

Single Photon Sensitive Lidar Systems: Current State-of-the-art And Challenges

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OUTLINE

- **Brief Introduction to NCALM**
- **Introduction to Single Photon Systems**
 - 1. Geiger Mode Systems**
 - 2. IceSat-2**
 - 3. SPL100**
- **SPL100 Analysis**
- **Challenges**
- **Conclusions**

National Center for Airborne Laser Mapping

MISSION

“On-Demand” Data Acquisition

Funded by National Science Foundation IF/EAR Since 2003 (current to 2023)

Based at UH and Operated in partnership with UC Berkeley

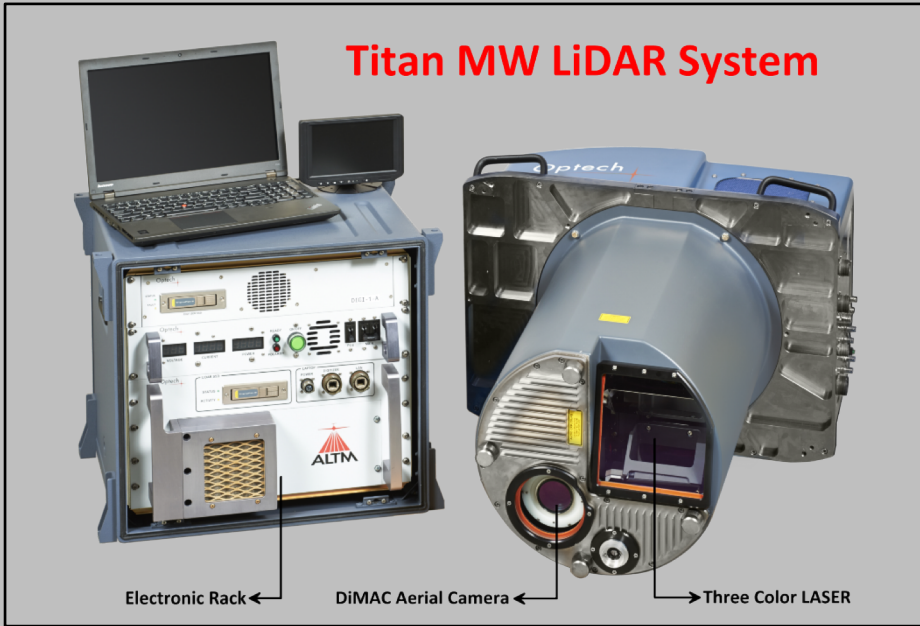
Primary Center Objectives:

1. Provide research quality remote sensing (geodetic imaging) data to the scientific community
2. Develops and implements emerging and new technologies, and
3. Educate and train students

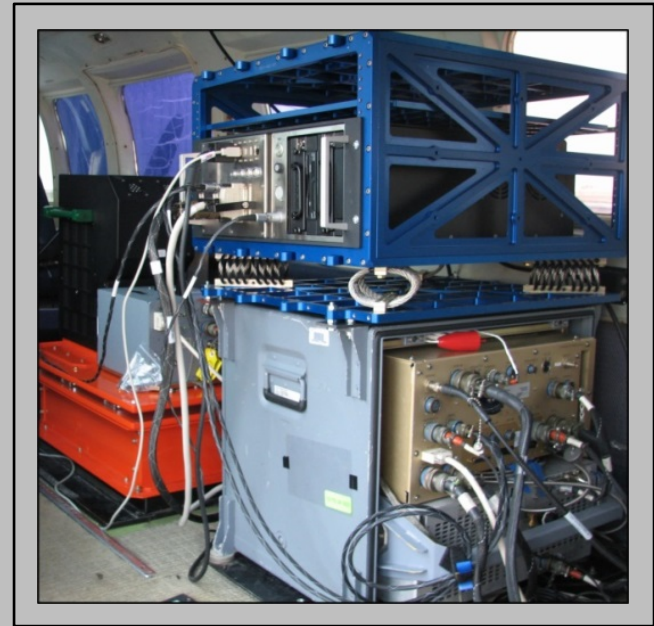
NCALM Acquisition Systems

LiDAR

Titan MW LiDAR System

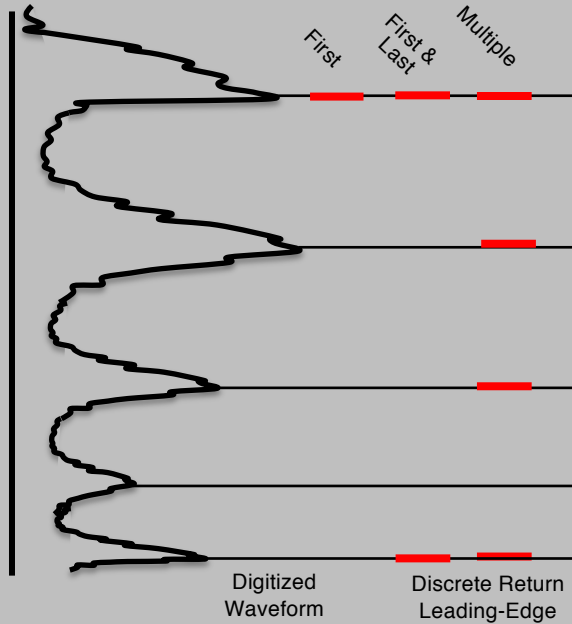
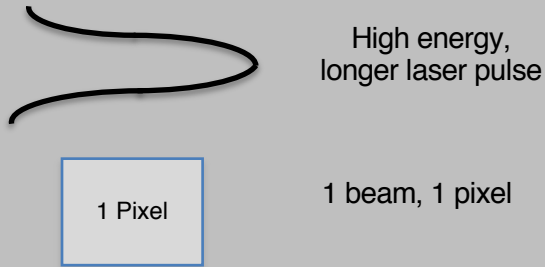


Hyperspectral Sensor



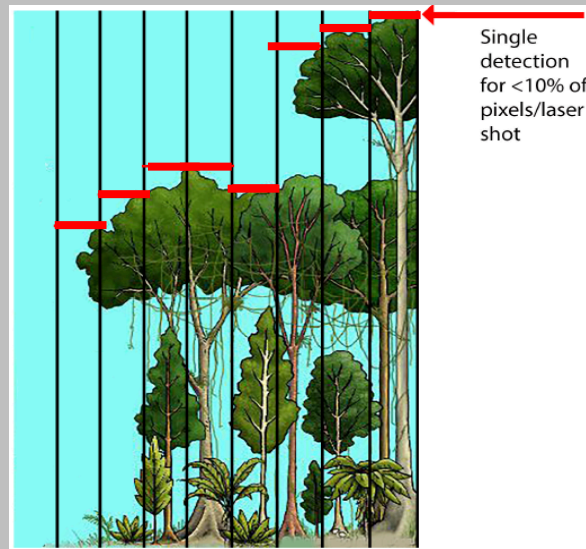
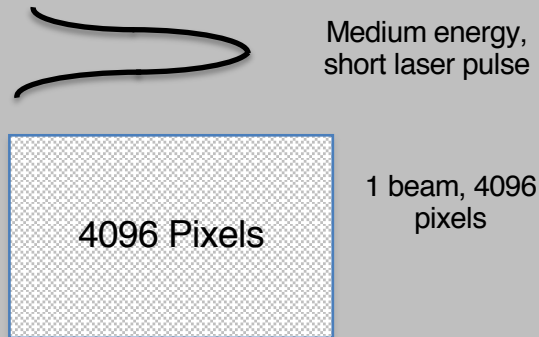
What is Single Photon Lidar?

Linear Mode LiDAR



Geiger Mode LiDAR (binary)

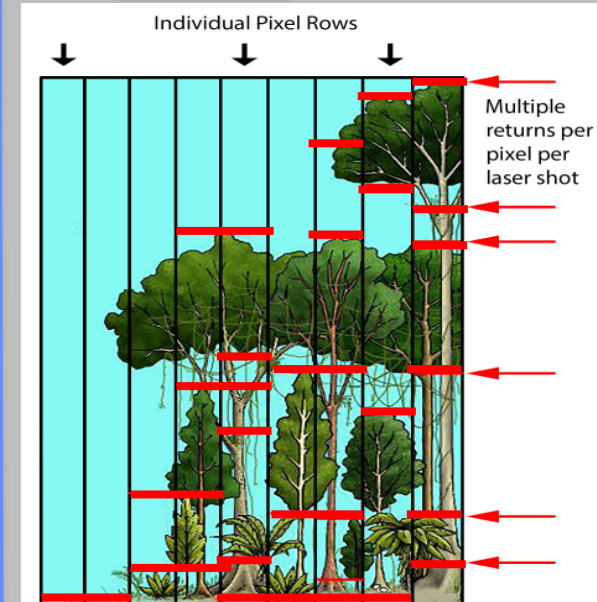
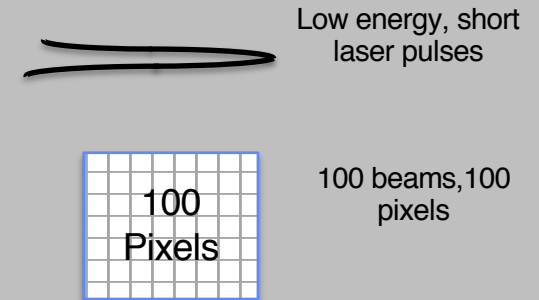
(Harris, ALIRT, MACHETE)



Geiger Mode LiDAR
Row of Detector Array

Single Photon Sensitive LiDAR

(IceSat-2, SPL100)



Single Photon LiDAR
Row of Detector Array

3D Imaging with Array-Based Laser Radar (Geiger)

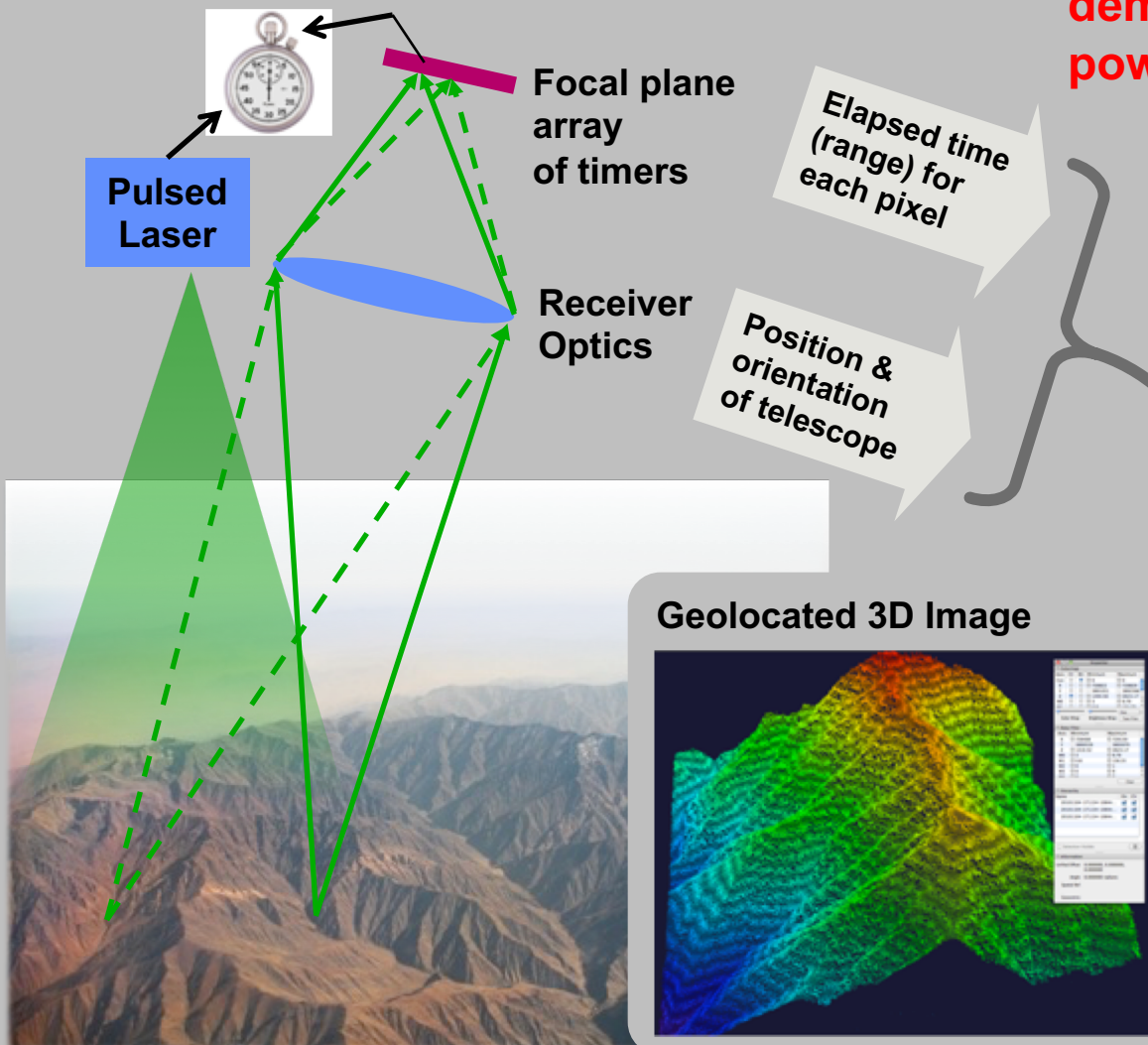


Slide Courtesy of:
Dale.Fried@3DEO.biz

Photon-counting
demands 100x less
power

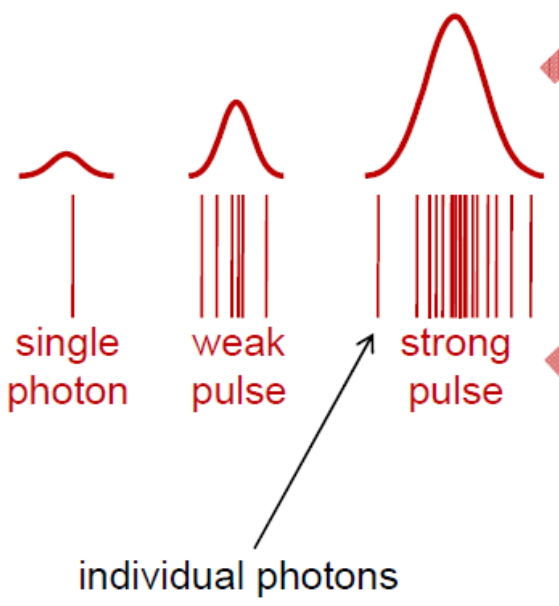
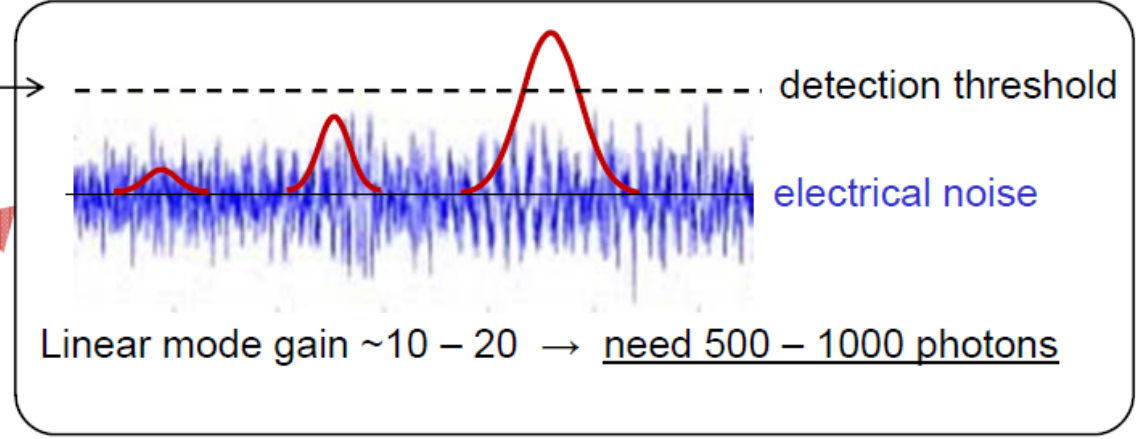
Key Differences from Flying Spot Systems:

- Massive parallelization of measurements
- Flood-illumination
- Lower scan frequencies
- Need enough laser power to illuminate all pixels

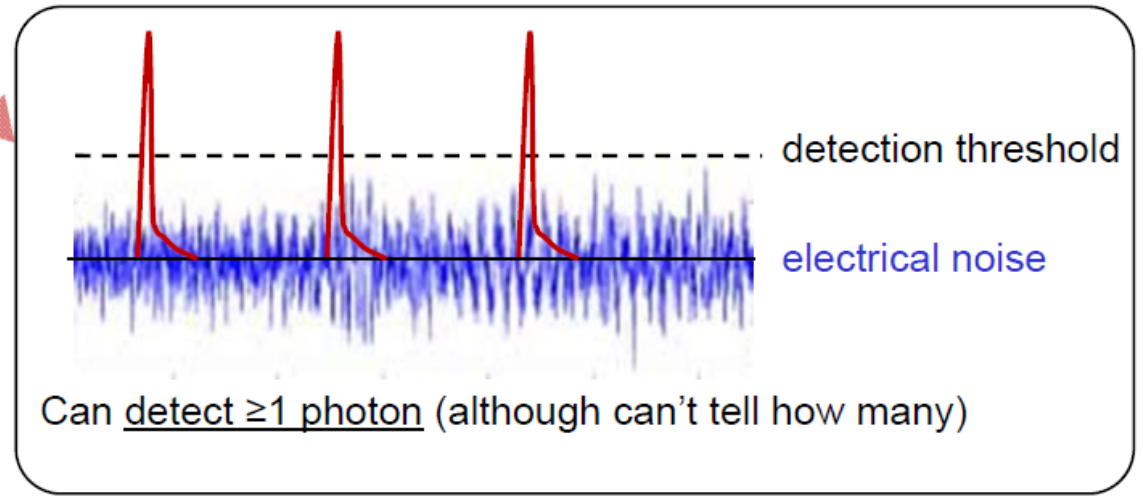


APD operating modes: Linear and Geiger

Linear-mode APD → analog response



Geiger-mode APD → digital response



Basics of single-photon detectors (SPDs)

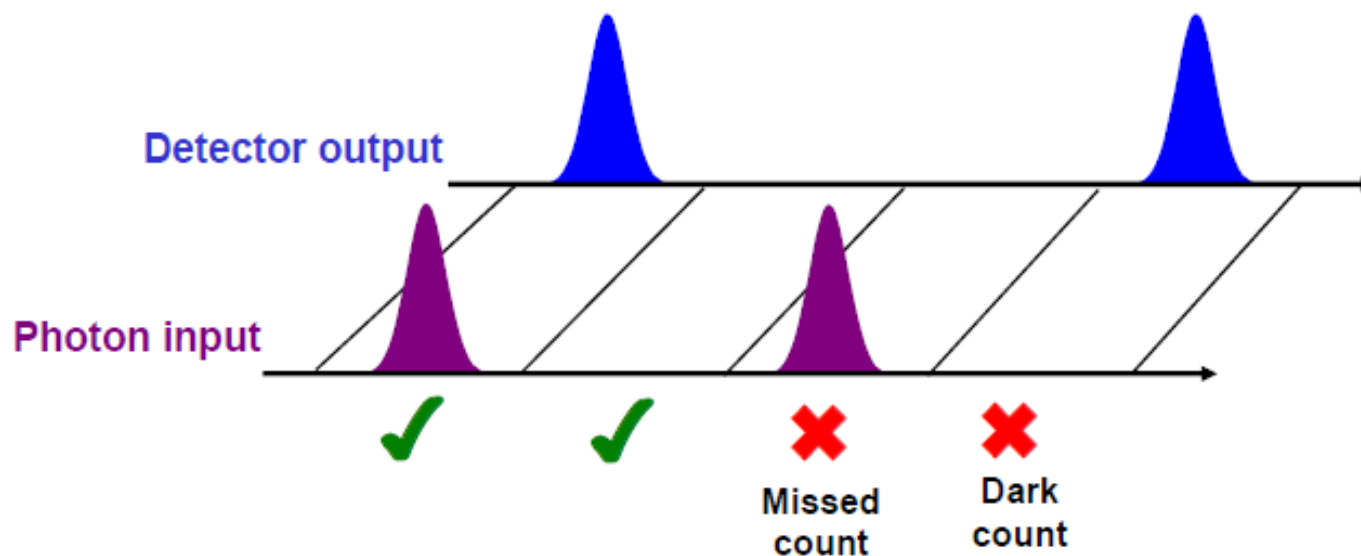
Ideal SPD:

- ✓ Always fires when photon arrives
- ✓ Never fires when photon does not arrive

Photon Detection Efficiency (PDE): **~30%**
probability that photon arrival causes detector to fire

Dark Count Rate (DCR): **~2 kHz**
probability that detector fires in absence of photon arrival

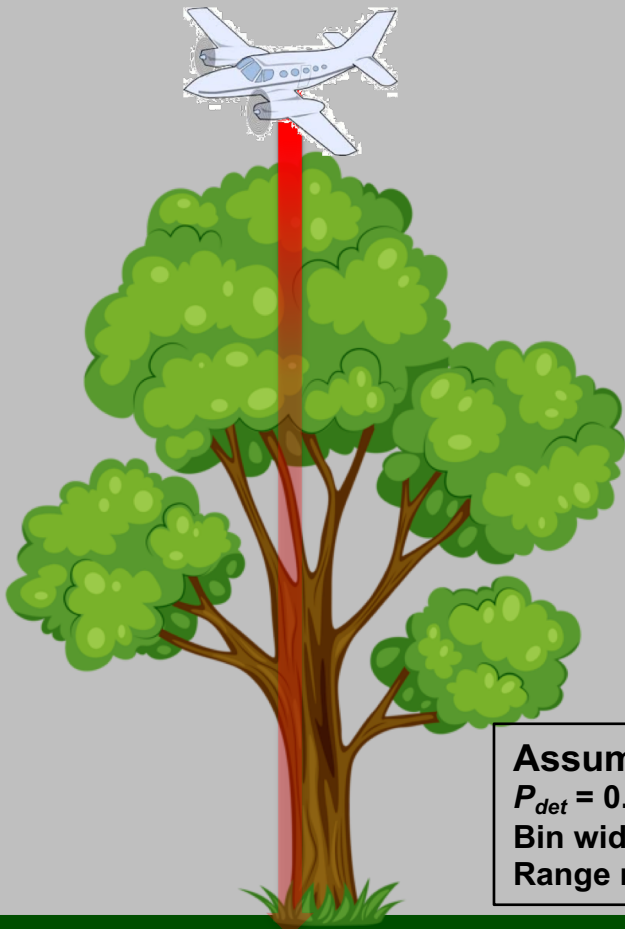
Detector fires	Yes	✓	✗ Dark count
	No	✗ Missed count	✓
		Yes	No
		Photon arrives	



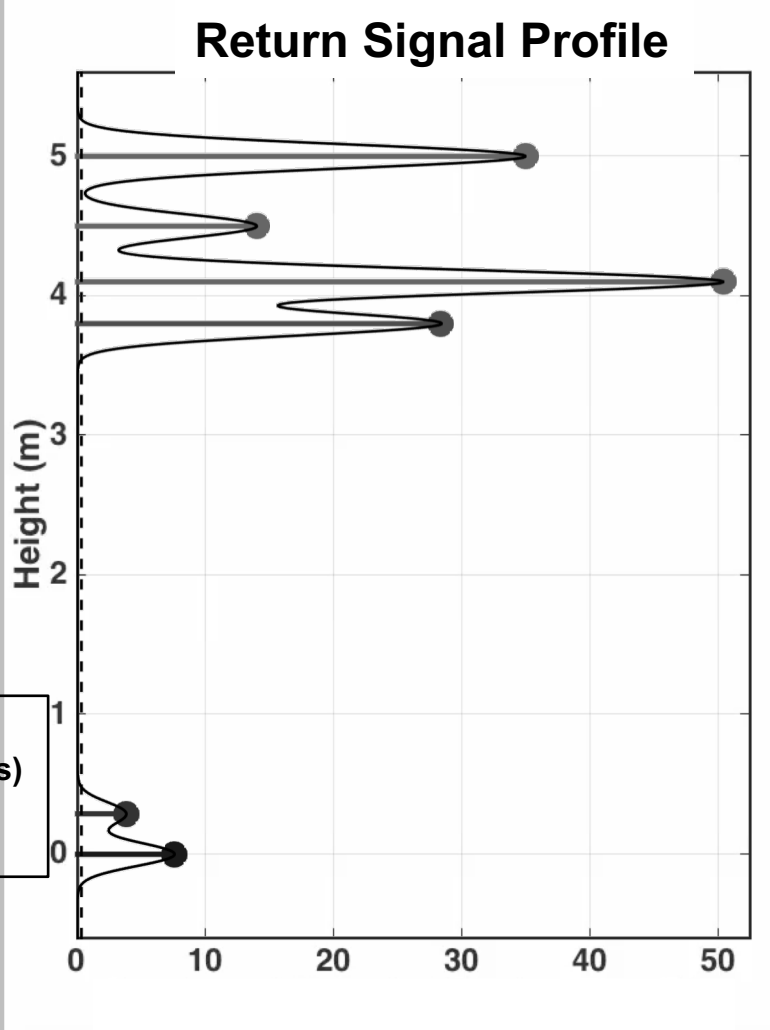
Detecting Photons One by One



Slide Courtesy of:
Dale.Fried@3DEO.biz



Assumptions:
 $P_{det} = 0.2$ (pixel fires on 20% of pulses)
Bin width = 0.5 ns
Range resolution = 20 cm FWHM

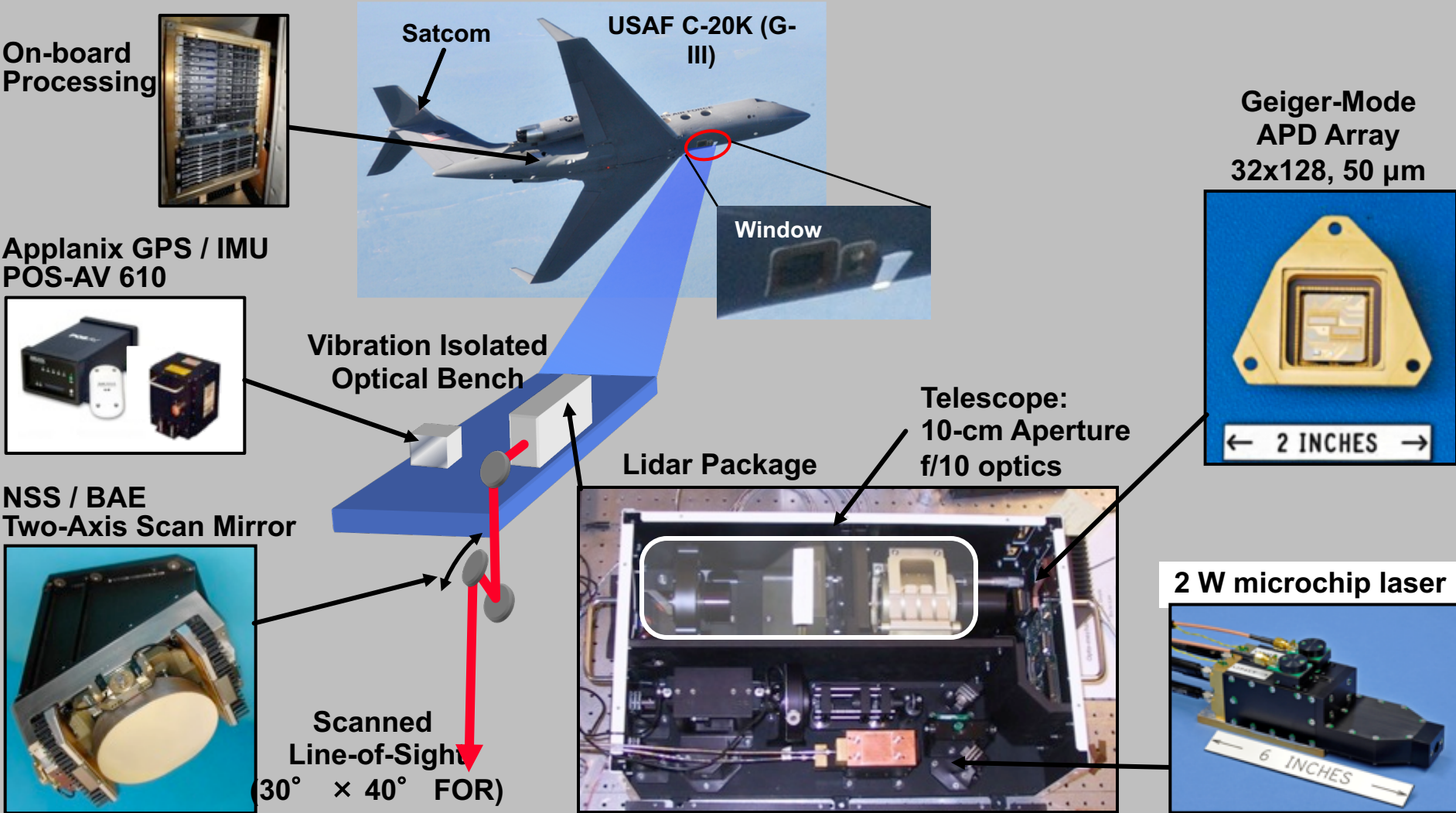


ALIRT 3D Imaging System

(Airborne Lidar Imaging Research Testbed; Operational Oct 2010 – Sept 2014)

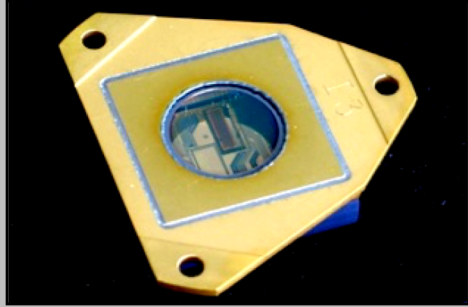


Slide Courtesy of:
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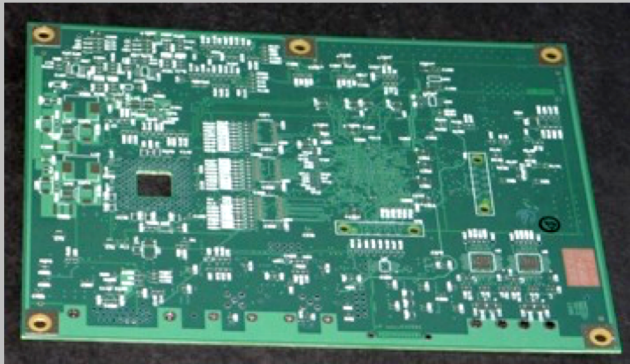


Geiger-Mode APD Array and Electronics (Camera)

 **LINCOLN LABORATORY**
MASSACHUSETTS INSTITUTE OF TECHNOLOGY



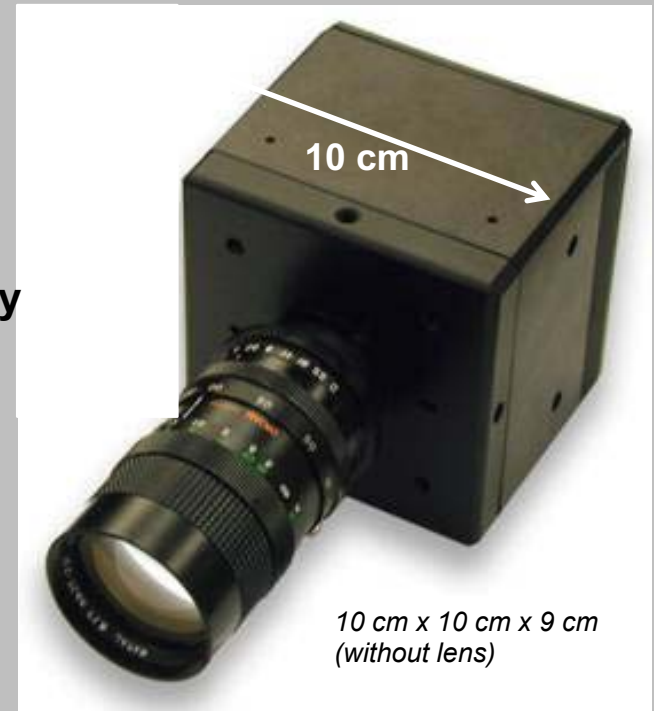
32 x 128 APD Detector Array



Headboard Controls Array
Function and Reads Out Data

Tech
Transfer
from MIT/LL

Now
Commercially
Available



Specifications of Harris IntelliEarth System

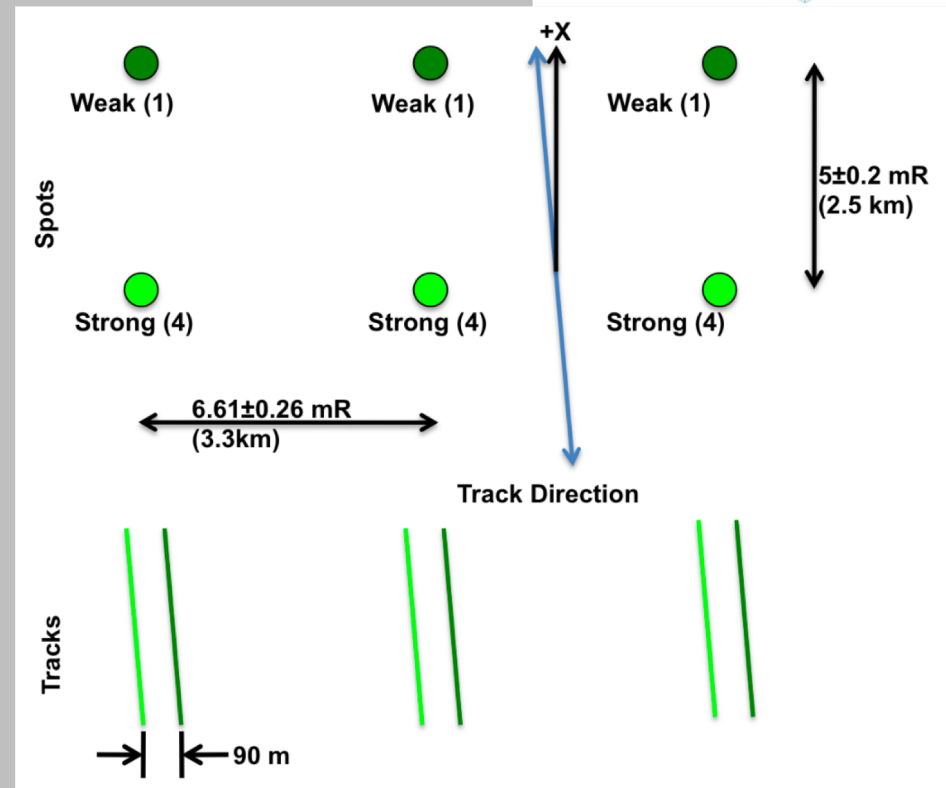
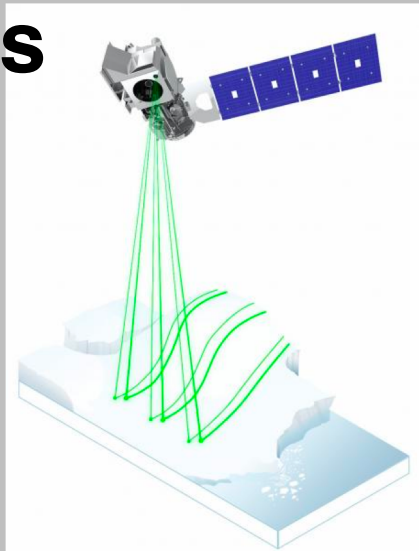
Harris Geiger –mode Specifications	
Mission	
Altitude range (AGL)	7,000 - >30,00 ft
Flight Speed	200 - 450knots
Swath Width	>20,000 ft
Palmer Scanner	
Scan Half Angle	15°
Aperture Diameter	27 cm
Transmit Laser	
Wavelength	1064 nm (Class IV)
Average Power	20 W
Pulse Width	550 ps
Pulse Repetition Frequency	50 kHz
NOHD/ENOHD	300m/2.2 km
GmAPD Receiver	
Array Size	32 x 128
IFOV	35 urads
PDE	30%
Timing Resolution	250-500ps
Coverage Rate (w 50% overlap)	
4 points per m²	1200 km²/hr
8 points per m²	1000 km²/hr
20 points per m²	700 km²/hr

Chart from Harris.com

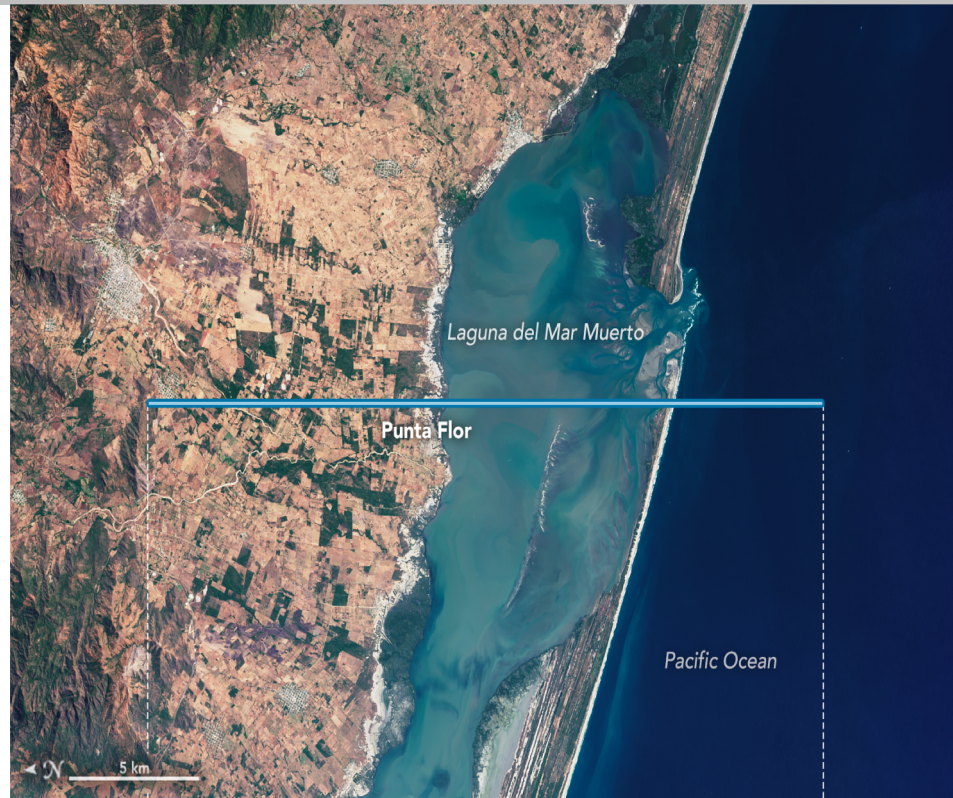
- **50 kHz * 4096 = 205 MHz !**
- **BUT:**
 - **Probability of Detection (PDET) – function of PDE, laser power, and LIDAR cross section of your target**
 - **PDET is normally around 15%**
 - **So, Only 600 detections (of 4096)**
- **AND:**
 - **Noise (Dark Count and Solar) plus crosstalk**
 - **Approximately 25% noise.**
 - **So, at best 450 detections**
- **ALSO:**
 - **Need to play statistical game, and averaging to separate true signals from noise**
 - **Not published, but rule of thumb for system is 30-50 positive detections per outgoing pulse**
- **Real Measurement Rate ~ 2 MHz**

Icesat-2 – Technical Specifications

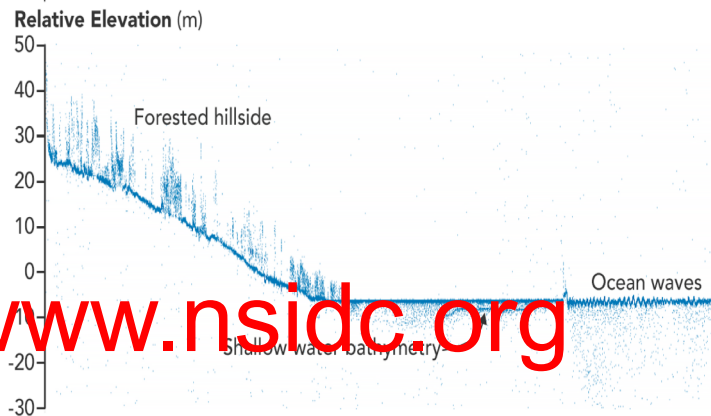
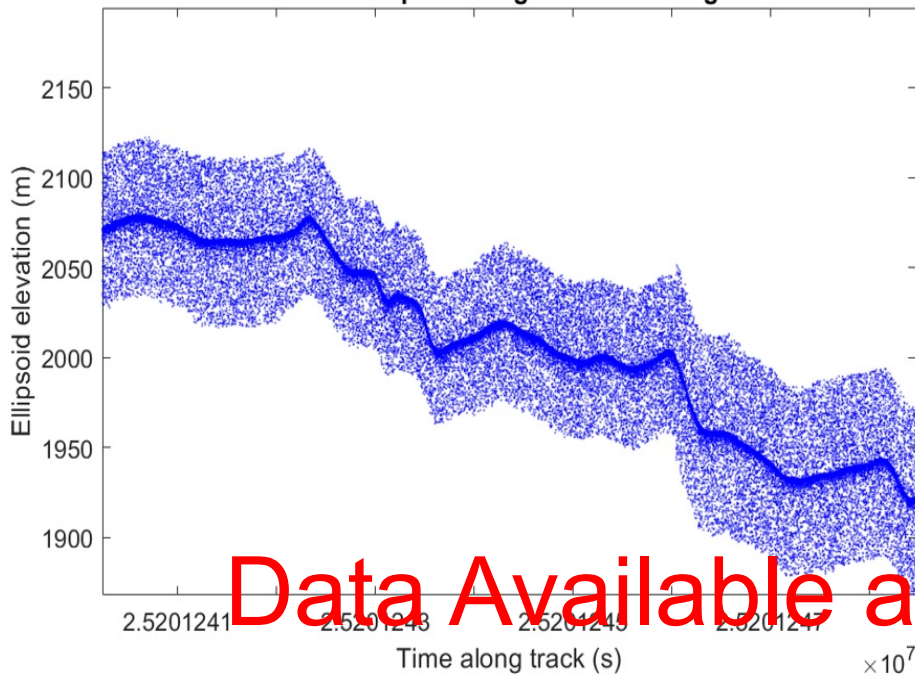
- Launched on 09/15/2018
- Data available as of 06/10/2019
- 17 m footprint
- 10 kHz (0.7 m)
- 6.5 m pointing accuracy
- 532 nm
- 1.5 ns pulse width
- 800 ps photon timing accuracy
- Photomultiplier tube
- ~3.2 ns dead time



Icesat-2 Data Samples



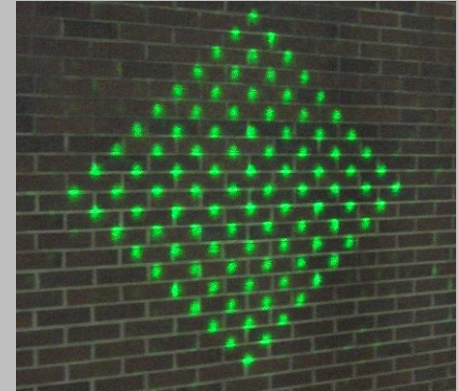
Photon ellipsoid height vs. time for gt3l



Data Available at: www.nsidc.org

SPL100 - Single Photon Lidar Technology

- 100 laser beamlets. Single photon returns from individual beamlets are imaged into a 10 x 10 detector, with low jitter and very fast recovery time
- Each pixel output is input to an independent channel of a high resolution (< 100 psec), multi-stop timer (1.6 nsec dead time).
- A high speed optical wedge scanner produces a conical scan and a large circular pattern on the ground.
- System records multiple events per pixel channel per shot. Currently working at 6.0 million points per second, with multiple stops.
- Operates at 532 nm, so it produces bathymetry if required.

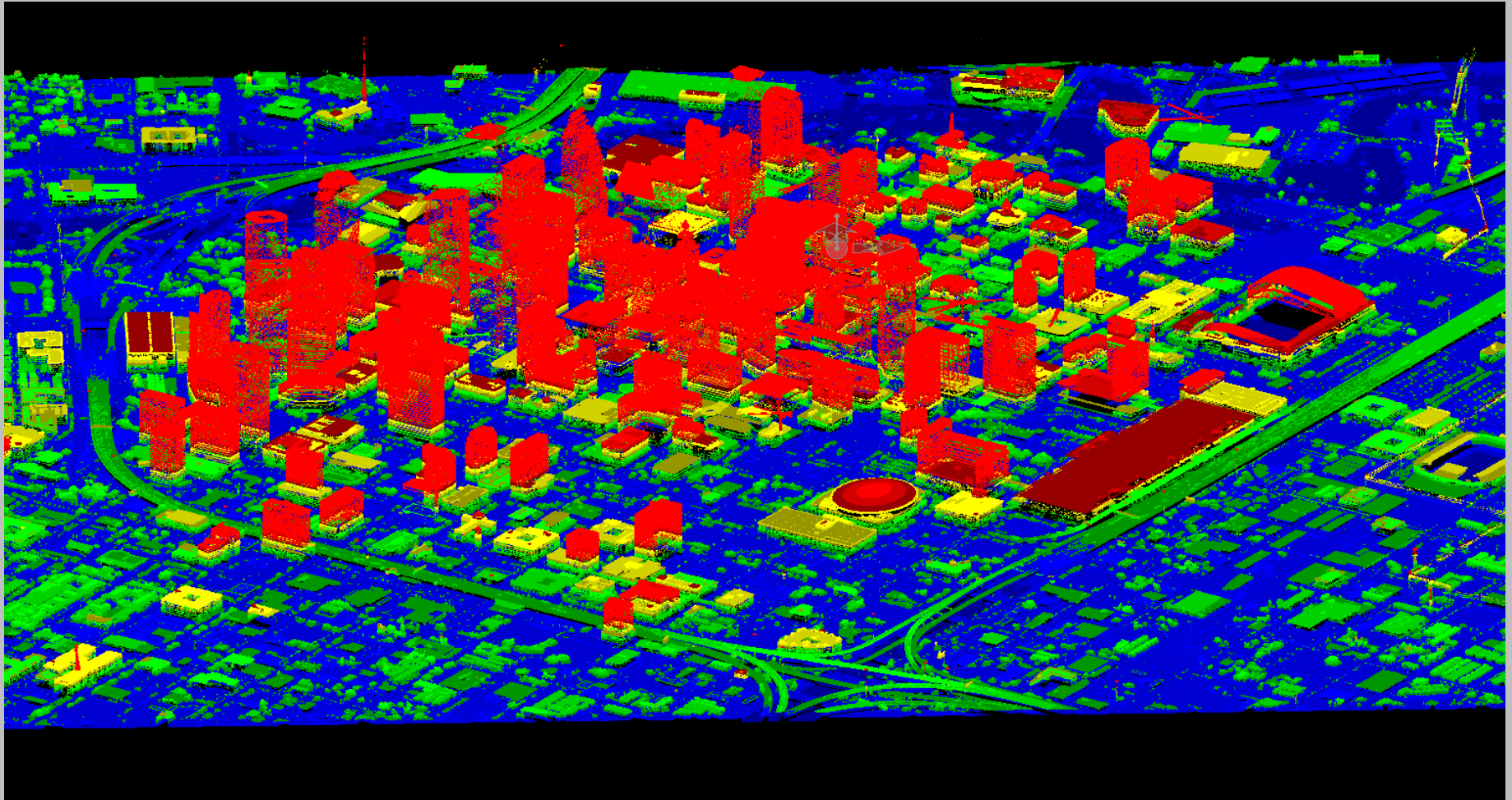


Silicon Photomultiplier (SiPM) Detectors

- Each detector is made up of dense arrays of Geiger Mode APDs (called microcells) - densities of 100-1000 per mm^2 – typically 1, 3, 6 mm size detectors
- Photons cause Geiger avalanche in individual microcells – other cells still armed and ready to detect photons
- Output voltage proportional to number of activated microcells
 - Detection probability of $\sim 25\%$ at 532 nm
 - Dark count rates of $\sim 30 \text{ kHz/mm}^2$

Houston Flight Campaign

- Collected near downtown Houston on February 25, 2017 with a flight altitude of 3500 m
- GPS and coincident Linear Mode LiDAR Collected by NCALM



Issues with SPL Data

- ~~Foliage Penetration/Multi Return Detection~~
- Intensity Characterization
- ~~Horizontal and Vertical Accuracy~~

A Comparison of Single Photon and Full Waveform LiDAR –
Mandlbürger, Lehner, Pfeifer

SPL Intensity vs. LML Intensity

Estimates of signal intensity from SPL are indirectly estimated by:

1. **Pulse width**, pulse width increases as the expected number of photons increases (used in SPL100);
2. **Normalized point density**, bright objects have a higher expected number of detected photons (Geiger).

Linear Mode Intensity
(at 532 nm)



Original SPL Intensity
(based on Pulse Width)



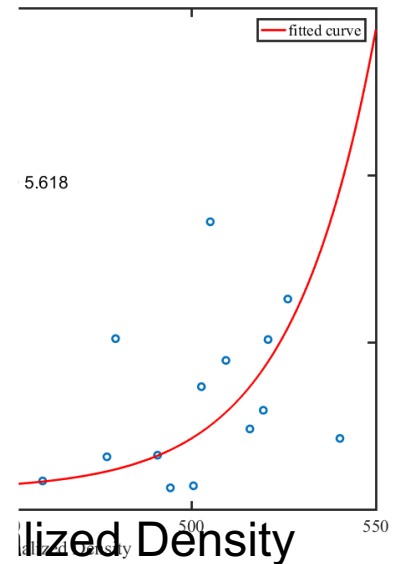
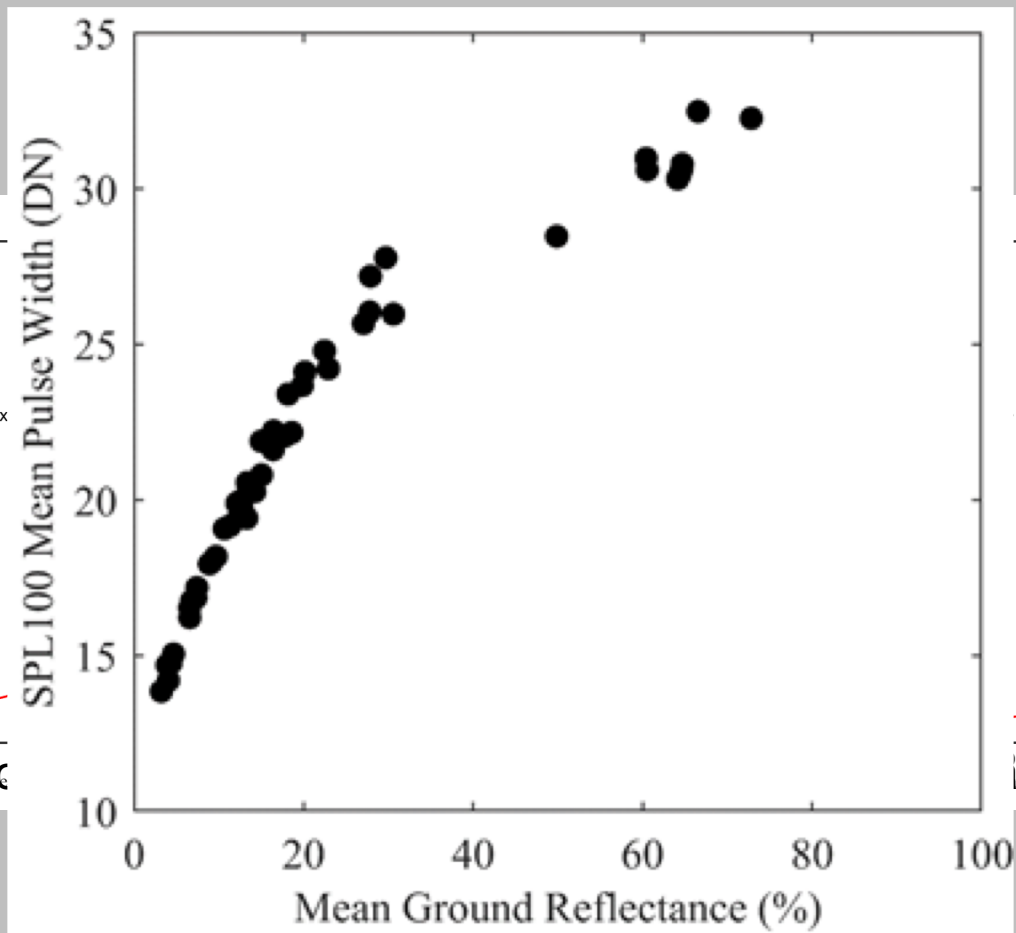
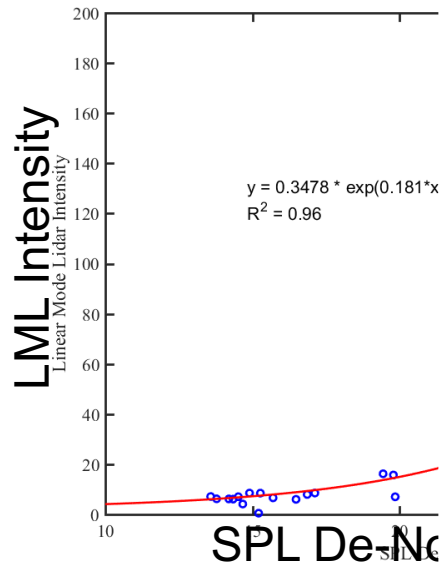
De-noised SPL Intensity
(Gaussian Filter)



SPL Normalized Density



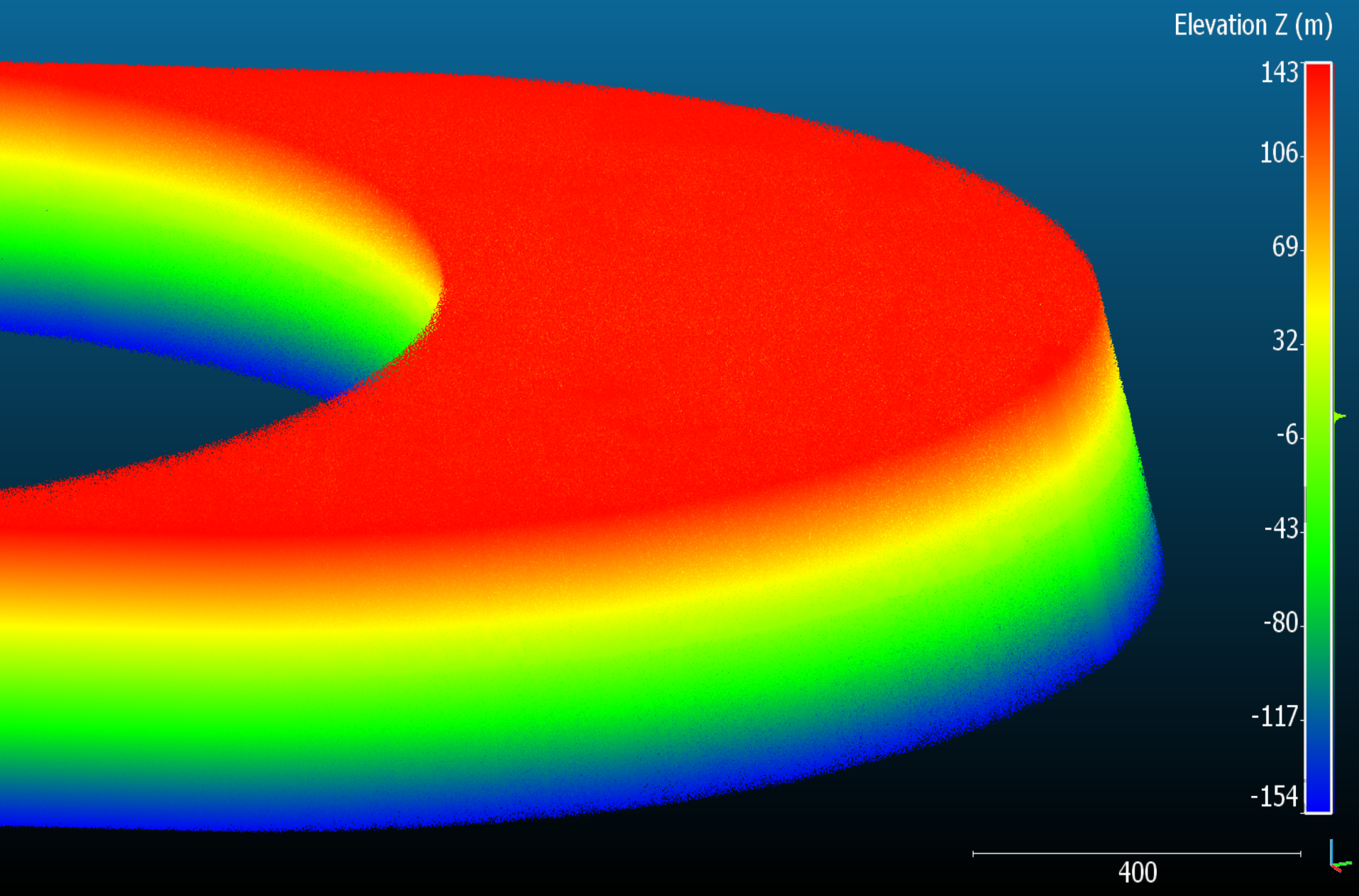
SPL Intensity Fitted Models



- Pulse Width Provides a Better Estimate of Intensity than Normalized Point Density, when # of photons returned is large.

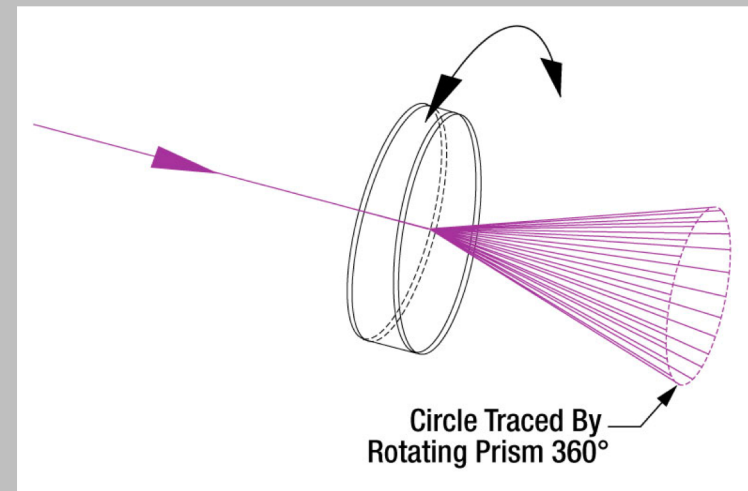
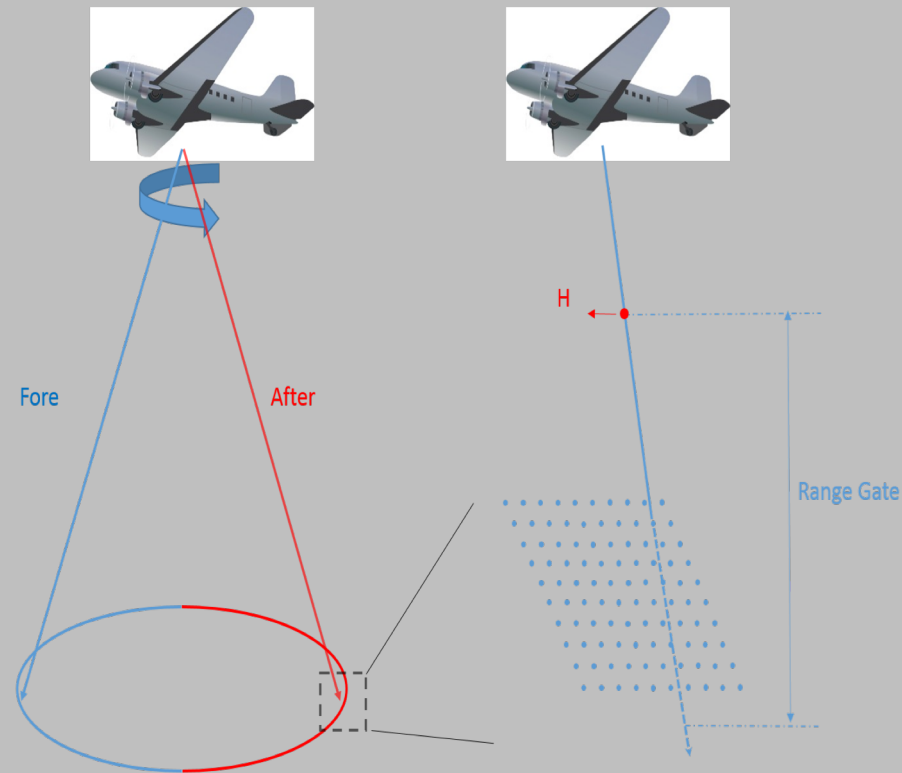
Open Challenges with SPL

Getting to that Final Point Cloud

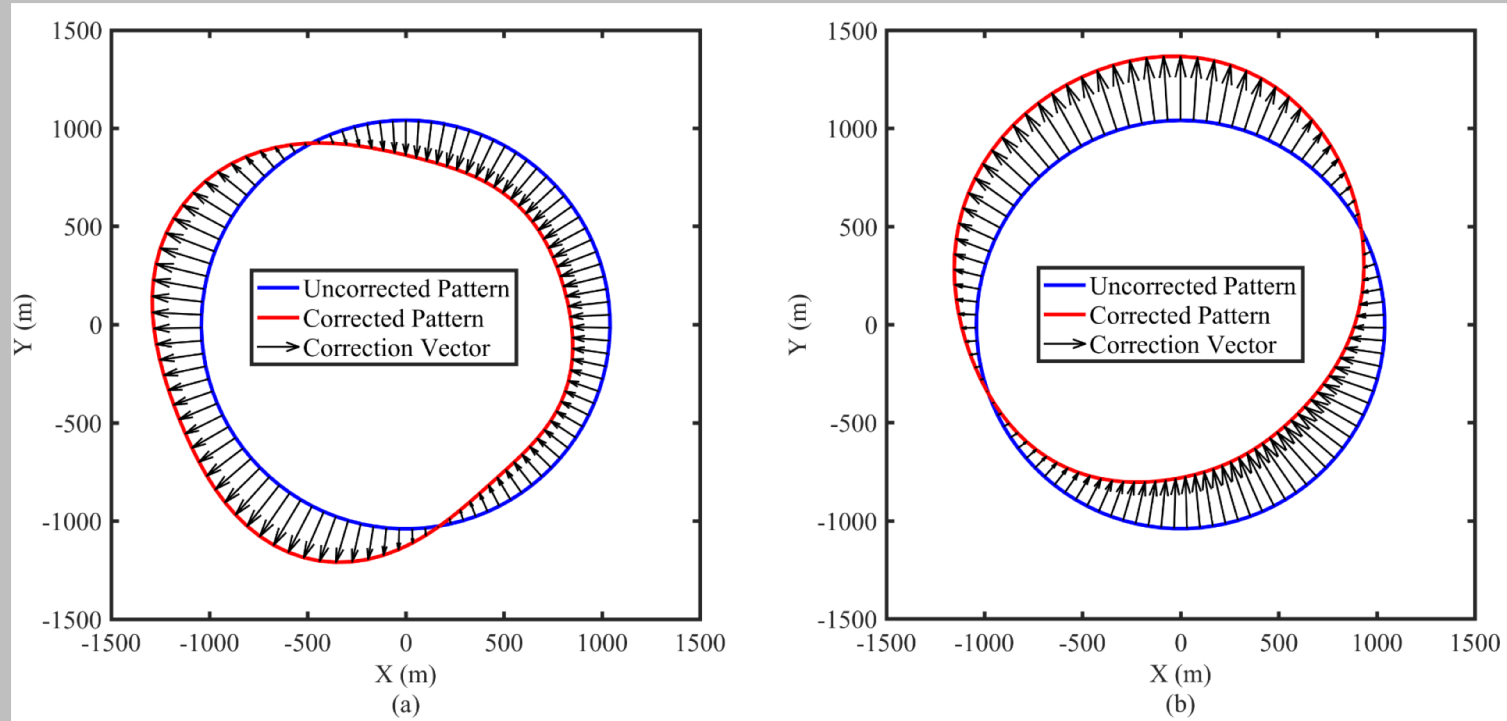


Calibration Model

- Pixel Stretch (laboratory)
- Range Bias (laboratory)
- Boresight (data driven)
- Scanner Wedge Misalignment (data driven) – Fourier Series
- Bundle Adjustment for Strip Matching (aka Coincidence processing).
- Filtering Required BEFORE Calibration
- Receiver centric versus laser centric models



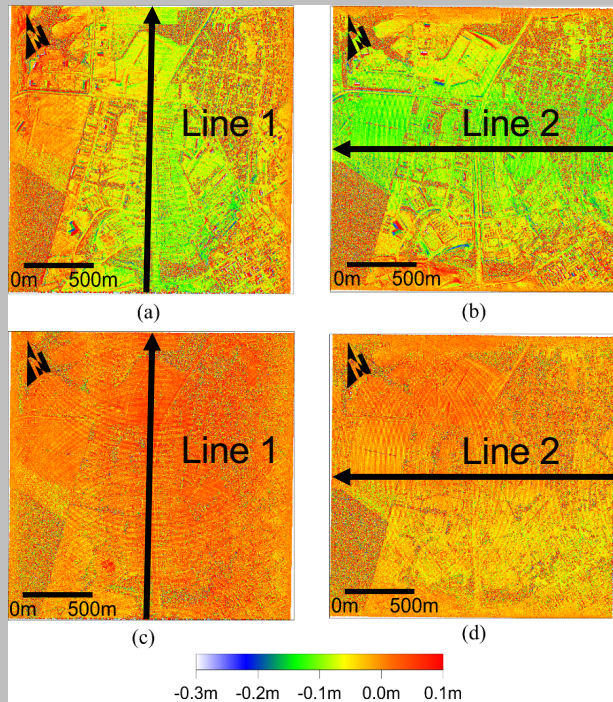
Scanner Wedge Calibration



(a), SPL100 SN1 sensor models and (b) SPL100 SN2 sensor models. The corrected pattern is estimated from the actual datasets and the Fourier Series Model coefficients.

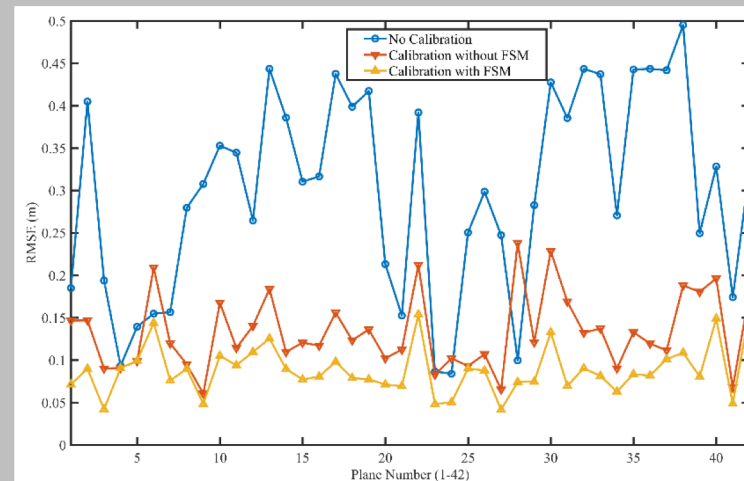
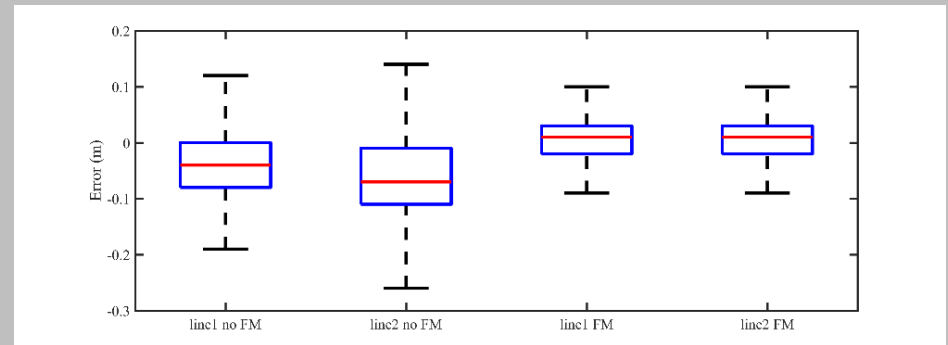
- Each system has a unique wedge calibration. Correlation to boresight parameters makes it important to periodically reassess.
- Pan, Z., Hartzell, P., and Glennie, C. (2017). "Calibration of an Airborne Single-Photon Lidar System With a Wedge Scanner." *IEEE Geoscience and Remote Sensing Letters*, 14(8), 1418-1422.

Wobble Correction with FSM



Conventional boresight calibration for (a) line 1, (b) line 2; calibration with Fourier Series Model (FSM) compensating wobbling for (a) line 1, (b) line 2.

Overall boxplot of all lines



Planar RMSE

Future Work

- Increase PDE and Decrease DCR
- Reliable Measure of Signal Strength (Intensity)
- Coincidence Processing to Overcome Pointing Accuracy Limitations
- New Models for Calibration
- Automated Filtering and Denoising algorithms without smoothing

Thank You!

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<http://ncalm.cive.uh.edu/>

Photo Credit: Darren Hauser, NCALM