Recent Advances in Photon-Counting, 3D Imaging Lidars

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Why Photon Counting?

- Most efficient 3D lidar imager possible; each range measurement requires only one detected photon as opposed to hundreds or thousands in conventional laser pulse time of flight (TOF) altimeters
- High efficiency translates to either
  - significantly less mass, volume, and prime power ; or
  - orders of magnitude more imaging capability
- Single photon sensitivity combined with fast recovery multistop timing capability enables lidar to penetrate porous obscurations such as vegetation, ground fog, thin clouds, water columns, camouflage, etc.
- Makes contiguous, high resolution topographic mapping and surveying on a single overflight possible with very modest laser powers and telescope apertures – even from orbital altitudes.

2nd Generation USAF “Leafcutter”

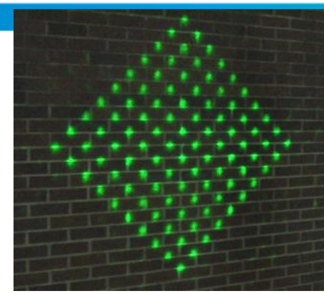
• Transmitter is a low-energy (6 μJ), high rep-rate (to 22 kHz), frequency doubled (532 nm), passively Q-switched microchip laser with a 710 psec FWHM pulsewidth.

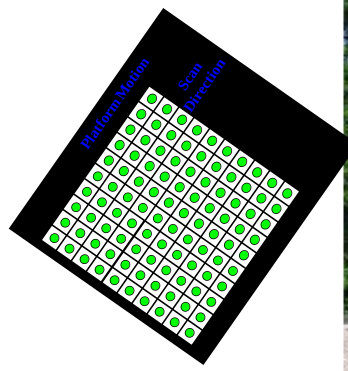
•Diffractive Optical Element (DOE) splits green output into 100 beamlets (~50 nJ @ 20 kHz = 1 mW per beamlet) in a 10 x 10 array. Residual 1064 nm energy can be used for polarimetry.

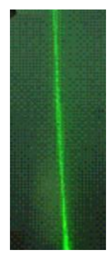
• Returns from individual beamlets are imaged by a 3 inch diameter telescope onto matching anodes of a 10x10 segmented anode micro-channel plate photomultiplier.

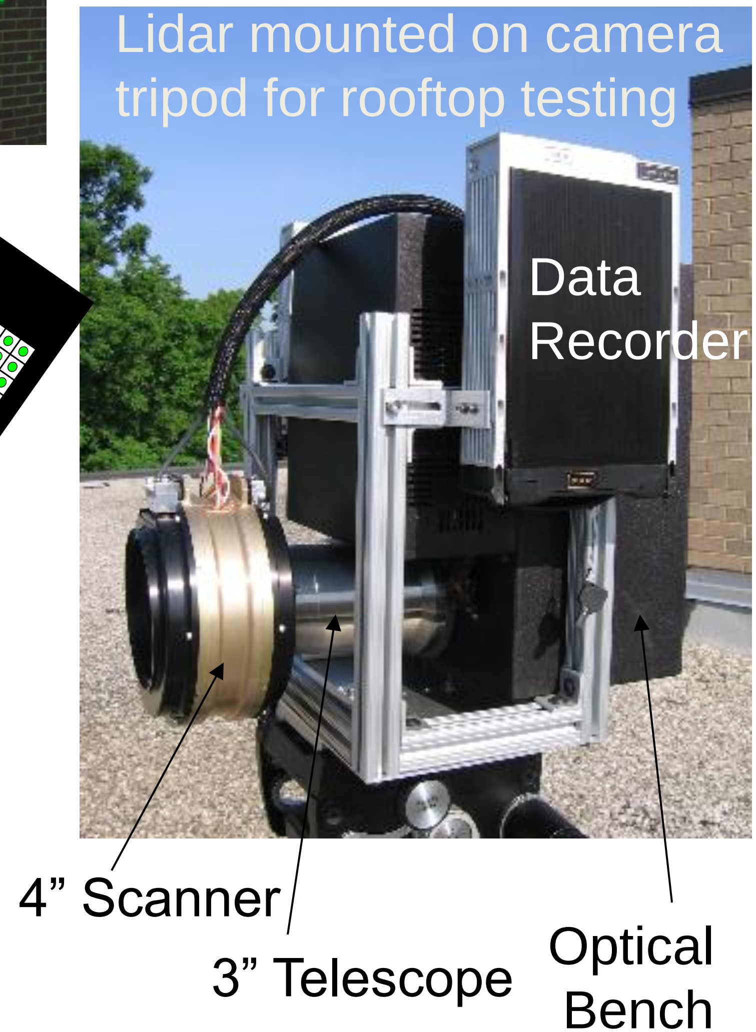
•Each anode output is input to one channel of a 100 channel multi-stop timer to form a 100 pixel 3D image on each pulse. Individual images are <u>contiguously</u> mosaiced together via the aircraft motion and an optical scanner (100 pixels @ 22 kHz = 2.2 million 3D pixels/sec!).

• The high speed, 4” aperture, dual wedge scanner can generate a wide variety of patterns. The transmitter and receiver share a common telescope and scanner.



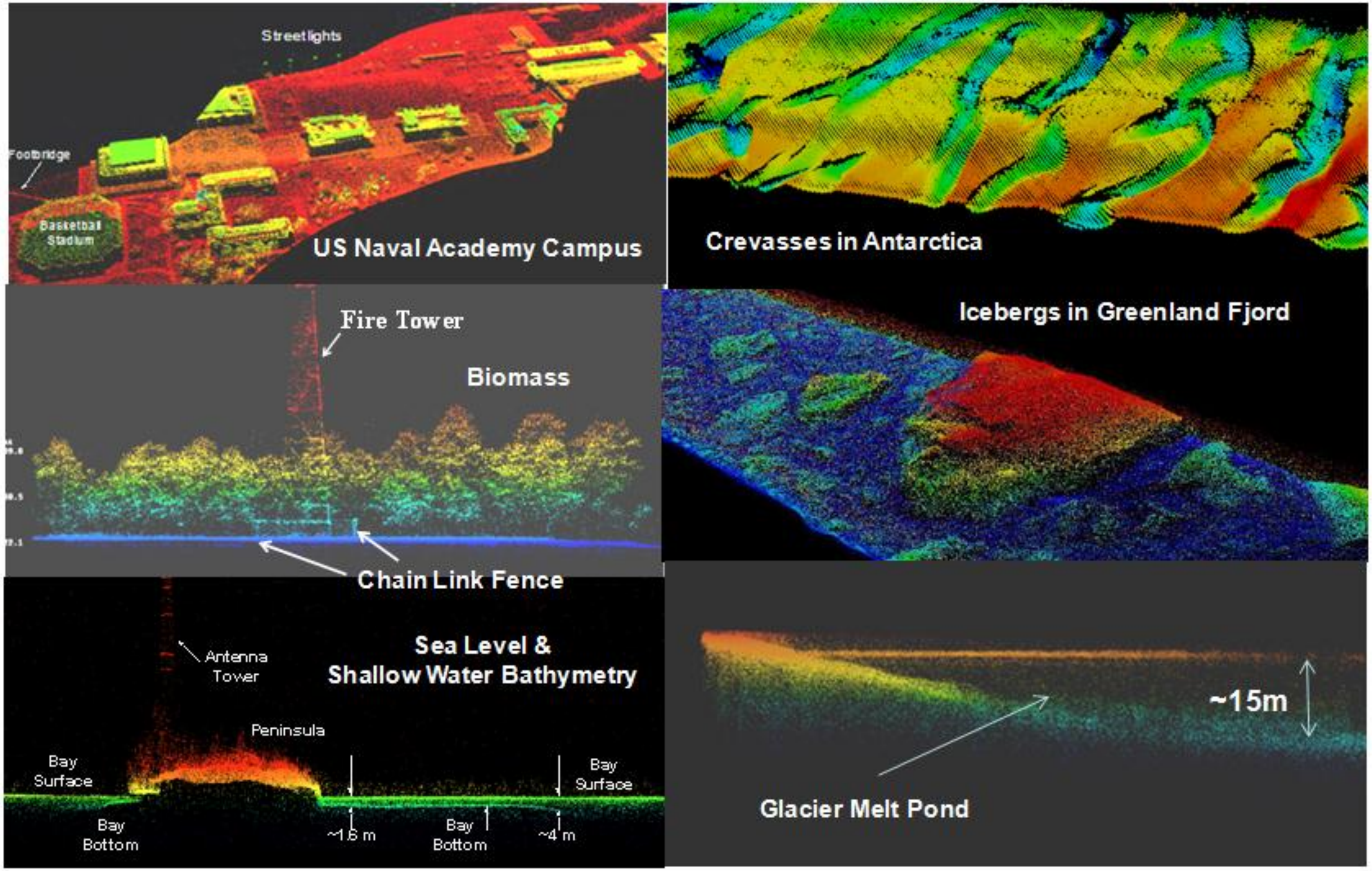






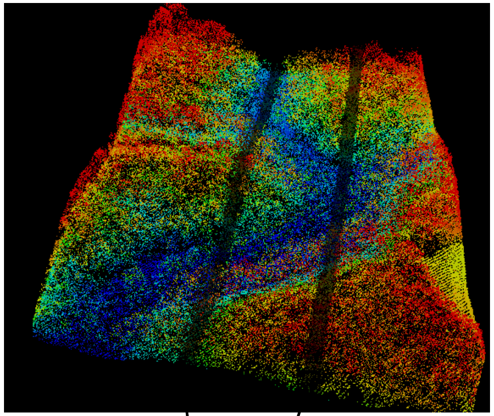
Sample Data from "Leafcutter"

Single Overflight at AGLs between 2 kft (left) and 8.2 kft (right)

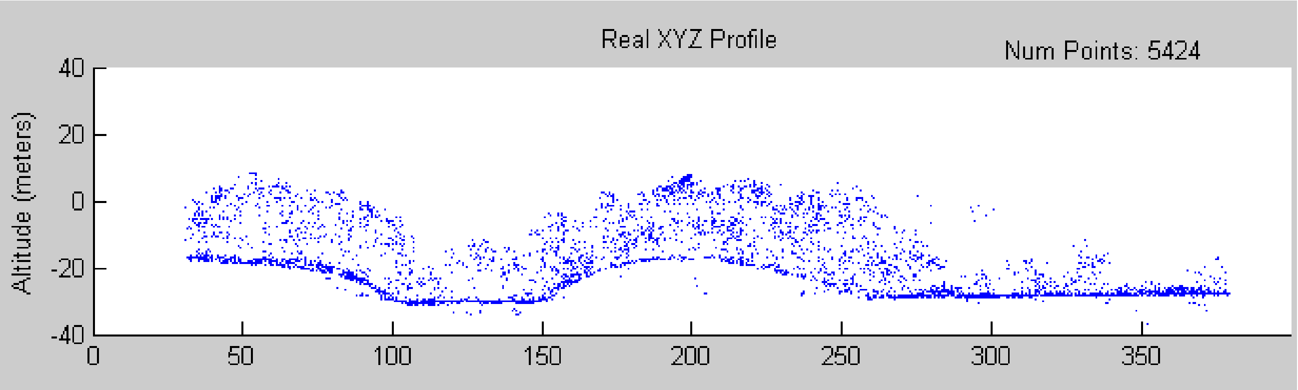


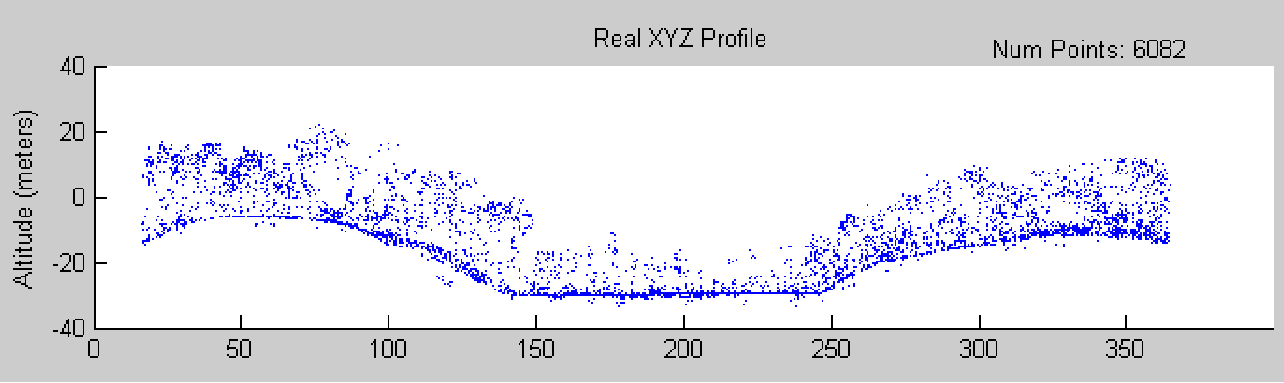
Tree Canopy Height

Applications: Forest Management , Biomass Measurement, Under Canopy Surveillance



10 m wide strips





NASA Mini-ATM for Cryospheric Studies

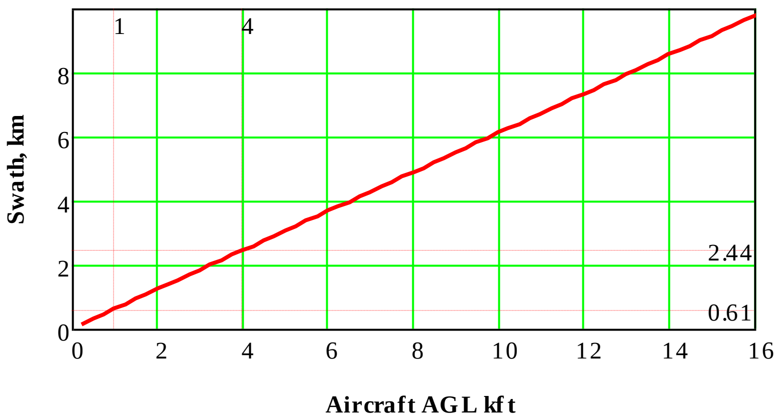
Designed for Viking 300 UAV
Weight: 28 lbs (including IMU)
Volume: ~1 cu ft (0.028m^3)
First flight data: 10/3/2012

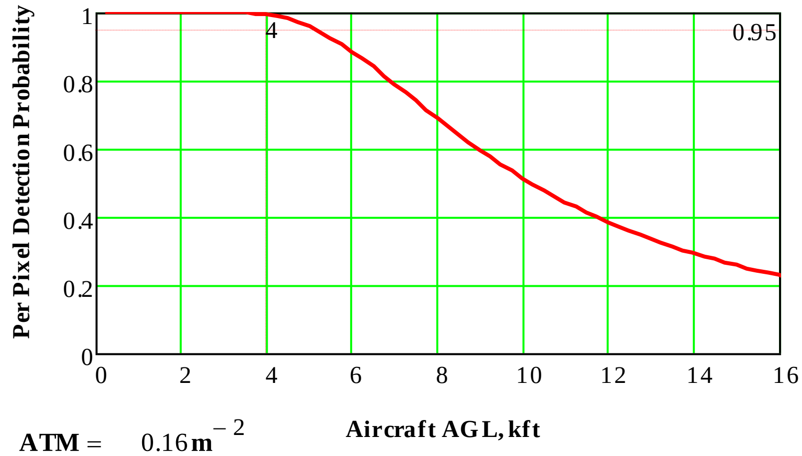
100 beams, 25 pixels (4 beams per anode)
Holographic conical scanner to $\pm$ 45 deg
Design speed = 56 knots

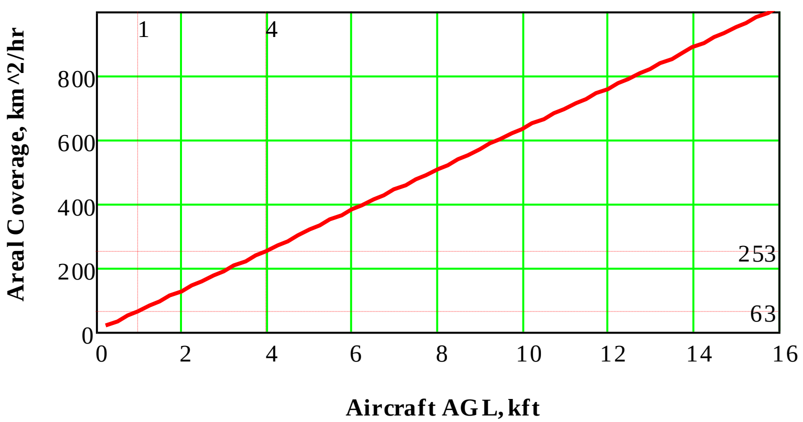
SigmaSpace
EXCELLENCE IN AEROSPACE TECHNOLOGY

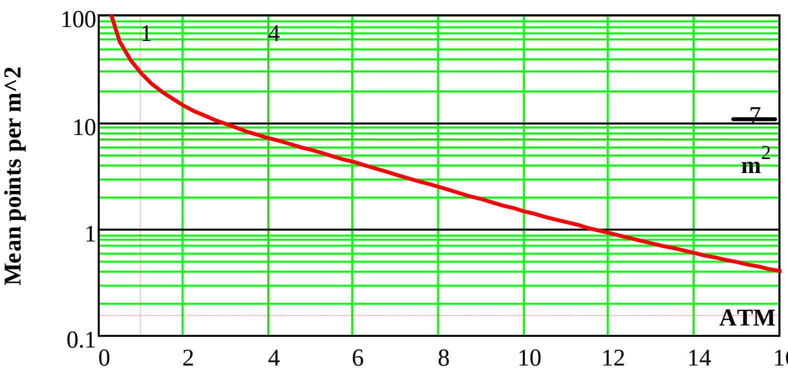
Mini-ATM Performance vs AGL (@ 56 knots)

(for cryosphere studies – exceeds ATM* performance at all AGLs)





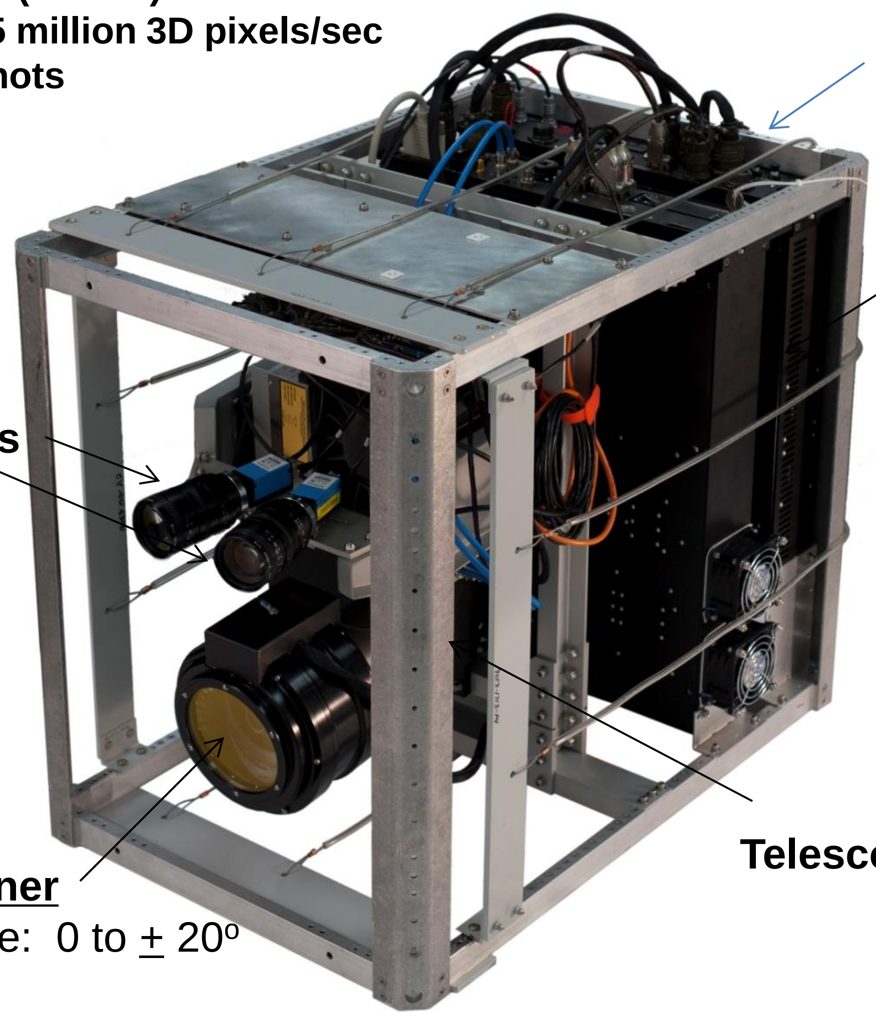




***ATM = Airborne Topographic Mapper (NASA)**

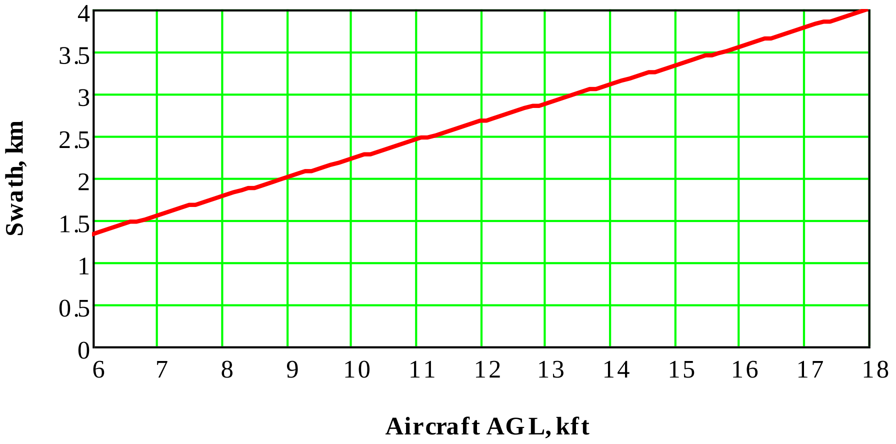
HRQLS
(High Resolution Quantum Lidar System)

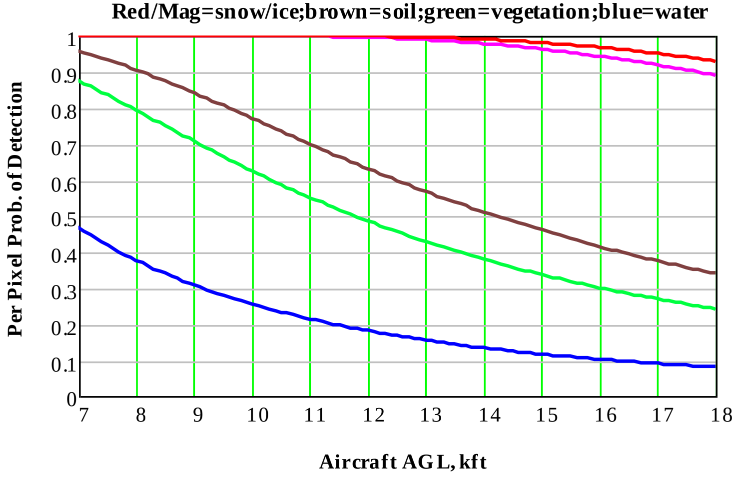
Size: 0.48m x 0.63m x 0.83 m (0.25m^3)
Measurement Rate: up to 2.5 million 3D pixels/sec
A/C Design Velocity: ≤200 knots
AGL Range: 6.5 to 18 kft

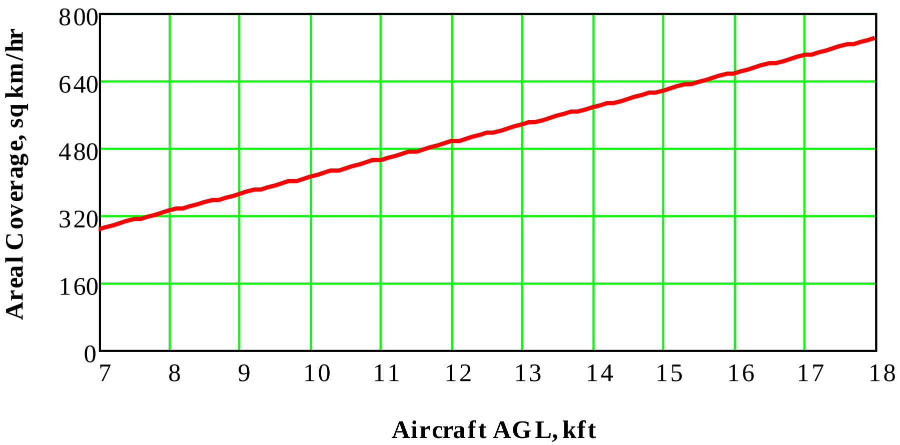


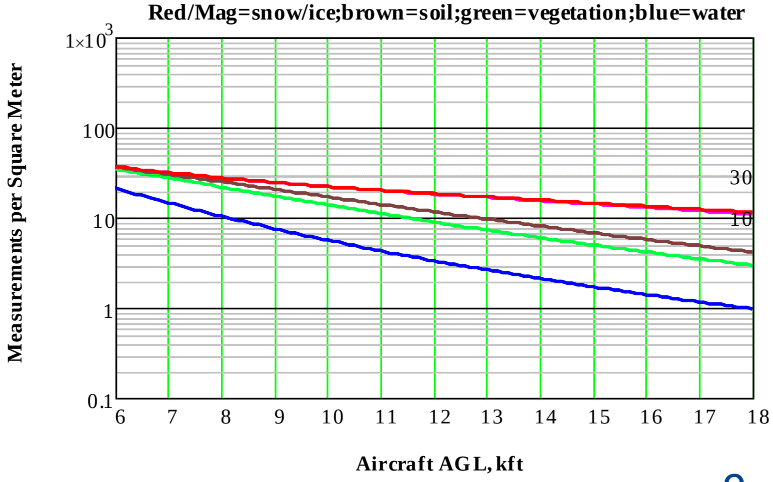
HRQLS Performance vs AGL

(@200 knots with maximum 20º scan angle*)

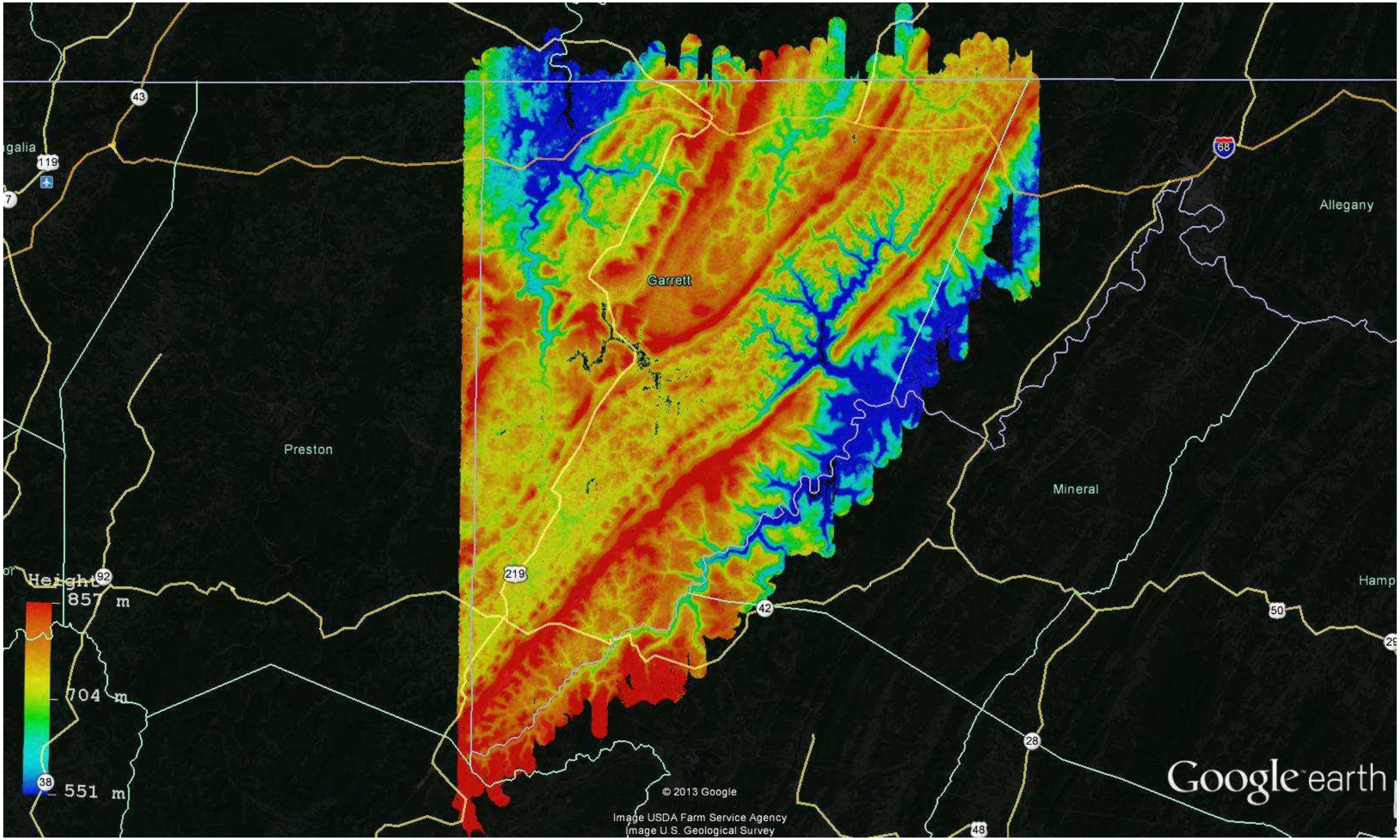








SPL 3D mapping of Garrett County, MD (1700 km²) in 12 hours for NASA Carbon Monitoring Study



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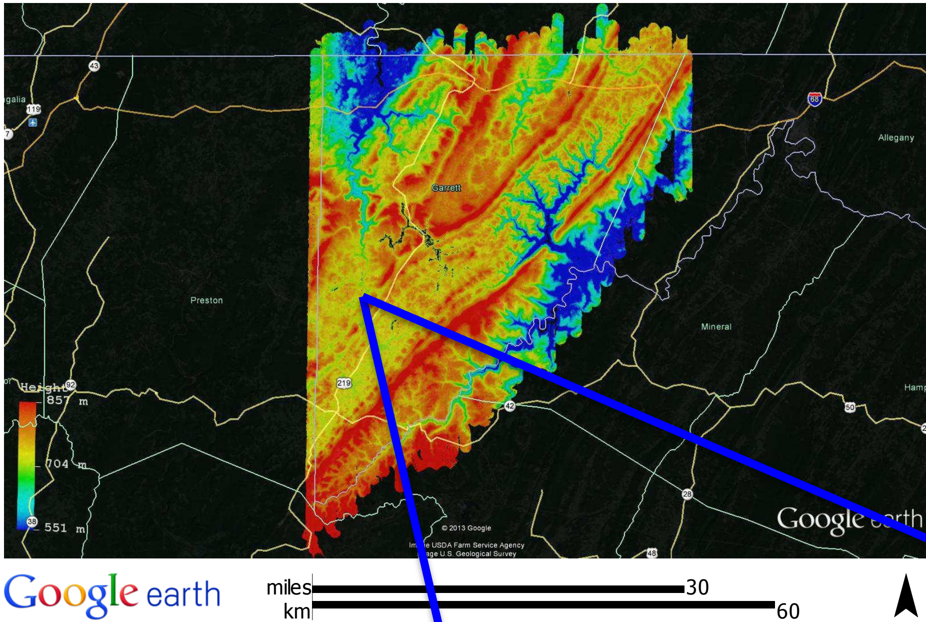
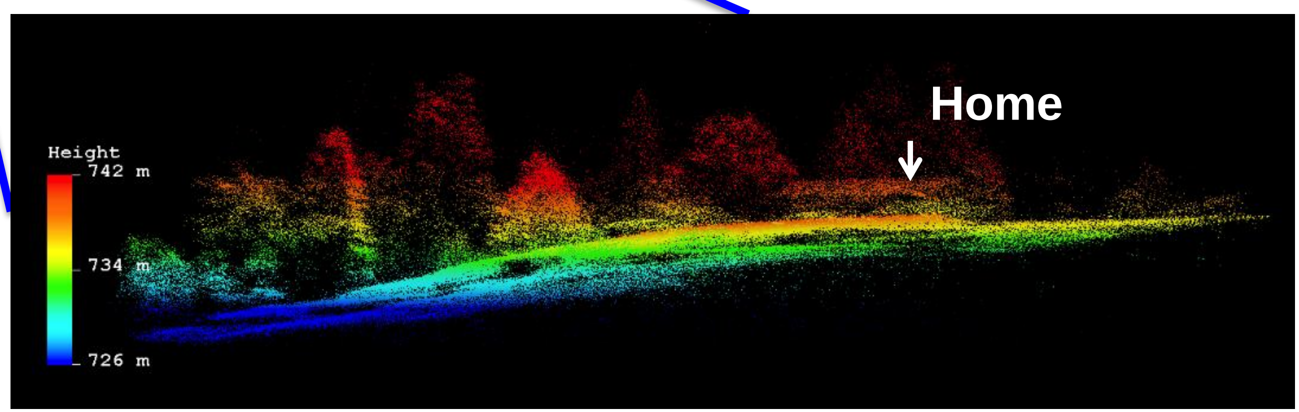
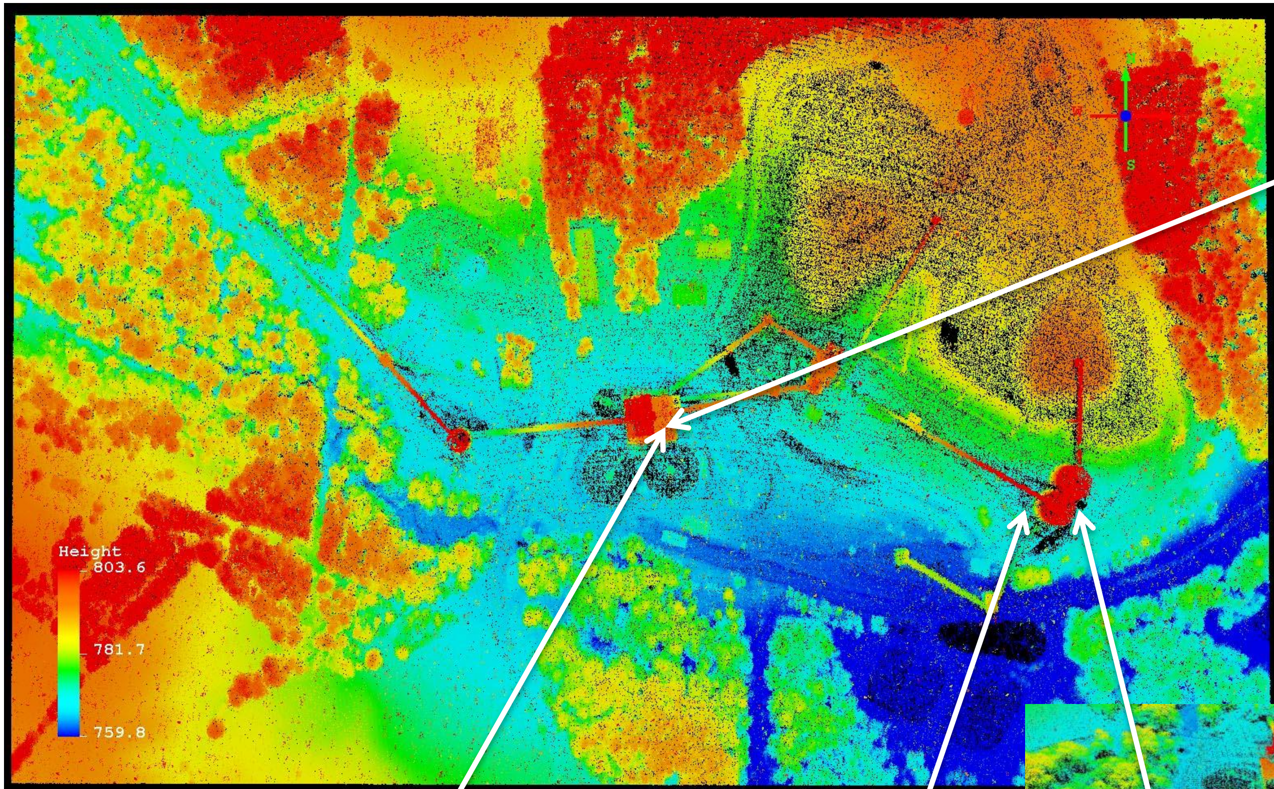


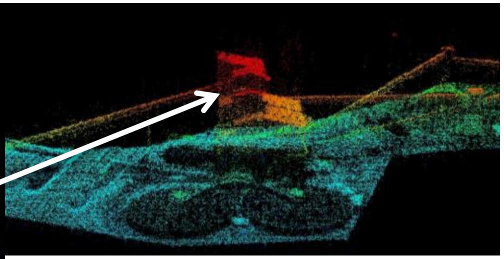
Rapid 3D mapping of an entire county (1,700 km²) in high spatial resolution

- Velocity = 150 knot (278 km/hr)
- Scan Angle = ±10 deg
- AGL = 7500 ft (2.3 km)
- Swath = 0.81 km
- Coverage: 224 km²/hr



Garrett County Coal Mine





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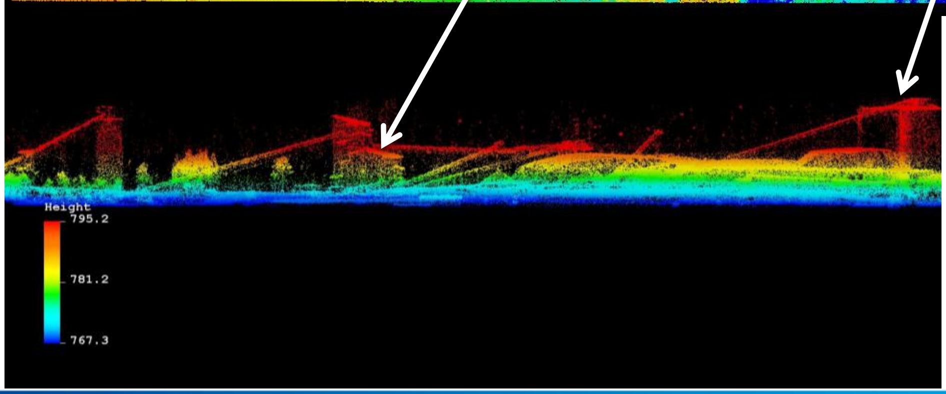
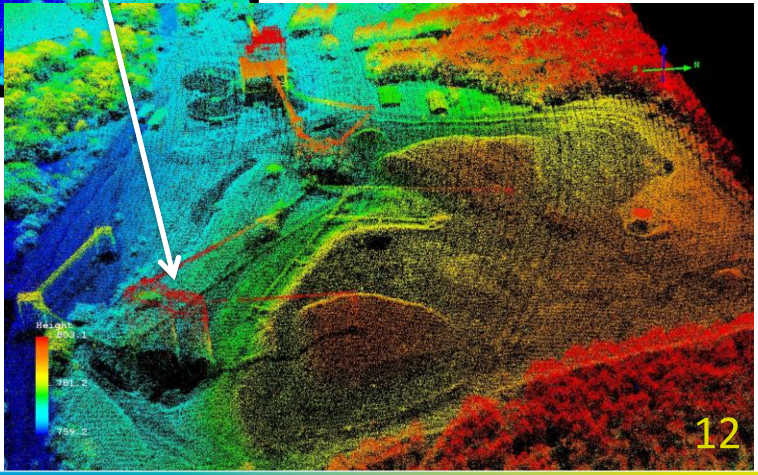
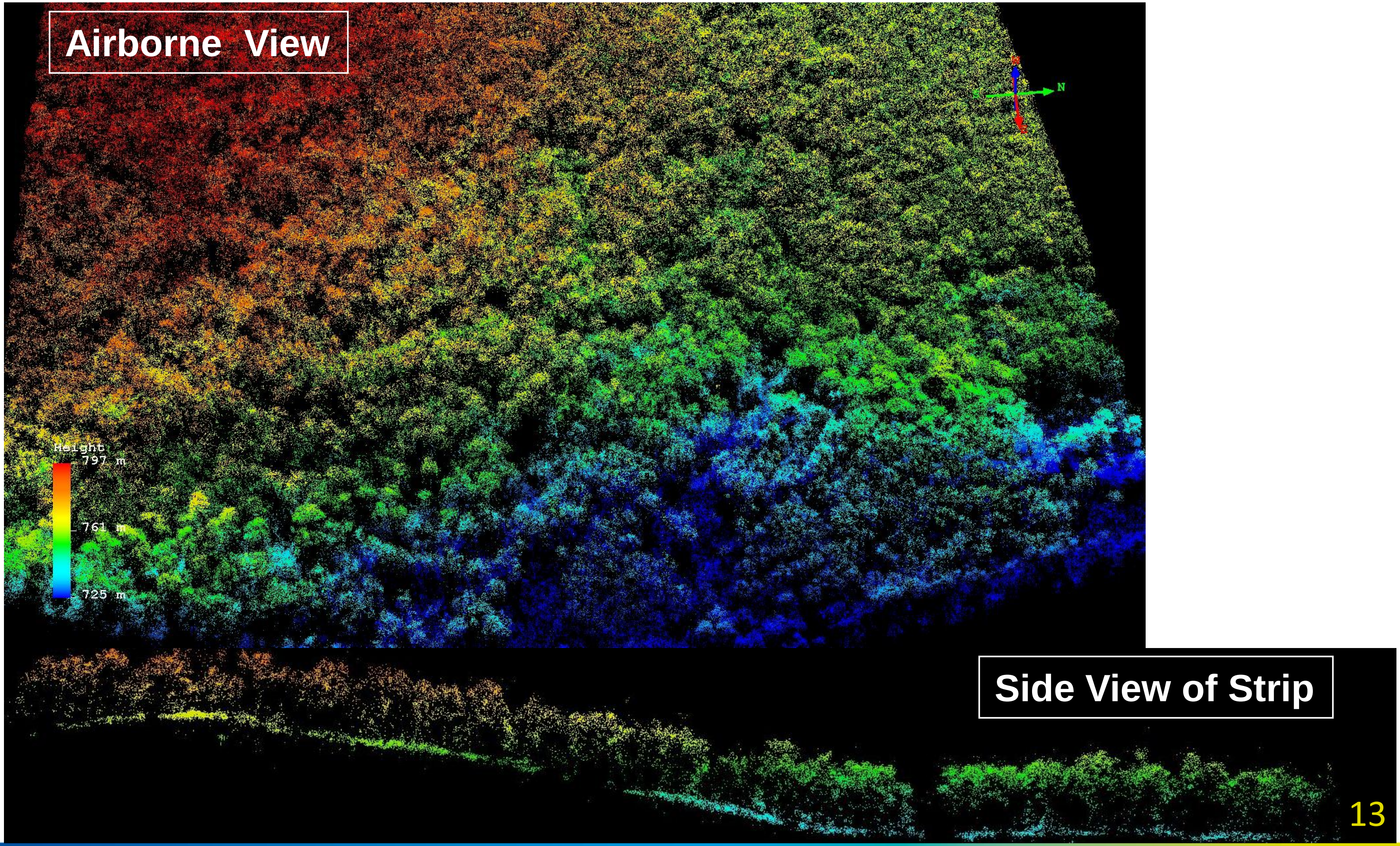




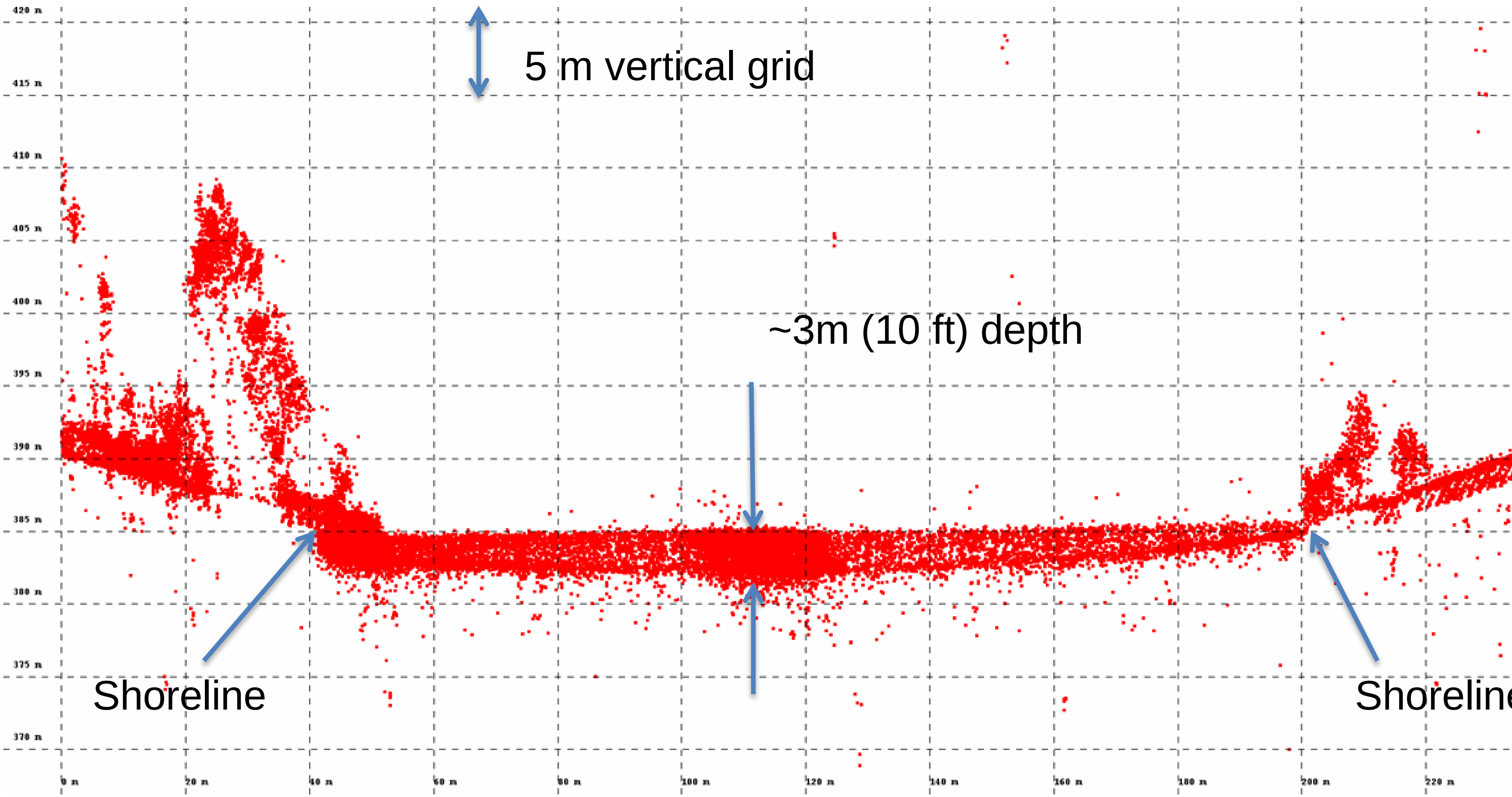
HRQLS: Tree Canopies

Heavily Forested, Mountainous Area in Garrett County, Maryland
Elevation: Blue (725 m) to Red (795m) ; Delta = 70 m



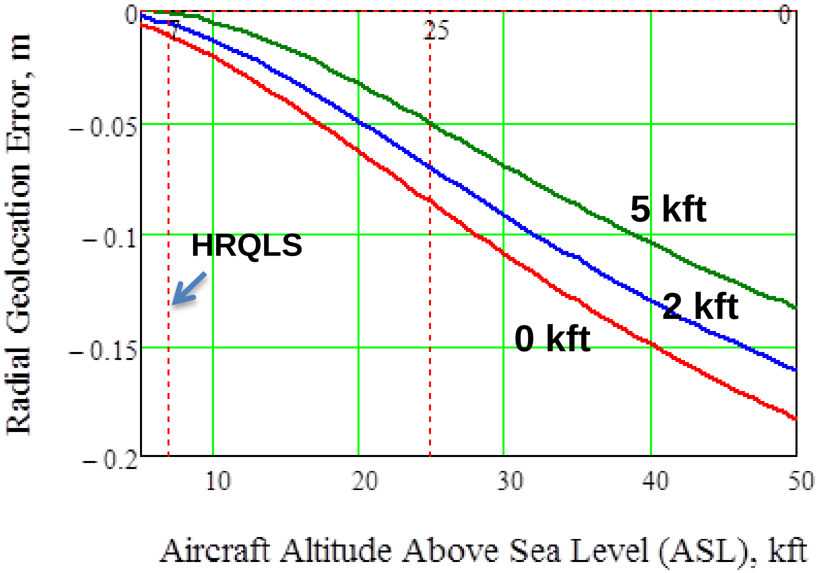
HRQLS: Bathymetry of Muddy Drainage Pond

From an AGL of ~2000 ft, HRQLS could penetrate to the bottom of a muddy construction drainage pond to its maximum depth of ~3 m (10 ft), corrected for water index of refraction. Particulate density appears to decrease near shoreline.



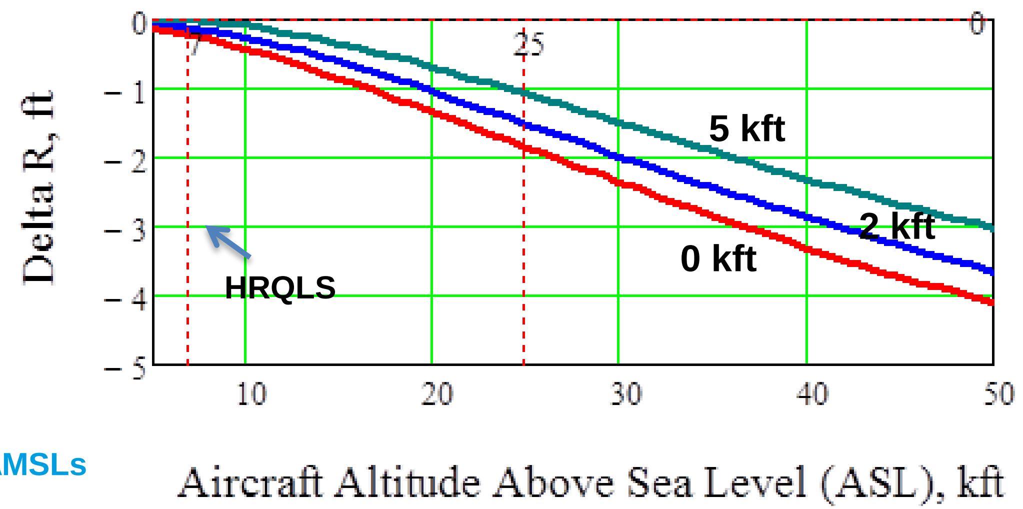
Nominal Atmospheric Corrections*

Nominal Radial Correction (m)



Surface Elevation Above Sea Level
Red = 0 kft
Blue = 2 kft
Green = 5 kft

Nominal Vertical Correction



- **Uses Marini-Murray Spherical Shell Model of the Atmosphere**
- **Model also takes into account effects of aircraft pitch, yaw, and roll. (These plots assume all attitude angles are zero)**

*Geolocation error is nominally a few cm at HRQLS AMSLs but grows to decimeter levels at higher altitudes.

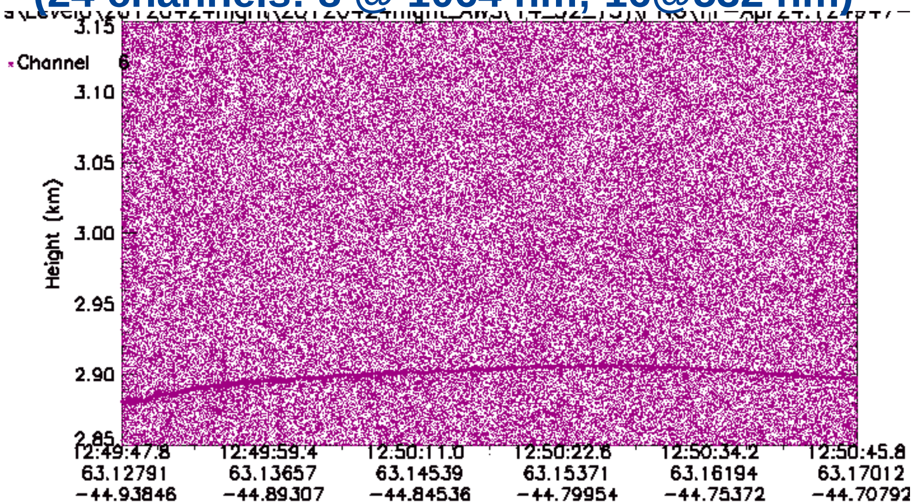
NASA MABEL Photon-Counting Lidar
Host Aircraft: NASA ER-2

Customer: NASA Goddard Space Flight Center
- **Completed in 10 months**
- **24 beam pushbroom lidar (16@532 nm, 8@1064 nm)**
- **First Flights: December 2010**
- **Operational AGL: 65,000 ft**
- **Precursor instrument to NASA ATLAS PC Lidar on ICESat-2 spacecraft to be launched into 500 km near-polar orbit**

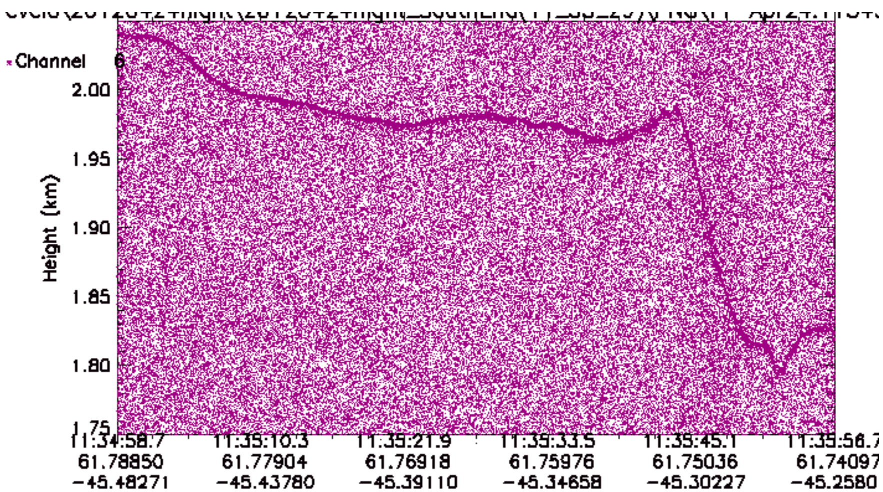
Sigma provided:
- **Electronic subsystems including proprietary TOF electronics**
- **Mechanical subsystems**
- **Thermal Control Systems**
- **Integration , test, and field operations support**

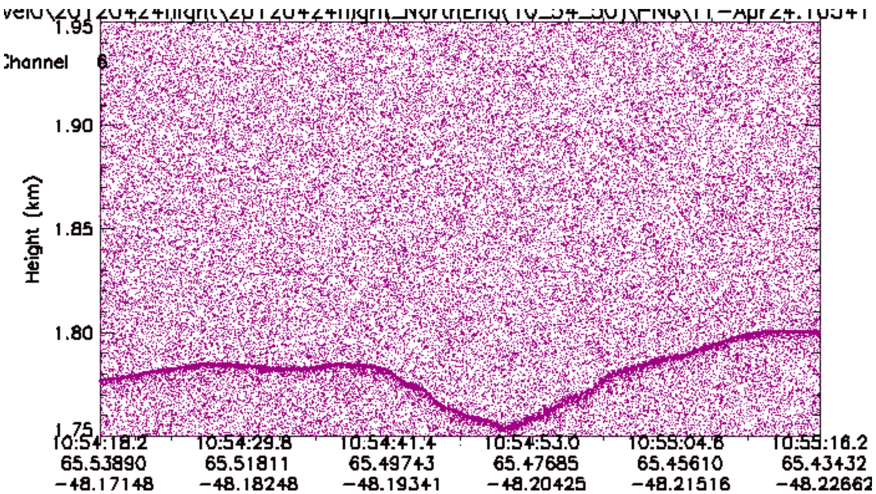
NASA MABEL Instrument

Photon-Counting in Greenland in daylight from 65,000 ft
(24 channels: 8 @ 1064 nm; 16@532 nm)

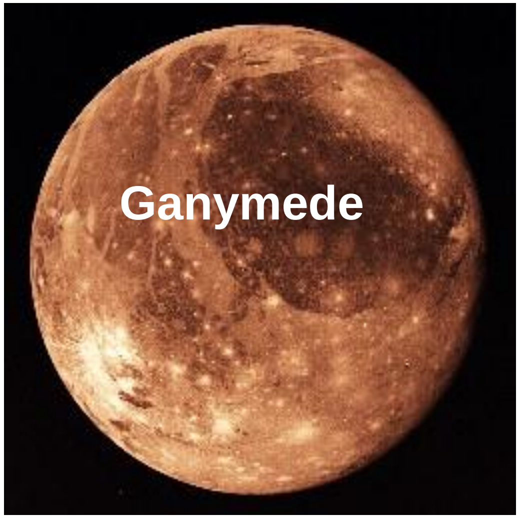


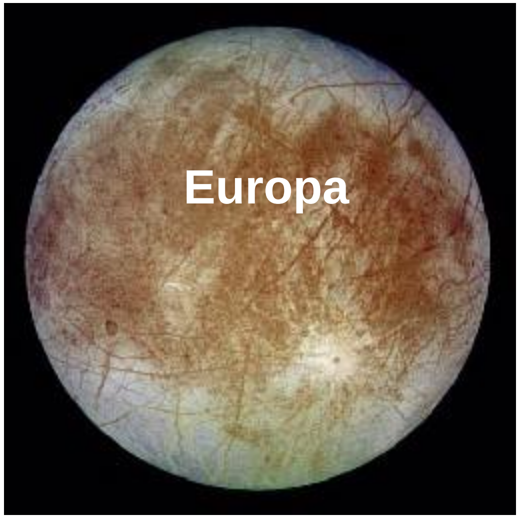
- April 24, 2012
- Sample Channel #6 profiling results (532 nm)
- 10 kHz laser fire rate





Jupiter Icy Moons Orbiter





JIMO 3D Imaging Goals

- Globally map three Jovian moons
- Horizontal Resolution: <10 m
- Vertical Resolution: < 1 m

Worst Case Constraints

- Europa (last stop) map must be completed within 30 days due to strong radiation field*
  - 348 orbits at 100 km altitude
  - 14.5 km mean spacing between JIMO ground tracks
- Surface Area: 31 million km^2

* More recent JPL studies have indicated that, with proper shielding, Europa operations could possibly be extended to 3 or 4 months, allowing higher resolution maps.

Contiguous Mapping of the Jovian Moons

h = 100 km = nominal spacecraft altitude for JIMO mission
v_g = 1.30 to1.83 km/sec = range of spacecraft ground velocities at Jovian moons
α= 5.72° = scanner cone half angle overfills mean 14.5 km gaps between groundtracks
δ = 10 m = minimum horizontal spatial resolution per pixel
N^2 = 100 = number of beamlets/detector pixels in 10x10 array
ρ=0.15* = nominal surface reflectance of Earth soil at 532 nm [*conservative since Visual Geometric Albedo = 0.68 (Europa), 0.44 (Ganymede), and 0.19 (Callisto)]
n_p = 3 = minimum signal photoelectrons per pixel (implies P_d >95% but forward and backward looks at the same pixel give P_d~99.8%.

Scanner Frequency, f_{scan}:
(ensures contiguous alongtrack coverage)

$$f_{scan} \geq \frac{v_g}{N\delta}$$

Laser Repetition Rate, f_{qs}:
(ensures contiguous coverage along conical scan circumference)

$$f_{qs} \geq \frac{2v_g h \tan\alpha}{(N\delta)^2}$$

Power-Aperture Product, *PA*:
(ensures desired signal strength)

$$PA = f_{qs} E_t A_r > f_{qs} \frac{n_p \pi h \nu N^2 h^2 \sec^2\alpha}{\eta_t \eta_c \eta_r \rho \cos\sigma T_0^2}$$

JIMO Mission Requirements

Jovian Moon	Europa	Callisto	Ganymede
Lunar Mass, *M* (kg)	4.80×10^{22}	1.08×10^{23}	1.48×10^{23}
Mean Volumetric Radius, *R*, km	1569	2400	2643
Surface Area, 10^6 km^2	31	72	87
Satellite Altitude, *h* (km)	**100**	**100**	**100**
Ground Velocity, v_g (km/sec)	1.30	1.63	**1.83**
Satellite Orbital Period, min	126	154	151
Mission Duration, D_i (Days)	**30**	56	60
3D Imager Resolution, δ (m)	**10**	**10**	**10**
Minimum Swath Width, *S* (km)	**14.4**	14.4	14.4
Scanner FOV Half Angle, (deg)	**5.72**	5.72	5.72
Minimum Scan Frequency, Hz	13.0	16.3	**18.3**
Minimum Laser Fire Rate, f_{qs} (kHz)	5.89	7.37	**8.27**
Minimum Lidar PA-Product, W-m^2	0.80	1.00	**1.12**

Bolded red numbers indicate which Moon is determining the instrument requirement.
The 5.72 deg scan half angle provides ~20 km swath vs 14.5 km mean ground track separation.
The large telescope FOV favors a conical scanner to easily correct for spherical aberration effects.

Laser Power – Telescope Aperture Trade

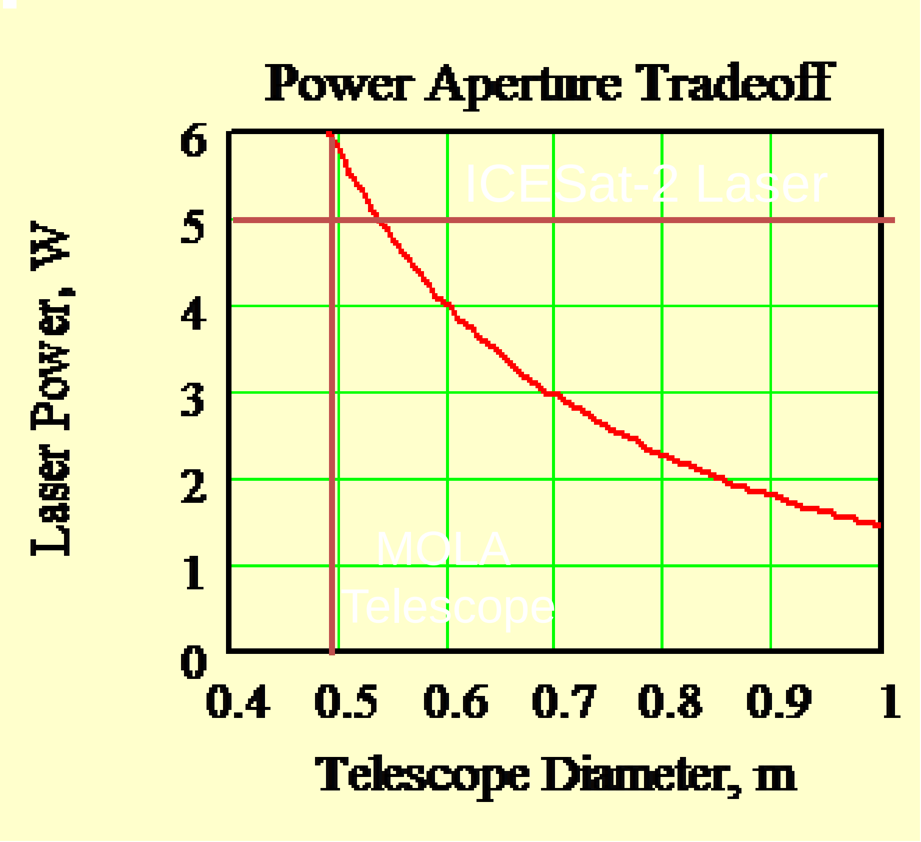
Power-Aperture Product: 1.12 W-m^2 (Worst Case Ganymede)

Min. Prob. of Detection per Pixel: P_d = 95% (15% surface reflectance)

<u>ICESat-2 Laser @ 532 nm</u>
Power: 0.5 mJ @10 kHz =5 W

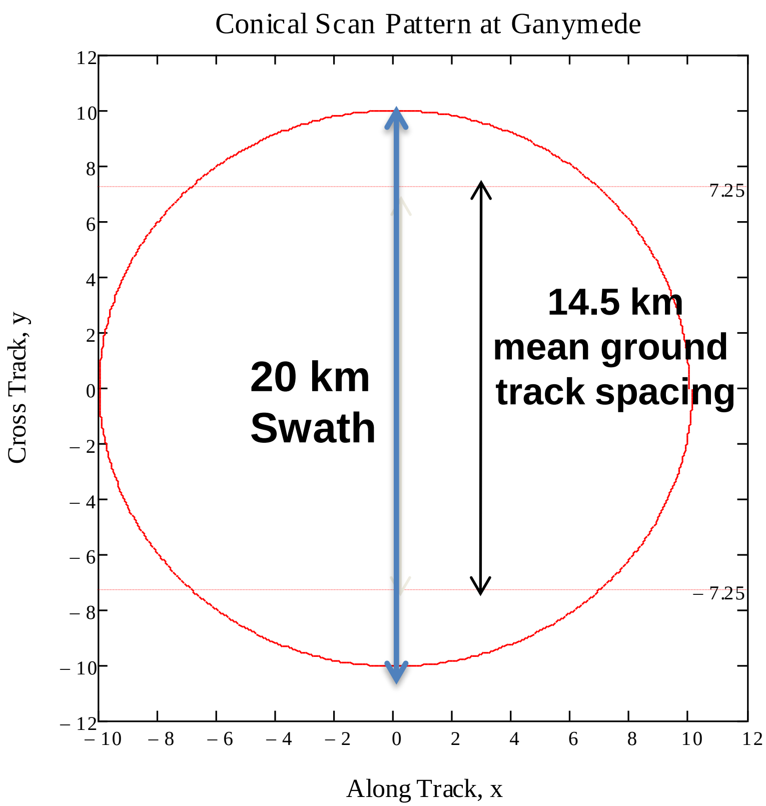
<u>Mars Orbiter Laser Altimeter</u>
Telescope Diameter: 50 cm

Since each 10m x 10 m ground pixel is looked at twice - i.e. in the forward and backward scan segments – the actual probability of detecting a given pixel is PD = $P_d(2-P_d)=0.95(1.05)=0.9975$

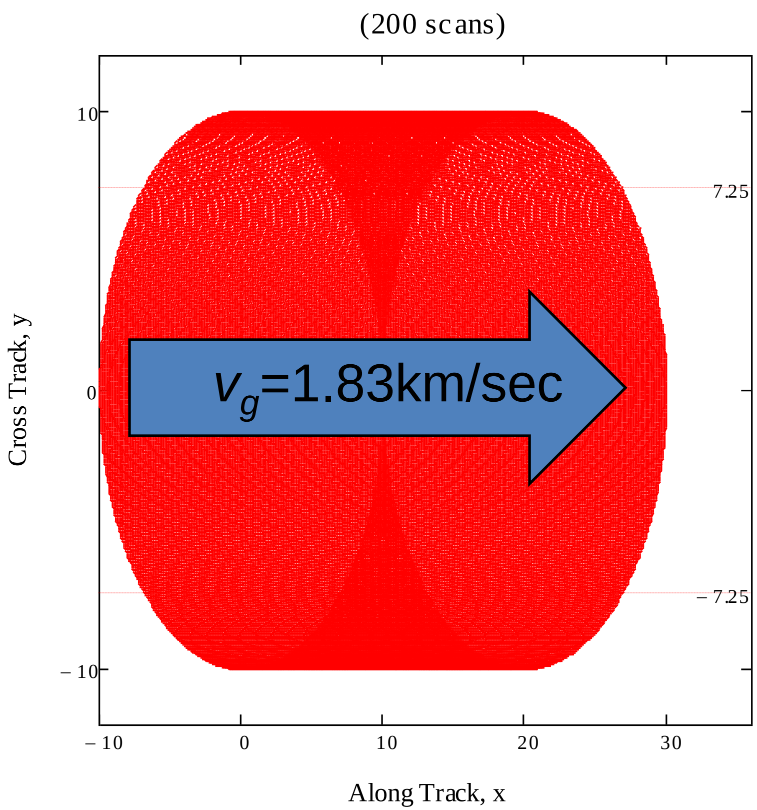


Scan Patterns at Ganymede*

forward and backward scans provide two looks at each ground pixel per pass



Single Scan (0.055 sec @18.3Hz)



200 scans (10.9 sec)

Projected DSN Data Rates*

Surface Range Measurements per Second: 100 beamlets @ 8.3 kHz = 0.83 MHz
Bits per Raw Range Measurement @ 100 km: 24 (1cm); 17(1m resolution)
Raw Data Rate:17 bits x 0.83 MHz = 14 Mbps (noise editing and no compression)
After Lossless Compression (Rice): (17+99*12)bits*8.3 kHz)/2 =5 Mbps
For 2020 DSN rates from Jupiter: 1sec of data requires 1sec of DSN station time
Sending cm accuracy topographic data from Mars or its moons would be trivial!

	Data Rate Today		Data Rate ~2020		Data Rate ~2030		
Spacecraft Capabilities	3m Antenna X-Band 100 W Xmitter		3m Antenna Ka-Band 180 W Xmitter		5m Antenna Ka-band 200 W Xmitter		1m Optical 1550 nm 50 W Xmitter
DSN Antennas	1 x 34m	3 x 34m	1 x 34m	Equiv to 3 x 34m	1 x 34m	Equiv to 7 x 34m	10m Optical
Mars (0.6 AU)	7 Mbps	20 Mbps	400 Mbps	*1.2 Gbps	*1.3 Gbps	*9.3 Gbps	5.5 Gbps
Mars (2.6 AU)	355 Kbps	1 Mbps	21 Mbps	64 Mbps	71 Mbps	*500 Mbps	300 Mbps
Jupiter	83 Kbps	250 Kbps	5 Mbps	15 Mbps	16 Mbps	115 Mbps	70 Mbps
Saturn	24 Kbps	71 Kbps	1.4 Mbps	4 Mbps	4.7 Mbps	33 Mbps	19 Mbps
Neptune	3 Kbps	8 Kbps	160 Kbps	470 Kbps	520 Kbps	3.7 Mbps	2.2 Mbps

*Geldzahler, B. (2009) http://www.spacepolicyonline.com/pages/images/stories/PSDS%20Sat%202%20Geldzahler-DSN.pdf.

Summary

•Our 100 beam scanning lidars have provided decimeter level (horizontal) and few cm (vertical) resolution topographic maps from aircraft AGLs up to 28 kft*. Data rates vary between 2.2 and 3.2 million 3D pixels per second.

•The multibeam pushbroom NASA MABEL lidar has operated successfully at AGLs up to 65 kft

•Our low deadtime (1.6 nsec) detectors and range receivers permit multiple range measurements per pixel on a single pulse.

•Our moderate to high altitude lidars built to date have been designed to provide contiguous topographic coverage on a single overflight at aircraft speeds up to 220 knots (407 km/hr).

•We are currently implementing inflight algorithms to edit out solar and/or electronic noise and to correct for atmospheric effects in preparation for near realtime 3D imaging.

•Our smallest lidar, Mini-ATM, designed for cryospheric measurements, weighs only 28 pounds (12.7 kg) , occupies 1 ft^3 (0.028 m^3), has a $\pm$ 45 degree conical scan, fits in a mini-UAV, and covers more area with higher spatial resolution than the much larger and heavier predecessor NASA ATM system.

•Using a laser comparable to that developed for the ATLAS lidar on ICESat-2 and a MOLA-sized telescope (~50 cm) in a 100 km orbit , one could globally map the three Jovian moons with better than 5 m horizontal resolution in 1 month (Europa) or 2 months (Ganymede and Callisto) each.

*Sigma customer has not yet given permission to show 28 kft data but spatial resolution is comparable to HRQLS images at almost 4x the AGL.