Apparent Optical Properties (AOPs)
Emmanuel and Charlotte

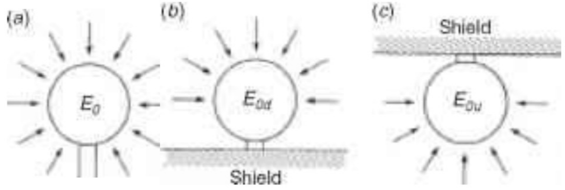
A good AOP depends weakly on the external environment and strongly on IOPs.

Historically IOPs were hard to measure (but easy to interpret).

AOPs are easier to measure using radiometers (but often harder to interpret).

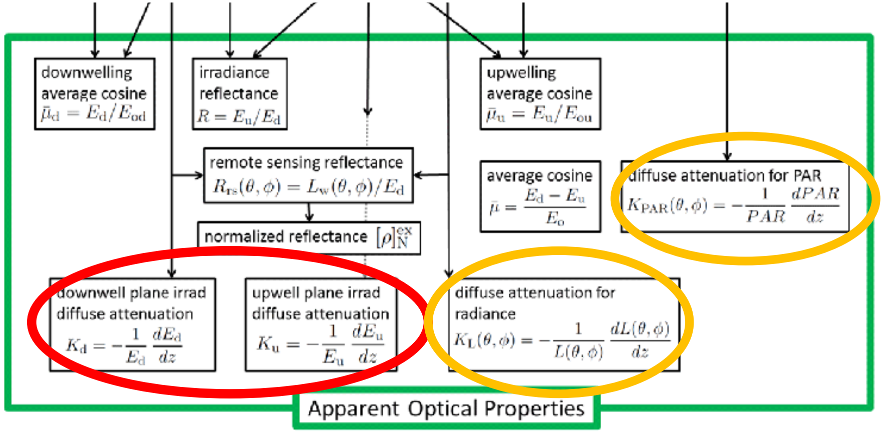
Thanks to slides by Mobley and Roesler

Diffuse attenuation coefficients of irradiance - The K-functions



AOP name	Symbol	Definition	Units
diffuse attenuation coefficients (K functions)			
of radiance in any direction $L(\theta,\phi)$	$K(\theta,\phi)$	$-d\ln L(\theta,\phi)/dz$	m^{-1}
of upwelling radiance L_u	K_{Lu}	$-d\ln L_u/dz$	m^{-1}
of downwelling irradiance E_d	K_d	$-d\ln E_d/dz$	m^{-1}
of upwelling irradiance E_u	K_u	$-d\ln E_u/dz$	m^{-1}
of scalar irradiance E_o	K_o	$-d\ln E_o/dz$	m^{-1}
of PAR	K_{PAR}	$-d\ln PAR/dz$	m^{-1}

Ocean Optics Book



Why not use irradiance as an AOP ?

Ocean Optics Book

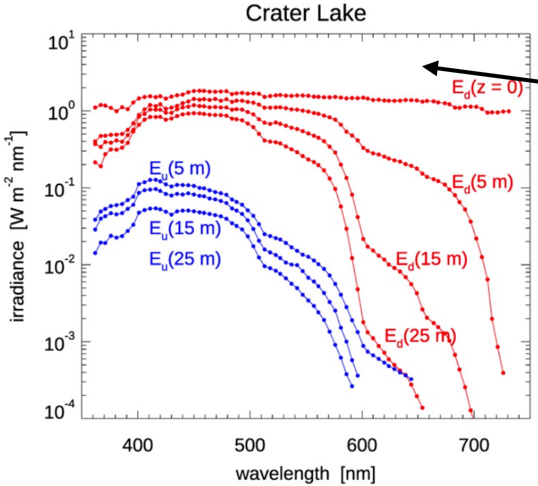


Figure 2.2: Spectral downwelling and upwelling irradiances measured in Crater Lake, Oregon, USA. Plotted from data tabulated in Tyler and Smith (1970).

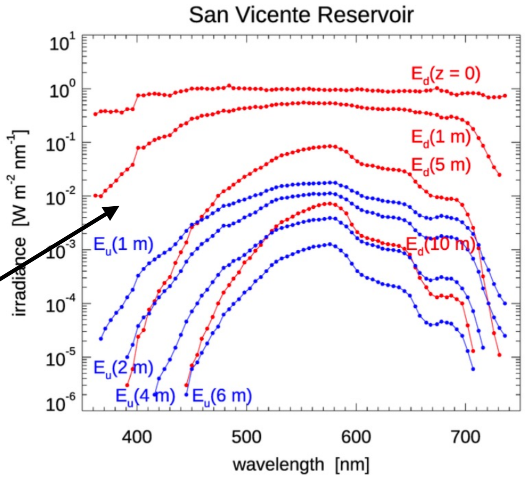


Figure 2.3: Spectral downwelling and upwelling irradiances measured in San Vicente Reservoir, California, USA. Plotted from data tabulated in Tyler and Smith (1970).

➔ Relatively easy to measure

➔ Do they fit all the criterias ?

➔ Highly variable depending on external conditions (ex: Cloud overpass)

K-functions : much stronger contenders:

$$K_d(z,\lambda) \triangleq -\frac{1}{E_d(z,\lambda)}\frac{d\,E_d(z,\lambda)}{dz} = -\frac{d\ln E_d(z,\lambda)}{dz}$$

$$K(\lambda,z) = \frac{1}{z}\ln\left(\frac{E(\lambda,0^-)}{E(\lambda,z)}\right)$$

The depth derivative (slope) of the Irradiance on a log-linear plot

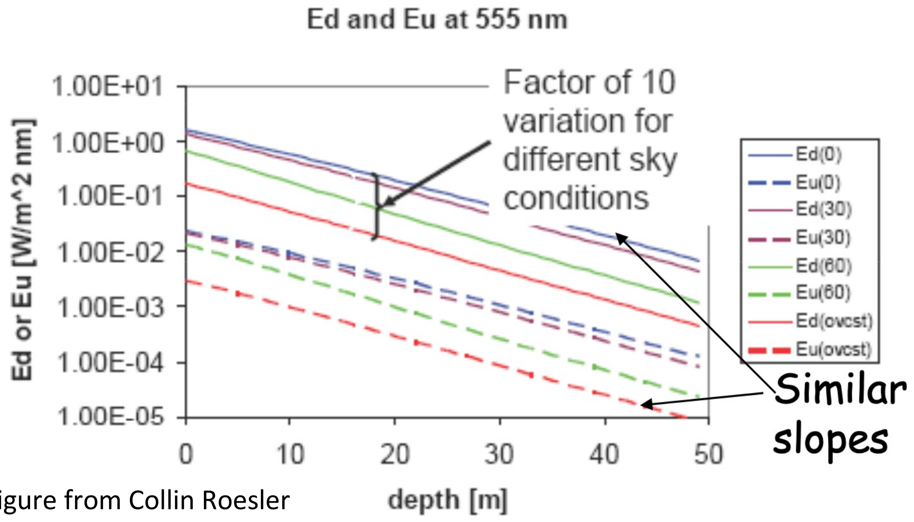
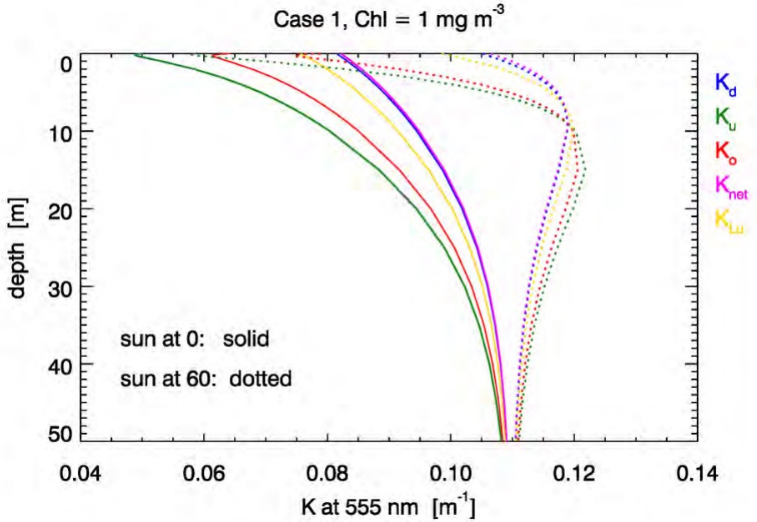


Figure from Collin Roesler



➔ What can you say about the different Kds (relationship to each other and to the sun angle) ?

K's have a strong dependance on IOPs

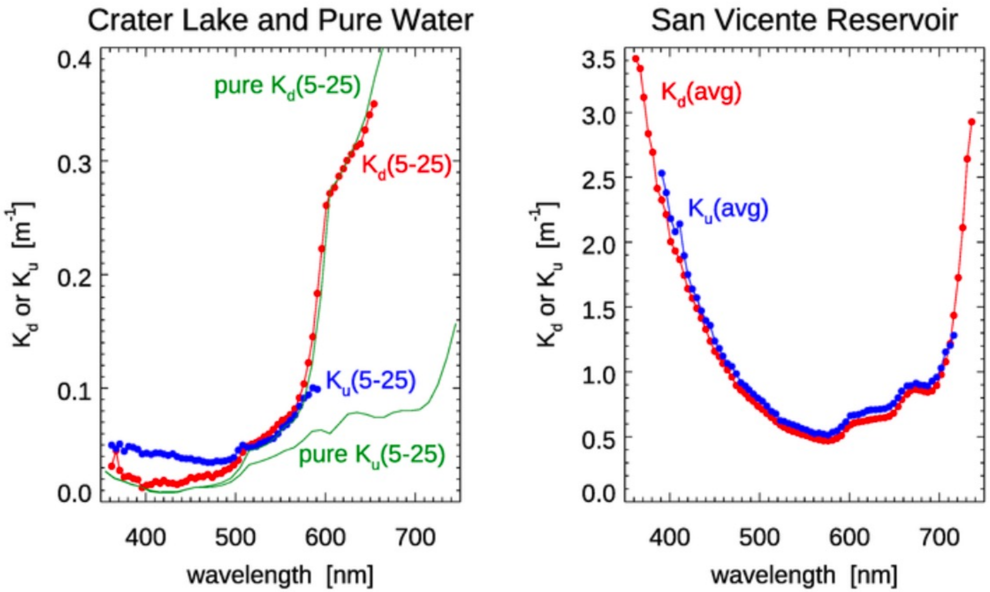


Figure 4.2: The red curve in the left panel is the average K_d between 5 and 25 m in Crater Lake; the blue curve is the average K_u between 5 and 25 m. The green curves are for optically pure water, including Raman scattering effects. The right panel shows K_d and K_u for San Vicente Reservoir.

Crater Lake :

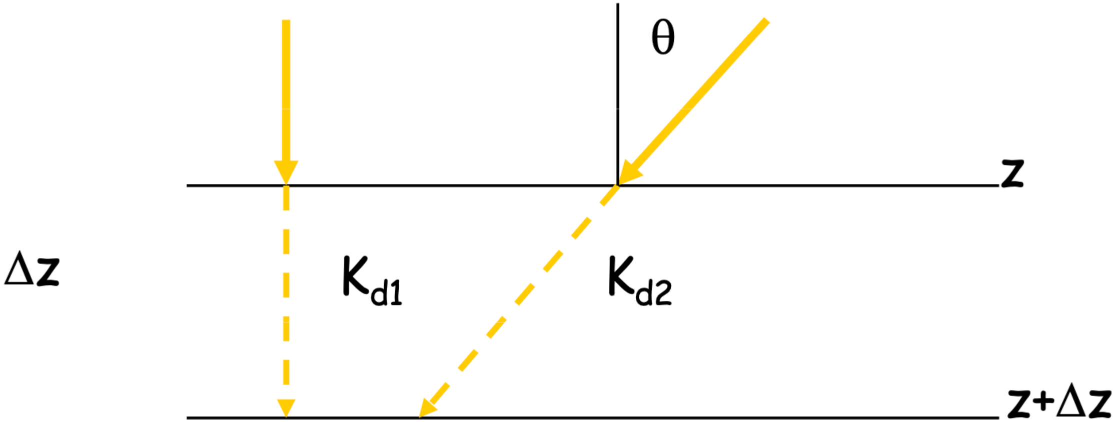
- Spectra very close to that of pure water
- Completely dominated by the absorption of pure water

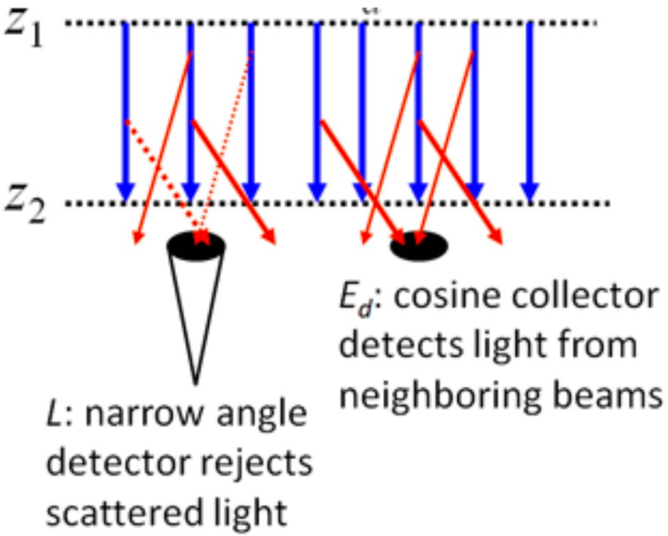
San Vincente :

- K's 100X larger than Crater lake at small wavelengths (<415 nm) → Absorption by CDOM.
- At red wavelengths : Only 2X as much as Crater lake's Kd and Ku.

→ Note that they didn't use Ed(0) in the Kd computation …

Dependance on solar angle





Kd describes the loss of Ed from z to z+Δz, but the pathlength traveled is $r = \Delta z/\cos\theta$

➔ c > Kd or Kd < c ?

➔ How does Kd1 compare to Kd2 ?

$$K_d(z,\lambda) \triangleq -\frac{1}{E_d(z,\lambda)} \frac{d\,E_d(z,\lambda)}{dz}$$

Convergence at depth

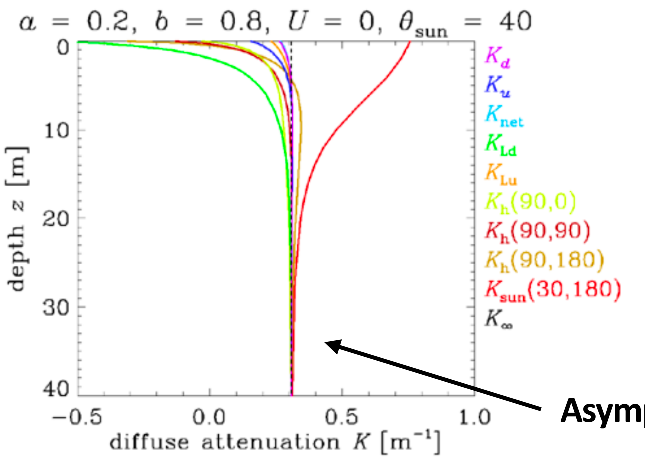
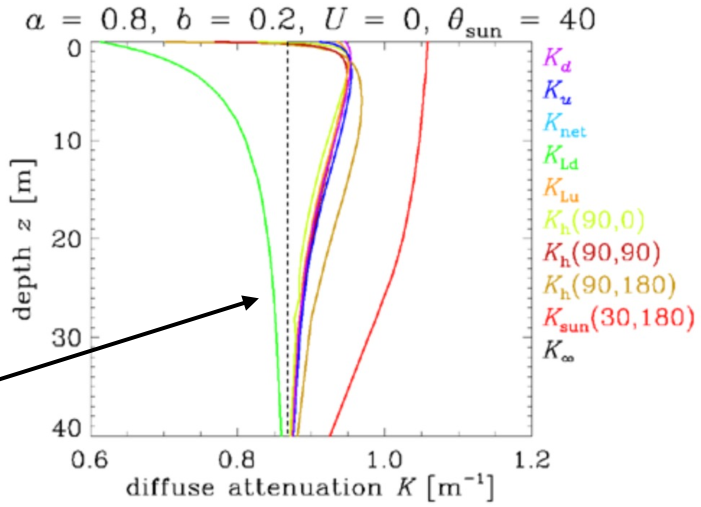


Figure 4.3: Computed K functions for "highly scattering" water. The Sun was at a zenith angle of 40 deg and the sea surface was level. The optical depth is numerically equal to the geometric depth.

Asymptotic regime



Same but highly absorbing water

Figures from the Ocean Optics Book

At depth (and far from the bottom !), irradiance is no longer affected by boundary conditions .

➔ For a given water body, the K's all approach the same value as you go deeper: the asymptotic diffuse attenuation coefficient, **K_∞** , which is an IOP (or at least depends solely on IOPs)

How do we measure it ?

In theory :

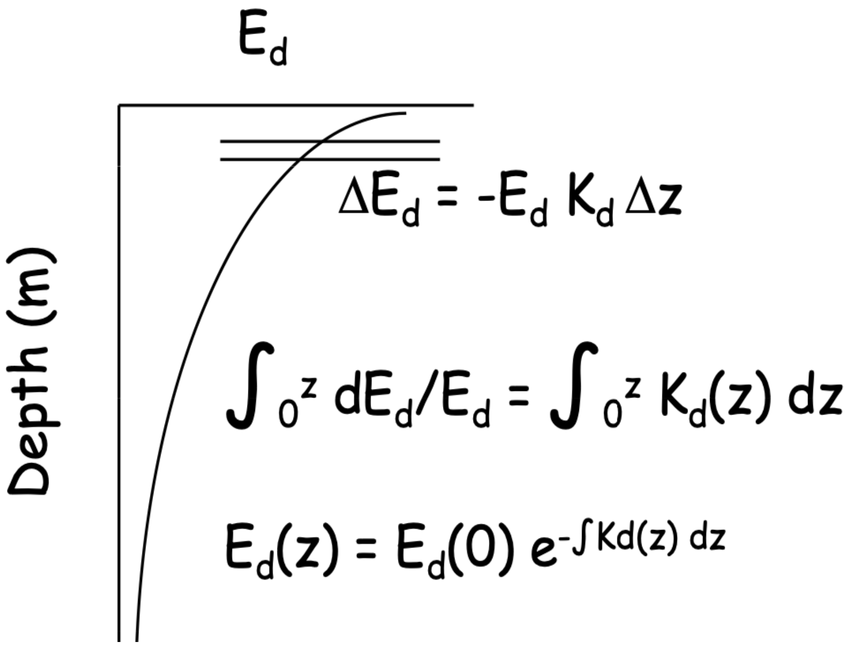
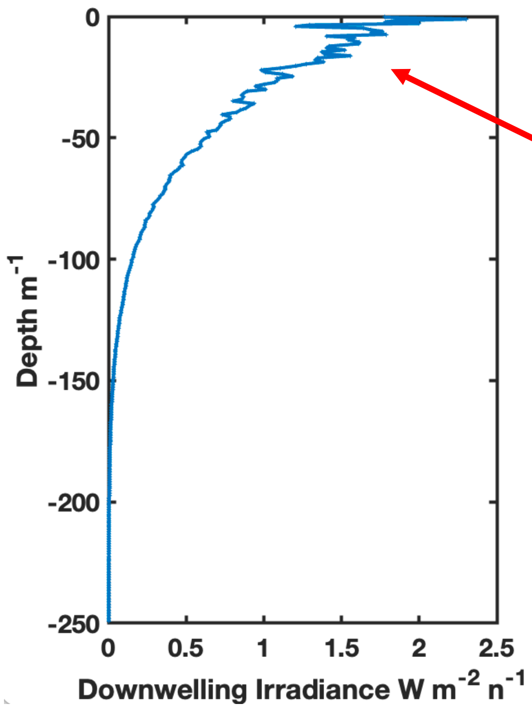


Figure from Collin Roesler

In real life :

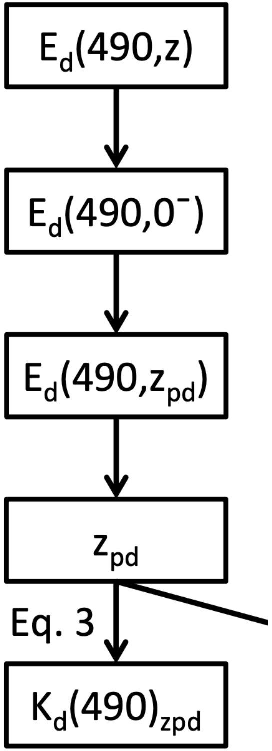


Wave focusing
Bubbles
Passing clouds

Assuming homogeneity : Ed (z) = Ed (0)exp(-Kd(z))

Organelli et al.,2016

Correction for the first few meters



Xing et al.,2020

Knowing it is noisy in the first few meters

→ You extrapolate to Ed(0)

→Compute zpd = depth at which Ed(zpd) =E(0-)/e.

→How accurate is this Ed (0) likely to be?

→How accurate is the zpd ?

$$K(\lambda, z) = \frac{1}{z} \ln\left(\frac{E(\lambda, 0^-)}{E(\lambda, z)}\right) \approx \frac{1}{zpd}$$

Dark values due to instrument

Representative sample

Passing clouds

Wave focusing

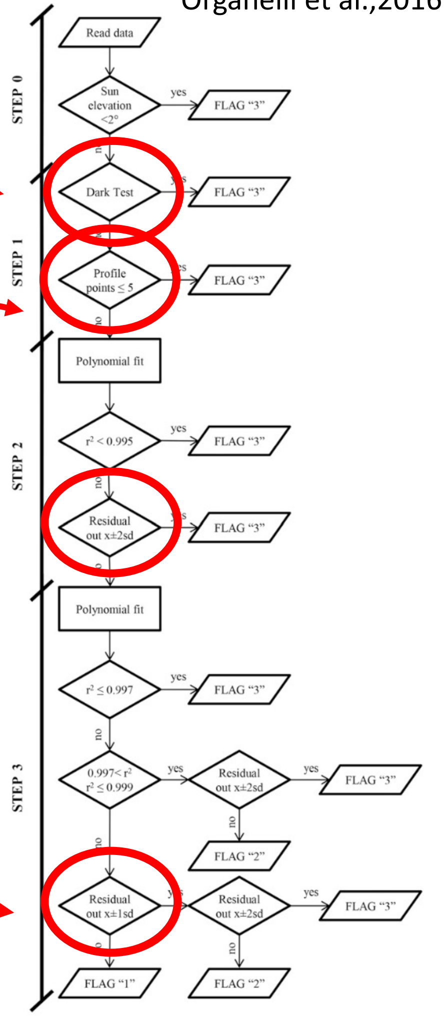
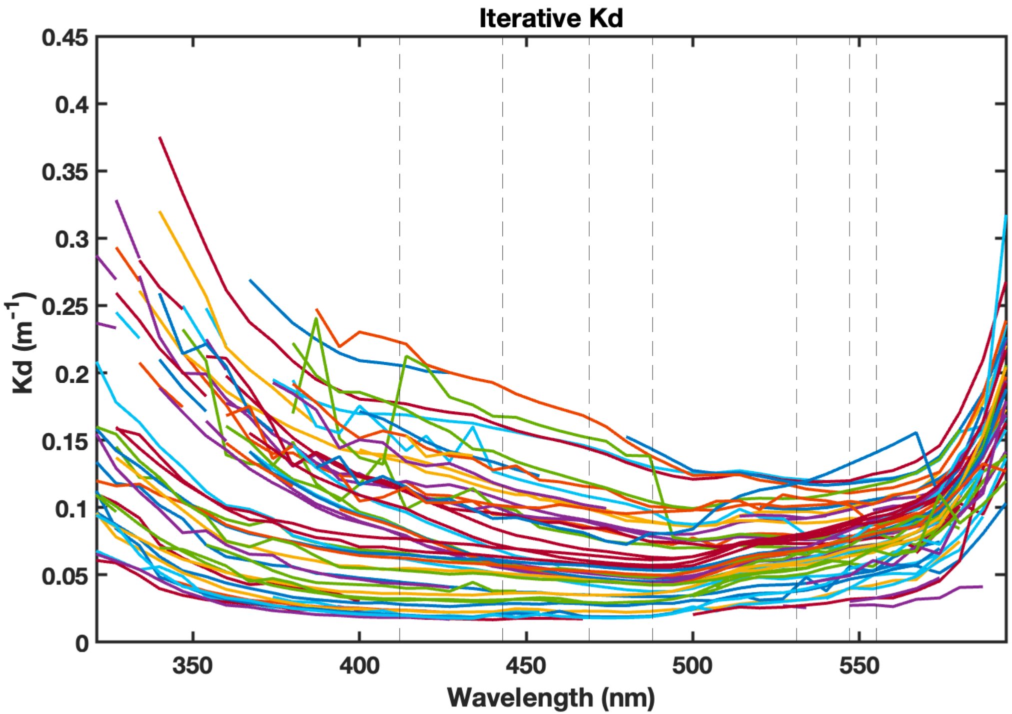
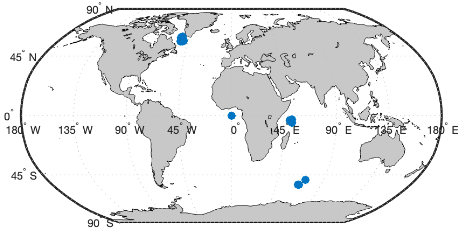


FIG. 6. Flowchart of the QC procedure for radiometric data acquired by Bio-Argo floats [e.g., $E_d(380)$]; "x" is the mean of residuals.

Current BGC-Argo floats have 2 wavelengths in common with satellites → as we are moving towards hyperspectral measurements, QC will have to be adapted for different wavelengths

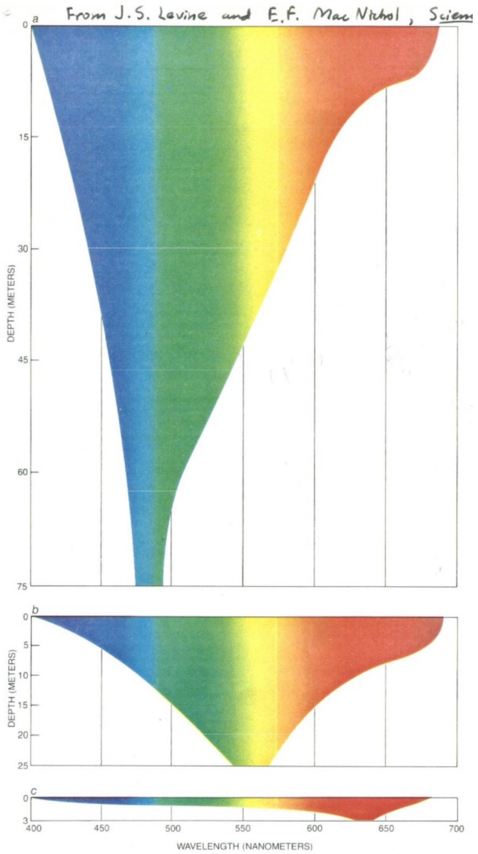




If you have light at surface (from Satellite) and K → can constrain the whole subsurface light field available for photosynthesis and photochemistry.

➔ Primary production, heat exchange etc …

What about KPAR



Is it constant with depth ?

Are all wavelengths attenuated with depth at the same rate ? NO

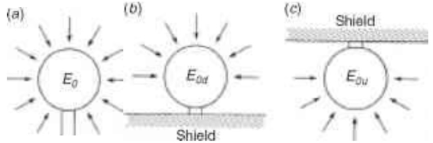
$$K_d(\mathrm{iPAR}, z) = \frac{1}{z}\ln\left(\frac{\mathrm{iPAR}(0^-)}{\mathrm{iPAR}(z)}\right)$$

➔ Is highly dependent on the layer in which you calculate it .

For a layer of 2 zpd (From Morel07) :

$$K_d(\mathrm{iPAR}) = 0.0665 + 0.874 K_d(490) - 0.00121 / K_d(490).$$

Average (mean) cosine



The average cosine gives the average of the cos(θ) as weighted by the radiance distribution.

➔ This tells you something about the directional pattern of the radiance.

$$\mu_d = E_d/E_{od}$$

$$\mu_u = E_u/E_{ou}$$

$$\overline{\mu} = \vec{E}/E_o = (E_d - E_u)/(E_{od} + E_{ou})$$

$$\bar{\mu}_\mathrm{d} \triangleq \frac{\int_0^{2\pi}\int_0^{\pi/2} L(\theta,\phi)\,\cos\theta\,\sin\theta\,d\theta\,d\phi}{\int_0^{2\pi}\int_0^{\pi/2} L(\theta,\phi)\,\sin\theta\,d\theta\,d\phi} = \frac{E_\mathrm{d}}{E_\mathrm{od}}\,.$$

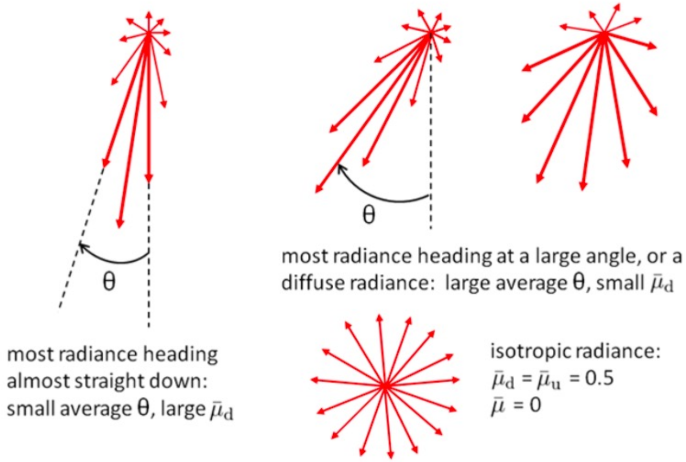


Figure 4.20: Illustration of average cosines as a measure of the directional nature of the radiance distribution.

Ocean Optics Book

What do they tell us ?

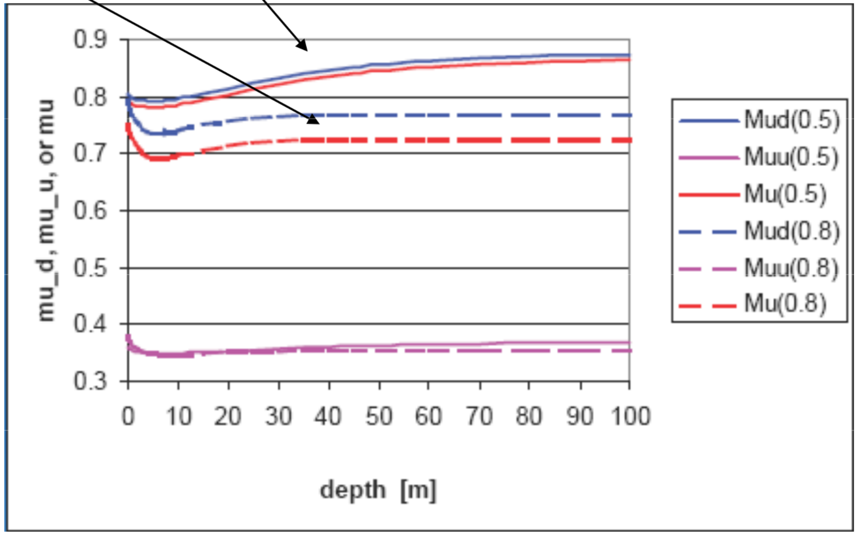
The more scattering → the faster is asymptotic attained

The more absorbing → the more collimated

$\mu_d = E_d/E_{od}$

$\mu_u = E_u/E_{ou}$

$\overline{\mu} = \vec{E}/E_o$

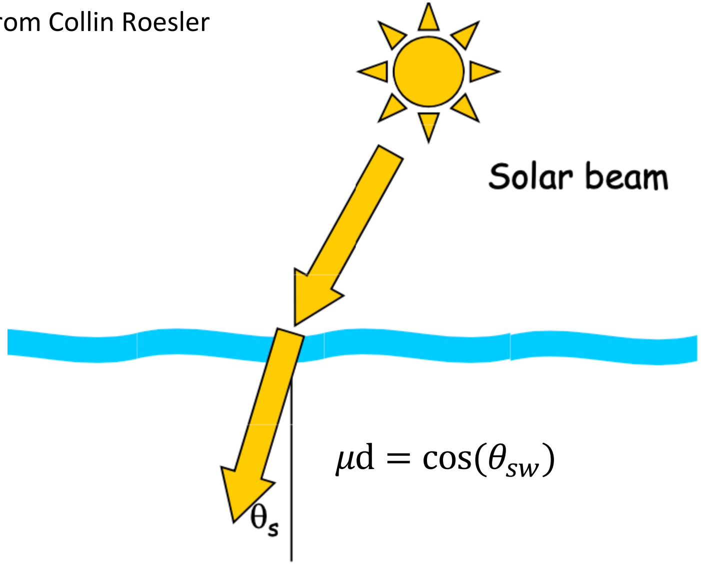


Mobley, 2004, Hydrolight with b=a (b/c=0.5) & b=4a (b/c=0.8).

Collin Roesler

AOPs are closely linked together and can be used in Inverse problem solving (more on that later …)

Figure from Collin Roesler



$\mu d = \cos(\theta_{sw})$

$$K_d \propto \frac{a + b_b}{\cos\theta_{sw}}$$

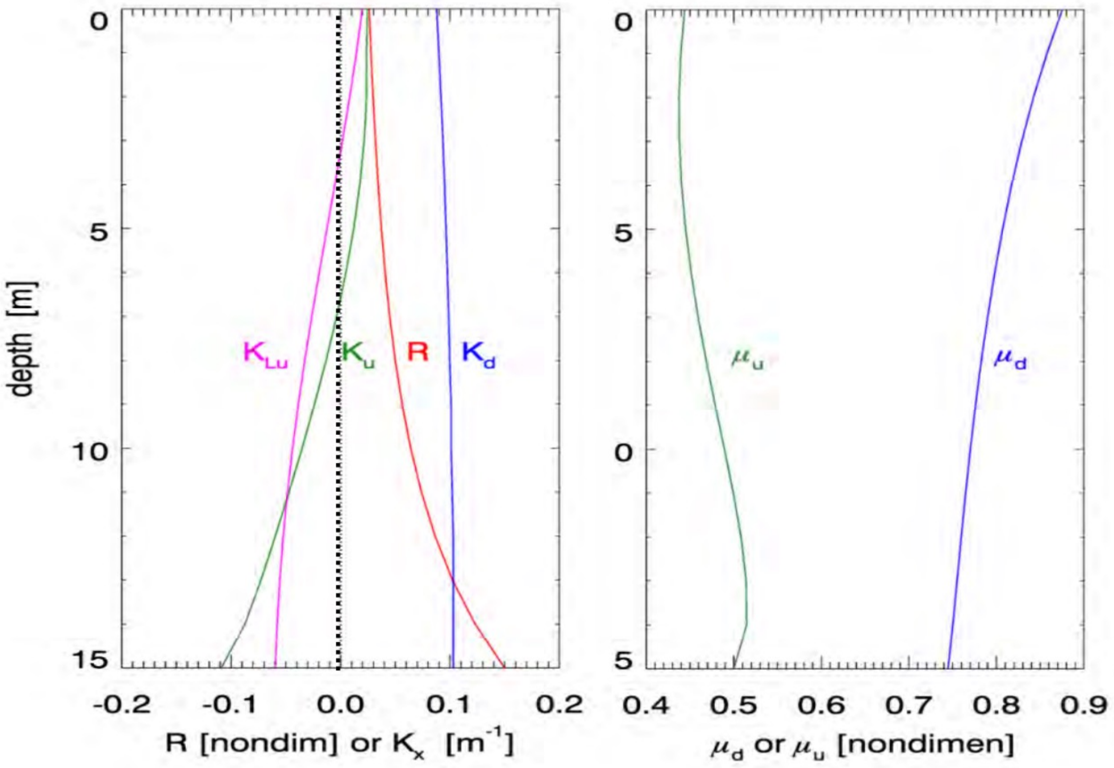
Effectively normalizing by the dependence on the sun.

$$Kd \propto \frac{a + b_b}{\mu_d}$$

!!Some add a component for diffuse skylight (Prieur, Sathyendranath, 1981)!!

$$\frac{1}{\bar{\mu}_d} = \frac{0.6}{\cos j} + \frac{0.4}{0.859}$$

Explain these AOPs…



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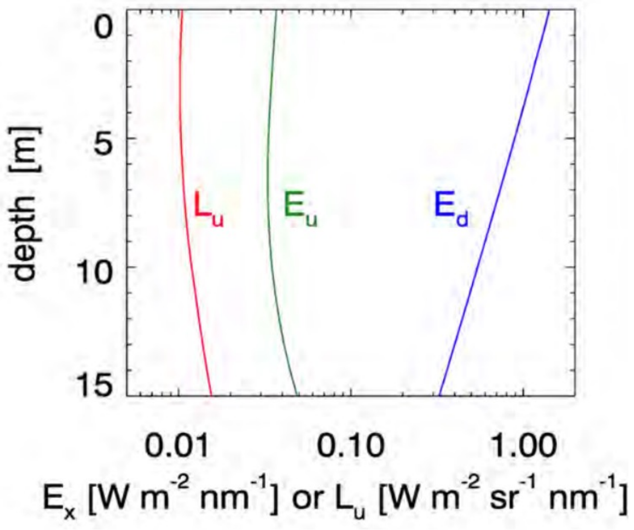
→Notice anything weird in the Kd profiles ?



→ Eu and Lu are increasing at the bottom …

A survey of methods to obtain ‘reflectance’
Based on review by Ruddick et al., 2019

Take away message:

There are many kind of ‘reflectance’.

In all, upwelled ‘light’ is normalized by downwelling ‘light’.

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Watch out for definitions.

In each I want you to think about what problems there may be.

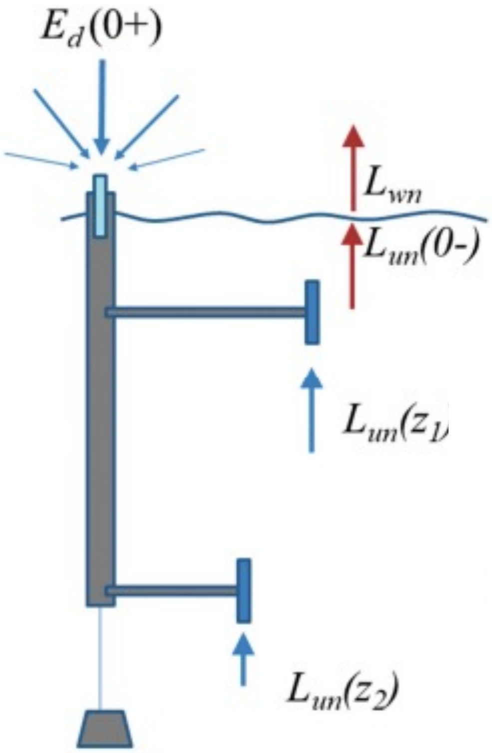
What do the satellite measure?
What reflectance is typically computed?

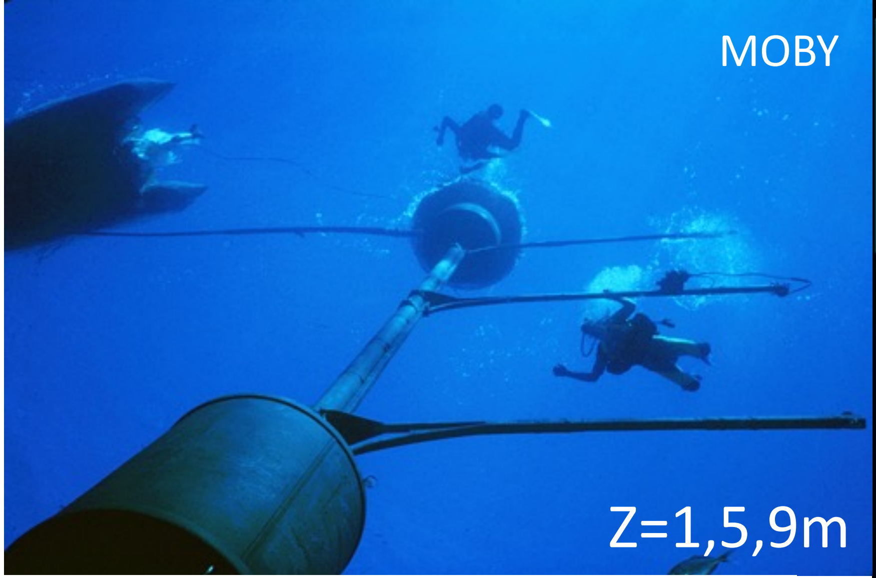
Radiance is typically measured off nadir to avoid glint.

Normalized by a model of plane irradiance.

Often, normalized further for nadir view and sun at nadir.

$$R_{rs} = \frac{L_{wn}}{E_d(0+)}$$





$$L_{un}(0^-) = L_{un}(z_1, t_1)exp[K_{Lu} z_1]$$

$$K_{Lu} = \frac{1}{z_2 - z_1} ln\left[\frac{L_{un}(z_1, t_1)}{L_{un}(z_2, t_2)} \frac{E_d^{0+}(t_2)}{E_d^{0+}(t_1)}\right]$$

$$L_{wn} = \frac{T_F}{n_w{}^2} L_{un}(0^-) \quad T_F/n_w^2 = 0.543$$

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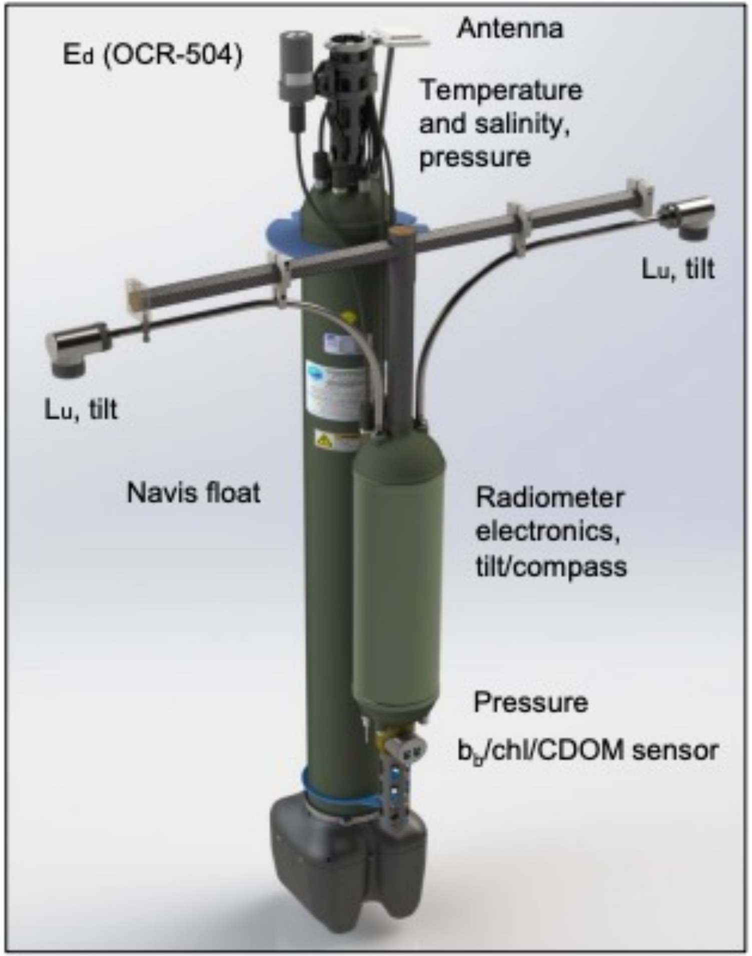
Z_1~10cm

HyperNAV



Profiling radiometers

$$R_{rs} = \frac{L_{un}(0^-)}{E_d(0+)}$$

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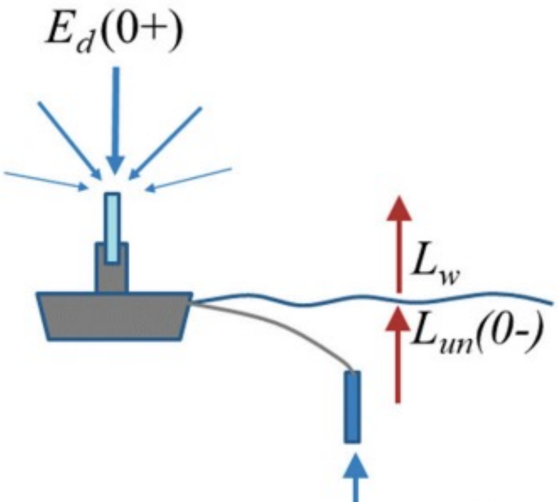

HyperNAV

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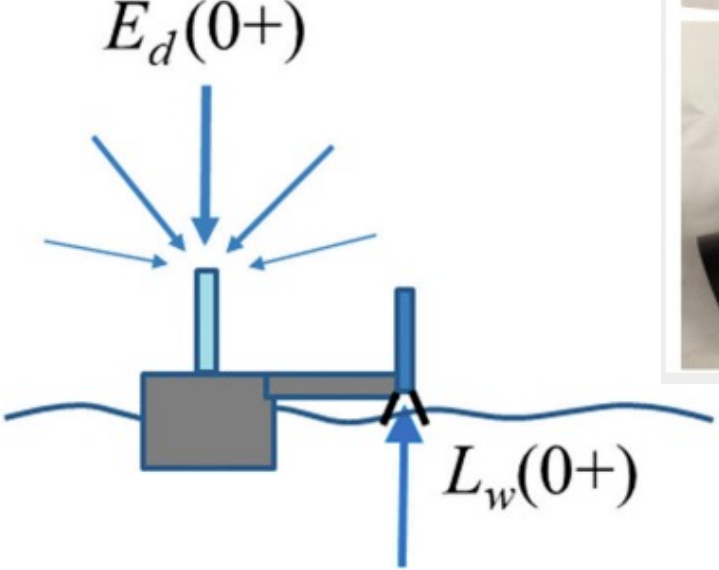
$$L_{wn} = \frac{T_F}{{n_w}^2} L_{un}(0^-) \quad T_F/n_w^2 = 0.543$$

Z_1~10cm

$$R_{rs} = \frac{L_{wn}}{E_d(0+)}$$

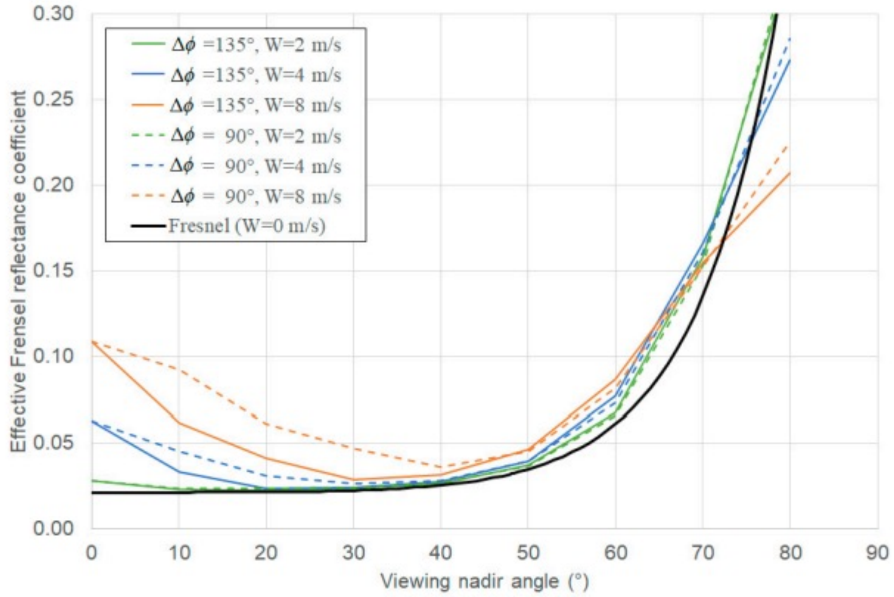


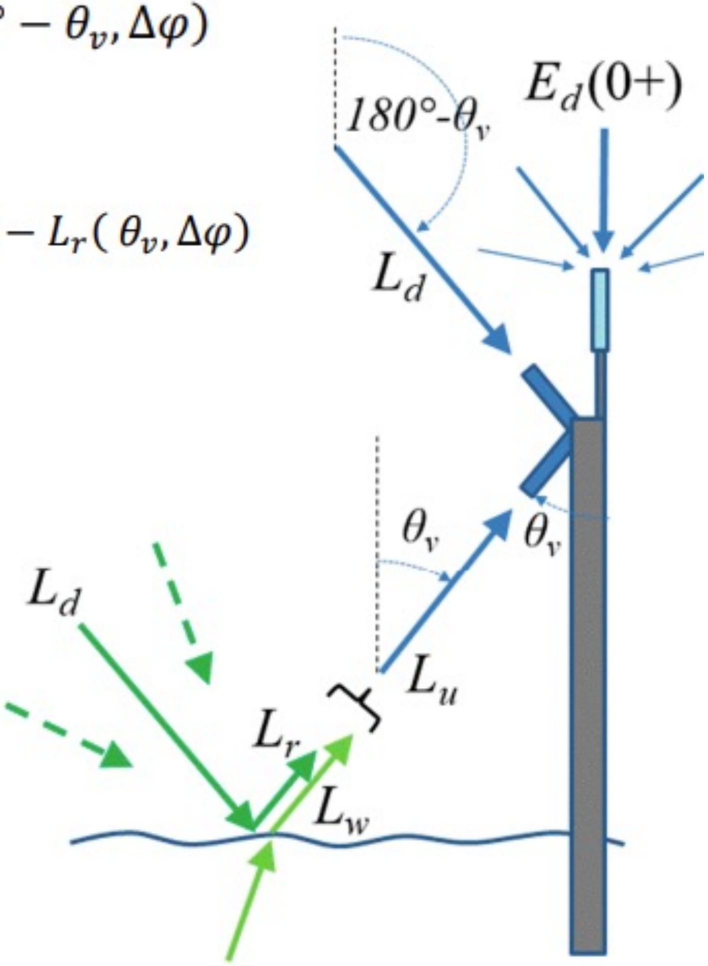
Lee et al., 2013

$$R_{rs} = \frac{L_w(\theta_v, \Delta\varphi)}{E_d(0+)}$$

$$L_r(\theta_v, \Delta\varphi) = \rho_F L_d(0^+, 180° - \theta_v, \Delta\varphi)$$

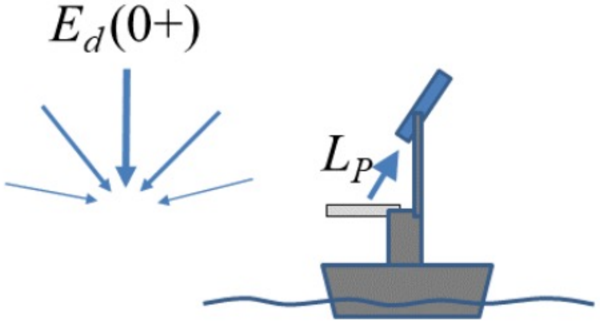
$$L_w(\theta_v, \Delta\varphi) = L_u(0^+, \theta_v, \Delta\varphi) - L_r(\theta_v, \Delta\varphi)$$





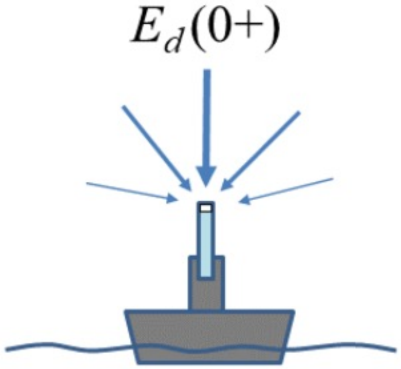
Mobley, 1999

An aside about radiance measurements:



$$E_d^{0+} = \frac{\pi * L_P}{\rho_P}$$

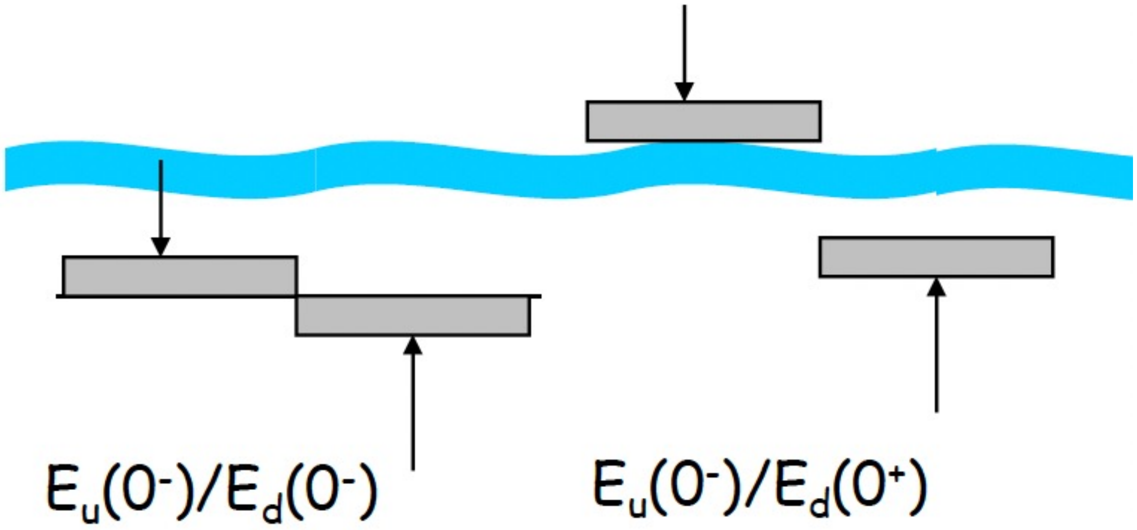
L



Plaque should be horizontal and above the height of all other structures or objects (including humans).

Irradiance reflectance

R_{rs}=Eu/Ed



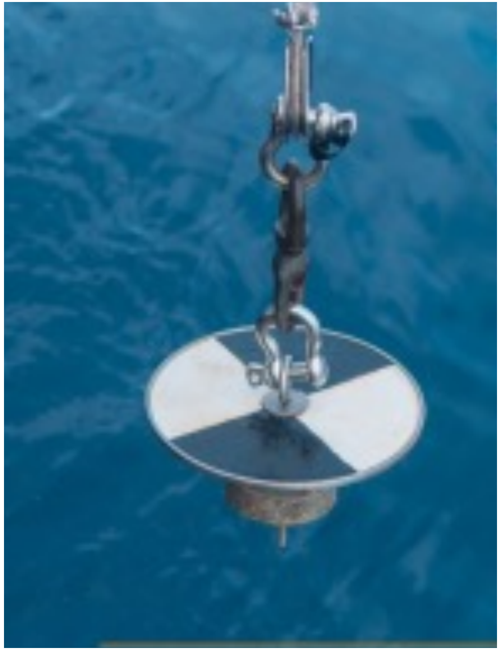
Secchi disk depth: theory

Contrast reduction theory for detecting target for any direction:

$$\frac{C_r(\theta,\phi,z)}{C_0(\theta,\phi,z_T)} = \exp[-cr + K(\theta,\phi,z)\, r\cos(\theta)]$$

- $C_r(\theta,\phi,z)$: apparent contrast of target
- $C_0(\theta,\phi,z_T)$: inherent contrast of target
- c: attenuation coefficient
- r: range
- $K(\theta,\phi,z)$: diffuse attenuation coefficient
- θ: viewing angle relative to straight up

Parameters are for *photopic* spectral response



Preisendorfer (1963), Duntley (1976) but work originated in 1940's

Watch for newer theory by ZP Lee

Parting words

AOPs are very useful quantities to obtain BGC information regarding the ocean.

Necessary to reconstruct the subsurface light field.

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Necessary to validate OCR measurements.