# Second-Generation, Scanning, 3D Imaging Lidars Based on Photon-Counting

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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 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 surveillance on a single overflight possible with modest laser powers and telescope apertures – even from orbital altitudes.

# Sigma Imaging Lidar Projects

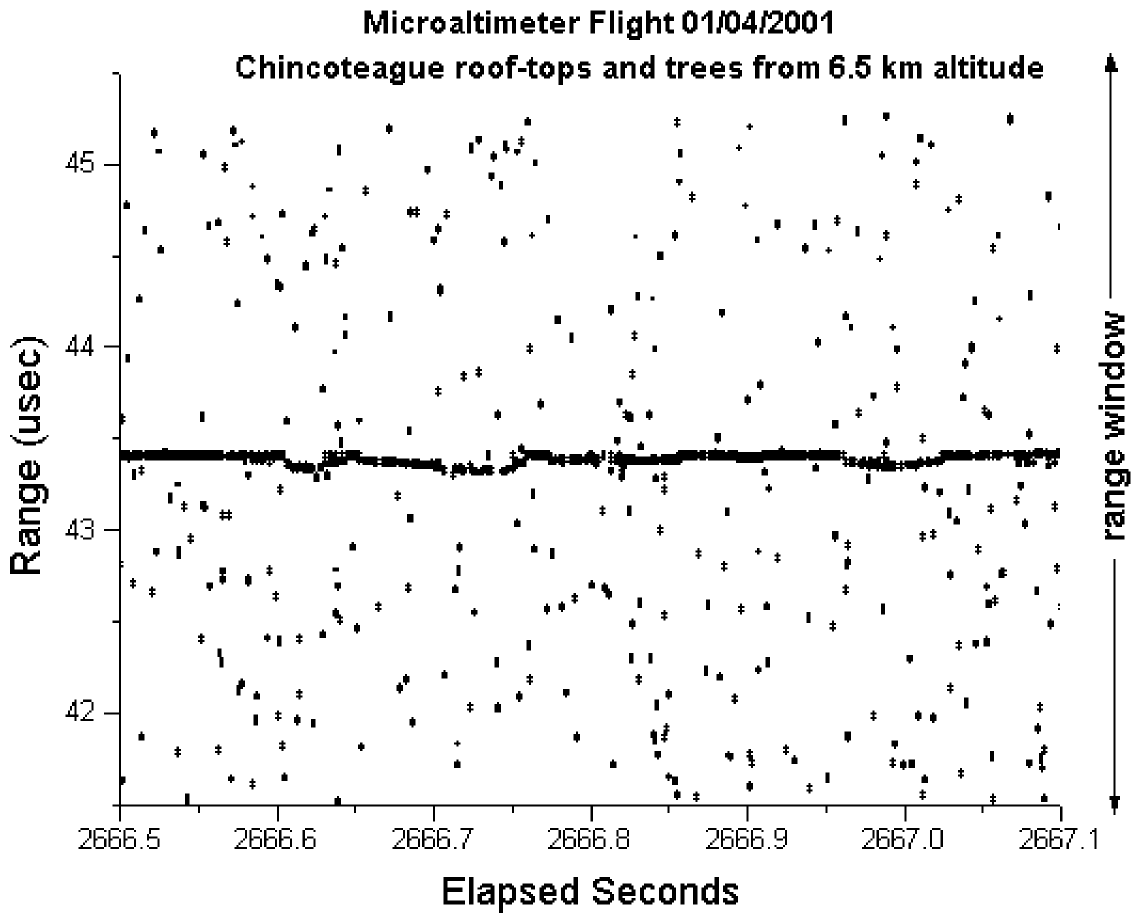
- **1st Generation (feasibility demonstration)**
  - NASA “Microaltimeter” (NASA Goddard Space Flight Center) – up to 6.7 km altitude (1999-2002)
- **2nd Generation (15-20 cm horizontal resolution and contiguous coverage)**
  - CATS Underwater 3D Imaging Lidar (Univ. of Florida at Gainesville/ Sigma/Fibertek Corp. for US Navy) – 0.6 km design altitude (Cessna), 20 cm horizontal resolution, 5 m depth penetration
  - USAF 3D Imaging and Polarimetric Lidar (Phase II SBIR) – 1 km design altitude (Aerostar Mini-UAV), 15 cm horizontal resolution, tree canopy penetration
- **Future Generation (few meter horizontal resolution and contiguous global coverage from space)**
  - 3D Topographic, Polarimetric and Hyperspectral Mapping of three Jovian Moons from Orbit ( NASA HQ 1 yr Advanced Study)
  - Goal: Globally contiguous map of Europa in 1 month, 10 m horizontal, 1 m vertical resolution, Ganymede & Callisto in 2 months
  - 100 km orbital altitude –2W laser power, 70 cm aperture, internal scanner

# IIP Multikilohertz Microlaser Altimeter ("Microaltimeter')

## Town of Chincoteaque (Jan. 4, 2001, 1:50 pm EST)

## 0.6 seconds of raw data over full 4 $\mu$sec range window

**Laser Power= 7.6 mW (2 $\mu$J@ 3.8 kHz), Telescope Aperture = 14 cm, Est. Mean Signal = 0.88 pe**
**Each point is a single photon time of flight measurement to surface (signal) or a single solar photon scattered by the surface or atmosphere (noise)**



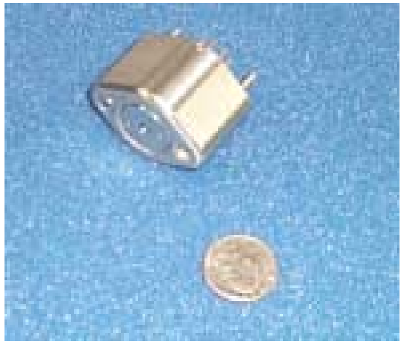

**600 m**

**Empire State Building**

**443 m**

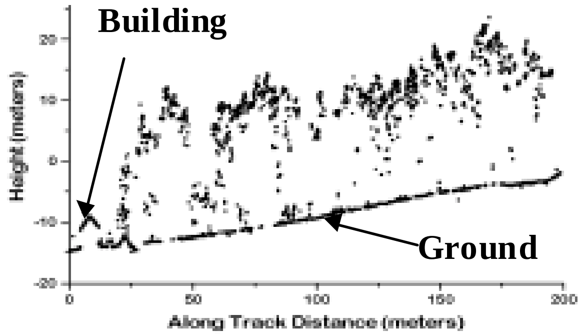
# *IIP Airborne Multi-kHz Microlaser Altimeter*

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

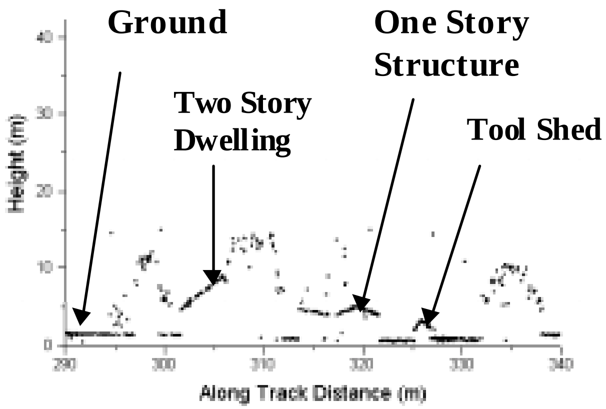


**Diode-Pumped Passively Q-switched Nd:YAG Microchip Laser including TEC cooler and DoublingCrystal**

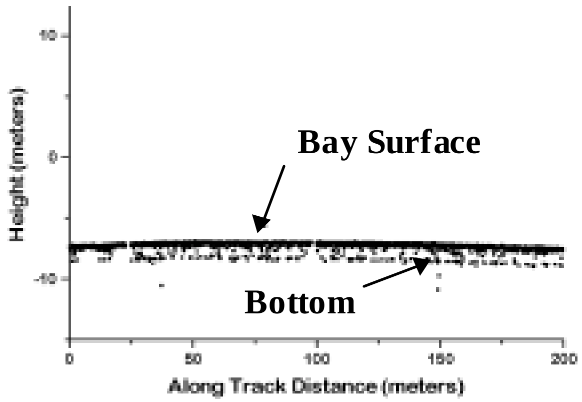
- **Engineering Flight Parameters**
  - NASA P-3 Aircraft, Wallops Flight Center
  - Locale: Chincoteague, VA & Chesapeake Bay
  - Flight Altitudes: 3.5 to 6.7 km (11,000 to 22,000 ft)
  - Early afternoon (maximum solar background)
  - Laser Energy: < 2 μJ @ 532 nm
  - Laser Repetition Rate: 3.8 kHz
  - Laser Power: ~7 mW
  - Effective Telescope Diameter: 14 cm
  - Mean Signal Strength per Laser Fire: ~ 0.88 pe




**Tree Canopy Heights**

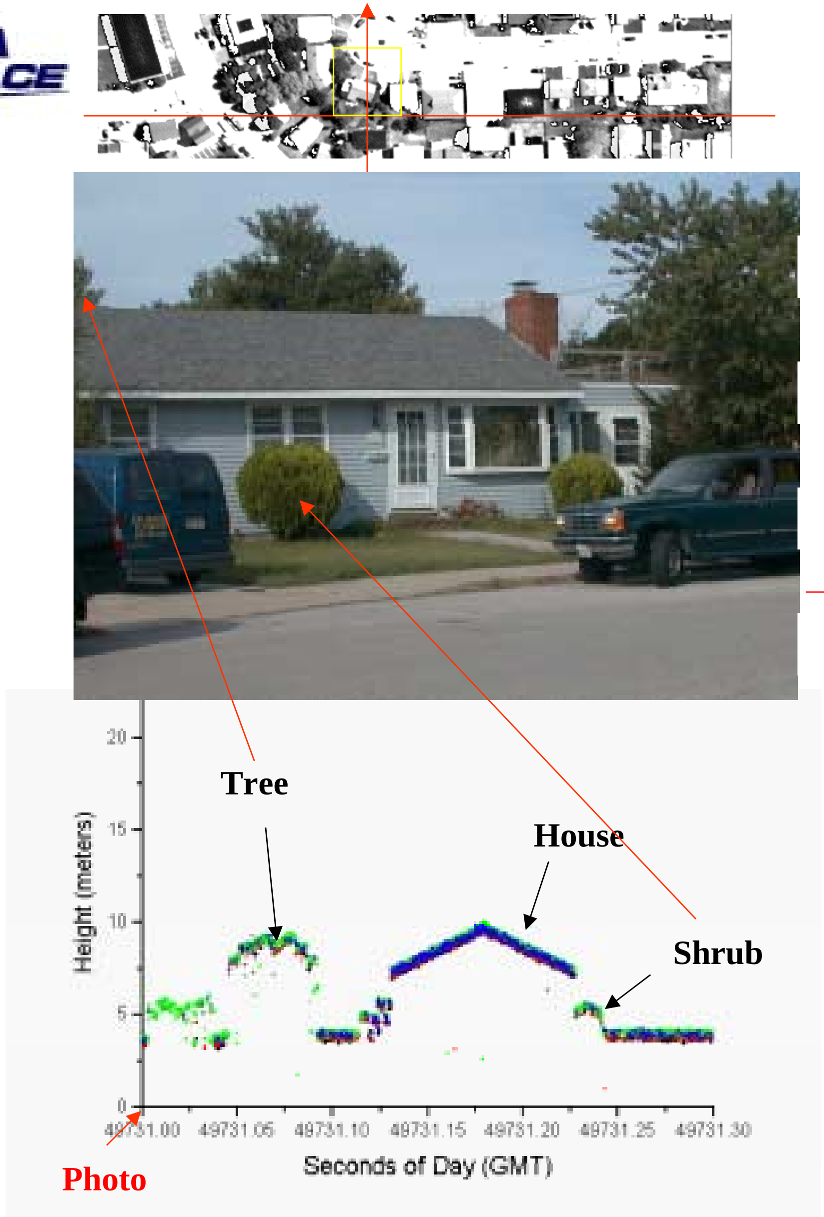


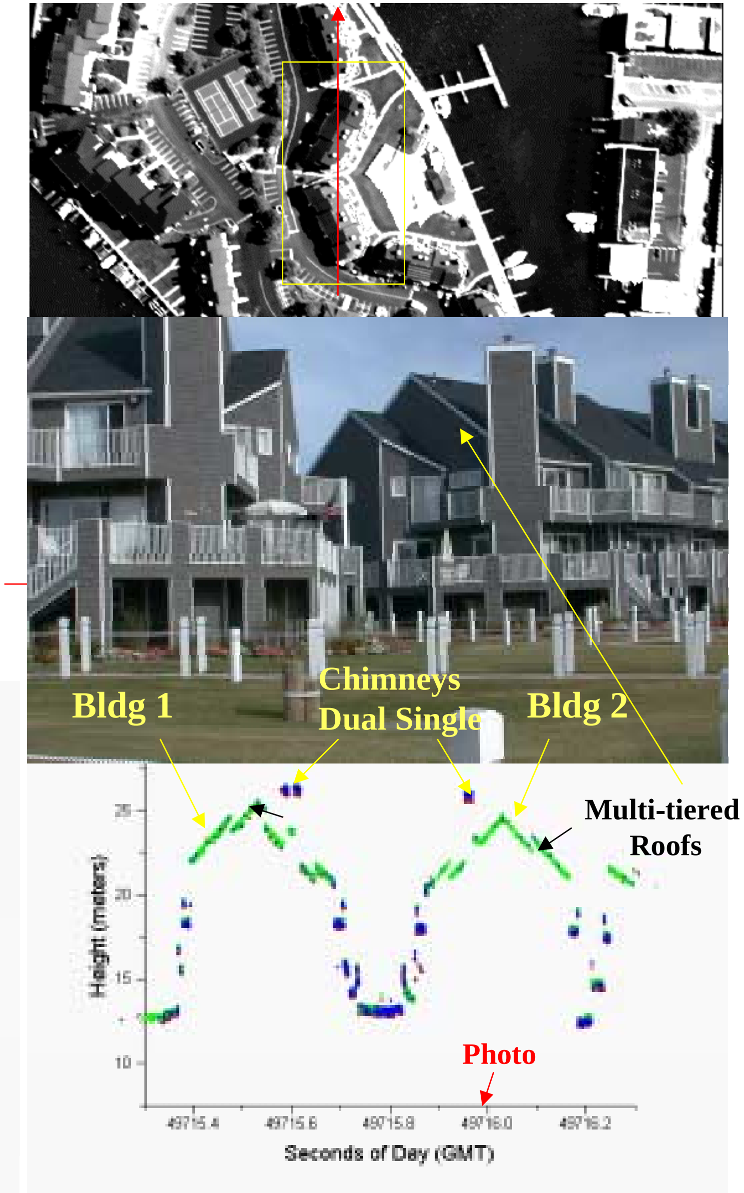

**Buildings and Trees**




**Shallow Water Bathymetry**

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.

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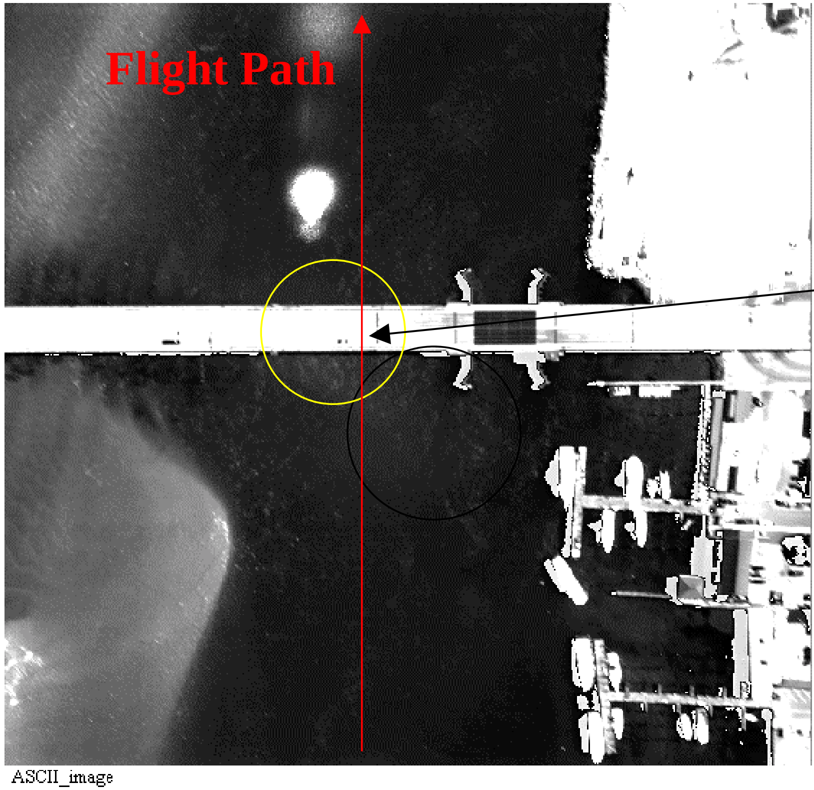
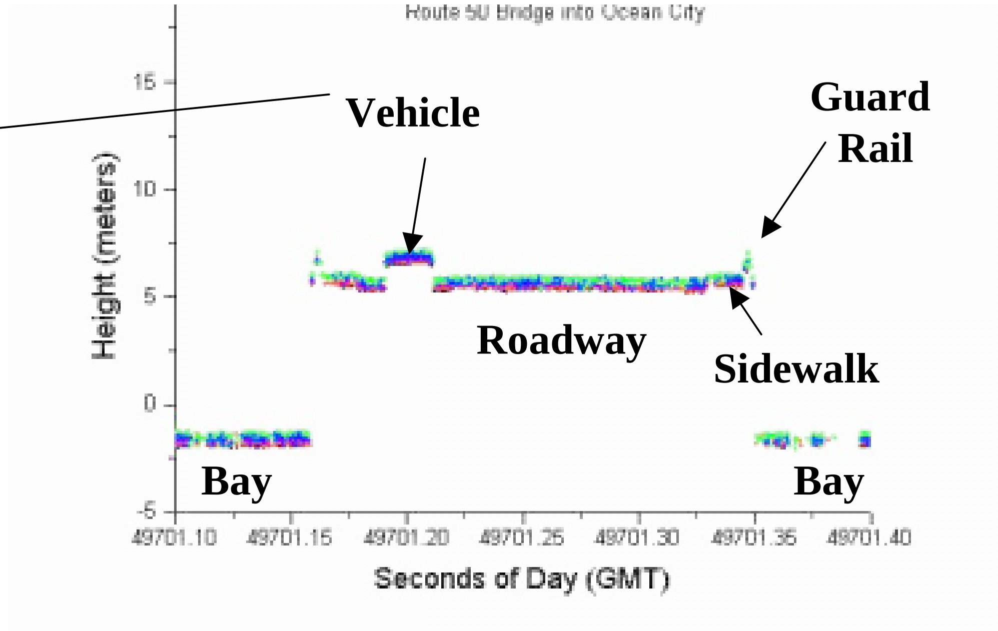
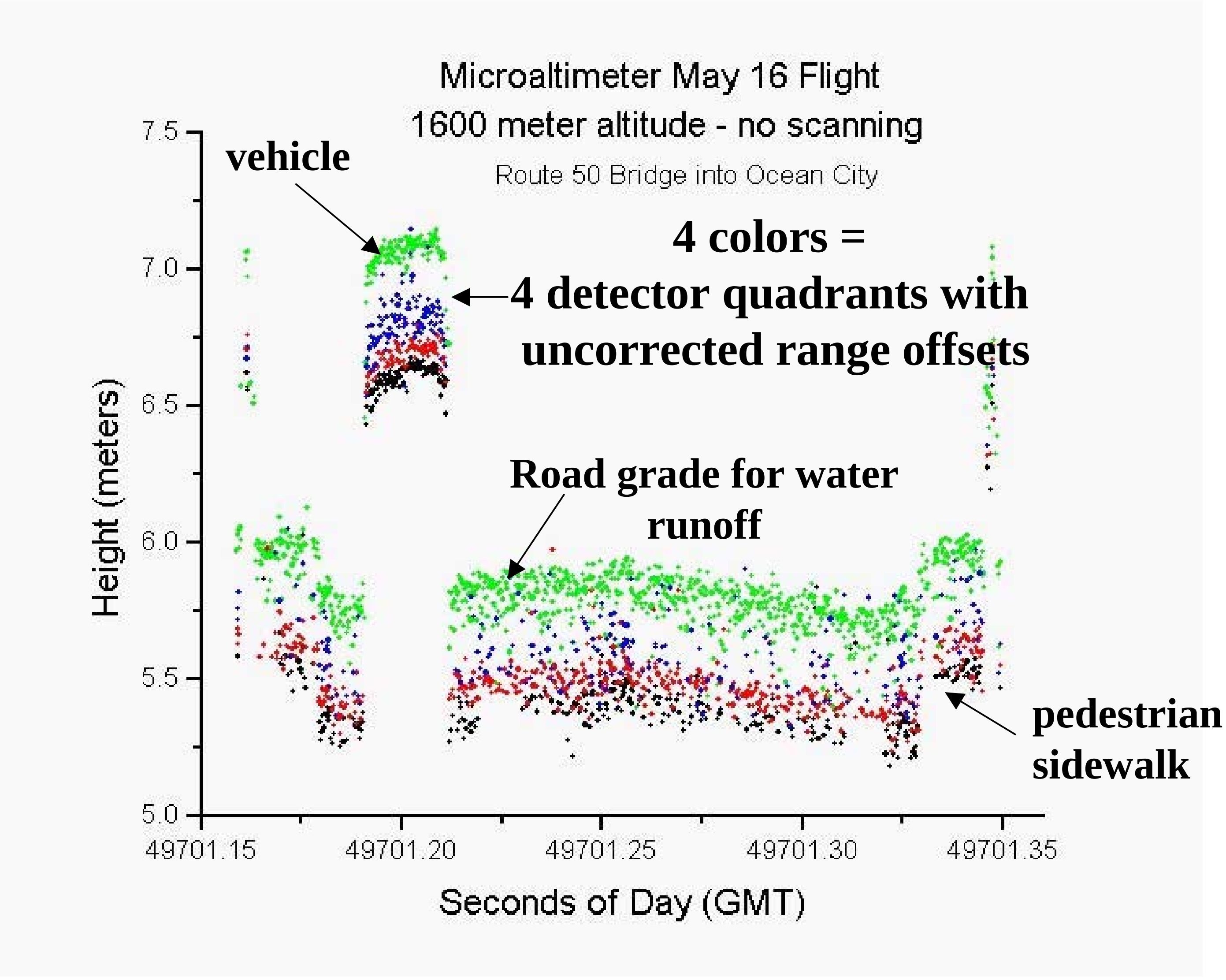
# Bridge and Moving Vehicle (Route 50 Bridge into Ocean City, MD)



# Bridge and Moving Vehicle (High Resolution Vertical View)

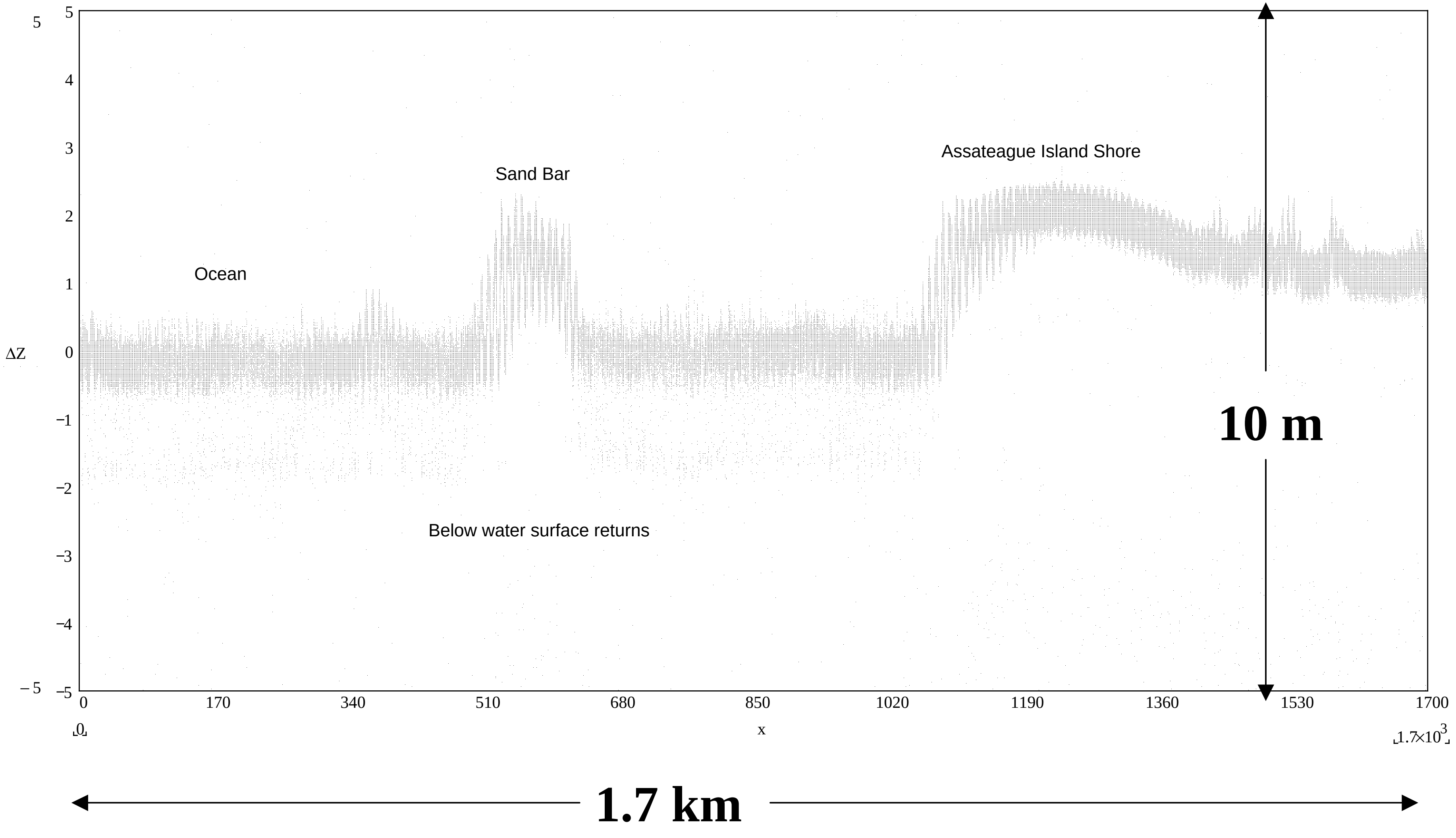


# Shallow Water Bathymetry Example

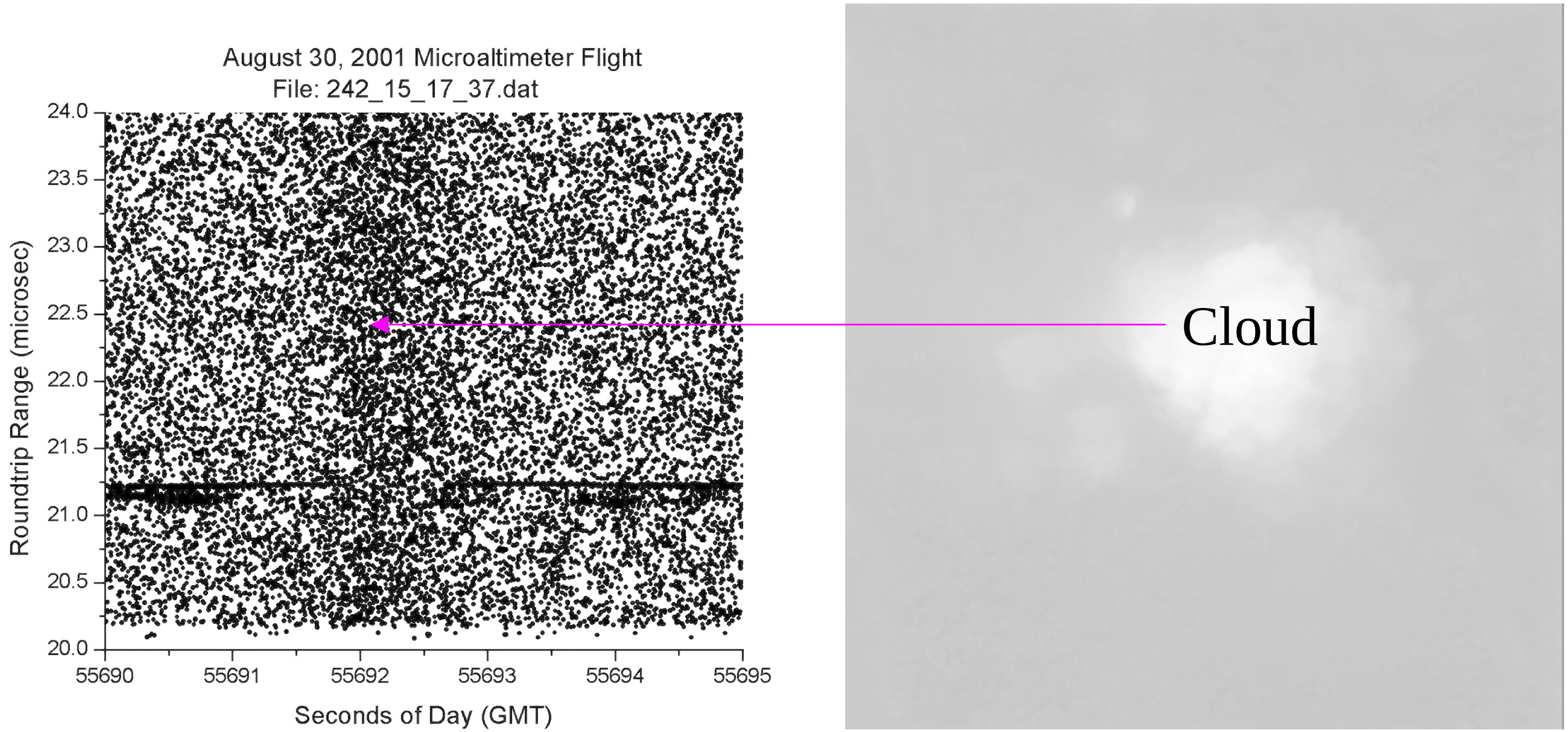
## Airborne Microaltimeter: Assateague Island Beach (VA)

### 1.7 km along-track profile (~ 20 secs of data),Vertical scale: ± 5 m

### 20 Hz scanner on, raw 3D profile projected into 2D plane



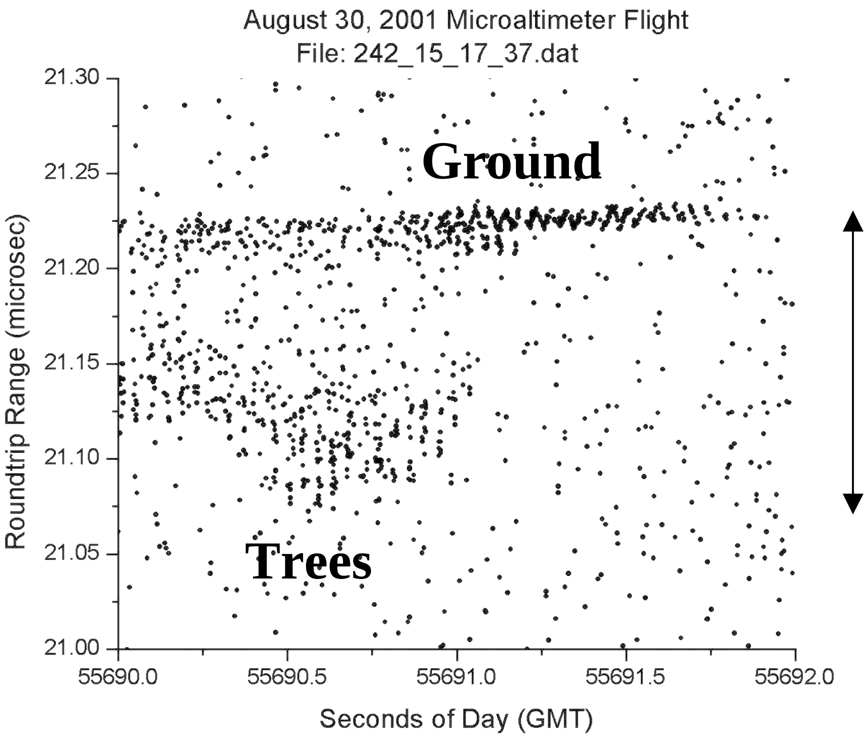
# Extreme Haze & Clouds



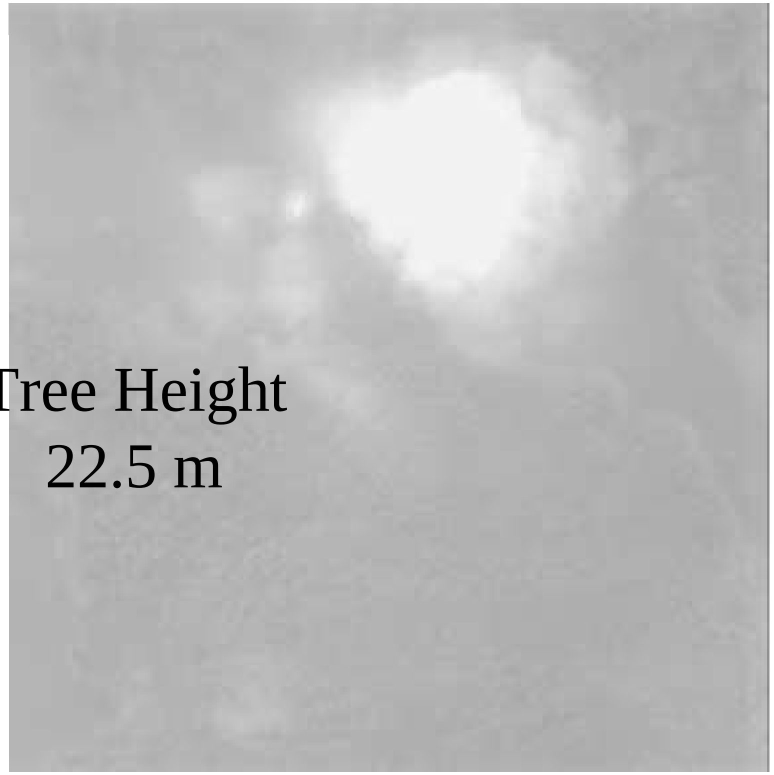

**Raw Altimeter Data**
**20 Hz Conical Scanner On**
**Altitude = 17,500 ft (5.3 km)**

**CCD Camera Image**
**(no contrast enhancement)**

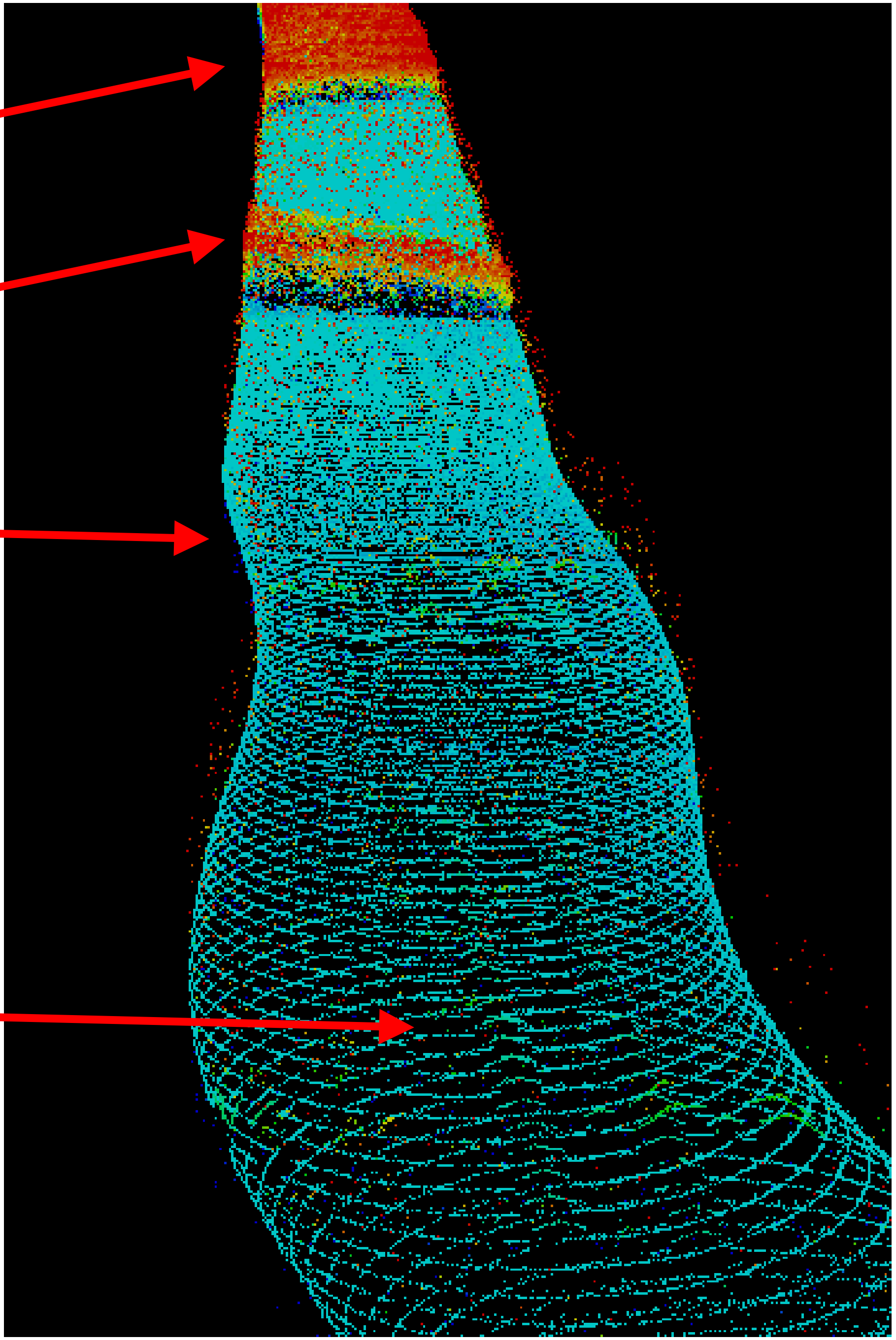
# Extreme Haze and Clouds (Zoom View)




**Raw Altimeter Data**
**20 Hz conical scanner on**
**Altitude = 17,500 ft (5.3 km)**




**Enhanced Contrast CCD Image**



Start of forest

Stand of trees

Route 354

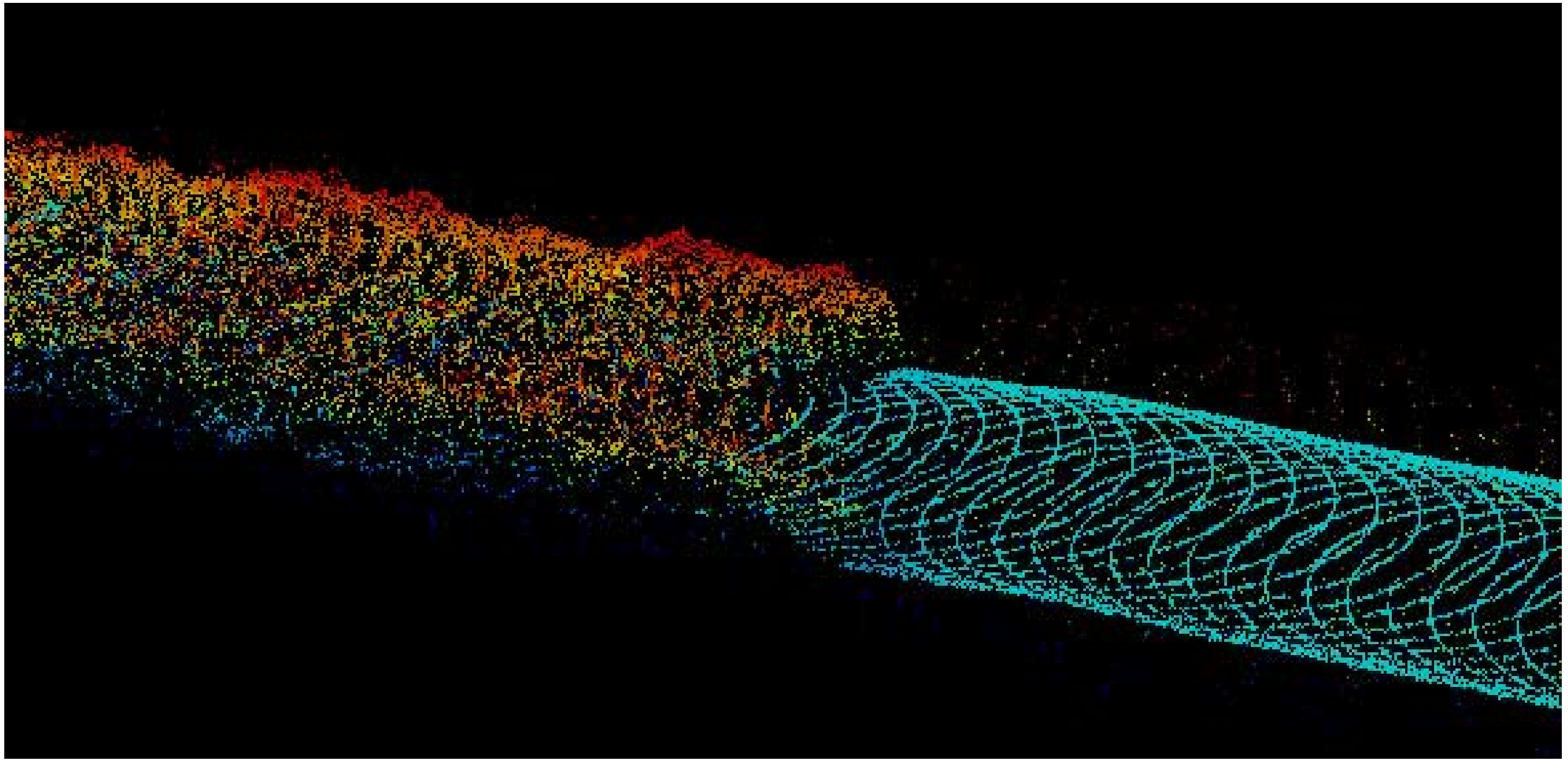
**Microaltimeter point cloud data**

Parallel long buildings

Courtesy: Jan McGarry, NASA Goddard Space Flight Center

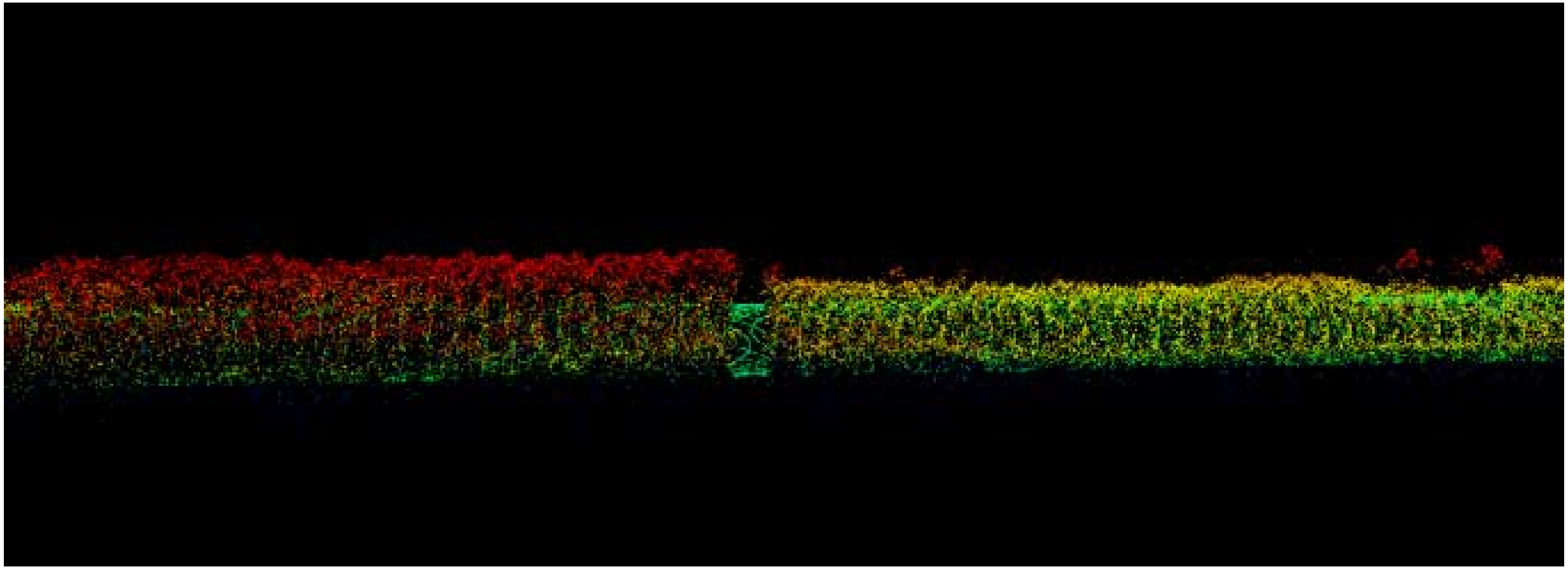
Flight line

# Start of Forest



Courtesy: Jan McGarry, NASA Goddard Space Flight Center

# Further Along Flight Path

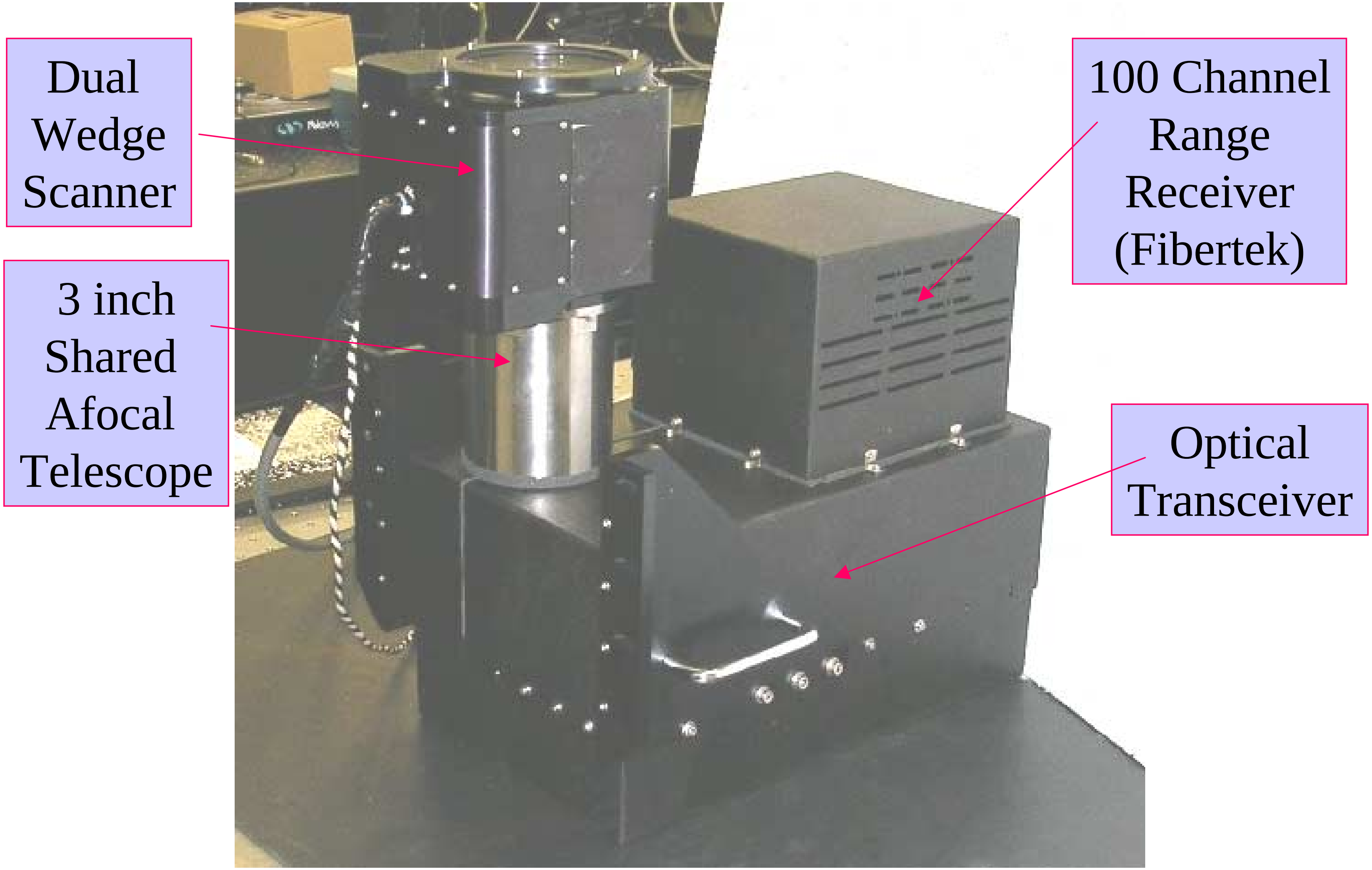


Courtesy: Jan McGarry, NASA Goddard Space Flight Center

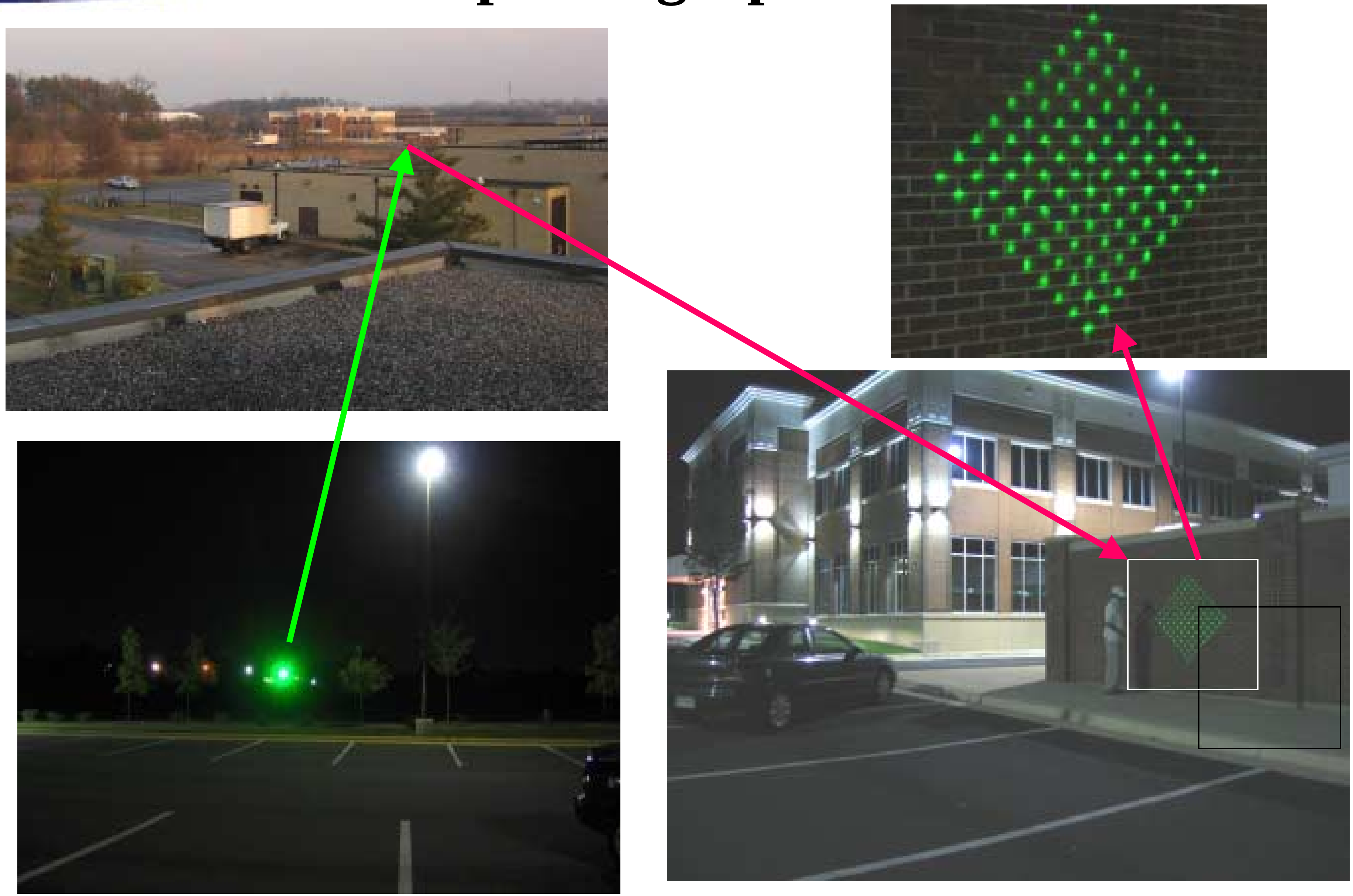
# Second Generation Upgrades

- More powerful, higher repetition rate microchip laser transmitter
- More efficient 10x10 anode microchannel plate photomultiplier and high resolution (± 92 psec) 100-channel, multistop timer
  - Greater QE (40% vs 10%) and Counting Efficiency (28% vs 7%) results in four-fold signal increase in signal counts/sensitivity
  - Faster tube response and lower transit time jitter in microchannels improves range resolution
  - Larger number of anode segments and timing channels increases spatial resolution while reducing scan speed and laser repetition rate requirements
- Holographic element in transmitter path produces 10 x10 array of spots at the target, each of which is imaged onto a single detector pixel
- Replace free-running single wedge conical scanner with more flexible counter-rotating dual optical wedge scanner synchronized to the laser pulse train
  - Provides contiguous wide area scans on a single overflight
  - Provides a variety of 1-D and 2-D scans for different platform velocities
  - Synchronization to pulse train eliminates need to record wedge angular positions on every shot and reduces sensitivity to variations in laser repetition rate.
- Add polarimetry channel to utilize residual 1064 nm power
- Much smaller telescope/opto-mechanical package fits into mini-UAV

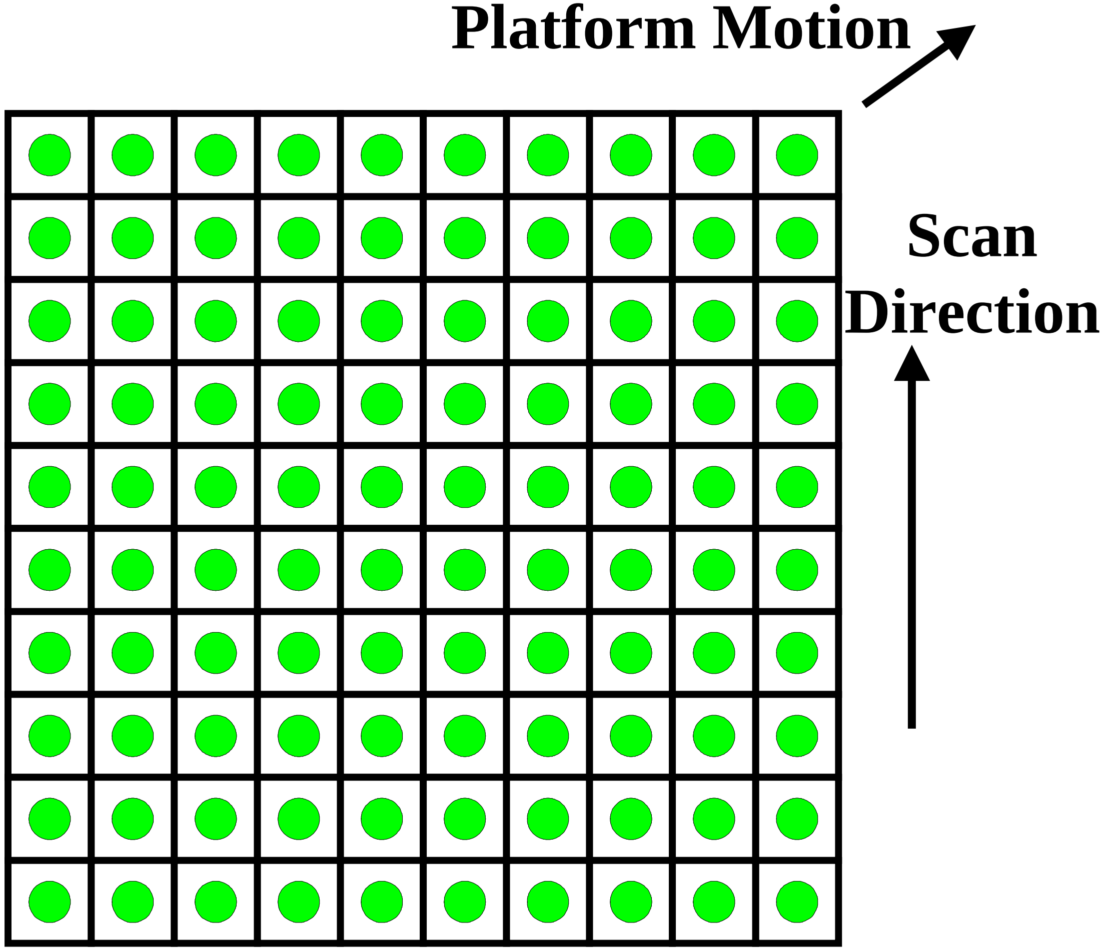
# CATS Underwater 3D Imaging Lidar
## (Univ. of FL at Gainesville, Sigma, Fibertek)



# Rooftop Holographic Element Demo



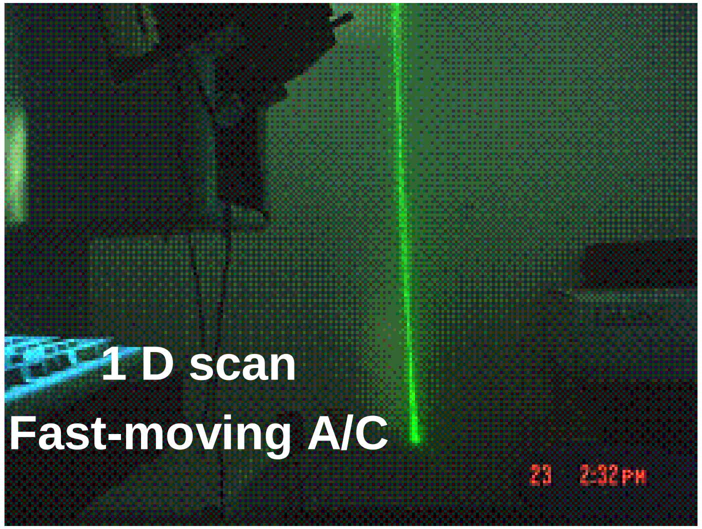
# Holographically Transformed Transmitter Beam Imaged onto Multi-anode or Array Detector

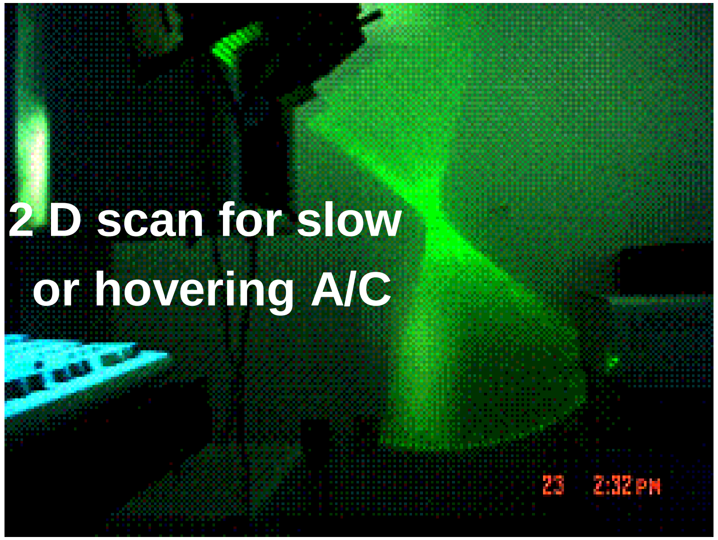



Beamlet Images Centered on Anode Elements

- Hologram converts Gaussian transmit beam into NxN quasi-uniform intensity spots in the far field with ~80% efficiency
- Transfers energy from Gaussian center peak to detector perimeter for better uniformity of detection ($\pm$ 12%)
- Reduces optical crosstalk between pixels
- Each pixel sees reduced beam spreading by target (~1/N)
- Individual pulses produce 10x10 3D images which are then mosaiced together by the scanner and platform motion

# Dual Wedge Optical Scanner Synched to 8 kHz Pulse Train





- Laser Fire Rate: 8 kHz
- Scan Rate: 20 Hz
- Laser Fires per Scan: 400
- 3D pixels per scan: 40,000 (with 10x10 holographic element)
- Angular Scan Repeatability between Cycles: 1 part in $10^5$ or $\pm$0.07 pixel (~1cm @ 1 km altitude)

# Mini-UAV-based 3D Imaging and Polarimetric Lidar: USAF Phase II SBIR

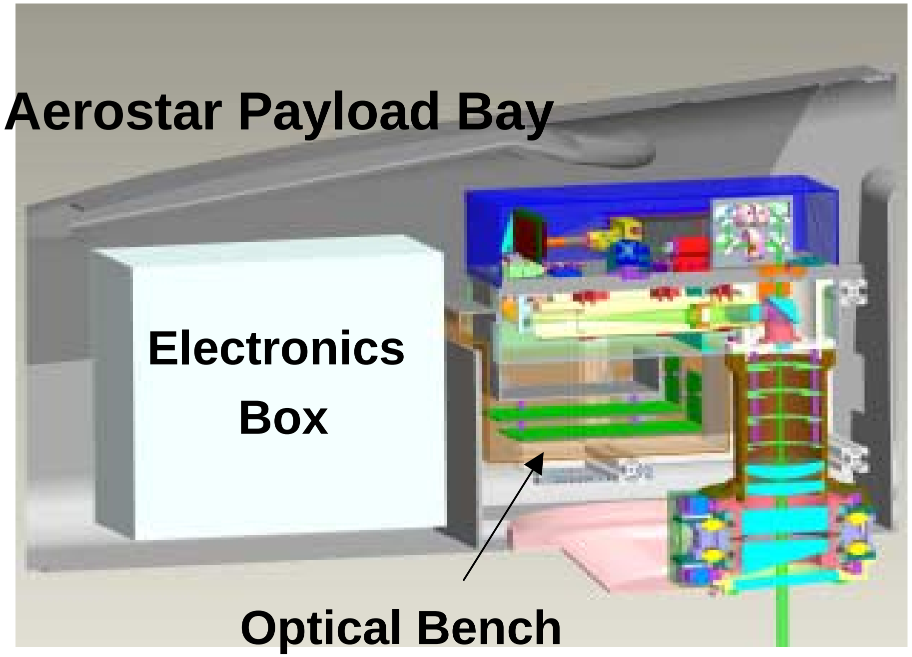
**Challenge:** Develop a high resolution lidar sensor for use in a mini-UAV

**Mission Parameters**

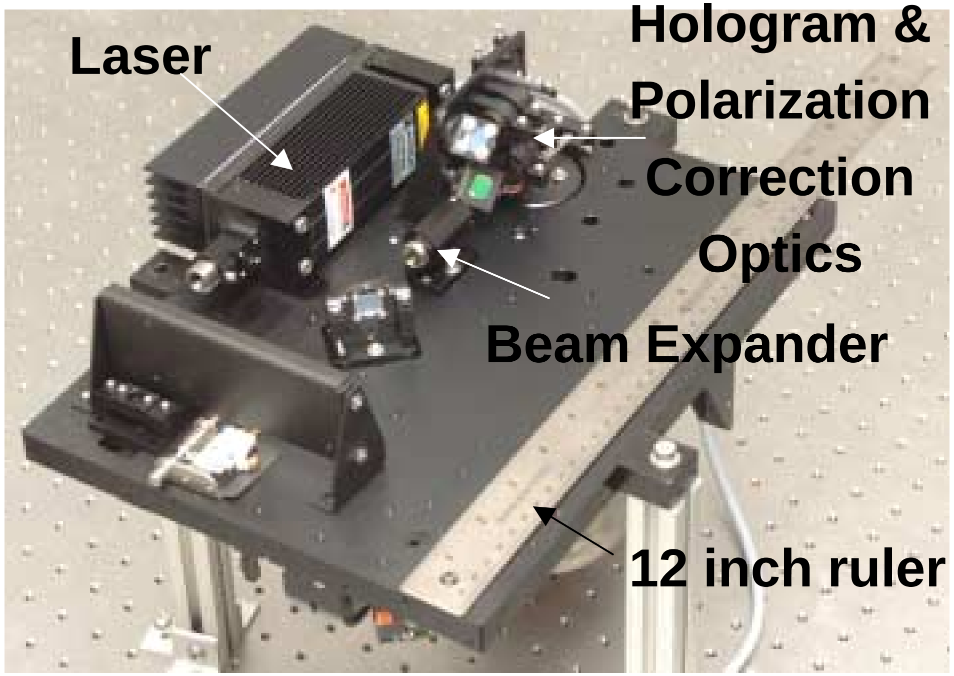
- Operating altitude: ~1 km
- Swath: 150 m
- Spatial Resolution:
  - Imager: Horiz: 15 cm; Vert:<5cm
  - Polarimeter: Horizontal: 1.5 m
- Mean Ground Velocity: 161 km/hr
- Areal Coverage: 24 sq. km/hr

**Payload Parameters**

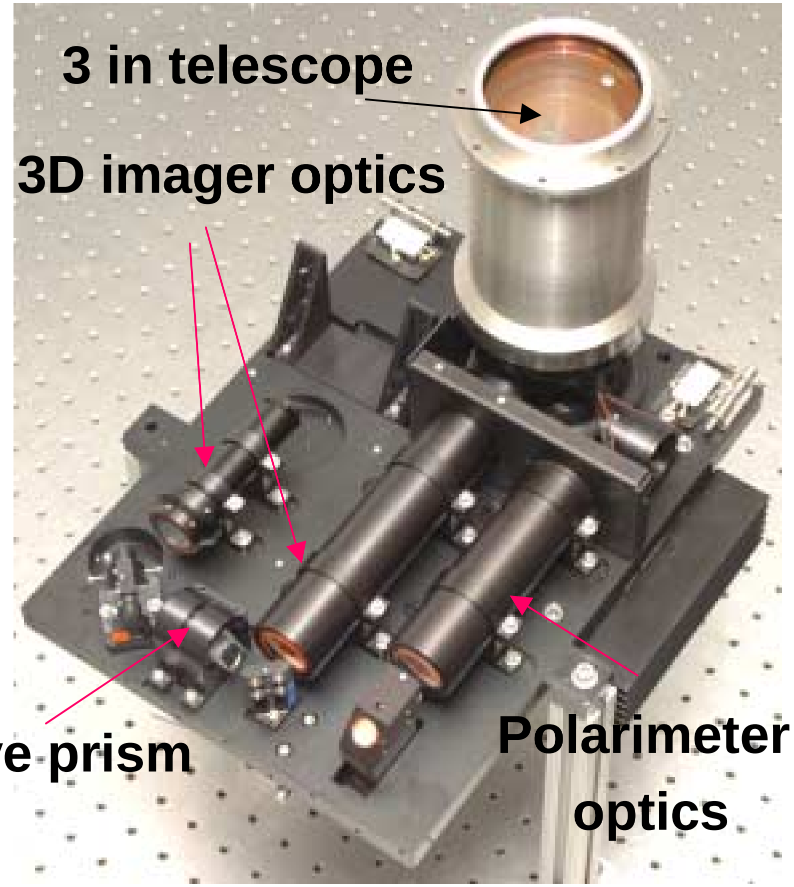
- Physical Size & Mass (incl. NAV):
  - Optical Bench: 13"Lx12"Wx17"H, 43 lb
  - NAV/Electronics Box: 12"Lx12"Wx12"H, 30 lb
- Prime Power: 271 W (est.)
- 2.2 million 3D pixels per sec (100 pixels @ 22 kHz)

# USAF OPTICAL BENCH
# (3D Imager & Polarimeter)




**Transmit side**

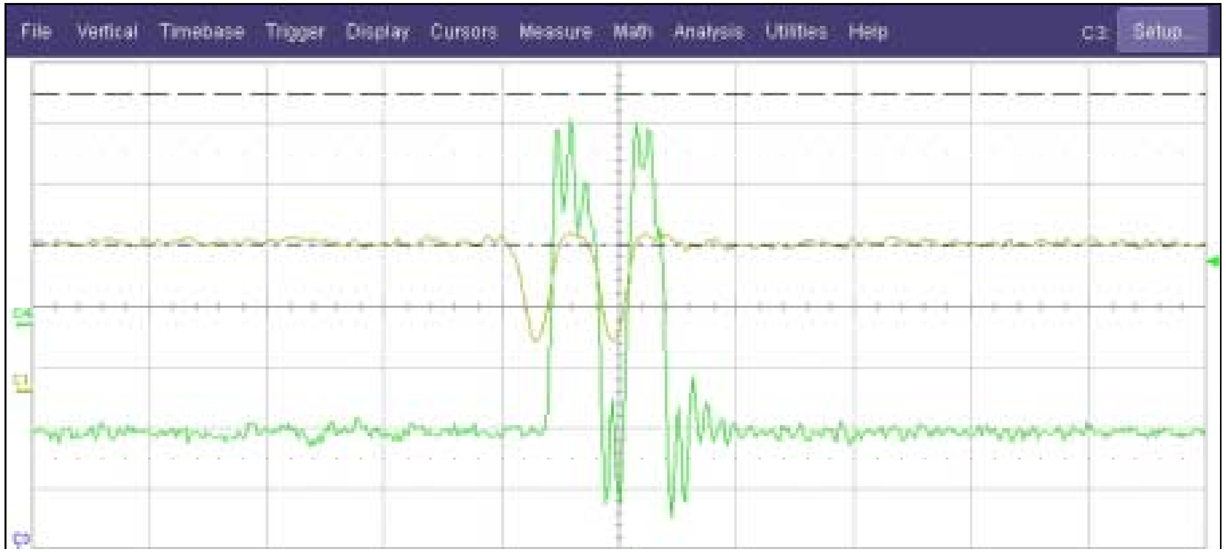



**Receive Side**

# Sigma 100 Channel Imaging Detector and Range Receiver

- Detector is Hamamatsu 10x10 Segmented Anode Photomultiplier (QE = 32%, risetime < 200 psec)
- Output signals from 100 detector anodes are amplified and input to two 50-channel Time-of-Flight Field Programmable Gate Arrays (TOF FPGA)
- Timing resolution of $\pm$92 psec is determined by average FPGA cell delay (corresponds to $\pm$ 1.5 cm range resolution)
- Number of stops allowed per channel is limited only by memory buffering constraints
- Recovery time per pixel is less than 2 nsec (~one foot minimum distance between detected objects)
- TOF FPGA continuously calculates calibration data such that temperature and voltage variation effects can be subtracted during data analysis and post-processing stages
- 120 GB of Ultra-DMA data storage is currently provided to support missions up to several hours.

# 2 nsec Receiver Recovery Time




**Yellow Trace = Amplifier Input (150mV), Green Trace = Comparator Output**

- Each anode (pixel) can see multiple objects separated by as little as one foot (30 cm) in a single pulse return
- Important for seeing objects
  - against a high solar background or
  - through semi-porous volumetric scatterers such as ground fog, tree canopies, turbid water, battlefield dust, camouflage, etc

# Summary

- **Basic photon-counting imaging lidar concept was demonstrated successfully under NASA Instrument Incubator Program (IIP) on the NASA P-3 Aircraft**
- **Second generation instruments provide contiguous, high resolution, wide swath 3D topographic and polarimetric maps on a single overflight using:**
  - **Low energy, subnanosecond pulse microchip lasers operating at rates up to 22 kHz (2.2 million pixels per second) and holographic beam shapers**
  - **High QE, segmented anode Microchannel Plate Photomultipliers**
  - **Multichannel, multistop range receivers with better than ± 92 psec timing (± 1.5 cm range) resolution and <2.3 nsec deadtime (<35 cm range recovery per pixel)**
  - **Laser-synchronized dual wedge optical scanners provide flexible scans for a variety of host platforms and eliminate the need to record wedge positions on every fire.**
- **Single photon ranging makes lidar very sensitive and highly efficient**
  - **One photon per range measurement implies maximum "bang" per photon**
  - **Sees single photon per pixel returns from distant targets day or night.**
  - **Post-Detection Poisson Filters easily extract the signal from the solar background during daylight operations.**
- **Single photon sensitivity combined with multistop detection and timing allows volumetric imaging on a single pulse through semi-porous obscurations such as extreme atmospheric haze, optically thin clouds, dust, vegetation, turbid water columns or camouflage**
- **High resolution imaging from space can be accomplished with modest telescopes (<1 m) and output powers (few watts).**