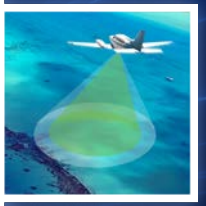
TELEDYNE OPTECH
Everywhereyoulook™

46 years in Laser Bathymetry: Myths and Reality

Dr. Viktor Feygels



17th Annual JALBTCX Airborne Coastal Mapping and Charting Technical Workshop
Silver Spring Civic Center, MD 20910
July, 2016

Accuracy & Productivity Matter

Oscar Wilde visited Leadville, Colorado in 1882 and gave a lecture on the **Ethics of Art** at the famous Tabor Opera House. Afterward he was taken to a "dancing saloon" where Oscar remarked "I saw the only rational method of science criticism I have ever come across. Over the piano was printed a notice: "

"Please Do Not Shoot
The Pianist
He Is Doing His Best"

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My 46 Years with Hydro Lidars

1970 My 46 Years with Hydro Lidars Now

1970-1997
Bottom return is a noise!

1995-now
Bottom return is the signal!

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My Nostalgia

The Soviet Union received its first DC-3 in 1935. Although a total of 18 DC-3s had been ordered on 11 April 1936, the Soviets purchased 21 DC-3s for operation by Aeroflot before World War II. A production license was awarded to the Soviets on 15 July 1936. Russian designer Lisunov spent two years at the Douglas Aircraft Company, between November 1936 and April 1939 translating the design.

My Nostalgia

My First Lidar

Russian lidar was a top-secret till 1984-1986. In a classified journal, we reported “accidental” sea-bottom returns in 1971. We operated the “STRELA” (Arrow) system in December 1970 in the Black Sea, near Soudak, and achieved more than 50(!) meter maximum depths in very clear (for Black Sea standards) water (1973).

“Strela” was airborne, scanning, 532-nm, pulsed laser (50 Hz in 1970; 100 Hz in 1973) with 7-mJ pulses of 7-8 ns width.

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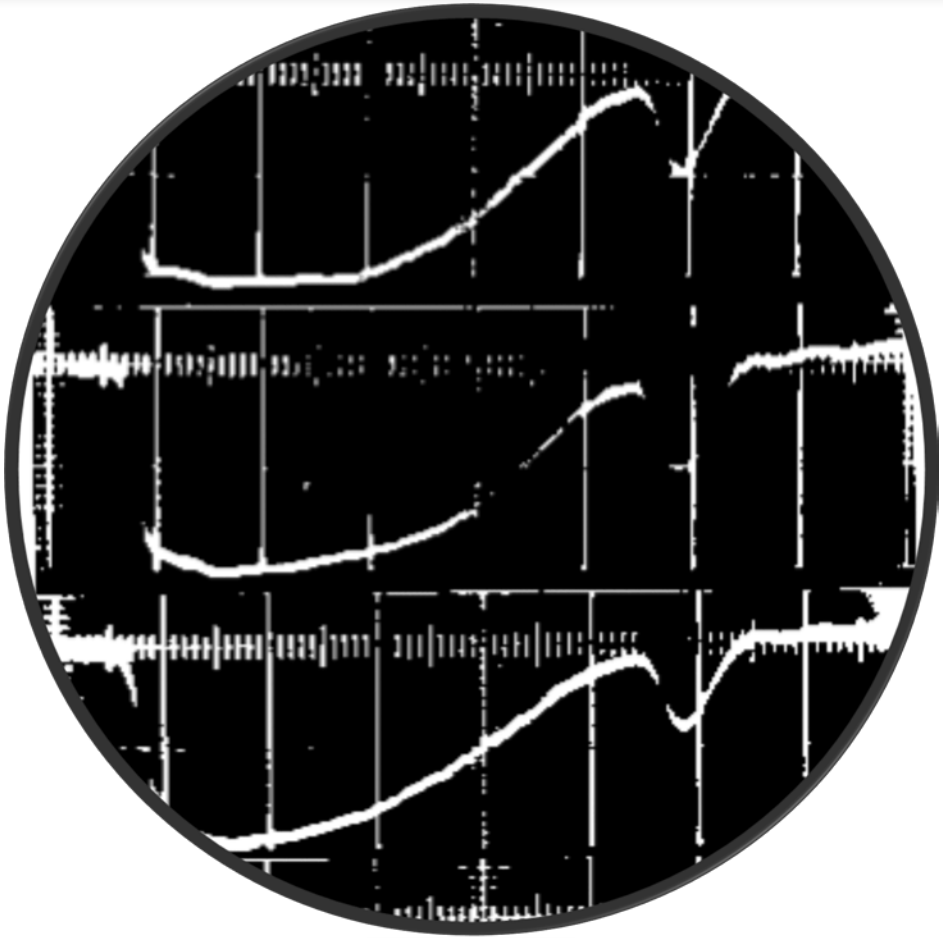
Return Signals (1970-1971) – Spy View



Bottom depth, m	30m
K_d , m^{-1}	0.09
PRR, Hz	50, 100 (1973)
Pulse duration, ns	7-8
Pulse peak power, MW	~1.0 (532nm)

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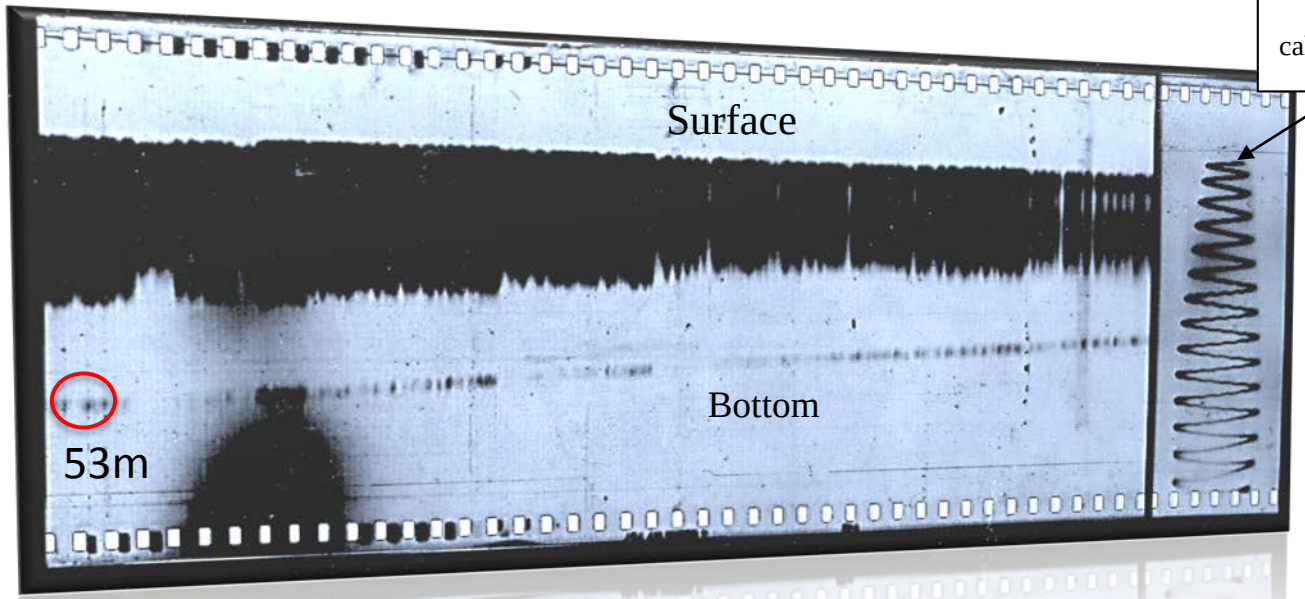
“Strela” (“Arrow”), 1970-1976

Analog Visualizer

December 06, 1973, Black sea; “Strela” system.



Condition: Black Sea

K_d near	0.1 m^{-1};
Altitude	100m;
Max depth	53m!

The record technique: Oscilloscope with Z modulation (brightness) and 90mm photo camera with constant film moving;

Index of summation on the film 100 pulses for 1 mm of the film.

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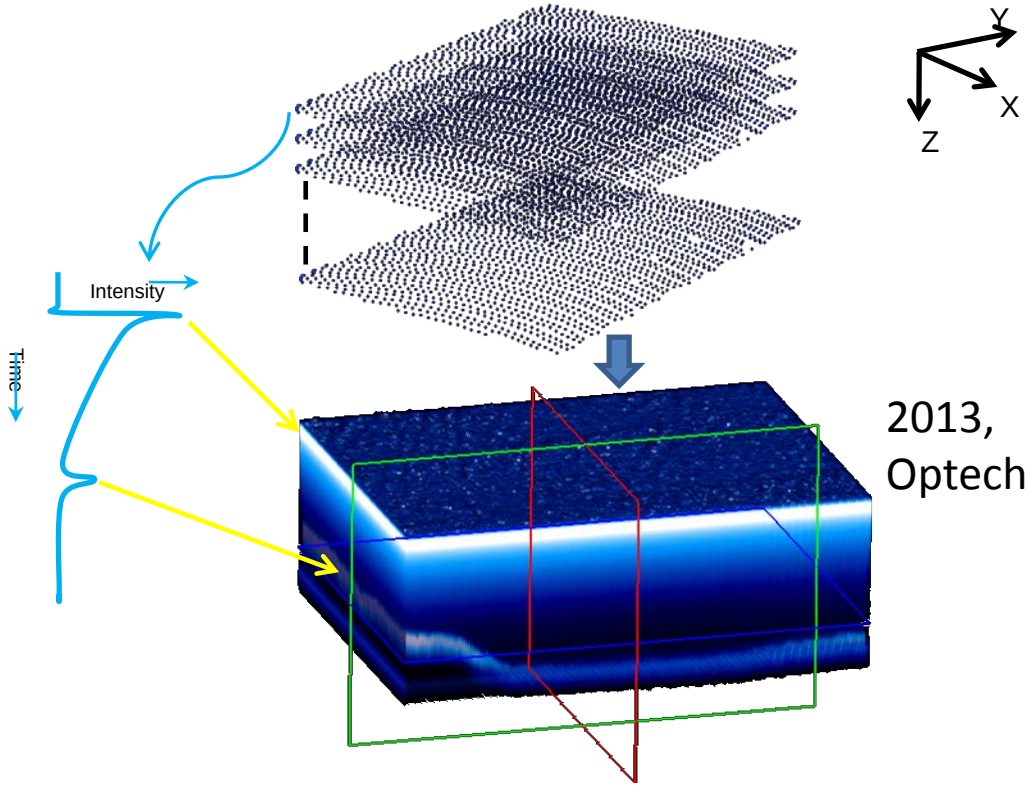
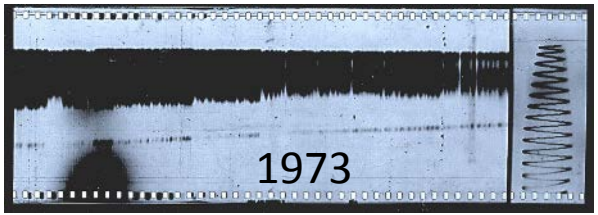
Concept of Water Column Visualizer, Optech, CZMIL, 2010



2013,
Optech



Military Applications

Ka-252 (Ka-27) with antisubmarine lidar

1980-1986

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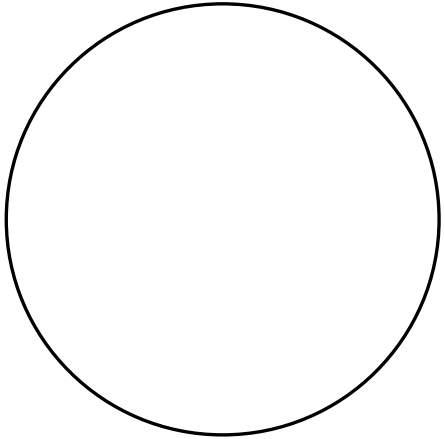
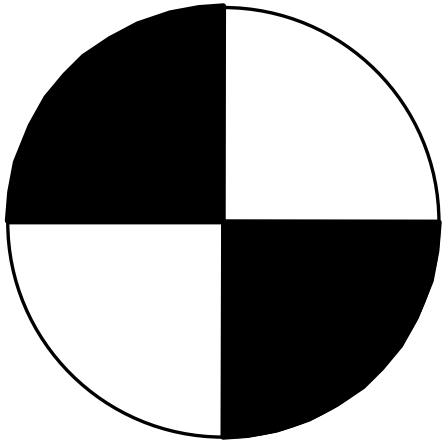
Types of Secchi Disk

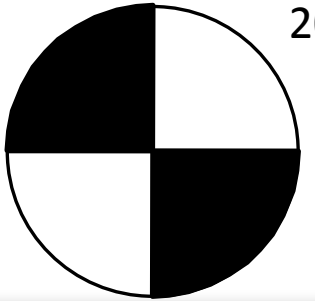
30 cm "classical" marine white disk



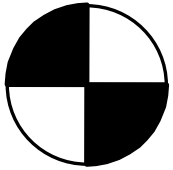
30 cm black & white disk



20 cm black & white disk



10 cm black & white disk



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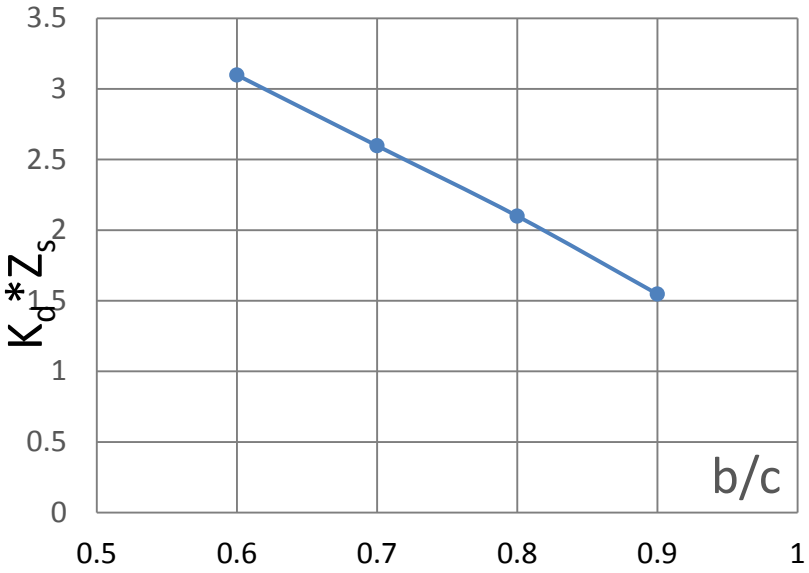
Timofeeva, A., in: *Optical Aspects of Oceanography* (Jerlov, N., Steemann Nielsen, E., eds.), New York: Academic Press 1974, 177.



- The result relates to 30cm white Secchi disk only!
- Secchi disk measurement should always be taken off the shady side of a boat or dock between 9 am and 3 pm
- "Coastal" regressions between Kd and Secchi depth are of regional applicability
- Secchi Depths are not considered meaningful below a 3 meter value

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Riegl Spec and Secchi Disk Depth

Range Measurement Performance	
Measuring Principle	time of flight measurement, echo signal digitization, online waveform processing, full waveform recording for post processing
Hydrography	
Typ. Measurement Range [3]	1.5 Secchi depth for bright ground (ρ≥80 %) [4]

$$K_d \cdot Z_{Secchi} = 1.5$$

$$D_{\max} = 1.5 \cdot Z_{Secchi} = 1.5 \frac{1.5}{K_d}$$

$$K_d \cdot D_{\max} = 2.25 \qquad \rho = 0.8 \qquad ?$$

$$\text{For } \rho = 0.15 \Rightarrow K_d \cdot D_{\max} = 1.45 \qquad ?$$

10 cm black & white disk

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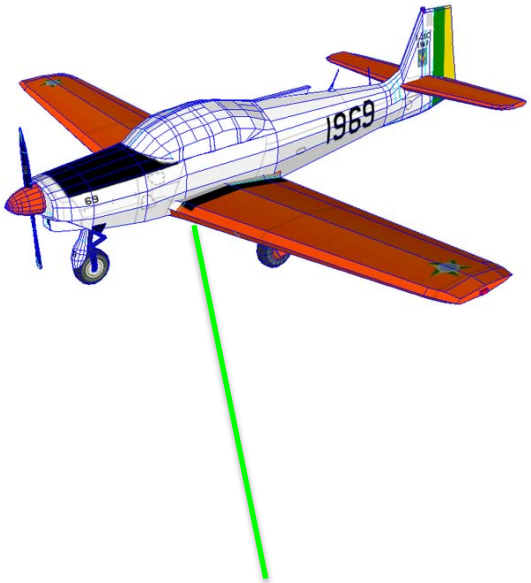
Shipborne Lidars vs. Airborne Lidars



$$H_{ship} = 10 - 20m$$

$$S^{ship} \sim \frac{\exp(-2K_{sys}^{ship} h)}{(H_{ship} + nh)^2}$$

$$H_{air} = 400 - 600m$$

$$S^{air} \sim \frac{\exp(-2K_{sys}^{air} h)}{(H_{air} + nh)^2}$$

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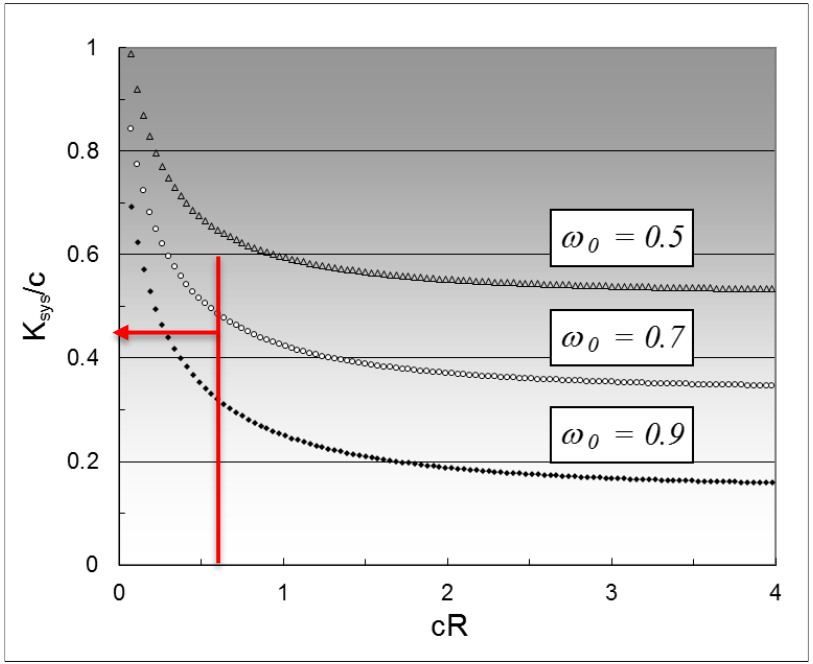
Shipborne Lidars vs. Airborne Lidars

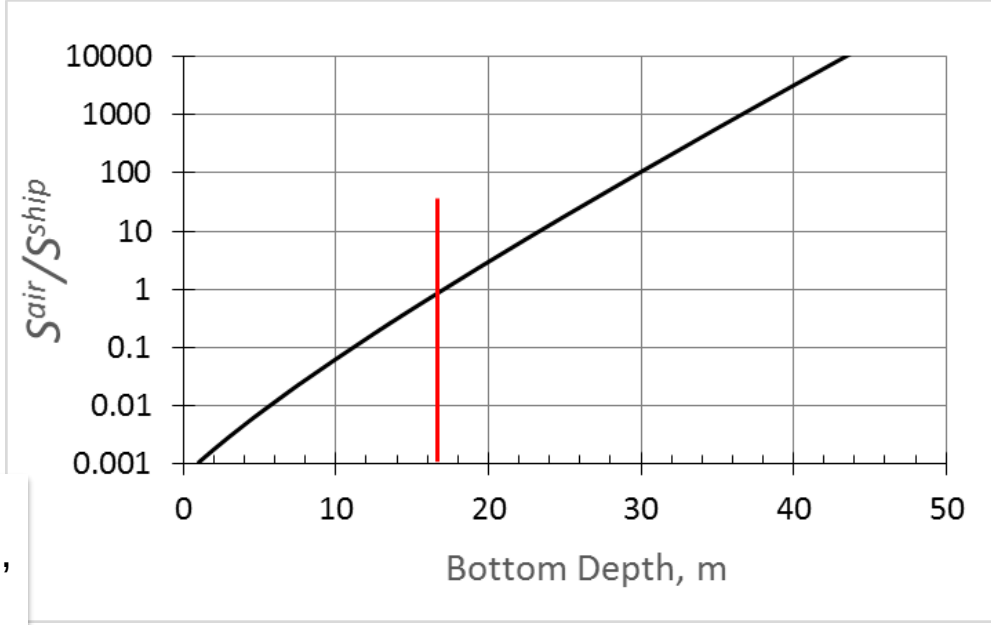
c – beam attenuation coefficient, m^{-1};
R – receiver FOV radius on water surface.



Gordon H.R. "Interpretation of airborne oceanic lidar: effects of multiple scattering", *Appl. Opt.* 24, 1985.

Input:

- $c = 0.75 m^{-1}$; ω_0=0.75;
- H_{ship}= 10m; H_{air}=400m.
- FOV_{ship}=150 mr (cR=0.6; K_{sys}/c =0.44);
- FOV_{air}=30 mr (cR=4.5; K_{sys}/c =0.29)



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My Experience with Shipborne Lidars

Experience was negative!

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Bathymetry with UAS: Regulation

The basic (for “light” UAV) rules are:

- Fly below 400 feet and remain clear of surrounding obstacles
- Keep the aircraft within visual line of sight at all times
- Remain well clear of and do not interfere with manned aircraft operations
- Don't fly within 5 miles of an airport unless you contact the airport and control tower before flying
- Don't fly near people or stadiums
- Don't fly an aircraft that weighs more than 55 pounds
- Don't be careless or reckless with your unmanned aircraft; you could be fined for endangering people or other aircraft

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UAS Crashes

https://www.rt.com/usa/167396-pentagon-crash-400-military-drones/

Pentagon crashed more than 400 military drones

Published time: 20 Jun, 2014 20:56
Edited time: 20 Jun, 2014 21:01

Get short URL

Northrop Grumman / Chad Slattery / Handout via Reuters / Reuters

While unmanned drones have become a popular weapon of choice during the United States' wars in Iraq and Afghanistan, a new report reveals that hundreds of them have been involved in major accidents around the world.

Following an investigation into more than 50,000 pages of federal and military records, the Washington Post found that more than 400 large American drones have crashed since 2001, with almost half of the accidents each causing millions of dollars in damages.

Tags
Arms, Military, Scandal, Accident, Human rights, Terrorism, USA, Planes, Security, CIA, Air Force, Drones, Intelligence, Al-Qaeda

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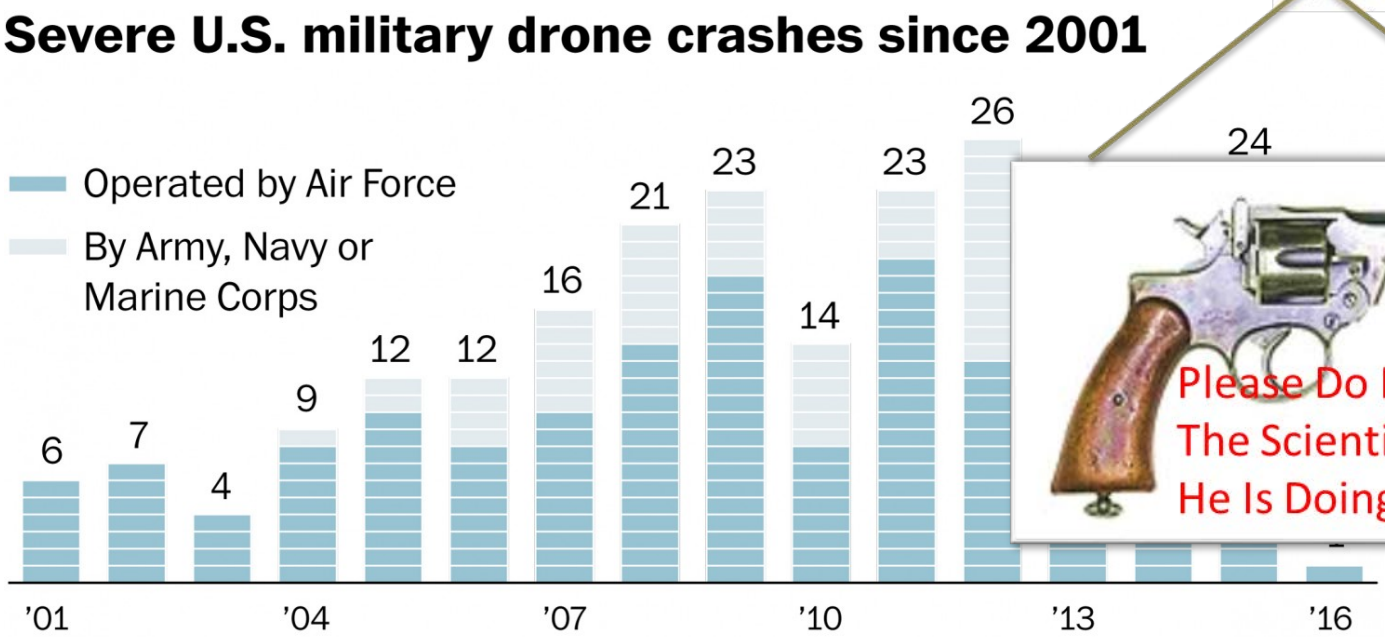
Military Drone Crashes Since 2001



Note: Data as of Jan. 7. These accidents are categorized by the military as Class A: mishaps that destroyed the aircraft or caused at least $2 million in damage.

Sources: Staff reports

THE WASHINGTON POST

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Bathy Lidar with High Repetition Rate

$S(h)$

Some theory (Dr. Yuri Kopilevich)

The transversal (horizontal) resolution of an airborne lidar system is determined by the lidar sensitivity distribution throughout the plane transversal to the lidar axis at a given slant depth, *h*.

In the diffuse small-angle approximation, **the effective radius**, *S(h)*, of the **sensitivity distribution** (for 1/e level) is:

$$S(h) = \frac{R_{sounding}(h) \cdot R_{receiver}(h)}{\sqrt{R^2_{sounding}(h) + R^2_{receiver}(h)}} \qquad R^2_{s,r}(h) = \frac{1}{4} H^2 \Theta^2_{s,r} + \frac{b_s}{m^2} \cdot \frac{2}{3} \cdot h^3$$

where R_s and R_r are the radii of sounding beam and fictitious "receiving" beam (with the initial spatial and angular characteristics being those of the lidar receiver), *H* is the slant altitude of the lidar carrier, b_s is the small-angle forward scattering coefficient, *m* is parameter of Dolin's VSF model, and $\vartheta_{s,r}$ are the sounding-beam divergence and the receiver field-of-view angle, respectively (both parameters are half angles at 1/e level).

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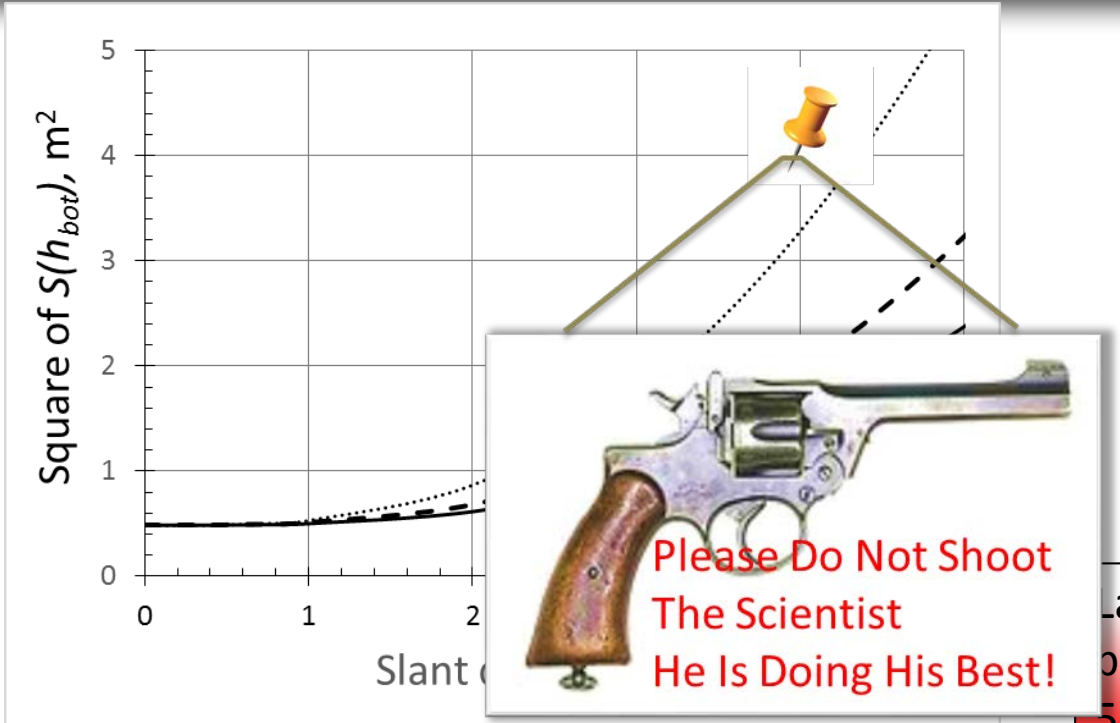
Bathy Lidar with High Repetition Rate



The Hypothetical Lidar sensitivity square, $\pi \cdot S(h_{bot})^2$, as a function of slant depth for three values of b_s:

- 0.4 m^{-1} (solid line);
- 0.6 m^{-1} (dashed line);
- 1.2 m^{-1} (dotted line).

Hypothetical Lidar :

- Altitude 500m
- Optical FOV 10mr
- Laser beam div. 1.5mr
  Riegl -880 0.2mr!
- b_s 0.4; 0.6; 1.2m^{-1}
- m 7.0

Laser beam divergence 0.2mr is better than diffraction limit for 532nm for beam diameter 2.5 mm

Why we need150-500kHz of PRF for the receiving the same information in the water?

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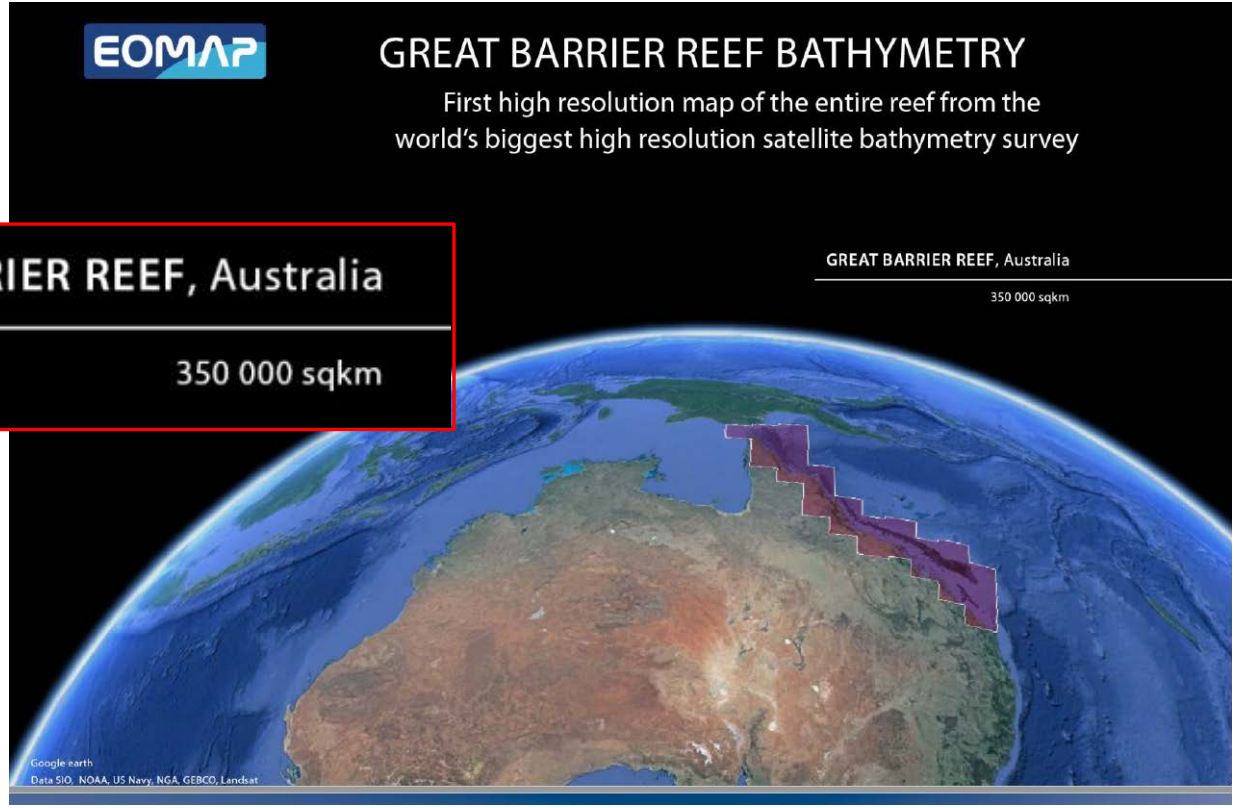
Passive Bathymetry from Space



GREAT BARRIER REEF, Australia

350 000 sqkm

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Passive Bathymetry from Space

EOMAP

Disclaimer

Earth observation data are in general recorded under changing environmental conditions. EOMAP value adding software corrects for most relevant environmental conditions. However, with respect to the physical nature of the remote sensing method the achievable product quality can differ due to varying observation angles, varying atmospheric, surface and in-water conditions or changing sensor raw data quality with each scene. Therefore, EOMAP cannot take any responsibility caused by the usage and interpretation of the remote sensing products. Of course, EOMAP will undertake all possible efforts to assure a constant product quality.

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Passive Bathymetry from Space

Ref: Validation of EOMAP Landsat satellite derived bathymetry of the Great Barrier Reef

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Bathymetry from Space

Table of Pros and Cons for “passive” bathymetry

Pro	Con
Big square of coverage (e.g. Great Barrier Reef (~ 19,000 km2 of reef	Method works for very clear waters ONLY
easurement	Depth limitation (K_d*D_{max} ≈ 1.2-1.5), what is equivalent of depth not more than 15m-20 in very clean waters. Remember, this parameter for CZMIL= 3.75-4.0
t, team, hotels, etc.	Horizontal accuracy: “It is considered that the bathymetry data (for GBR, VF) have an overall maximum horizontal positioning error of 40 m ” [1] Vertical accuracy: For Class 1 pixels (best!) 75% of pixels gives the absolute depth error of 1 m +/- 25% of real depth; at 10 m true depth, depth estimate from 75% of pixels lie within an error band 9-11 m +/- 2.5 m.[1]

[1] Great Barrier Reef Bathymetry (GBR) Survey, Published Nov. 18th 2013 © EOMAP GmbH & Co. KG(see attachment)

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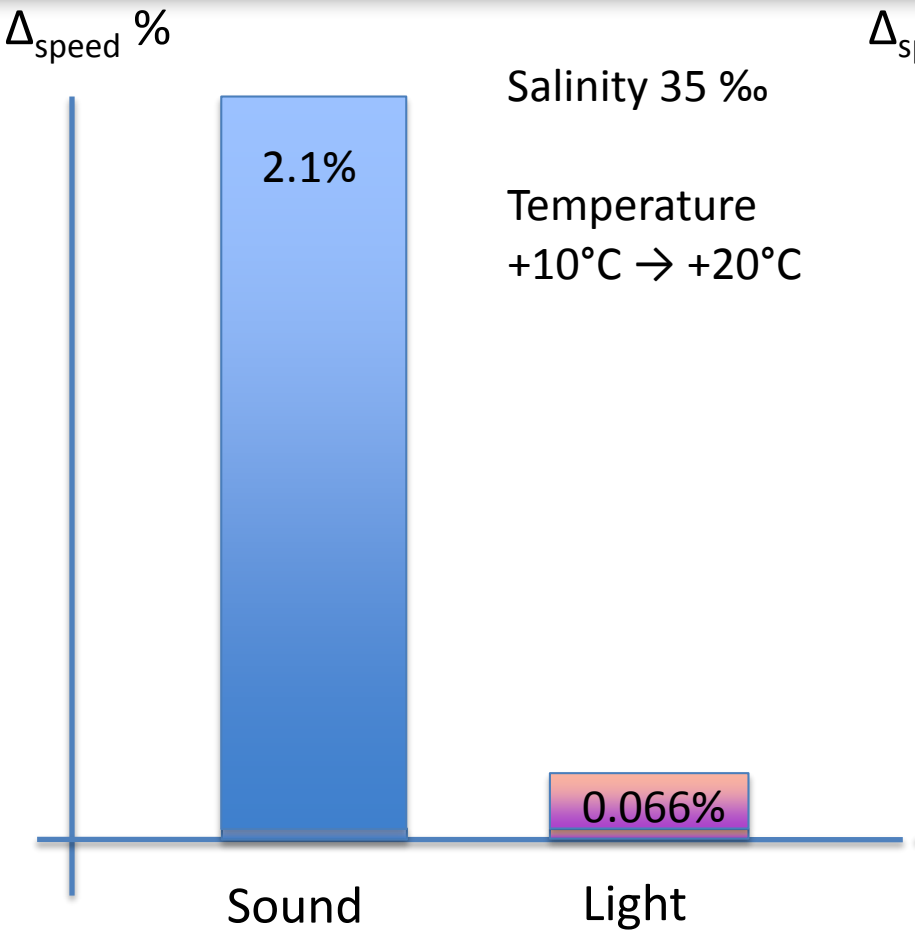
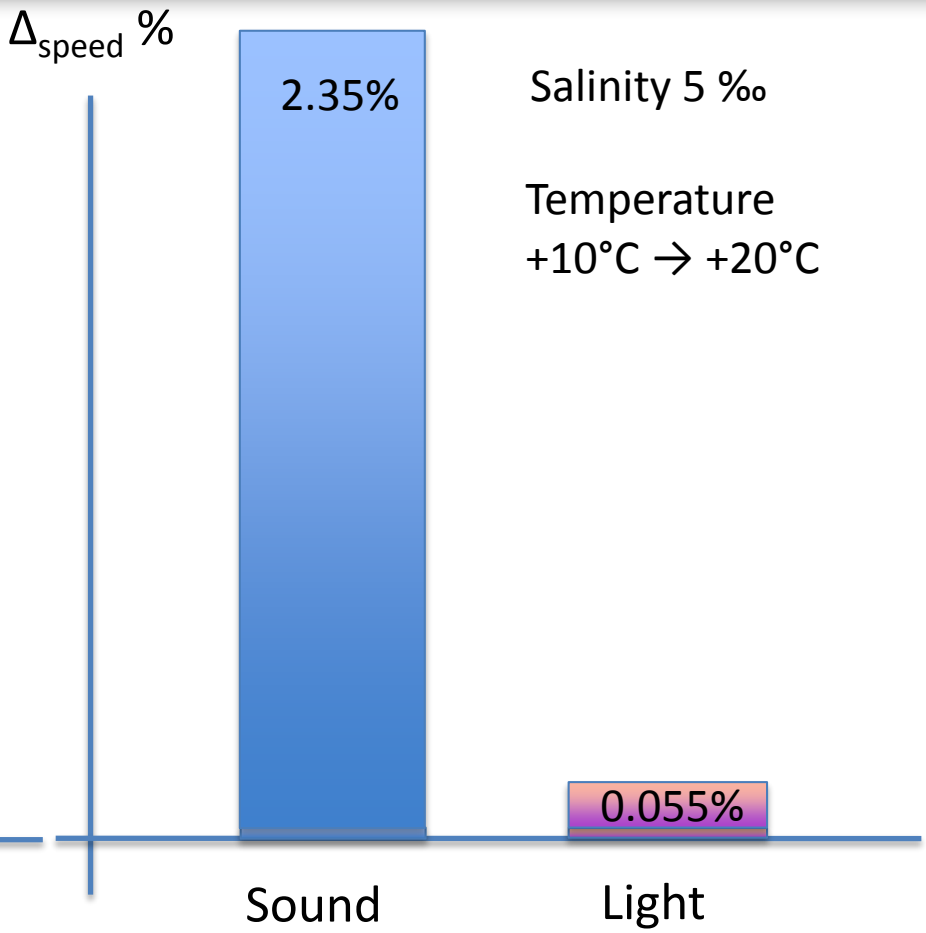
Why Sonar Data Is Used as a Reference for Lidar Bathymetry?



Salinity 35 ‰

Temperature
+10°C → +20°C



Salinity 5 ‰

Temperature
+10°C → +20°C

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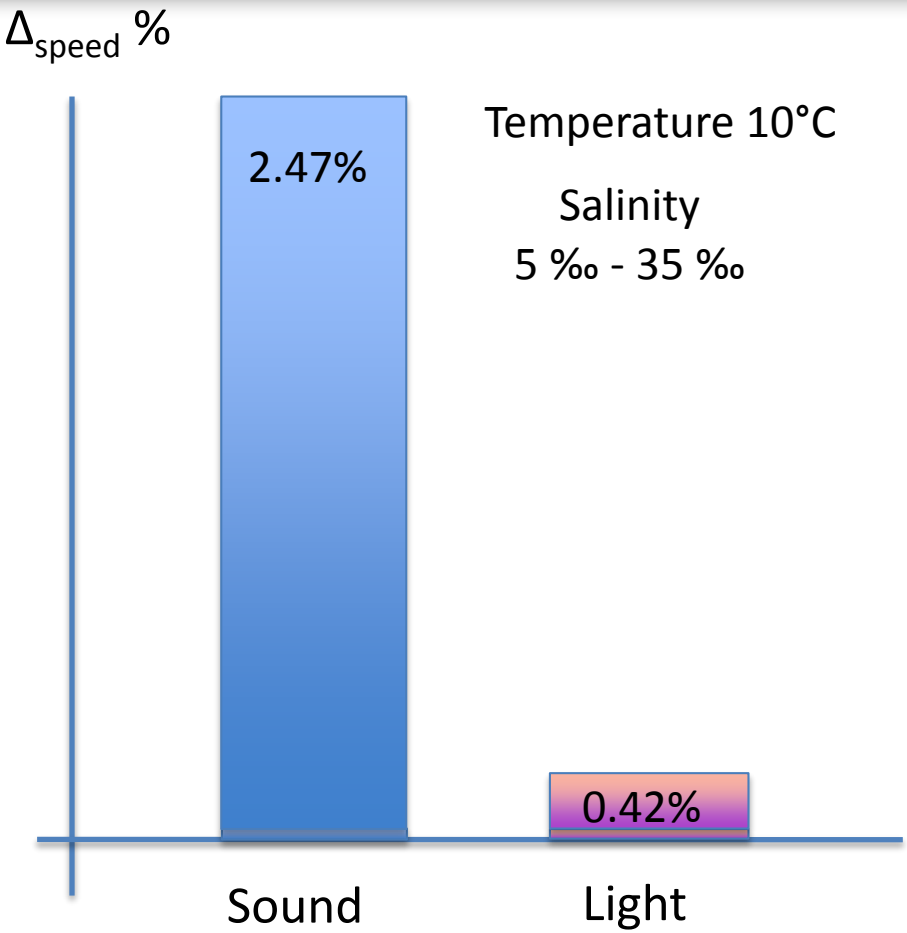
Why Sonar Data Is Used as a Reference for Lidar Bathymetry?



Temperature 10°C

Salinity
5 ‰ - 35 ‰

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Deep Water Bathy with Photon counting Lidars ?

Effect of Background solar photons

(courtesy of Minsu Kim and Adjid Sampath)

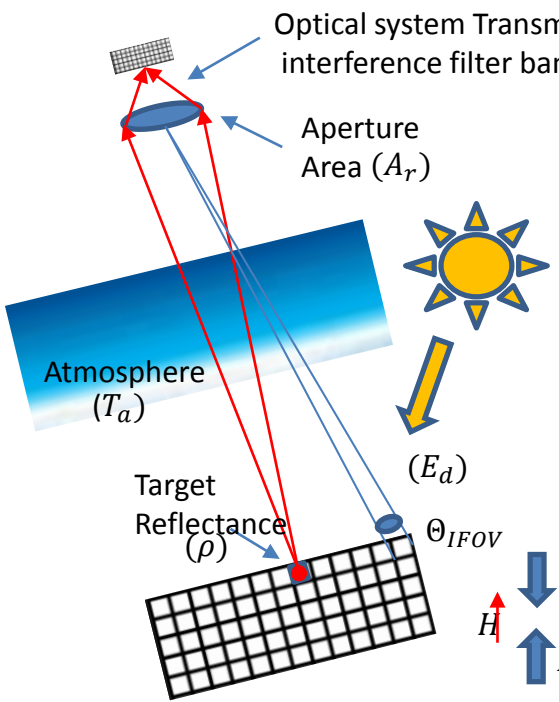
Laser wavelength width < 0.01 nm

1.0 1.0 35 µrad

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

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

HARRIS



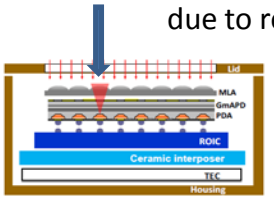
$$L = \frac{\rho}{\pi} E_d$$

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

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

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

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



SigmaSpace

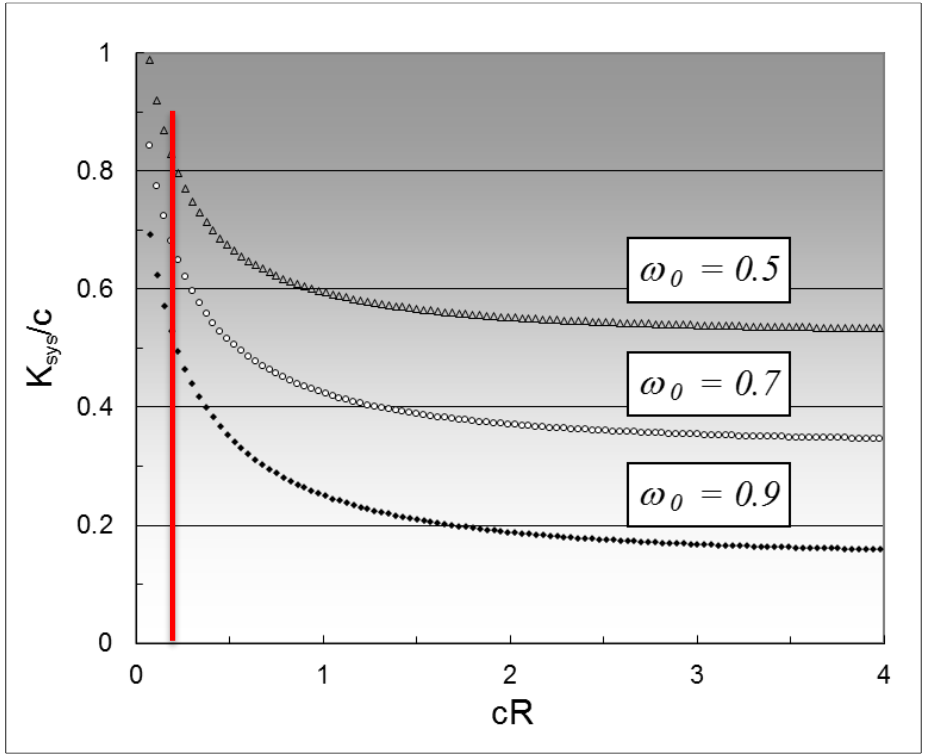
50x50cm, 7500ft
IFOV = 200micro rad

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

2.3 km AGL,
5m x 5m → 50cm GSD
→ IFOV = 50 cm/2.5km
→ = 200 µ rad

Optical power onto a FPA pixel due to a few reflected **laser** photons / ns

Deep Water Bathy with Photon counting Lidars ?



$$S \sim \exp(-2K_{sys}h)$$

$$\frac{c}{(3 \div 5)} \leq K_{sys} \leq c$$

SigmaSpace

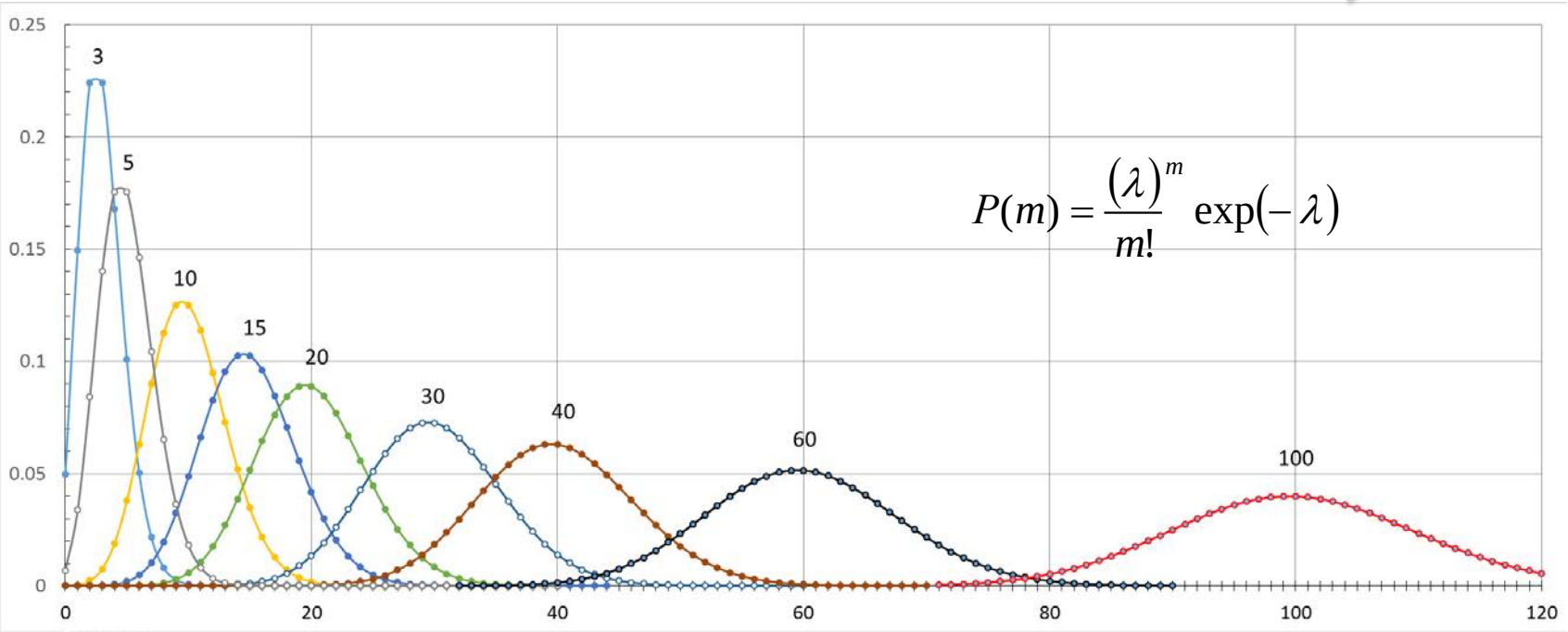
cR = 0.2mr*2300*0.8/2=0.184

Due to small FOV, *cR<<1*

$$K_{sys} \approx c$$

Poisson Distribution for Various Numbers of Photoelectrons

Due to small FOV, *number of photons, m,* is not too large



$$P(m) = \frac{(\lambda)^m}{m!} \exp(-\lambda)$$

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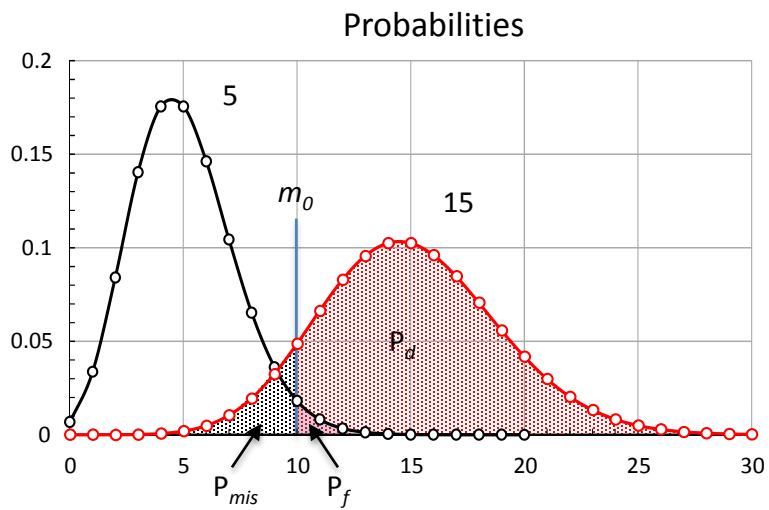
Probabilities

Poisson probability distribution for
"noise only" (=5) and for
"useful signal + noise" (=15)



$$P_f = 1 - \sum_{m=0}^{m_0-1} \frac{(\overline{m}_n)^m}{m!} \exp(-\overline{m}_n)$$

$$P_d = 1 - \sum_{m=0}^{m_0-1} \frac{(\overline{m}_s + \overline{m}_n)^m}{m!} \exp(-(\overline{m}_s + \overline{m}_n))$$

$$P_{mis} = \sum_{m=0}^{m_0-1} \frac{(\overline{m}_s + \overline{m}_n)^m}{m!} \exp(-(\overline{m}_s + \overline{m}_n))$$

$$P_{mis} + P_d = 1$$

$\overline{m}_s$ ($\overline{m}_n$) is the mean number of "signal" ("noise") photoelectrons registered during the observation time interval Δt;

m_0 is discriminator threshold

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Automatic object detection?

$$P_f^{(N)} = 1 - \left[1 - P_f^{(1)}\right]^N$$

$$P_d^{(N)} = \left[P_d^{(1)}\right]^N$$

N=10	
P false alarm	***P false alarm***
(1 interval)	*(N intervals)*
1.0E-01	6.513E-01
1.0E-02	9.562E-02
1.0E-03	9.955E-03
1.0E-04	9.996E-04
1.0E-05	1.000E-04
1.0E-06	1.000E-05
1.0E-07	1.000E-06

N=100	
P false alarm	***P false alarm***
(1 interval)	*(N intervals)*
1.0E-01	1.000E+00
1.0E-02	6.340E-01
1.0E-03	9.521E-02
1.0E-04	9.951E-03
1.0E-05	9.995E-04
1.0E-06	1.000E-04
1.0E-07	1.000E-05

N=10	
P detection	***P detection***
(1 interval)	(N intervals)
0.9	3.487E-01
0.99	9.044E-01
0.999	9.900E-01
0.9999	9.990E-01
0.99999	9.999E-01
0.999999	1.000E+00
0.9999999	1.000E+00

N=100	
P detection	***P detection***
(1 interval)	(N intervals)
0.9	2.656E-05
0.99	3.660E-01
0.999	9.048E-01
0.9999	9.900E-01
0.99999	9.990E-01
0.999999	9.999E-01
0.9999999	1.000E+00

E.g., at *N*=100, to ensure $P_f^{(100)} = 0.01$ one needs $P_f^{(1)} = 0.0001$

to ensure $P_d^{(100)} = 0.9$ one needs $P_d^{(1)} = 0.999$

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Situation with 2 coming noise photons

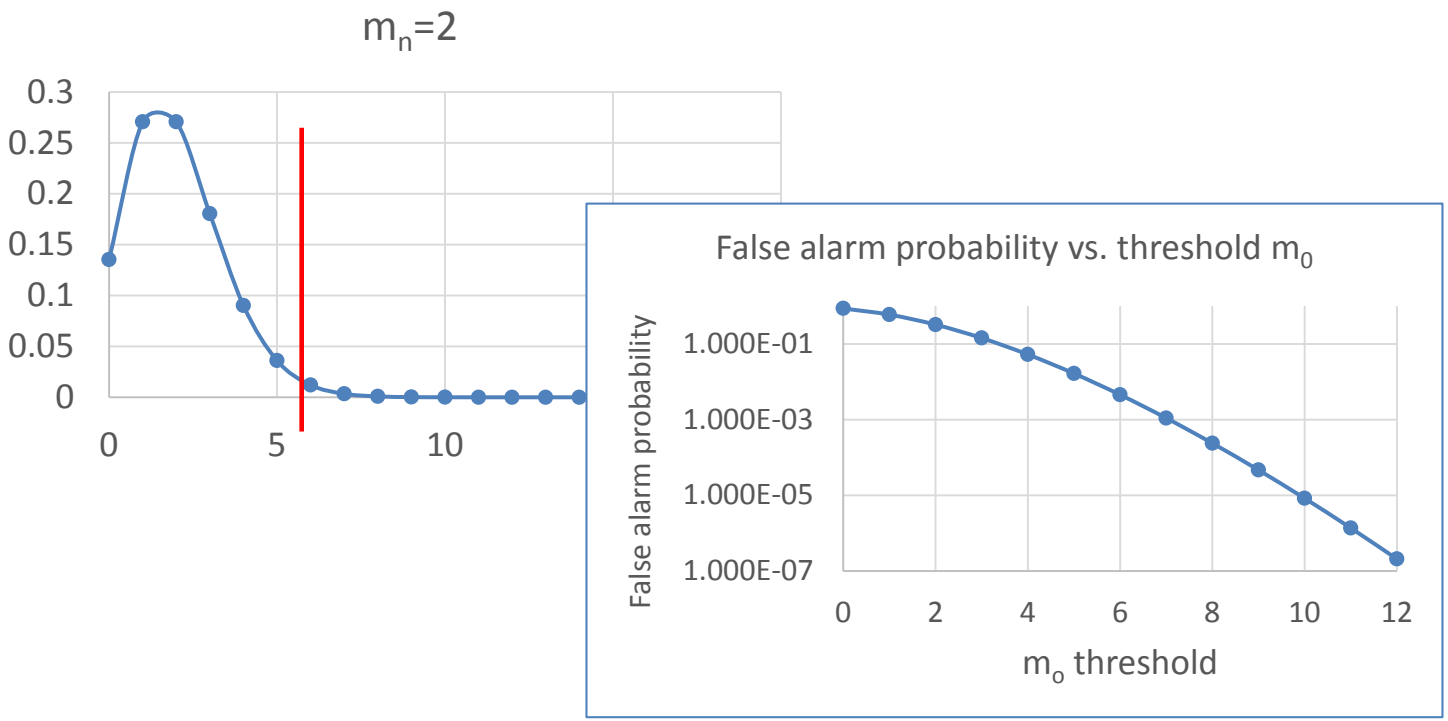

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Table for Calculations

Probability of false alarm and detection as a functions of number of noise and signal photons and threshold

m_0	m_n and m_n+m_s												
	1	2	3	4	5	10	12	15	16	20	23	24	30
1	0.264	0.594	0.801	0.908	0.960	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2	0.080	0.323	0.577	0.762	0.875	0.997	0.999	1.000	1.000	1.000	1.000	1.000	1.000
3	1.90E-02	0.143	0.353	0.567	0.735	0.990	0.998	1.000	1.000	1.000	1.000	1.000	1.000
4	3.66E-03	0.053	0.185	0.371	0.560	0.971	0.992	0.999	1.000	1.000	1.000	1.000	1.000
5	5.94E-04	0.017	0.084	0.215	0.384	0.933	0.980	0.997	0.999	1.000	1.000	1.000	1.000
6	8.32E-05	4.53E-03	0.034	0.111	0.238	0.870	0.954	0.992	0.996	1.000	1.000	1.000	1.000
7	1.02E-05	1.10E-03	0.012	0.051	0.133	0.780	0.910	0.982	0.990	0.999	1.000	1.000	1.000
8	1.13E-06	2.37E-04	3.80E-03	0.021	0.068	0.667	0.845	0.963	0.978	0.998	1.000	1.000	1.000
9	1.11E-07	4.65E-05	1.10E-03	8.13E-03	3.18E-02	0.542	0.758	0.930	0.957	0.995	0.999	1.000	1.000
10	1.00E-08	**8.31E-06**	2.92E-04	2.84E-03	1.37E-02	0.417	0.653	0.882	0.923	0.989	**0.998**	0.999	1.000
11	8.32E-10	1.36E-06	7.14E-05	9.15E-04	5.45E-03	0.303	0.538	0.815	0.873	0.979	0.996	0.997	1.000
12	6.36E-11	2.07E-07	1.61E-05	2.74E-04	2.02E-03	0.208	0.424	0.732	0.807	0.961	0.991	0.995	1.000
13	4.52E-12	2.93E-08	3.40E-06	7.63E-05	6.98E-04	0.136	0.318	0.637	0.725	0.934	0.983	0.989	1.000
14	3.00E-13	3.87E-09	6.70E-07	1.99E-05	2.26E-04	0.083	0.228	0.534	0.632	0.895	0.969	0.980	0.999
15	1.87E-14	4.80E-10	1.24E-07	**4.89E-06**	6.90E-05	0.049	0.156	0.432	0.533	0.843	0.948	0.966	**0.998**
16	0.00E+00	5.61E-11	2.16E-08	1.13E-06	1.99E-05	0.027	0.101	0.336	0.434	0.779	0.918	0.944	0.996
17	0.00E+00	6.19E-12	3.57E-09	2.48E-07	5.42E-06	0.014	0.063	0.251	0.341	0.703	0.877	0.913	0.993
18	0.00E+00	6.48E-13	5.59E-10	5.16E-08	1.40E-06	0.007	0.037	0.181	0.258	0.619	0.825	0.872	0.987

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Results

$$SNR = \frac{\overline{m}_s}{\sqrt{\overline{m}_n}}$$

Assumptions:

$P_f = 10^{-5} – 10^{-6}$;

$P_d = 0.997\text{-}0.998$.

$$D = \overline{m}_s \Big/ \left[(\overline{m}_s + \overline{m}_n) \cdot \overline{m}_n \right]^{1/4}$$

For this conditions we have:

Number of noise electrons	Number of signal electrons	SNR	D index
2	21	14.84	8.06
4	26	13	7.86
20	46	10.28	7.63
40	60	9.4	7.54
100	90	8.5	7.29

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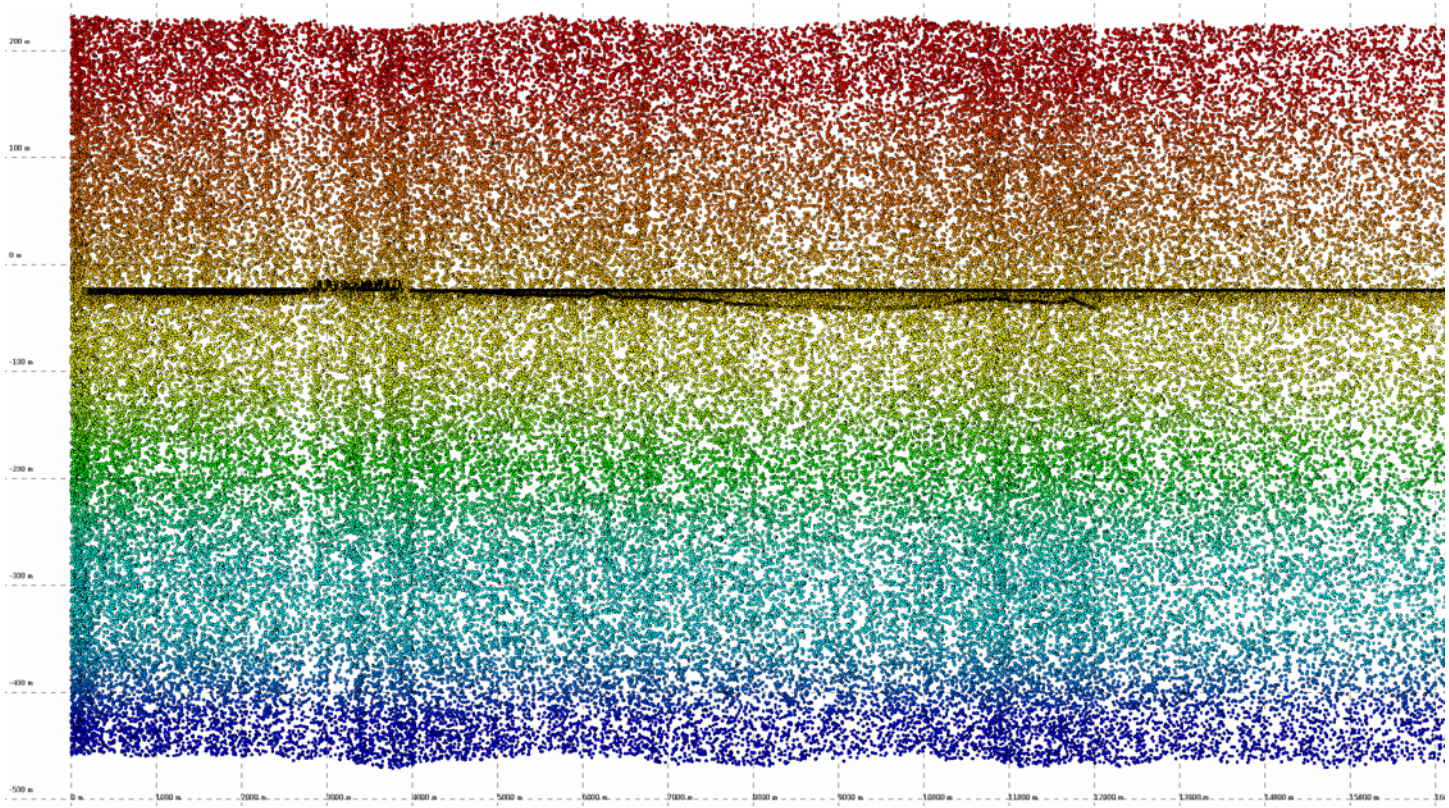
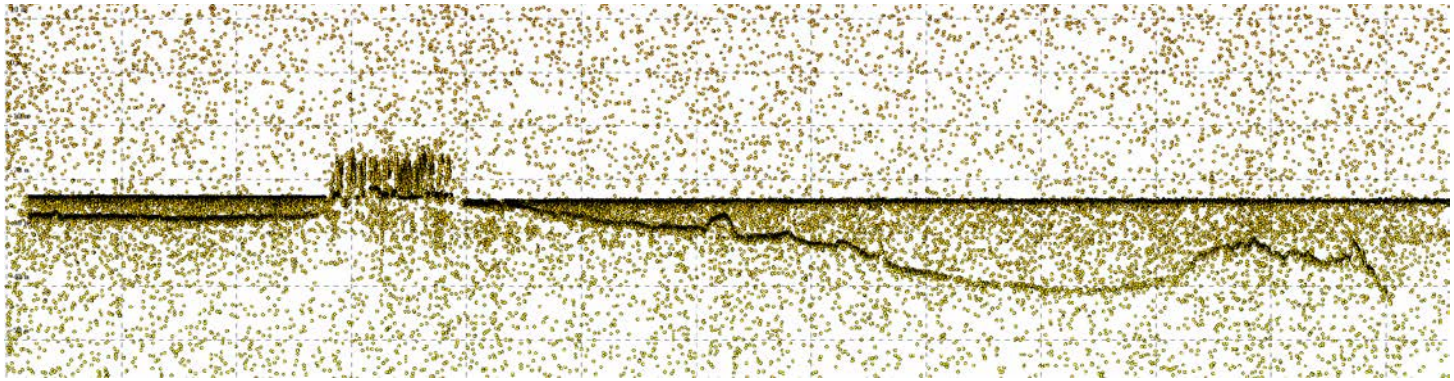
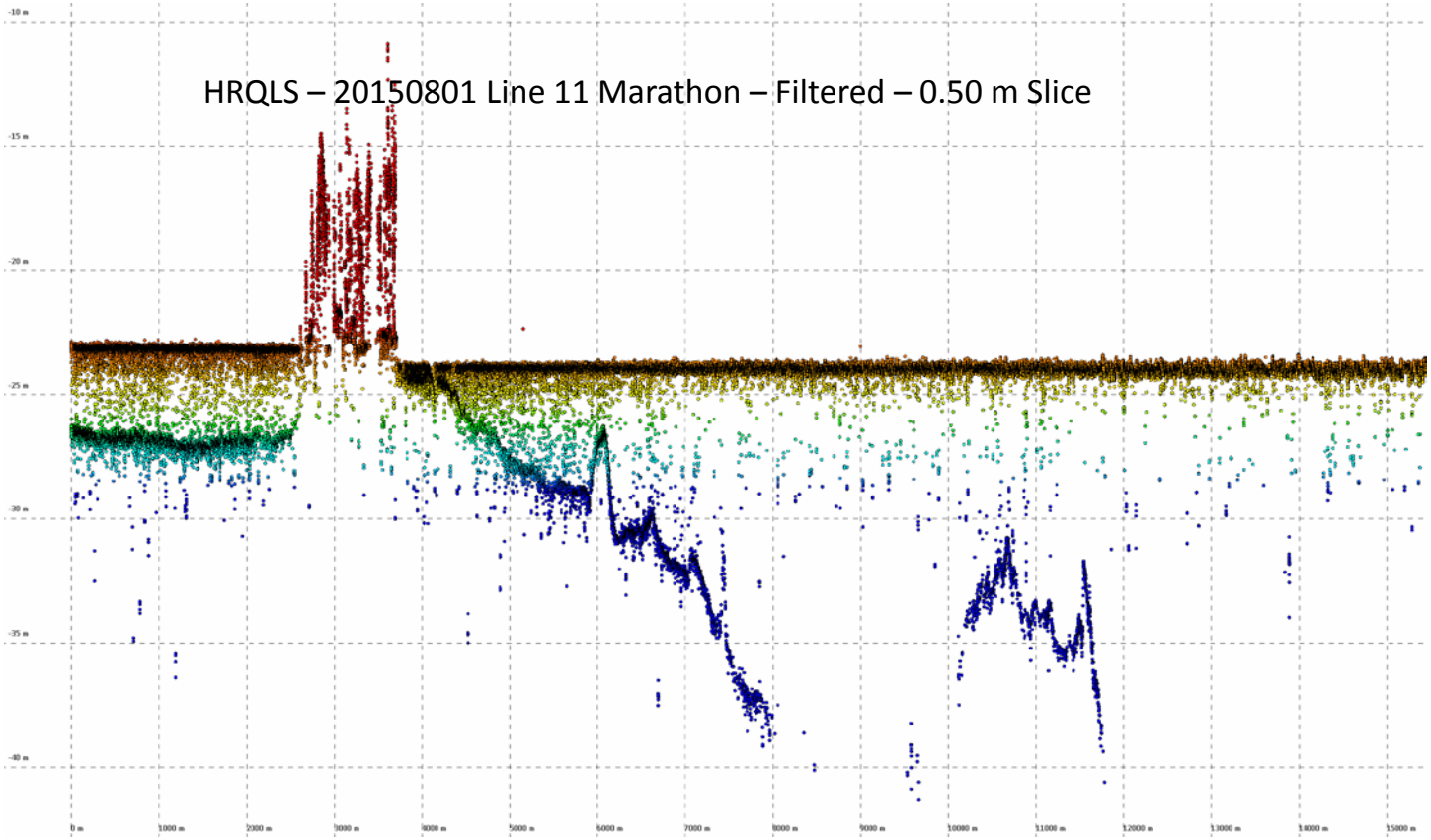
HRQLS – 20150801 Line 11 Marathon – Unfiltered – 0.50 m Slice

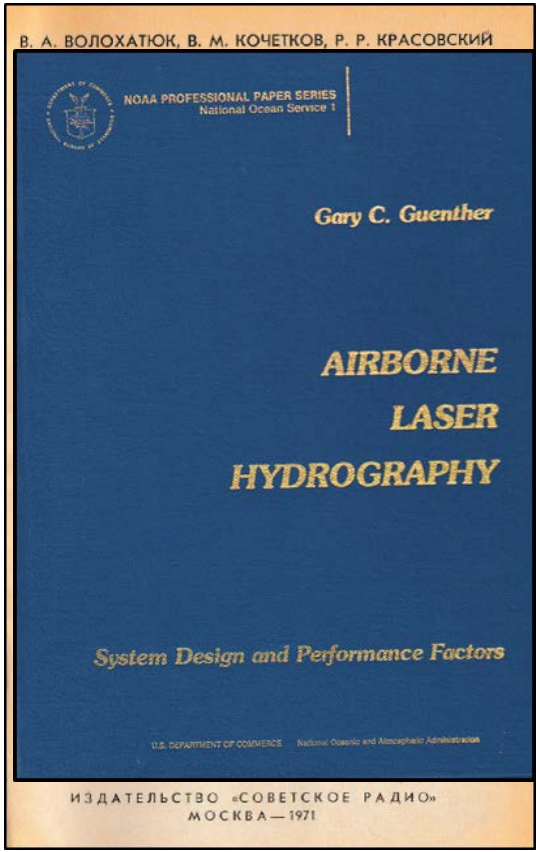


HRQLS – 20150801 Line 11 Marathon – Unfiltered – 0.50 m Slice




HRQLS – 20150801 Line 11 Marathon – Filtered – 0.50 m Slice
-10 m
-15 m
-20 m
-25 m
-30 m
-35 m
-40 m
0 m
1000 m
2000 m
3000 m
4000 m
5000 m
6000 m
7000 m
8000 m
9000 m
10000 m
11000 m
12000 m
13000 m
14000 m
15000 m

Acknowledgements



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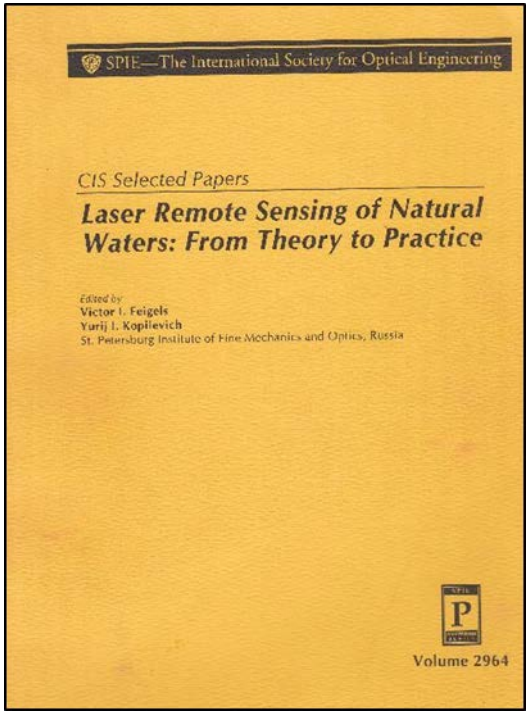
Acknowledgements



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