Radiometric Analysis of Single-photon Lidar Bathymetry

Minsu Kim, PhD

SGT Inc. / USGS

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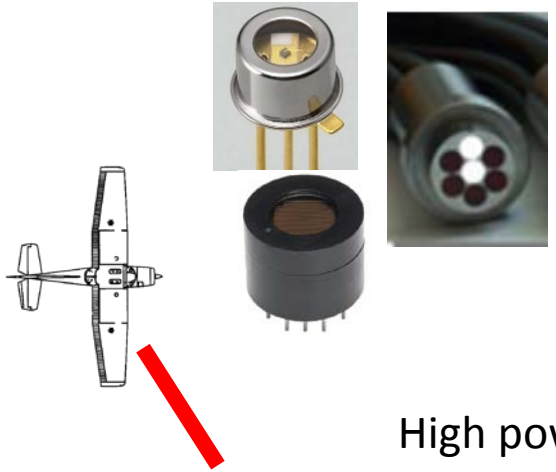
Silver Spring, MD

USGS
science for a changing world

Earth Resources Observation and Science (EROS) Center

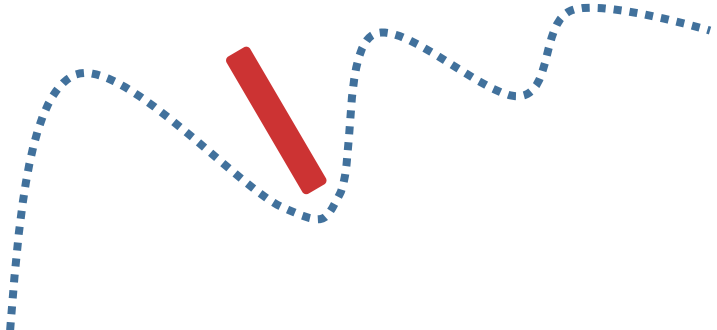
Conventional lidar



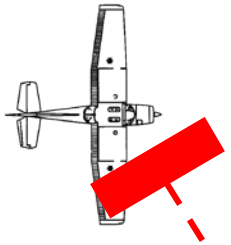
High power focused beam

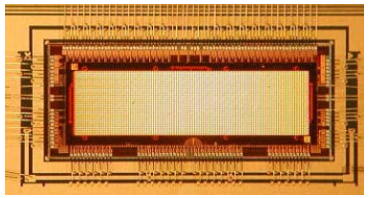
Single (or several) detectors
PMT or APD

Multiple returns + intensity

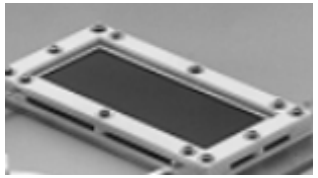


Photon counting lidar

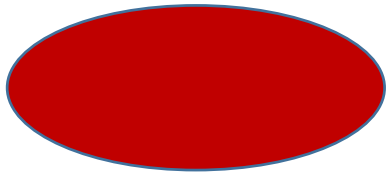


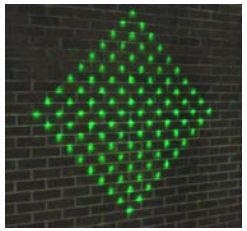


128 x 32



10 x 10

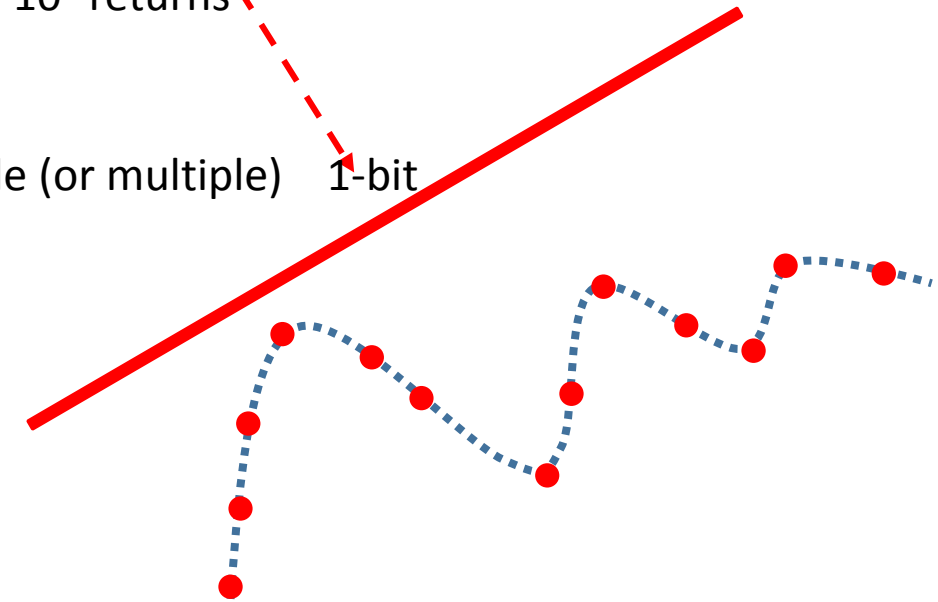




Low power wide illumination

Detector array (GmAPD FPA , MCP-PMT)
10^2 – 10^3 returns

Single (or multiple) 1-bit



Why photon counting lidar ?

PERGAMON

Journal of Geodynamics 34 (2002) 503–549

JOURNAL OF GEODYNAMICS

www.elsevier.com/locate/jog

Photon-counting multikilohertz microlaser altimeters for airborne and spaceborne topographic measurements

John J. Degnan

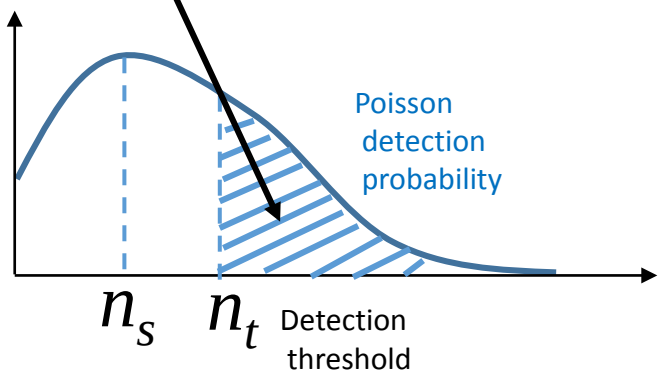
Geoscience Technology Office, Code 920.3, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

Normalized sampling rate

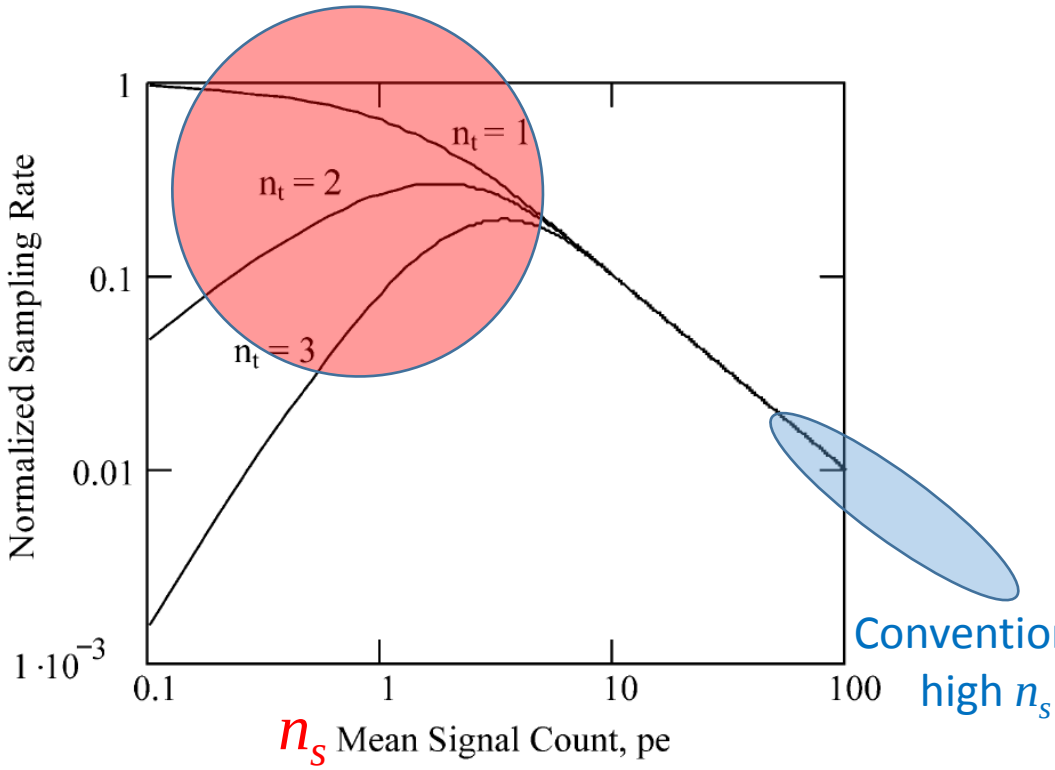
$$= \frac{\text{\# of laser pulses that detect a return}}{\text{Max \# of photo-electron } (PRR \cdot n_s)}$$

$$= \boxed{\frac{1}{n_s}\left(1 - e^{-n_s}\sum_{k=0}^{n_t-1}\frac{n_s^k}{k!}\right)}$$

Laser power
Optical system (T, A_R)
Environment(T_a , ρ)
Detector(QE)



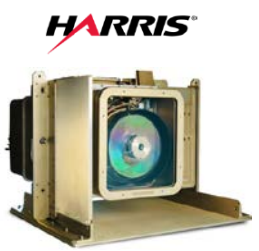
Photon counting lidar
low n_s , n_t



Conventional lidar
high n_s , n_t

Photon counting lidar : 2~3 orders of magnitude efficient!

Photon-counting lidar



NASA IIP
(7mW→1W→5W)

Very low ? … ! Laser power + **Photon counting Detector Array** + **Scanning system (high alt. → great coverage)**

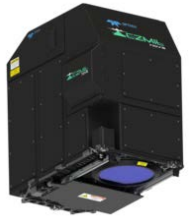
Efficient Optical system

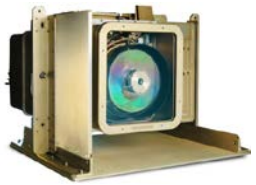
Flash (flood illumination)

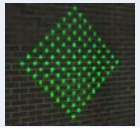
Point determination & Noise

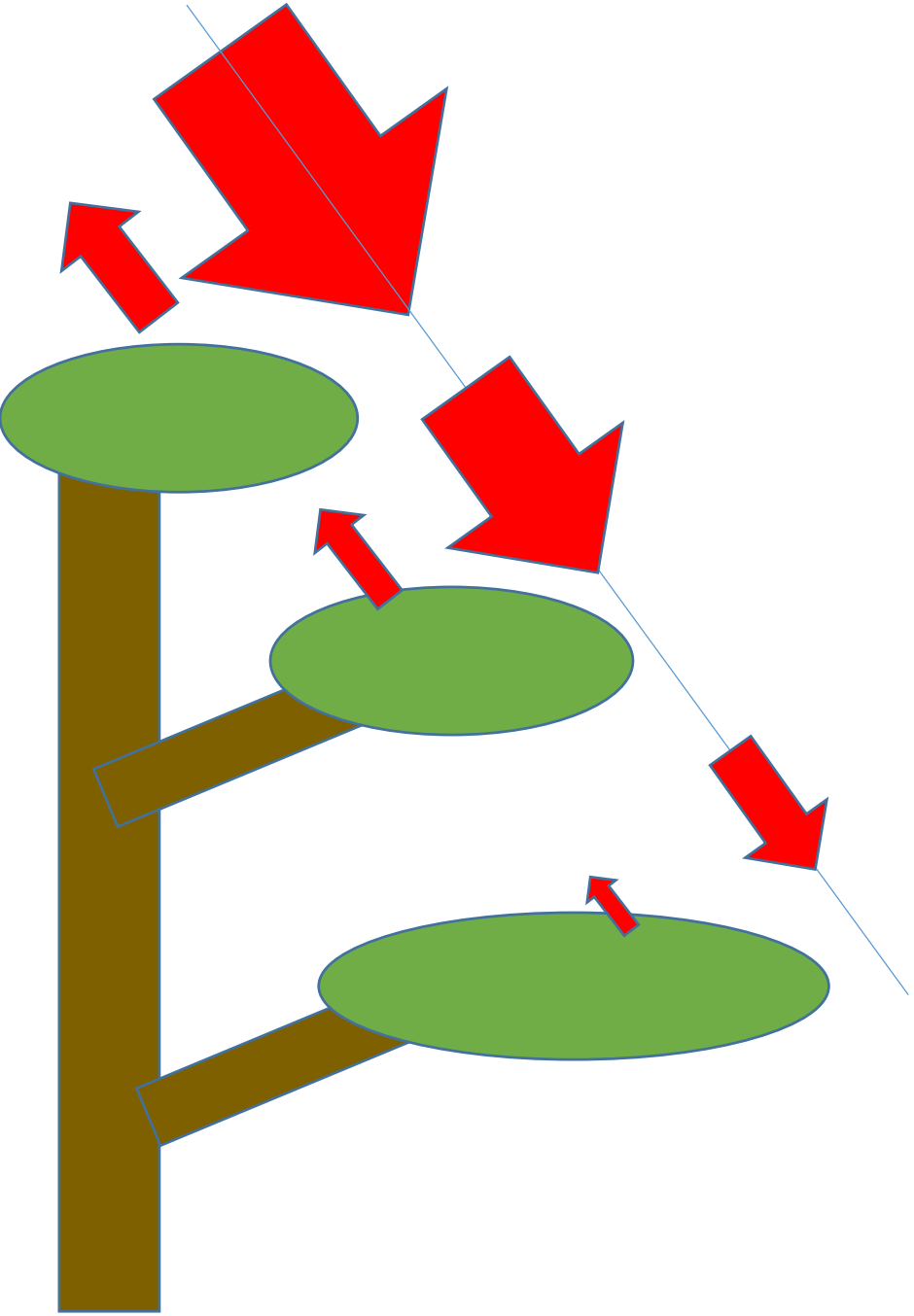
Pseudo-Intensity

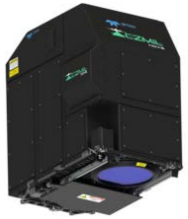
Radiometry of SPL bathymetry



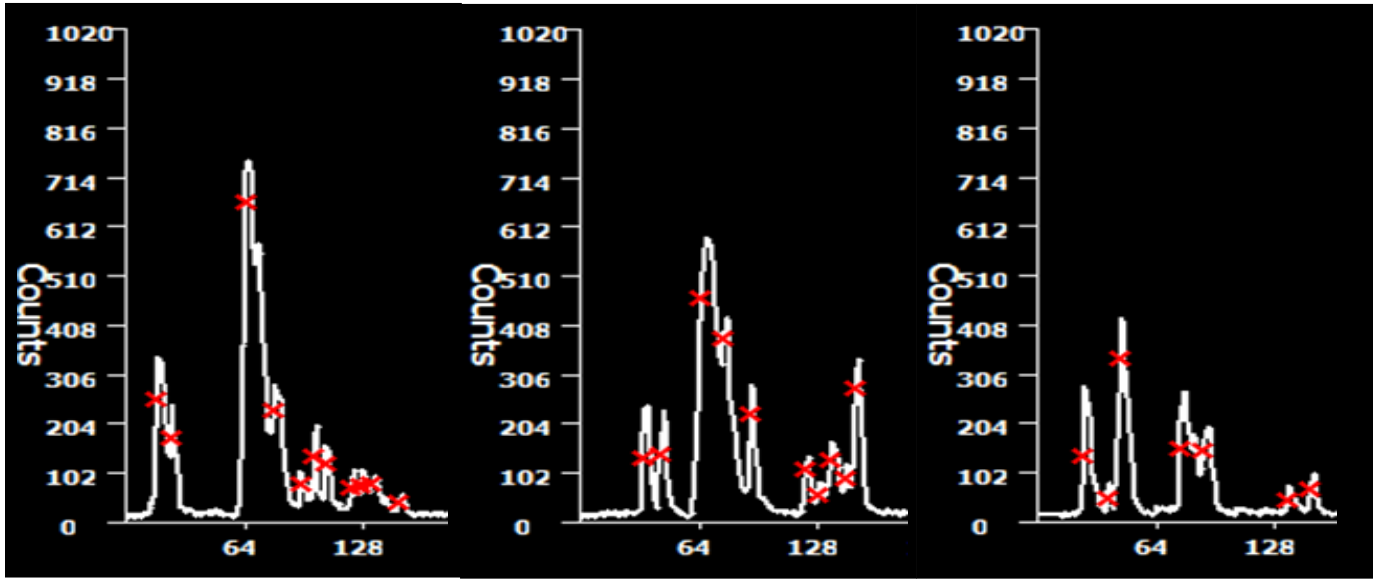


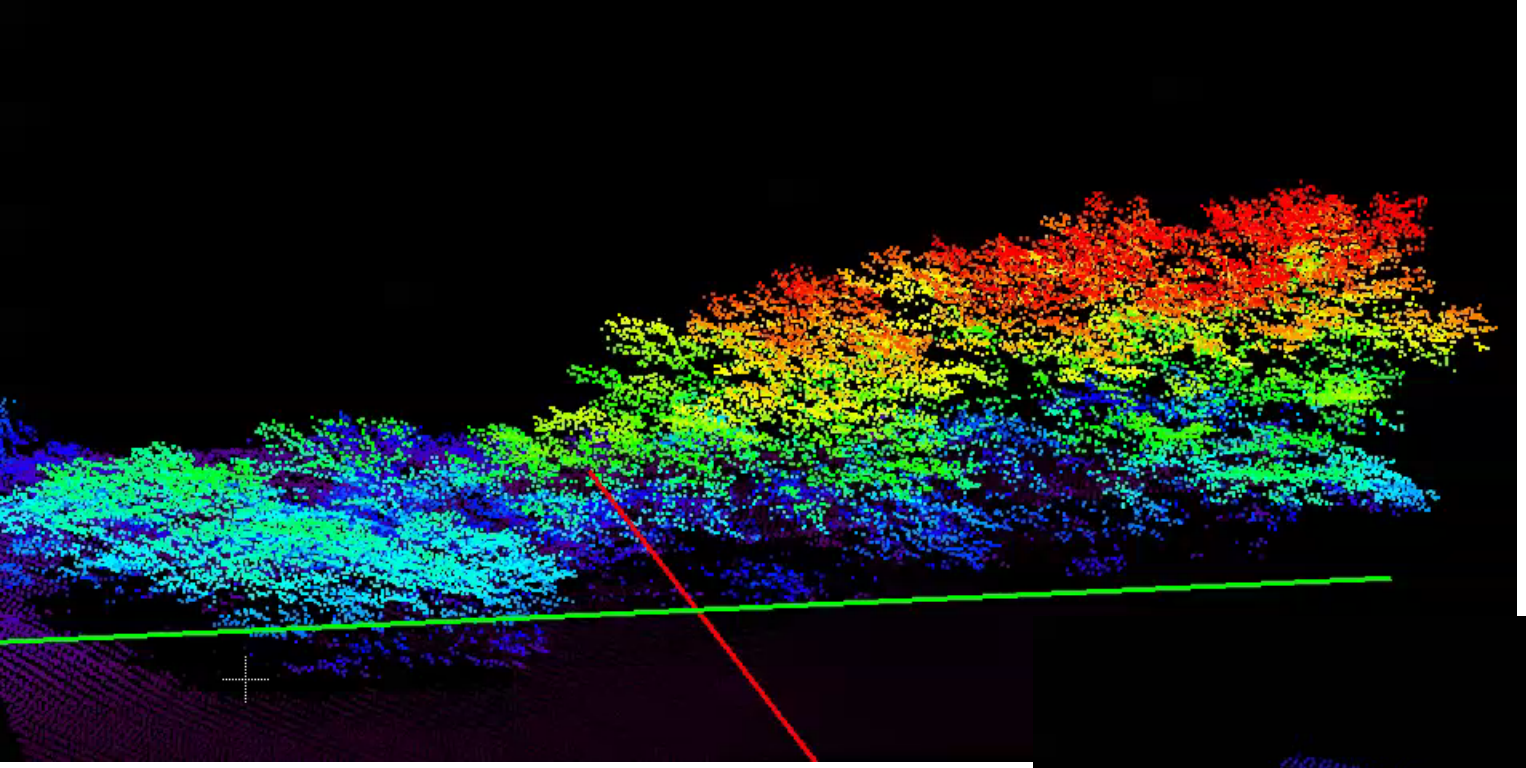
	Conventional Topo	High-end Topo-bathy	HRQLS	IntelliEarth
Avg laser power [W]	Several W (1064 nm)	30 (532), 50(1064)	5 (532)	20 (1064)
Pulse energy [μ J] width [ns] peak power [KW]	~ 100	3000 (10 KHz) ~ 2 1500	1 (50 KHz)  0.5 2.5	0.1 (50 KHz) 0.5 0.2
Detector	APD	PMT	MCP-PMT	GmAPD
IFOV [mrad]	~ 0.2	2 - 40	0.2	0.035
Aperture [cm]	< 10	20	13	27
Points per second	up to 0.5 M	0.1 M	5 M	200 M ?
	2 M	1 M	10 M	20 M
	TIM, several	full waveform, up to 30	TIM, several	on/off 1 (no dynamic quenching)



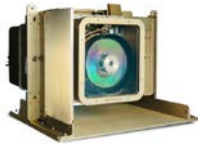


Forest waveforms

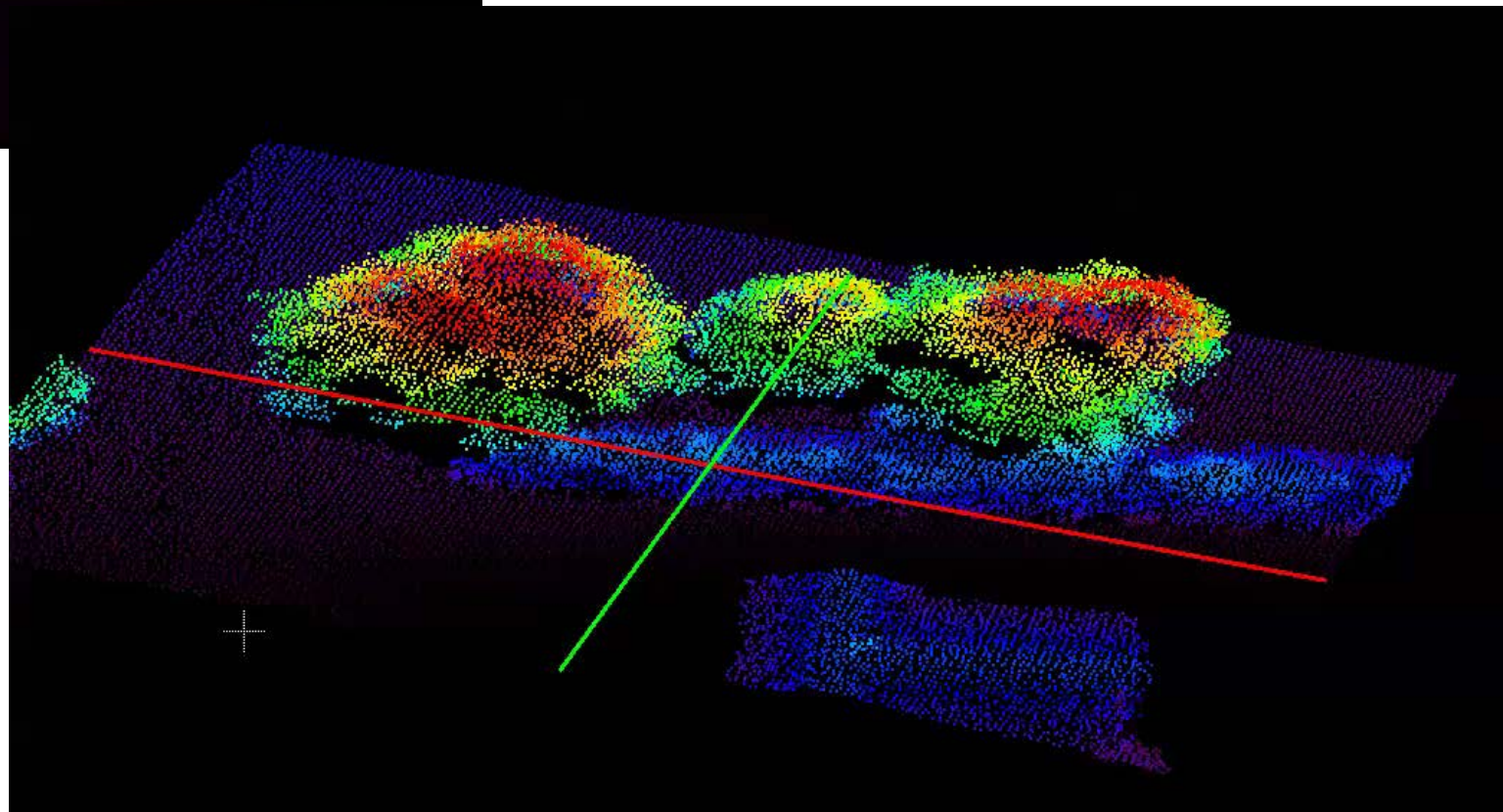


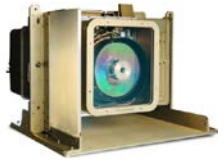


Canopy structure



Hollow canopy





Class IV Nd:YAG laser
20 W, 500 ps, 50 KHz , 4K pixels
➔ 0.4 mJ / pulse
➔ Q_0 = 0.1 µJ / pixel
➔ Peak power, P_0 ~ 200 W

1 W, 700 ps, 25 KHz, 100 pixels
➔ 0.04 mJ / pulse
➔ Q_0 = 0.4 µJ / pixel
➔ Peak power, P_0 ~ 600 W

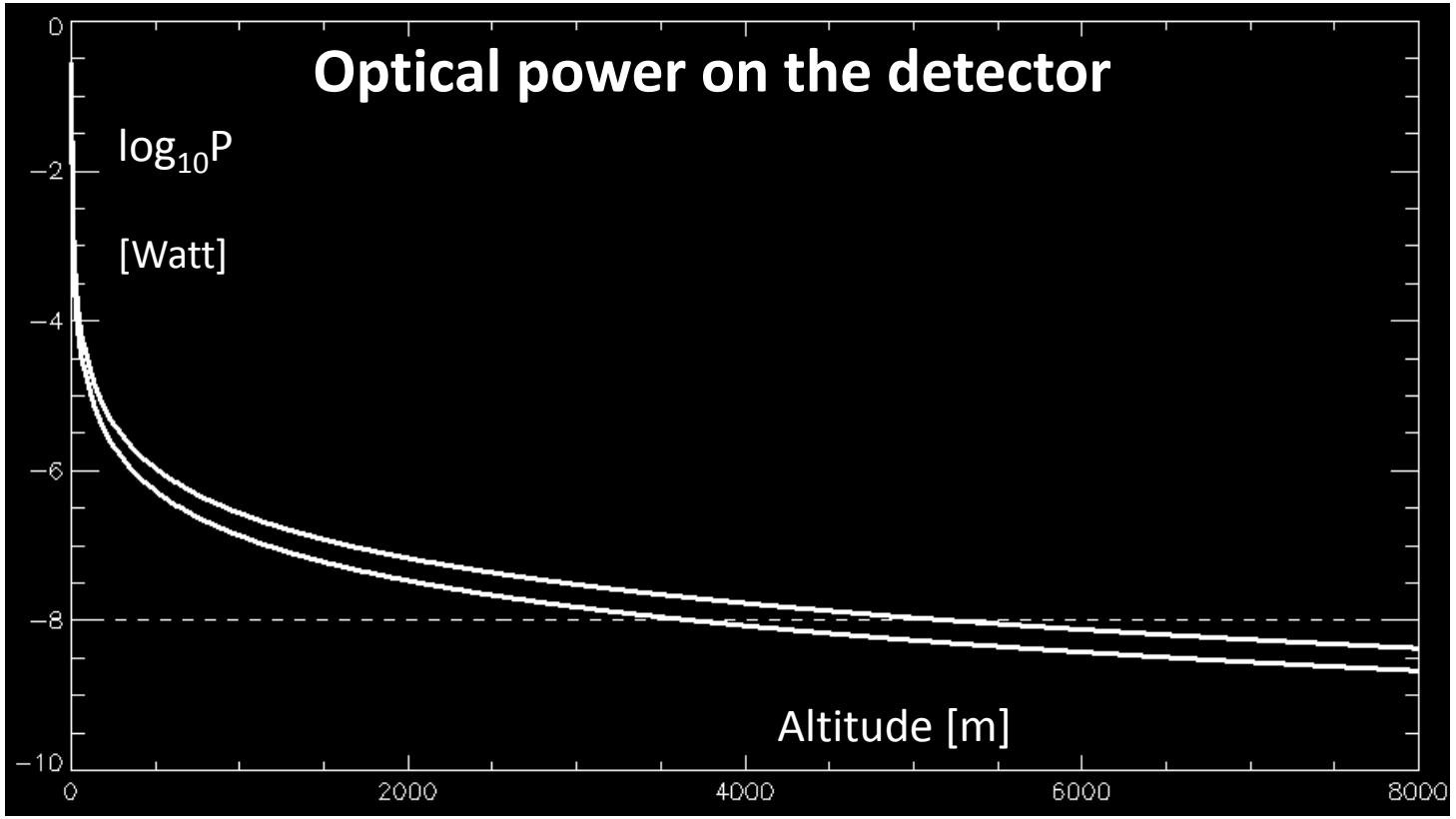
Atmospheric transmittance ~ 1.0
Optical system transmittance ~ 0.5
Surface reflectance ~ 0.3

EB ?

1 photon / ns
onto detector

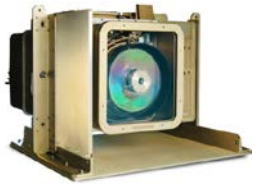
Single photon energy ➔ optical power

532 → ~ 4 × 10^{-17} J ➔ 4 × 10^{-8} W
1064 → ~ 2 × 10^{-17} J ➔ 2 × 10^{-8} W



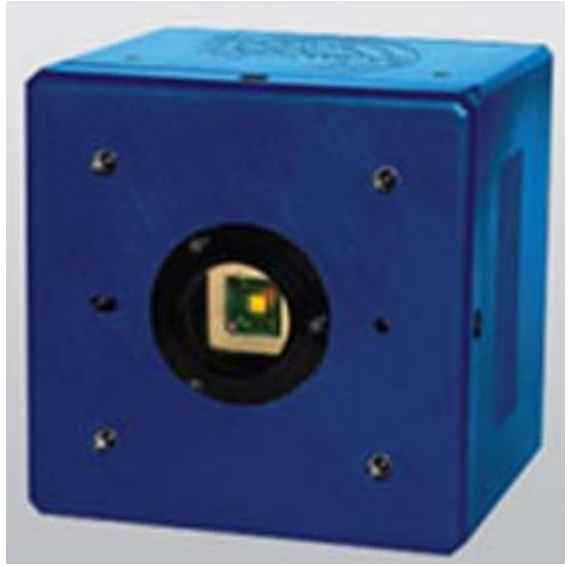
P ~ 10^{-8} W

HARRIS



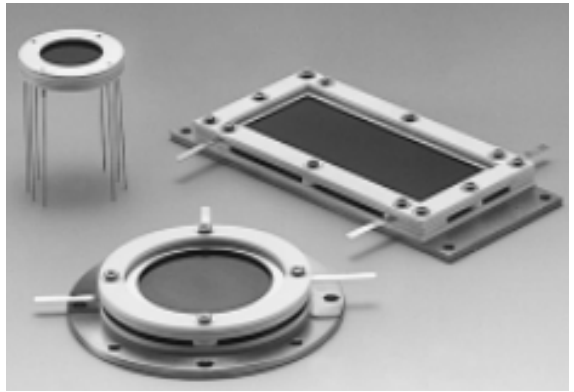
SigmaSpace

Princeton Lightwave



Falcon 128 x 32 GmAPD 3D camera

HAMAMATSU



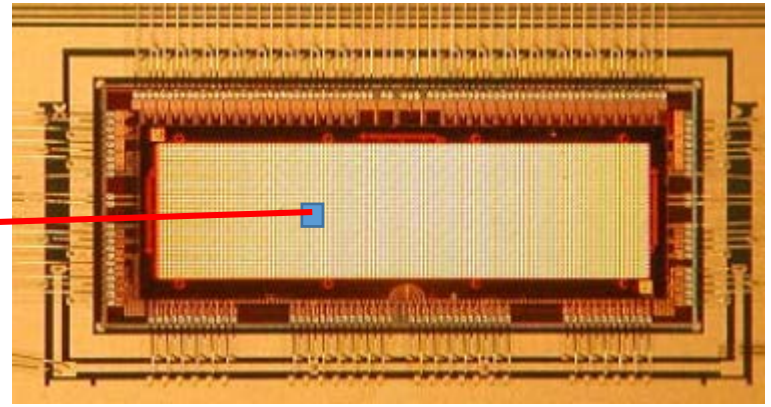
MCP (Microchannel plate)

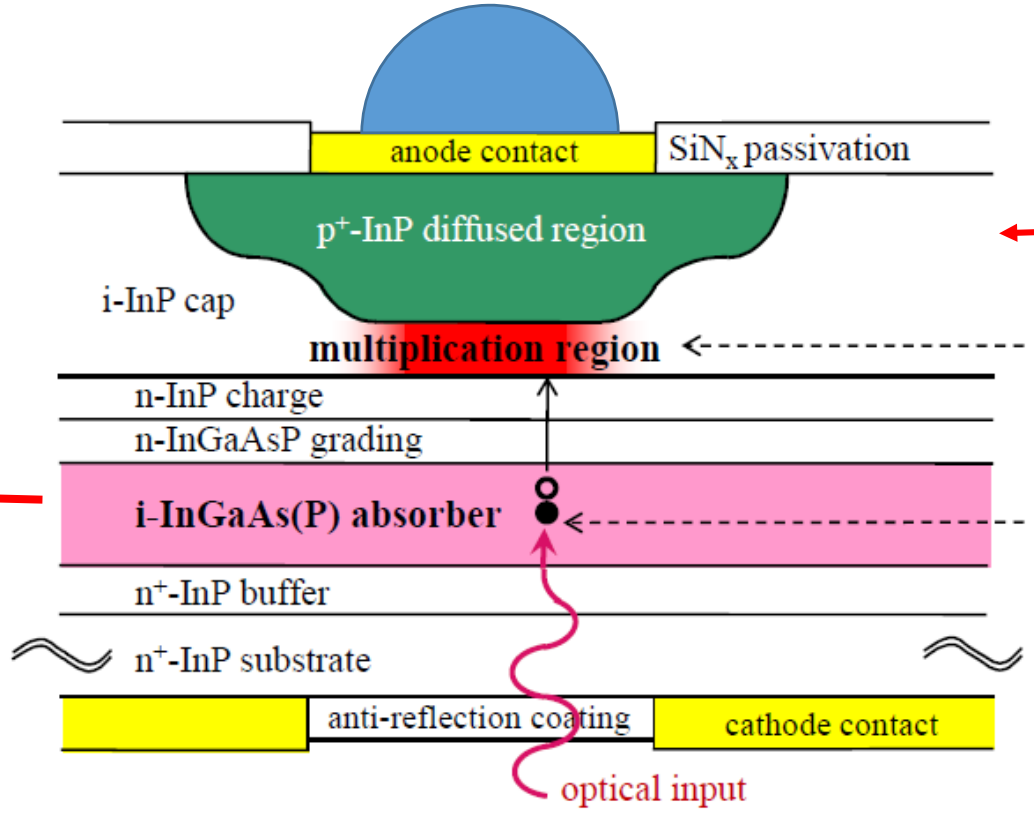
Must Quench (release high reverse bias)
: long reset time to prevent afterpulse
→ long hold-off time

trapped carriers in the multiplication region

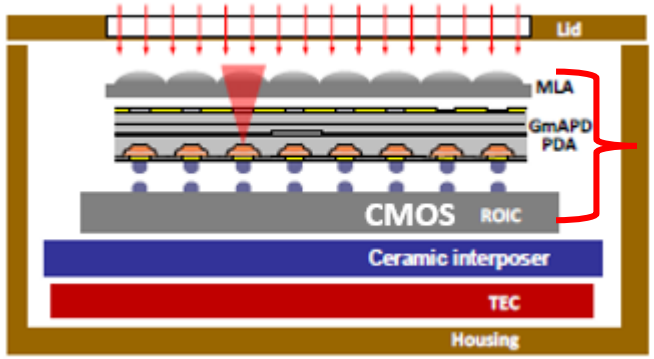
PLI GmAPD camera

128 x 32 chip stack
on interposer





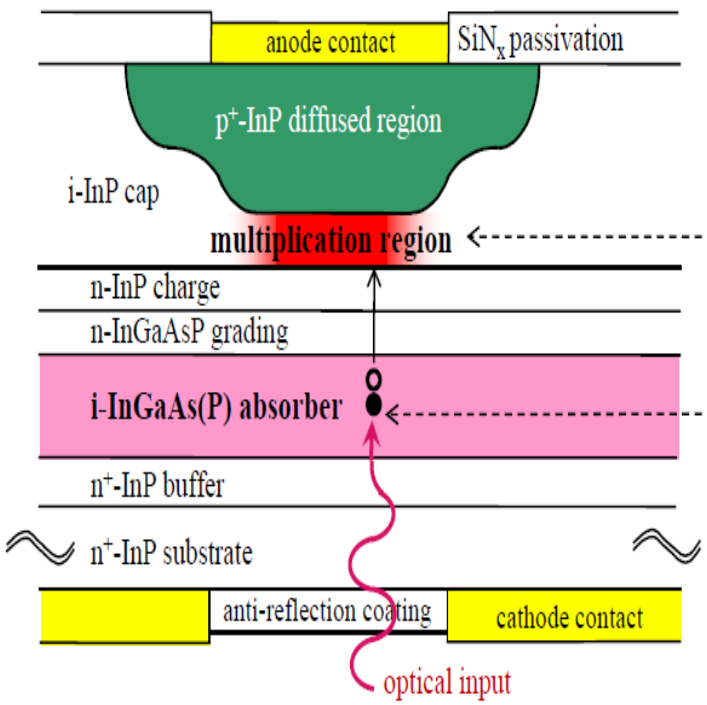
Good sensitivity
to Nd:YAG
(1064 nm)

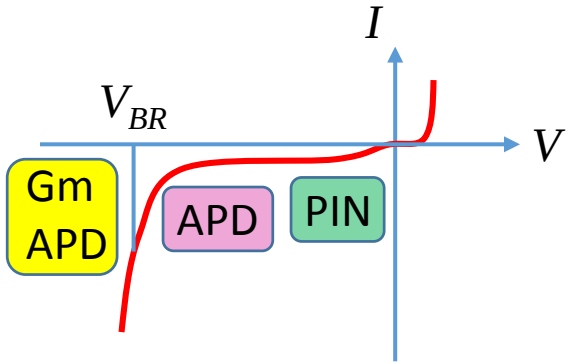


FPA
Chip stack

Gm APD

x 10^6 s (infinite)

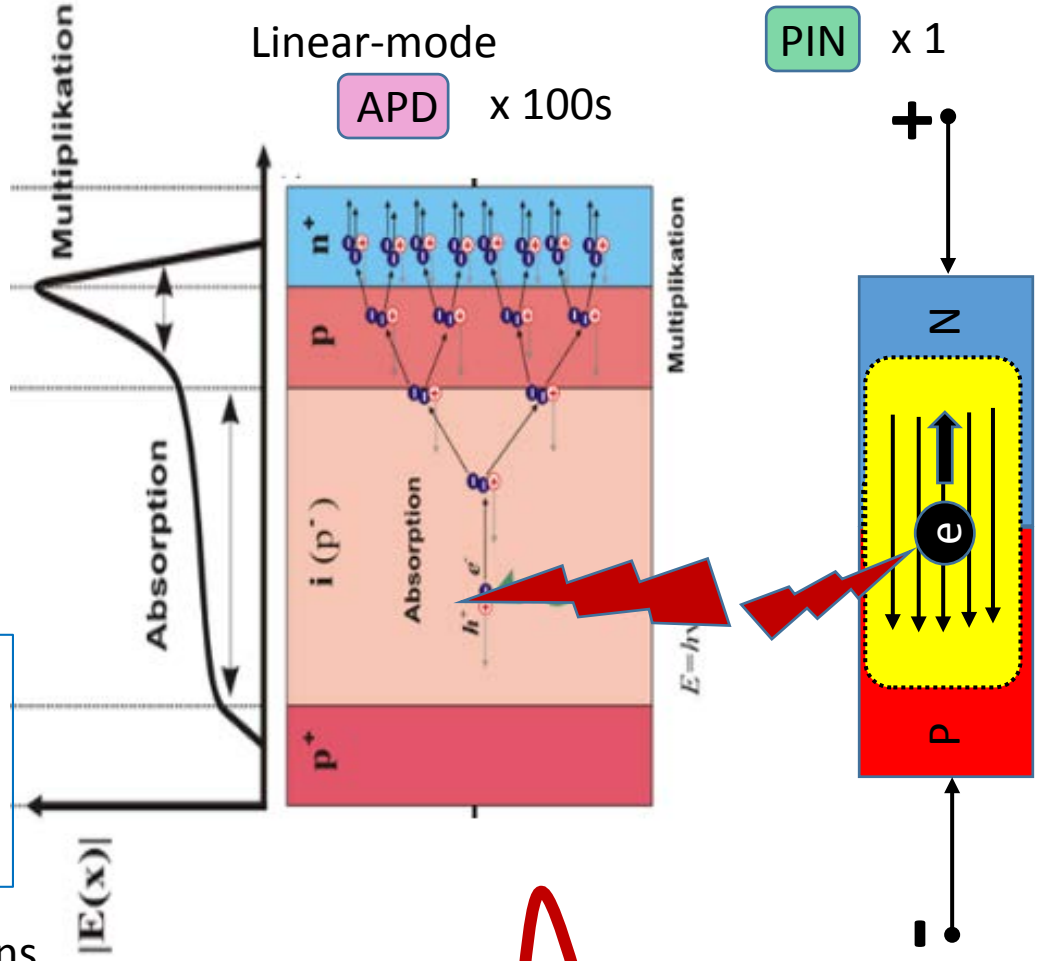




Linear-mode

APD x 100s

PIN x 1



SigmaSpace

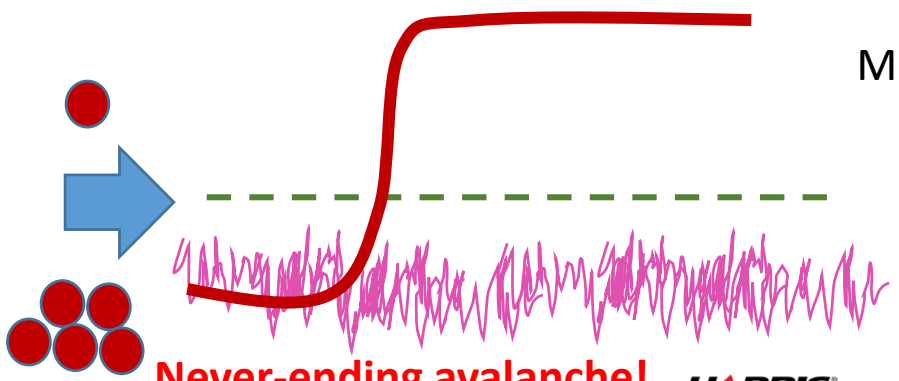
MCP-PMT multi-anode

1-bit → no intensity info

➔ Multiple returns!

dead time ~ 1.6 ns

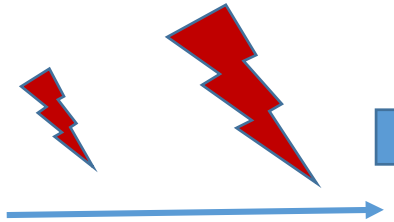
Minimum 1000s of photons

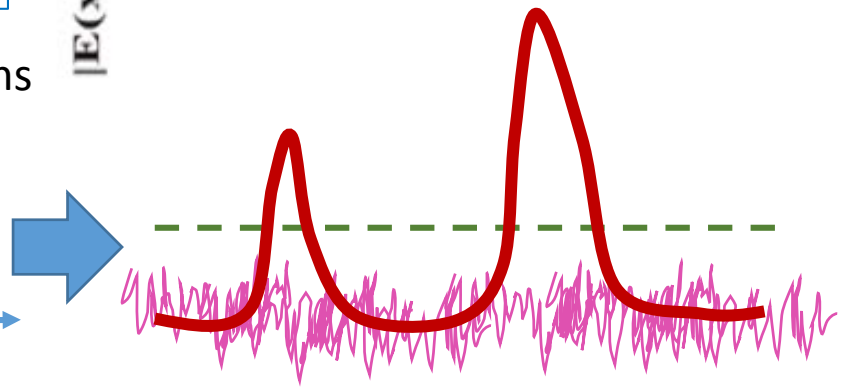


Never-ending avalanche! HARRIS

(no quenching → single return only)

1-bit trigger device → no intensity info

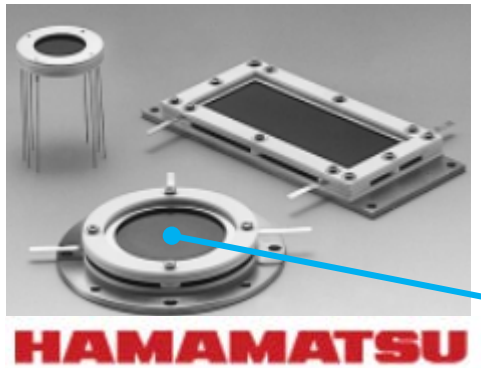




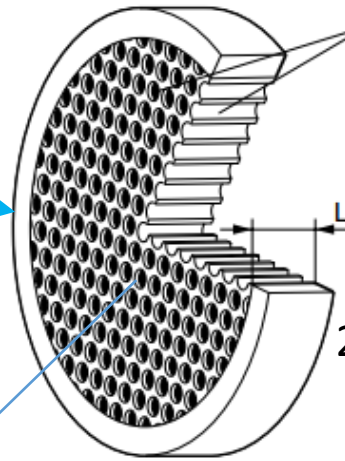
Multiple returns from 1 pulse!

Linear response (intensity → surface reflectance)

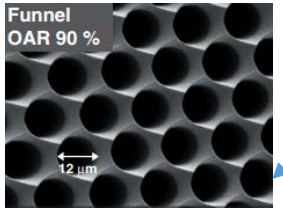
Micro Channel Plate(MCP)
Multi-anode MCP-PMTs

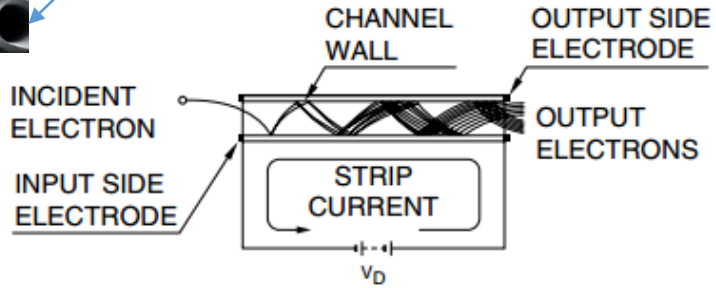


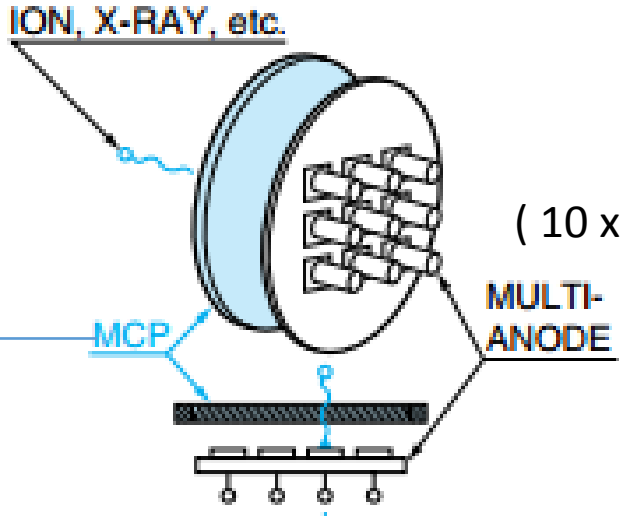
Schematic structure of MCP

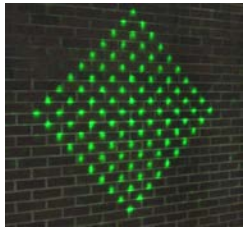


2-3 MCPs stacking





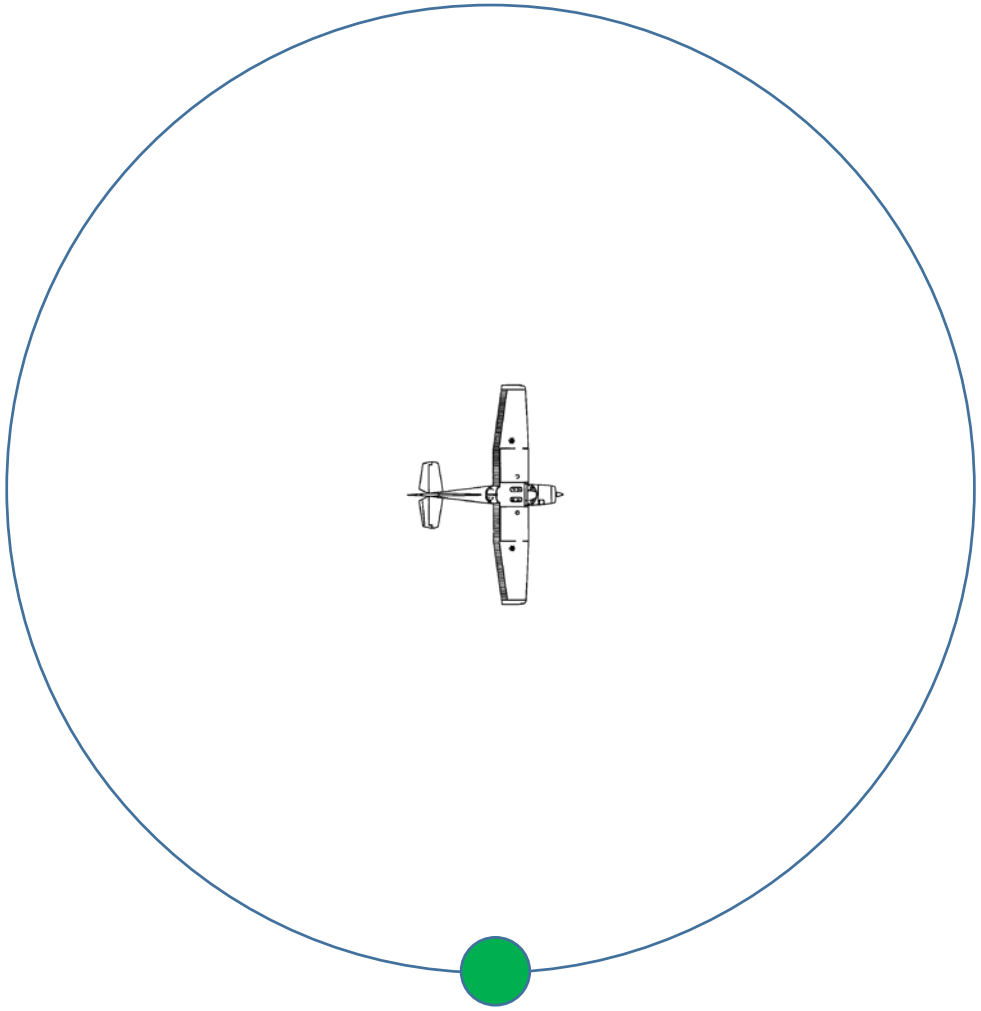


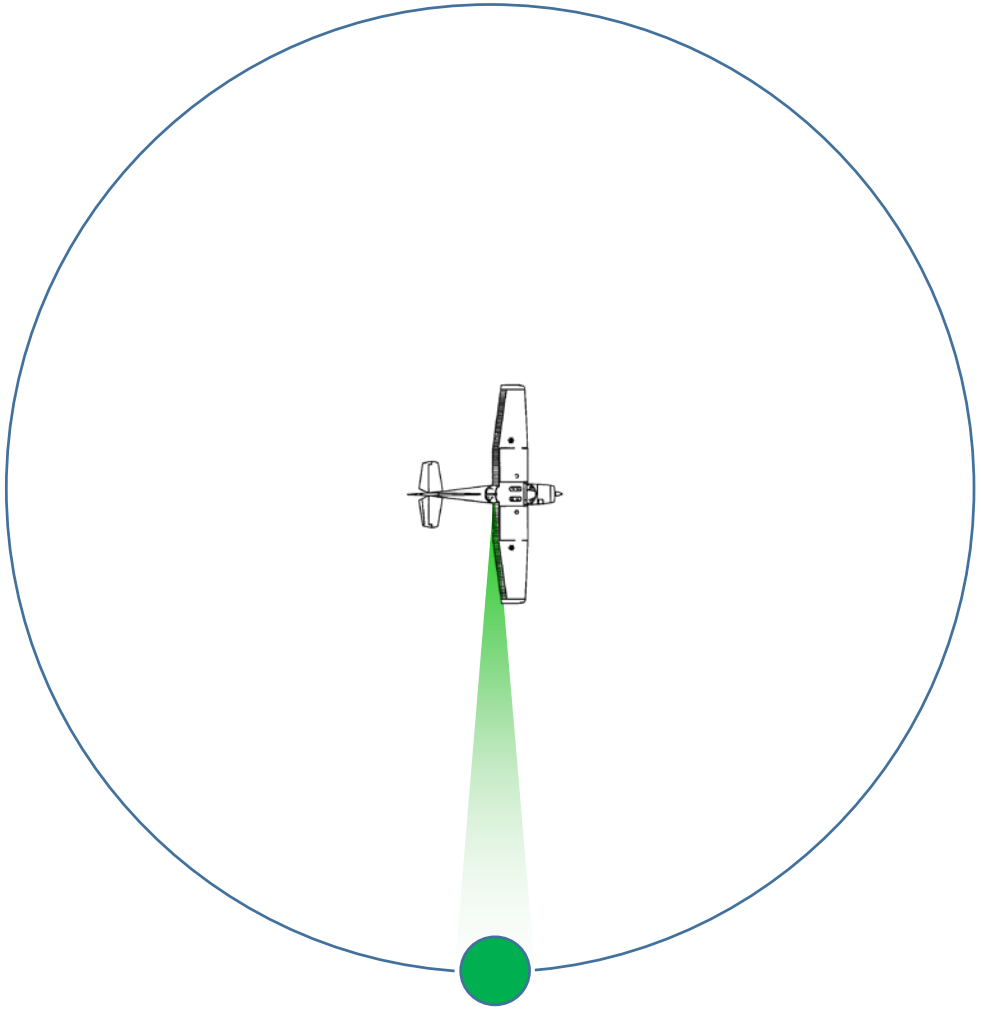


(10 x 10)

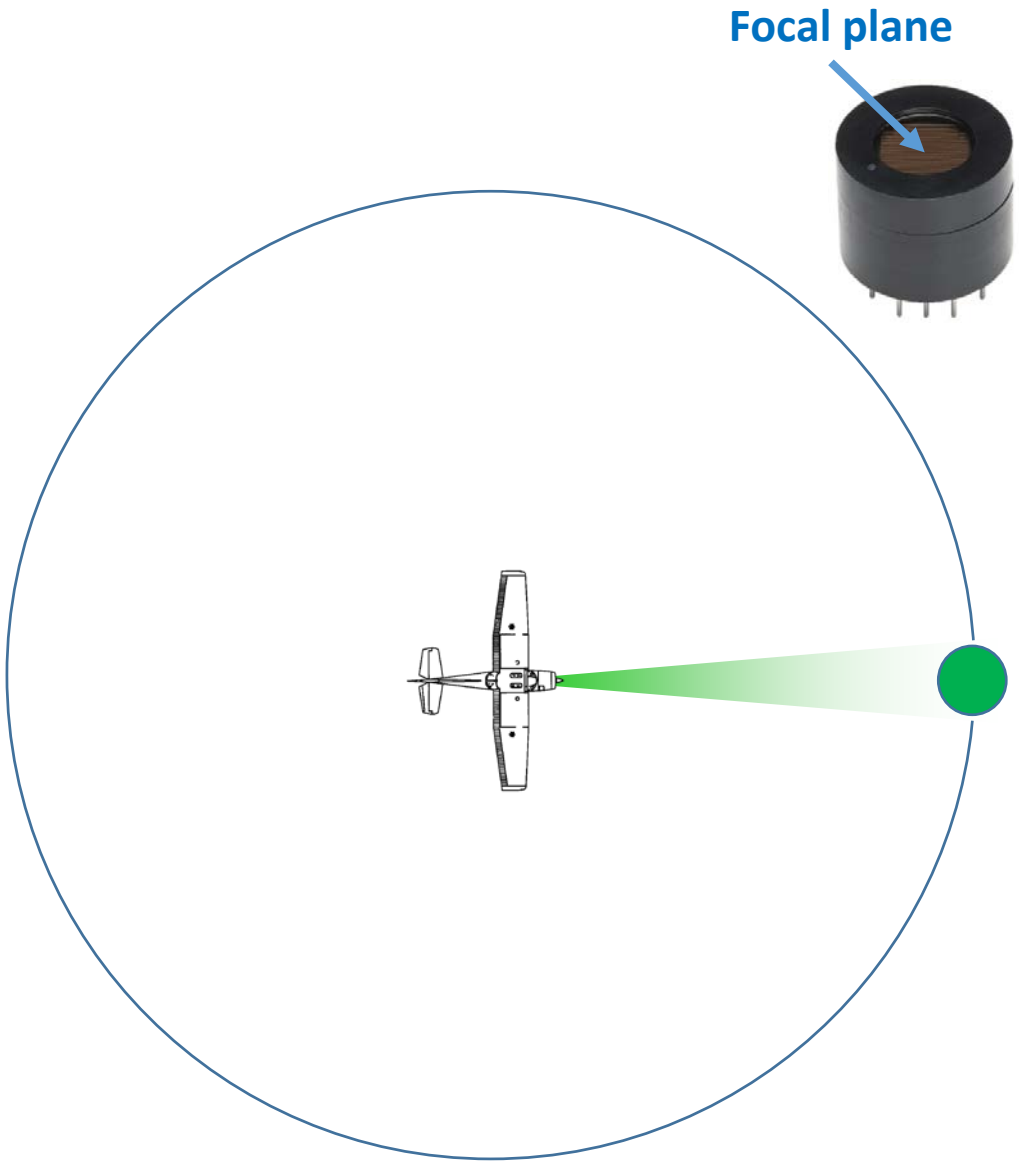
2 x 50-CH ➔ 100 timer

(multiple returns from each channel)

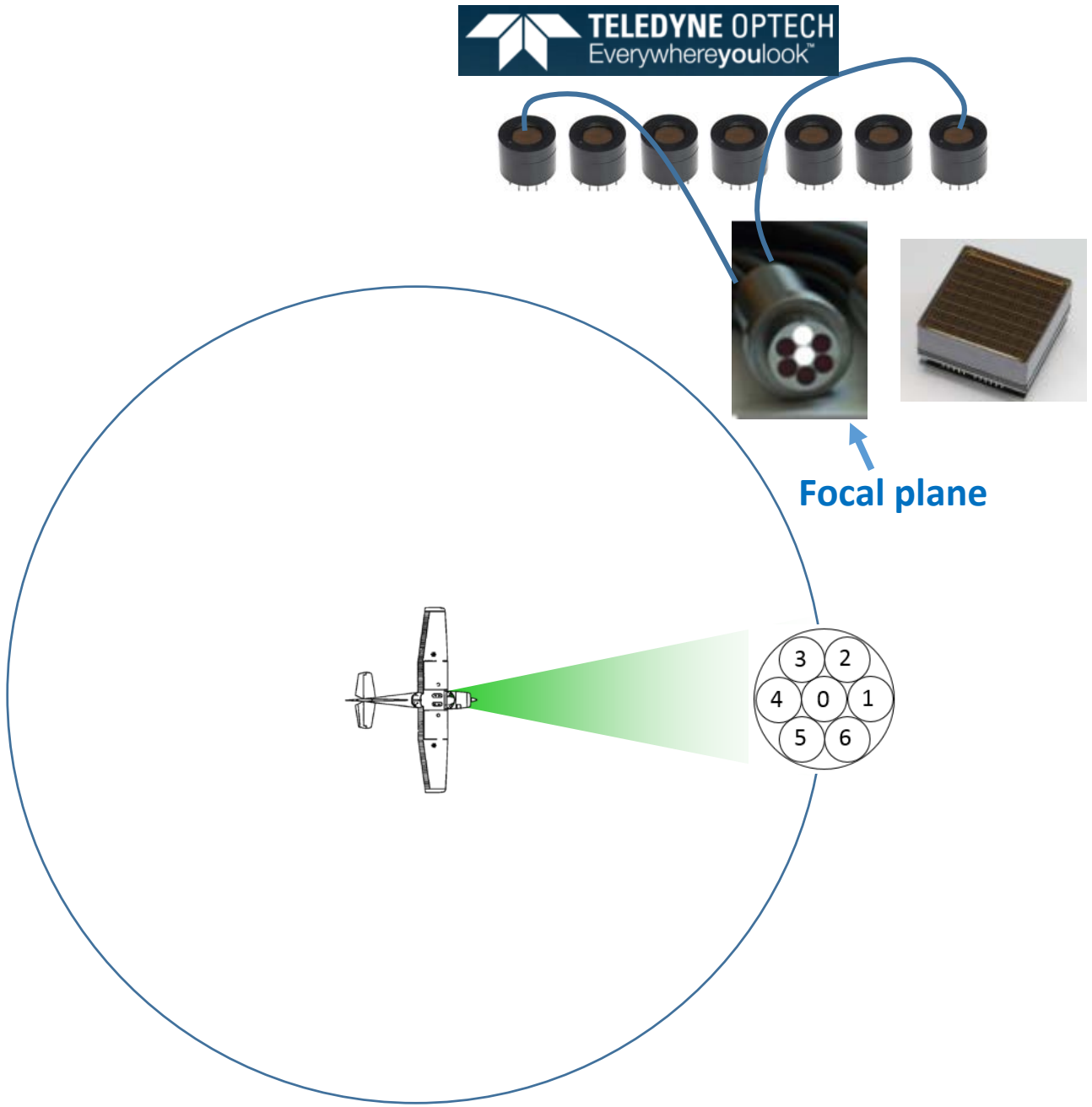




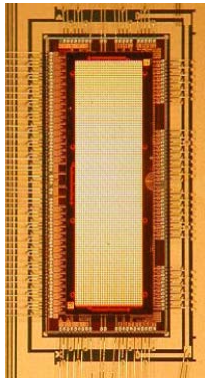
Single detector system

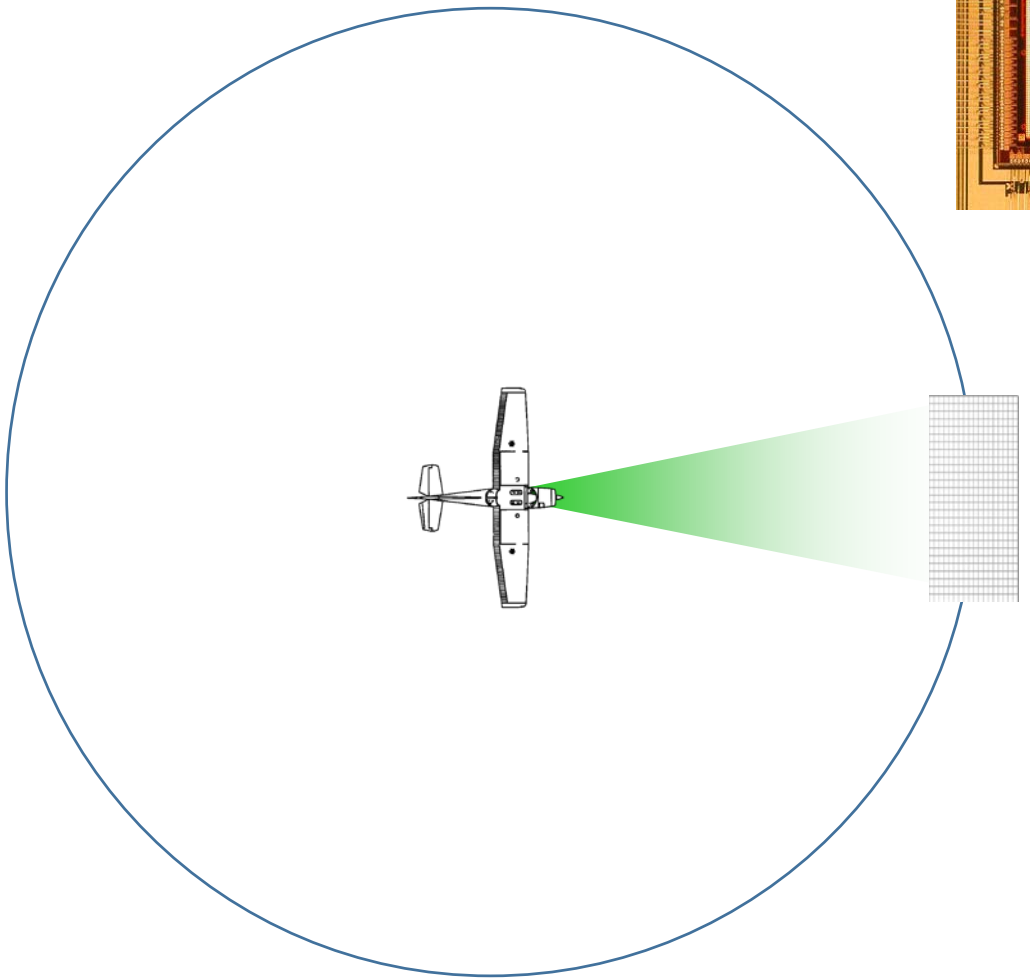


Multiple detector system

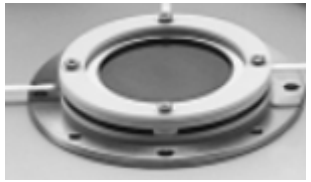


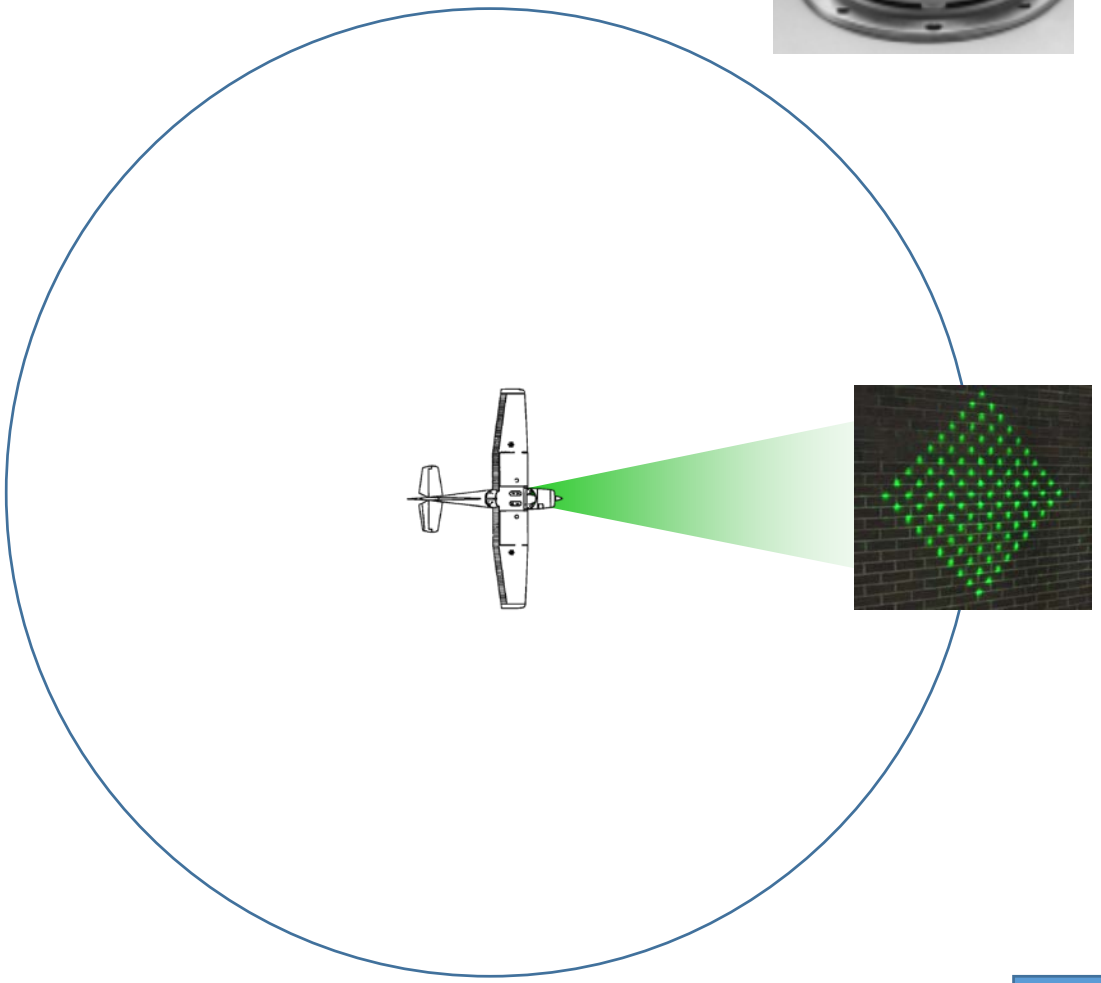
HARRIS



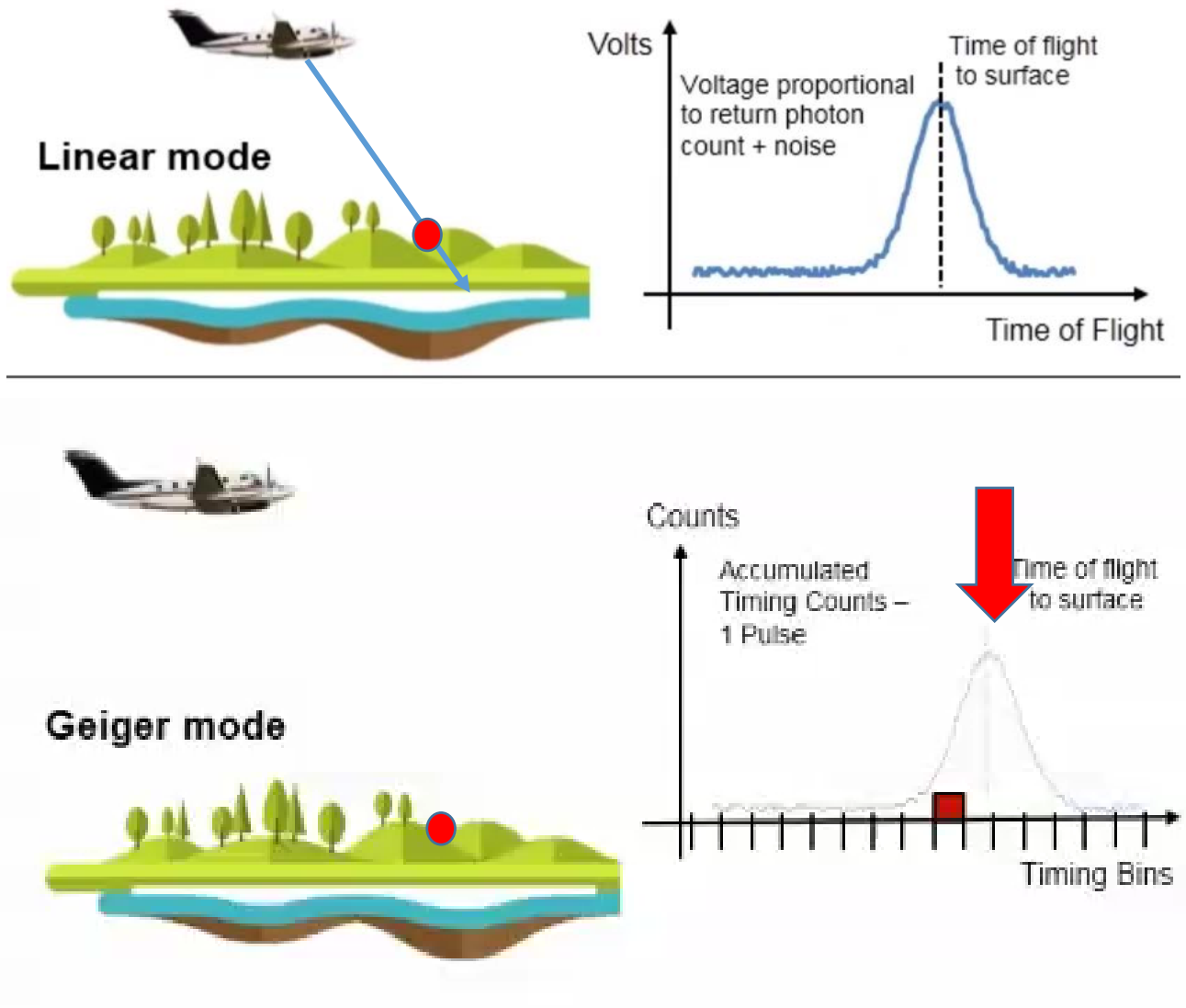


SigmaSpace
EXCELLENCE IN AEROSPACE TECHNOLOGY



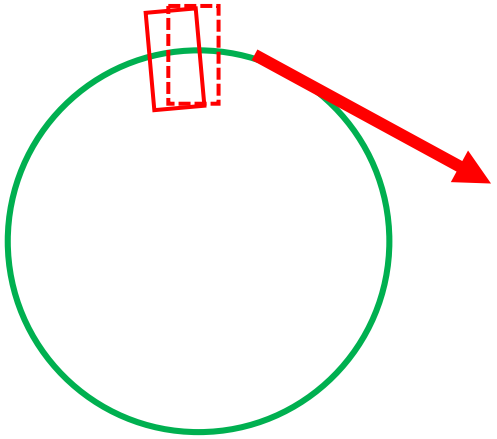


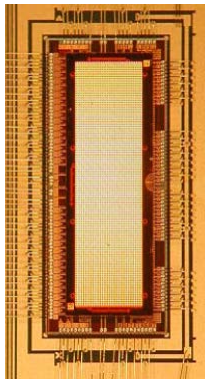
How a point is determined in GmAPD lidar ?



Geiger-mode sensors sample the same spot on the ground multiple times

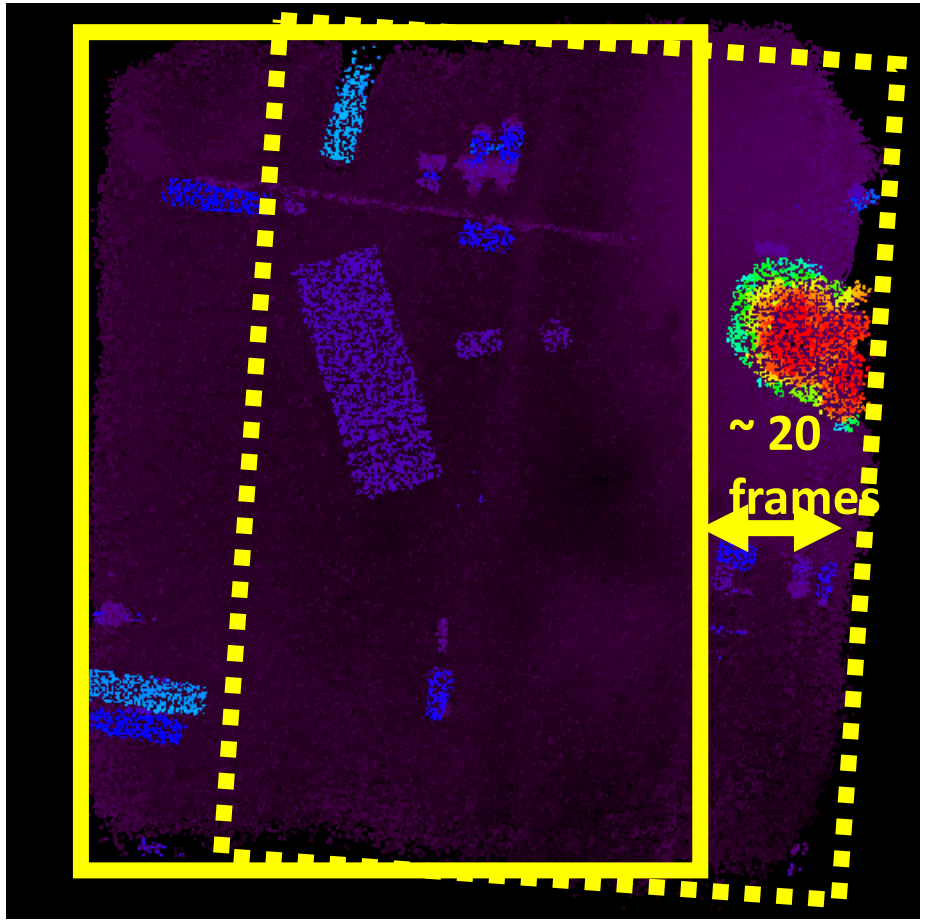
MTF target, Hanscom AB, MA

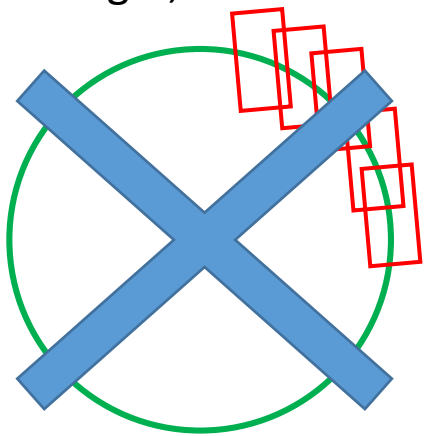




Sortie_0937_CTA-05a_id7442

20140923034233





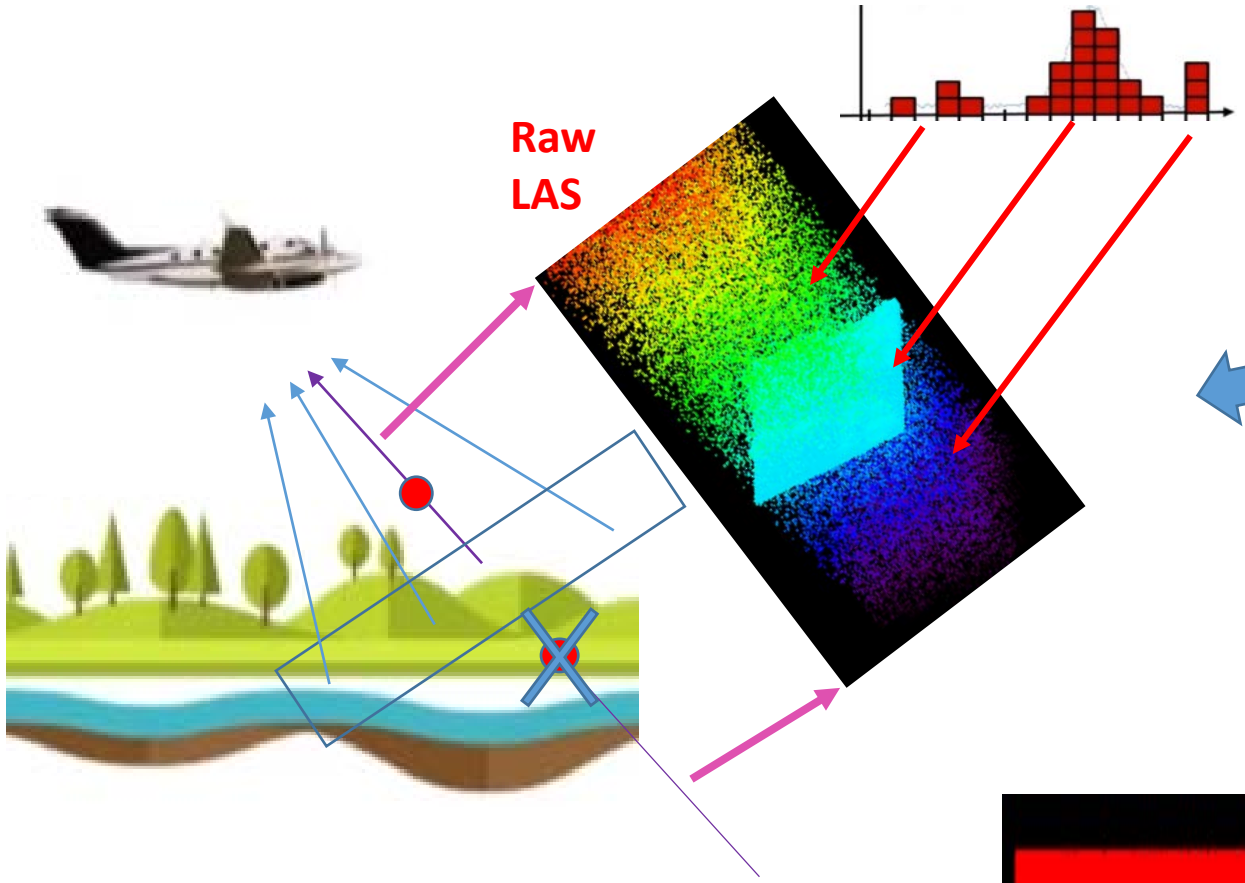
Very high (~ 99%) Frame overlapping rate

is a must! Why?

To overcome low point confidence(high false alarm prob.)

➔ To ensure the real surface points to survive the noise-filtering

Noise filtering

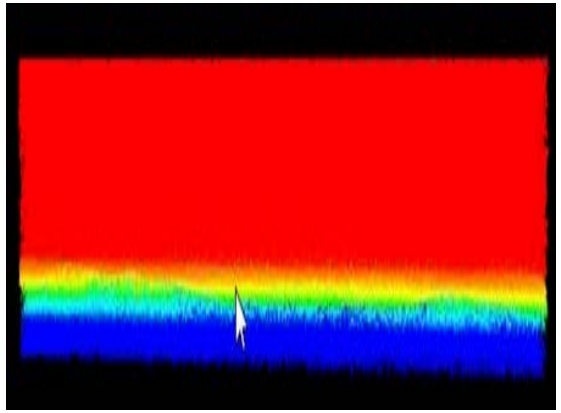


Thermal-trigger
Solar background photon
Laser-leak between pulses

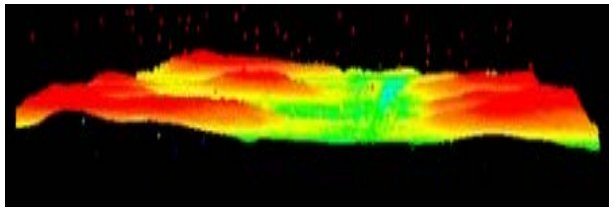
HARRIS

Major noise source
: **solar** background photon

SigmaSpace



CRR: Correlation range receiver



Why big difference in solar background contribution ?

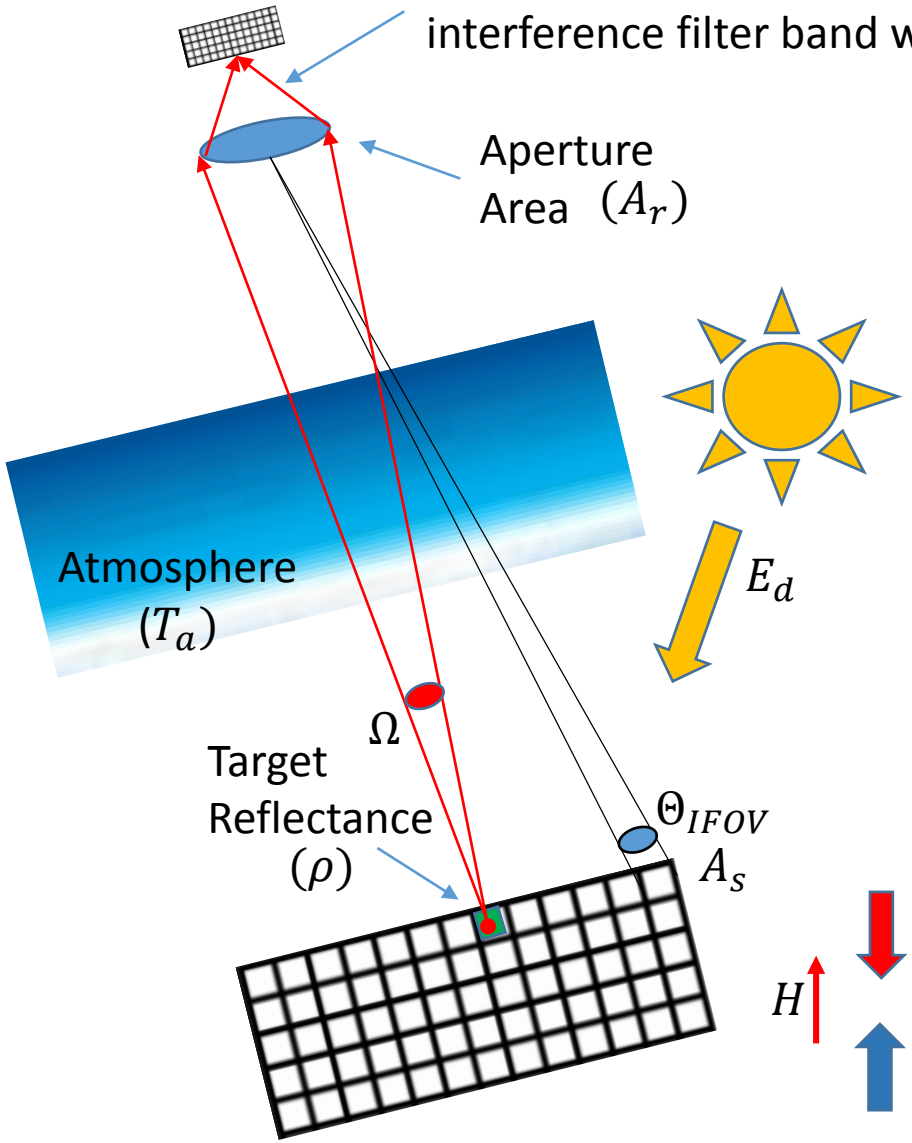
Noise : surface reflected solar photons

P : *altitude independent*, $P \propto (\Theta_{IFOV})^2$

$$P = T T_a \rho A_r E_d \Delta\lambda \, (\Theta_{IFOV})^2/4$$

0.5 $Wm^{-2}nm^{-1}$ 1.0 **35 µrad**

0.5 1.0 0.3 $\pi(0.27)^2/4$



$$L = \frac{\rho}{\pi} E_d$$

$$\Omega = \frac{A_r}{H^2}$$

$$A_s = \frac{\pi D_s^2}{4} = \frac{\pi(\Theta_{IFOV} H)^2}{4}$$

$P \sim 10^{-12}$ W

Optical power onto a FPA pixel due to reflected **solar** photons

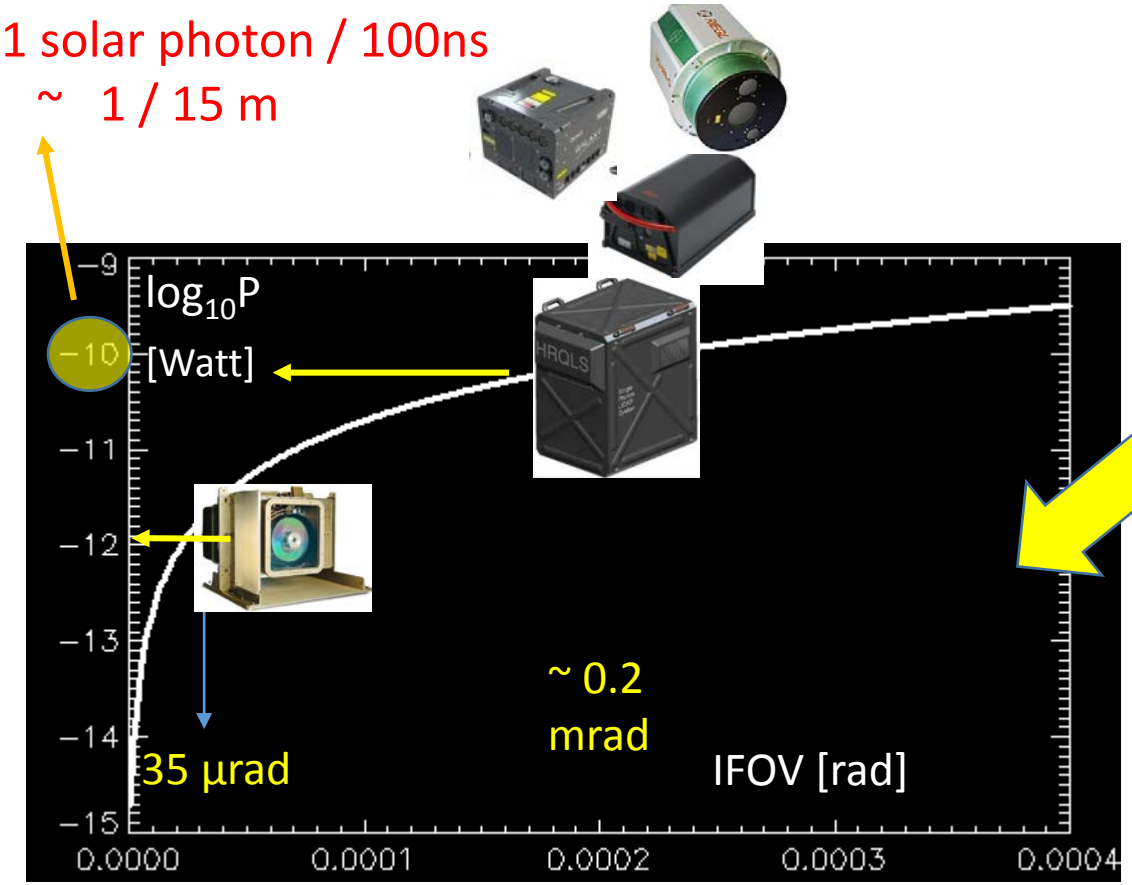
IFOV = **200** µrad

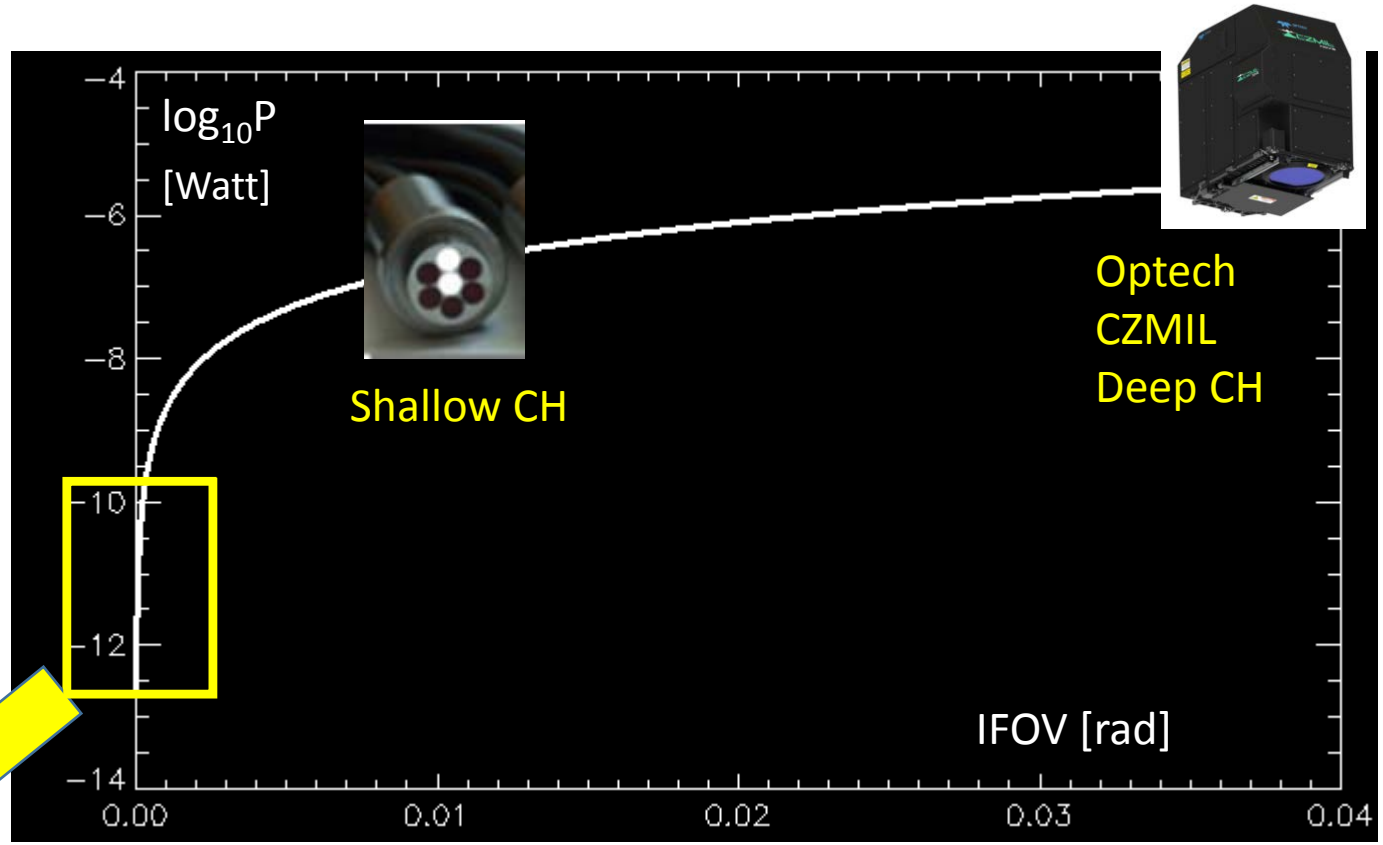
13 cm, $E_{d,532nm}$ =1.0

20% more ρ

Effect of IFOV on solar background

1 solar photon / 100ns
~ 1 / 15 m





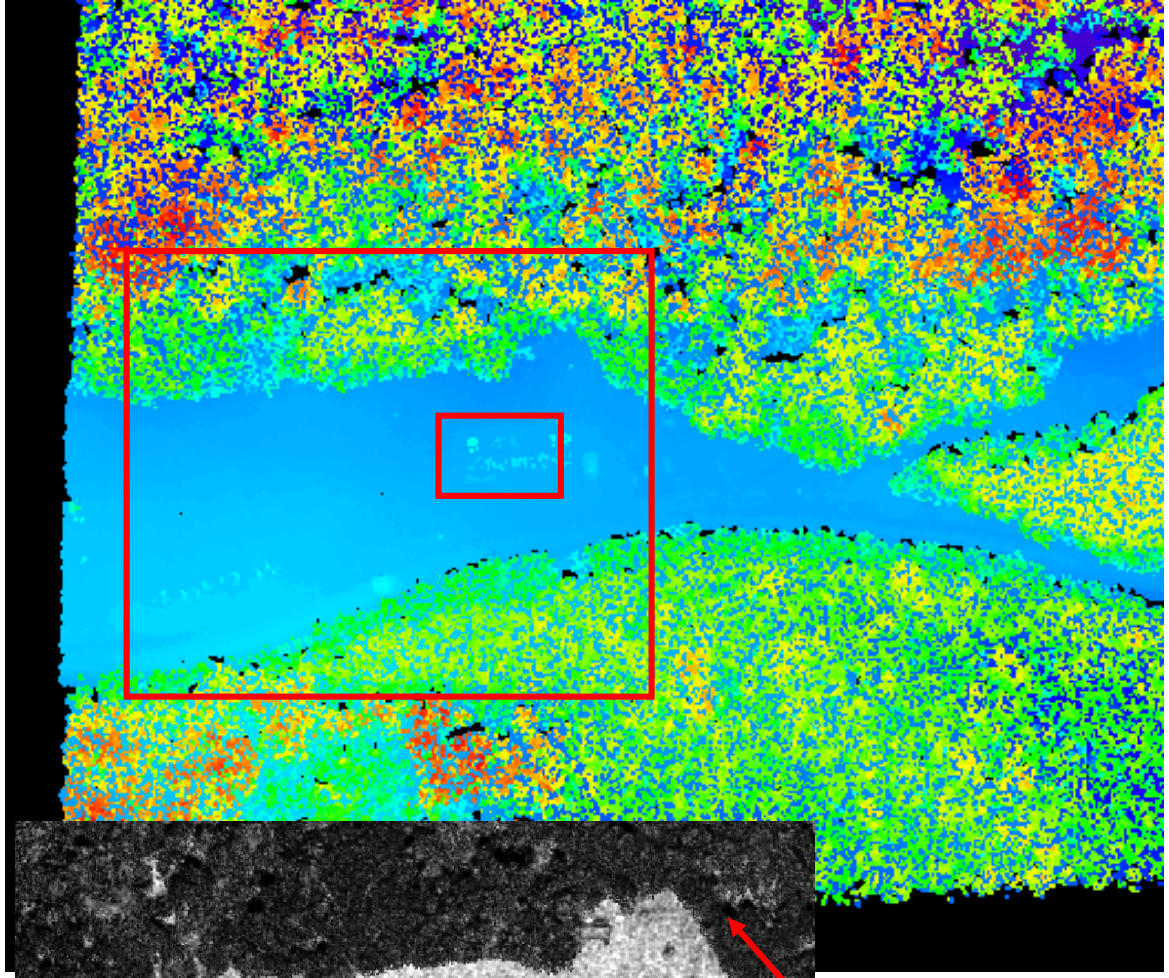
Single photon energy ➔ optical power

532 → ~ 4 × 10^{-17} J ➔ 4 × 10^{-8} W
1064 → ~ 2 × 10^{-17} J ➔ 2 × 10^{-8} W

Intensity image ← → 2D point density of projected area (pixel)

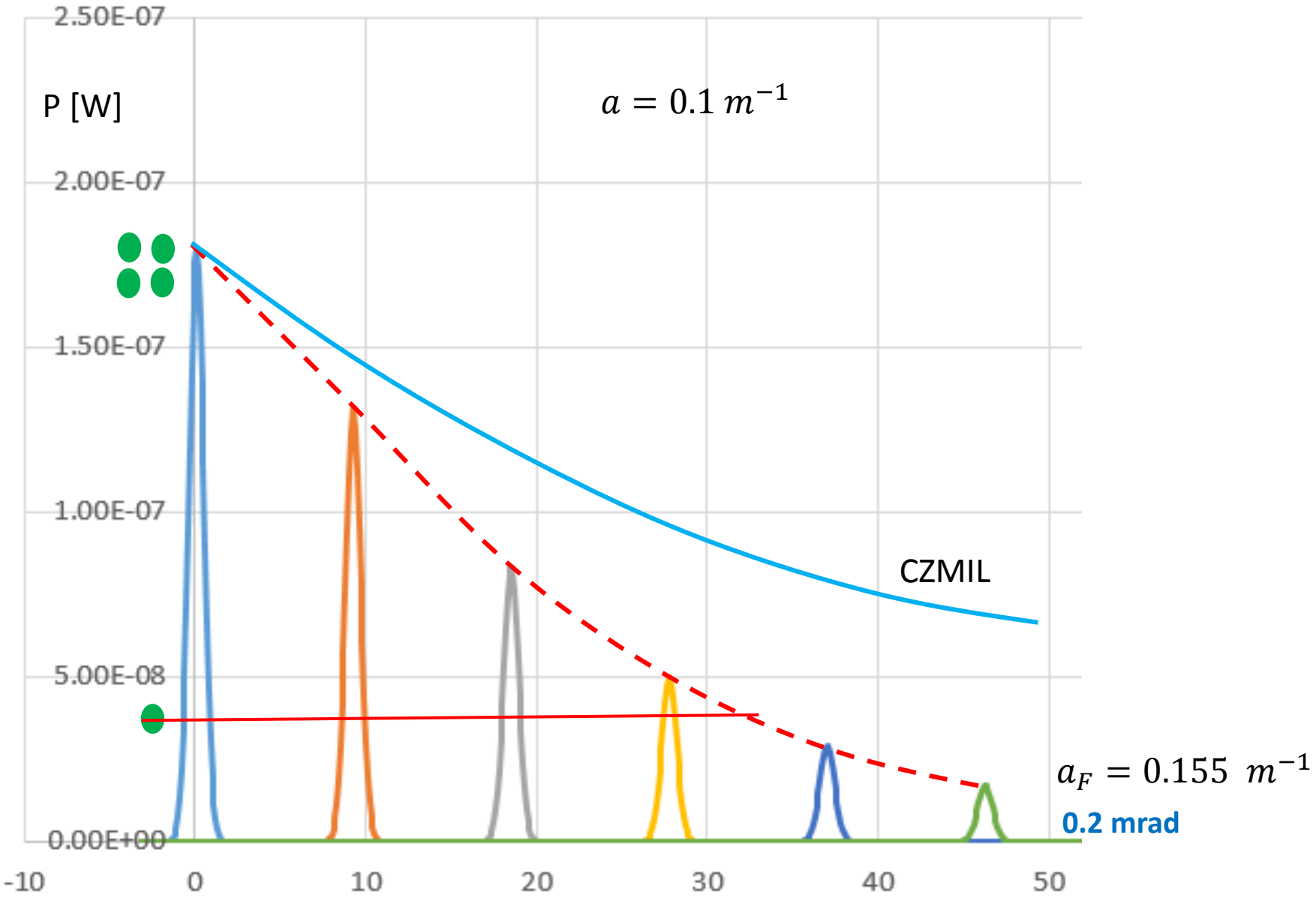
GmAPD lidar
: noise-cleaned point cloud
SPL
: Without removing solar background noise

Sortie_0938_Pt Target - Camps and Pad - 3a_id7395

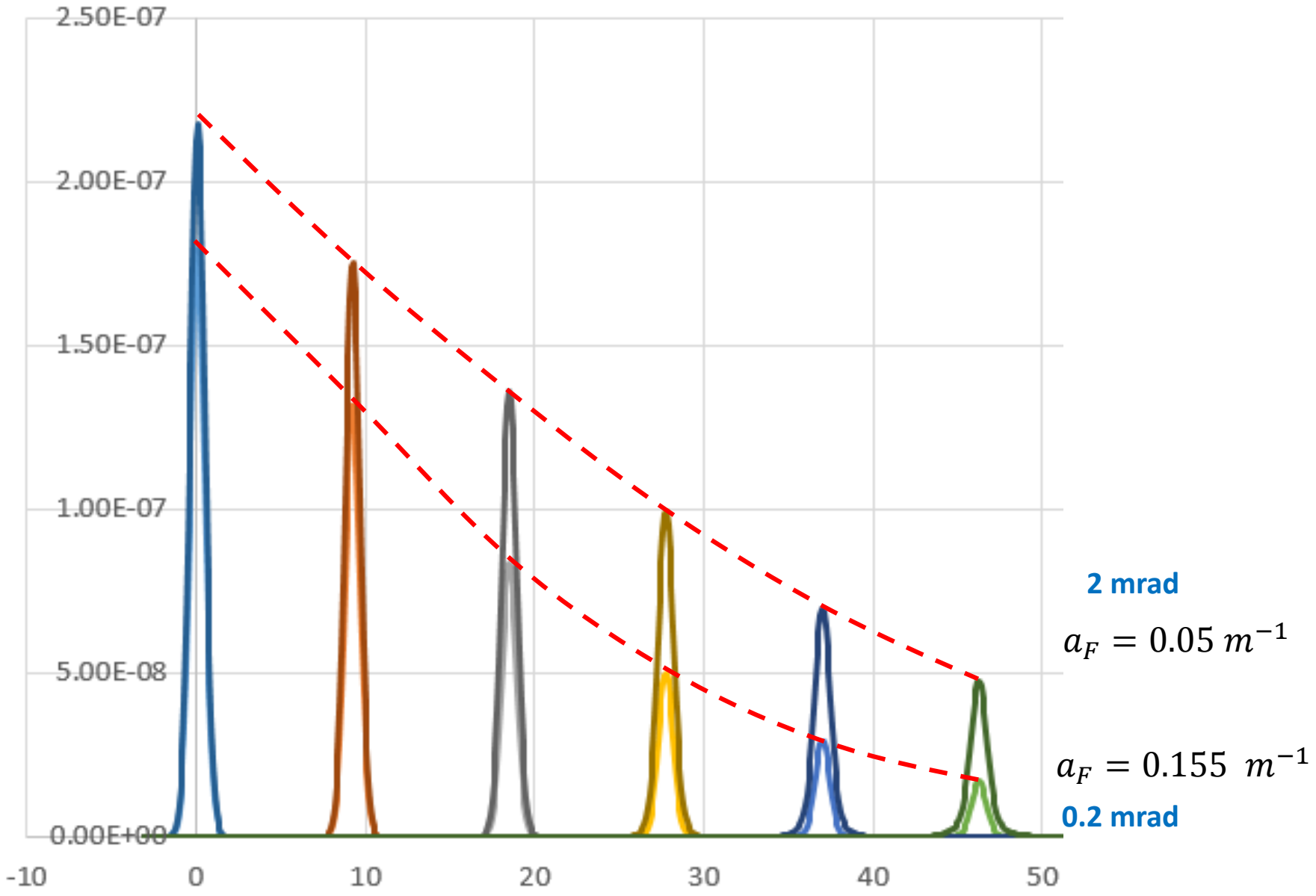


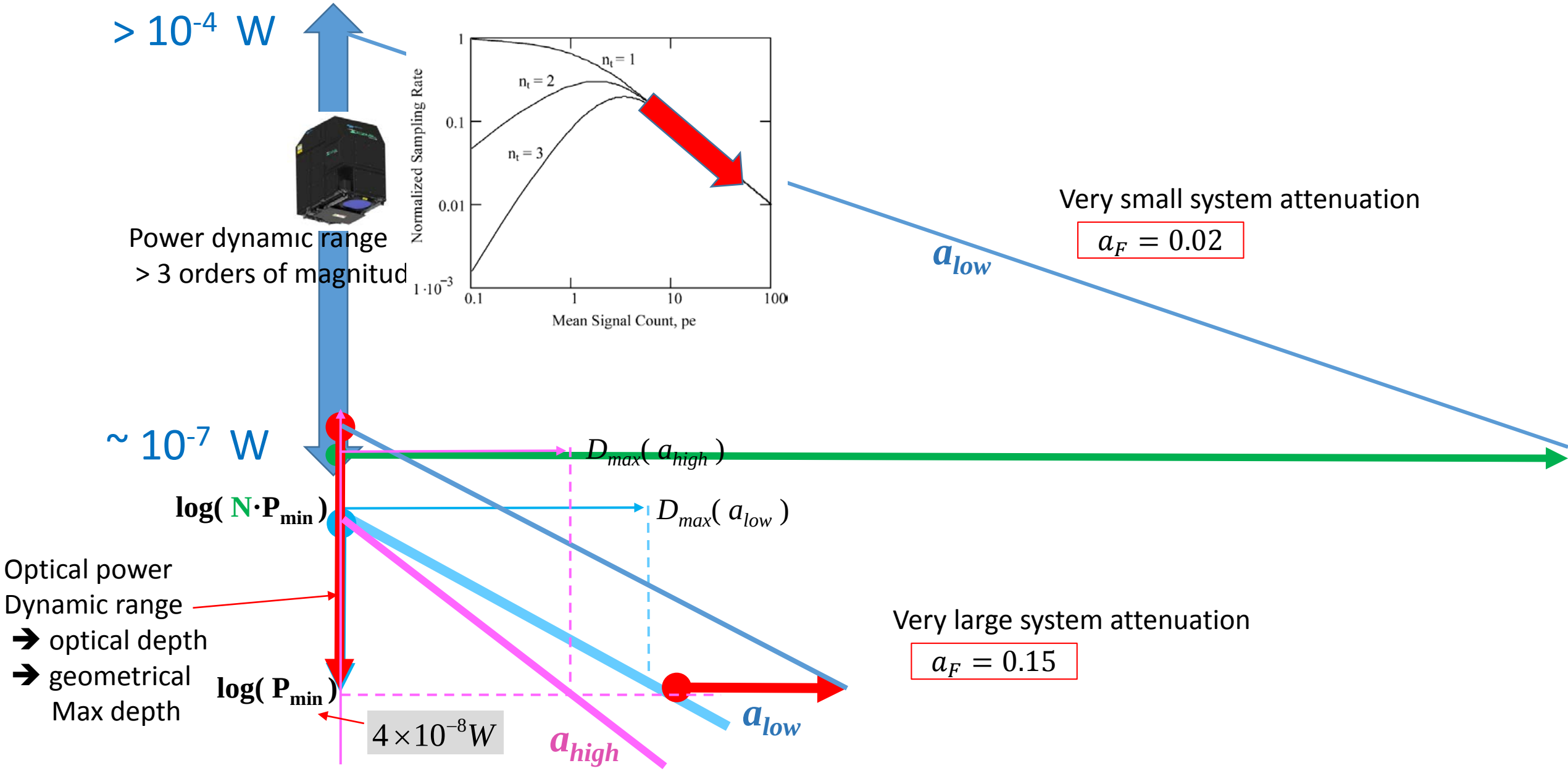
Should be nearly the same reflectance ??

→ Issue with noise-cleaning

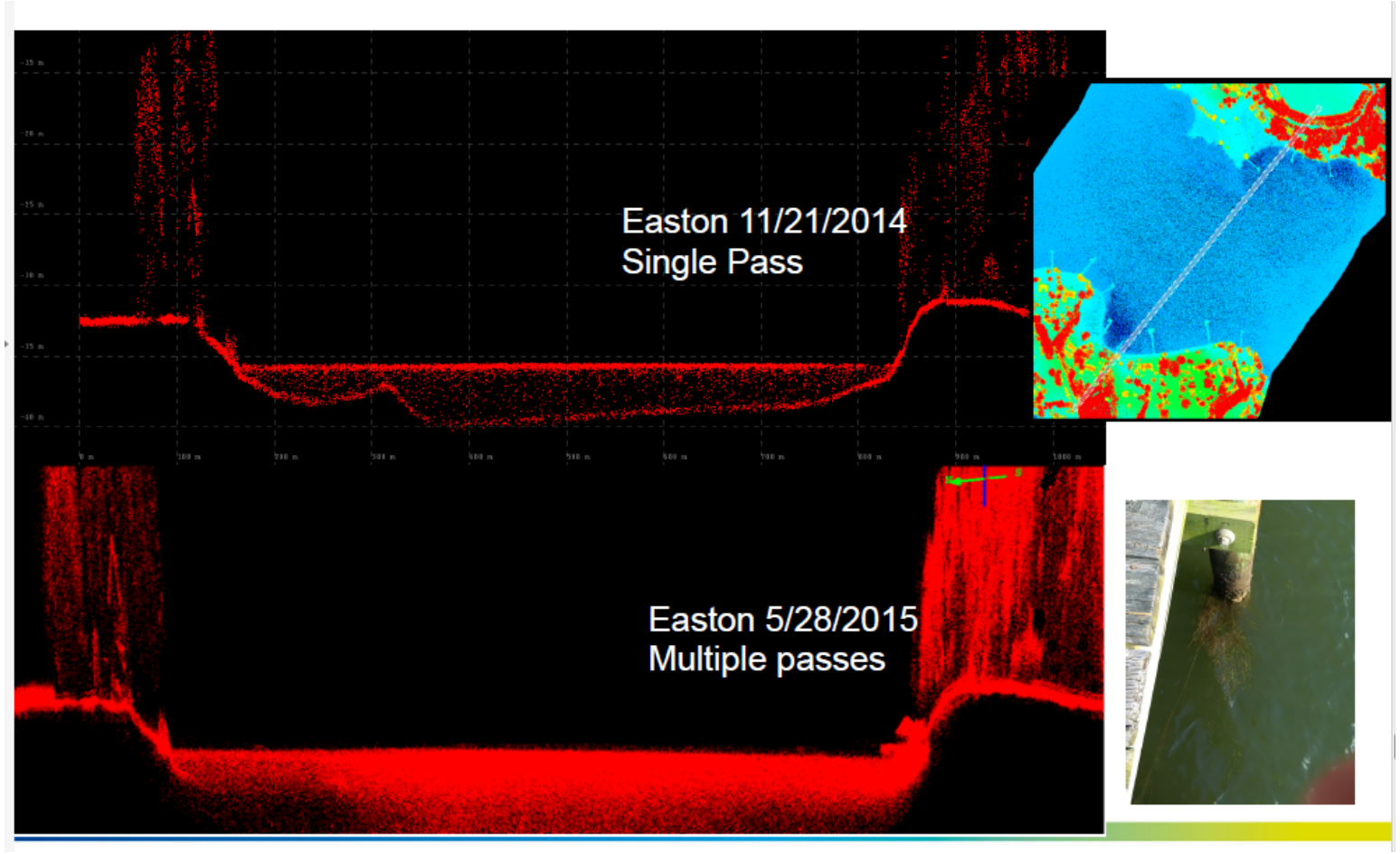


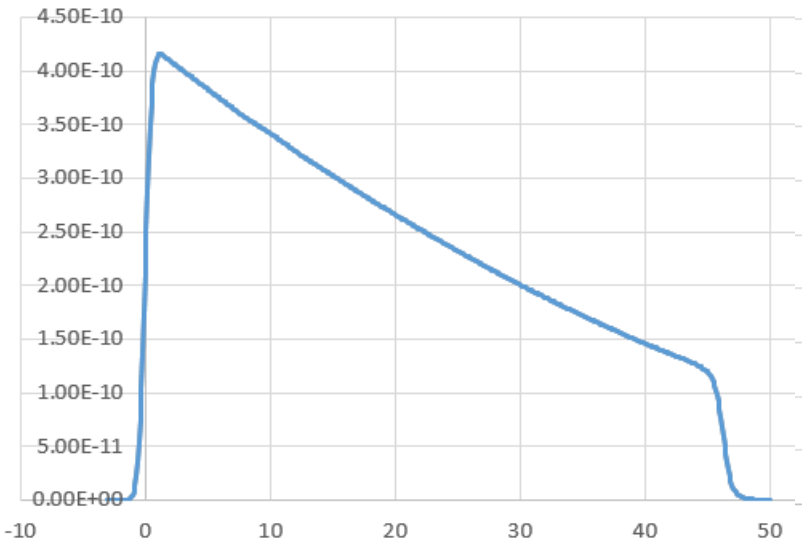
Advance Waveform Simulator


2.50E-07
2.00E-07
1.50E-07
1.00E-07
5.00E-08
0.00E+00
-10
0
10
20
30
40
50
2 mrad
$a_F = 0.05\ m^{-1}$
$a_F = 0.155\ m^{-1}$
0.2 mrad


> 10-4 W
Power dynamic range
> 3 orders of magnitud
Normalized Sampling Rate
Mean Signal Count, pe
nt = 1
nt = 2
nt = 3
1
0.1
0.01
1·10−3
0.1
1
10
100
Very small system attenuation
$a_F = 0.02$
a_{low}
~ 10-7 W
$D_{max}(a_{high})$
$D_{max}(a_{low})$
log(N·Pmin)
Optical power
Dynamic range
➔ optical depth
➔ geometrical
Max depth
log(Pmin)
$4\times10^{-8}W$
a_{high}
a_{low}
Very large system attenuation
$a_F = 0.15$

What are those points in the water???





Volume return ?
Suspended object ?
Solar photon noise ?

Integration of the
entire volume backscattering
→ Less than a single photon energy

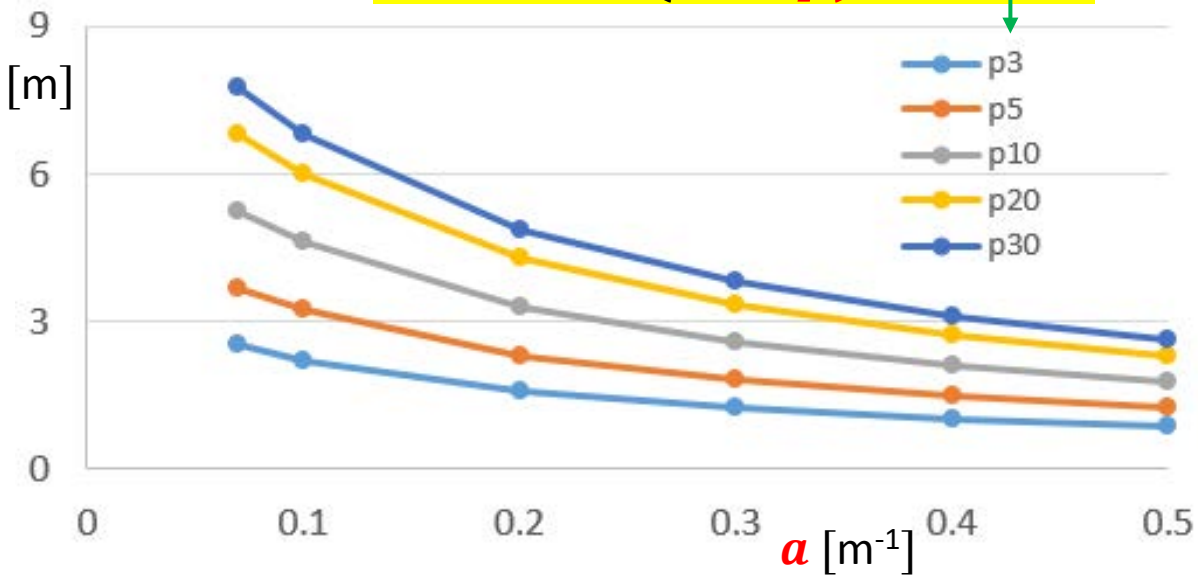
➔ No contribution from volume return
➔ Most (All) from Solar background

Effect of IFOV and max depth

Attenuation due to F-function of HRQLS system
(mainly due to a small FOV relative to beam divergence)

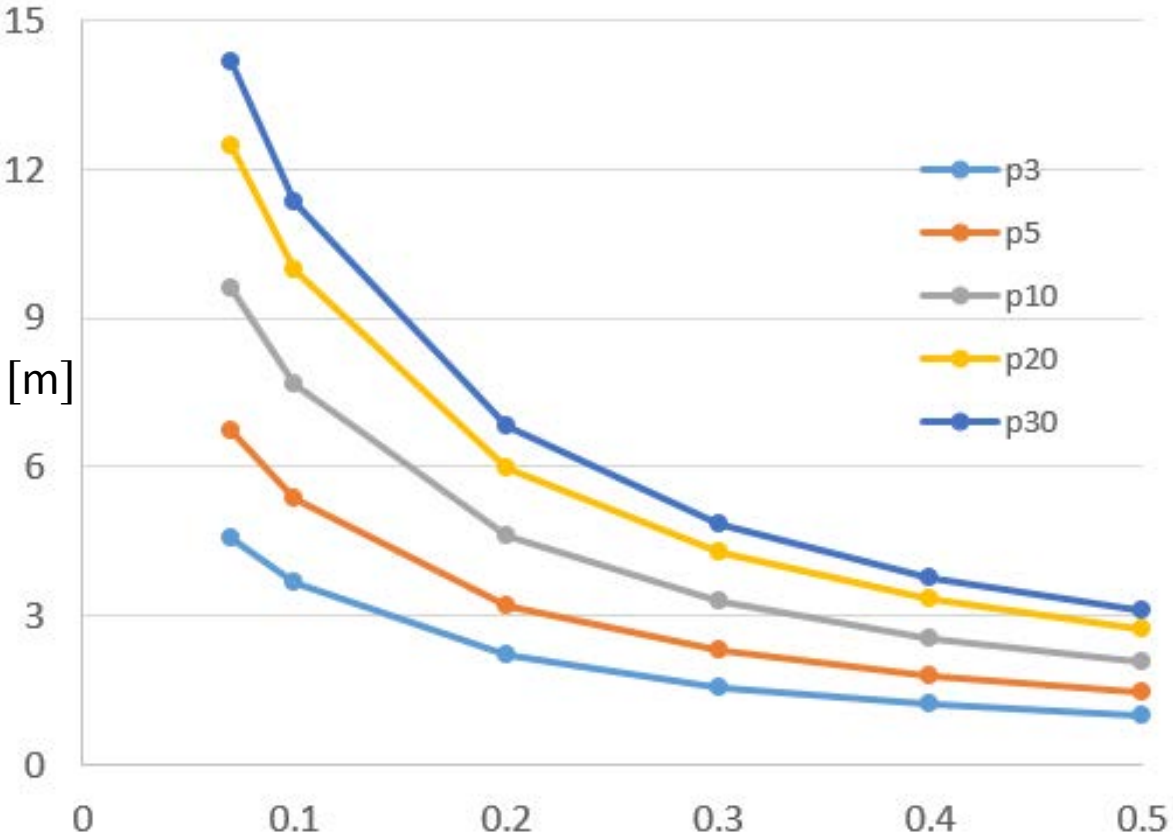
$a_F \sim 0.15 m^{-1}$

$$D_{max} = \frac{1}{2(a+a_F)} ln(N)$$



(if IFOV = 2 mrad)

$a_F \sim 0.05 m^{-1}$



Altitude [m] (e.g. 400) :	1000
Air incident angle [deg], e.g. 20) :	20
pulse energy (mJ) :	0.001
optical transmittance (0 - 1.0) :	0.36
receiver pupil radius (cm) :	6.5
theta_off_angle (e.g. +/- in mrad, 2) :	0
Receiver FOV (exp[-1] level in mrad) :	0.2
Receiver source model	Gauss
Beam div (exp[-1] level in mrad) :	0.1
Beam source model	Gauss
FWHM sys res, 0 for t0 :	1.0
Asymmetry, ignore if 1, surf	1
bottom	1

Numerical

Simulation time interval [ns]	0.1
min power [W] to stop calculation :	1.0e-14
z0 expansion factor (> 1.0) :	1.1
max number of discrete rv (integer) :	50
max points on z-plane for g :	100
max cumulative g_function (~ 0.92 - 0.97)	0.95
Simulation mode :	FULL_WAVEFORM

surface_reflectance (0 - 0.02) :	0.002
Select IOP simulation method :	a+bb driven
a+bb (0.06 - 1.0 /m) :	0.2
Dolin alpha (5 - 8) :	7

Independent IOPs

beta_pi, [1/m/sr] :	0.001
forward scattering (0.2 - 4.0 /m) :	0.2

a+bb driven IOPs

single scattering albedo (w0, 0.7 - 0.9) :	0.8
bb/b (0.015 - 0.04) :	0.02
beta_pi/bb (0.5 - 0.8) :	0.65
bottom_reflectance (0 - 0.5) :	0.2
Bottom slope [deg], (+) rising) :	0
depth (m) :	0.1

Object (target) simulation

Select object type	NO
cuboid side, sphere or cylinder diameter	2.0
object length or height (m) :	2.0
object reflectance :	0.05
object shift (m) :	0.0
object suspension height (m) :	0

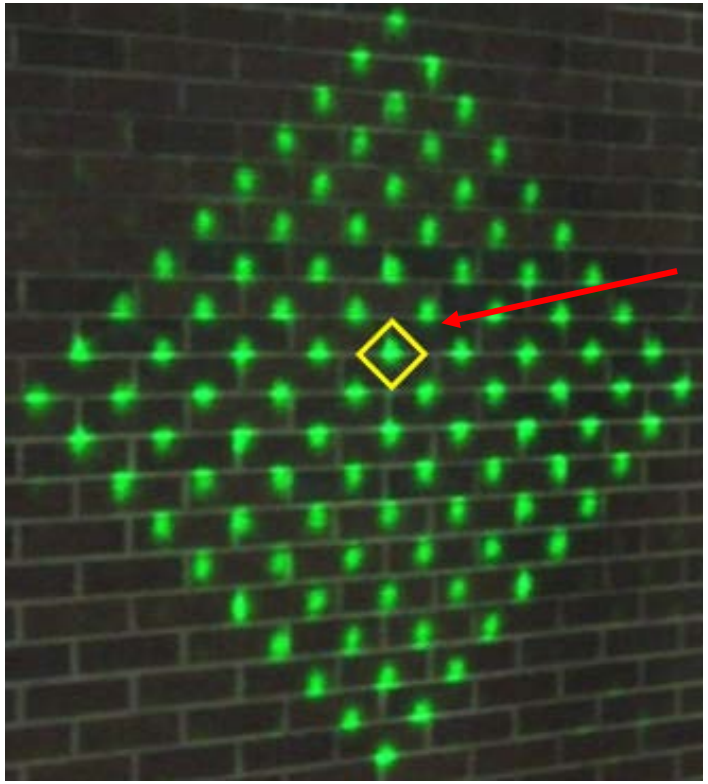
Lidar waveform simulator

Theory : Radiative Transfer of a Laser pulse through the abs/scat medium

Bluebook II Ch.5

Waveform simulation : Bluebook II Ch.6

Presented at JALBTCX, Chicago



IFOV ~ 0.2 [mrad]

Beam **Divergence** ~ **0.1 ?**