An improved measure of maximum lidar depth

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$D^{max} = 3 / K_d$ or $2 / K_d$???

K , τ (OD)

IOP's

Kd

Lidar sytem attenuation

Proof with CZMIL

Secchi disk depth ?

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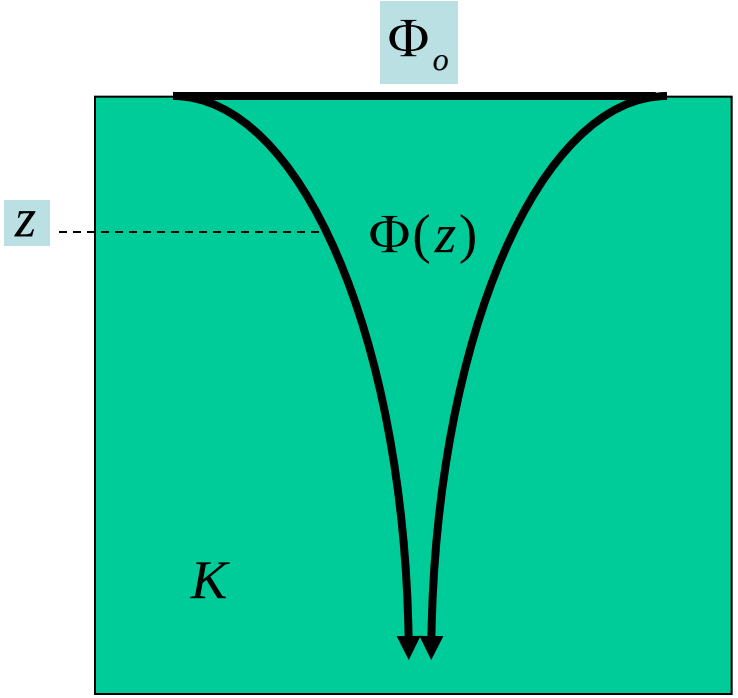
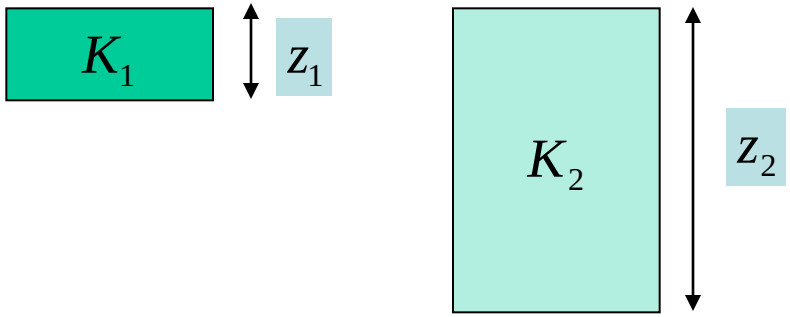
Attenuation coefficient (K), Optical Depth (τ)



$$\tau_1 = K_1 \cdot z_1 \qquad \tau_2 = K_2 \cdot z_2$$



$$\frac{d\Phi}{dz} = -K \cdot \Phi$$

$$\Phi(z) = \Phi_o \exp\left[-\boxed{K \cdot z}\right]$$

$$\Phi(z) = \Phi_o \exp\left[-\boxed{\int_0^z K(z') \cdot z' dz'}\right]$$

τ

$$z = 1/K \;\Rightarrow\; \tau = 1$$

Geometrical distance per unit OD

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Maximum lidar depth

Gas tank volume x Mile / Gal = Distance

$$1/Drag$$

$$Drag = D_{Road} + D_{Car}$$

$\tau^{\max}$ x Meter / τ = Depth

$$1/K_{lidar}$$

$$K_{lidar} = K_{water} + K_{system}$$

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Terrain (Water) or Car (System) ?

$$Drag = D_{Road} + D_{Car}$$

High – end System

Ksystem ↓

$$K_{lidar} = K_{water} + K_{system}$$

low – end System

Ksystem ↑

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Inherent Optical Properties (IOP's)

There's only 2 types of (fundamental) IOP's :

$$a, \quad \beta(\theta)$$

beam attenuation coefficient, single scattering albedo, phase function
forward (backward) scattering coefficient, backscattering coefficient

Apparent Optical Properties (AOP's)

Ambient (L)

downwelling average cosine, upwelling average cosine
downwelling scalar irradiance attenuation
upwelling scalar irradiance attenuation
downwelling plane irradiance attenuation K_d
upwelling plane irradiance attenuation
downwelling radiance attenuation
upwelling radiance attenuation
irradiance reflectance, photosynthecally available radiation attenuation coefficient

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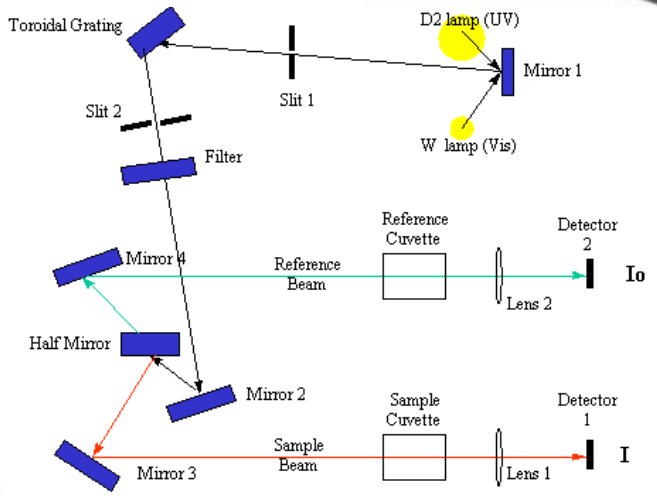
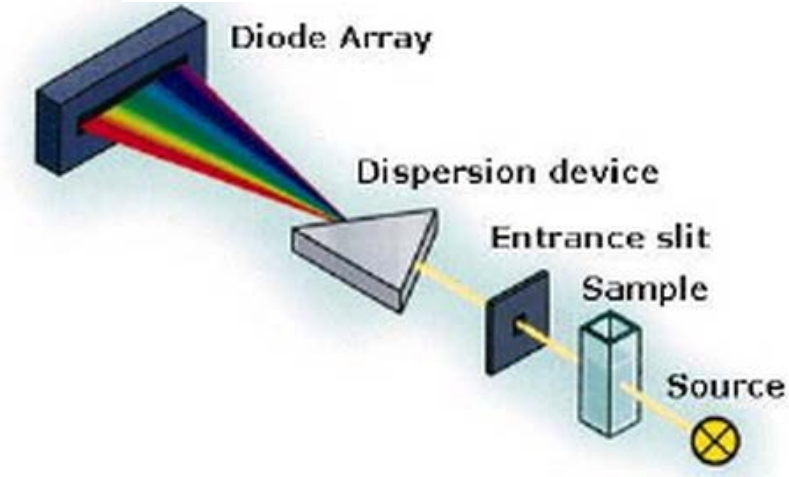
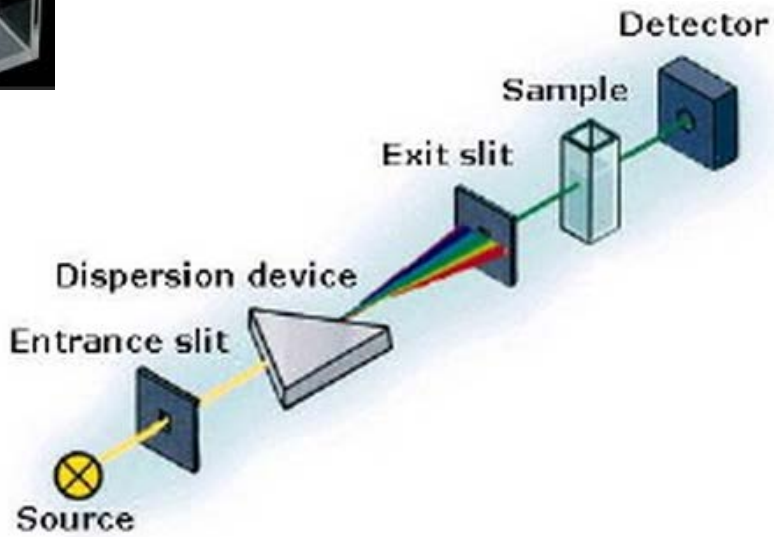
Spectrophotometer







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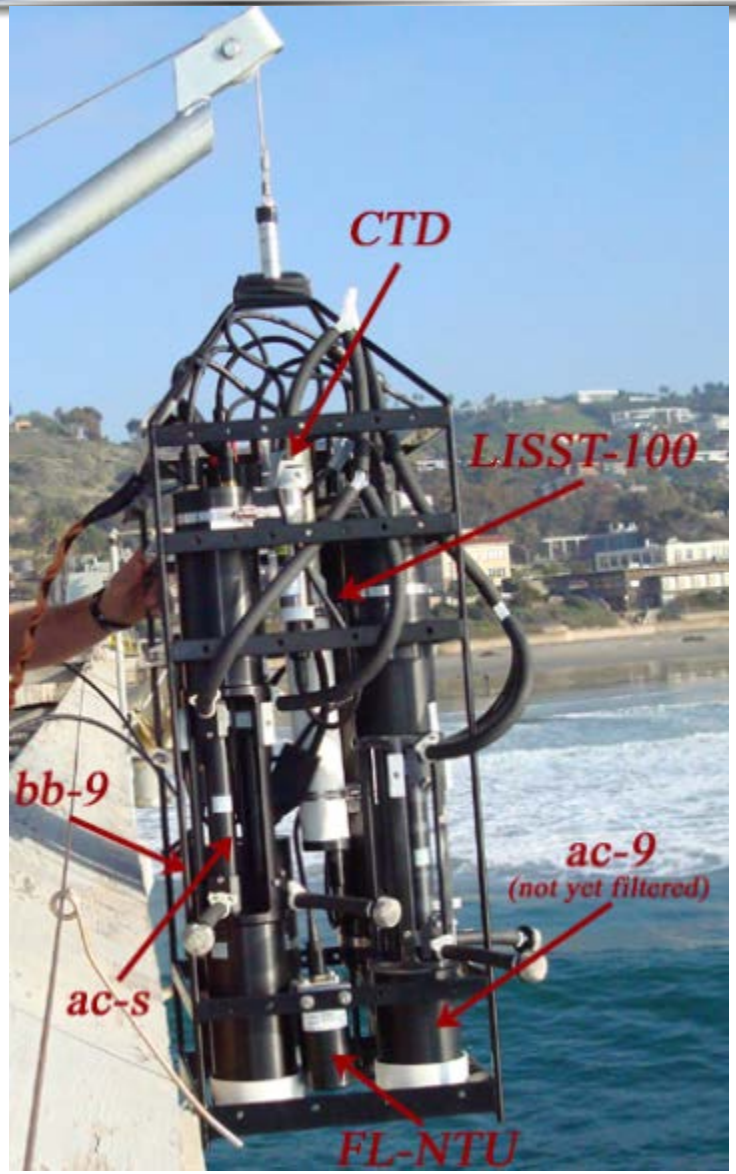
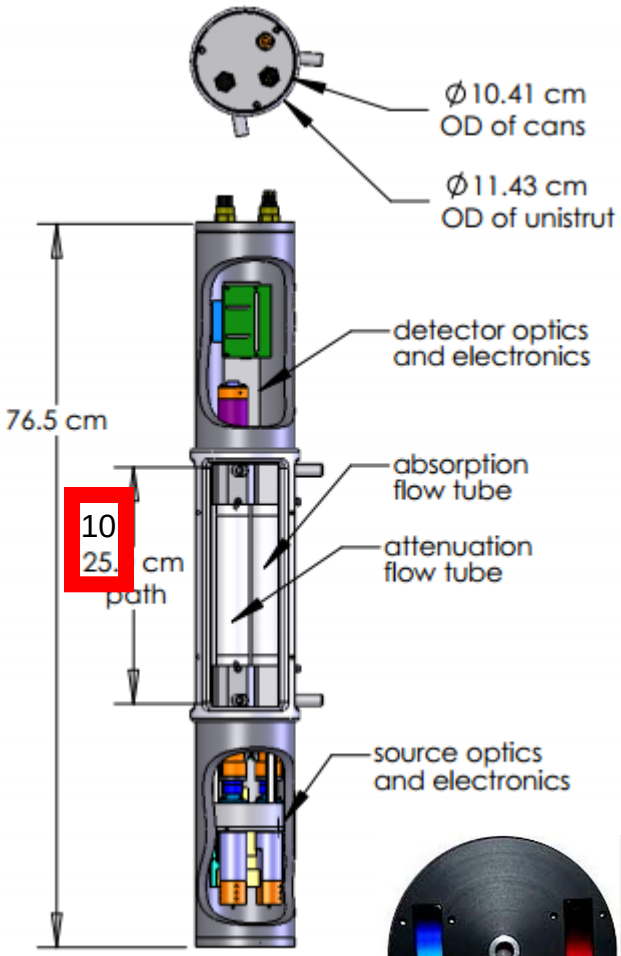
ACS (in-situ, long cuvette, abs+scat)



WetLabs, Inc.



Incandescent

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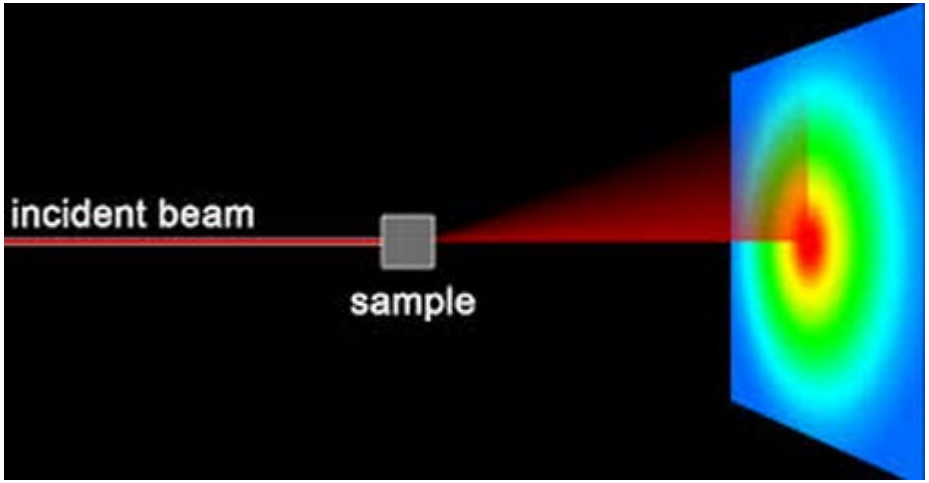
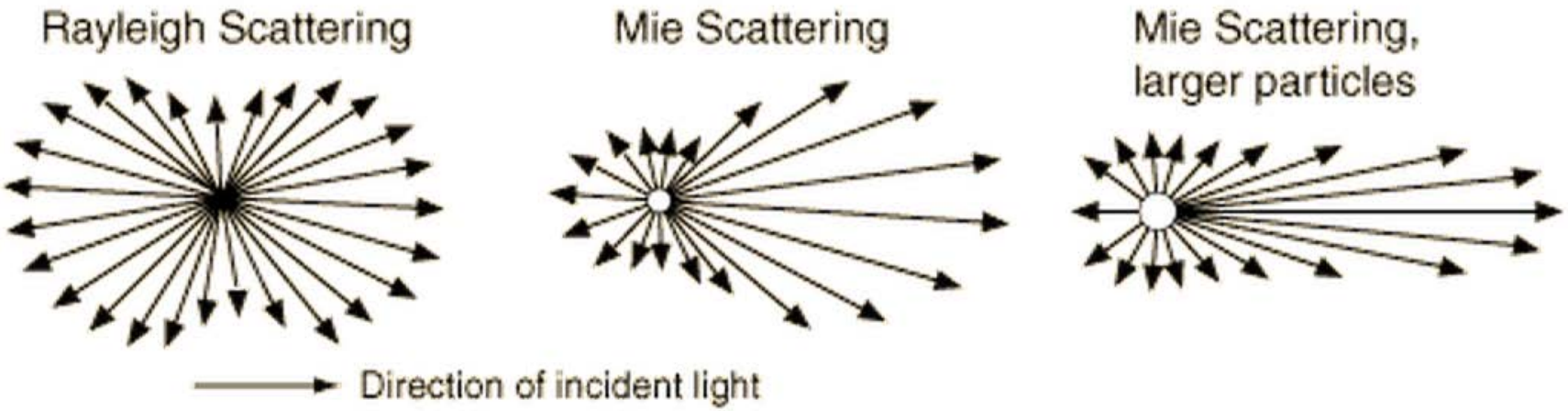
Volume scattering function (VSF)





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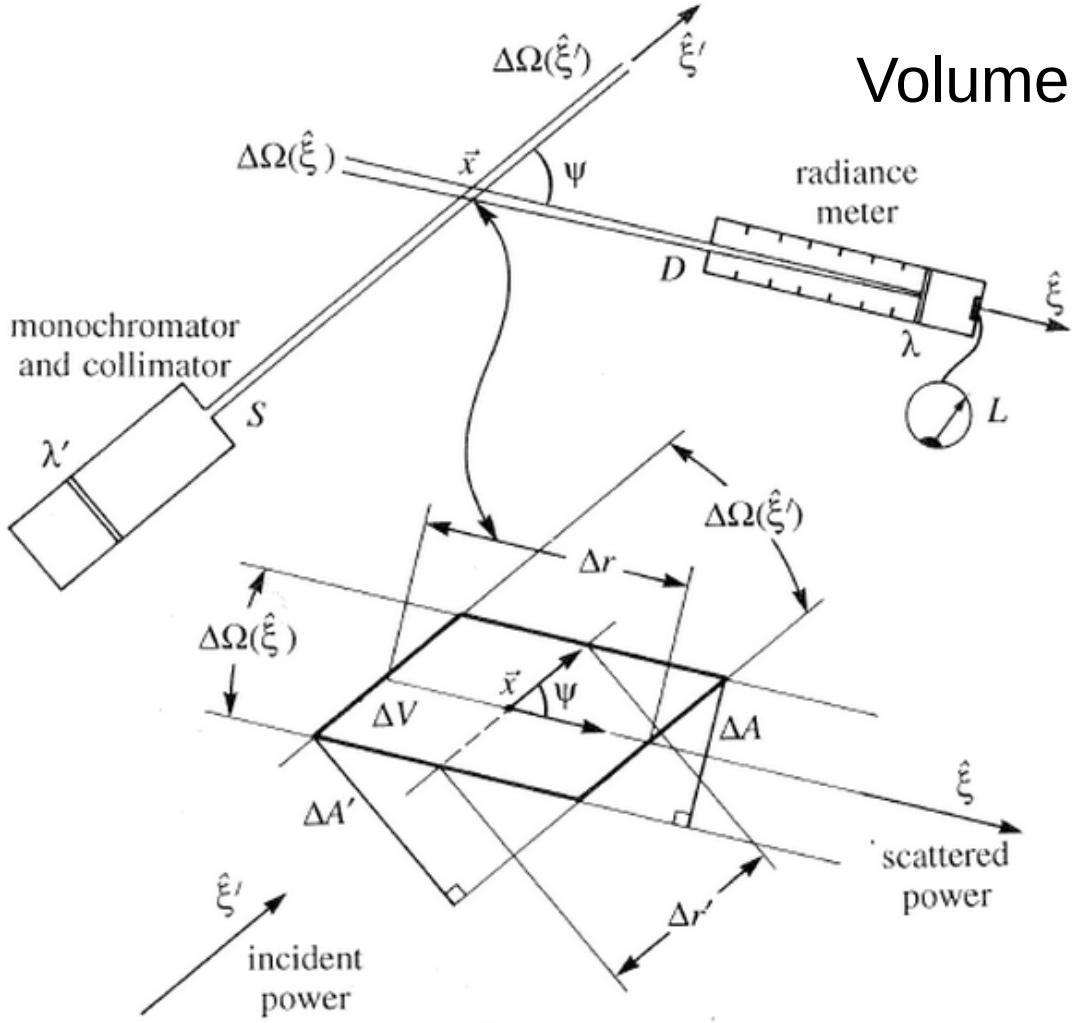
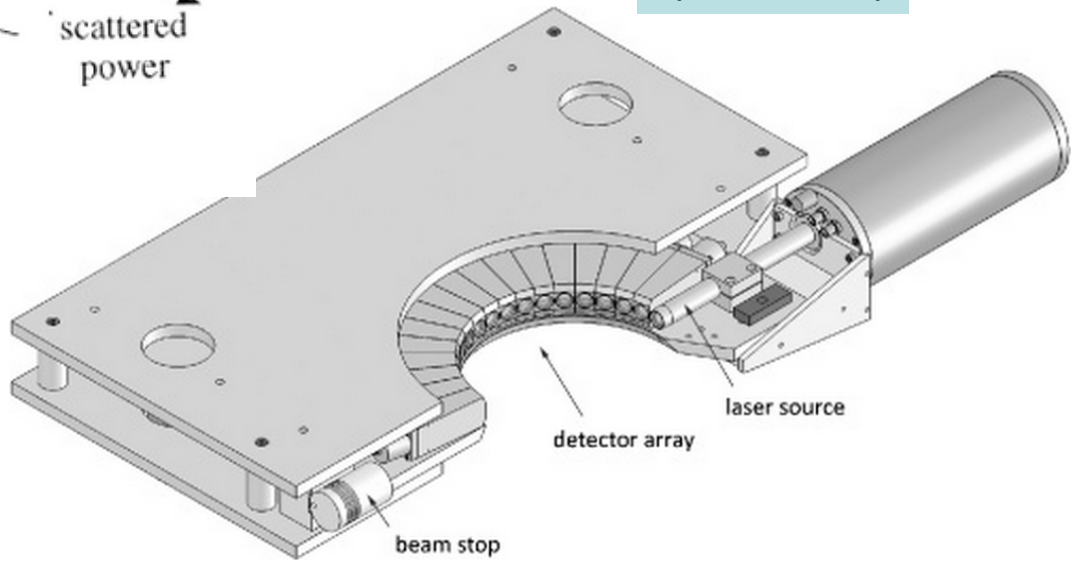
Volume scattering function (VSF)



MASCOT
(Wetlabs Inc)



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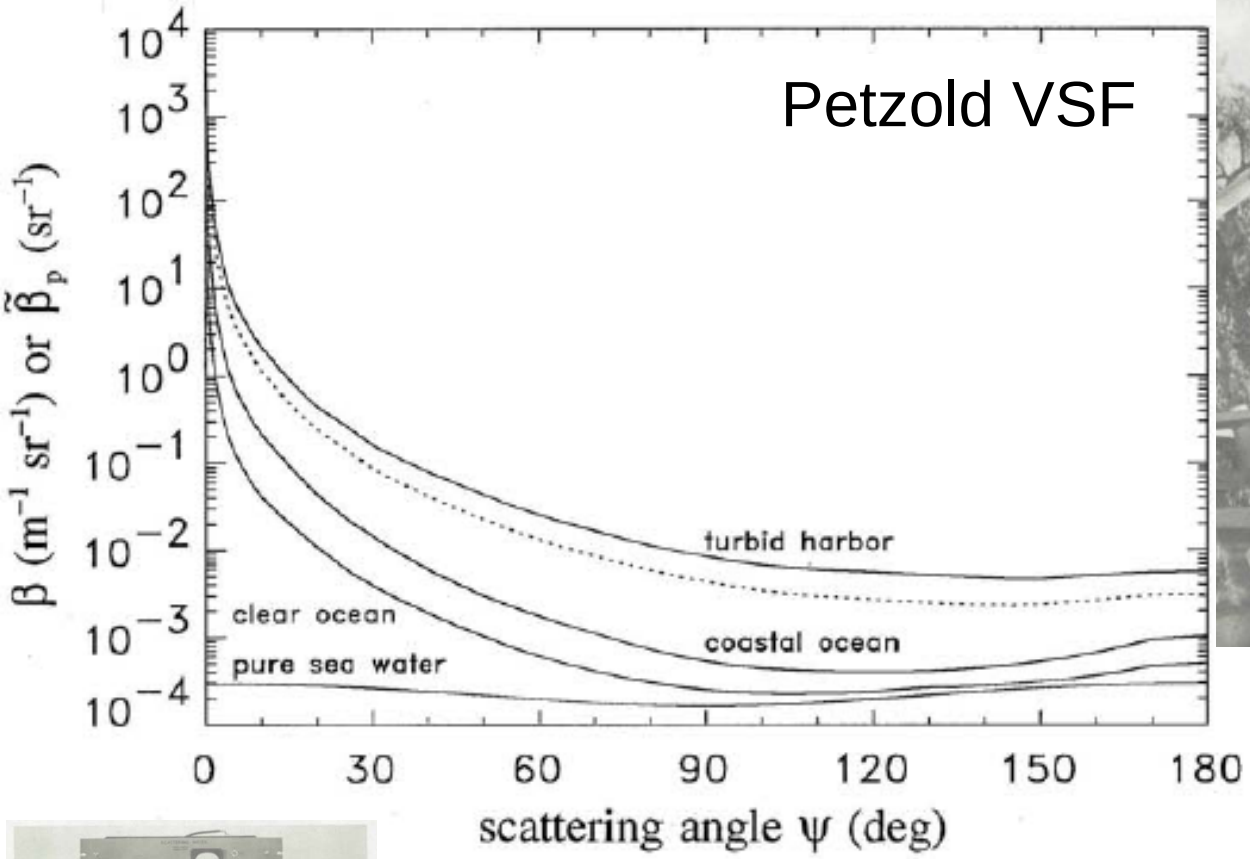
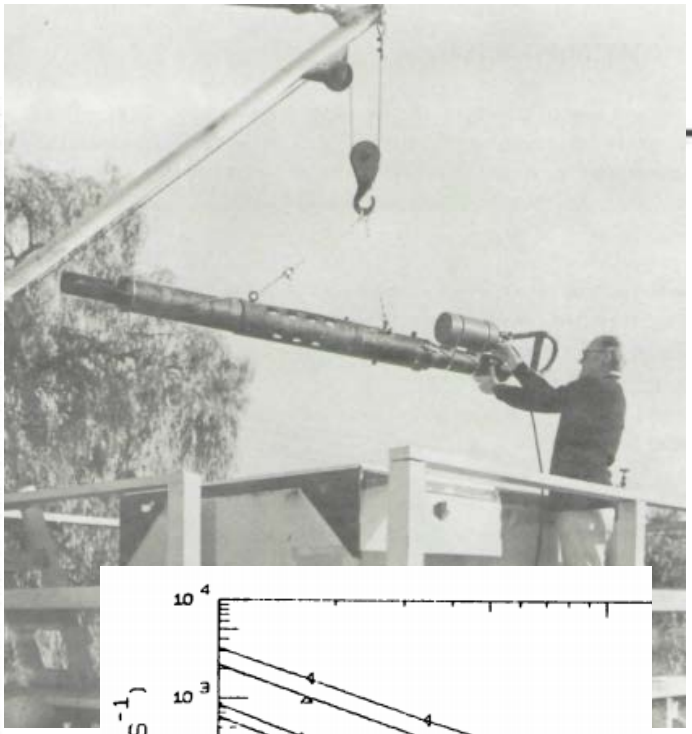
Petzold VSF





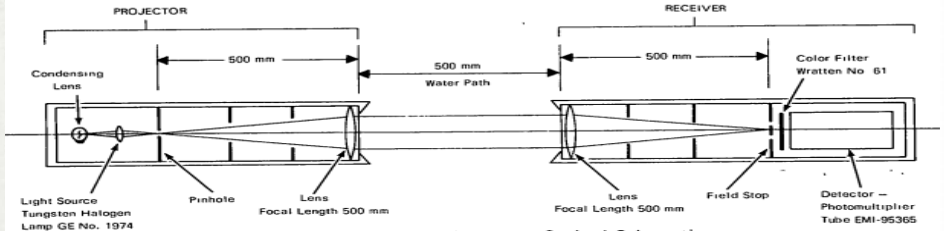
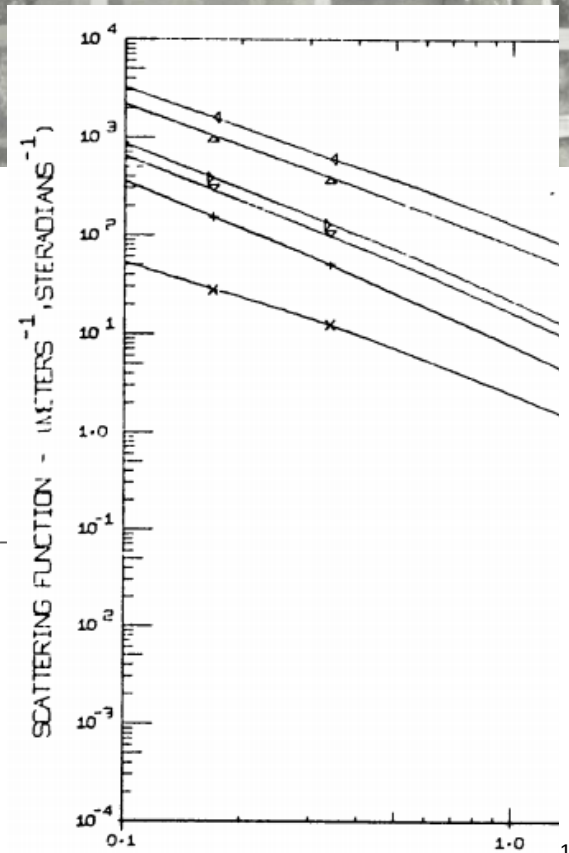


Figure 2. Low Angle Scattering Meter Optical Schematic.

VERTICAL DIMENSIONS ARE EXAGGERATED



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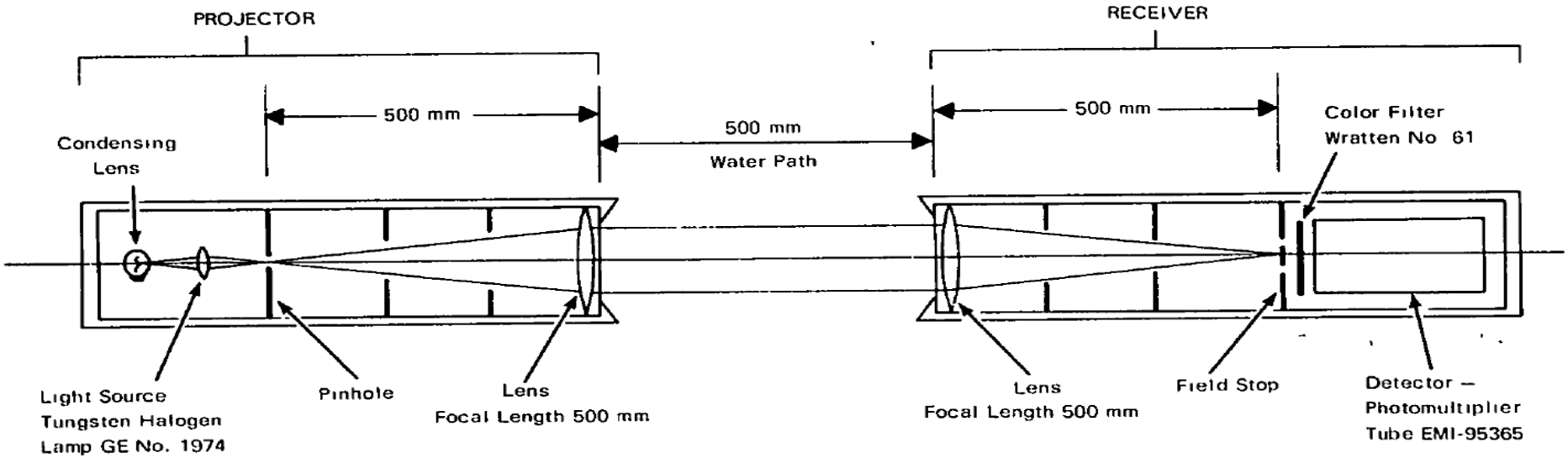

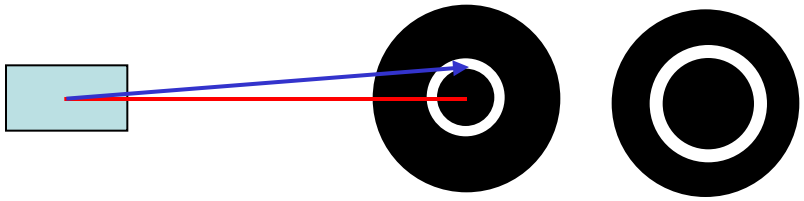

32-ring photodiode
➔ Scattering angle range 0.04 – 7.5 (15) degree

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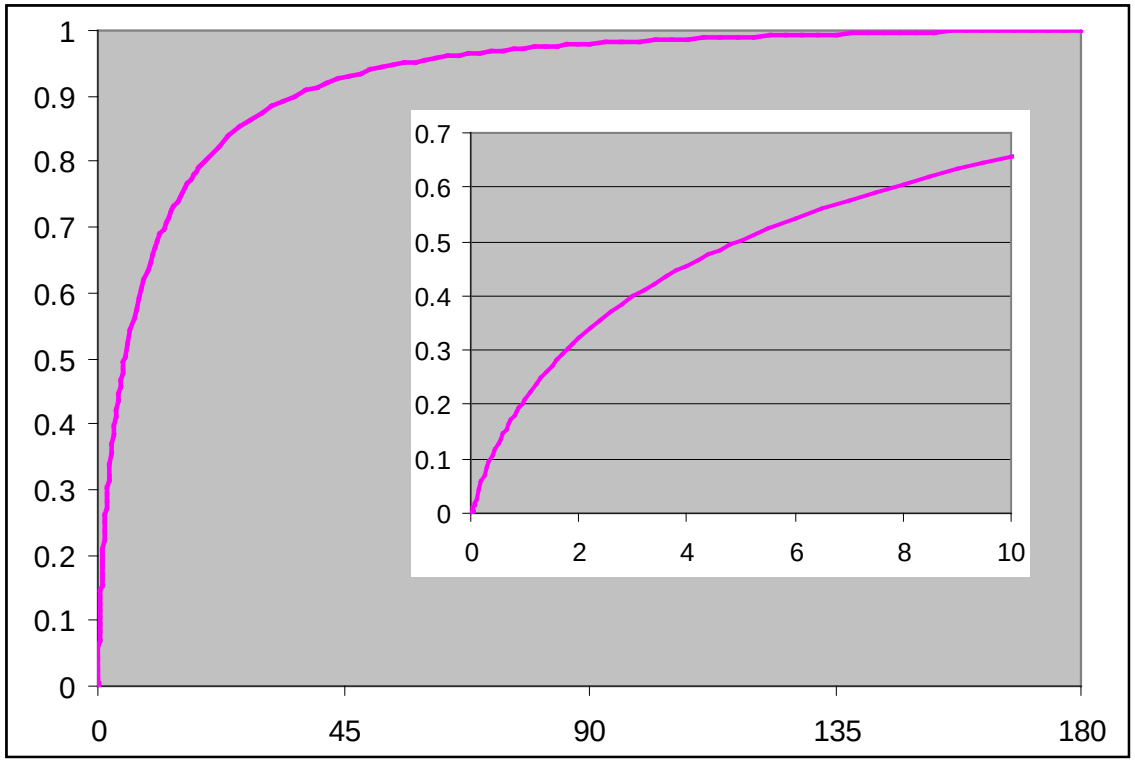
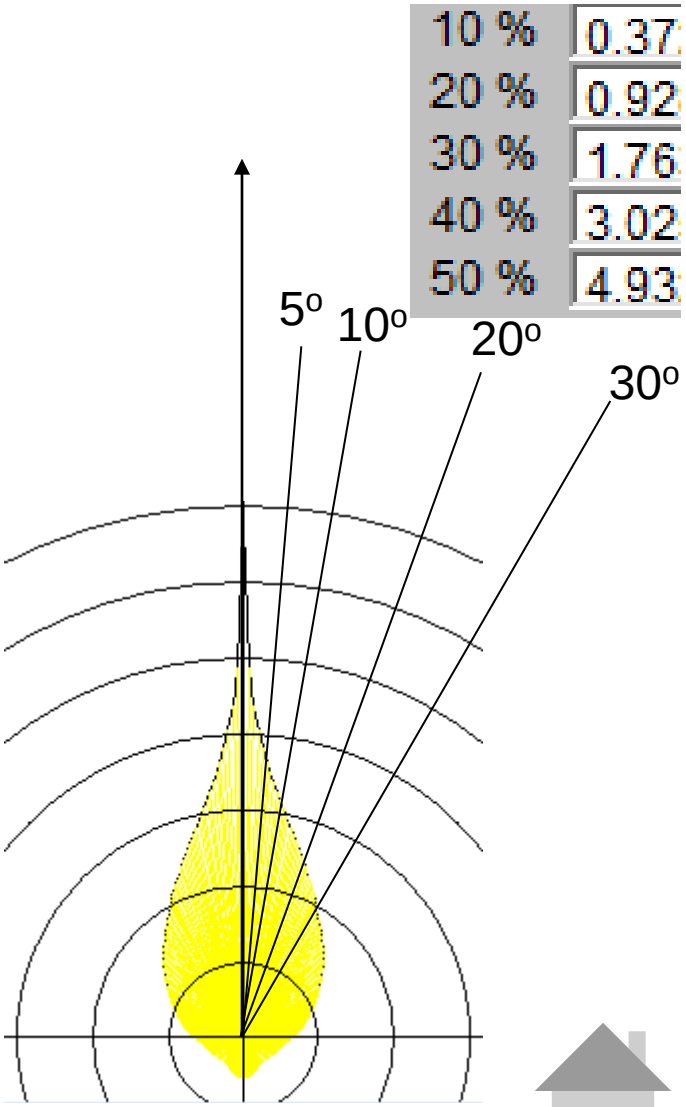
Cumulative scattering

$$2\pi\int_0^{\theta}\beta(\theta)\sin\theta d\theta$$

Petzold average particle PF





$$b_b / b = 0.02$$

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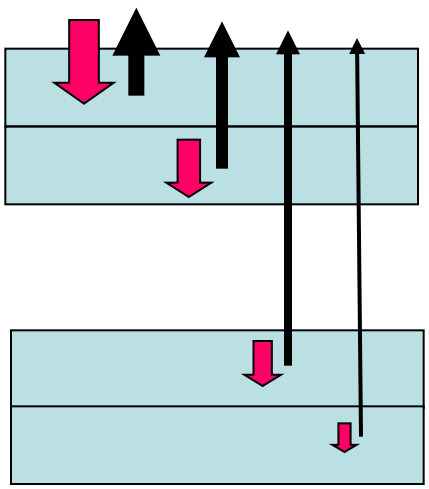
What is K_d ?

$$E_d(z) = E_d(0)\exp\left(-\int_0^z K_d(z')dz'\right)$$

(1) AOP but strong correlation with IOP

(2) ~90% light from $1/K_d$ → remote sensing

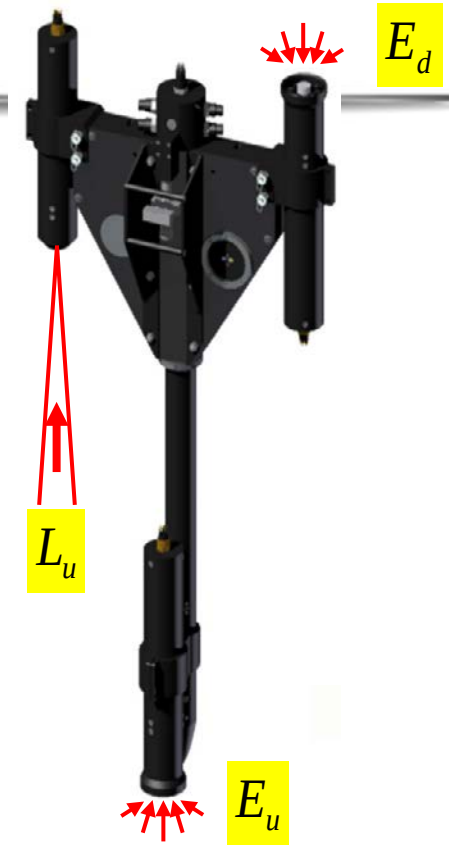


$$\int_0^z R \cdot E_d(z')\exp(-K_u \cdot z')dz'$$

$$= \int_0^z R \cdot E_d(0)\exp(-2K_d \cdot z')dz'$$

$$\propto \quad \{1-\exp(-2K_d \cdot z)\}$$

$$z = 1/K_d \quad \Rightarrow \quad 1-e^{-2} \approx 0.9$$



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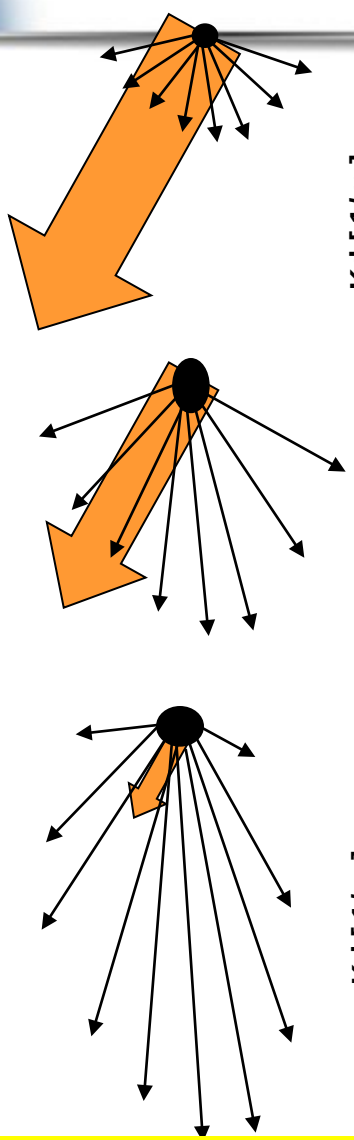
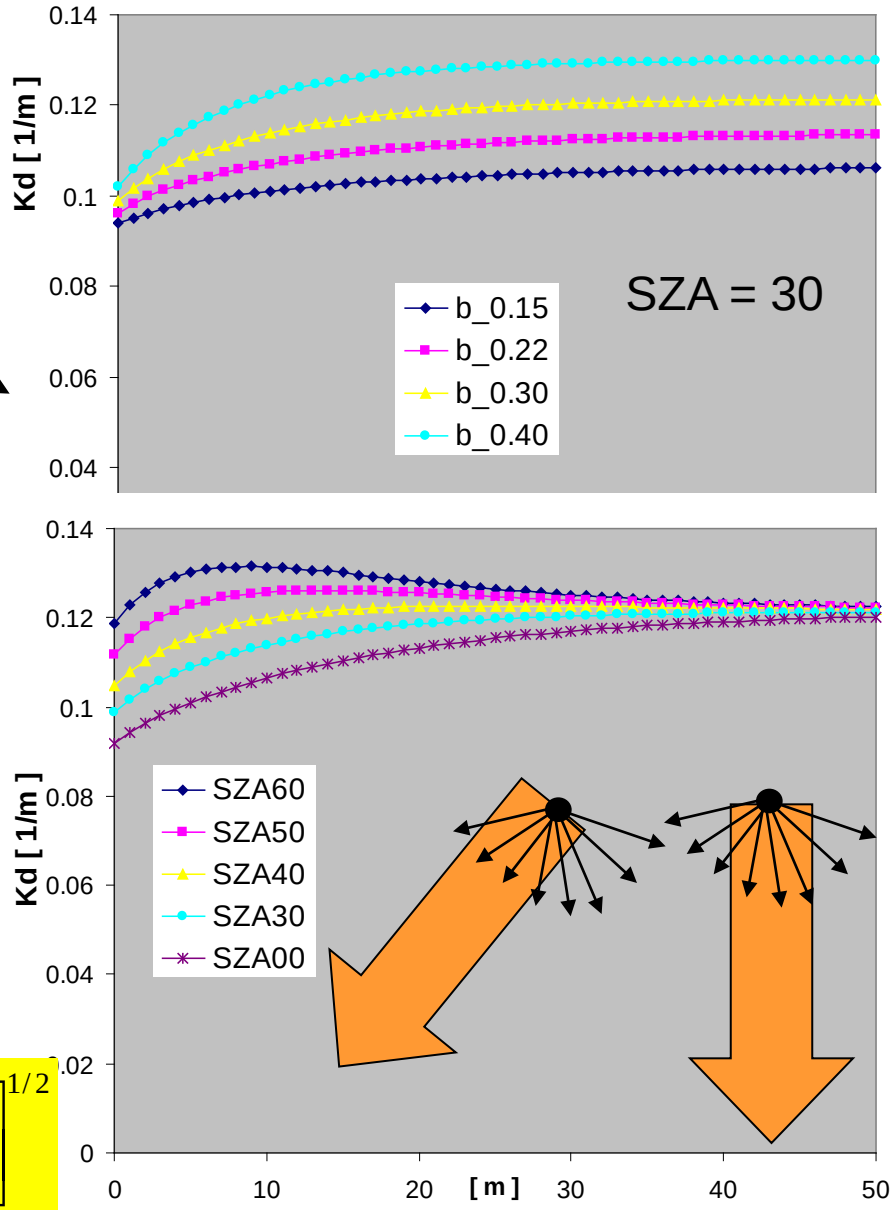
Kd : (a),(b), and SZA





$$K_d \approx a + b/6$$

$$K_d \approx \frac{1.07 \cdot a}{\cos\theta_{sw}}$$

$$K_d \approx \frac{a}{\cos\theta_{sw}}\left[1 + \left(0.425\cos\theta_{sw} - 0.19\right)\frac{b}{a}\right]^{1/2}$$

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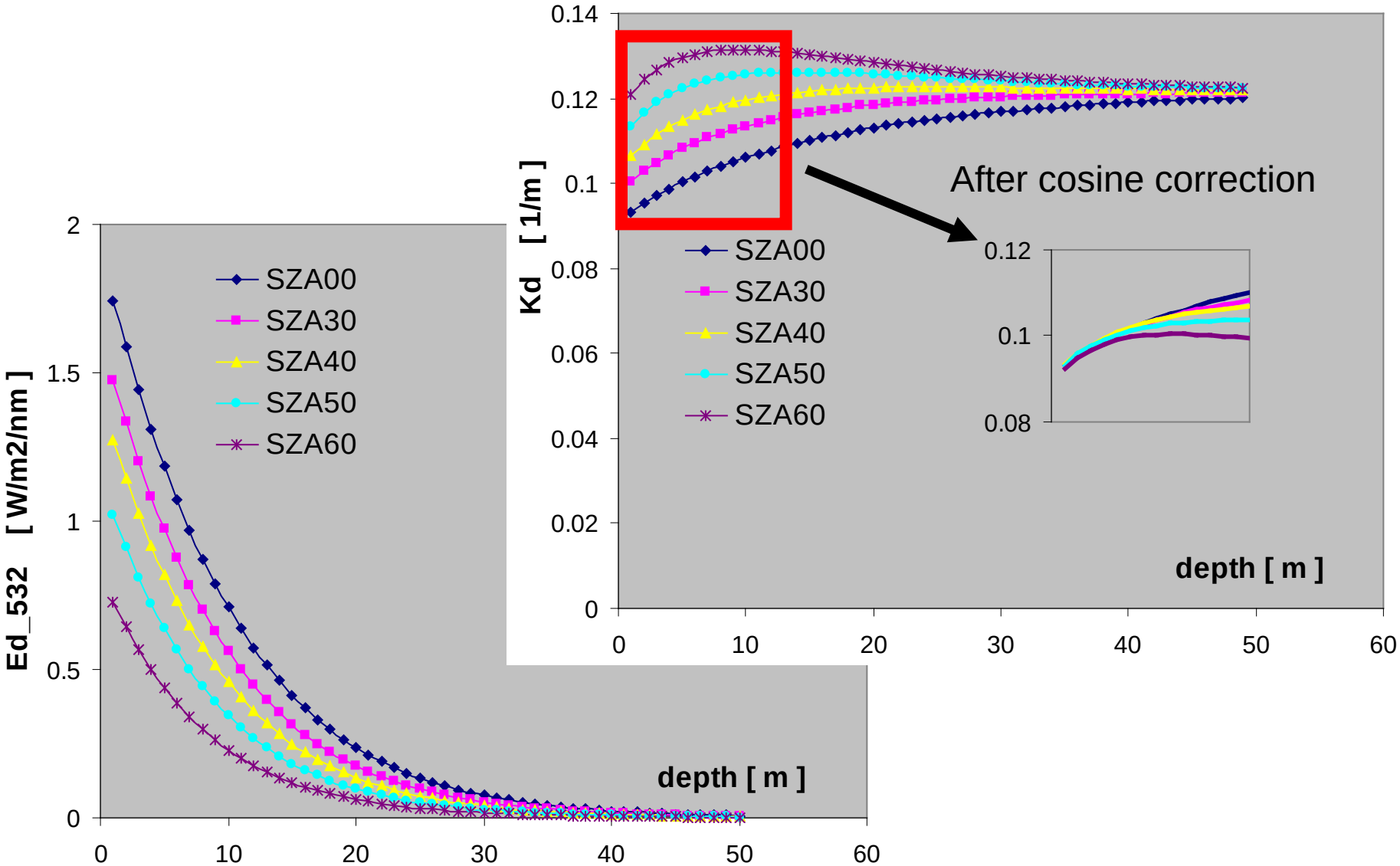
Kd and solar zenith angle (SZA)



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Normalization of Kd

$$\| K_d \| = \frac{K_d}{D_0} = \frac{K_d}{\frac{f}{\cos\theta_w} + 1.12(1-f)}$$

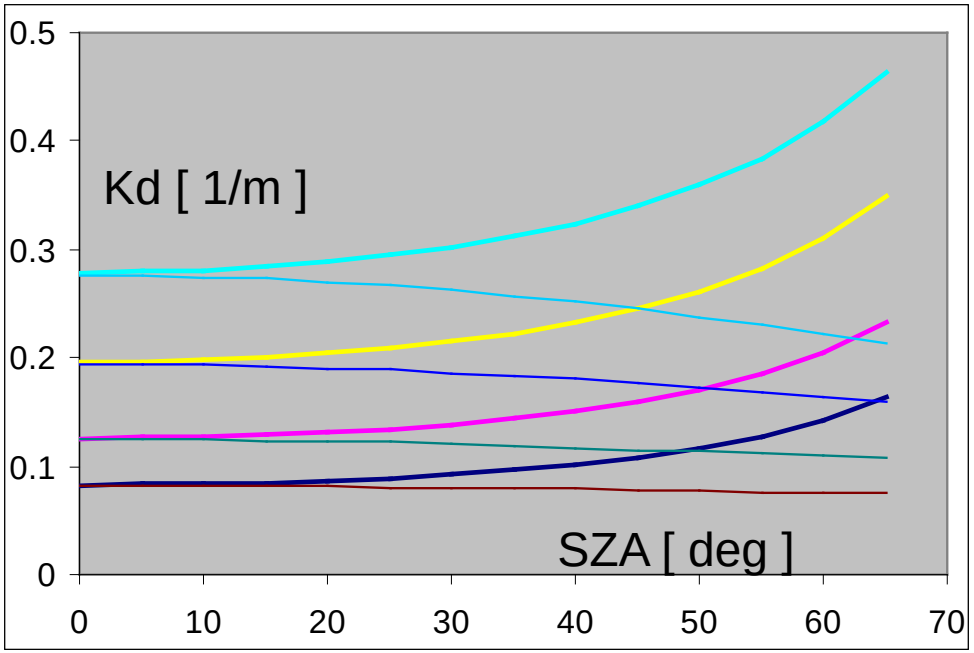
H. R. Gordon

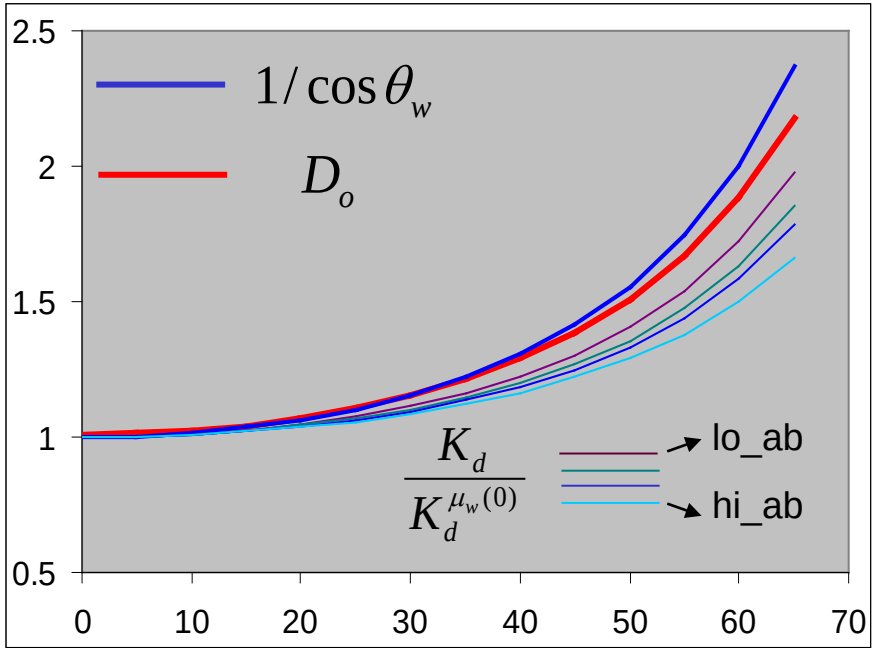
$$\mu_w = \cos\theta_w$$

$$f(\mu_w)$$

$$\downarrow$$

$$D_0(\mu_w) \Leftarrow D_0(f, \mu_w)$$





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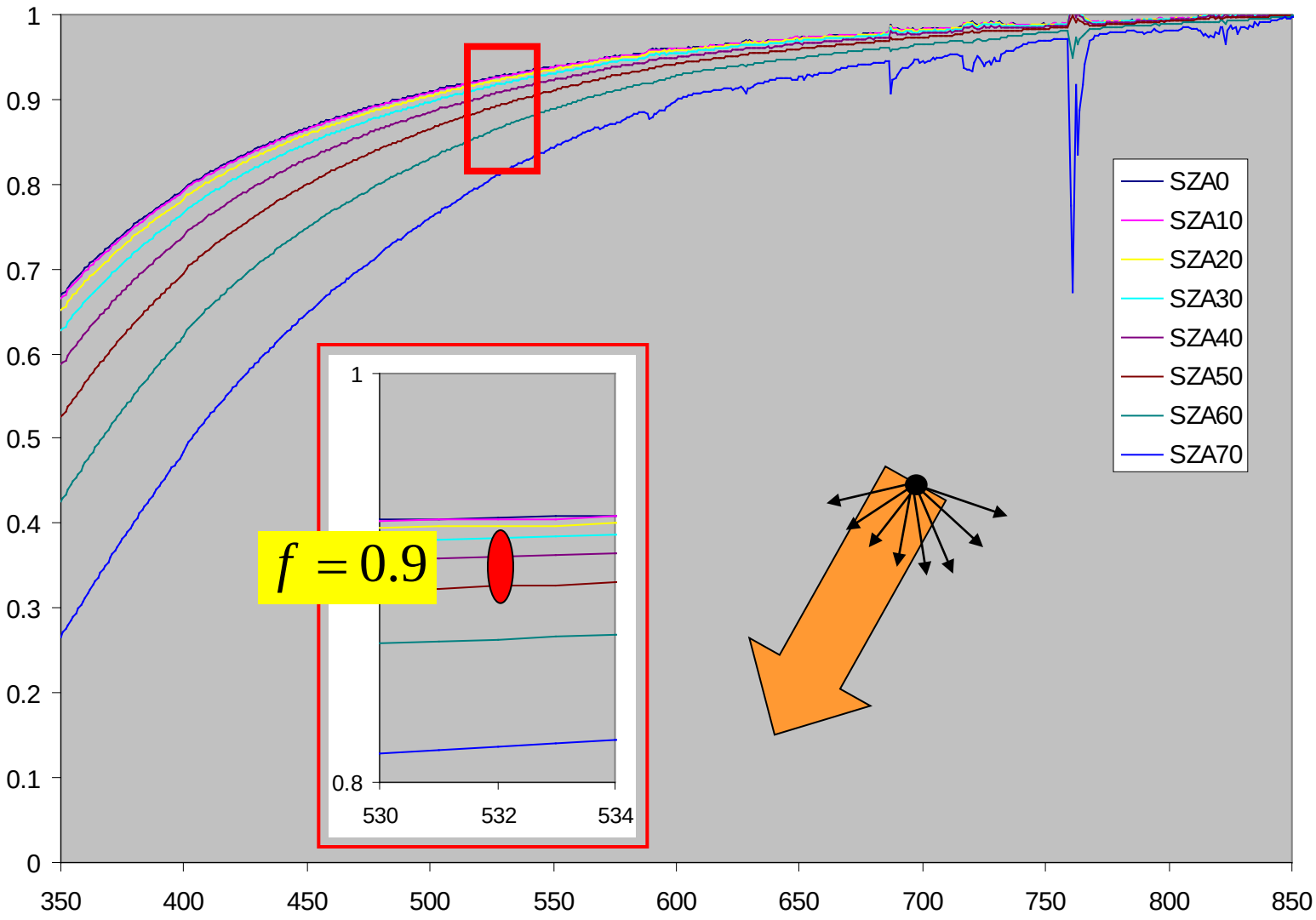
$$f = \frac{E_d^{Sun}}{E_d^{Sun} + E_d^{Sky}}$$



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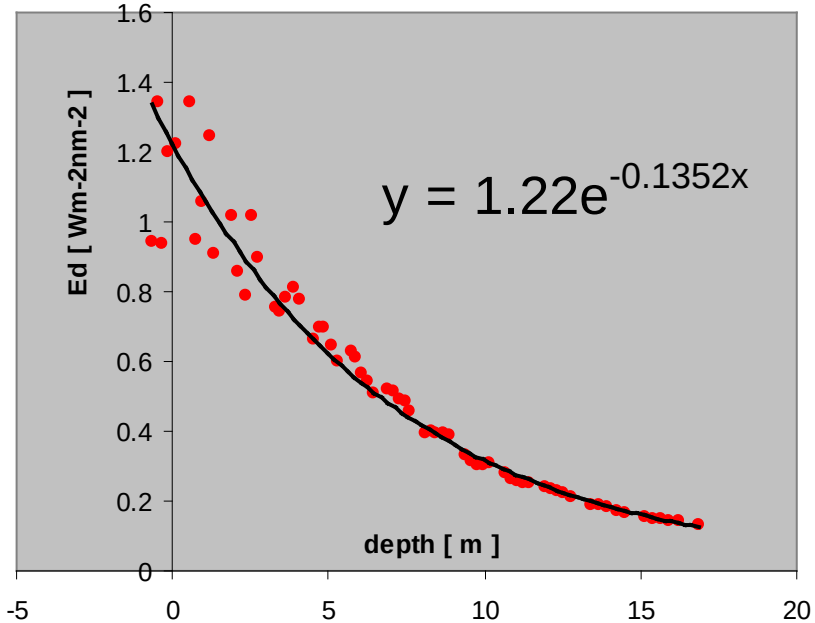
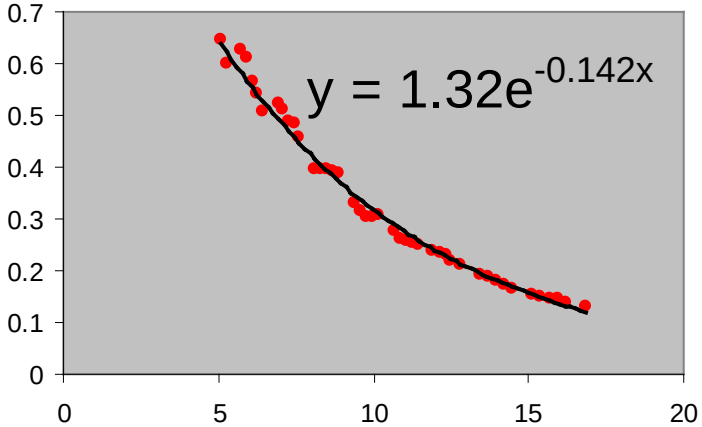
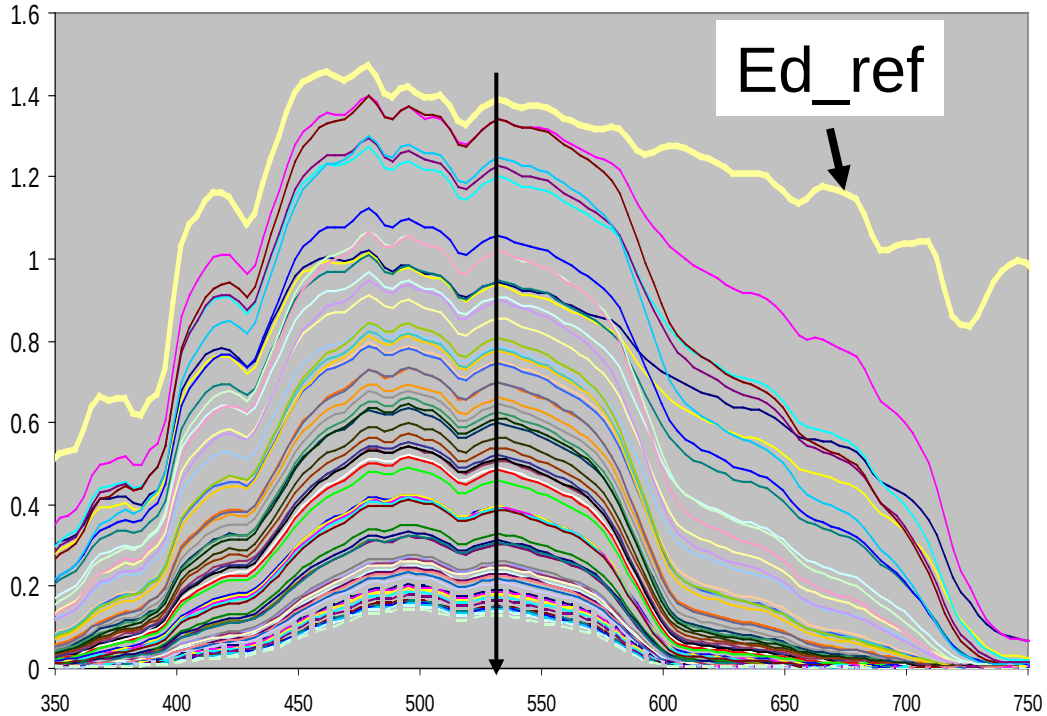
In – situ K_d 532 nm

K_d 532 nm





E_d Vertical Profile



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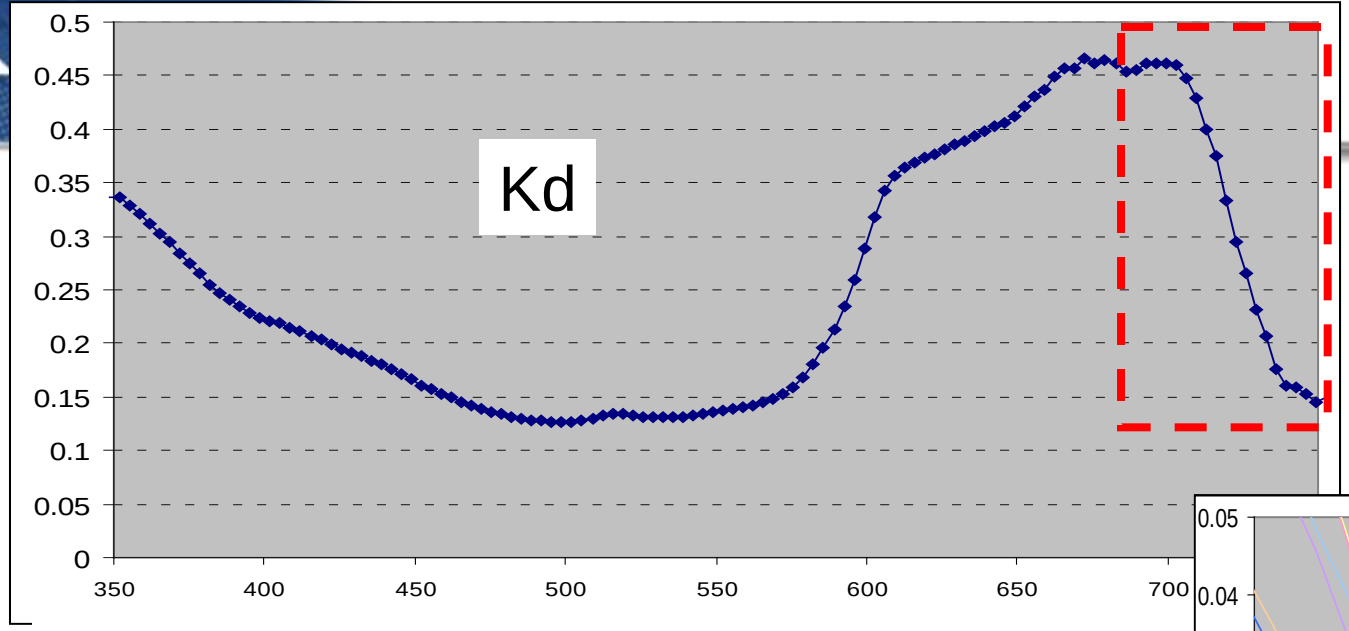

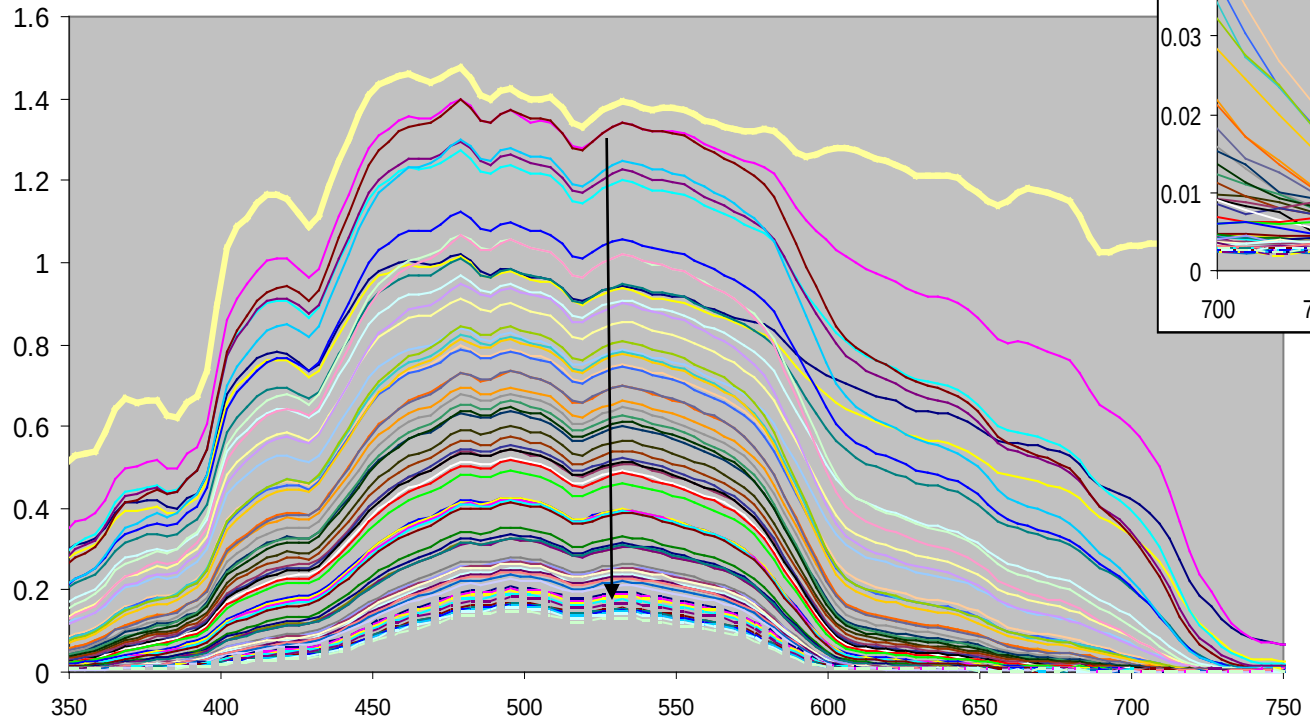

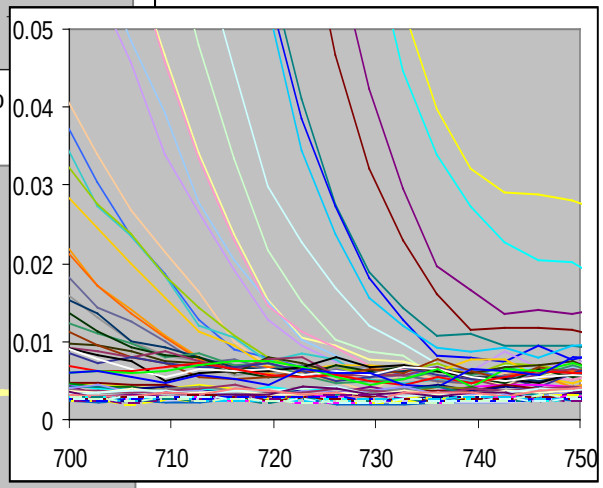

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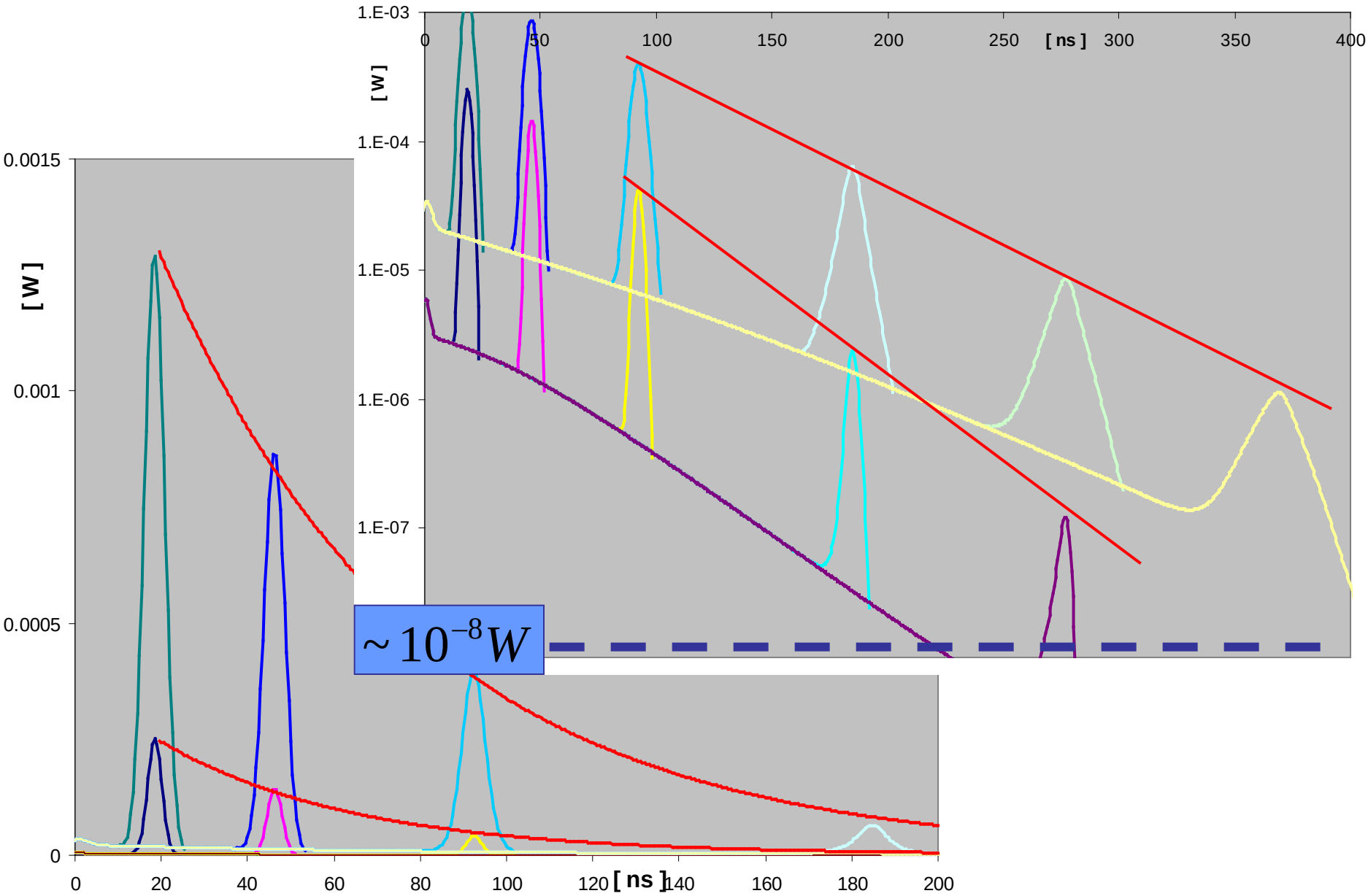
System attenuation



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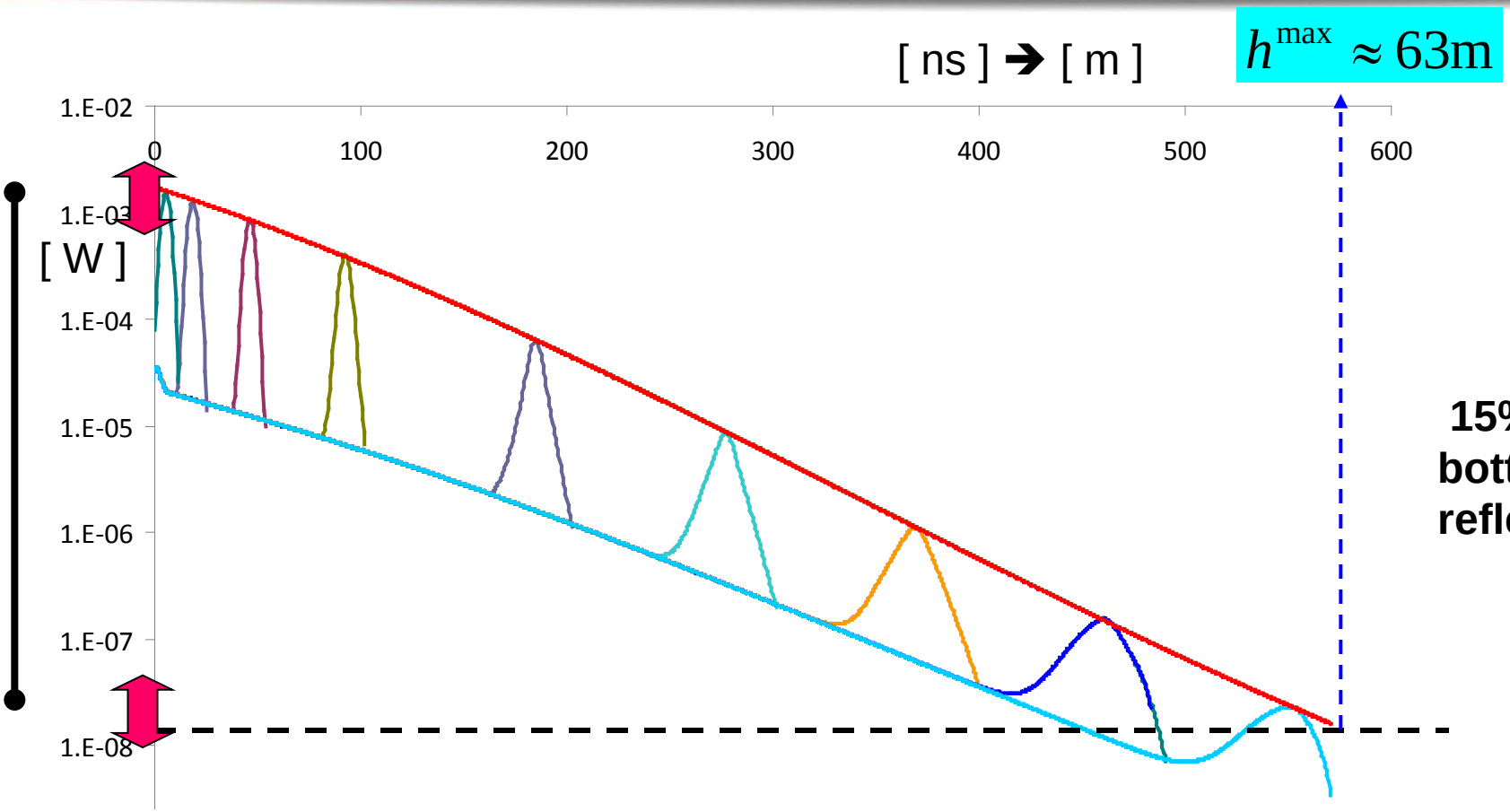
Maximum lidar depth



15% bottom reflectance

$$\ln\left(P_0 / P_{\min}\right)/2 = \int_0^{h_{\max}} K_{sys}(h)dh$$

$$P(h) = P_0 \exp\left(-2\int_0^{h} K_{sys}(h')dh'\right)$$

$$= \tau_{\Theta}^{\max} \approx 4.6 - 5.8$$

$$\left(\log(AW) - 4\right)\cdot 11 = h_{Wayne}$$

System capacity!

nothing to do with environment

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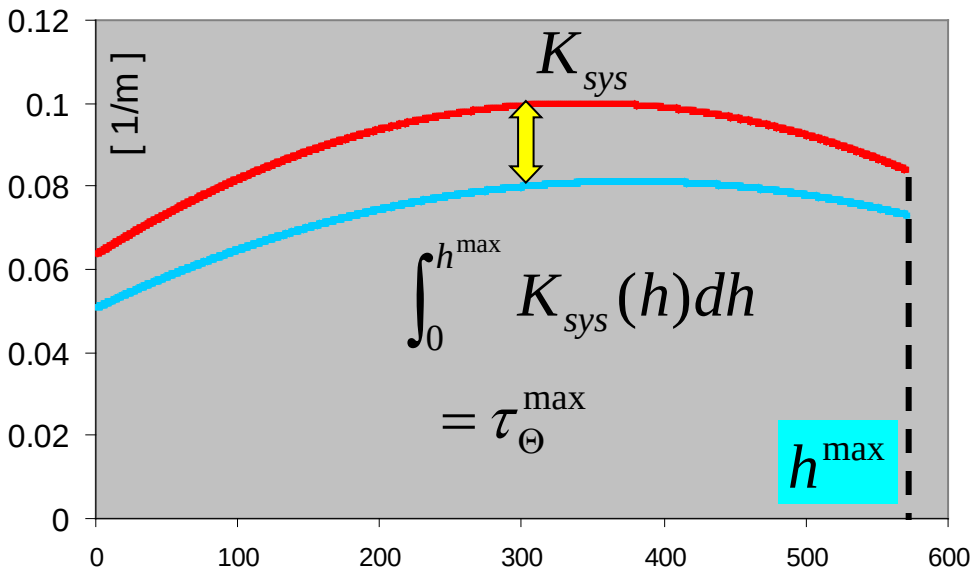
System attenuation



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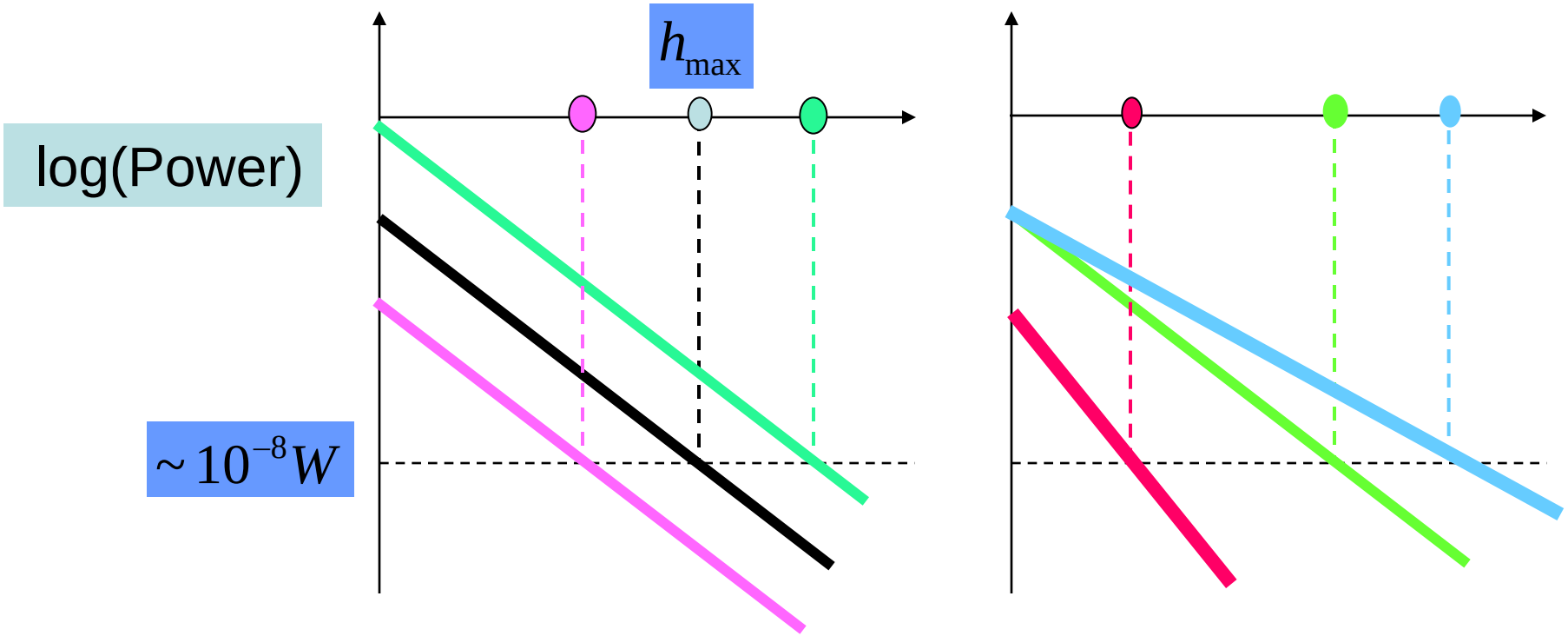
Factors related to the maximum depth

Laser pulse energy, pulse duration
System response function, Solid angle (due to FOV)
Optical transmittance, Aperture area
Pulse radiance distribution function
Receiver sensitivity distribution function
Bottom reflectance (15%)

Water absorption
Scattering (VSF)
Field of view (FOV)



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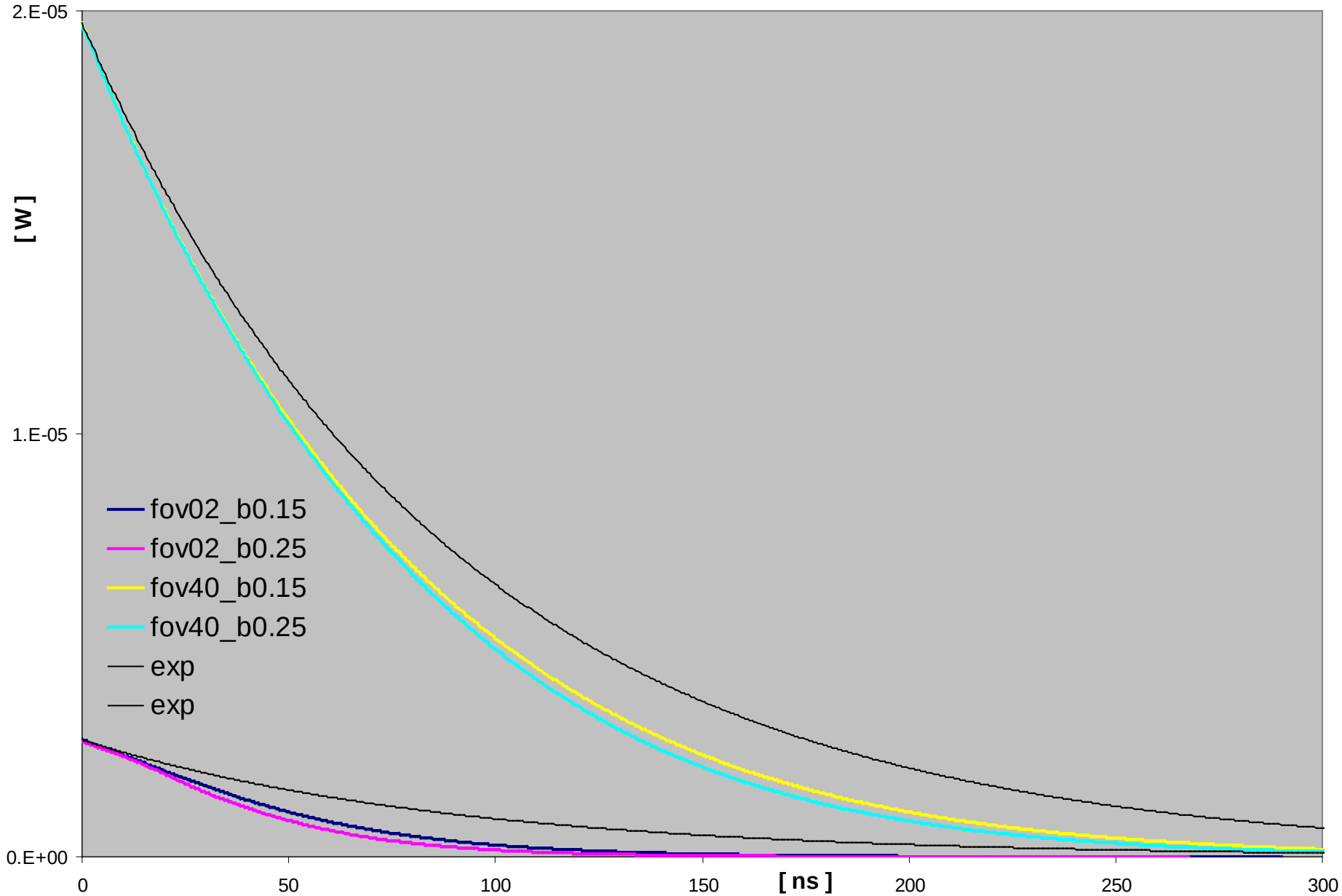
FOV 2, 40 mr, b = 0.15, 0.25 [1/m], a = 0.06 [1/m]



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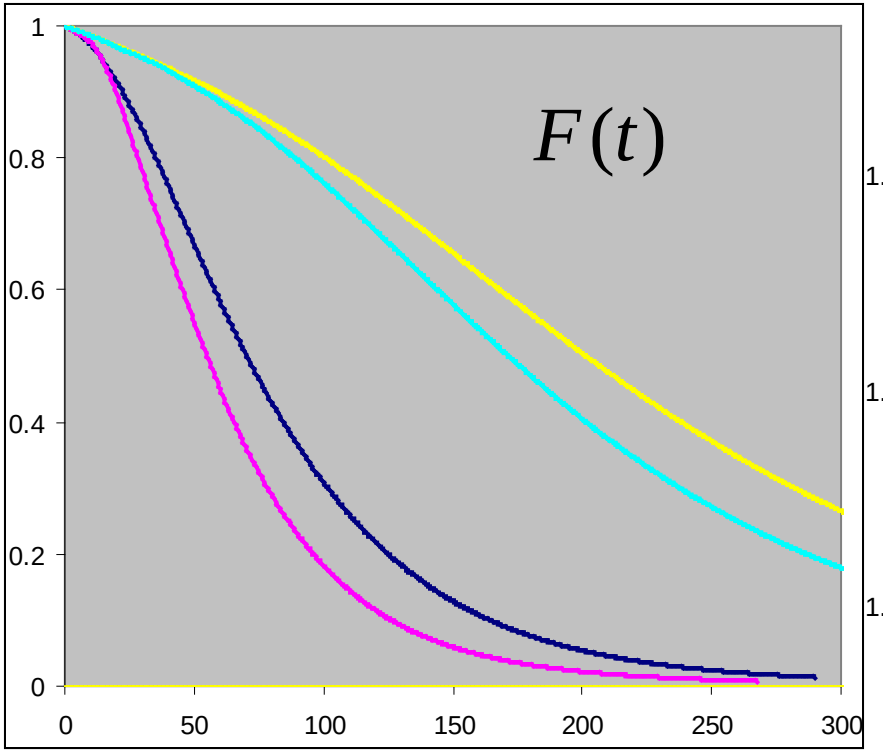
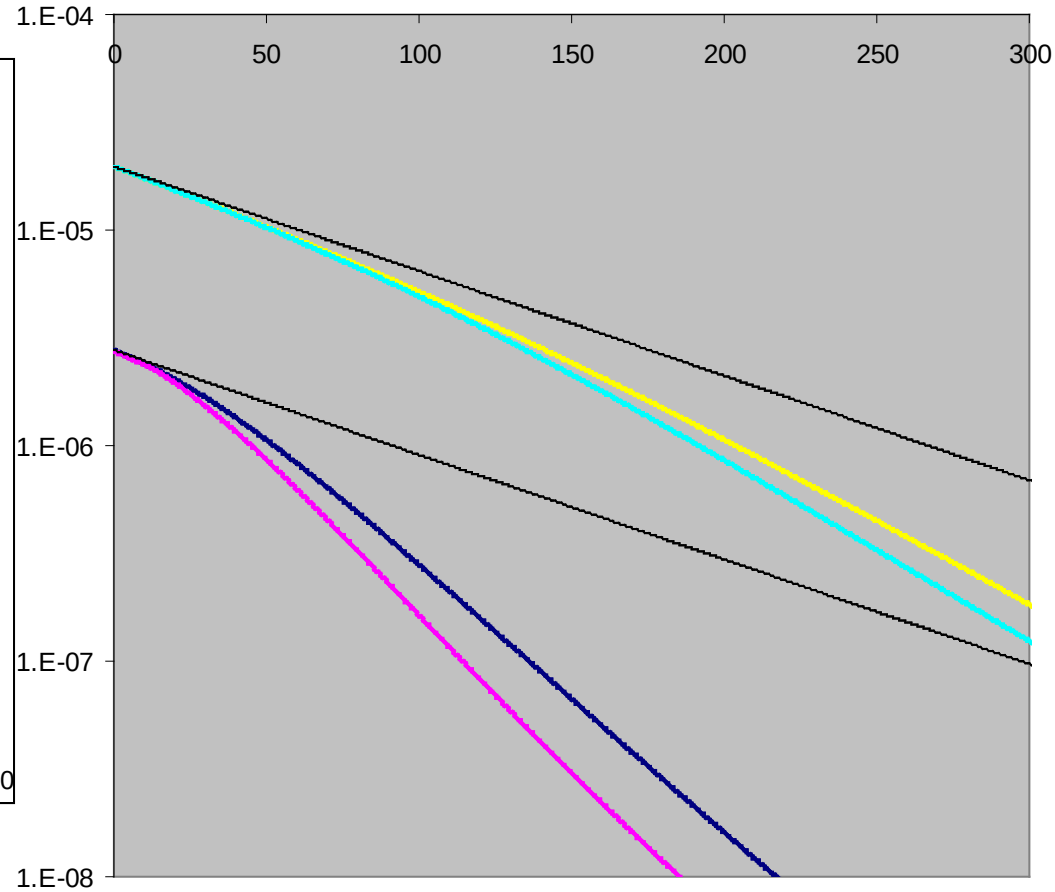
FOV 2, 40 mr, b = 0.15, 0.25 [1/m], a = 0.06 [1/m]





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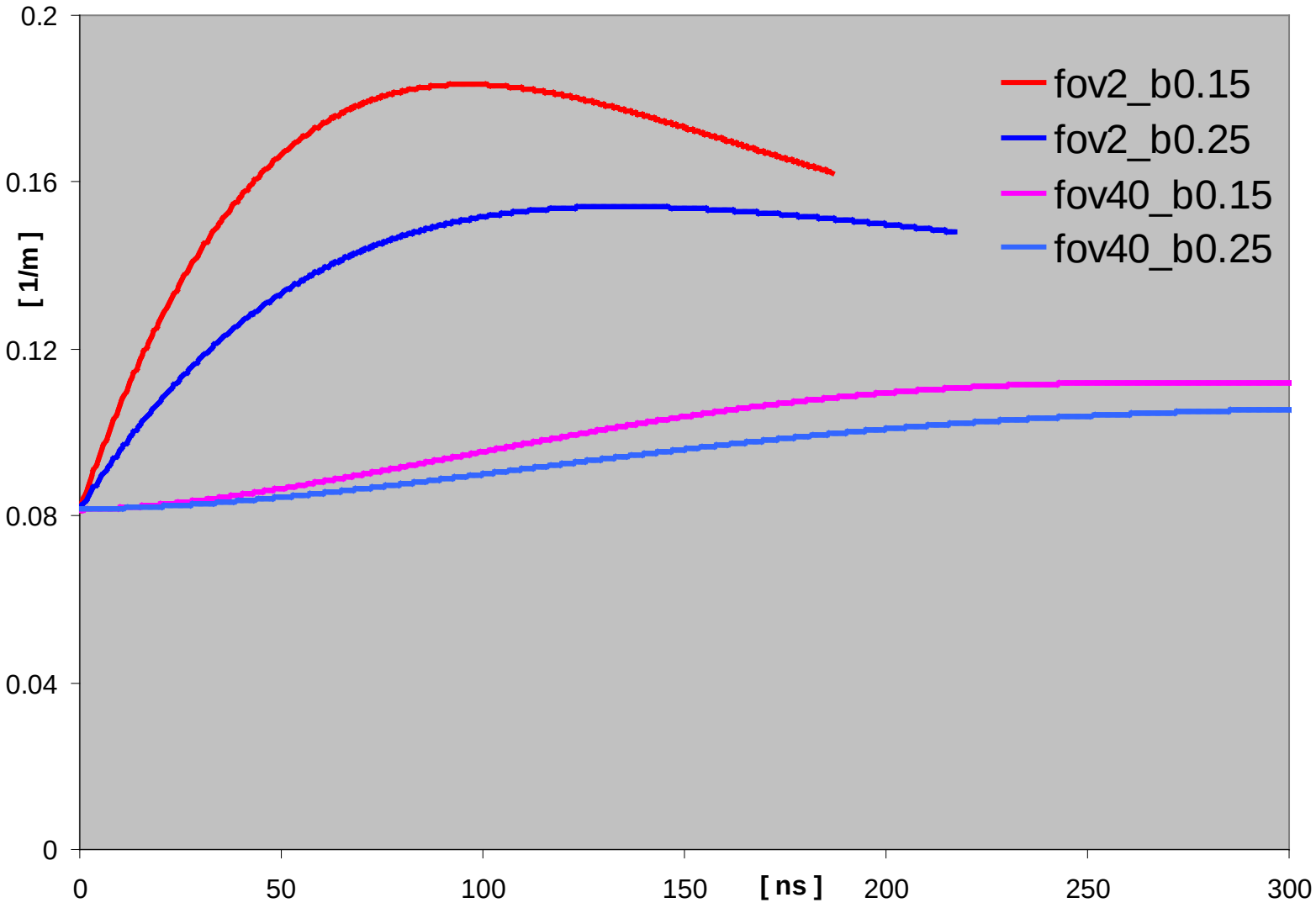
System attenuation



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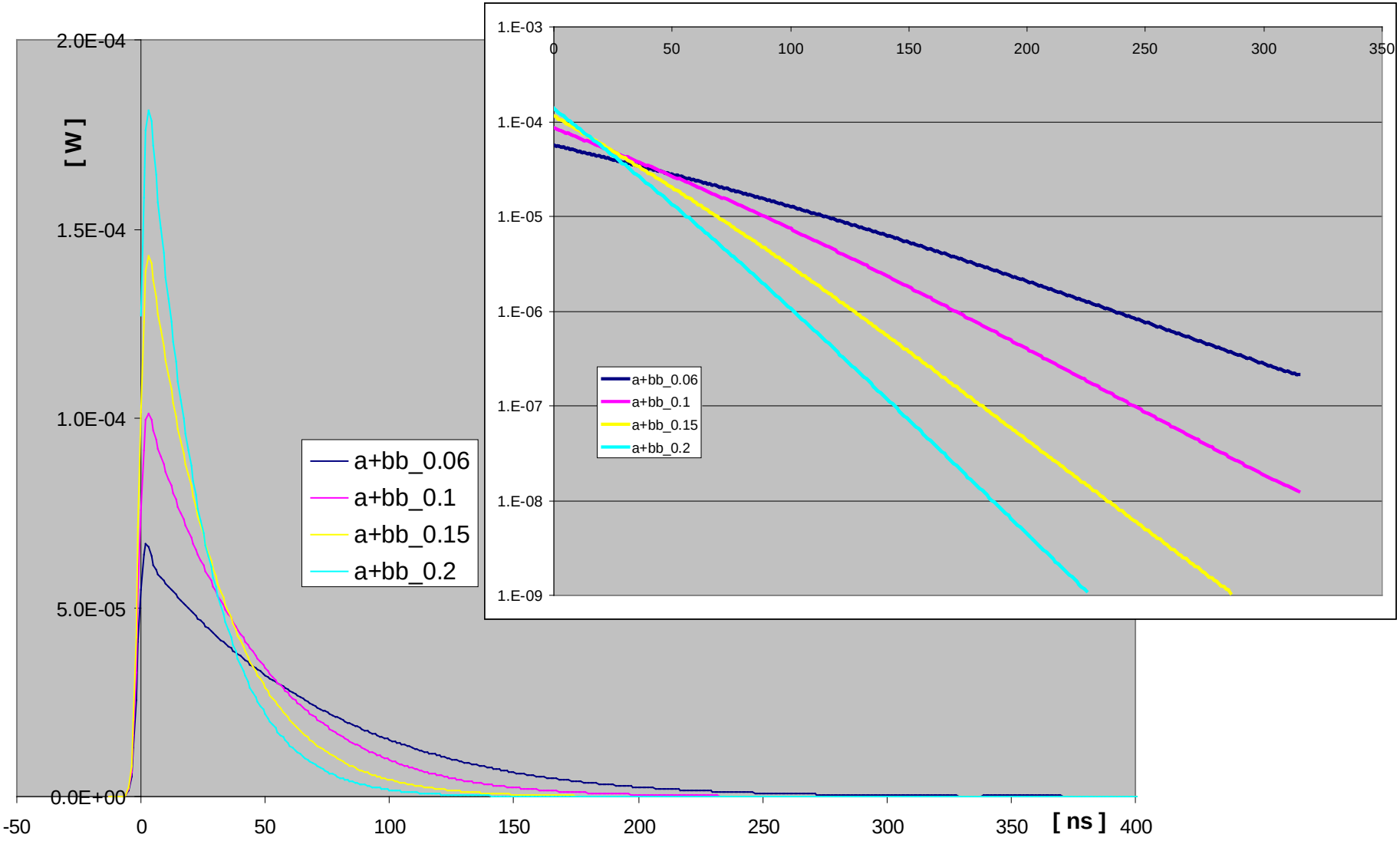
CZMIL 40 mrad, b/(a+b) = 0.8



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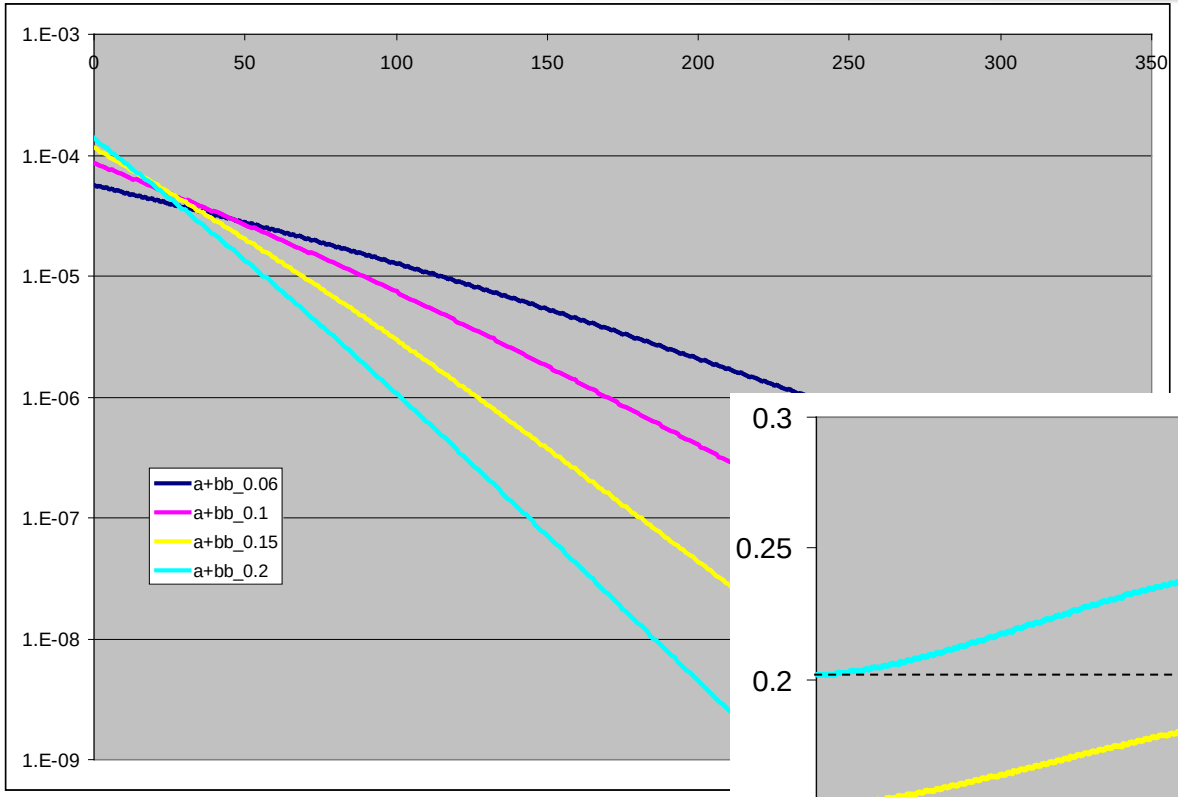
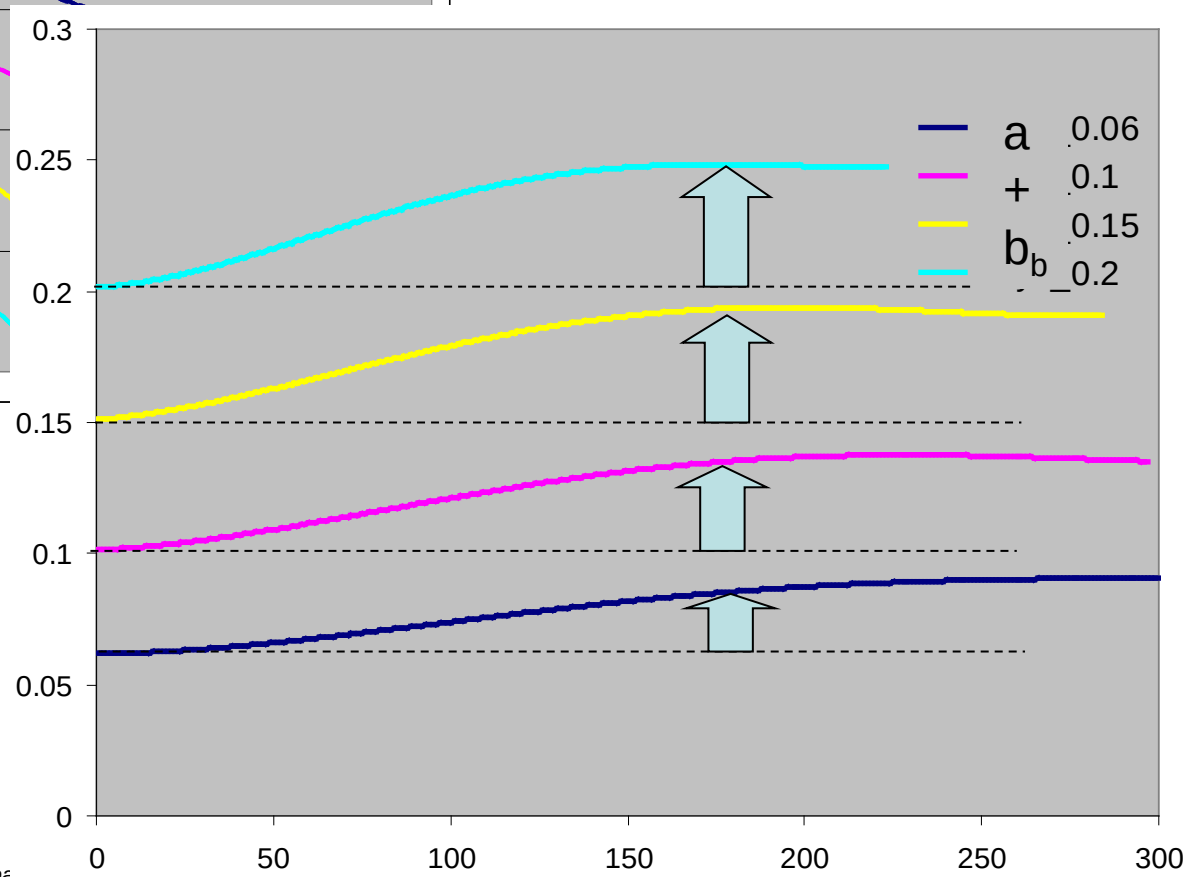
Effect of (a) , (b) on K_{sys}



b/(a+b) = 0.8



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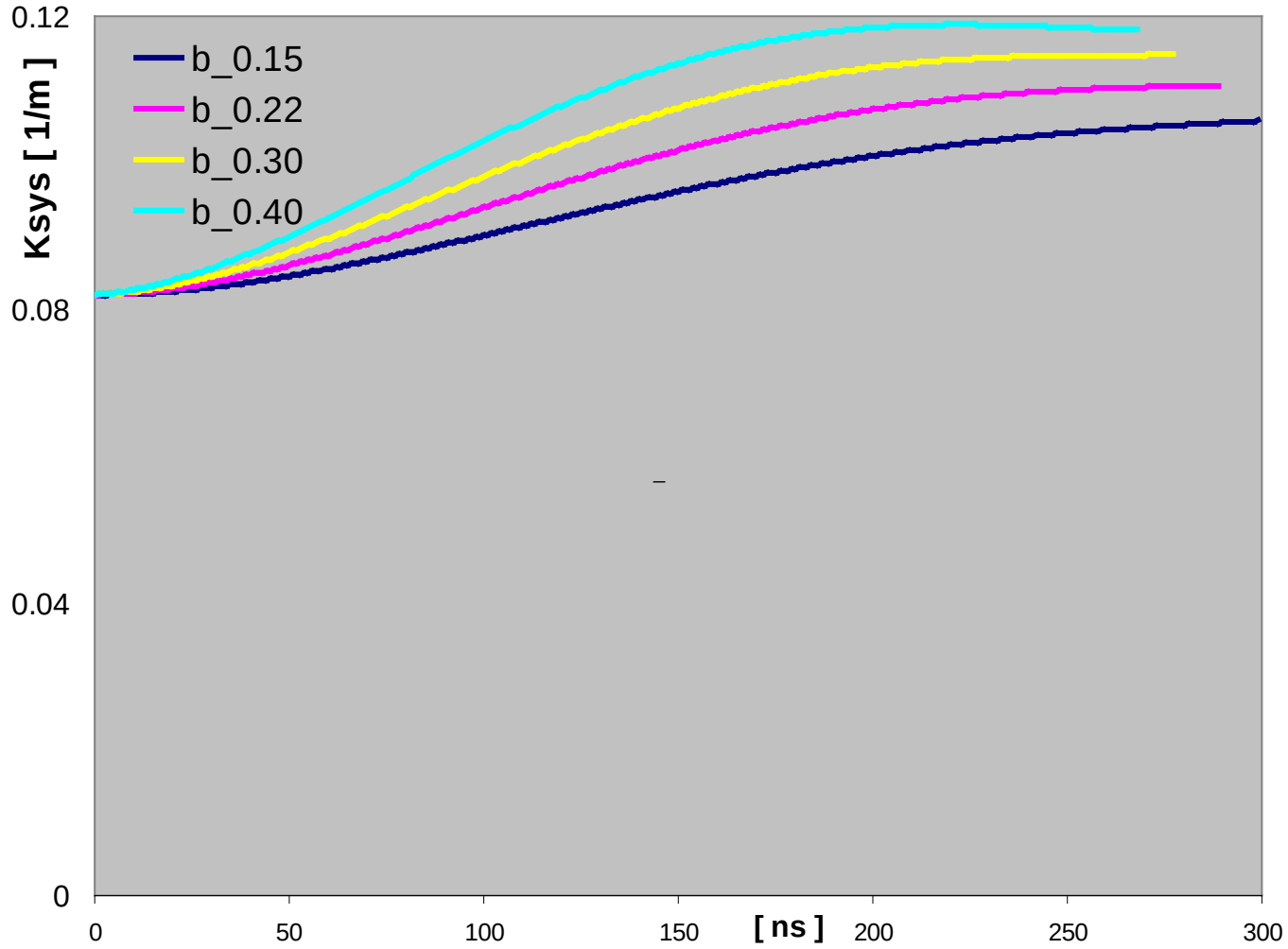
a = 0.08 fixed, effect of (b) on (K_{sys})



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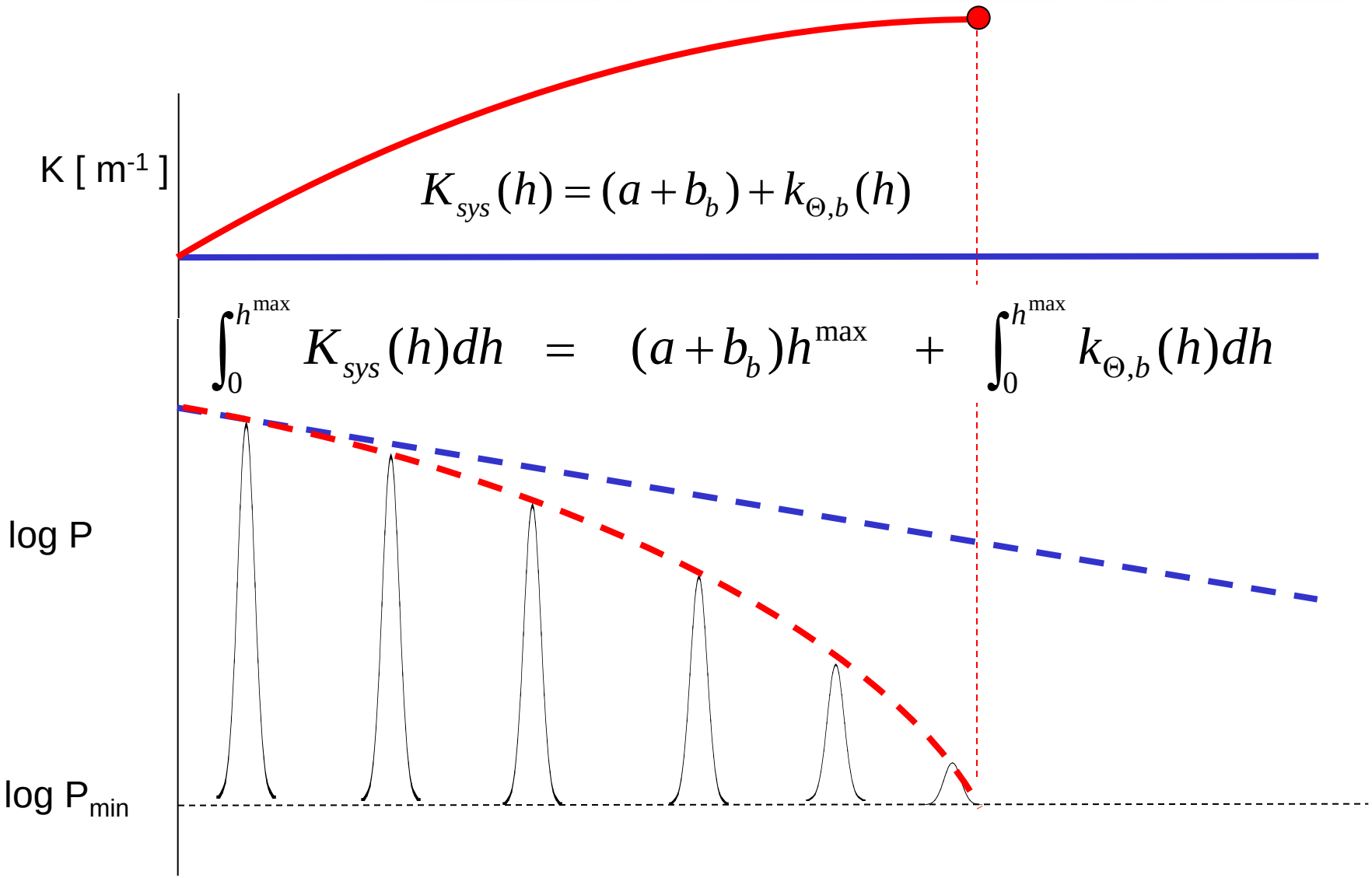
System attenuation



$$K_{sys}(h) = (a + b_b) + k_{\Theta,b}(h)$$

$$\int_0^{h^{\max}} K_{sys}(h)dh = (a + b_b)h^{\max} + \int_0^{h^{\max}} k_{\Theta,b}(h)dh$$

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Suggested formula for max lidar depth

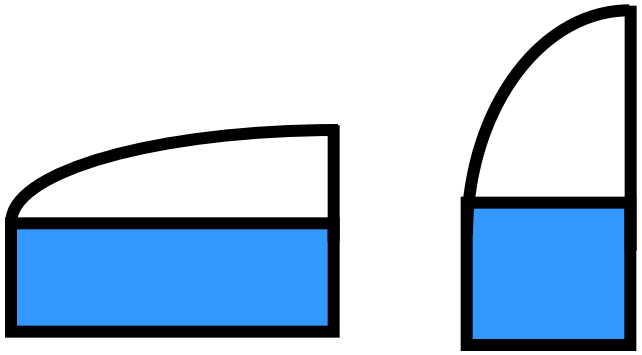
$$\int_0^{h^{\max}} K_{sys}(h)dh = (a+b_b)h^{\max} + \int_0^{h^{\max}} k_{\Theta,b}(h)dh$$

$$K_{sys}(h) = (a+b_b)+k_{\Theta,b}(h)$$

$$\tau_\Theta^{\max} = (a+b_b)h^{\max} + \int_0^{h^{\max}} k_{\Theta,b}(h)dh$$

$$h^{\max} = \frac{\tau_\Theta^{\max}}{a+\psi(b)}$$

$$h^{\max} = \frac{4}{K_d}$$



$$D_{\max} = h_{\max}\cos\theta_w$$

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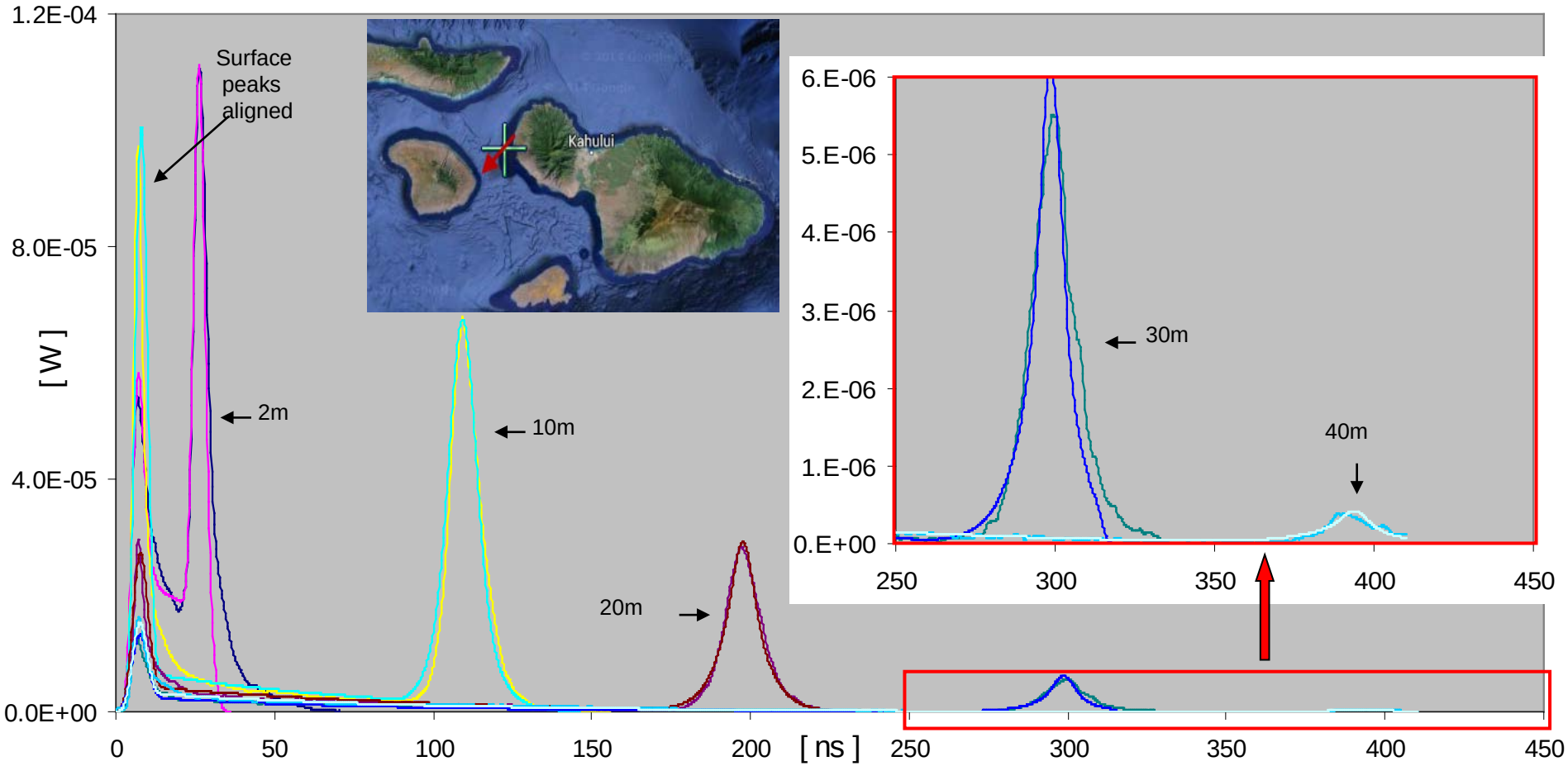
CZMIL data (Maui, HI)



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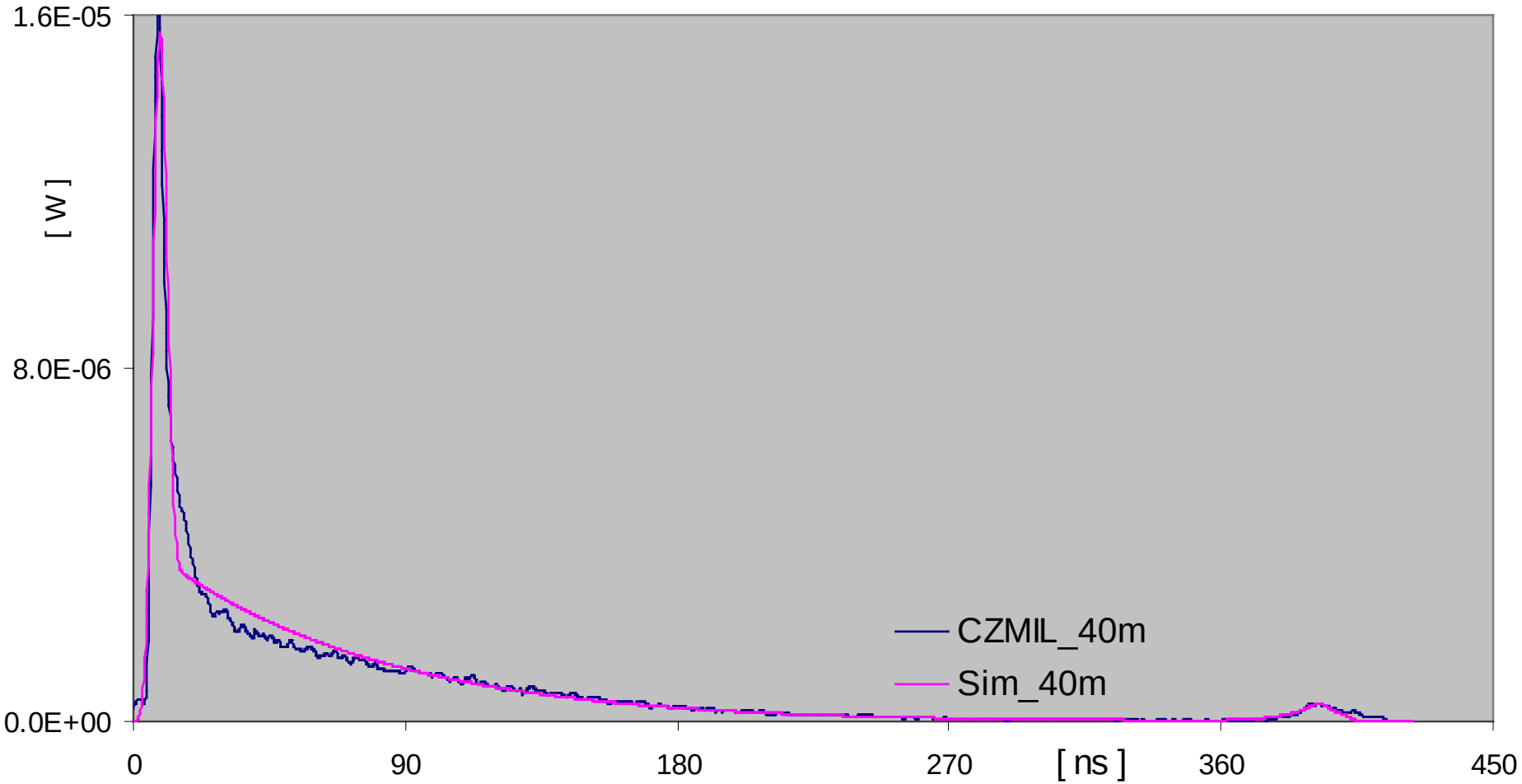

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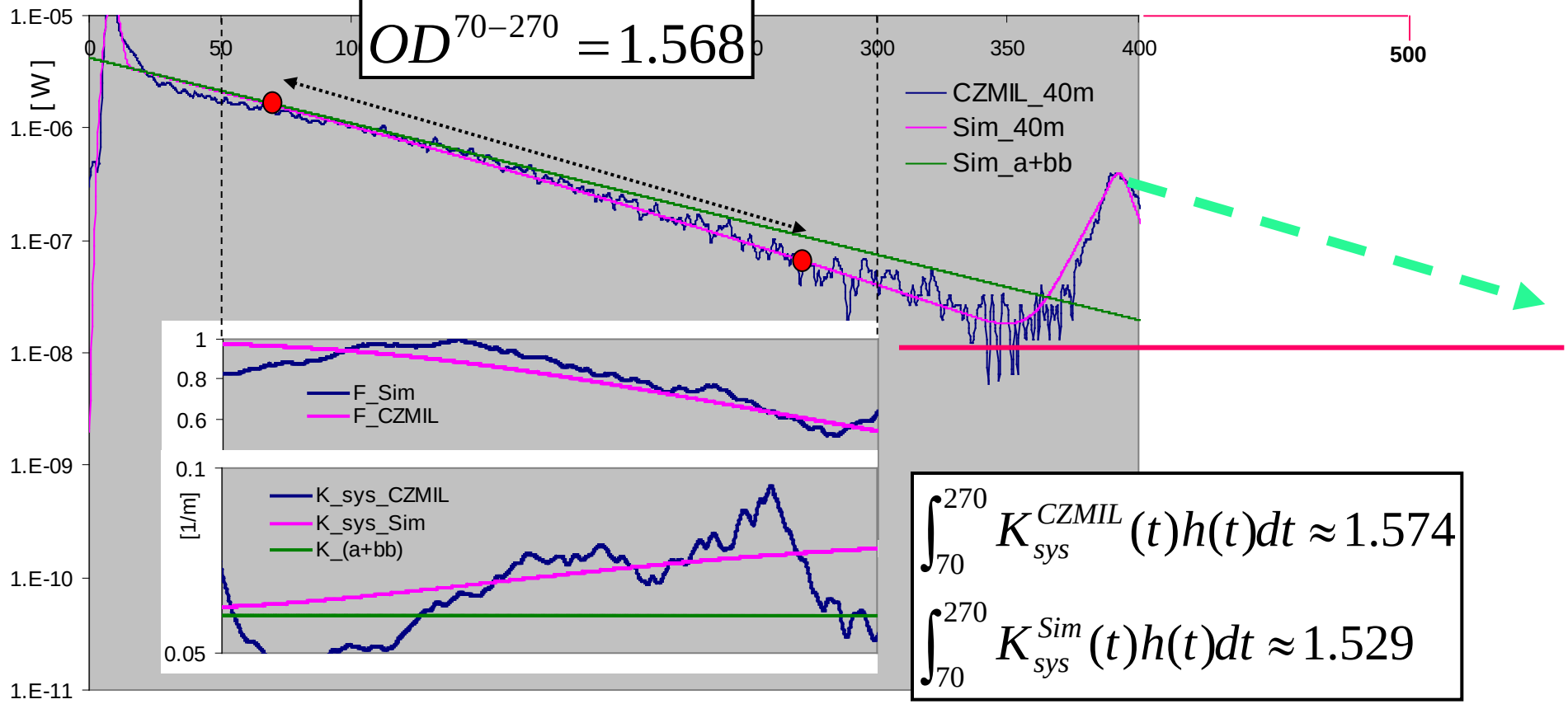
System attenuation coefficient K_{sys}

$$\overline{K}_{sys}^{70-270} = 0.071$$

$$OD^{70-270} = 1.568$$



$$\int_{70}^{270} K_{sys}^{CZMIL}(t)h(t)dt \approx 1.574$$

$$\int_{70}^{270} K_{sys}^{Sim}(t)h(t)dt \approx 1.529$$

CZMIL τ_{Θ}^{max} **Proved !!!**

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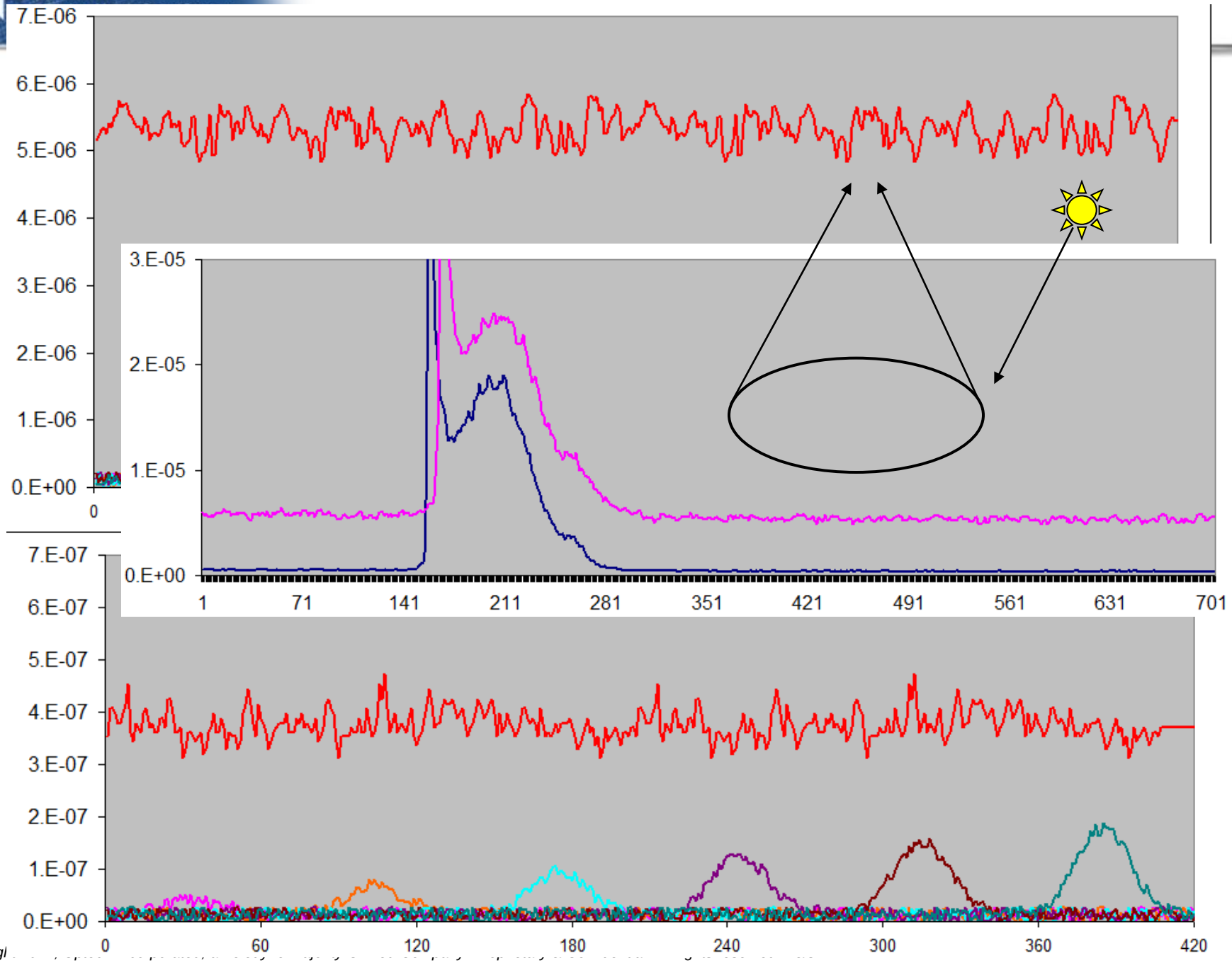
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71
141
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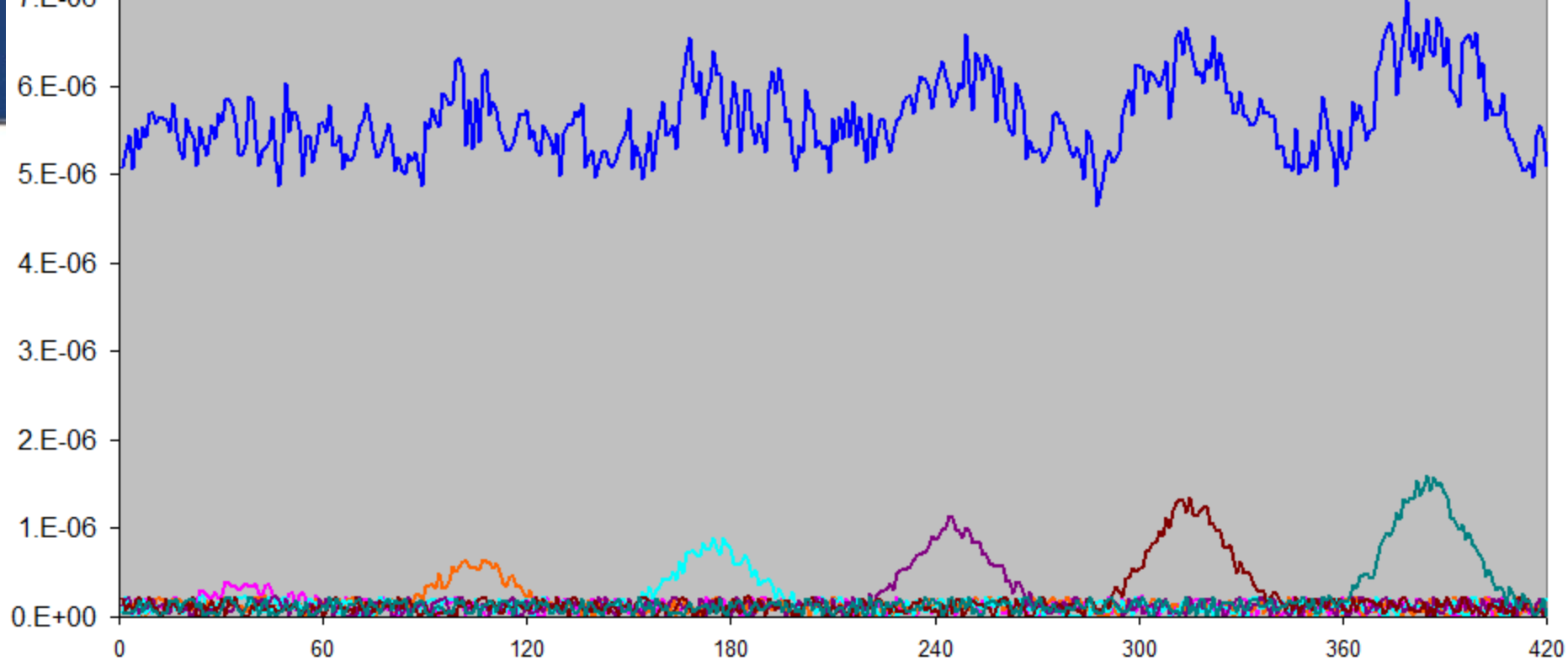
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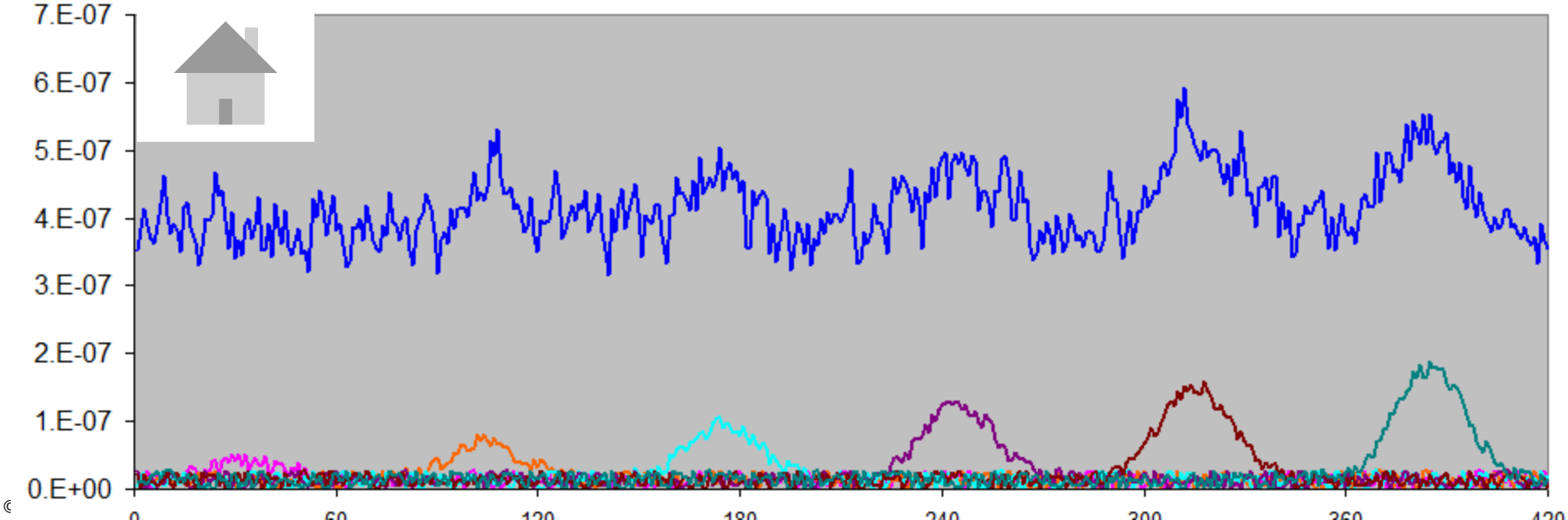
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Secchi Disk Depth

$$C_V = \frac{L_t - L_{bg}}{L_t + L_{bg}}$$

$$C_V(z) = C_V(0)\exp\left[-\left(c + K_d\right)\cdot z\right]$$

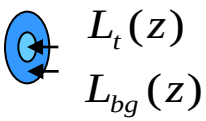
c : photoptic attenuation

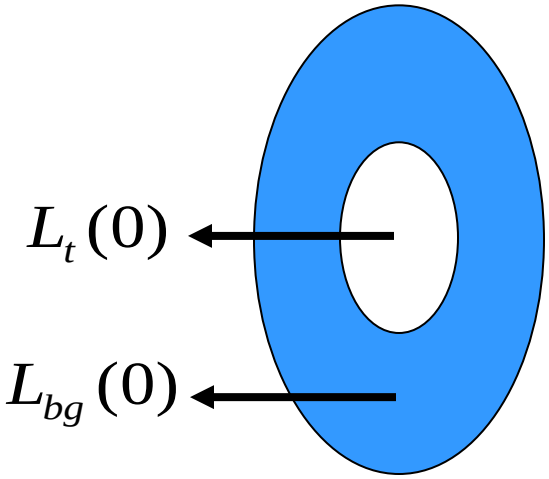
K_d : downwelling diffuse attenuation

$$Z_{SD} = -\frac{\ln\left(\tilde{C}_V / C_{V0}\right)}{c + K_d}$$

Limiting contrast = 0.002 – 0.02

Retina





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$$\hat{h}(\mathbf{k}) = \hat{h}_{system}(\mathbf{k}) \cdot \hat{h}_{water}(\mathbf{k})$$

optical system quality, FOV, sampling resol

water optical properties

$$S^{\delta}(t)$$

$$S(t) = \int S^{\delta}(t-\tau) \cdot p(\tau) d\tau$$
$$= \left(S^{\delta} * p\right)(t)$$

optical system quality, FOV, sampling resol

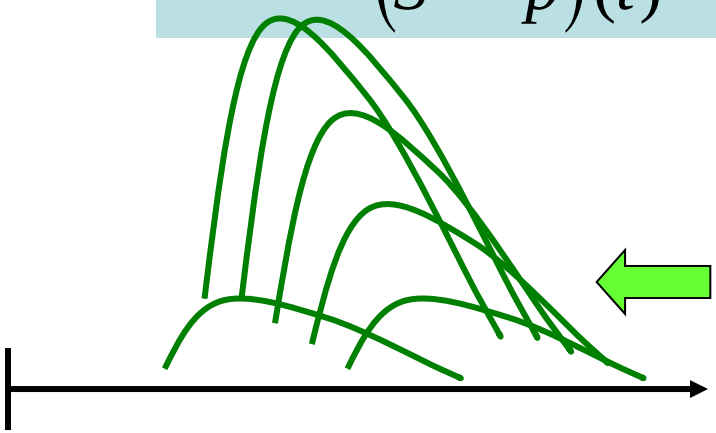
water optical properties

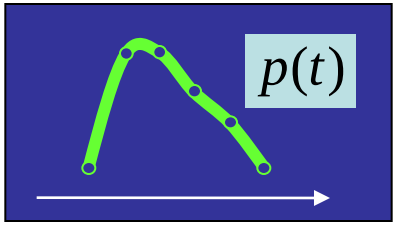
$$\left\| \hat{h}(\mathbf{k}) \right\|$$ MTF

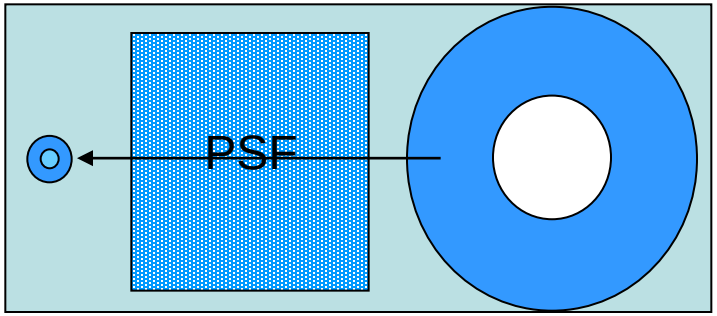
$$\hat{g}(\mathbf{k}) = \hat{f}(\mathbf{k}) \cdot \hat{h}(\mathbf{k})$$ OTF

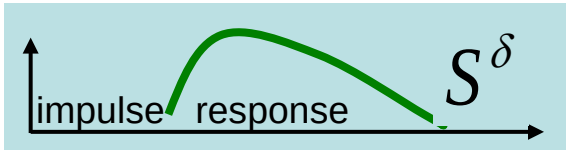
$$g(\mathbf{r}) = \int h(\mathbf{r}-\boldsymbol{\rho}) f(\boldsymbol{\rho}) d\boldsymbol{\rho}$$

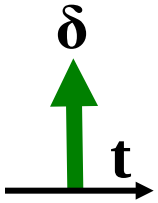
g h f

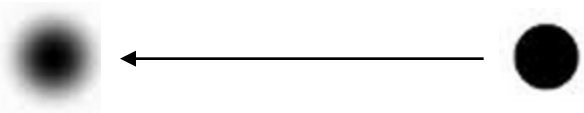












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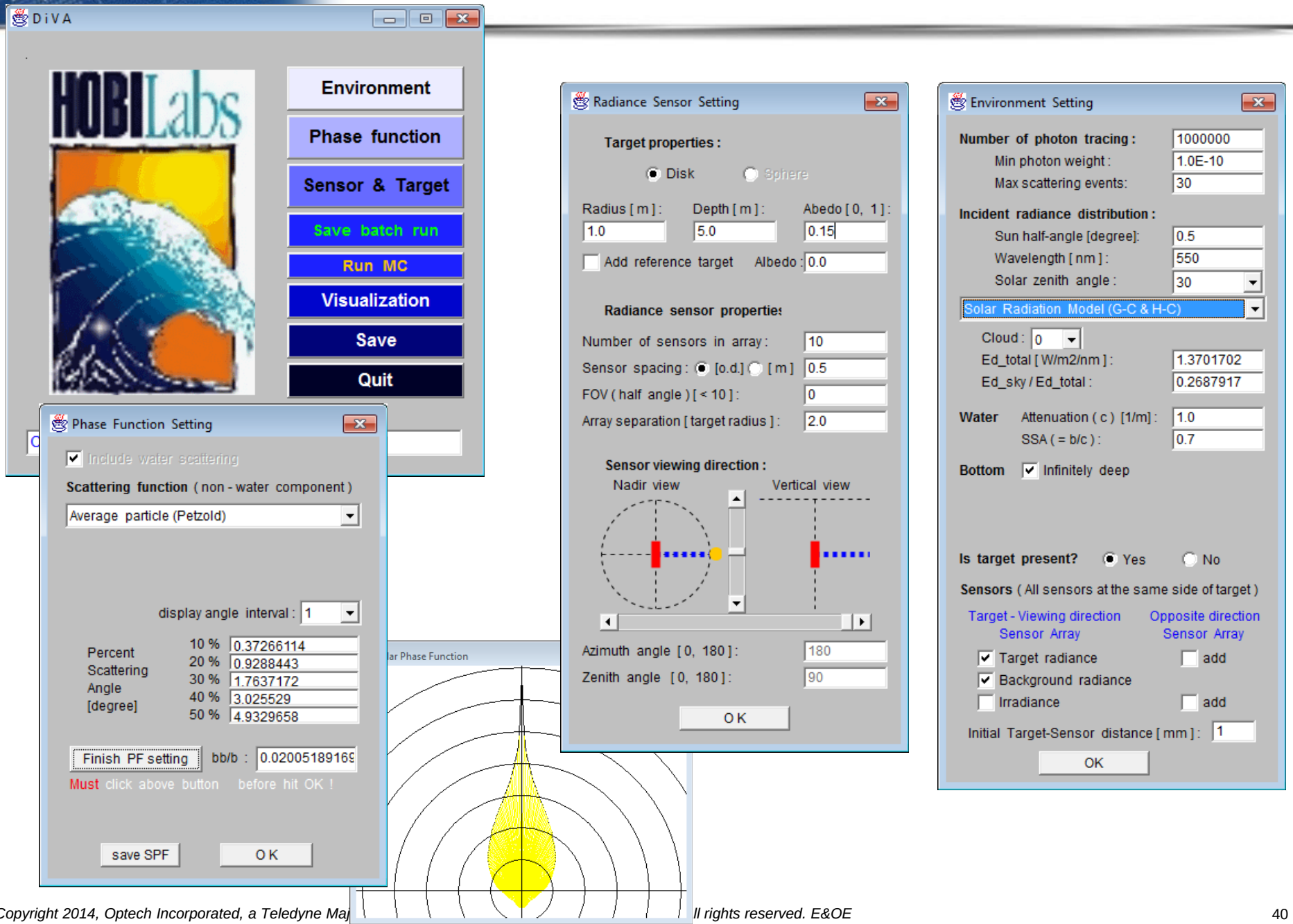
Secchi disk Visibility : Monte Carlo RT simulation



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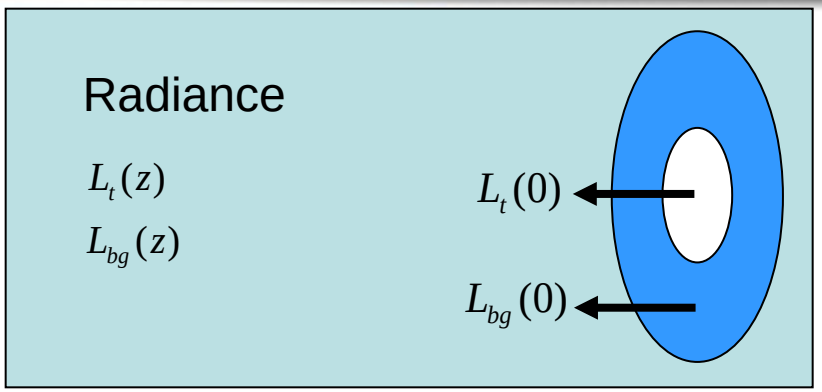
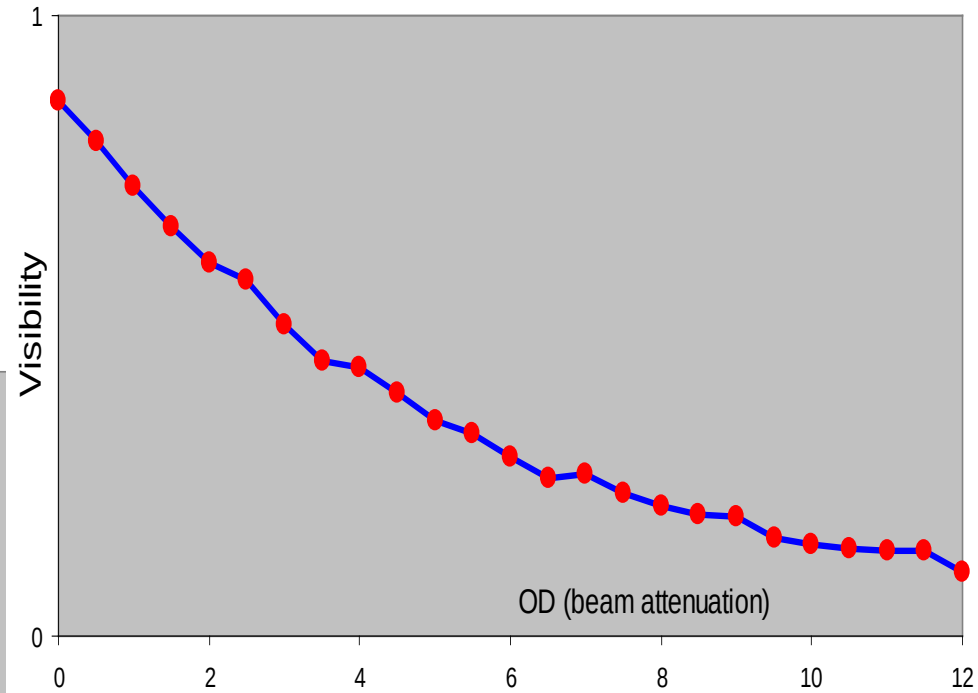
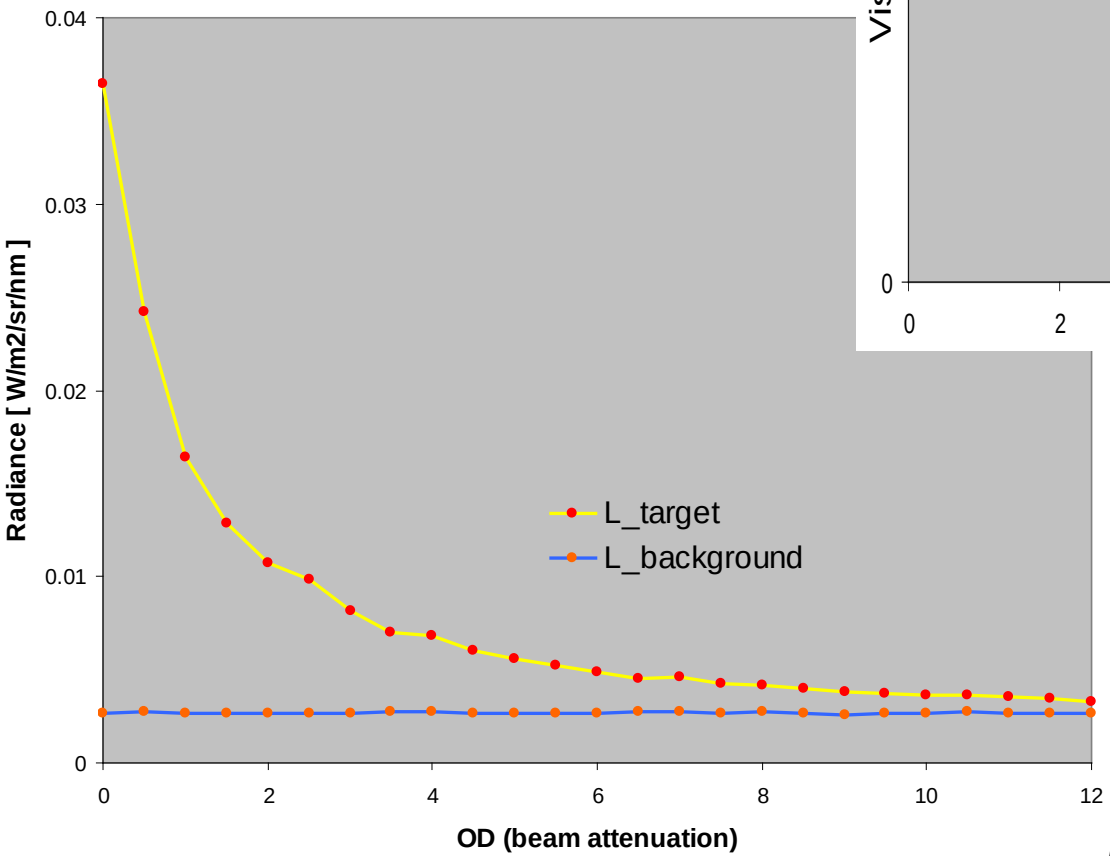
Visibility : Monte Carlo Simulation result







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Conclusion

- We live in EO era. ACS is affordable. Secchi disk? Really?
- Profiler in-situ? why not ACS and BB9?
  Easier to operate, absolute measure of water quality.
- (K_d x D_{max}) is not too bad, but too fuzzy.
- Let's use standard IOP's (a , b) instead of (K_d).
- We suggest system optical depth capacity.
  (based on the dynamic range of detectable power)
- $K_{sys} = (a + b_b) + k(b, \Theta)$
- $D_{max} = \tau_{max} / (a + \psi(b))$
- We proved CZMIL O.D. capacity ~ 5.8 .
- Still want the (K_d x D_{max})? Then, know the limitations.
  Manufacturers! Please be honest with your OD value.
  And provide proof, if you can.

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JALBTC X **for the Data**

Enjoy your lunch!

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