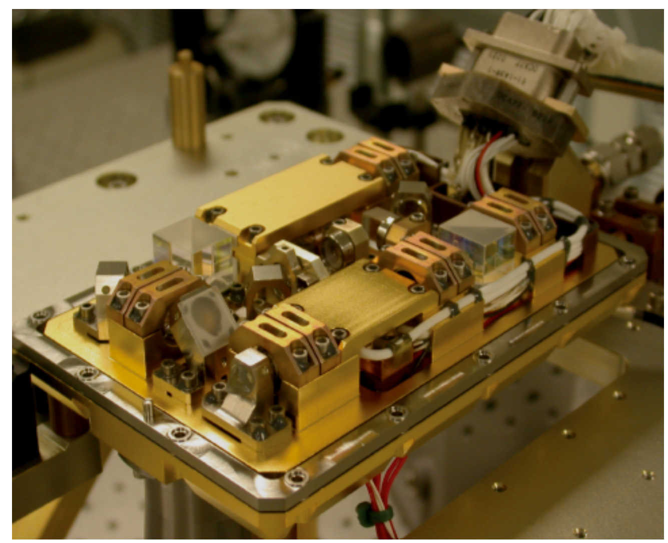
- Developed by JHU/APL under NASA's Discovery Program
- Launched on 8/3/2004 from KSC, arriving Mercury orbit on March 18, 2011

Mercury Laser Altimeter (MLA)

Electro-Optics & timing electronics assembly

Laser pulse energy	***20 mJ***
Pulse rate	***8 Hz***
Pulse width	***6 ns FWHM***
Wavelength	***1064.30 ±0.05 nm***
Beam divergence	***80 μrad (TEM00)***
Receiver aperture	***11.5 cm diameter, X4***
Receiver field of view	***400 μrad***
Receiver optics transmission	***77%***
Receiver optical bandwidth	***0.7 nm FWHM***
Detector quantum efficiency	***>35%***
Receiver dark noise equivalent power (NEP)	***200 pW (over 33 MHz Noise BW)***
Receiver timing electronics	***6 channel event timers***
Receiver timing accuracy	***<1 ns***
Operation duty cycle and lifetime	***30 min/12 hour orbit, for 365 earth days***
Data rate while in operation	***2.4 kbits/s***
Weight	***7.4 kg***
Size	***30x30x30 cm***
Electrical power consumption while in operation	***23 W***

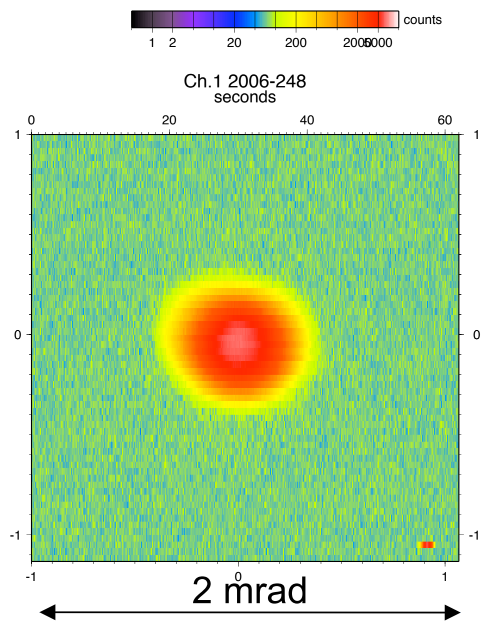
2 stage laser transmitter



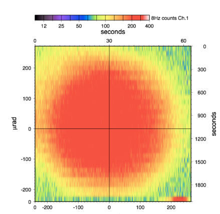
Venus Flybys

Passive Radiometry Scans

Venus shine seen by MLA during first flyby in Oct. 2006. The spacecraft pointing was shown to be accurate to ~30 urad

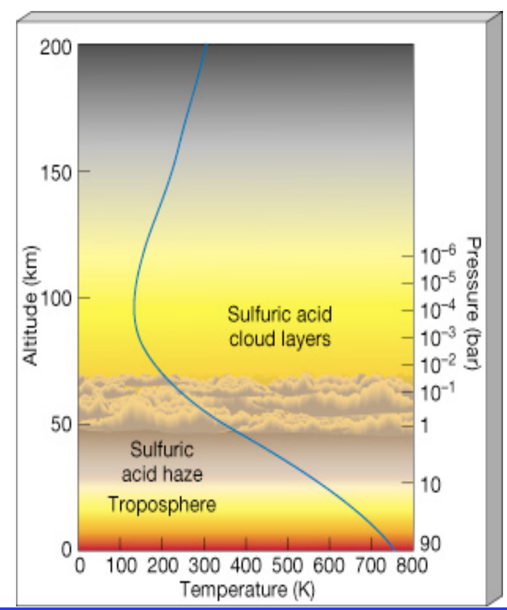


Venus shine seen by MLA during second flyby.

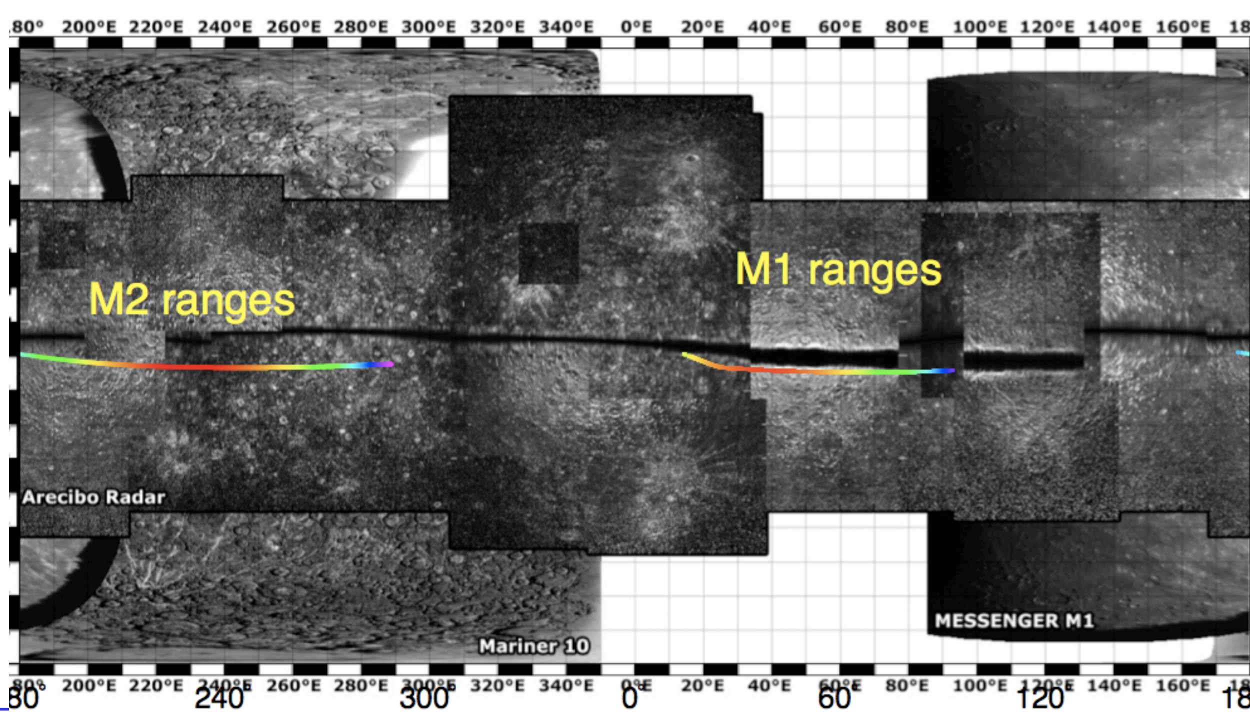


Laser Ranging

- Laser pulses were transmitted to Venus atmosphere during the closest approach (~200km) during the 2nd Venus flyby, but no signal was detected, indicating the apparent cloud and haze cross section was below 0.001/ $m^{-1}sr^{-1}$.



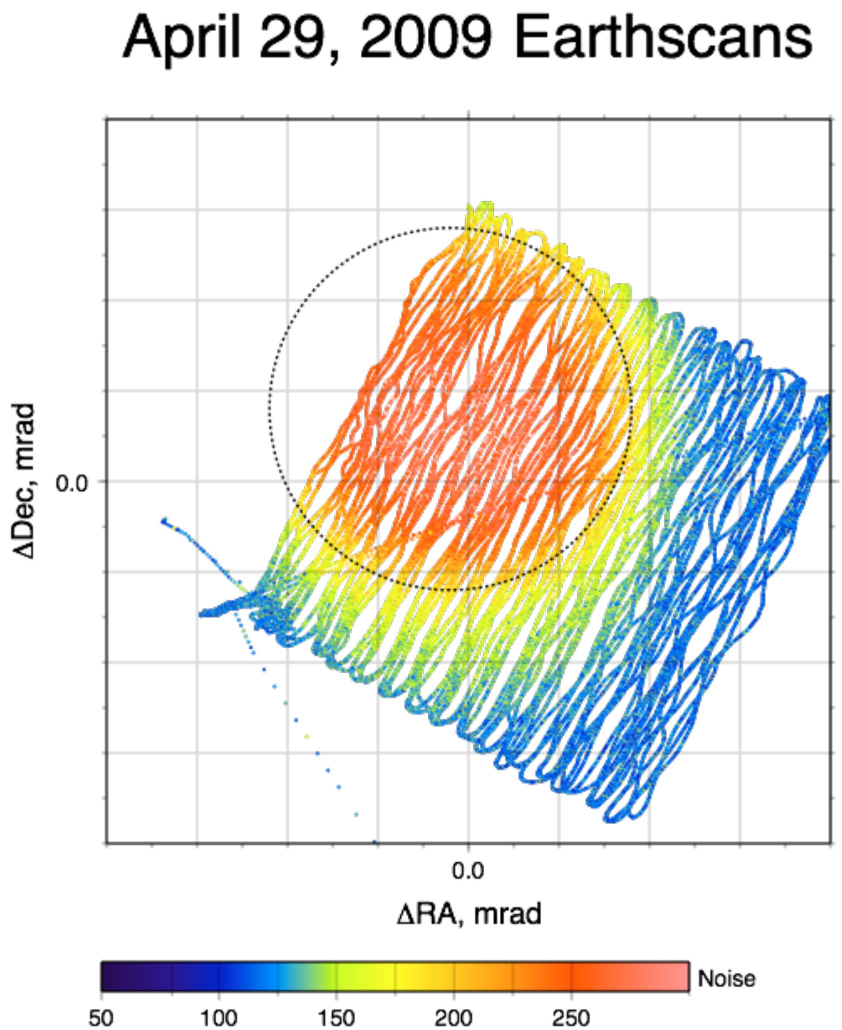
Mercury Flyby on Jan. 14, 2008



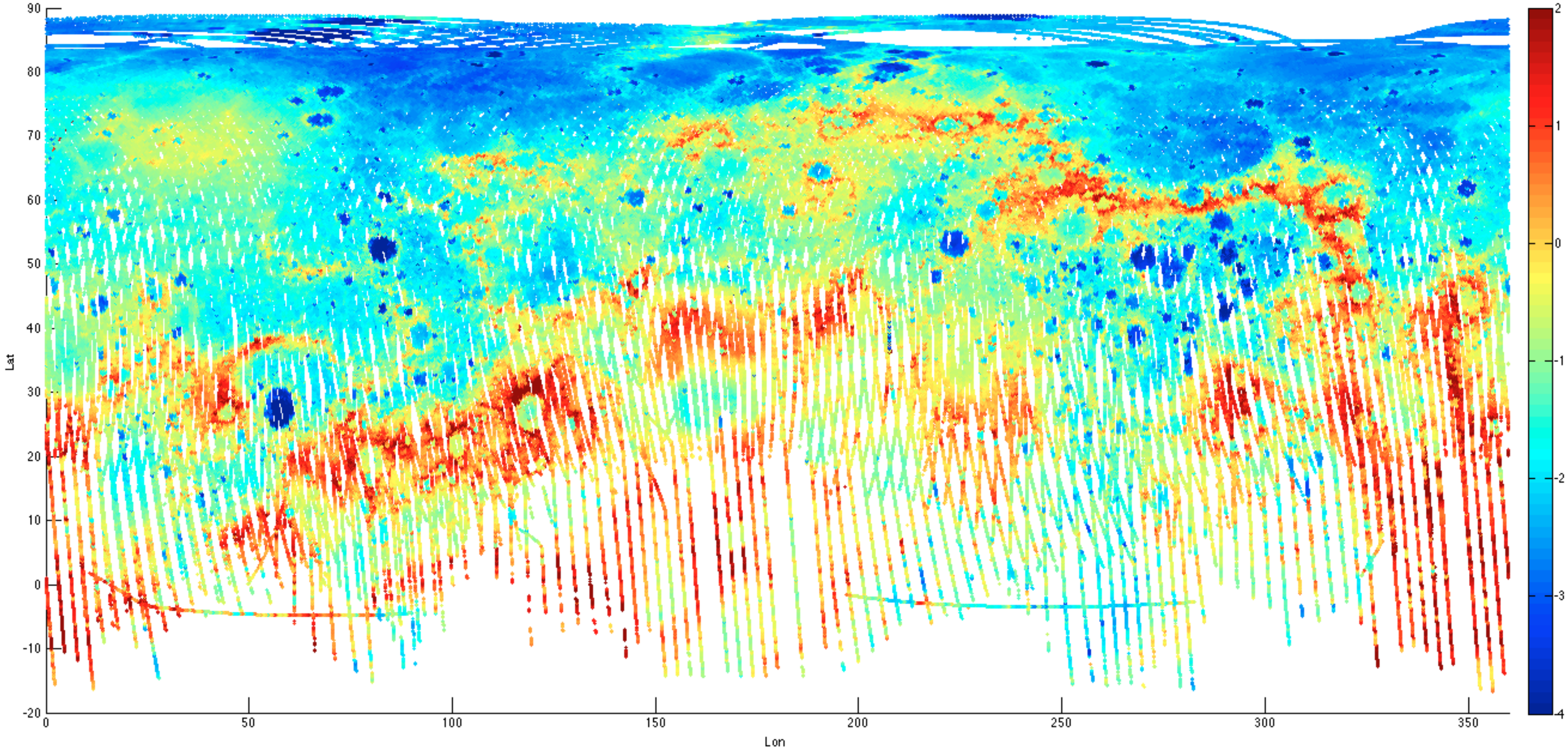
MLA was pointed to Mercury for about 10 minutes about the closest approach

Earth Shine Seen by MLA over 135 million km

MLA could still see earth shine from nearly 1 AU away with an estimated cw optical power of ~10 pW.



MLA Measurement Coverage on Mercury



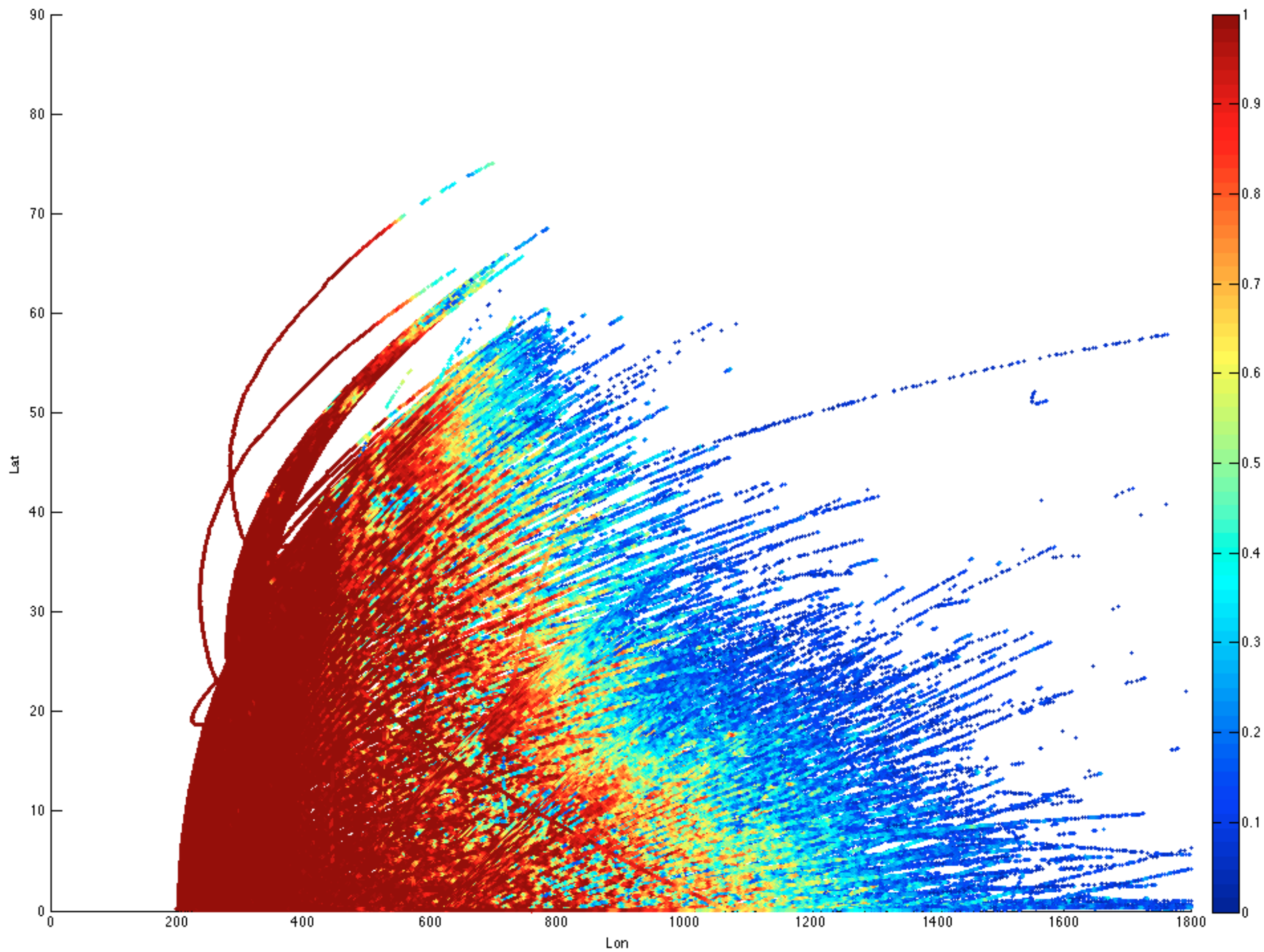
MLA measurement coverage, >5 millions range measurements, as of 12/31/2011

MLA Range Measurement Performance

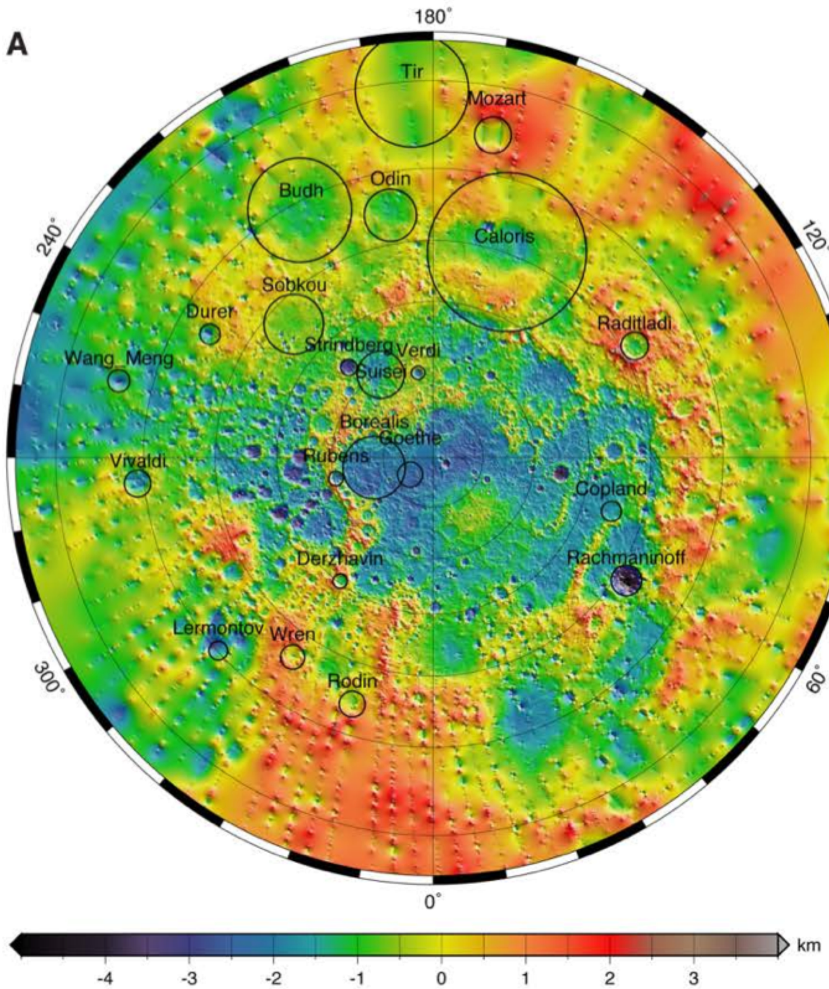
MLA is the first space lidar that has to range to surface at oblique angle

MLA ranged to >1500 km in nadir direction

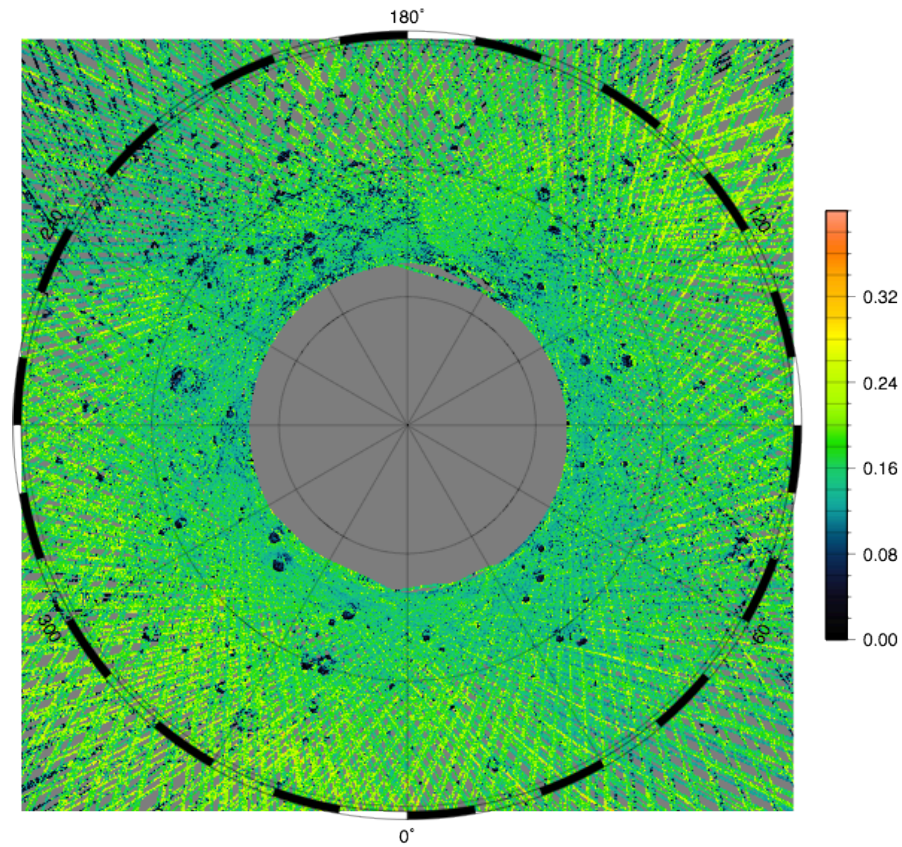
MLA range to 700 km at 70° slant angle.



MLA Measurement Results



Mercury Topography, north pole to 5 deg South
from MLA Data Mar-Oct, 2011
(Zuber *et. al.*, *Science* Apr, 2012)

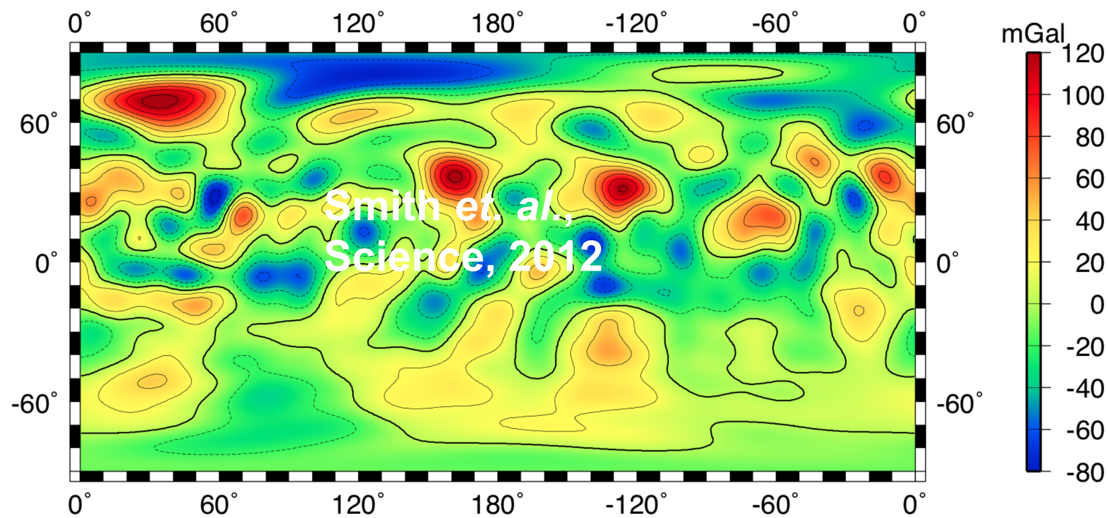


Surface Reflectance
North pole to 75 deg N
(Neumann *et. al.*, LPSC 2012)

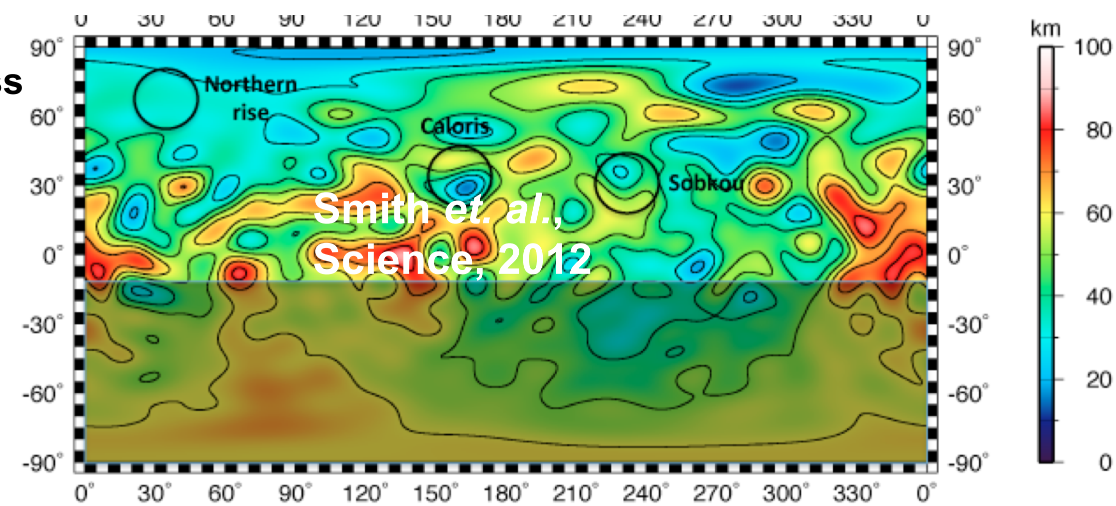
Sample MLA Science Results - Gravity

GSFC

Mercury gravity anomaly derived from MLA measurements



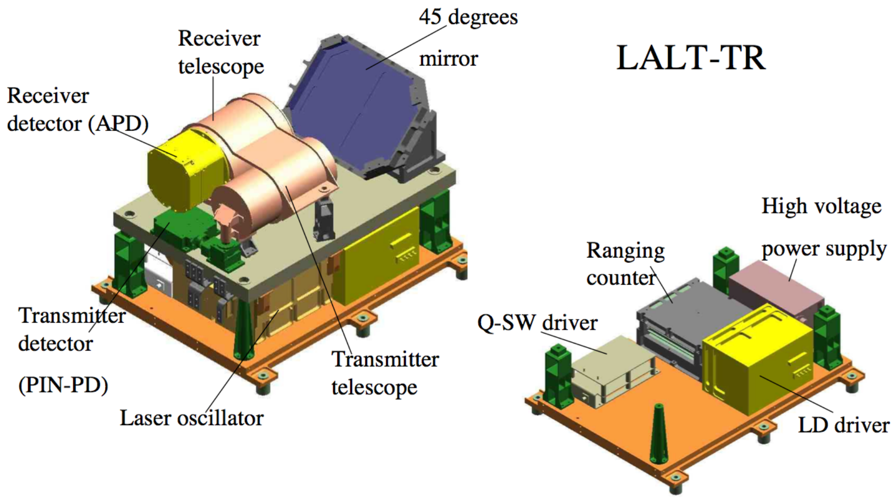
Mercury crustal thickness derived from MLA measurements

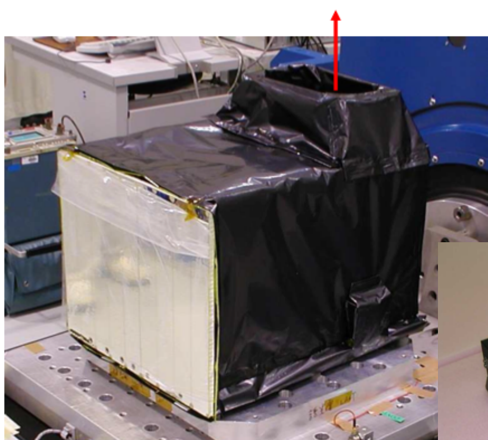


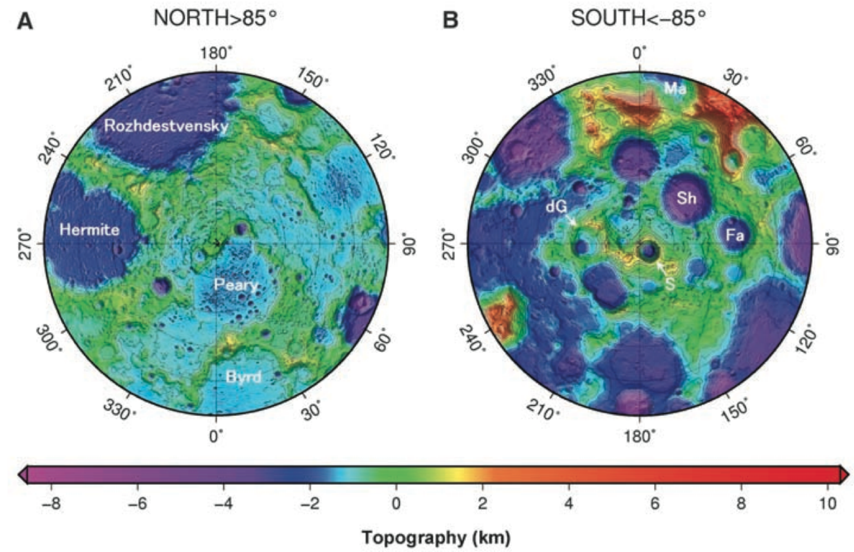
Going Back to the Moon

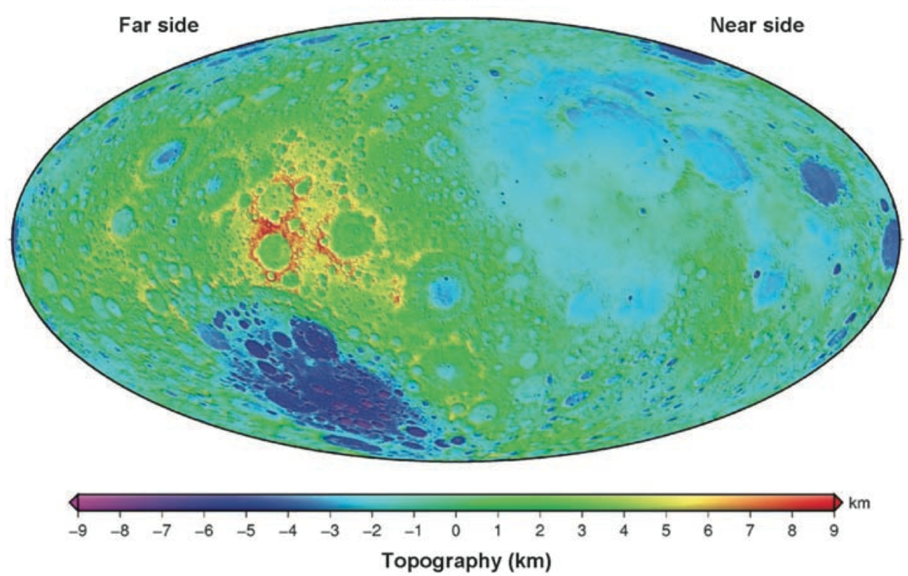
Kaguya-LALT (2007)

Structure of LALT(2)









Chang'E-1 Laser Altimeter (2007)

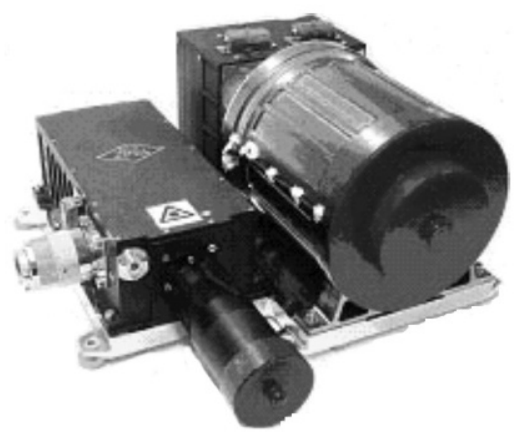
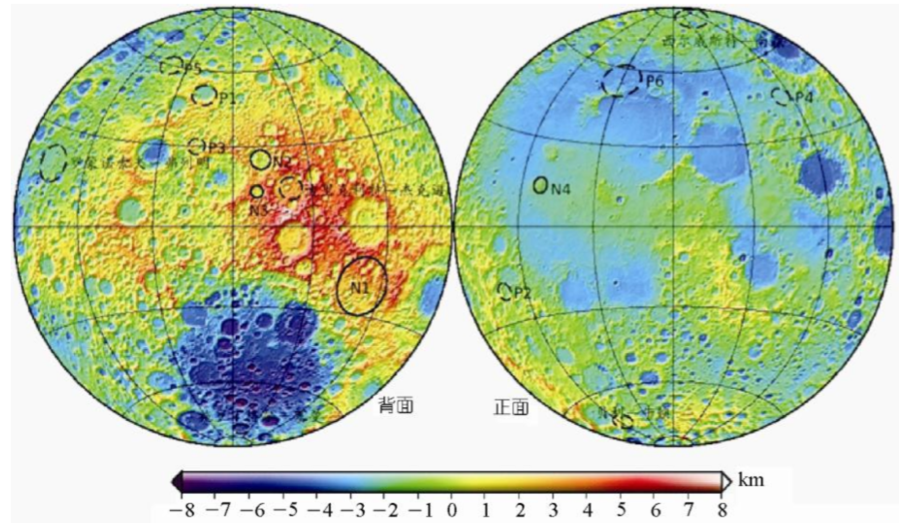
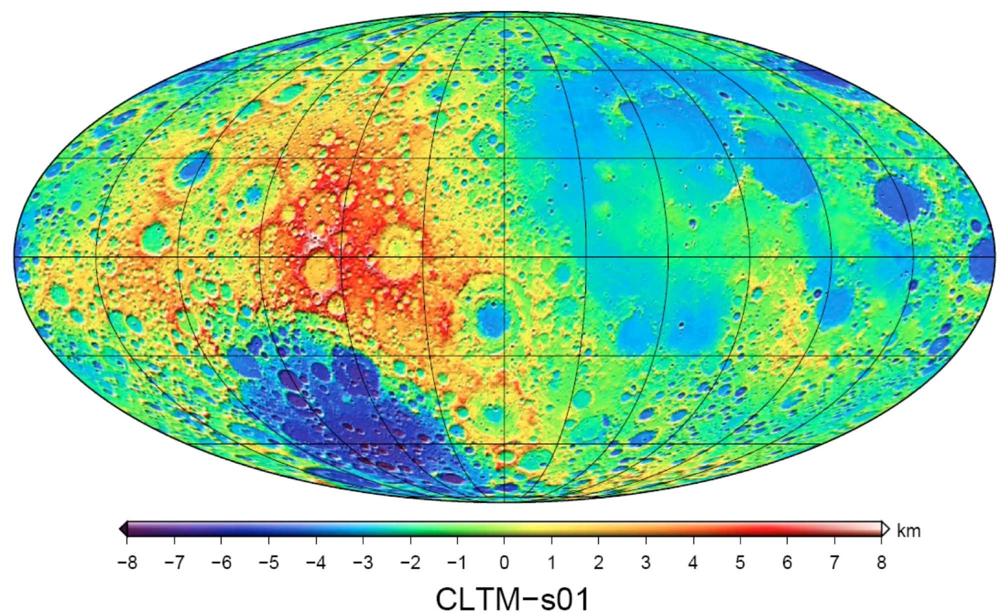


Table 1 Chang'E-1 LAM Instrument Characteristics

Characteristics	Values
Effective distance range	200km±25km
Footprint	120m@200km
Wavelength	1064nm
Energy	150mJ
Width of Laser Pulse	<7ns
Repeat rate	1Hz
Receiver telescope diameter	140mm
Telescope focal length	538mm
Distance resolution	0.96m
Distance error	<±5m
Data rate	384bps
Weight	15.7Kg
Power	25W
Life	1 Year





Chandrayaan-1 LLRI (2007)

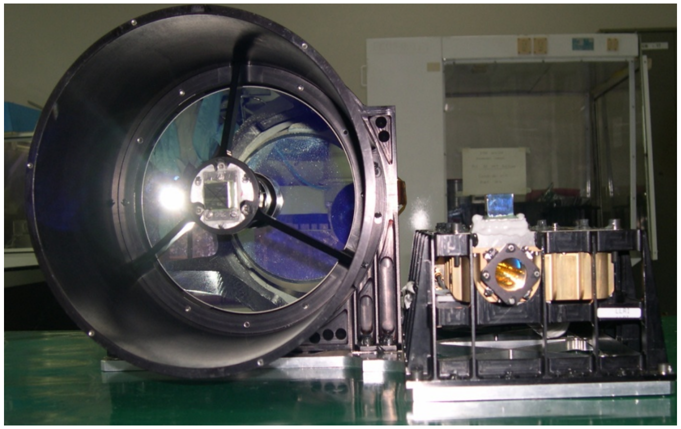
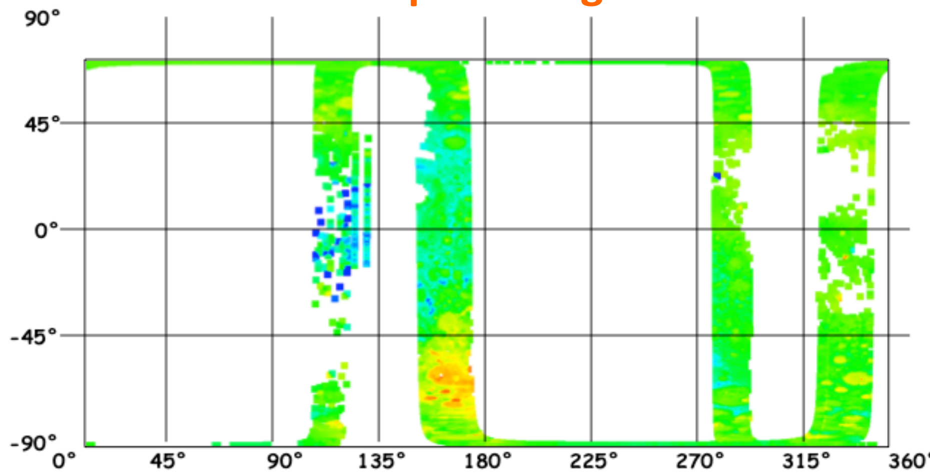
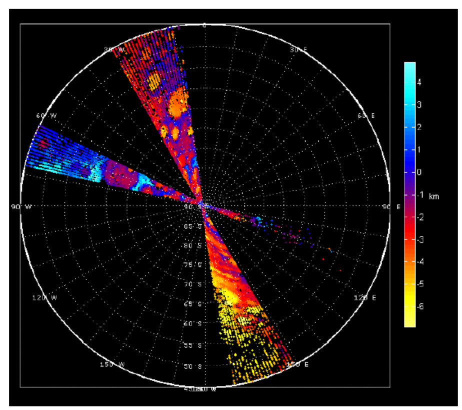


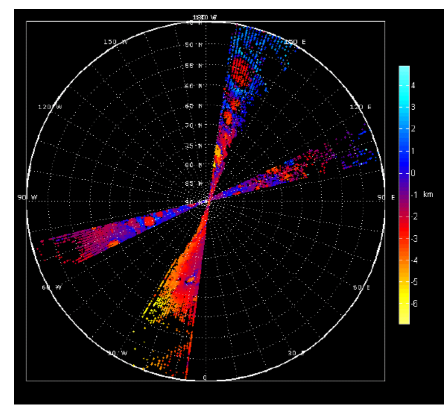
Table 1. *Specifications of the lunar laser ranging instrument.*

Laser wavelength	: 1064 nm
Laser type	: Nd:YAG diode-pumped Q-switched laser
Laser energy	: 20 mJ
Beam divergence	: 0.5 mrad (half)
Pulse width	: 10 ns
Pulse repetition rate	: 10 Hz
Transmitter optics	: 38 mm Galilean telescope
Receiver optics	: Reflective, 170 mm
Detector	: Avalanche photo detector
Vertical resolution	: 5 m
Footprint on Moon	: 100 m
Power	: Less than 15 watts
Weight	: Less than 10 kg

Color Coding of LLRI Points till 01-Jan-2009 Near Equator regions

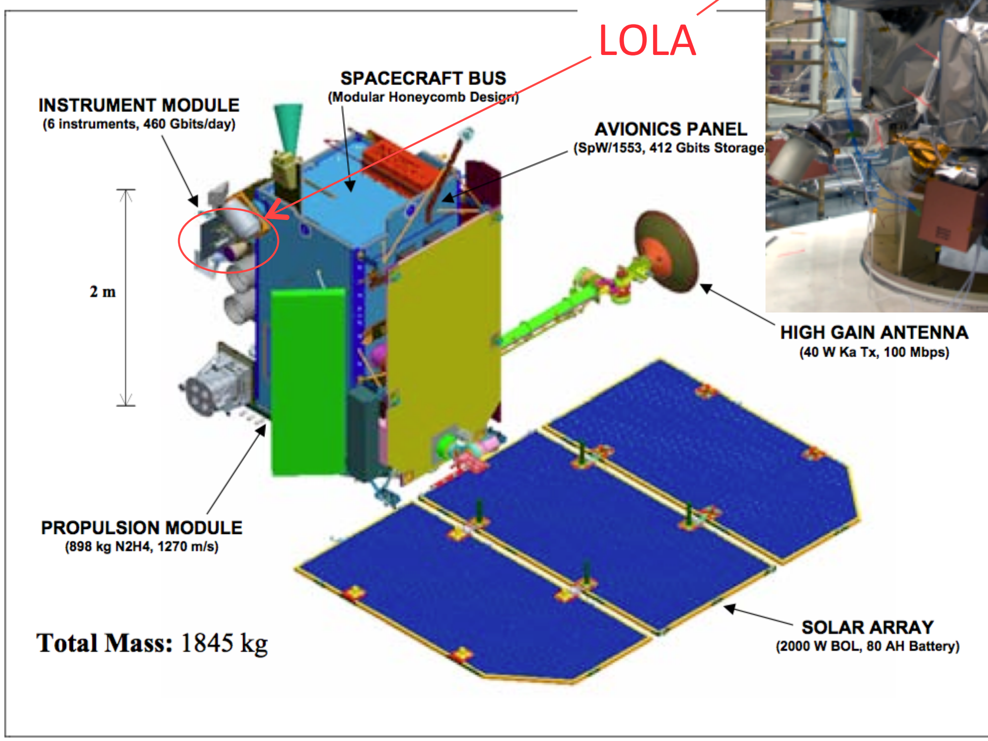




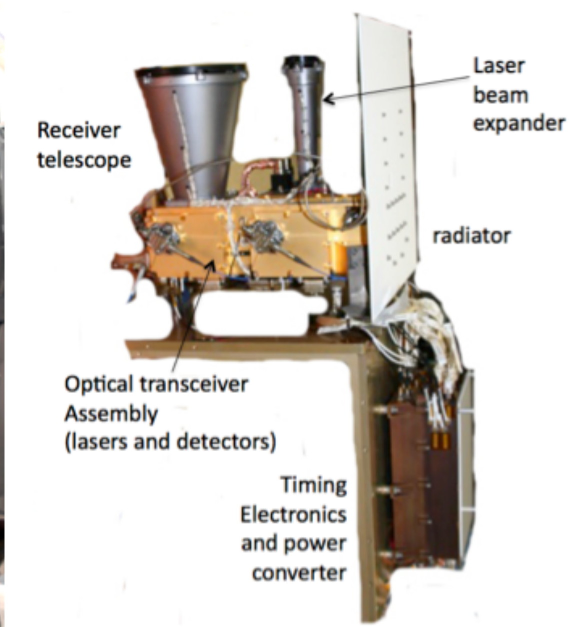


Lunar Reconnaissance Orbiter (LRO, 2009) the Lunar Orbiter Laser Altimeter (LOLA) GSFC/ Lunar Orbit

- **Launched June 18, 2009, still in orbit and collecting data**
- LOLA is one of the 7 payload instruments on LRO
- Objectives are to measure lunar surface topography and to establish a global lunar geodetic coordinate system.



LOLA

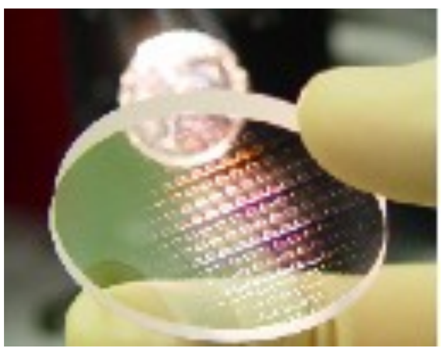


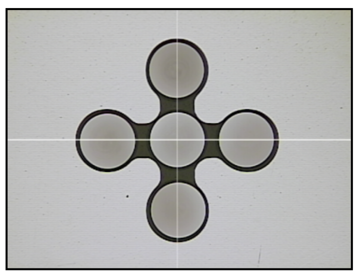
Parameter	Value
Laser Wavelength	1064.4 nm
Pulse Energy	2.7/3.2 mJ (laser1/laser2)
Pulse Width	~ 5 ns
Pulse Rate	28 ± 0.1 Hz
Beam Divergence	100 ± 10 μrad
Beam Separation	500 ± 20 μrad
Receiver Aperture Diameter	0.14 m
Receiver Field of View	400 ± 20 μrad
Receiver Bandpass Filter	0.8 nm
Detector responsivity	300 kV/W
Detector active area diameter	0.7 mm
Detector electrical bandwidth	46 ± 5 MHz
Timing Resolution	0.5 ns

Smith et al., *Space Science Reviews*, 2010

LOLA - 1st Multi-beam Space Lidar

- Use of a diffractive optical elements (DOE) to split the laser to illuminate five spots on ground
- Use of an optical fiber array to direct each spot into a separate receiver channel
- Make five measurements from a single laser shot to give range, slope and direction

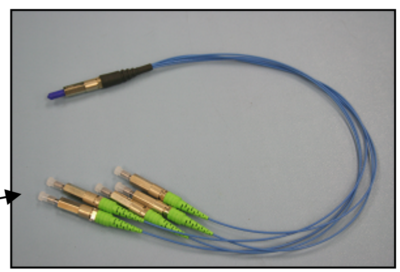


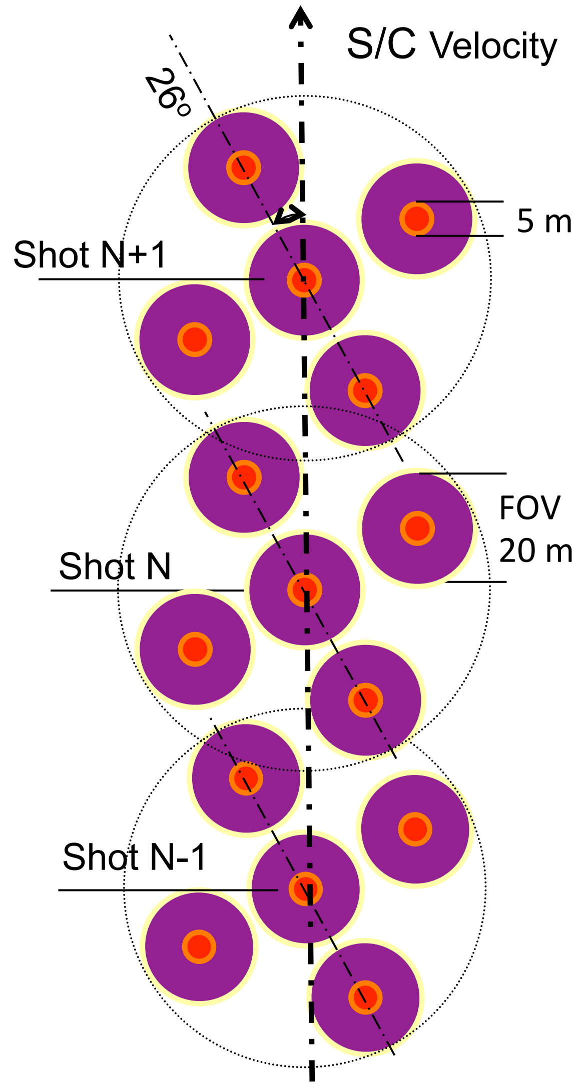


Fiber Pattern at telescope focal plane

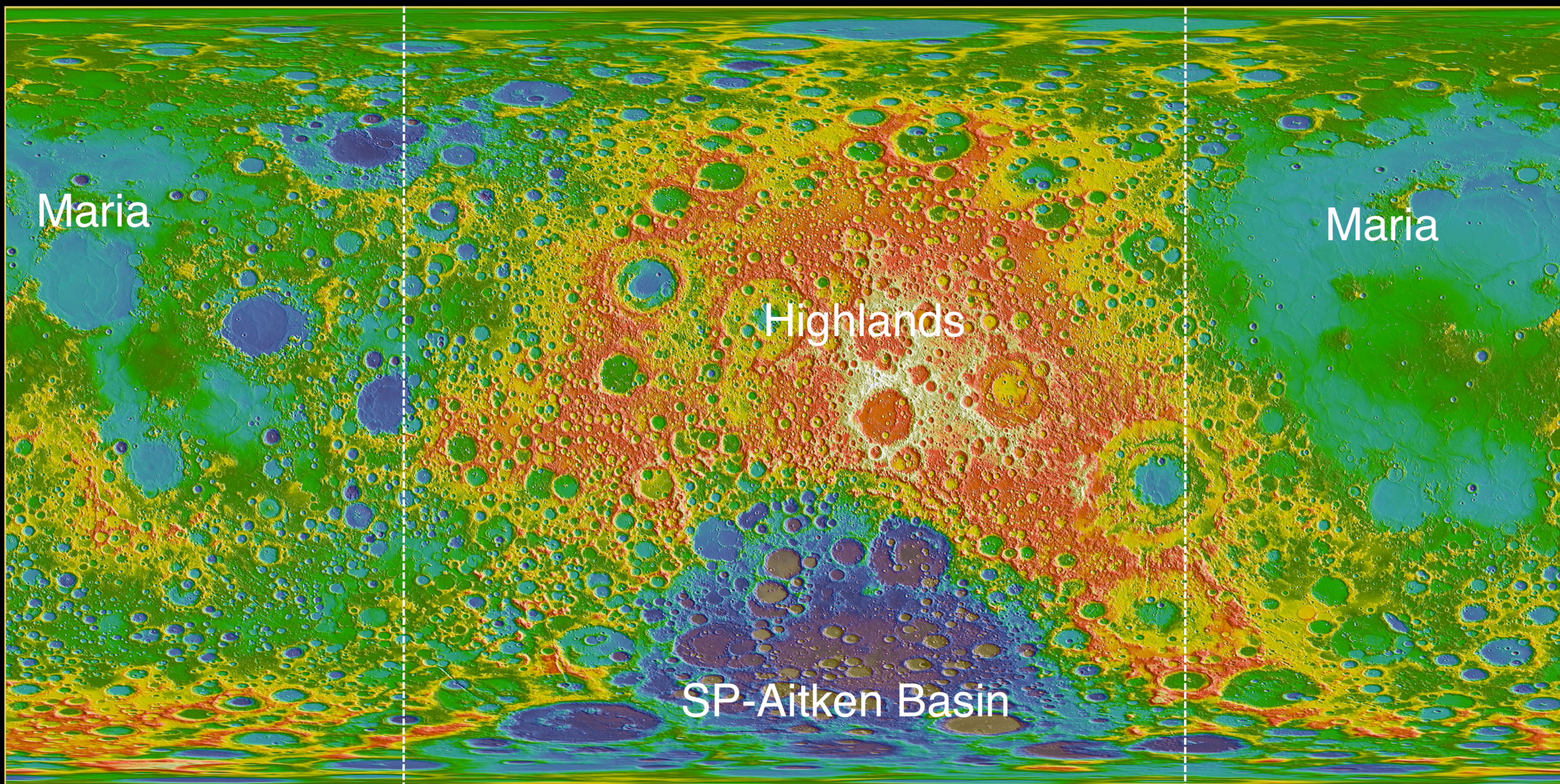
DOE and the optical fiber array

Each fiber couples to a separate Si APD detector



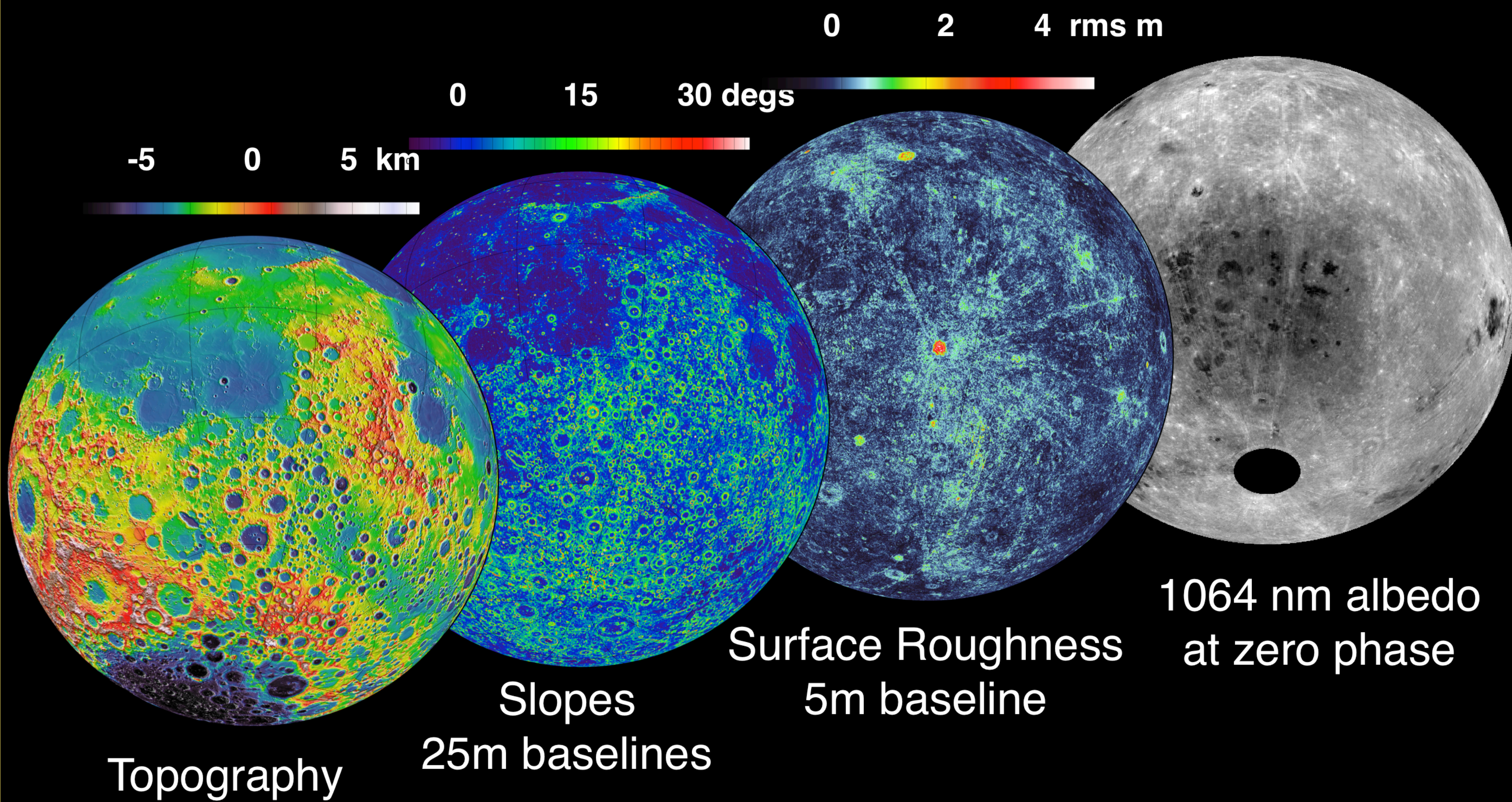


Topography of the Moon



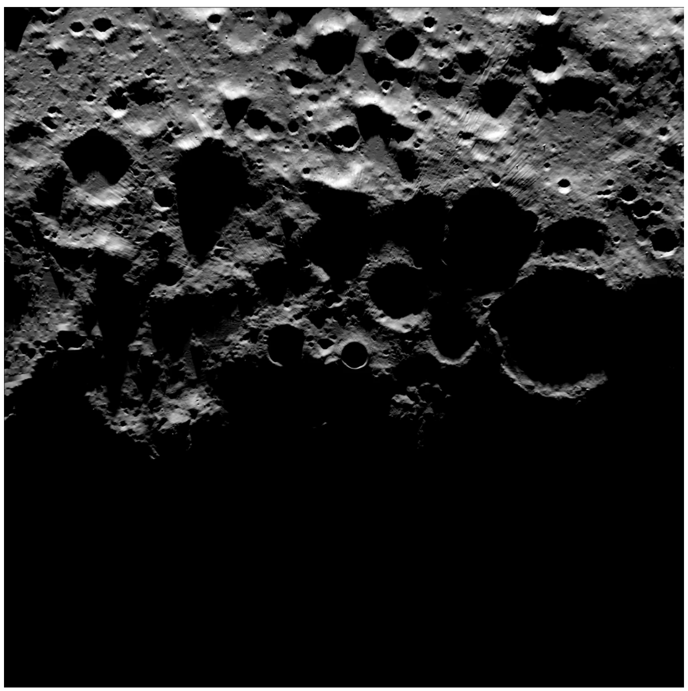
- 5.5 billion altimeter measurements; ~2 billion laser shots
- 20-m along-track resolution; 0.7-km average orbit track spacing at equator

LOLA Global Datasets

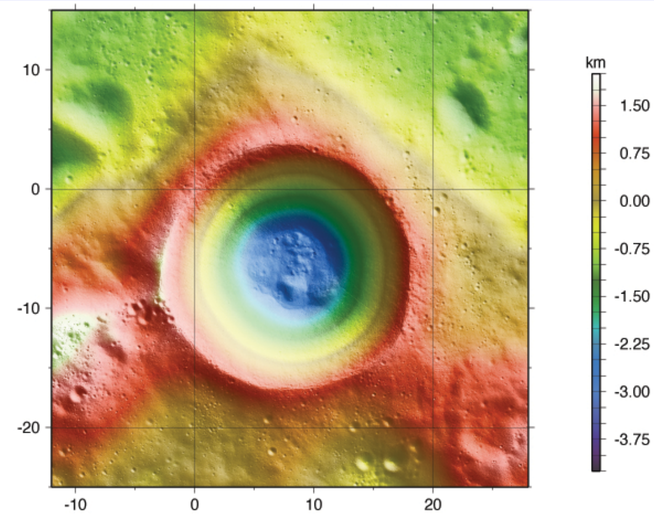


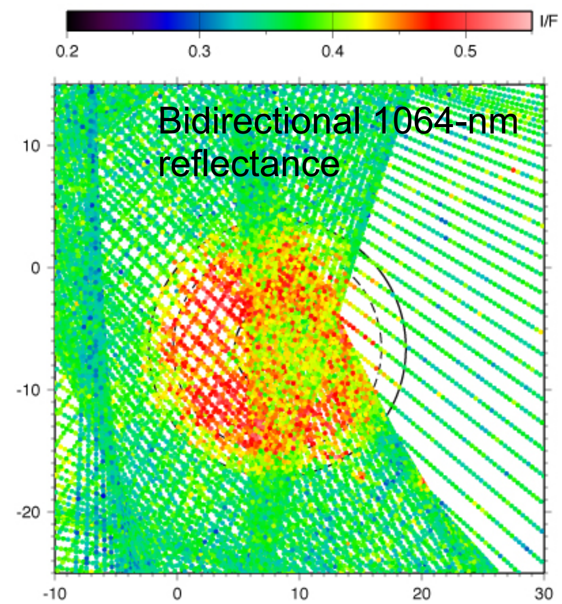
Shackleton Crater; Lunar South Pole

- Shackleton Crater
  - Is adjacent to lunar south pole
  - Lies mostly in permanent shadow
  - Has anomalously high 1064-nm reflectivity
  - Lacks a hydrogen signature from neutron flux



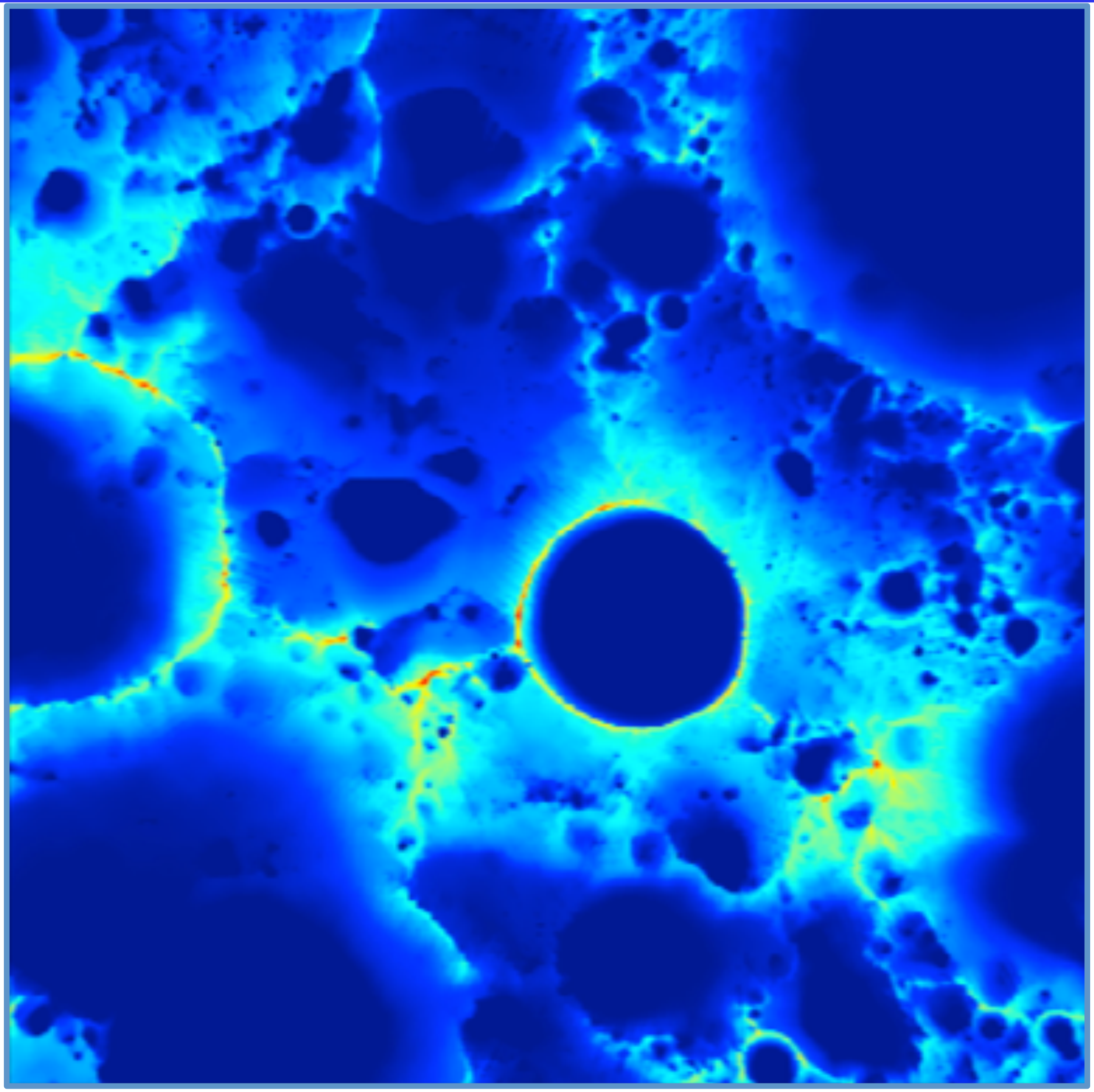
Mazarico et al. (2011)





Zuber et al. (2012)

South polar regions of "eternal light"



- Several small areas close to south pole are in sunlight for most of month.
- Most illuminated area appears to be ~10 km wes of Shackeleton rim.

Head et al. [2010]

Smith et al. [2010]

Observing Lidar Light from Space

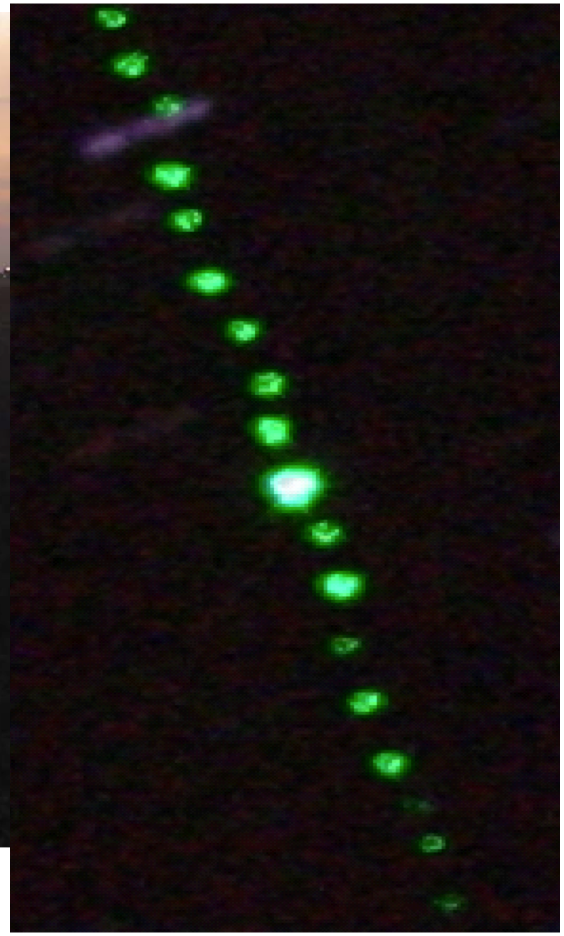
- Lidar made by NASA were designed to be safe for people and amateur astronomers with commercial equipments.
- It is extremely difficult to observe lidar light from space without official help from NASA on the spacecraft ephemeris and other details.

Observing Lidar Light from Space - ICESat

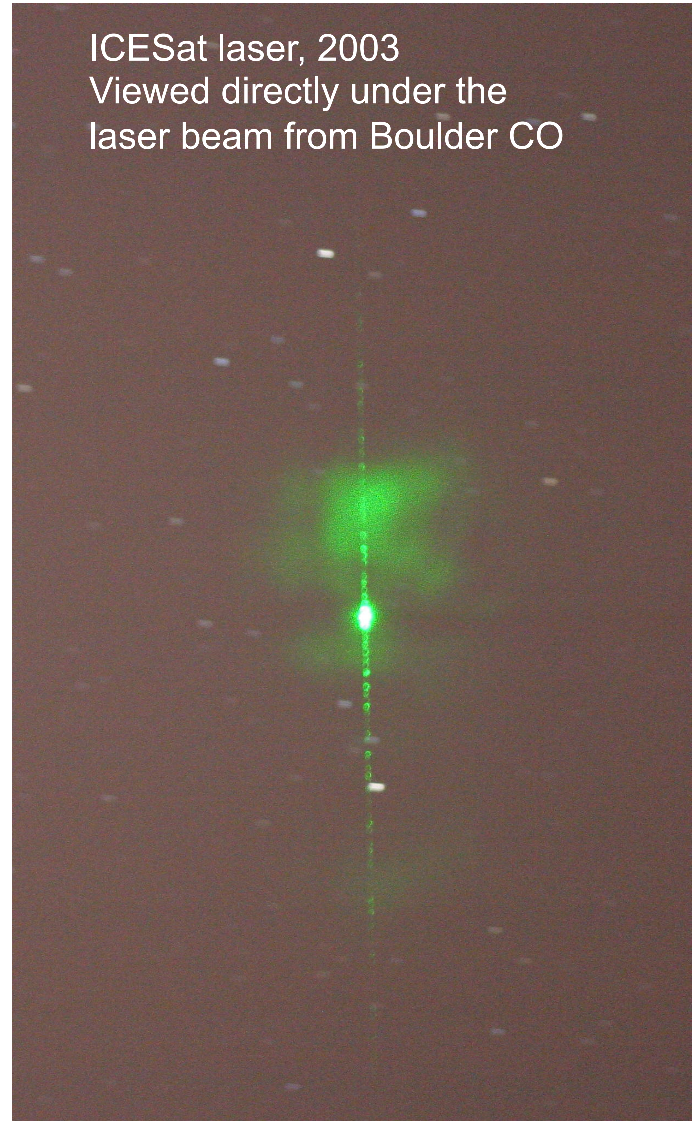
- The 532 nm laser light from ICESat/GLAS was visible to unaided human eyes.
- The laser light from ICESat/GLAS was green, brighter than Venus, and hit only once on each passing

Observing Lidar Light from Space - ICESat

11/6/2003
Santa Rosa, NM
~120' from ICESat ground track



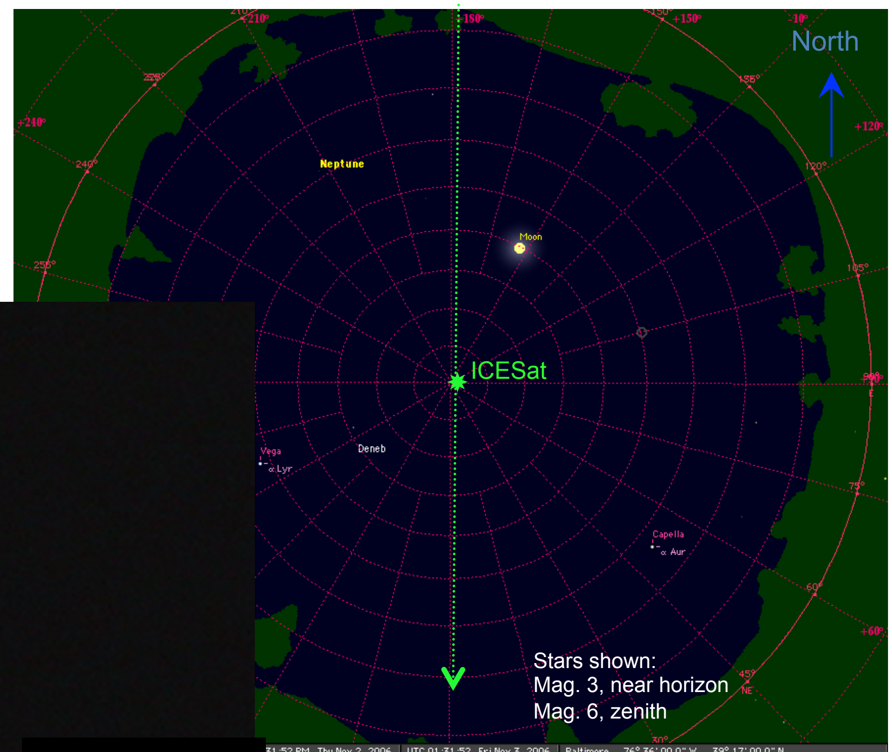
ICESat laser
appeared as a streak to human eyes when viewed through thin clouds

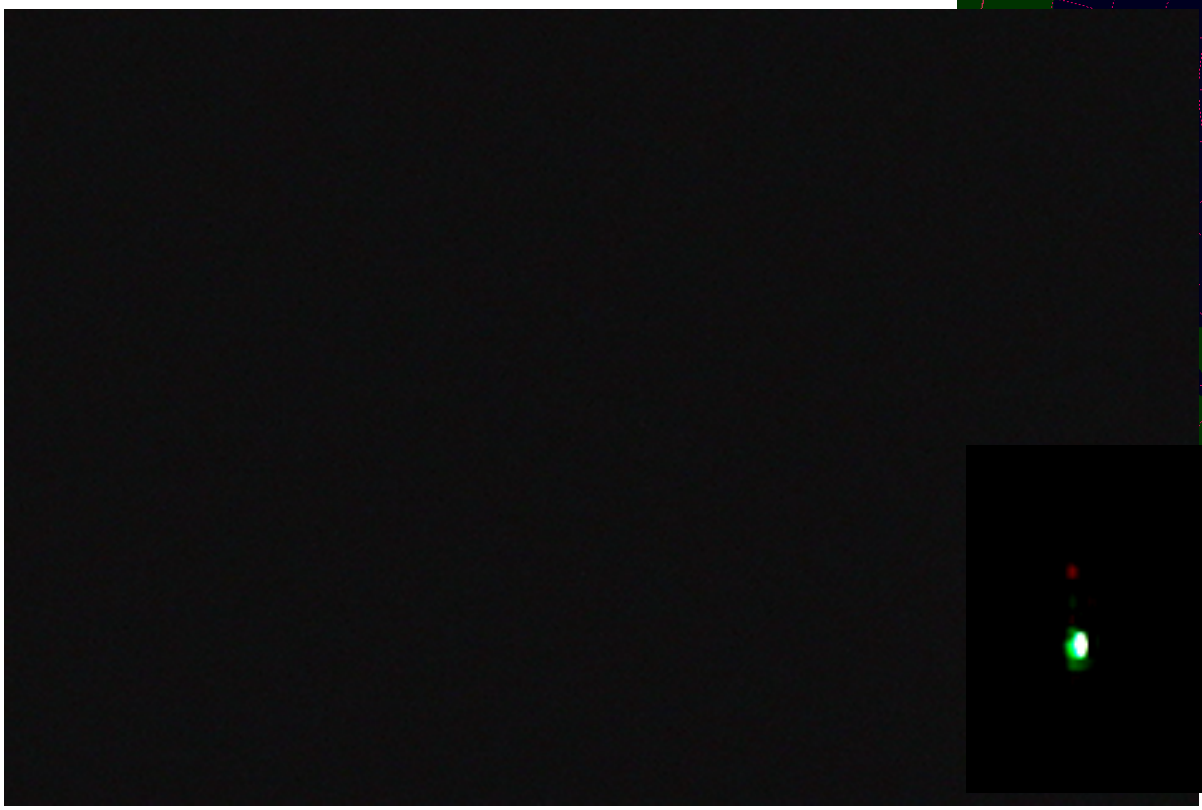


ICESat laser, 2003
Viewed directly under the laser beam from Boulder CO

Observing Lidar Light from Space - ICESat

11/2/2006
ICESat over NASA GSFC
Recorded with an old Sony video camera



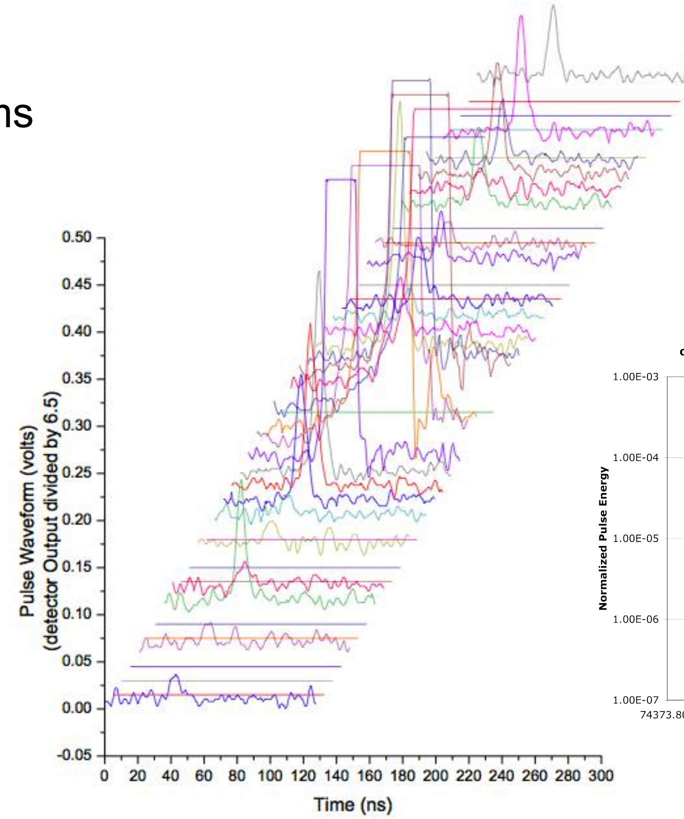


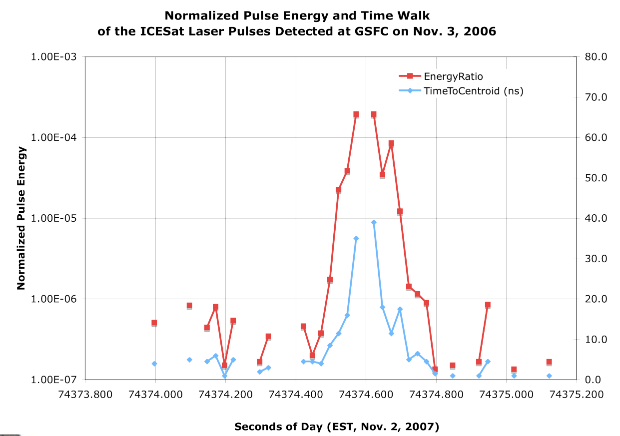
s,

Observing Lidar Light from Space - ICESat

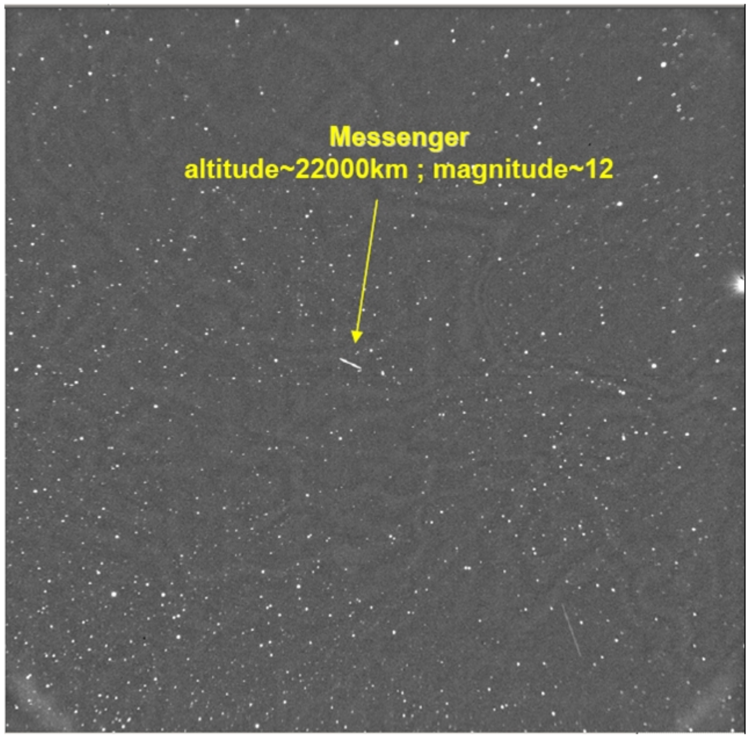
11/2/2006
ICESat over NASA GSFC
Recoding laser pulse waveforms

The GLAS EM detector and aft optics piggy backed on a Meade 10" telescope. A diffuser was placed in front of the detector to attenuate the signal by ~1000 and widen the field of view to +/-3° FWHM.



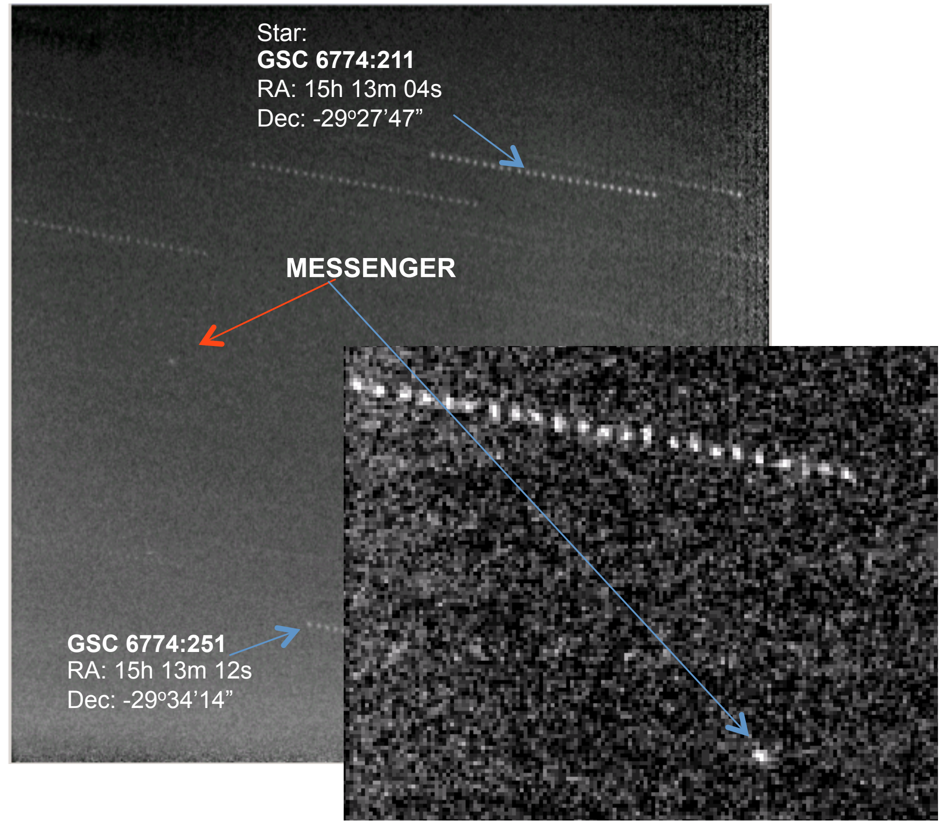


Sunlit MESSENGER Spacecraft – Earth Fly-by, 2005



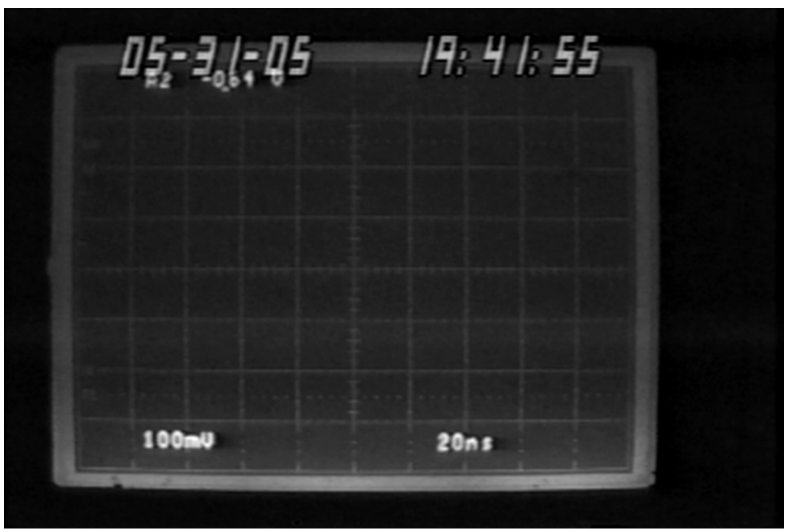
This image, taken with the TAROT CNES telescope (Latitude: 43.75deg N - Longitude: 6.92deg E) in southeastern France, reveals the position of MESSENGER as a streak of light near the center. At the time that the image was taken, 20:16:39 UTC (8:16 pm), the MESSENGER spacecraft was about 21,640 km above the eastern Atlantic Ocean near the western coast of Africa - due west of Luanda, Angola and due south of Cote d'Ivoire.

Photo credit: Régis Bertrand, B. Deguine and S. Rios-Bergantinos, CNES (Centre National d'Etudes Spatiales)



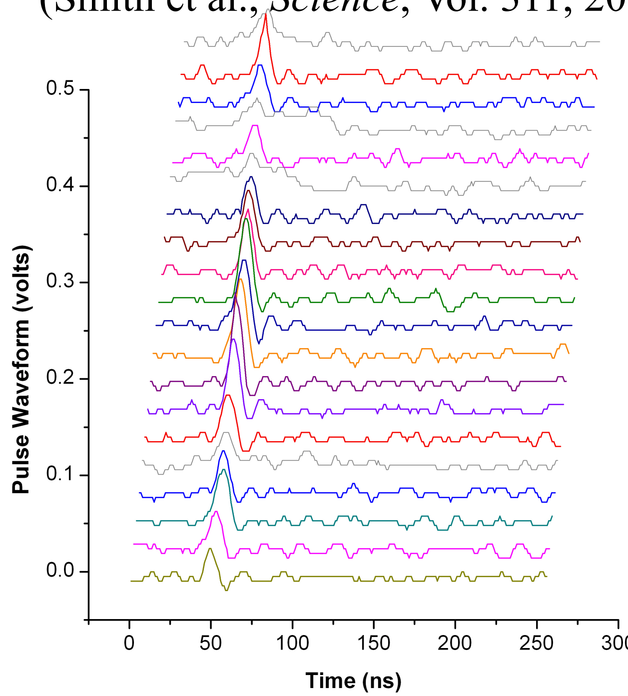
Images of the sunlit MESSENGER spacecraft shortly after the Earth fly-by at 120,000 km distance. MESSENGER appeared as a 17th Visual Magnitude star. The raw images were taken with a 14" Meade LX200GPS telescope and a SBIG ST-9E CCD camera. The image shown above is the sum of 27 raw images, each with 3 seconds exposure time. The spacecraft position solved from these images using Astrometrica software was, Time: August 3, 2005 01:27:08 (UTC), RA: 15h 13m 11.18s, DEC: -29º29'02.8", which agreed with the predicted ephemeris to within 8 arc-seconds.

MLA–Earth Two-way Laser Ranging during Earth Flyby in 2005



- 1st successful 2-way laser ranging: >24 million km at ~20cm precision
- Verified instrument performance
- Detected relativity effect (~500m longer light path due to solar gravity)
- Confirmed link equation for deep space laser ranging and communication

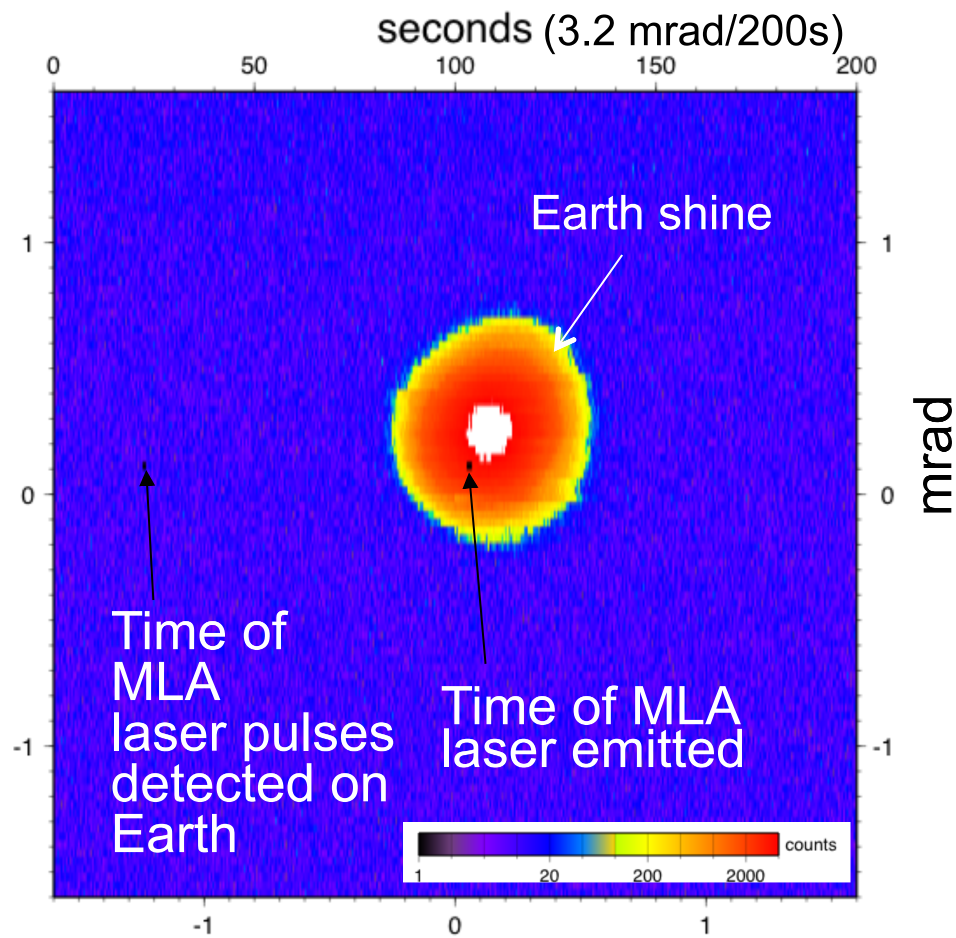
(Smith et al., *Science*, Vol. 311, 2006)



Check Optical Alignment from Earth Shine during Earth Flyby

- One of the MLA receiver channels was configured as a high performance radiometer, sensitive to cw Earth shine light;
- The Earth shine image taken by MLA gave a measure of MLA receiver FOV alignment wrt the spacecraft coordinate system;
- The timing of the Earth shine signal and the detection of the MLA laser on Earth gives a measure of MLA bore sight offset <110 urad (~1/4 FOV).

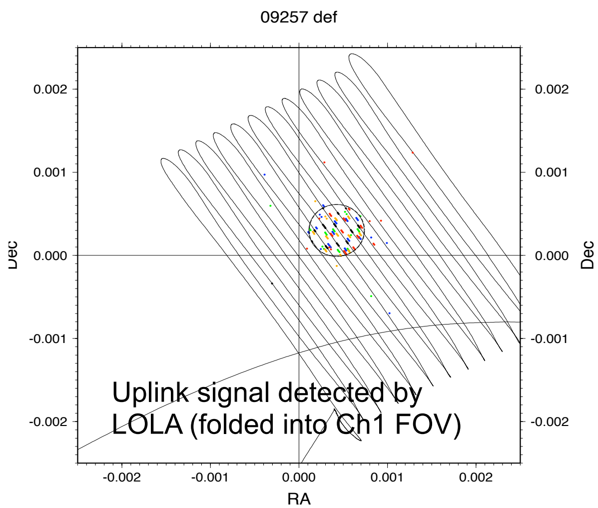
MLA Response to Earth Shine vs. scanning angle

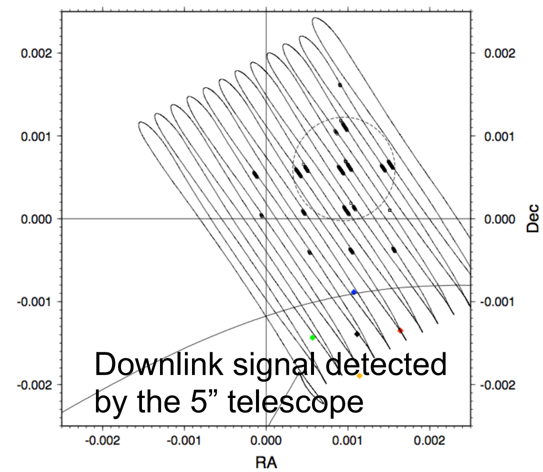


LOLA Diagnosis Tests
– Earth Scan (2009)

- Two-way laser ranging test between LOLA and SLR station on Earth in Aug. 25, and Sept. 13-14, 2000
  - Scanning the LOLA laser beam about the SLR station at NASA GSFC
  - SLR station tracking LOLA and transmitting and receiving laser pulses
  - Solving LOLA pointing and bore-sight from the time tags of the laser pulses
  - Recording LOLA laser pulse energy and pulse shape using an oscilloscope

NASA GGAO 1.2 m Telescope Facility (8/24/2009)





The test results verified DOE far field pattern and revealed a bore sight shift at low temperature

Future Space Lidar Systems

- ADM-Aeolus Wind Lidar, ESA, launch 2013
- BepiColumbo Laser Altimeter, ESA, launch 2015
- ICESat-2/ATLAS, NASA, launch 2016
- OSIRIS-REx Laser Altimeter (OLA), NASA/CSA, launch 2016

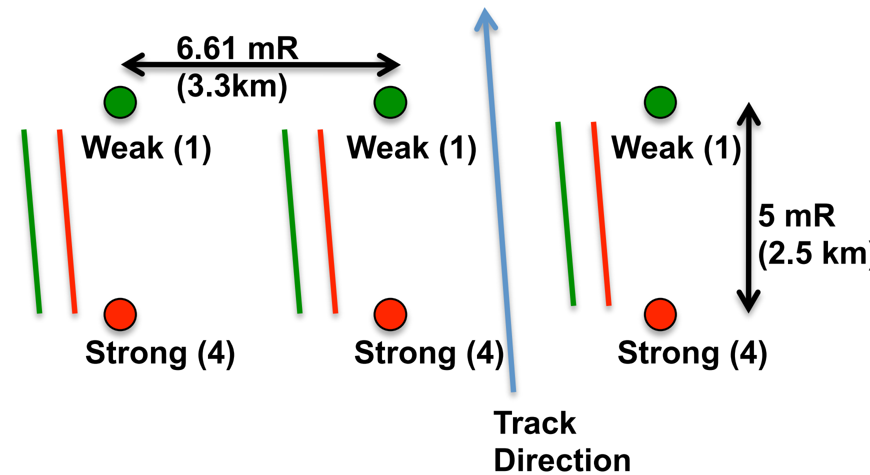
- MERLIN (MEthane Remote sensing LIdar missioN), DLR/CNES
- ASCENDS (Active Sensing of Carbon-dioxide Emission over Nights, Days, and Seasons), NASA
- LIST (LIdar Surface Topography), NASA

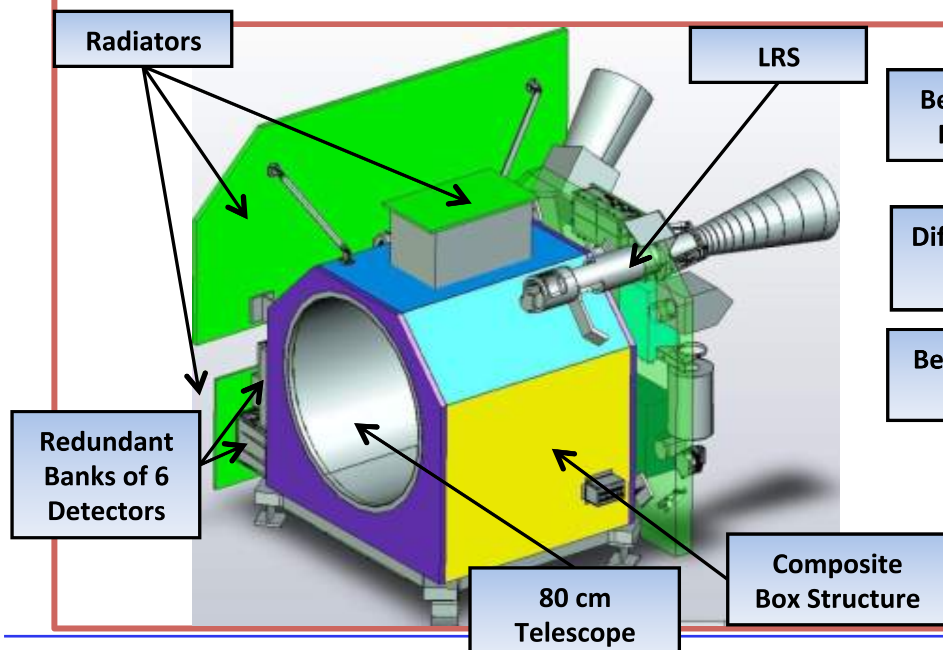
ICESat2/ATLAS Instrument Overview

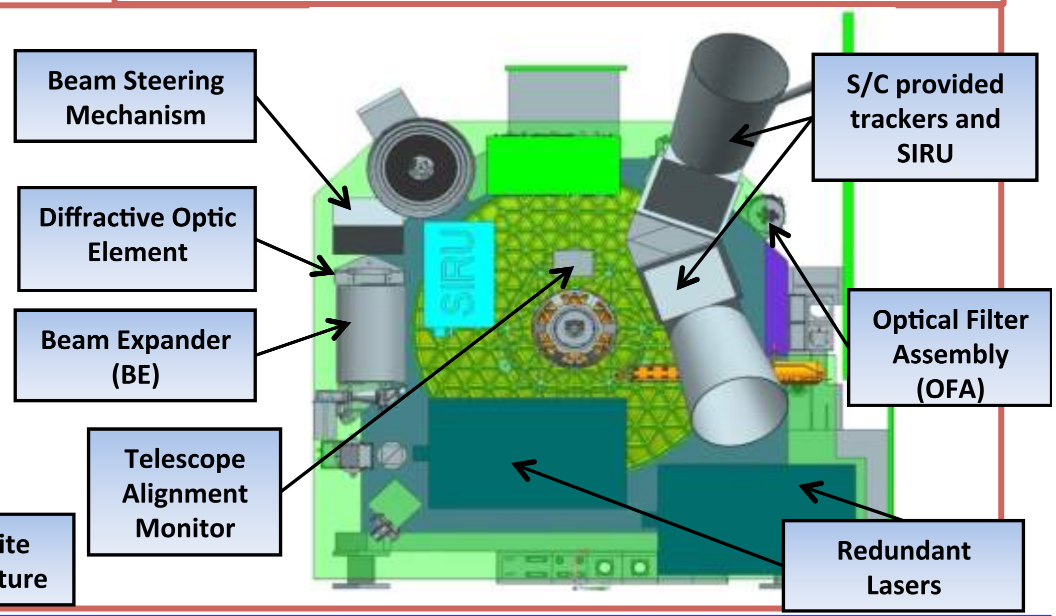
Multi-beam Micropulse Laser Altimeter

- Single laser beam split into 6 beams
- 10 m ground footprints
- 10 kHz rep. rate laser (~1mJ)
- Multiple detector pixels per spot
- On-board boresight alignment system
- Laser Reference System gives absolute laser pointing knowledge

Ground Track and Footprint





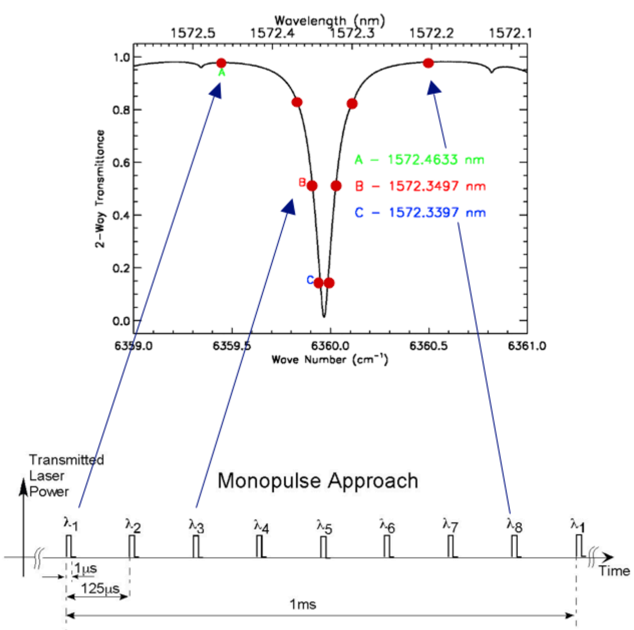


ASCENDS Mission & Laser Sounder Approach

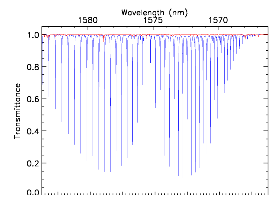
Earth Orbit, Column CO2 concentration

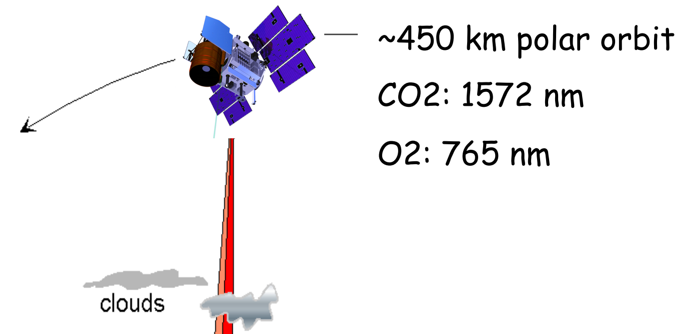
Simultaneous laser measurements:

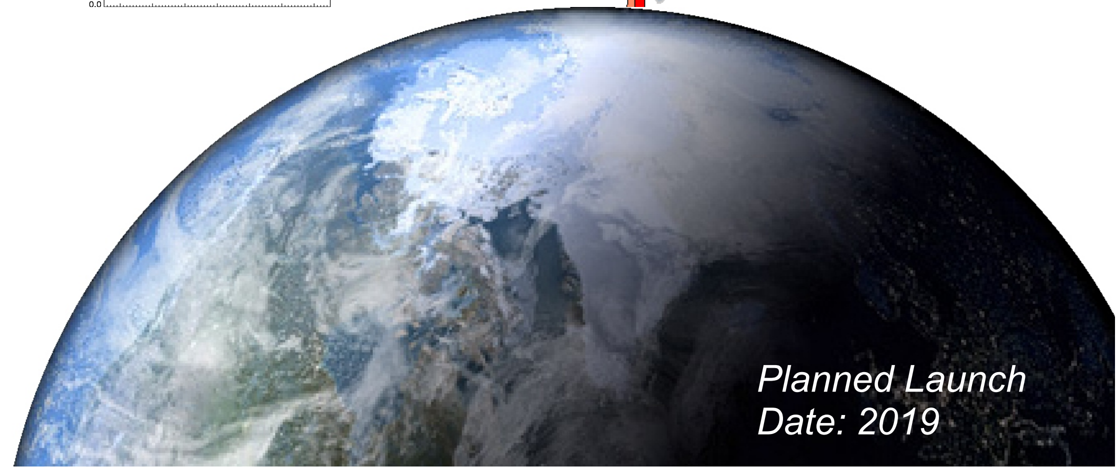
1. CO2 lower tropospheric column
   One line near 1572 nm
2. O2 total column (surface pressure)
   Measure 2 lines near 765 nm
3. Altimetry & atmospheric backscatter profile from CO2 signal:



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



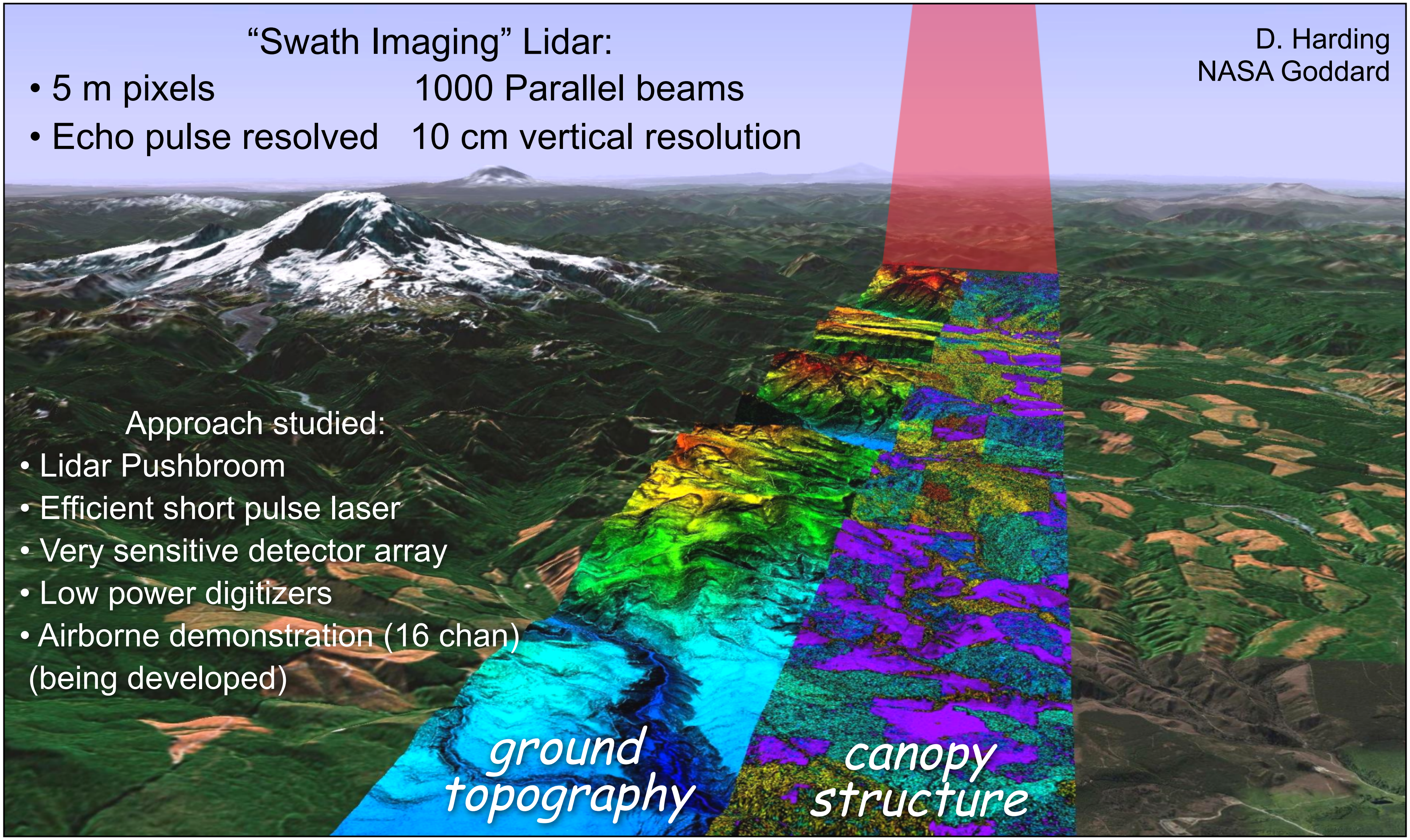




Measurements use:

- Single frequency tunable pulsed lasers
- 8-10 KHZ pulse rates
- Time gated Photon counting receiver
- High SNRs (~ 1000 in 10 sec)

Lidar Surface Topography Mission (LIST)



Summary:

- Dramatic progress since early 1990s
- Many space lidar observations demonstrated:
  - Planetary topography
  - Land & sea ice, tree heights, water height
- Enabled new geophysical science & discoveries
- Space lidar is now a primary tool for science !