A universal parameter for the comparison of lidar bathymeters

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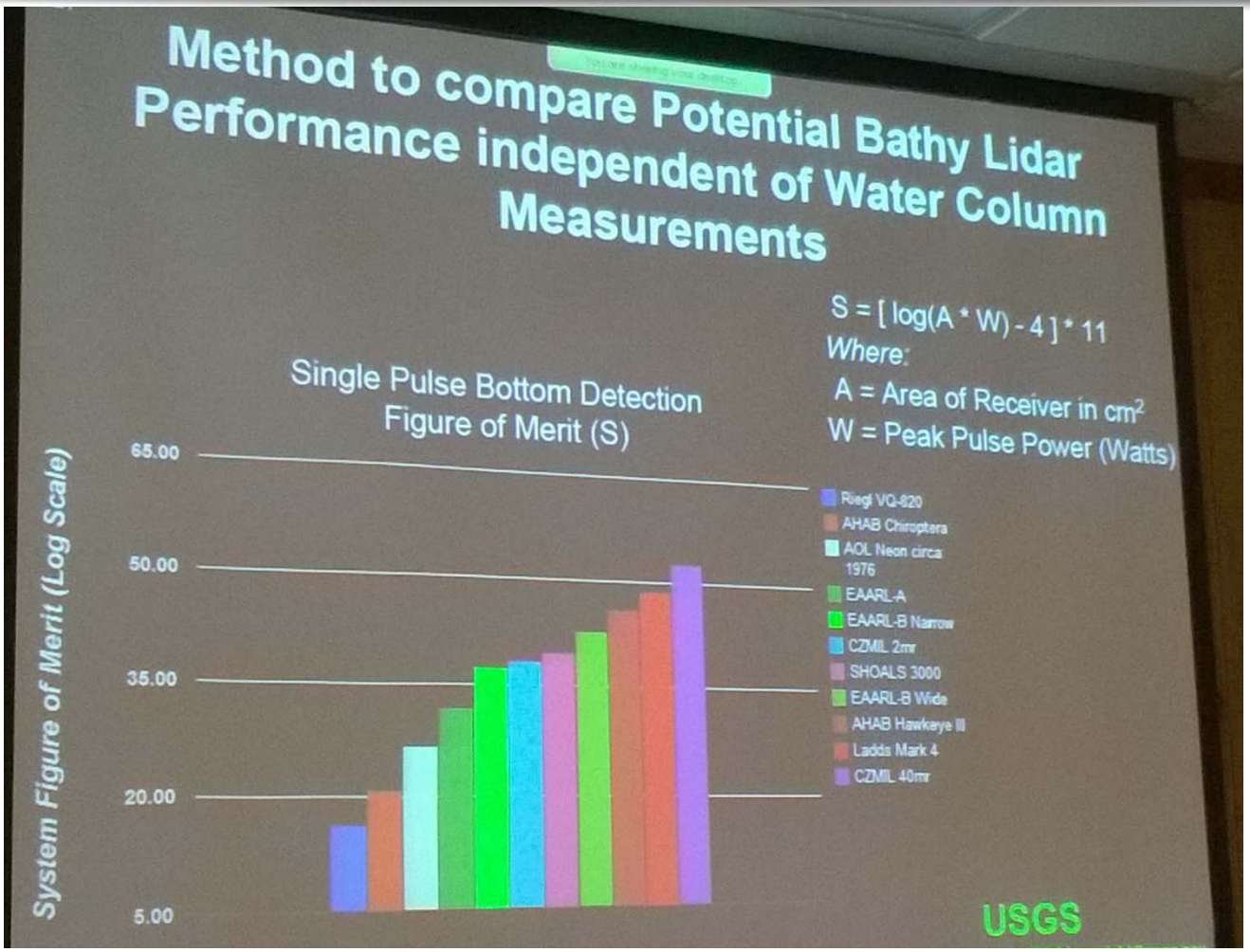
Yesterday: Wayne Wright (USGS) presentation



$$S = [\log(A \cdot W) - 4] \cdot 11$$

A – area of receiver in cm^2;
W – laser peak power, W

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FAQ

Question:
Is it possible to have a universal parameter for the comparison of lidar bathymeters?

Answer:

No, because every lidar has something specific in the system, such as:

- Photoreceiver type (PMT, APD, streak-tube, etc.)
- Values of laser beam divergence and receiver FOV
- Noise level of digitizer
- Requirements for false alarm probability

But using the specific software (see Optech "Ocean Scientific") we can predict the capability of every lidar system for different water conditions (if you know water properties! ☺)

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FAQ #2

Question:
Is it possible to have a universal parameter for the comparison of lidar bathymeters after some principal assumption?

- The atmosphere and surface state are the same
- The bottom reflectance is the same
- The altitude and depth are the same
- **The single pulse Field-of-view is the same and near optimal**
- The water properties are the same

Answer:

Yes

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Ocean-Scientific (2001, 2003, 2005)

Optech “Ocean-Scientific” software estimates the lidar system performance by evaluating the so-called *D*-index of discriminability, which determines the probability of bottom detection at a given false alarm rate using the Neyman–Pearson criterion.

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Ocean-Scientific

Ocean-Scientific is a multi-purpose and powerful instrument for a priori estimation of airborne lidar system performance; it allows:

- *to compare the effectiveness of different lidars* for the given task and specific conditions, including water clarity and surface roughness, the flight parameters and meteorological situation;
- *to optimize the following parameters of a lidar:*
  - laser pulse energy
  - laser wavelength
  - lidar carrier altitude
  - receiver pupil diameter
  - receiver field-of-view angle
  - optical filter bandwidth
- *to furnish bathymetric survey cost saving* via not wasting flights under conditions that would yield poor results

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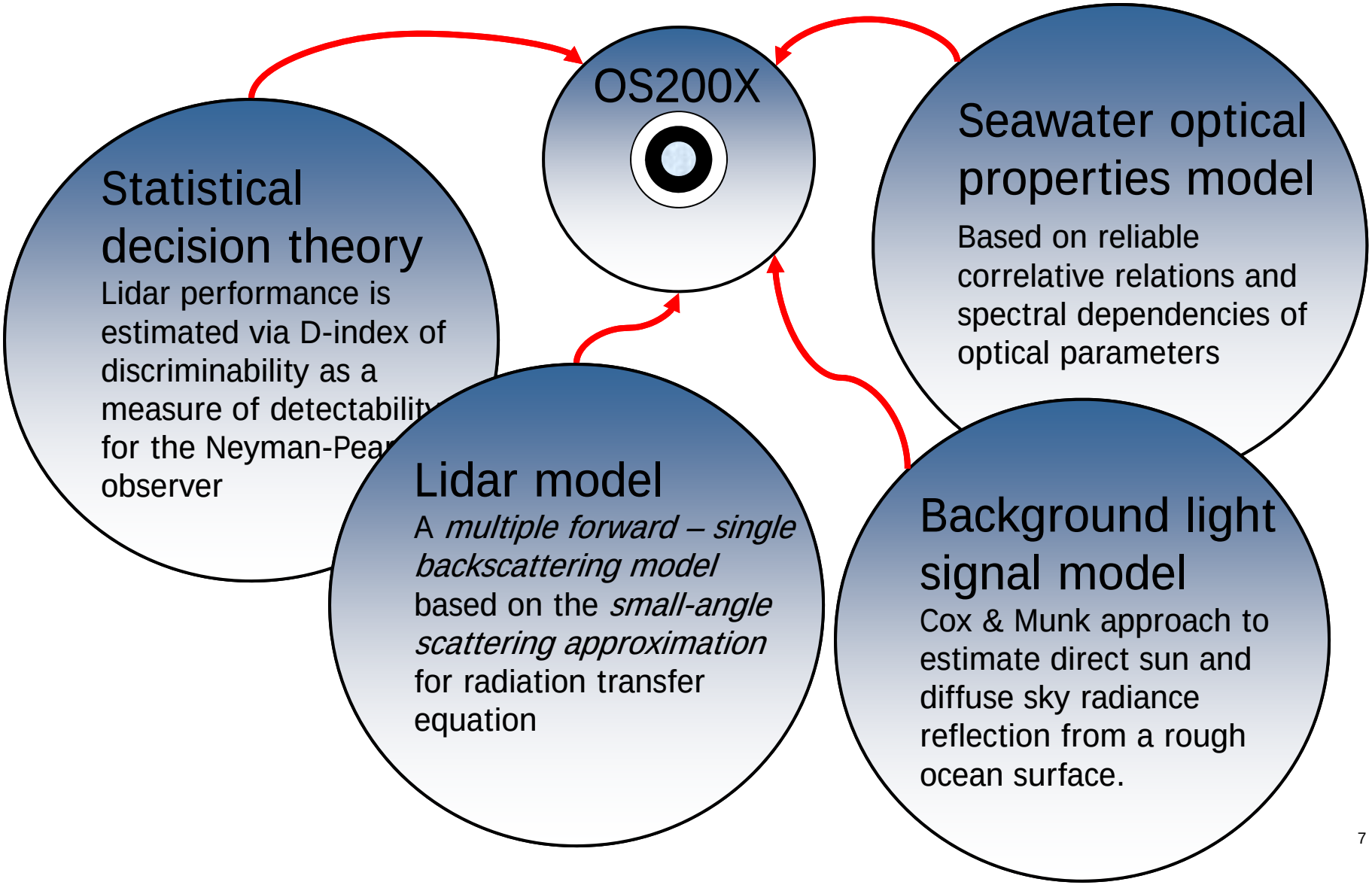
OS2001-OS2005: Basic Concepts



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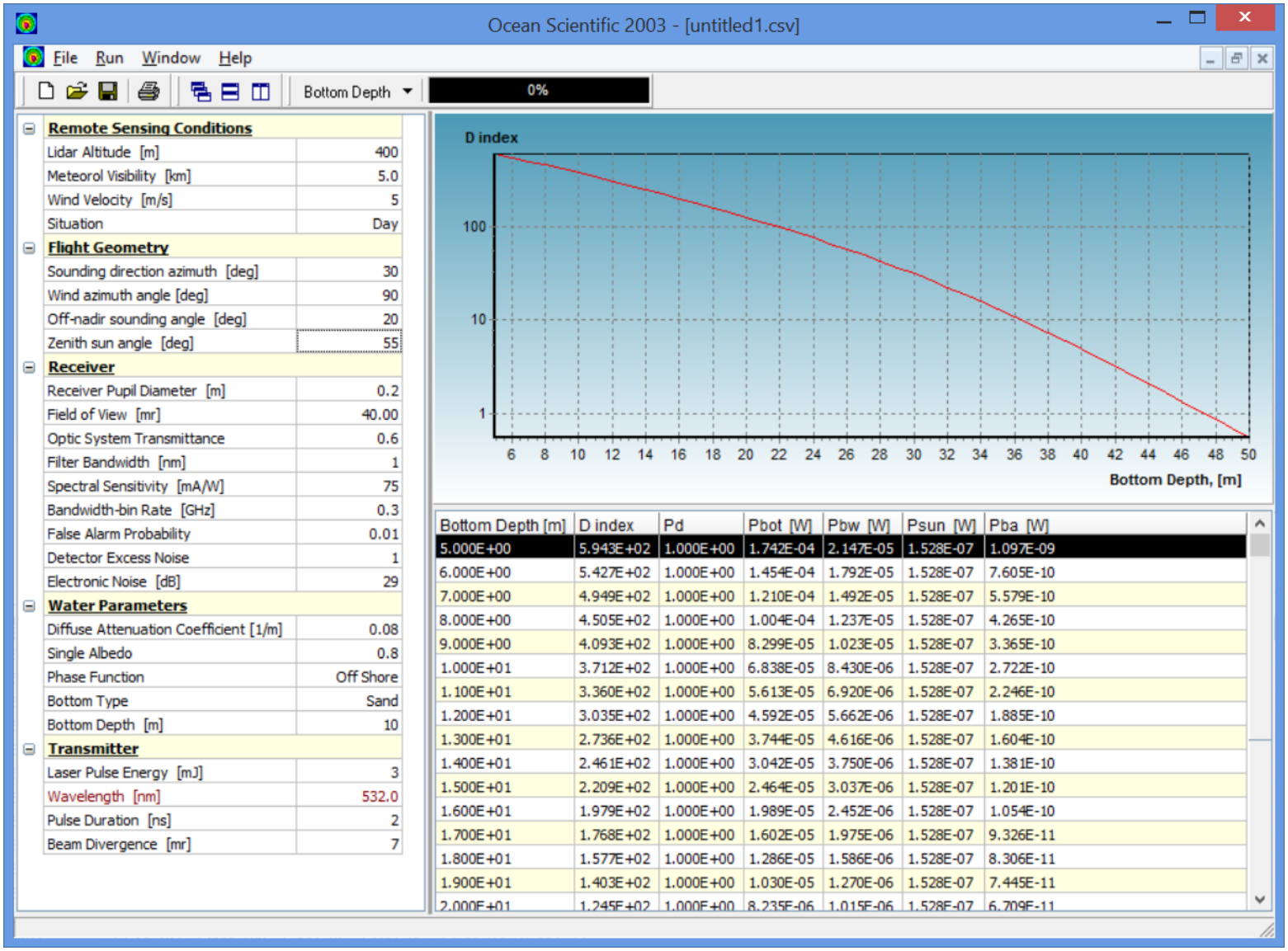
OS2005: main screen



Bottom Depth [m]	D index	Pd	Pbot [W]	Pbw [W]	Psun [W]	Pba [W]
5.000E+00	5.943E+02	1.000E+00	1.742E-04	2.147E-05	1.528E-07	1.097E-09
6.000E+00	5.427E+02	1.000E+00	1.454E-04	1.792E-05	1.528E-07	7.605E-10
7.000E+00	4.949E+02	1.000E+00	1.210E-04	1.492E-05	1.528E-07	5.579E-10
8.000E+00	4.505E+02	1.000E+00	1.004E-04	1.237E-05	1.528E-07	4.265E-10
9.000E+00	4.093E+02	1.000E+00	8.299E-05	1.023E-05	1.528E-07	3.365E-10
1.000E+01	3.712E+02	1.000E+00	6.838E-05	8.430E-06	1.528E-07	2.722E-10
1.100E+01	3.360E+02	1.000E+00	5.613E-05	6.920E-06	1.528E-07	2.246E-10
1.200E+01	3.035E+02	1.000E+00	4.592E-05	5.662E-06	1.528E-07	1.885E-10
1.300E+01	2.736E+02	1.000E+00	3.744E-05	4.616E-06	1.528E-07	1.604E-10
1.400E+01	2.461E+02	1.000E+00	3.042E-05	3.750E-06	1.528E-07	1.381E-10
1.500E+01	2.209E+02	1.000E+00	2.464E-05	3.037E-06	1.528E-07	1.201E-10
1.600E+01	1.979E+02	1.000E+00	1.989E-05	2.452E-06	1.528E-07	1.054E-10
1.700E+01	1.768E+02	1.000E+00	1.602E-05	1.975E-06	1.528E-07	9.326E-11
1.800E+01	1.577E+02	1.000E+00	1.286E-05	1.586E-06	1.528E-07	8.306E-11
1.900E+01	1.403E+02	1.000E+00	1.030E-05	1.270E-06	1.528E-07	7.445E-11
2.000E+01	1.245E+02	1.000E+00	8.235E-06	1.015E-06	1.528E-07	6.709E-11

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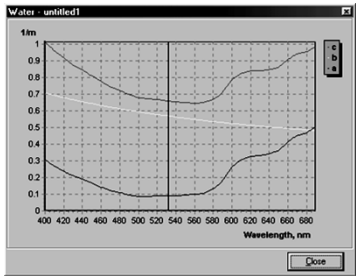
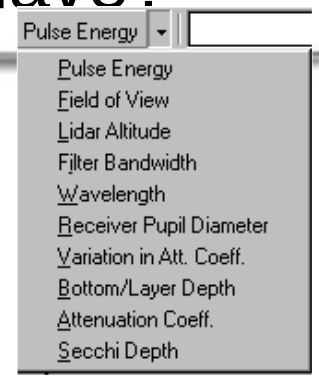
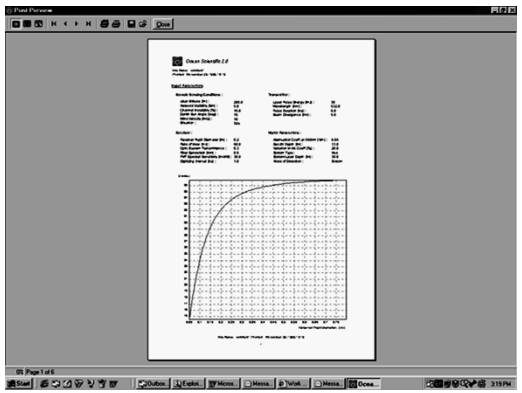
OS2001-OS2005: what we can have?



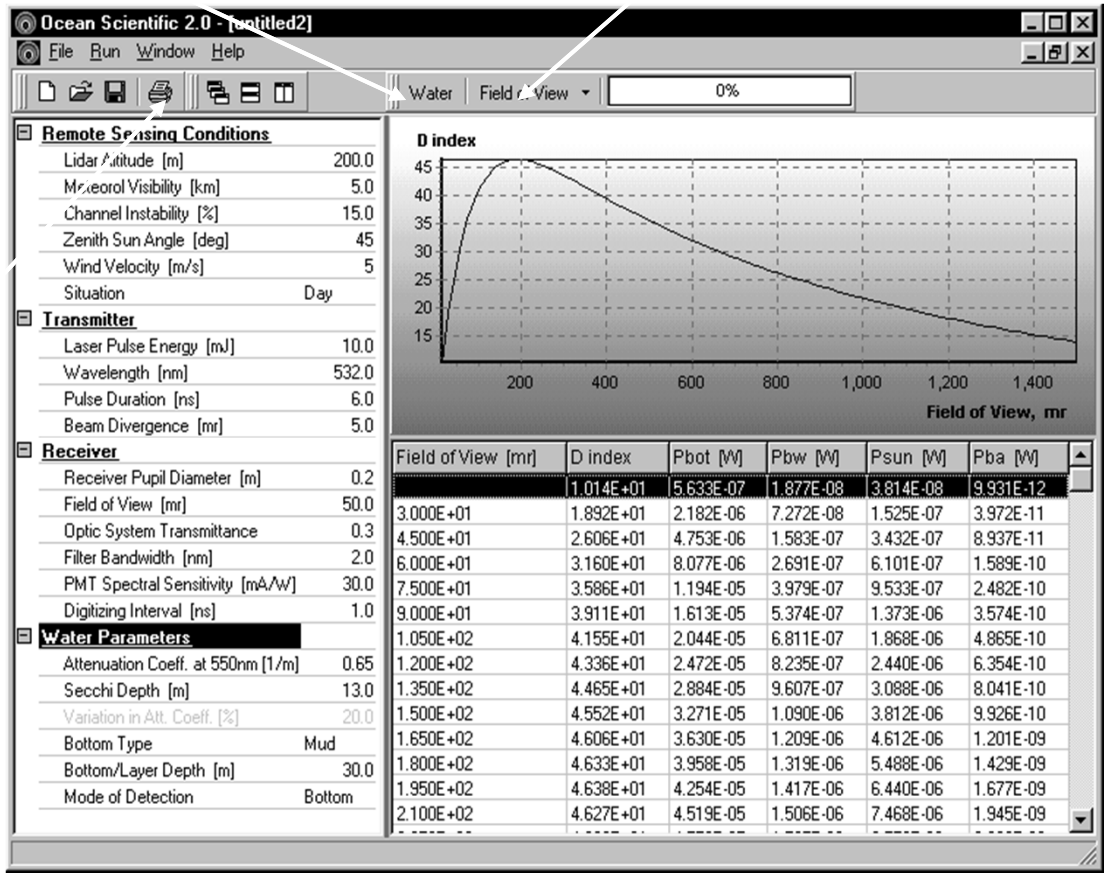
Water

Cycles for optimization





Paper report



Field of View [mr]	D index	Pbot [W]	Pbw [W]	Psun [W]	Pba [W]
	1.014E+01	5.633E-07	1.877E-08	3.814E-08	9.931E-12
3.000E+01	1.892E+01	2.182E-06	7.272E-08	1.525E-07	3.972E-11
4.500E+01	2.606E+01	4.753E-06	1.583E-07	3.432E-07	8.937E-11
6.000E+01	3.160E+01	8.077E-06	2.691E-07	6.101E-07	1.589E-10
7.500E+01	3.586E+01	1.194E-05	3.979E-07	9.533E-07	2.482E-10
9.000E+01	3.911E+01	1.613E-05	5.374E-07	1.373E-06	3.574E-10
1.050E+02	4.155E+01	2.044E-05	6.811E-07	1.868E-06	4.865E-10
1.200E+02	4.336E+01	2.472E-05	8.235E-07	2.440E-06	6.354E-10
1.350E+02	4.465E+01	2.884E-05	9.607E-07	3.088E-06	8.041E-10
1.500E+02	4.552E+01	3.271E-05	1.090E-06	3.812E-06	9.926E-10
1.650E+02	4.606E+01	3.630E-05	1.209E-06	4.612E-06	1.201E-09
1.800E+02	4.633E+01	3.958E-05	1.319E-06	5.488E-06	1.429E-09
1.950E+02	4.638E+01	4.254E-05	1.417E-06	6.440E-06	1.677E-09
2.100E+02	4.627E+01	4.519E-05	1.506E-06	7.468E-06	1.945E-09

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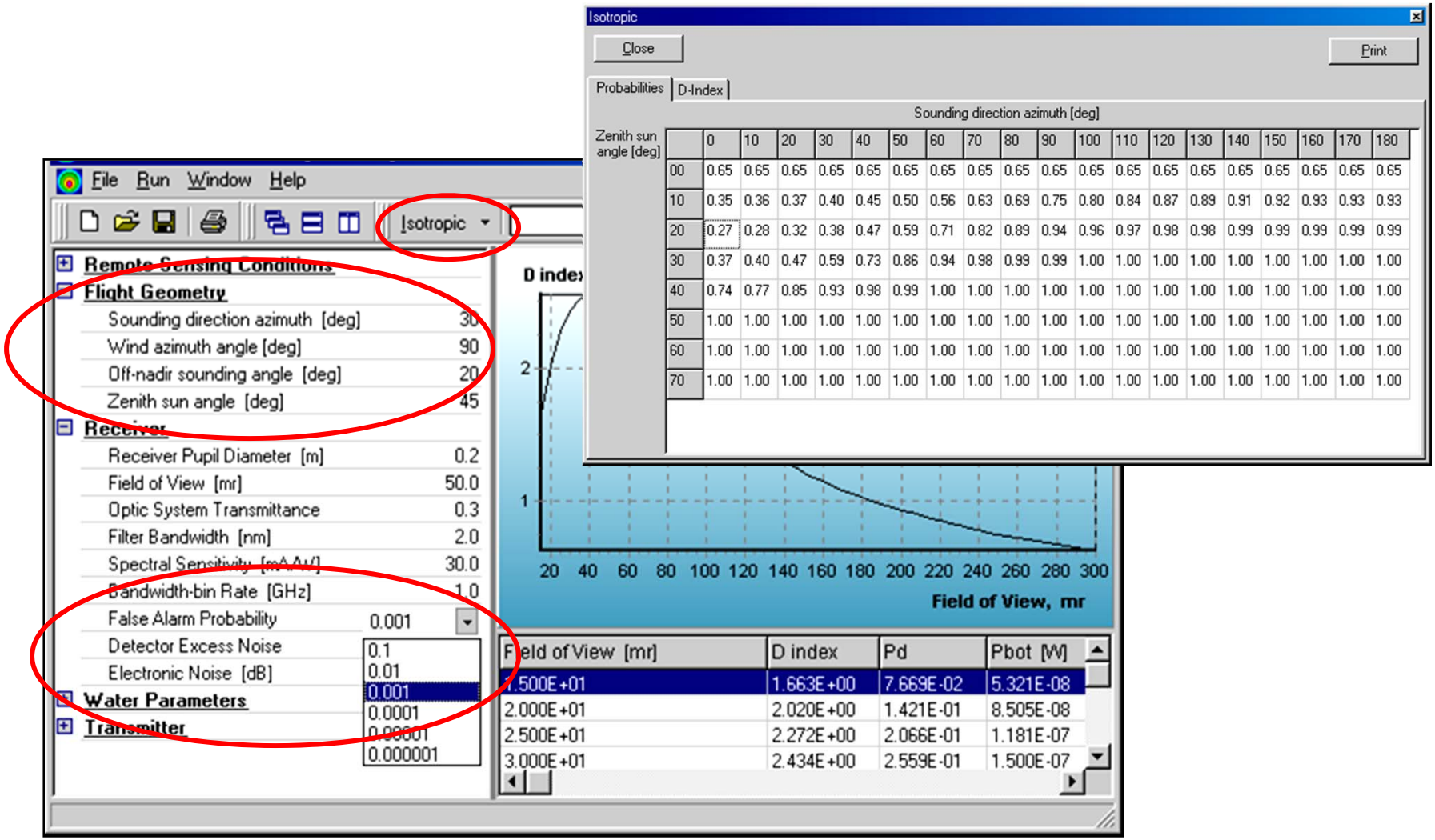
OS2005: extra capabilities



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Signal-to-noise ratio (SNR) is the best-known example of discriminability index. It has been favorably used for signal detection problems in radar applications.

SNR is based on the fact, that noise distribution is:

- Normal
- The standard deviation of noise distribution is not a function of the signal

But SNR does not work in the optical region, because:

- The emitted photoelectron distribution of the photocathode is Poisson
- The noise distribution (and standard deviation) is a function of the signal

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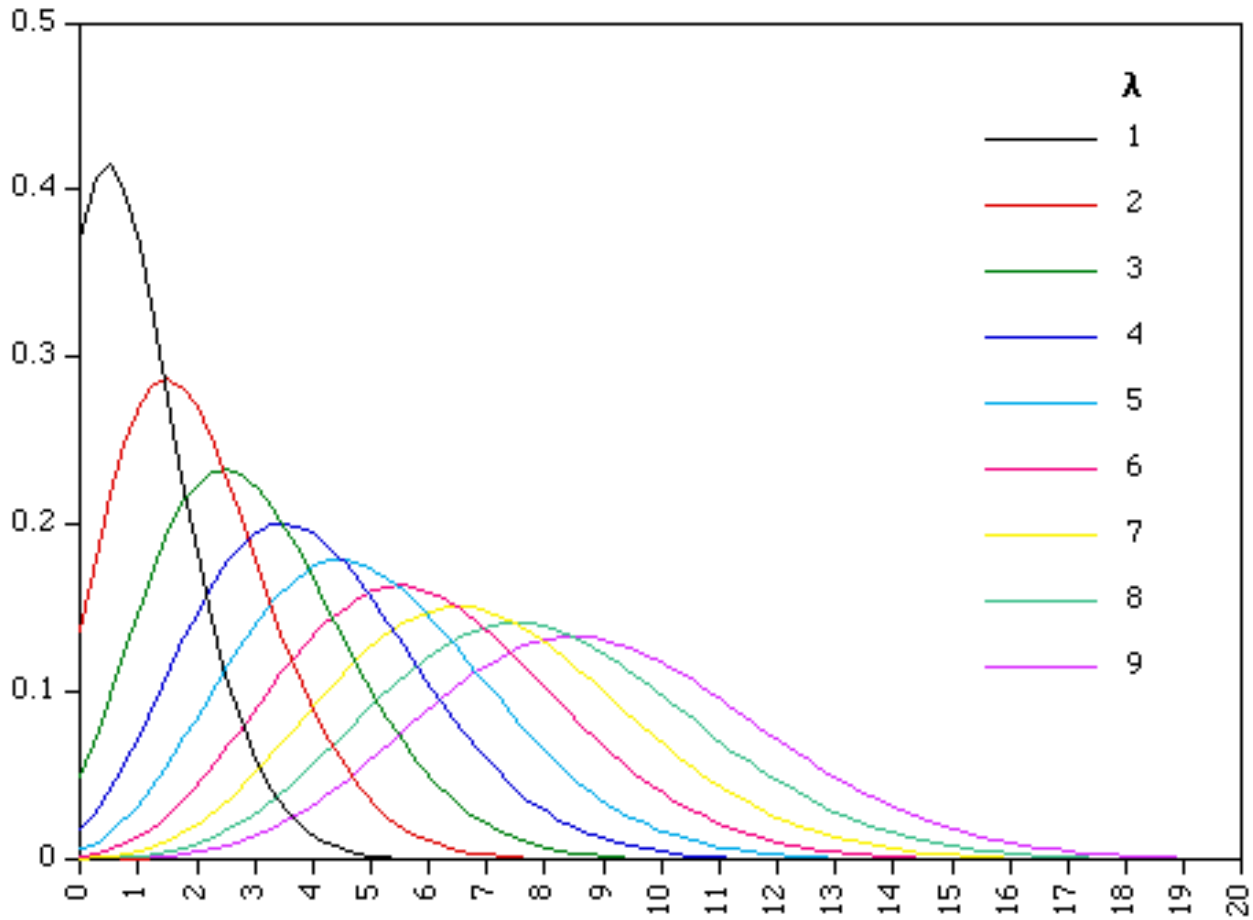
Poisson distribution



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Criterion for lidar comparison: D-index of discriminability

$$D = \left|(i_B - i_A)\right| / (S_A \cdot S_B)^{1/2}$$

Where:

i_A and i_B are the mean values for distributions; A and B, respectively (A- noise only; B – signal and noise;

S_A and S_B are the corresponding standard deviations

If $S_A = S_B \Rightarrow D = SNR$

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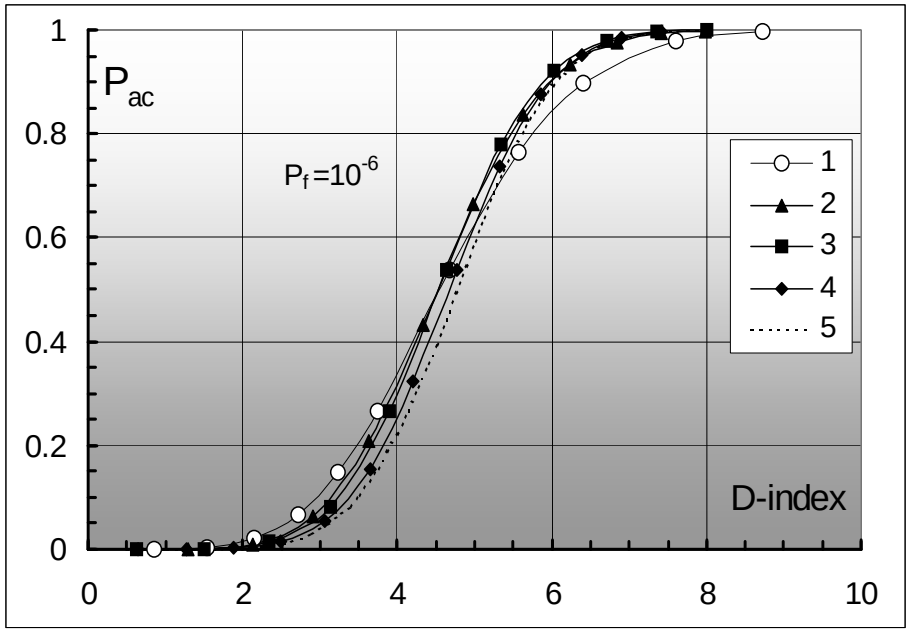
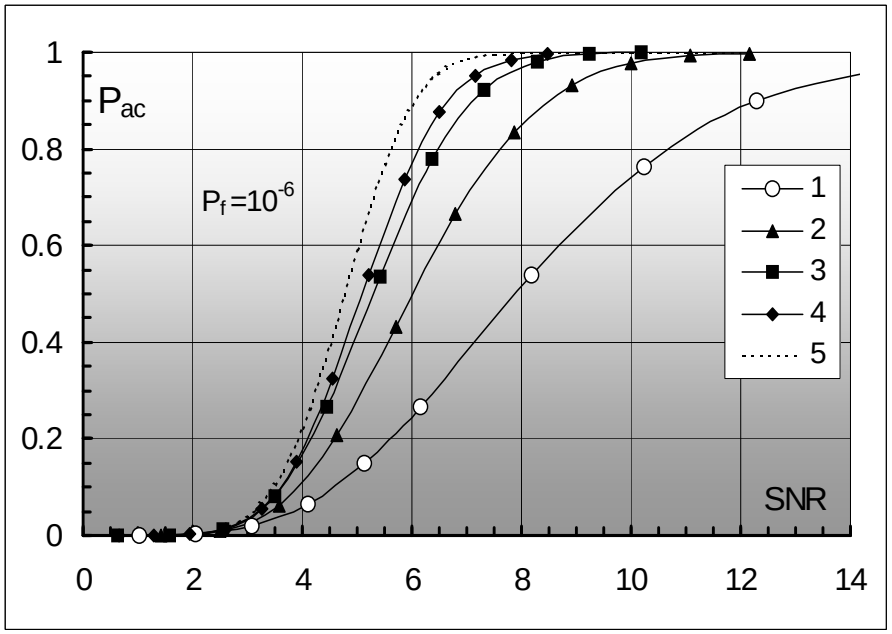
Application of D-index of discriminability





The acquisition probability, P_{ac} ,versus the D-index and SNR for fixed $P_f = 10^{-6}$. Curves 1 – 4 correspond to Poisson distributions with m_n = 1; 8; 40; and 151. Curves 5 correspond to approximations

$$\mathrm{P}_{ac} = \tfrac{1}{2} Erfc\left[Erfc^{-1}(2\mathrm{P}_f) - D\right]$$

$$\mathrm{P}_{ac} = \tfrac{1}{2} Erfc\left[Erfc^{-1}(2\mathrm{P}_f) - SNR\right]$$

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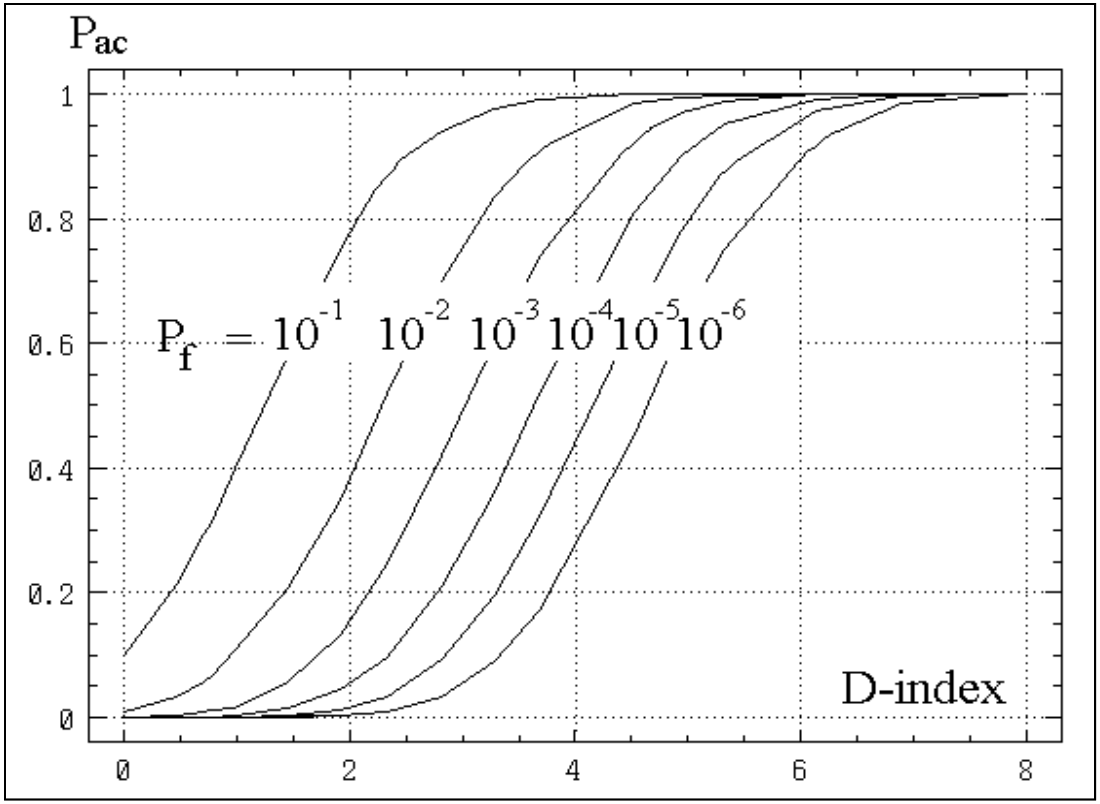
Application of D-index of discriminability



The connection between D-index and the acquisition probability, P_{ac}, for different levels of false-alarm probability, P_f , in the case of Poisson distribution.

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Evaluation of D-index

$$D = \left|(i_B - i_A)\right| / (S_A \cdot S_B)^{1/2}$$

$$i_A = i_{bw} + i_{ba} + i_{sun};$$

$$i_B = i_A + i_{bot}$$

$$i_{bw,\ ba,\ sun,\ bot} = P_{bw,\ ba,\ sun,\ bot} \cdot s_\lambda$$

s_λ is the detector spectral sensitivity (in A/W)

The number of photoelectrons per time interval, Δt, is given by the formula:

$$\overline{m} = \frac{P \cdot S_\lambda \cdot \Delta t}{e}$$

where:
P is mean input signal power;
e is the electron charge.
With typical values of Δt = 1 ns and S_λ = 70-80 mA/W, for $P = 10^{-8}$ W (such a signal power corresponds to practical limits of detectability) one has $\overline{m} \approx 2 \div 4$.

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Distribution functions for lidar response at photo-detector output - Poisson distributions:

$$p_{sn}(m) = \frac{\left(\overline{m}_s + \overline{m}_n\right)^m}{m!} \exp\left(-\left(\overline{m}_s + \overline{m}_n\right)\right)$$

$$p_n(m) = \frac{\left(\overline{m}_n\right)^m}{m!} \exp\left(-\overline{m}_n\right)$$

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

$\overline{m}_n$ is the same for "noise" photoelectrons.

For Poisson processes p_n and p_{sn}

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

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

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Formalization of statistical approach

False alarm probability P_f

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

Acquisition probability, P_{ac}

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

with m_0 being the threshold of discriminator.

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Lidar equations

$$P_{bot}(h) = P_0 \frac{\rho_{bot}}{\pi} \Sigma \eta \frac{e^{-2l_{Atm}}}{(Hn+h)^2} (1-\rho_{Fr})^2 e^{-2K_{sys}h}$$

$$P_{bs}(h) = P_0 \frac{c\tau_{pulse}}{2n} \beta_\pi \cdot \Sigma \cdot \eta \frac{e^{-2l_{Atm}}}{(Hn+h)^2} (1-\rho_{Fr})^2 \cdot e^{-2K_{sys}h}$$

$$K_{sys} = K_d - \frac{1}{2h} \ln F(h)$$

$\Rightarrow K_{sys}$ depends on:
1) the water IOP's K_d and b_f ;
2) the lidar system parameters (FOV, divergence), and
3) the depth $\Rightarrow$

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$$P_{sun} = P_{glt} + P_{sky} + P_{bsun} \sim \Sigma\, \eta \Omega_R \Delta\lambda$$

where

P_{sky} is the diffused sky radiance reflected by the surface

P_{bsun} is natural light backscattered in sea water column

P_{glt} caused by specular reflection of sunlight over ocean waves

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Proportion between return signal components

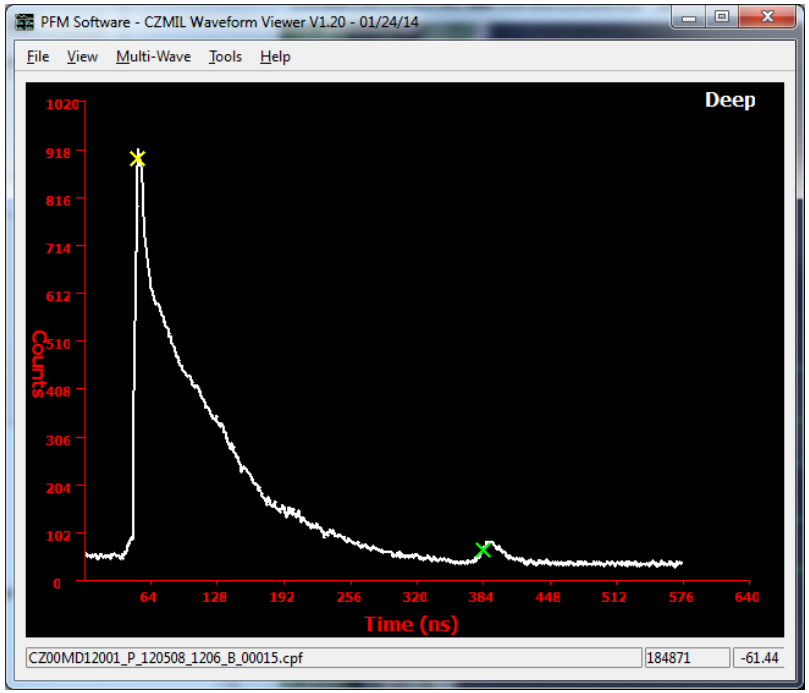
$$P_{bot}(h) = P_0 \frac{\rho_{bot}}{\pi} \Sigma \eta \frac{e^{-2l_{Atm}}}{(Hn+h)^2} (1-\rho_{Fr})^2 e^{-2K_{sys}h}$$

$$P_{bs}(h) = P_0 \frac{c\tau_{pulse}}{2n} \beta_\pi \cdot \Sigma \cdot \eta \frac{e^{-2l_{Atm}}}{(Hn+h)^2} (1-\rho_{Fr})^2 \cdot e^{-2K_{sys}h}$$

$$\frac{\rho_{bot}}{\pi} >> \frac{c\tau_{pulse}}{2n} \beta_\pi$$

$$P_{bot} >> P_{bs}$$

$$P_{bot} > \sigma_{P_{sun}}$$



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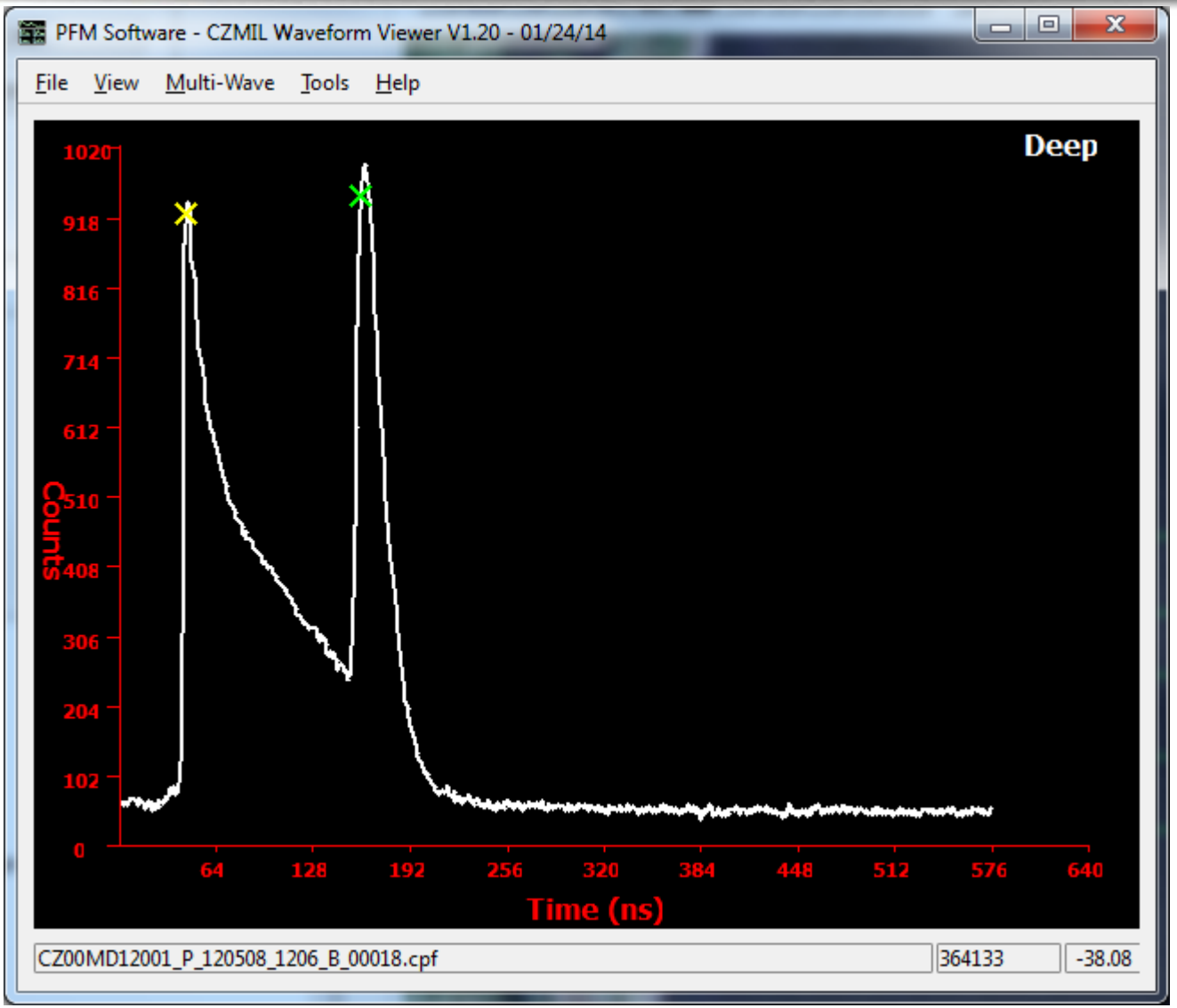
CZMIL operator screen copy



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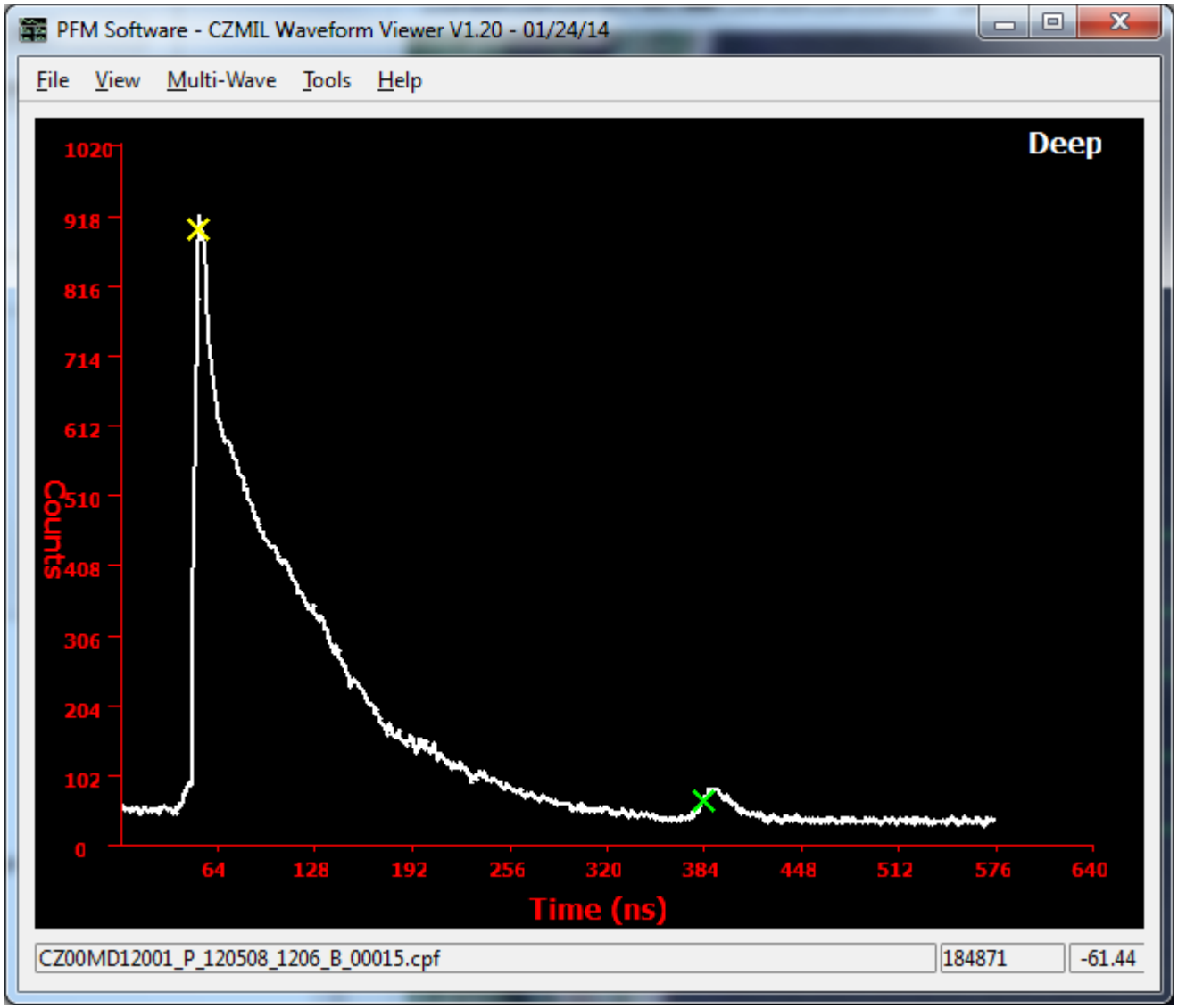
CZMIL operator screen copy



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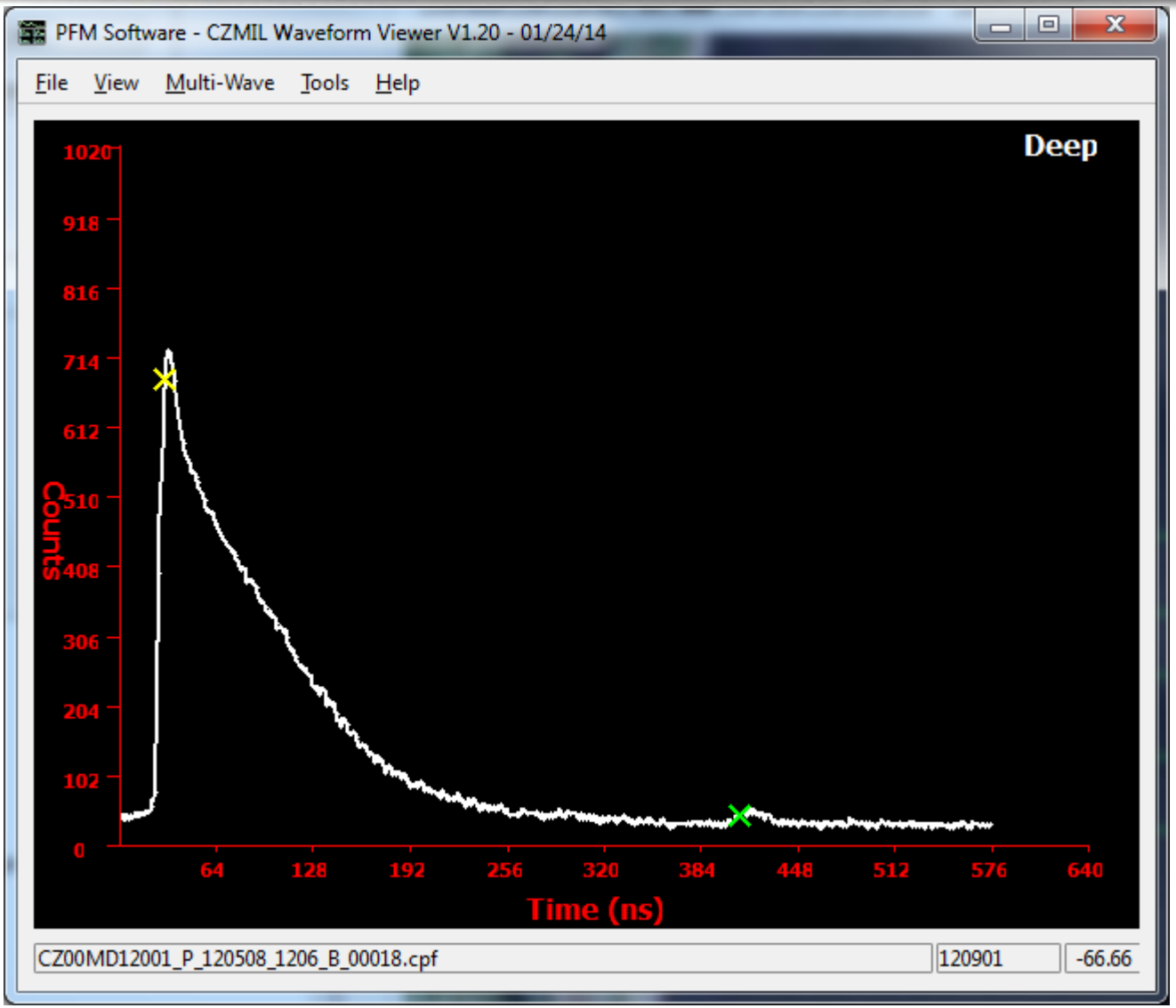
CZMIL operator screen copy



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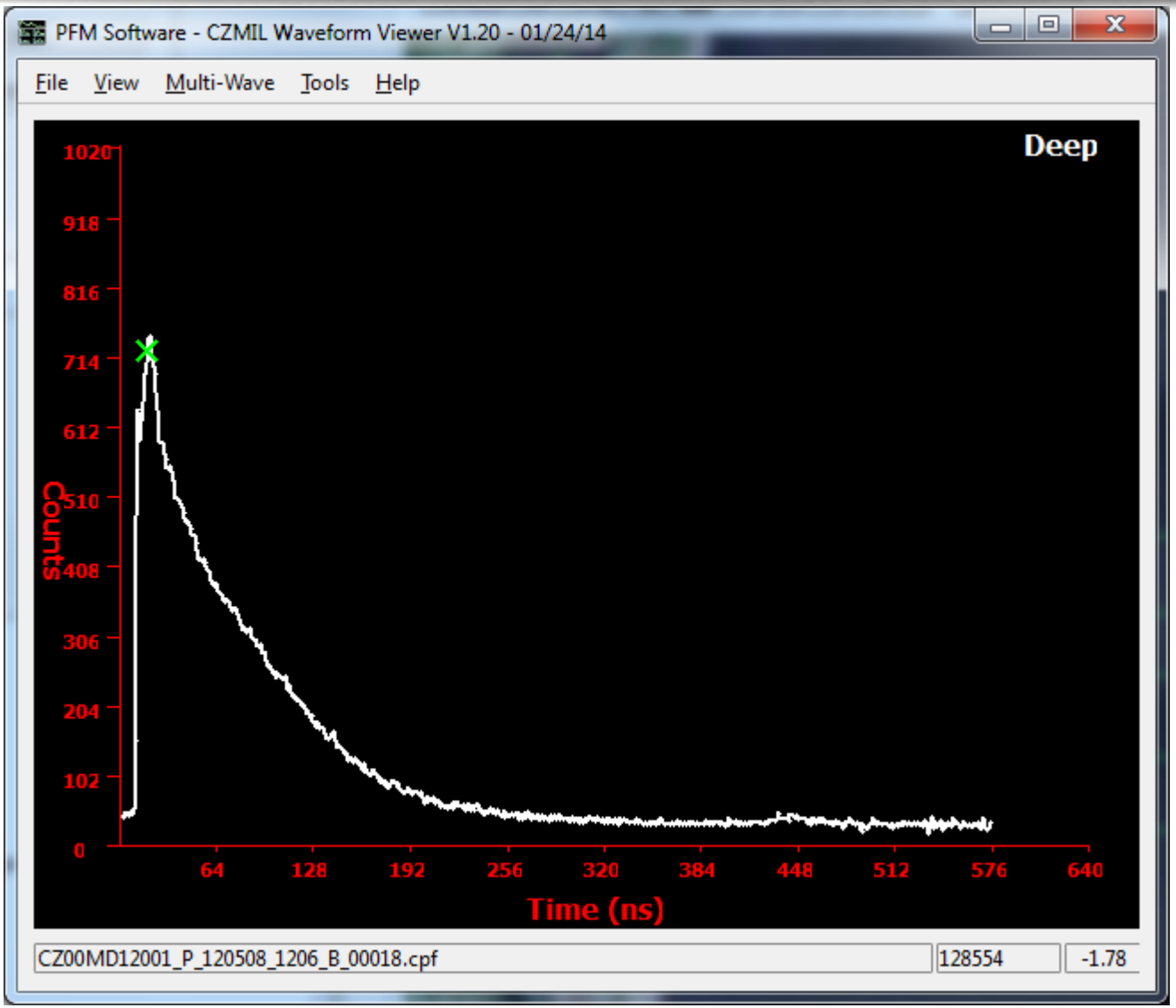
CZMIL operator screen copy



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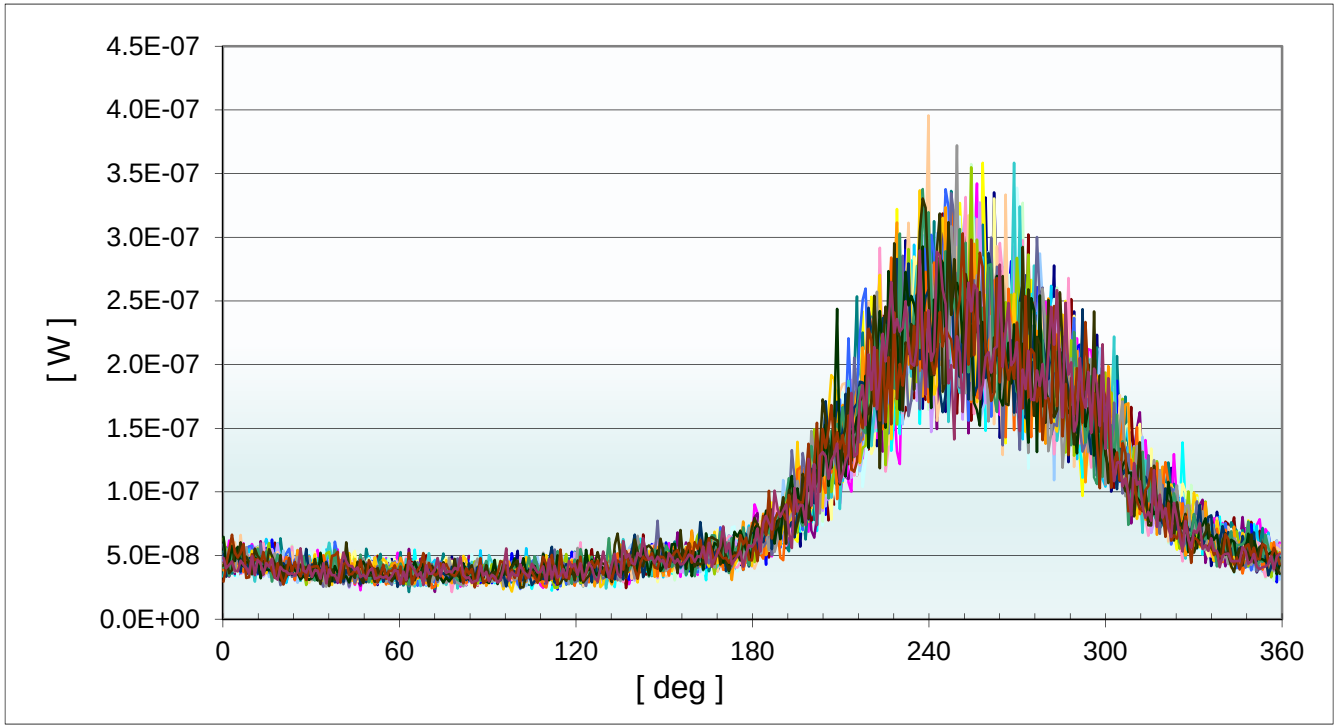
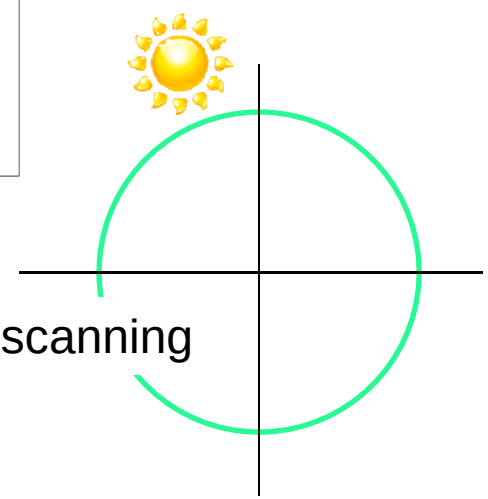
Bright sunny day; Zenith sun angle = 35°

CZMIL: sun background standard deviation, W



$$P_{bot} > \sigma_{P_{sun}}$$

$$P_{bot} < P_{sun}$$



Circular scanning

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Assumptions for all bathymetrical systems

$$P_{bot}(h) = P_0 \frac{\cancel{\rho_{bot}}}{\pi} \Sigma \eta \frac{\cancel{e^{-2l_{Atm}}}}{\cancel{(Hn+h)^2}} \cancel{(1-\rho_{Fr})^2} \cancel{e^{-2K_{sys}h}}$$

$$P_{bs}(h) = P_0 \frac{c\tau_{pulse}}{2n} \cancel{\beta_\pi} \cdot \Sigma \cdot \eta \frac{\cancel{e^{-2l_{Atm}}}}{\cancel{(Hn+h)^2}} \cancel{(1-\rho_{Fr})^2} \cdot \cancel{e^{-2K_{sys}h}}$$

$$P_{sun} \sim \Sigma \eta \cancel{\Omega_R} \Delta\lambda$$

The atmosphere and surface state are the same

The bottom reflectance is the same

The altitude and depth are the same

The Field-of-view is the same and near optimal

The water properties are the same

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Equations

$$P_{bot}(h) \sim P_0 \, \Sigma \eta$$

$$P_{bs}(h) \sim P_0 \Sigma \cdot \eta << P_{bot}(h)$$

$$P_{sun} \sim \Sigma \, \eta \cdot \Delta\lambda$$

$$\Sigma = \pi d_0^{\,2}/4$$

$$\overline{m} = \frac{P \cdot S_\lambda \cdot \Delta t}{e} \sim P$$

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

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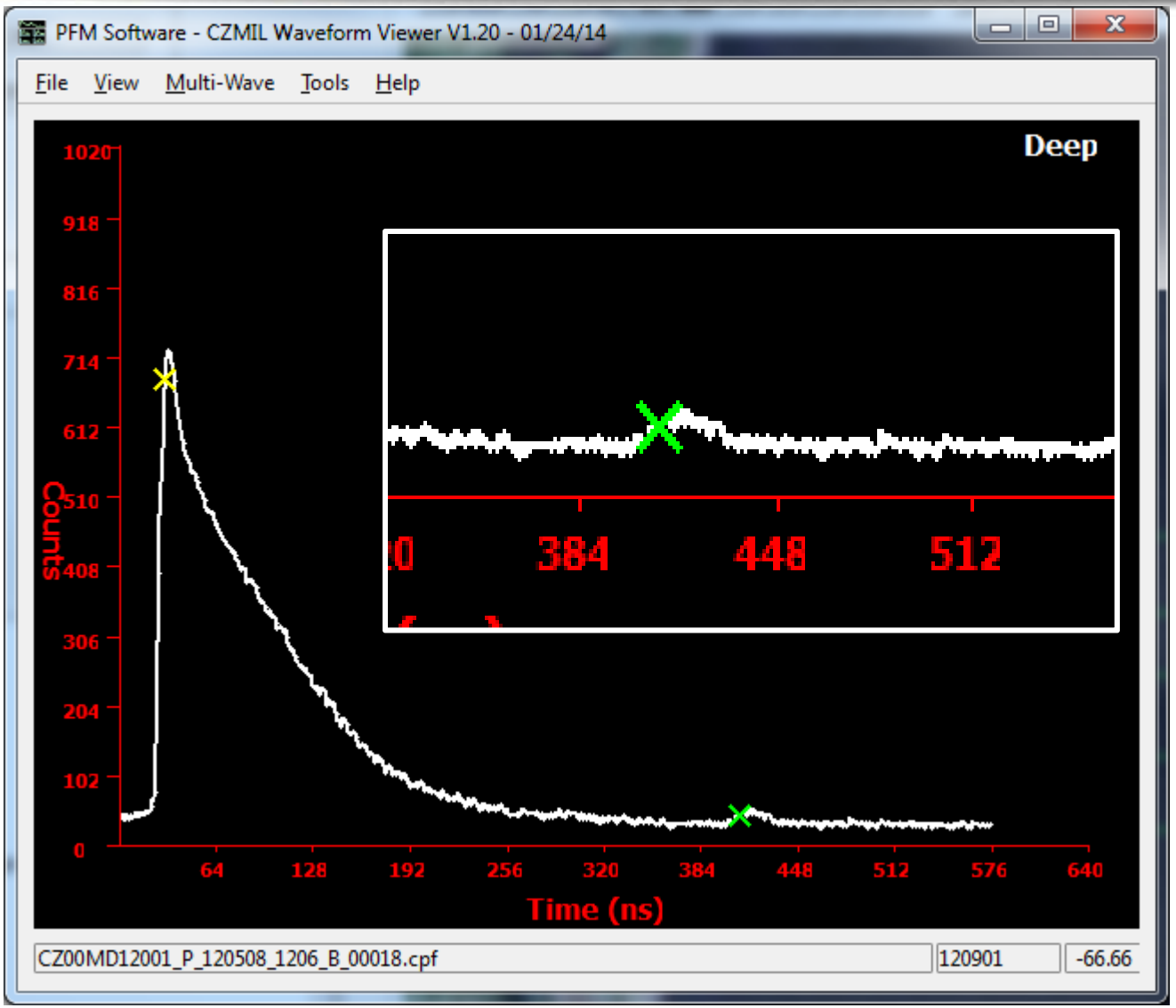
CZMIL practical case



$$P_{bot} >> P_{bs}$$

$$P_{bot} > \sigma_{P_{sun}}$$

$$P_{bot} < P_{sun}$$

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Equations

$$\overline{m}_n >> \overline{m}_s > \sqrt{\overline{m}_n}$$

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

$$D \approx \frac{\overline{m}_{bot}}{\sqrt{\overline{m}_{sun}}}$$

$$D \sim \frac{P_0 \Sigma \eta}{\sqrt{\Sigma \eta \cdot \Delta\lambda}} \sim P_0 \cdot d_0 \cdot \sqrt{\frac{\eta}{\Delta\lambda}} = C_{BL}$$

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The universal parameter C_{BL}

$$C_{BL} = P_0 \cdot d_0 \cdot \sqrt{\frac{\eta}{\Delta\lambda}} \qquad [kW \cdot m \cdot (nm)^{-1/2}]$$

where:

P_0 is the transmitter (laser) pulse power;

d_0 is the diameter of input receiver optics;

η is the optical transparency of transmitter-receiver;

$\Delta\lambda$ is the bandwidth of receiver spectral selector

$$C_{BL}^{CZMIL} = 1500 \cdot 0.2 \cdot \sqrt{\frac{0.62}{1}} = 232.4; \quad kW \cdot m \cdot (nm)^{-1/2}$$

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Maximal penetration optical depth

Maximal penetration optical depth for system X (comparison with CZMIL; K_d*D_{max}= 4.0-4.2)

$$(K_d D_{\max})_X = (K_d D_{\max})_{CZMIL} + \ln(C_{BL}^{X} / C_{BL}^{CZMIL}) / 2$$

$$C_{BL}^{CZMIL} = 232.4; \quad kW \cdot m \cdot (nm)^{-1/2}$$

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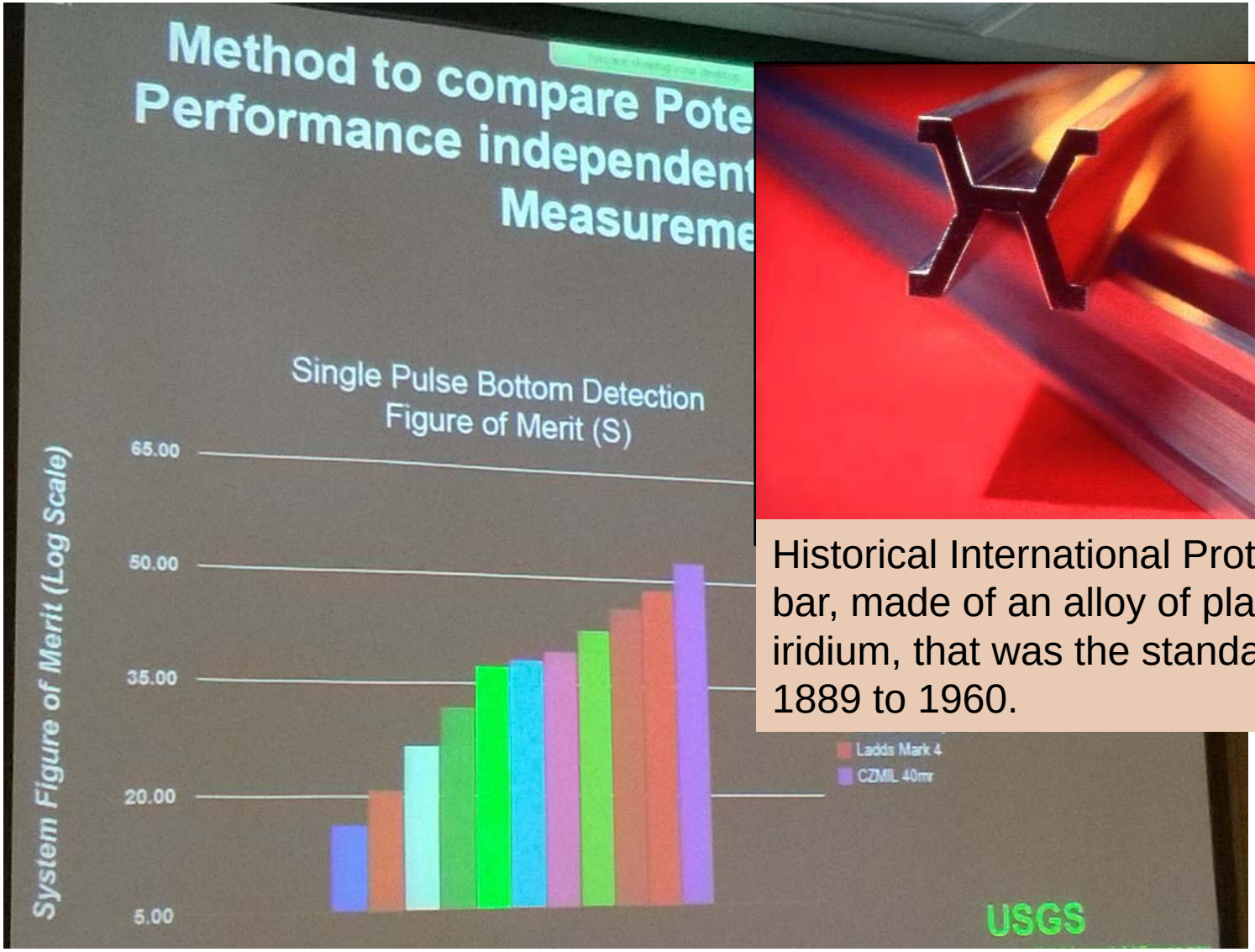
CZMIL as a “meter bar”



Historical International Prototype Metre bar, made of an alloy of platinum and iridium, that was the standard from 1889 to 1960.

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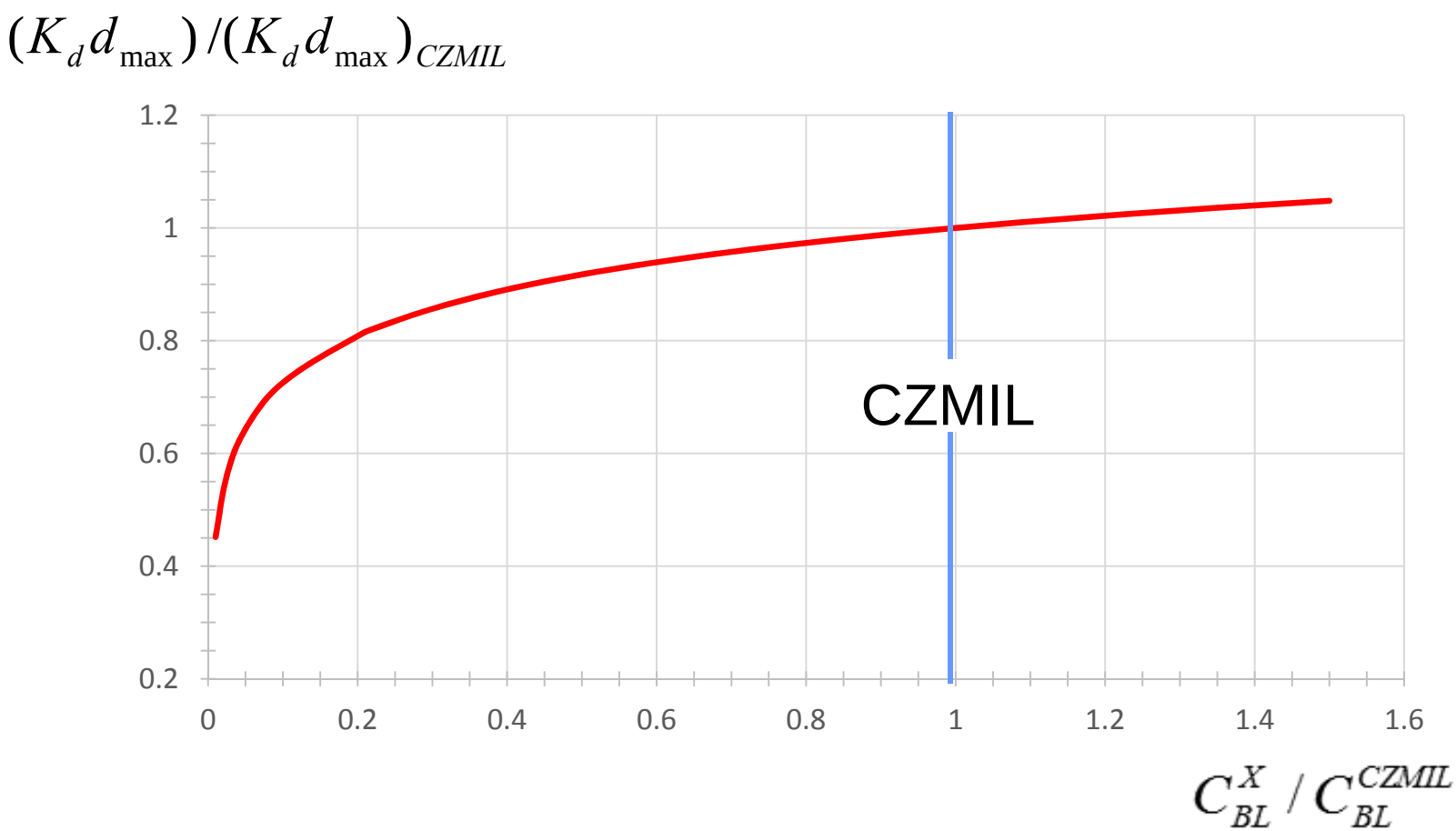
Prediction of K_d*d_{max} *as a function of* $C_{BL}^{X} / C_{BL}^{CZMIL}$

Assumption: water body is homogenous



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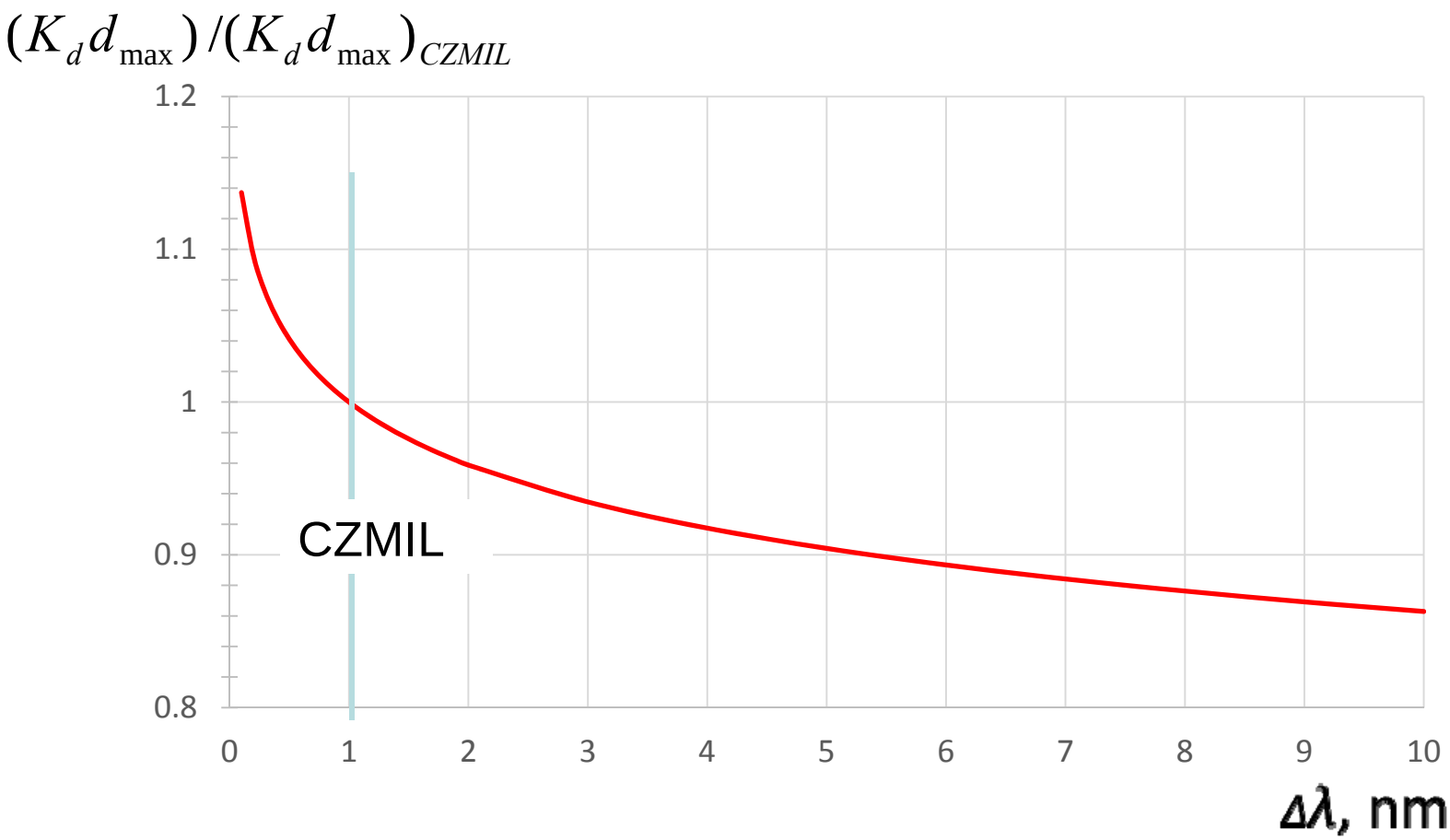
$(K_d{*}d_{max})/(K_d{*}d_{max})_{CZMIL}$ vs $\Delta\lambda$ for sunny day

Warning: all other parameters are CZMIL. Variable $\Delta\lambda$ only!



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Conclusions

- We have presented a universal parameter to compare lidar bathymeters which can be used under certain assumptions to compare lidar systems and to predict the maximum penetration.

- We have demonstrated, that for the bathymetric lidars the most important parameters are:
  The laser pulse power;
  The diameter of the input lens;
  The bandwidth of optical filter

- For more accurate systems comparison (and optimization) a special computer program can be used

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