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Photon Counting Laser Radar

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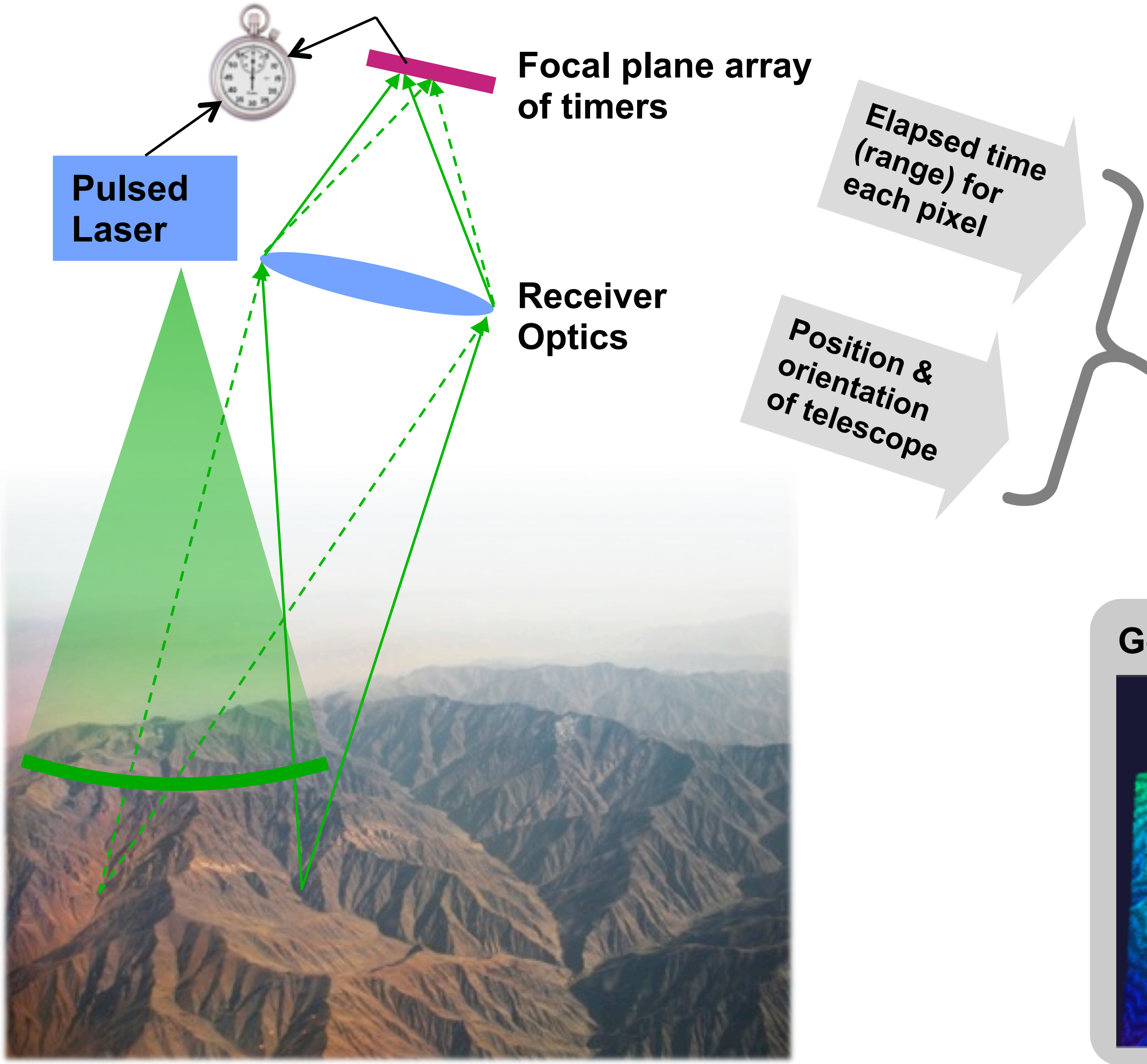
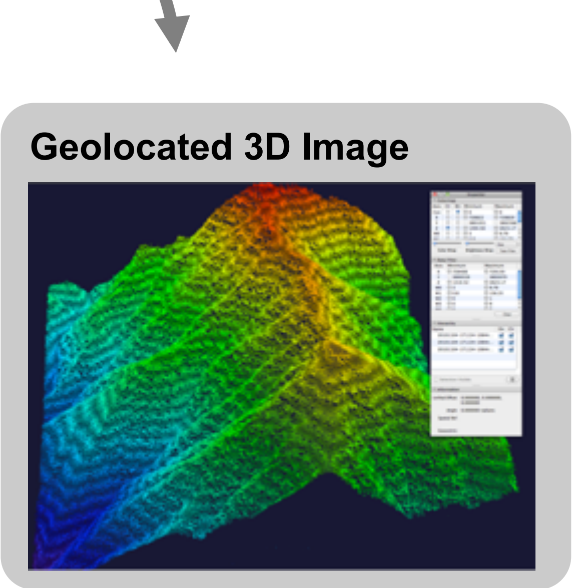
3-D Imaging with Laser Radar



Advantages:
- E/O-like resolution: 30 cm from 20 kft
- Radar-like ranging: 20 cm from 20 kft
- Active illumination: Night-time imaging

Disadvantages:
- Requires clear line-of-sight (no clouds)
- Active illumination: limited power results in limited area



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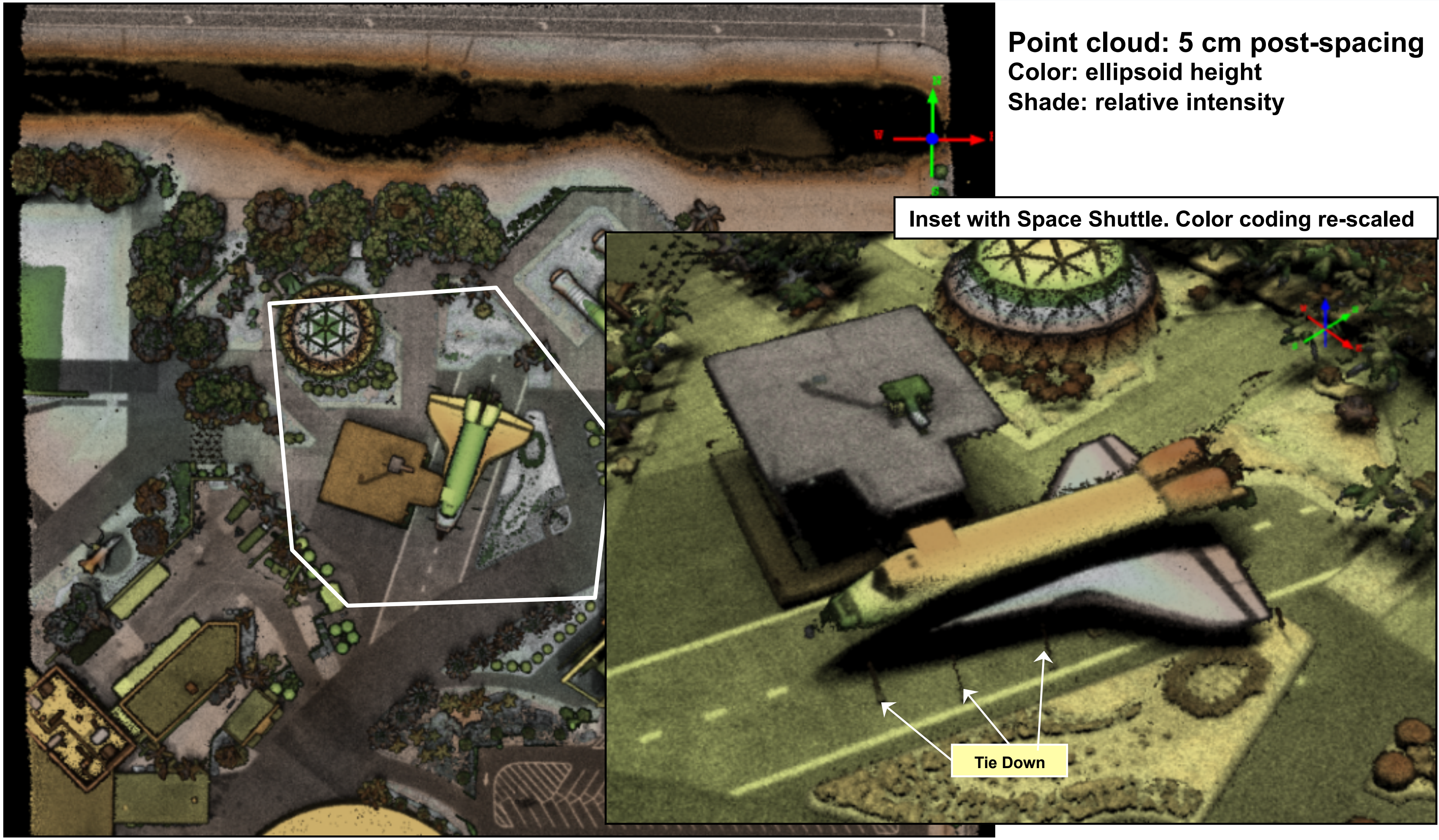
Example 3-D Imagery: Kennedy Space Flight Center



Point cloud: 5 cm post-spacing
Color: ellipsoid height
Shade: relative intensity

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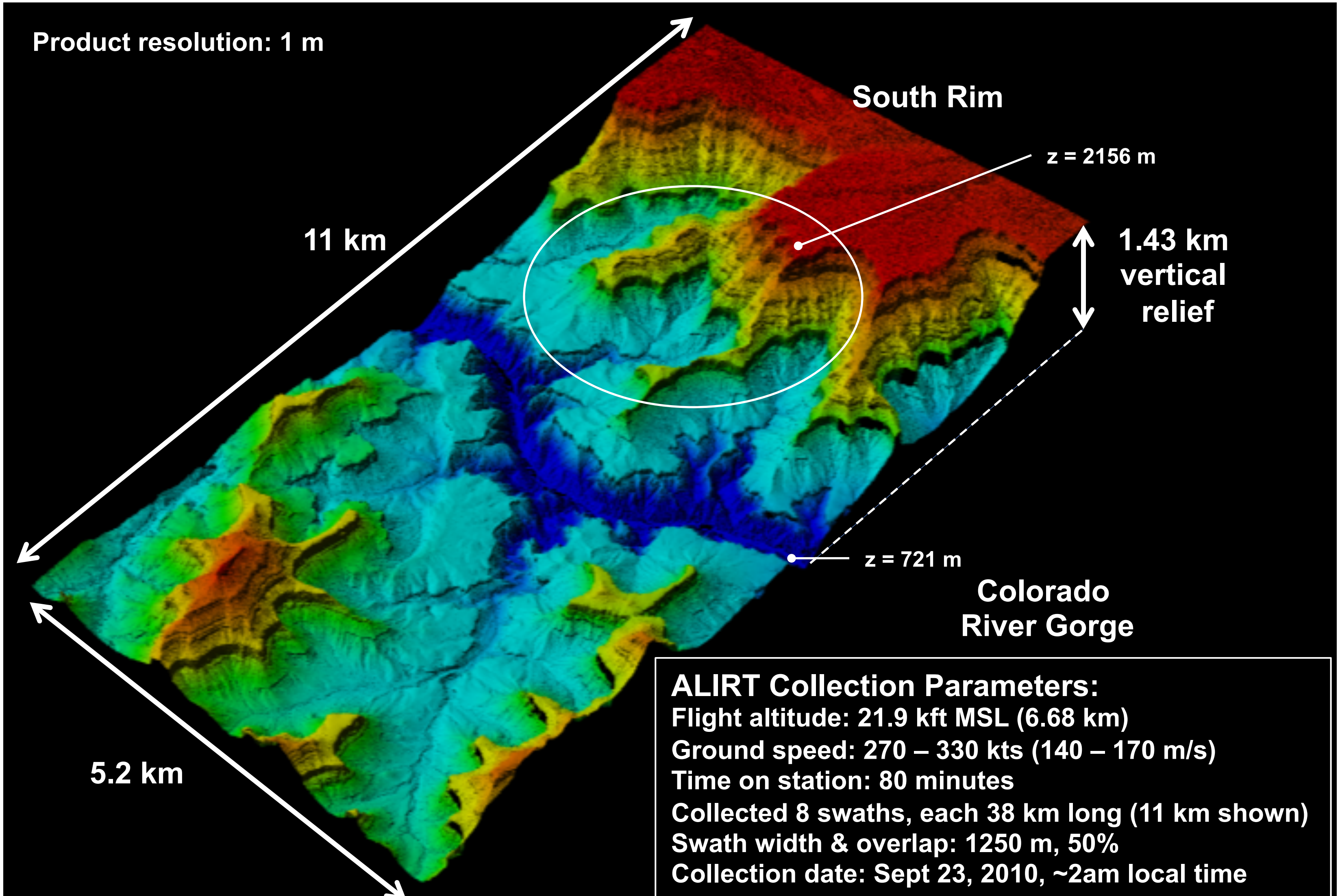
Example 3D Imagery: Grand Canyon



ALIRT Collection Parameters:
- Flight altitude: 21.9 kft MSL (6.68 km)
- Ground speed: 270 – 330 kts (140 – 170 m/s)
- Time on station: 80 minutes
- Collected 8 swaths, each 38 km long (11 km shown)
- Swath width & overlap: 1250 m, 50%
- Collection date: Sept 23, 2010, ~2am local time

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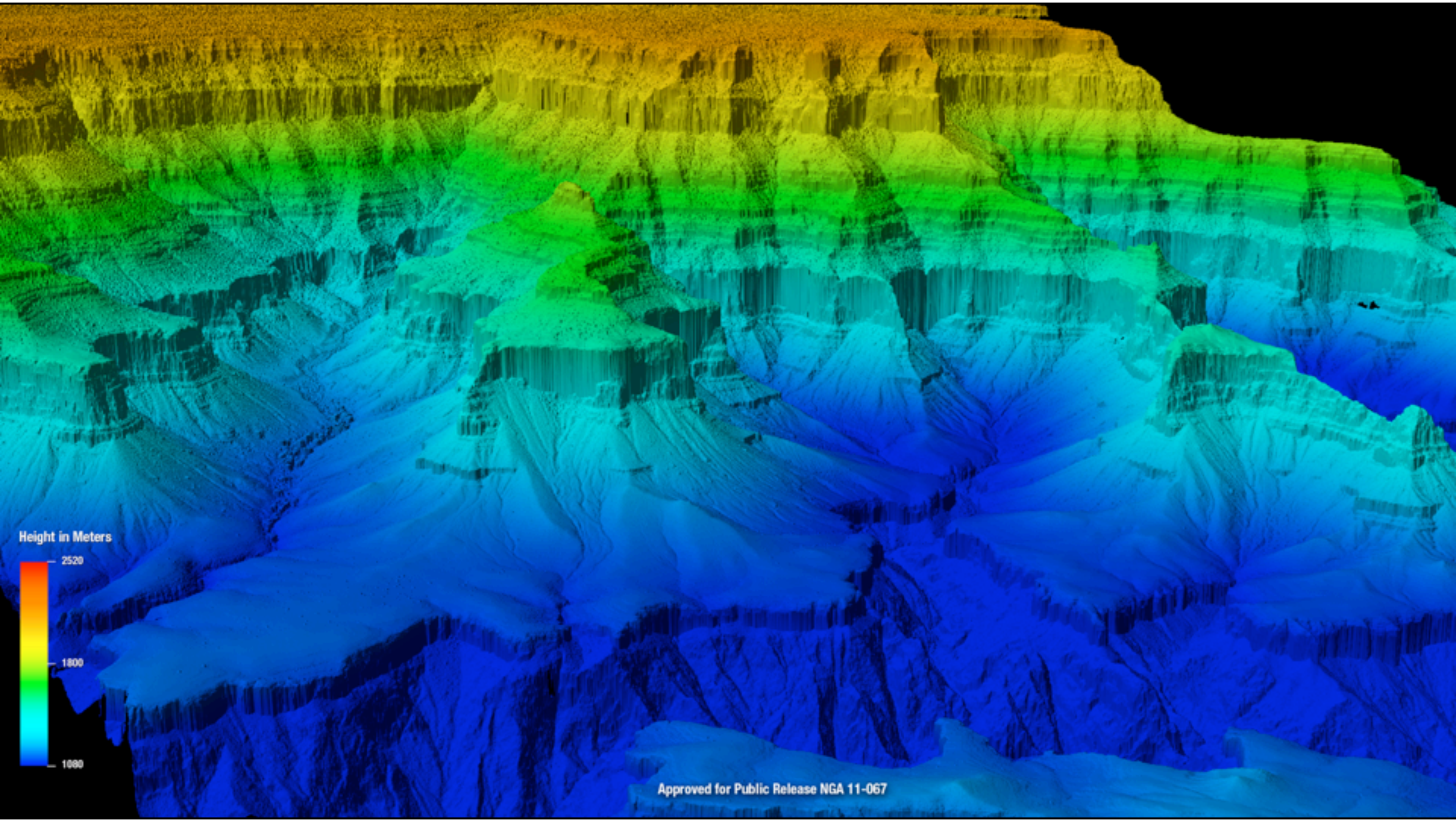
Example 3-D Imagery: Grand Canyon South Rim

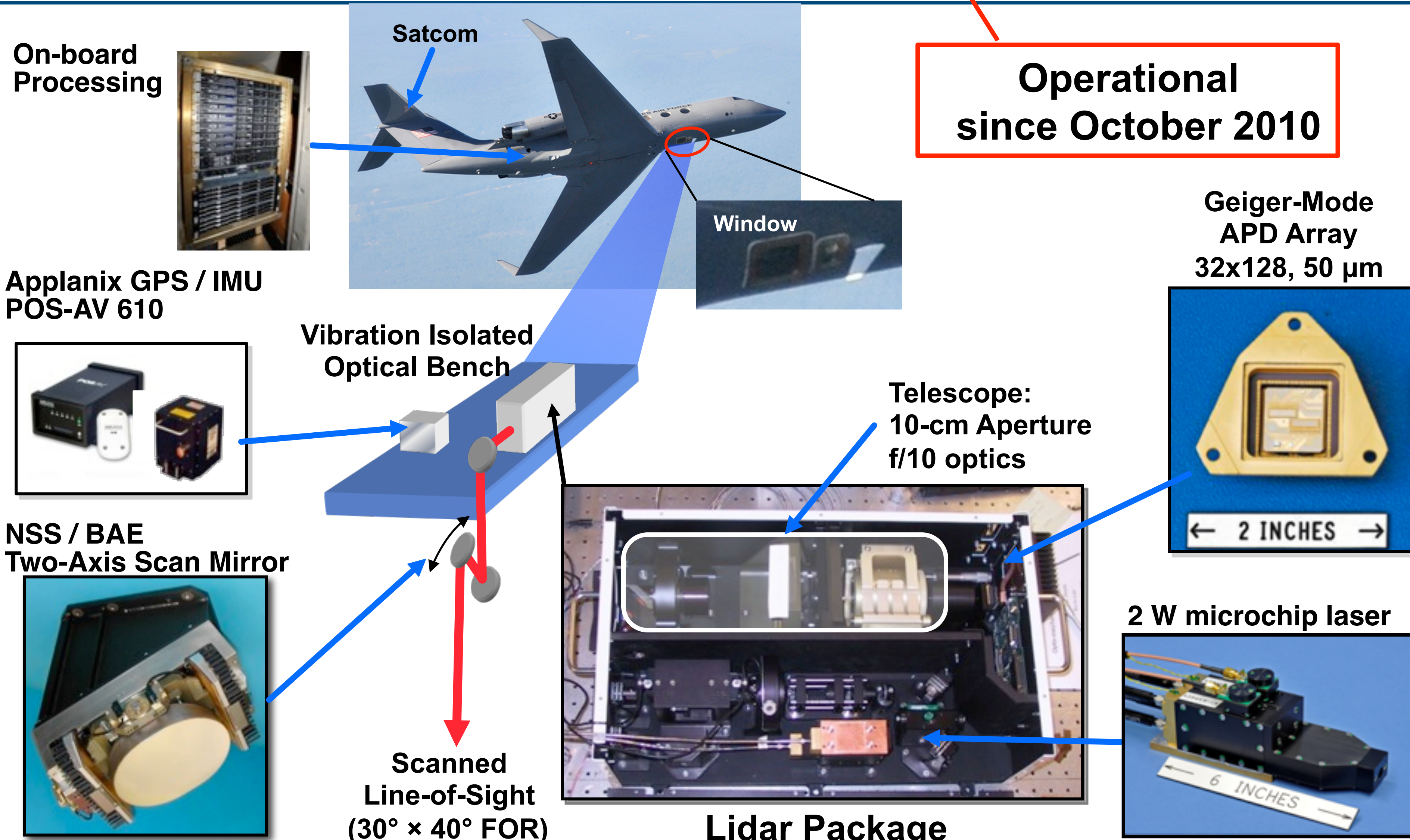


Outline

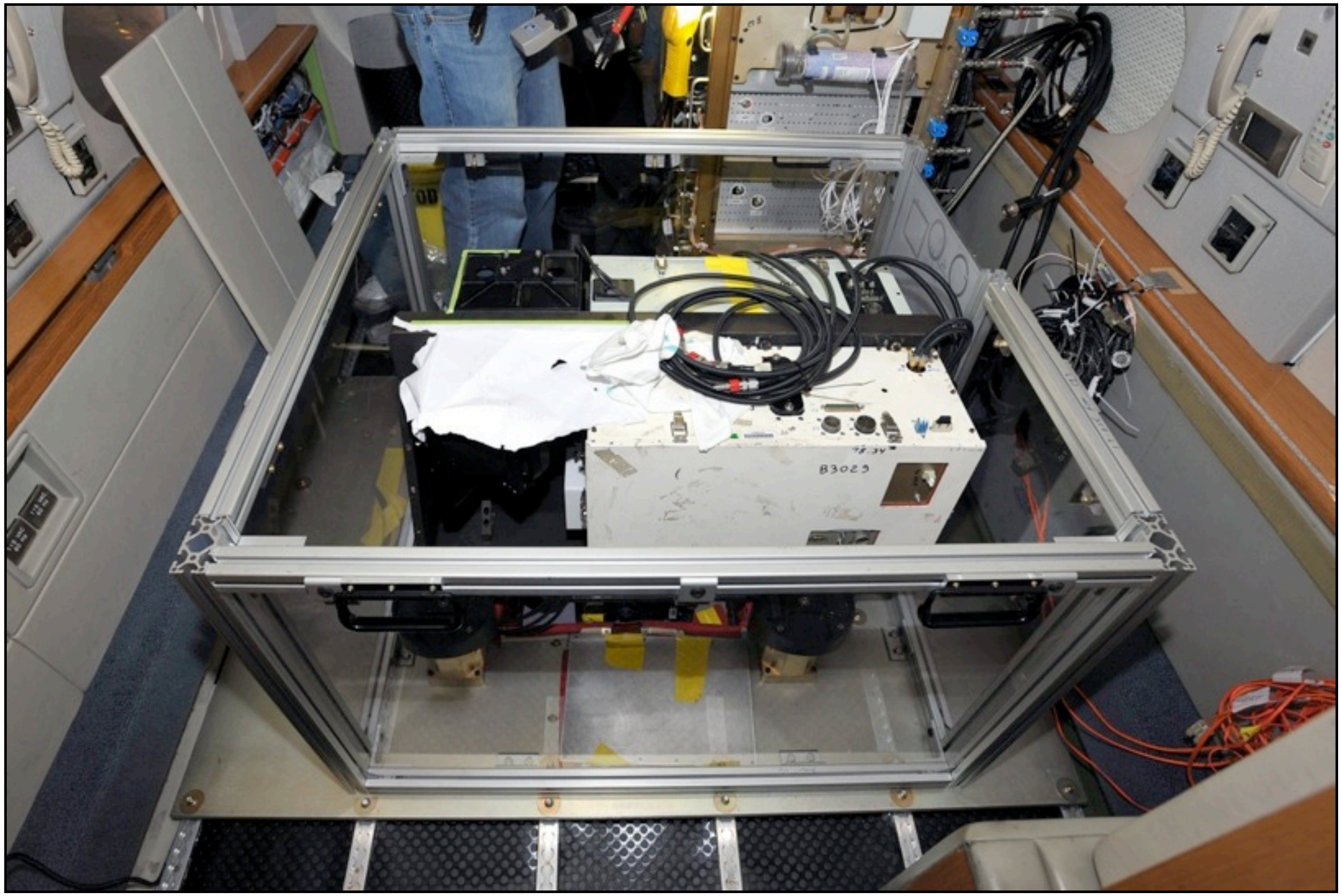
- Overview of 3-D Ladar
- ALIRT system
  - Hardware and processing
  - Example collections and data utility
- Ladar system considerations
  - Detector technology
  - Scanning
  - Signal & laser power
  - Measurement rates

ALIRT 3-D Imaging System

(Airborne Lidar Imaging ~~Research Testbed~~)

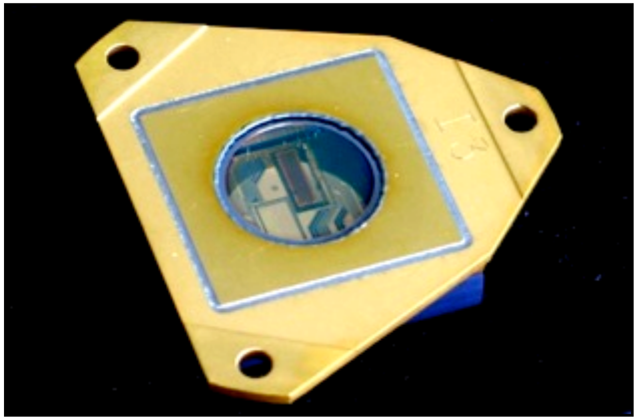


System in Aircraft

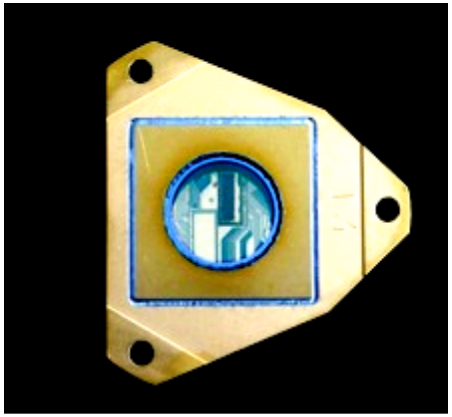


Operation and Processing Stations

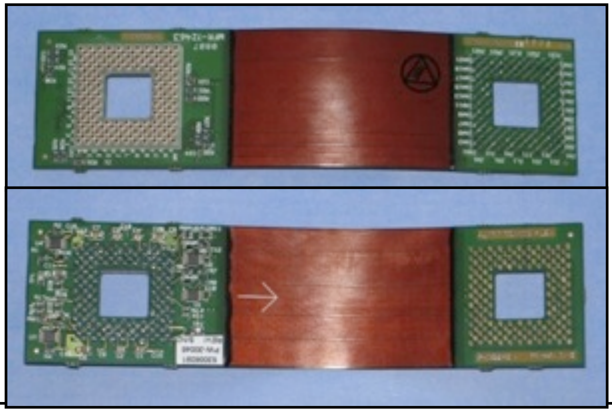
Geiger-Mode APD Array and Headboard



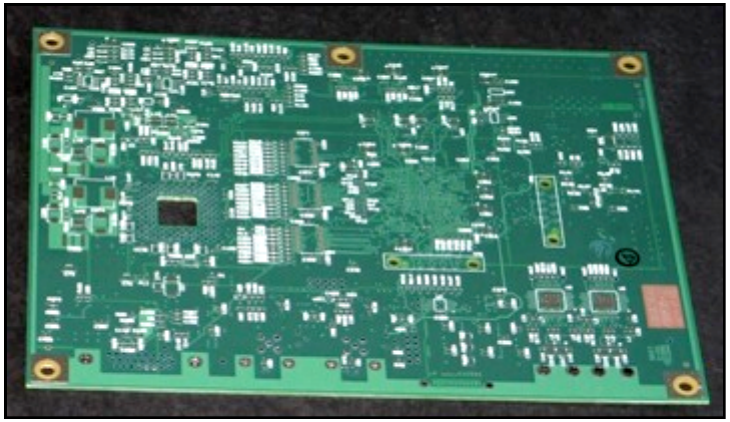
32 x 128 APD Detector Array



Straight-On
View of Array

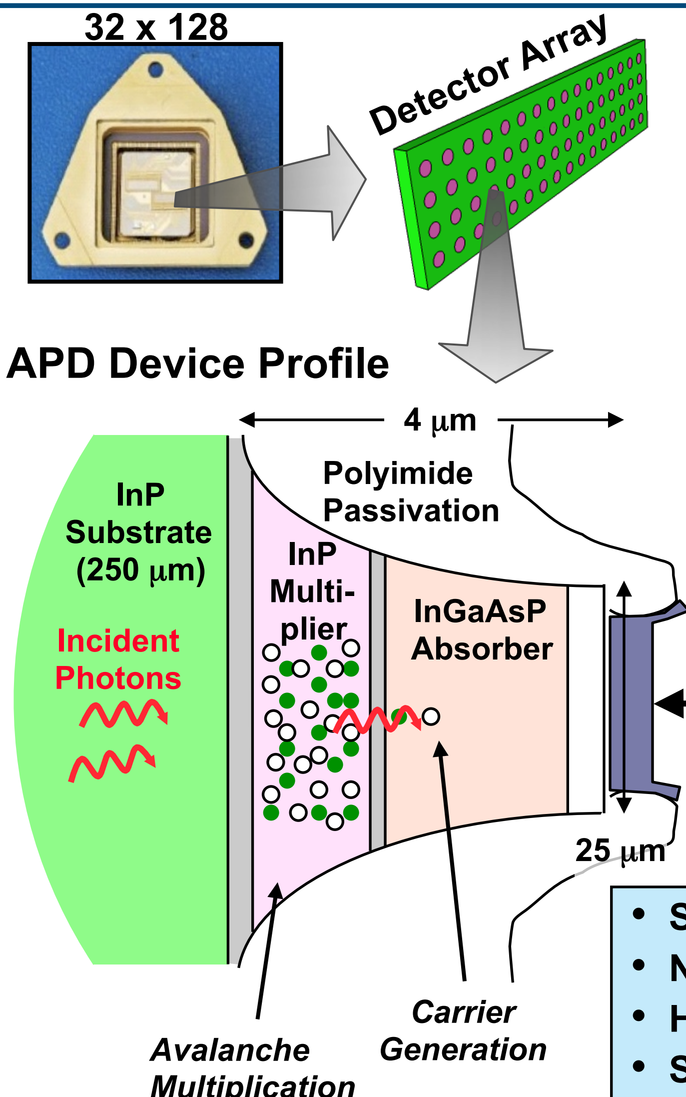


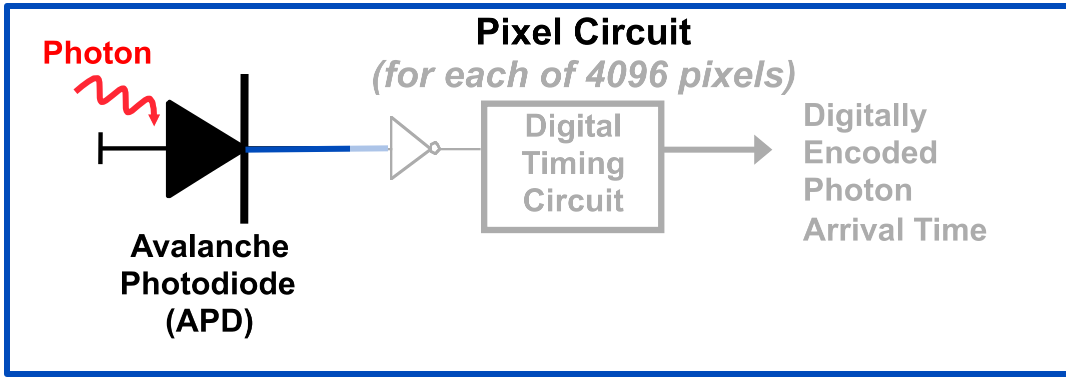
Flex Print Connects Array With Headboard



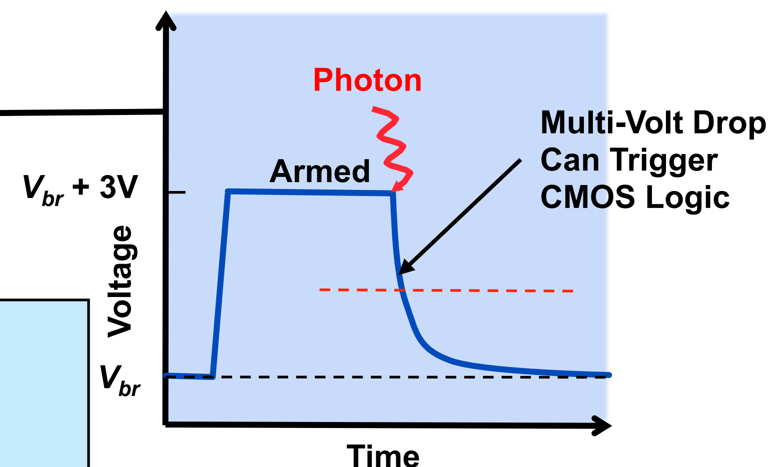
Headboard Controls Array Function and Reads Out Data

Geiger-Mode Imager: Single-Photon Detection





- Single-photon sensitivity
- Noiseless readout
- High-bandwidth timing
- Scalable to large arrays



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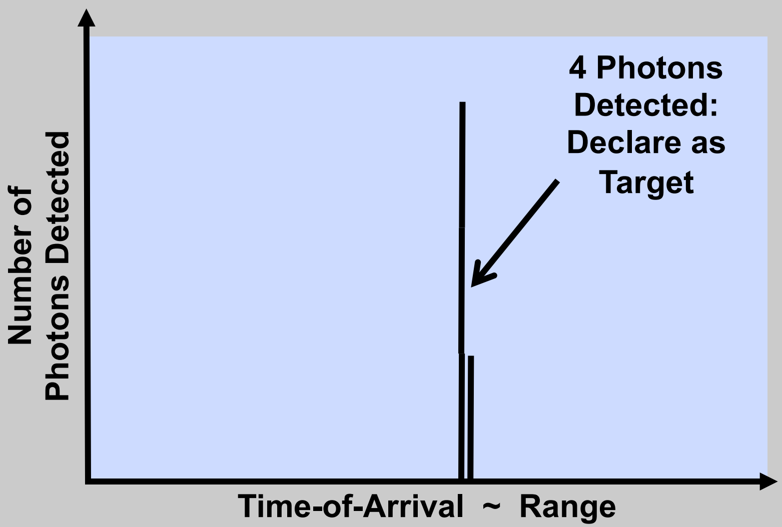
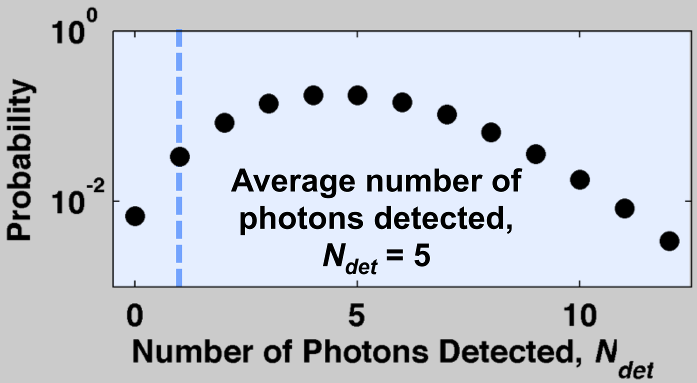
Photon Counting

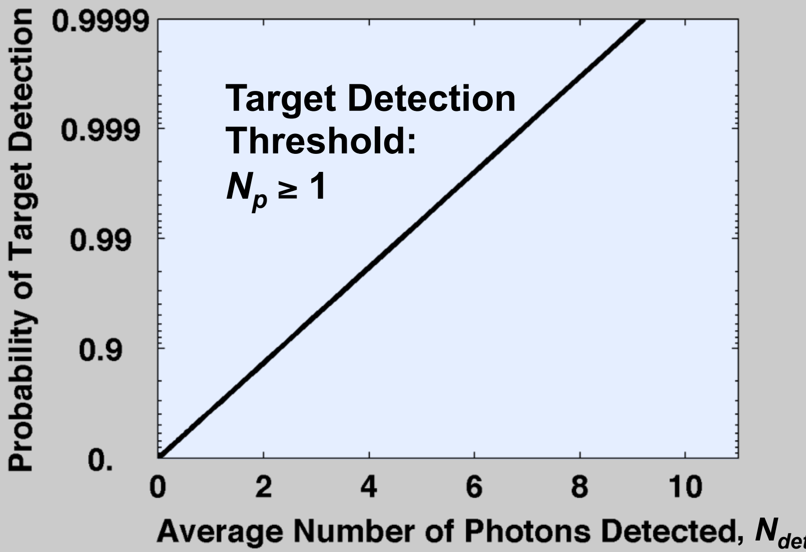
Single-photon detection is the most efficient use of light

- Photons are detected one at a time
- Times-of-arrival are recorded
- No readout noise penalty
- No photons wasted



Detection is a random process





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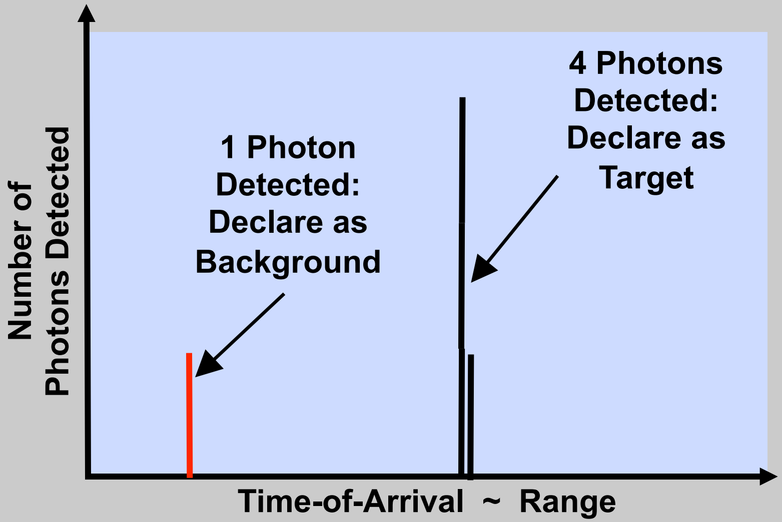
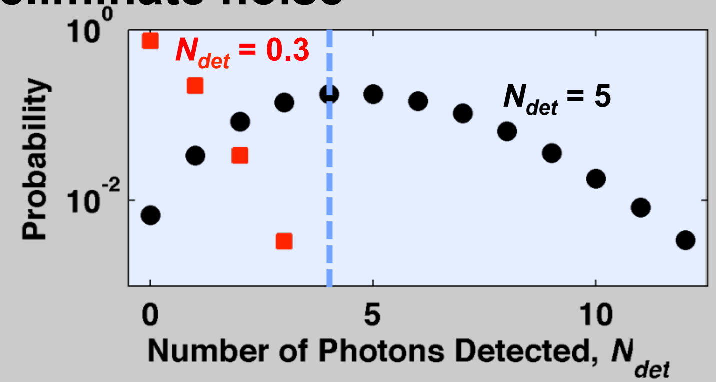
Photon Counting with Background

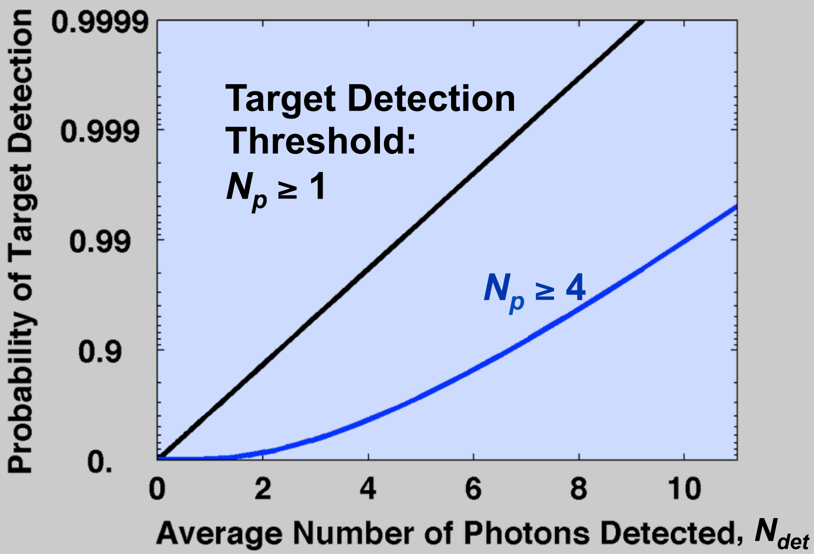
Noise (dark & light)

- Individual noise detections are indistinguishable from signal detections
- Noise detections are randomly distributed in time
- Signal detections are clustered



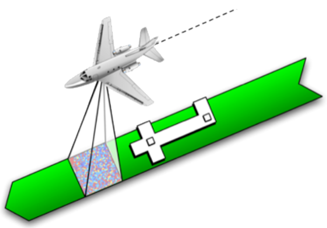
Exploit clustering of signal to eliminate noise





ALIRT Processing Workflow

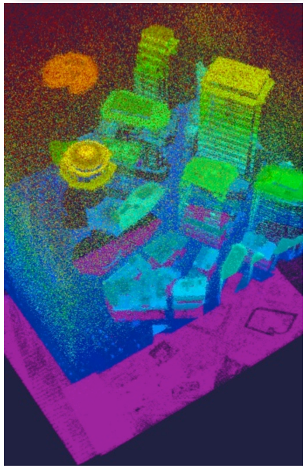
Level 0



Raw Data Streams

- Range measurements
- GPS IMU
- Mirror encoders
- GPS base station
- Meta data

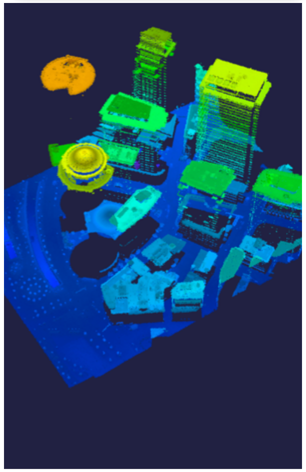
Level 1



Noisy Point Cloud

- All range measurements in one big set

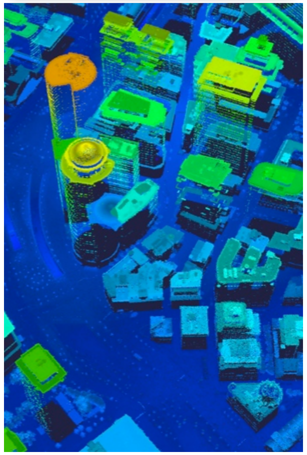
Level 2



Gridded Point Cloud

- Noise removed by coincidence processing
- Single points created from multiple range measurements

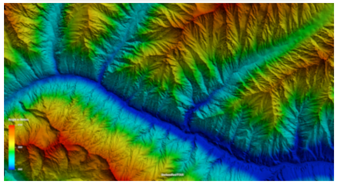
Level 3

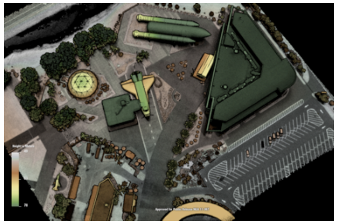


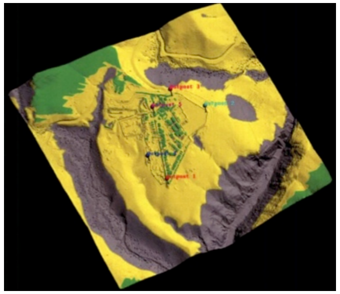
Aggregated Point Clouds

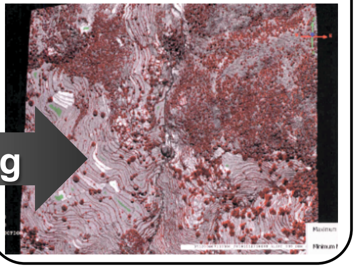
- Many L2 products intelligently aggregated

Level 4









Transform → Coincidence → Registration → Finishing

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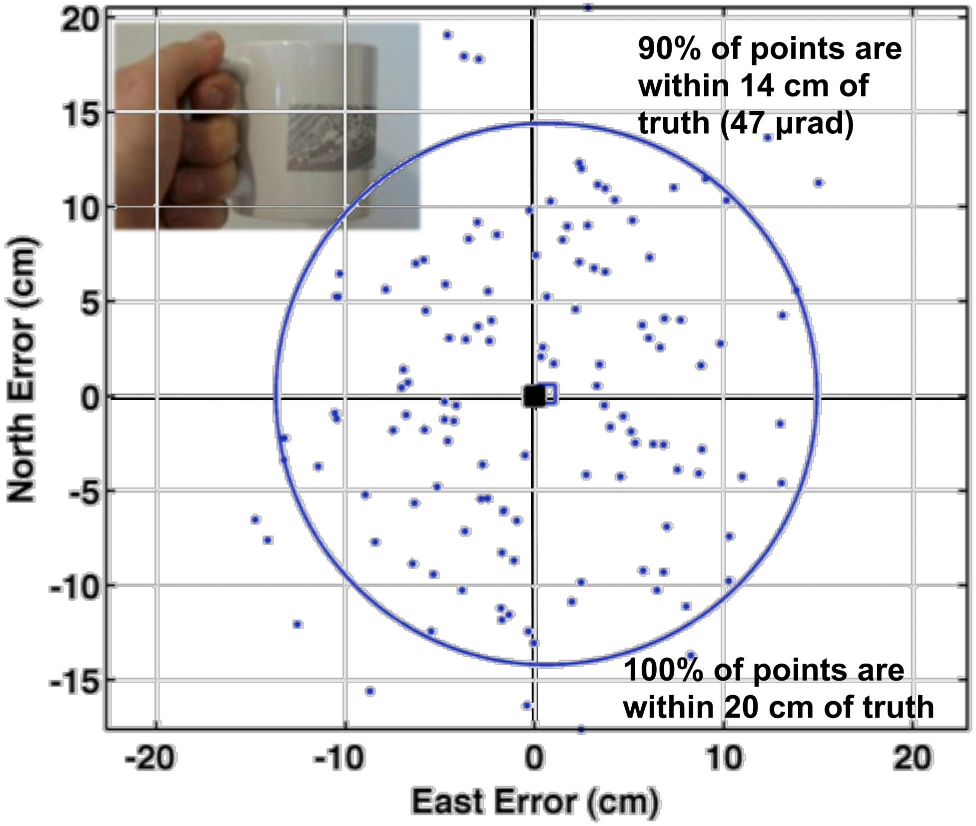
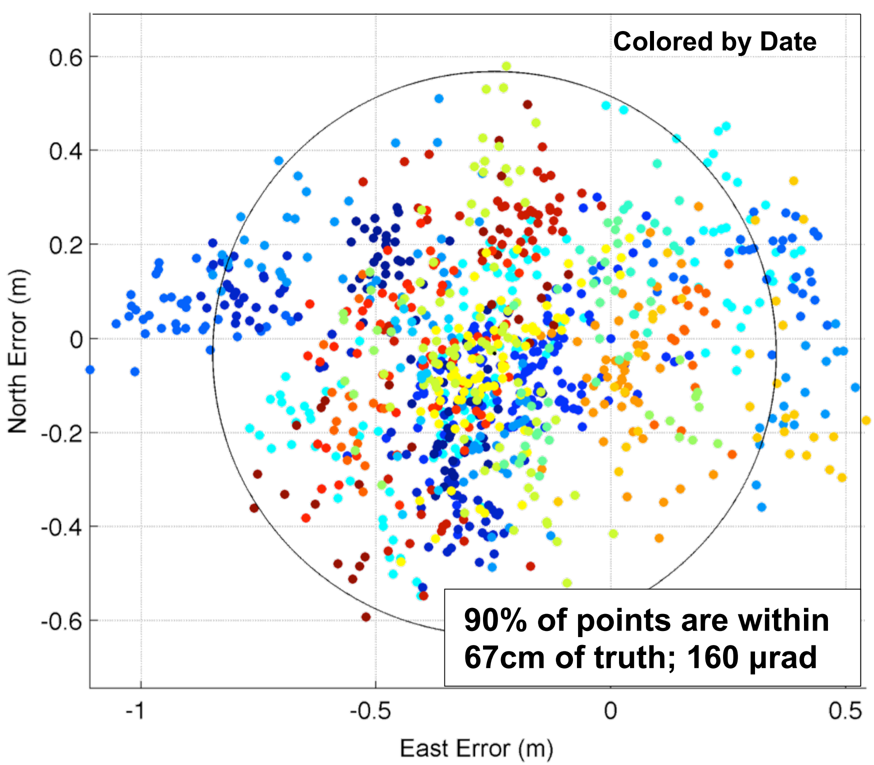
ALIRT Absolute Geolocation Capability



Absolute CE$_{90}$ = 14 cm from 10 kft

Maintains capability over
- **Many weeks**
- **Entire 30° x 40° field-of-regard**

Typical Performance



Absolute CE$_{90}$ <70cm from 13.5 kft
Maintains capability over
- **Many months**
- **Entire 30° x 40° field-of-regard**

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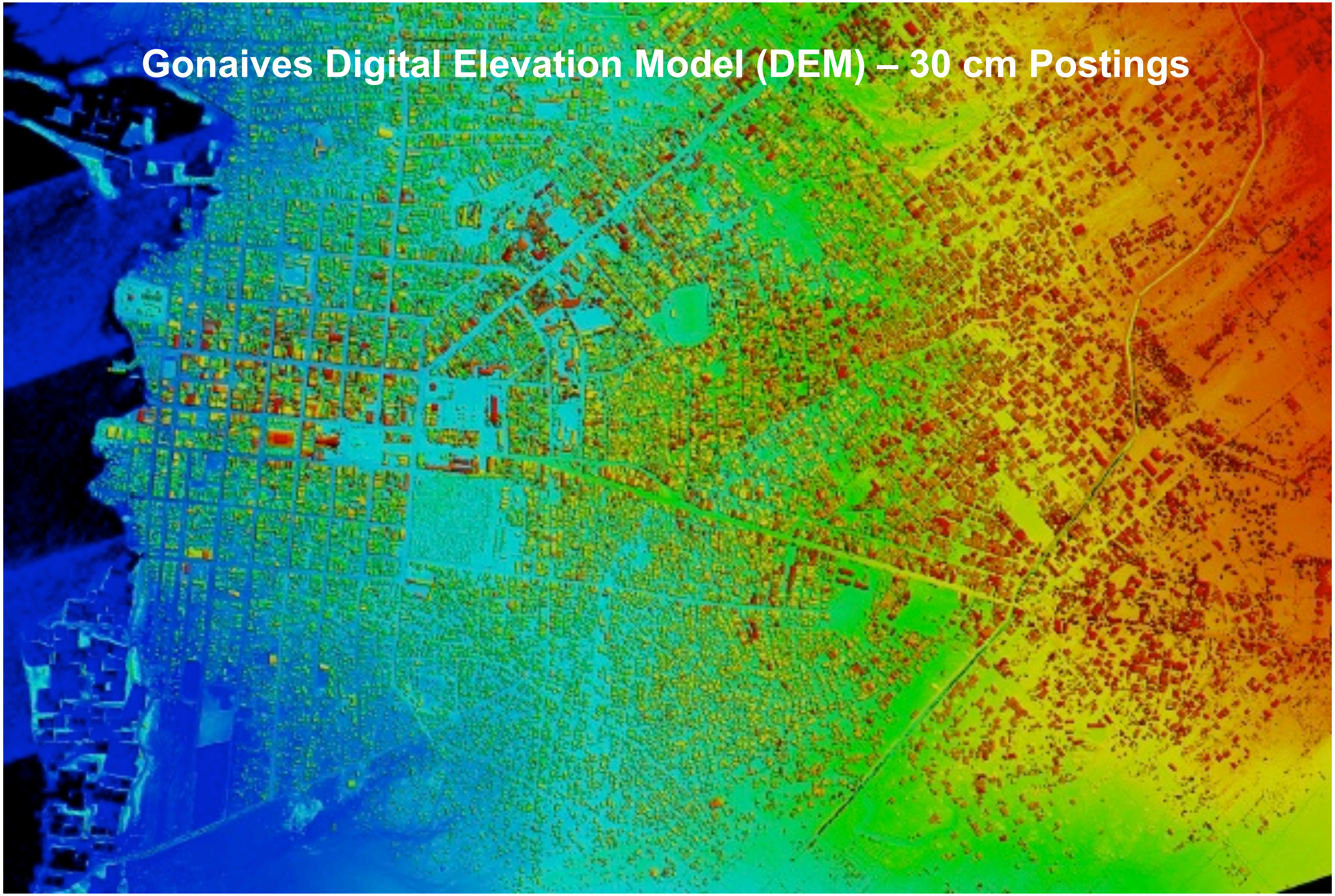
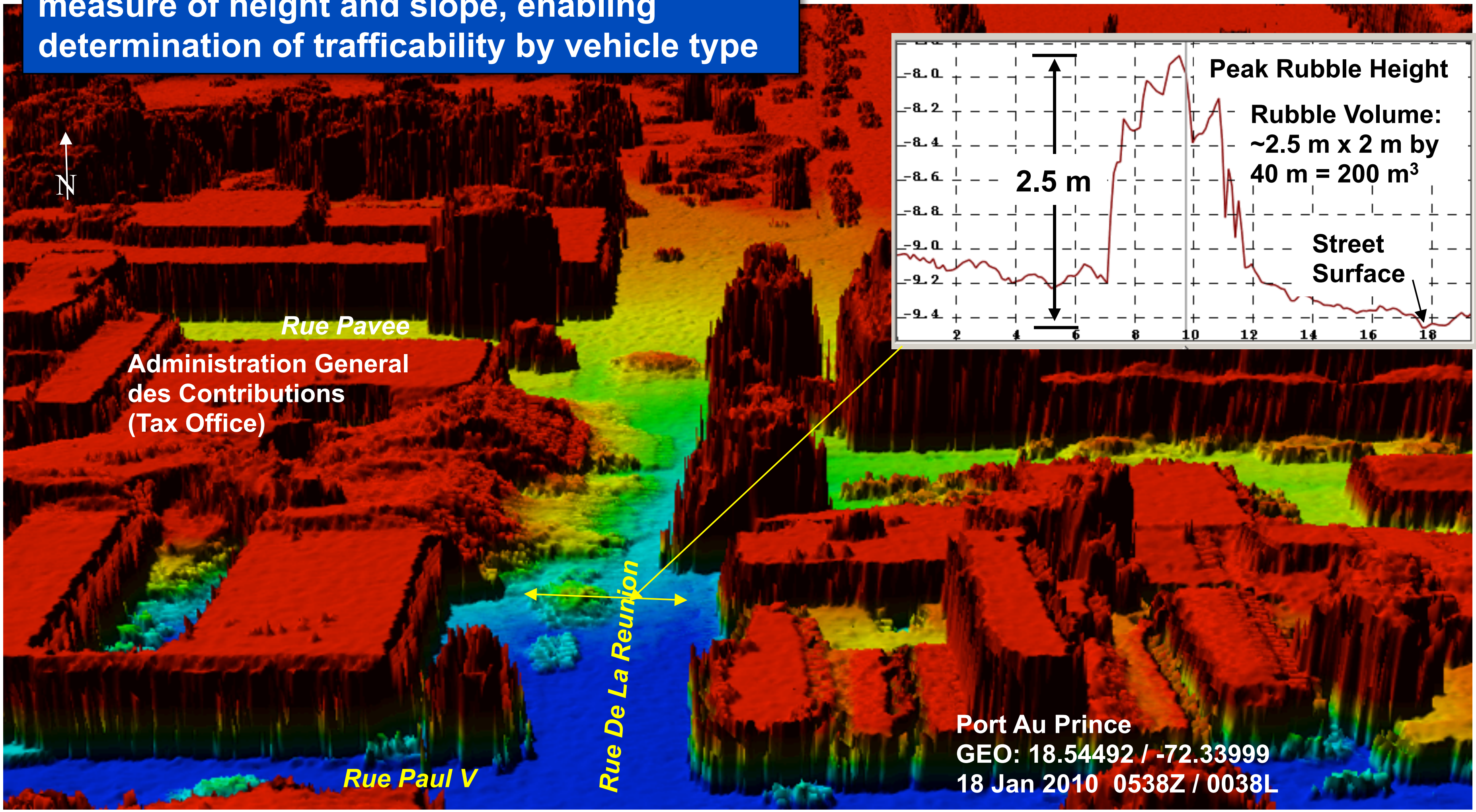
ALIRT Collection Areas: Haiti Disaster Relief Efforts

Wide-Area Mapping Example Over Haiti

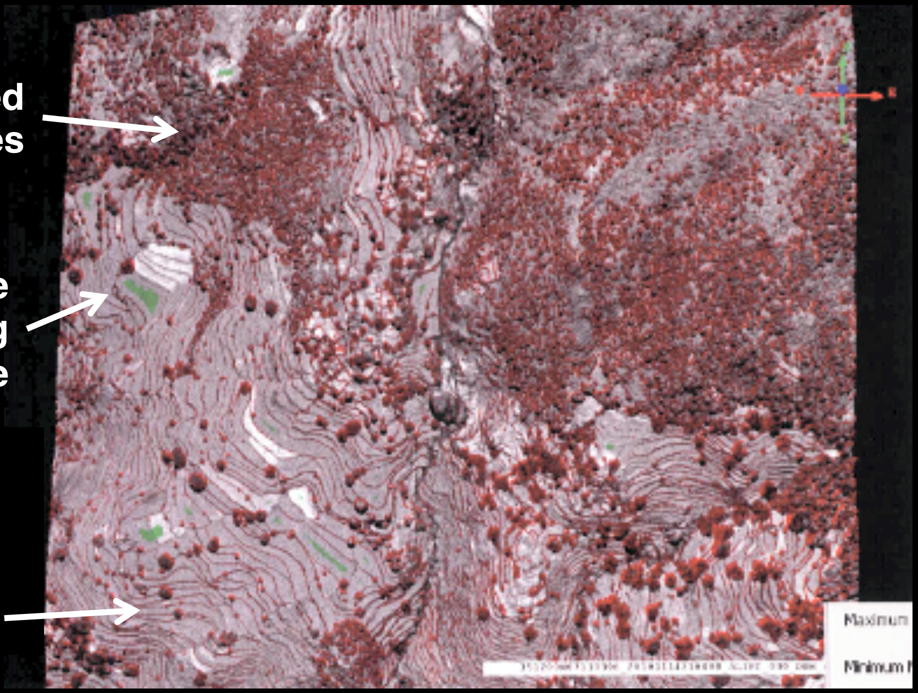


Example of Trafficability Analysis

Geometric data allows direct and precise measure of height and slope, enabling determination of trafficability by vehicle type



Helicopter Landing Zone Determination



LANDING ZONE CRITERIA

Radius: 10 m
Vertical variation: 1 m
Max Slope: 5°

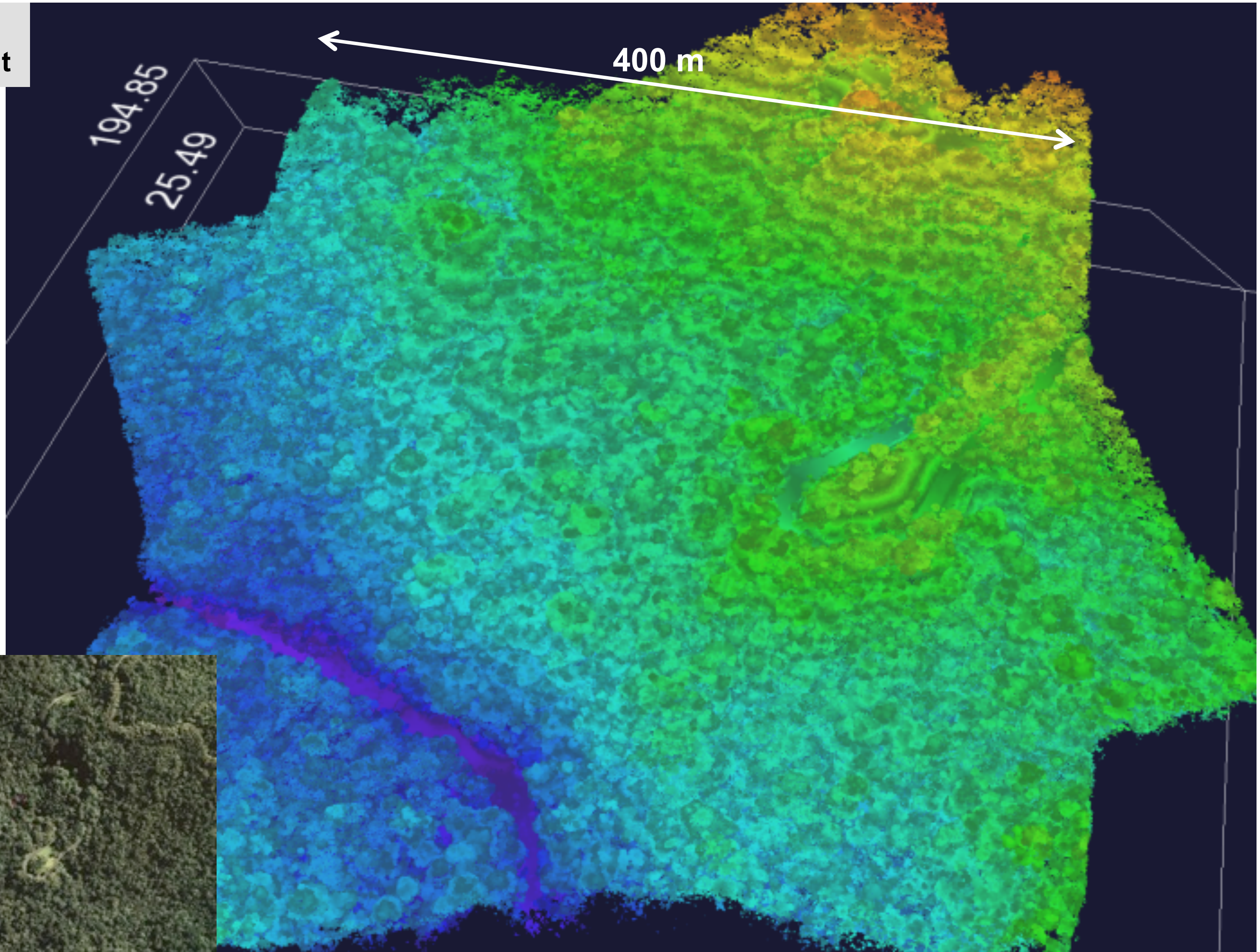
Key:

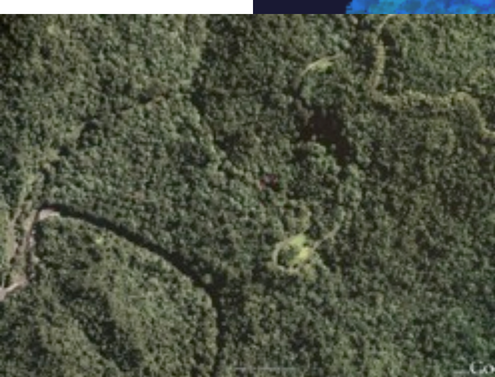
- Passed
- Failed
- Obstruction

- Current state-of-the-art algorithms are robust
- Challenges include getting data to end user quickly and in an appropriate format

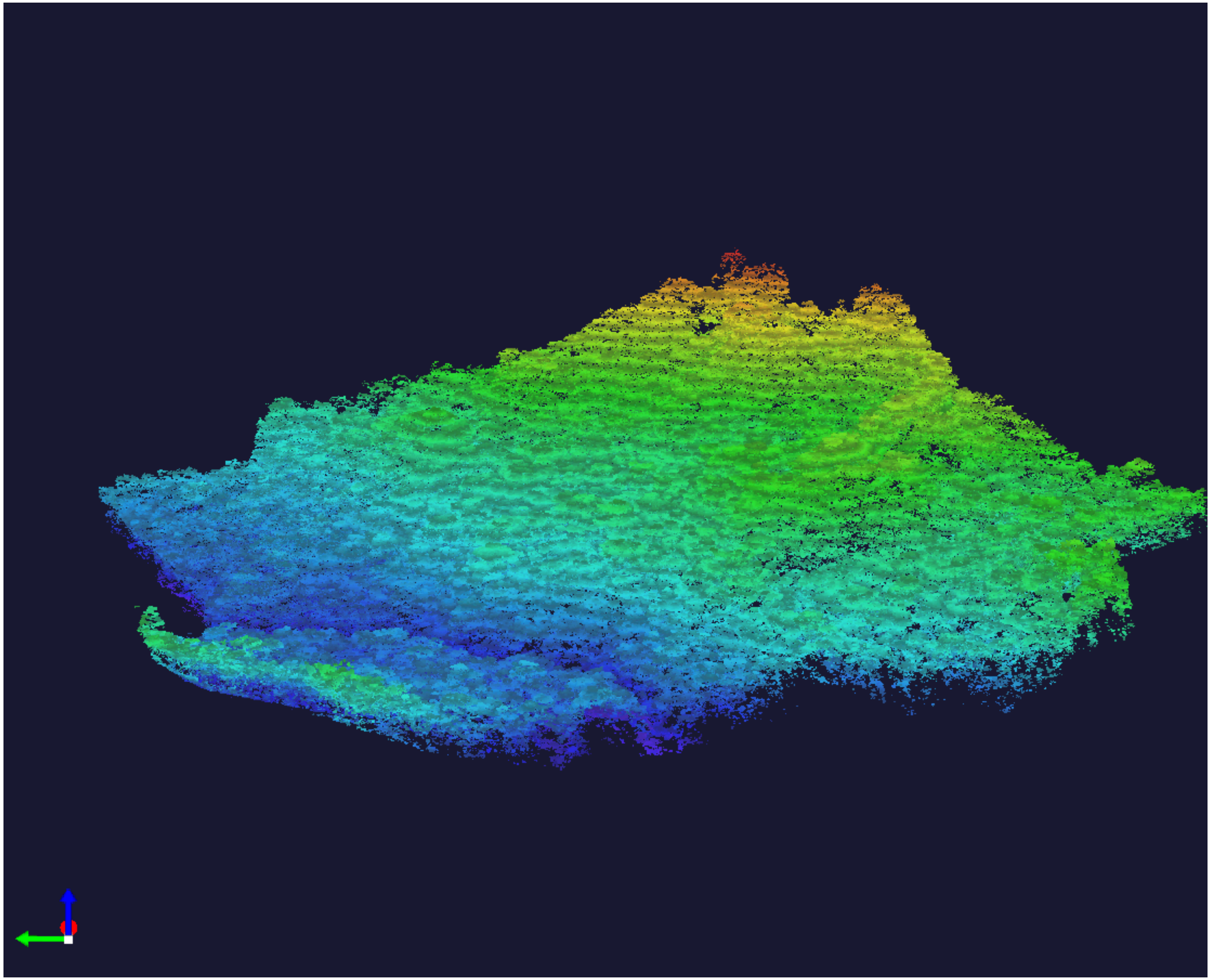
Rain Forest in El Yunque National Forest, Puerto Rico

Colorbar: ellipsoid height





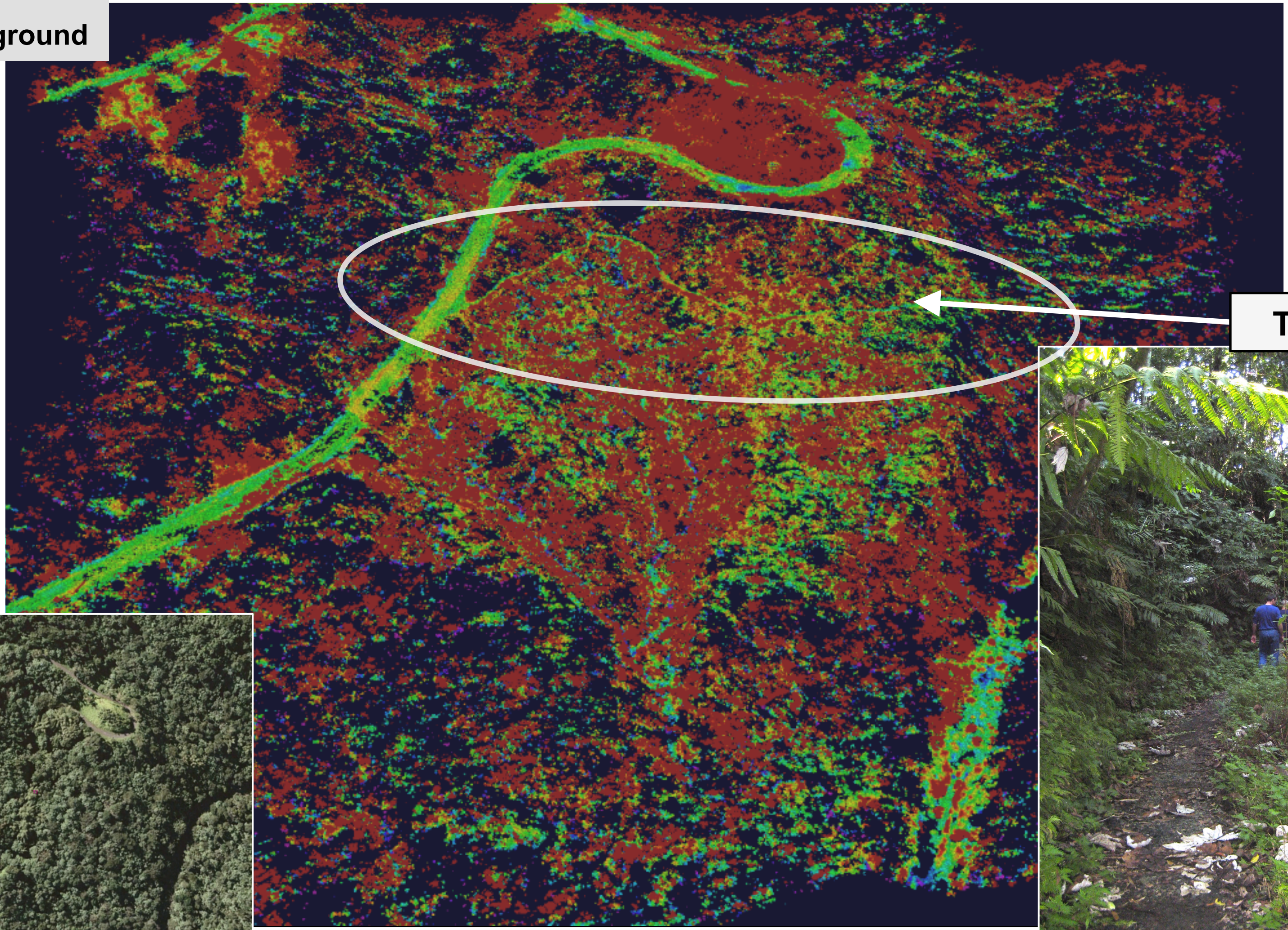
Rain Forest FOPEN - El Yunque National Forest



Collection parameters:
Flight altitude: 10 kft AGL
Imaging time: 15 sec in each of two passes
Laser: 1 W, 8 kHz, 1064 nm

Trail Detection

Colorbar:
height above ground



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FALCON-I Foliage Penetration System

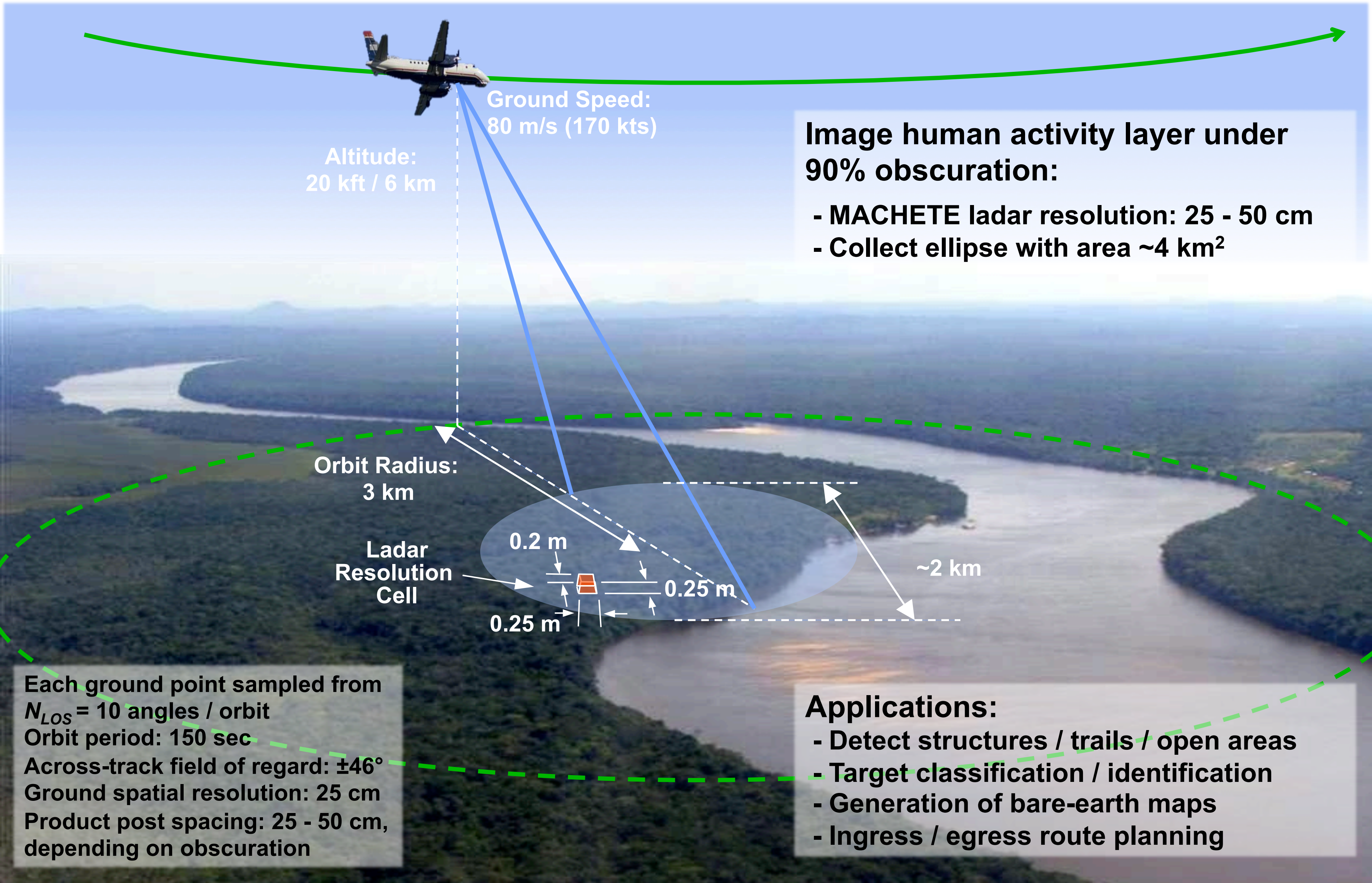

Image human activity layer under 90% obscuration:

- MACHETE ladar resolution: 25 - 50 cm
- Collect ellipse with area ~4 km^2

Each ground point sampled from
N_{LOS} = 10 angles / orbit
Orbit period: 150 sec
Across-track field of regard: ±46°
Ground spatial resolution: 25 cm
Product post spacing: 25 - 50 cm, depending on obscuration

Applications:

- Detect structures / trails / open areas
- Target classification / identification
- Generation of bare-earth maps
- Ingress / egress route planning

Outline

- Overview of 3-D Ladar
- ALIRT system
  - Hardware and processing
  - Example collections and data utility
- Ladar system considerations
  - Detector technology
  - Scanning
  - Signal & laser power
  - Measurement rates

Detector Technology

Detector Operating Mode	Detector Format: Single- or Few-Pixel	Detector Format: Large Array
Linear-Mode		
Photon-Counting		

10^3 - 10^5× more detectors

100× less light

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Detector Technology

Detector Operating Mode		Detector Format: Single- or Few-Pixel	Detector Format: Large Array
		Single- or Few-Pixel + Sophisticated readout circuitry possible - Lower collection rate	**Large Array** + High collection rate - Simple pixel readout circuit
	Linear-Mode + Simple noise rejection - Need lots of light; require 1000 detected photons - Compromised range resolution	**Most commercial systems**	**New products**
	Photon-Counting + Most efficient use of every photon; requires average of only 10-15 detected photons + Tight range resolution +/- Post-processing - High data volume	**Early demonstrations**	**Specialized systems**

10^3 - 10^5× more detectors

100× less light

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Detector Technology

	Detector Format: Single- or Few-Pixel	**Detector Format**: Large Array
	+ Sophisticated readout circuitry possible - Lower collection rate	+ High collection rate - Simple pixel readout circuit
Detector Operating Mode: Linear-Mode + Simple noise rejection - Need lots of light; require 1000 detected photons - Compromised range resolution	**Most commercial systems** + COTS: Optech, Leica, Reigl, etc + Simple detection - Accurate, fast scanning - Lower collection rate - Medium range: 0.3 - 3 km	**New products** + 3D video + Simple, compact - Short ranges: 0.1 - 1 km
Detector Operating Mode: Photon-Counting + Most efficient use of every photon; requires average of only 10-15 detected photons + Tight range resolution +/- Post-processing - High data volume	**Early demonstrations**	**Specialized systems:** (e.g. ALIRT, JIGSAW, HALOE, FALCON-I) Cameras becoming available + Long-range: 3 – 15 km + Country-sized collection rates - Accurate scanning

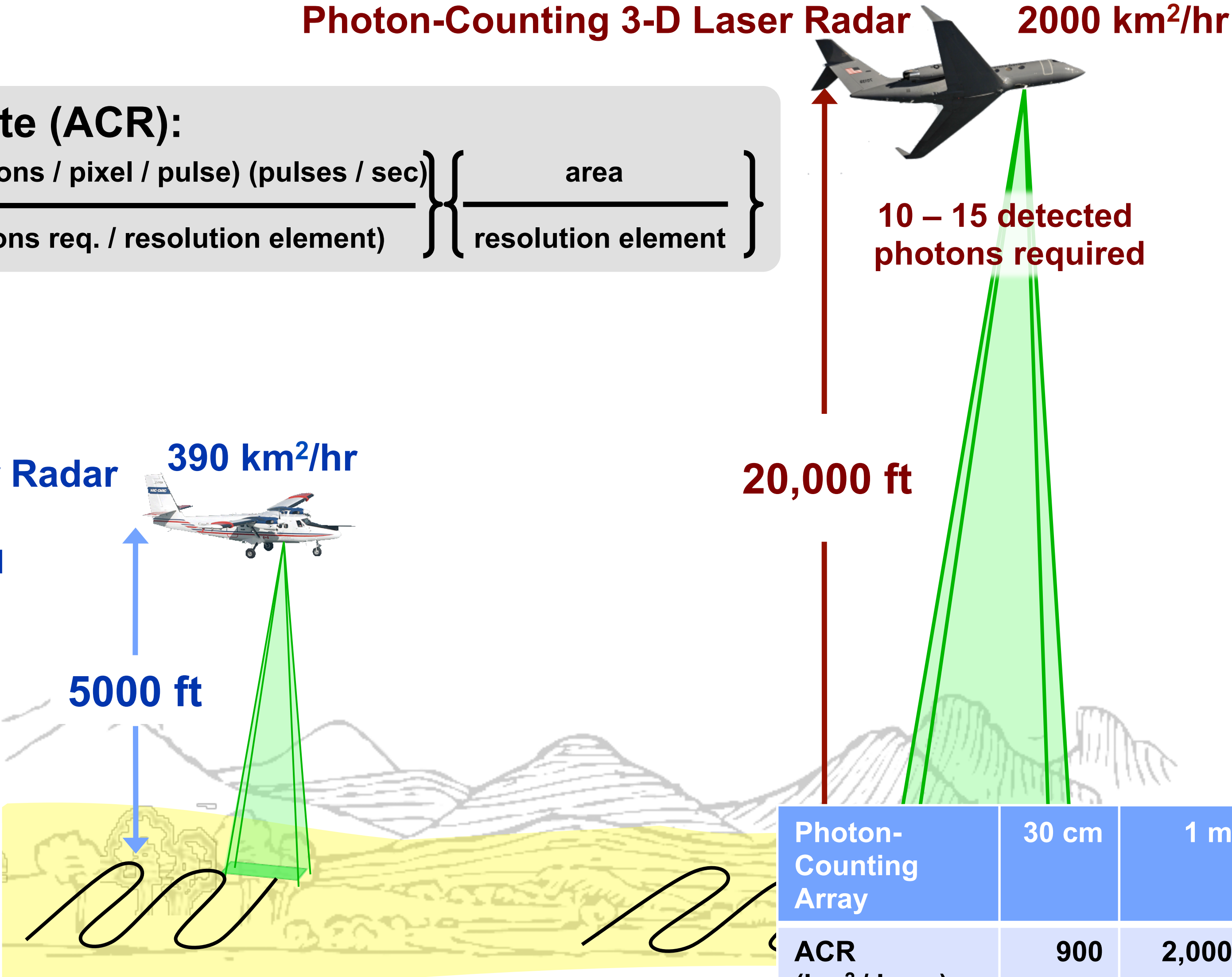
10^3 - 10^5× more detectors

100× less light

Area Collection Rate Comparison

Area Collection Rate (ACR):

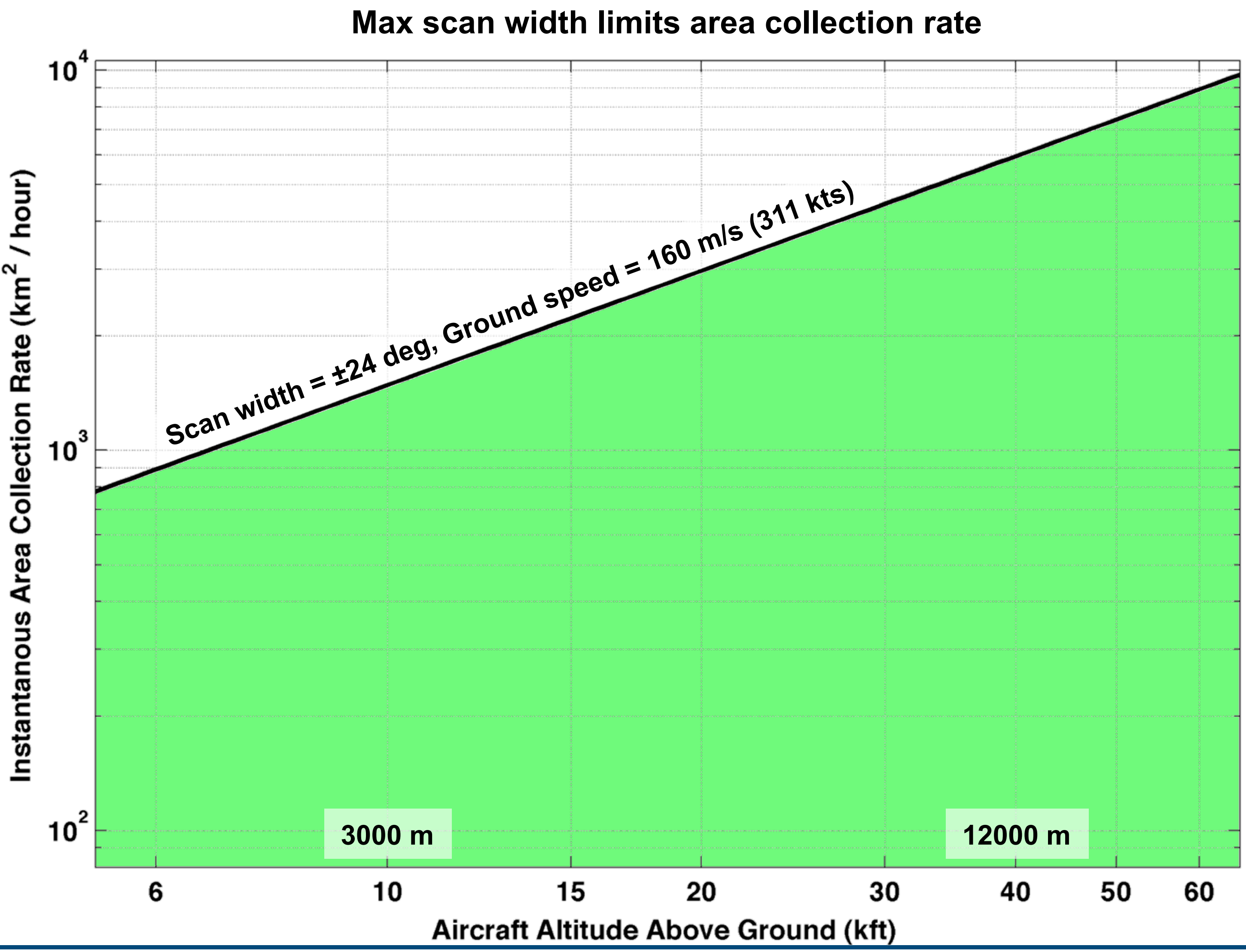
$$ACR = \left\{ \frac{N_{pixels}\ \text{(avg num. detections / pixel / pulse) (pulses / sec)}}{\text{(avg num. of detections req. / resolution element)}} \right\} \left\{ \frac{\text{area}}{\text{resolution element}} \right\}$$



Linear-Mode Single-Pixel	30 cm	1 m
ACR (km^2 / hour)	90	390
Altitude (ft)	1,600	5,200

Photon-Counting Array	30 cm	1 m
ACR (km^2 / hour)	900	2,000
Altitude (ft)	6,600	20,000

Area Collection Rate Limitations



Note: scanning more than 2x wider often results in image degradation due to shadowing.

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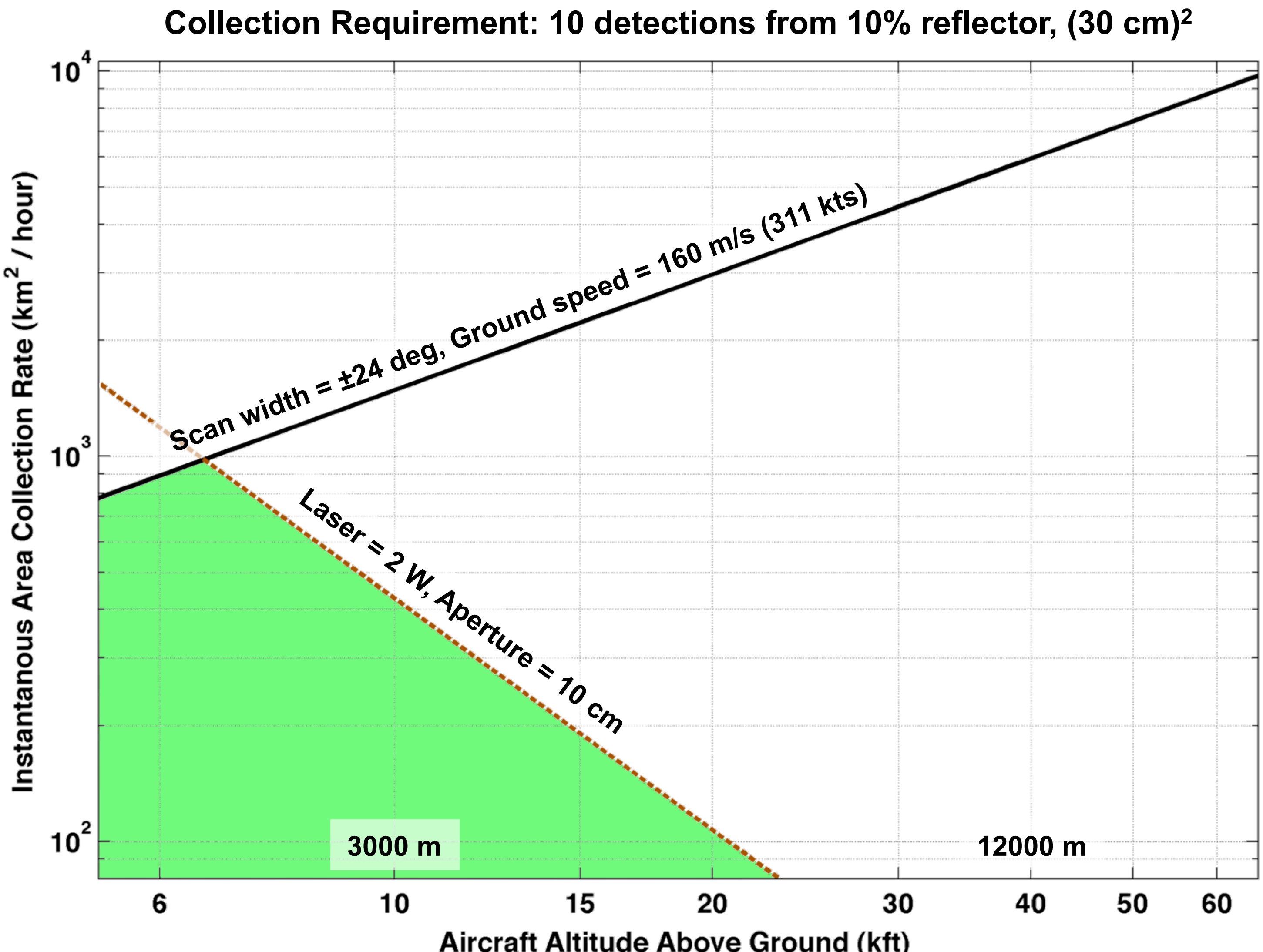
Area Collection Rate Limitations



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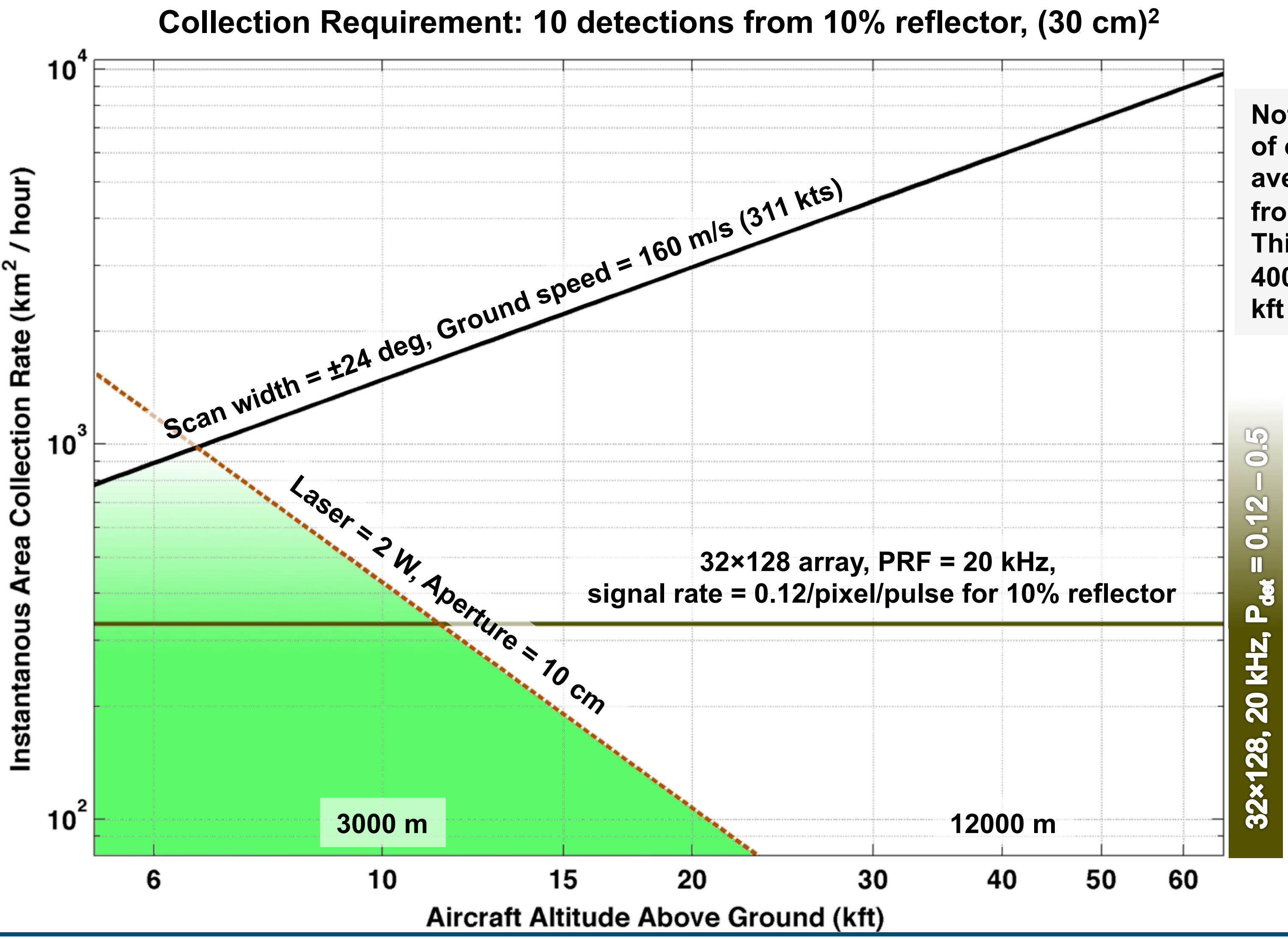
Area Collection Rate Limitations



Note: the practical limit of operation is an average of 5 detections from a 20% reflector. This allows an ACR of 400 km² / hour from 20 kft AGL

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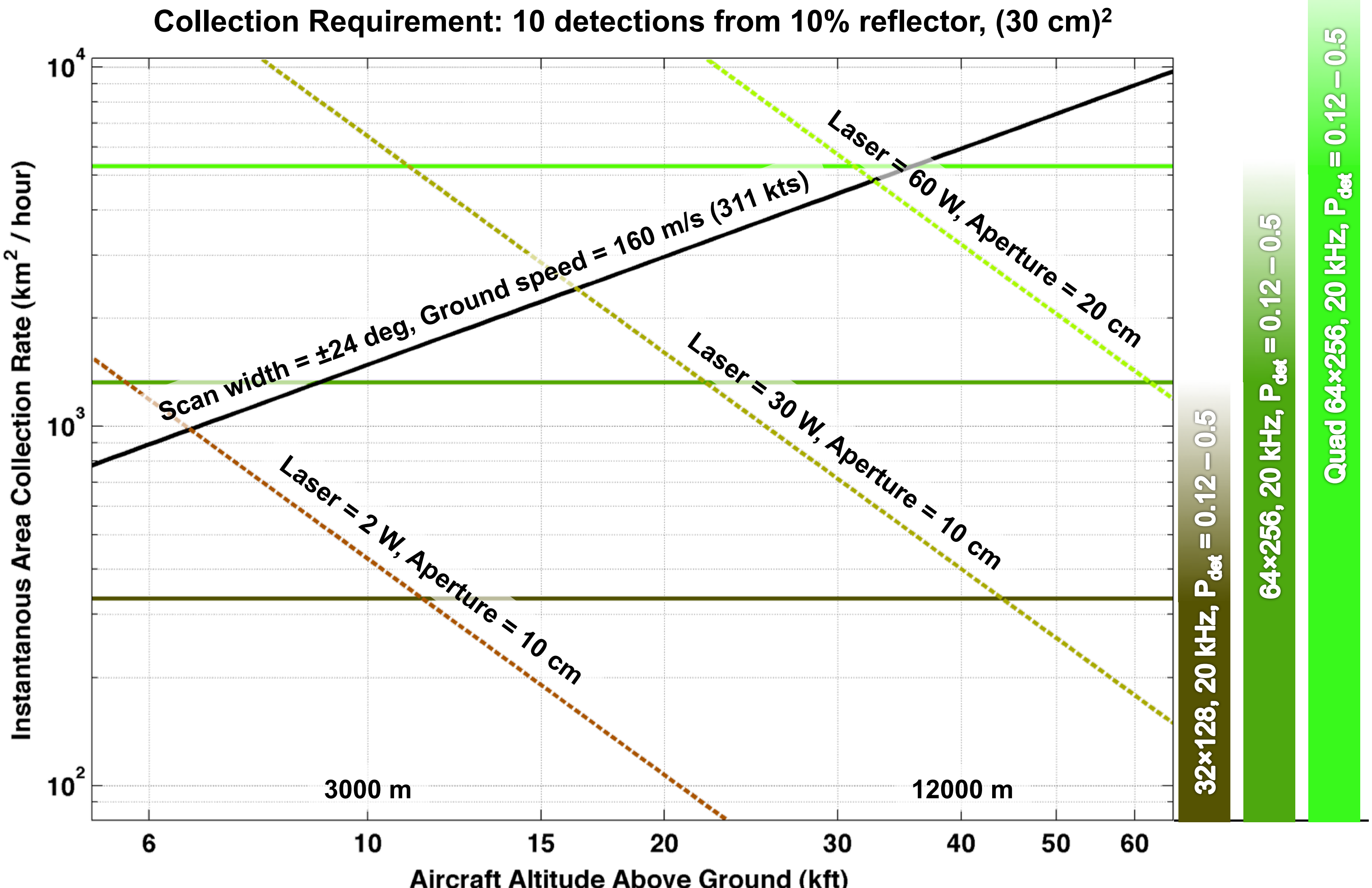
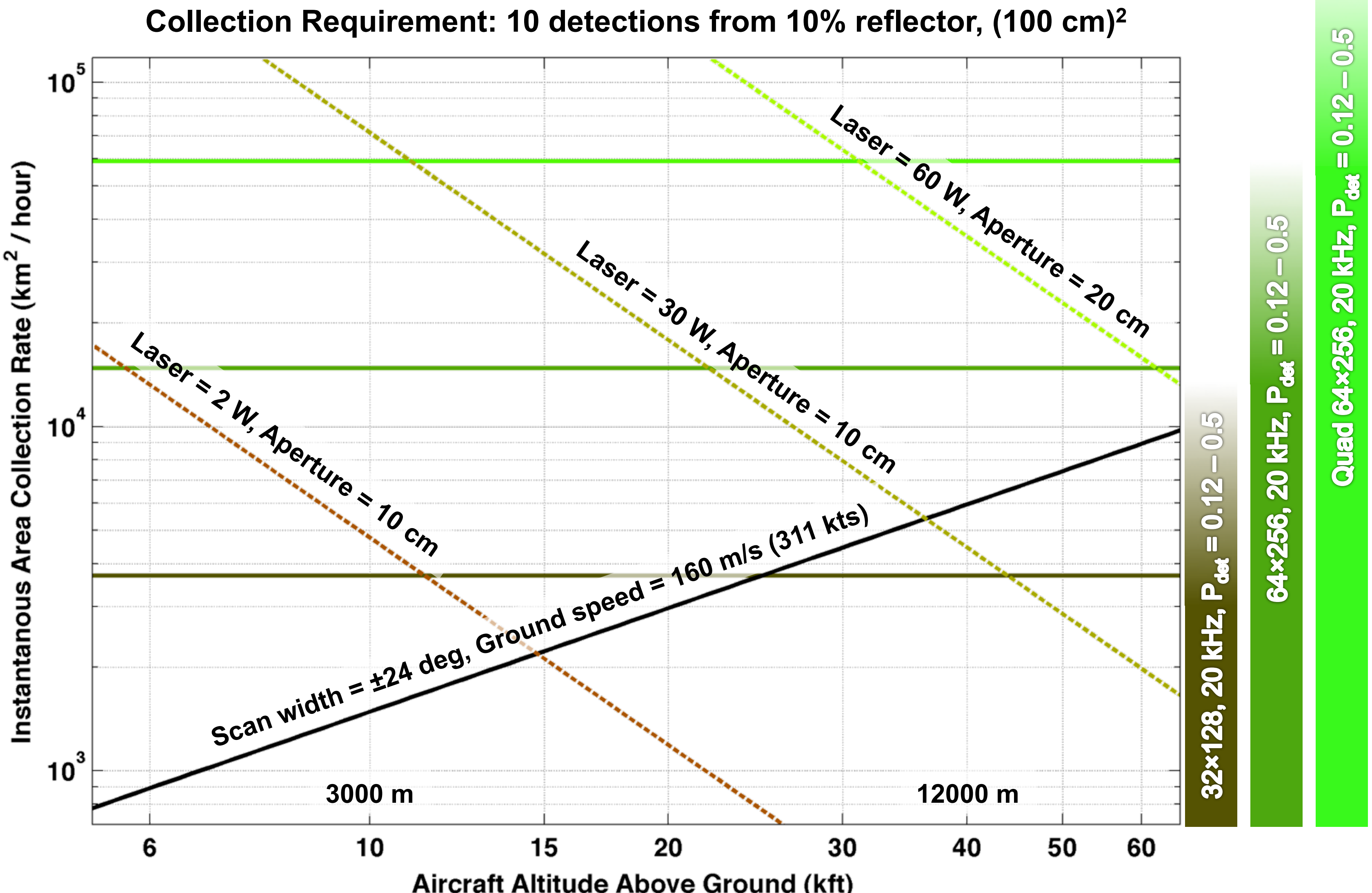
Area Collection Rate Scaling



Area Collection Rates: 1 m Resolution



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Conclusions

- **Airborne laser radars can rapidly collect human-scale 3-D maps**
  - **Wide-area maps of terrain and urban areas**
  - **Foliage poke-thru**
- **Arrays of photon-counting detectors are enabling a new generation of ladar systems**
  - **Photon-counting = light efficiency = reduced size/weight/power**
  - **Larger arrays = higher measurement rates = reduced operating costs**
  - **High ACR systems must fly higher, thereby requiring photon-counting technology**
- **Large arrays of Geiger-Mode APDs have been field-proven**

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Backup