Sampling the World in 3D by Airborne LIDAR –

Assessing the Information Content of LIDAR Point Clouds

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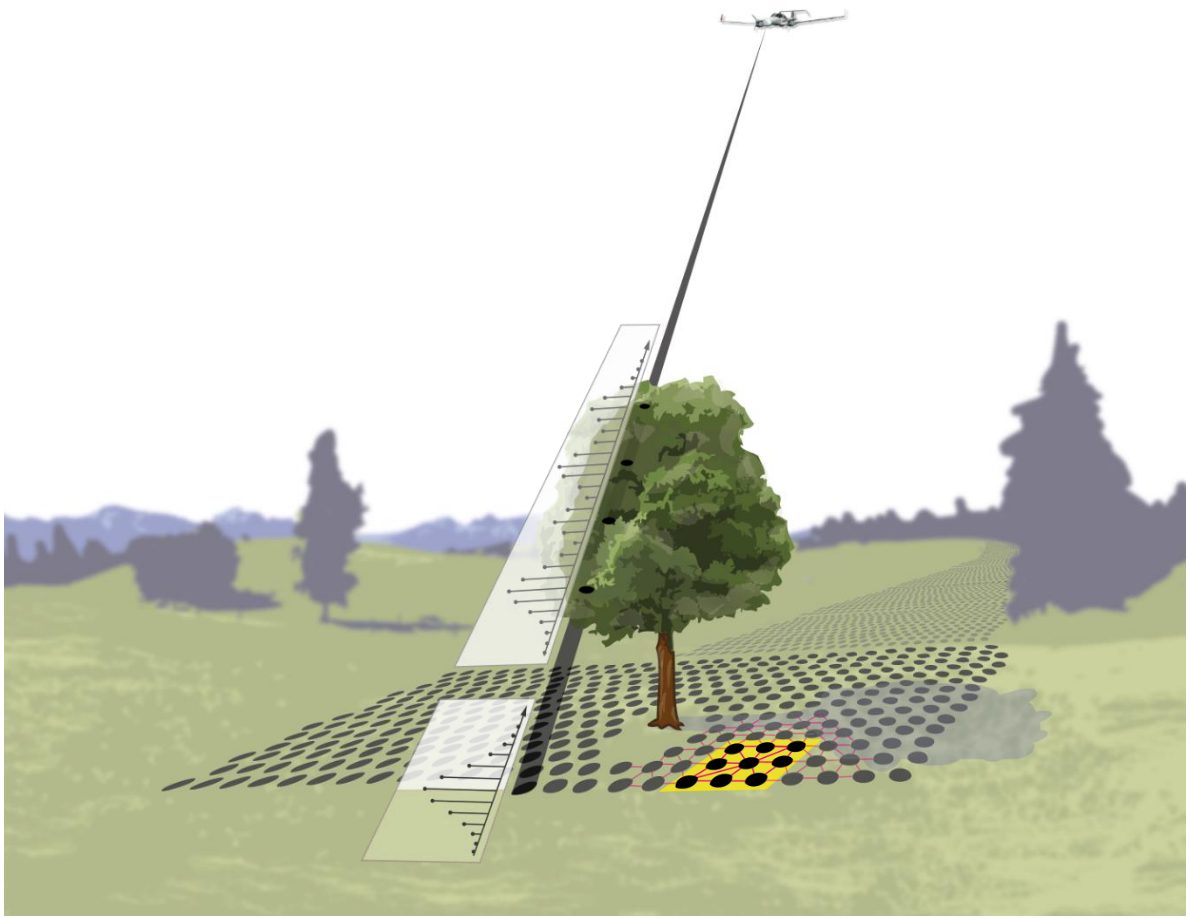
RIEGL LMS GmbH



- sequential data acquisition
- surface sampling at laser footprints
- “sampling” footprint ← → single point of point cloud (PC)
- organizing measurements in scan lines
  - intra-line spacing
  - inter-line spacing
- “2D” resolution limited by footprint size
- sampling density impacts information content of PC
- resolution in 3rd dimension
- echo-digitization with full waveform analysis → best multi-target resolution

instrument specification

density and spacing

LIDAR spec

performance envelope

scanner performance

impact of terrain

example on 3D sampling

acquisition time

How long does the acquisition actually take?

What will be the point cloud's sampling quality?

LIDAR density and spacing specification
(ASPRS Version 1.0, Draft 2)

LDSS point spacing	LDSS point density
1-dimensional metric	2-dimensional metric
point-to-point distance	points in a given area
unit: meters (feet, yards, cm …)	unit: points per m^2 (ft^2, …)

LIDAR Guidelines and Base Specification → **Nominal Point Spacing (NPS)**
(U.S. Geological Survey, National Geospatial Program,Version 13)

spatial sampling frequency	point density
1-dimensional metric	2-dimensional metric
inverse of point spacing (1/NPS)	average points in a given area
unit: points per meters (feet, yards, …)	unit: points per m^2 (ft^2, …)

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LIDAR density and spacing specification
(ASPRS Version 1.0, Draft 2)

Unbiased LiDAR Data Measurement (Draft)

Ty Naus, Fugro Horizons, Inc.

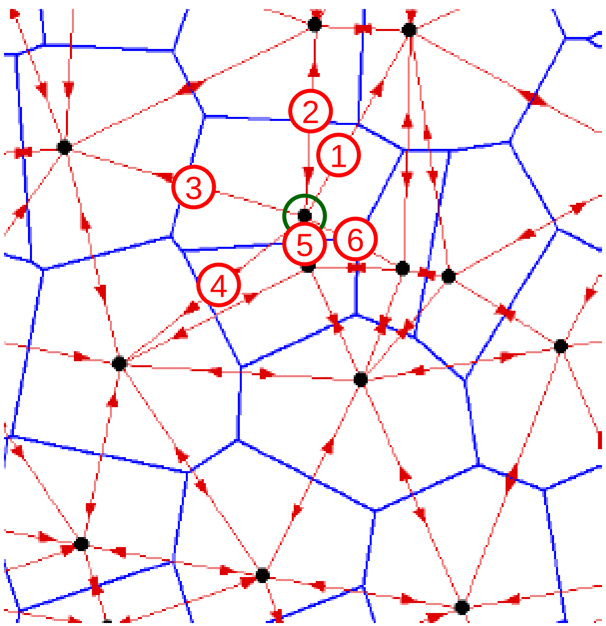
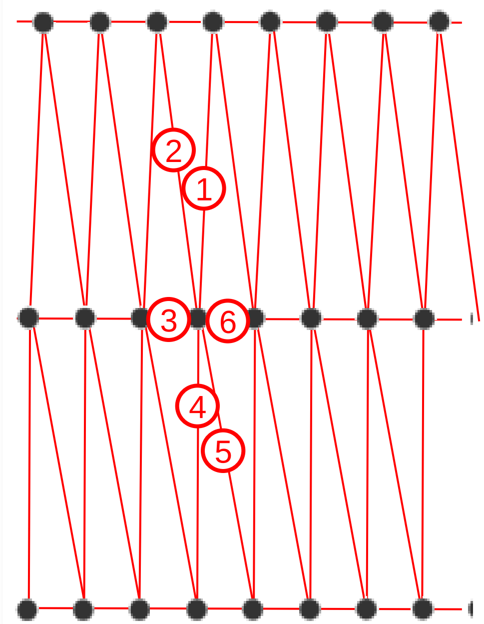


Figure 7b: Voronoi polygons shown in blue for actual LiDAR point distributions – the triangulation edges are shown in red.

$$d_{p-p} = \frac{1}{N}\sum_{i=1}^{N} d_i$$

average or maximum?

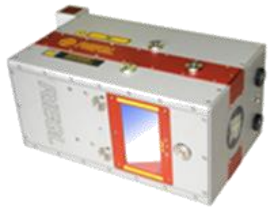


$$d_{p-p} = \max\left(d_i\right)$$

	Instrument A	Instrument B	Instrument C
scan mechanism	rotating polygon	oscillating mirror	oscillating mirror
number of channels	single channel	dual laser output	dual laser output
flight altitude, AGL [1]	50 m - 3500 m	150 m - 3500 m	150 m – 5000 m
laser pulse rate	100 kHz - 400 kHz	2 x 40 kHz – 2 x 250 kHz	2 x 50 kHz – 2 x 250 kHz
measurement rate	66 kHz - 266 kHz	80 kHz - 500 kHz	100 kHz - 500 kHz
pulses in the air	up to 12	2 x up to 2	not disclosed
field of view	0 deg - 60 deg	0 deg - 75 deg	0 deg - 75 deg
scan rate	10 LPS – 200 LPS	0 LPS- 2 x 200 LPS	0 LPS- 2 x 280 LPS

	Instrument A	Instrument A2
scan mechanism	rotating polygon	rotating polygon
number of channels	single channel	dual channel
flight altitude, AGL [1)]	50 m - 3500 m	50 m – 3500 m
laser pulse rate	100 kHz - 400 kHz	2 x 100 kHz – 2 x 400 kHz
measurement rate	66 kHz - 266 kHz	123 kHz – 532 kHz
pulses in the air	up to 12	2 x up to 12
field of view	0 deg - 60 deg	0 deg – 60 deg
scan rate	10 LPS – 200 LPS	2 x 10 LPS- 2 x 200 LPS

Instrument A
***RIEGL* LMS-Q780**



Instrument A2
***RIEGL* LMS-Q1560**

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instrument A

instrument A2

instrument B

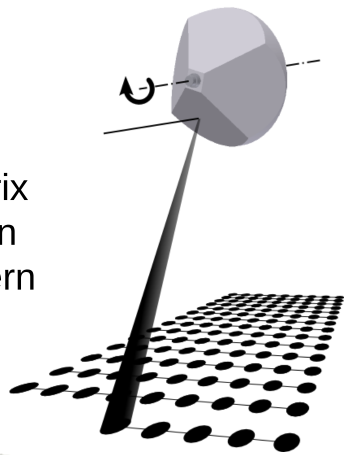
instrument C

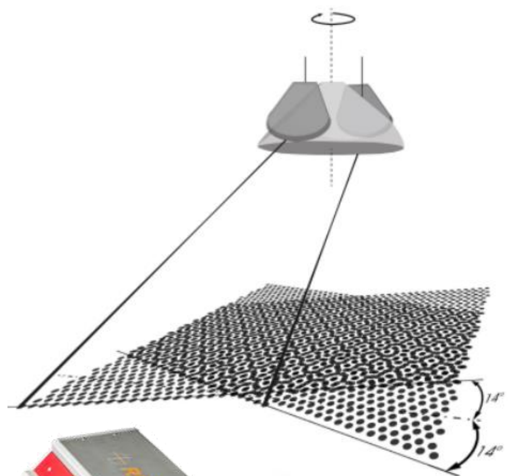
rotating polygon,
single channel

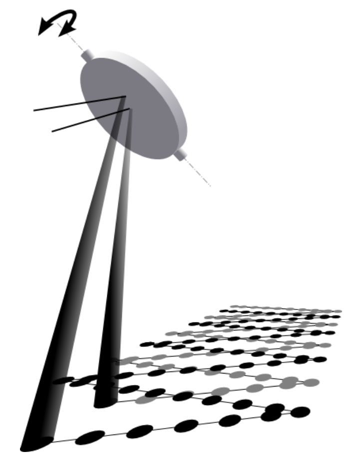
rotating polygon,
dual channel

oscillating mirror,
dual laser output

matrix
scan
pattern







RIEGL **LMS-Q780**

RIEGL **LMS-Q1560**

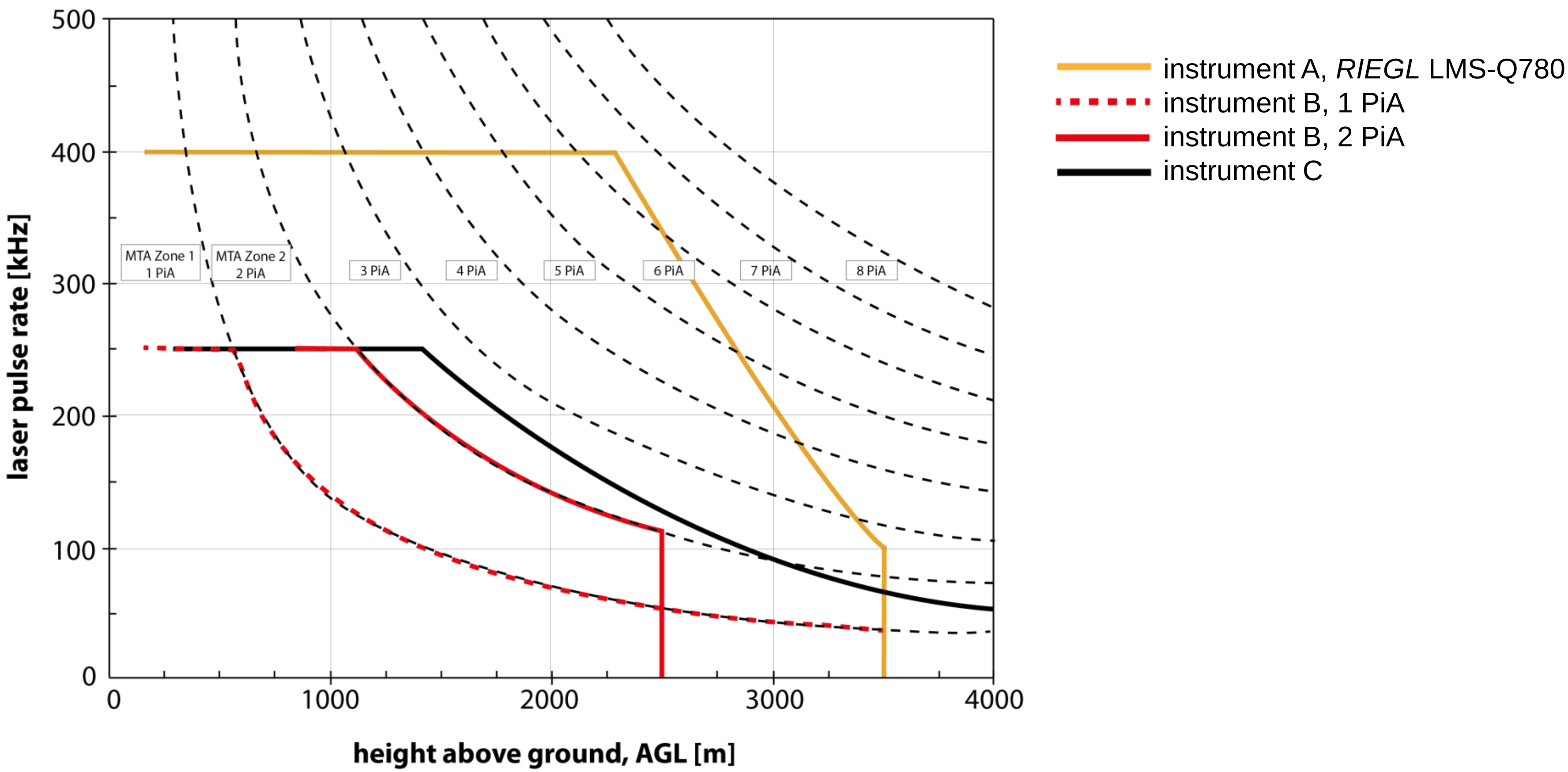
	Instrument A	Instrument B	Instrument C
scan mechanism	rotating polygon	oscillating mirror	oscillating mirror
number of channels	single channel	dual laser output	dual laser output
flight altitude, AGL [1)]	50 m - 3500 m	150 m - 3500 m	150 m – 5000 m
laser pulse rate	100 kHz - 400 kHz	2 x 40 kHz - 2 x 250 kHz	2 x 50 kHz - 2 x 250 kHz
measurement rate	66 kHz - 266 kHz	80 kHz - 500 kHz	100 kHz - 500 kHz
pulses in the air	up to 12	2 x up to 2	not disclosed
field of view	0 deg - 60 deg	0 deg - 75 deg	0 deg - 75 deg
scan rate	10 LPS – 200 LPS	0 LPS- 2 x 200 LPS	0 LPS- 2 x 280 LPS

performance envelope

scan speed vs FOV

[1)] 10% reflectance, 90% detection probability, 40 deg FOV, 23 km visibility

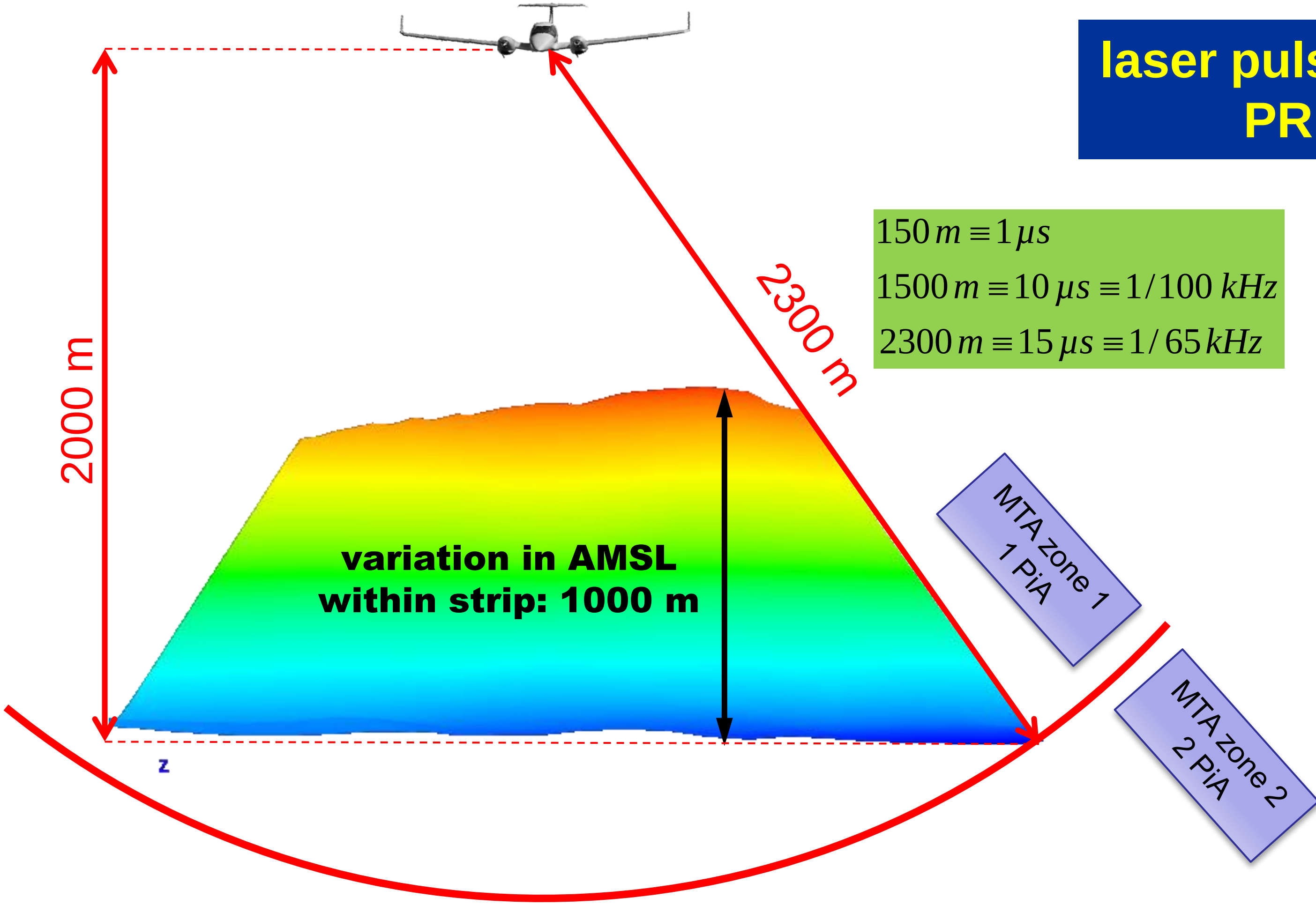
FOV .. field of view, AGL .. above ground level, LPS… lines per second

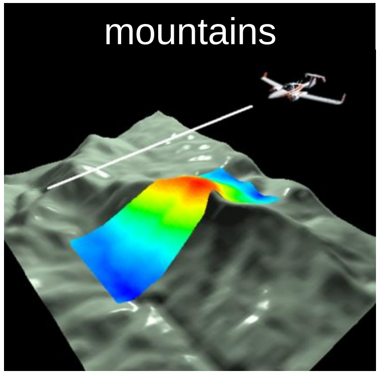


[1)] 10% reflectance, 90% detection probability, 40 deg FOV, 23 km visibility

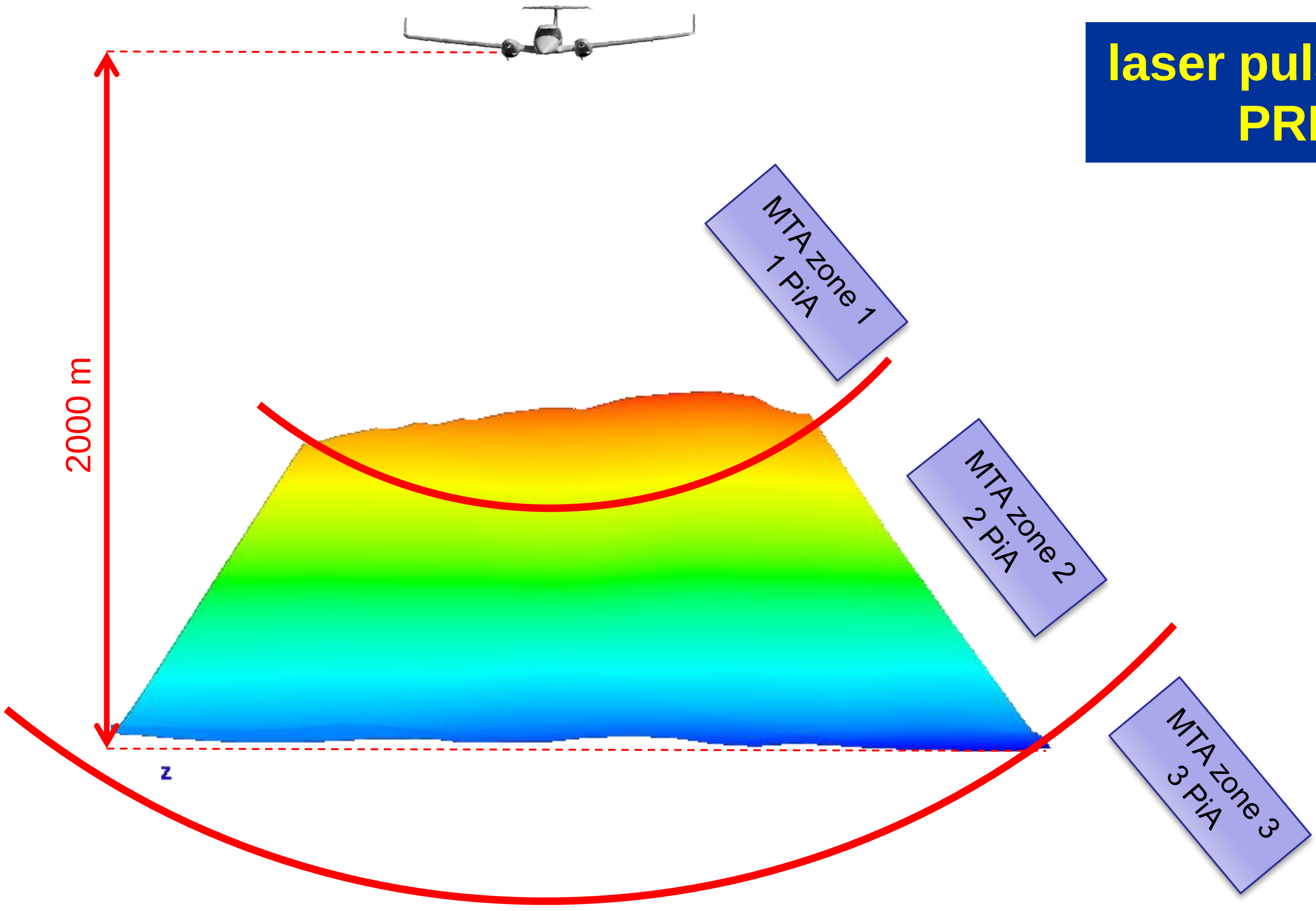
laser pulse repetition rate
PRR = 65 kHz

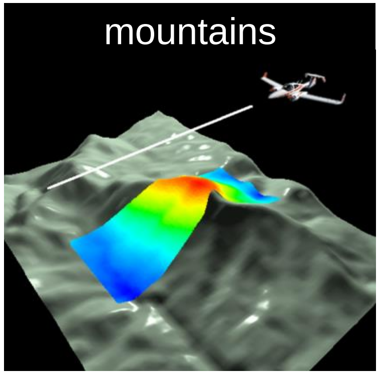
$$150\,m \equiv 1\,\mu s$$
$$1500\,m \equiv 10\,\mu s \equiv 1/100\,kHz$$
$$2300\,m \equiv 15\,\mu s \equiv 1/65\,kHz$$



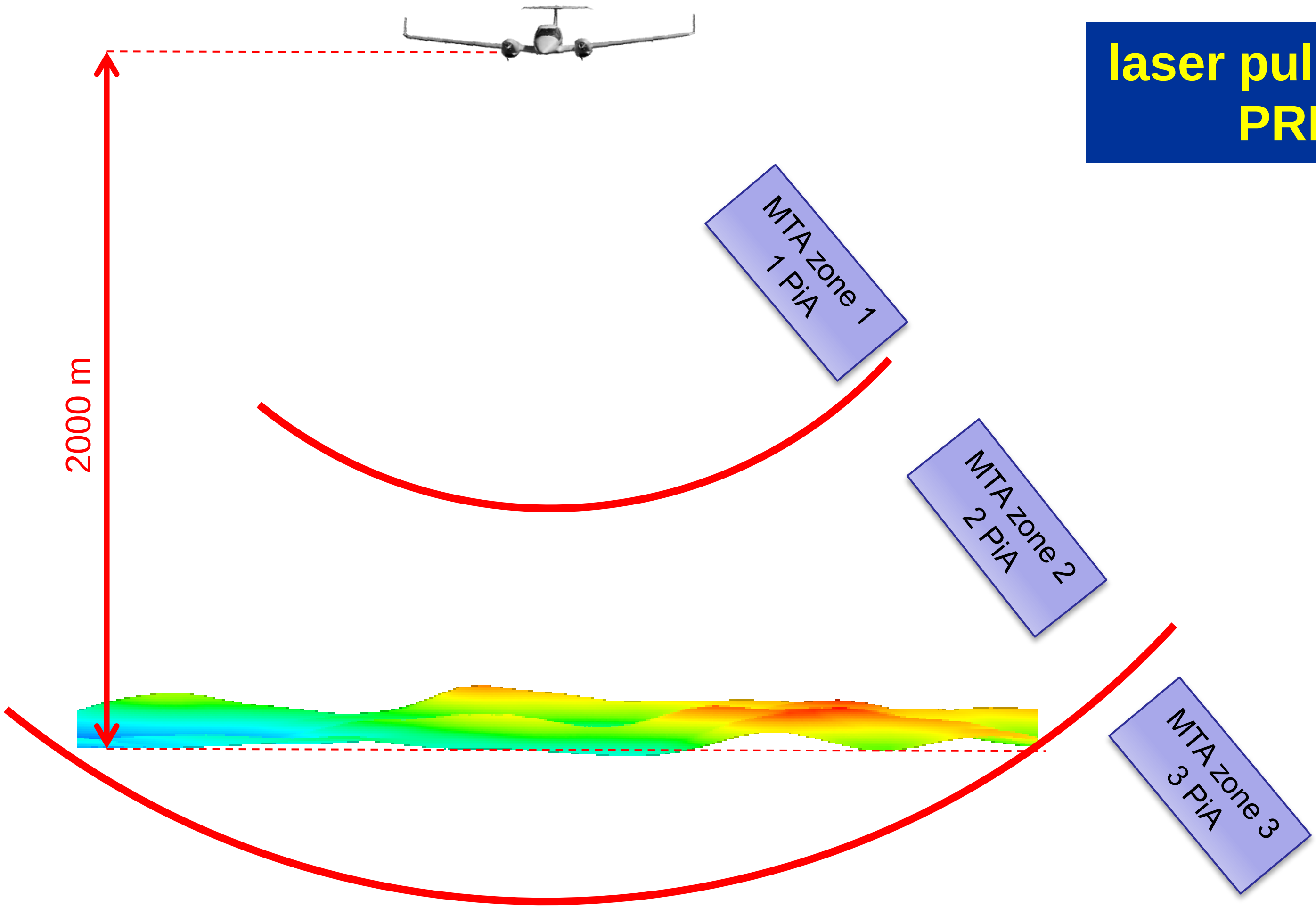


laser pulse repetition rate
PRR = 130 kHz

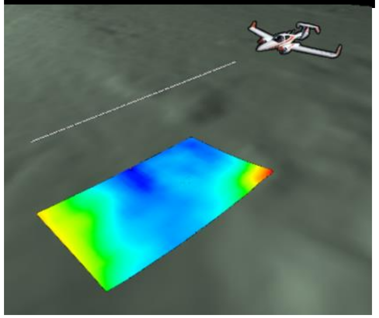


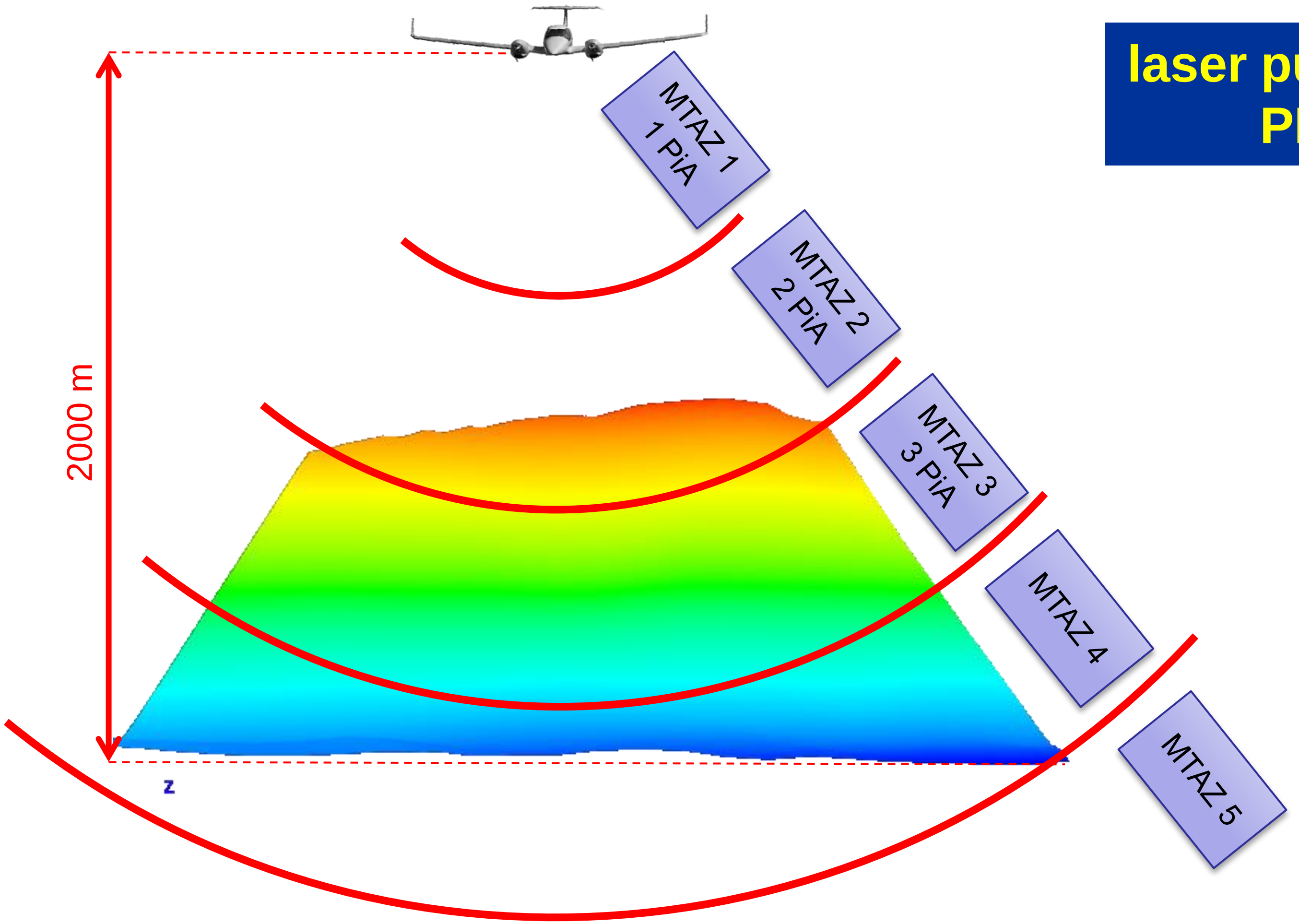


laser pulse repetition rate
PRR = 130 kHz

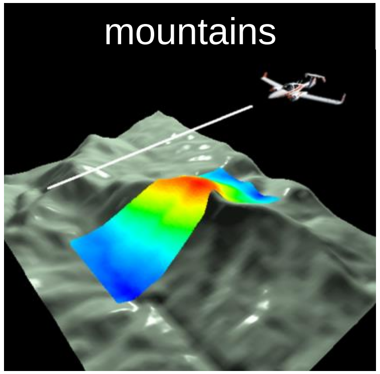


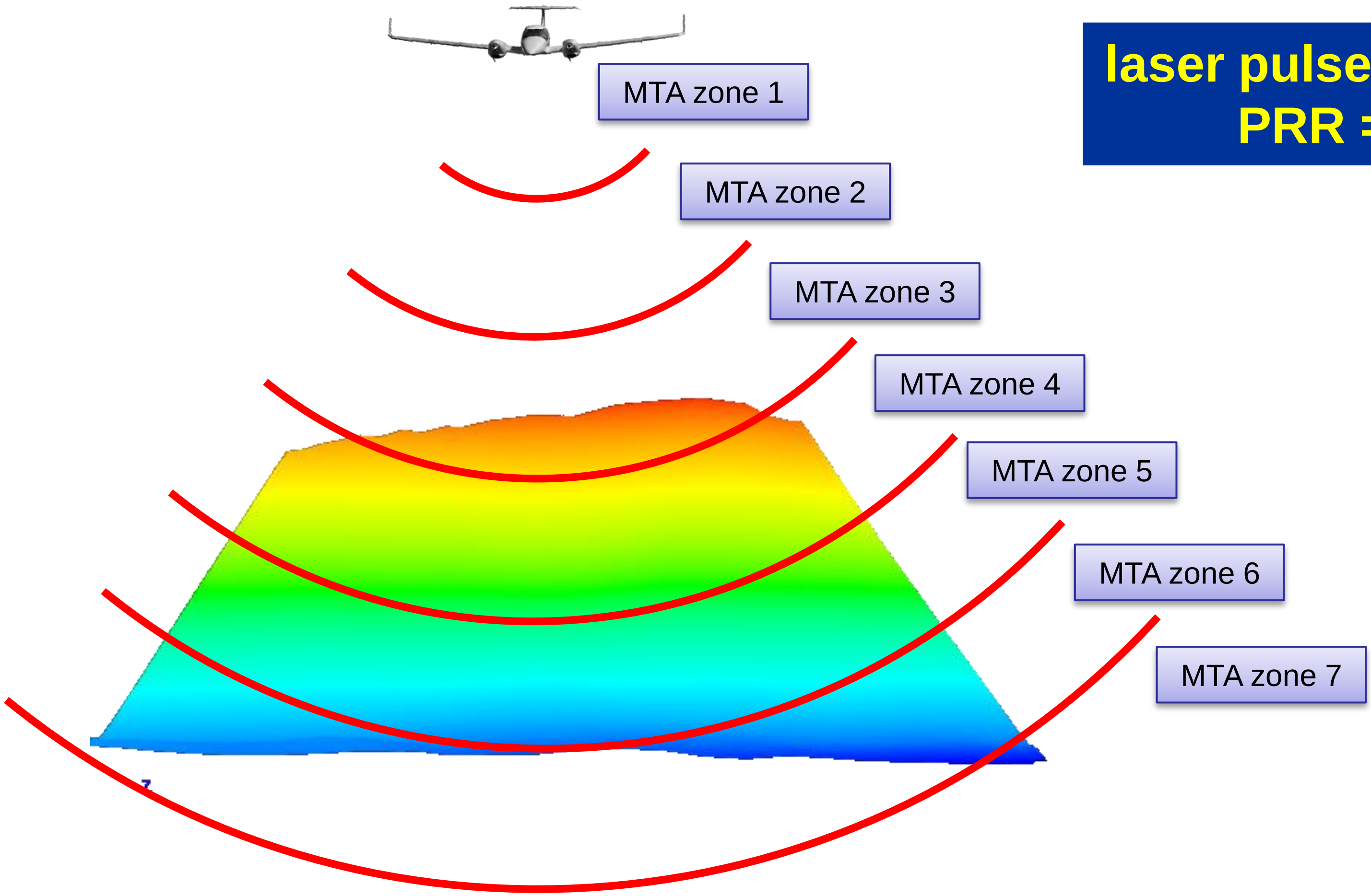
flat terrain



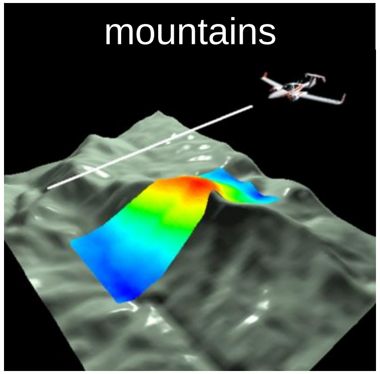


laser pulse repetition rate
PRR = 250 kHz





laser pulse repetition rate
PRR = 400 kHz



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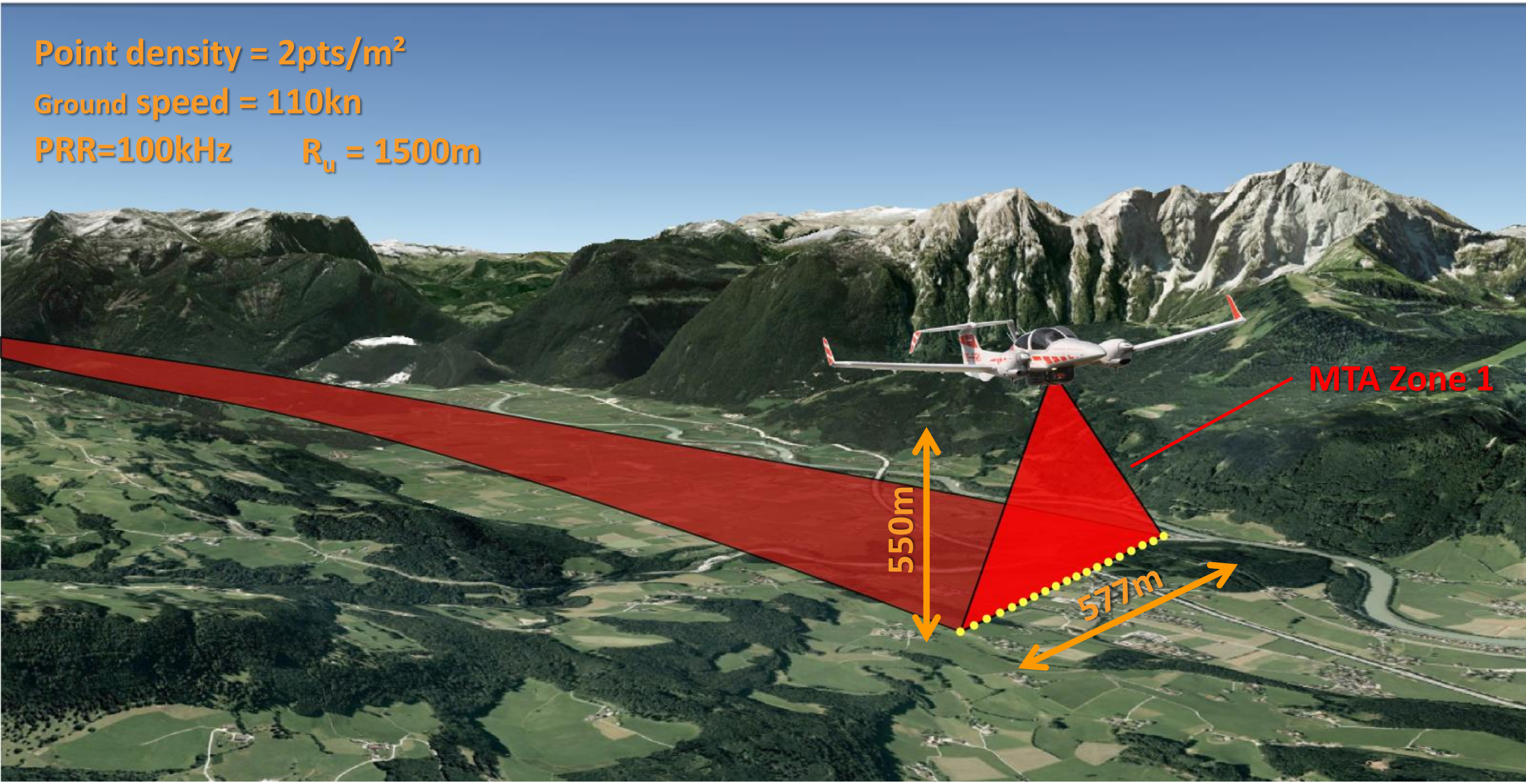
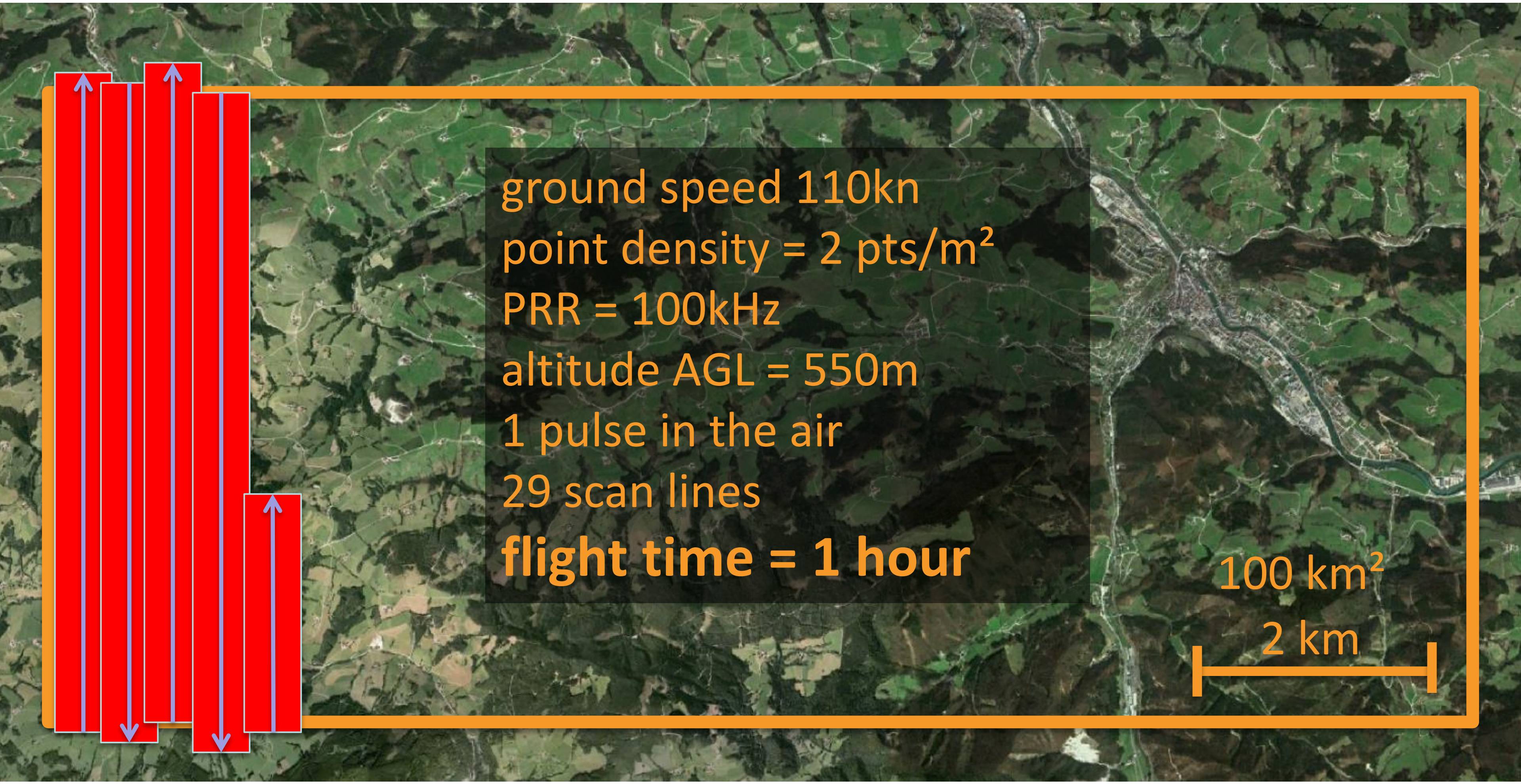
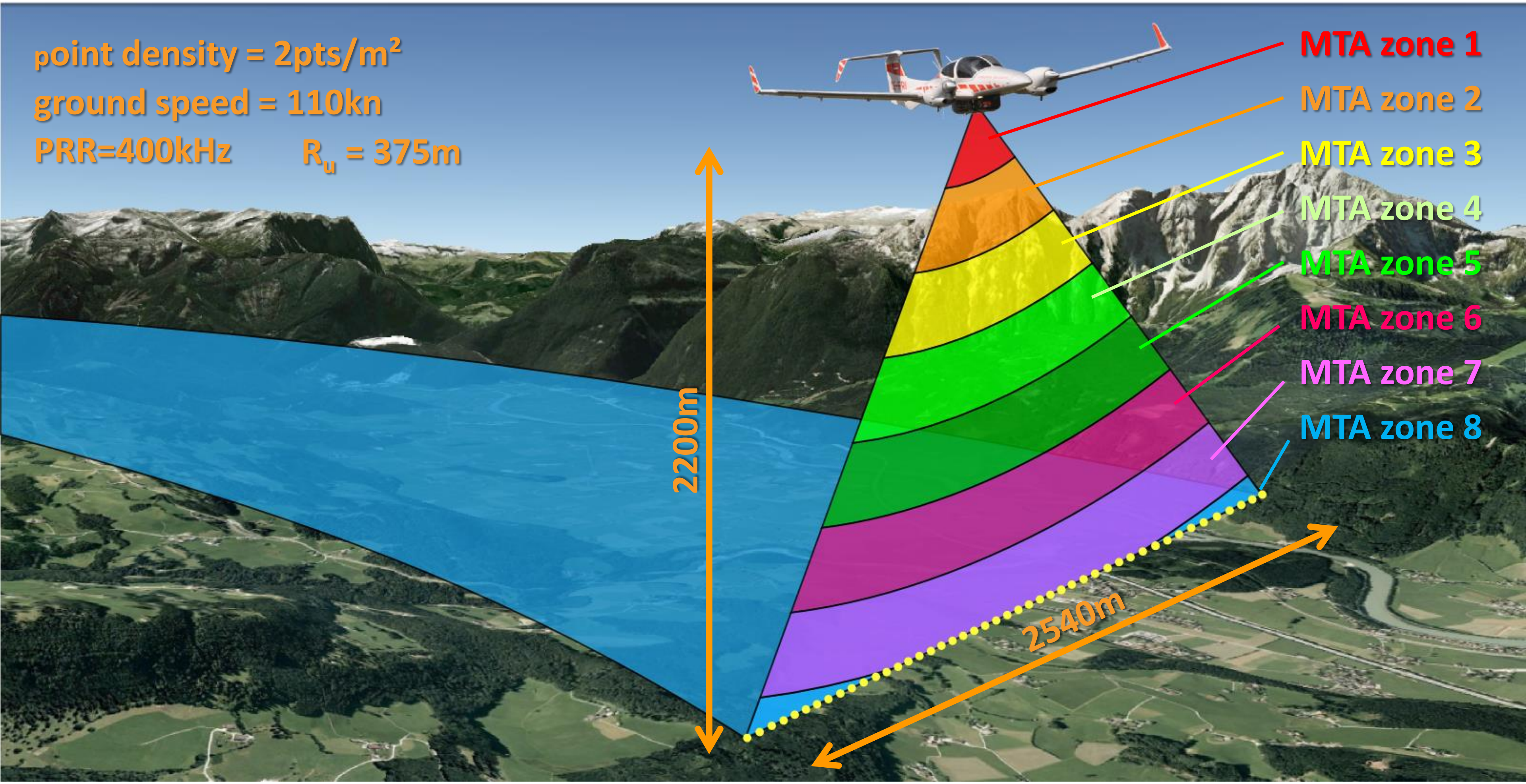


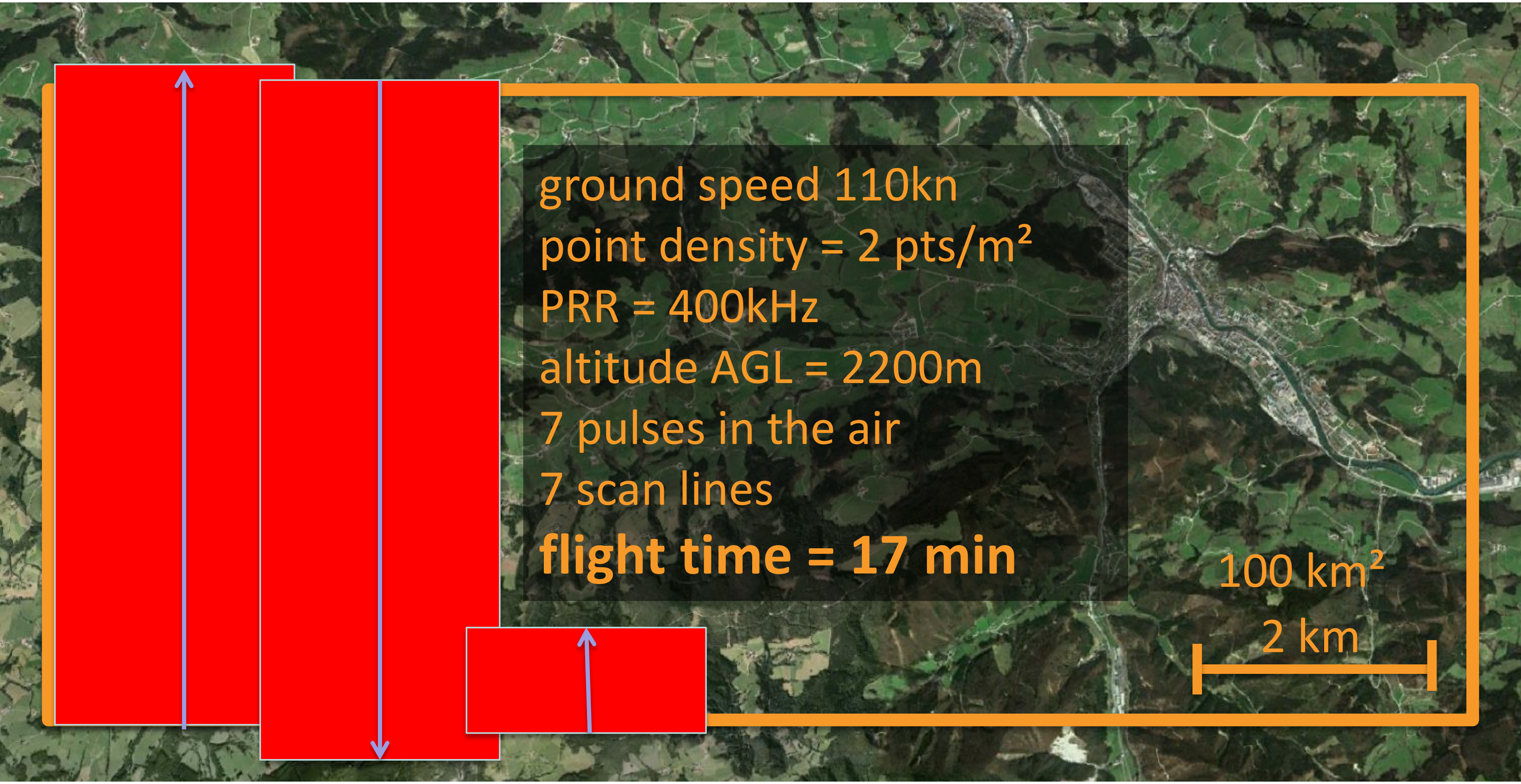
Single pulse in the air…

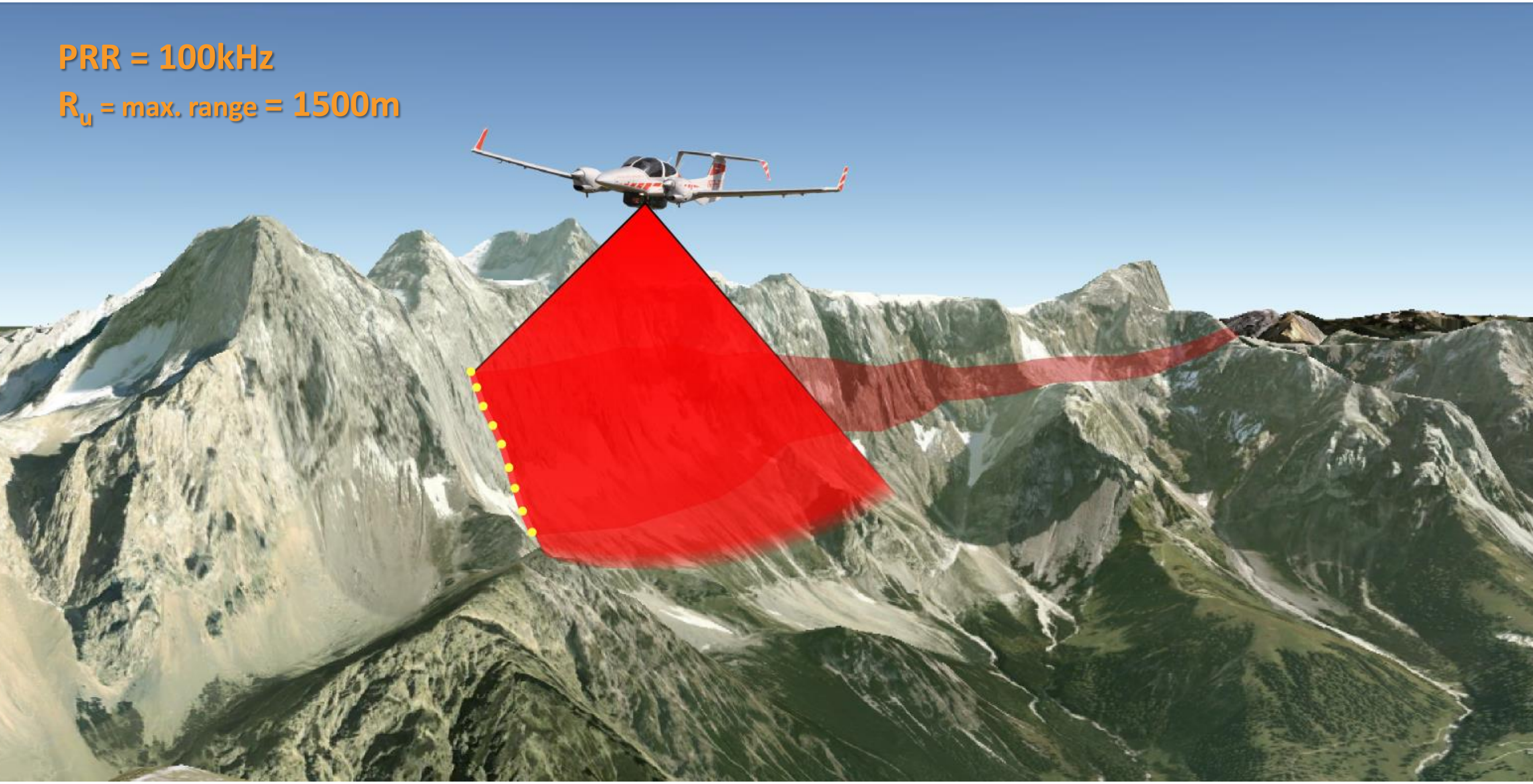


...long flights

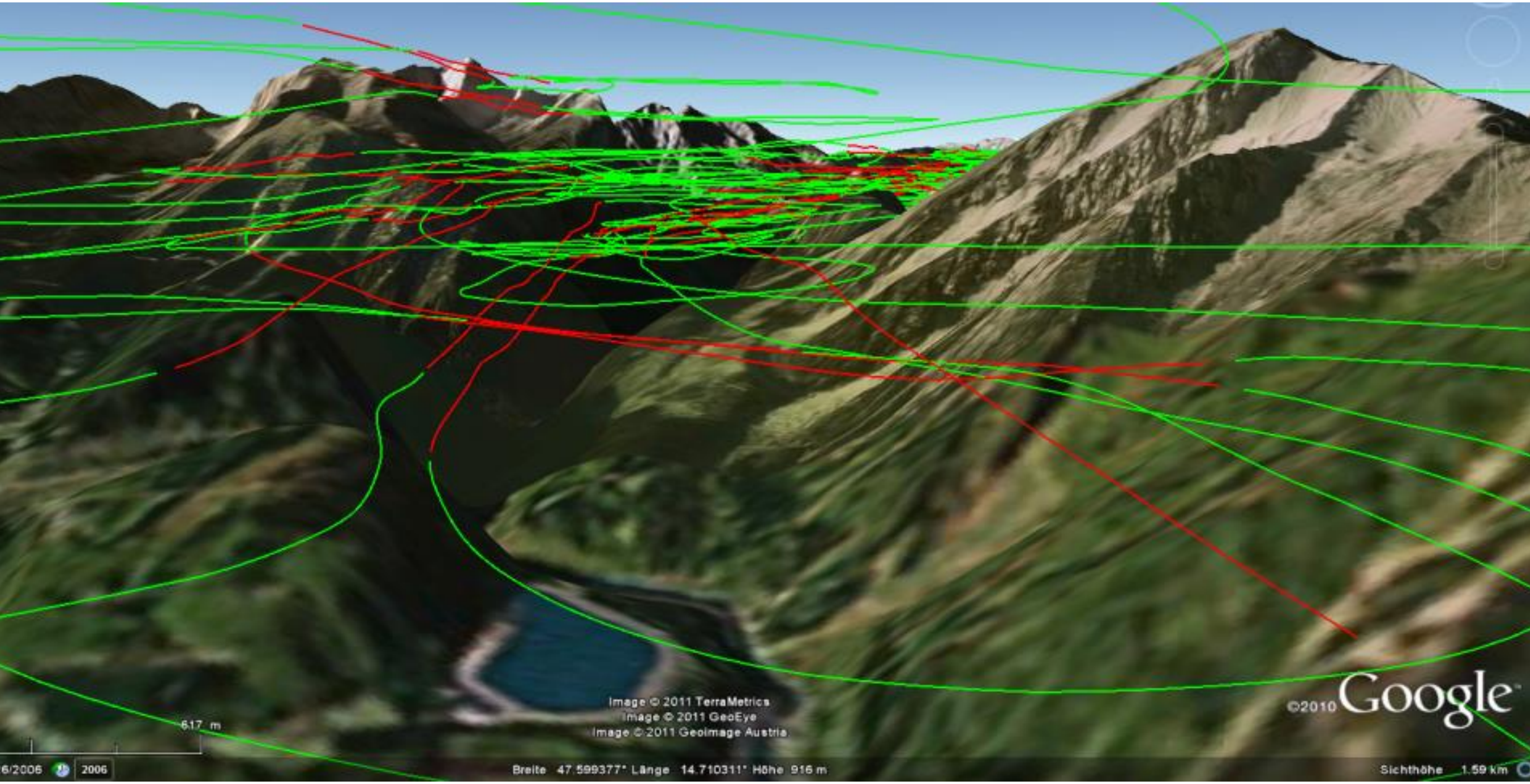


Multiple pulses in the air...

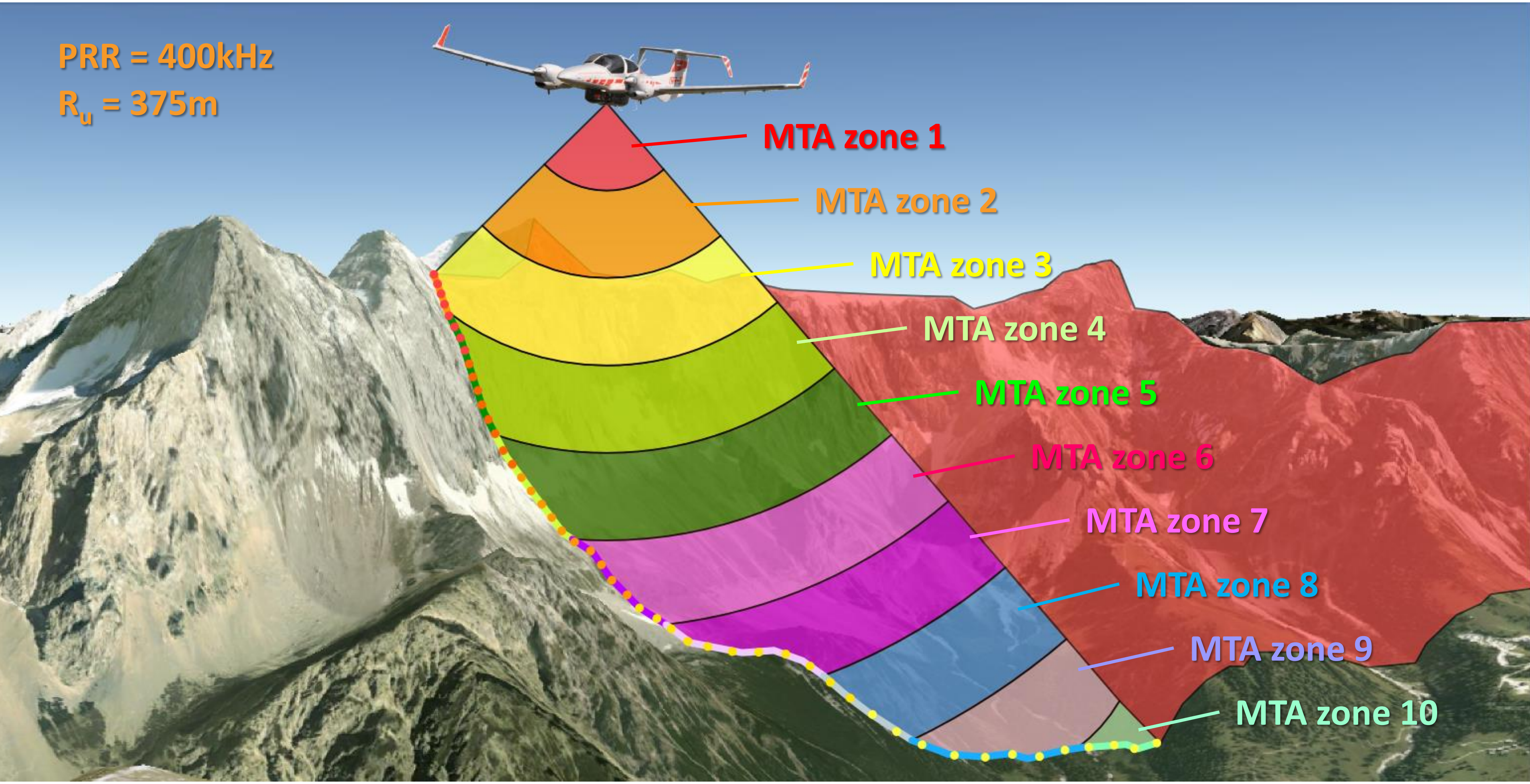

ground speed 110kn
point density = 2 pts/m²
PRR = 400kHz
altitude AGL = 2200m
7 pulses in the air
7 scan lines
flight time = 17 min
100 km²
2 km



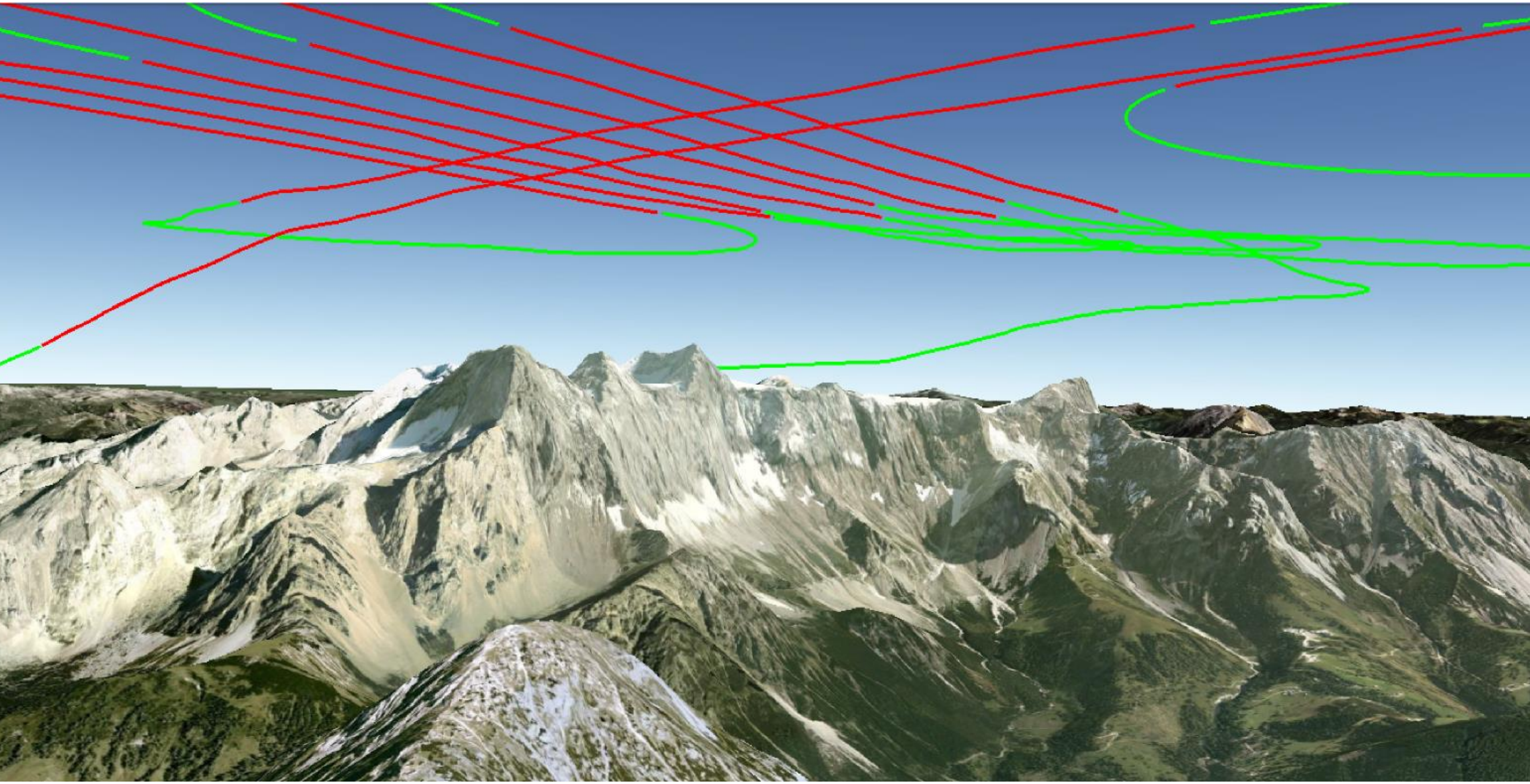
Single pulse in the air…



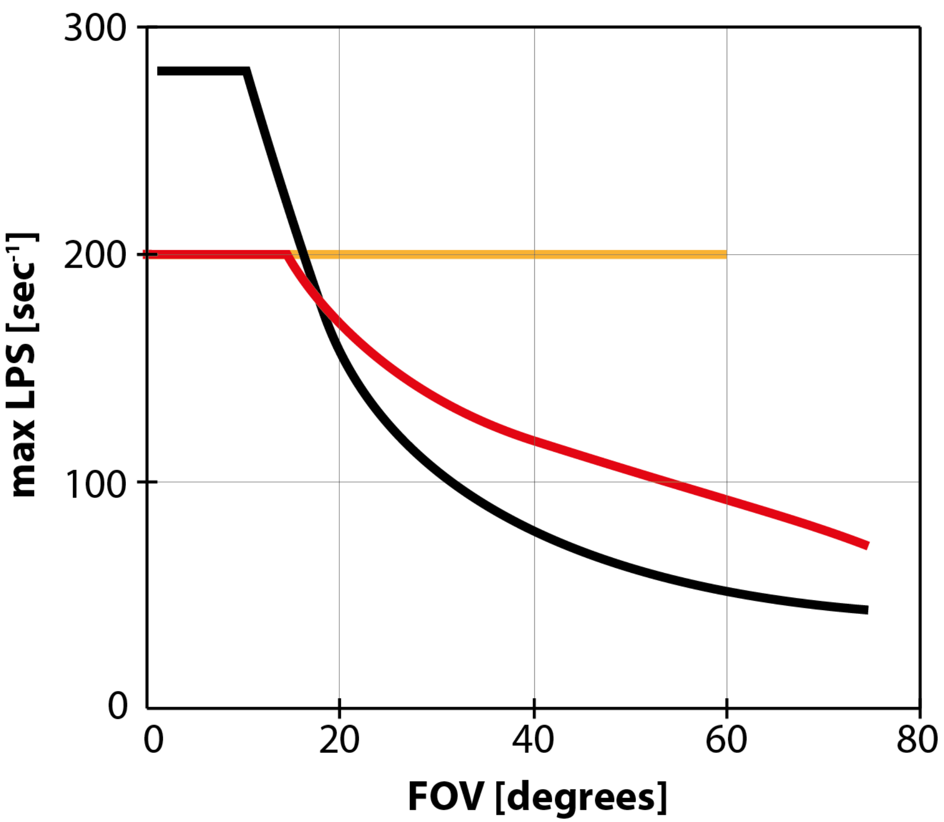
…difficult flights

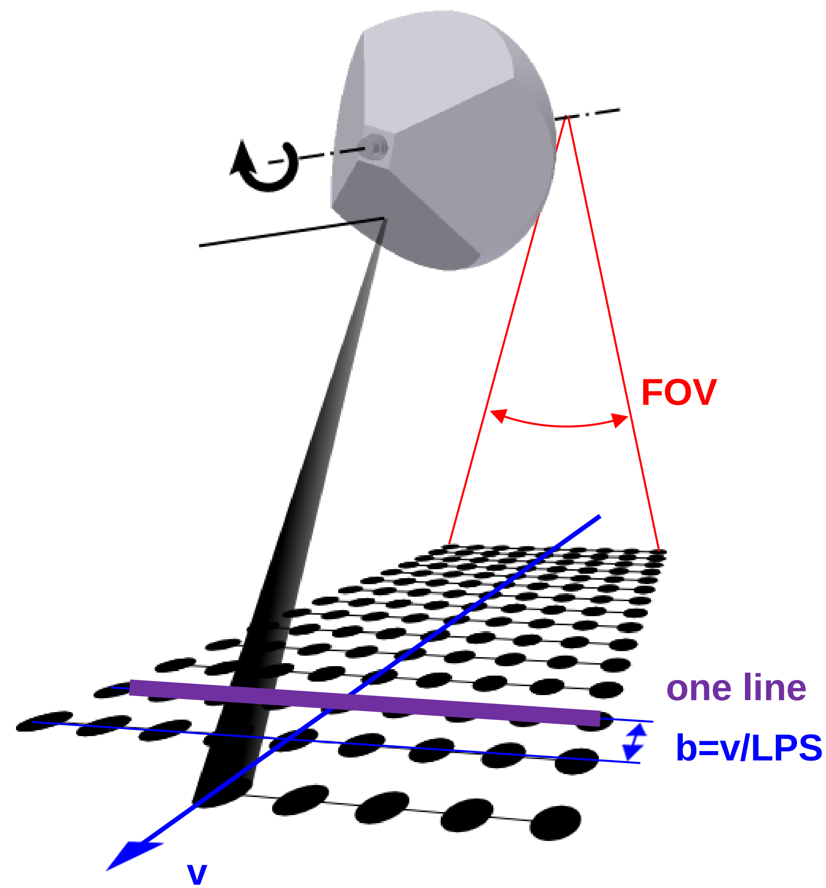


multiple pulses in the air



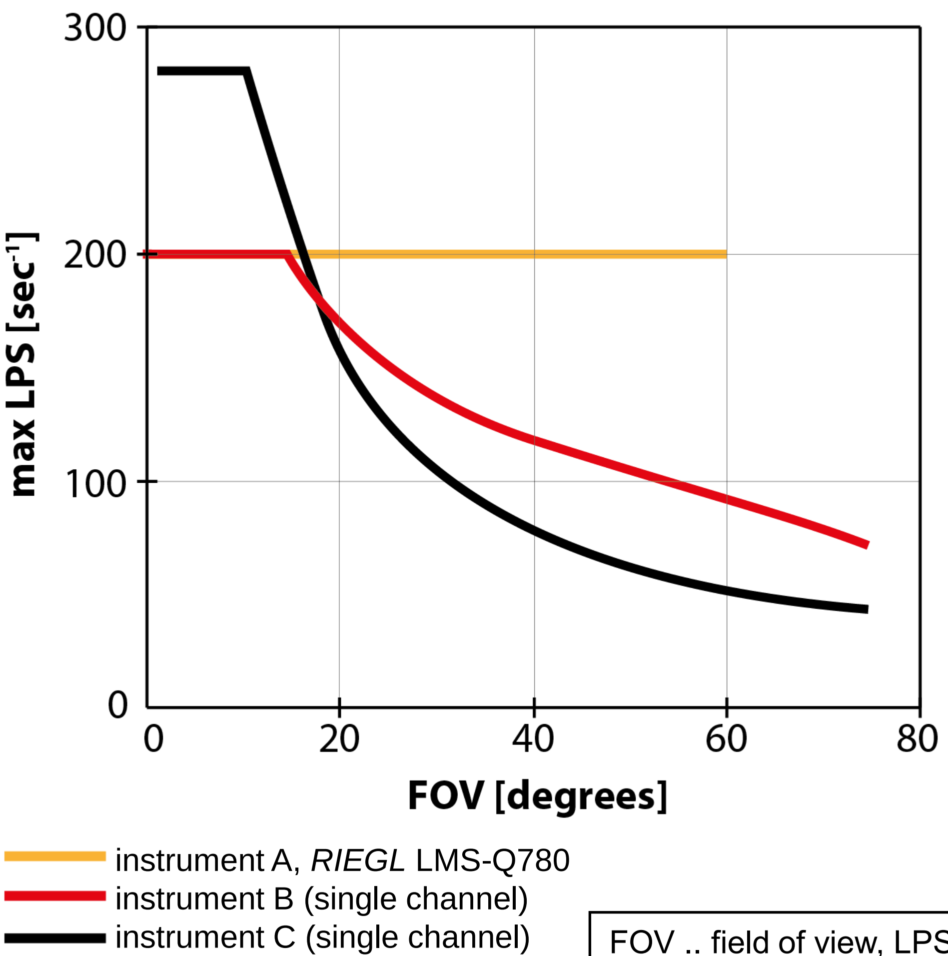
…safe flights

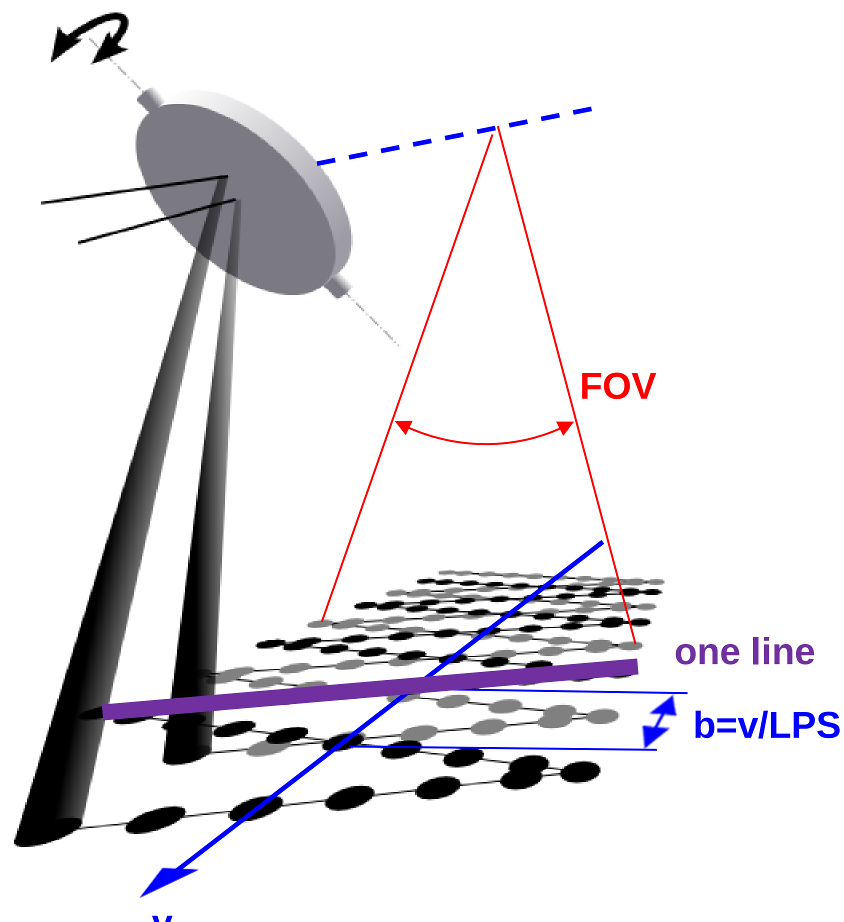




- instrument A, *RIEGL* LMS-Q780
- instrument B (single channel)
- instrument C (single channel)

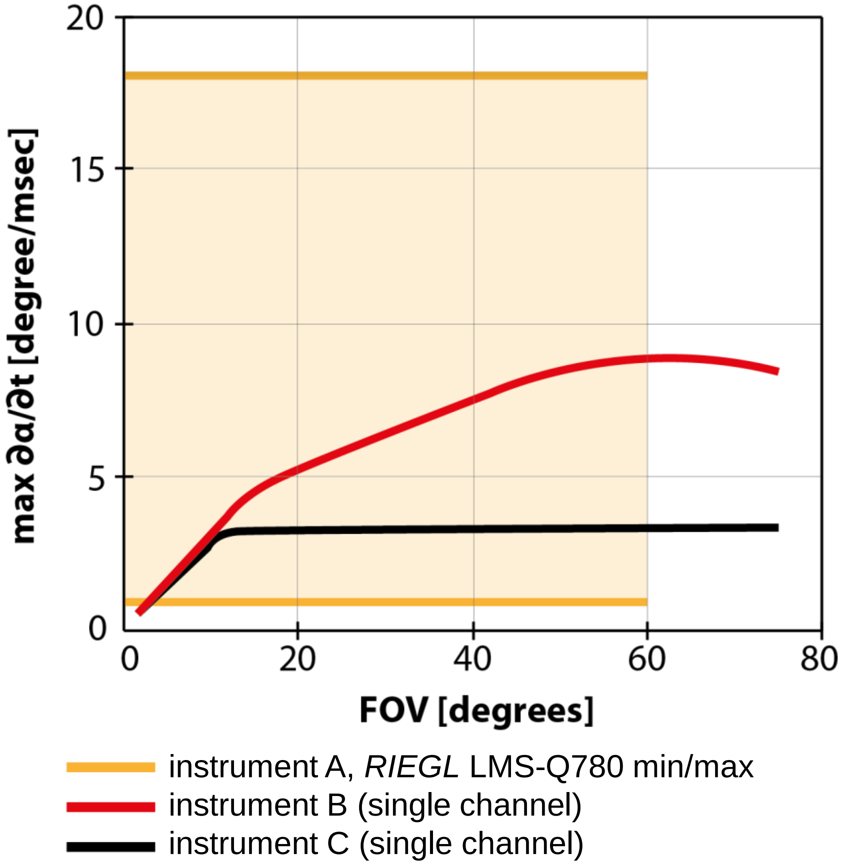
FOV .. field of view, LPS… lines per second, v .. speed over ground, b .. line spacing

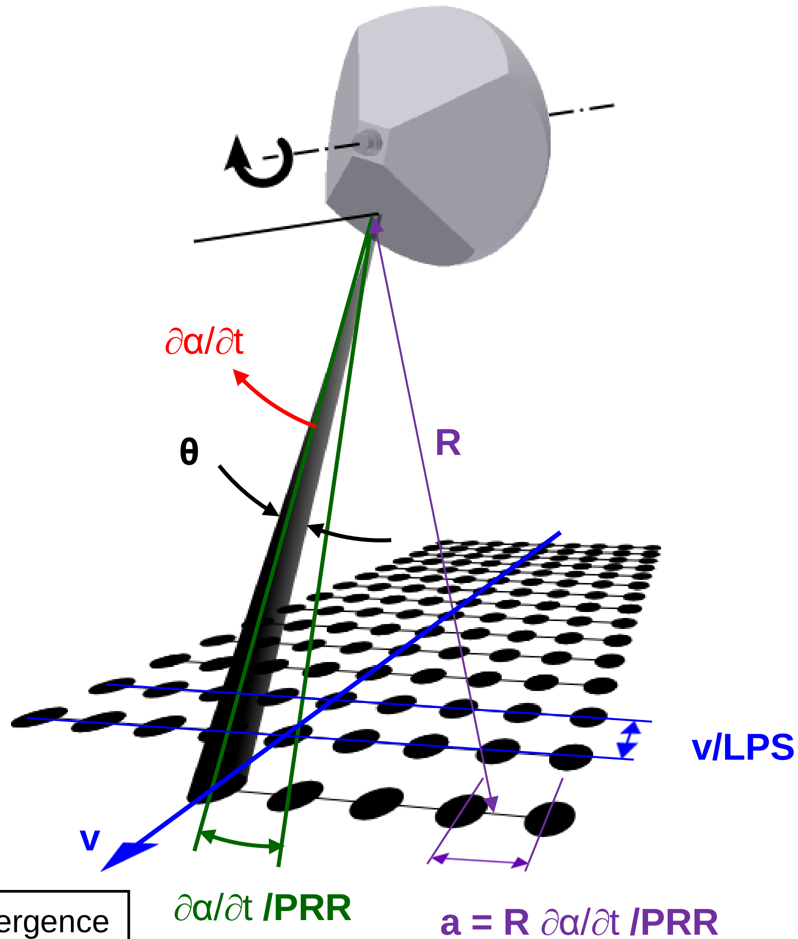




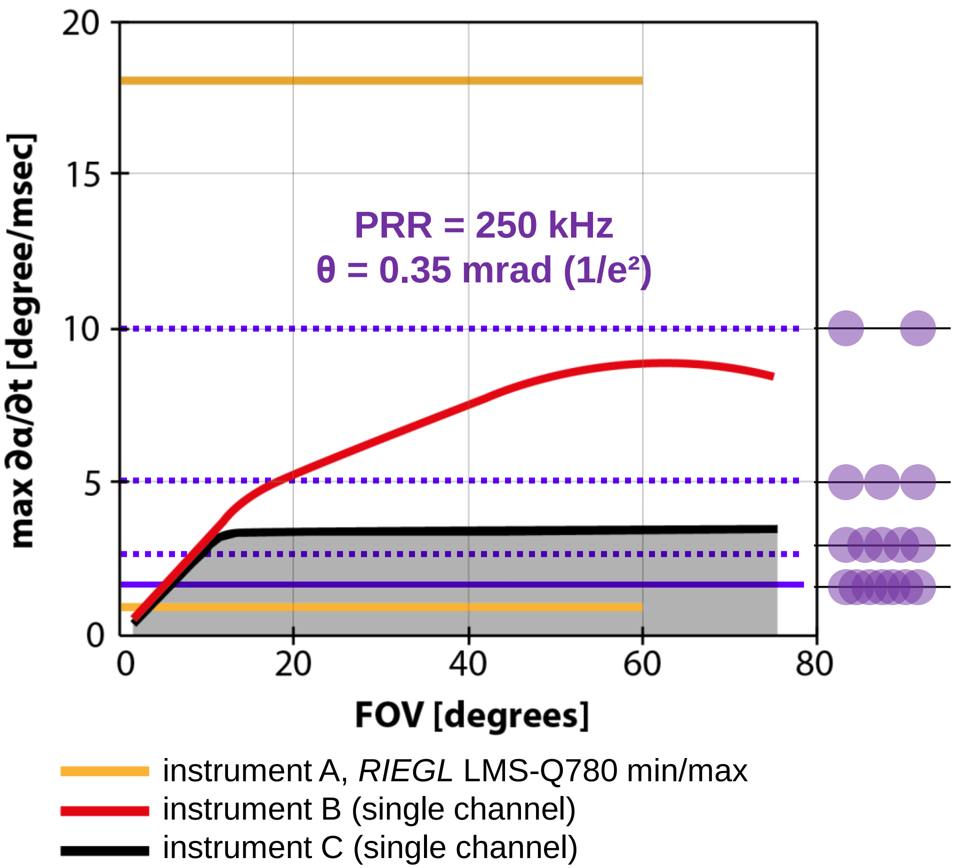
FOV .. field of view, LPS… lines per second, v .. speed over ground, b .. line spacing

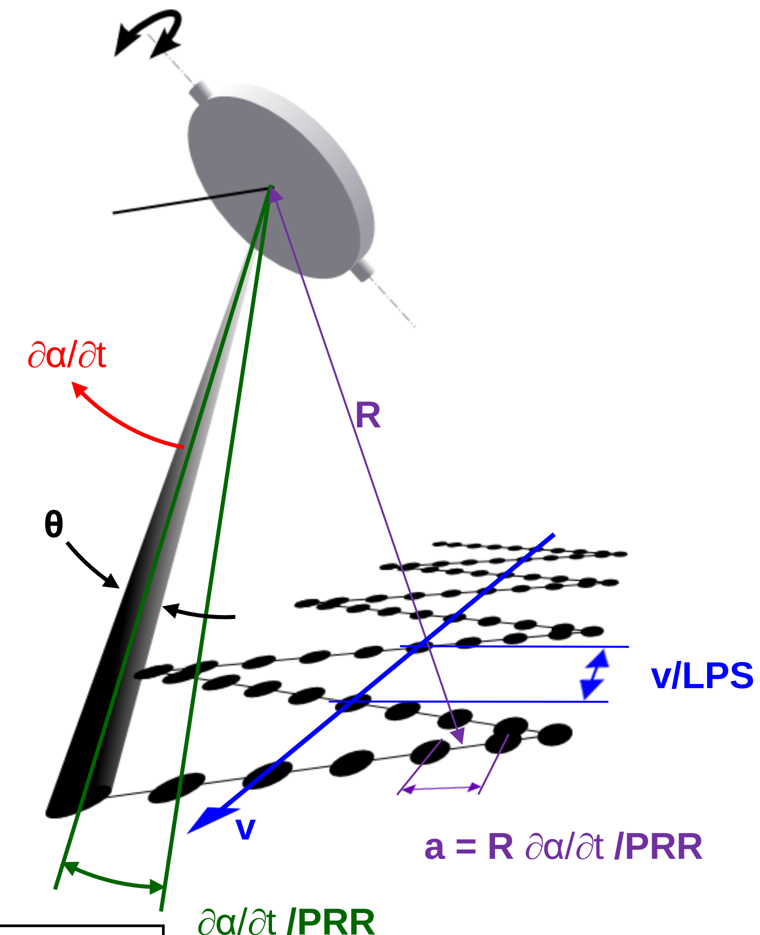
scan speed (lines per second) vs FOV



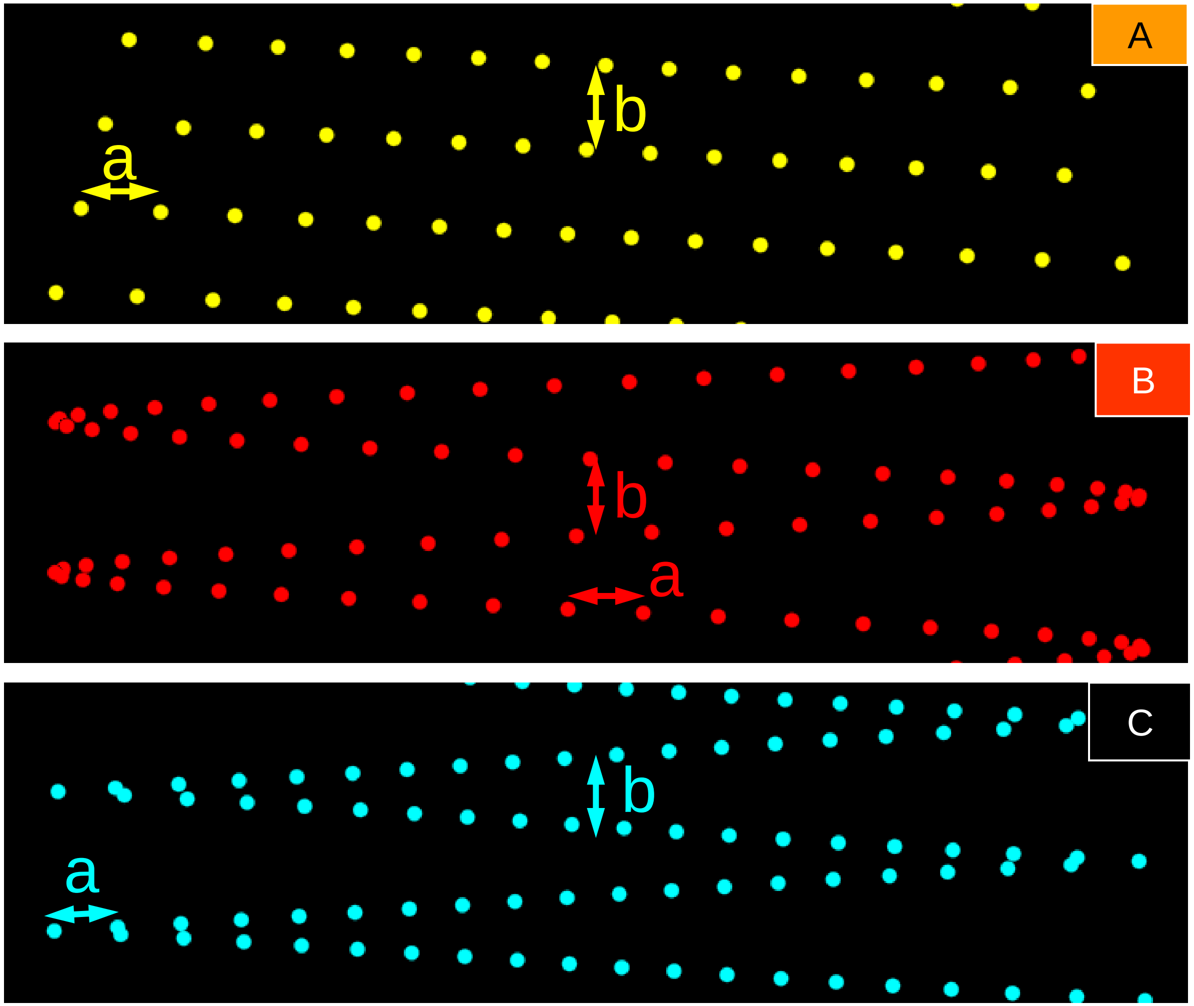


∂α/∂t… angular speed, PRR… laser pulse repetition rate, θ .. beam divergence





∂α/∂t… angular speed, PRR… laser pulse repetition rate, θ .. beam divergence

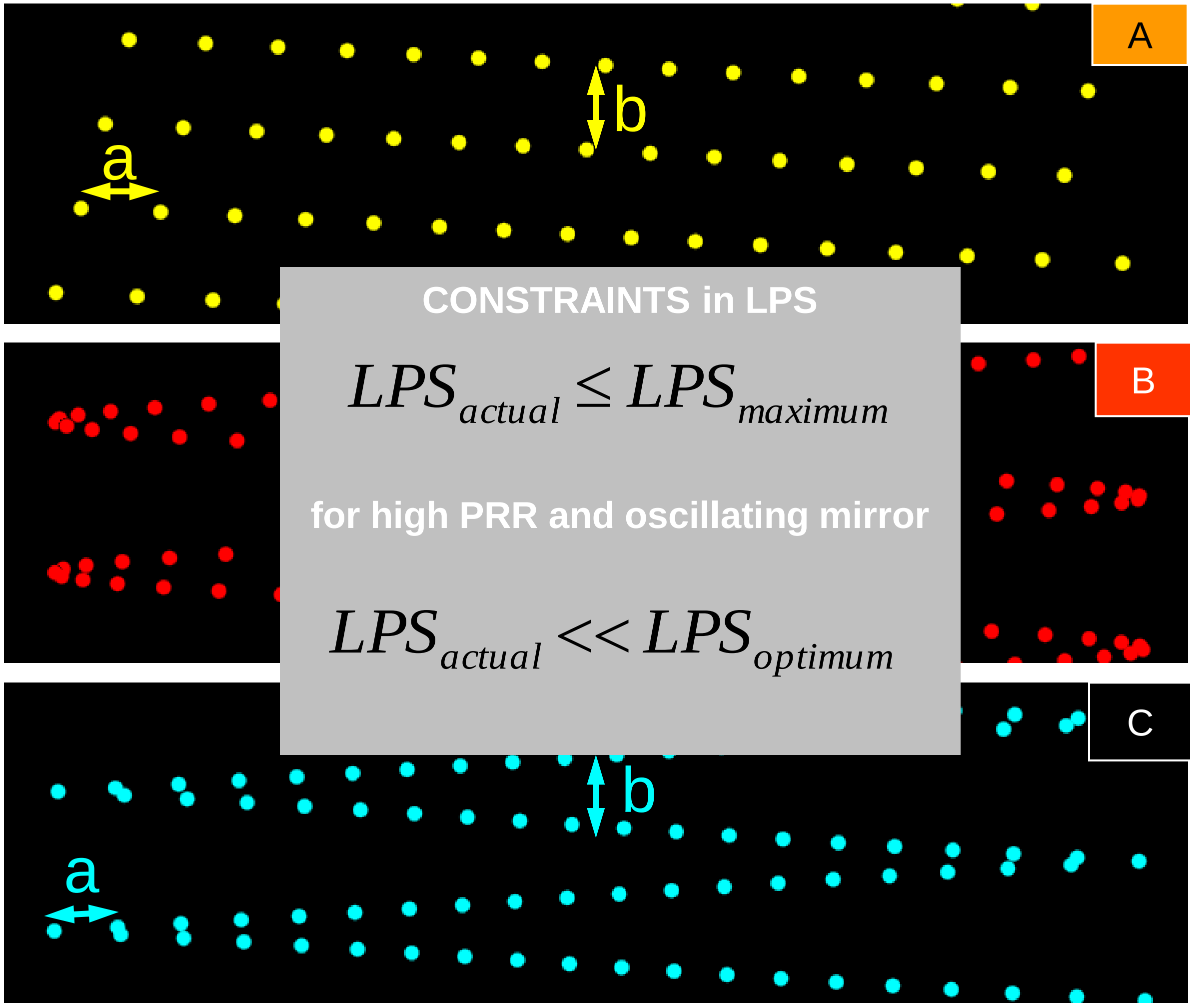


$$a = b \quad \Rightarrow$$

$$LPS_{optimum} = \cos\left(\frac{FOV}{2}\right)\sqrt{\frac{2}{\pi}}\sqrt{\frac{v.PRR}{AGL}}$$

$$LPS_{optimum} = \sqrt{\frac{2}{\pi.FOV}}\sqrt{\frac{v.PRR}{AGL}}$$

$$LPS_{optimum} = \cos\left(\frac{FOV}{2}\right)\sqrt{\frac{1}{FOV}}\sqrt{\frac{v.PRR}{AGL}}$$



CONSTRAINTS in LPS

$$LPS_{actual} \leq LPS_{maximum}$$

for high PRR and oscillating mirror

$$LPS_{actual} << LPS_{optimum}$$

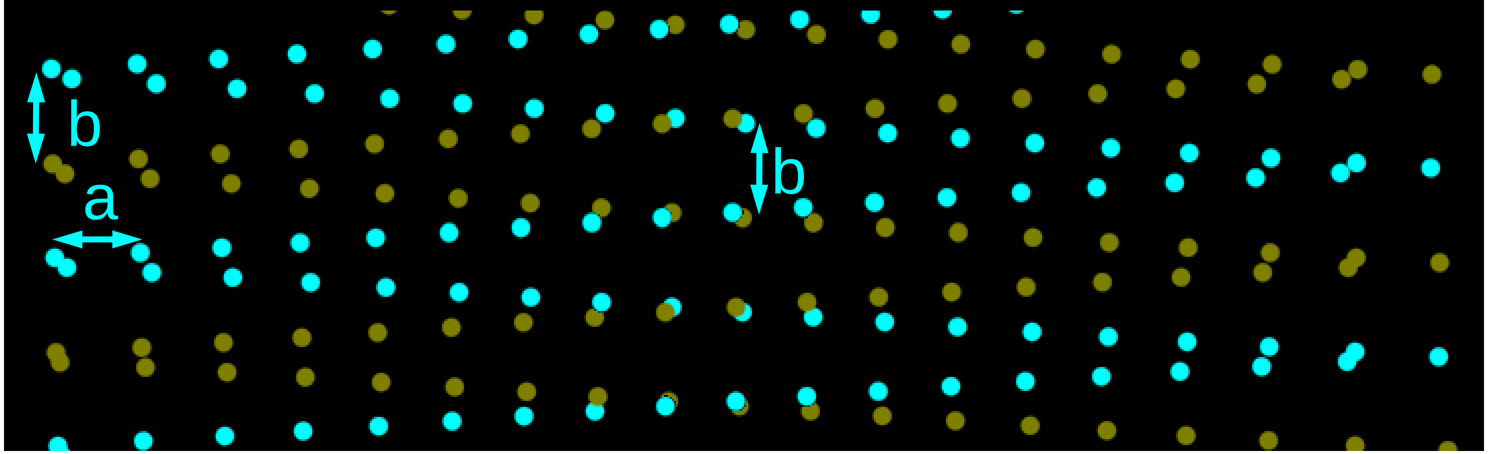
$$a = b \quad \Rightarrow$$

$$LPS_{optimum} = \cos\left(\frac{FOV}{2}\right)\sqrt{\frac{2}{\pi}}\sqrt{\frac{v.PRR}{AGL}}$$

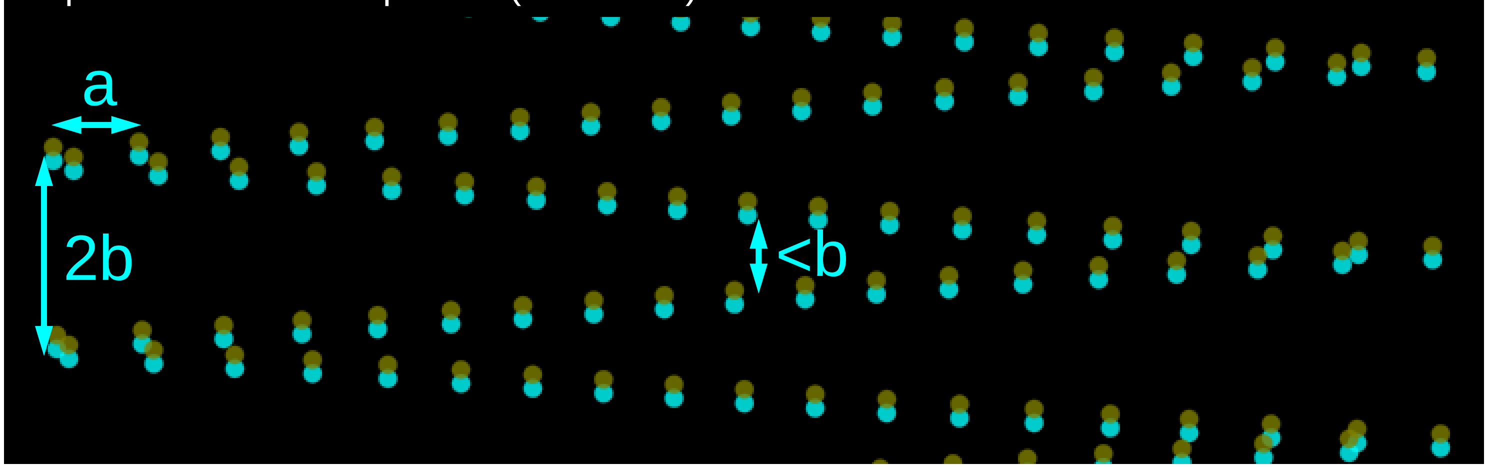
$$LPS_{optimum} = \sqrt{\frac{2}{\pi.FOV}}\sqrt{\frac{v.PRR}{AGL}}$$

$$LPS_{optimum} = \cos\left(\frac{FOV}{2}\right)\sqrt{\frac{1}{FOV}}\sqrt{\frac{v.PRR}{AGL}}$$

out-of-phase interference pattern (desired)



in-phase interference pattern (undesired)

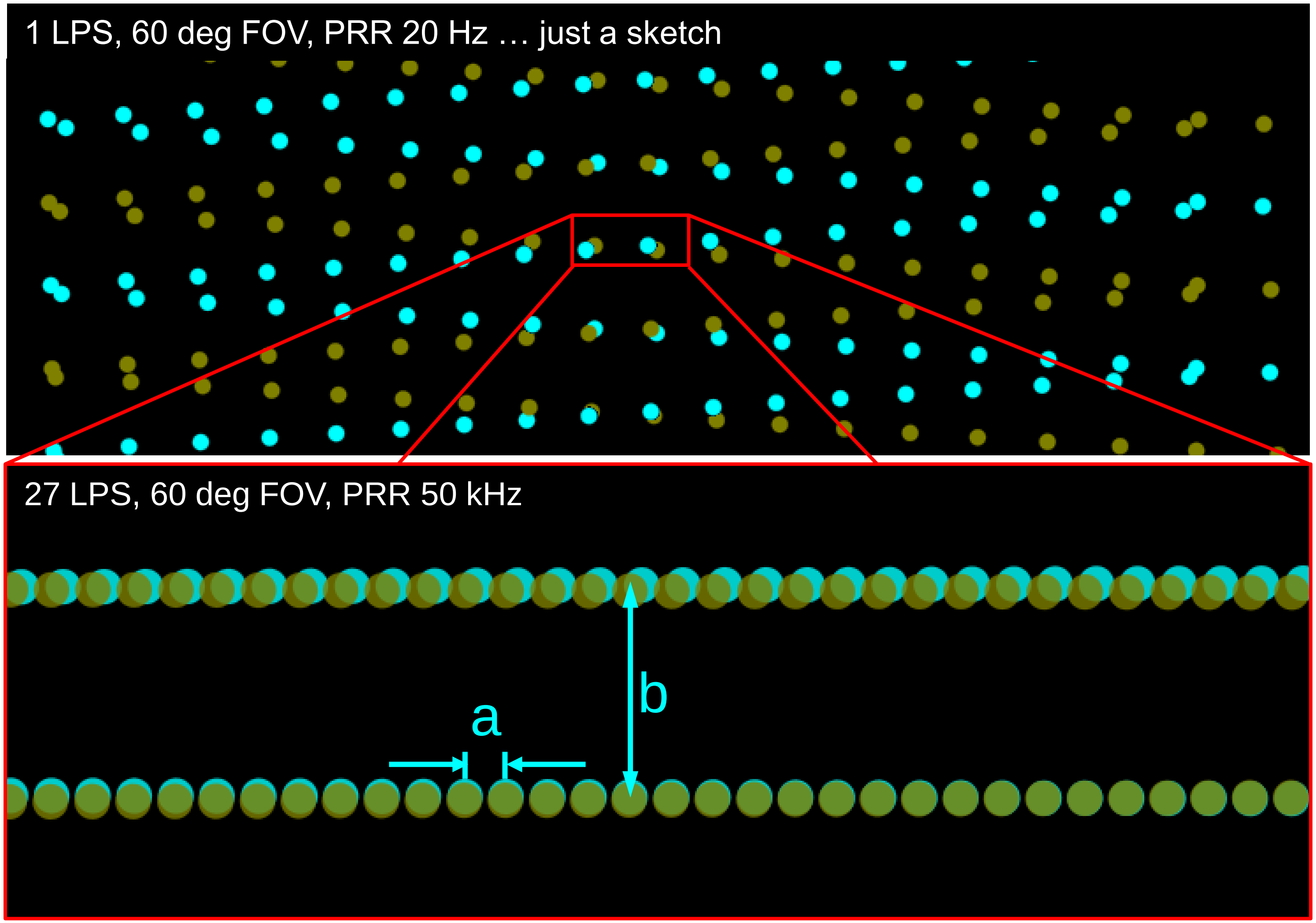


phase depends on
- speed
- AGL
- LPS

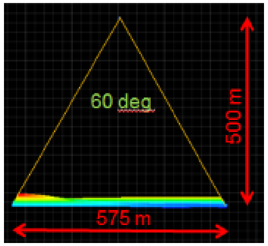
in any case:

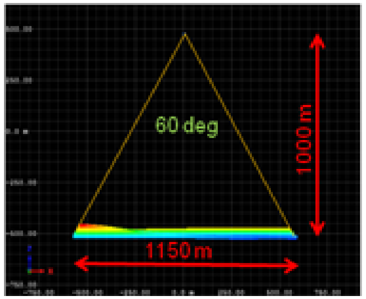
2x “point density”

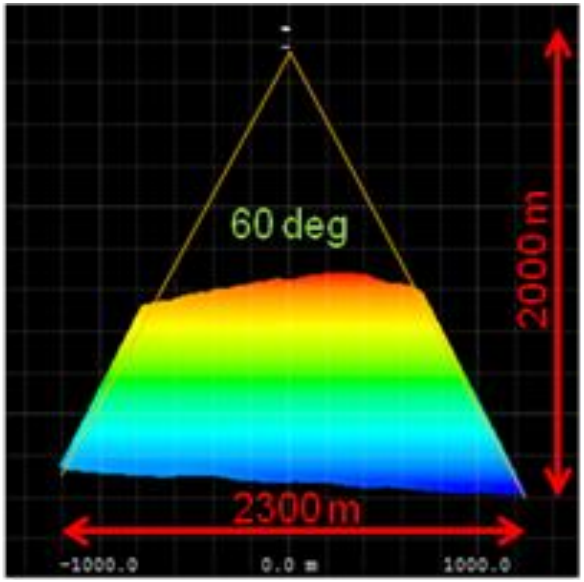
but:
“point spacing” ?


1 LPS, 60 deg FOV, PRR 20 Hz … just a sketch
27 LPS, 60 deg FOV, PRR 50 kHz
a
b

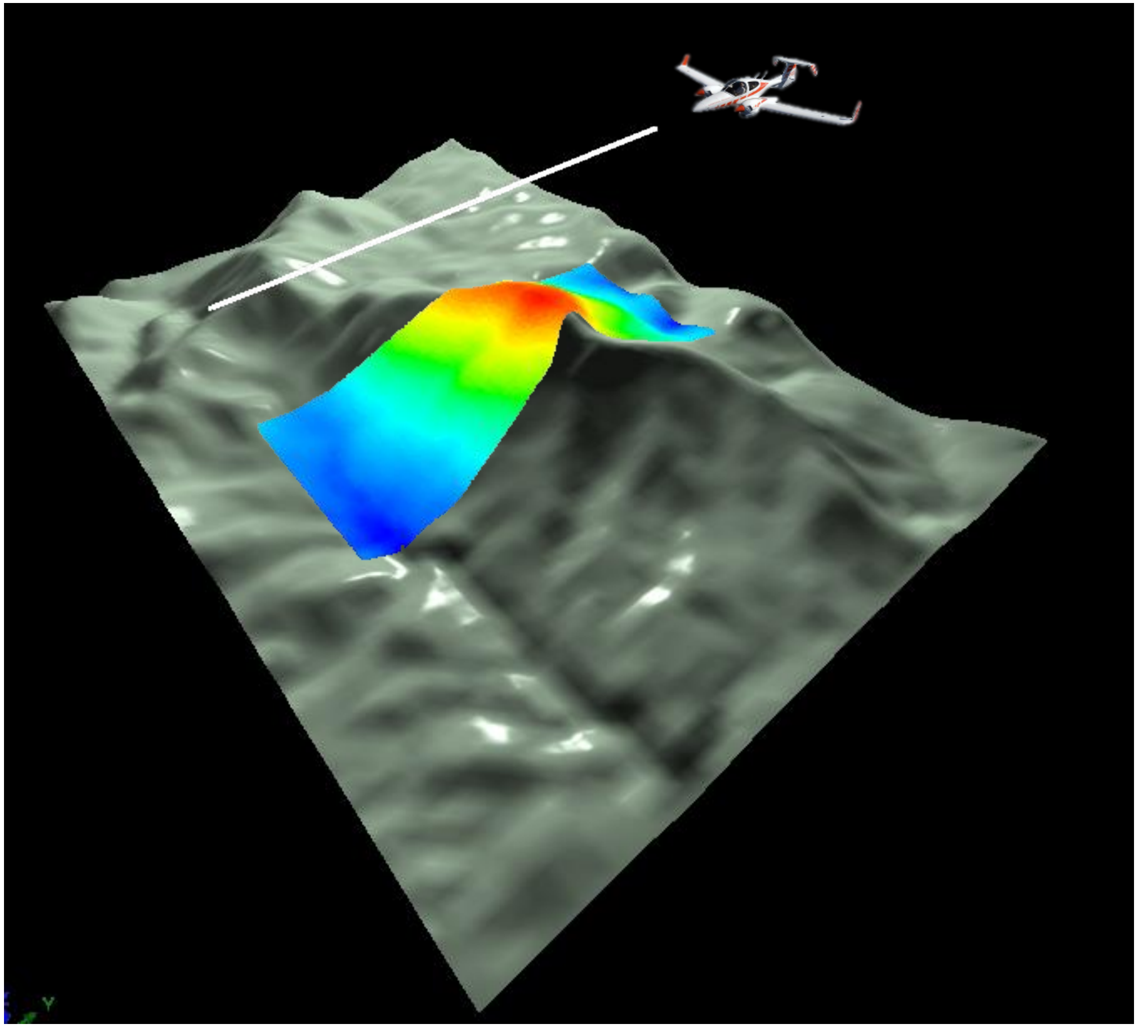
	scenario 1	scenario 2	scenario 3
application	corridor mapping	high density survey	wide area mapping
terrain	flat	flat	mountainous
AGL	500 m	1000 m	2000 m – 1000 m
speed	60 kn	120 kn	140 kn
FOV	60 deg	60 deg	60 deg







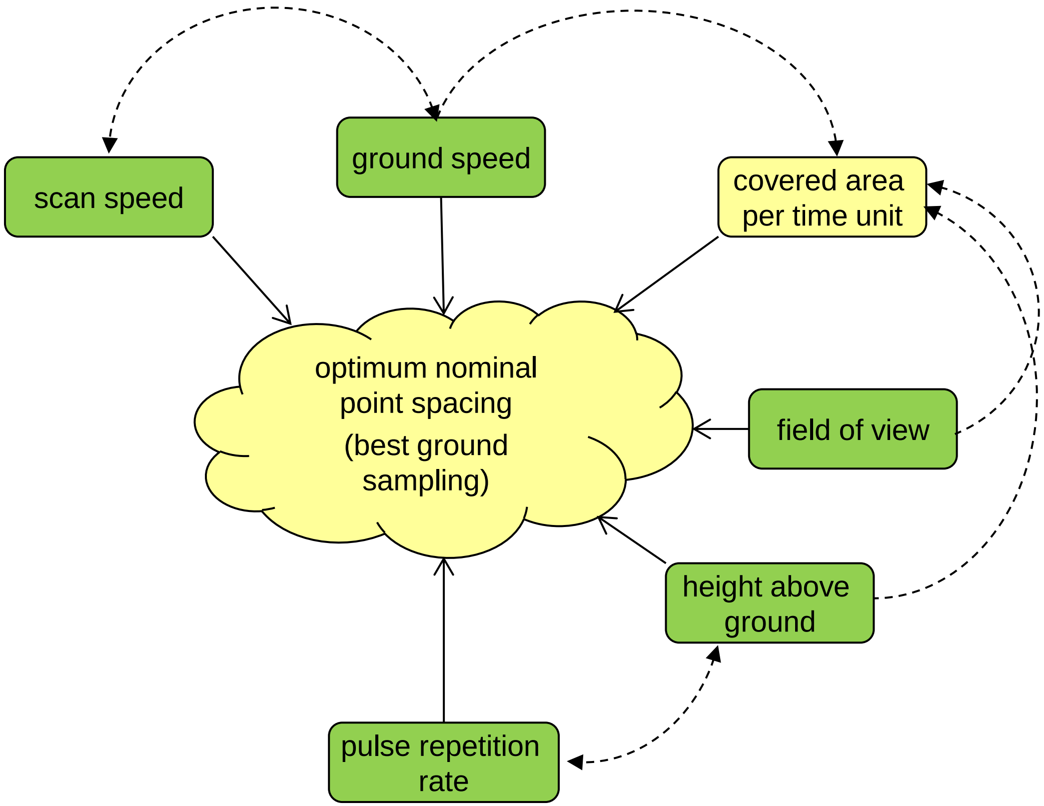
simulation of point distribution on terrain



mountainous terrain

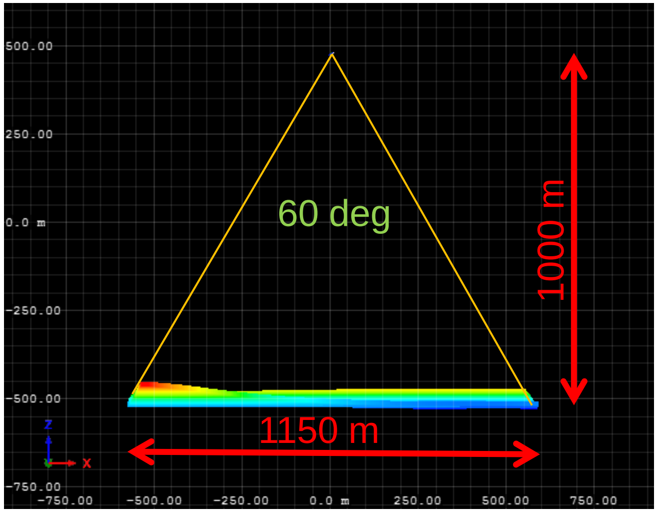
- variation in AMSL 1000 m
- scenario 3

- defining test area (scenarios 1 – 3)
- choosing optimum flight parameters
  - performance envelope → PRR_{max}
  - calculating $LPS_{optimum}$ → LPS_{actual}
- generating trajectory
- “mounting” LIDAR & generating “pulses”
- intersecting beams with terrain
- analyzing / visualizing point clouds

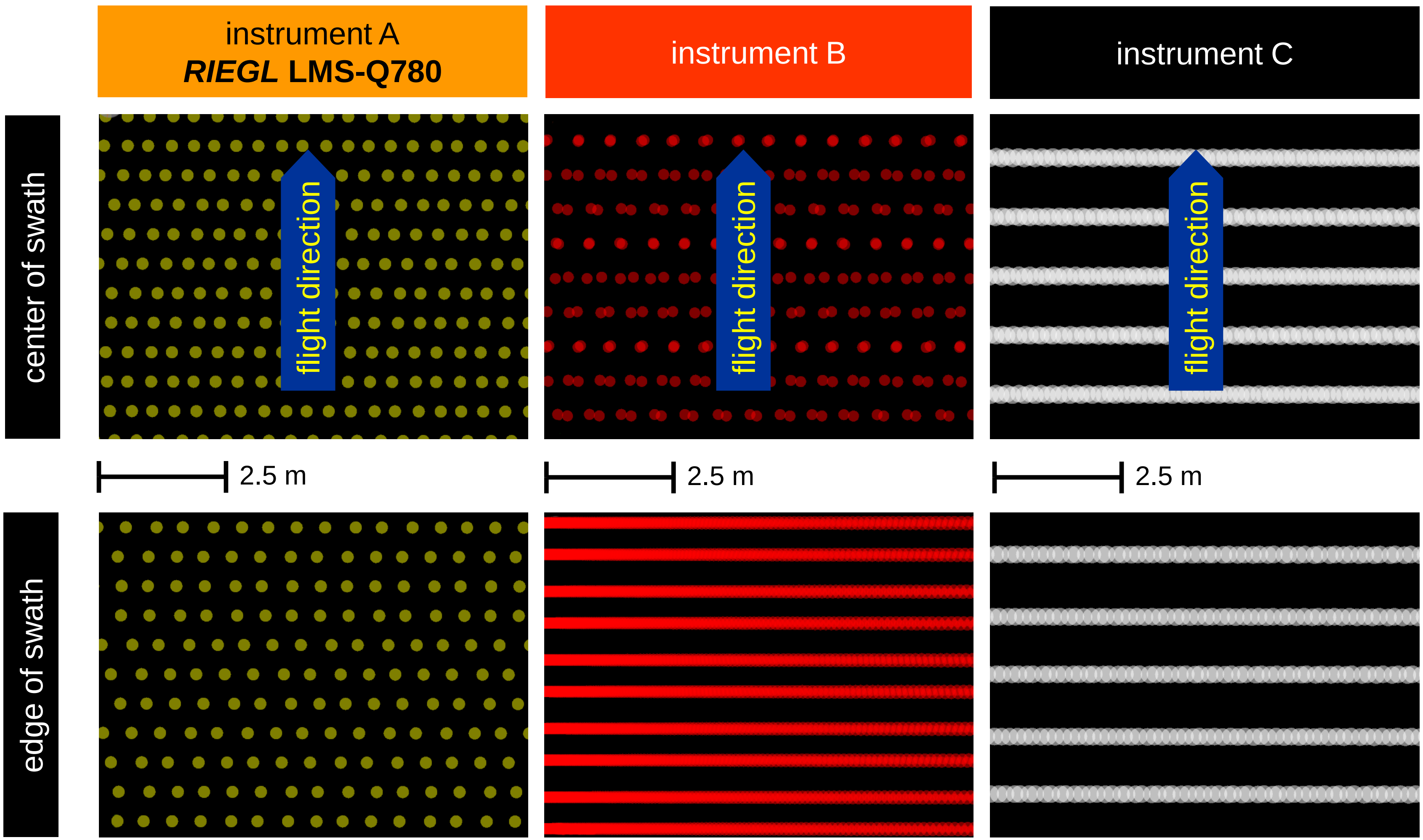


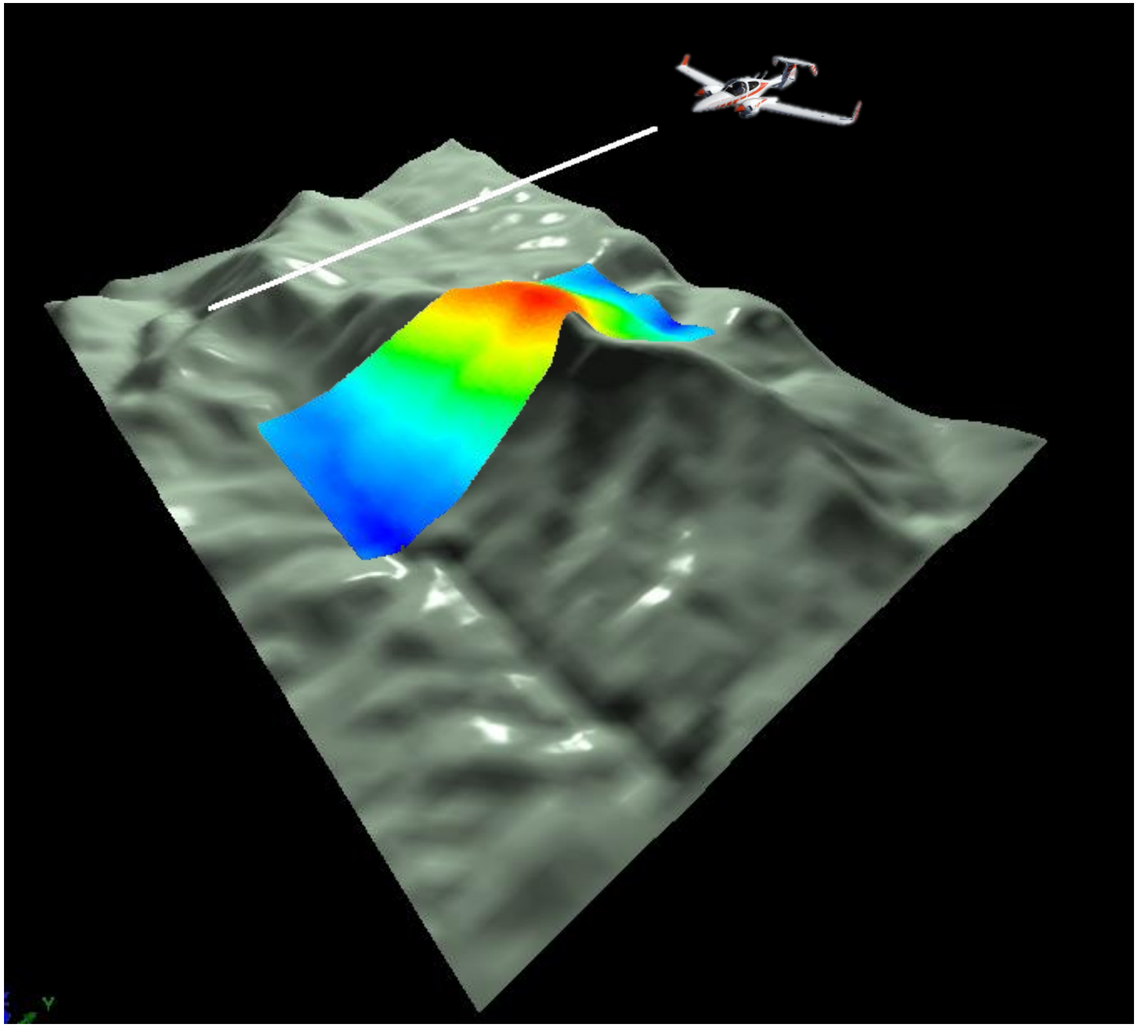
Performance on flat terrain

- AGL at 1000 m
- speed over ground 120 kn
- FOV of 60 degrees
- optimum operating parameters for all instruments



	AGL	FOV	MR	LPS	across spacing	along spacing	point density
instrument A	1000 m	60 deg	1x 266 kHz	1x 108 LPS	0.57 m	0.57 m	4.1 p/m²
instrument B	1000 m	60 deg	2x 250 kHz	2x 93 LPS	0.61 m	0.66 m	7.7 p/m²
instrument C	1000 m	60 deg	2x 250 kHz	2x **53 LPS**	0.30 m	**1.16 m**	7.7 p/m²


instrument A
RIEGL **LMS-Q780**
instrument B
instrument C
center of swath
flight direction
flight direction
flight direction
2.5 m
2.5 m
2.5 m
edge of swath

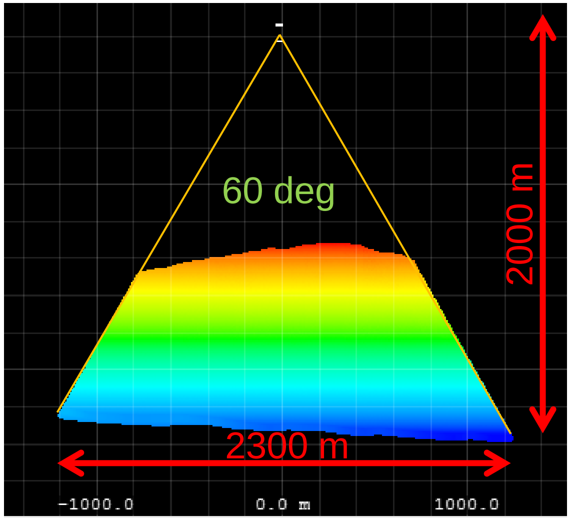


mountainous terrain

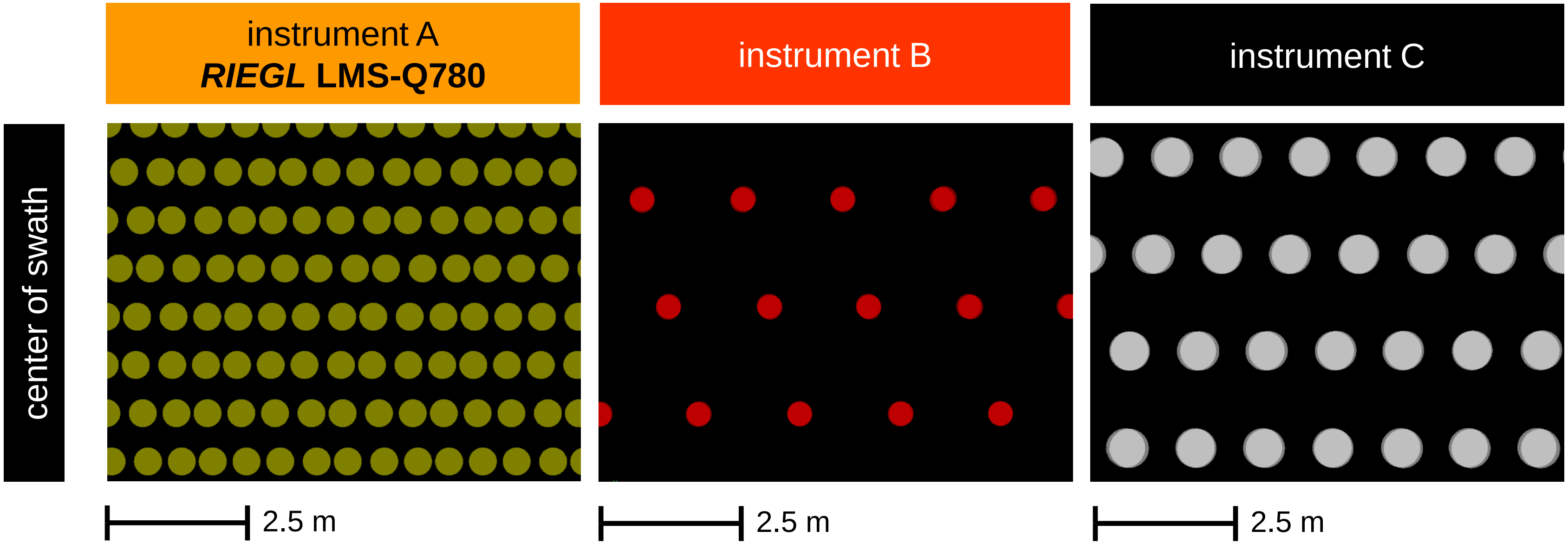
- variation in AMSL 1000 m
- scenario 3

Performance on mountainous terrain

- AGL from 1000 m to 2000 m
- speed over ground 140 kn
- FOV of 60 degrees
- optimum operating parameters for all instruments



	maximum AGL	FOV	meas. rate	LPS	across spacing	along spacing	avg. point density
instrument A	2000 m	60 deg	1x 266 kHz	1x 83 LPS	0.87 m	0.87 m	1.3 - 3.5 p/m²
instrument B	2000 m	60 deg	2x 63 kHz	2x 37 LPS	1.94 m	4.32 m	0.53 - 1.9 p/m²
instrument C	2000 m	60 deg	2x 66 kHz	2x 41 LPS	1.74 m	3.50 m	0.9 - 2.6 p/m²



- variation in terrain height permits only acquisition in MTA zone 1 (1 pulse in the air)
- dead time between zones reduces measurement rate even further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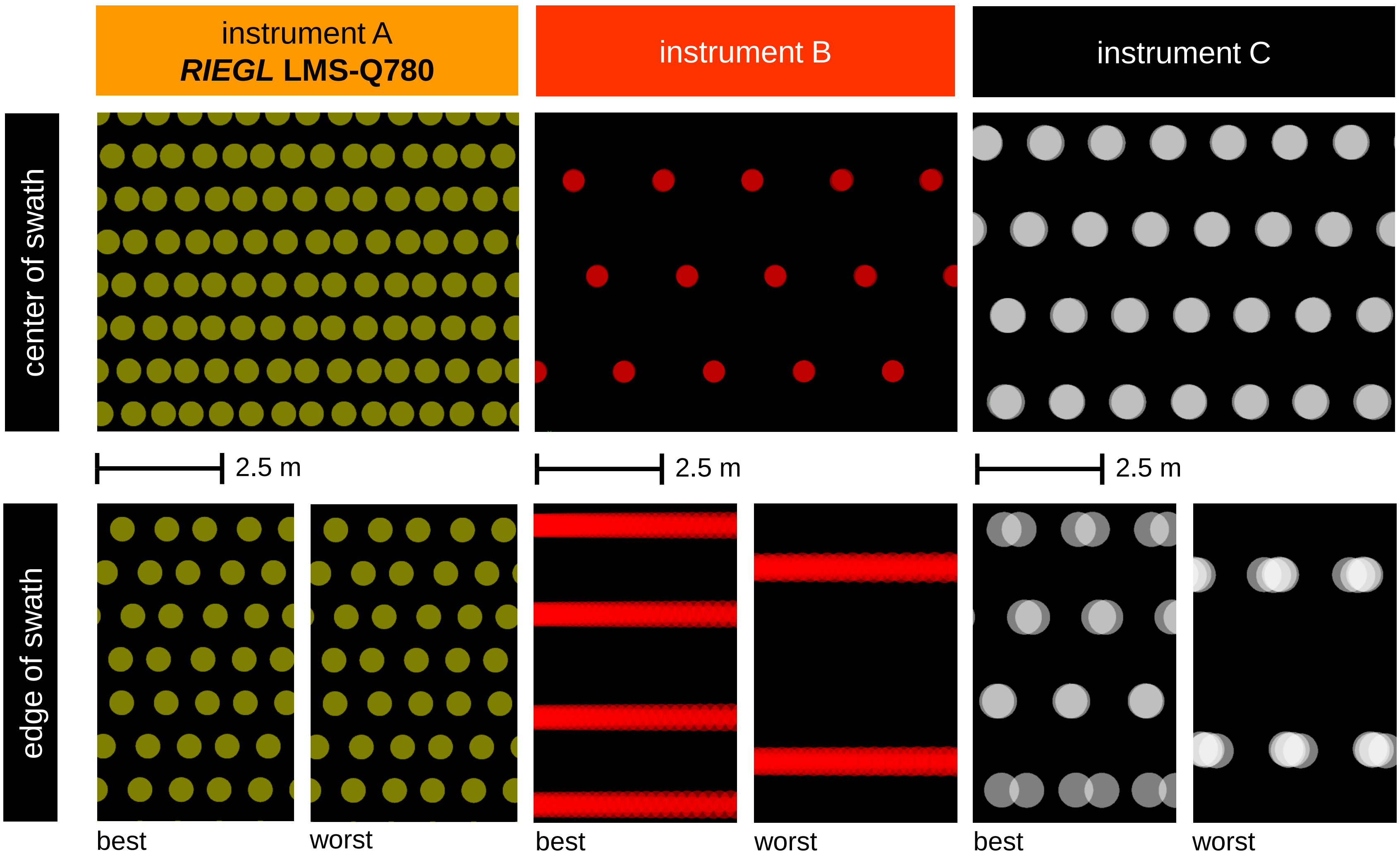
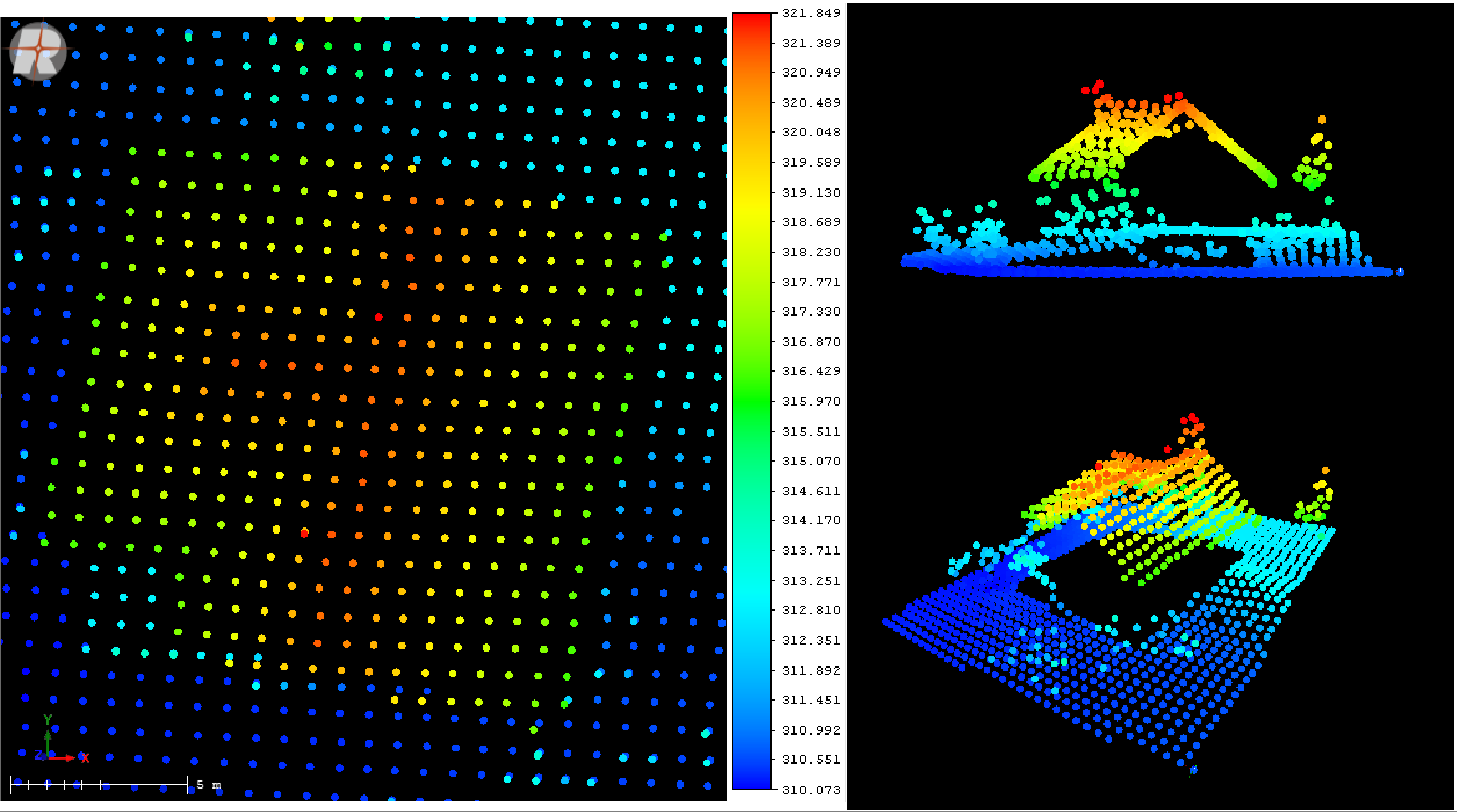
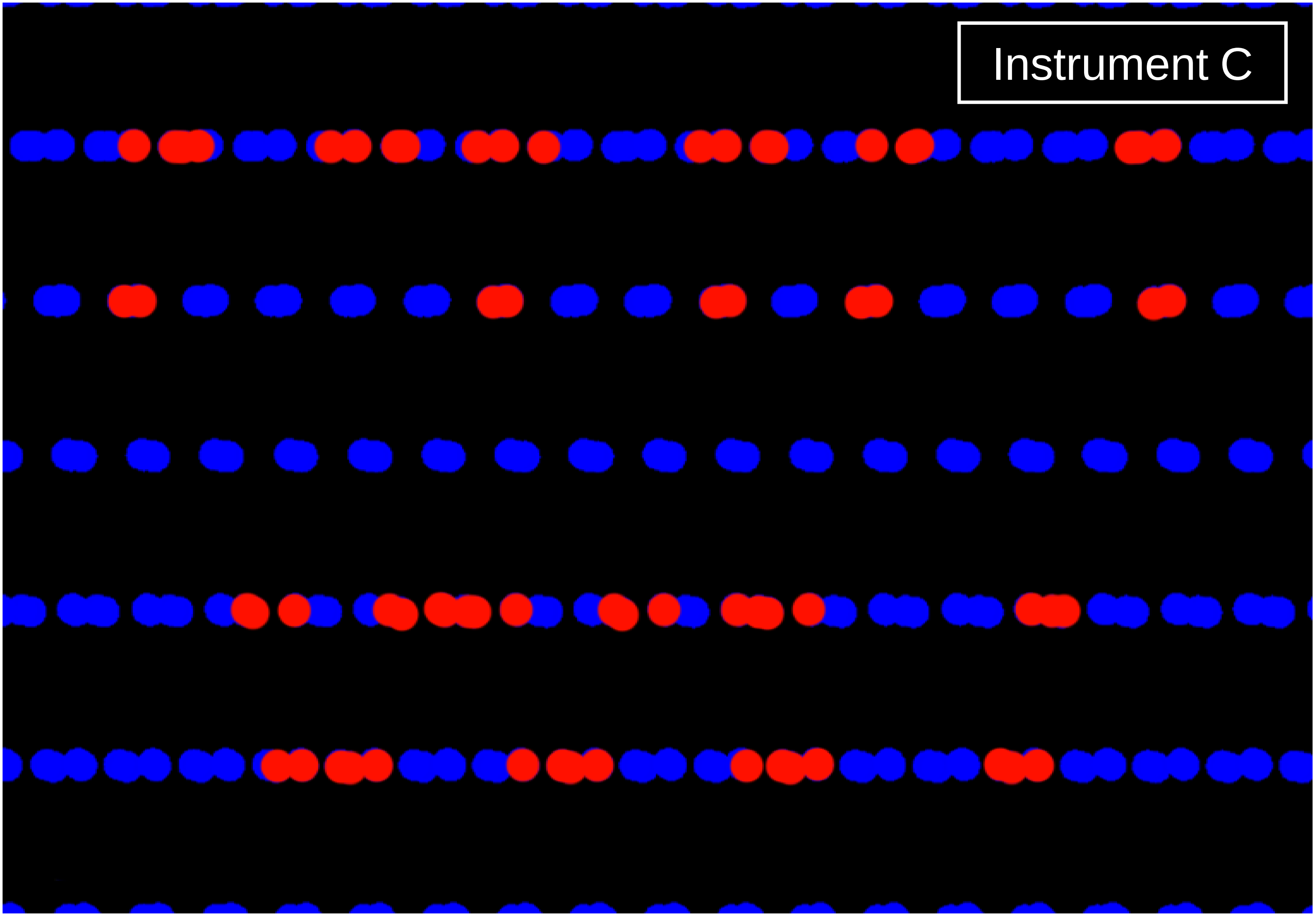

instrument A
RIEGL LMS-Q780
instrument B
instrument C
center of swath
2.5 m
2.5 m
2.5 m
edge of swath
best
worst
best
worst
best
worst

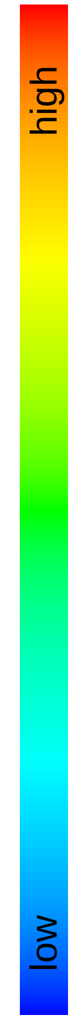


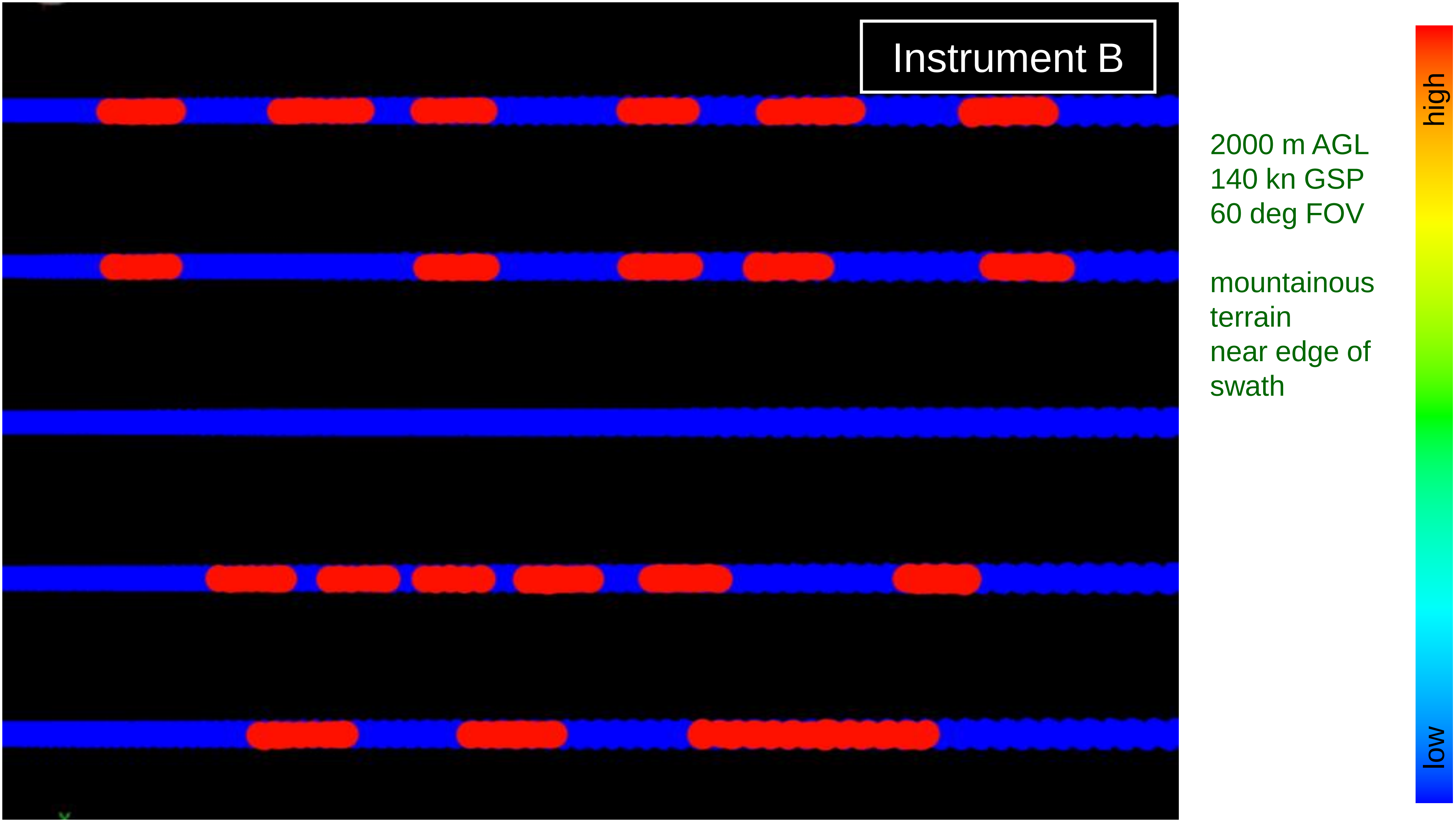
sampling objects – point spacing & spatial sampling frequency



2000 m AGL
140 kn GSP
60 deg FOV

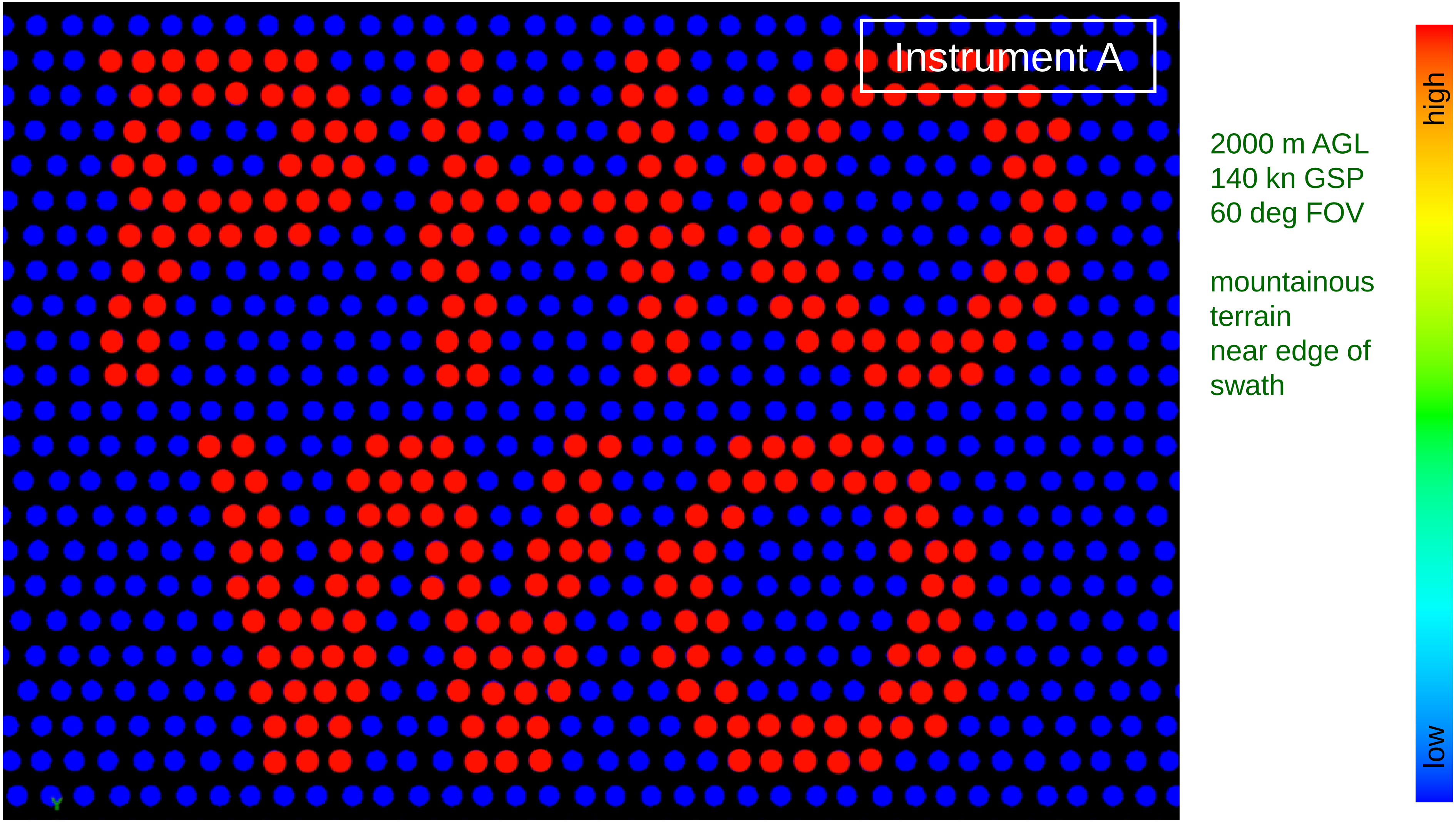
mountainous terrain near edge of swath





2000 m AGL
140 kn GSP
60 deg FOV

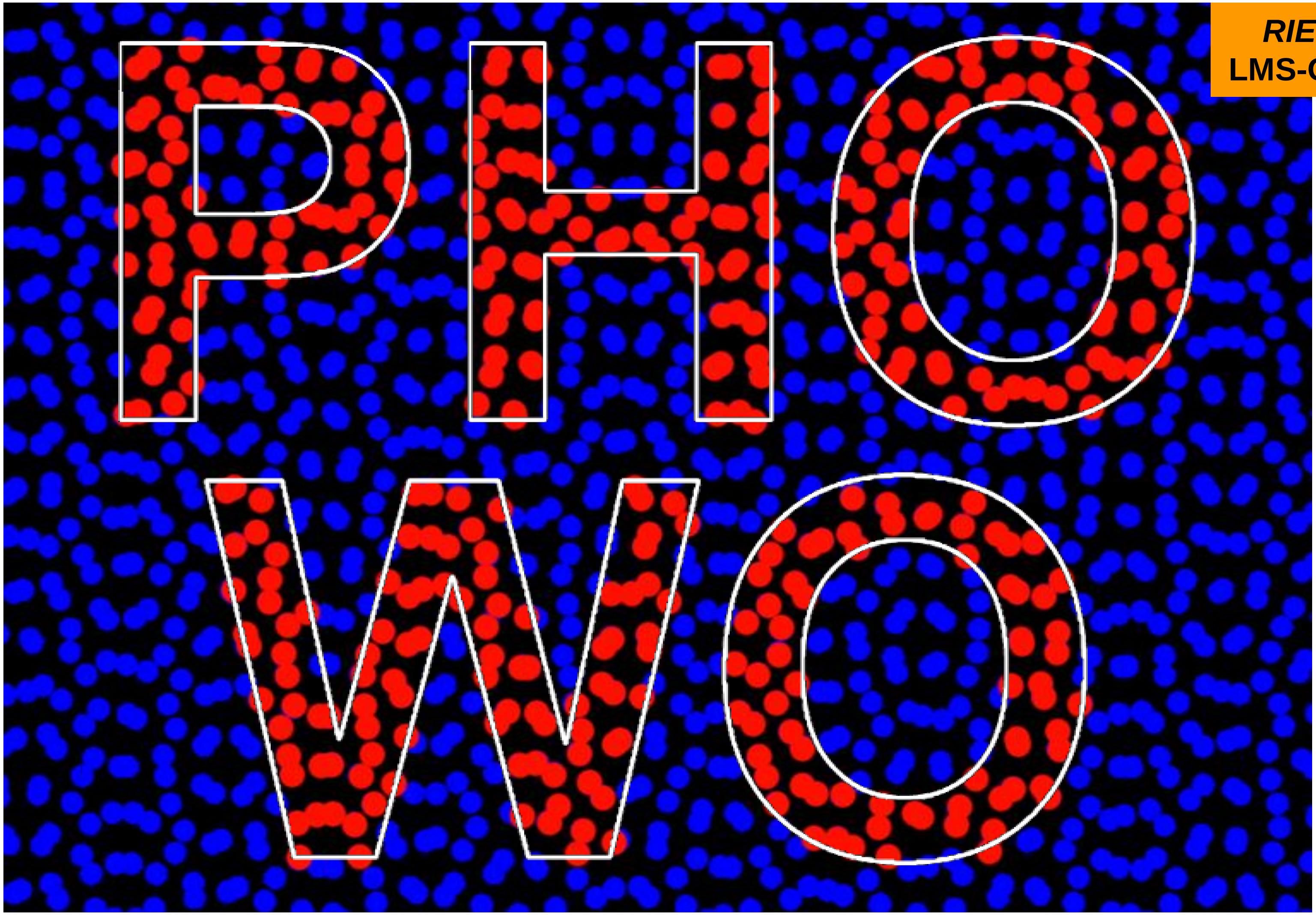
mountainous terrain near edge of swath



2000 m AGL
140 kn GSP
60 deg FOV

mountainous terrain near edge of swath

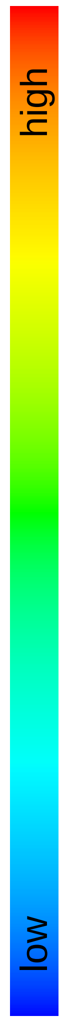
sampled object

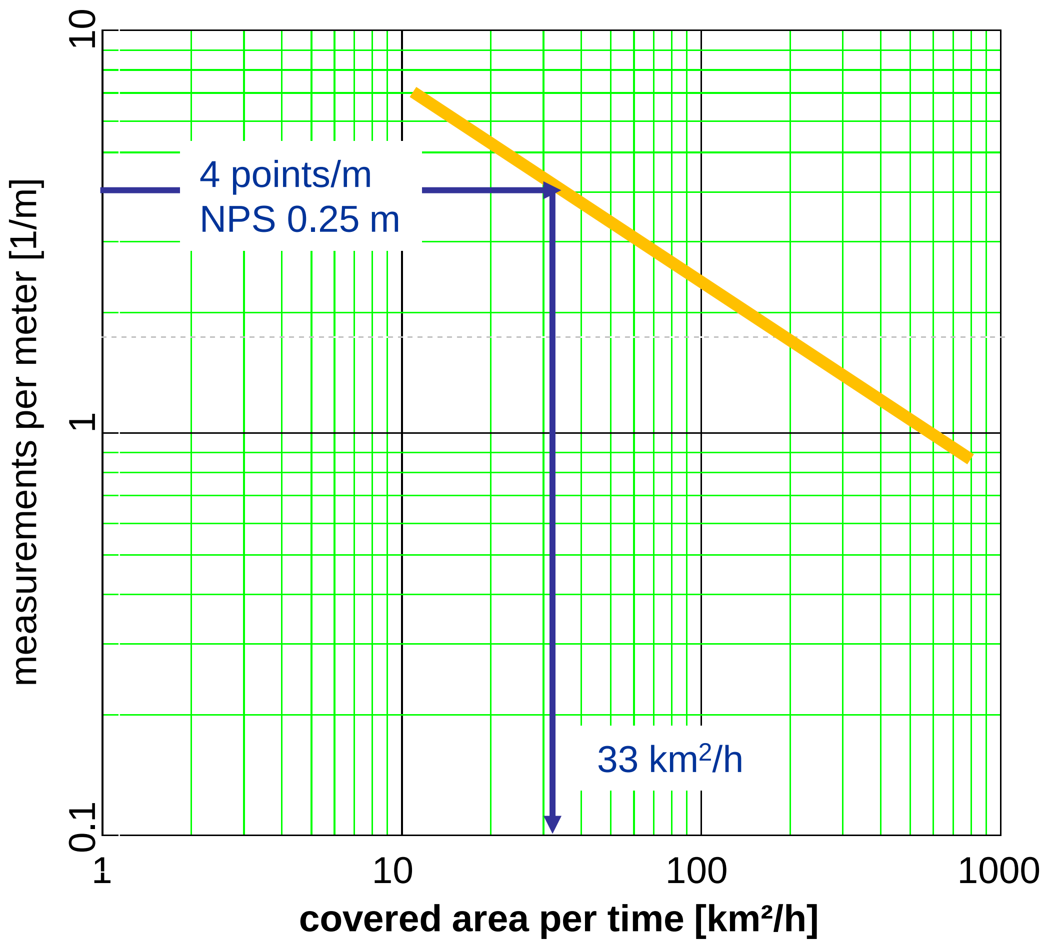


RIEGL
LMS-Q1560

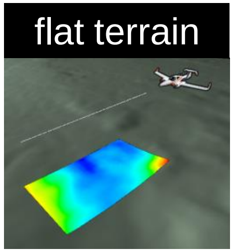
2000 m AGL
140 kn GSP
60 deg FOV

mountainous terrain near edge of swath

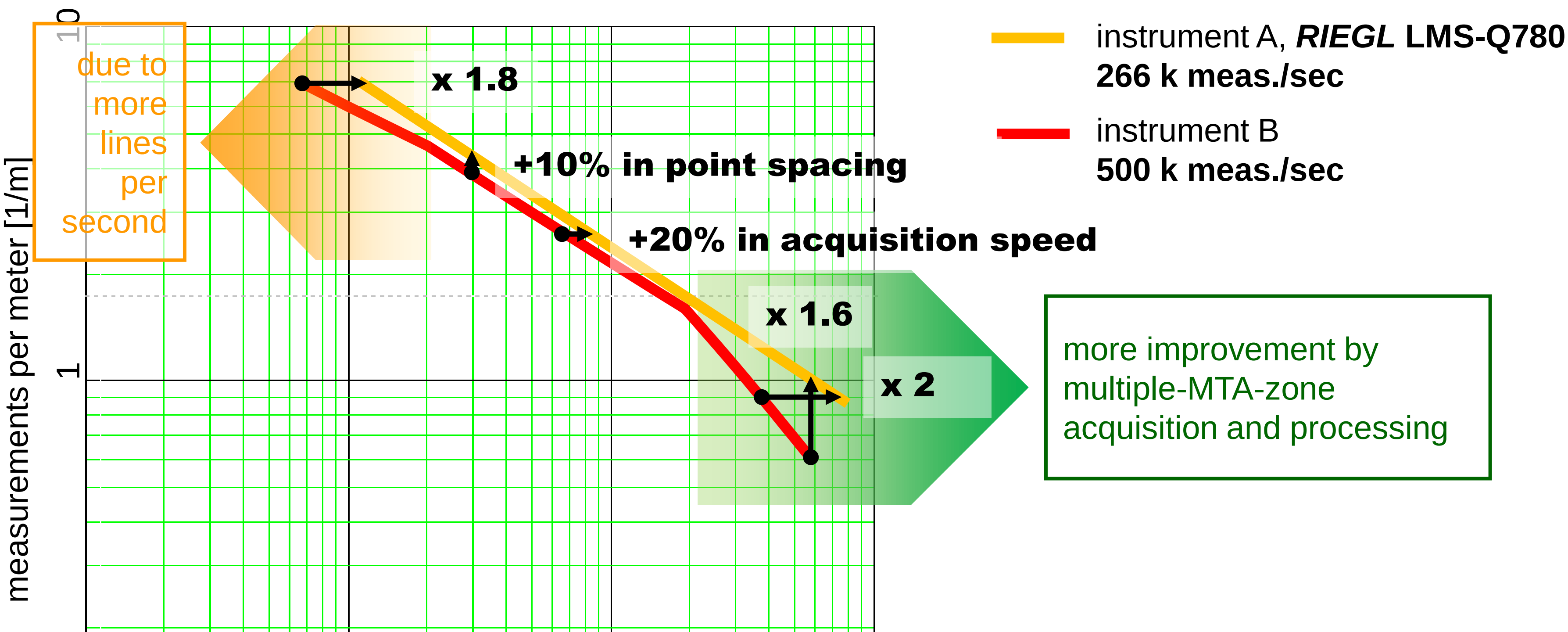


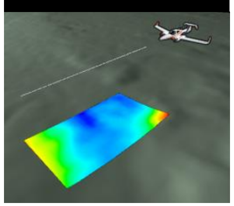


instrument A, ***RIEGL* LMS-Q780**
266 k meas./sec

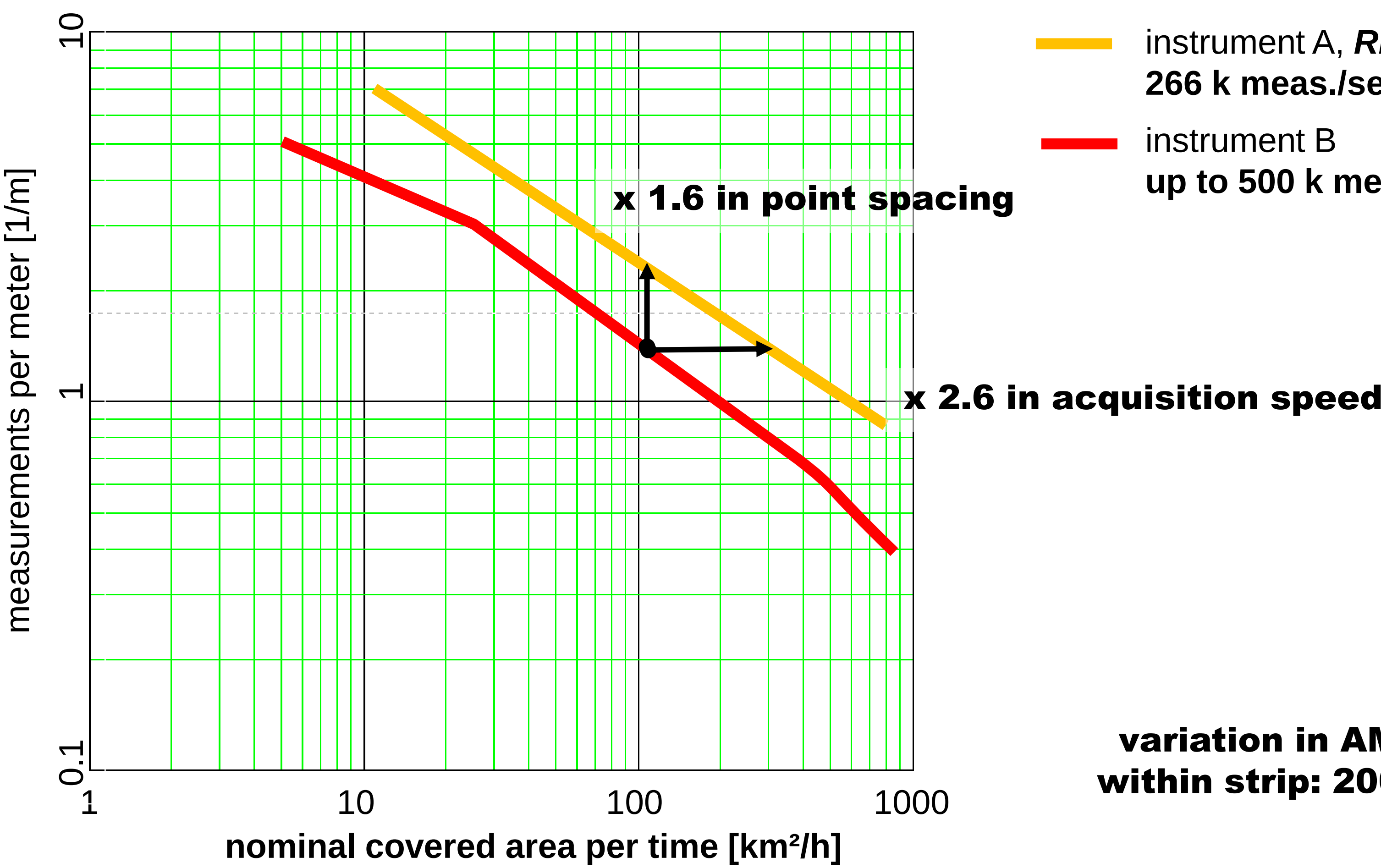


sampling frequency (1/NPS) vs acquisition speed





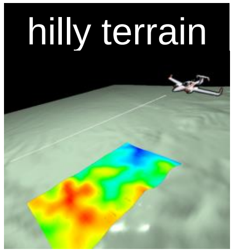
sampling frequency (1/NPS) vs acquisition speed

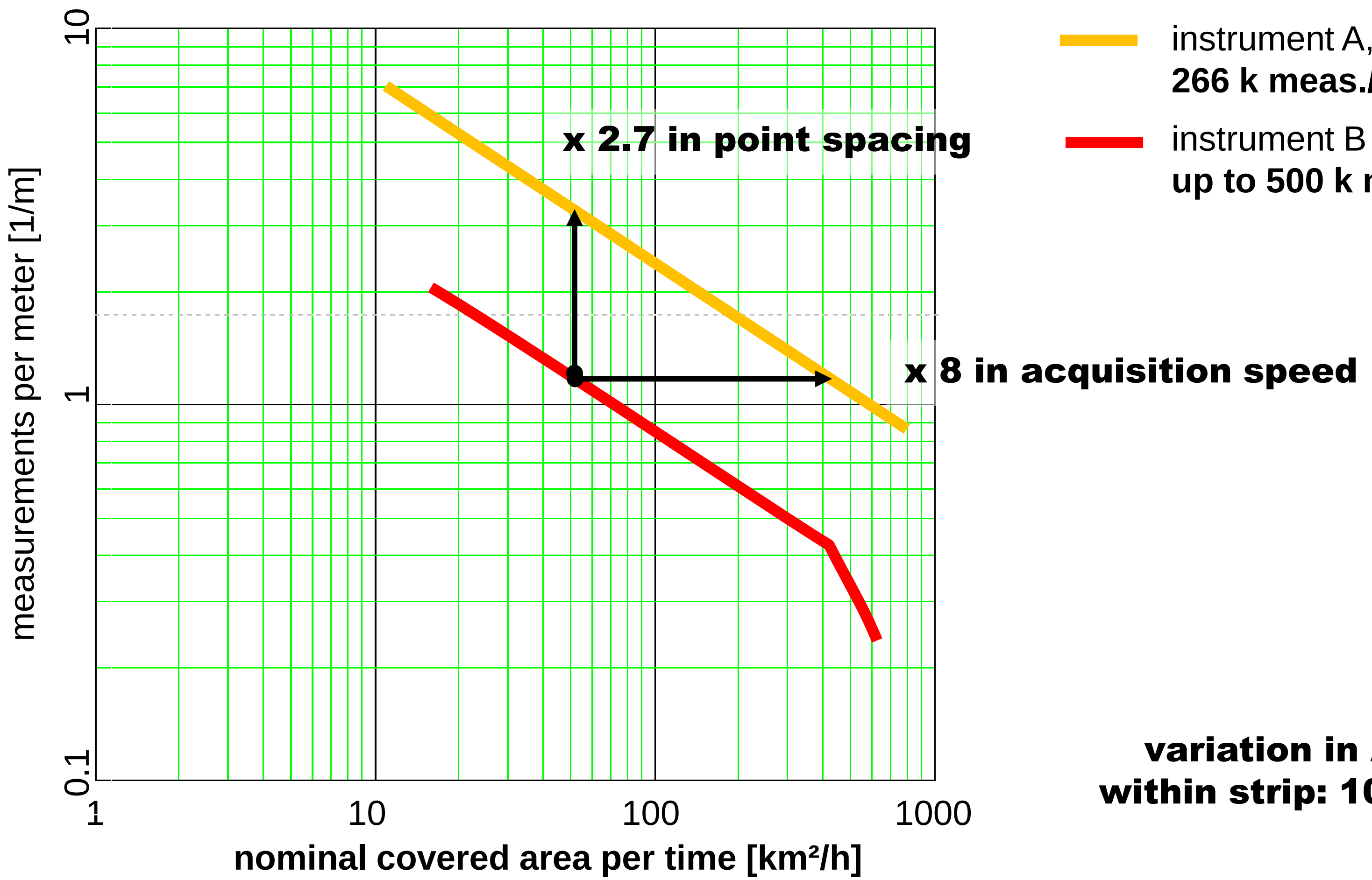


instrument A, ***RIEGL* LMS-Q780**
266 k meas./sec

instrument B
up to 500 k meas./sec

variation in AMSL within strip: 200 m

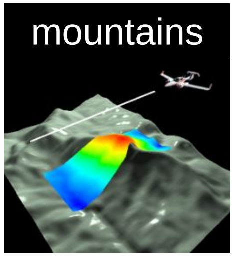




instrument A, ***RIEGL* LMS-Q780**
266 k meas./sec

instrument B
up to 500 k meas./sec

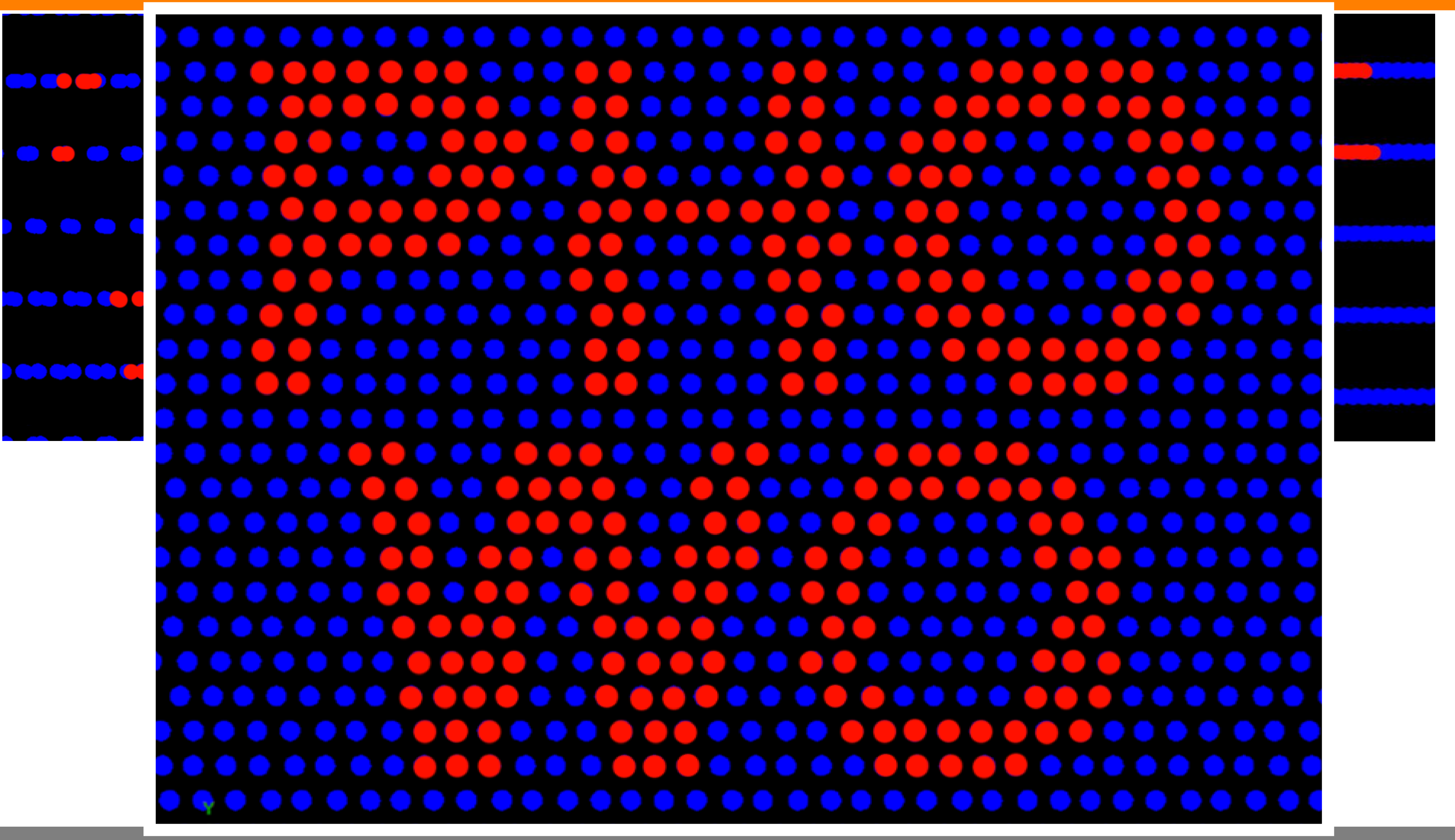
variation in AMSL
within strip: 1000 m



high ground sampling frequency low nominal point spacing	**AND**	high acquisition speed

- fast scan at high FOV (polygon mirror)
- no interference problems (single channel or sophisticated dual channel scanner design)
- wide performance envelope
- high pulse repetition rate at high AGL (high-MTA-zone processing capability)

“it is the point spacing, not the number of measurements on the ground”



Thank you!