Linear LiDAR versus Geiger-mode LiDAR: data properties and data quality

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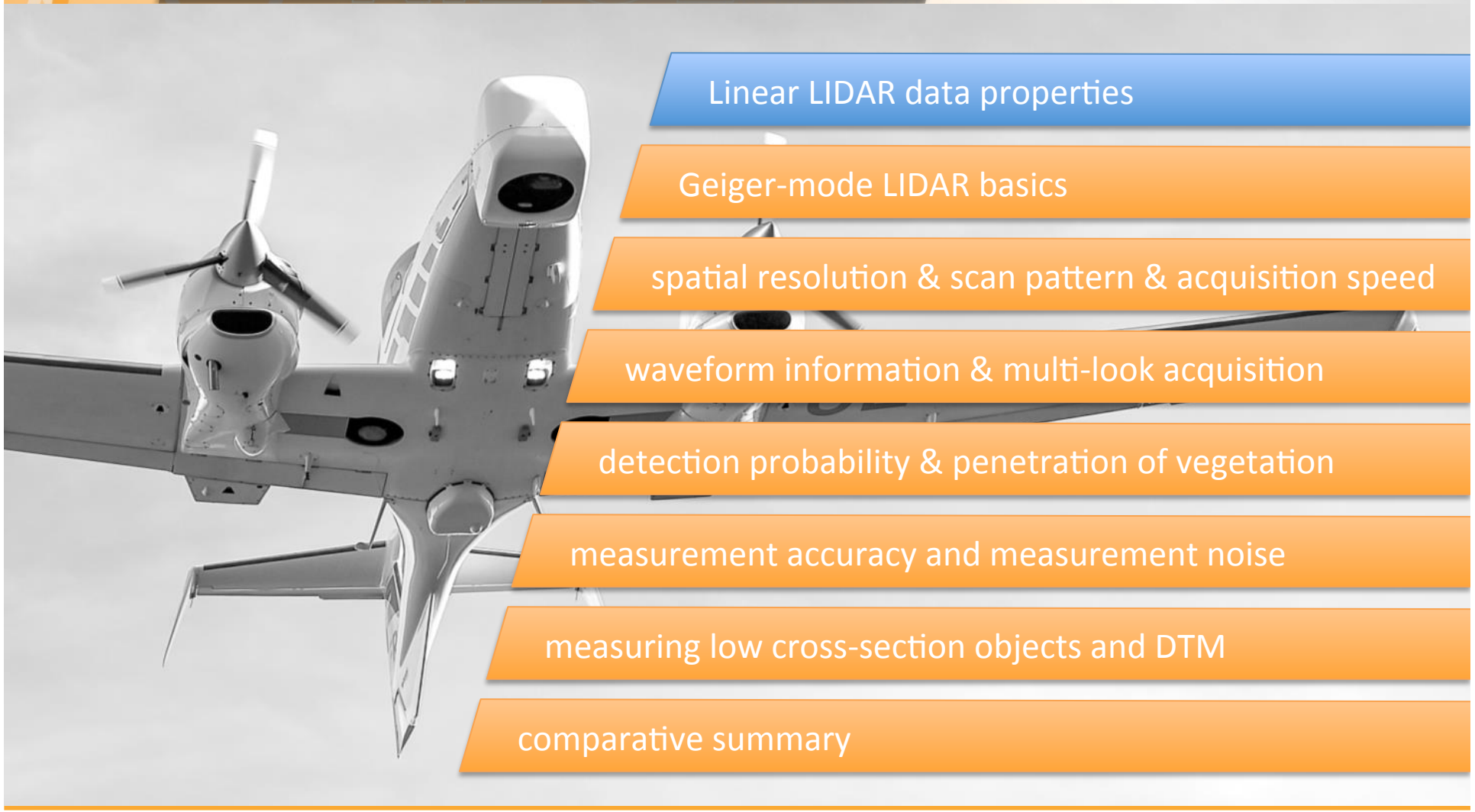
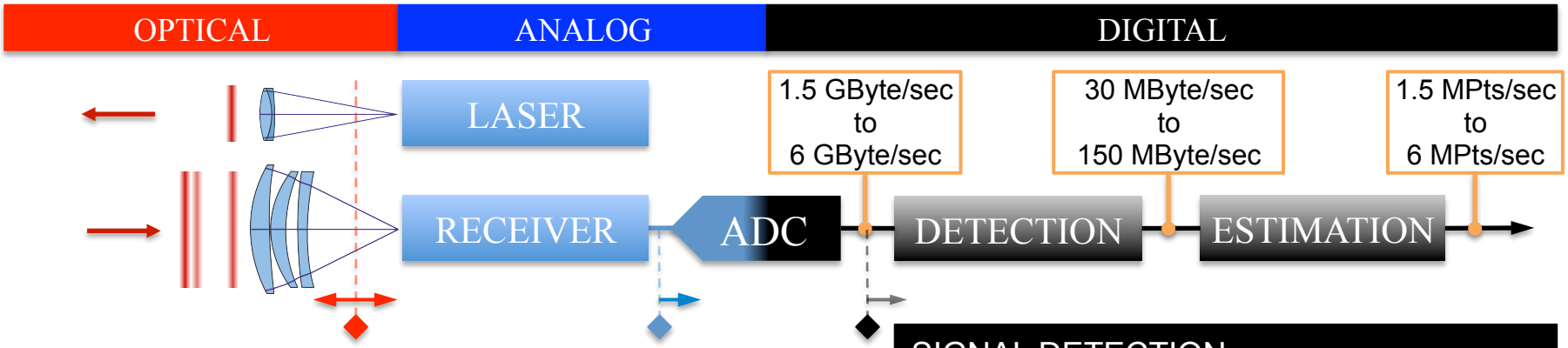
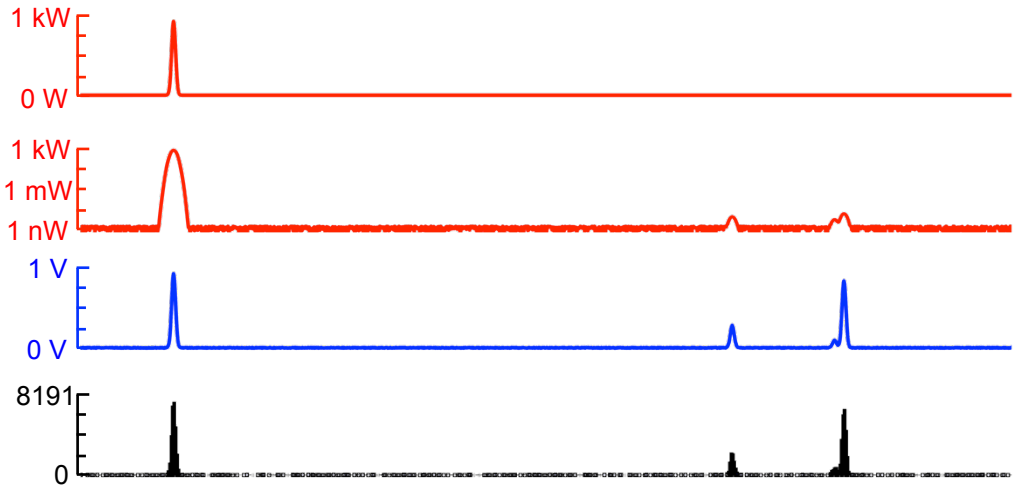
contents



Linear LIDAR with pure digital signal processing





SIGNAL DETECTION

- sample block / sample datagram for Full Waveform Analyses
- internal sample datagrams for Online Waveform Processing

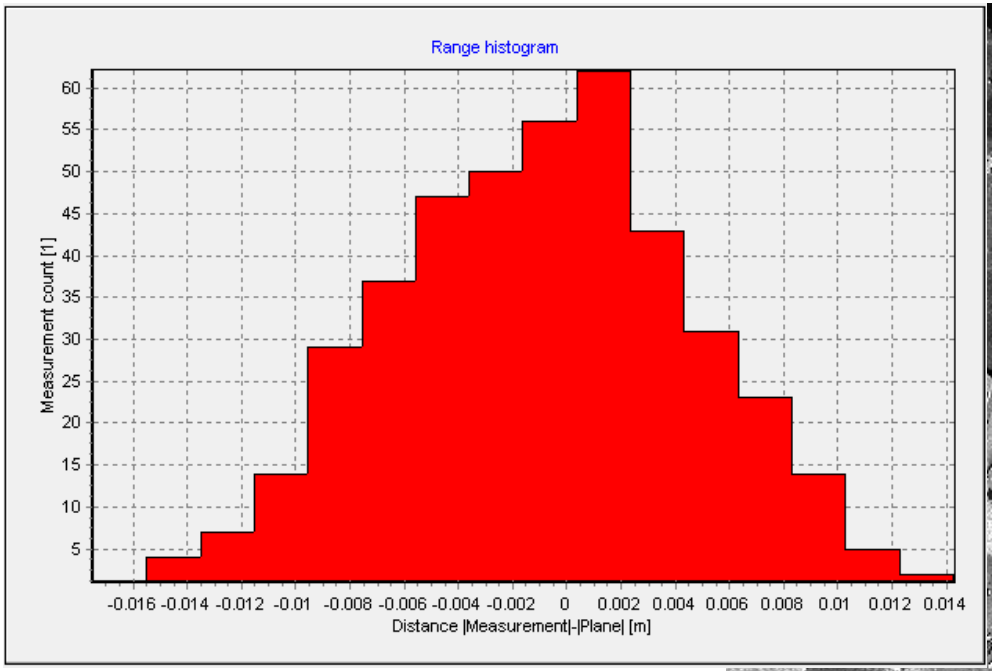
SIGNAL ESTIMATION

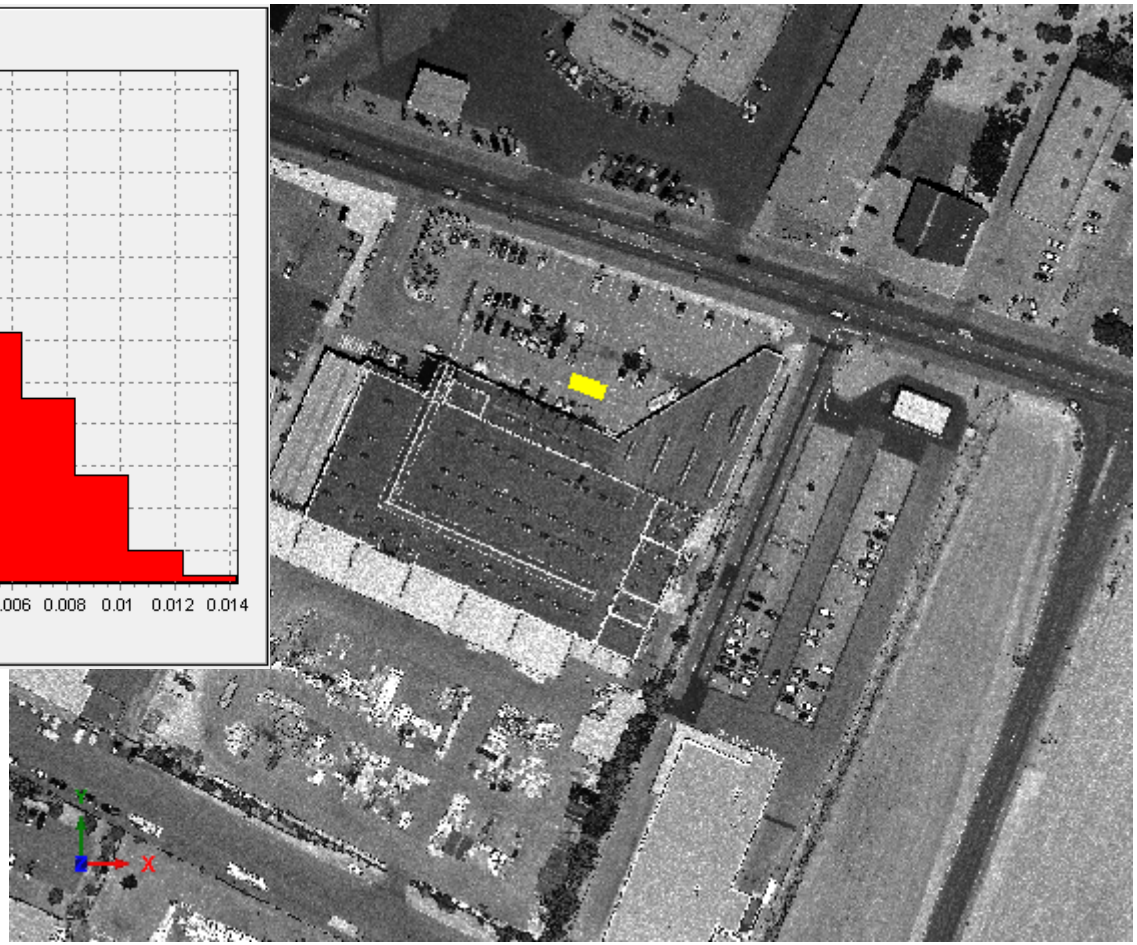
- temporal position / range
- signal strength / amplitude / reflectance
- pulse width / pulse shape deviation
- backscatter coefficient of turbid media

Linear LIDAR with pure digital signal processing

- high ranging accuracy
- low range noise / high precision
- highest multi-target resolution
- valuable pulse shape information for cleaning up point clouds, assisting classification, filtering
- solid basis for radiometric measurements

Linear LIDAR:
ranging precision – relative accuracy





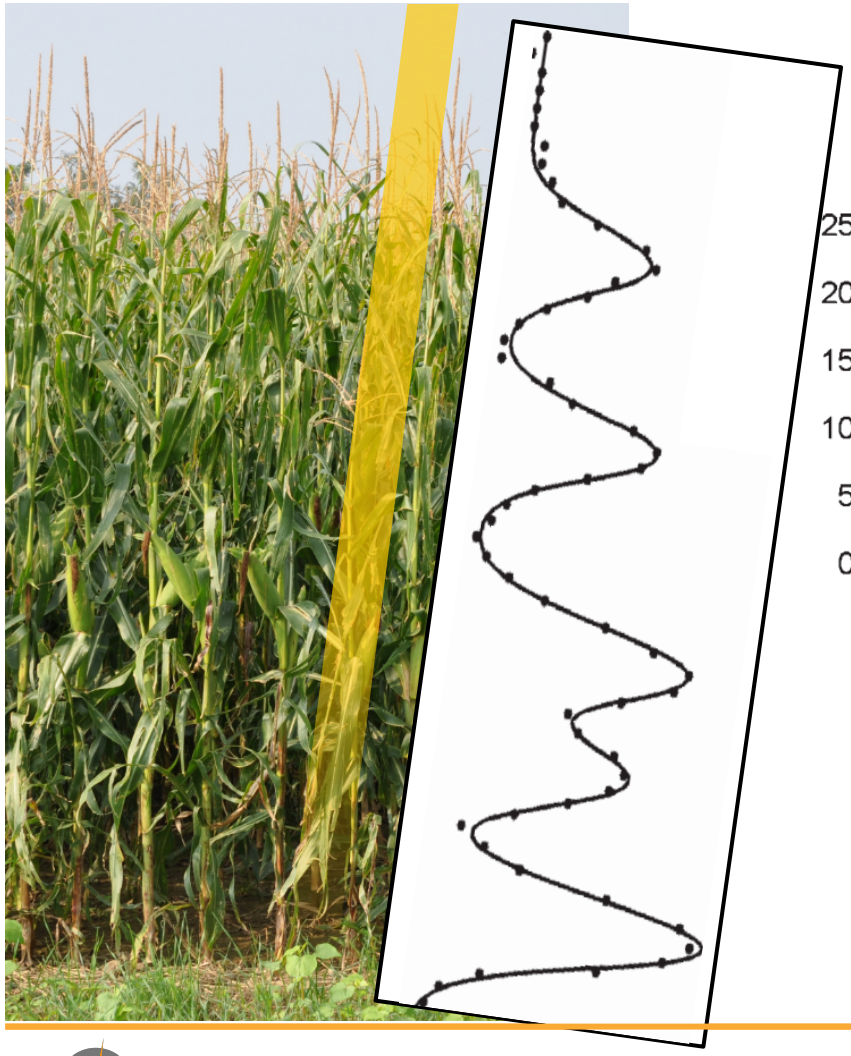
- 425 measurements on flat 30 m² area of parking lot
- least-square fitting of plane
- standard deviation 5 mm

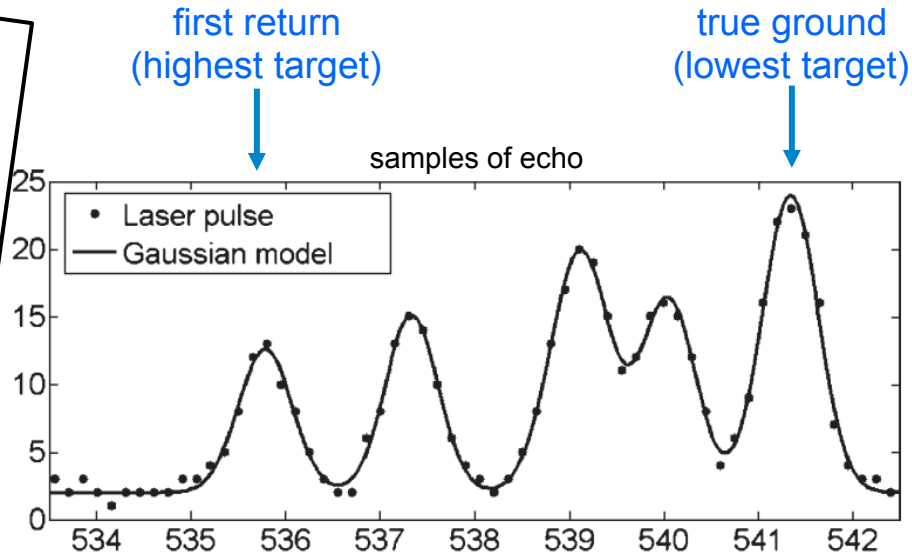
Linear LIDAR with pure digital signal processing

RIEGL®

- precision 10 mm typ
- relative accuracy 15 mm typ
- absolute accuracy 25 mm typ
- spatial resolution 15 cm typically (AGL 600 m)

Linear LIDAR with pure digital signal processing

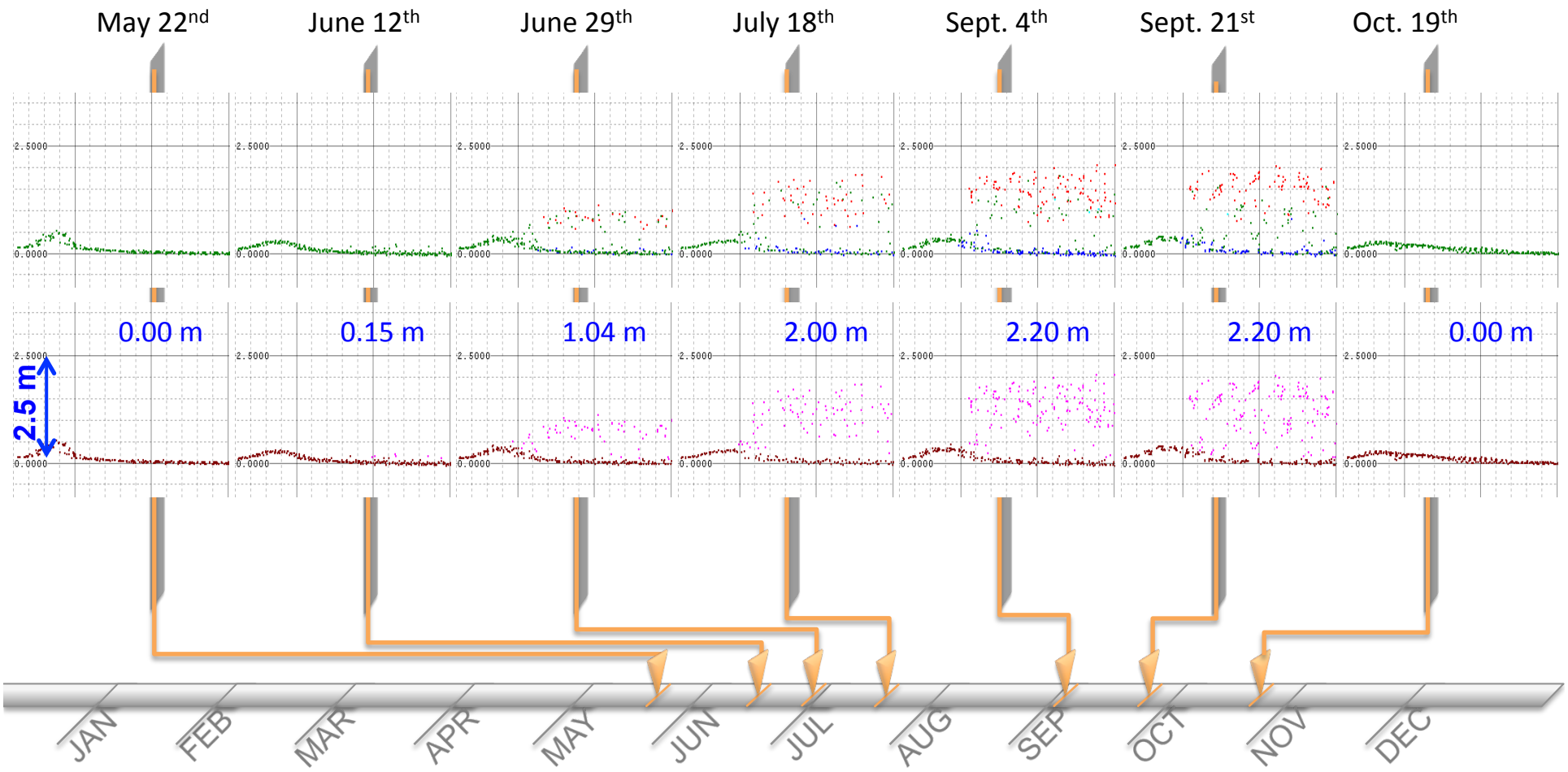




Gaussian decomposition

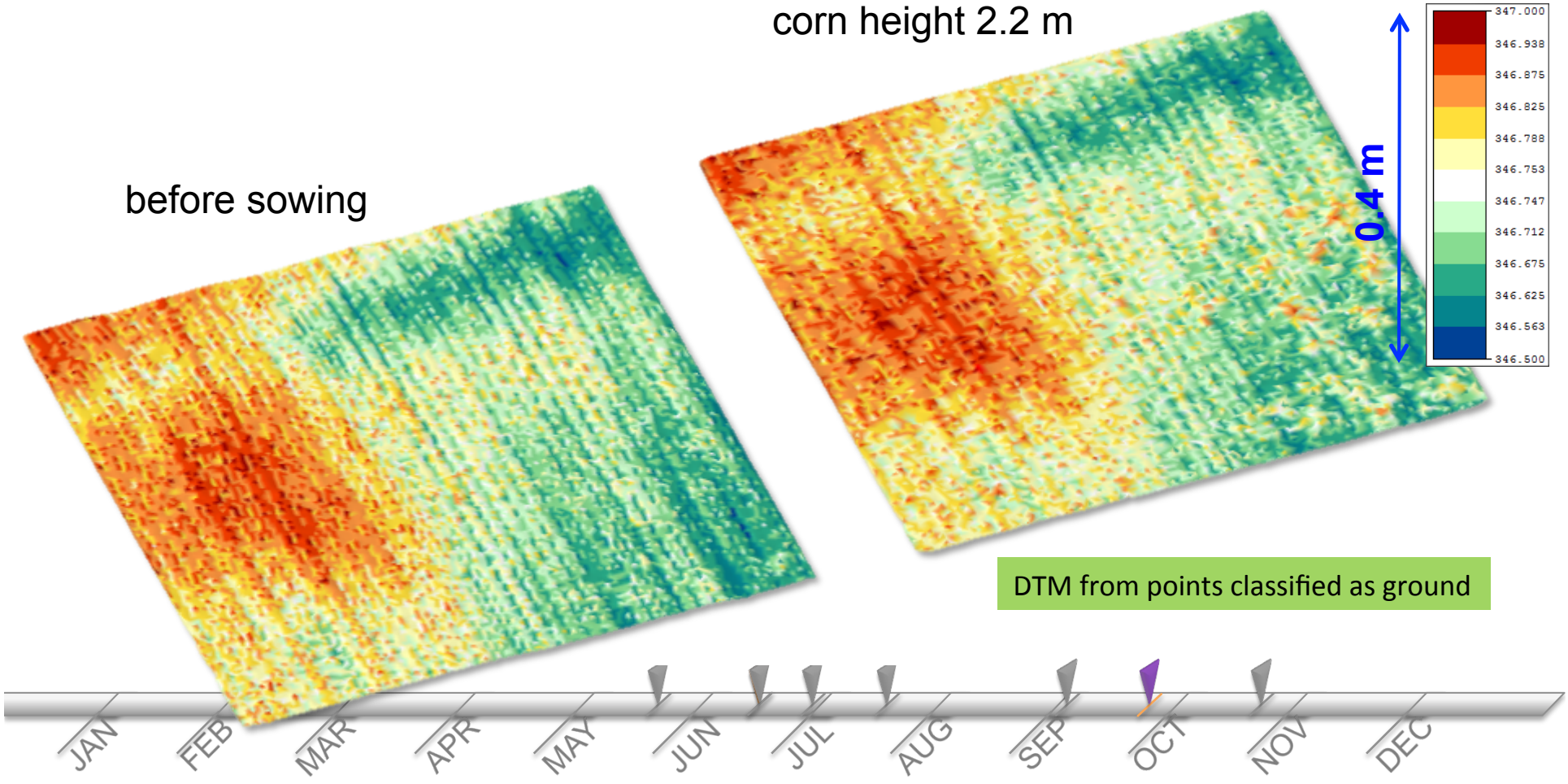
- fits Gaussian system response
- estimates pulse width
- estimates target‘s depth (width)
- robust and fast
- *RIEGL* RiANALYZE

Linear LIDAR with pure digital signal processing



RIEGL

Linear LIDAR with pure digital signal processing



RIEGL

Linear LIDAR: radiometrically calibrated data

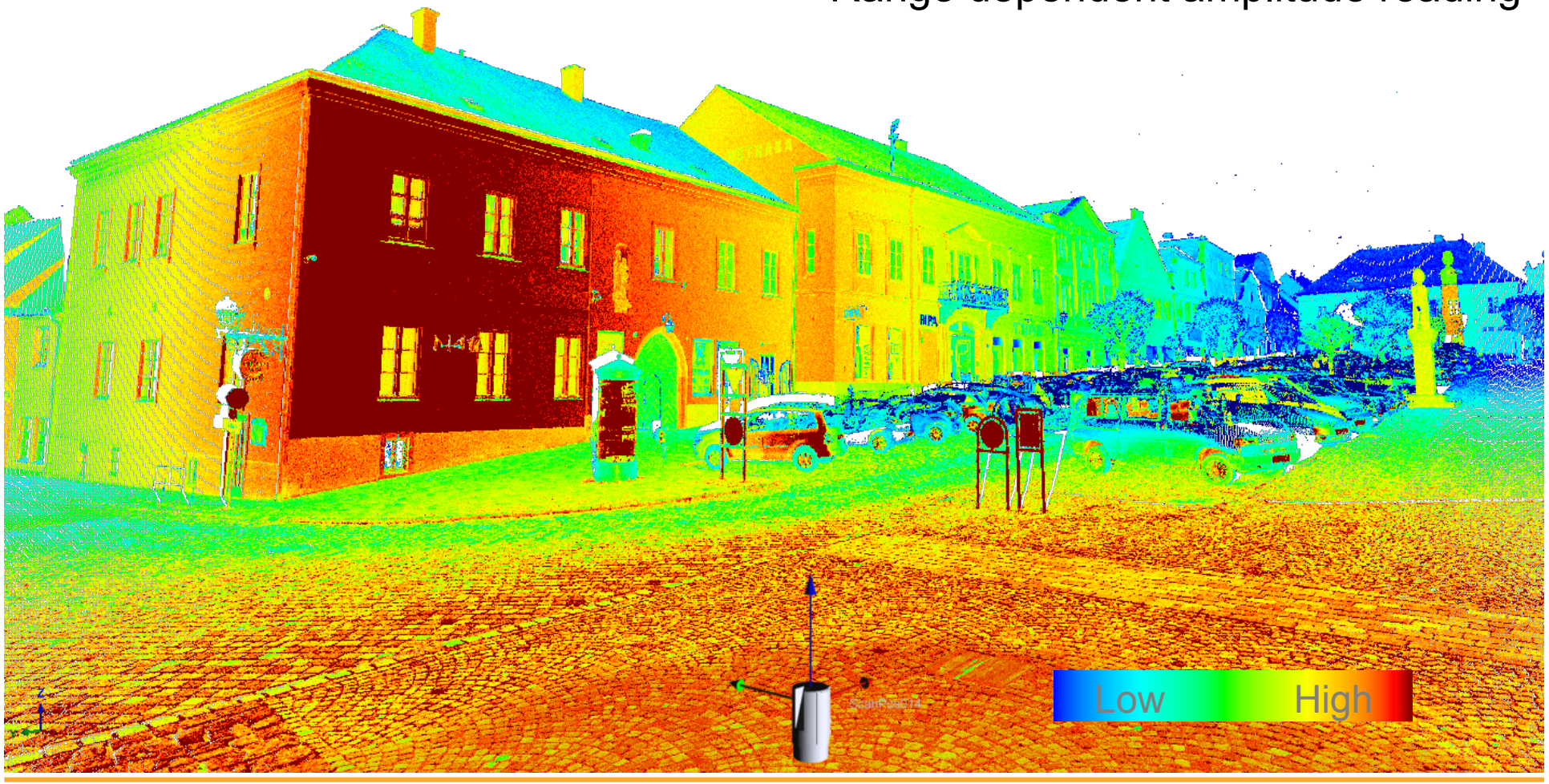
for all *RIEGL* instruments:

- factory calibration of amplitude and reflectance for each LIDAR unit
- *RIEGL's* **amplitude** readings
  - calibrated ✔
  - given for the **optical regime** in dB relative to detection threshold ✔
- *RIEGL's* **reflectance** readings are
  - calibrated ✔
  - in dB relative to a white diffusely reflecting target ✔
- benefits for the user
  - improved visual inspection of scans
  - automatic retrieval of retro-reflecting targets
  - straightforward radiometric calibration of data sets

Linear LIDAR: radiometrically calibrated data

RIEGL

Range dependent amplitude reading

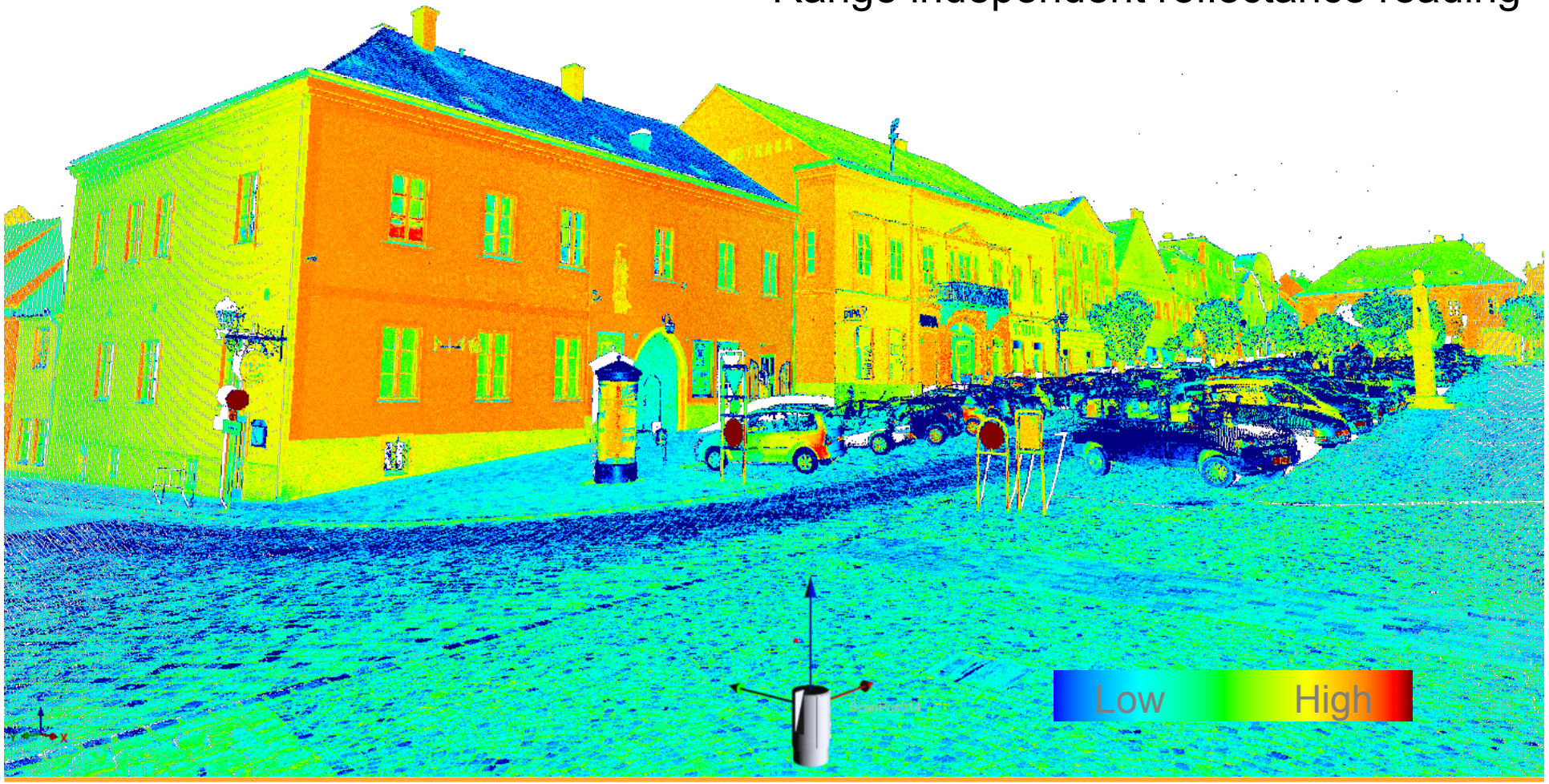


RIEGL

Linear LIDAR: radiometrically calibrated data

RIEGL®

Range independent reflectance reading

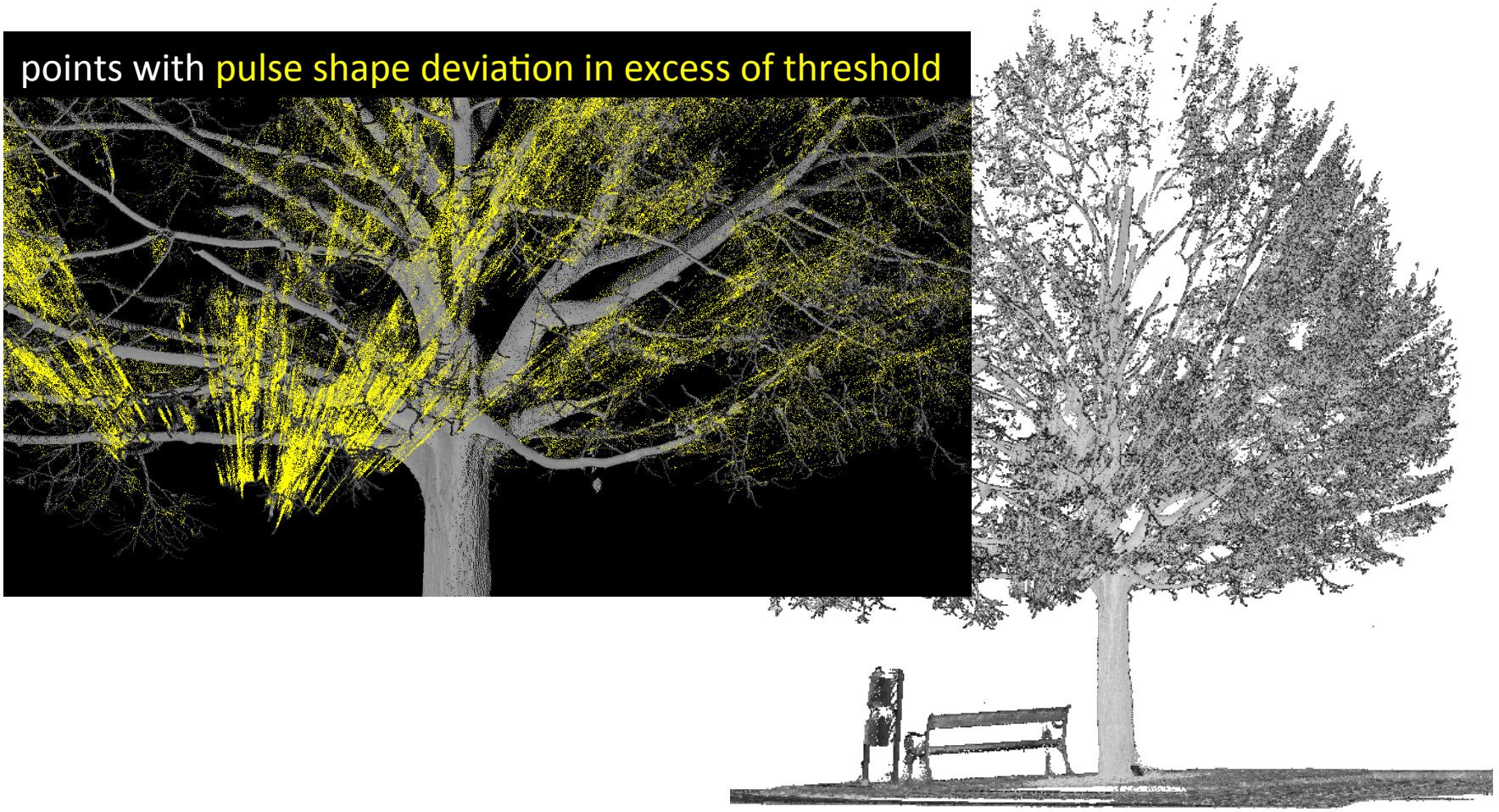


RIEGL

Linear LIDAR: pulse shape attribute

all points (regardless of pulse shape deviation)

Linear LIDAR: pulse shape attribute



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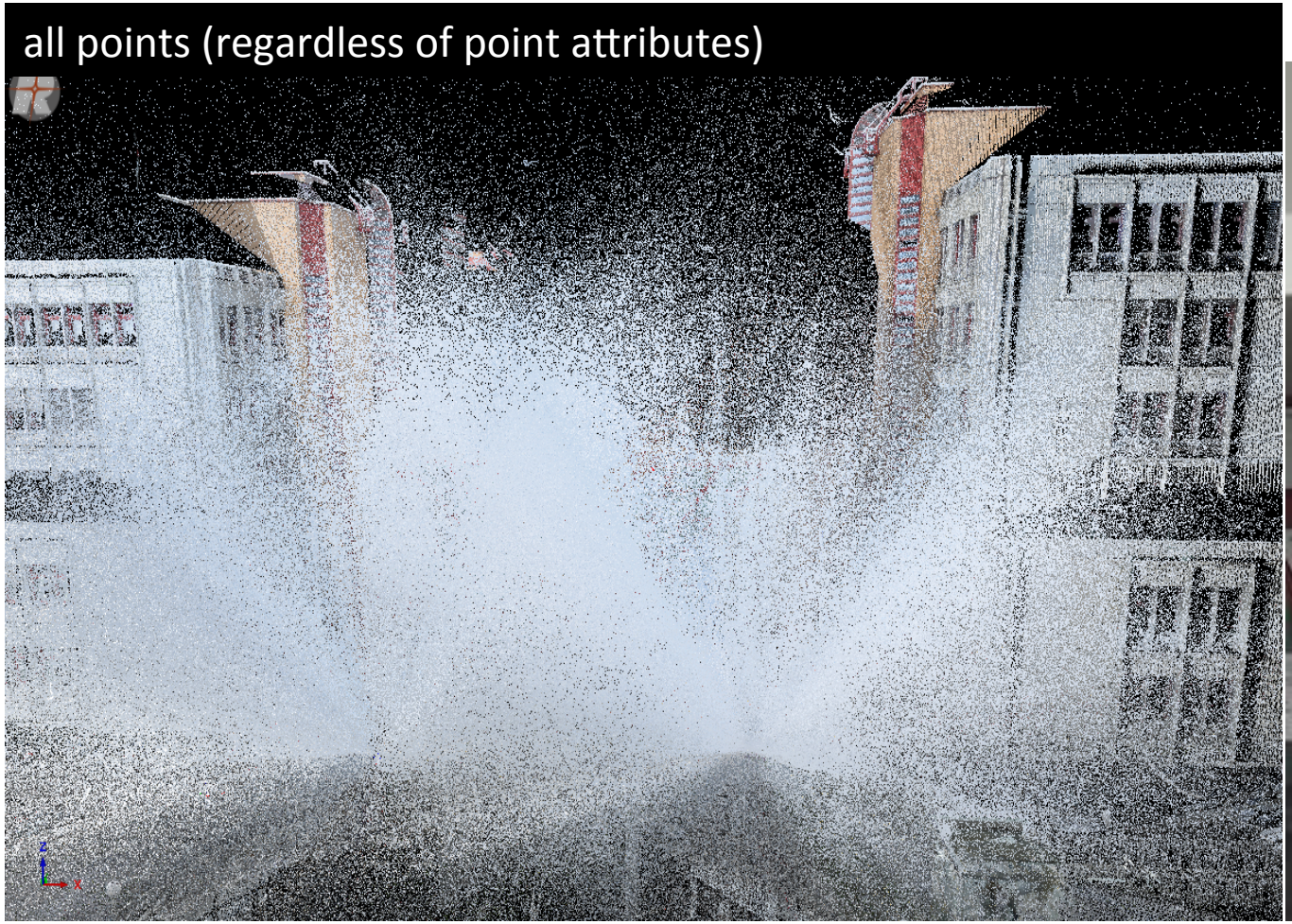
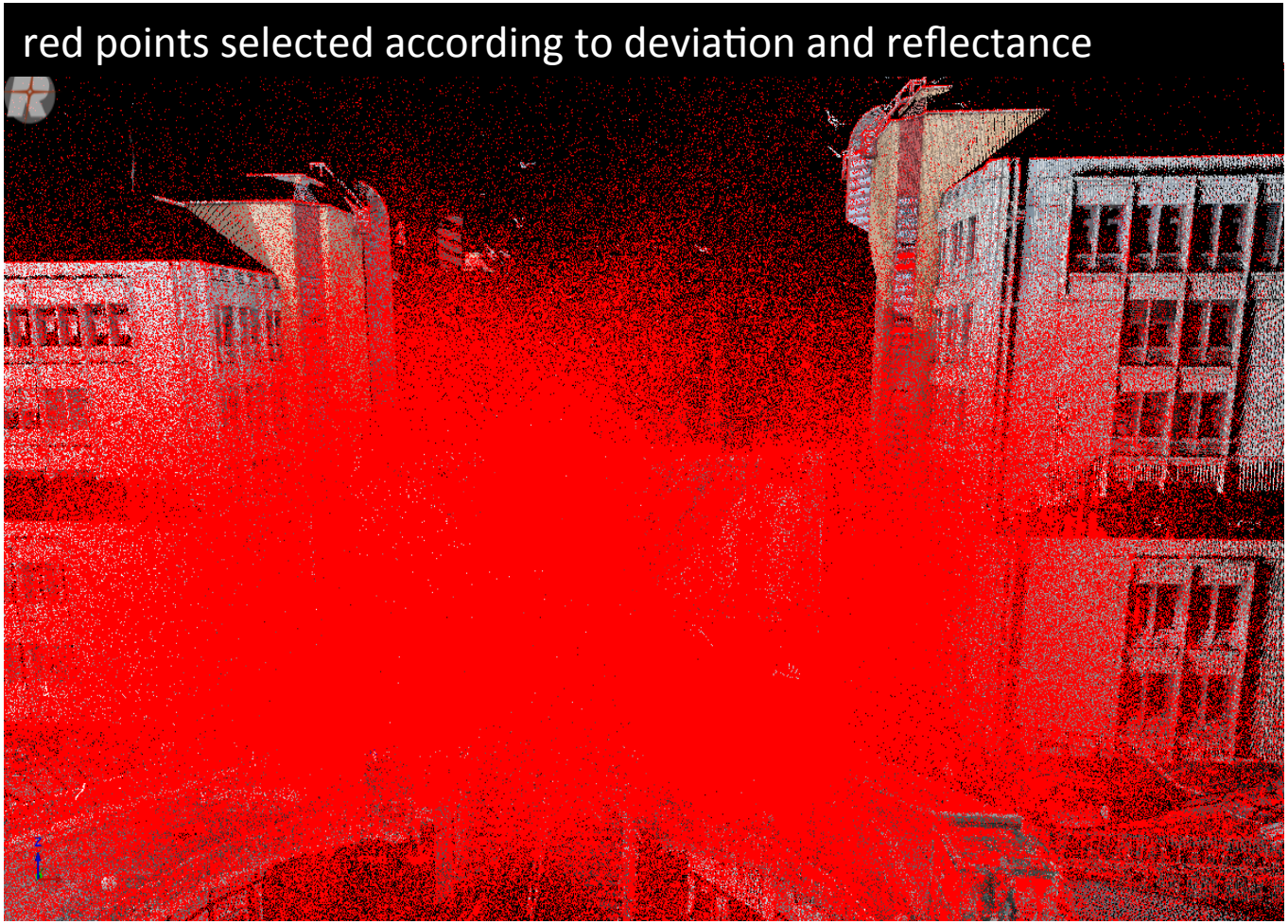
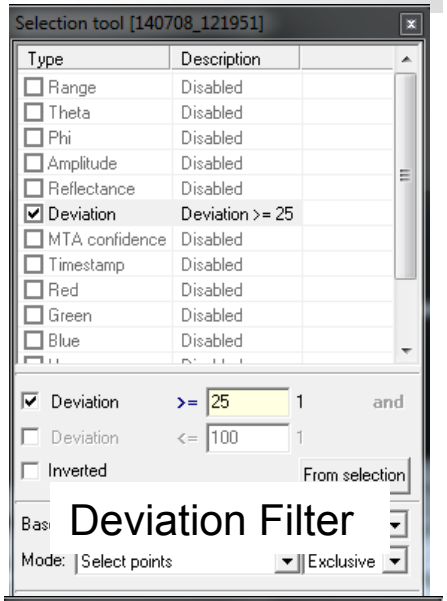
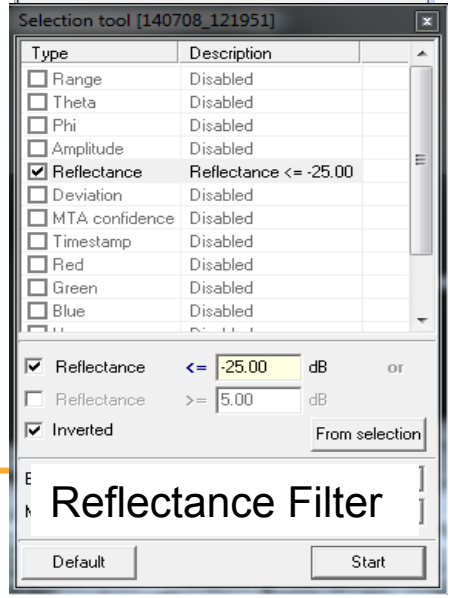


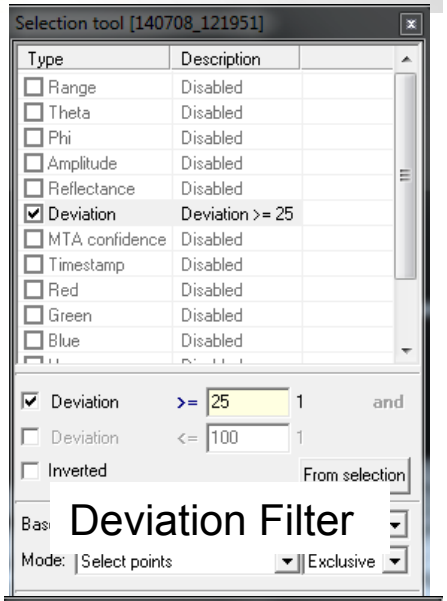
Linear LIDAR: pulse shape attribute

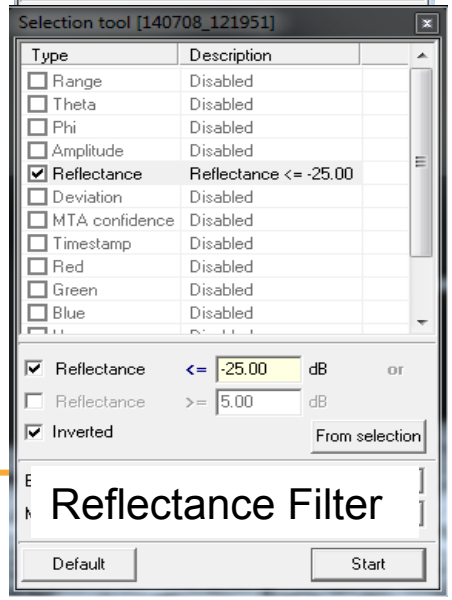






Linear LIDAR:
attribute pulse shape deviation





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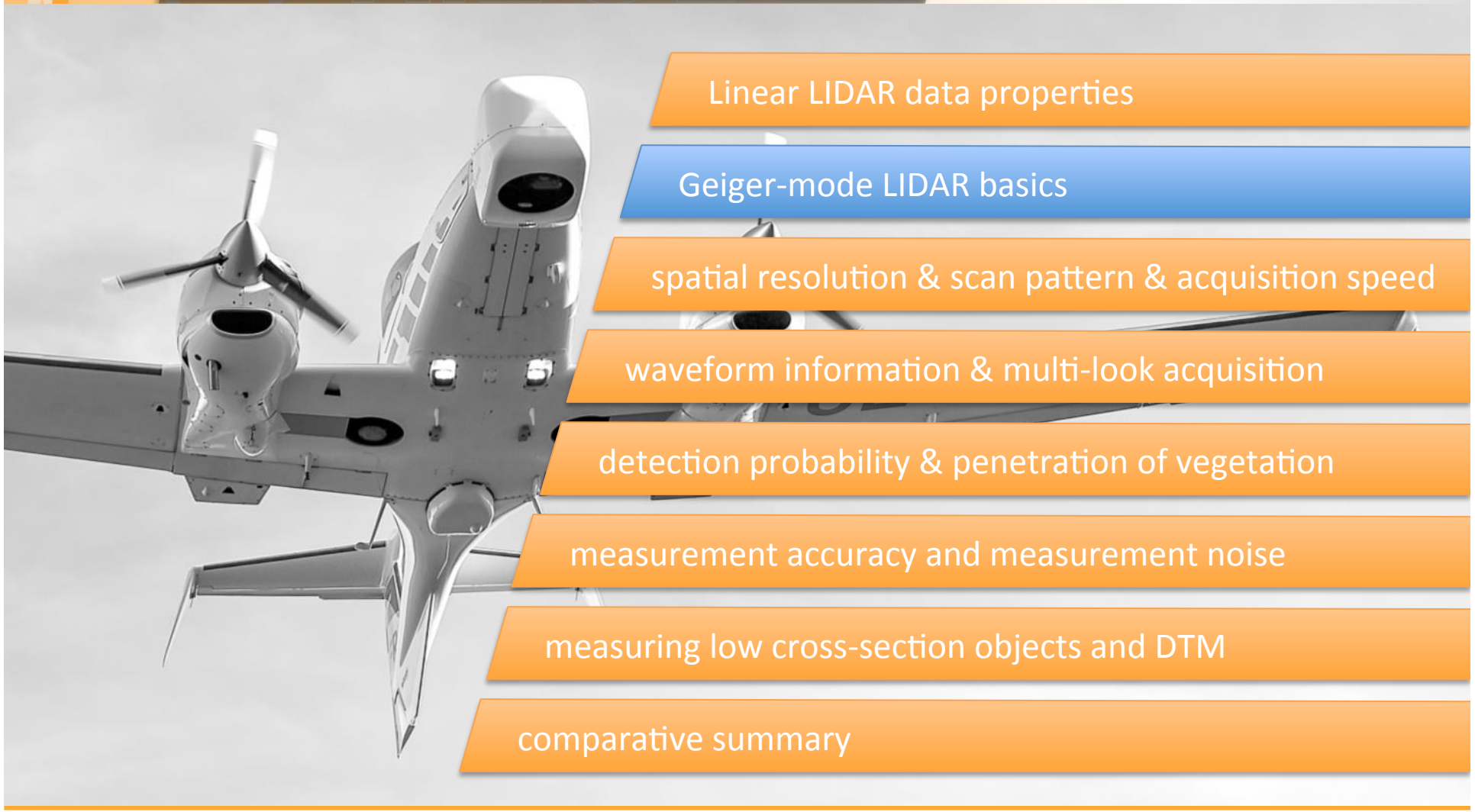
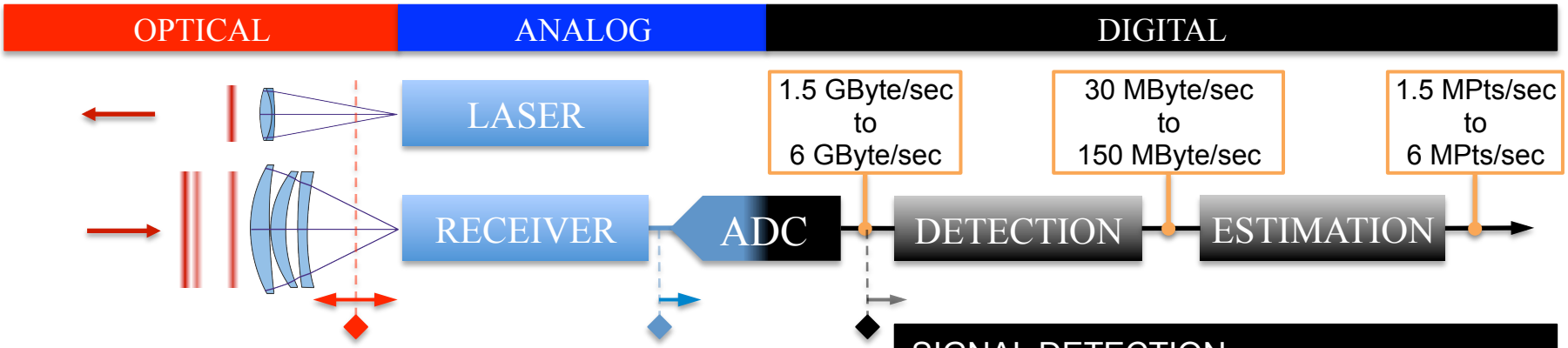
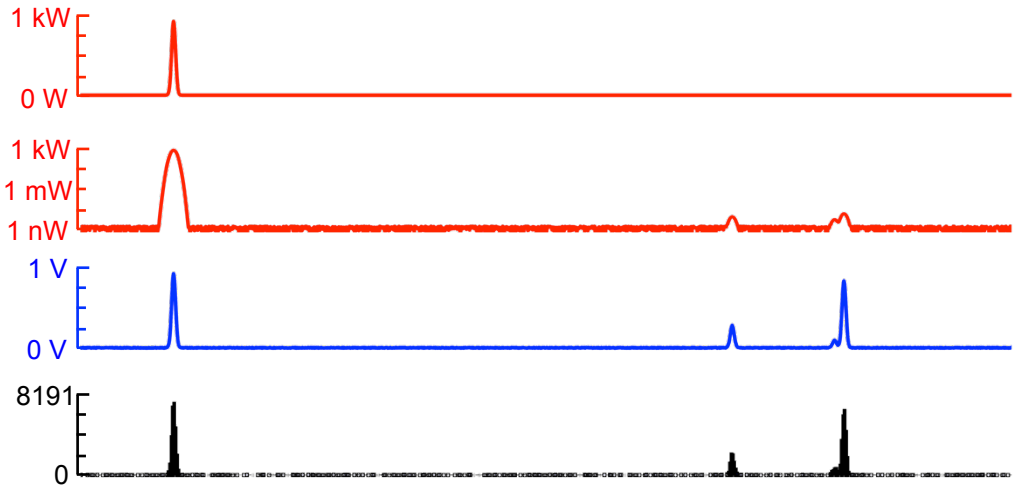


Linear LIDAR with pure digital signal processing





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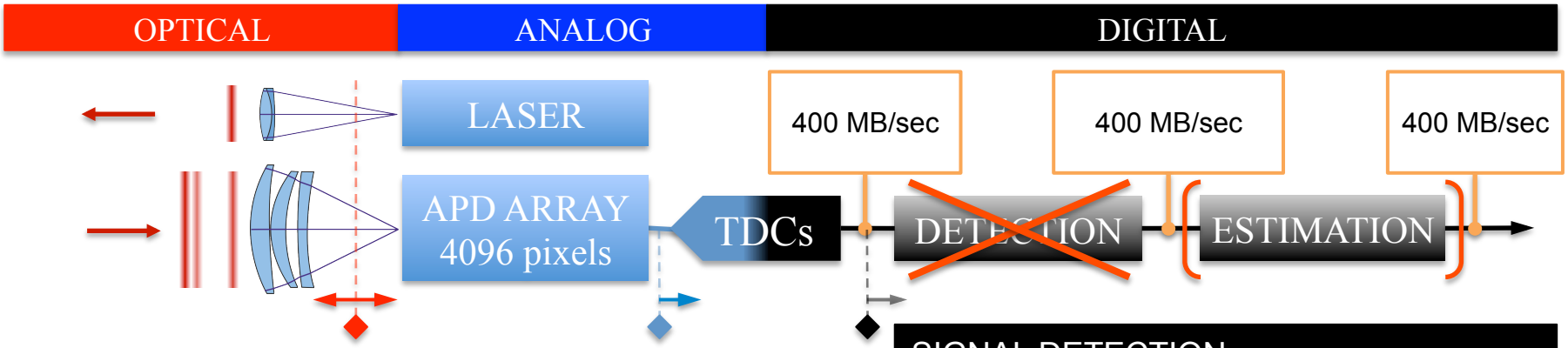
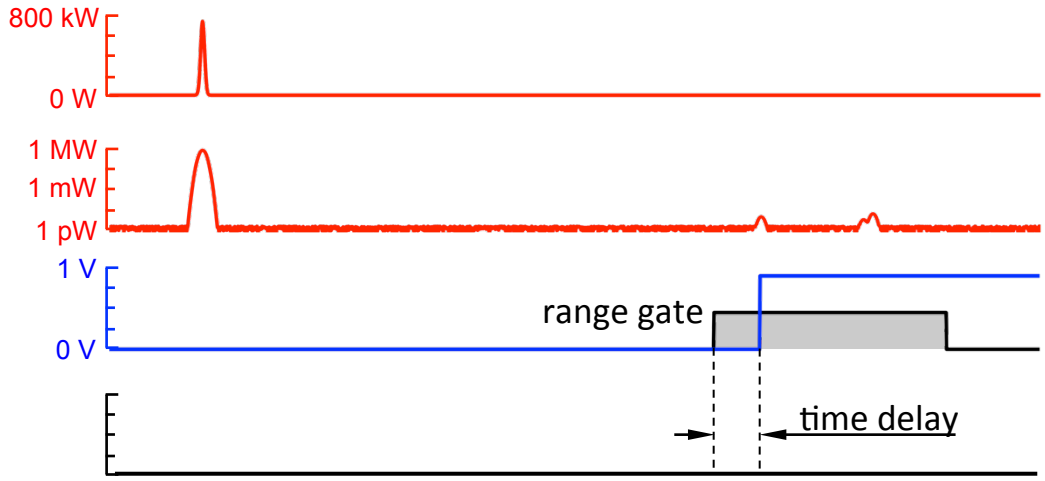
Geiger-mode processing





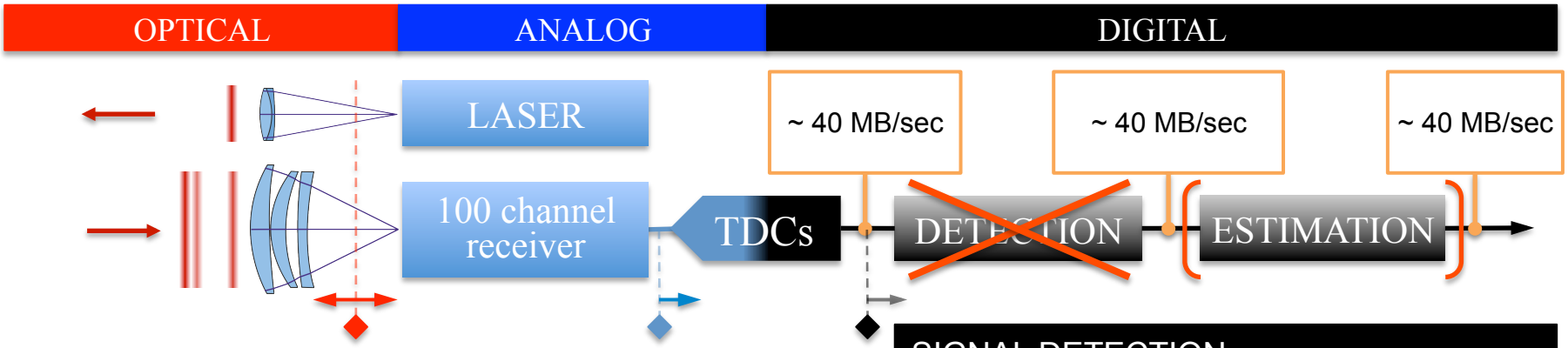
SIGNAL DETECTION

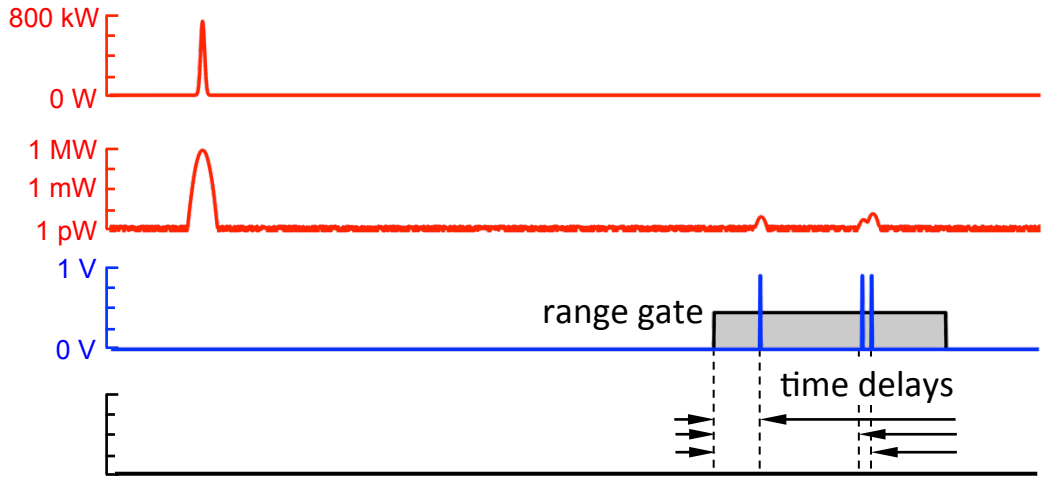
- inside Geiger mode APD array
- changed by varying laser power
- changed by varying photon detection efficiency (PDE)

SIGNAL ESTIMATION

- temporal position / range
- ~~signal strength / amplitude / reflectance~~
- ~~pulse width / pulse shape deviation~~
- ~~backscatter coefficient of turbid media~~

Single Photon LIDAR processing





SIGNAL DETECTION

- inside array
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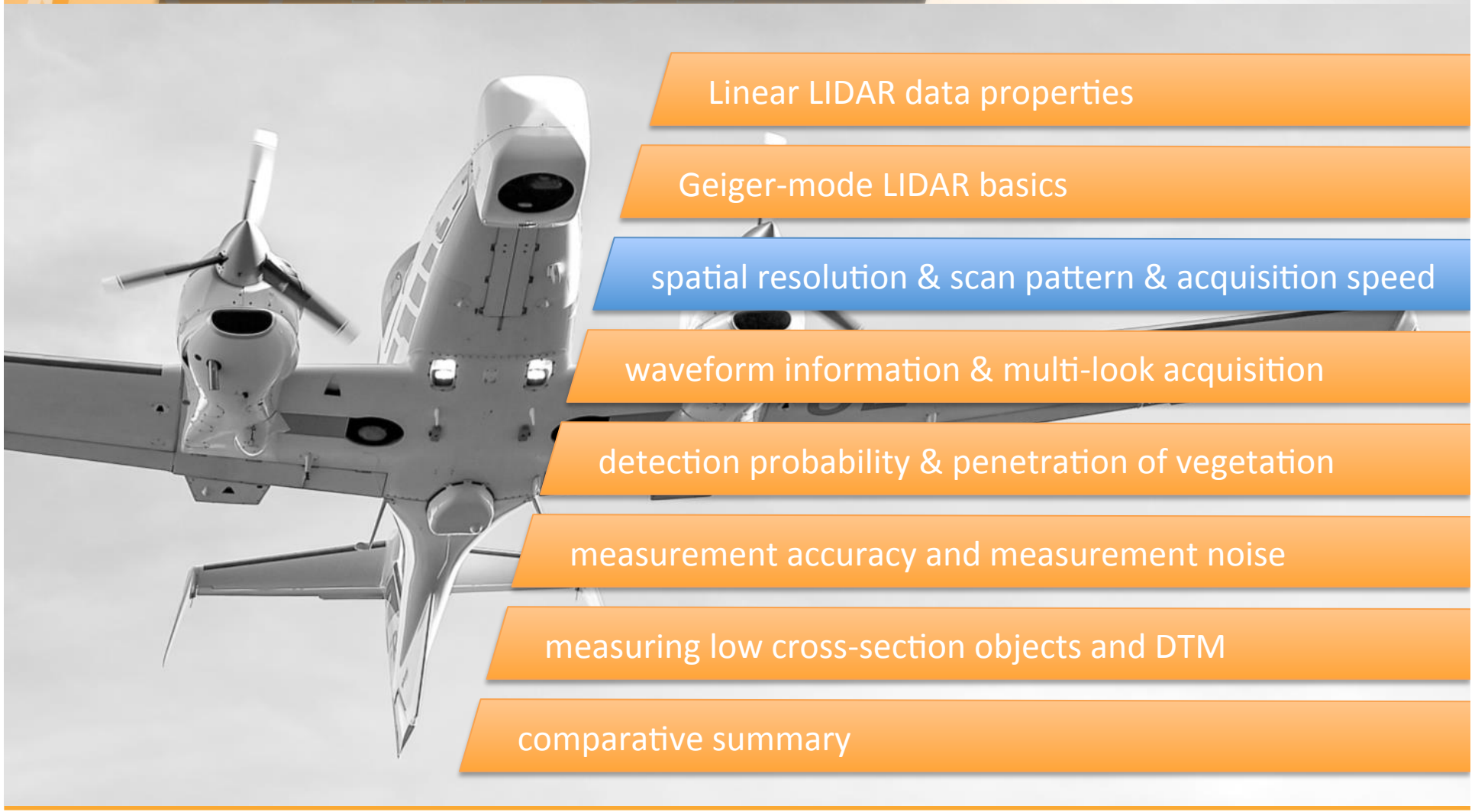
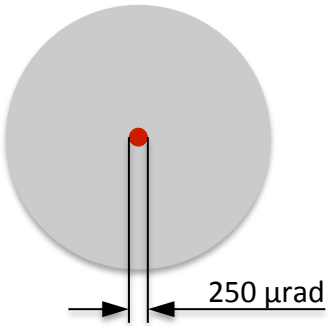


what a difference a detector makes: spatial resolution

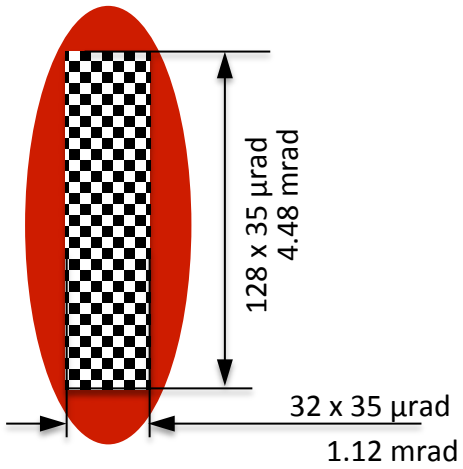
Linear LIDAR

- spatial resolution fundamentally limited by beam divergence of laser
- beam divergence typically 250 µrad (1/e²)
- iFOV of receiver significantly larger
- measurement beam axis defined by emission instant of laser pulse



Geiger Mode LIDAR

- spatial resolution fundamentally limited by iFOV of a single pixel of APD array
- instantaneous field-of-view (iFOV) 35 µrad [1)]
- beam divergence significantly larger
- measurement beam axis defined by reception instant of photons



1) example taken from Rhoads, R., "Geiger-mode LiDAR mapping: High density, high volume airborne 3D imaging", p. 14, Capturing Reality 2015

what a difference a detector makes: spatial resolution

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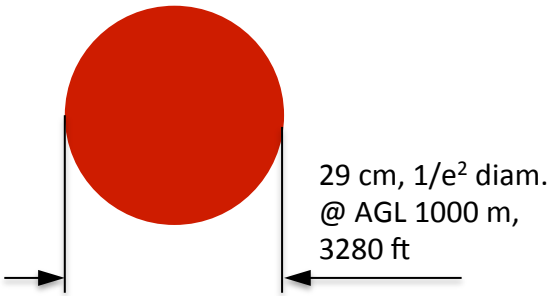
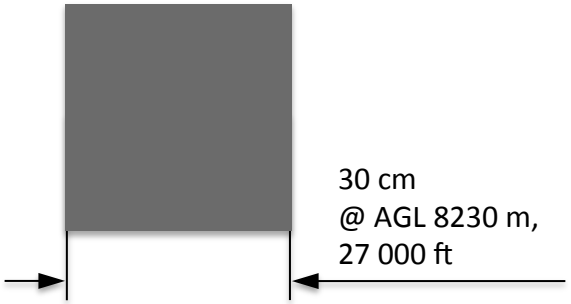


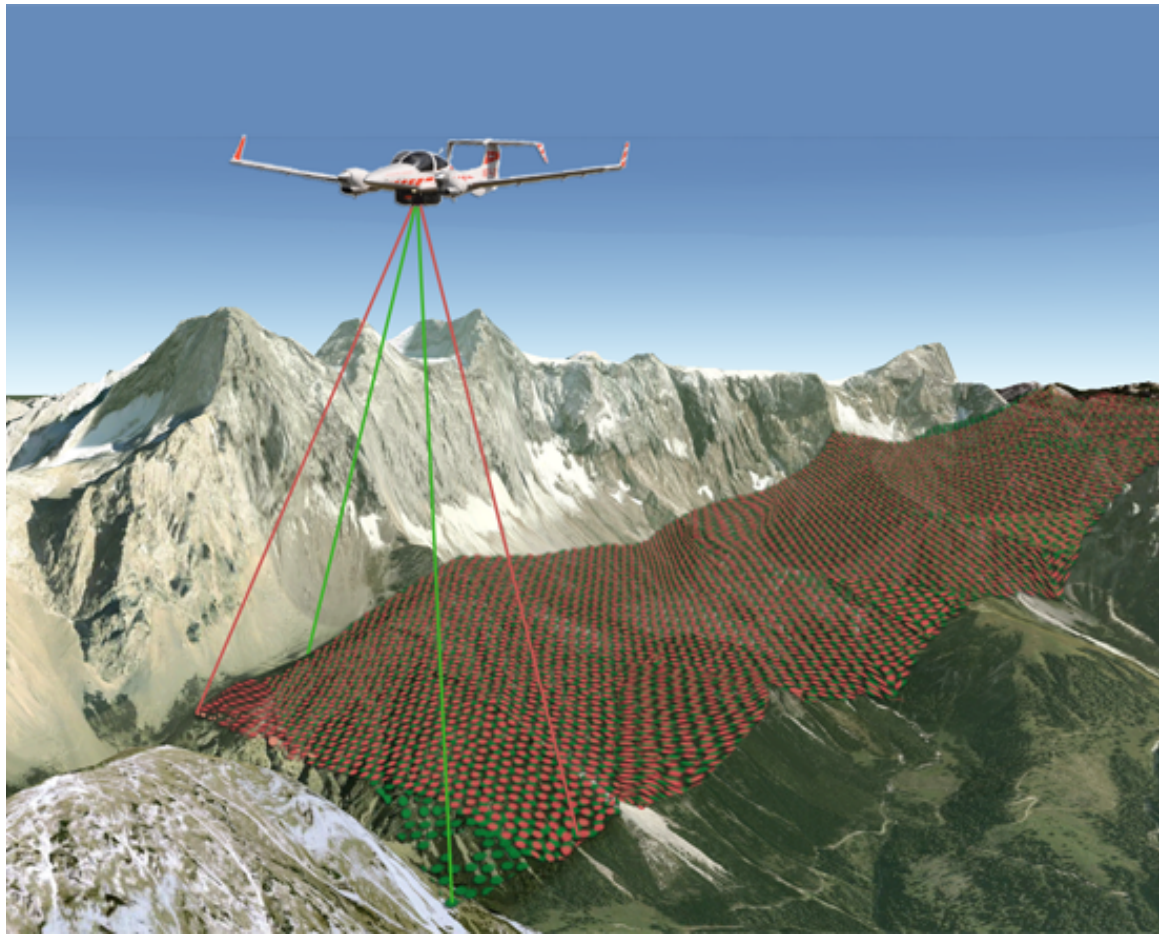


1) example taken from Rhoads, R., "Geiger-mode LiDAR mapping: High density, high volume airborne 3D imaging", p. 14, Capturing Reality 2015

what a difference a detector makes: scan pattern

RIEGL LMS-Q1560
forward / backward looking

- tilt of scan lines maintains strict **nadir** look in the center
- forward / backward elsewhere with maximum at the **edges** of swath



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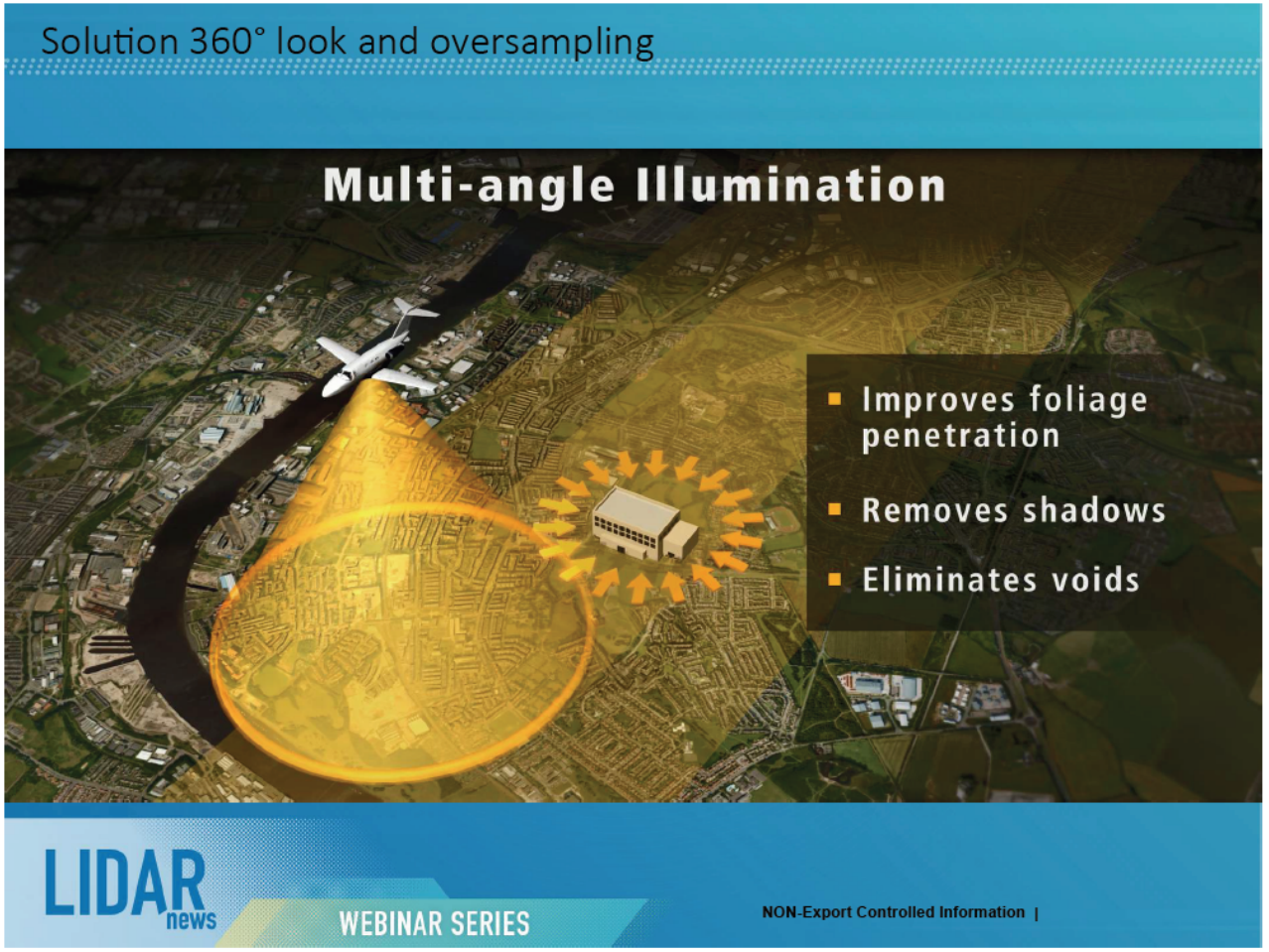
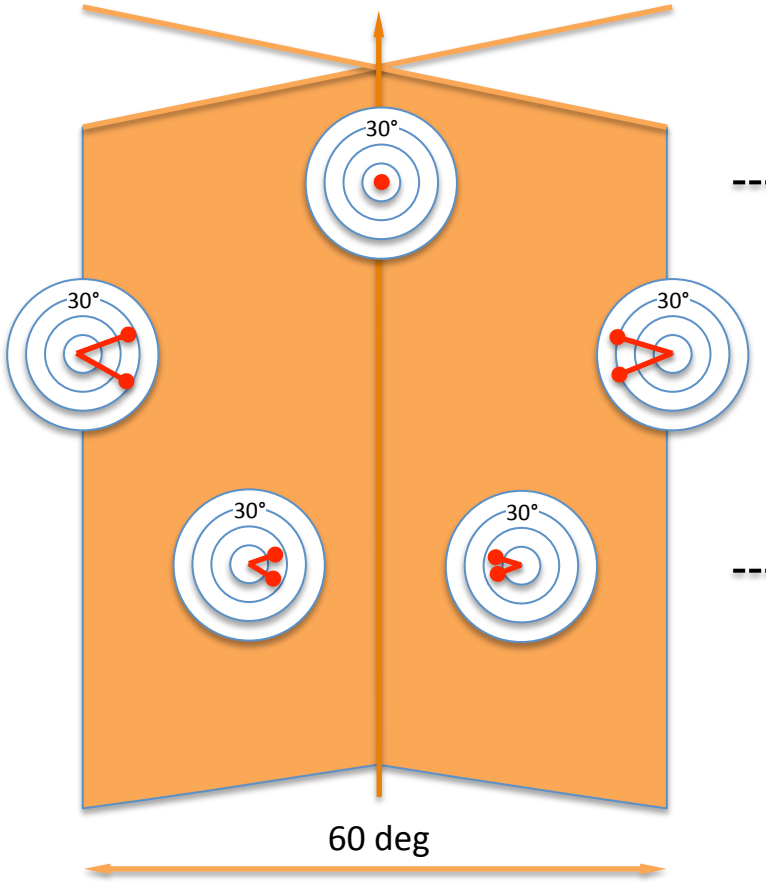


Romano, M., "A New Industry Standard: Commercial Geiger-mode LIDAR", LIDAR News webinar, March 24th, 2015

what a difference a detector makes: scan pattern

RIEGL LMS-Q1560

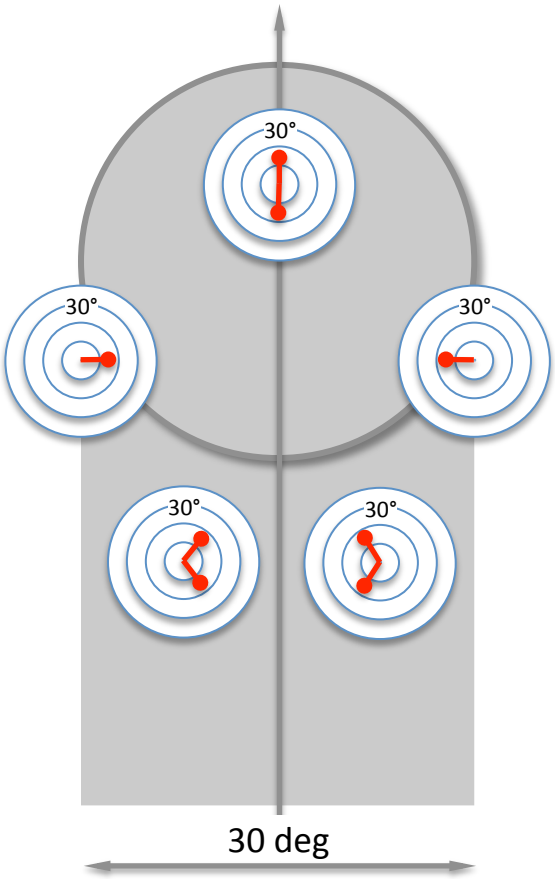


center of swath

edge

center of overlap @ 50%

conical scan pattern

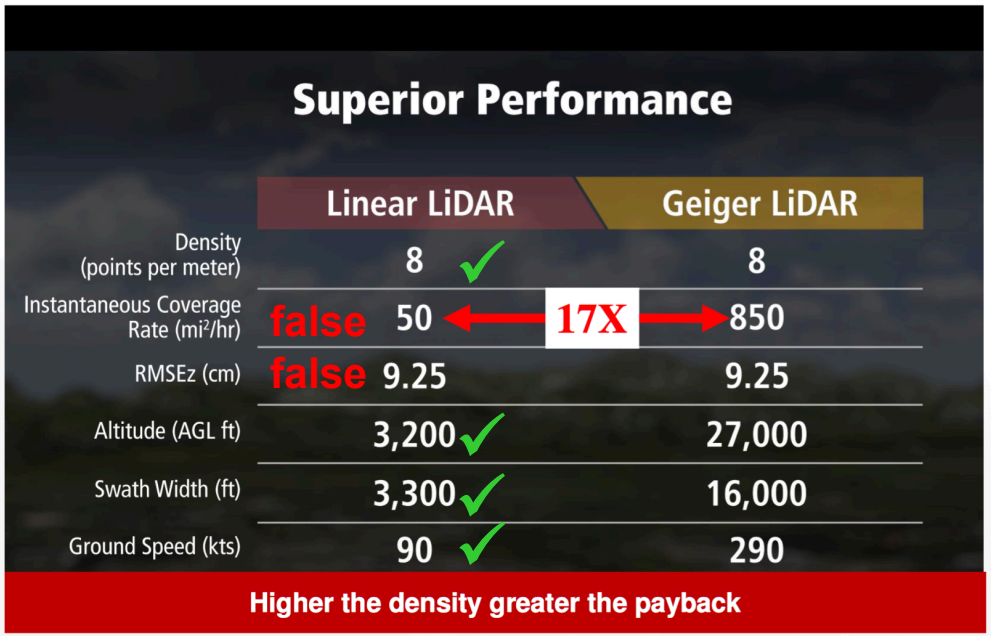


acquisition speed

RIEGL LMS-Q1560
8 pts/m2
95 mi²/hr, (240 km²/h)
2 cm
3250 ft, (990 m)
3750 ft, (1140 m)
117 kts

Collection Comparison @ 8PPM

HARRIS



Rhoads, R., “Geiger-mode LiDAR mapping: High density, high volume airborne 3D imaging”, Capturing Reality 2015, Nov 24th 2015, Salzburg, Austria

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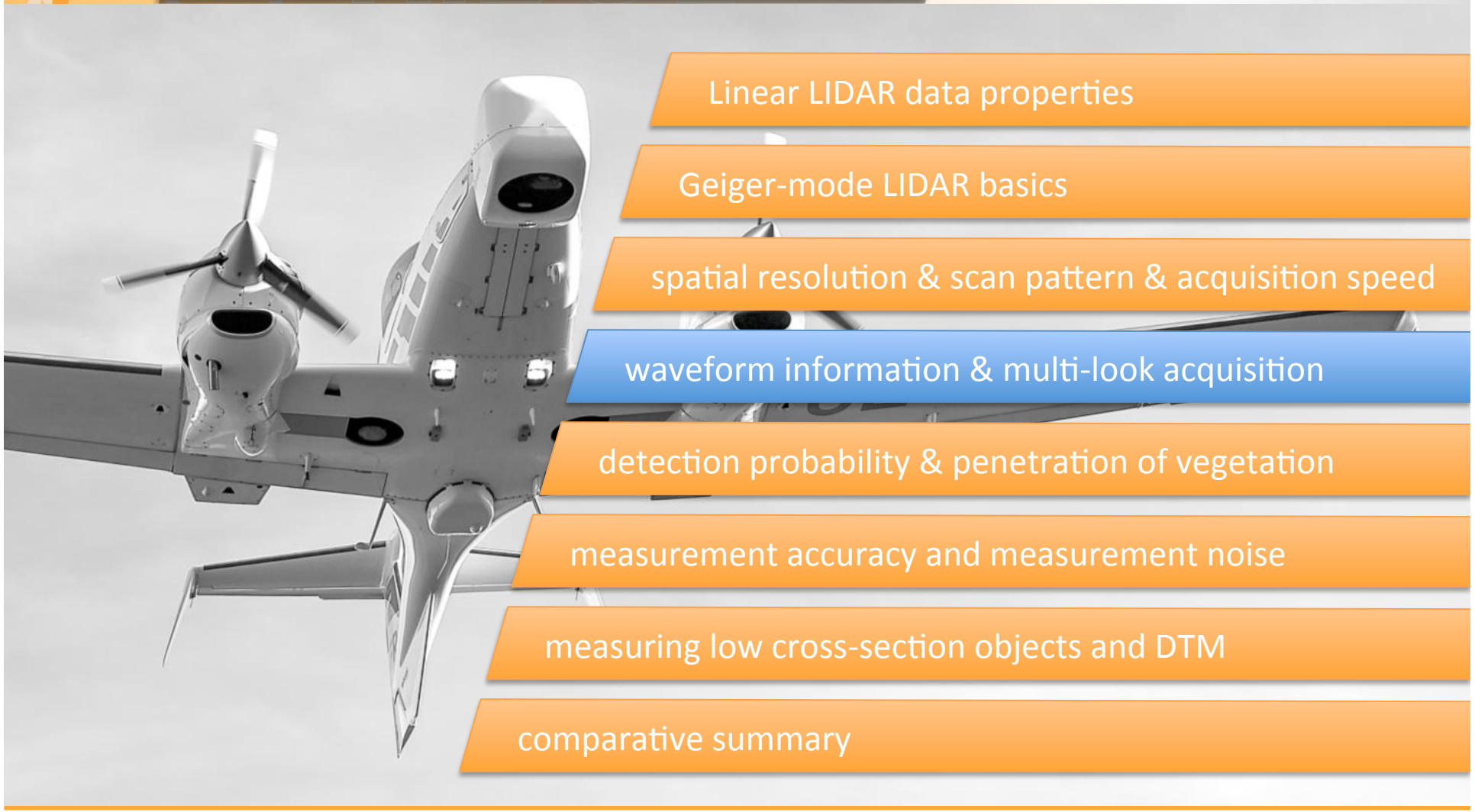
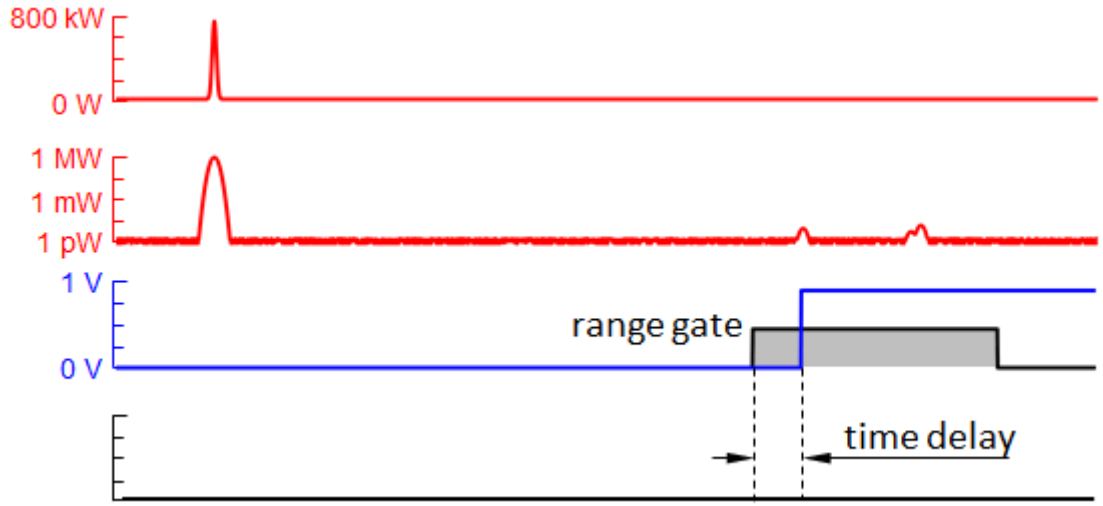


what a difference a detector makes: Geiger-Mode waveforms?

Linear LIDAR's waveforms are key to best multi-target resolution, radiometric calibration and advanced filtering

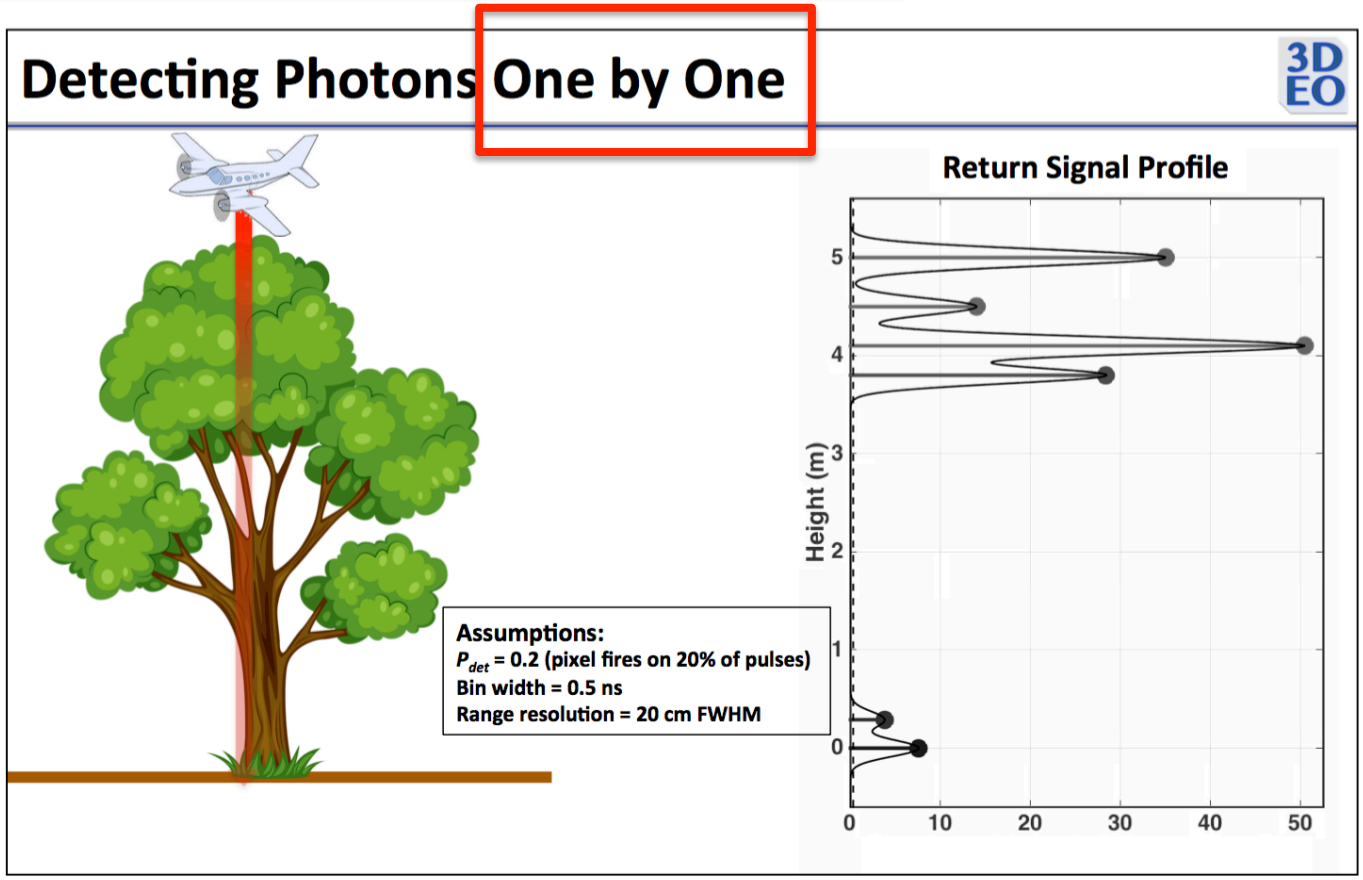


SIGNAL ESTIMATION

- temporal position / range
- ~~signal strength / amplitude / reflectance~~
- ~~pulse width / pulse shape deviation~~
- ~~backscatter coefficient of turbid media~~

How to acquire waveforms with a **binary** detector?

what a difference a detector makes: Geiger-Mode waveforms?



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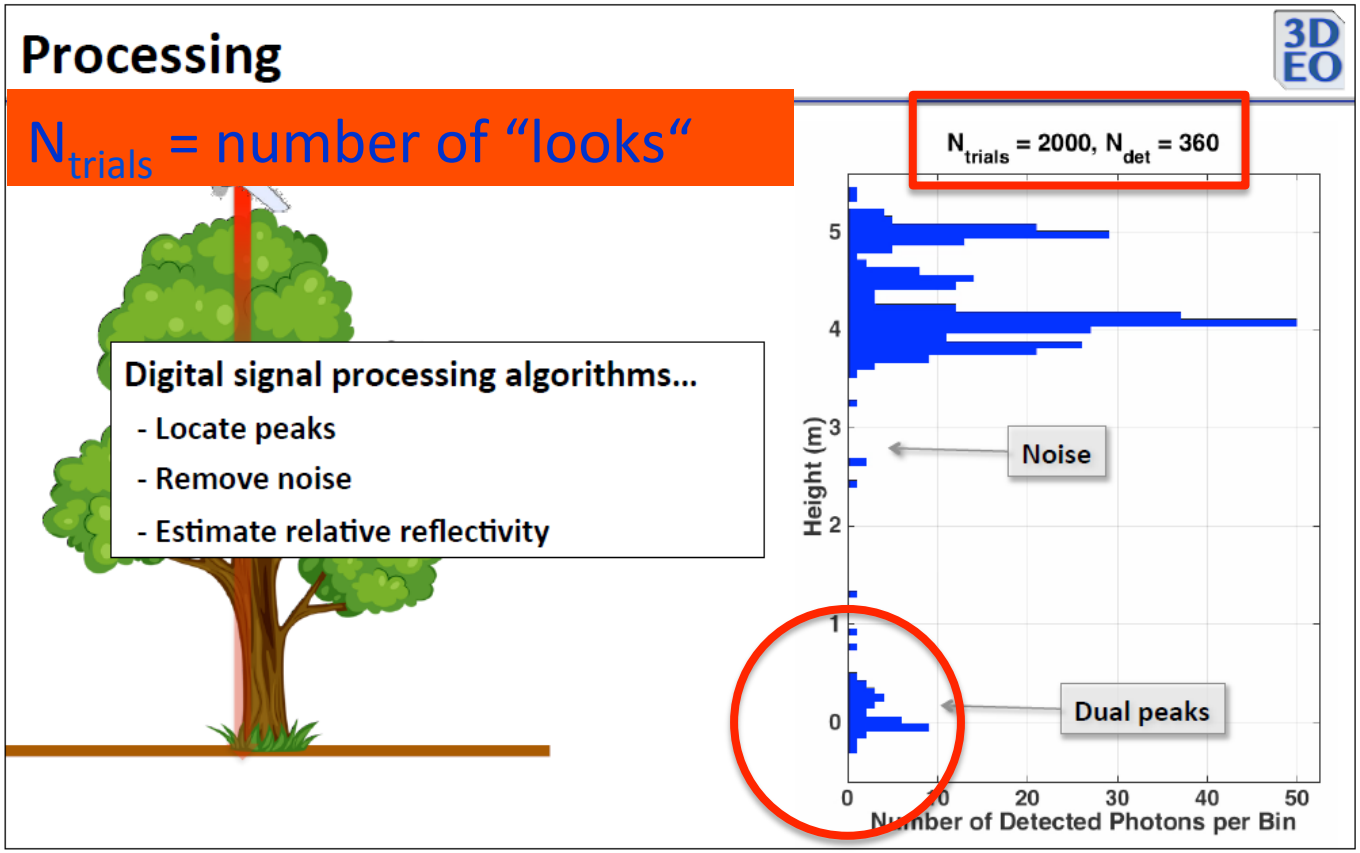
what a difference a detector makes: Geiger-Mode waveforms?



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Geiger-mode multi-look data acquisition

GmAPD Multi-Look/Multi-Pulse Collection

HARRIS

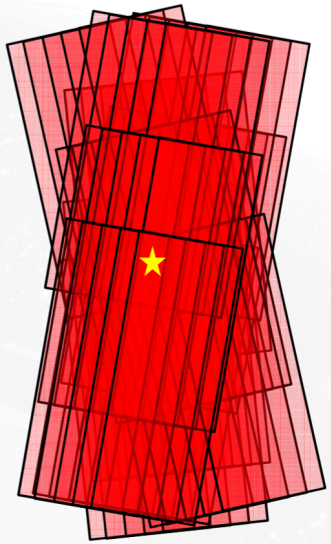
Multi-look approach

- 4096 measurements per laser flash
- 50,000 flashes per second
- Approx= 205 million elevation measurement per second

- Every spot illuminated 100's of times

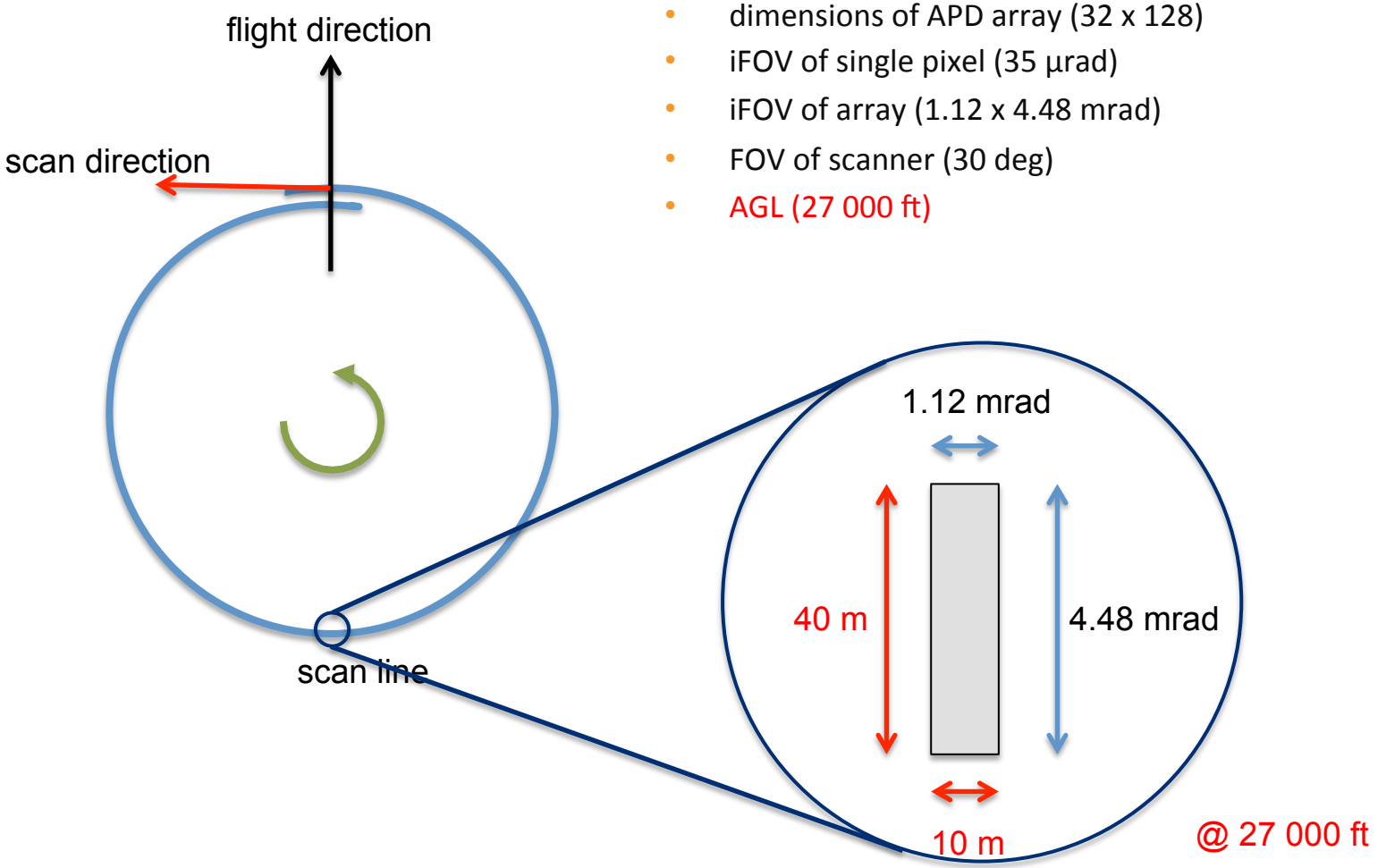
- The dozens of photon detections are processed to determine the real objects

- Programmable Forward/Sidelap



Rhoads, R., "Geiger-mode LiDAR mapping: High density, high volume airborne 3D imaging", at Capturing Reality 2015, Nov 24th 2015, Salzburg, Austria

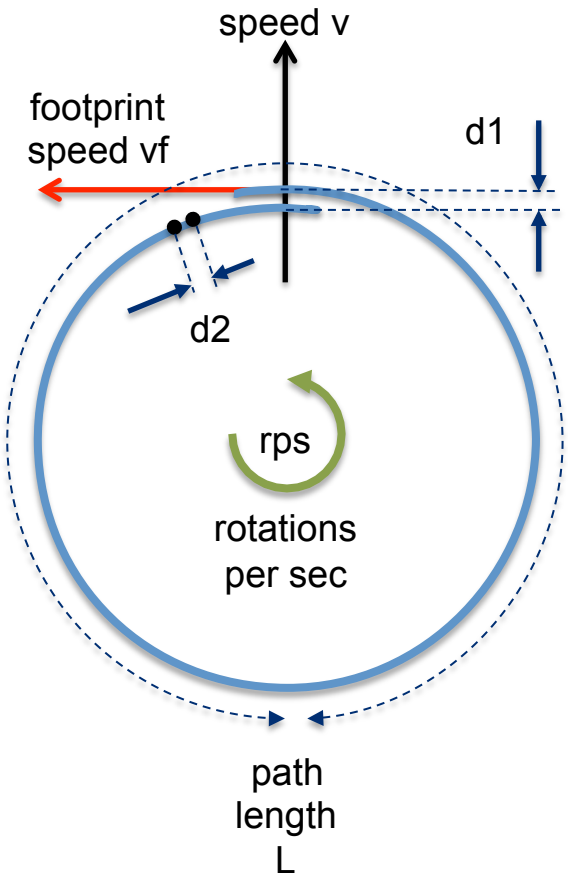
Geiger-mode multi-look data acquisition



- dimensions of APD array (32 x 128)
- iFOV of single pixel (35 µrad)
- iFOV of array (1.12 x 4.48 mrad)
- FOV of scanner (30 deg)
- AGL (27 000 ft)

Geiger-mode multi-look data acquisition

calculating the number of looks



speed 290 kts	rps 7.5 sec^{-1}
AGL 27 000 ft	PRR 50 kHz

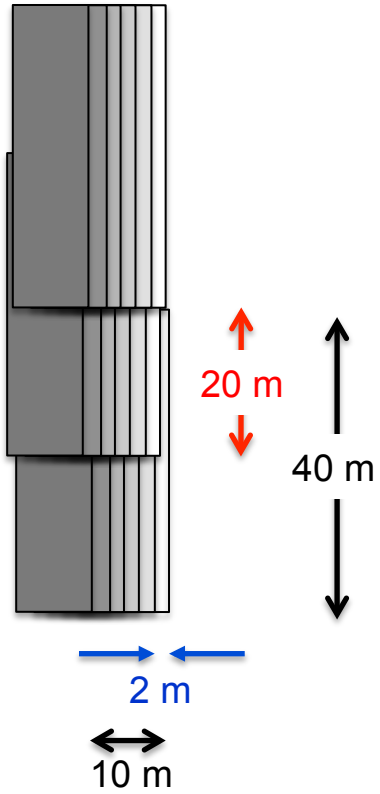
$$d1 = \frac{v}{rps}$$ 20 m

$$L = 2\pi \cdot AGL \cdot \tan\left(\frac{\alpha}{2}\right)$$ 13.8 km

$$vf = L \cdot rps$$ 104 km/s

$$d2 = \frac{vf}{PRR}$$ 2 m

number of looks (forward scan, center)
10m/2m x 40m/20m = 5 x 2 = 10



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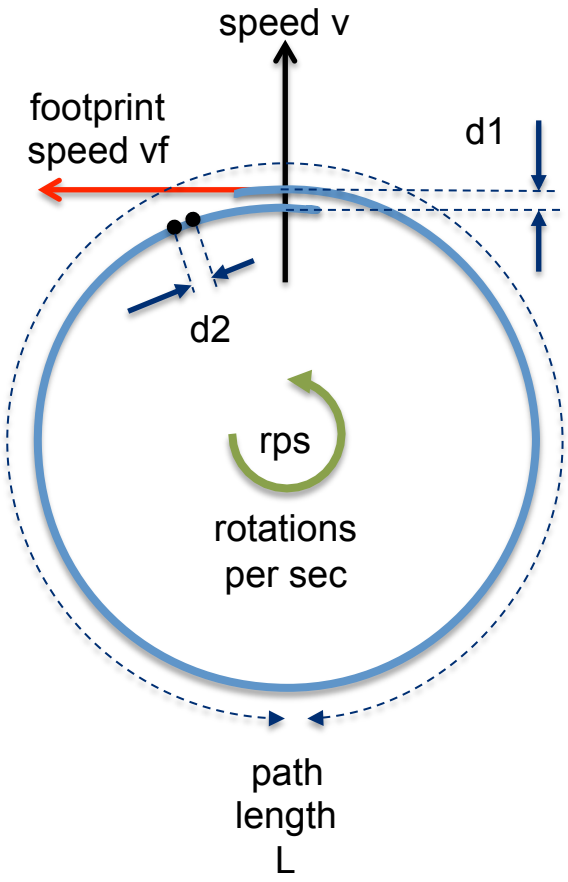


speed 290 kts

AGL 27 000 ft

rps 18.6 sec^{-1}

PRR 50 kHz

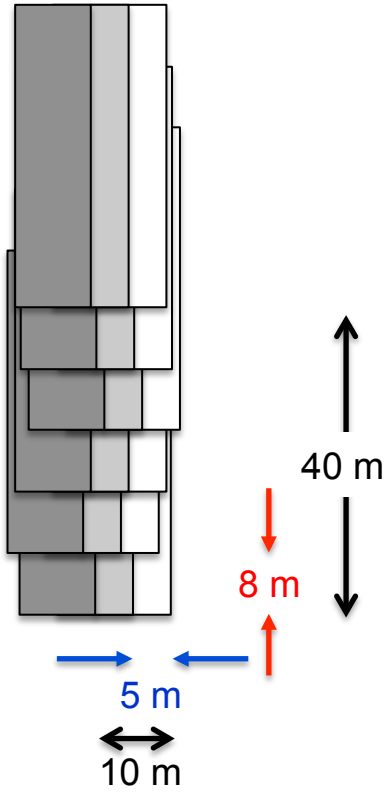
$$d1 = \frac{v}{rps}$$ 8 m

$$L = 2\pi \cdot AGL \cdot \tan\left(\frac{\alpha}{2}\right)$$ 13.8 km

$$vf = L \cdot rps$$ 258 km/s

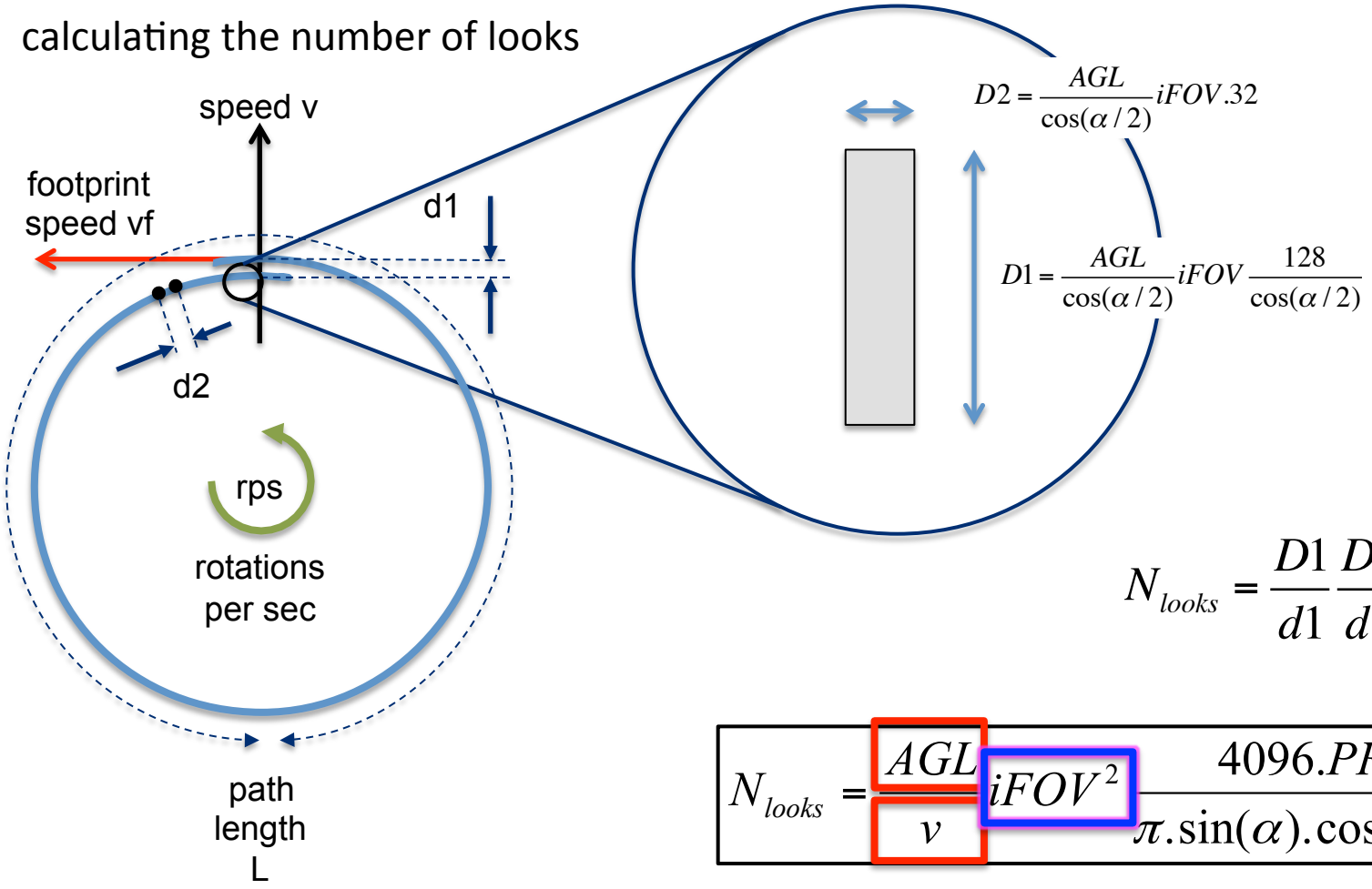
$$d2 = \frac{vf}{PRR}$$ 5 m

number of looks (forward scan, center)
10m/5m x 40m/8m = 2 x 5 = 10



Geiger-mode multi-look data acquisition

calculating the number of looks

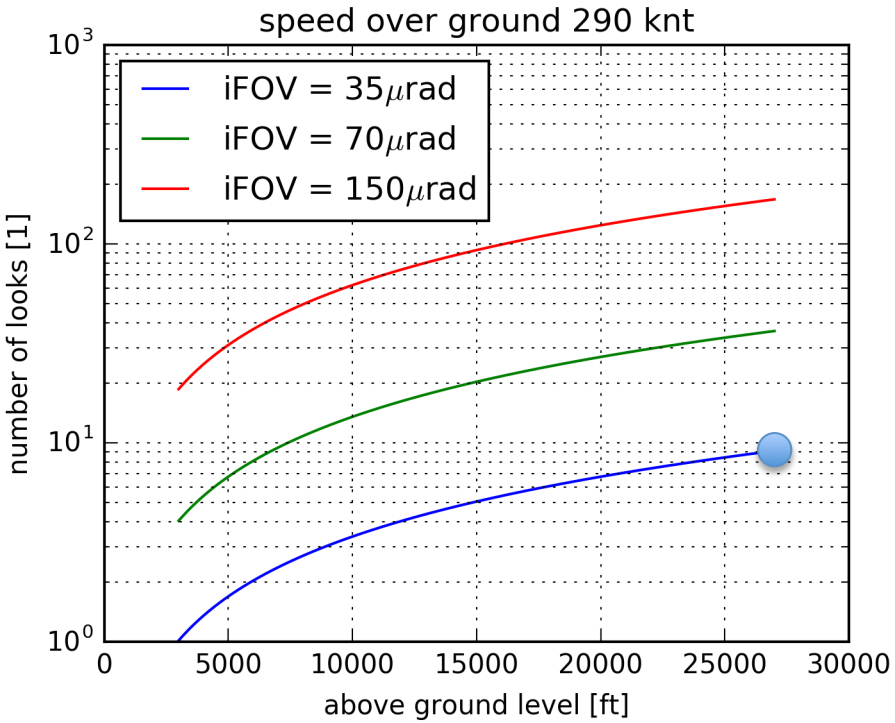


$$N_{looks} = \frac{D1}{d1}\frac{D2}{d2}$$

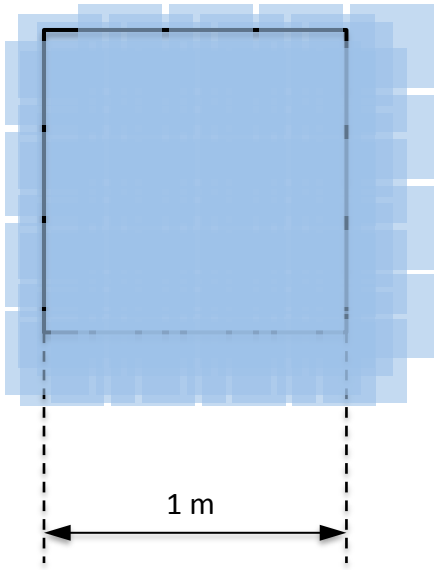
$$N_{looks} = \frac{AGL}{v} iFOV^2 \frac{4096.PRR}{\pi.\sin(\alpha).\cos(\alpha/2)}$$

Geiger-mode multi-look data acquisition

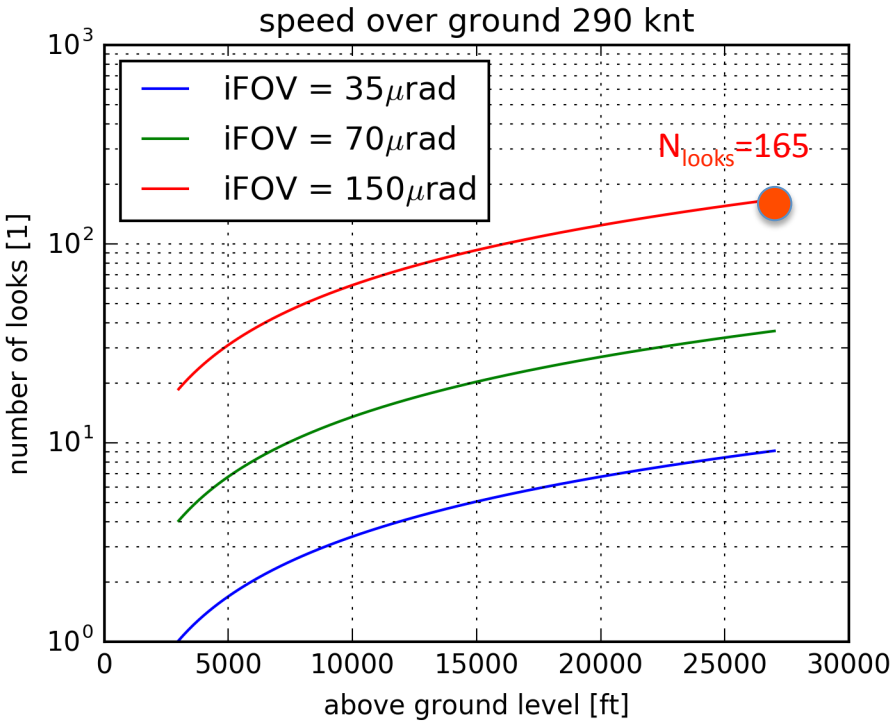
number of looks as a function of AGL and speed

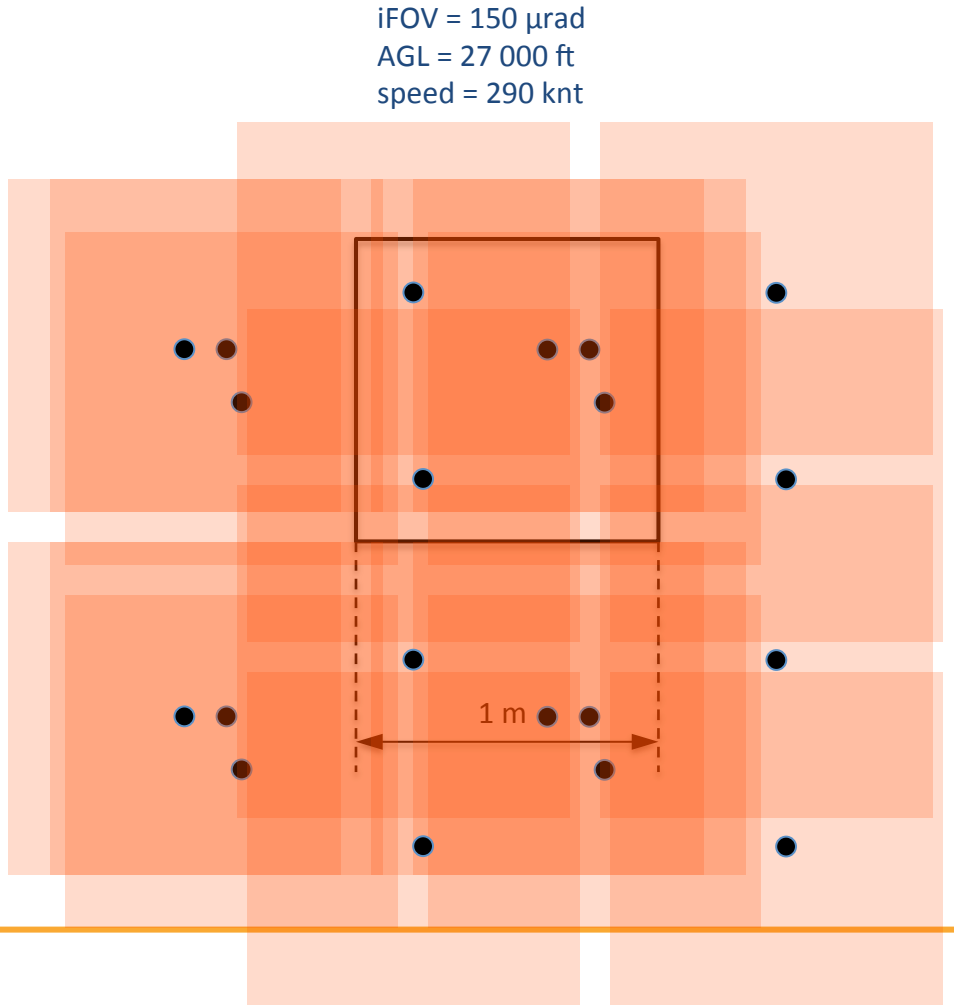


iFOV = 35 µrad
AGL = 27 000 ft
speed = 290 knt



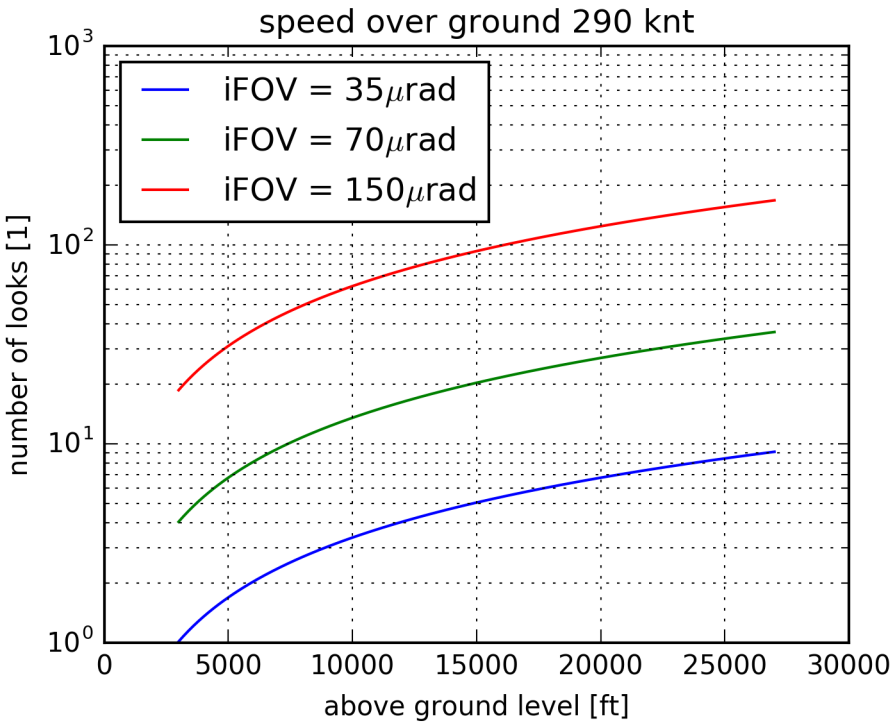
Geiger-mode multi-look data acquisition

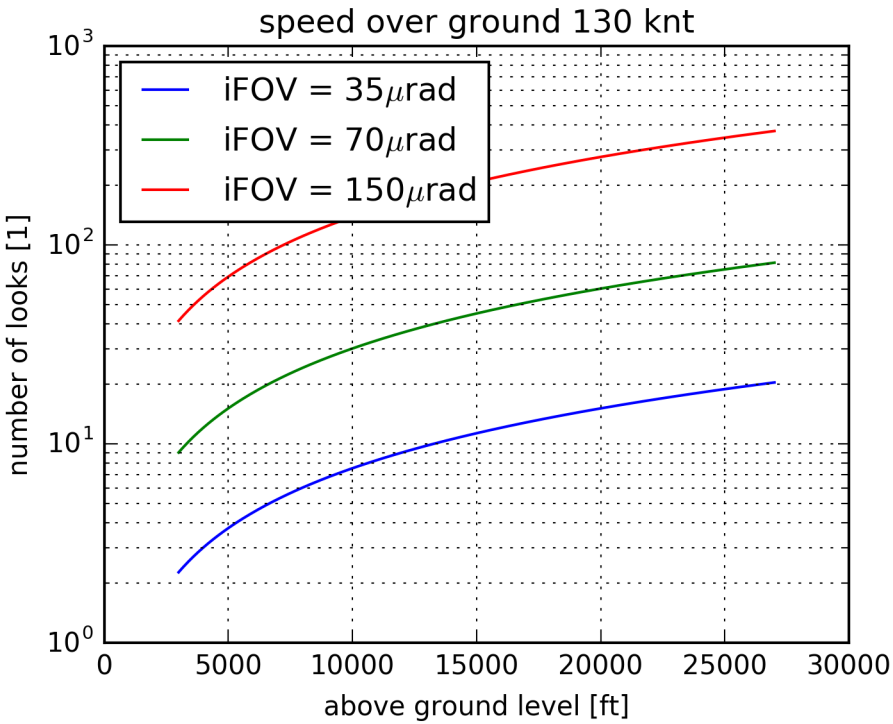




Geiger-mode multi-look data acquisition

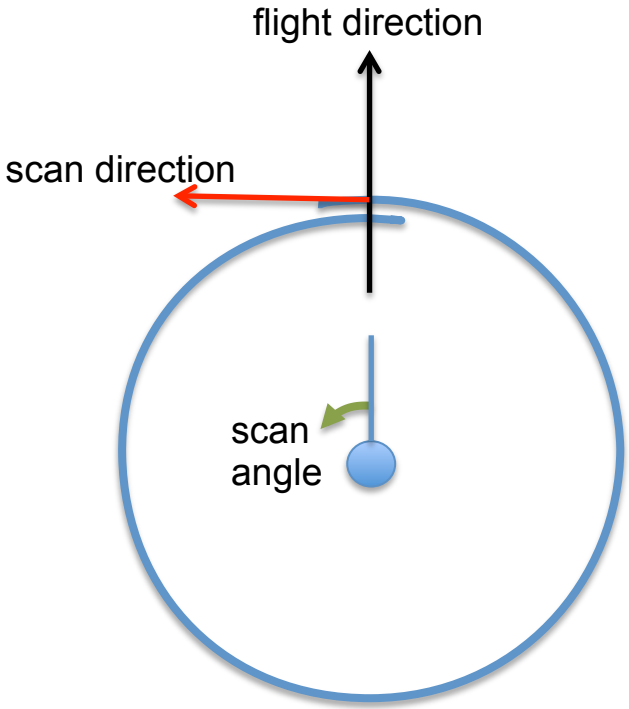
number of looks as a function of AGL and speed



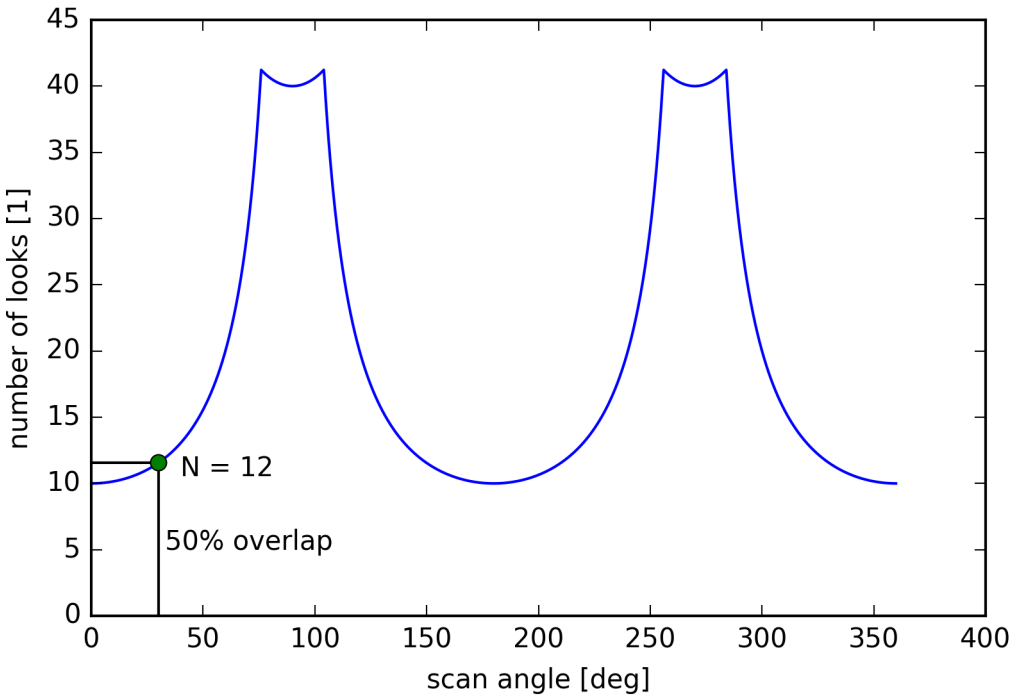


Geiger-mode multi-look data acquisition

number of looks along scan line



AGL 27 000 ft, 290 knt, iFOV 35 μrad, PRR 50 kHz



Geiger-mode multi-look data acquisition

GmAPD Multi-Look/Multi-Pulse Collection

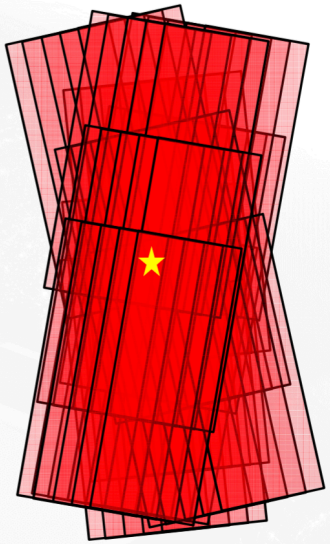
HARRIS

Multi-look approach

- 4096 measurements per laser flash
- 50,000 flashes per second
- Approx= 205 million elevation measurement per second

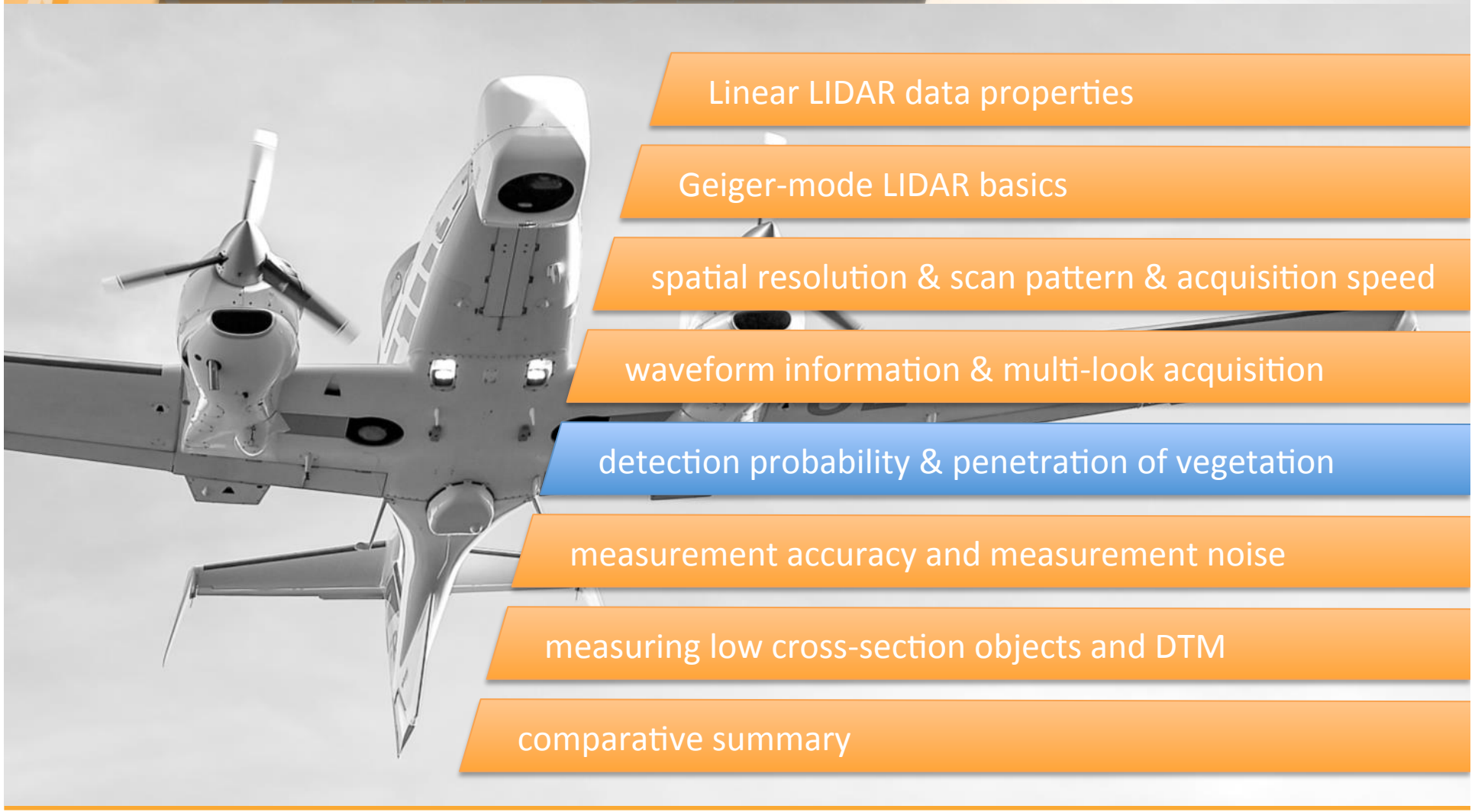
?

- Every spot illuminated 100's of times
- The dozens of photon detections are processed to determine the real objects
- Programmable Forward/Sidelap



Rhoads, R., "Geiger-mode LiDAR mapping: High density, high volume airborne 3D imaging", at Capturing Reality 2015,
Nov 24th 2015, Salzburg, Austria

contents

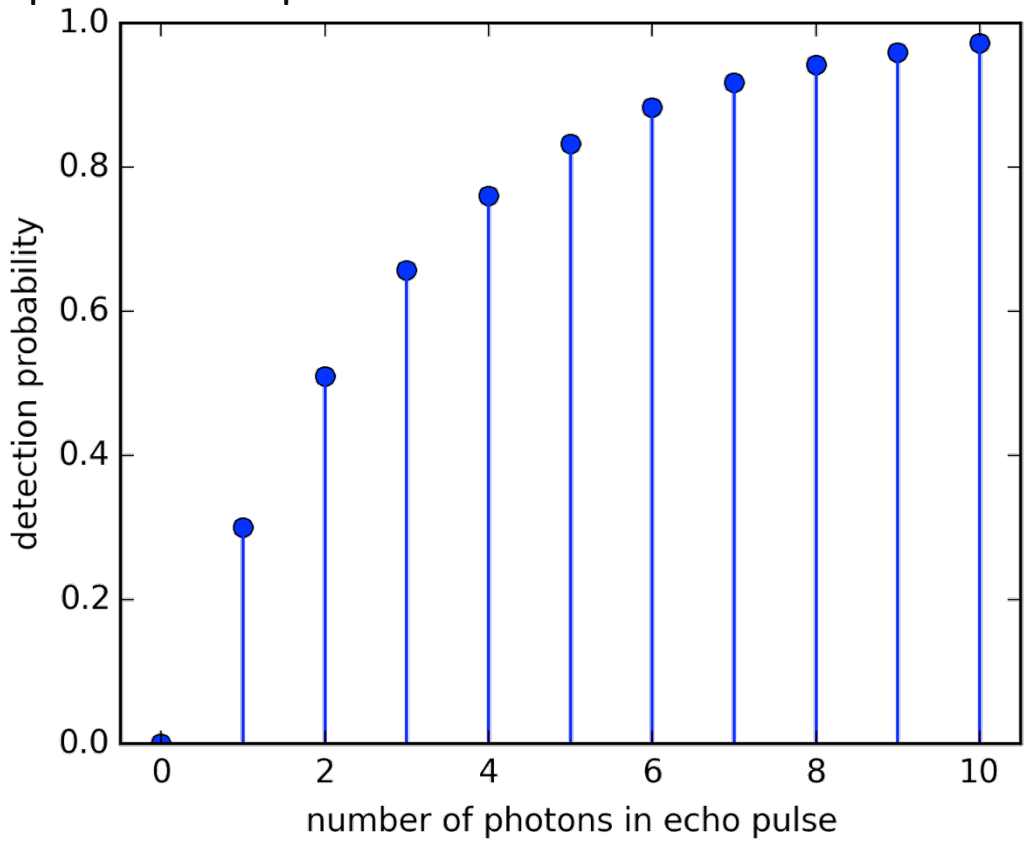


detection probability for deterministic number of photons

- photon detection efficiency (PDE = 0.3)
- detection probability for exactly N photons in a pulse?

probability that any of N photons triggers is complementary to that every photon does not trigger

$$PD(N) = 1 - (1 - PDE)^N$$



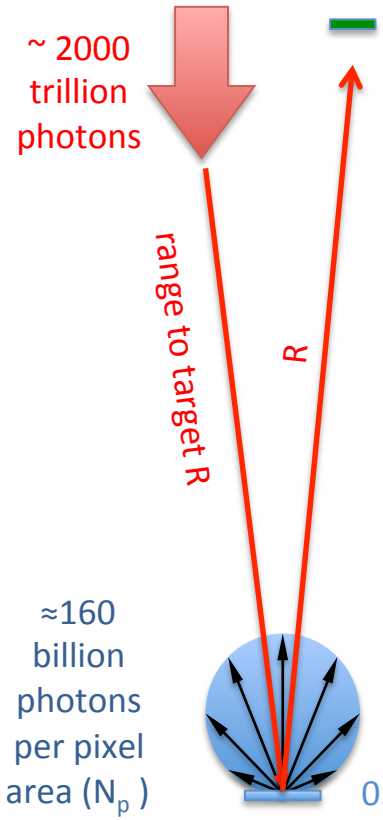
average number of photons received

- target area is illuminated by large number of photons
  - Geiger-Mode LIDAR per pixel [1] : ~ 160 x 10^9 = 160 G photons = 0.16 T photons
  - Linear LIDAR per laser footprint [2]: ~ 120 x 10^{12} = 120 T photons
- interaction with target
  - reflectance varies typically between 10% and 100%
  - fill factor of cross section varies typically between 0% and 100%
- photons collected by receiver for 100% reflectance and 100% fill factor
  - GeigerMode LIDAR [1] : ~ 10 photons
  - Linear LIDAR [2]: ~ 44k photons

1) Rhoads, R., "Geiger-mode LiDAR mapping: High density, high volume airborne 3D imaging", p. 14, Capturing Reality 2015, Nov 24th 2015, Salzburg, Austria. Information extracted: 20 W, 50 kHz, 4096 pixels, data from page 21, especially AGL = 27,000 ft, visibility 23 km. Information assumed : receiver aperture 25 cm
2) specification of *RIEGL* LMS-Q1560, with PRR = 400 kHz, with AGL = 1000 m, visibility 23 km

average number of received photons

- where have all the photons gone?



receiver aperture, d

photon density

~ 200 photons / m²
@ ρ=100%, f=100%

$$\frac{N_p \cdot \rho \cdot f}{\pi R^2} \eta_{atm}$$

$$N_p \cdot \rho \cdot f$$

collected photons

$$N_p \cdot \rho \cdot f \frac{(d/2)^2}{R^2} \eta_{atm}$$

~ 13photons
@ ρ=100%, f=100%

depends on
- pulse energy
- AGL
- receiver aperture
- atmospheric attenuation

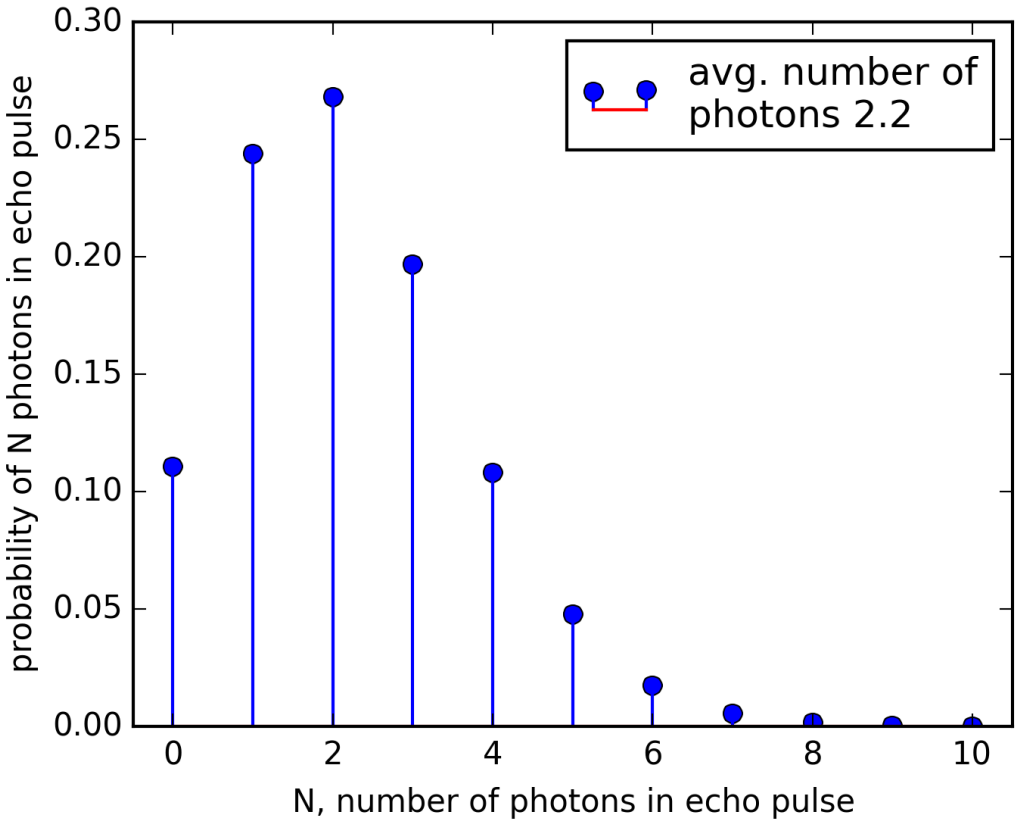
0.3 x 0.3 m diffusely reflecting target, reflectance ρ, fill factor f

Poisson distribution

average number of photons ✔

how many photons do we actually receiver in every look?

- not the same number every look
- stochastic process
- probability given by Poisson distribution



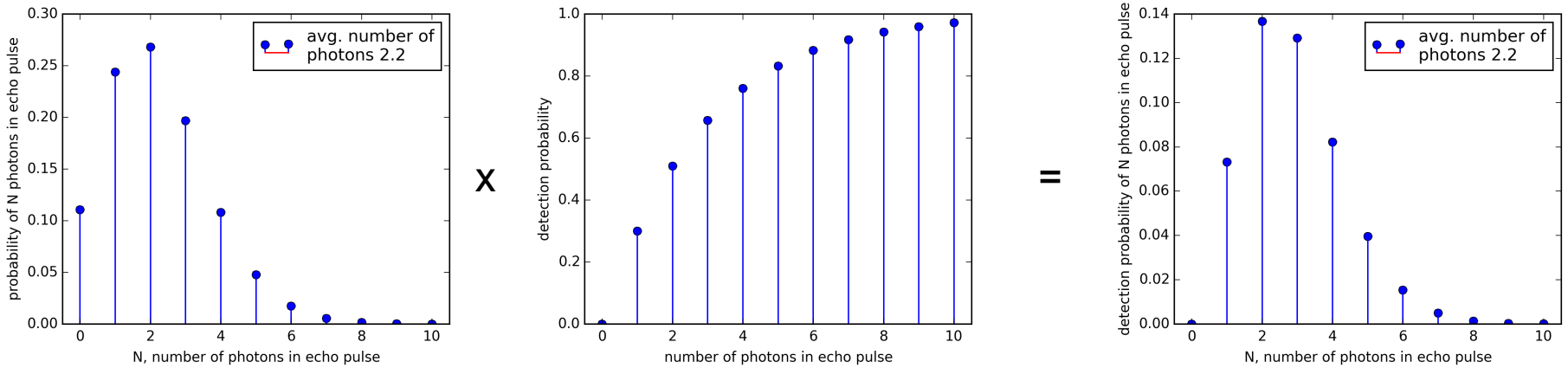
Poisson distribution is a discrete probability distribution that expresses the probability of a given number of events occurring in a fixed interval of time and/**or space** if these events occur with a **known average rate** and independently of the last event.

https://en.wikipedia.org/wiki/Poisson_distribution

detection probability for an average number of photons

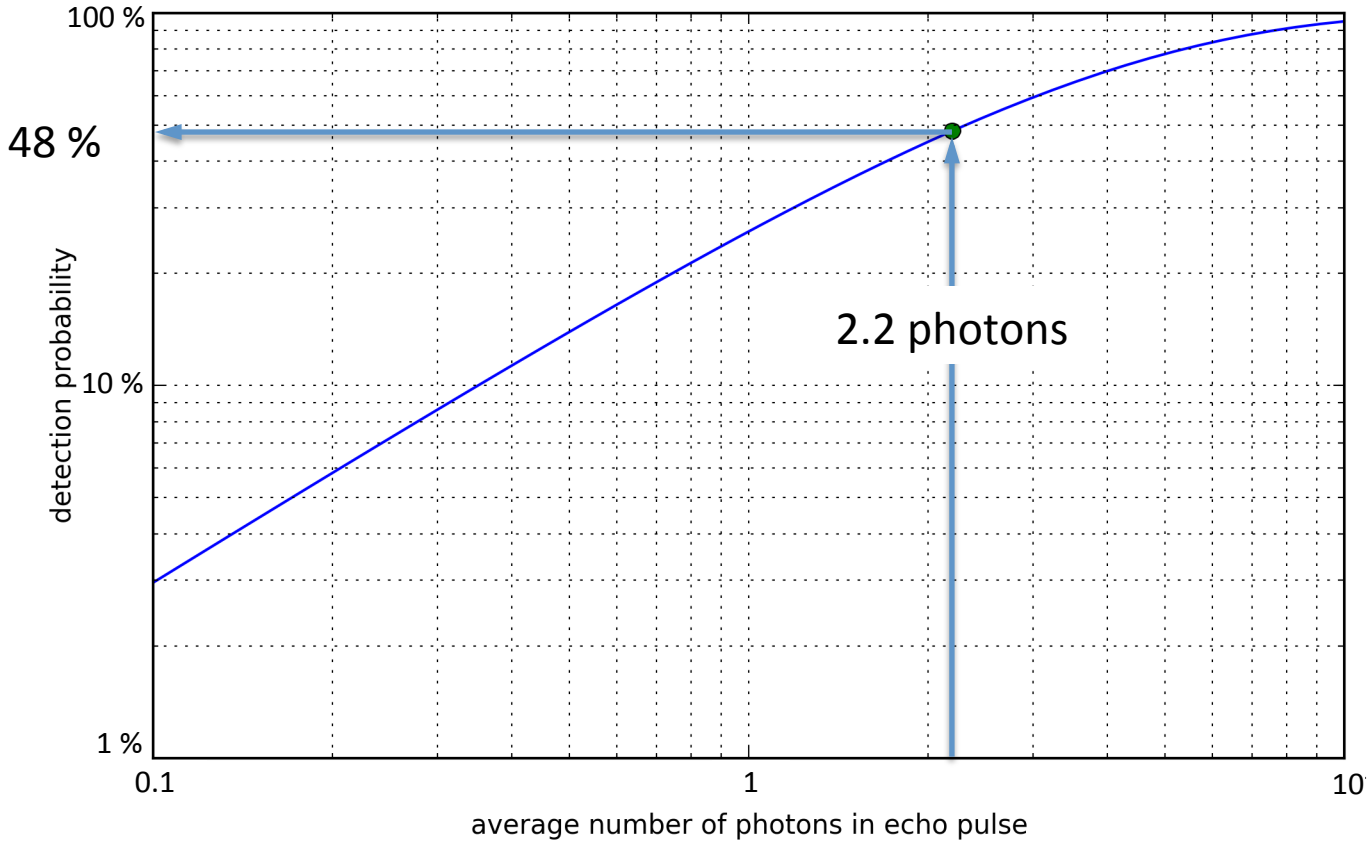
given average number of photons, e.g., 2.2

1. Poisson distribution gives the probability for receiving a specific number of photons
2. For each such specific number the detection probability is well known
3. multiply probability mass functions
4. sum up all probabilities

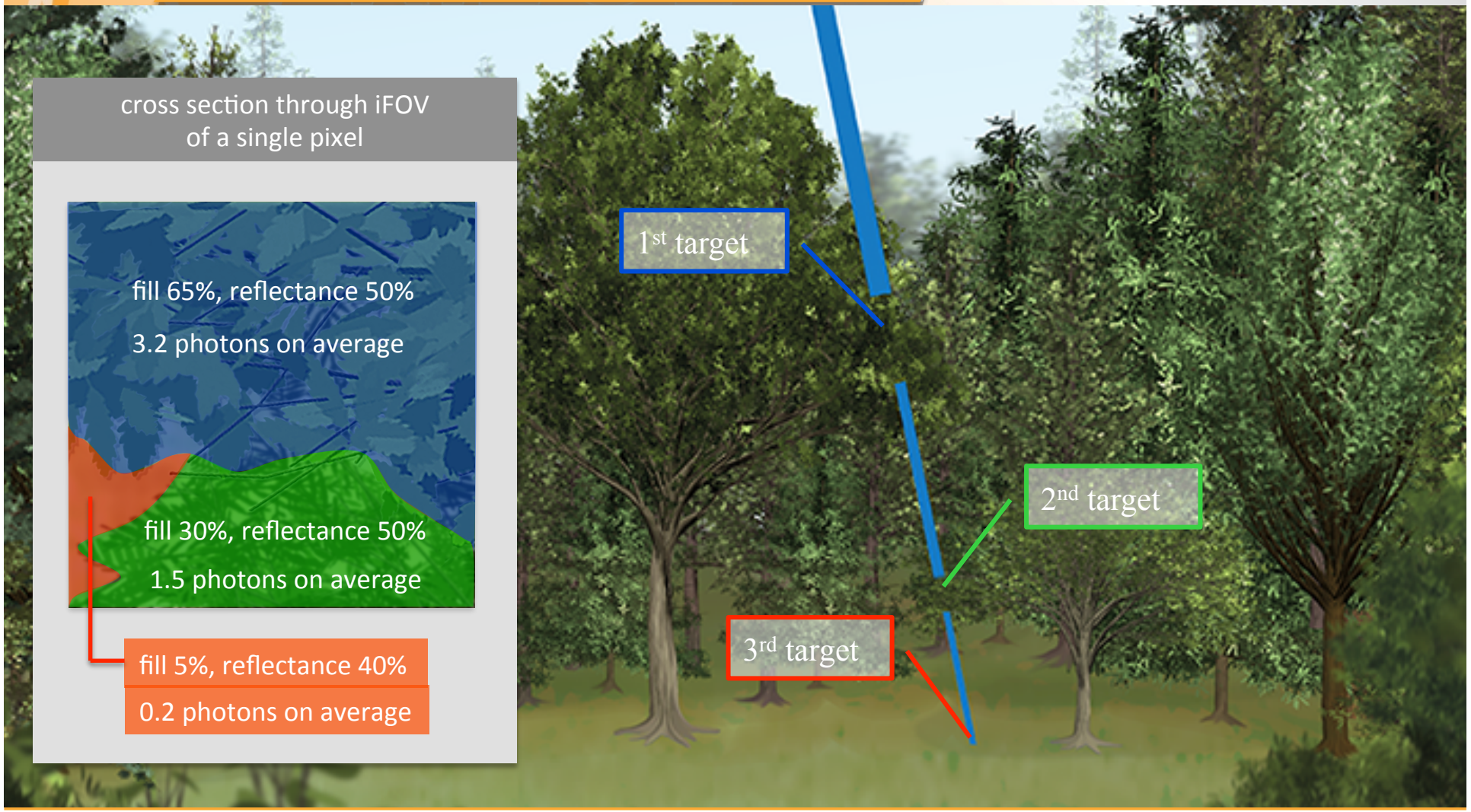


expected detection probability for an average number of 2.2 photons per received pulse: 48%

detection probability for an average number of photons

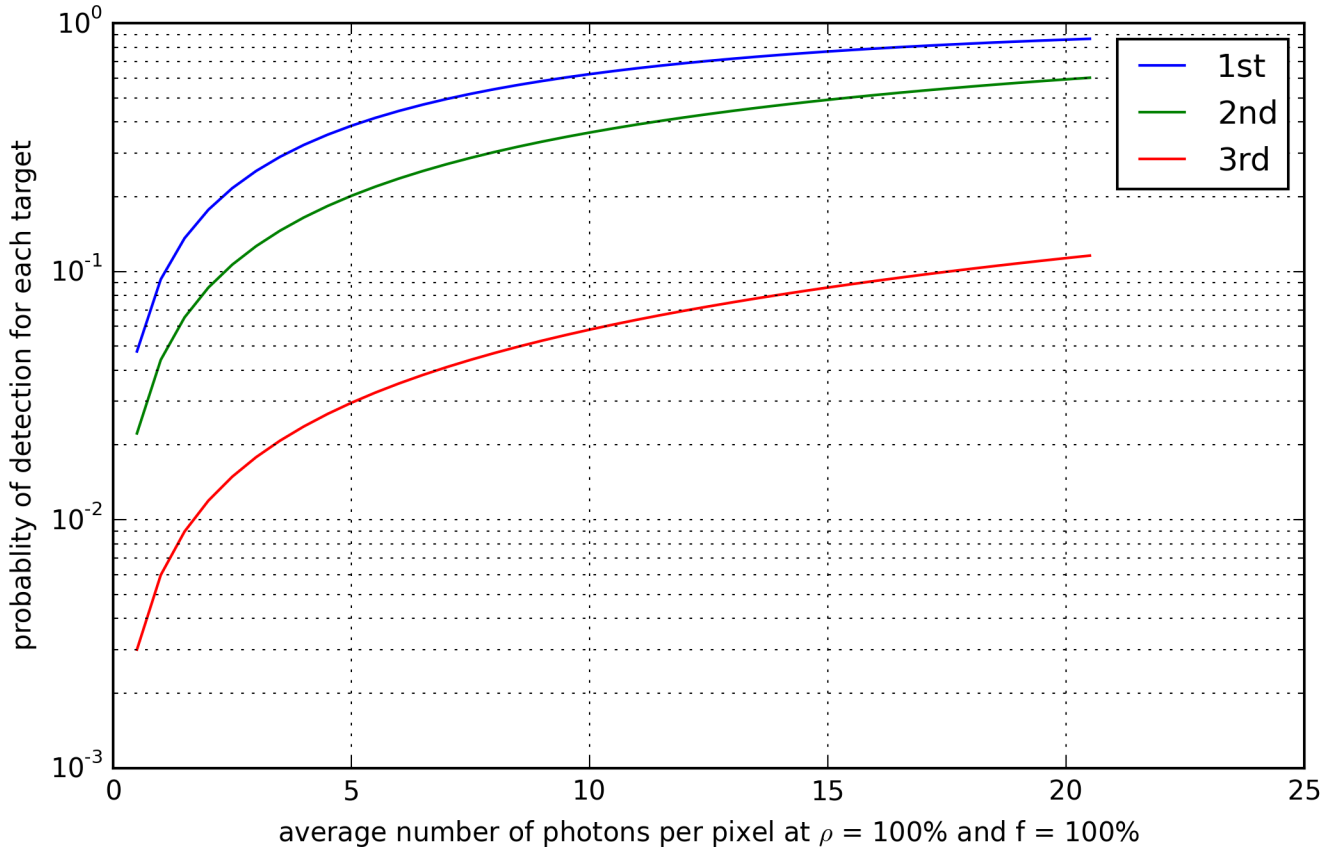


Geiger-Mode LIDAR: example for penetrating canopy



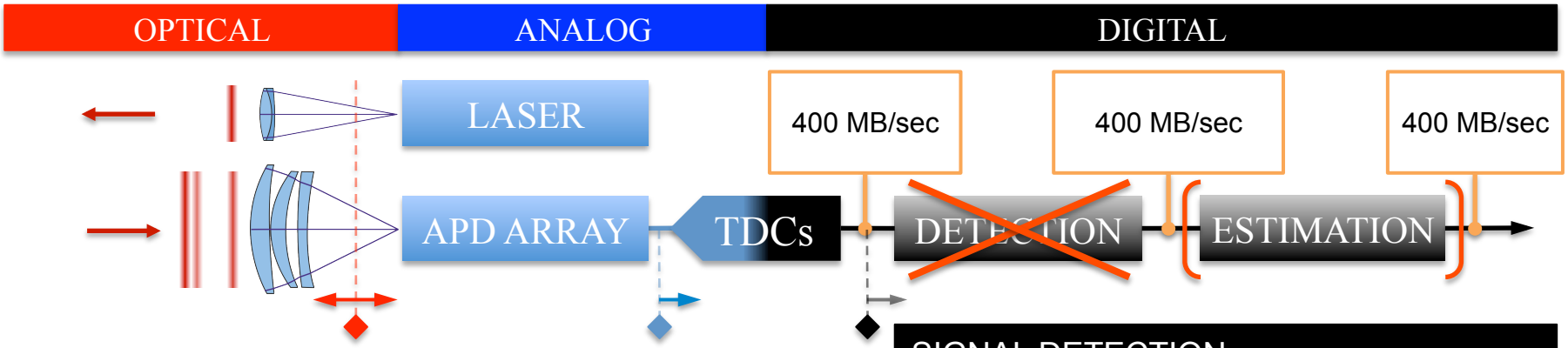
Single Photon LIDAR: example for penetrating canopy

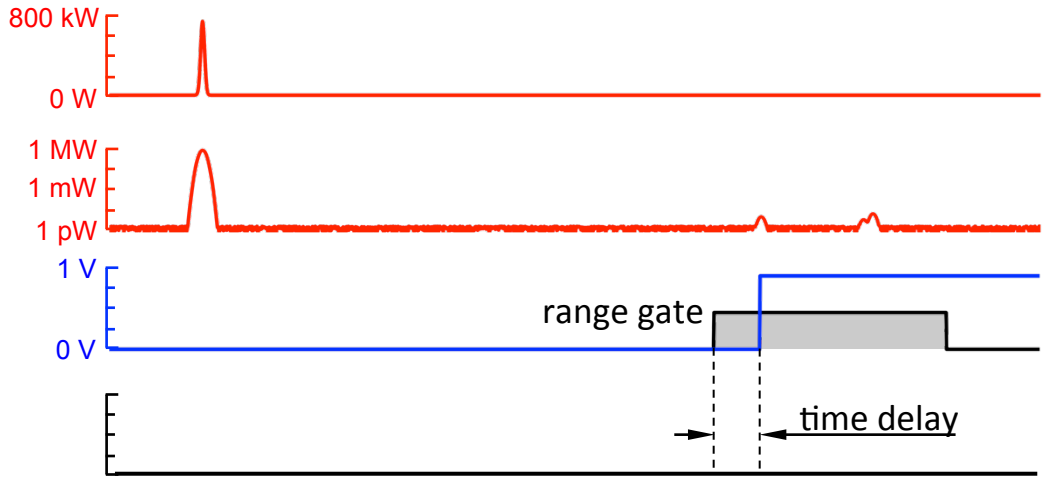
for a detector with NO DEAD TIME (Single Photon LIDAR)



fill x refl	in dB
0.65 x 0.5 ..	-5 dB
0.30 x 0.5 ..	-8 dB
0.05 x 0.4 ..	-17 dB

Geiger mode processing





SIGNAL DETECTION

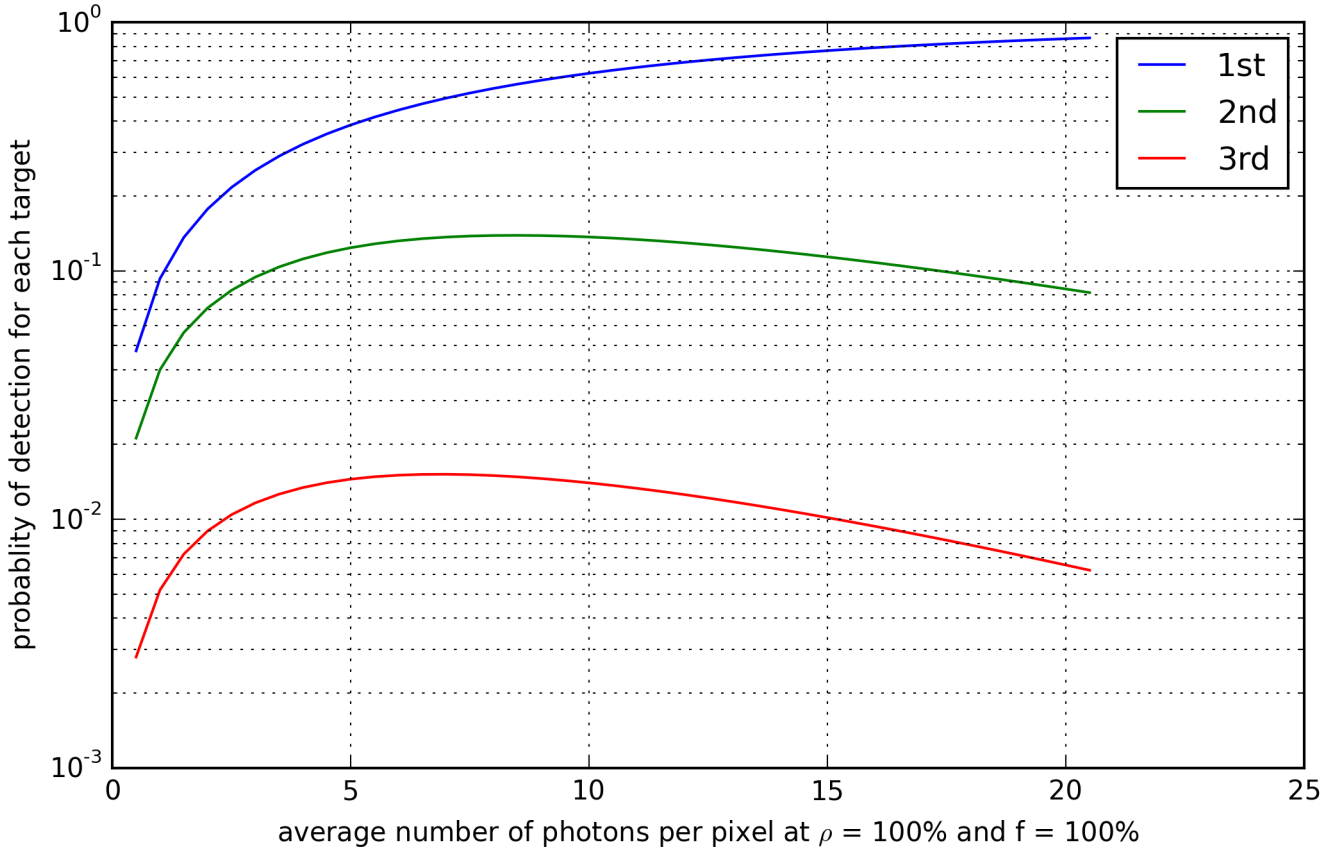
- inside Geiger mode APD array
- changed by varying laser power
- changed by varying photon detection efficiency (PDE)

SIGNAL ESTIMATION

- temporal position / range
- ~~signal strength / amplitude / reflectance~~
- ~~pulse width / pulse shape deviation~~
- ~~backscatter coefficient of turbid media~~

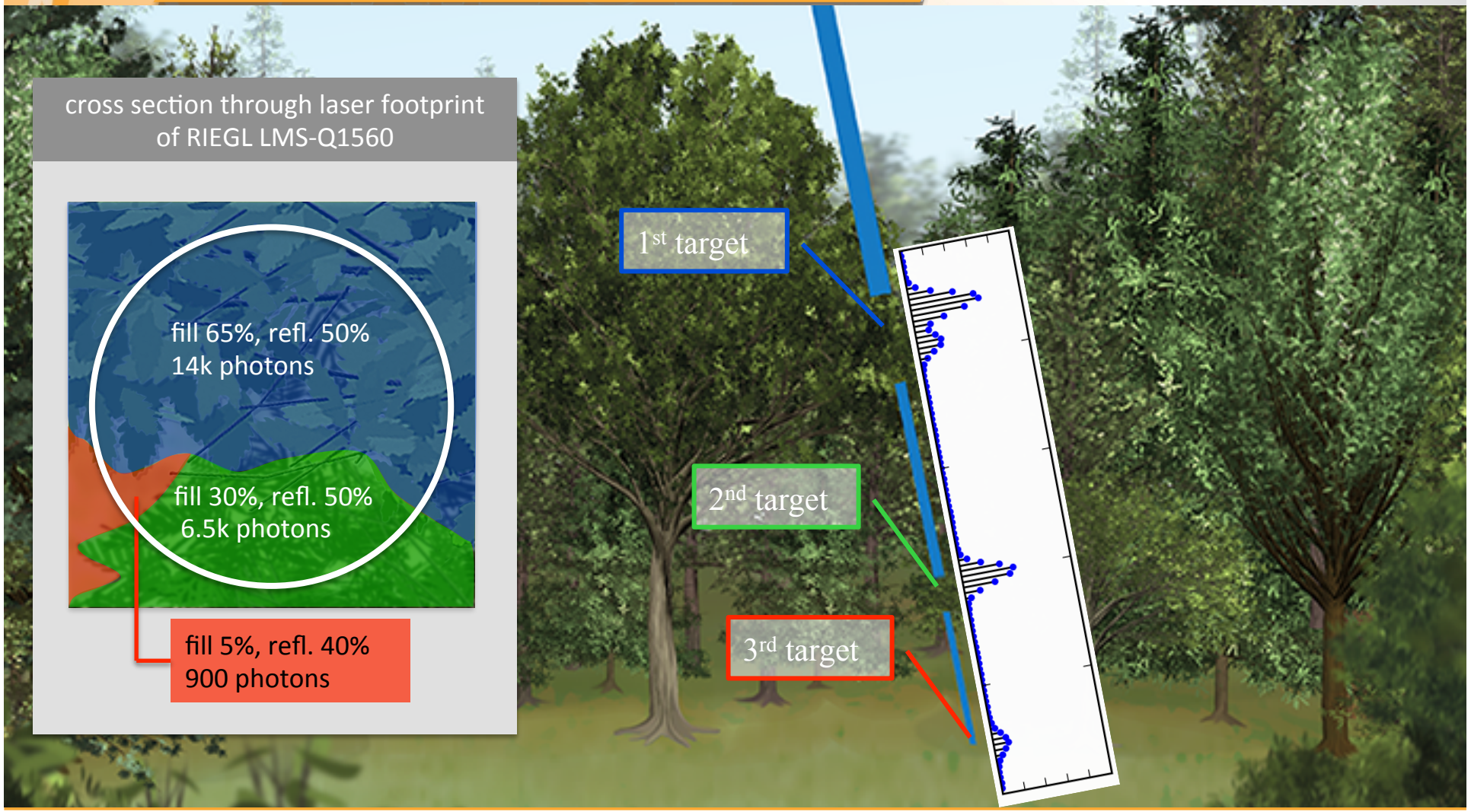
Geiger-Mode LIDAR: example for penetrating canopy

for a Geiger-mode detector (triggers only once per look)

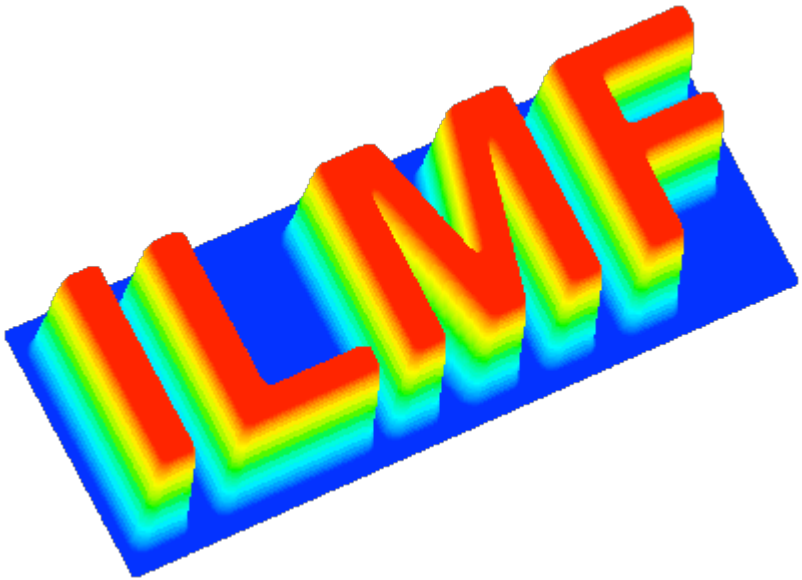


fill x refl	in dB
0.65 x 0.5 ..	-5 dB
0.30 x 0.5 ..	-8 dB
0.05 x 0.4 ..	-17 dB

example for penetrating canopy



hiding an object beneath canopy



high elevation

low elevation

dense canopy
with 5% transparency
to ground

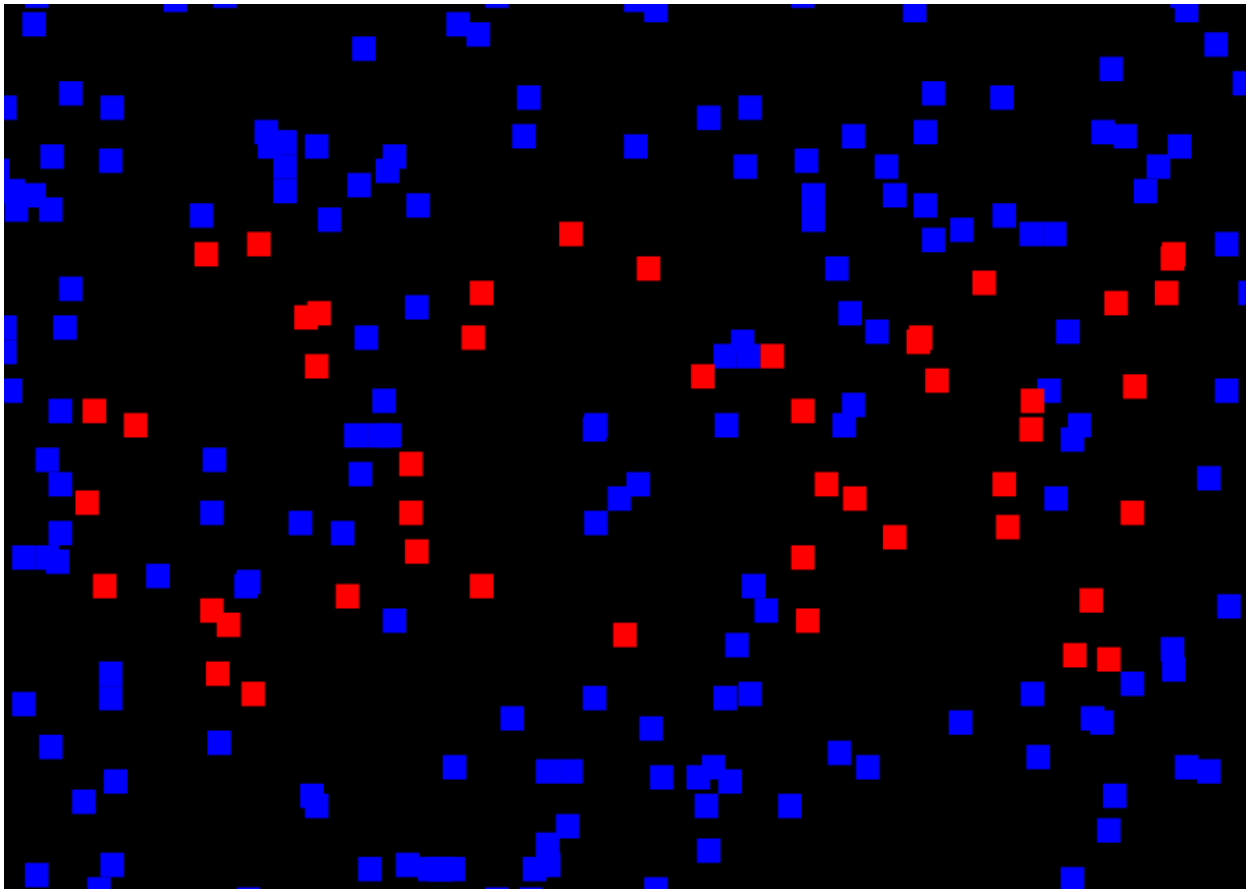
hiding an object beneath canopy

high elevation

low elevation

dense canopy
with 5% transparency
to ground

object below canopy - GmLIDAR

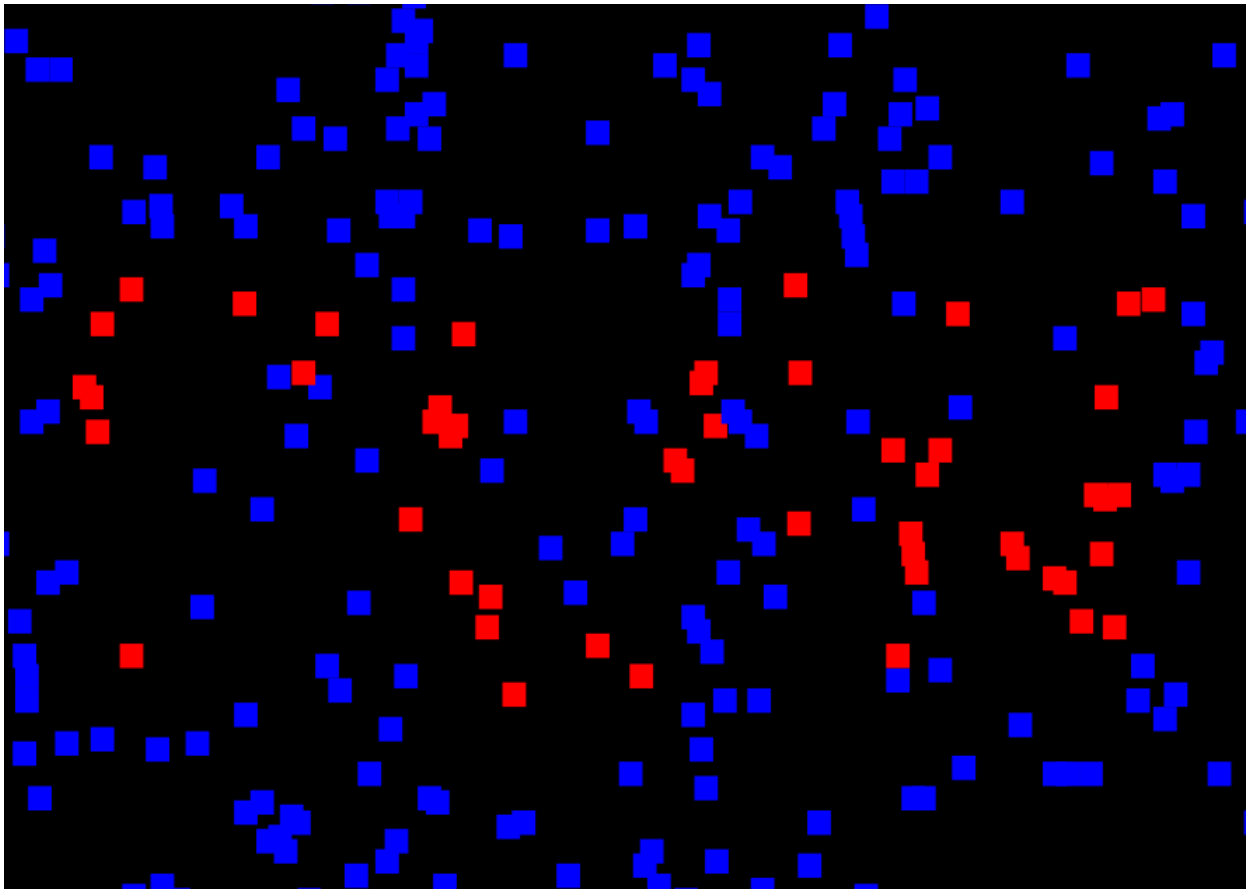


pixel with high elevation

pixel with low elevation

forward look –
center of swath

object below canopy - GmLIDAR

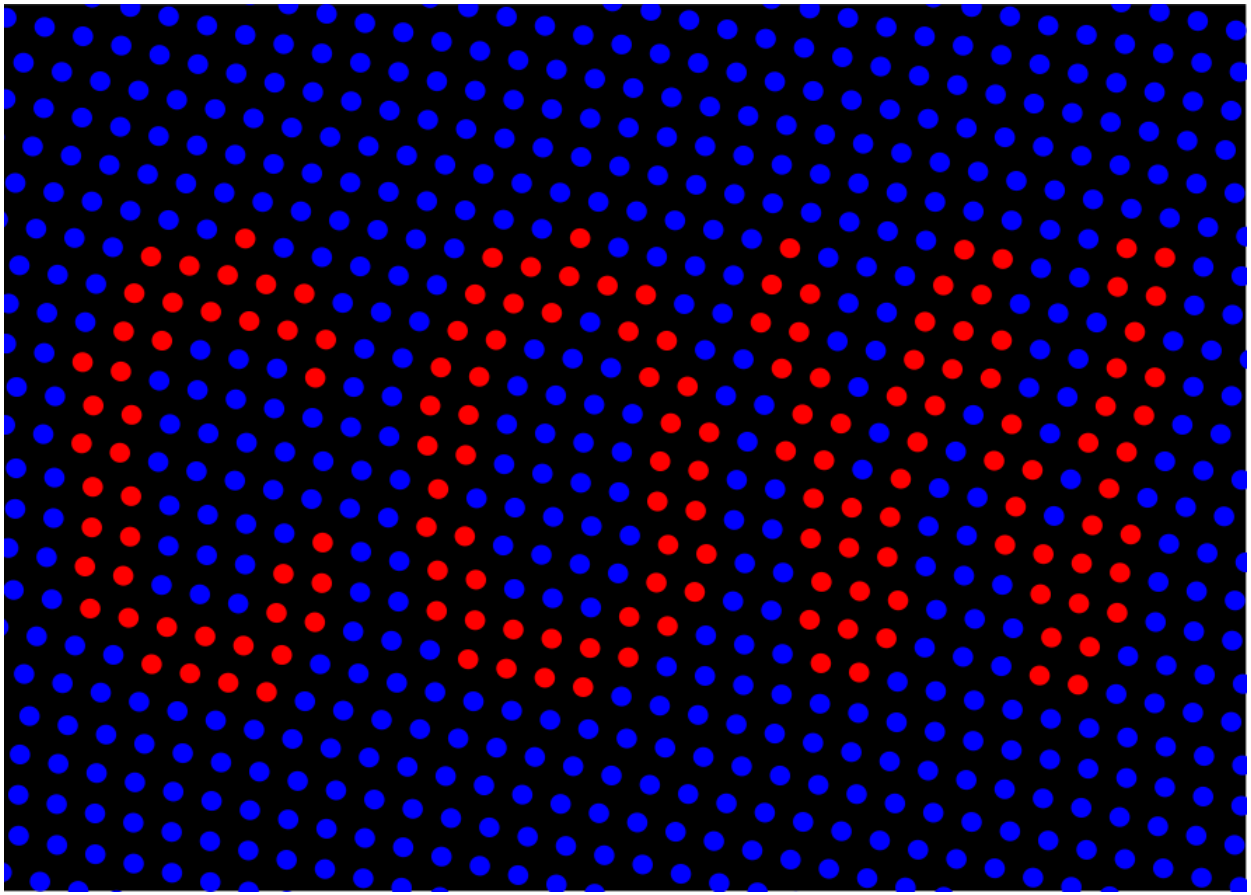


pixel with high elevation

pixel with low elevation

backward look –
center of swath

object below canopy – *RIEGL* LMS-Q1560

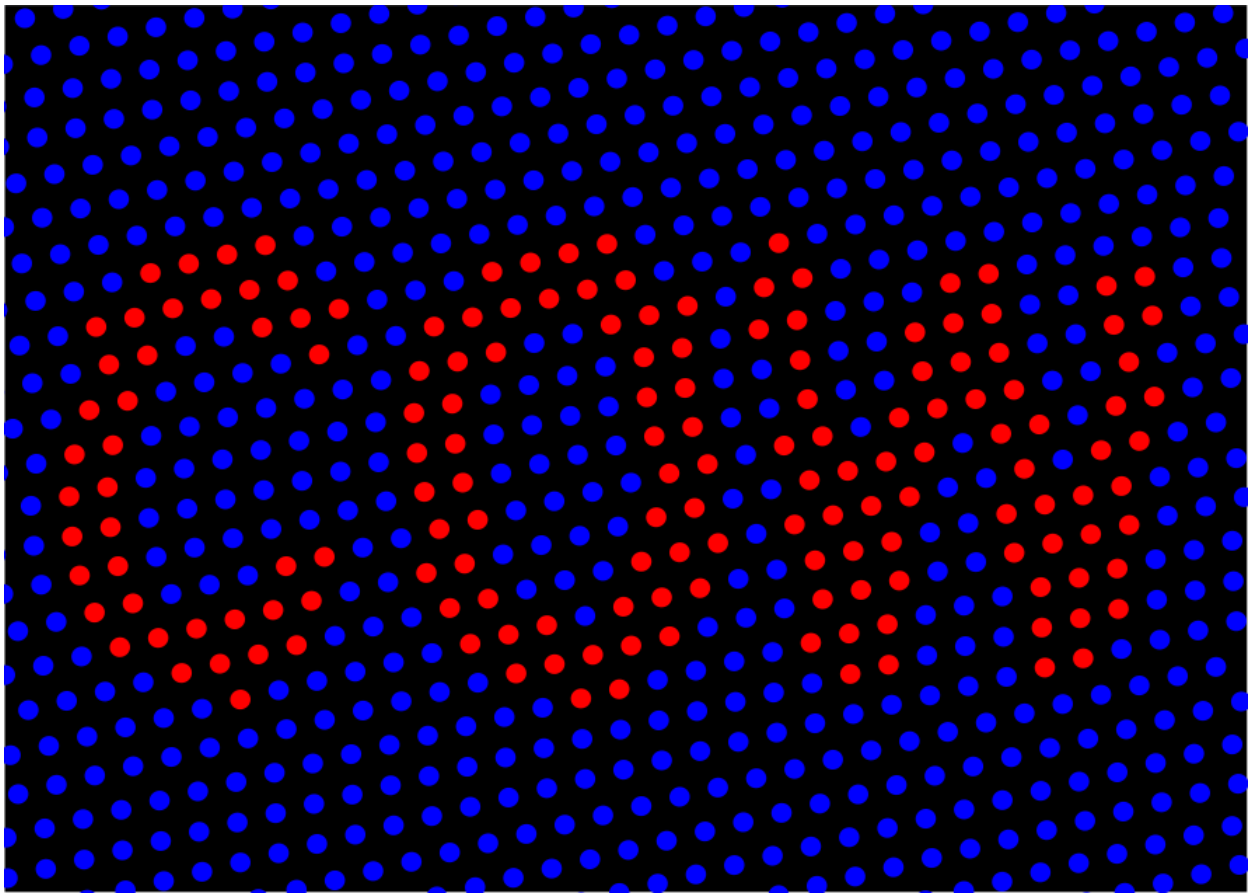


pixel with high elevation

pixel with low elevation

channel 1–
center of swath

object below canopy – *RIEGL* LMS-Q1560

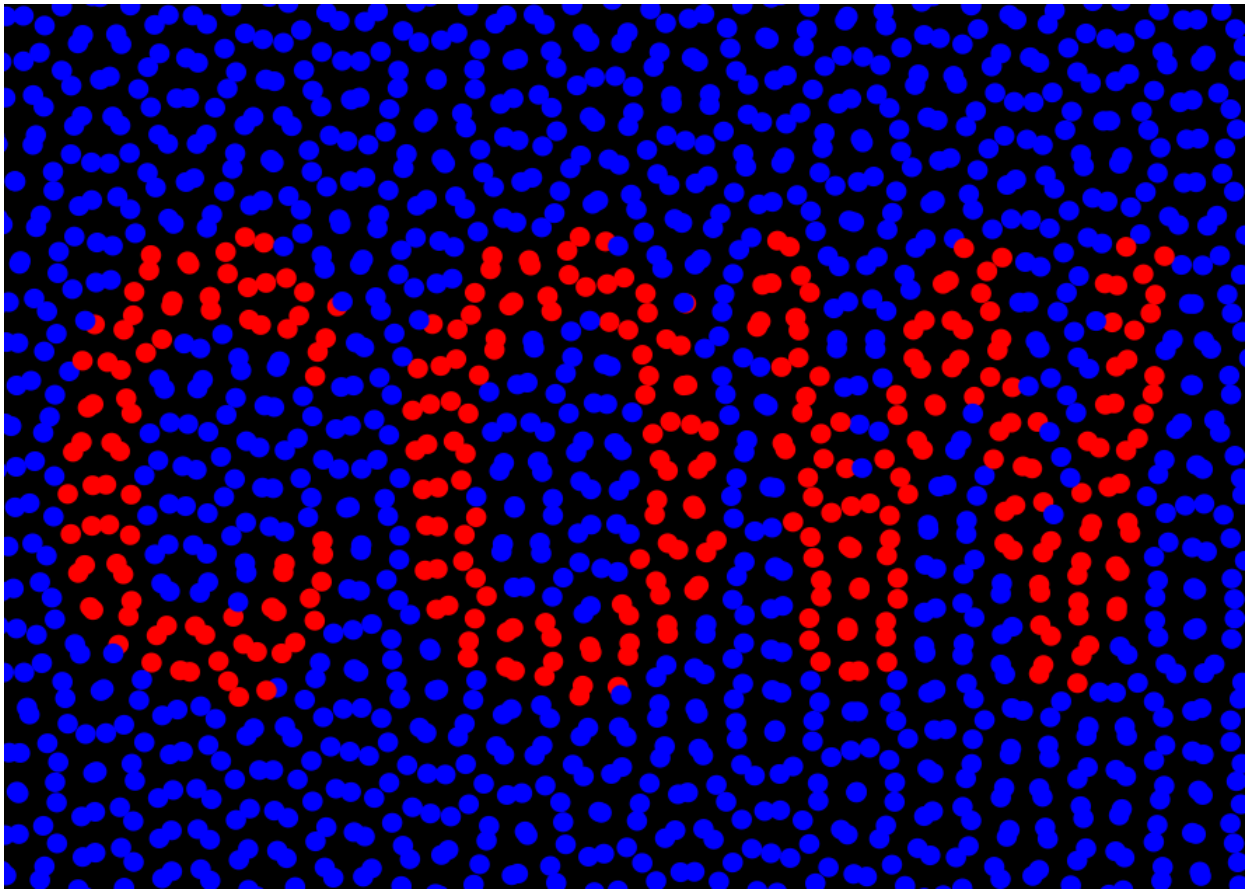


pixel with high elevation

pixel with low elevation

channel 2–
center of swath

object below canopy – *RIEGL* LMS-Q1560

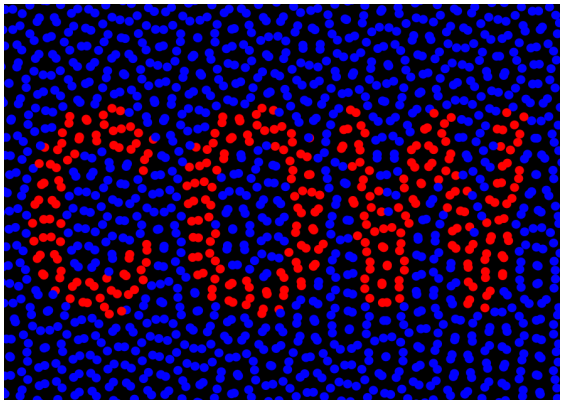


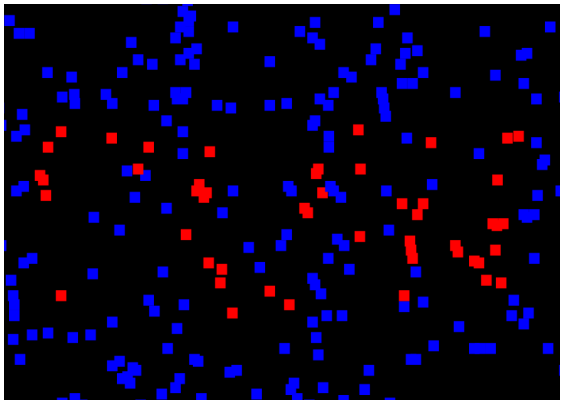
pixel with high elevation

pixel with low elevation

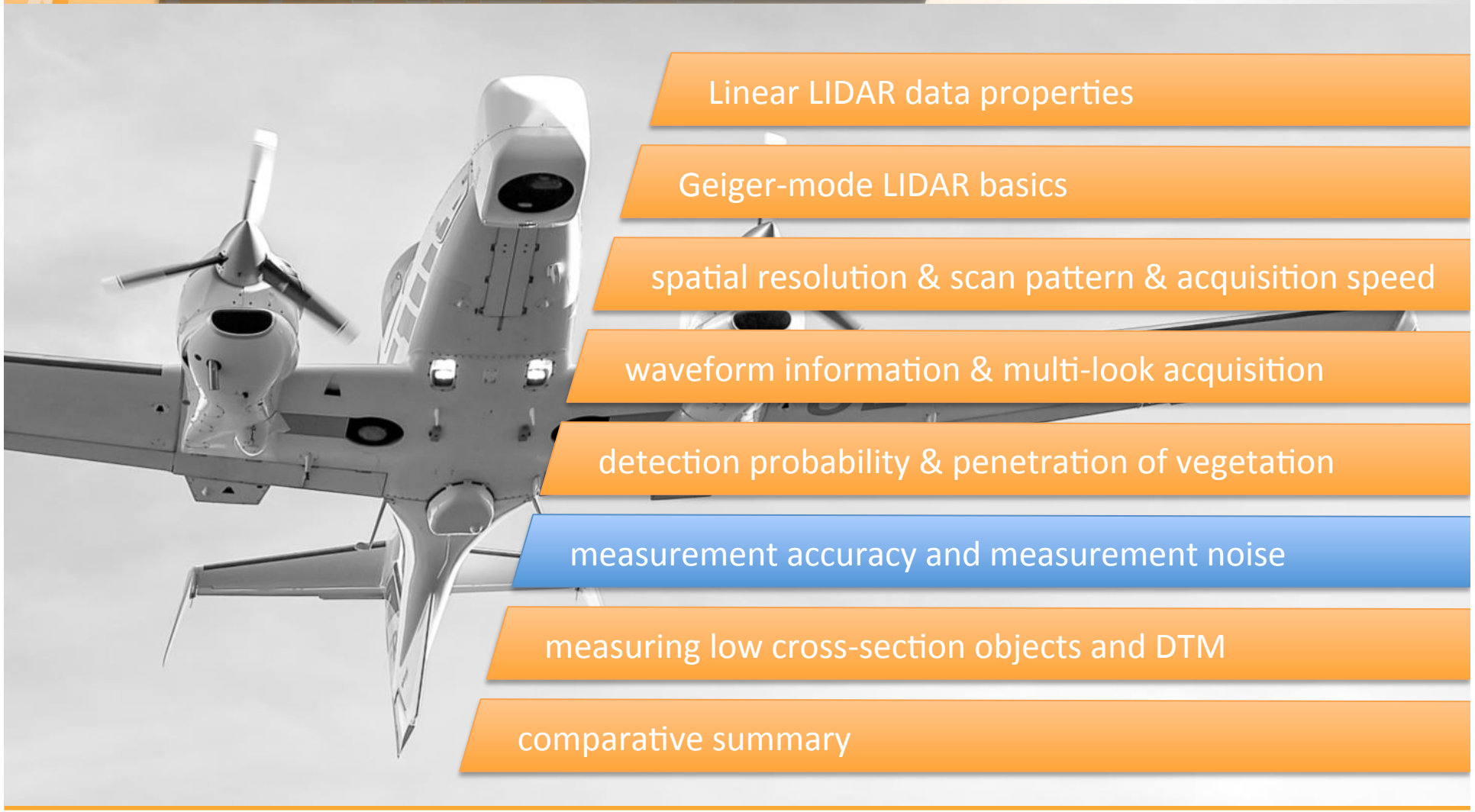
both channels –
center of swath

object hidden beneath canopy



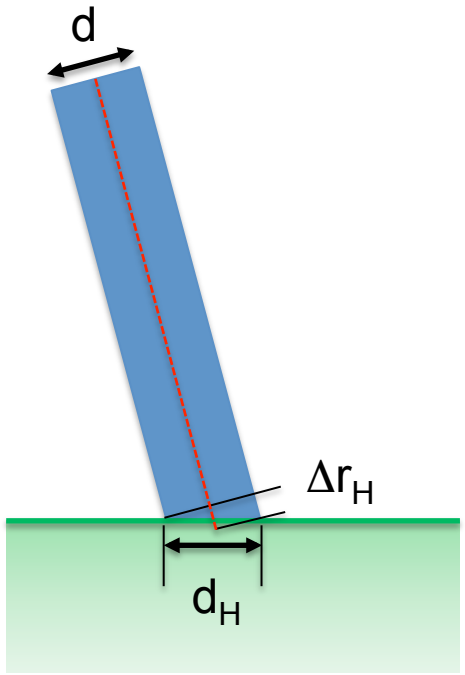


contents



range noise – Geiger Mode LIDAR

horizontal flat target

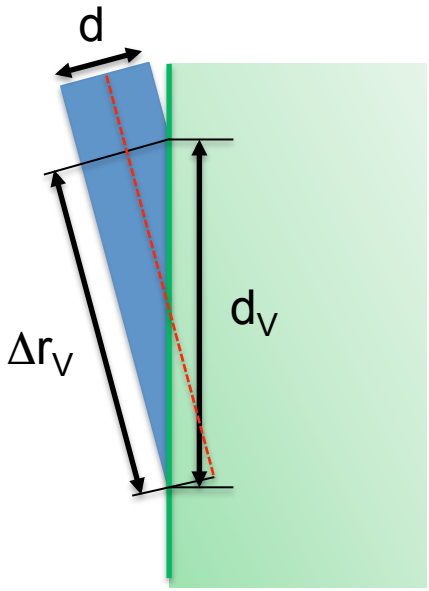


AGL = 27000 ft
R = 8520 m
iFOV = 35 µrad
d = 30 cm

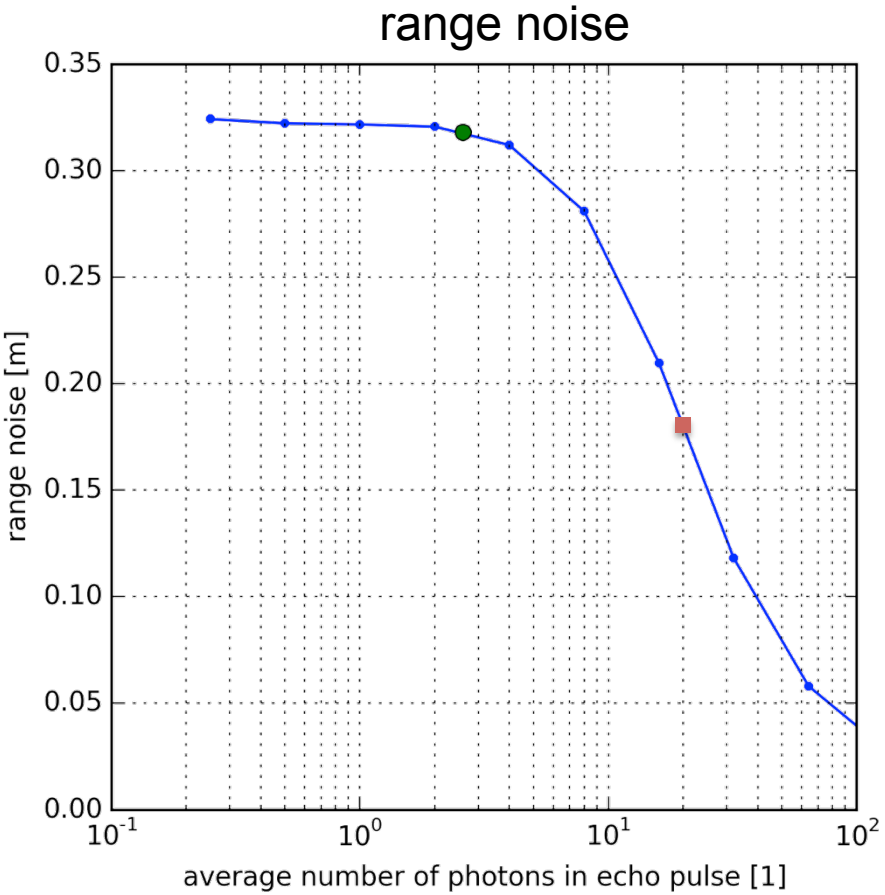
d_H = 31 cm
Δr_H = 8 cm

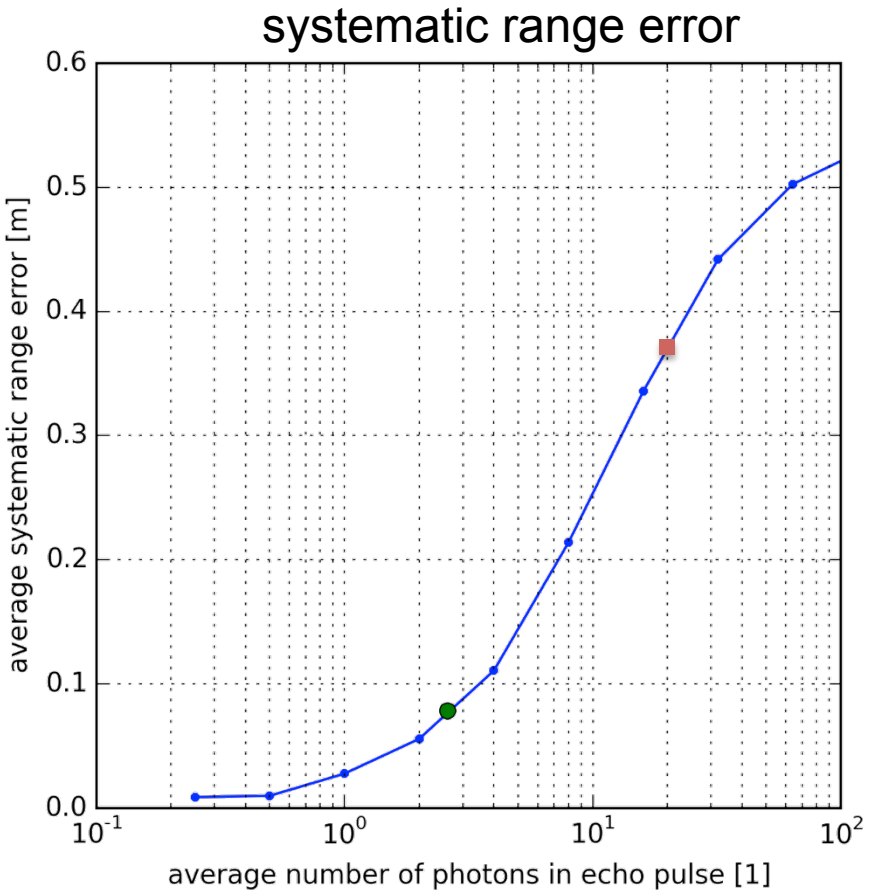
d_V = 116 cm
Δr_V = 112 cm

vertical flat target



range noise – Geiger Mode LIDAR

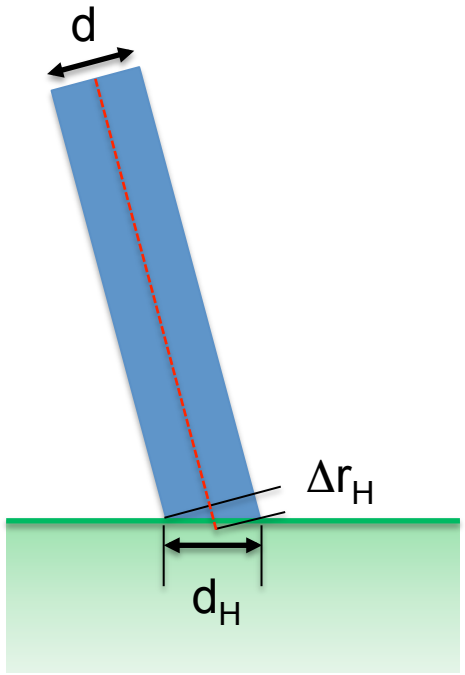




examples **vertical wall**: 2.6 photons on average, 1 σ = 32 cm, systematic range error 8 cm
20 photons on average, 1 σ = 18 cm, systematic range error 37 cm

range noise – Linear LIDAR

horizontal flat target

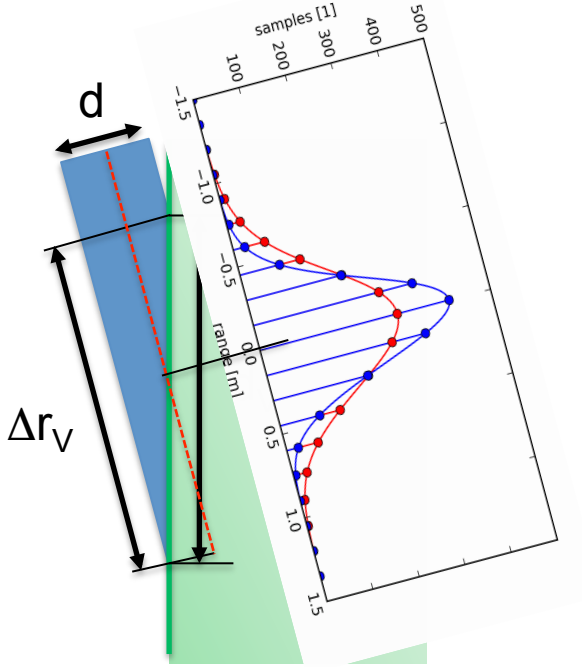


AGL = 1000 m
R = 1035 m
iFOV = 250 µrad
d = 26 cm

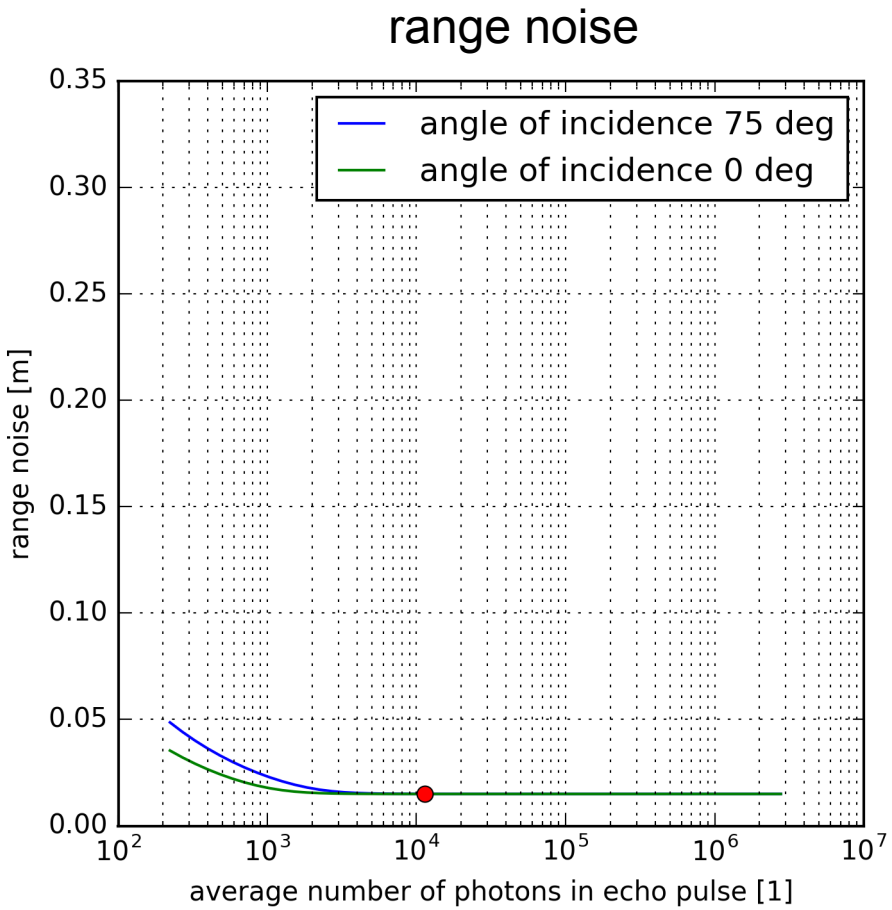
d_H = 27 cm
Δr_H = 7 cm

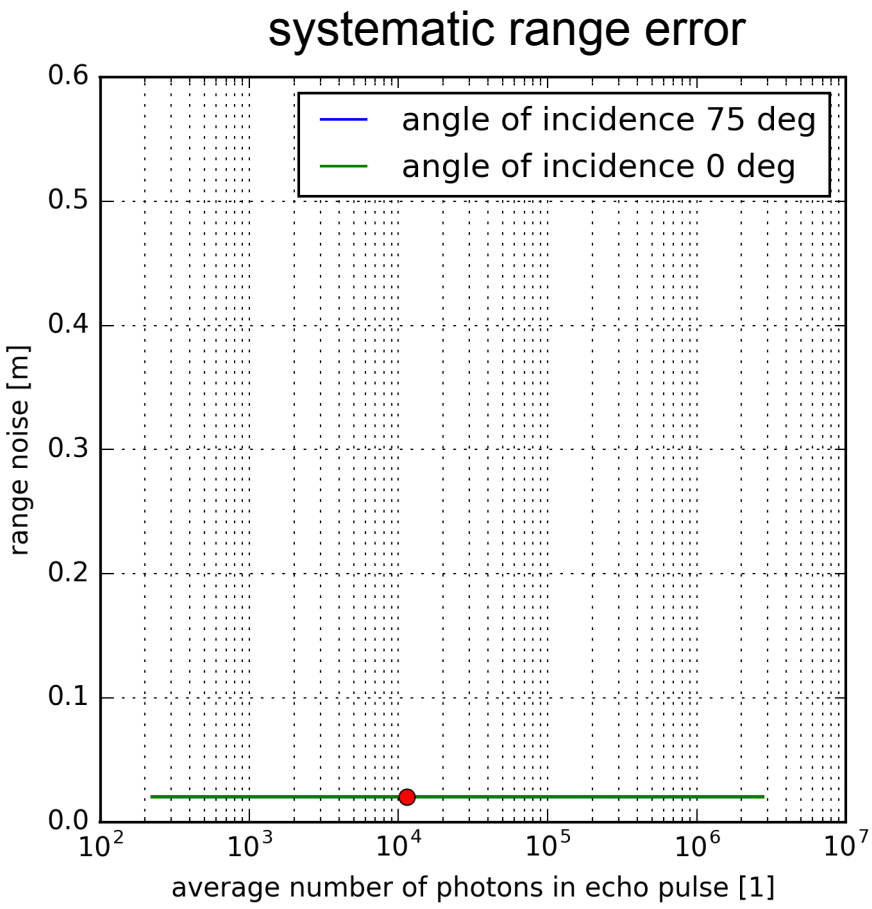
d_V = 100 cm
Δr_V = 97cm

vertical flat target



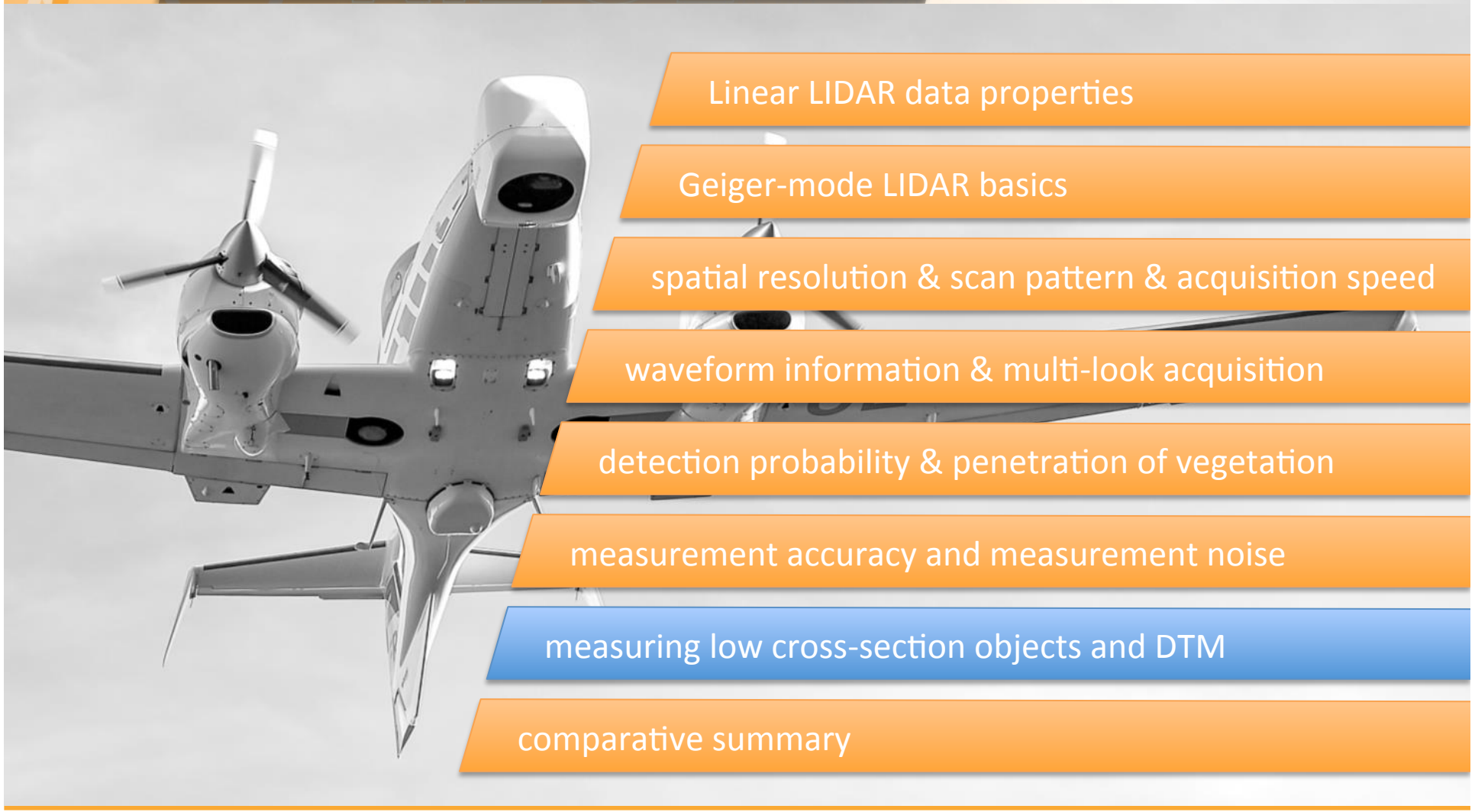
range noise – Linear LIDAR





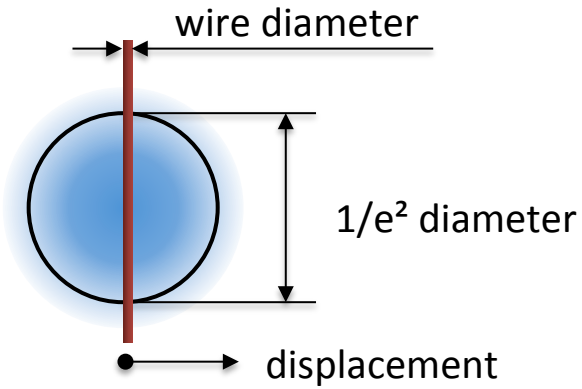
example **vertical wall:** 11k photons on average, 1 σ = 1.5 cm, systematic range error 2 cm

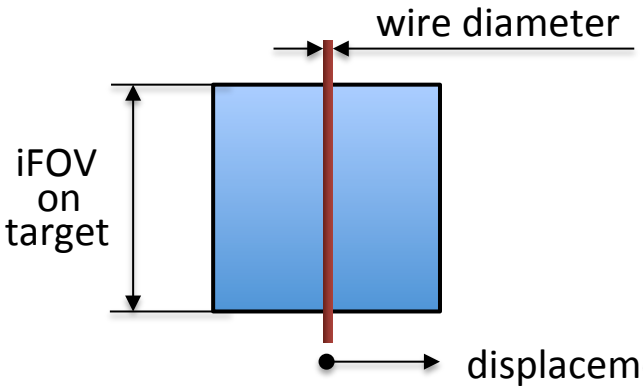
contents

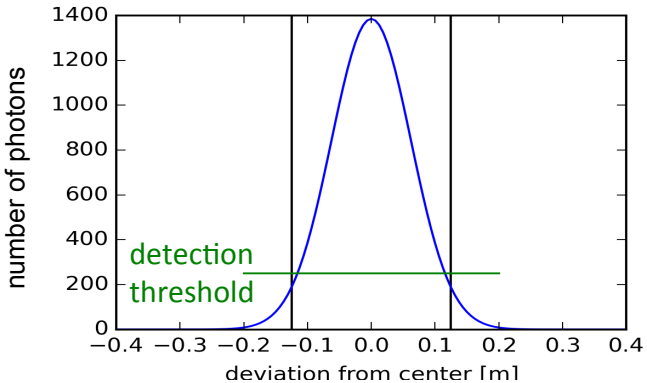


small objects and vegetation

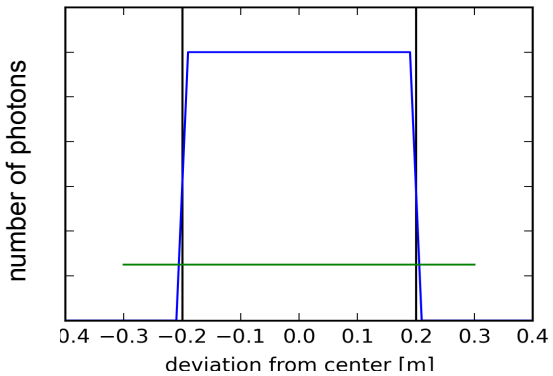
- objects like power lines, poles, buildings, small structures, street inventory, etc.
- example: wires of power lines, modelled by wire diameter (1 cm, 2 cm) and reflectivity 40%





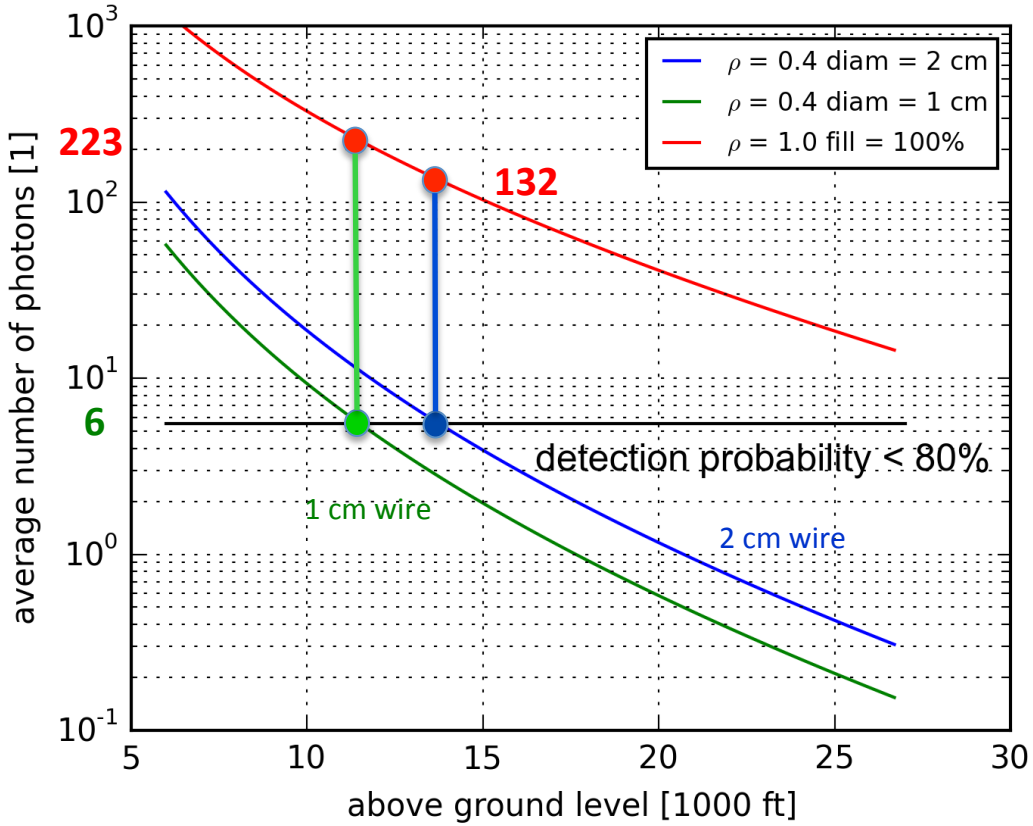


LMS-Q1560
AGL 1000 m
wire diam. 1 cm
wire refl. 40%



small objects and vegetation

estimated average number of photons for GmLIDAR, visibility 23 km, iFOV 35µrad

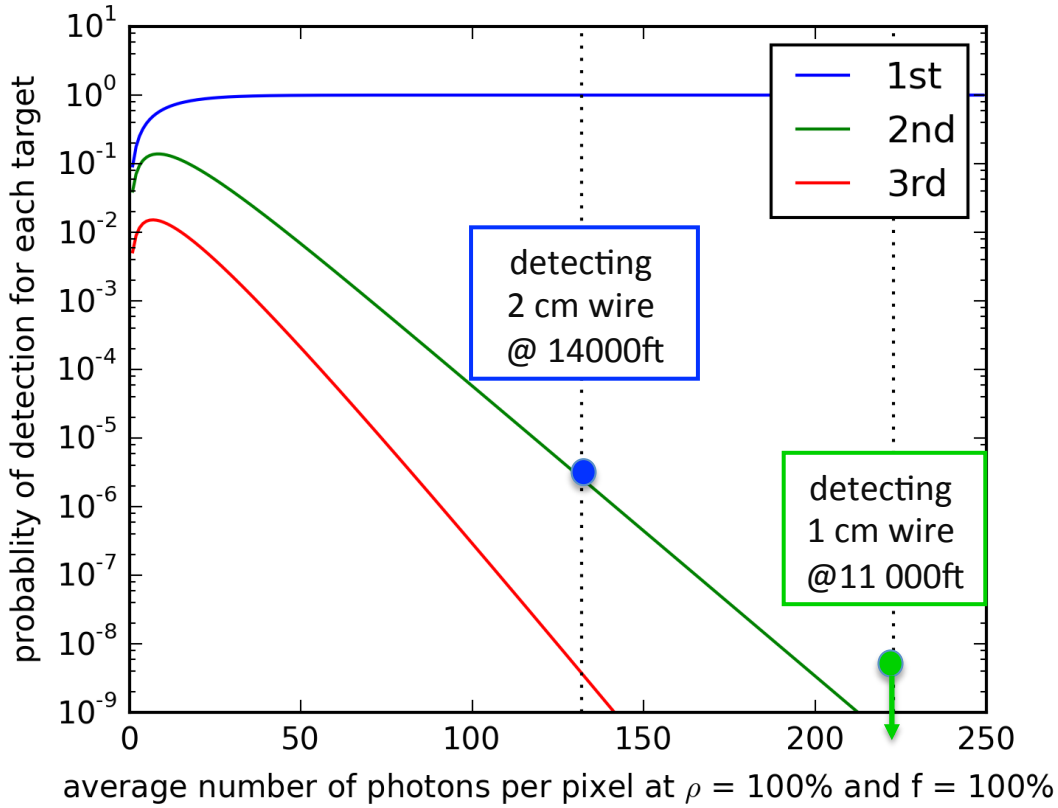


for 1 cm wire:
AGL = 11 500 ft
ground speed = 110 kts
PRS = 18 Hz
number of looks in
center of swath = 10
average number of photons for 100%
reflectance and 100% fill factor: 223

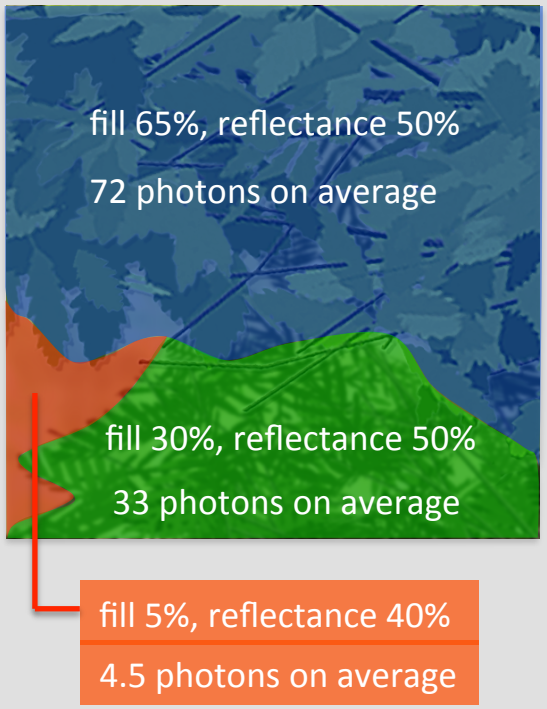
for 2 cm wire:
AGL = 13 800 ft
ground speed = 130 kts
PRS = 17 Hz
number of looks in
center of swath = 10
average number of photons for 100%
reflectance and 100% fill factor: 132

small objects and vegetation

target detection for dense canopy example

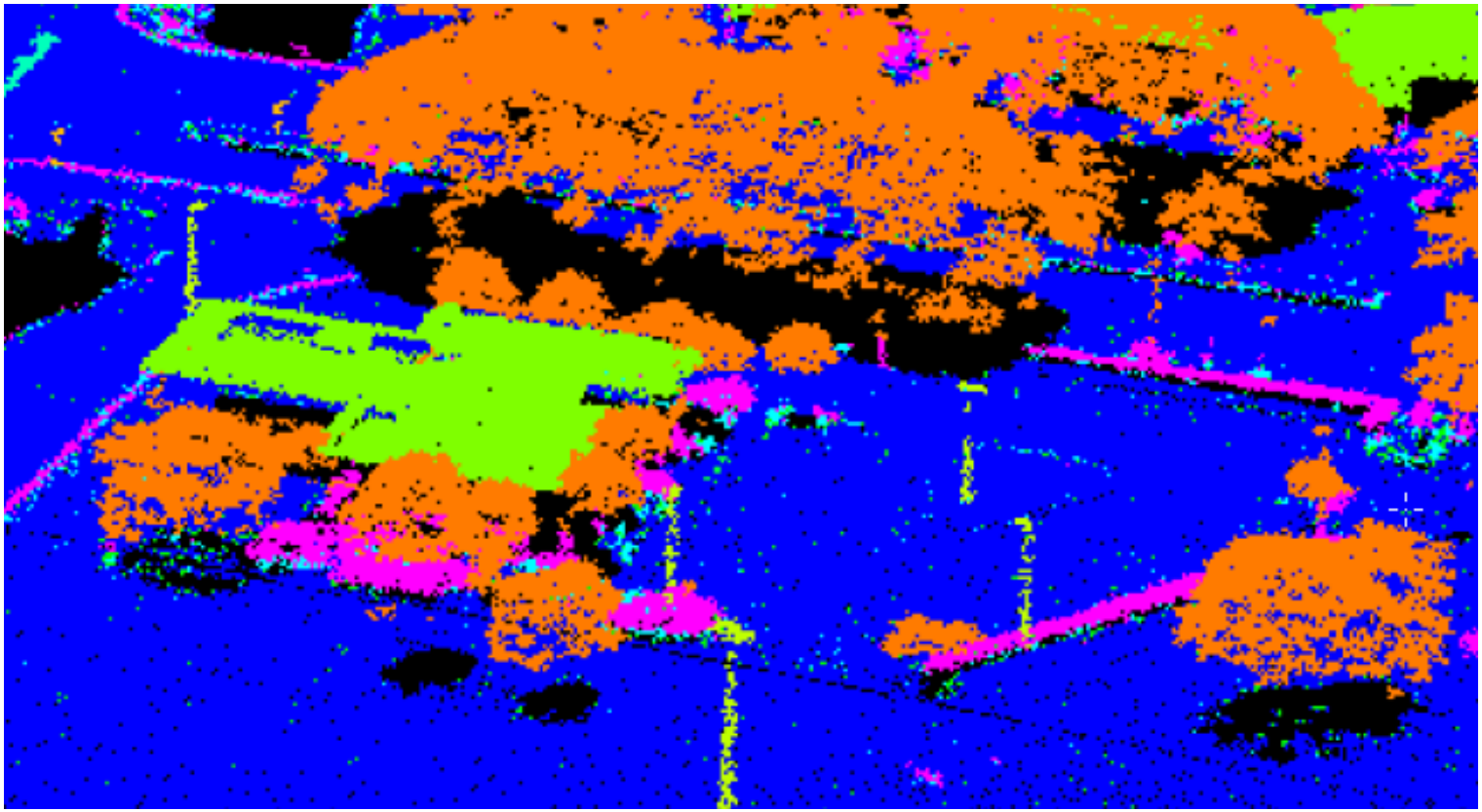


cross section through iFOV
of a single pixel



simultaneous acquisition of power lines and DTM?

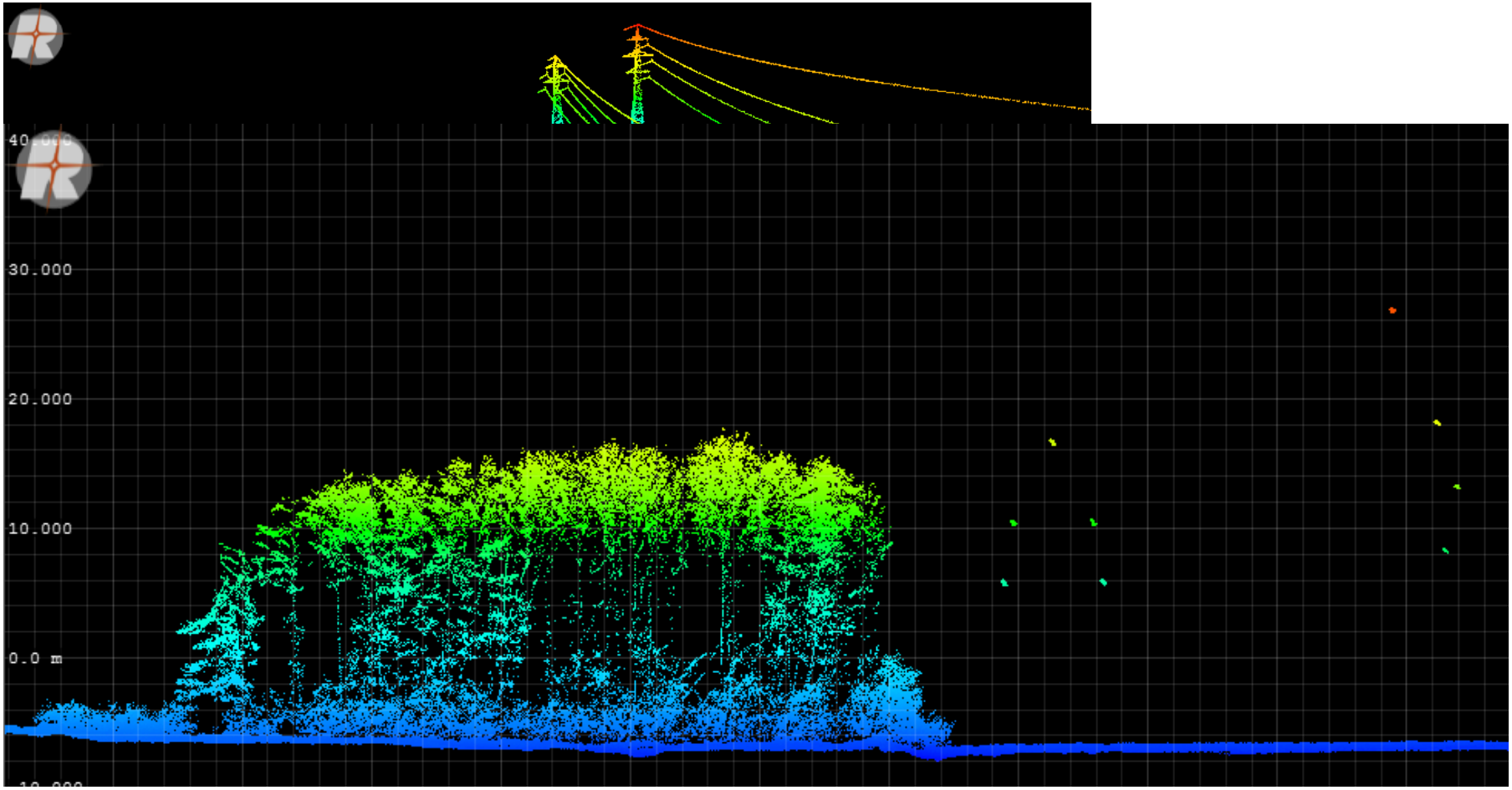
Geiger-Mode LIDAR: either / or. Not both at the same time



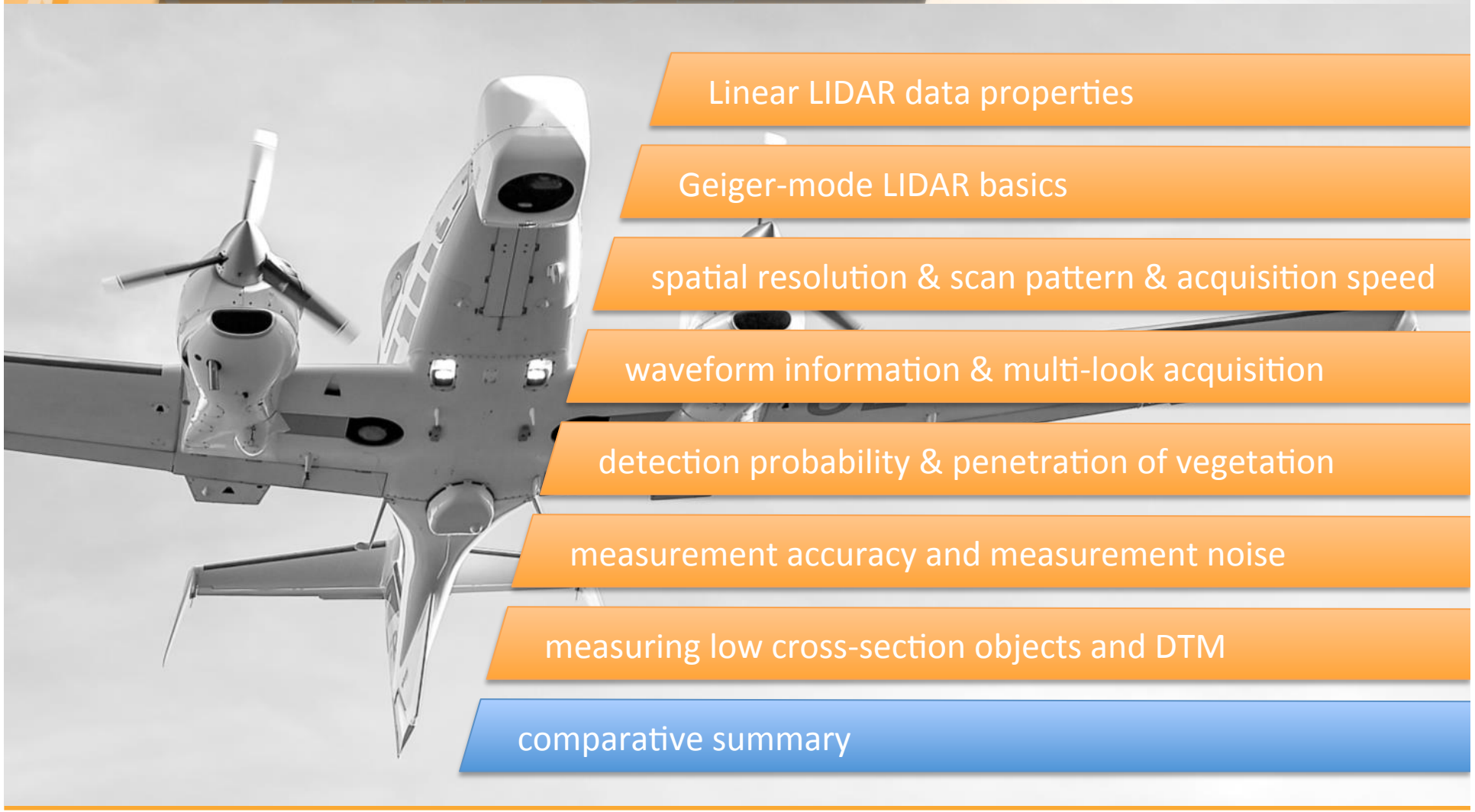
Rhoads, R., “Geiger-mode LiDAR mapping: High density, high volume airborne 3D imaging”, Capturing Reality 2015, Nov 24th 2015, Salzburg, Austria

simultaneous acquisition of power lines and DTM?

Linear LIDAR: example RIEGL LMS-Q1560, both at the same time



contents



summary

	Linear LIDAR	Single Photon LIDAR	Geiger Mode LIDAR	Dense Image Matching
acquistion speed for 8 meas/m²	240 km²/h	640 km²/h	2100 km²/h	~ 1000 km²/h
day and night operation	YES	~	~	NO
small objects & DTM simultaneously	YES	YES	NO	NO
penetration of dense foliage	YES	YES	NO	NO
radiometric calibration capability	YES	NO	NO	YES
multiple wavelengths	YES	NO	~	YES
real time data	YES	~	NO	NO
accuracy	+	~	~	~