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The Impact of Single Photon SLR Technology on Large Scale Topo-Bathymetric Mapping

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Sigma Space Corporation, Lanham, MD USA 20706
20th International Workshop on Laser Ranging
GFZ, Potsdam, Germany
October 10-14, 2016

Why Single Photon Lidars ?

- 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 and imagers

- 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 receivers, enables the lidar to operate in daylight and penetrate porous obscurations such as vegetation, ground fog, thin clouds, water columns, camouflage, etc.

- Makes contiguous, high resolution topographic and bathymetric mapping on a single overflight possible with very modest laser powers and telescope apertures – even from orbital altitudes.

- SPLs derive much of their heritage from early NASA work on the single photon sensitive SLR2000 system and the "Microaltimeter".

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2nd Generation "Leafcutter"

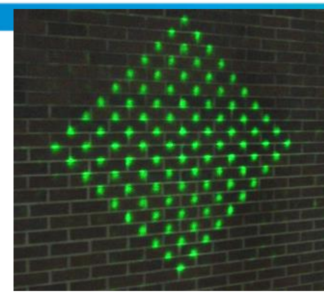
- Transmitter is a low-energy (6 μJ), high rep-rate (to 22 kHz), frequency doubled (532 nm), passively Q-switched microchip laser with a 710 psec FWHM pulsewidth.

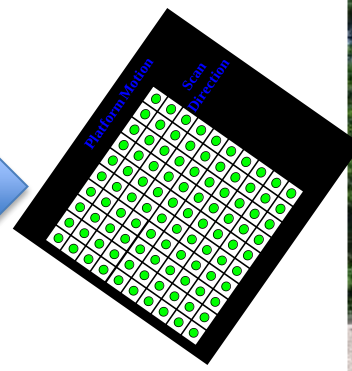
- Diffractive Optical Element (DOE) splits green output into 100 beamlets (~50 nJ @ 20 kHz = 1 mW per beamlet) in a 10 x 10 array. Residual 1064 nm energy can be used for polarimetry.

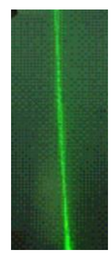
- Returns from individual beamlets are imaged by a 3 inch diameter telescope onto matching anodes of a 10x10 segmented anode micro-channel plate photomultiplier.

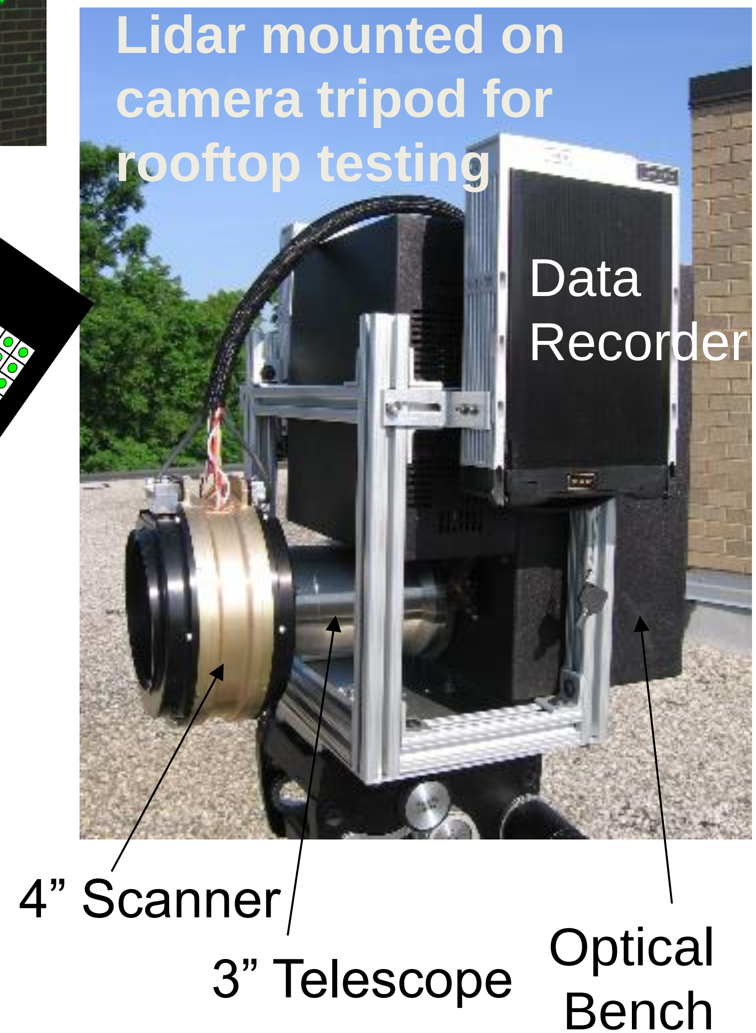
- Each anode output is input to one channel of a 100 channel multi-stop timer to form a 100 pixel 3D image on each pulse. Individual images are contiguously mosaiced together via the aircraft motion and an optical scanner (100 pixels @ 22 kHz = 2.2 million 3D pixels/sec!).

- 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 with matching (small) FOV for solar noise reduction.









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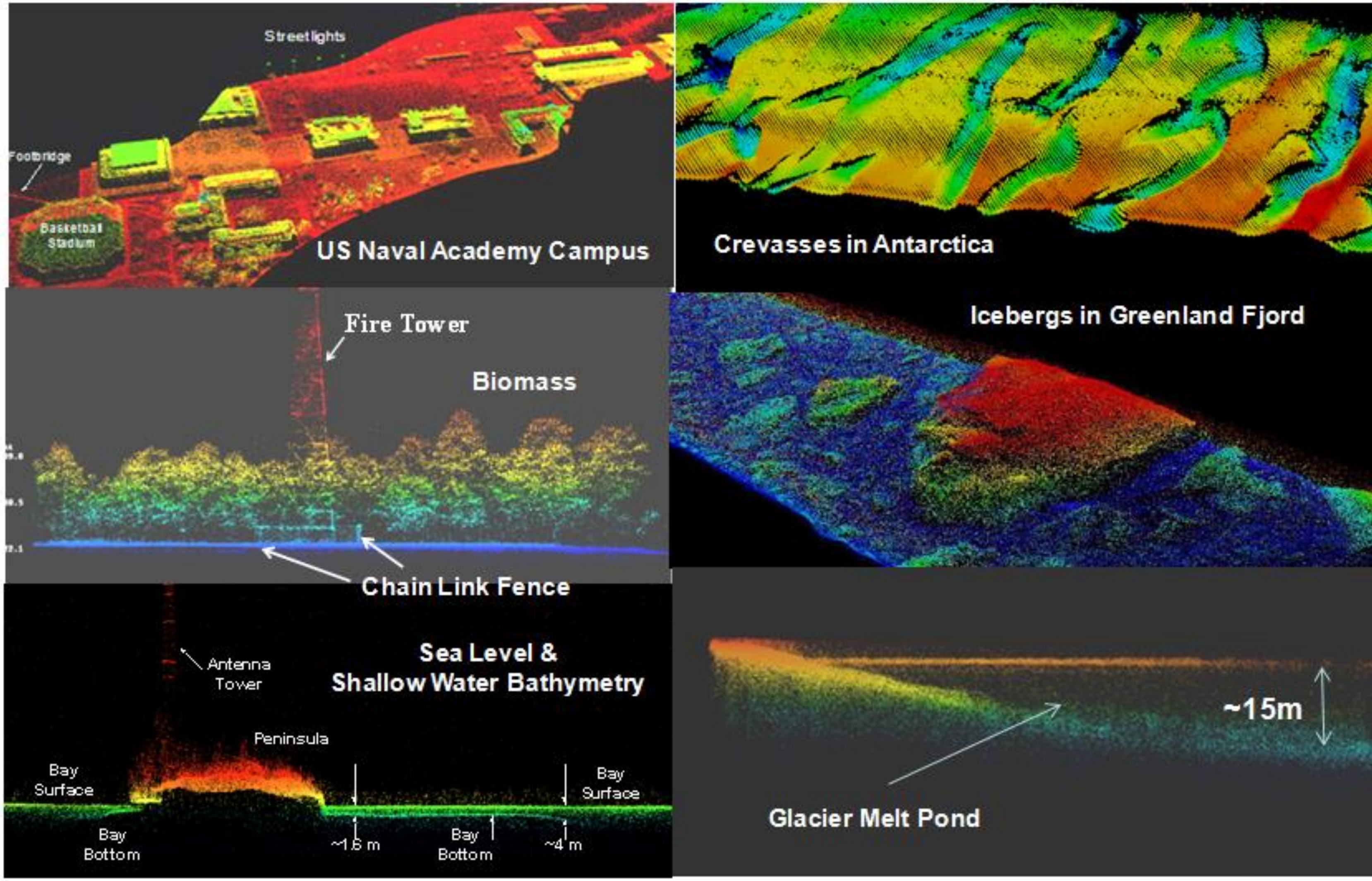
Sample Data from “Leafcutter”

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



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Sigma Single Photon LiDARs (SPLs)

Operating altitudes ranging from 2,000 to 65,000 ft.

Multiple Altimeter Beam Experimental LiDAR (MABEL) -Pushbroom

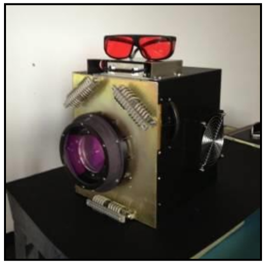
Nominal Flight AGL: 65,000 ft
Platform : NASA ER-2
Customer: NASA GSFC
16 beams @ 10 kHz = 0.16 Megapixels/sec

High Altitude LiDAR (HAL) -Scanning

Nominal Flight AGL:: 25,000 to 36,000 ft
Platform : Various
Customer: Government Agencies
100 beams@ 32 kHz = 3.2 Megapixels/sec

High Resolution Quantum LiDAR System (HRQLS1 and 2) - Scanning

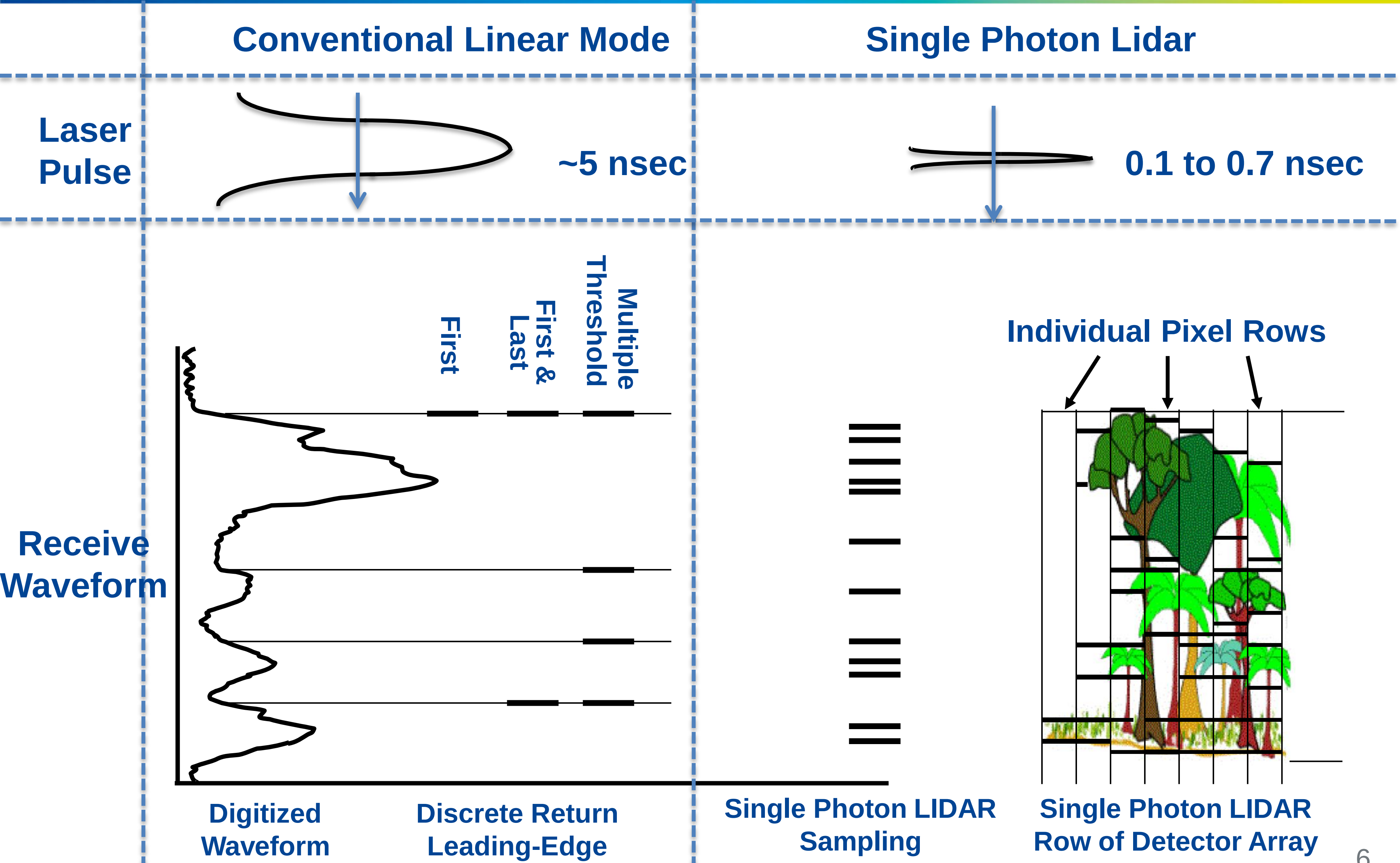
Flight Altitude: 6,500 to 15,000 ft AGL
Platform : King Air B200
Sigma Self-funded
100 beams @ 25 kHz/60 khz = 2.5/6 Mp/sec



Miniature Airborne Topographic Mapper (Mini-ATM) - Scanning

Flight Altitude: 2000 to 6000 ft AGL
Platform : Viking 300 UAV
Customer: NASA Wallops

Conventional Lidar vs SPL



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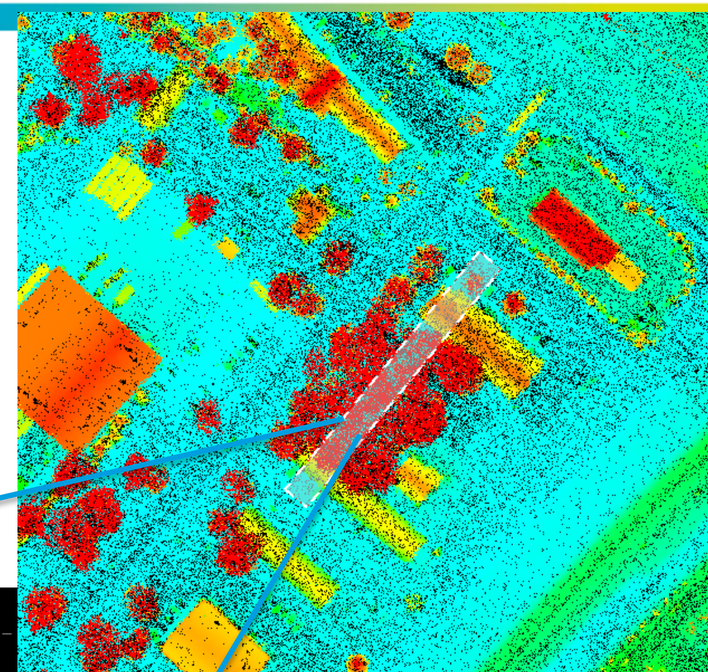
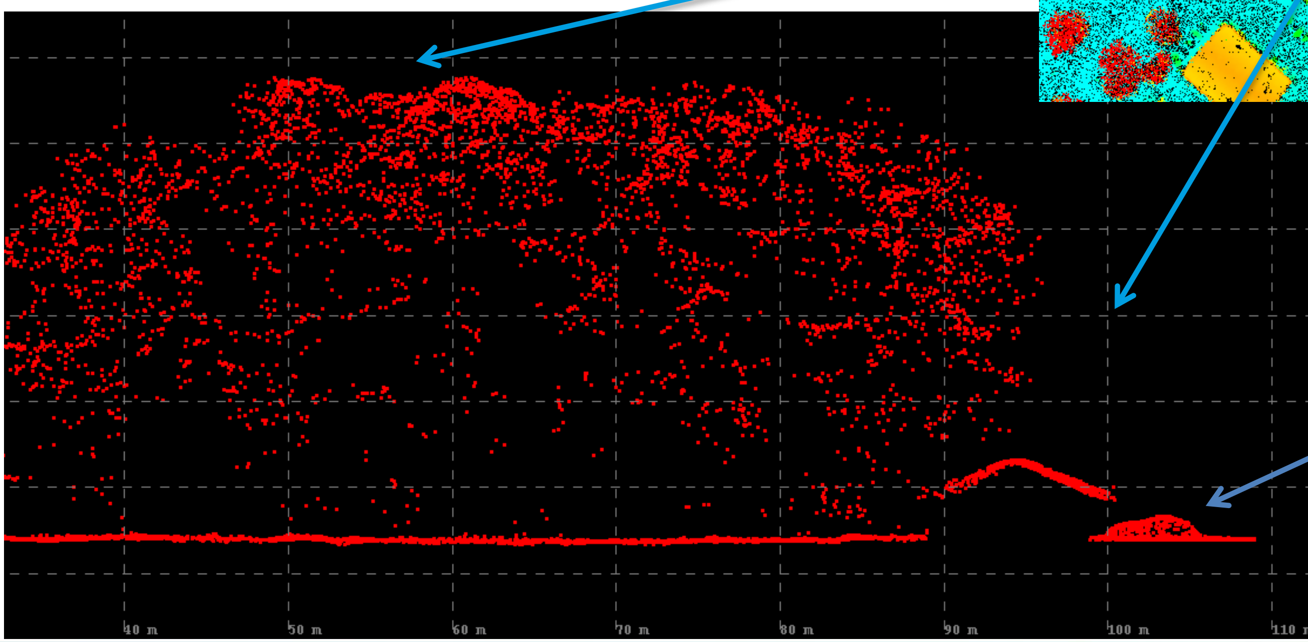
HRQLS 3D Mapping, Easton, MD

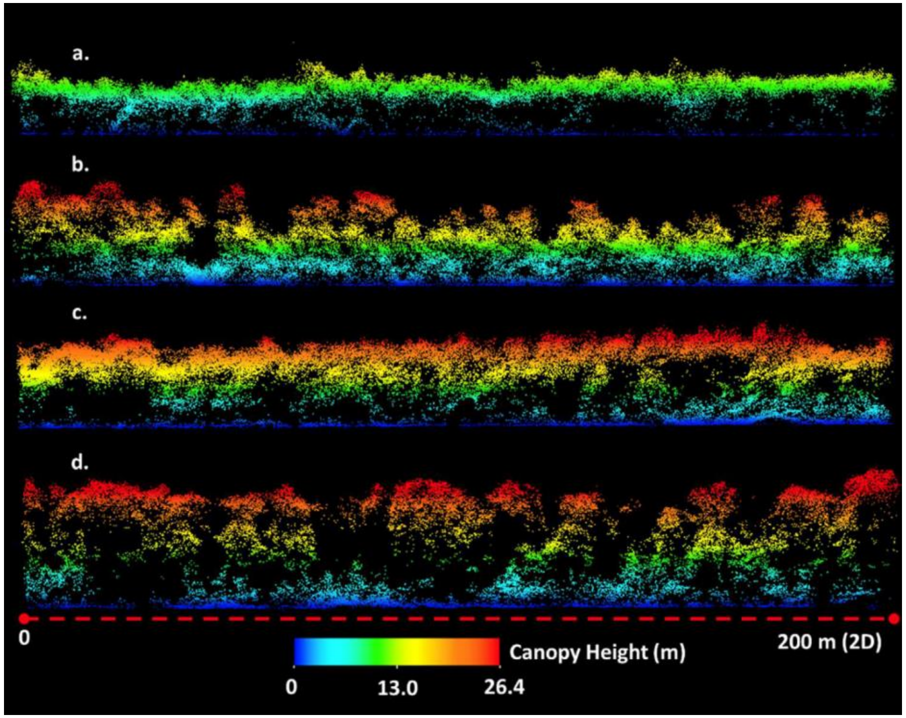
Sample:
Single Pass
AGL: 7500 ft
Velocity: 180 knots

Profile:
110 m long
10 m height





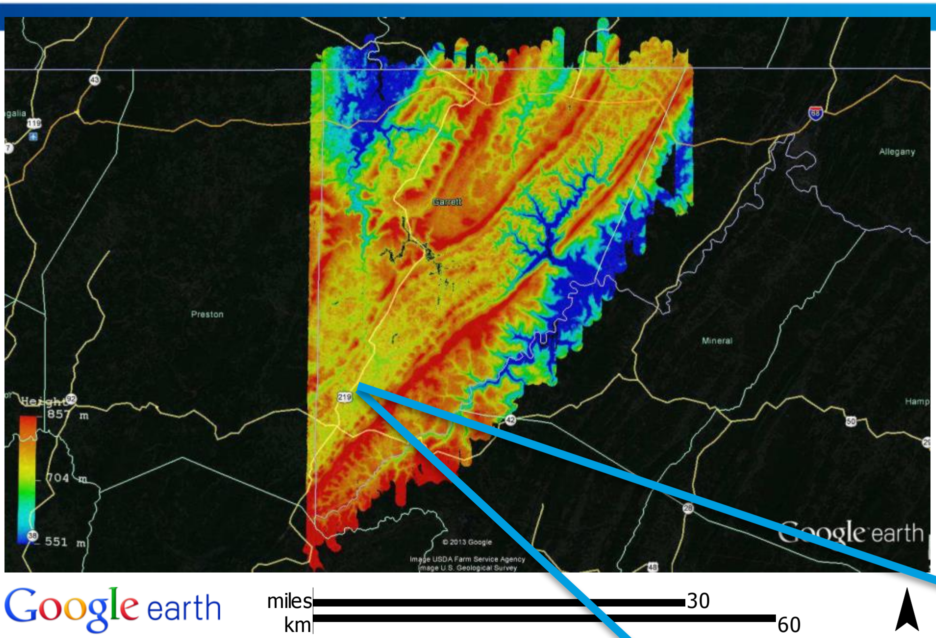
Detecting Different Forest Growth Patterns



HRQLS-1 SPL point cloud profiles showing different growth patterns within a 1 square kilometer of forested area in Garrett County, MD.(a) Short even aged stand with little understory vegetation. (b) Uneven aged stand composed of tall trees and dense midstory vegetation. (c) Even aged stand with some mid and understory growth. (d) Tall open stand with distinct understory vegetation (Courtesy of the University of Maryland [8]).

Swatantran, A; Tang, H.; Barrett, T.; DeCola, P.,; Dubayah, R. "Rapid, High-Resolution Forest Structure and Terrain Mapping over Large Areas using Single Photon Lidar", Scientific Reports 6 (2016)

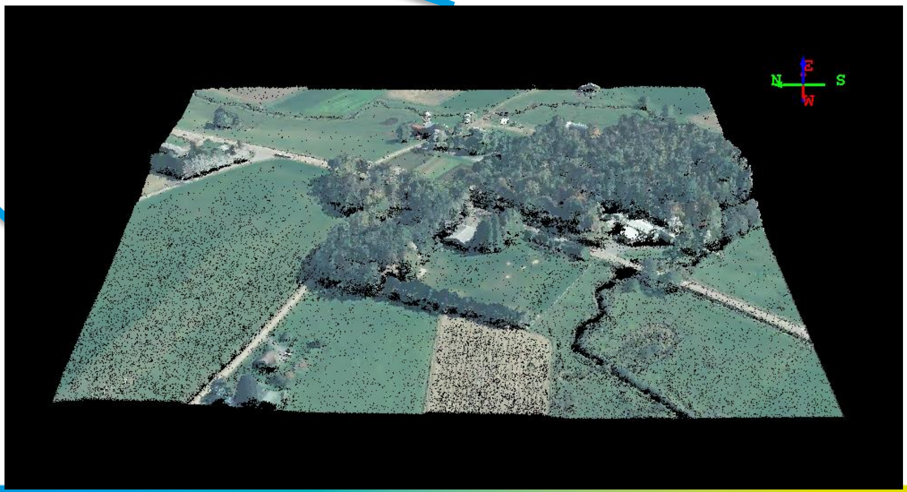
SPL 3D Mapping: Garrett County, MD



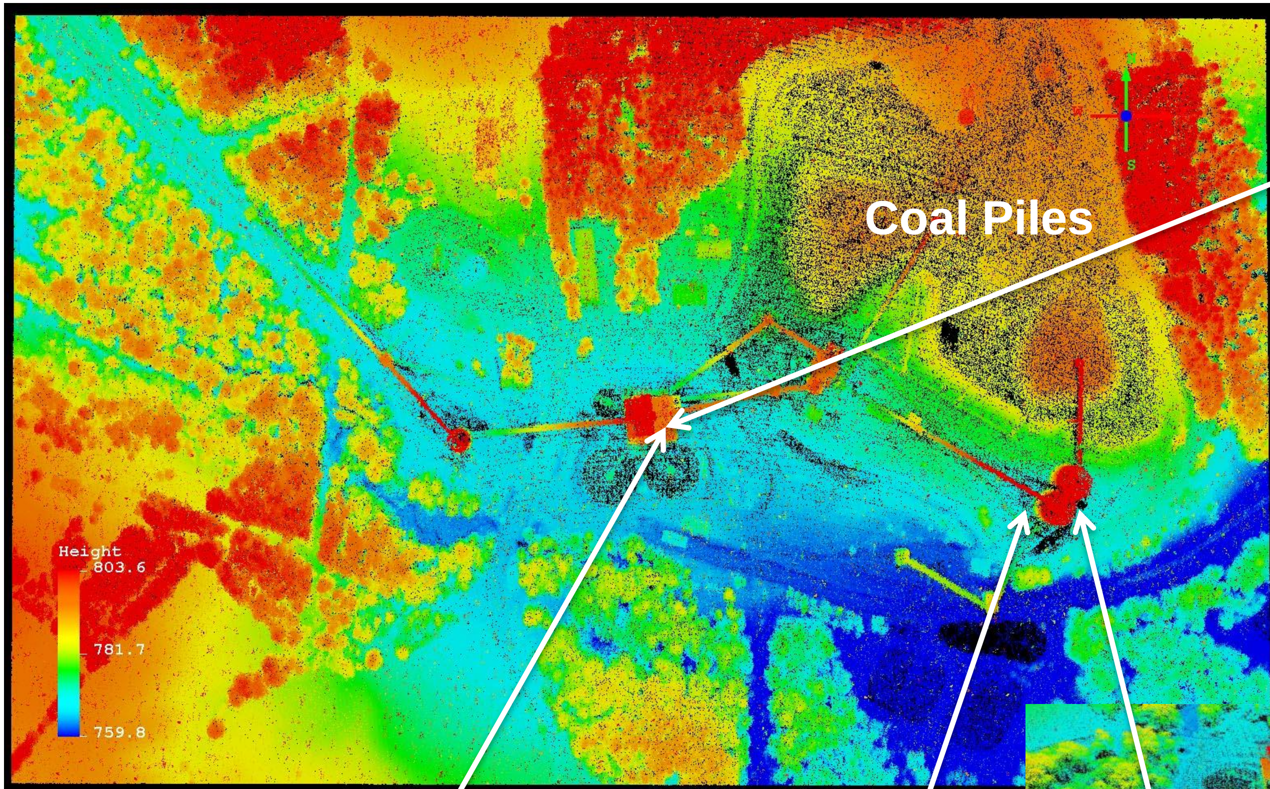
Garrett County, MD (1,700 km^2) acquired in:

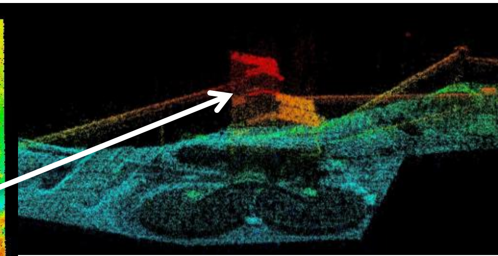
- **12 hours (including ferry and turns)**
- **1.4 Km swaths, 180 Knots**
- **50% overlap**
- **Mean Density: 12 points/m^2**

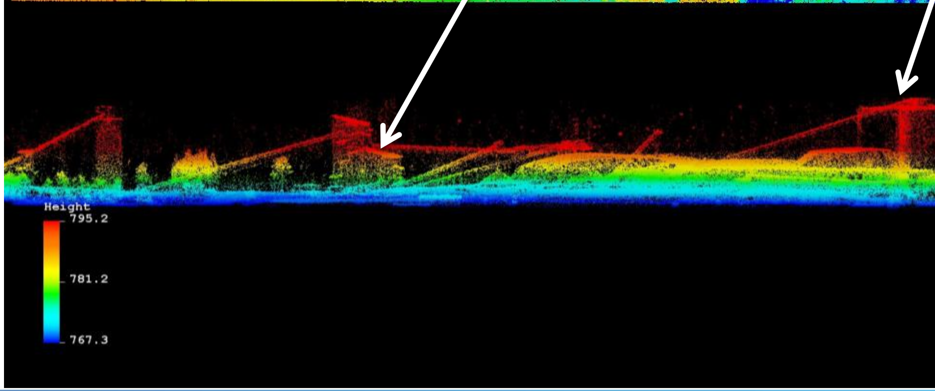
RGB Overlay of 3D Lidar Data

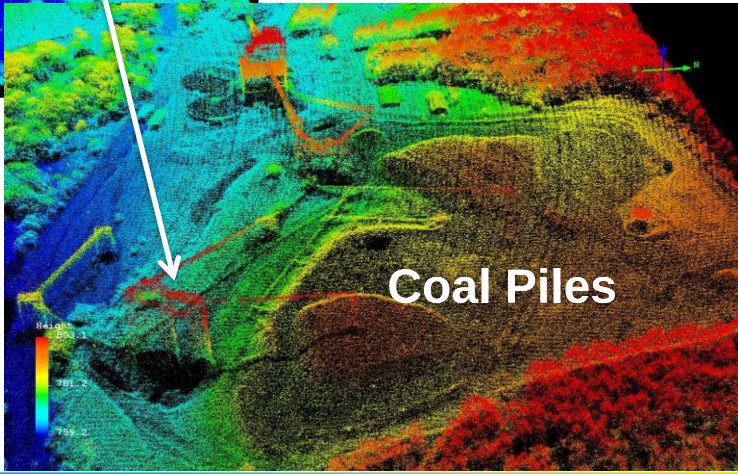


Garrett County Coal Mine







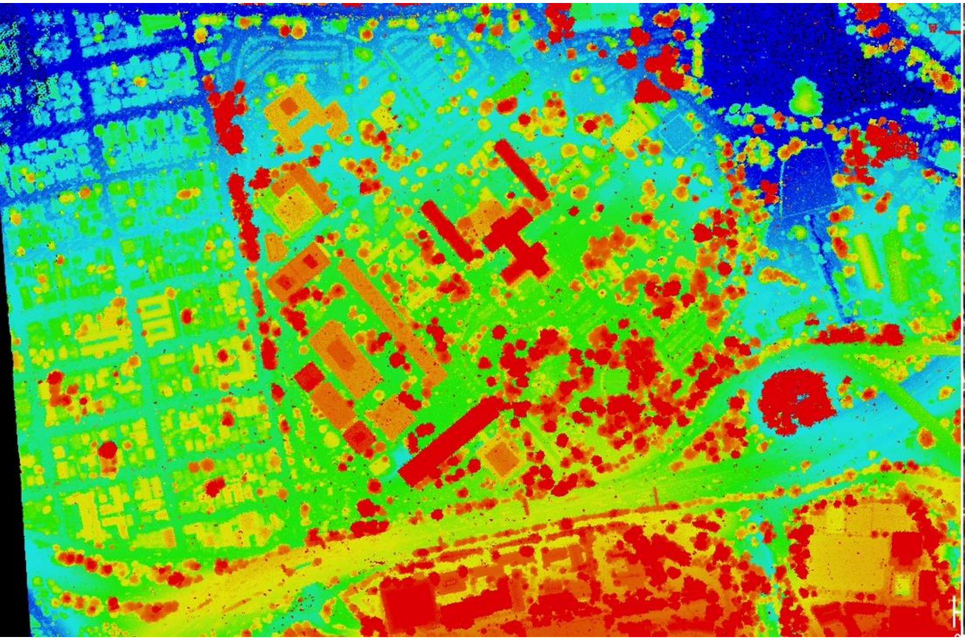


Velocity = 150 knot (278 km/hr)
Scan Angle = ±17 deg
AGL = 7500 ft (2.3 km)
Swath = 1.36 km
Coverage: 378 km^2/hr

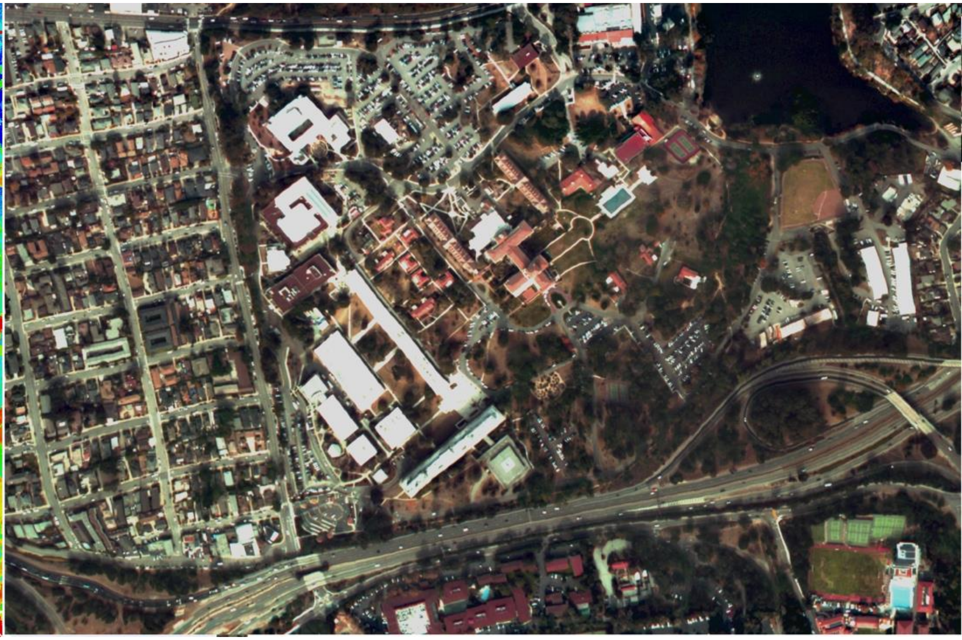
SPL 3D Mapping: Monterrey, CA

Naval Postgraduate School Campus

LiDAR



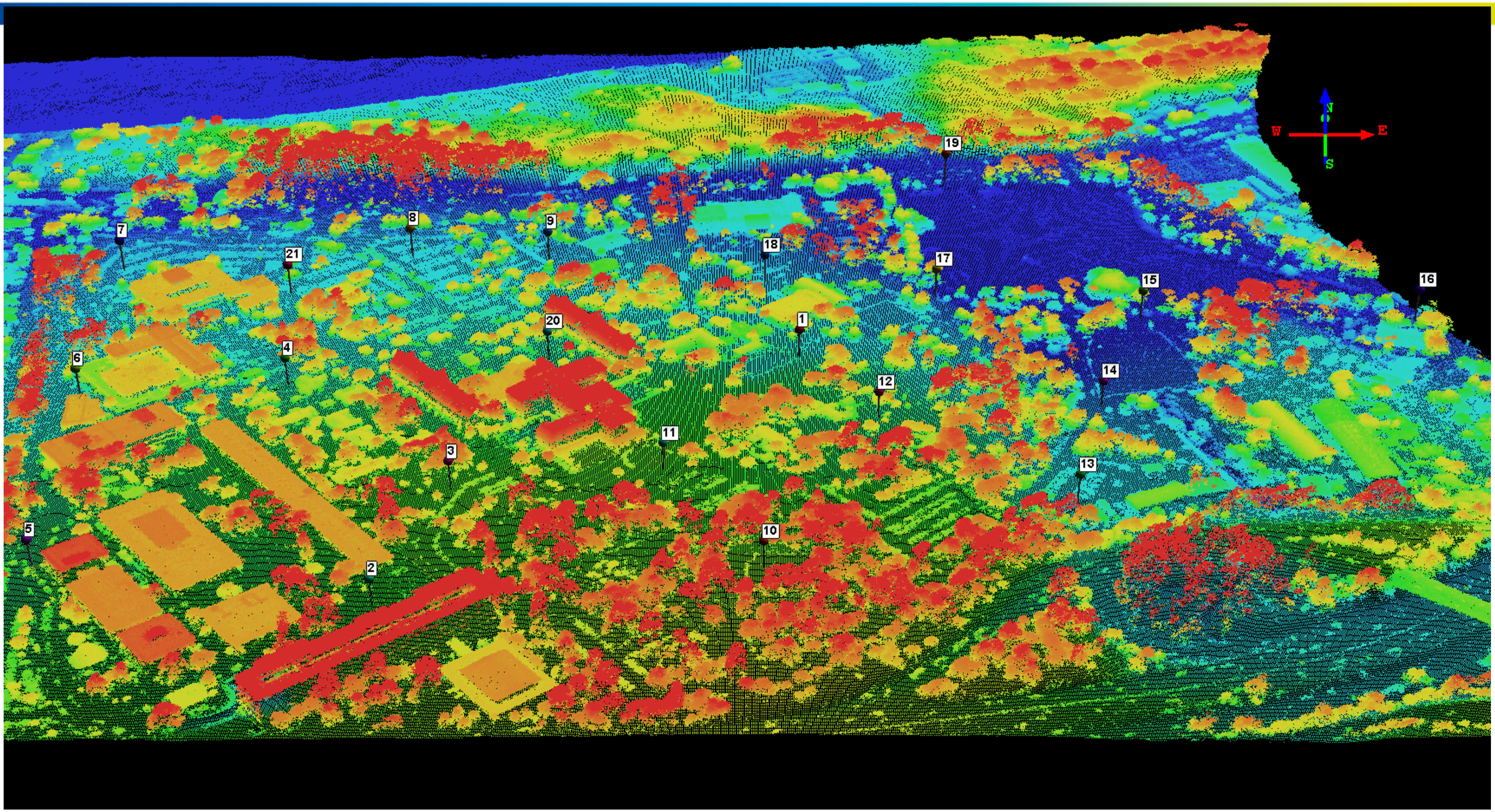
EO



Single Pass, Altitude 7500 ft, 180 kts,1.4 km swath, >12 points/m^2

Classified Point Cloud, colored by RGB

SPL Vertical Accuracy Assessment: Ground Truth Points

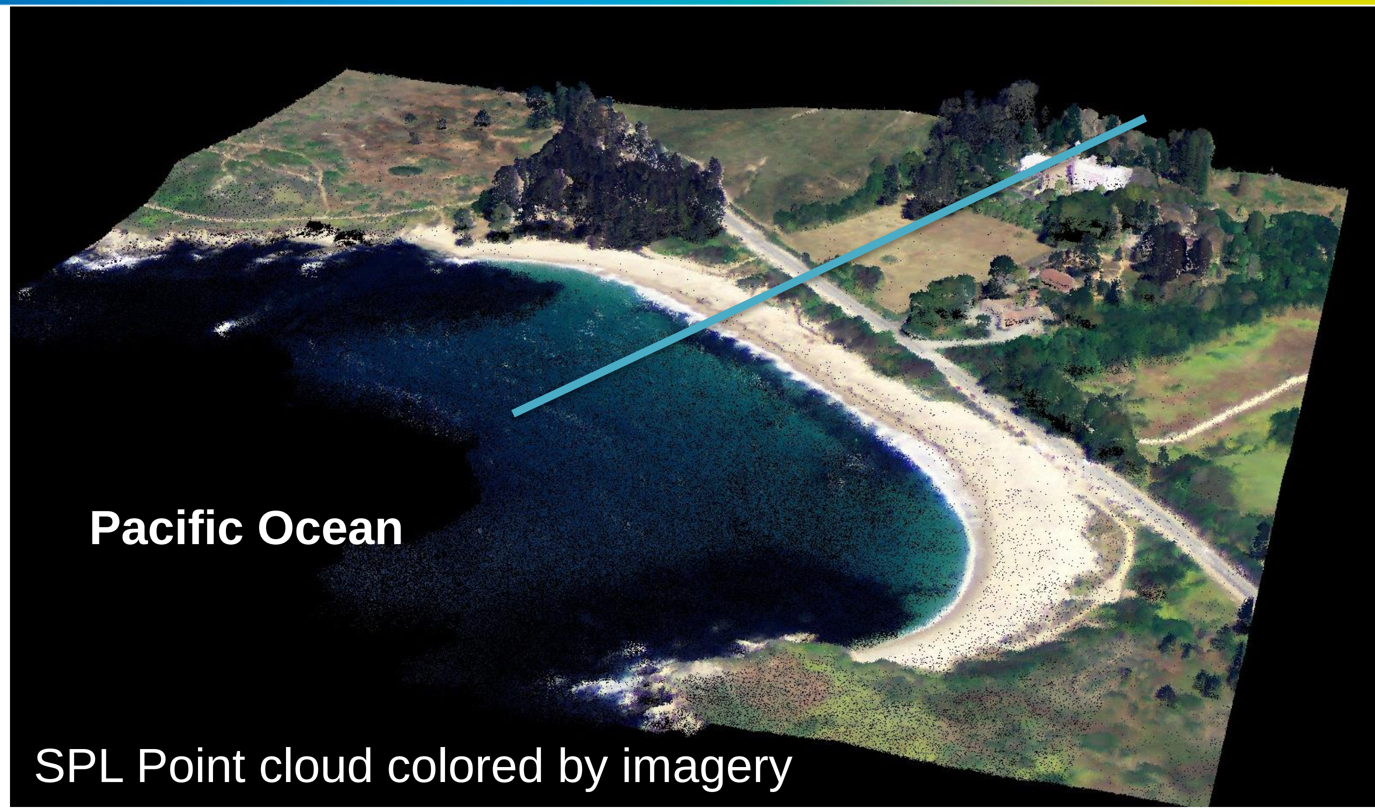


Ground Truth: 21 points measured by the Naval Postgraduate School to 3cm vertical accuracy and supplied in the same coordinate system as the point cloud (WGS84, UTM Zone 10N, ellipsoid height, meter)

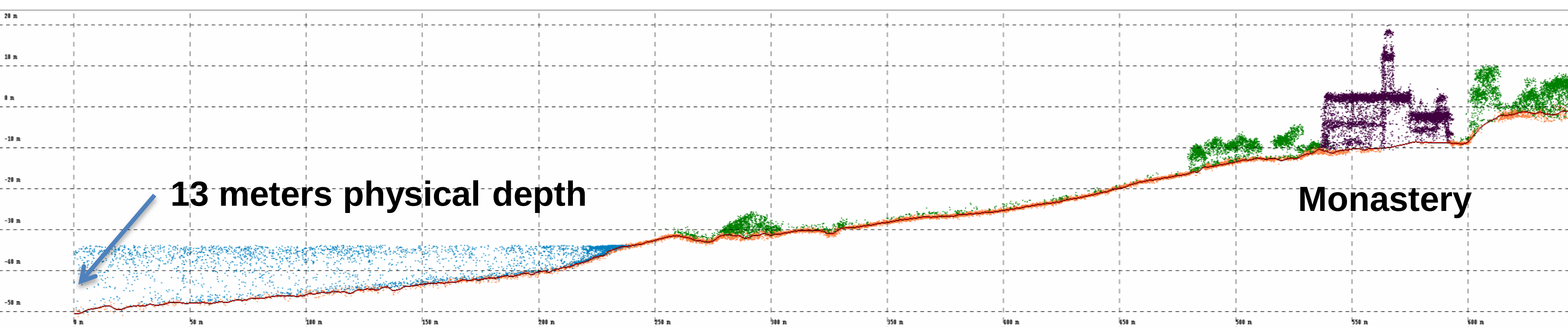
Standard deviation relative to ground truth: 9.3cm

SPL Bathymetry, Pt. Lobos, CA

Sample:
Double Pass
AGL: 7500 ft
Velocity: 180 knots



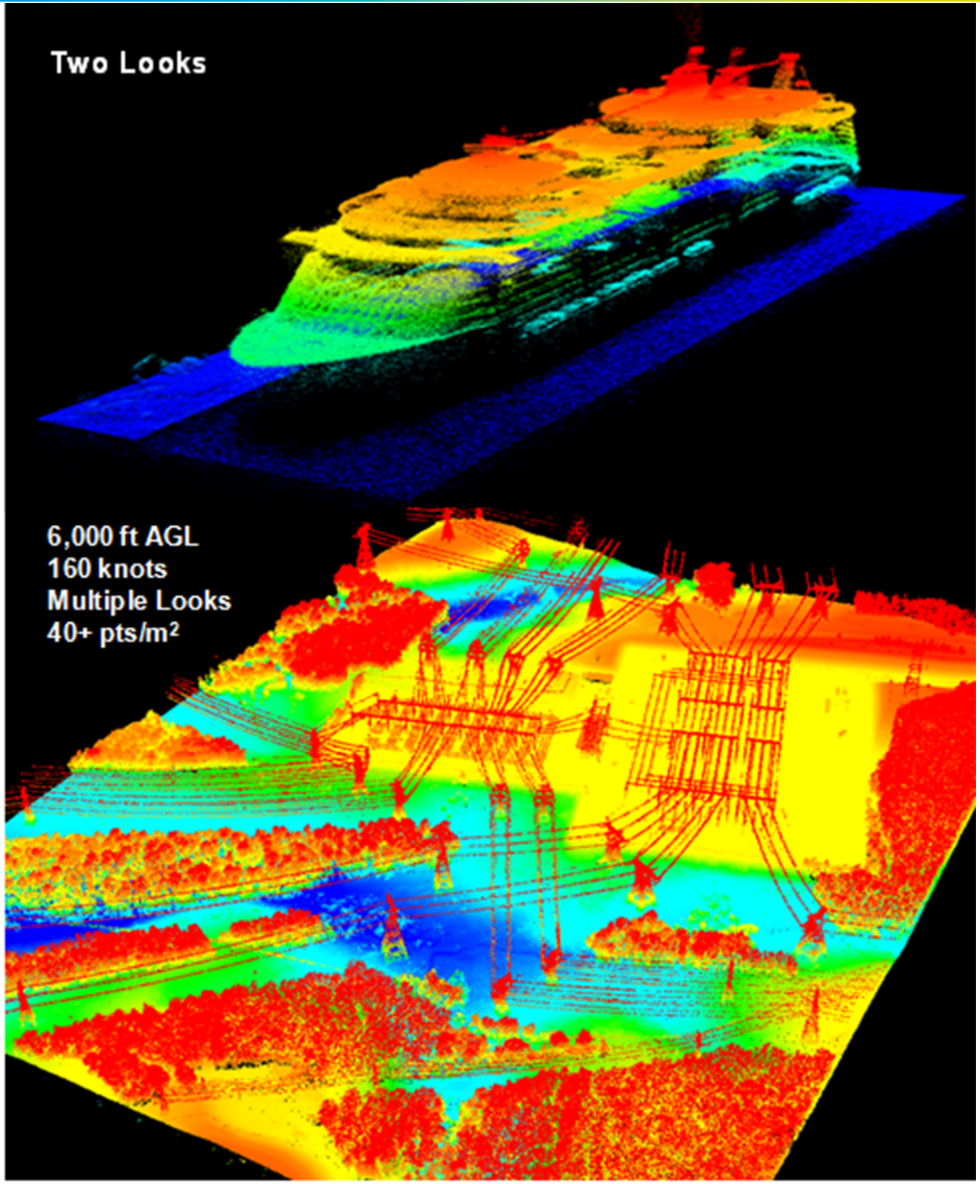
Profile



HRQLS-1 High Density Images

HRQLS-1 image of a Cruise ship docked in Ft. Lauderdale, Florida

HRQLS-1 image of a powerline grid in North Carolina

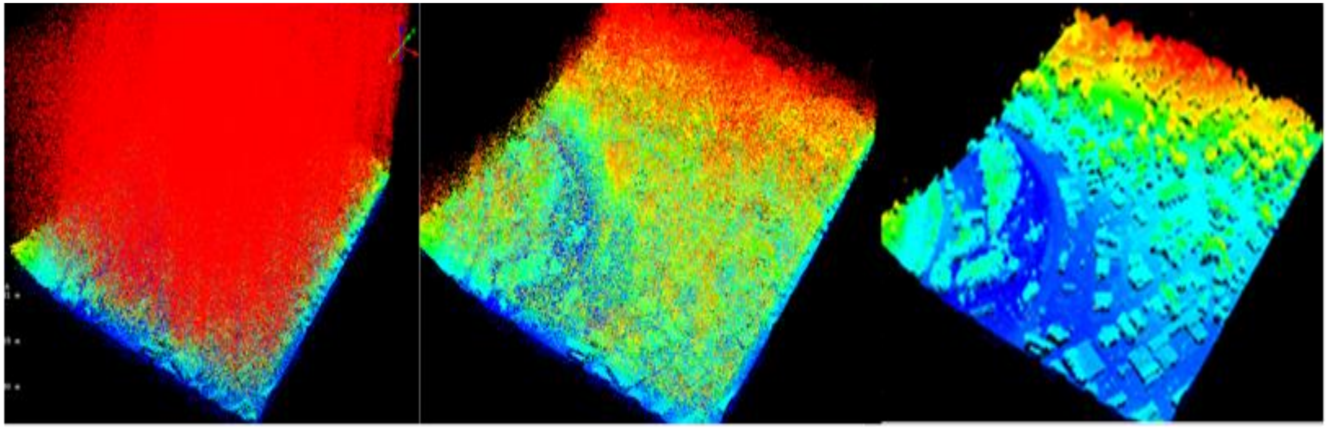


Multistage Noise Filter

HRQLS data over town of Oakland, MD

Originally, our SPL data was filtered following download of all surface data and noise into a point cloud generator. We have recently developed and successfully tested a multistage filter that, due to the high spatial correlation of up to 100 surface returns within a single pulse, can be implemented on a single pulse or small number of consecutive pulses. The goal is to reduce both onboard data storage requirements and data download/preprocessing times and ultimately permit the real time display or transmission of “clean” 3D images.

- 1^{st} stage rapidly isolates the surface returns (including forested areas) from the solar background and typically discards ~ 94% of the raw noise
- 2^{nd} stage acts on single pulse returns and, using Poisson statistics and 1^{st} stage noise estimates, discards > 90% of the 1^{st} stage residual noise.
- 3^{rd} stage (algorithms completed, code under development) is designed to remove isolated noise counts in the immediate vicinity of actual target surfaces.



Raw/Unfiltered 1^{st} Stage Filter   2nd Stage Filter

SPL vs Geiger Mode

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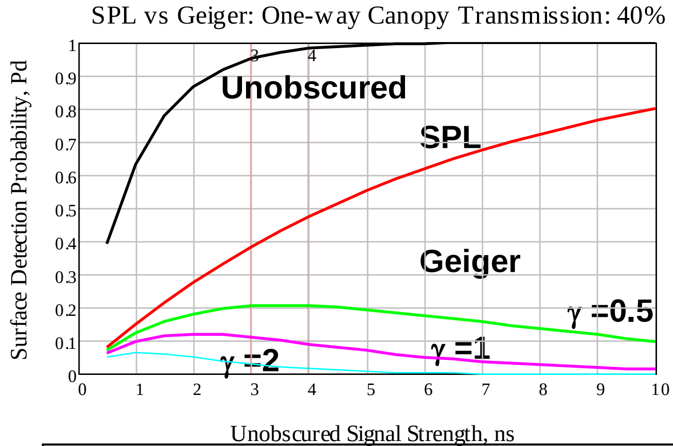
In Geiger Mode, the Avalanche PhotoDiode (APD) recovery time is very long (~50 nsec if actively quenched and ~1600 nsec if passively quenched). The probability of detecting a target beneath a canopy with one-way transmission T_c is given by

$$PD(n_s,\gamma) = \exp\left[-\frac{\gamma n_s}{2}\left(1-T_c^2\right)\right]\left[1-\exp\left(-T_c^2 n_s\right)\right]$$

where n_s is the expected number of detected photoelectrons from the unobscured target,

$$\gamma = \frac{\rho_c}{\rho_t}$$

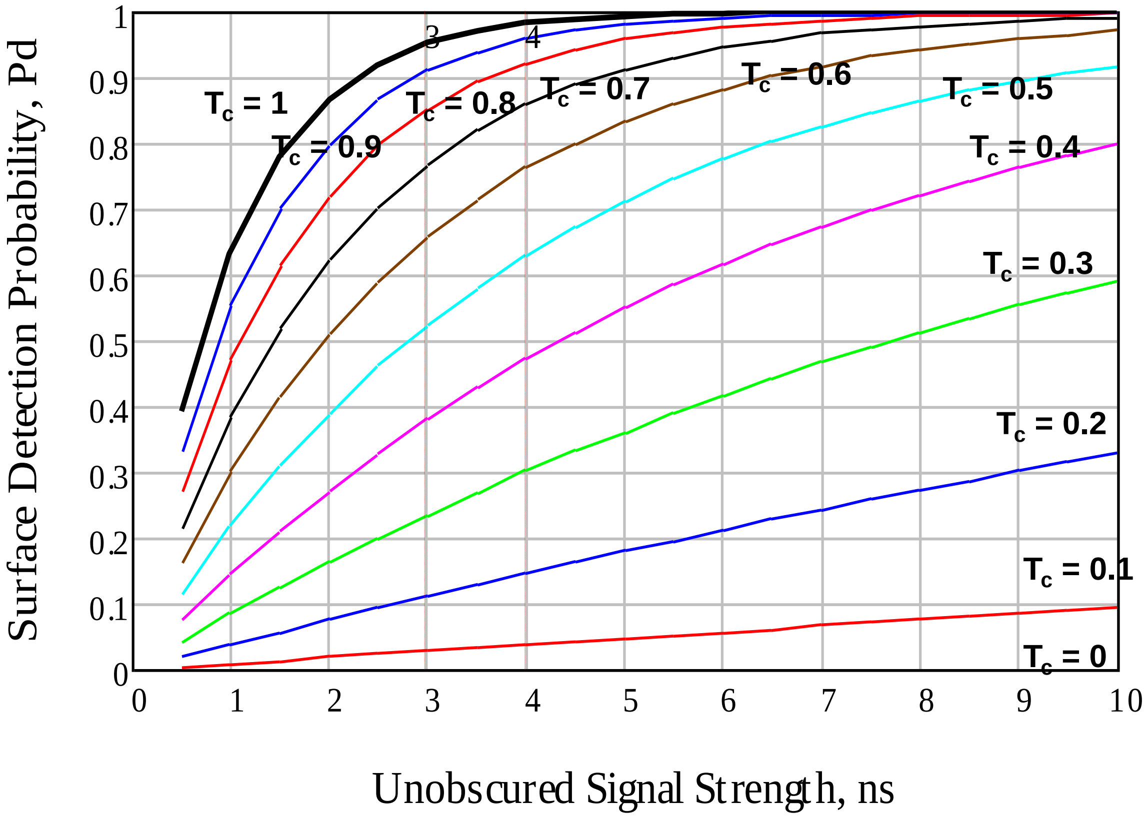
and ρ_c and ρ_t are the reflectances of the canopy and target respectively. The second term in the equation gives the probability of detecting the signal with the Sigma multistop receiver while the first term gives the probability of disabling the receiver due to the detection of a canopy return. In contrast, the Sigma SPL detector /receiver has a very short recovery time on the order of 1.6 nsec and therefore only the second term in the equation is relevant.



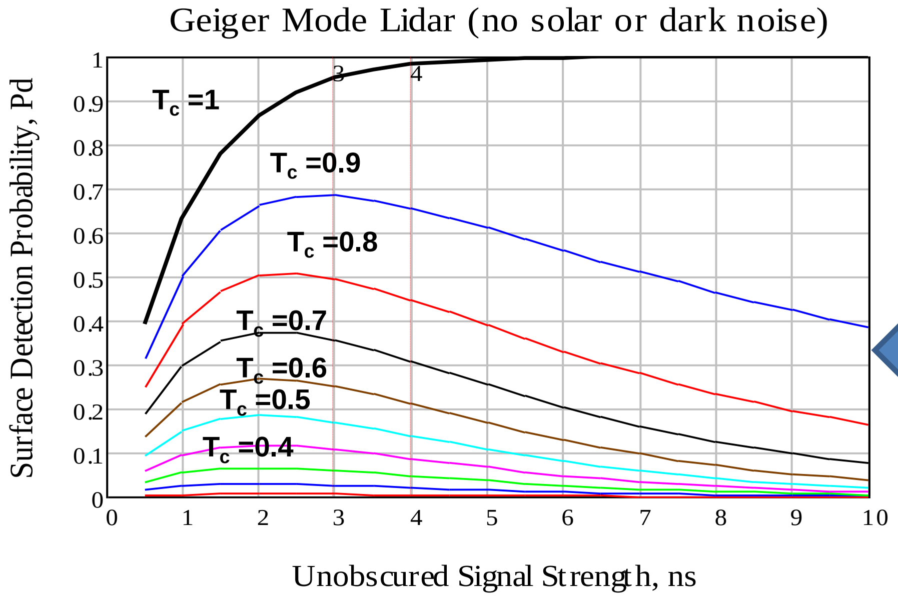
The black curve in the plot shows the probability of detecting the unobscured target vs the mean signal strength. The red curve gives the same probability for the Sigma multi-stop SPL receiver in the presence of a 40% transmissive tree canopy (T_c^2 =0.16) . The remaining curves show the Geiger Mode probabilities for different values of γ. For n_s =5, the probability of detecting the unobscured target is ~100%. The Sigma multistop receiver has a 57% probability while the single stop Geiger Mode receiver has only a 7% probability for γ = 1, even in the absence of solar noise (night operations) or detector dark counts.

SPL Surface Detection Probability vs Canopy Transmission and Unobscured Signal Strength

For 532 nm wavelength, Sigma SPLs are usually designed to generate n_s =3 and 4 for green vegetative (ρ_s = 0.1) and dry vegetation/soil (ρ_s = 0.15) target surfaces respectively . Unlike Geiger Mode systems, more laser energy per beamlet always improves the surface detection probability.



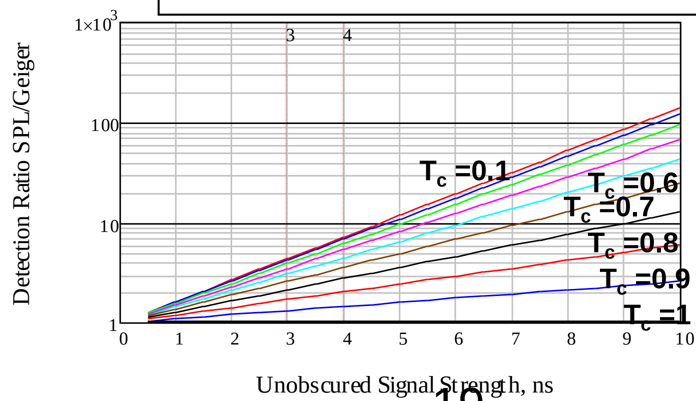
Geiger Mode Penetration of Tree Canopies



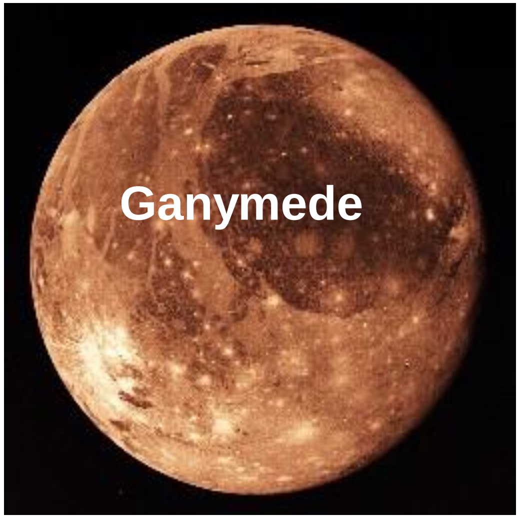
As the tree canopy transmission increases, one can only obtain higher surface detection probabilities if one reduces the probability of a canopy return by lowering the laser pulse energy. (Verified by experiments at MIT/LL)

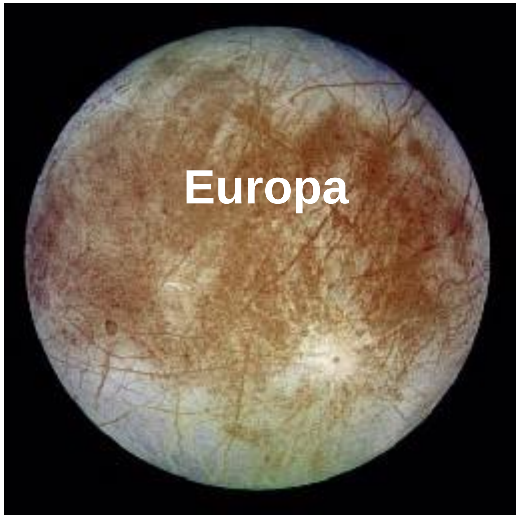
*These graphs do not include additional detection probability reductions for Geiger Mode due to solar noise or detector dark counts.

This graph shows the Sigma SPL probability of sub-canopy surface detection relative to Geiger Mode as function of tree canopy transmission and unobscured signal strength. As the tree canopy transmission decreases and the unobscured signal strength increases, the relative surface return rate increases by orders of magnitude.



Jupiter Icy Moons Orbiter





JIMO 3D Imaging Goals

- Globally map three Jovian moons
- Horizontal Resolution: <5 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.

Summary

•Our 100 beam scanning SPLs have provided decimeter level (horizontal) and few cm RMS (vertical) resolution topographic maps from aircraft AGLs up to 28 kft*. Data rates to date vary between 2.2 and 6 million 3D pixels per second., up to 60 times faster than conventional multiphoton lidars.

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

•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 ± 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.

•Our low deadtime (1.6 nsec) detectors and range receivers permit daylight operation and multiple range measurements per pixel on a single pulse, allowing penetration of volumetric scatterers (tree canopies, water columns, ground fog, etc.) .

•Our moderate to high altitude lidars built to date have been designed to provide contiguous topographic and bathymetric maps on a single overflight at aircraft speeds up to 220 knots (407 km/hr). Point densities and geolocation errors are compliant with USGS QL1 standards.

•We are currently flight testing the upgraded HRQLS-2 lidar which is designed to fly at altitudes between 11and 15 kft. It will participate in USGS sponsored field trials later this month.

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

***Sigma customer for HAL has not yet given permission to show 28 kft data but spatial resolution is comparable to HRQLS-1 images at almost 4x the AGL. (28 kft vs 7.5 kft)**

Point Lobos, CA, Fly-Thru & Flood Simulation