Globally Contiguous, High Resolution Topographic Mapping of Planets and Moons via Photon-Counting

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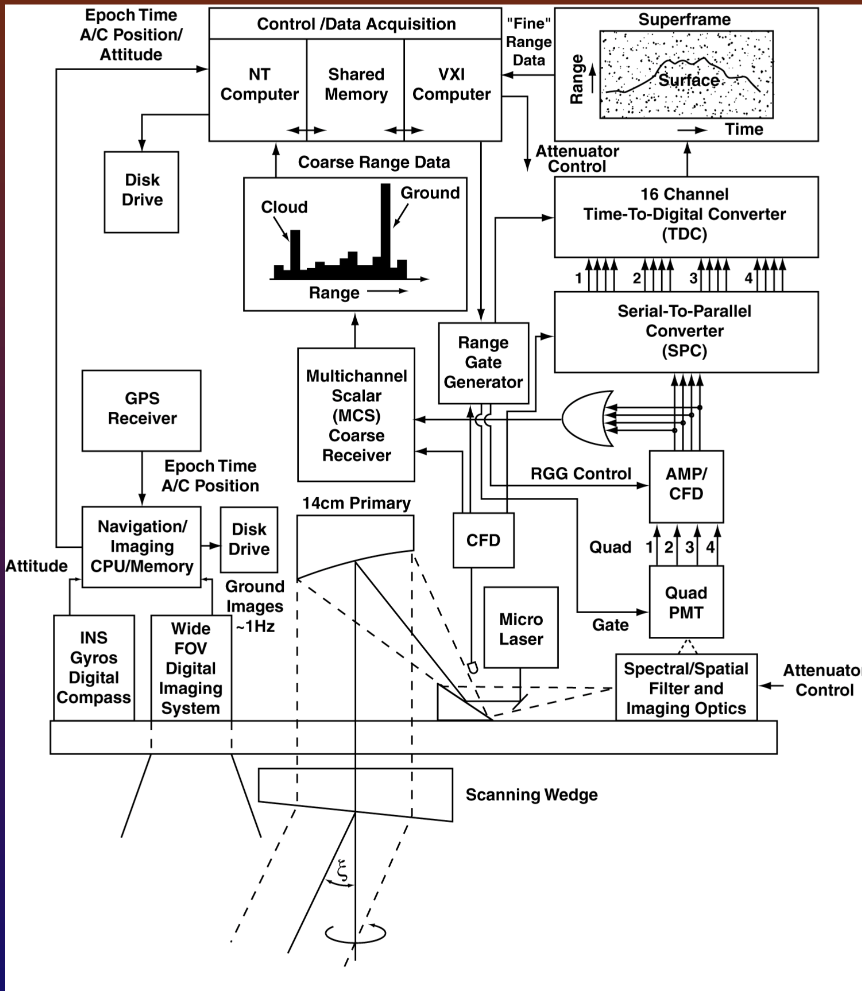
Overview

- Advantages of Photon-Counting
- Airborne Instrument Heritage and Sample Data
  - NASA 1st Generation "Microaltimeter"
  - Sigma/USAF 2nd Generation 3D Imaging and Polarimetric Lidar
- Globally Mapping Planets and Moons
  - Requirements for Contiguous Mapping from Space
  - NASA JIMO Mission to Jupiter (Callisto, Europa, Ganymede)
  - Photon-Counting Cross Track Channel (CTC) Lidar proposed to GSFC for NASA ICESat II
  - Technical challenges
- Summary

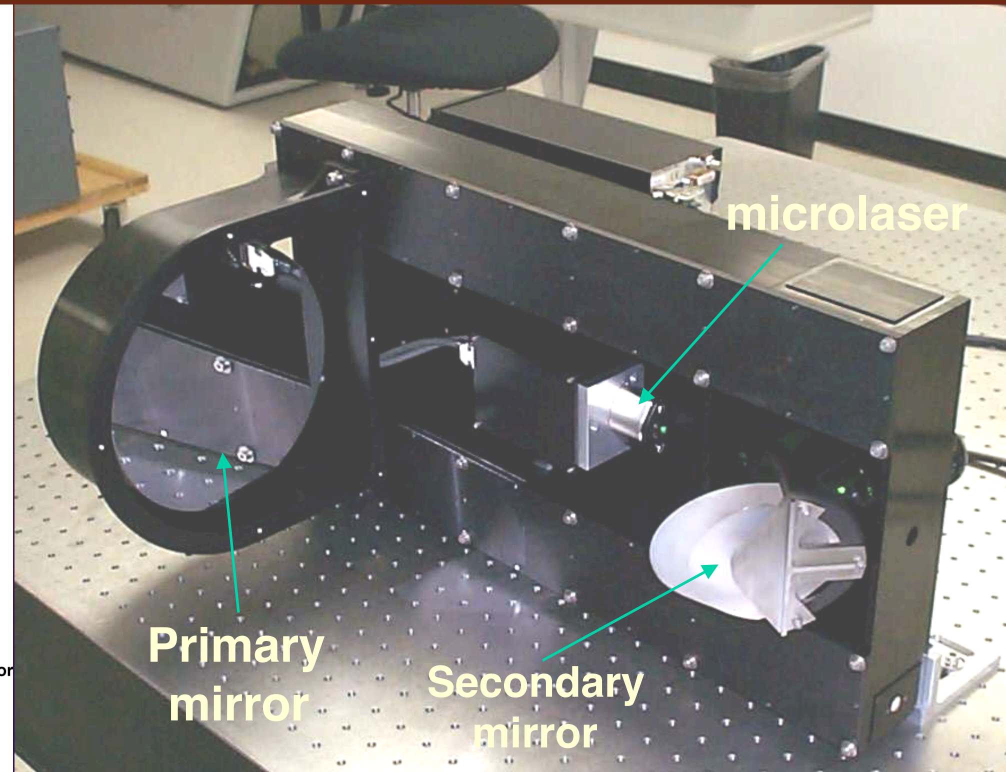
Why Photon Counting?

- 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 multistop timing capability enables lidar to penetrate semi- porous obscurations such as vegetation, ground fog or haze, thin clouds, water columns, camouflage, etc.
- Makes contiguous, high resolution topographic mapping on a single overflight possible with modest laser powers and telescope apertures – even from orbital altitudes.

First Generation NASA Microlaser Altimeter

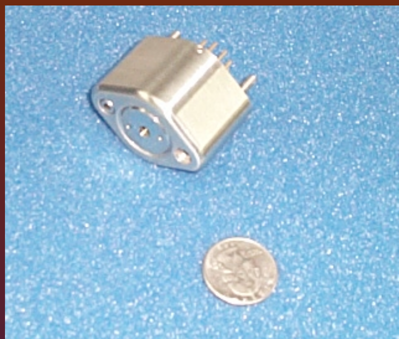


Block Diagram



IIP Optical Bench (laser side)

NASA PI: John Degnan
GSFC Team Members:
Jan McGarry, Tom Zagwodzki,
Phil Dabney, Jennifer Geiger



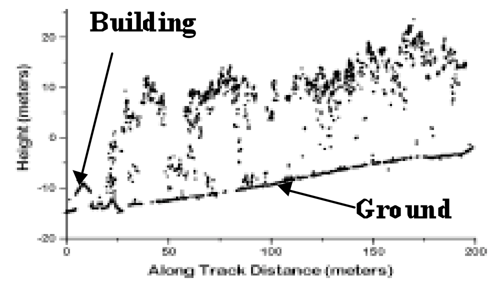
Diode-Pumped Passively Q-switched Nd:YAG Microchip Laser including TEC cooler and

DoublingCrystal

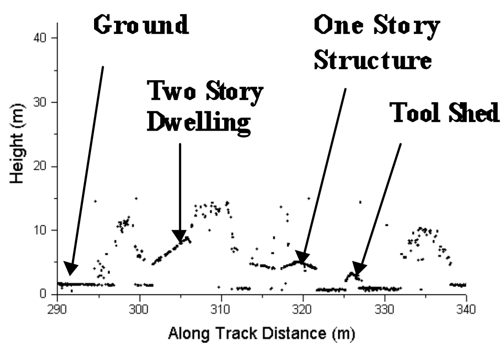
IIP Airborne Multi-kHz Microlaser Altimeter

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

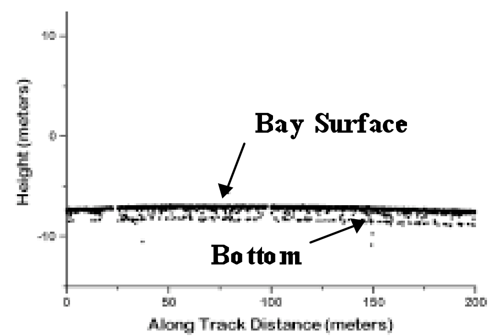
- **Engineering Flight Parameters**
  - NASA P-3 Aircraft, Wallops Flight Center
  - Locale: Chincoteague, VA & Chesapeake Bay
  - Flight Altitudes: 3.5 to 6.7 km (11,000 to 22,000 ft)
  - Early afternoon (maximum solar background)
  - Laser Energy: < 2 μJ @ 532 nm
  - Laser Repetition Rate: 3.8 kHz
  - Laser Power: ~7 mW
  - Effective Telescope Diameter: 14 cm
  - Mean Signal Strength per Laser Fire: ~ 0.8 pe



Tree Canopy Heights



Buildings and Trees



Shallow Water Bathymetry

RAW PROFILING DATA!

J. Degnan, J. McGarry, T. Zagwodzki, P. Dabney, J. Geiger, R. Chabot, C. Steggerda, J. Marzouk, and A. Chu, "Design and performance of an airborne multikilohertz, photon-counting microlaser altimeter", Int. Archives of Photogrammetry and Remote Sensing, Vol. XXXIV-3/W4, pp. 9-16, Annapolis, MD, 22-14 Oct. 2001.

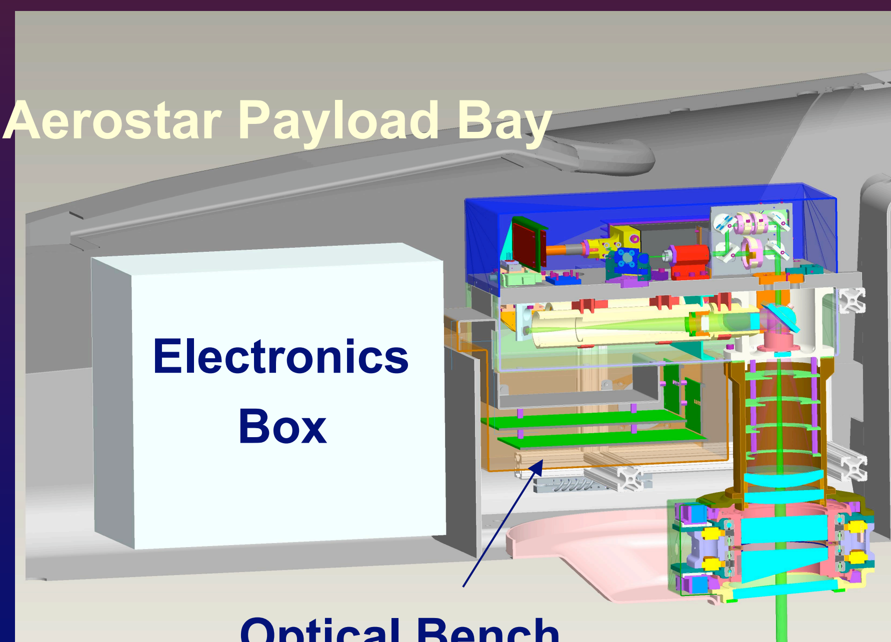
2nd Generation 3D Imaging and Polarimetric Lidar

Mission Parameters

- Operating altitude: ~1 km
- Maximum Swath: 524 m
- Spatial Resolution:
  - Imager: Horiz: 15 cm; Vert:<5cm
  - Polarimeter: Horizontal: 1.5 m
- Mean Ground Velocity: 161 km/hr
- Areal Coverage: 24 sq. km/hr

Payload Parameters

- Physical Size & Mass (incl. NAV):
  - Optical Bench: 13"Lx12"Wx17"H, 43 lb
  - NAV/Electronics Box: 12"Lx12"Wx12"H, 30 lb
- Prime Power: 400 W (est.)
- 2.2 million 3D pixels per sec (100 pixels @ 22 kHz)



Sigma Space 3-D Imaging Lidar Technology

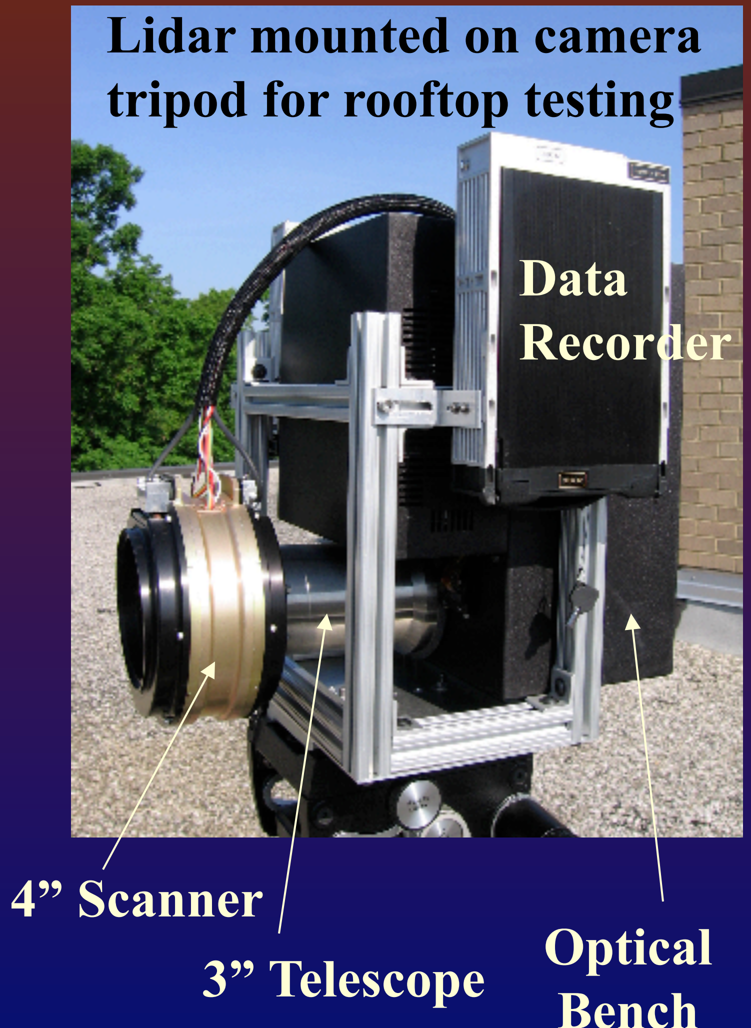
- Transmitter is a low-energy (6 μJ), high rep-rate (to 20 kHz), frequency doubled (532 nm), passively Q-switched microchip laser with a 710 psec pulsewidth.

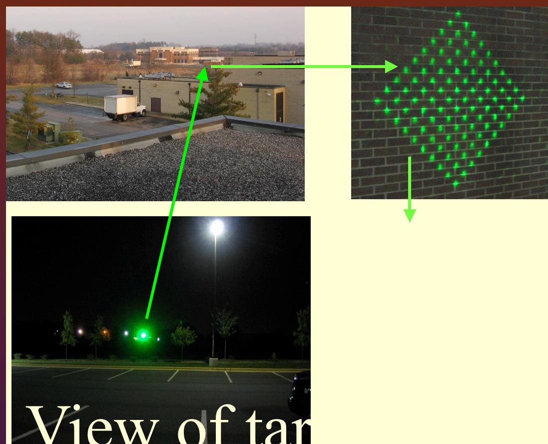
- Diffractive Optical Element (DOE) splits green output into 100 beamlets (~50 nJ @ 20 kHz = 1 mW per beamlet) in a 10 x 10 array. Residual 1064 nm energy is used for polarimetry.

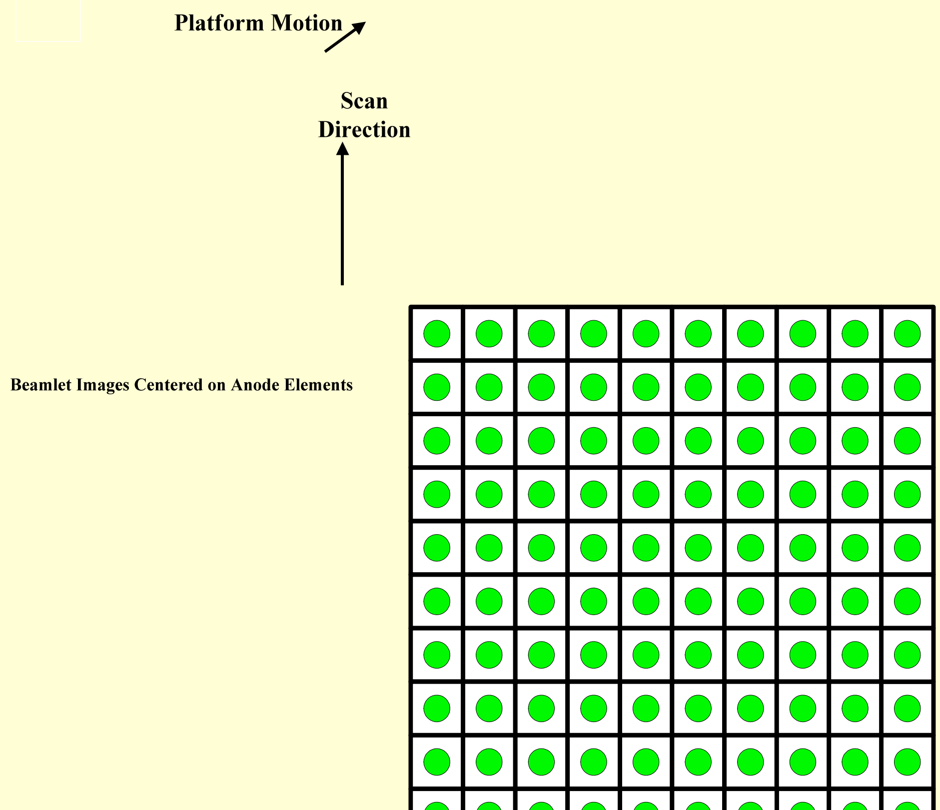
- Returns from individual beamlets are imaged by a 3 inch diameter telescope onto one anode of a 10x10 segmented anode micro-channel plate photomultiplier.

- Each anode output is input to one channel of a 100 channel, high resolution (± 92 psec or ± 1.4cm), multi-stop timer to form a 100 pixel 3D image on each pulse. Individual images are mosaiced together by the aircraft motion and an optical scanner (100 pixels @ 20 kHz = 2 million 3D pixels/sec).

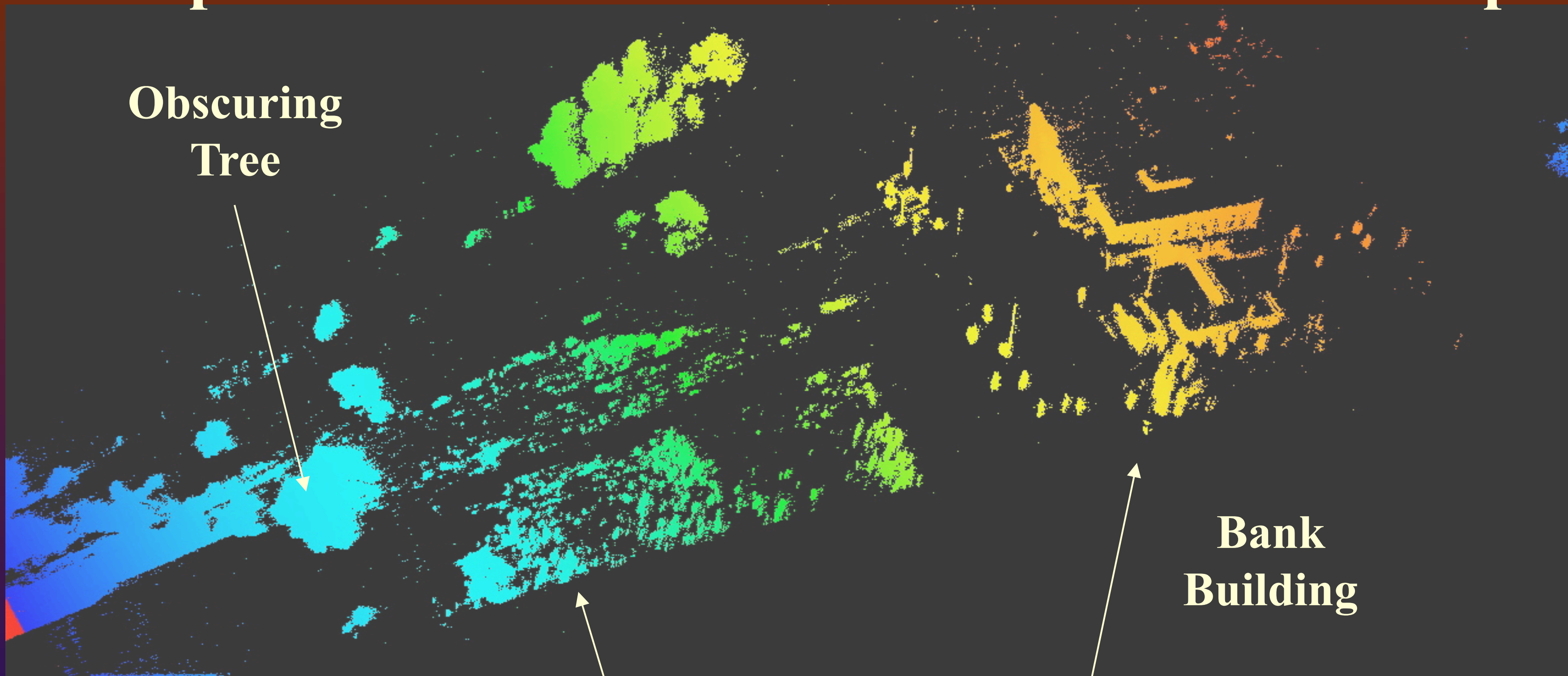
- The high speed, 4" aperture, dual wedge scanner is synchronized to the laser pulse train and can generate a wide variety of patterns. The transmitter and receiver share both the telescope and scanner.

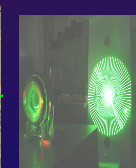



View of tar


Platform Motion
Scan Direction
Beamlet Images Centered on Anode Elements

Top view of 3D lidar data taken from our rooftop

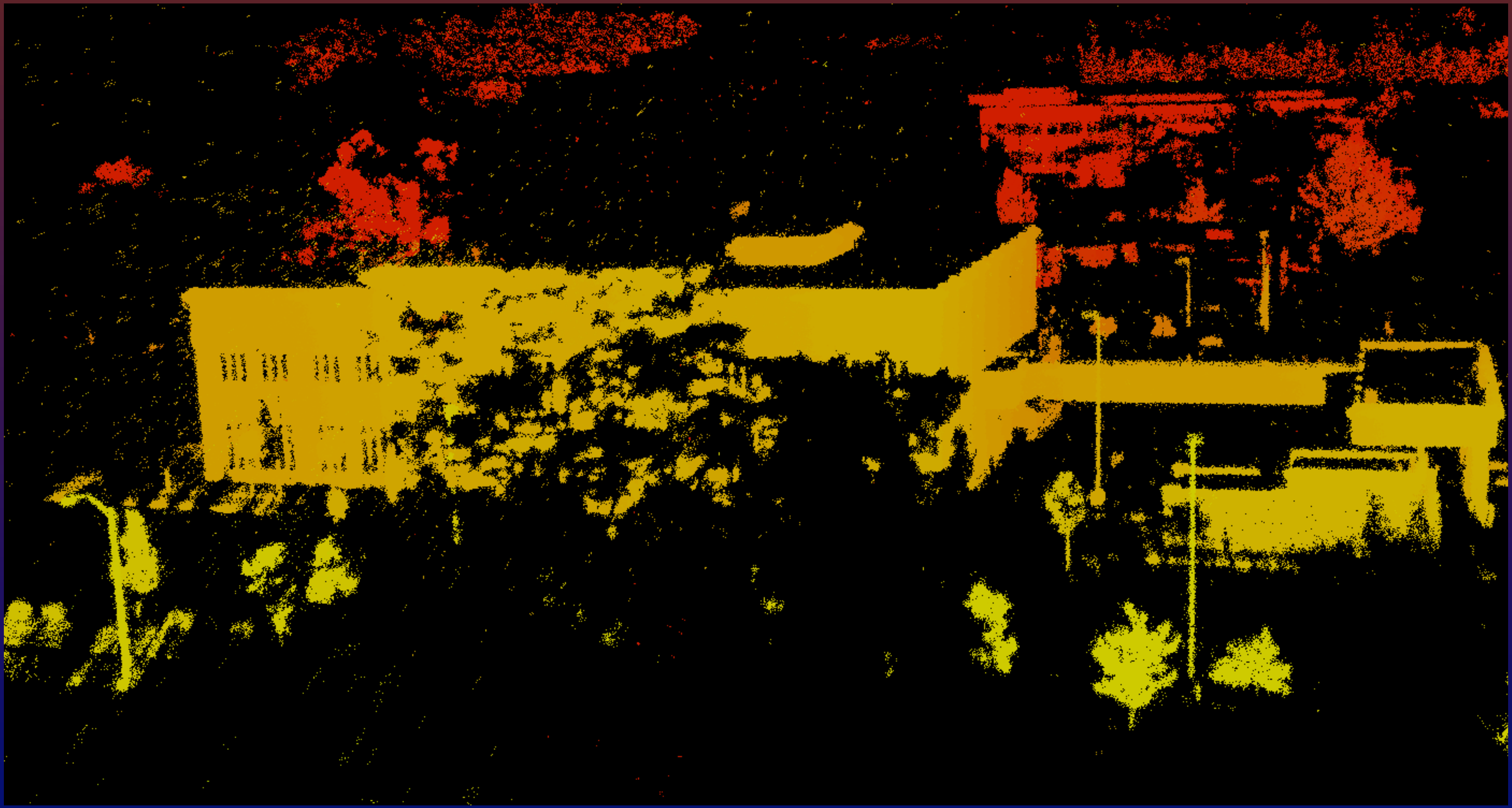


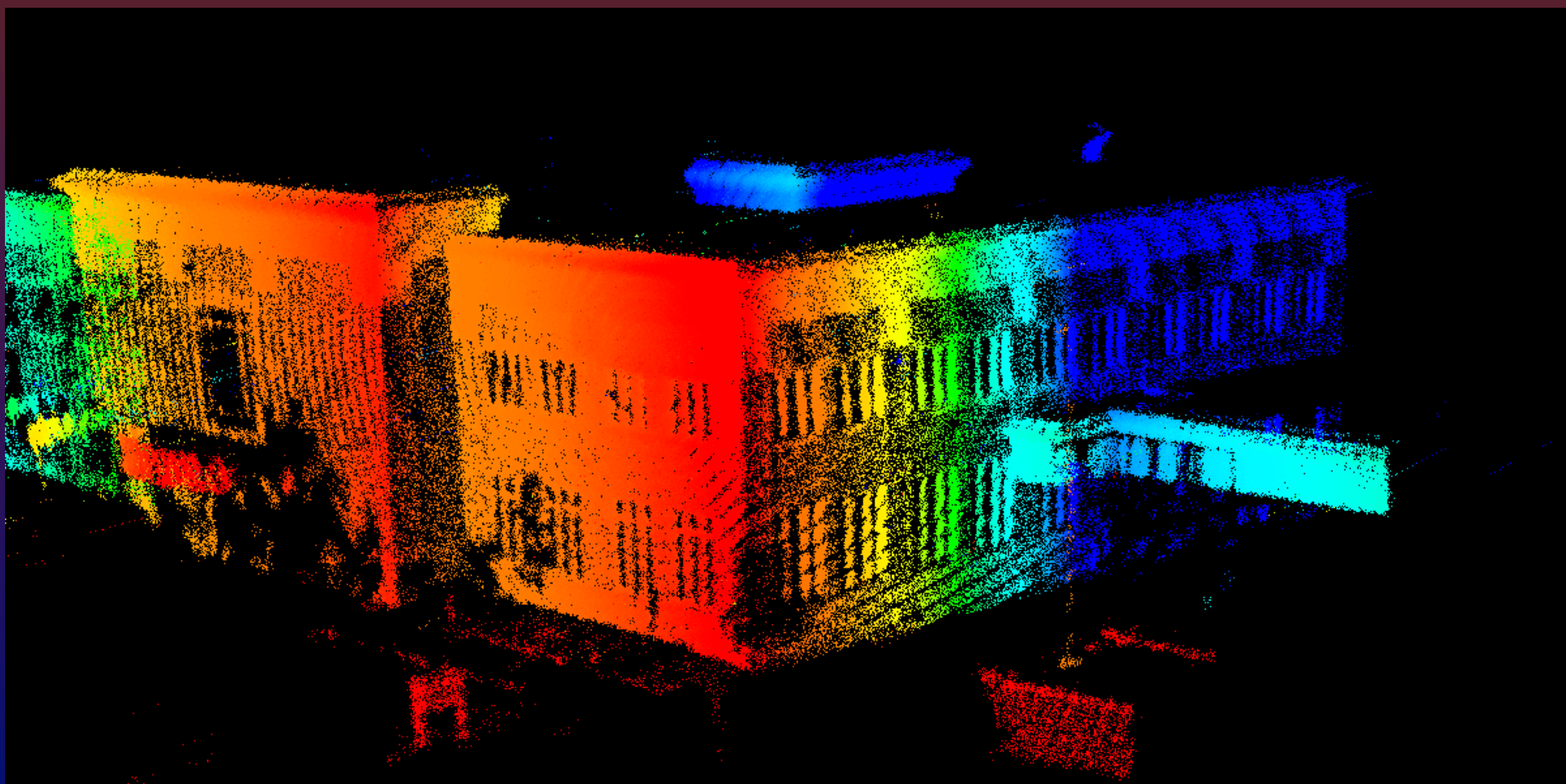


Lidar Location

Rotating Line Scan Pattern

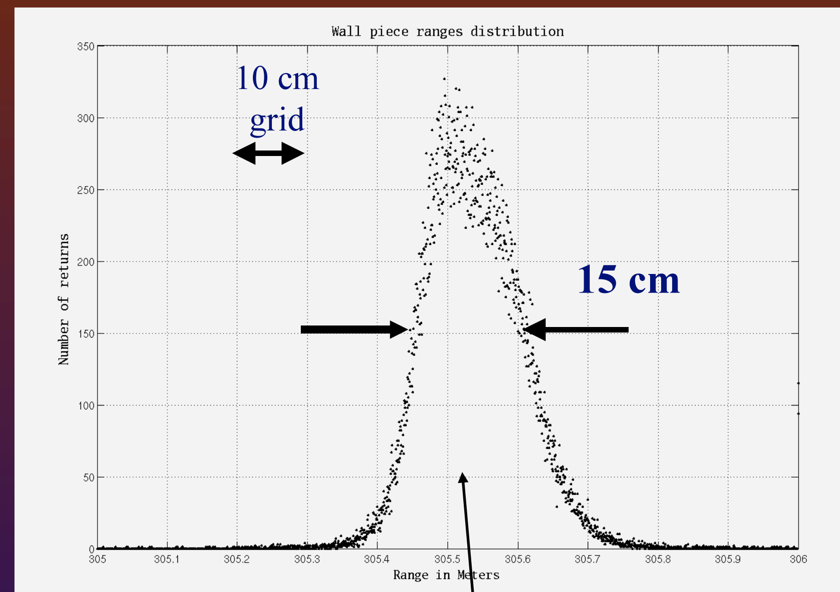
Close-up View of 3D Lidar Data

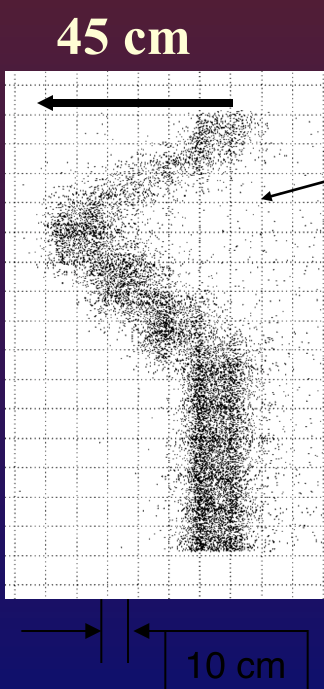


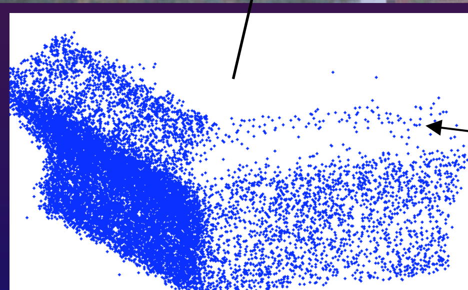


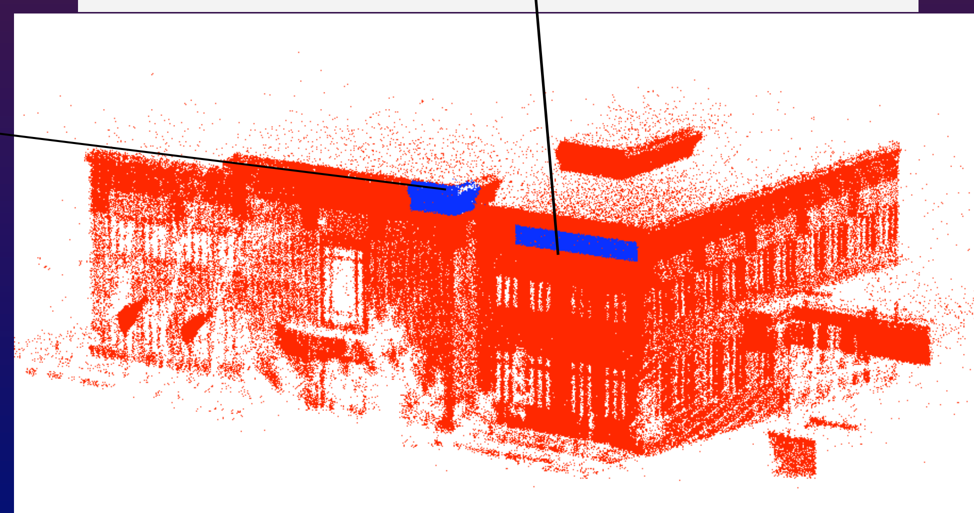
Lidar Resolution

Laser Pulsewidth = 710 psec FWHM
Detector Impulse response = 170 psec
Timing Resolution = ± 93 psec

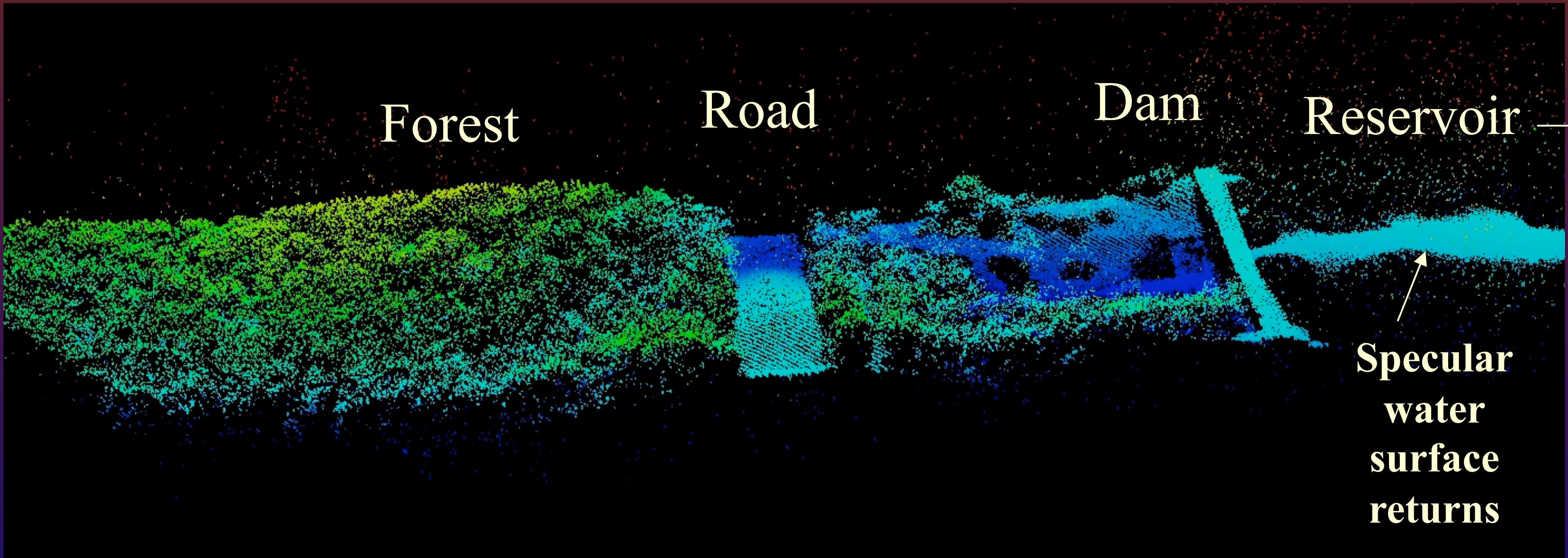






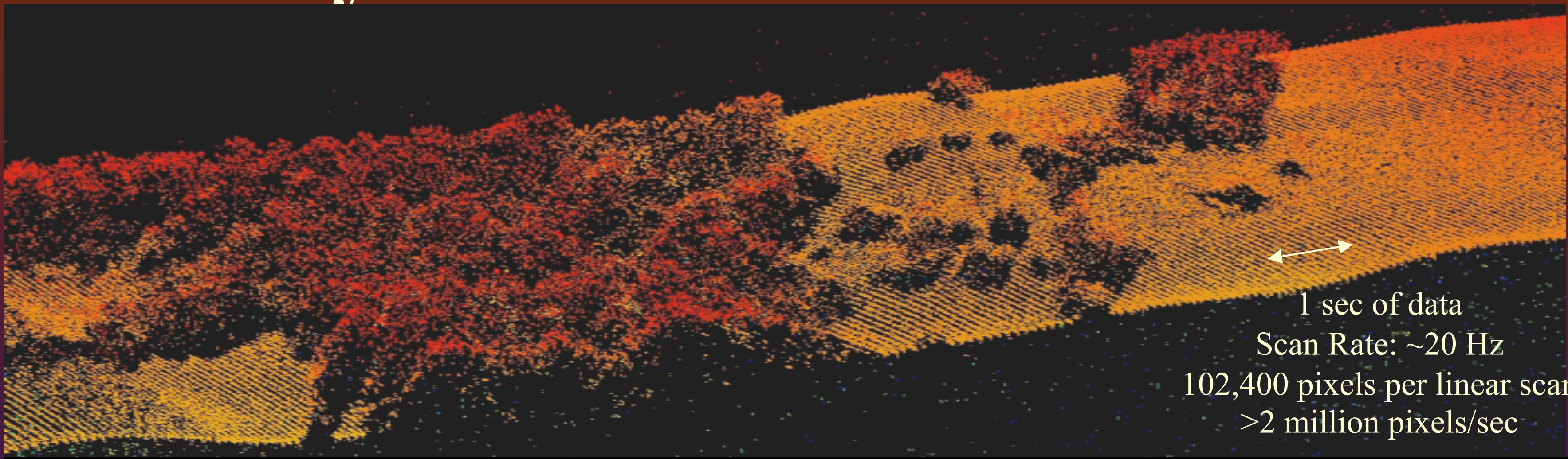


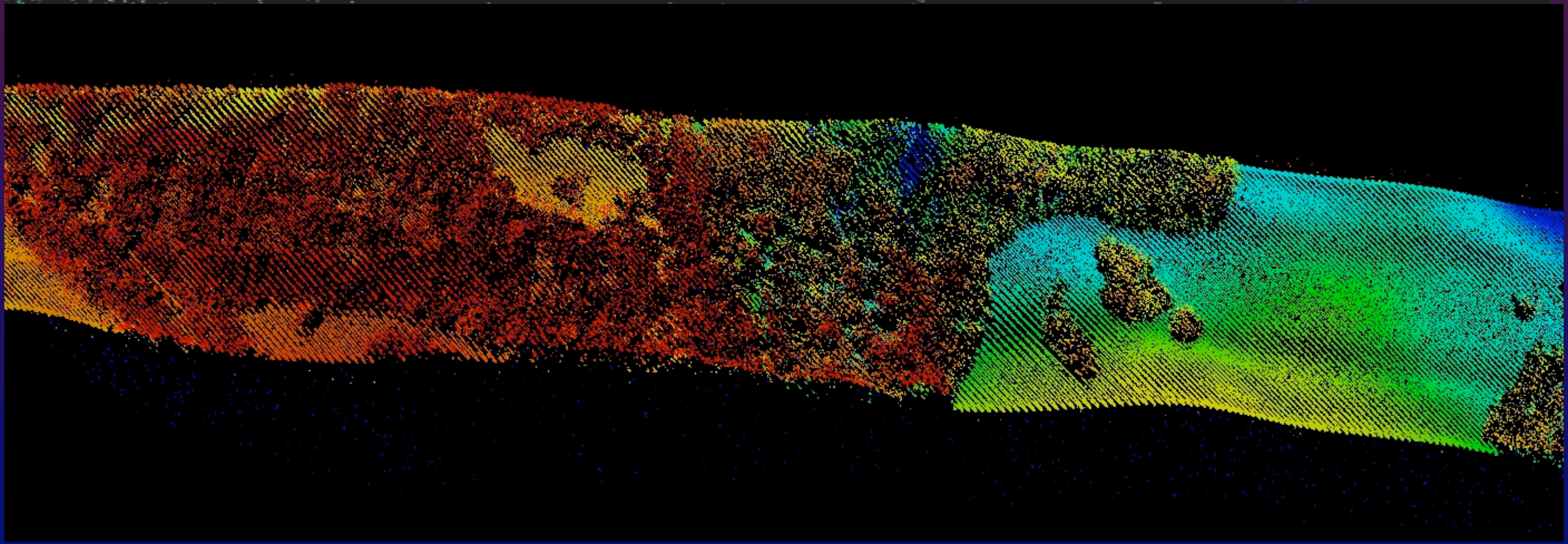
First Test Flight, August 29, 2007 Daytime Lidar View of Triadelphia Reservoir, Prince George's County, MD



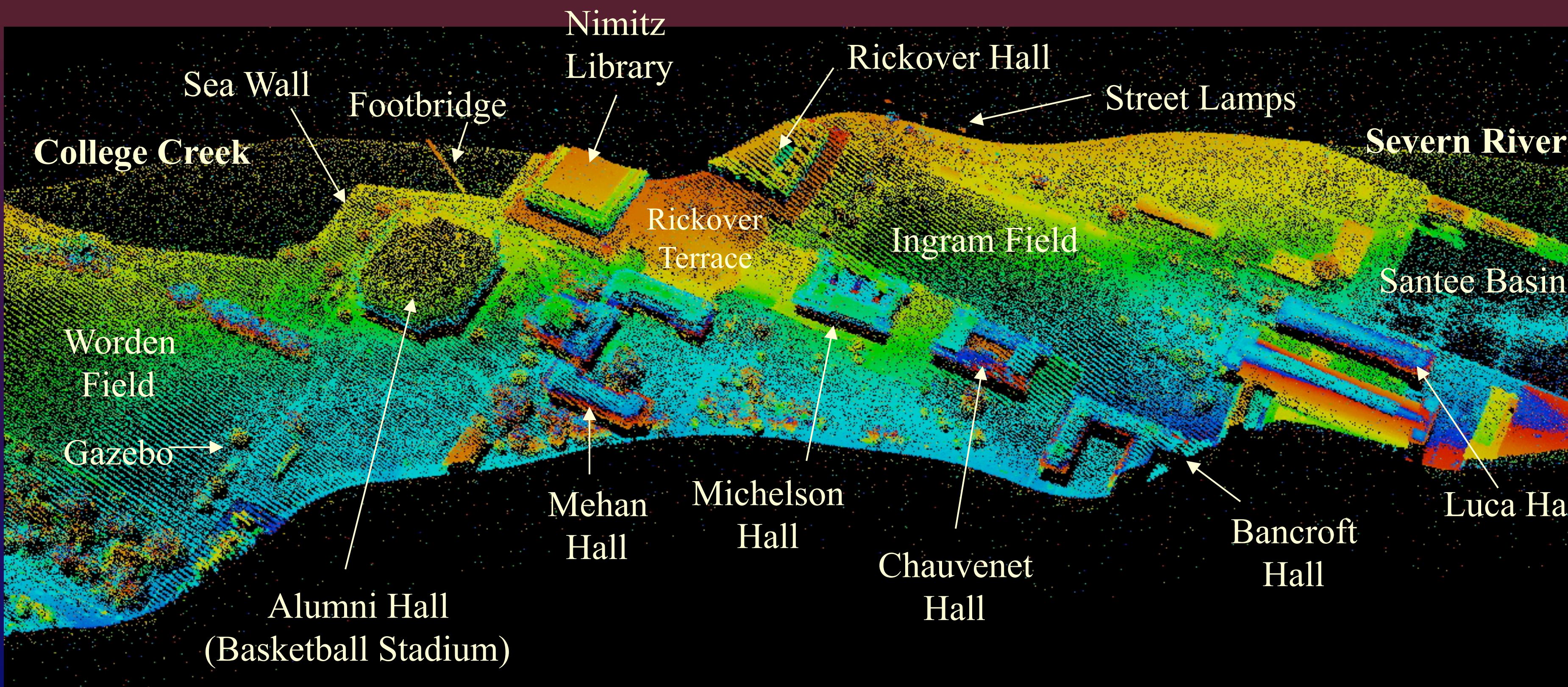
•This preliminary flight image was obtained on a single overflight just after noon from an altitude of 1800 ft.

Daytime View of Treed Areas

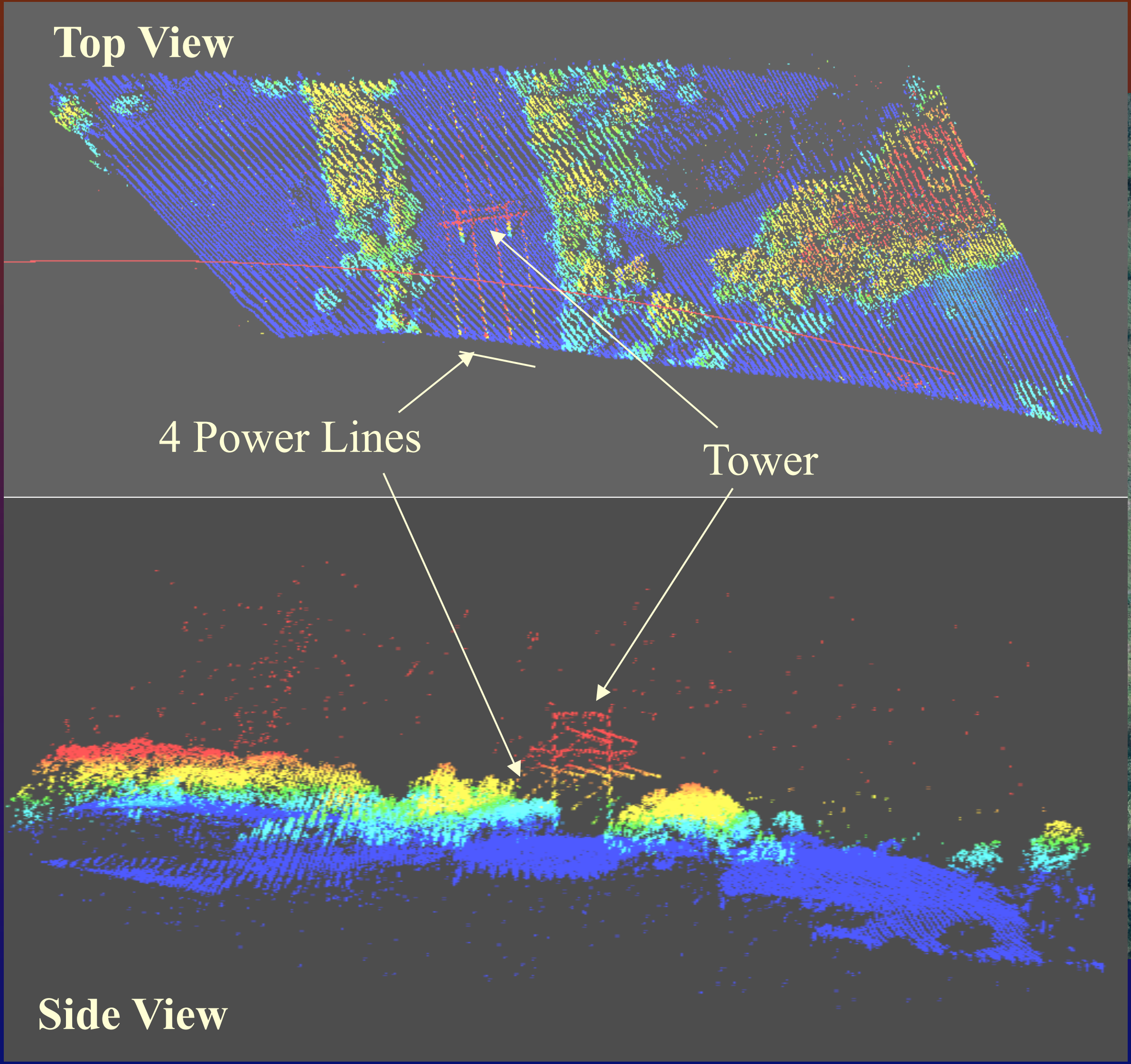




Night View
US Naval Academy Campus, Annapolis, MD



Power Lines and Towers



Scaling Laws for Contiguous Mapping

v_g = ground velocity of aircraft/spacecraft
s = swath width
N^2 = number of detector pixels in NxN array
δ = horizontal spatial resolution per pixel
R = aircraft/spacecraft altitude
n_p = signal photoelectrons per pixel (n_p = 3 implies P_d >95%)
C_a = altimeter constant

Scanner Frequency:

$$f_{scan} \geq \frac{v_g}{\sqrt{2}(N\delta)}$$

Laser Repetition Rate:

$$f_{qs} \geq \frac{2v_g s}{(N\delta)^2}$$

Power-Aperture Product:

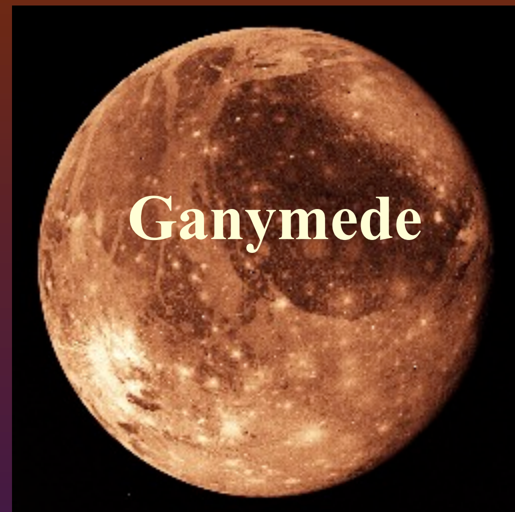
$$P_t A_r = \frac{2n_p v_g s R^2}{C_a \delta^2}$$

JIMO Mission Requirements

Jovian Moon	Europa	Callisto	Ganymede
Lunar Mass, M_i (kg)	4.80×10^{22}	1.08×10^{23}	1.48×10^{23}
Mean Volumetric Radius, R_i, km	1569	2400	2634
Orbital period about Jupiter, Days	3.551	16.7	7.15
Surface Area, km^2	3.094×10^{7}	7.238×10^{7}	8.718×10^{7}
Satellite Altitude, r_i (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**
Polarimeter/Hyperspectral Resolution, $N\delta$ (m)	**100**	**100**	**100**
Swath Width, s_i (km)	**14.4**	14.4	14.4
Scanner FOV Half Angle, (deg)	**5.72**	5.72	5.72
Scan Frequency, Hz	9.2	11.5	**12.9**
Lidar PA-Product, W-m^2	0.797	0.998	**1.12**
Min. Laser Fire Rate, f_{qs} (kHz)	3.74	4.68	**5.26**

Bolded numbers indicate which Moon is determining the instrument requirement.

NASA's Jupiter Icy Moons Orbiter (JIMO)



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

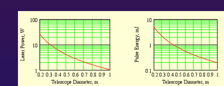
- •348 orbits at 100 km altitude
- •14.5 km mean spacing between JIMO ground tracks

•Surface Area: 31 million km^2

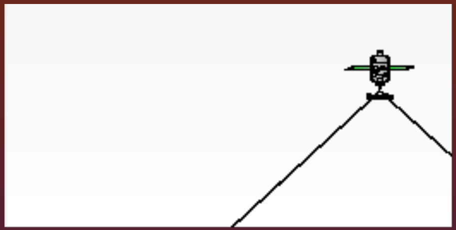
Photon-Counting Lidar

•>95% probability of detection per pixel

•Power-Aperture Product: 1.12 W-m^2

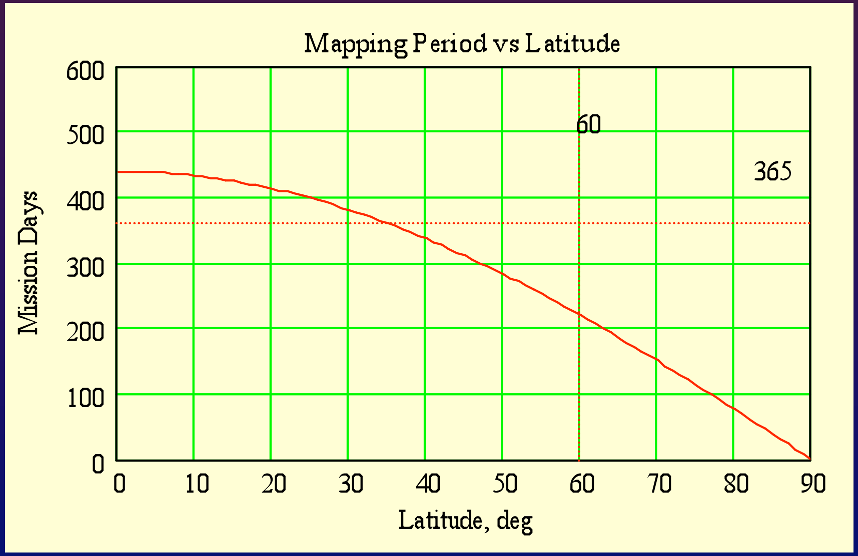


Cross Track Channel (CTS) Lidar Concept



•Assuming 16 beams over 3 km oriented at 45° to flight direction for semiannual yaw rotation, we obtain:

- •16 tracks 141 m apart = 2.1 km actual swath
- •Latitudes above 80° are mapped seasonally (>4 times/yr)
- •Latitudes below 35° are mapped less than once per year



•A single 10 W laser transmitter is within the state-of-the-art and can support up to 16 channels with 82% surface return rate over ice and snow in a standard clear atmosphere and provides some signal margin for poorer atmospheres.

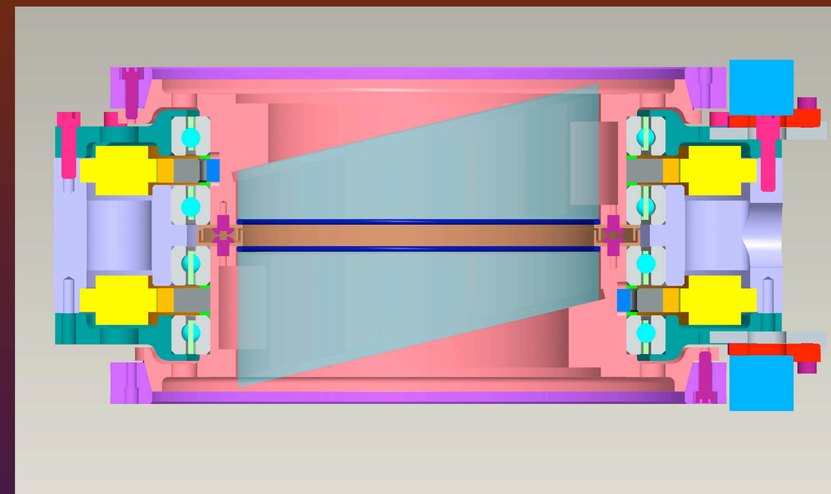
•Reducing the number of channels marginally increases the return rate while significantly reducing the spatial coverage.

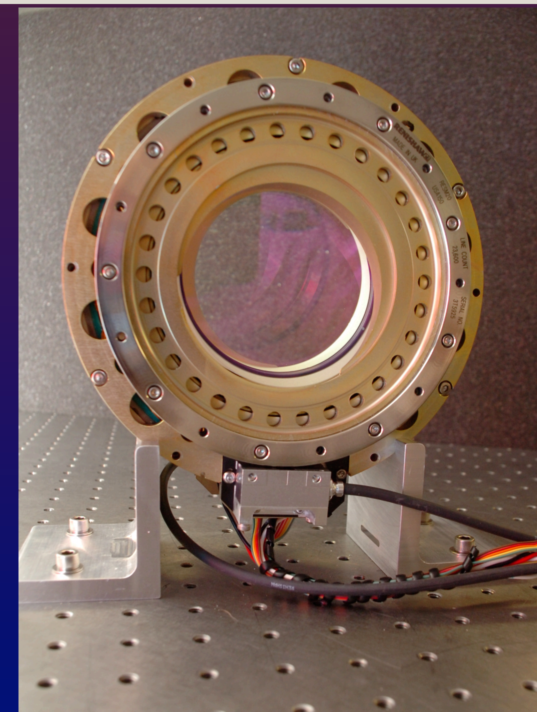
Technical Challenges: 3D Imaging from Space

- Requires Larger Power-Aperture Product ("pushbroom" and scanning lidars)
  - Laboratory lasers already meet or exceed functional reqirements.
  - Sigma is currently developing a 10 W (1 mJ @ 10 kHz) laser with a 15% wallplug efficiency goal.
- Internal Scanners for Contiguous 3D Imaging (Sigma Patent Pending)
  - Large telescope apertures (0.7 to 1 m) make external mechanical scanners unattractive
  - Smaller scanners can sometimes be placed behind primary telescope.
  - Scanner should not impart angular momentum to the spacecraft (luckily the momenta of counter-rotating wedges cancel each other)
- Transmitter Point-Ahead Compensation
  - Consequence of finite speed of light, long pulse flight times (few msec) and high scan speeds
  - Maintains narrow receiver FOV for noise control in photon-counting mode
  - Requires relative phase control of independent transmit and receive scanners as currently demonstrated in synchronized Sigma/USAF dual wedge scanner.
- Requires rugged, long-lived, vacuum-compatible, and rad-hard components. Hopefully, all (except for scanner) will be developed for Cross Track Channel (CTC) lidar under NASA's ICESat-II program.

Direct-Drive Annular Ring Motor Scanner

- Developed as part of 1 yr NASA HQ JIMO study and used in Sigma/USAF lidar.
- Compact design.
- No net angular momentum due to counter-rotating wedges
- No slippage (as in belt-driven or other friction drives) for improved repeatability of ground scans.
- Motors/bearings are space and vacuum qualifiable.
- Several inch clear apertures readily available (adequate for internal scanning but also scalable to larger apertures).
- Wedge rotations synchronized to external clock with relative phase control for arbitrary scan pattern.





Transmitter Point Ahead
(single wedge conical scanner)

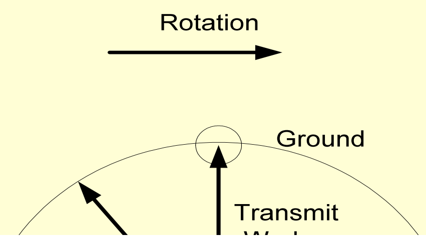


Figure 1: Providing transmit point-ahead compensation in a single wedge conical scanner. The green circles indicate the position of the

Summary

- Photon-counting lidars can detect single photon surface returns and thereby increase the spatial coverage and resolution by orders of magnitude relative to conventional multi-photon lidars for a given Power-Aperture Product.
- Rooftop and airborne tests have demonstrated the feasibility and accuracies of photon-counting lidars operating in daylight.
- Photon-counting lidars are ideal for planetary and lunar mapping missions where instrument mass, size, and prime power are heavily constrained. They are especially attractive for the outer planets and their Moons due to lower solar background relative to Earth (e.g. 25x less for Jupiter).
- The Cross Track Channel (CTC) instrument on NASA's ICESat-II mission, if approved, will space qualify all of the components needed for future interplanetary pushbroom lidars, including transmitter, detector, and timing electronics. Optically scanned systems will require further independent development.