Surface Topography and Vegetation

Lidar Breakout Workshop

September 8, 2020

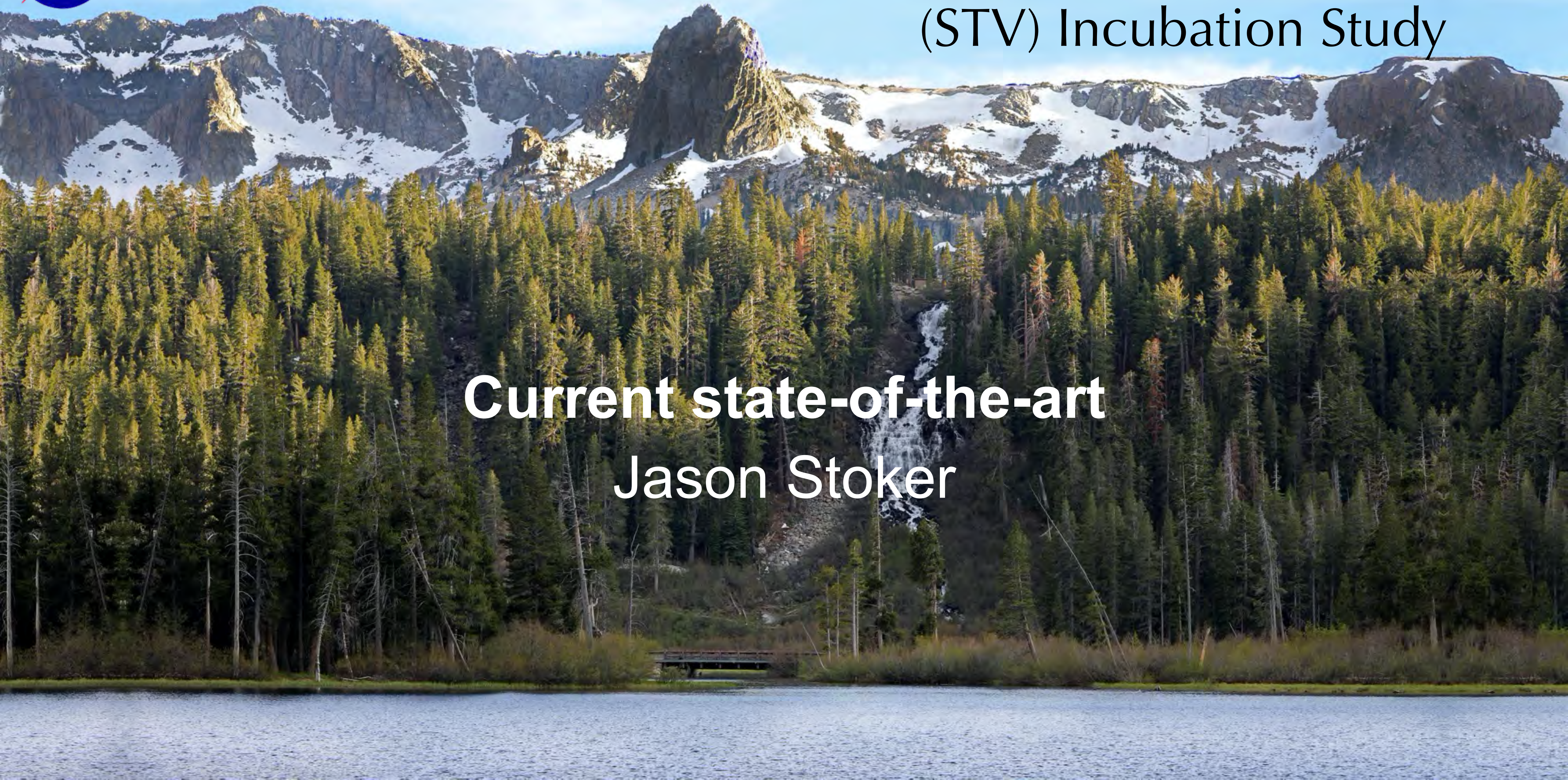
Meeting will begin at 8:15 am PT/11:15 am ET

Q&A/Polls: https://arc.cnf.io/sessions/qkrg/#!/dashboard

Agenda (Times are ET/PT)

Lidar STV Technology Breakout			
8:15 am (PT) / 11:15 am (ET)	Welcome	Jason Stoker, USGS	5 minutes
11:20-11:40 (ET)	Introduction of overall study objectives	Andrea Donnellan, NASA JPL	20 minutes
11:40-12:00 (ET)	Introduction on technology scope being considered	David Harding, NASA GSFC	20 minutes
12:00-12:30 (ET)	Review of the state of the art	Jason Stoker, USGS	30 minutes
12:30-12:45 (ET)	Poll discussion #1		15 minutes
12:45-1:00 (ET)	Break		15 minutes
Invited Speed Talks on Emerging Lidar Technology			
1:00-1:10 (ET)	CASALS SmallSat for lidar and spectral imaging	Guan Yang, NASA GSFC	10 min
1:10-1:20 (ET)	3D Imaging Using Photon Counting Lidar	Luke Skelly, MIT- Lincoln Labs	10 min
1:20-1:30 (ET)	Asynchronous lidar and MSL	Craig Glennie, U of Houston, USACE	10 min
1:30-1:40(ET)	Multi-spectral lidar	Chris Hopkinson, University of Lethbridge	10 min
1:40-1:50 (ET)	Geiger-mode lidar for STV	Steve Blask, L3Harris	10 min
1:50-2:00 (ET)	Some new ideas for lidars for Earth Science	Carl Weimer, Ball Aerospace	10 min
2:00-2:15 (ET)	Poll discussion #2		15 minutes
2:15-3:00 (ET)	Discussion/wrap up	Jason Stoker, USGS	45 minutes

Surface Topography and Vegetation
(STV) Incubation Study



Current state-of-the-art

Jason Stoker

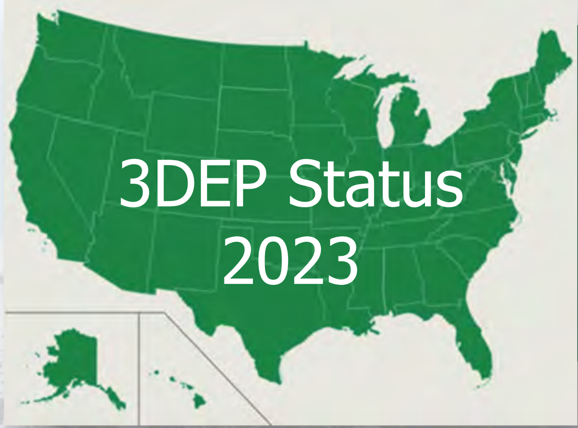
Lidar: the tool of choice for 3DEP in CONUS

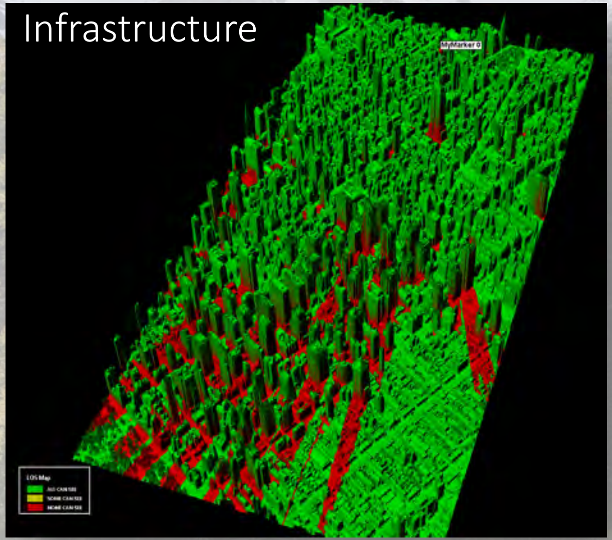
Why lidar?

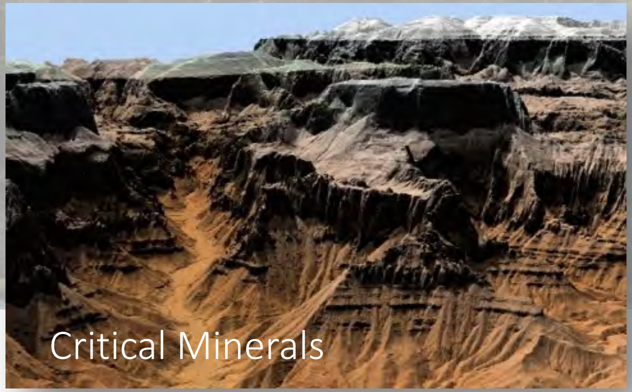
- High resolution
- High accuracy
- High precision
- Foliage penetration (FOPEN)
- Bathymetry ability
- Complete vertical canopy structure

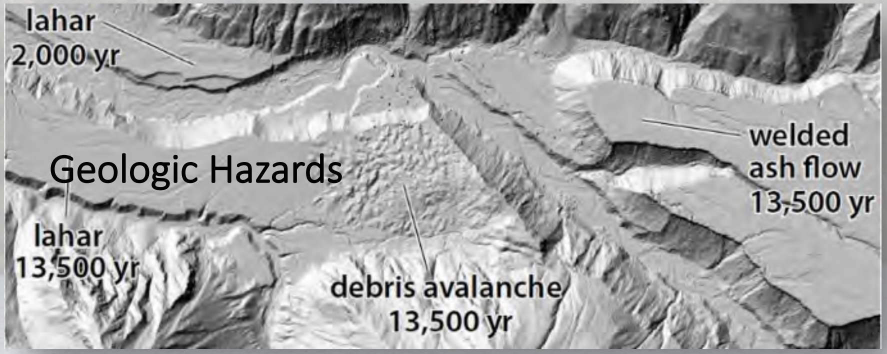
3D Elevation Program (3DEP) Goal

Complete acquisition of nationwide lidar (IfSAR in AK) in 8 years to provide the first-ever national baseline of consistent high-resolution elevation data collected in a timeframe of less than a decade





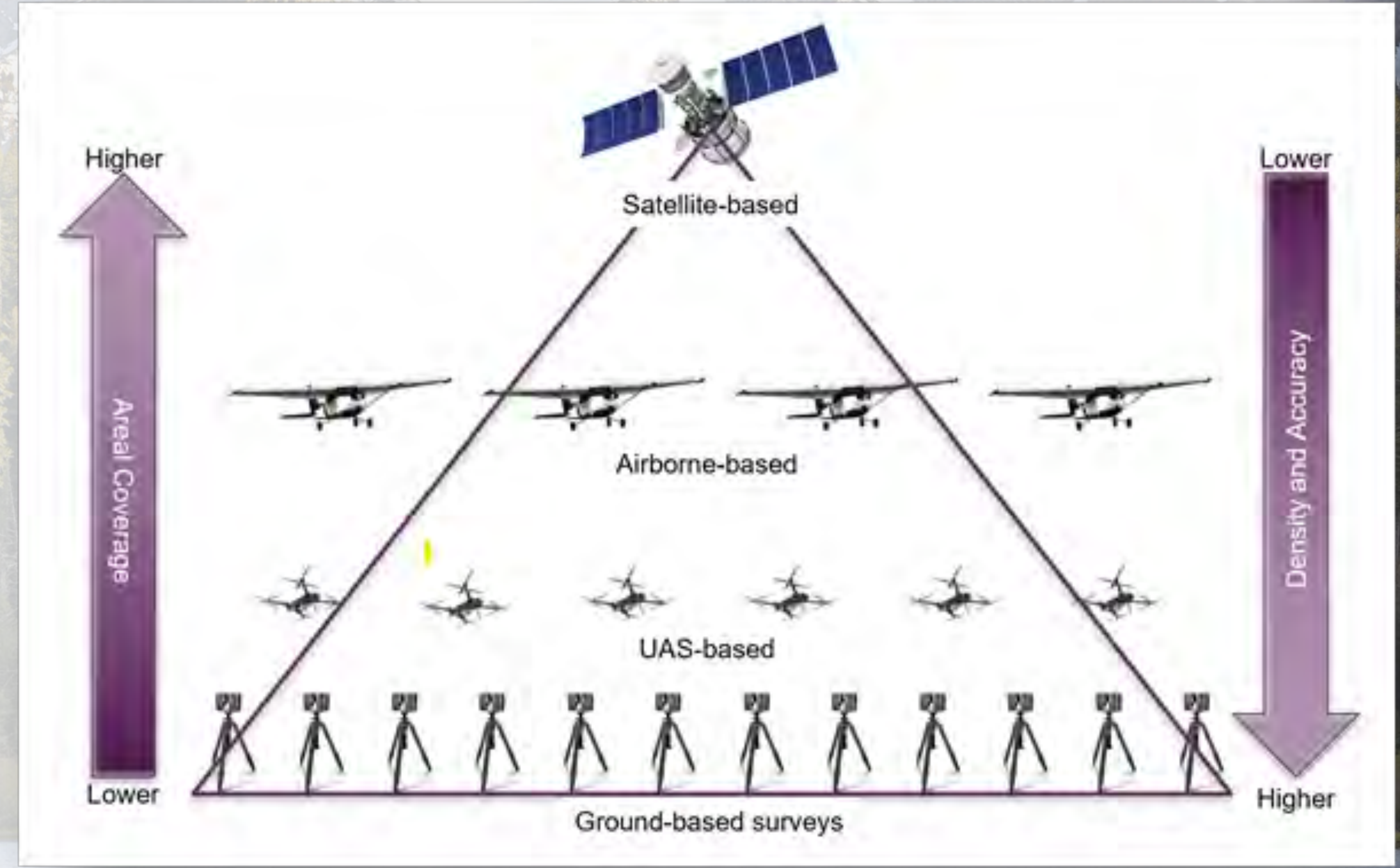




Lidar is platform agnostic

You can put lidar sensors on any remote sensing platform:

- Tripod
- Backpack
- Car/Train
- Helicopter
- Blimp
- UAS
- Airplane
- Balloon
- Satellite
- Kite!



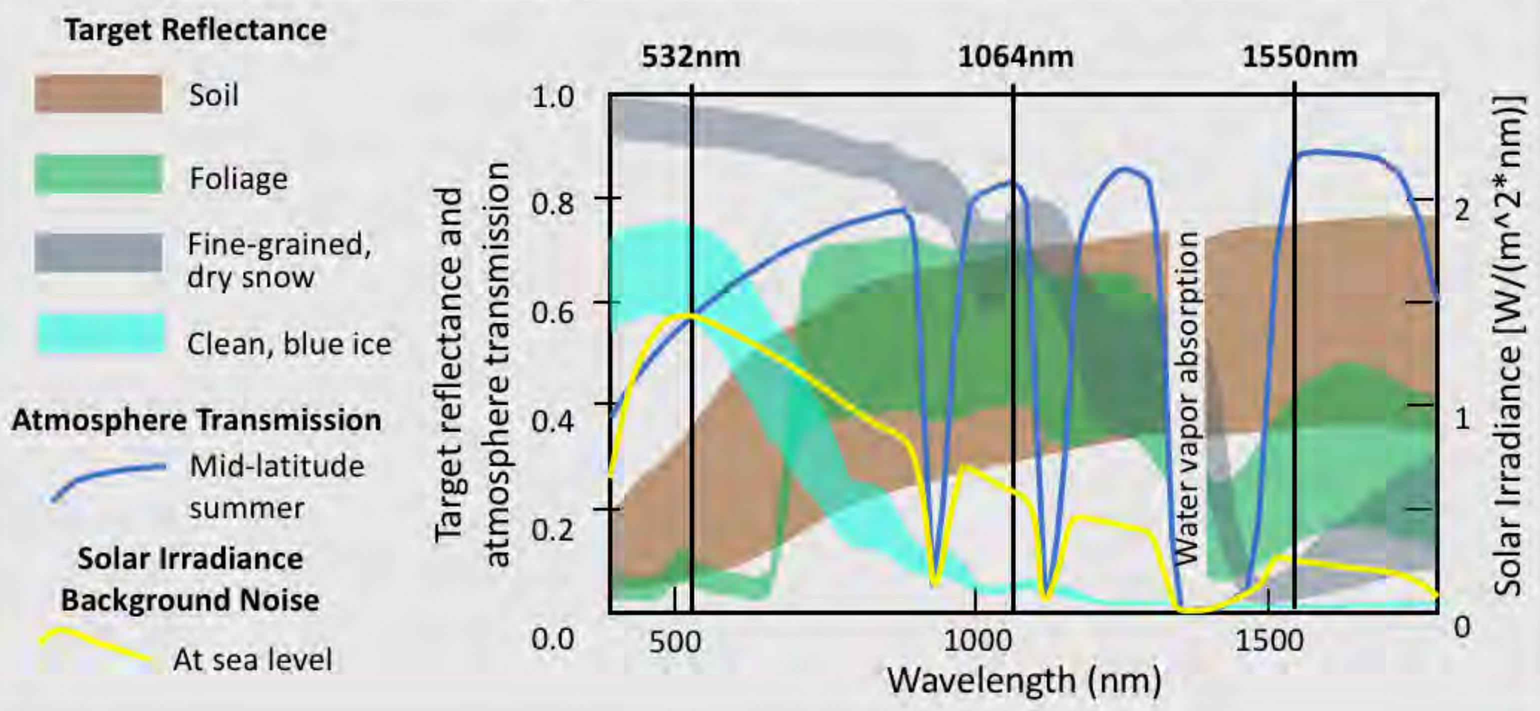
What makes a lidar a lidar?

- **Ranging**
  - **Laser**
  - **Detector**
- Orientation (IMU/INS)
- Position (GNSS, other)
- Optional:
  - Scanning mirror
  - Beam splitter

Goddard SPACE FLIGHT CENTER

Signal and Noise Wavelength Dependencies

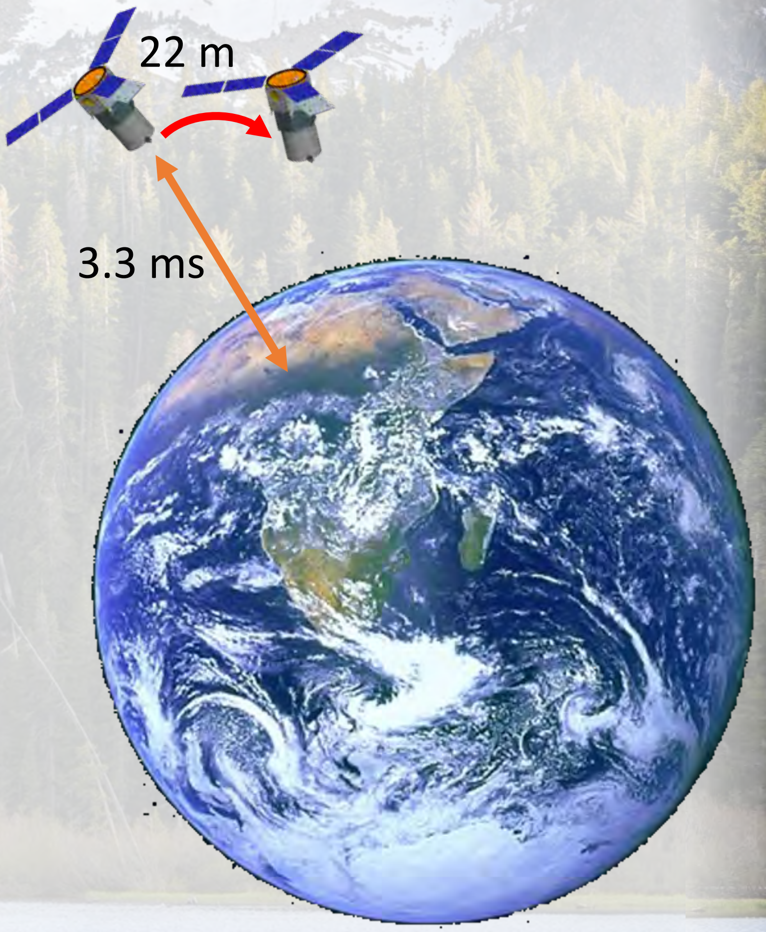
Parameter	532 nm	1064nm	1550nm
Foliage and soil reflectance	Low to moderate	Moderate to high	Low to high
Snow, firn and ice reflectance	High to very high	Low to high	Very low to low
Atmosphere transmission	Moderate	High	Very high
Solar background noise	Moderate	Low	Very low



6/3/2020 David Harding, NASA/GSFC 25

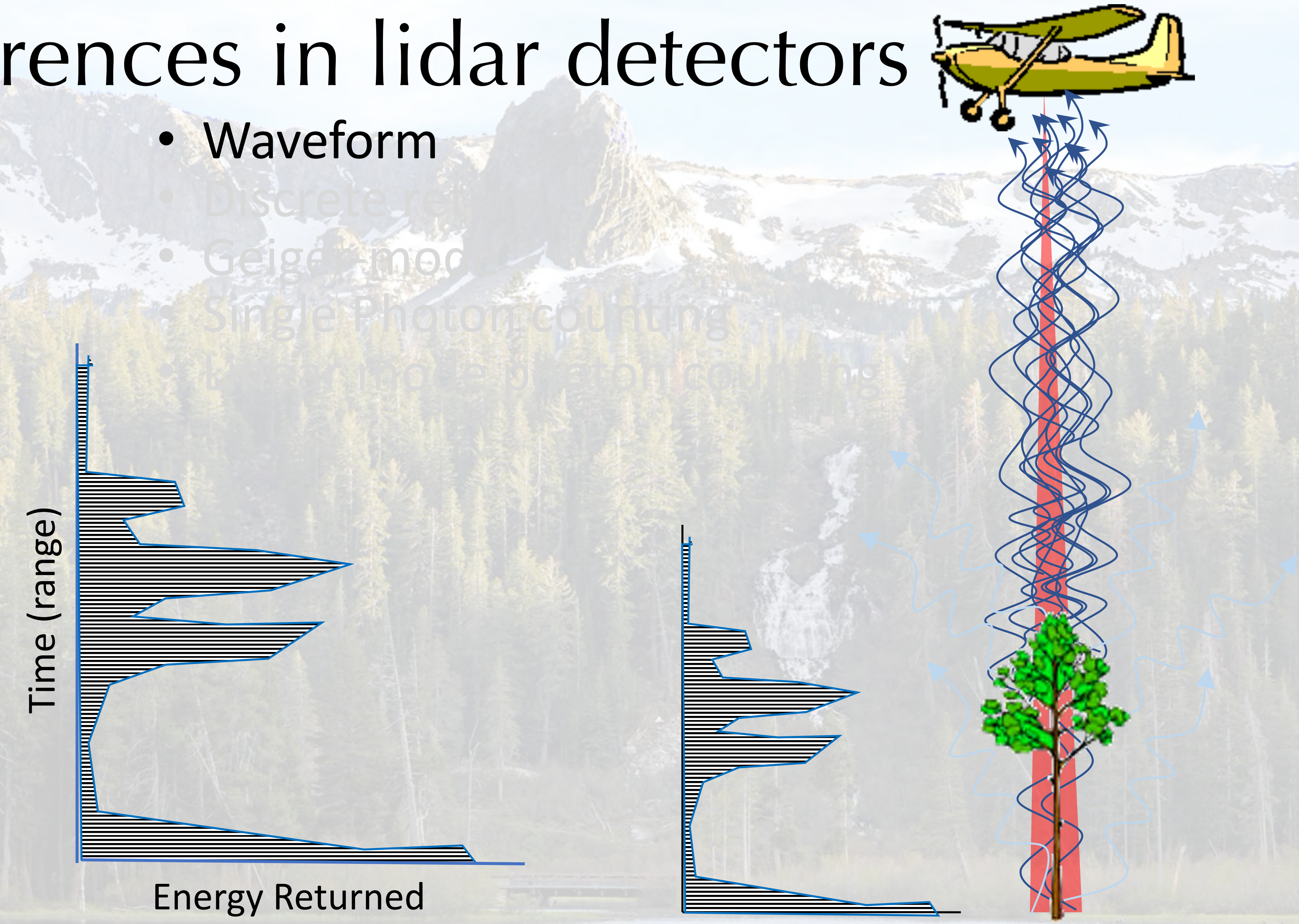
Why is space lidar so hard?

- Speed of light: approx. 300,000 km / s
- Altitude of ICESat-2: 481.194 km
  - One pulse takes ~0.0016 seconds x 2 (out-back) = ~0.0032 seconds (3.3 milliseconds)
- ICESat-2 flies at 6.9 km (4.3 miles) per second
- So in the time it takes to send one laser pulse and receive it back, the platform is already ~22 meters down the road
- To capture these returning photons you incredibly precise timing and
  - either need a big telescope/laser footprint, very sensitive detectors, (or both) or get creative………



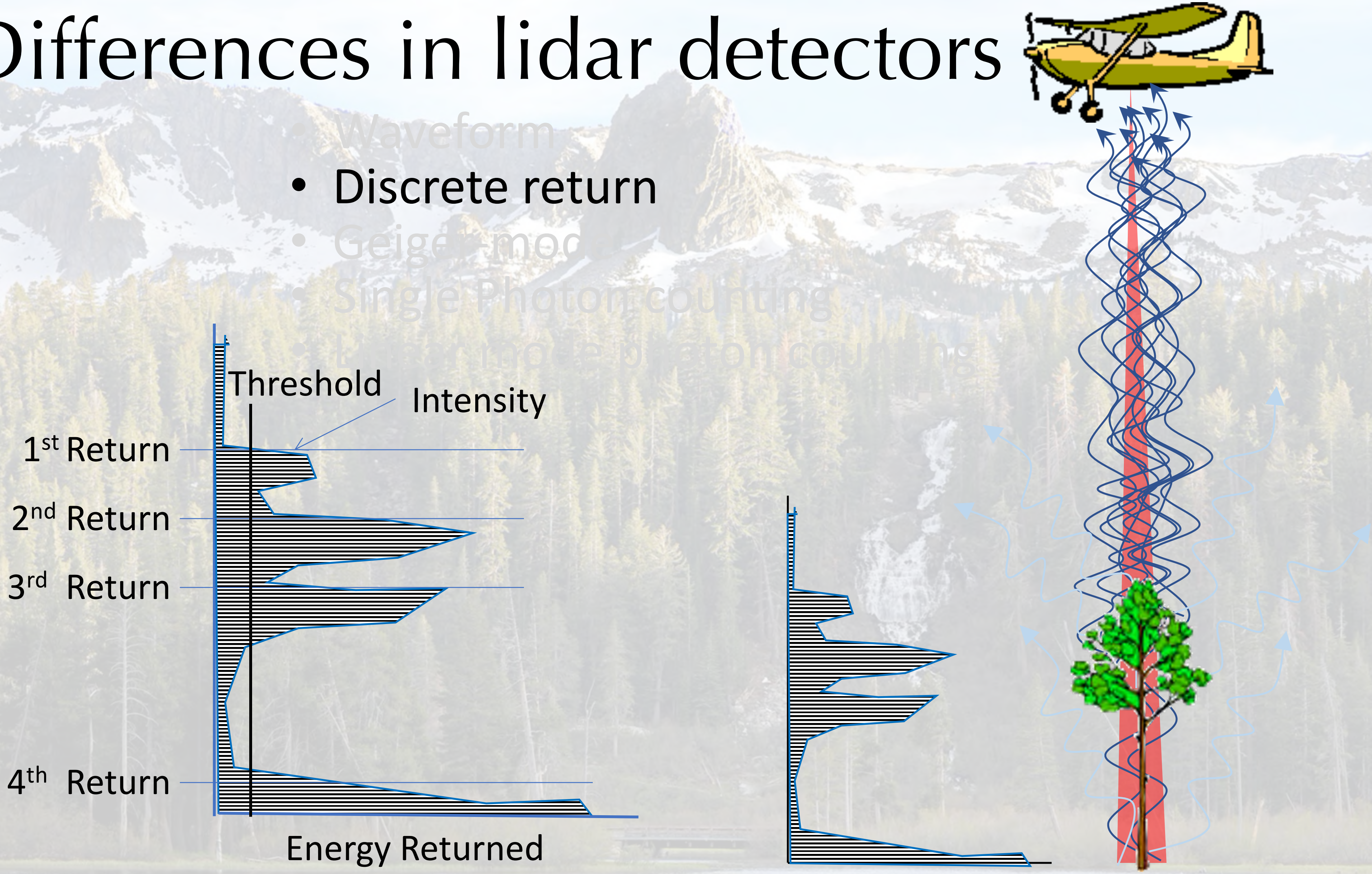
Differences in lidar detectors

- Waveform



Differences in lidar detectors

- Waveform
- Discrete return
- Geiger-mode
- Single Photon counting
- Linear mode photon counting



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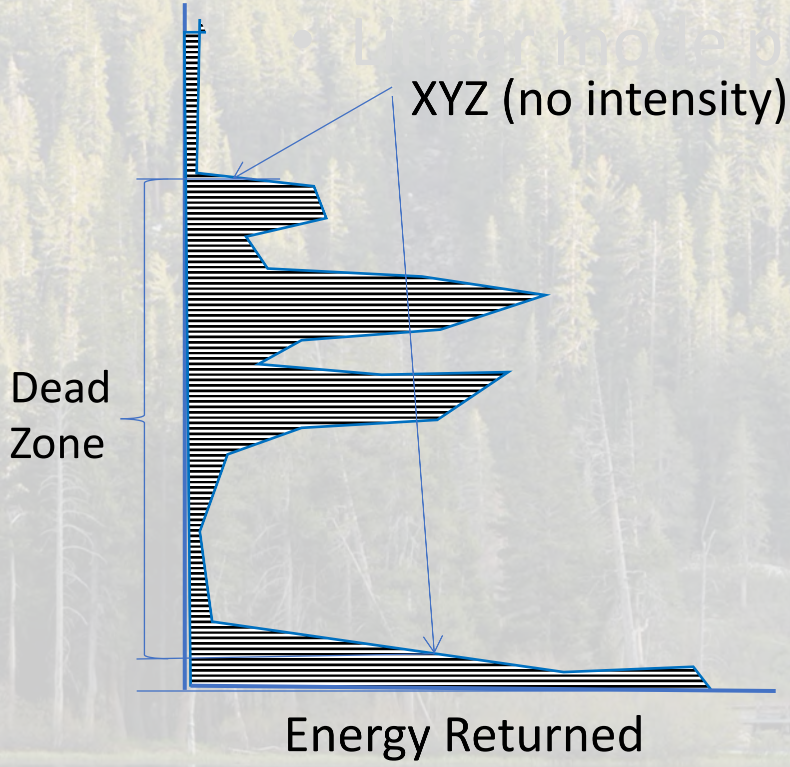
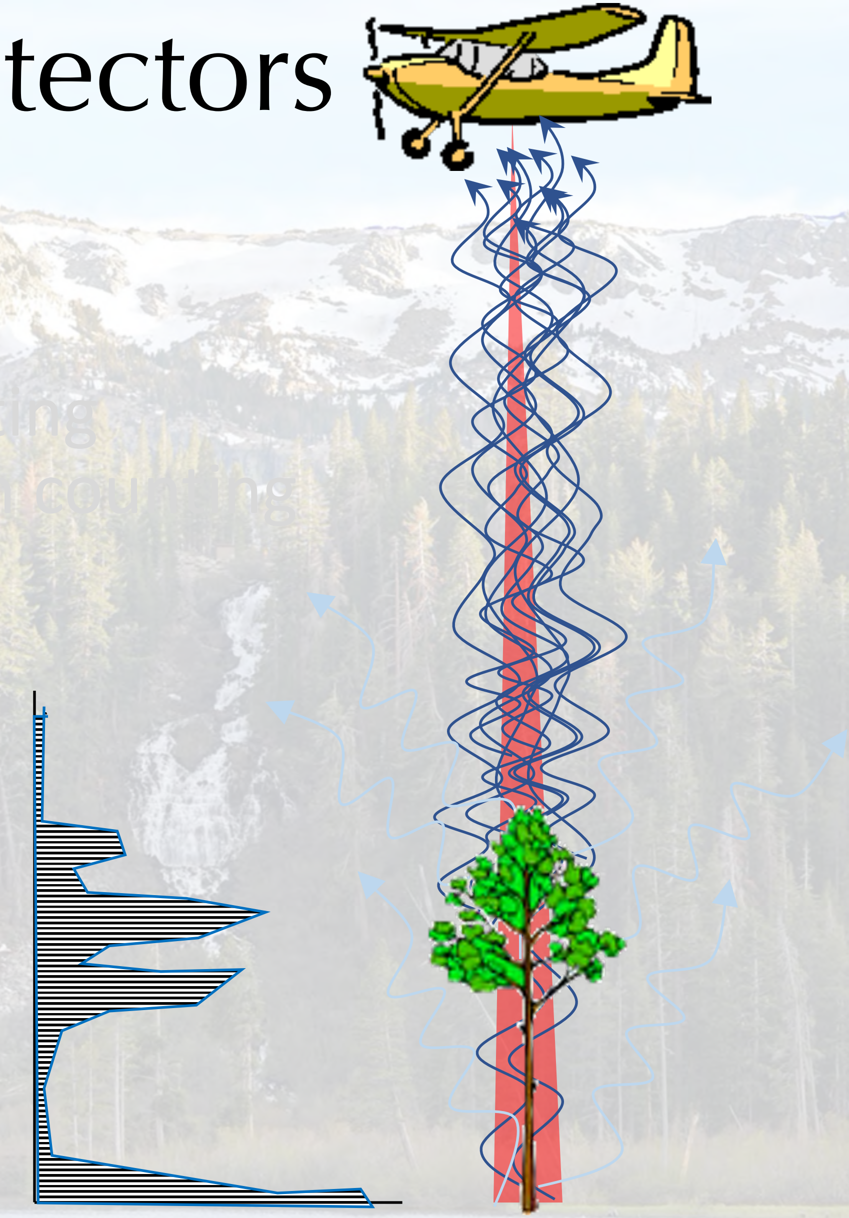
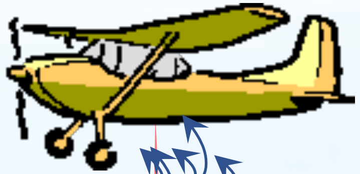
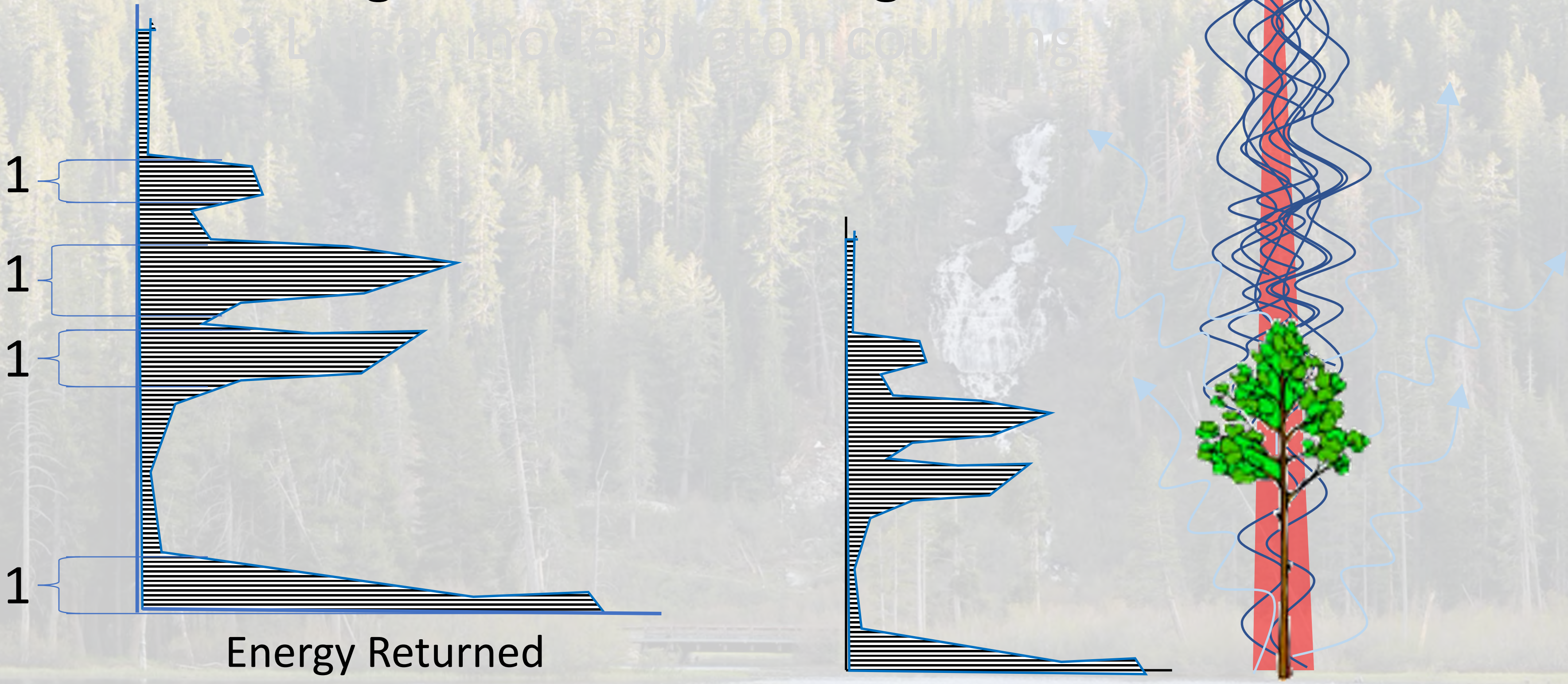




Differences in lidar detectors

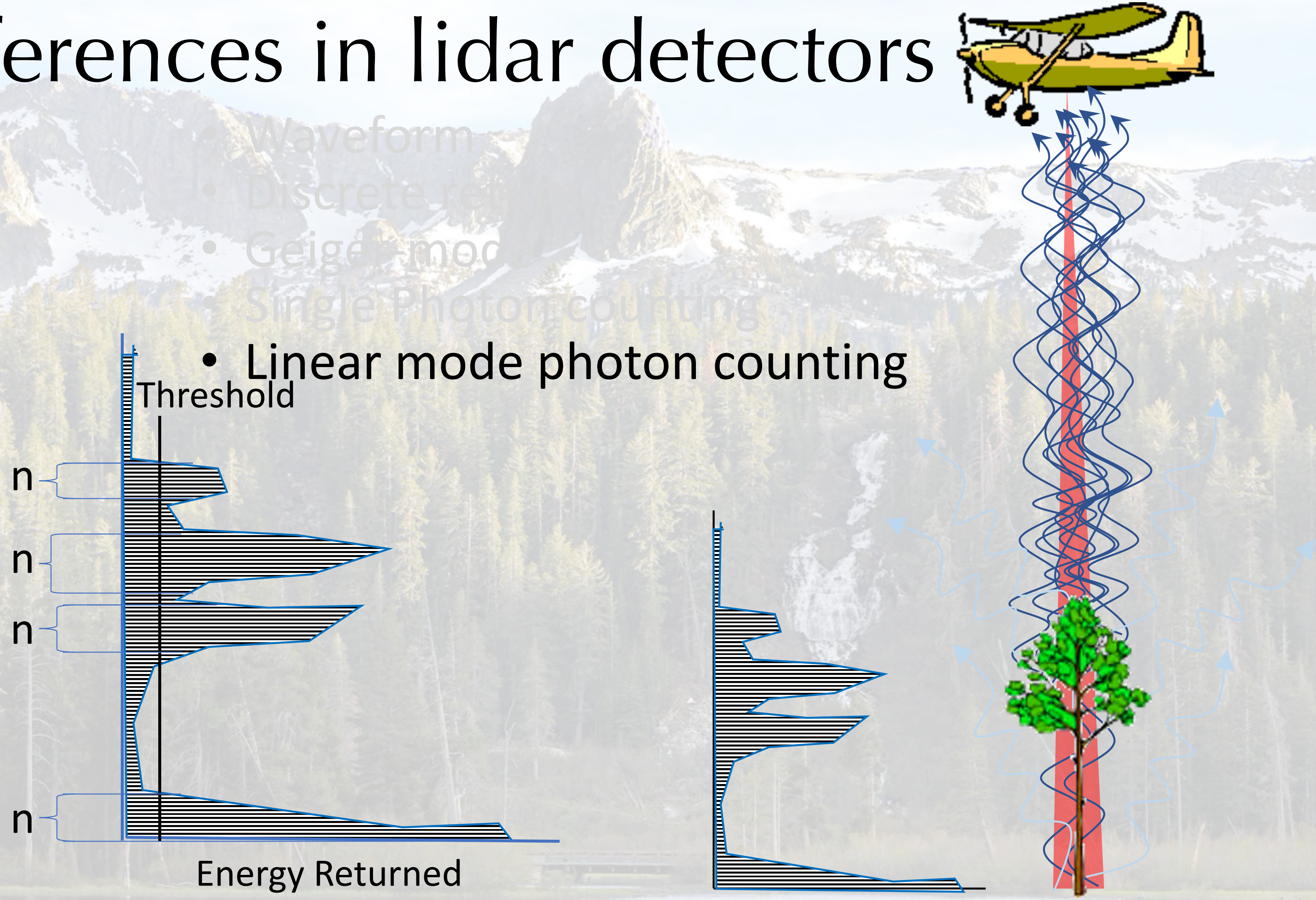


- Waveform
- Discrete re
- Geiger mod
- Single Photon counting



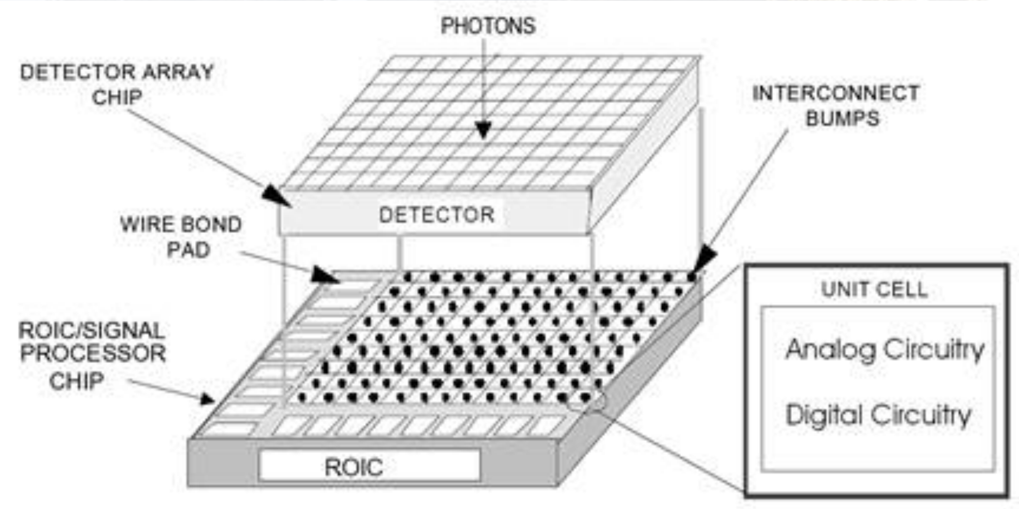
+ Differences in lidar detectors

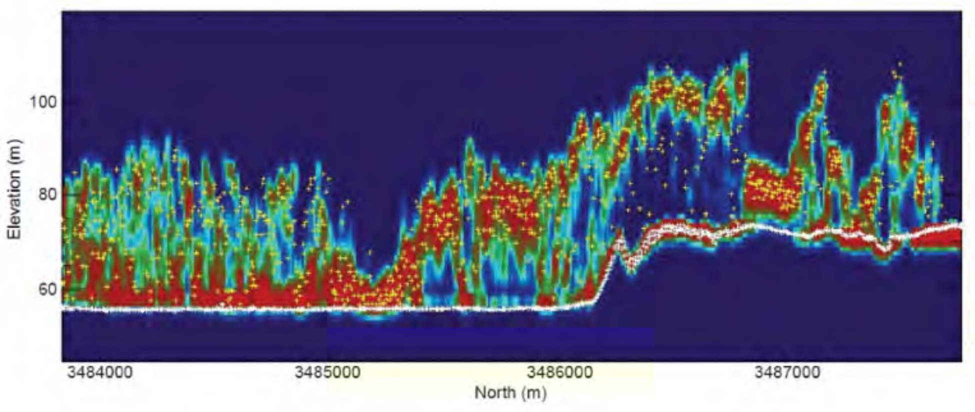
- Waveform
- Discrete re
- Geiger mod
- Single Photon counting
- Linear mode photon counting



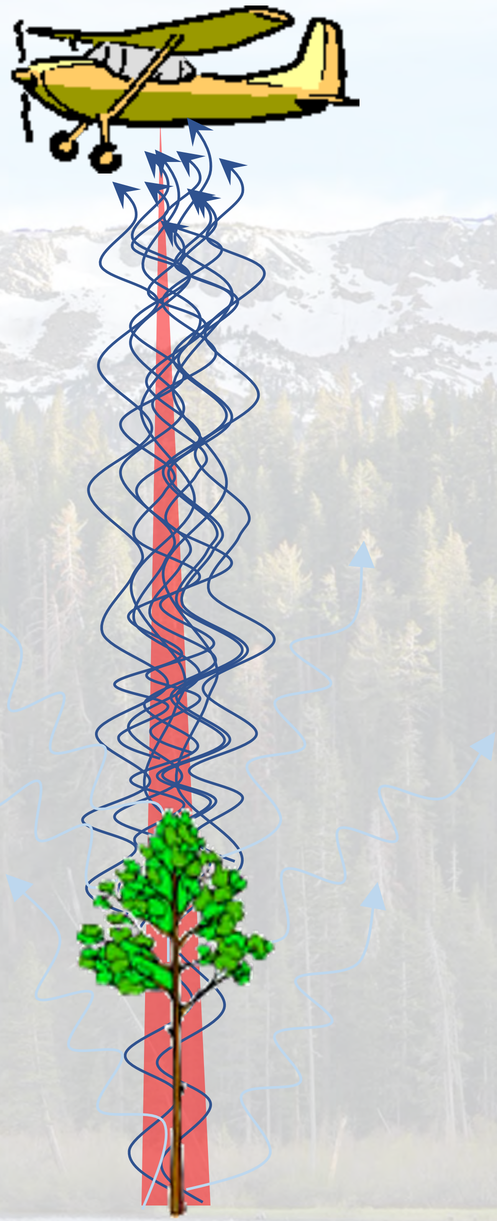
Differences in lidar detectors

- FLASH array



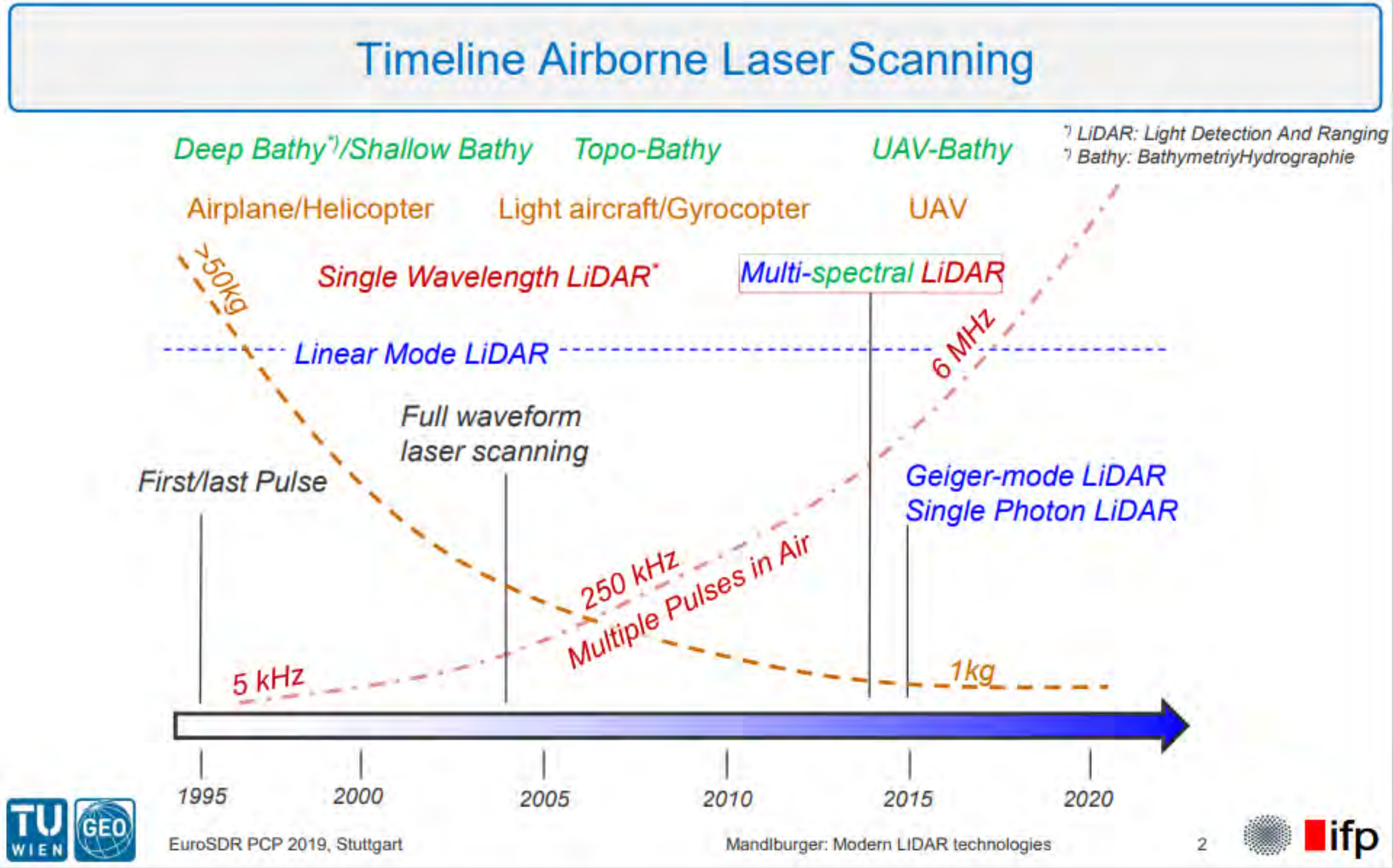


Courtesy of Ball Aerospace



Current state of the art examples

Airborne



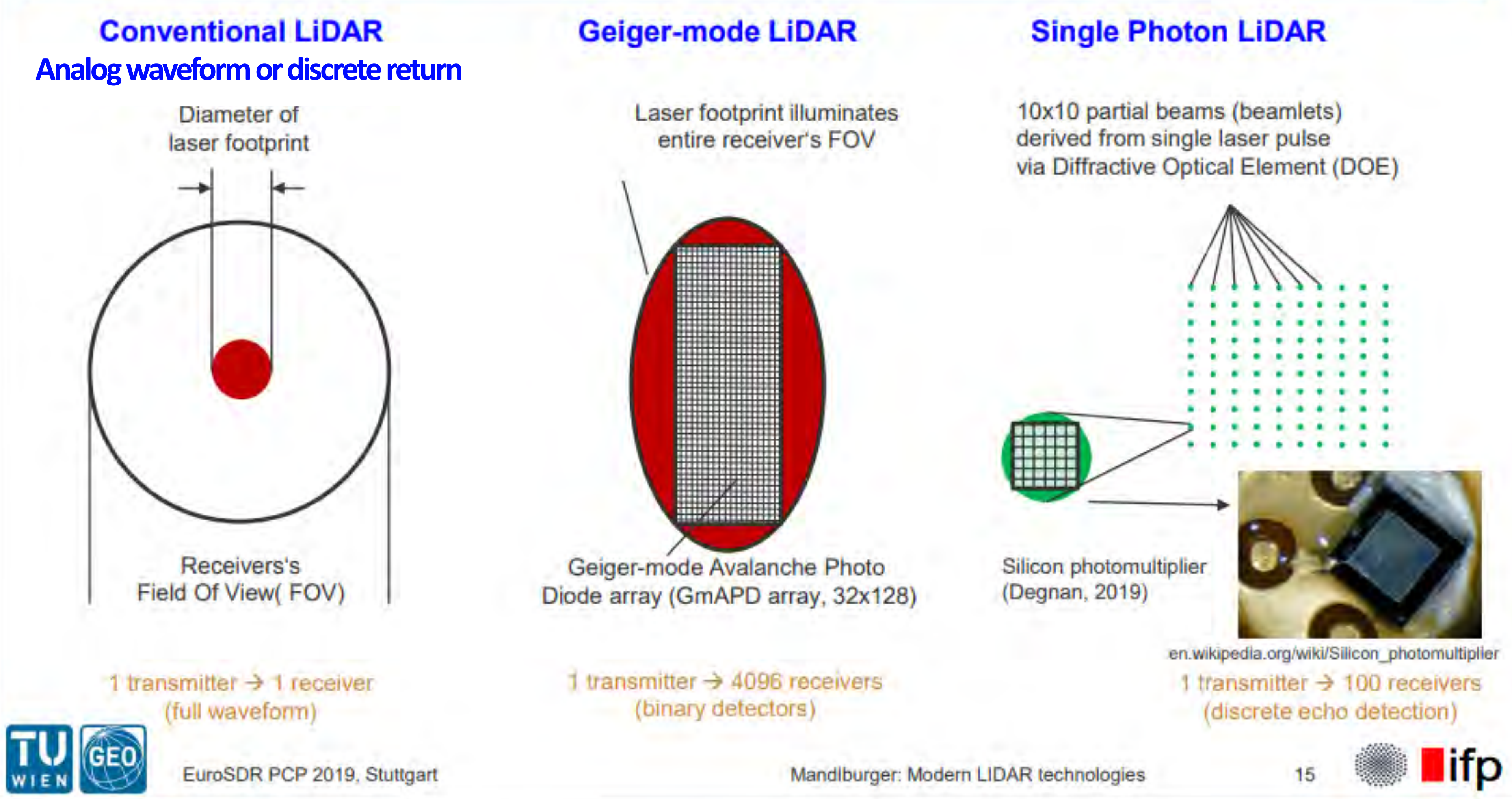
http://pcp2019.ifp.uni-stuttgart.de/presentations/01-2019_EuroSDR_PCP_Stuttgart_Mandlburger.pdf

Airborne Lidar Systems

- Flying heights range from 150m-6500m AGL (L3Harris quotes 10km max AGL)
- Wavelengths typically 532, 1064, 1550 nm
- Pulse rates usually programmable
- Waveform and discrete returns possible
- Scan angle FOV variable based on systems and mission designs
- Intensity per return captured
- Multiple pulses in air
- Number of points and accuracies variable based on flight planning and survey control

Supplier	System	Subsystem
Teledyne Optech	ALTM Galaxy	Galaxy CM2000
		Galaxy Prime
		Galaxy T2000
	Eclipse	
	Orion	C
		H
		M
	Pegasus	
		HA-500
	Titan	
	CZMIL NOVA	
Leica Geosystems	SPL100	
	Terrain Mapper	
	City Mapper	
	ALS80	CM
		HP
		HA
Riegl Gmbh	LMS-Q680i	
	VQ-780i	
	VUX-1LR	
	VQ-1560i	
	VQ-1560i DW	
L3 Harris	IntelliEarth	

Analog-mode, Geiger-mode and Single Photon LiDAR



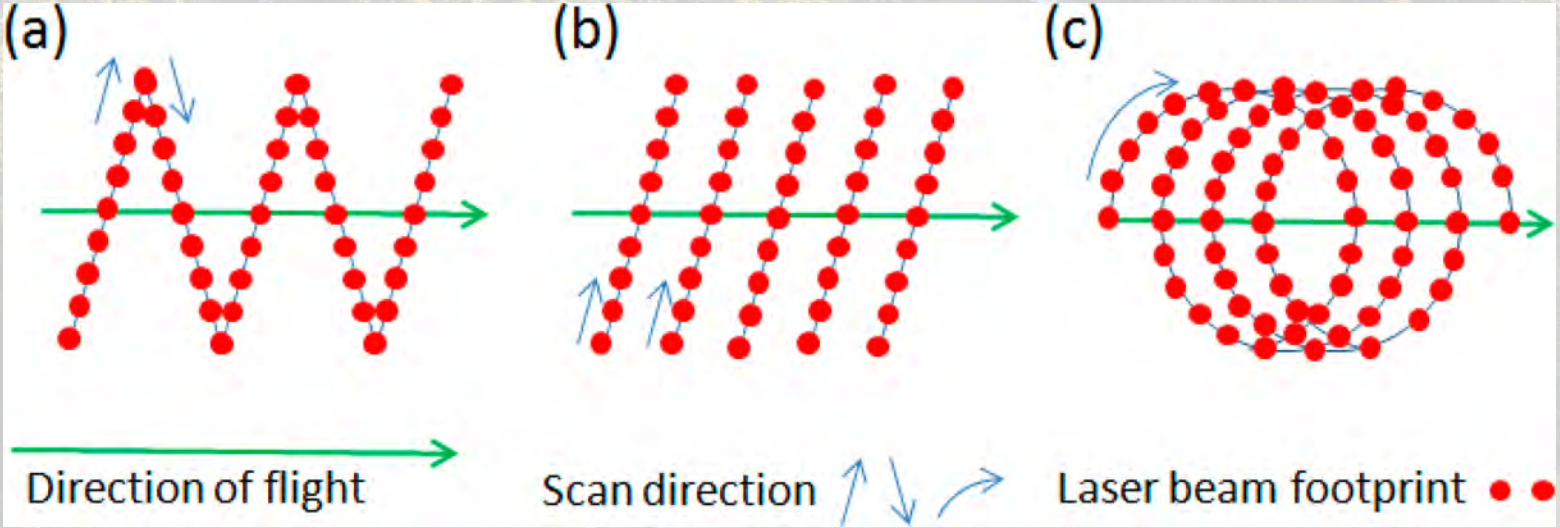
Adapted from http://pcp2019.ifp.uni-stuttgart.de/presentations/01-2019_EuroSDR_PCP_Stuttgart_Mandlburger.pdf

How these systems are different

Palmer/circular scanner

Both SPL and GML employ Palmer scanners- which allow for fore and aft looks along flight line

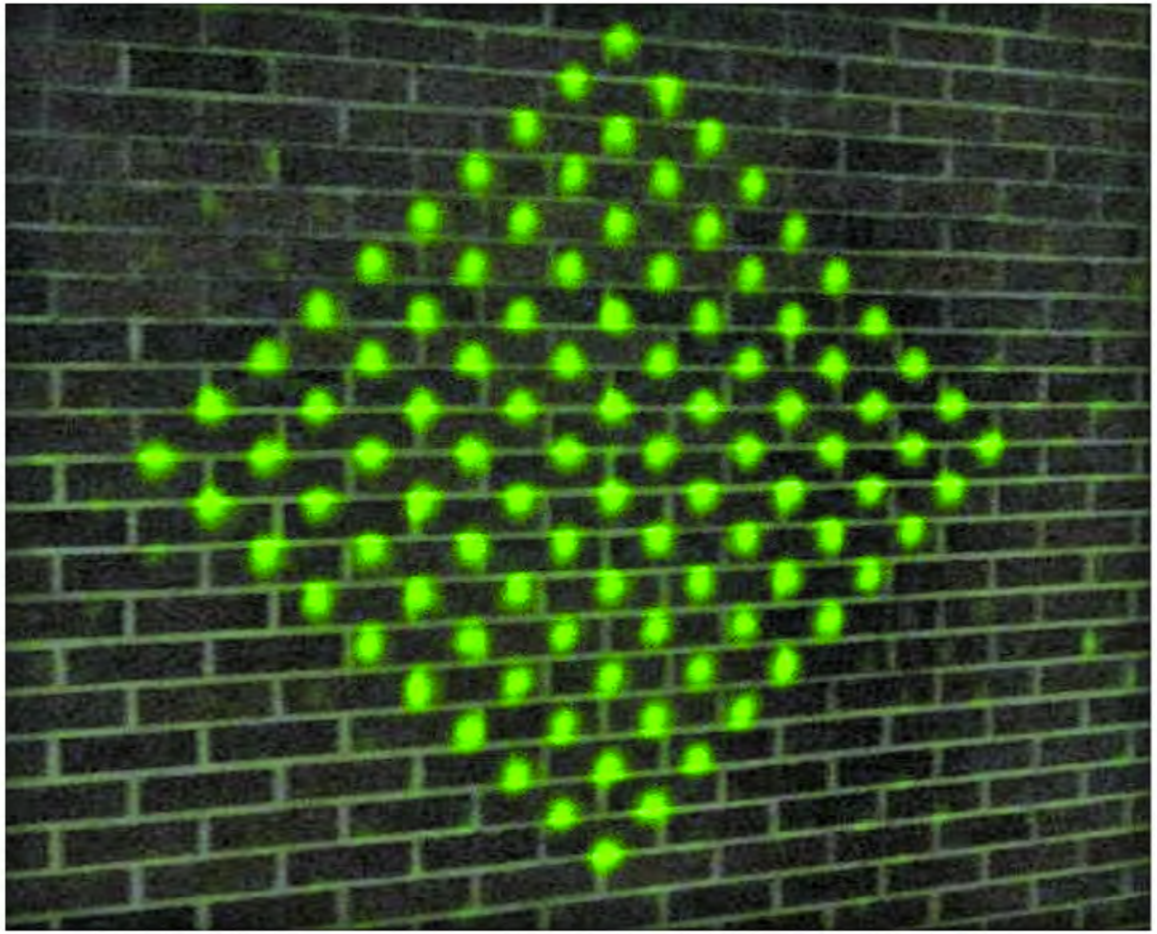
Not unique to these systems however



From: Fernandez-Diaz, J.C.; Carter, W.E.; Shrestha, R.L.; Glennie, C.L. Now You See It… Now You Don't: Understanding Airborne Mapping LiDAR Collection and Data Product Generation for Archaeological Research in Mesoamerica. *Remote Sens.* **2014**, *6*, 9951-10001.

SPL laser split in to 100 beamlets

Beamlets imaged on to an array of 10 × 10 micro-channel plate photomultiplier detectors

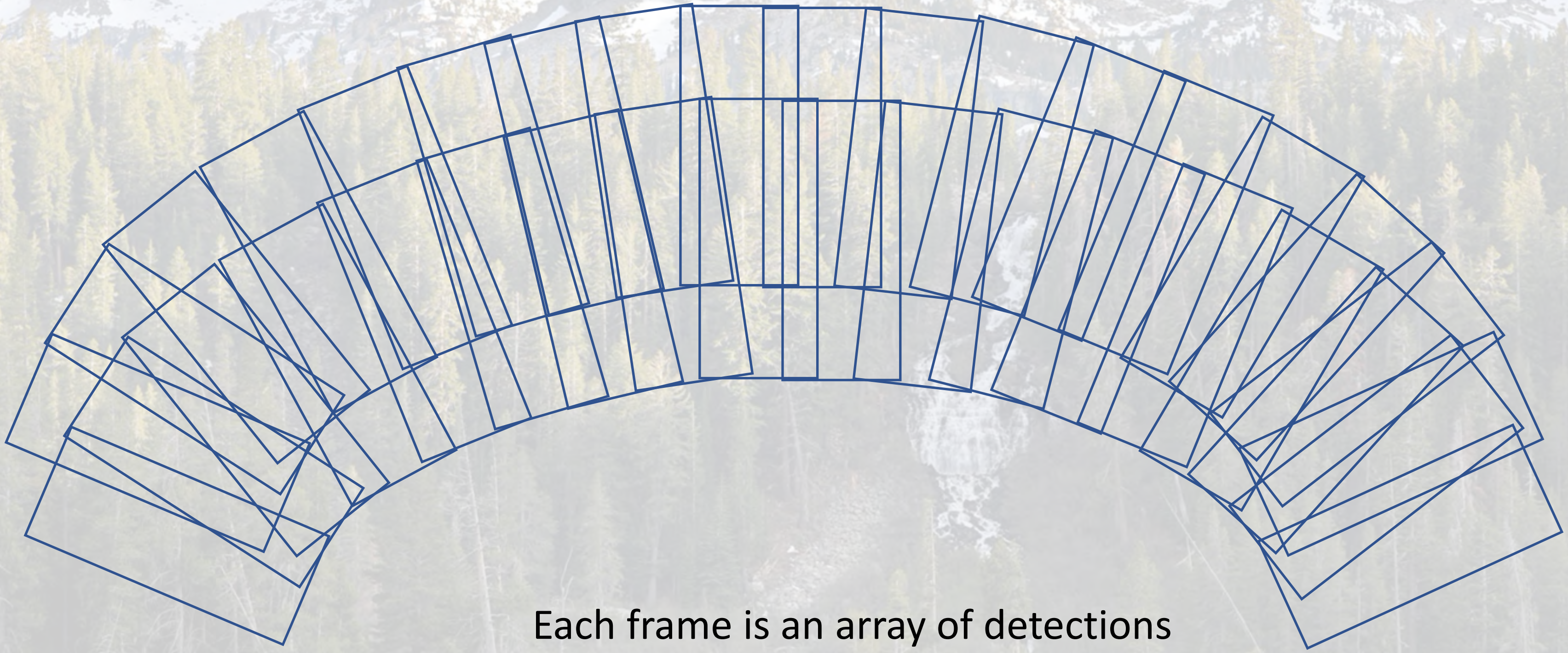


In SPL, the laser pulse is distributed through a holographic optical element to produce 100 individual beamlets.

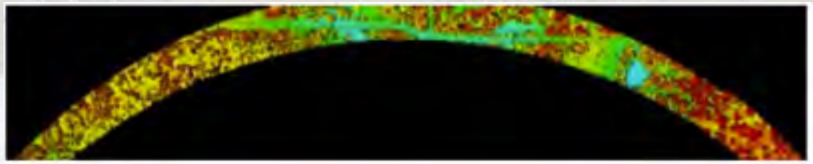
https://www.xyht.com/aerialuas/single-photon-lidar/

Building GML point clouds from aggregation

- Not exactly direct time-of-flight solution (is but isn't)



Each frame is an array of detections



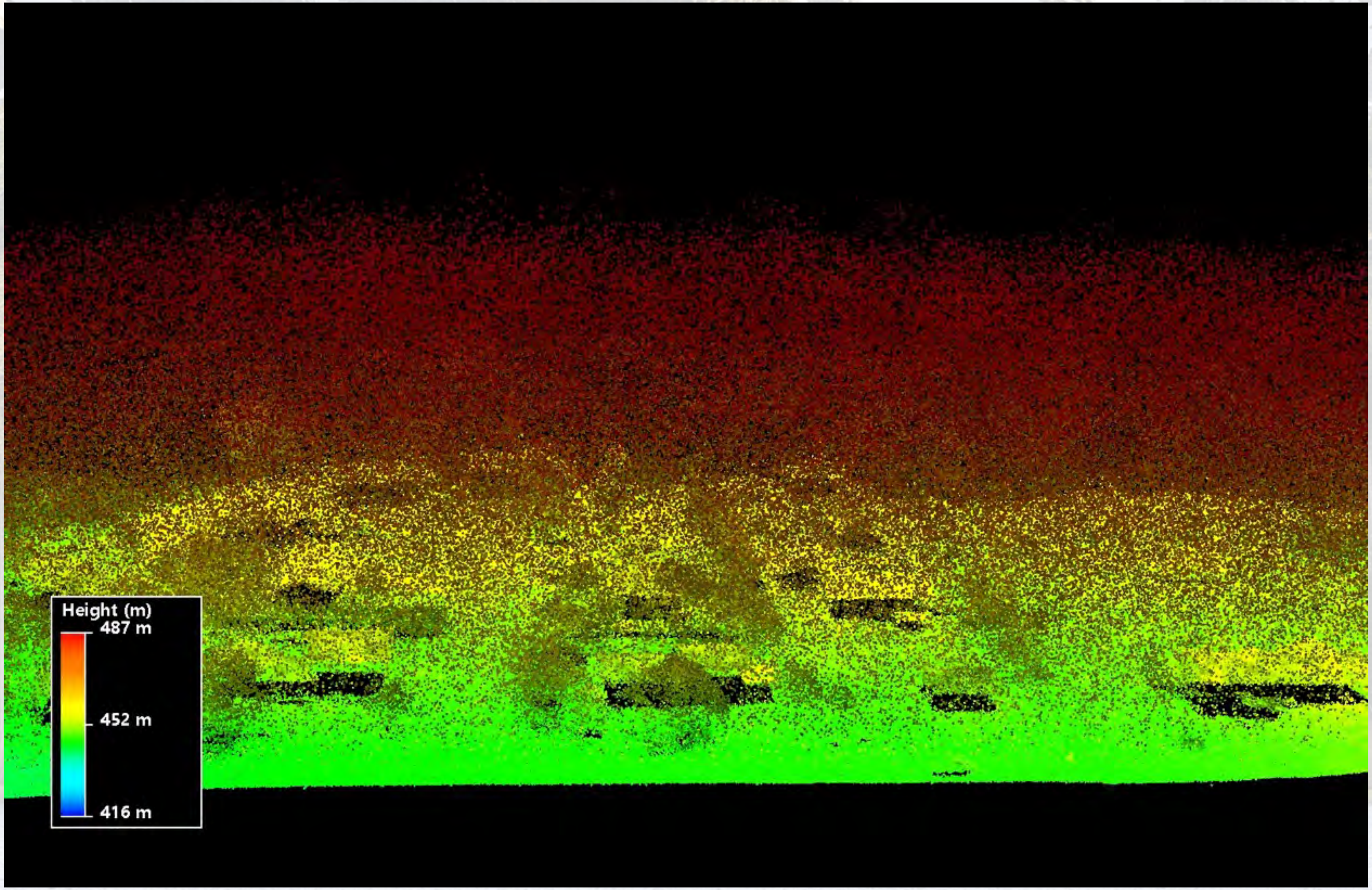
GML multi-look, multiple pulses

Building a histogram of photons from many angles

- Up to 4096 possible measurements per flash
- 50 khz
- Every spot is illuminated many times
- All the photons recorded are processed to determine if they are real objects
- Need multiple ‘hits’ per space to know if photons bounced off target, or just random solar photons hitting detector
- More hits you get, higher your probability is that it is real feature

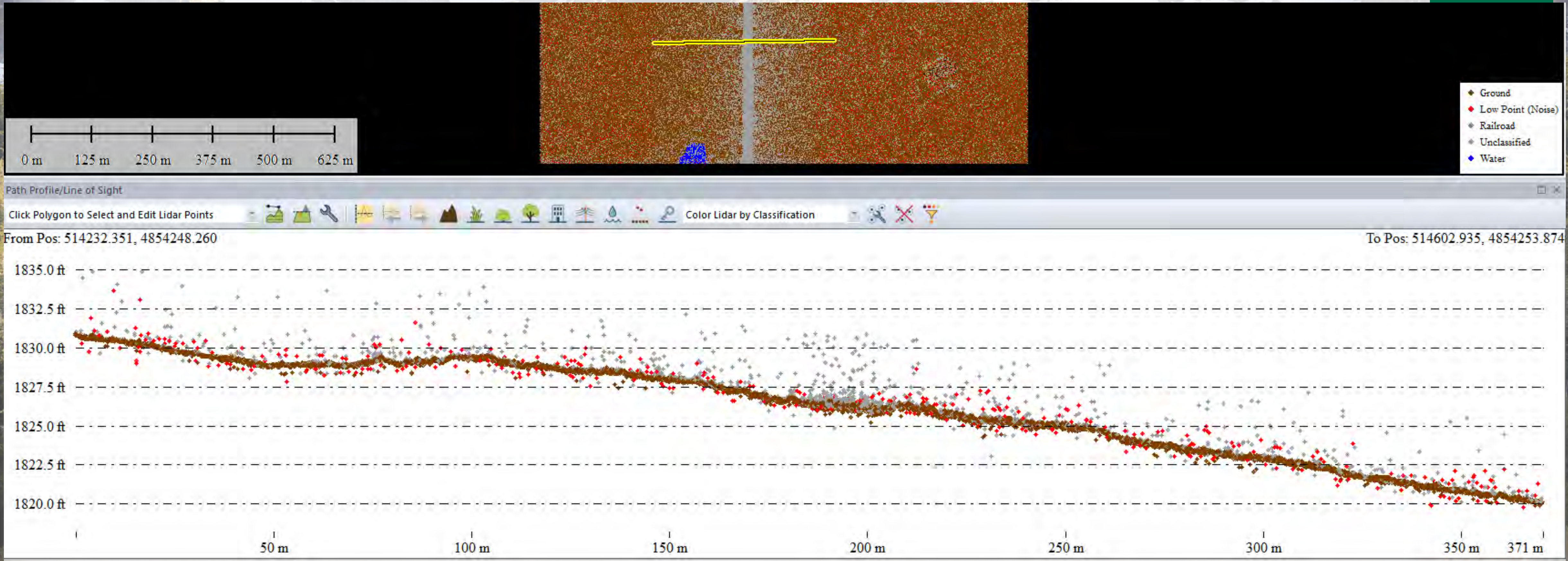
Single photon

Separating signal from noise



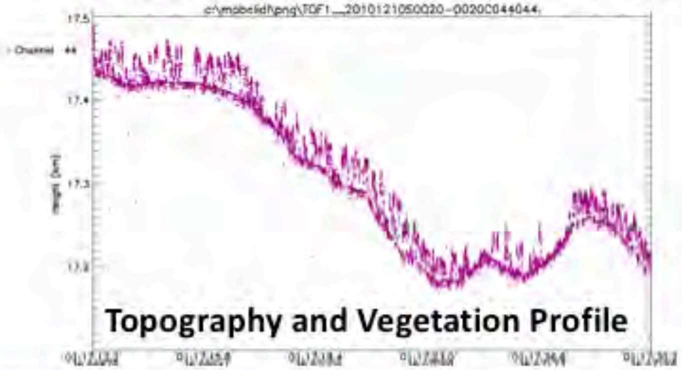
Push noise points to noise/withheld classes

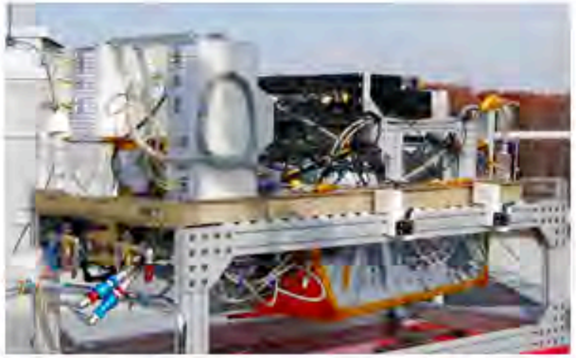
SD Single Photon Example



MABEL Airborne Two-color Photon Counting

- ***Multiple Altimeter Beam Experimental Lidar (MABEL)***
  - **The first high-altitude, dual-wavelength, photon-counting laser altimeter**
  - High pulse rate (up to 25kHz), low pulse energy laser transmitter at 532 nm and 1064 nm
  - Selectable profile spacings across 2 km swath (16 green and 8 NIR profiles) with 2m footprints oversampled along-track
  - Low noise, photon-counting detectors (PMT for green, SPCM for NIR)
    Four reflectance measurements
    - 532 nm and 1064 nm dual wavelength (footprints are not coincident)
    - Laser retro-reflectance at 0° phase "hot spot" and solar bi-directional reflectance
  - Flight altitudes up to 20km on ER-2
  - PI: Matt McGill
  - First-flight in 2010
  - Demo of ICESat-2 photon-counting measurement



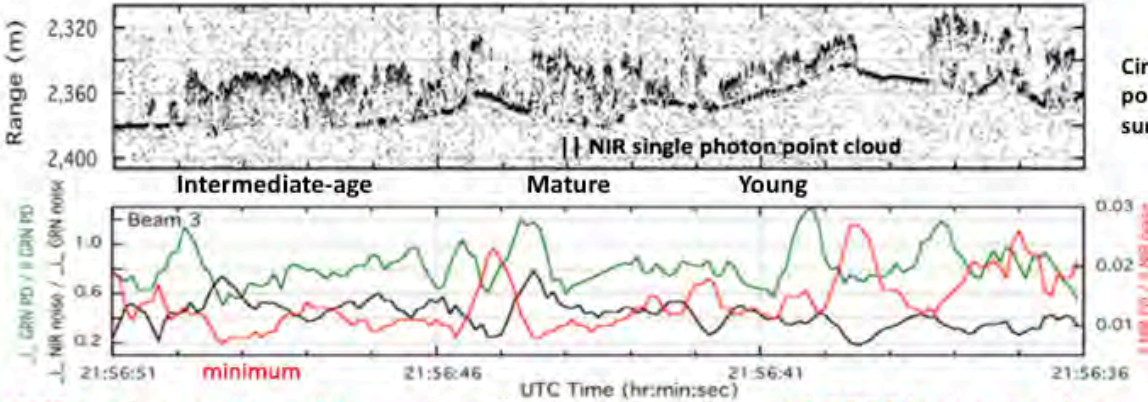


MABEL dimensions are 52" x 26" x 30"

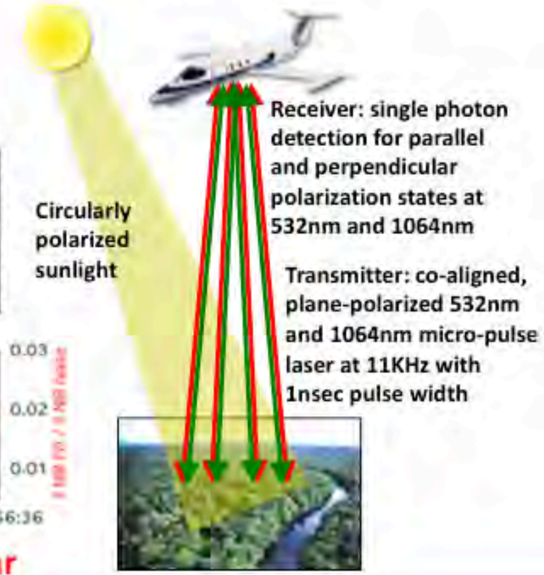
SIMPL Airborne Multi-channel Lidar

- ***Slope-imaging Multi-polarization Photon Counting Lidar (SIMPL)***
  - SIMPL is a eight-channel system that measures surface heights and physical properties by transmitting co-aligned 532nm and 1064nm beams and detecting laser and solar reflected photons in perpendicular and parallel polarization states.
  - The polarimetry characterizes targets based on dual-wavelength photon scattering properties, enabling definitive identification of liquid water, measurements of multi-scale roughness and extinction profiling through water, snow, ice and vegetation.
  - PI: David Harding
  - Co-I instrument scientist: Phil Dabney

Photon point cloud with solar background noise

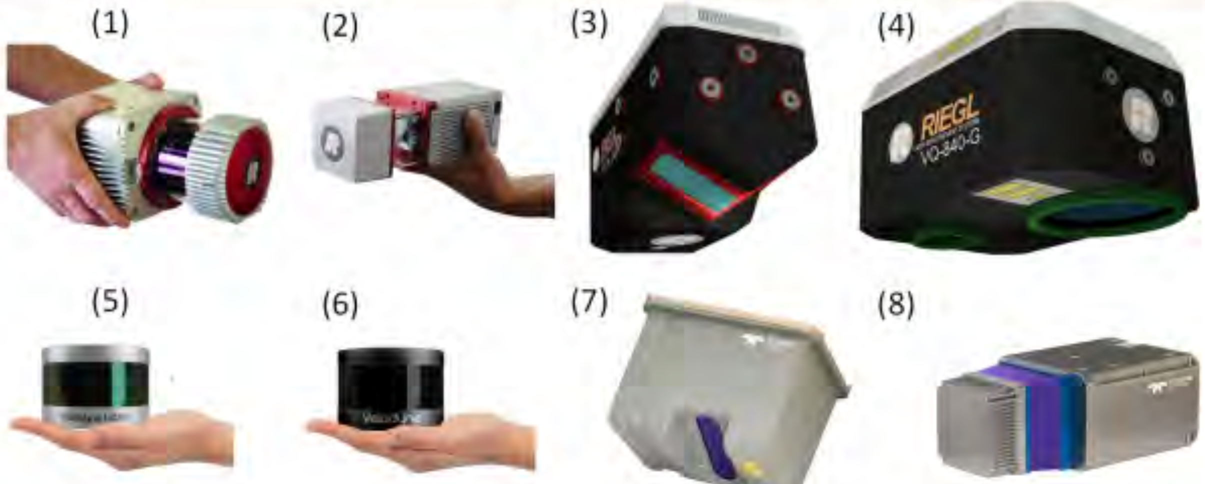


532nm laser _|_ vs || _|_ solar 1064 vs 532 || 1064 laser vs solar



UAV LiDAR – Sensor overview

ID	sensor	mass	wavelength	max range	prec/ acc	meas. rate	meam div.	footprint @50m agl	FOV	channels
		[kg]	[nm]	[m]	[mm]	[kHz]	[mrad]	[mm]	°	
1	VUX1-UAV	3.75	**1550**	300	**5/10**	500	**0.5**	**25**	330	1
2	miniVUX-2UAV	1.60	905	250	10/15	200	1.6 x 0.5	80 x 25	360	1
3	VUX-240	4.10	1064	**650**	15/20	1500	0.35	18	75	1
4	VQ-840-G	**12.00**	**532**	---	15/20	**200**	1.0 - 6.0	50 - 300	40	1
5	Puck LITE	**0.59**	903	**100**	**--/30**	300	3.0 x 1.2	150 x 60	360	32
6	Alpha Puck	3.50	903	300	--/30	**2400**	**3.0 x 1.5**	**150 x 75**	360	128
7	CL-90	3.85	1550	175	5/10	500	0.3	15	90	1
8	CL-360	3.50	1550	300	5/10	500	0.3	15	360	1



EuroSDR PCP 2019, Stuttgart

Mandlburger: Modern LIDAR technologies

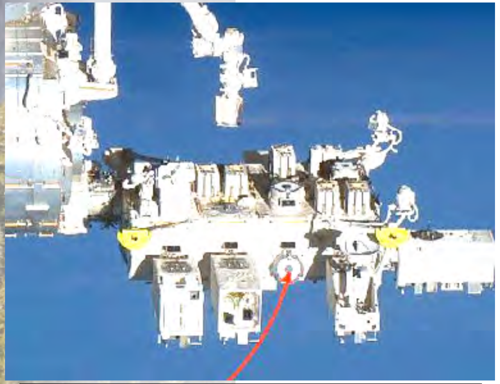
34

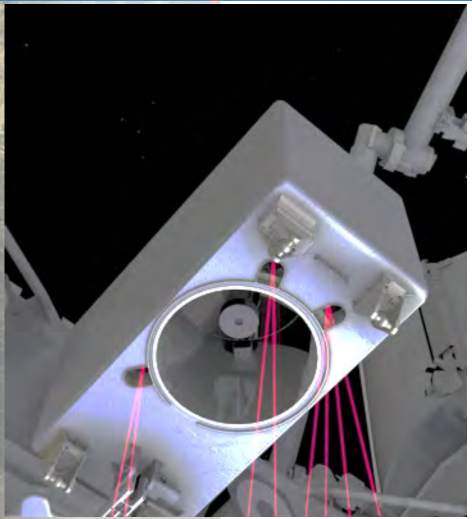
http://pcp2019.ifp.uni-stuttgart.de/presentations/01-2019_EuroSDR_PCP_Stuttgart_Mandlburger.pdf

Current state of the art examples

Spaceborne

GEDI Lidar on ISS and GLAS Lidar on ICESat Sampling Patterns





GEDI

8 equally spaced profiles for uniform sampling

1064 nm full-waveform

242 high-energy pulses per sec dithered between 2 profiles yields 60 m spacing

4.8 km

25 m

ICESat

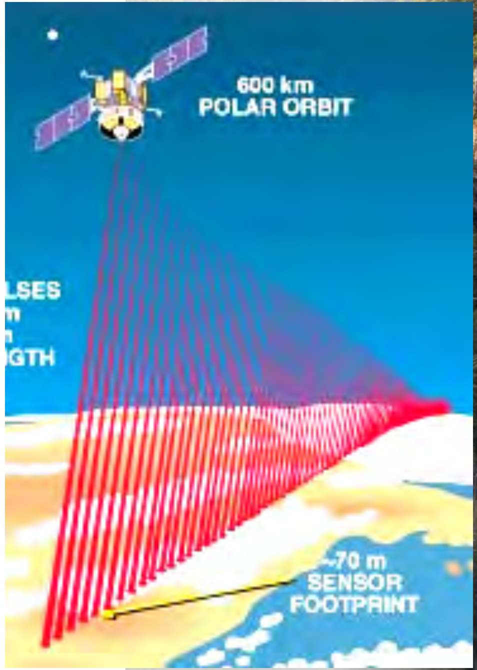
Single beam profile

1064 nm full-waveform

ICESat
40 high-energy pulses per sec yields 170 m spacing

~70 m

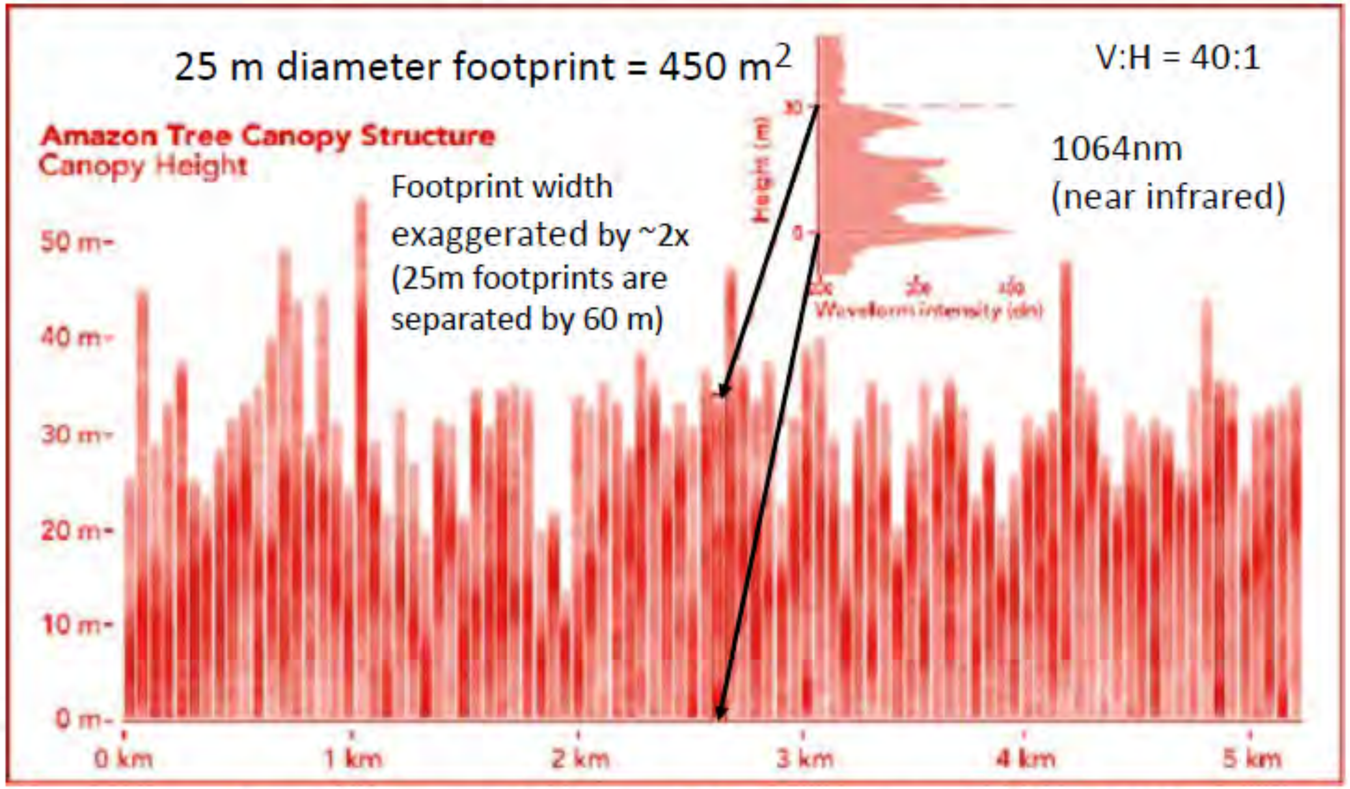
Three lasers were used with diameters that varied from 80 m to 50 m



GEDI Waveform Profile

Footprint Products:

- Waveform
- Ground elevation
- Canopy top height
- Percentile relative heights (RH)
- Canopy cover fraction and height profile
- Leaf area index and height profile
- Above ground biomass



Ground topography flattened to compare vegetation height

Graphic adapted from https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/iss-gedi

ATLAS Lidar on ICESat-2 and GLAS Lidar on ICESat Sampling Patterns

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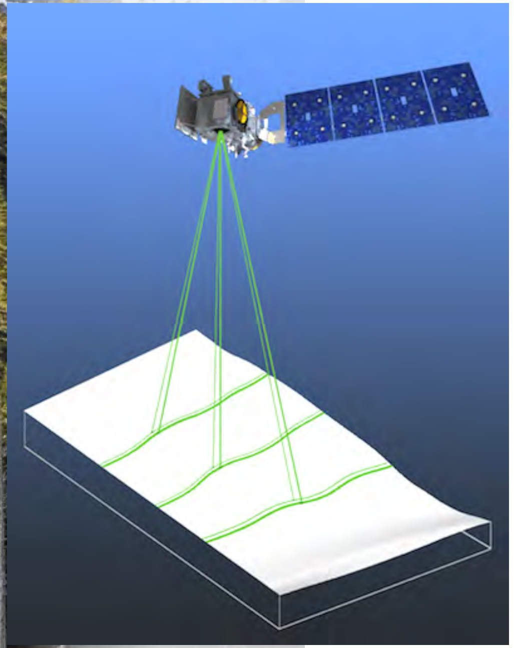
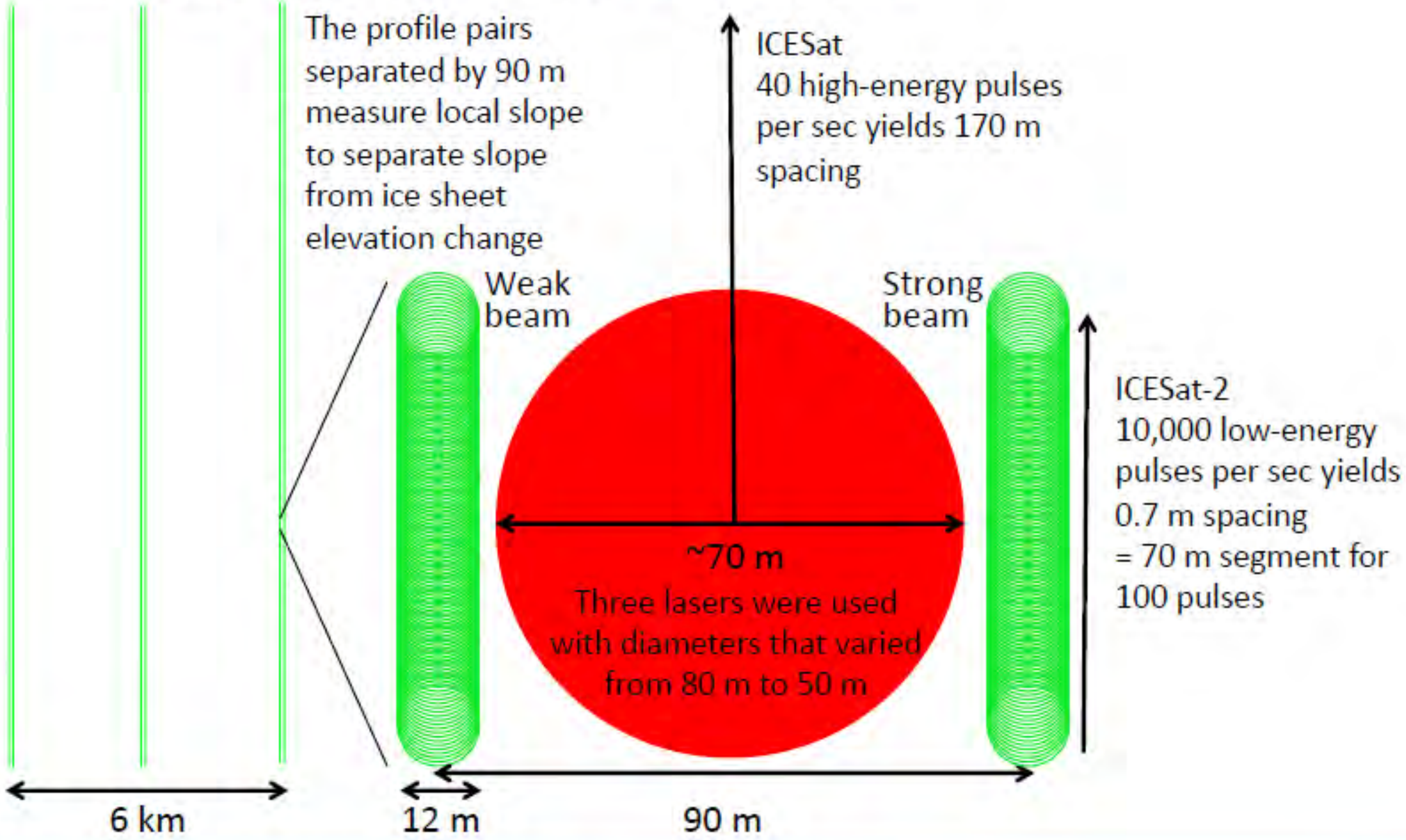
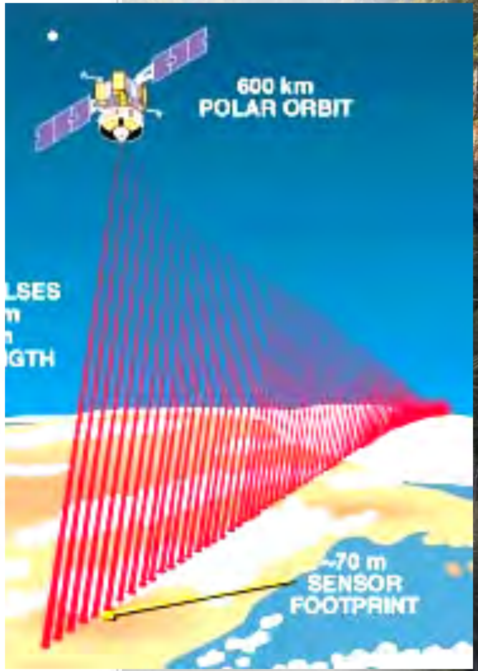
ICESat-2	ICESat
3 sets of profile pairs spread across 6 km	Single beam profile
532 nm micro-pulse photon counting	1064 nm full-waveform





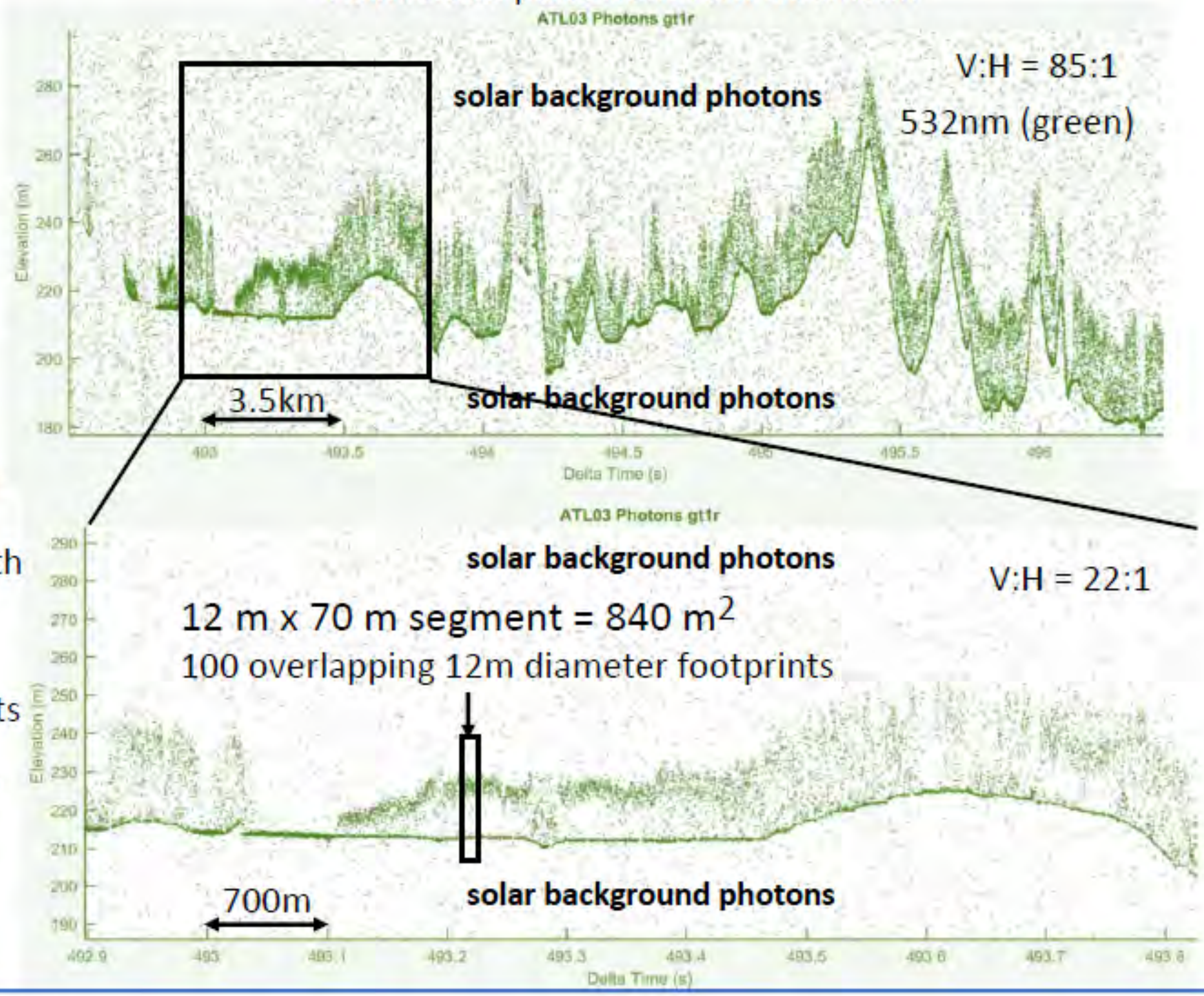


ICESat-2 Photon Point Cloud Profile

Land and Vegetation Height Products (ATL08):

- Single photons classified as ground, within-canopy, top-of-canopy and noise
- Canopy photon height above interpolated ground surface
- 12m x 70m segments (100 laser fires)
  - For all ground photons the min, mean, median, max, mode and skew
  - Ground elevation of inter-polated surface at center of segment
  - Stdev of ground photons with respect to the interpolated surface (roughness)
  - Linear-fit ground slope
  - For all canopy photon heights the centroid, min, mean, median, max and percentile relative heights (RH)
  - For top-of-canopy photons the stdev (roughness)
  - Canopy closure

Point cloud plots from Tom Neumann



Surface Topography and Vegetation
(STV) Incubation Study

Invited Speed Talks on Emerging Lidar Technology

Multi-Aperture and Asynchronous Lidar

Craig Glennie

National Center for Airborne Laser Mapping - University of Houston

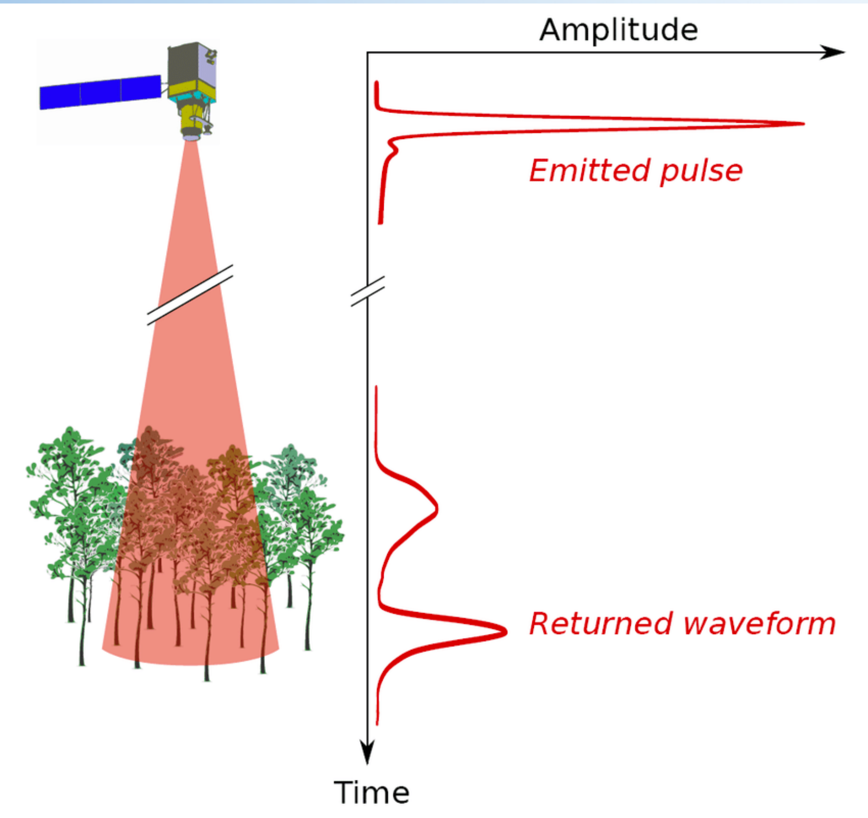
ERDC-CRREL

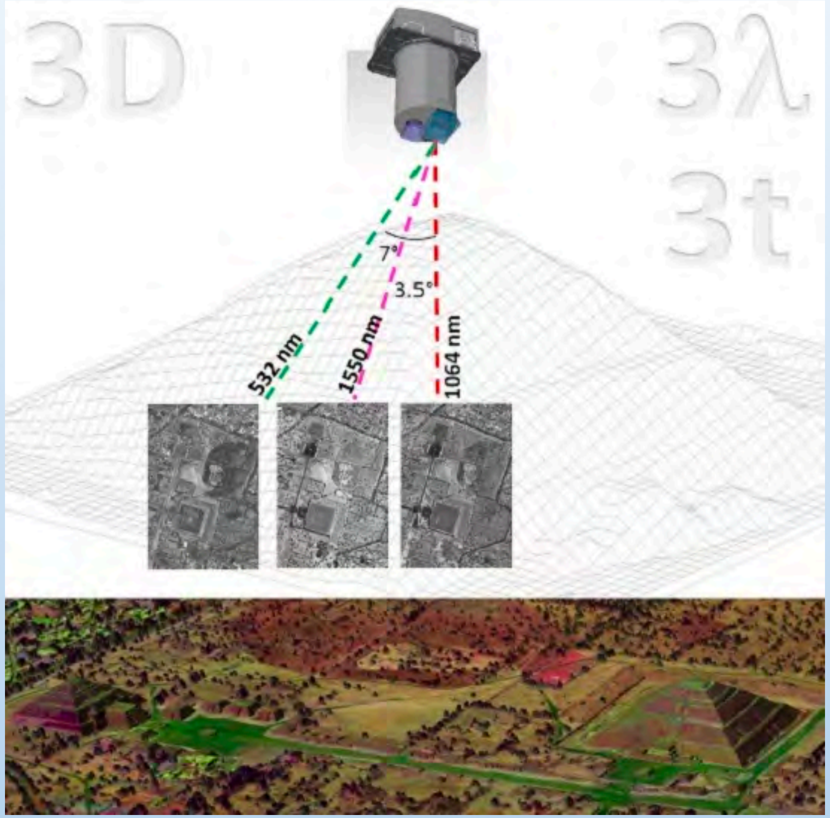
clglennie@uh.edu or Craig.L.Glennie@erdc.dren.mil

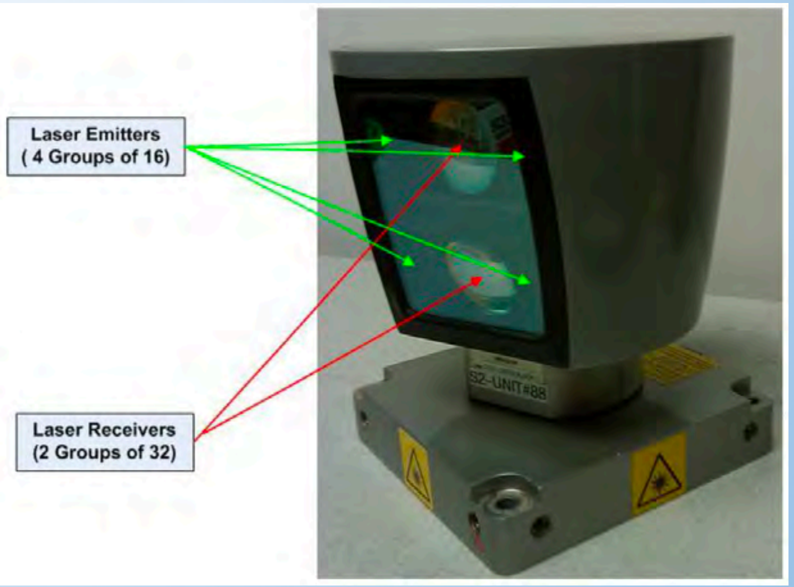
Commercial Linear Mode Systems

- Traditional sensors – one detector for each laser, often same optical path followed for in and out
- Decreased complexity – issues with calibrated intensity due to opposition surge (hotspot effect)
- Not efficient use of lidar energy
- Ability to record full waveform of return

Linear Mode Systems

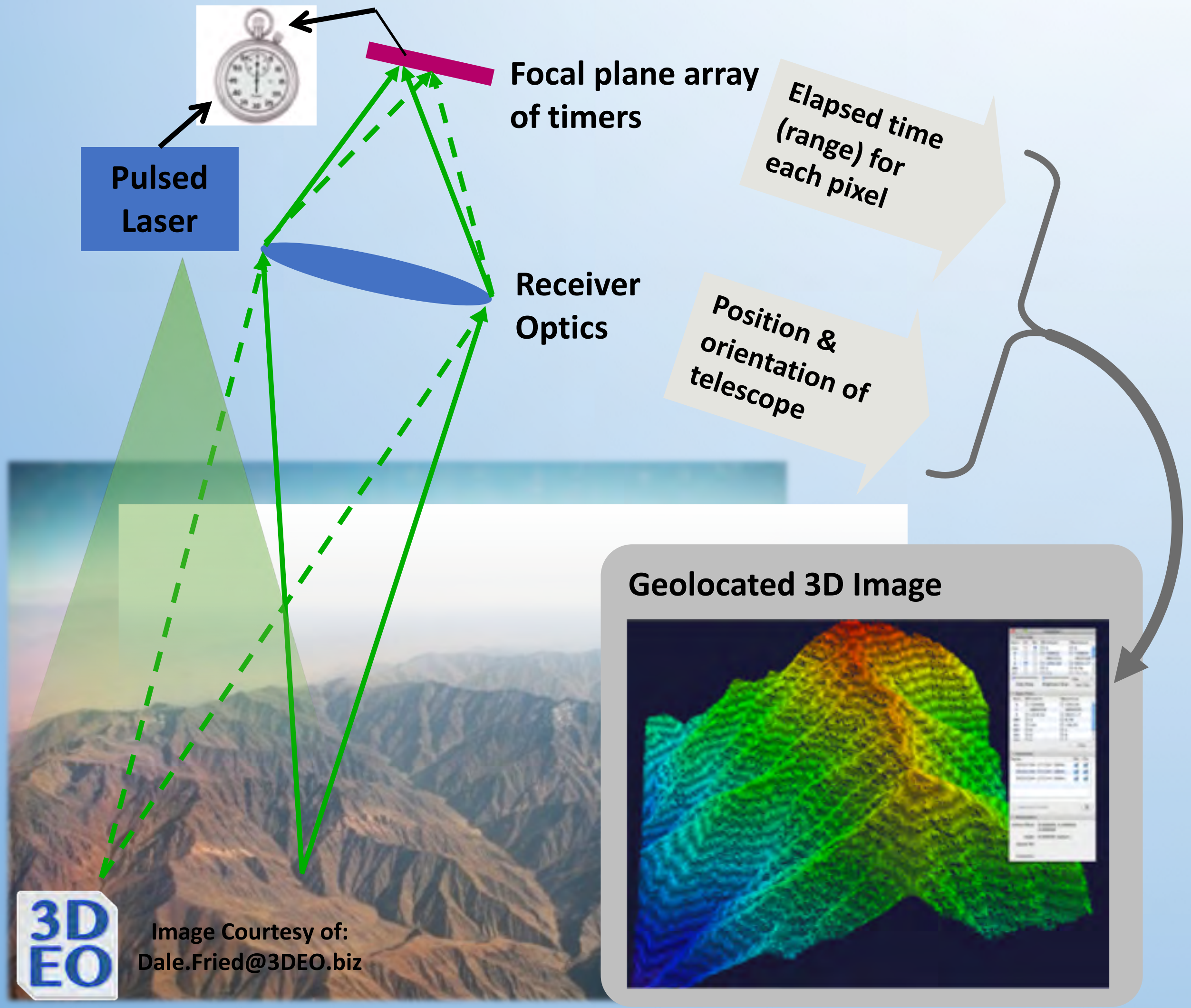




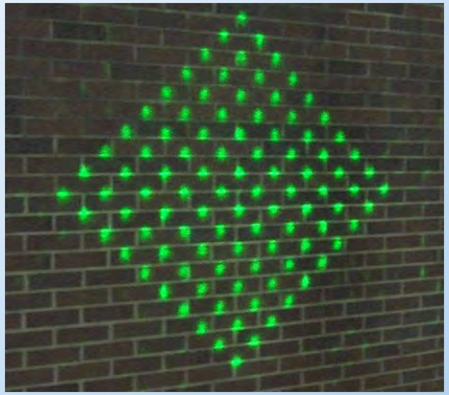


Single Photon Sensitive Systems

Geiger Mode



SPL100 - Hexagon



Next Generation Possibilities

- Newer designs contemplate decoupling the detector and laser
  - More efficient use of photon energy
  - Increase resolution using more detectors per laser
  - Improve redundancy and survivability of systems

Multi-Aperture Space Based LiDAR

Will Allen

HEXAGON | US FEDERAL

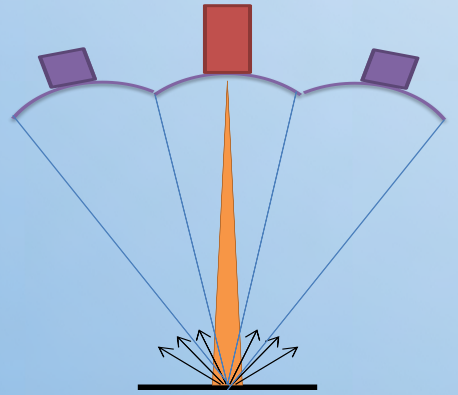
Multi-Aperture Space-based LiDAR

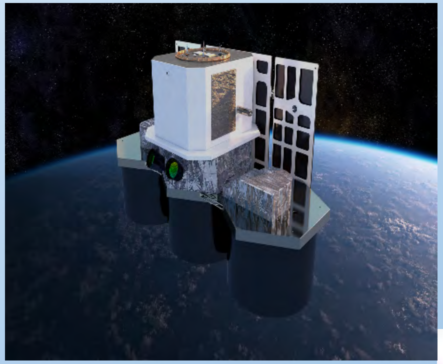
- Manned and unmanned airborne LiDAR systems are invaluable, but are vulnerable to attack from layered air defense systems capabilities in an Anti-Access/Area Denial environment (A2/AD).

- Design and CONOPS for integration into the ABMS Architecture to include integration with other sensor data for Multi-Domain Operations. Planned for Low Earth Orbit (LEO) satellite.

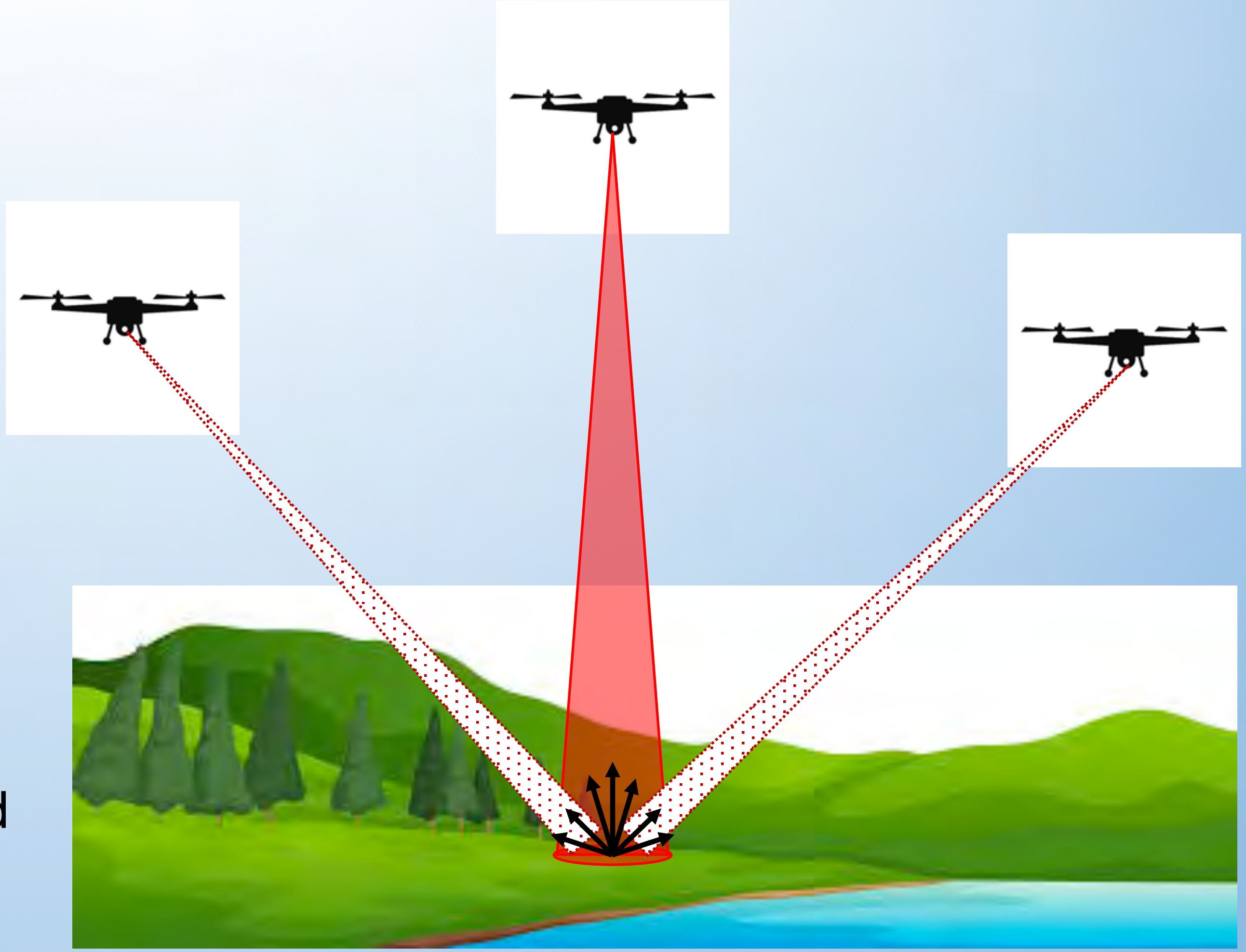
- Overcoming the layered air defense of advanced adversaries dictates the need to produce high resolution, highly accurate elevation data and foliage penetration (FOPEN) from space capable of surveying areas from 100,000m^2 to 1,000,000 m^2 in a single pass with spatial resolution from 1m, 50cm, down to 20 cm.

- Multi-aperture Space-based sensor, satellite, and downlink solution study in 2021 with demonstration Satellite by 2024.





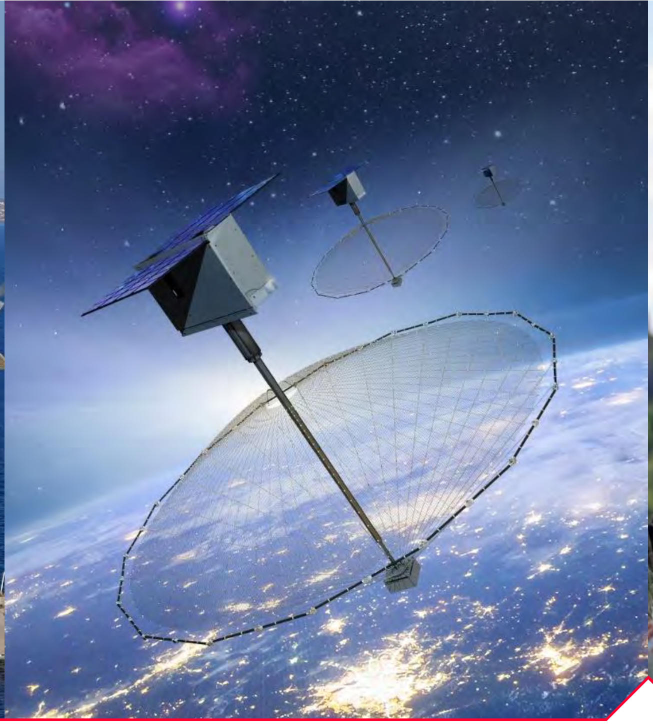
Asynchronous Lidar



- Fully decouple laser and detector
- Subject of NGA SBIR Call in late 2018
  - Phase 1: Overall System Design Development with Numerical Modeling and Simulation (6 months)
  - Phase 2: Experimental Validation (2 years)

Major Barriers to Asynchronous Lidar

- Accuracy of Time Transfer
  - One nanosecond = 30 cm
  - GNSS time transfer shown to be at 10-20 picosecond noise level (ideal).
- Baseline Determination between Source and Detector Drones
  - Realtime differential GNSS accuracy sufficient?
- Pointing Accuracy
  - Requires real-time knowledge of laser pointing
  - Likely require detector arrays to allow coincidence processing

Use of U.S. DoD visual information does not imply or constitute DoD endorsement.

L3HARRIS™

GEIGER-MODE LIDAR FOR STV

An Emerging Technology Overview for the
NASA Surface Topography and Vegetation (STV) Study

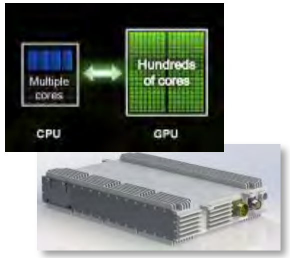
September 8, 2020

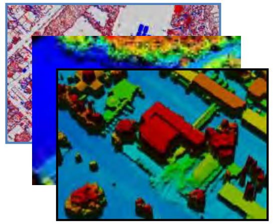
Steven G. Blask, Ph.D. | Sr. Scientist, Geospatial Engineering
Kristian L. Damkjer, Ph.D. | Lead, Software Engineering, Geospatial Software

Invited Speed Talk Outline

- L3Harris Technologies LIDAR Capabilities
- Basics of Geiger Mode LIDAR System Operation
- Example Surface Topography and Vegetation Geiger Mode LIDAR Imagery from Medium Altitude (10-30kft)

L3Harris Geiger Mode LIDAR Systems





Sensor Operations
- Mission Planning
- Flight Scheduling
- Ground Station Comms
- LIDAR Asset Management
- Operation & Maintenance

Sensors
- Radiometric Modeling
- Sensor Modeling
- 1064nm Geiger Mode Terrestrial LIDAR
- 532nm Geiger Mode Maritime LIDAR

Early/On-board Processing
- Sensor Calibration
- Coordinate Transforms
- Noise Filtering & Local Statistic Attribution
- Geo-registration
- Data Compression

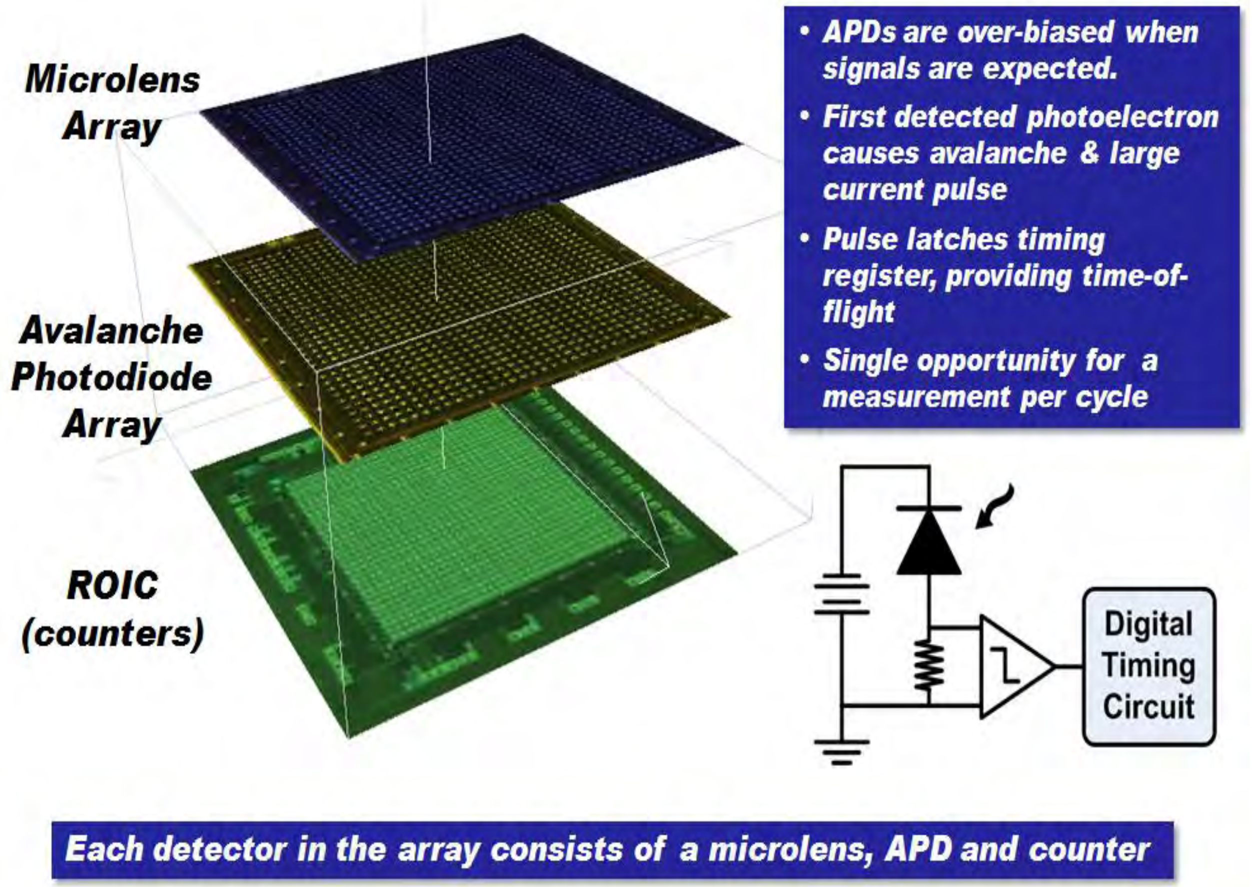
Exploitation
- Target Detection
- Change Detection
- DSM / DTM Generation
- Automated Feature Localization
- Volumetric Analysis
- Data Fusion
- Urban Site Models
- Custom Mission Products
- AI/ML

Data Management
- Scalable Deployed Ground PEDs
- Quality Control
- Custom Product Archives

Data Dissemination
- Factory Enterprise Ground PEDs
- SOA Based Dissemination Tools
- Custom Mission Driven Dissemination

L3Harris provides solutions in all facets of operational LIDAR systems

GmAPD Focal Plane Array Architecture



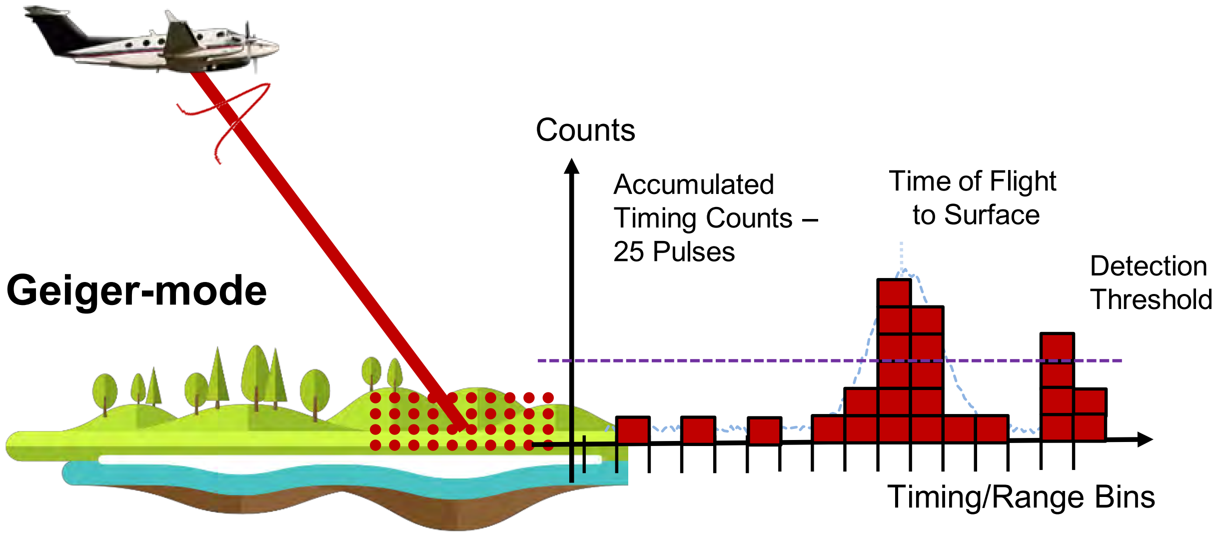
- GmAPD elements are integrated into a package with microlenses and digital timing circuitry to create a compact lidar detector array (32x32 shown, 32x128 COTS, >64x256 coming)
- MIT Lincoln Laboratory technology originally licensed to Princeton Lightwave, Inc., now commercially available from Ball Aerospace
- GmAPD detector arrays make excellent LIDAR receivers for the following reasons:
  - Low Timing Jitter
  - High Detection Sensitivity and Efficiency (low SWaP, better ACR and/or GSD)
  - Compact Detection Circuitry (larger FPA sizes)
  - Low Noise Detection: analog gain noise not an issue, but subject to solar background (use narrow bandpass and ND filters), dark count rate and cross talk (mitigated by processing)
- Commercial cameras being ruggedized to meet airborne Mil Specs, additional investment required for space-based platforms

GmAPD = Geiger-mode avalanche photodiode

Measuring Range Using GmAPD Detection w/ Multiple Pulses

Measure from single pulse

- Sensor illuminates frame (32x128 = 4096 detectors)
- Each detector potentially avalanches and records a measurement at *exactly one* timing bin
- Cannot determine if a single detection by itself is caused by *signal* or *noise*
- Multiple detections in a frame from a single pulse may be from *multiple surfaces*, even though a single detection can only measure a single surface



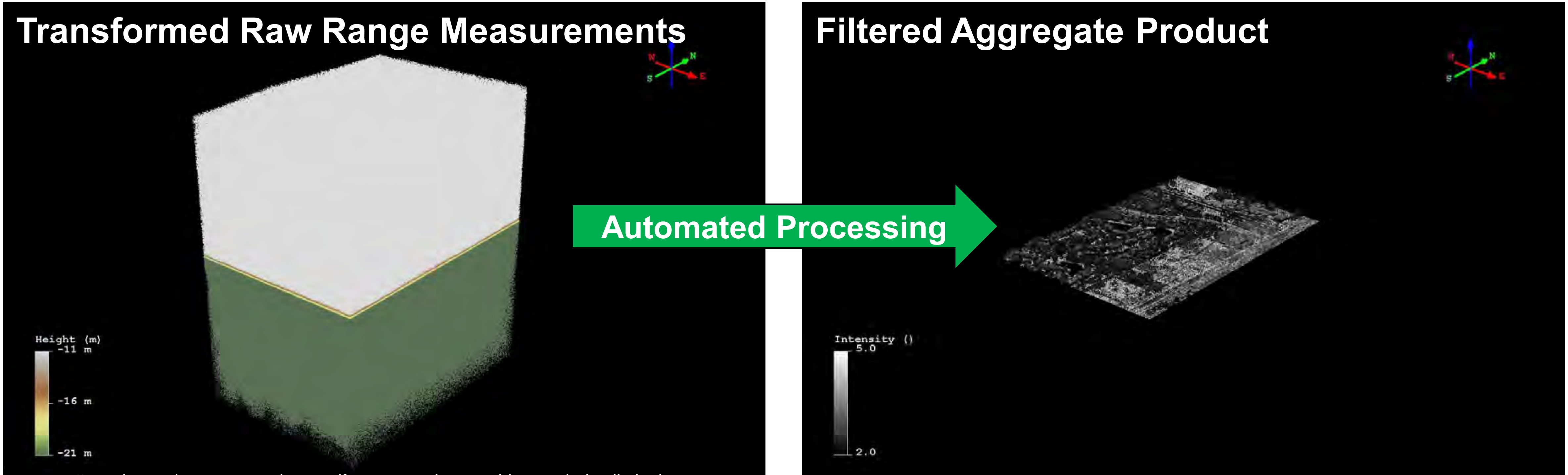
Aggregate signal from multiple pulses

- Resulting timing histogram approximates full waveform signal acquired by linear mode systems
- Identify potential targets via
  - Simple threshold as in linear mode scenario
    - Correlated cross talk noise returns can survive thresholding if the threshold is set too low relative to the number of pulses
  - *More sophisticated processing techniques*
- *Ancillary data can also be computed*
  - Intensity, pulse shaping, backscatter coefficients, etc.

L3Harris' Lidar Production System is designed around

1. Optimizing single pulse detection probabilities to ensure decent dynamic range
2. Tuning number of times an area is illuminated in order to meet production objectives while suppressing correlated/uncorrelated noise

Automated Processing Converts Raw Samples Into Final Product



Raw data only appears to be a uniform mass due graphics rendering limitations.

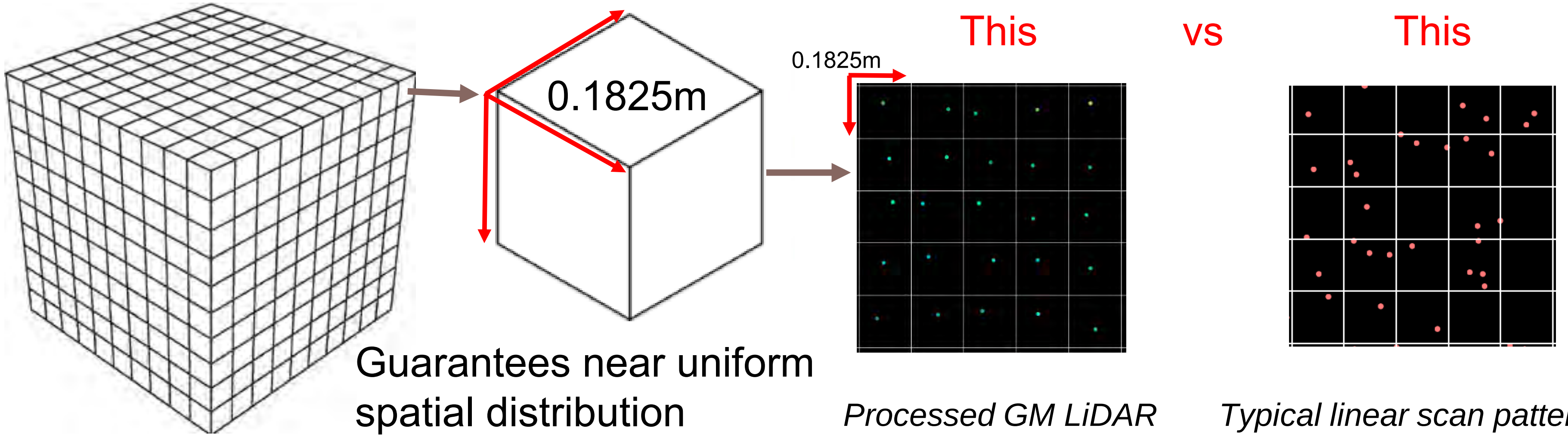
Spatial Distribution and Sample Uniformity

Aggregate consensus model using coincident processing from Geiger-Mode LiDAR frames

- Multiple frames are processed from fore/aft looks, overlapping swaths
- Raw data streams are processed into voxel space in ground coordinate frame
- Hard surface signal detection determined by #samples/voxel
- Resolving power is much higher than conventional systems at equivalent altitudes
- *Product GSD is determined through processing rather than collection*

Example

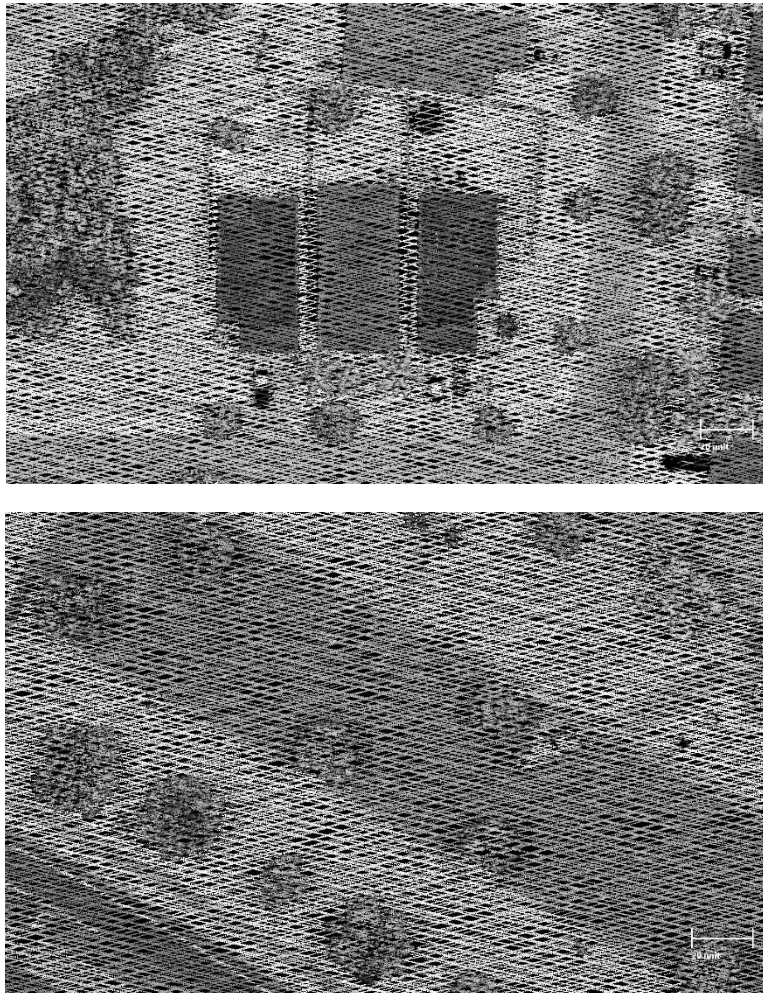
•To create 30 points per square meter calculation is $\frac{1}{\sqrt{30}} \approx 0.1825m$ voxel dimension



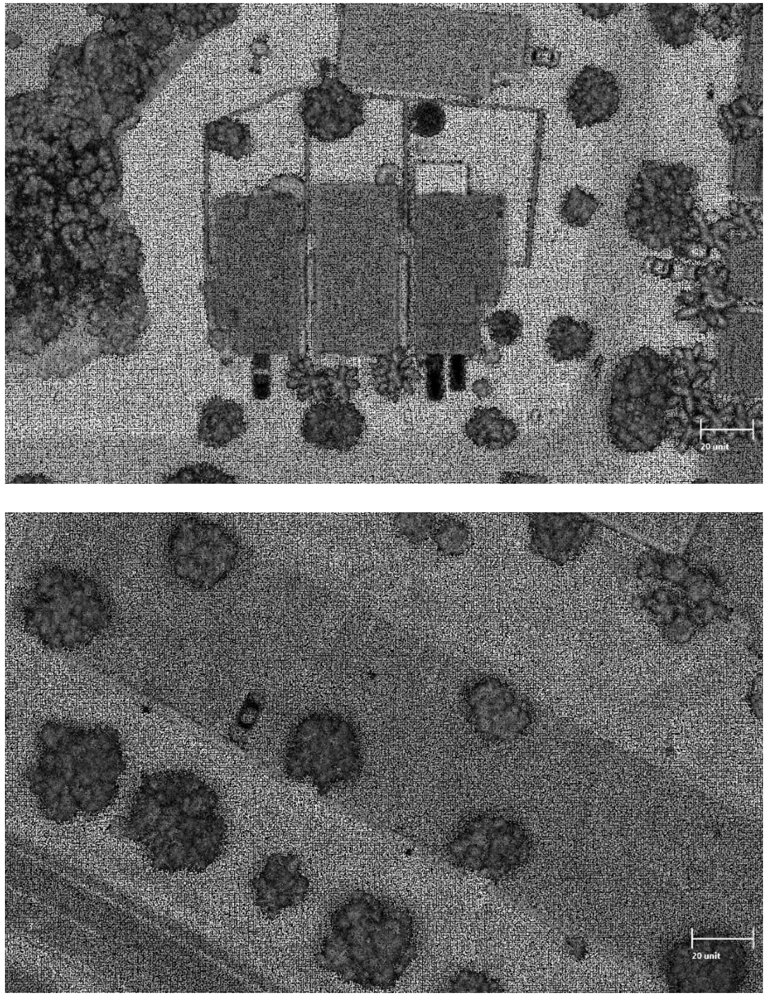
Processed GM LiDAR

Typical linear scan patterns

Spatial Distribution and Sample Uniformity Comparison



Linear-mode LiDAR



L3Harris Geiger-mode LiDAR

Linear-mode:

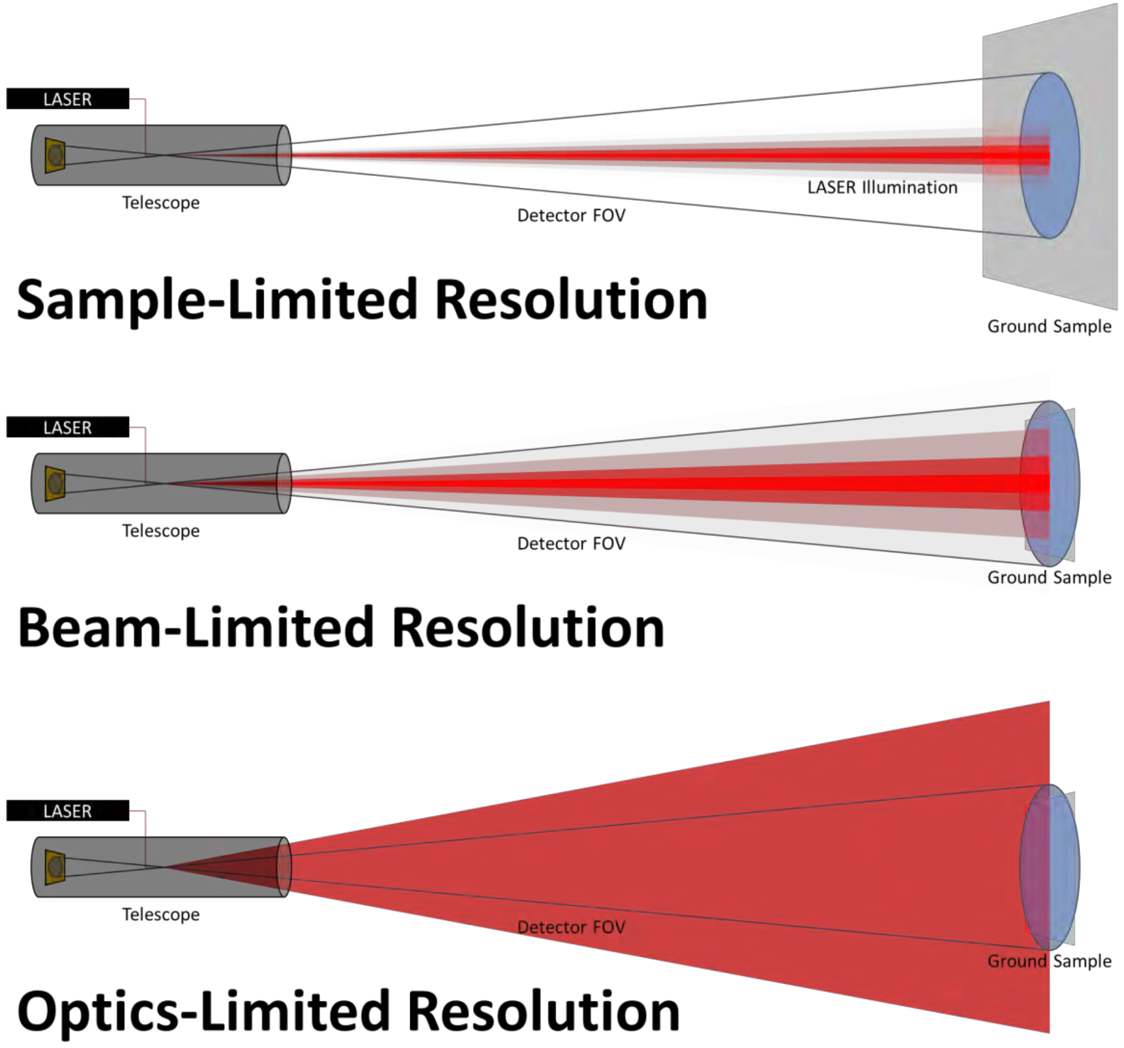
- Uniform sampling in time
- Improve uniformity at ground by modifying platform speed and scan rate
- Very little control over sample spacing pass-to-pass

Geiger-mode:

- Uniform sampling in time
- Array-based detections provide raw detections at several times product density
- Enables stratified sampling to create very uniformly sampled product

Resolution Should be a Concern for High-Res Products

- **Sampling can only limit achievable product resolution.**
- **The maximum product resolution is 2x the ANPS**
  - Assumes that sensor resolution is finer than product sampling
  - Assumes that product is uniformly sampled
- **Resolution depends on several other factors:**
  - LASER Beam Divergence
  - Sensor Optics
  - Diffraction
  - Look Angle
  - Atmosphere



Sampling beyond supported resolution does not improve quality, just increases data volume.

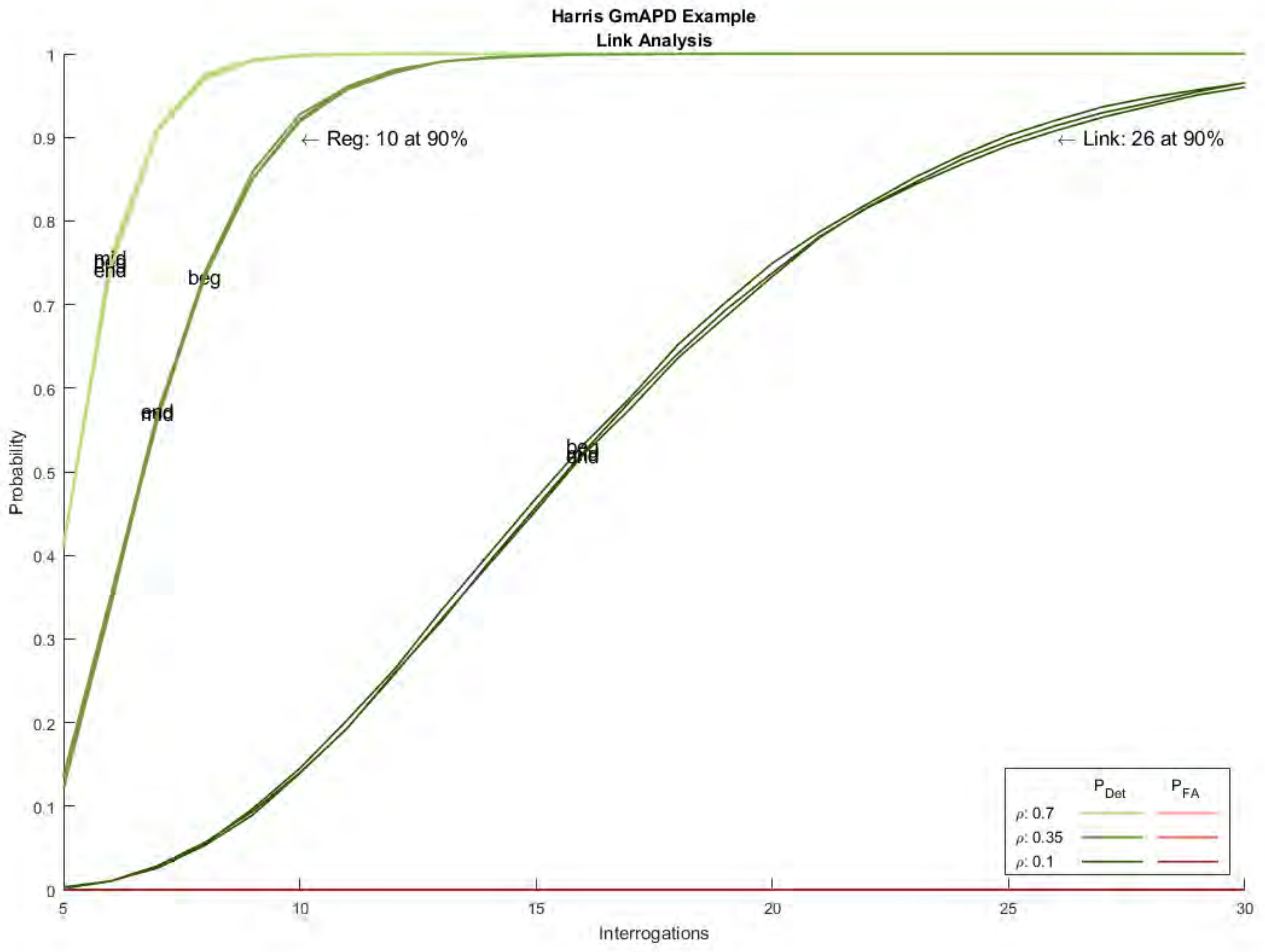
Basic Sampling Requirements Determined Through Link Analysis

Model Components:

- **LASER Pulse Energy**
- **LIDAR Telescope Optics**
- **Detector Array Size**
- **Collection Altitude**
- **Range to Target**
- **Atmospheric Attenuation**
- **Incoherent Background**
- **Cross-Talk**
- **Expected Scene Reflectivities**
- **Target Placement in Range Gate**

Provides:

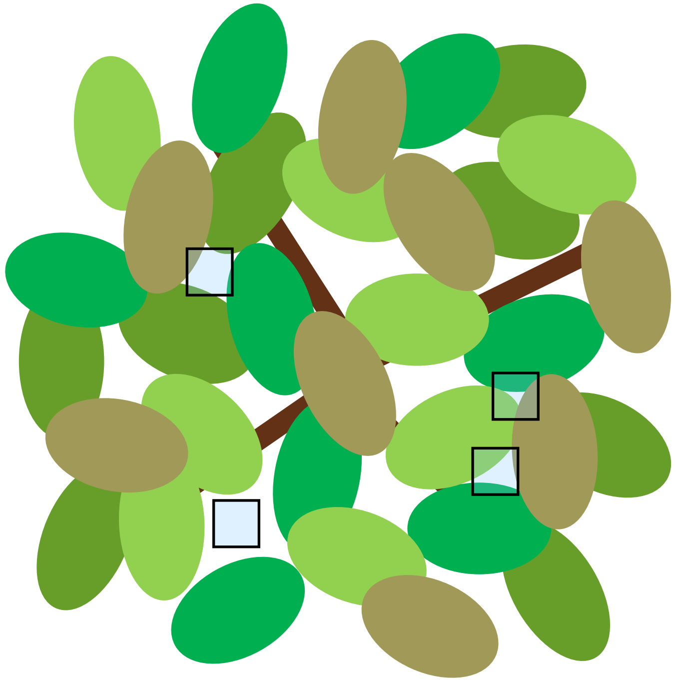
- **Interrogation Limits**
- **Sensor Tuning Parameters**



Foliage Penetration (FOPEN)

Foliage Impacts:

- **Foliage obscures ground, but not uniformly**
- **From detector's perspective, looking through a hole in foliage is just like seeing a primary surface**
- **Smaller detector FOV enables seeing through smaller holes**
- **When partial obscuration dominates, reducing sensor sensitivity allows more returns from ground by attenuating detections from canopy**
- **Look diversity builds up ground surfaces**

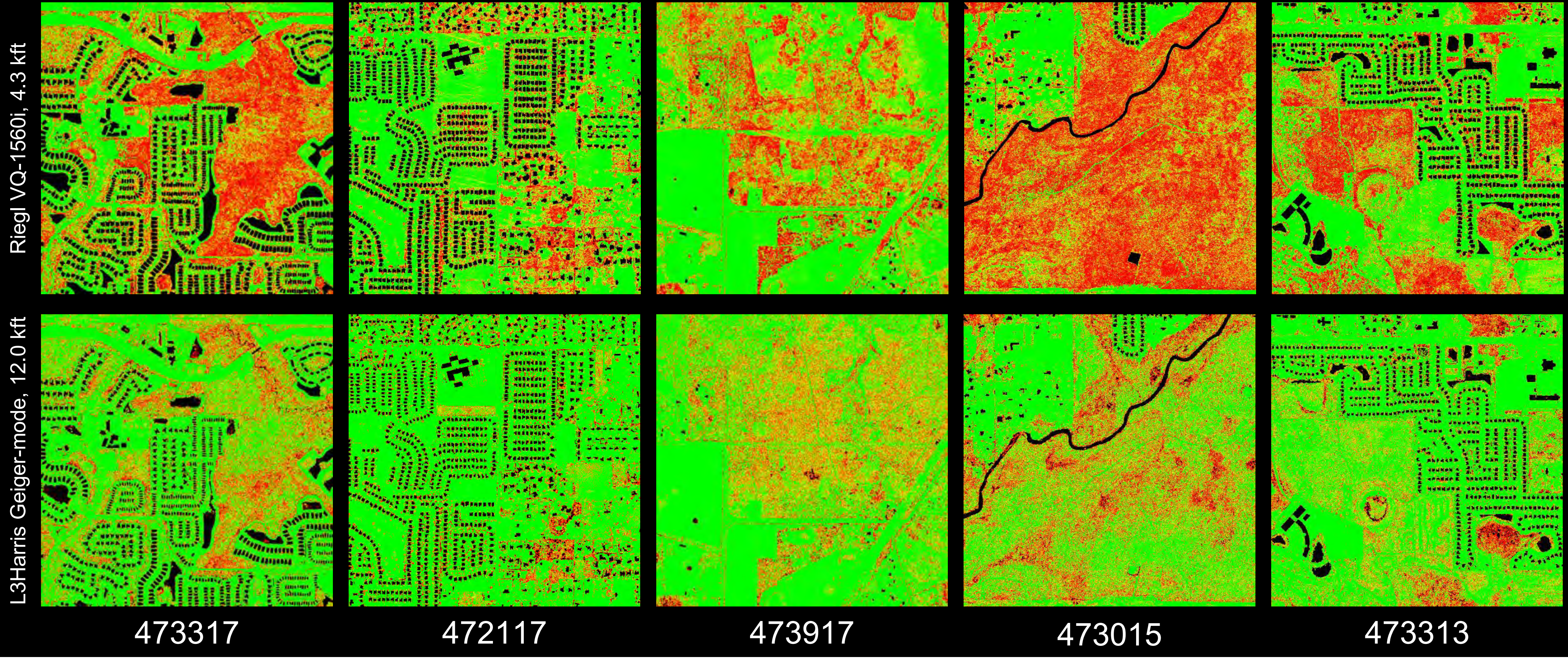


Detectors Relative to Canopy Gaps, Increasing Obscuration

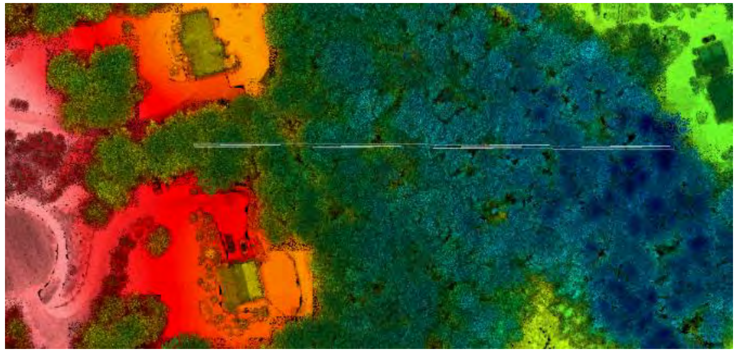
- **Linear-mode systems accommodate for the same effects. Primary difference: poke-through limited by beam divergence instead of detector FOV.**

Qualitative FOPEN Comparison

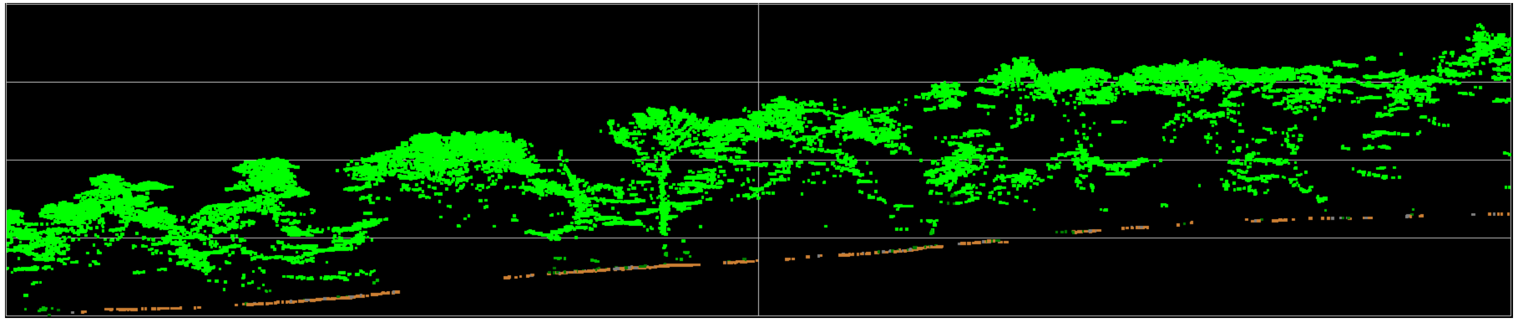
Ground Density Stoplight:
Red: ≤ 6.0 pt/m^2
Green: ≥ 24.0 pt/m^2

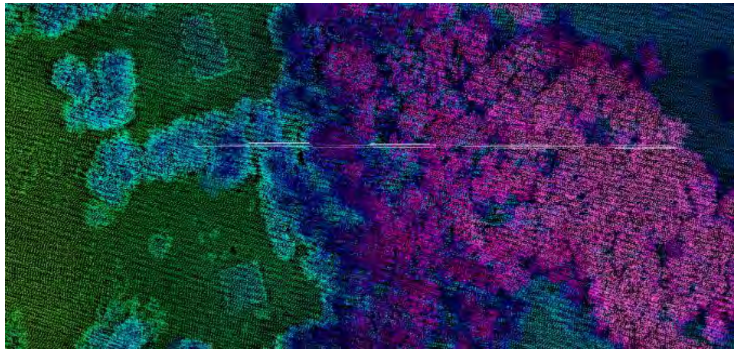


USGS Test Site Comparisons
Foliage Penetration - 1m Cross-Section

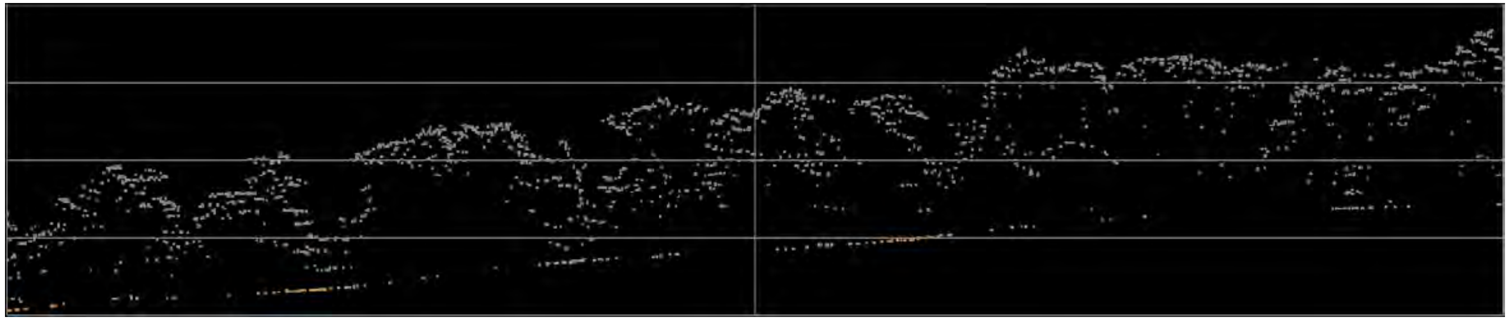


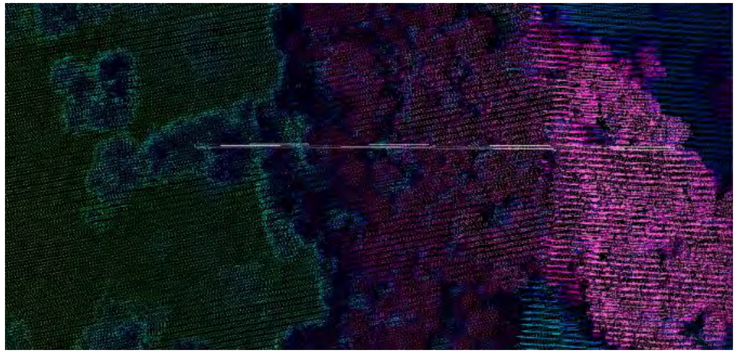
L3Harris Geiger 12,000 ft AGL 30PPSM Leaf On



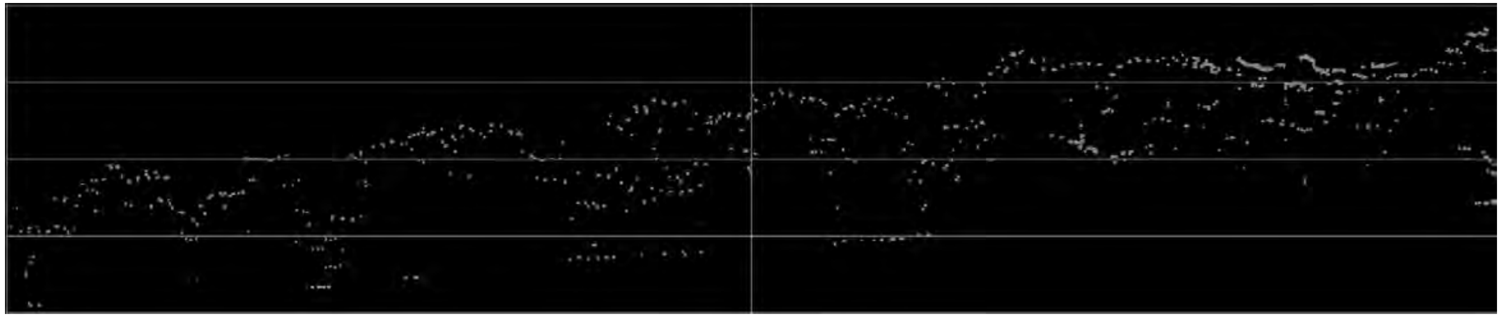


Riegl 680i 3,000 ft AGL 8PPSM **Leaf Off**

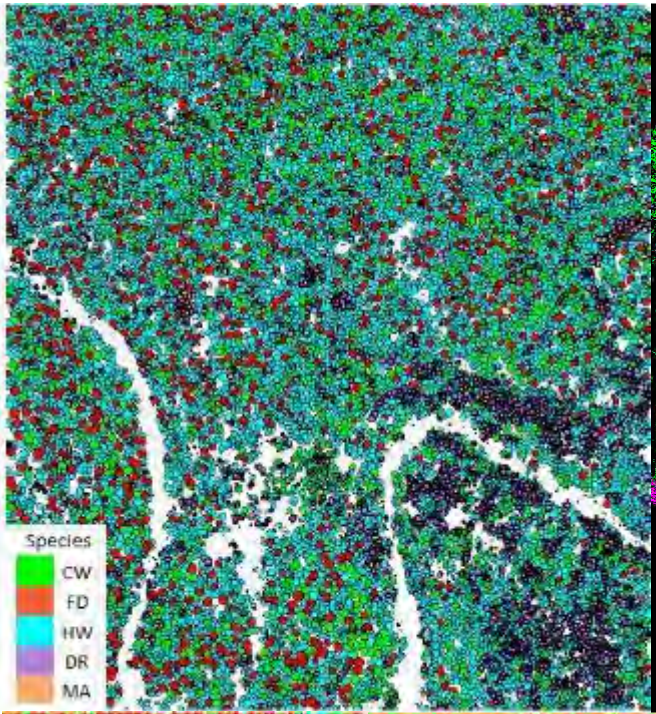


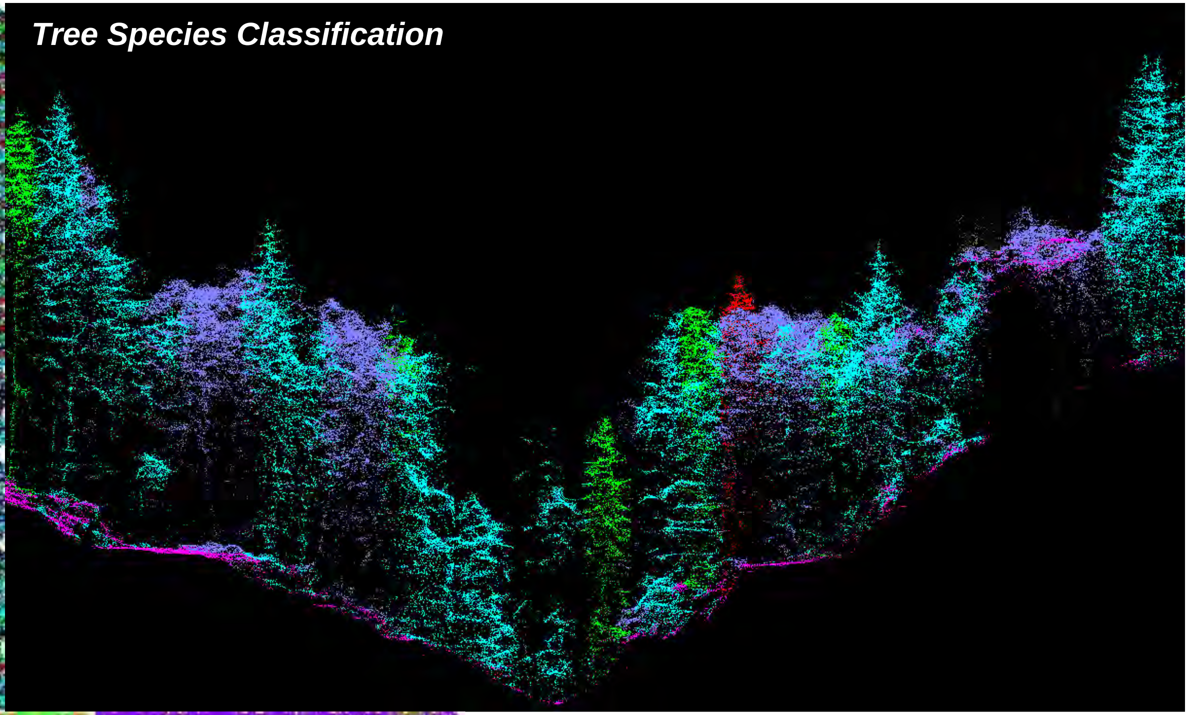


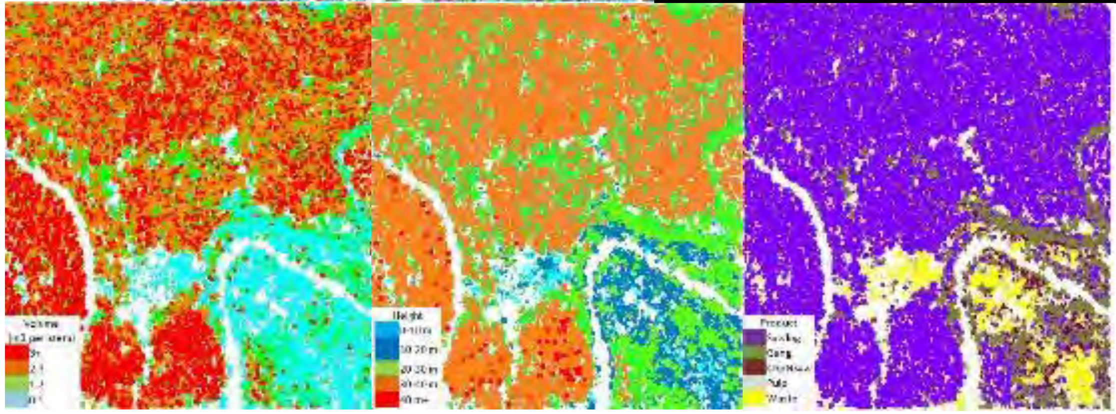
Leica ALS70 7,000 ft AGL 2PPSM Leaf On



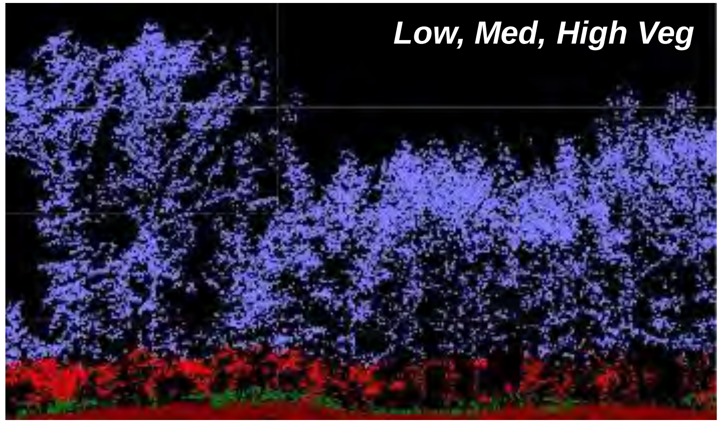
Example Vegetation Analysis Products
(3rd Party Forestry Analytics on L3Harris GM Data)







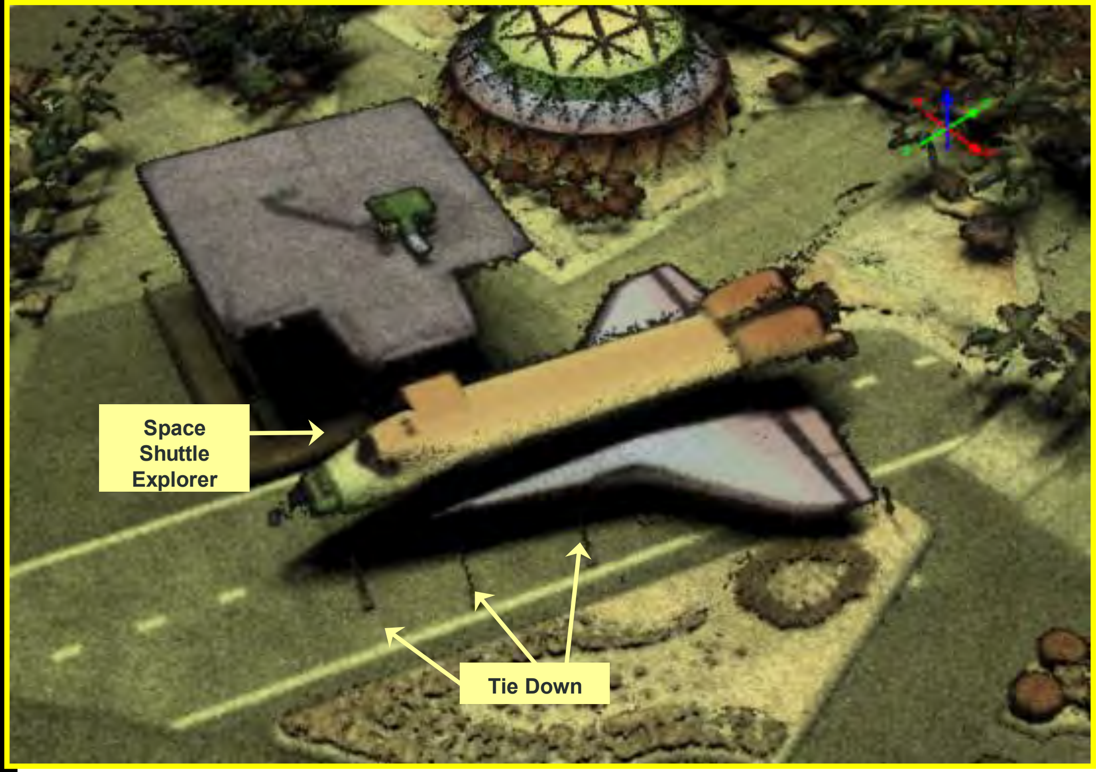
Volume Height Product



Imagery from L3Harris IntelliEarth™ LIDAR

Example Point Cloud - High Resolution

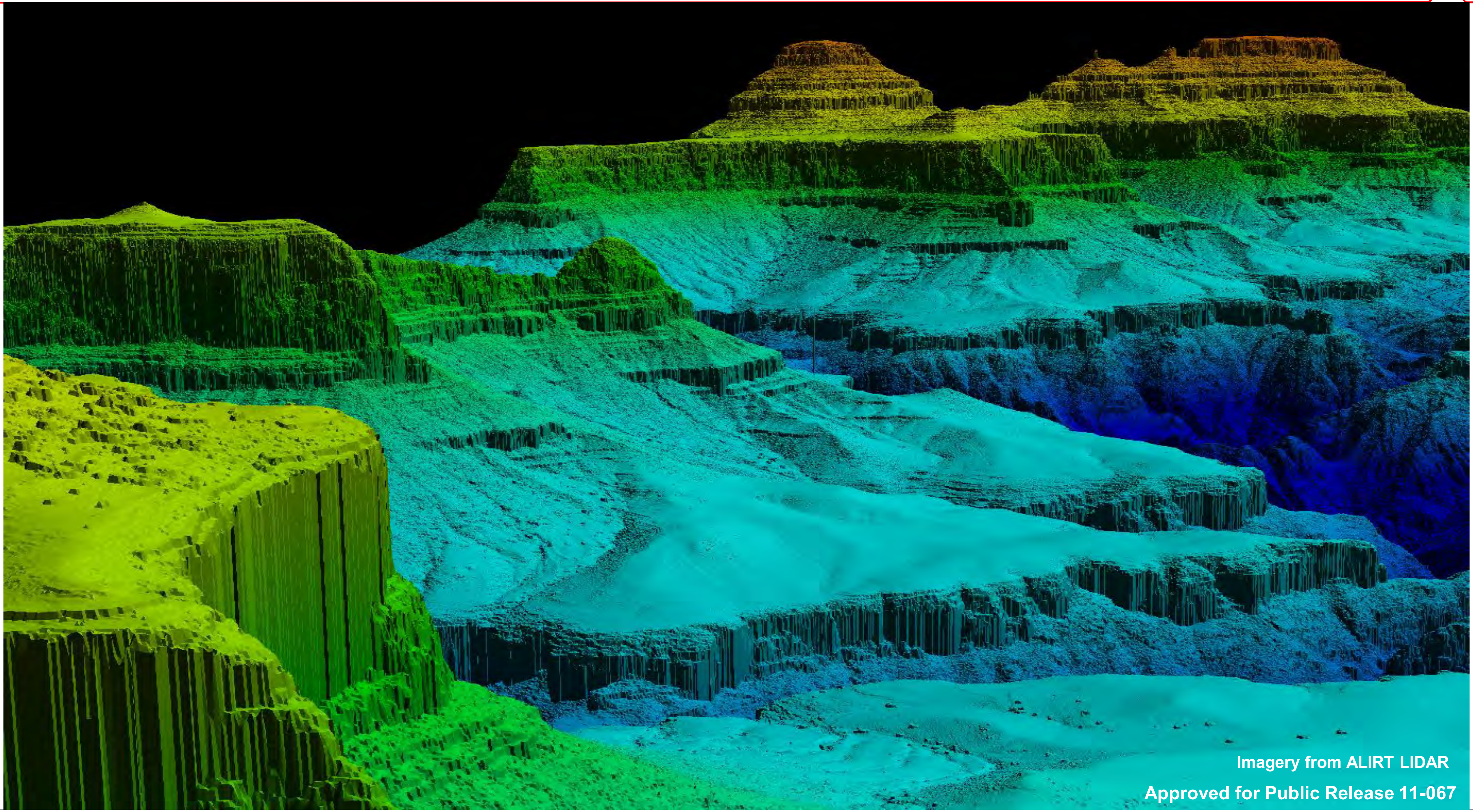
Lidar Point Cloud at 5cm post-spacing
Color Coding by Z Coordinate & Intensity



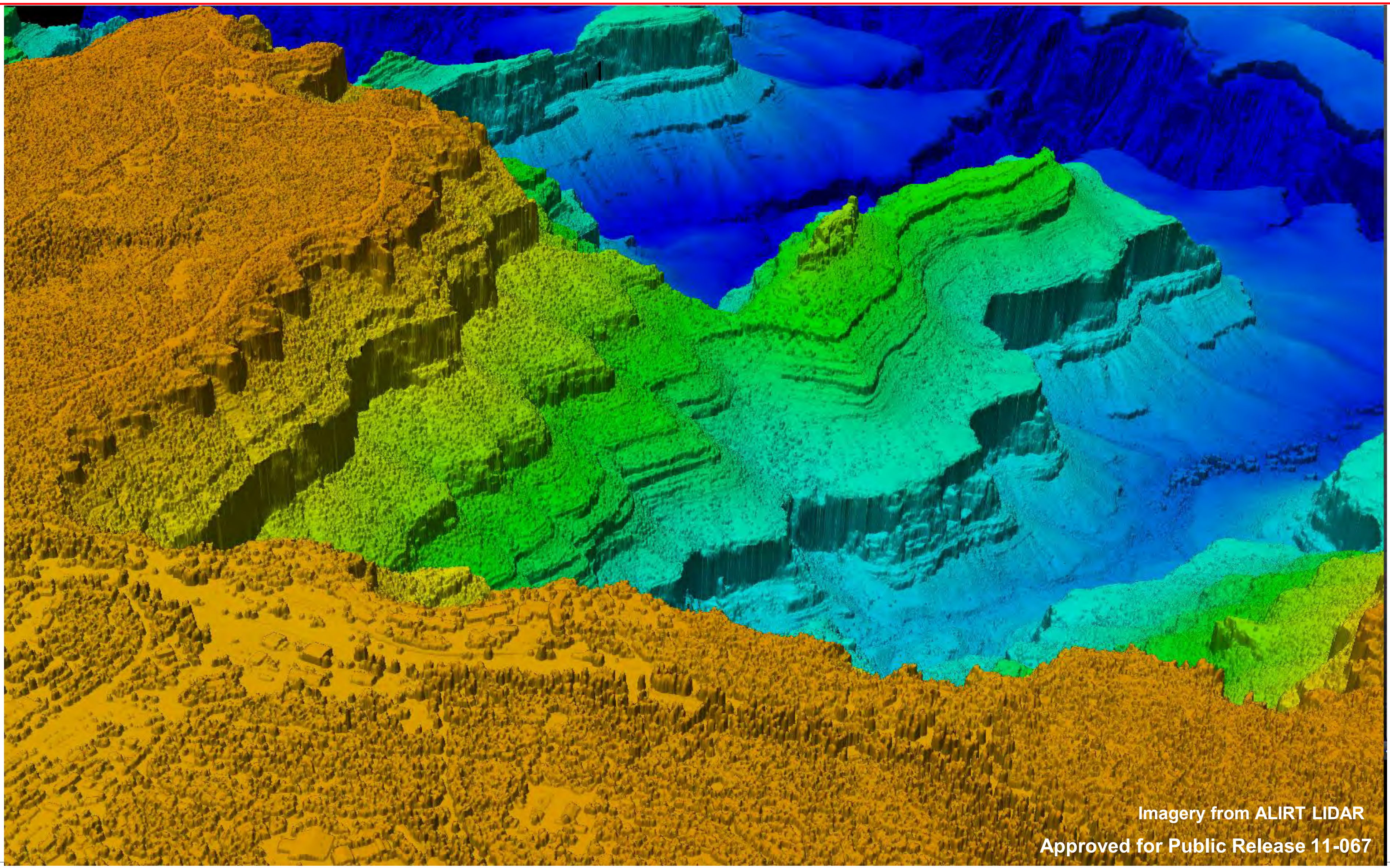
Approved for Public Release 11-067

Imagery from ALIRT LIDAR

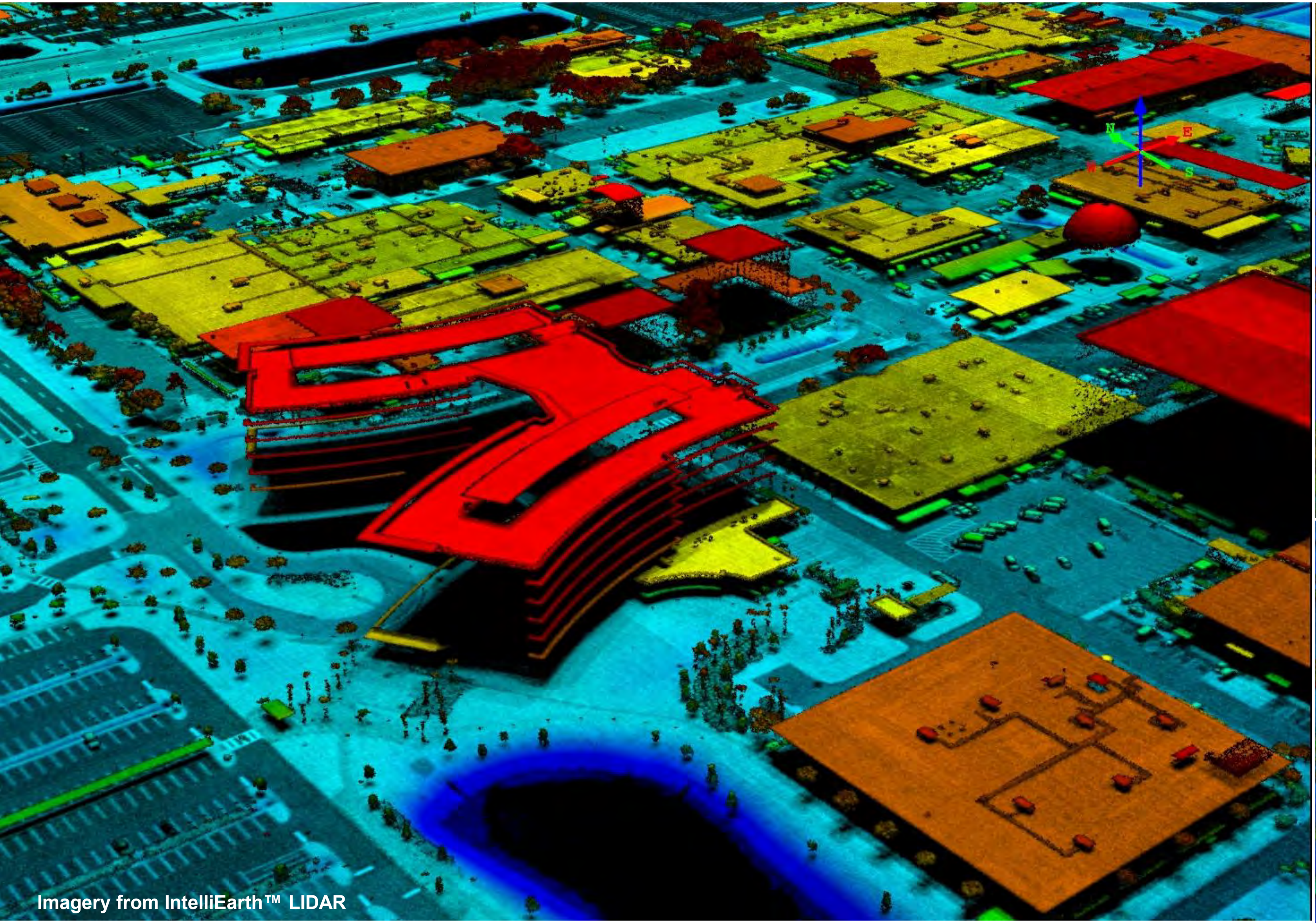
Example DSM - High ACR

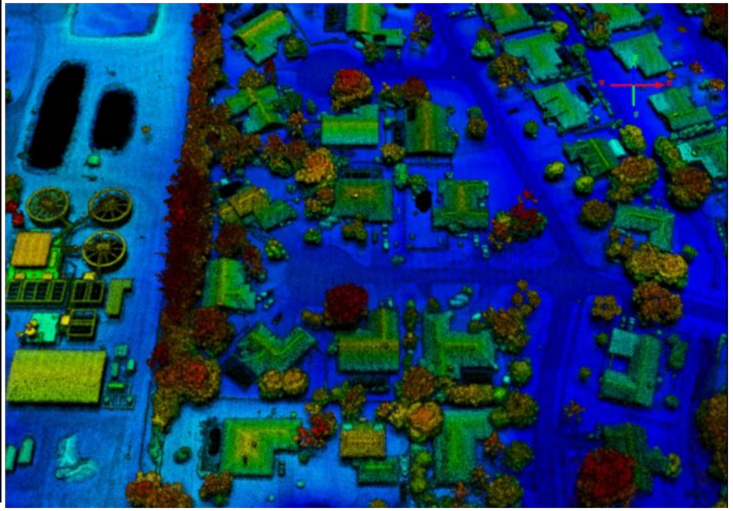


Example DSM - High ACR

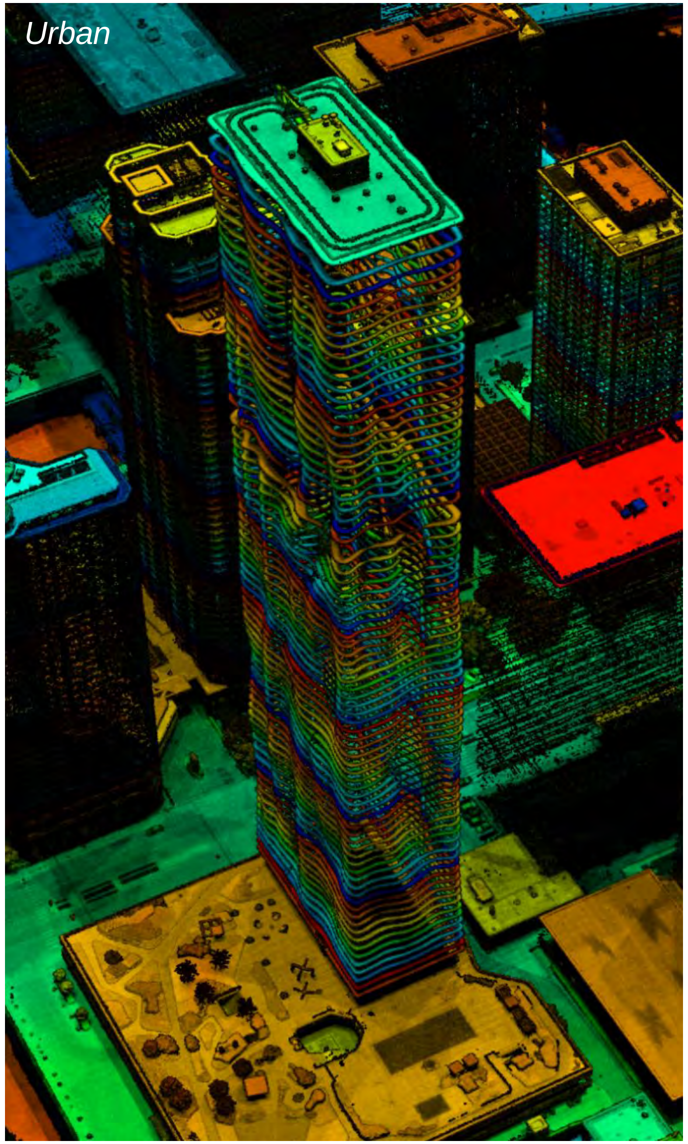


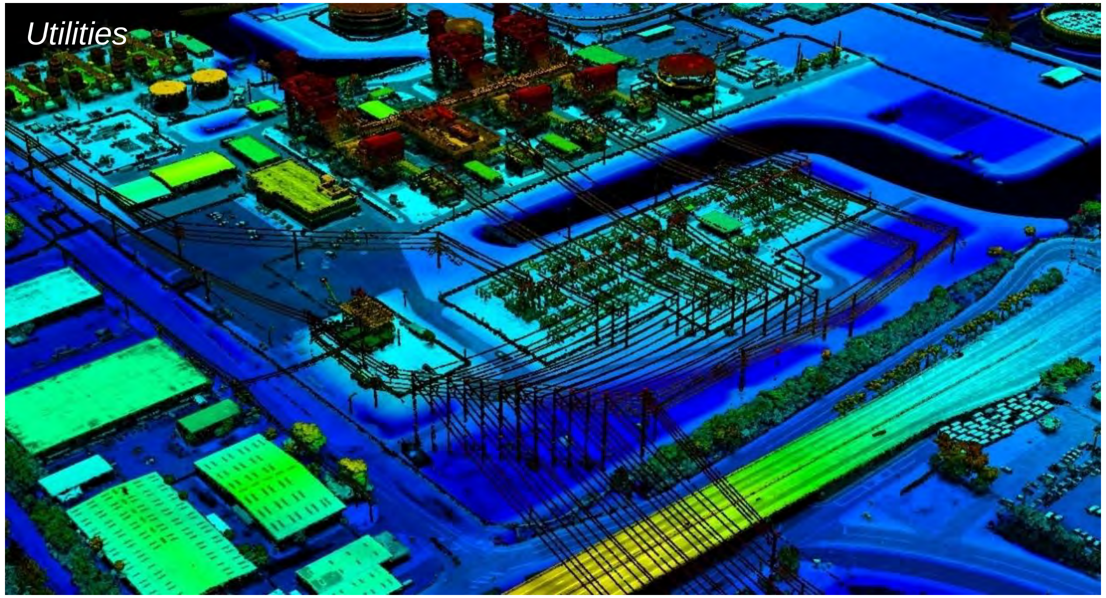
Example Point Clouds - High Resolution and High ACR

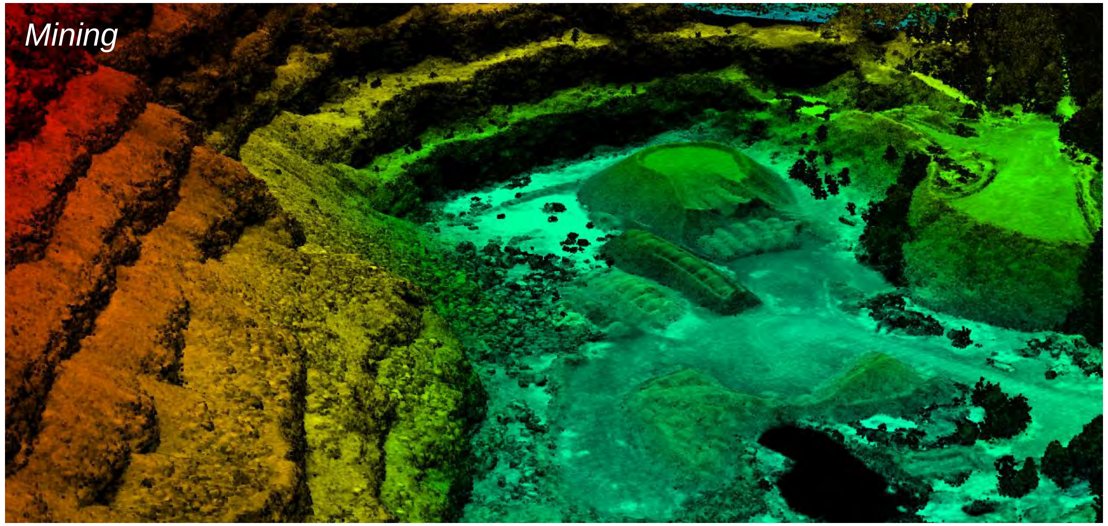




Example Point Clouds - High Resolution and High ACR

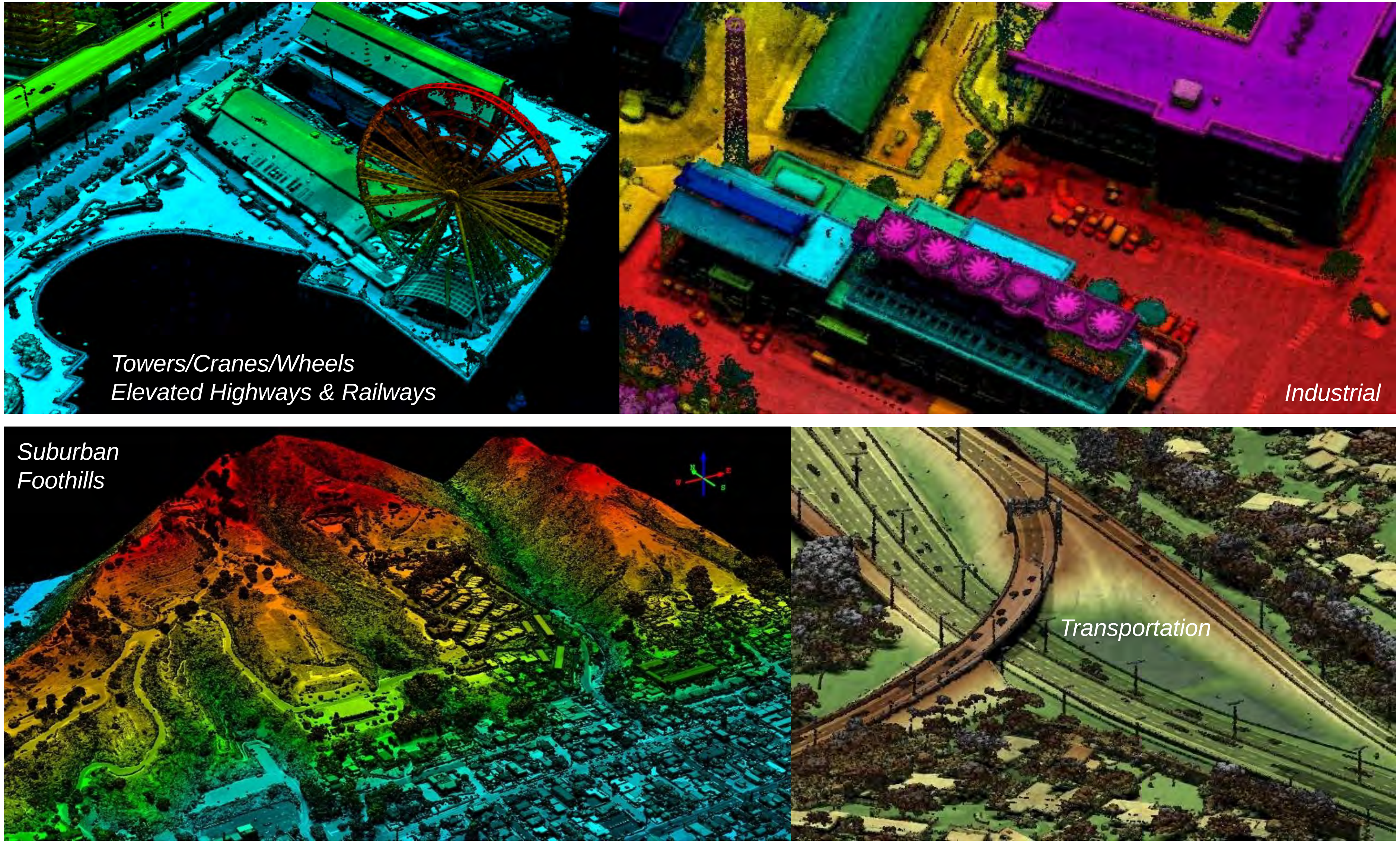






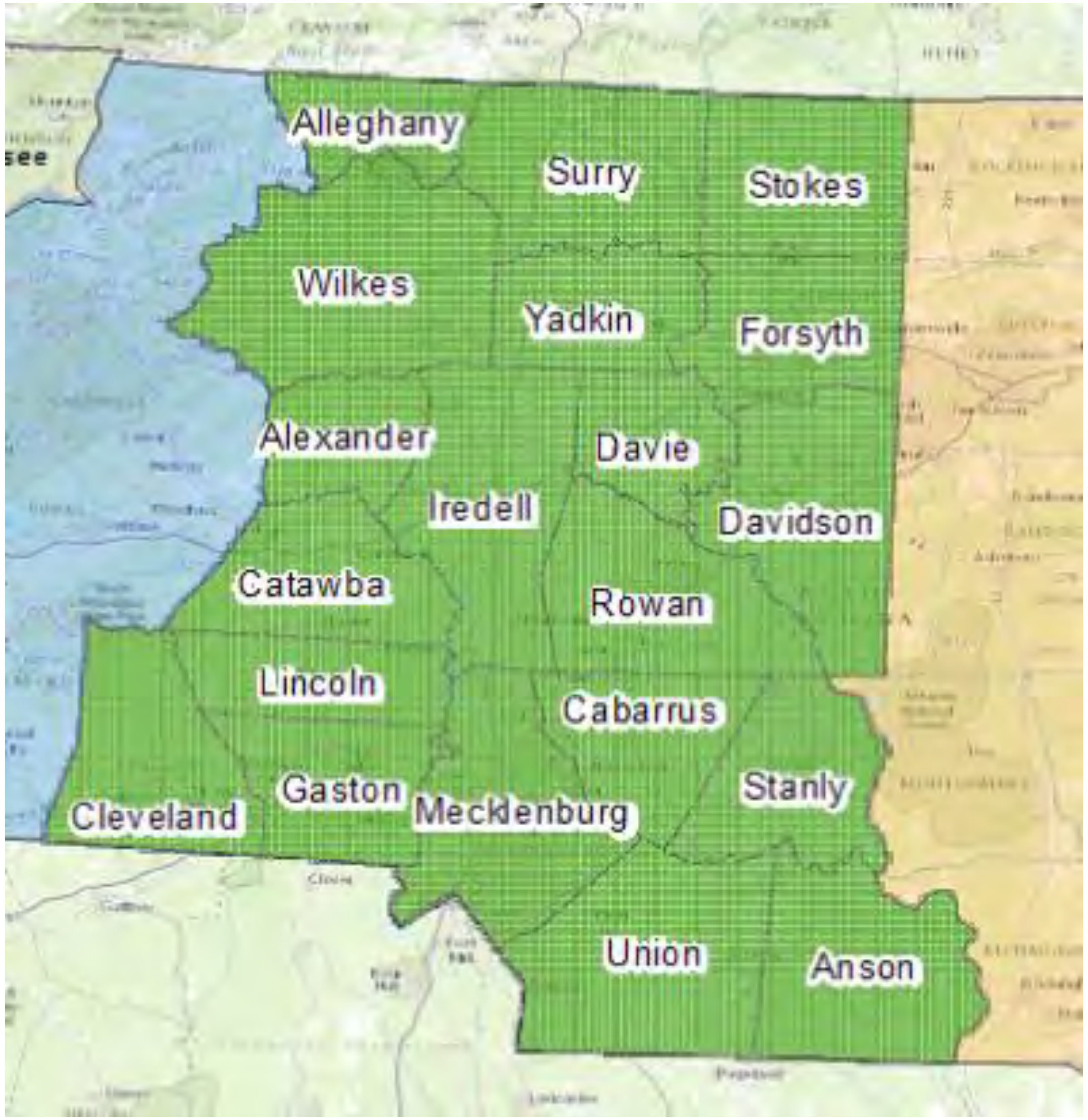
Imagery from L3Harris IntelliEarth™ LIDAR

Example Point Clouds - High Resolution and High ACR



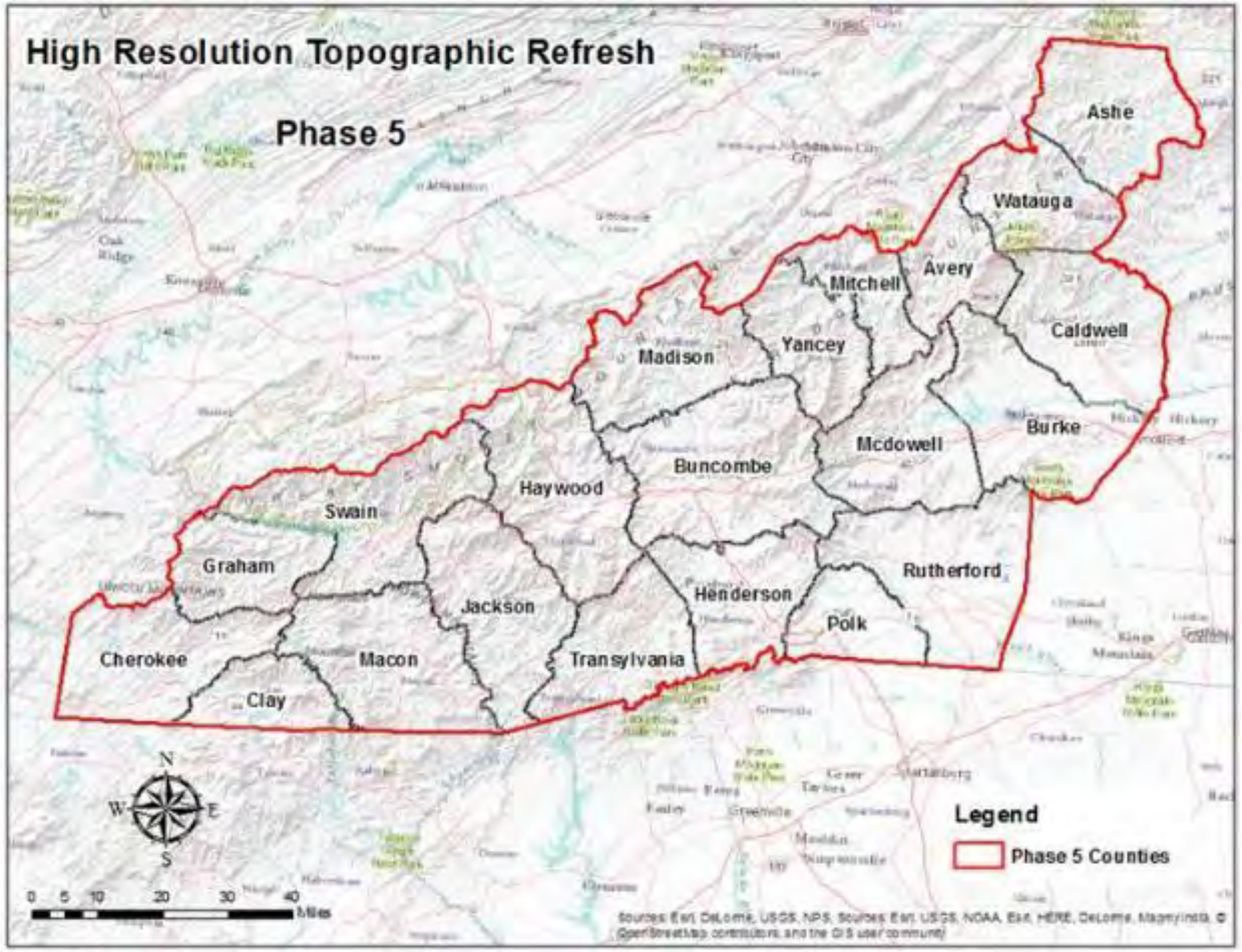
Imagery from L3Harris IntelliEarth™ LIDAR

North Carolina Phase 4 & 5 (State & Local Gov't)

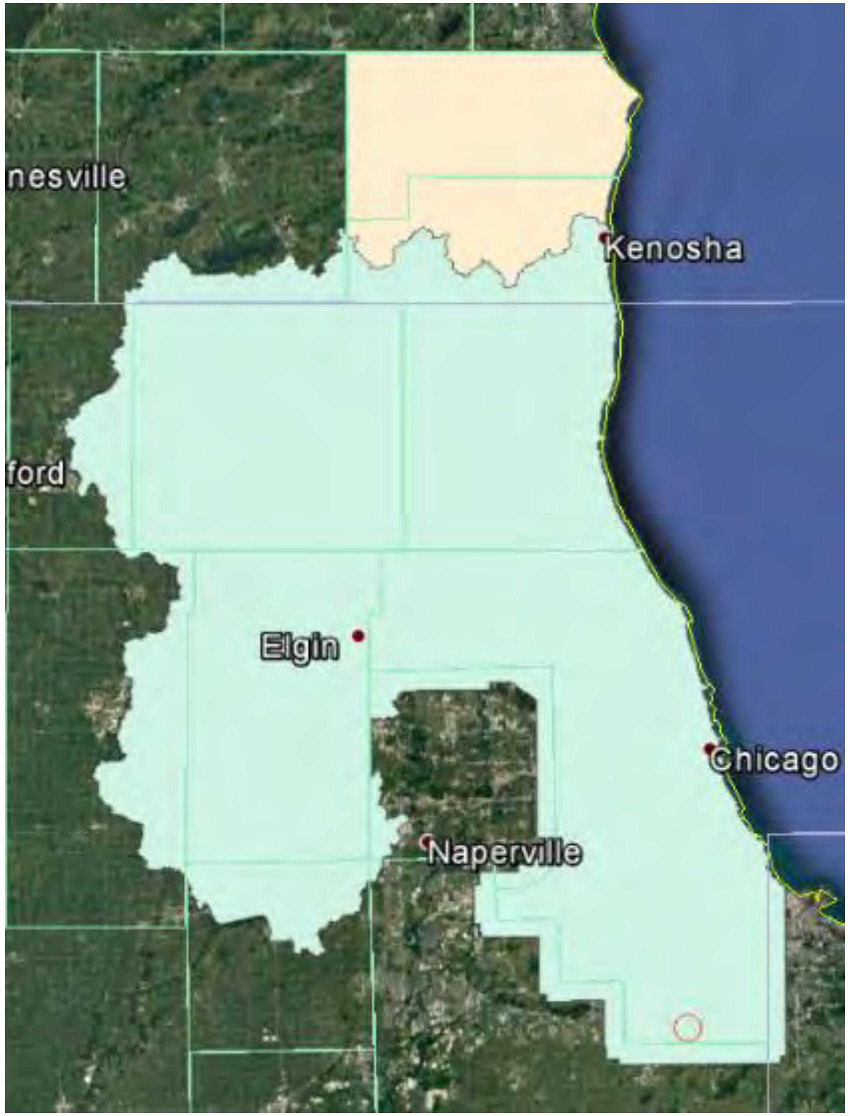


Collected and processed 40 Counties

Total: 18,700 mi² / 8 ppsm (pts per sq meter)



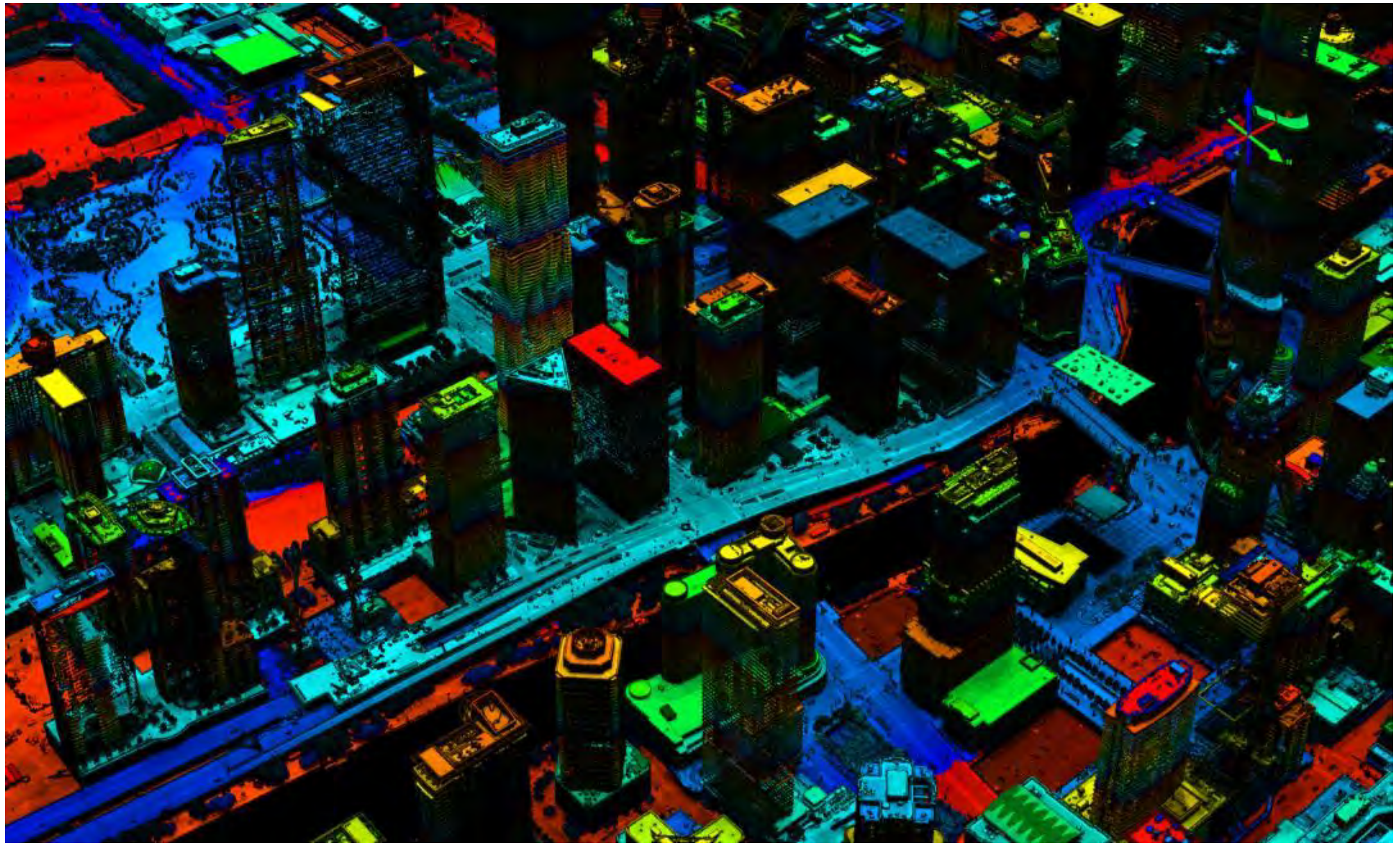
NE Illinois/SE Wisconsin (USGS/State & Local Gov't)



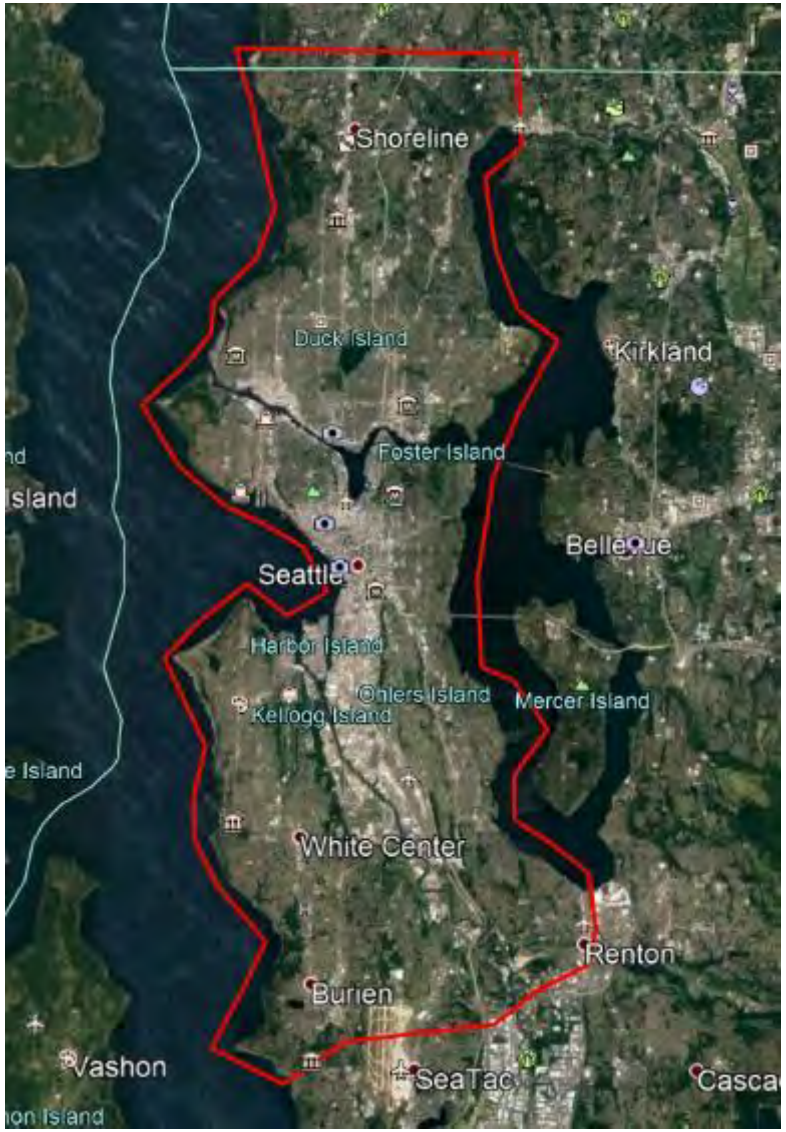
NE IL 4 Counties (Cook, Kane, Lake & McHenry) 3,313 mi^2

SE WI (Racine & Kenosha) 503 mi^2

Total: 3,816 mi^2 / 20 ppsm

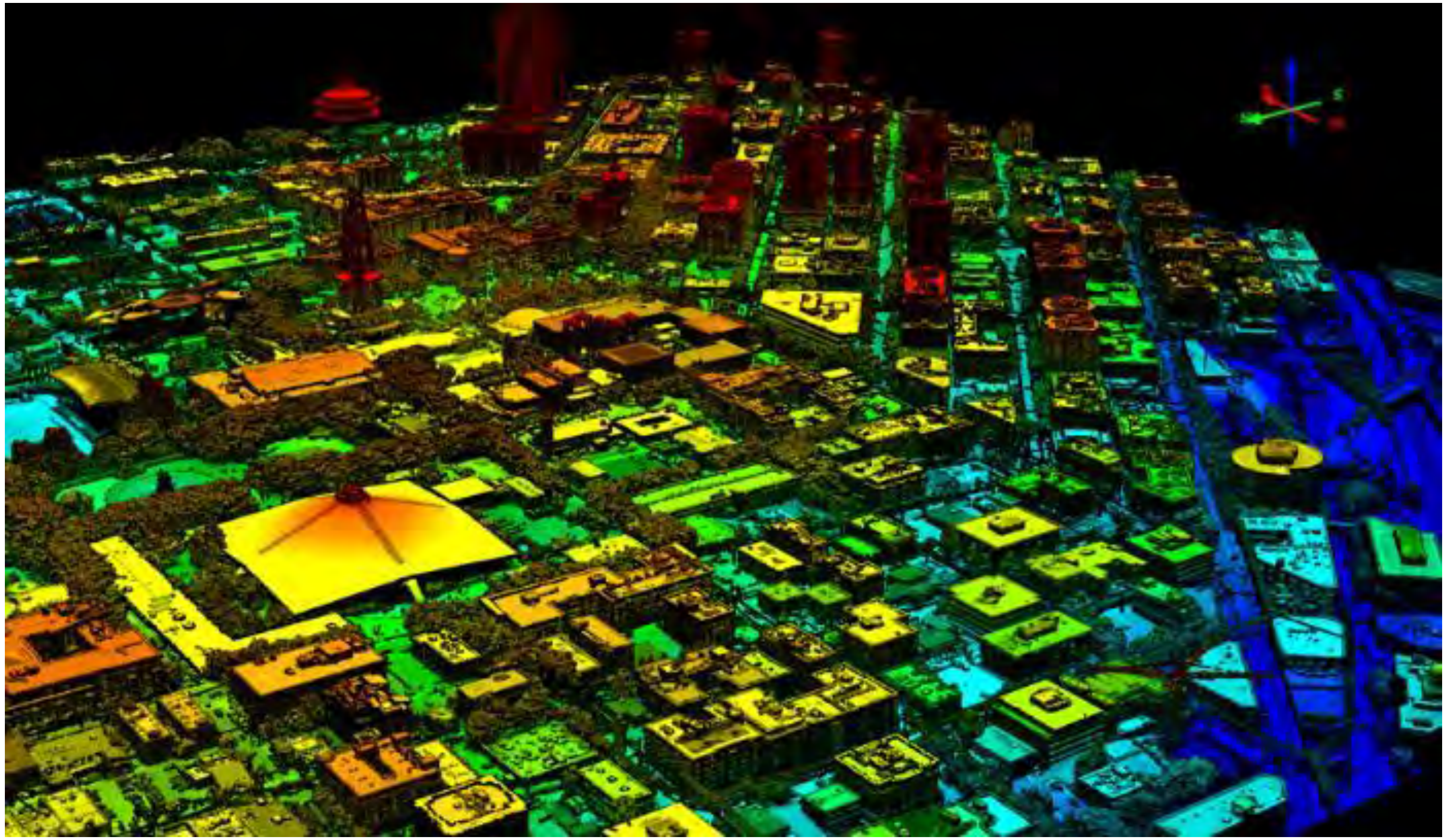


Utility Pilot

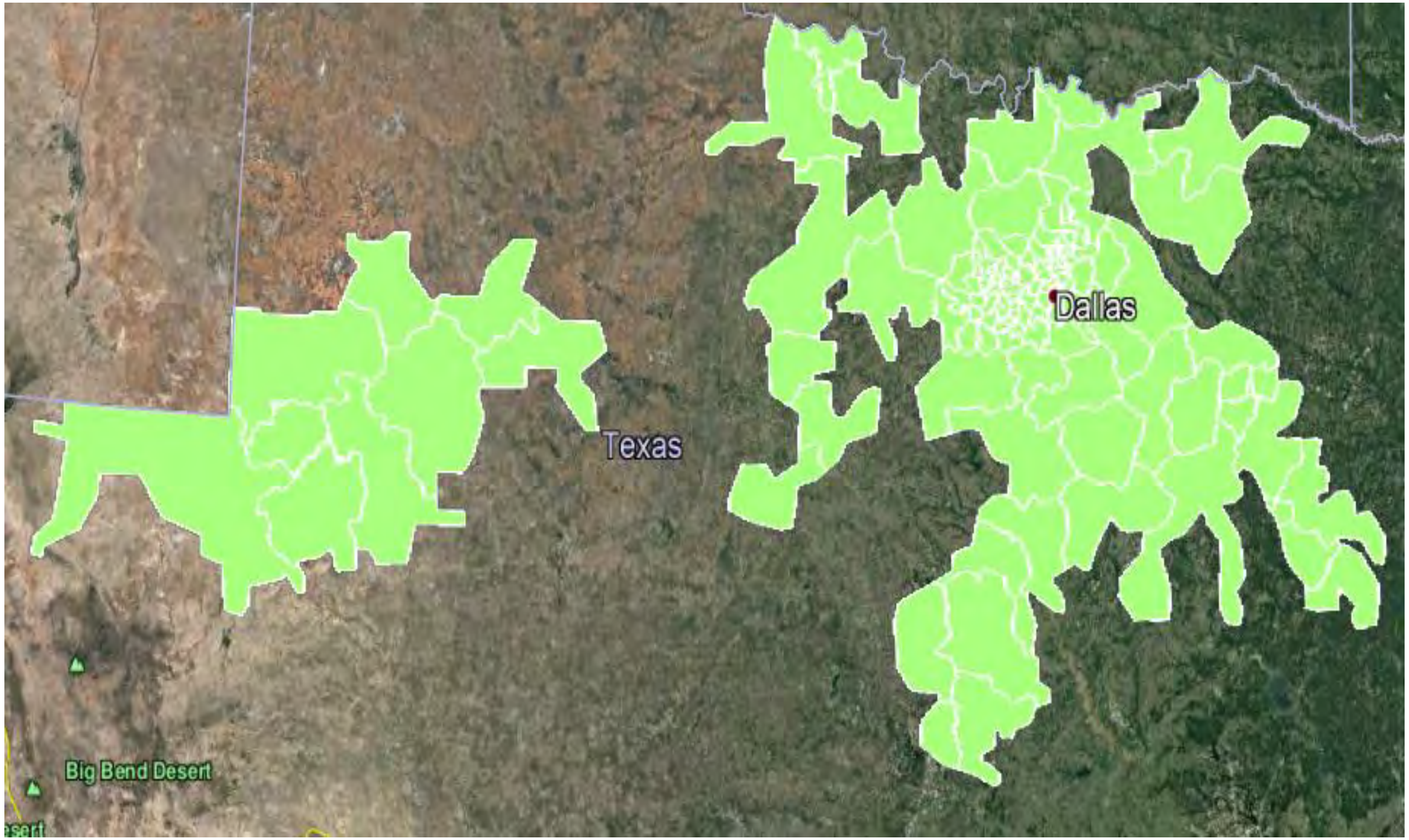


Collected and processed

Total: 130 mi² / 30 ppsm



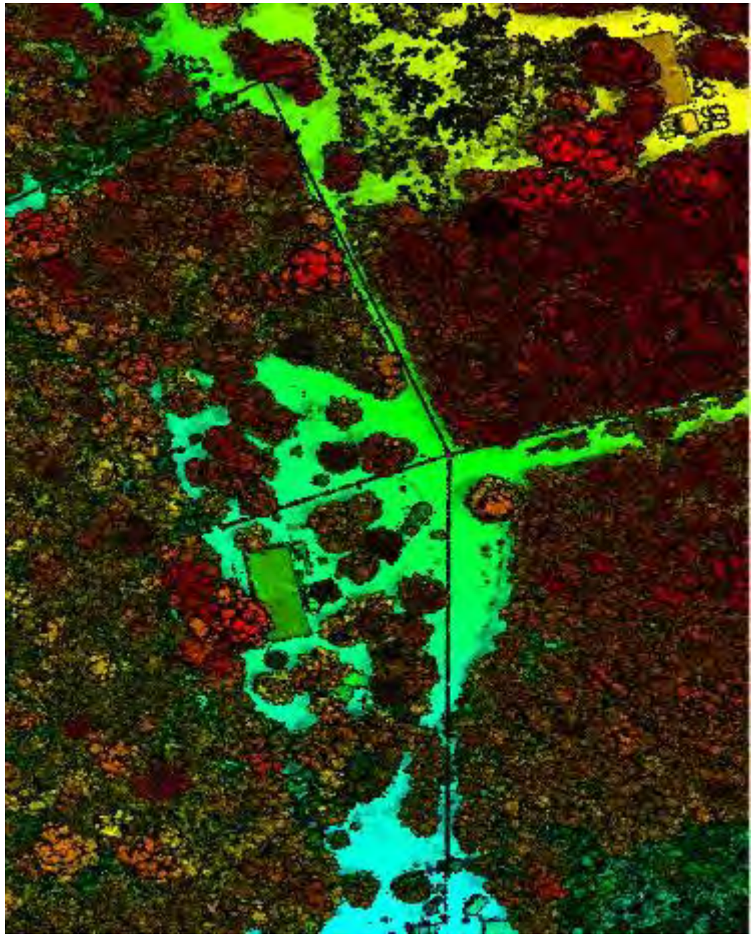
Utility Project



Equal to the size of the state of Florida

Collected and processed

Total: 54,000 mi^2 / 30 ppsm



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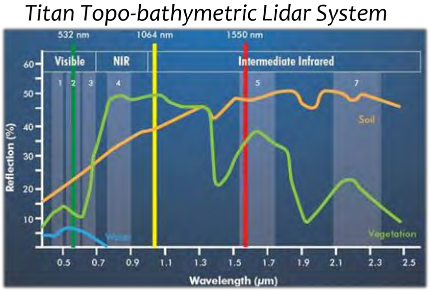
Imagery from L3Harris IntelliEarth™ LIDAR

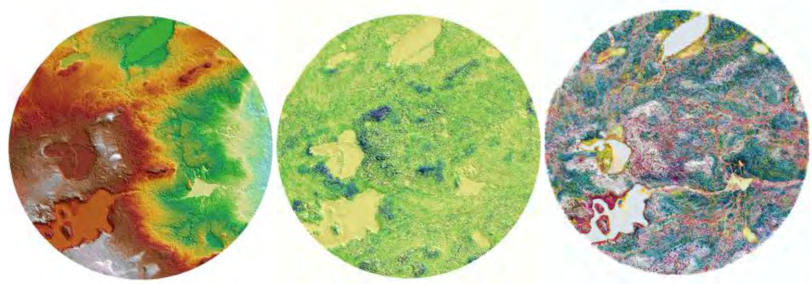
Multispectral Lidar
The fusion of active geometric & optical data

University of Lethbridge
FIAT LUX

Titan Topo-bathymetric Lidar System



Professor Chris Hopkinson
ARTeMiS Laboratory, University of Lethbridge,
Alberta, Canada



Lidar Terrain **Lidar Canopy** **Intensity Composite**

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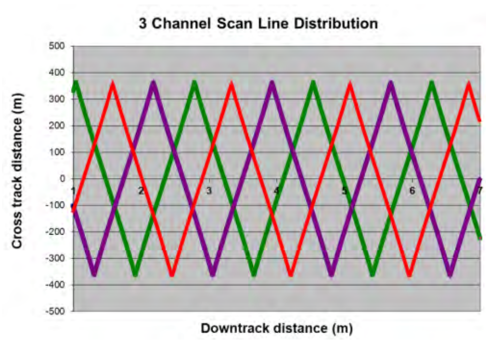
Teledyne Optech Titan multi-channel sensor

University of Lethbridge
FIAT LUX

TELEDYNE OPTECH Everywhereyoulook



Flight direction

	Channel 1	Channel 2	Channel 3
Laser wavelength (nm)	1550	1064	532
Look angle (degrees)	3.5 forward	nadir	7.0 forward
Pulse Repetition Frequency (kHz)	50-300	50-300	50-300
Beam Divergence at 1/e, (mRad)	0.35	0.35	0.7
Pulse Energy (µJ)	50-20	~15	~30
Pulse Width (ns)	3.0 - 3.5	3.0 - 3.5	2.5 - 3.0

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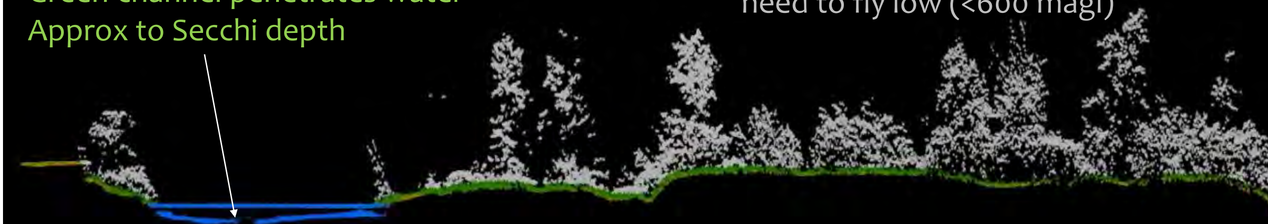
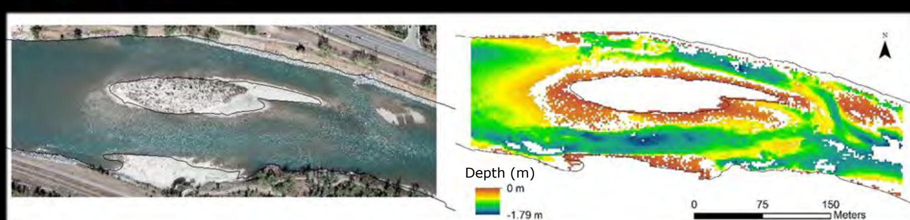
Basic Titan 3D point cloud
with bathymetry

Green, NIR & SWIR channels sample terrain, vegetation & bathymetry.

Good for nearshore mapping but need to fly low (<600 magl)

Green channel penetrates water
Approx to Secchi depth





Images:
Maxim Okhrimenko

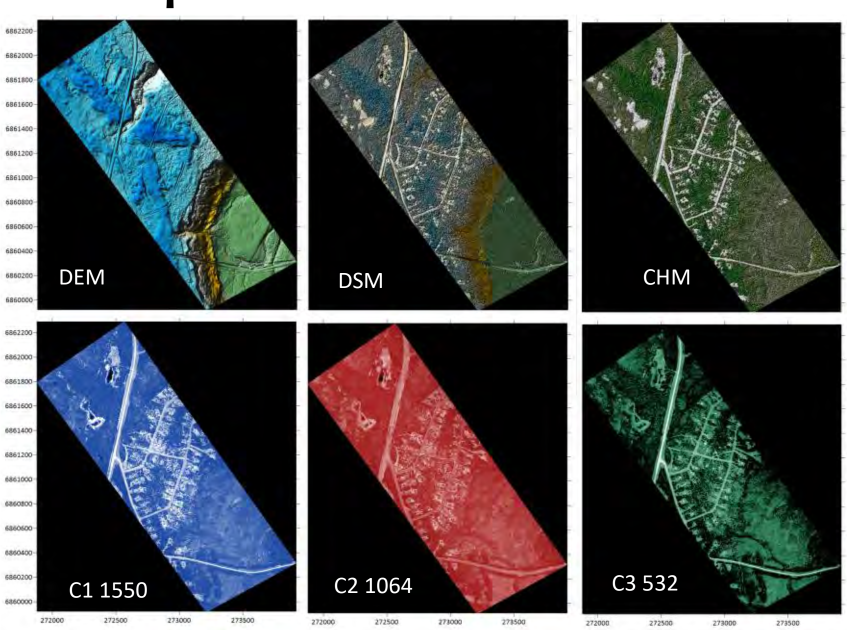
Okhrimenko & Hopkinson, 2019a

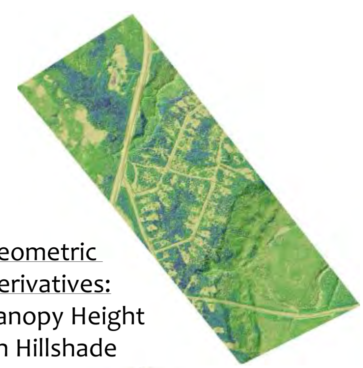
Chris Hopkinson, University of Lethbridge

Lidar STV Technology Breakout

3

Multispectral Lidar Derivatives





Geometric Derivatives: Canopy Height on Hillshade

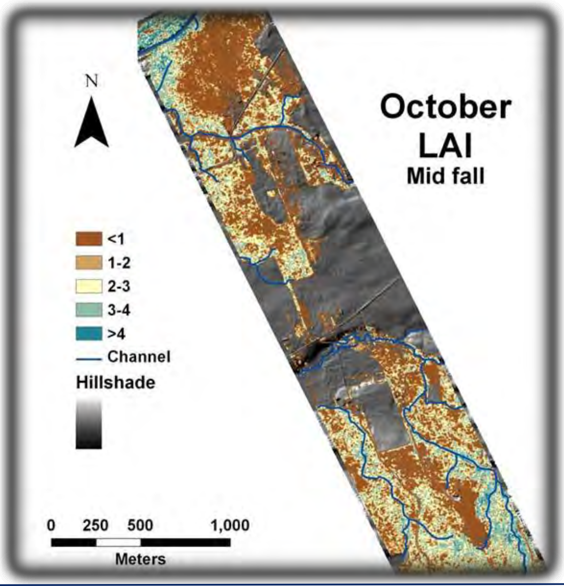
Optical Derivatives: Multispectral lidar composite

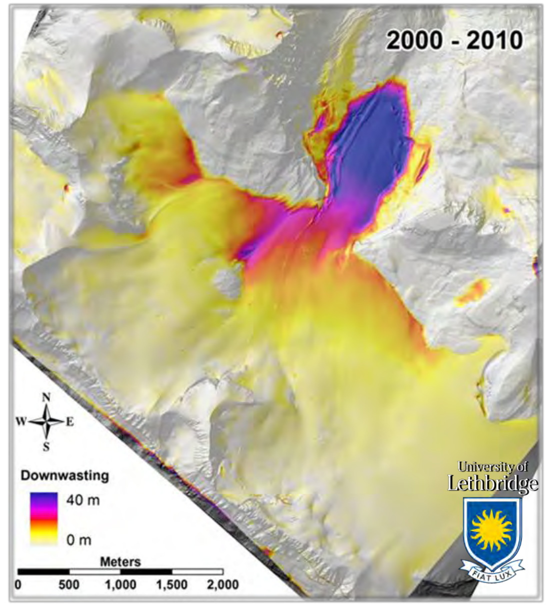
Chris Hopkinson, University of Lethbridge

Lidar STV Technology Breakout

4

3D Canopy & Terrain Changes





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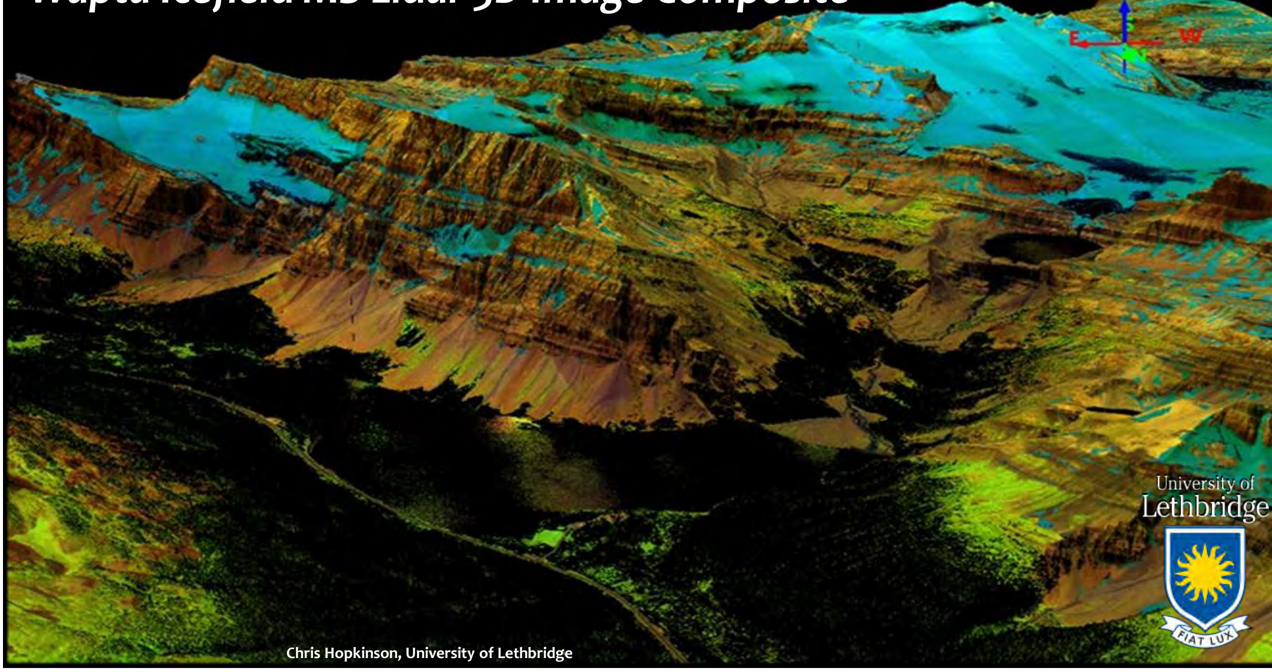
Lidar STV Technology Breakout

5

Wapta Icefield MS Lidar 3D Image Composite



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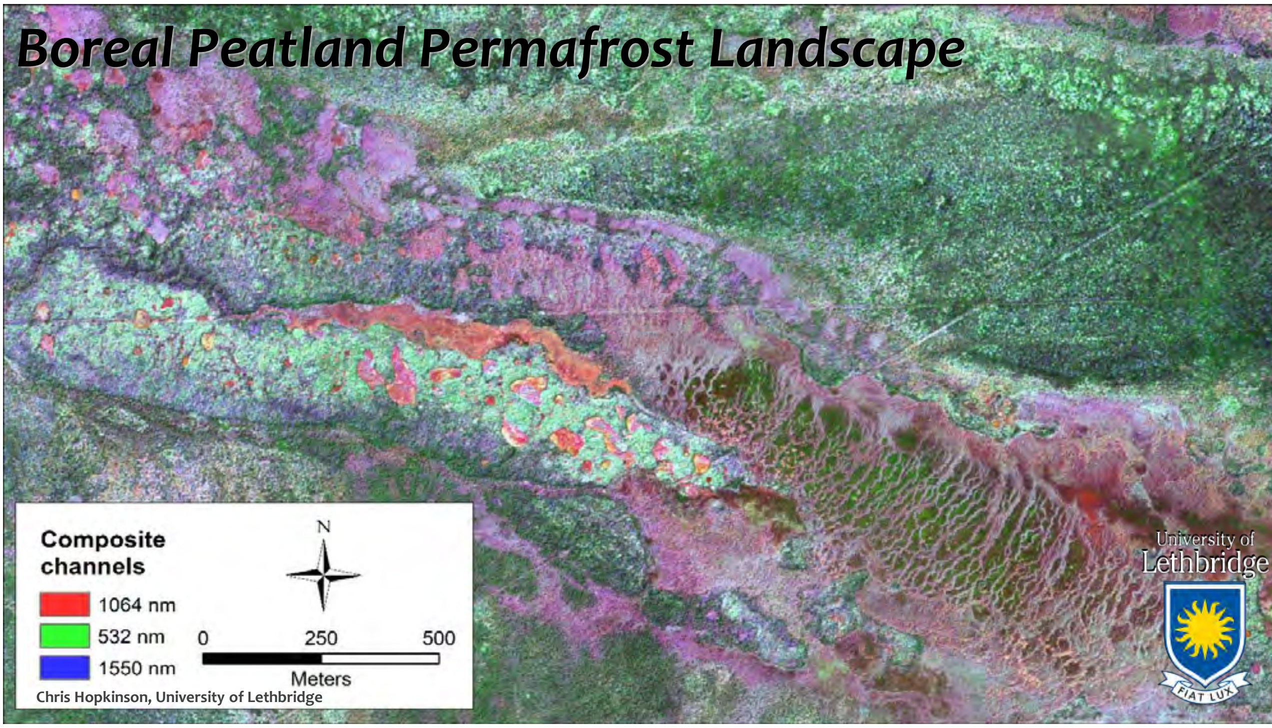
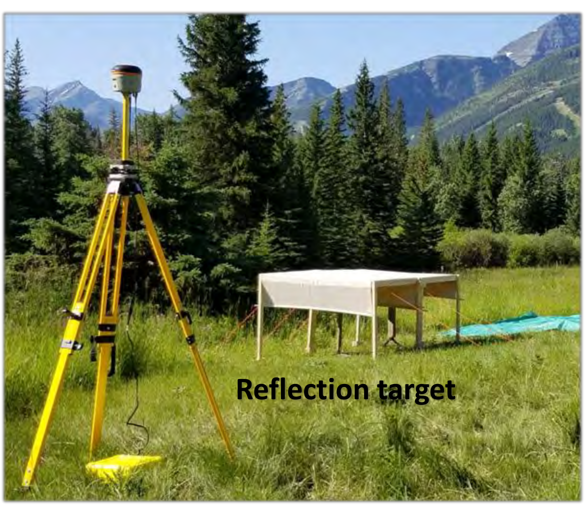
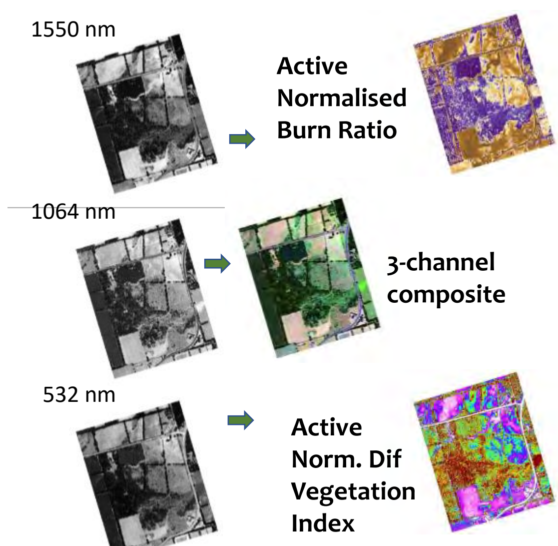


7

Developing new active indices





Okhrimeko et al. 2019

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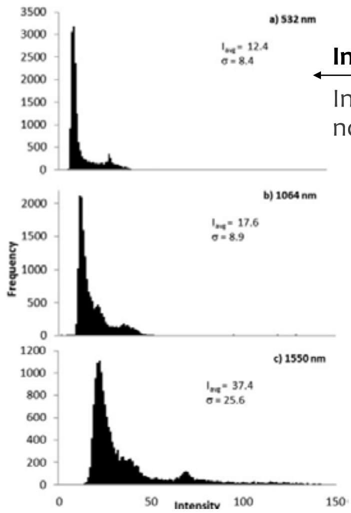
Lidar STV Technology Breakout

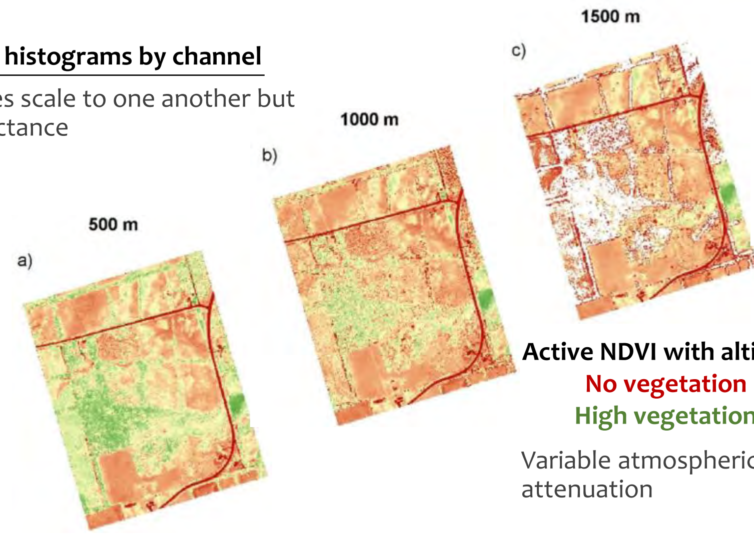
8

Radiometric properties & consistency



Intensity histograms by channel

Intensities scale to one another but not reflectance



Active NDVI with altitude
No vegetation
High vegetation

Variable atmospheric attenuation

Hopkinson et al. 2016
Okhrimenko et al. 2019

Okhrimenko & Hopkinson, 2019b

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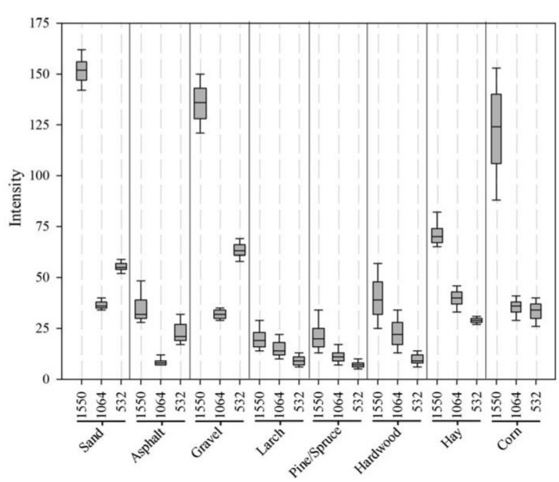
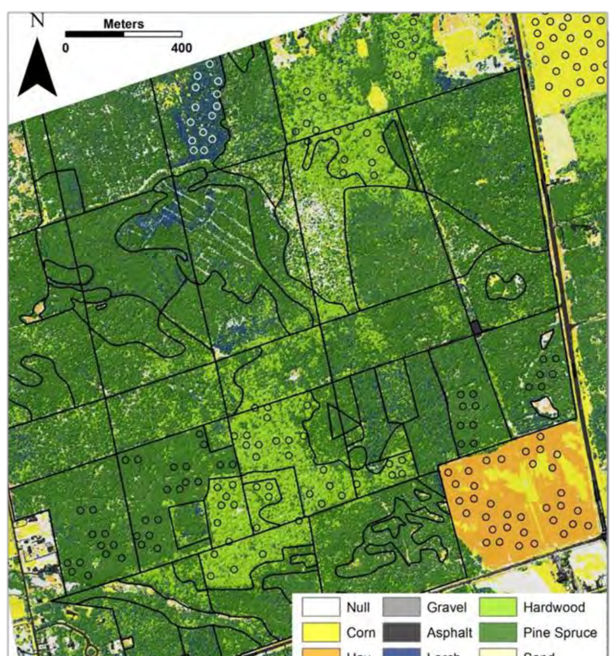
MS Intensity-based land cover classification





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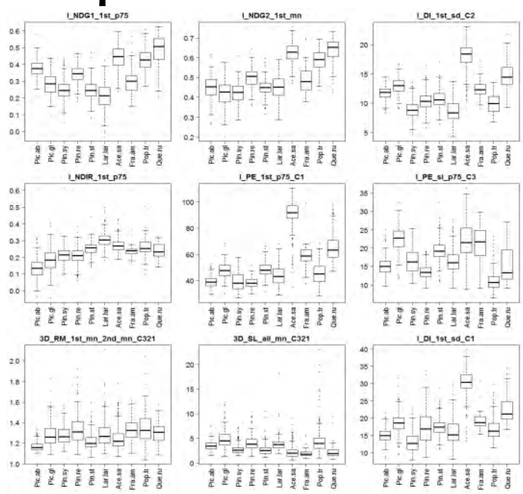
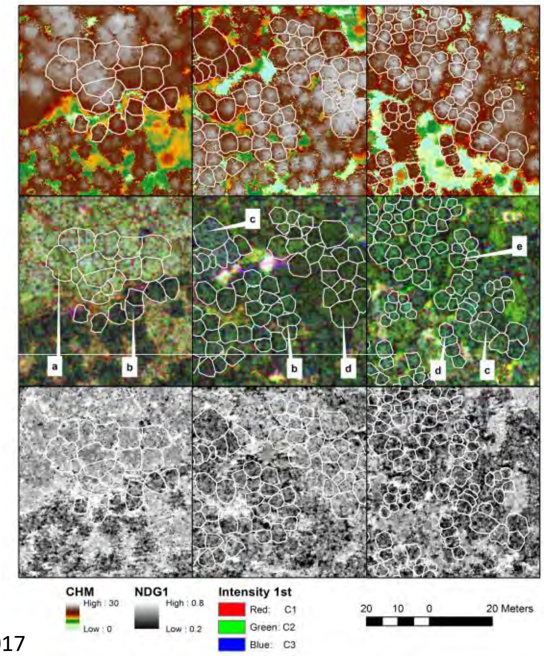
Hopkinson et al. 2016

Structure- & Intensity-based tree species classification

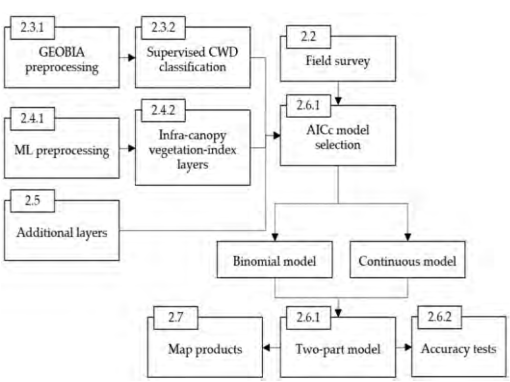


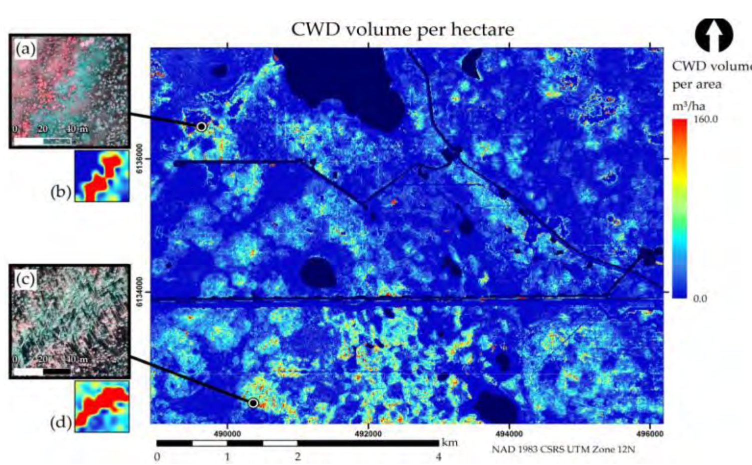


Individual crowns segmented & species classified using Random Forest

Brindusa et al. 2017

Optical object-oriented + active normalised ratio under-story fusion classification workflow



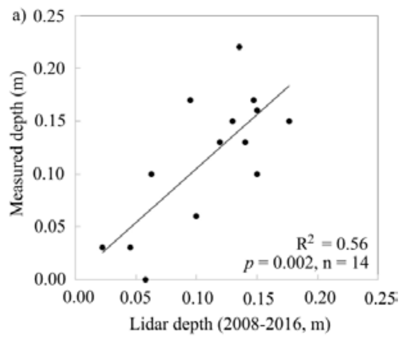


Course Woody Debris volumes modeled from combined image & MSL NBR data. MSL model 12% better than optical only

Queiroz et al. 2020
McDermid Lab, University of Calgary

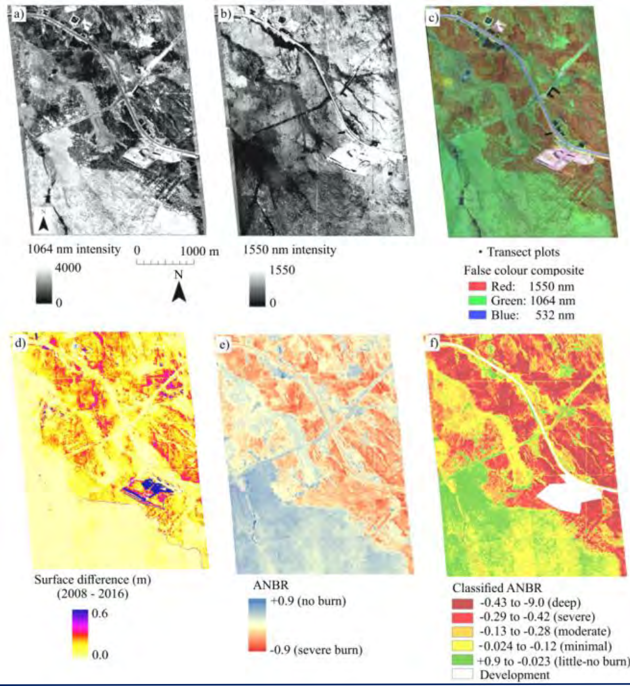
Mapping peatland burn depth & severity

$$ANBR = \frac{NIR_{1,064\ nm} - SWIR_{1,550\ nm}}{NIR_{1,064\ nm} + SWIR_{1,550\ nm}}$$



MSL used to map peat burn depth.
Depth visibly correlates with ANBR.

Chasmer et al. 2017



Thank you!

The ARTeMiS Team
Clean Harbours
Campus Alberta
Alberta Innovates

NSERC
Canada Foundation Innovation
Western Diversification Program

Alberta Innovates Technology Futures
Natural Resources Canada
TELEDYNE OPTECH Everywhereyoulook
University of Lethbridge
FIAT LUX
ARTEMIS

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University of Lethbridge

FIAT LUX

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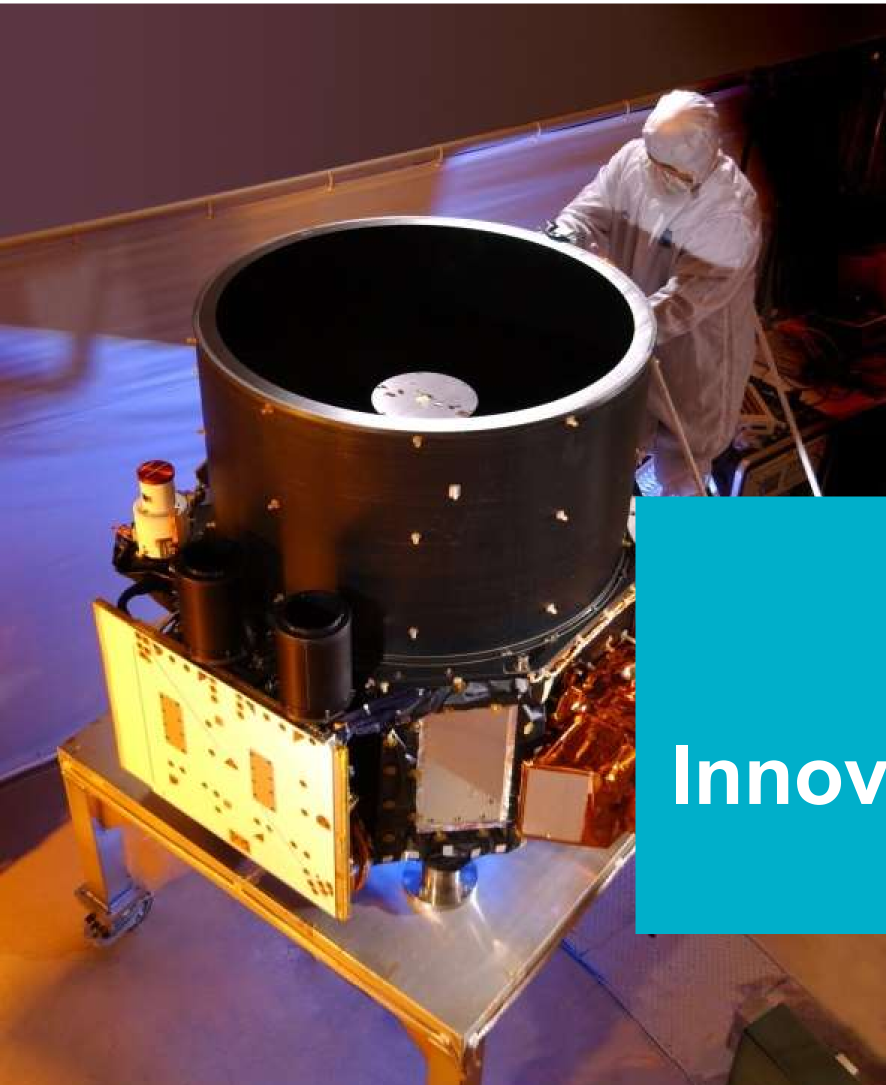
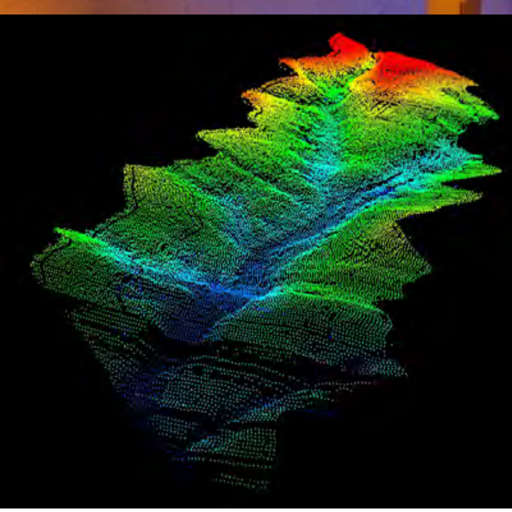




The Next Step
Innovative Lidars for Earth Sciences

Carl Weimer (Ball), Yong Hu (LaRC)

Science - Michael Lefsky (CSU), Jason Stoker (USGS), Ingrid Burke (Yale), Mike Lieber (Ball), Wenbo Sun (LaRC), Yuping Huang & Knut Stamnes (Stevens)

Engineering – Mike Adkins, Jeff Applegate, Eric Coppock, Rex Craig, Jeremy Craner, Tom Delker, Brian Donley, Bill Good, Tanya Ramond, Lyle Ruppert , Dave Waller

Surface Topography and Vegetation
September 2020

Funding from NASA: ESTO, ARM, Orion plus team's individual institutions

Motivation

- We built CALIPSO, and with the community, we are continually using it as a Pathfinder to explore new applications → remember it is dual wavelength, dual pol, 14 years on-orbit
- Previous laser altimeters/lidars used to study Earth's atmosphere, surface, ocean subsurface and vegetation have been very successful → we are learning from them all to design what is needed next:
  - LITE - Atmosphere
  - ICESat – Topography (Atmosphere)
  - CALIPSO – Atmosphere (Oceans, Topography)
  - ICESat II – Topography (Atmosphere, Oceans)
  - GEDI – Forest, Topography
  - ADM Aeolus – Wind (aerosols)

A path forward:

- **Understand** what currently limit the measurements
- **Identify** new technologies and architectures that overcome those limits
- **Verify** through modeling and field demonstrations that the approach is viable
- **Explore** ways to reduce costs of missions without sacrificing science

Our Current Approach – Adaptive Lidar (TRL 7 Airborne, TRL 5+ Space)

Lidar Weakness	Our Solution
Single (or few) line transects yield poor coverage	Use detector arrays and multiple reconfigurable beams
Cloud Obscuration	Forward looking imagers find gaps and adapt lidar beams locations
Fixed laser pulse amplitudes aren’t well matched to different scenes	Model Predictive Control Architecture allows databases to be created stored used in control

Adaptive Lidar System (Our Definition)

Design the lidar system so that it can autonomously:

- ***Optimize*** instrument performance by maintaining the SNR in an acceptable range by distributing energy between beams
- ***Maximize*** the science return by increasing the number of measurements being made
- ***Collect measurements at the spatial scales*** that maximize the science content
- ***Respond to changes in the scene*** (cloud, forest density, type of ecosystem) and ***remember*** them for future control – Exploring here Deep Learning (DL)

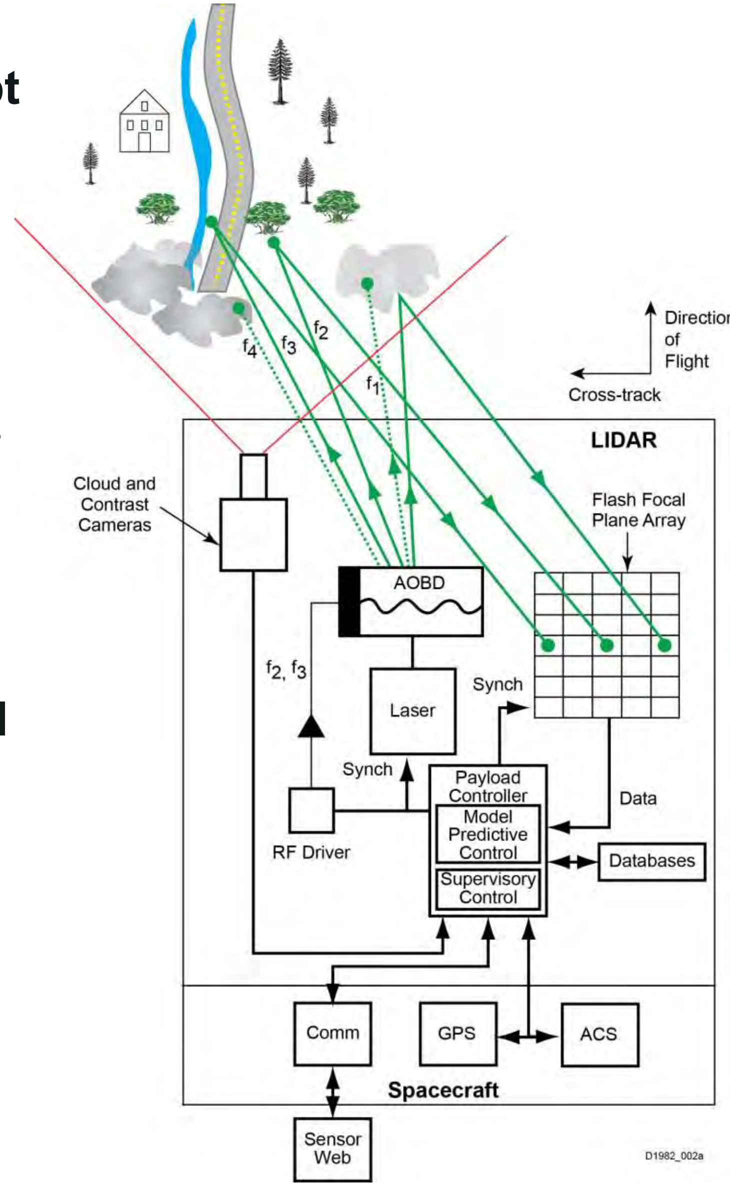
To achieve these goals use information from:

- Feedback or feed-forward from the lidar
- Secondary instruments integrated with the lidar
- Previous passes over the region with DL extracted info
- Other satellites that have passed over (Sensor Web)
- Previously collected data stored in databases/maps

Feed-forward Samples approaching scene

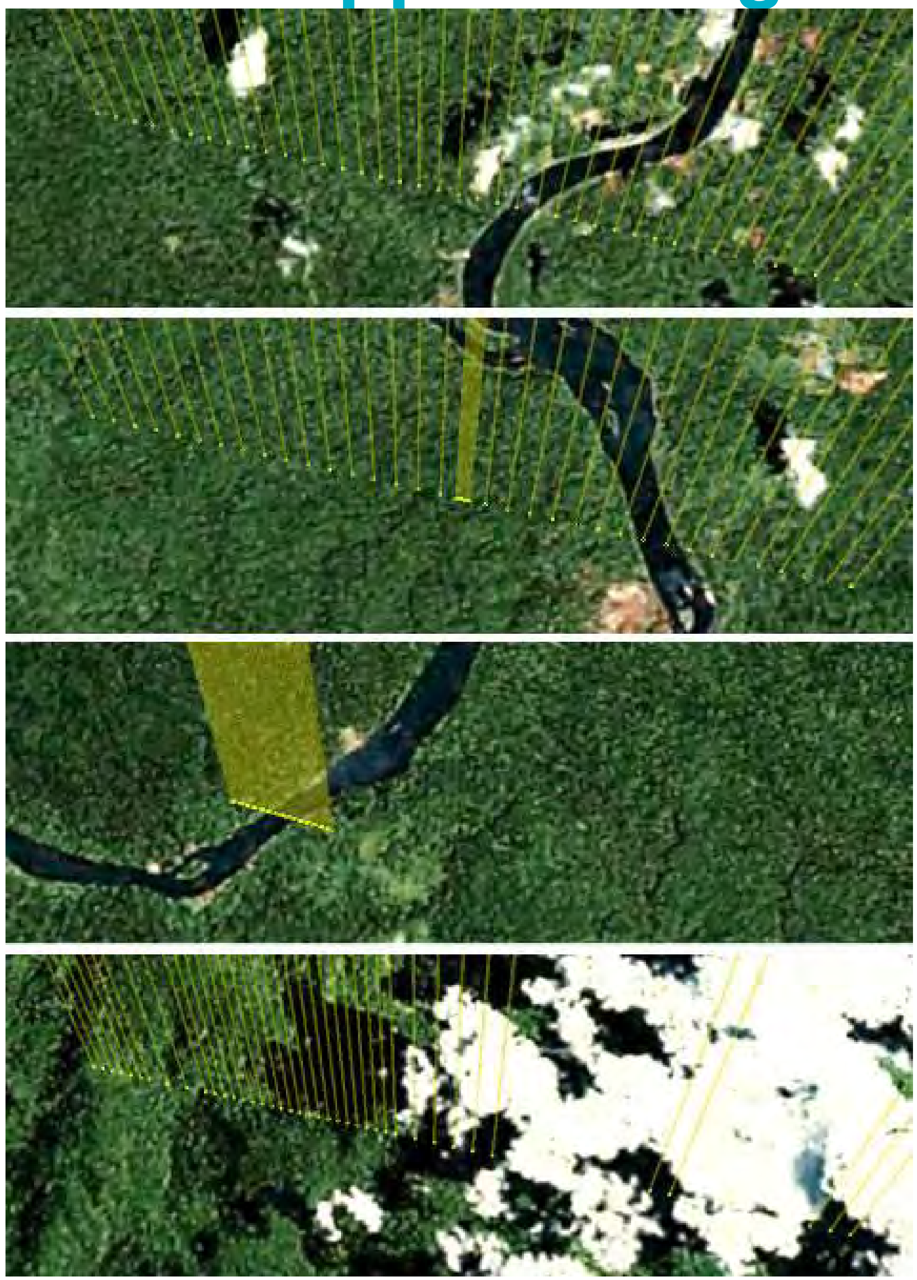
An Adaptive Lidar Demonstration
- Electronically Steerable Flash Lidar (ESFL) (IIP 2008)

- **Beam locations, intensities and number can be changed for every laser pulse - can adapt to the scene and environment based on:**
  - Lidar Response (to optimize performance)
  - Secondary Camera (to track patterns)
  - GPS/IMU (to track specific features/transects defined by lat/long)
  - On-board digital elevation maps (provides ranges and features)
- **Five Aircraft Flight weeks over forest, water, and cloud scenes (AITT 2009)**
  - Forest comparisons done by co-Is Lefsky, Stoker
- **Modeling for space done by LaRC, CSU, Ball**



Telescopes not shown

Use full sensor suite and autonomy to respond to the approaching scene



Sparse Spatial Sampling

Combined Dense and Sparse

Dense along Waterway

Steer Around Clouds

STK simulation

Three Enabling Technologies

A. Lidar Imaging Focal Plane Arrays
B. Acousto-Optics Beam Deflectors
C. Model Predictive Control System Architecture

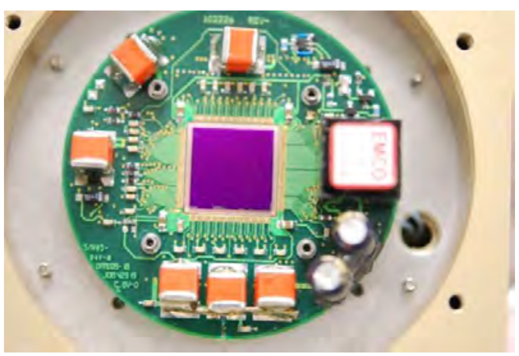
A. Examples of Lidar Imaging Technology

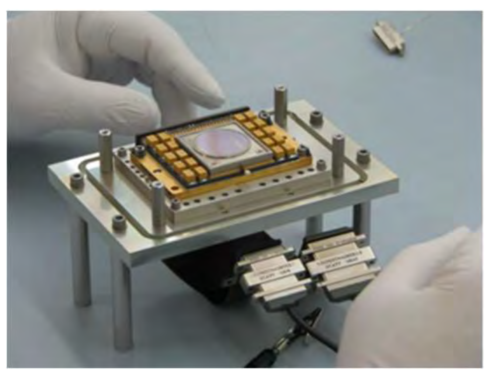
New Technologies based on CMOS "Smart Pixels"

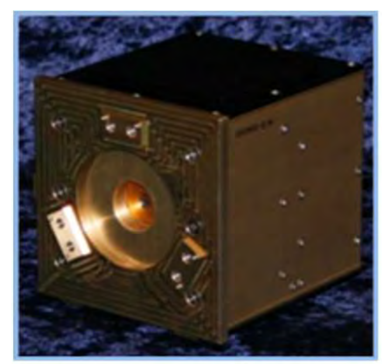
- Photolithographically produce detector arrays and "read out integrated circuits (ROICs) and bond them together
- Detectors can be p/n photodiodes or avalanche photodiodes in linear or geiger (photon counting) mode
- For each detector pixel, create a "unit cell" in the ROIC that contains amplifiers, high speed timing network, and temporary data storage
- Can create full profiles of distributed scenes (clouds, water, aerosols, forest canopy) or just surface topography (ground, tree top)
- Numerous companies developing related technology in the US
- Cryo-cooled versions yield lower noise, at higher cost/complexity

Advanced Scientific Concepts ← Linear → Raytheon Vision Systems

GmAPD → Ball (MIT-LL, PLI)

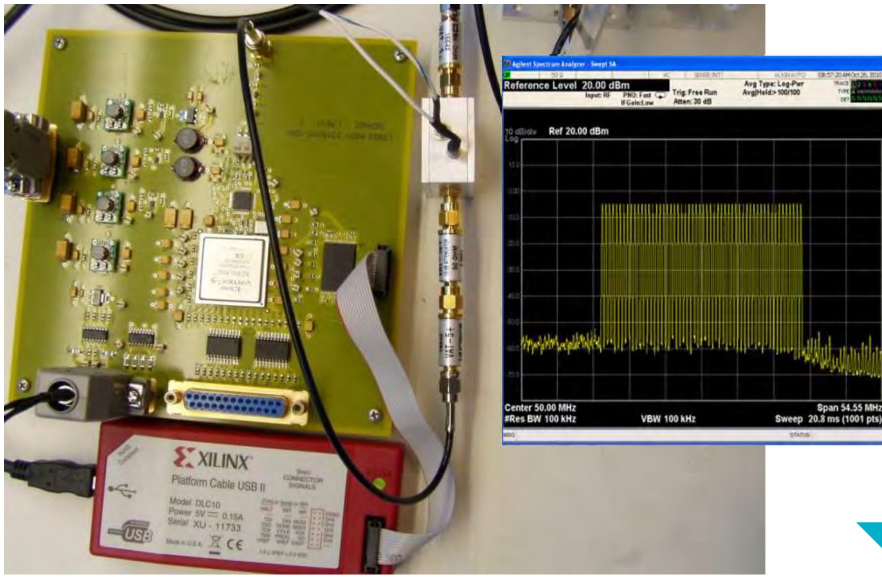






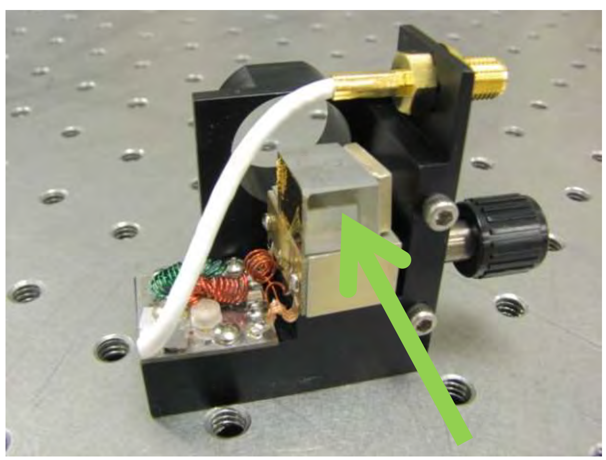
B. Beam Control using Acousto Optic Beam Deflectors

Direct Digital Synthesizer in an fpga creates RF tones



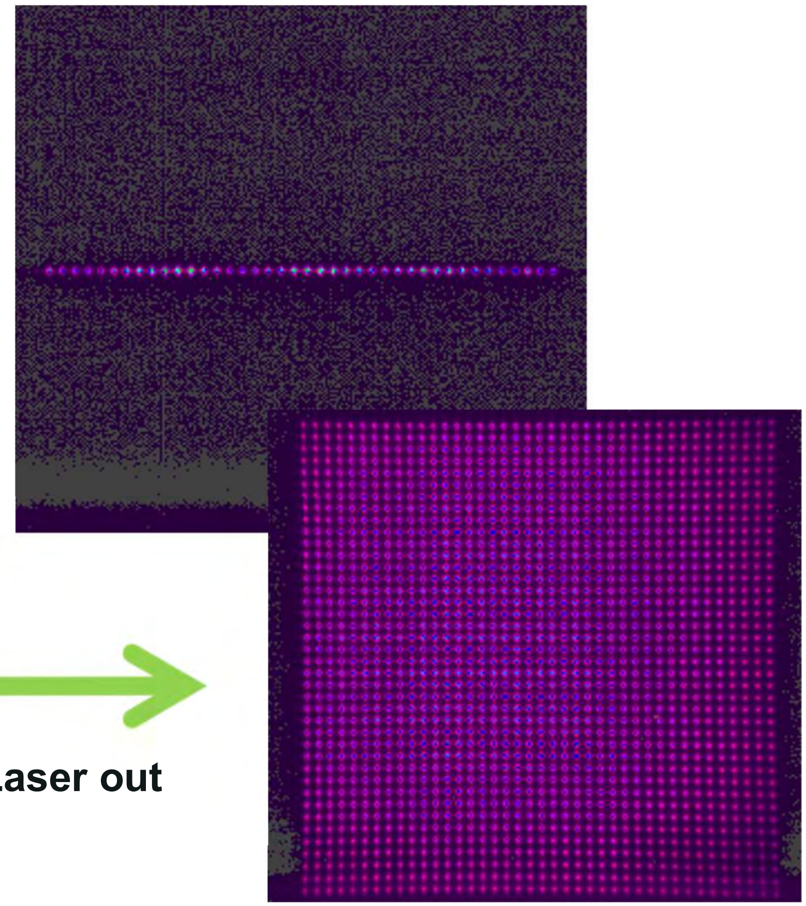
Output deflected beamlets in one or two dimensions

RF tones applied to piezo creating transmissive grating in crystal

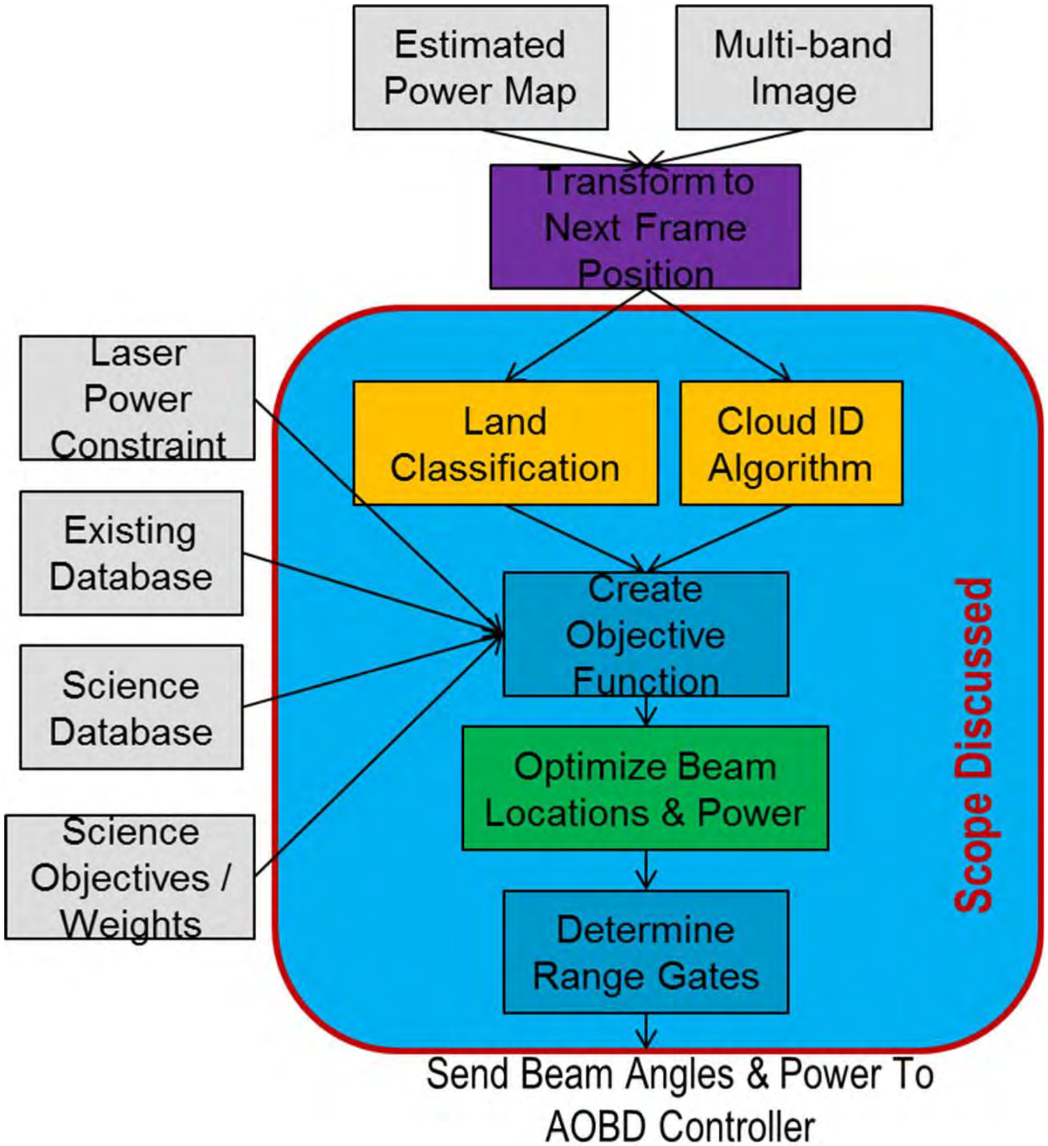


Laser is transmitted through the crystal

Laser out



C. Model Predictive Control (MPC) (AIST 2014) - The Optimizer Block



- Combines the knowledge derived from scientific studies of different scenes with the constraints of the system
- Always working to maximize science return via beam control (angles and amplitudes)
- At the lowest level software, a fast response is required since satellite is moving at 7 km/sec
- Works with distributed sensors across multiple platforms (constellations and trains), including cubesats and smallsats
- Can utilize different types of forward looking imagers – mutli, hyper spectral, stereo, etc
- Leverages extensive work done for autonomous cars, chemical plants, building thermal controls
- Emerging Technology we are working – combining MPC with Deep Learning (DL)

Our Emerging Approaches
Orthogonal Laser Modes (TRL 2-3)

Lidar Weakness	Our Solution
Multiple scattering in clouds, forests, snow, or water leads to biases and reduces detectability	Utilize laser beam modes that can "identify" and effectively remove multiple scattering
Solar Background limits daytime performance	Utilize receivers that are sensitive only to the laser mode, not sunlight

Two Approaches to New Laser Modes

- Laguerre Gauss spatial modes (ACT 2014)
  - Encodes “Orbital Angular Momentum” onto beam, and matched filters (e.g. vortex coronagraph) at receiver could separate out laser from background
  - Higher order modes found to be unstable under scattering
  - More work could be done to combine polarization and create vector vortex beams – On Hold

- Temporal-Frequency Modes (or “Temporal Orthogonal”) (ATI QRS 2020)
  - Developed for Quantum Information Science (but not entangled photons)
  - Sub-mm ranging - Demonstrated at short ranges
  - Rejects sunlight with a perfect coherent matched filter using nonlinear crystal (Quantum Parametric Mode Sorter- QPMS) – Demonstrated
  - Inherently photon counting, and can shift scattered light to bands with optimal detectors - Demonstrated
  - Radiative Transfer Models for scattering of these modes - Ongoing
  - Lidar demonstrations and lab testing refinement – Ongoing
  - Full Instrument with Field Demonstrations – Future
  - Complete system design for space – Future

Thank you for taking the time to listen!

Advantages and Disadvantages of lidar imaging arrays

Advantages:

- Scalable to a large number of pixels
  - Each a lidar sensor
  - Now 256×256 = 65 kpixels
  - Though this isn't always good if there isn't enough laser power!
- Low power consumption
- Compact Size
- High Speed Operation (up to 1GHz clocks and 60 Hz frame rates)
- Dense spatial coverage of scene
- Rapidly evolving along with semiconductor industry
- Various detector arrays have been developed (silicon, InGaAs, InP, HgdTe)

Disadvantages:

- Expensive to design/fabricate - new designs require multiple iterations
- Challenging to keep ROIC noise below the detector noise
- High Operability (i.e. low number of defects) is challenging
- Dynamic ranges are typically low (100-500 APDs; few 1000 PIN)
- Ultimately – Requires substantial laser power to illuminate this number of pixels and achieve adequate Signal-to-Noise at long ranges

Answer- Use beam control to always illuminate the "correct" number of pixels with the best form of beam