2013 Summer Course

on Optical Oceanography, Remote Sensing, Radiative Transfer Theory, and HydroLight

Curtis Mobley

Apparent Optical Properties and the BRDF

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University of Maine
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Apparent Optical Properties (AOPs)

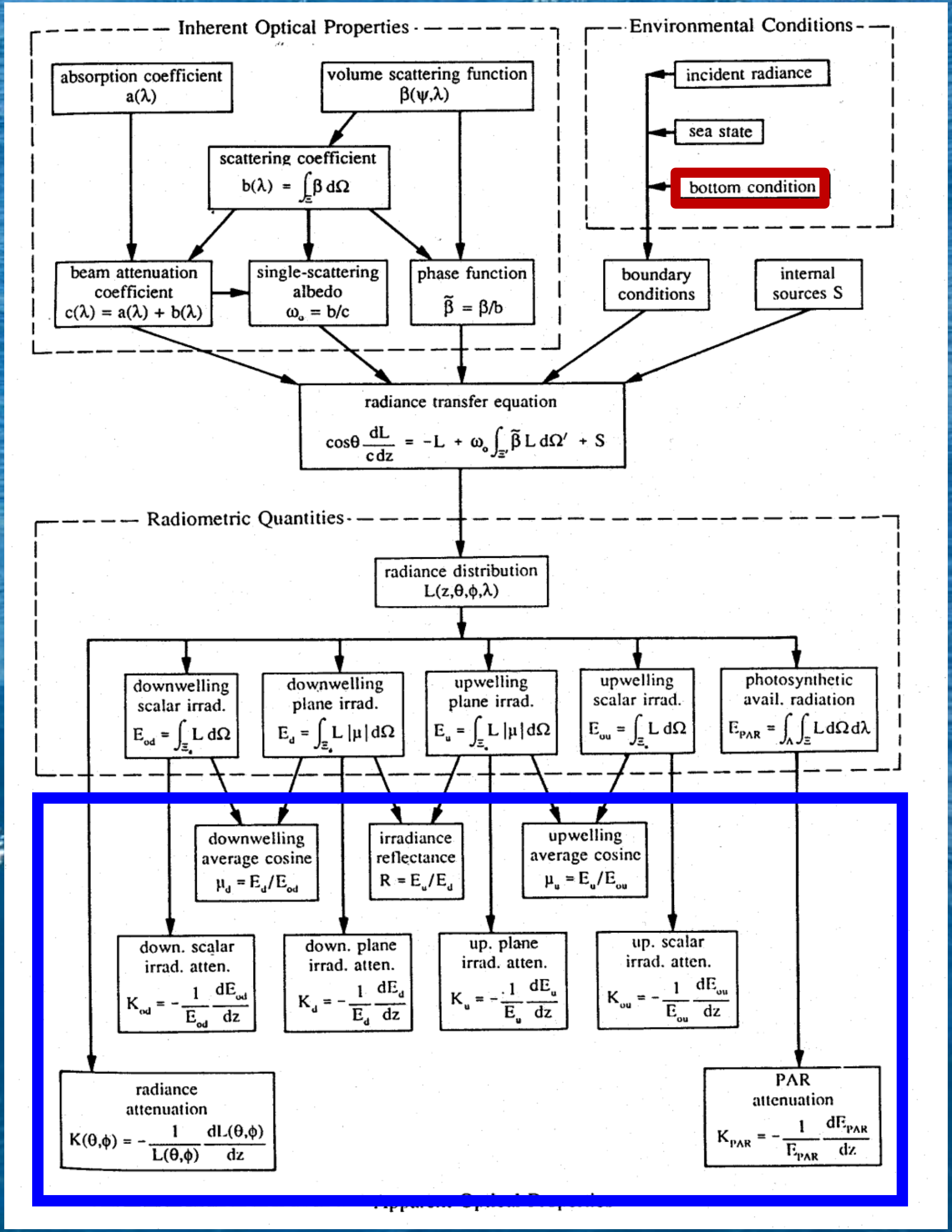
AOPs are quantities that

- depend on the IOPs and on the radiance distribution, and

- they display enough stability to be useful for approximately describing the optical properties of the water body

AOPs can NOT be measured in the lab or on water sample; they must be measured in situ

Radiance and irradiances are NOT AOPs—they don’t have stability



Apparent Optical Properties

A good AOP depends weakly on the external environment (sun zenith angle, sky condition, surface waves) and strongly on the water IOPs

AOPs are usually ratios or derivatives of radiometric variables

Historically, IOPs were hard to measure (but easy to interpret). This is less true today because of advances in instrumentation.

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

www.oceanopticsbook.info/view/overview_of_optical_oceanography/apparent_optical_properties

In a Perfect World

Light Properties: measure the radiance as a function of location, time, direction, wavelength, $L(x,y,z,t,\theta,\phi,\lambda)$, and you know everything there is to know about the light field. You don’t need to measure irradiances, PAR, etc.

Material Properties: measure the absorption coefficient $a(x,y,z,t,\lambda)$ and the volume scattering function $\beta(x,y,z,t,\psi,\lambda)$, and you know everything there is to know about how the material affects light. You don’t need to measure b, b_b, etc.

Nothing else (AOPs in particular) is needed.

Reality

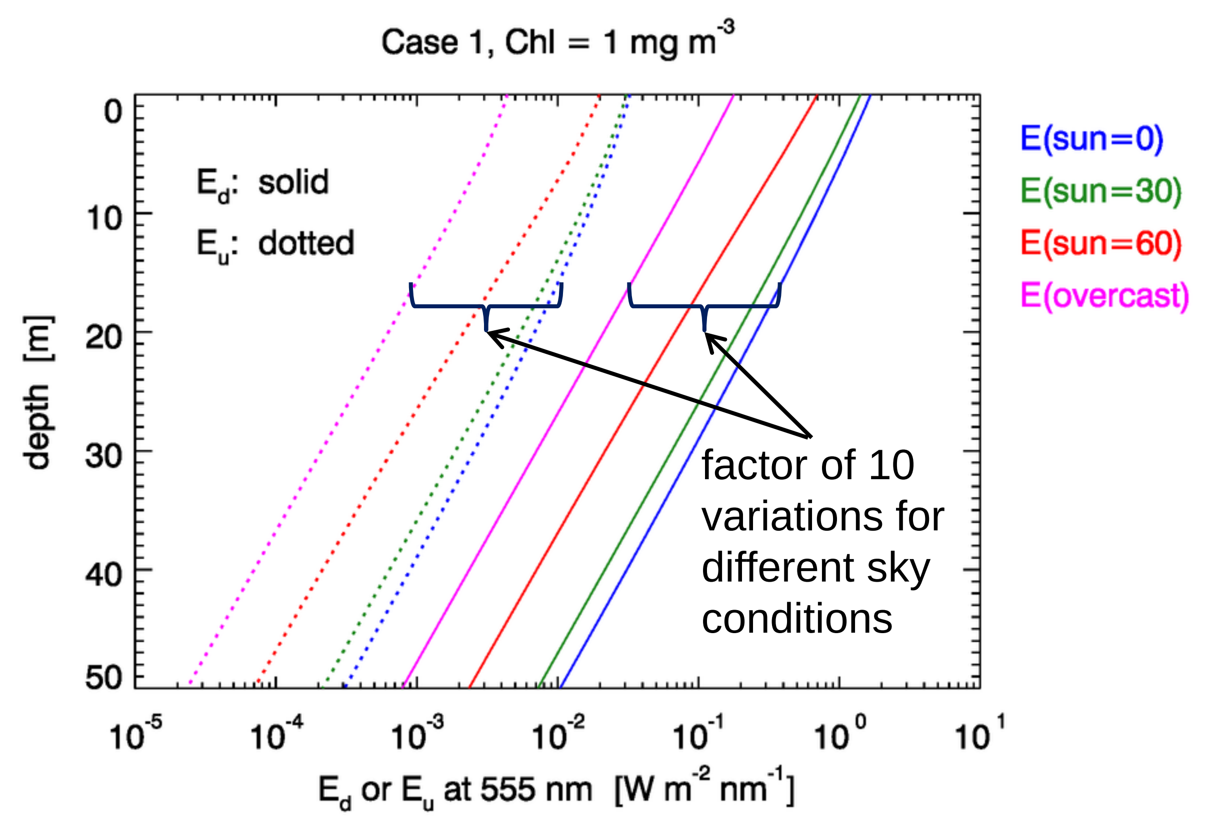
$L(x,y,z,t,\theta,\phi,\lambda)$ is too difficult and time consuming to measure on a routine basis, and you don't need all of the information contained in L, so therefore measure irradiances, PAR, etc. (ditto for VSF vs b, b_b,….)

Idea

Can we find simpler measures of the light field than the radiance, which are also useful for describing the optical characteristics of a water body (i.e., what is in the water)?

E_d and E_u

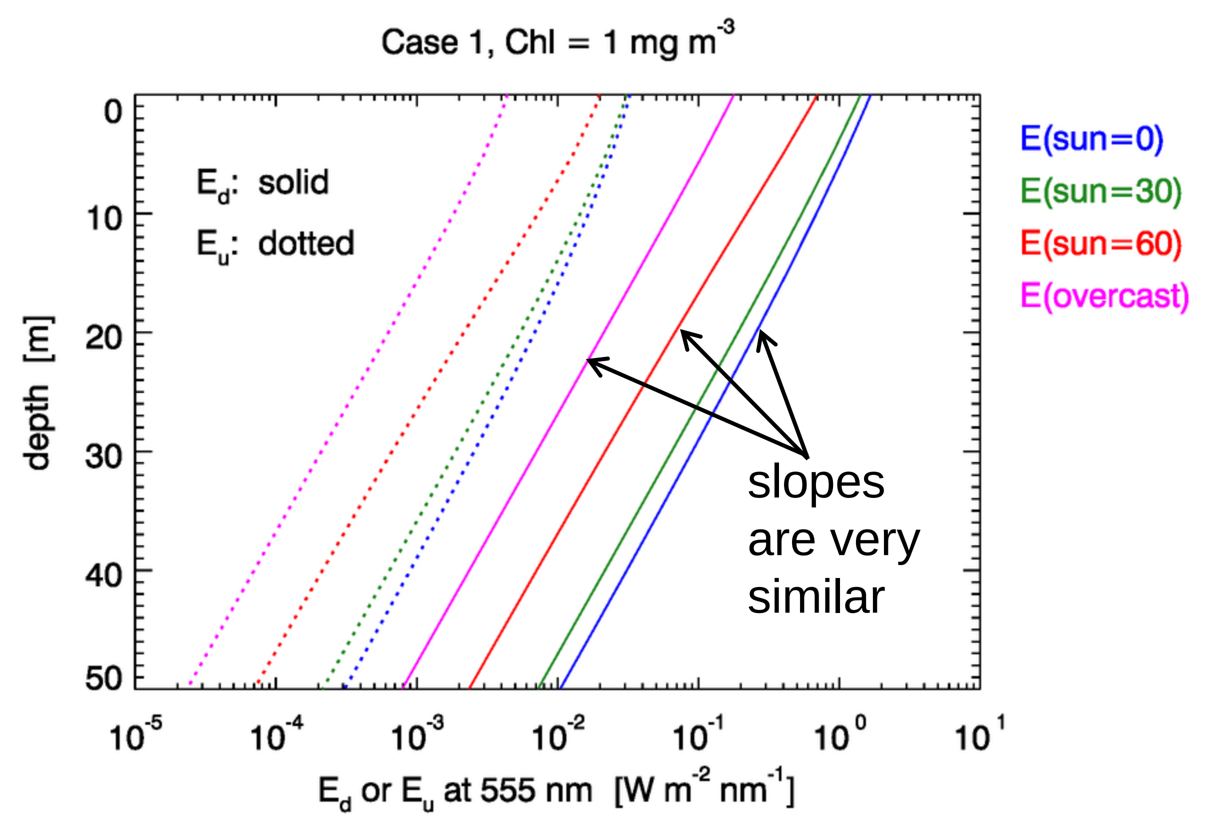
HydroLight runs: Case 1 water, Chl = 1.0 mg/m^3, etc
Sun at 0, 30, 60 deg in clear sky, and solid overcast



factor of 10 variations for different sky conditions

Note: E_d and E_u depend on the radiance and on the abs and scat properties of the water, but they also depend strongly on incident lighting, so not useful for characterizing a water body. Again: irradiances are NOT AOPs!

E_d and E_u



Magnitude changes are due to incident lighting (sun angle and sky condition); slope is determined by water IOPs.

This suggests trying...

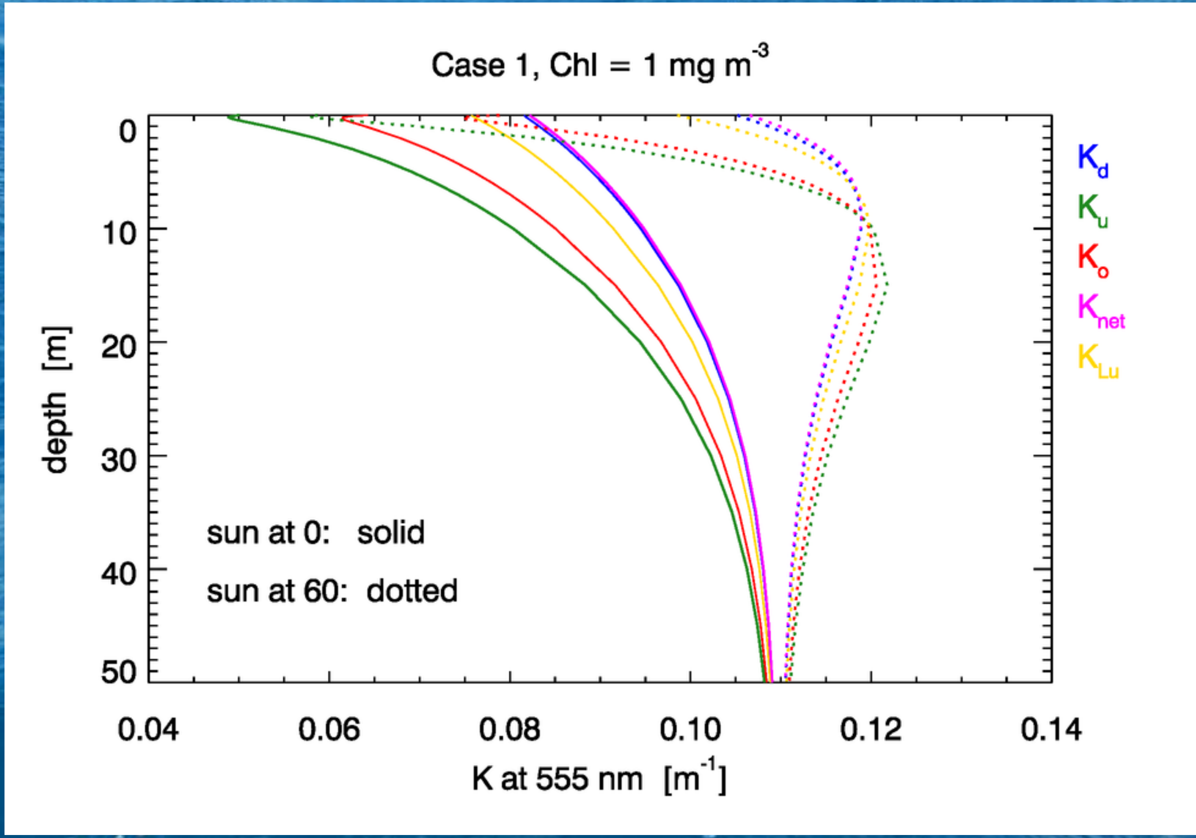
…the depth derivative (slope) on a log-linear plot as an AOP.

This leads to the diffuse attenuation coefficient for downwelling plane irradiance:

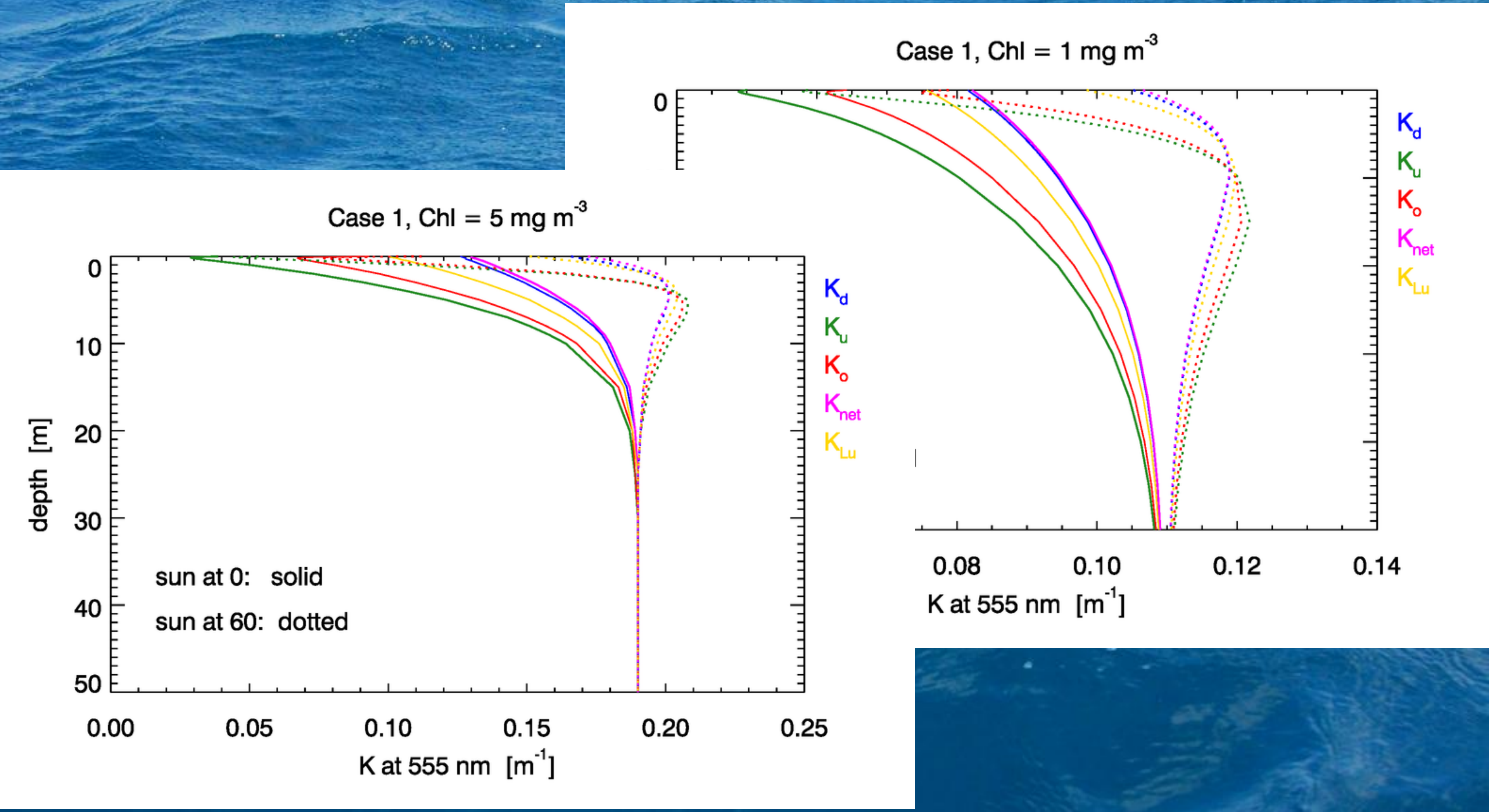
$$\begin{aligned} K_d(z,\lambda) &= -\frac{d\ln E_d(z,\lambda)}{dz} \\ &= -\frac{1}{E_d(z,\lambda)}\frac{d\,E_d(z,\lambda)}{dz} \qquad (\mathrm{m}^{-1}) \end{aligned}$$

We can do the same for E_u, E_o, $L(\theta,\phi)$, etc, and define many different K functions: K_u, K_o, $K_L(\theta,\phi)$, etc.

How similar are the different K's?

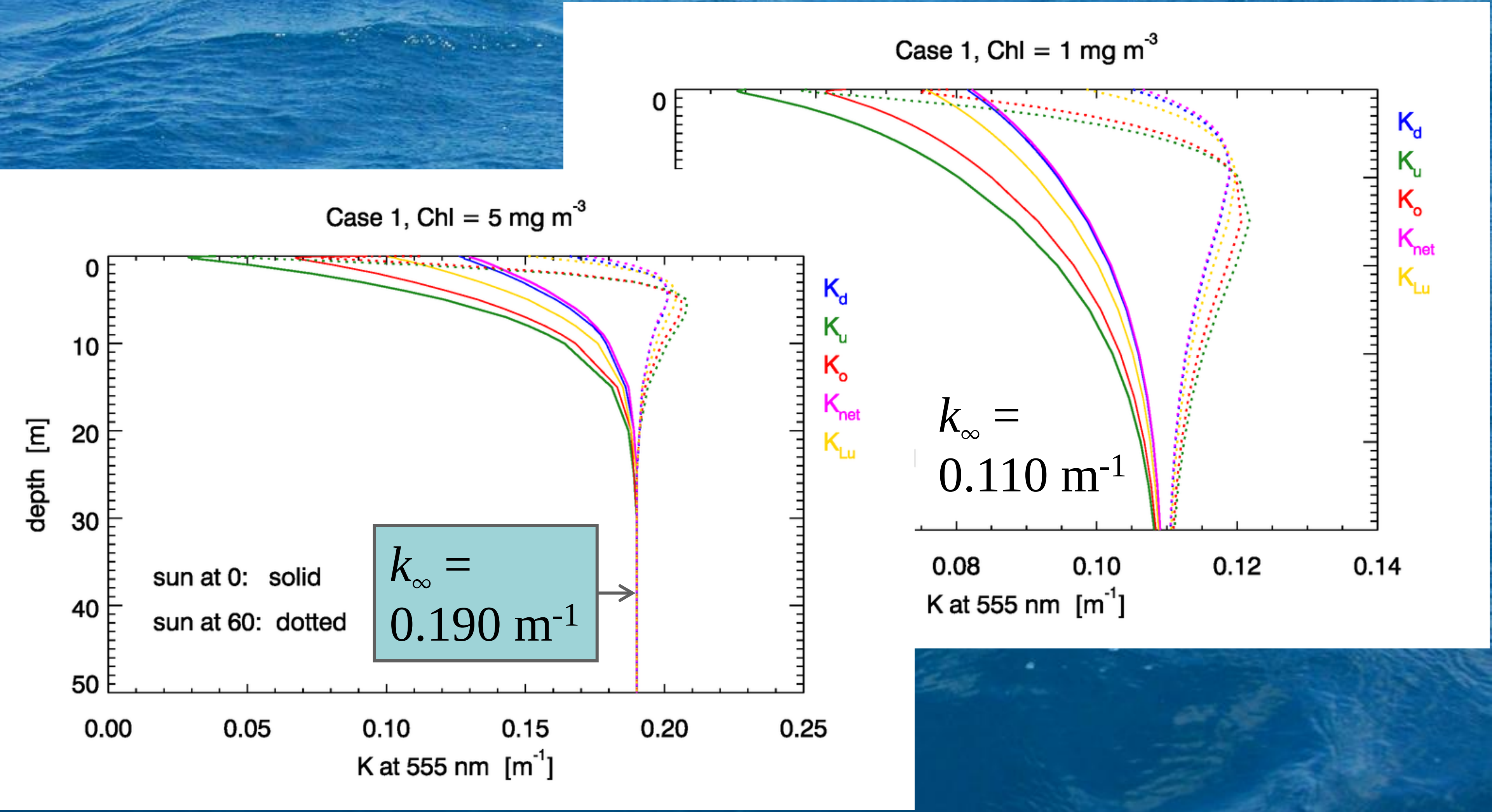


How similar are the different K’s?



NOTE: The K’s depend on depth, even though the water is homogeneous, and they are most different near the surface (where the light field is changing because of boundary effects)

Asymptotic Values



$k_\infty =$ 0.110 m^{-1}

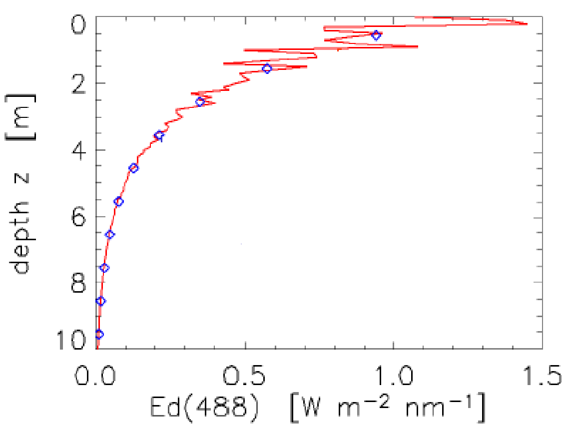
$k_\infty =$ 0.190 m^{-1}

The K’s all approach the same value as you go deeper: the asymptotic diffuse attenuation coefficient, k_∞, which is an IOP.

Something to Think About

- Suppose you measure $E_d(z)$
- but the data are very noisy in the first few meters because of wave focusing, or bubbles, or…
- so you discard the data from the upper 5 meters
- You then compute K_d from 5 m downward, and get a fairly constant K_d value below 5 m
- You then use $E_d(z) = E_d(0)\exp(-K_d z)$ and the computed K_d from 5 m downward to extrapolate $E_d(5\text{ m})$ back to the surface

How accurate is this $E_d(0)$ likely to be?



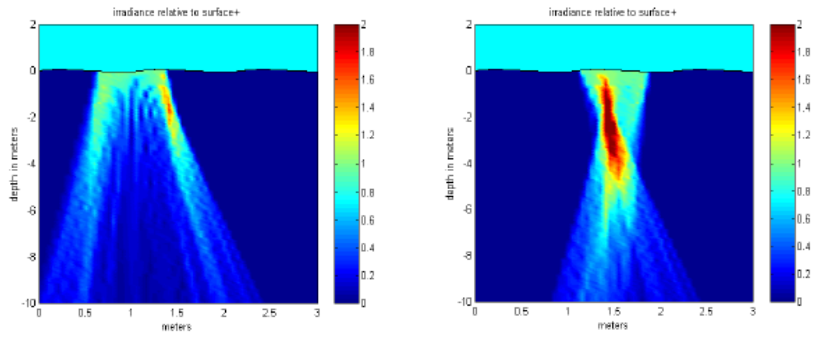
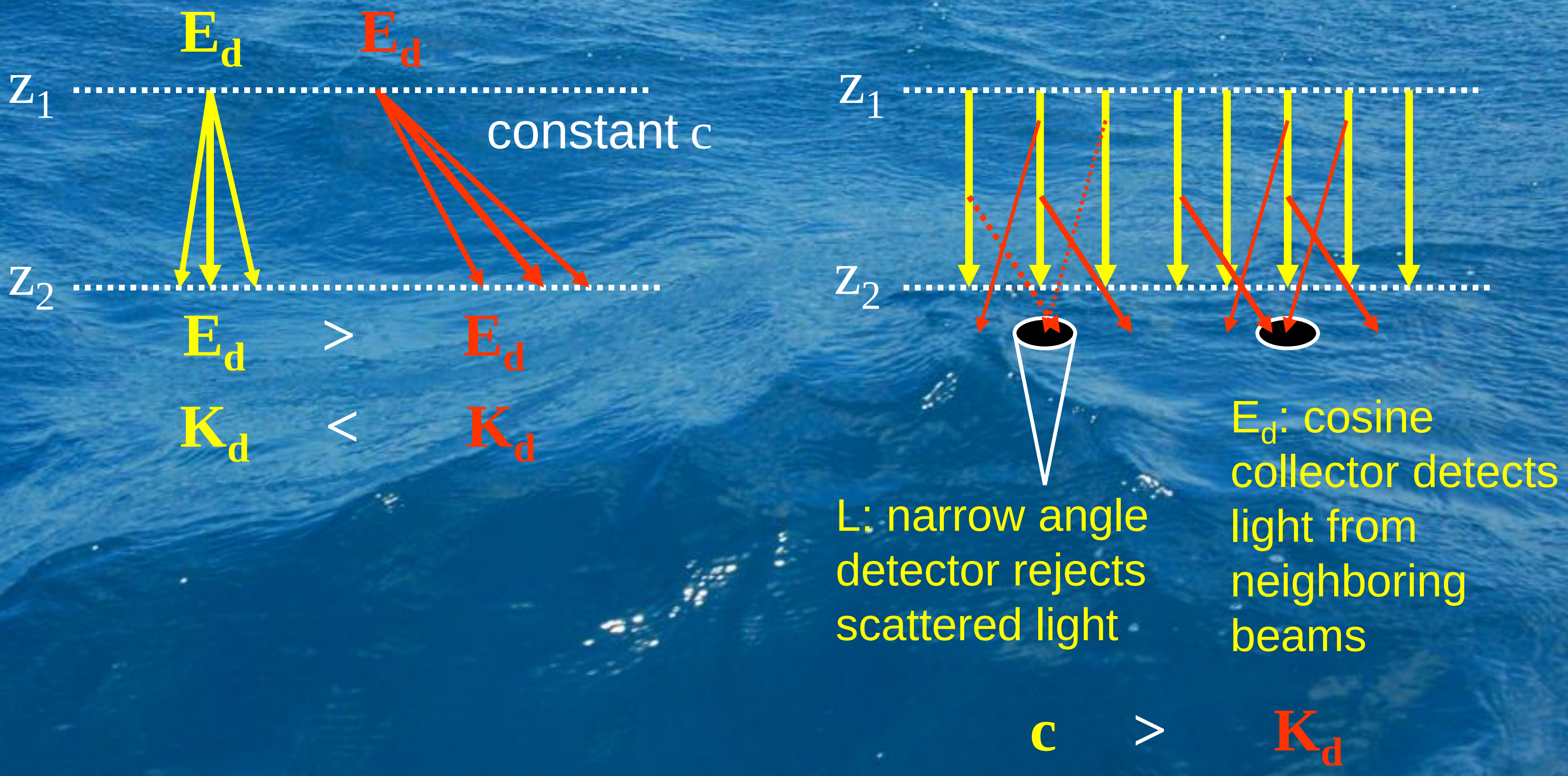


Fig. 2. An example of calculated irradiance relative to the irradiance just above the sea surface. The absorption coefficient is 0.07 m^{-1} and the scattering coefficient is 0.39 m^{-1}; the wave surface is wavelength L=[1.1 0.55 0.05] m and amplitude A= [0.05 0.01 0.0008]m. The beam is 0.8 m wide and enters vertically. Fig.3a shows the beam entering near the trough of a wave, generating a divergent beam. On Fig.3b the light enters near the crest of a wave, generating a convergent beam with a focal area.

wave focusing, from Zaneveld et al, 2001, Optics Express

Beam attenuation $c \neq$ diffuse attenuation K



E_d E_d

z_1

constant c

z_2

$E_d > E_d$

$K_d < K_d$

z_1

z_2

L: narrow angle detector rejects scattered light

E_d: cosine collector detects light from neighboring beams

$c > K_d$

Virtues and Vices of K's

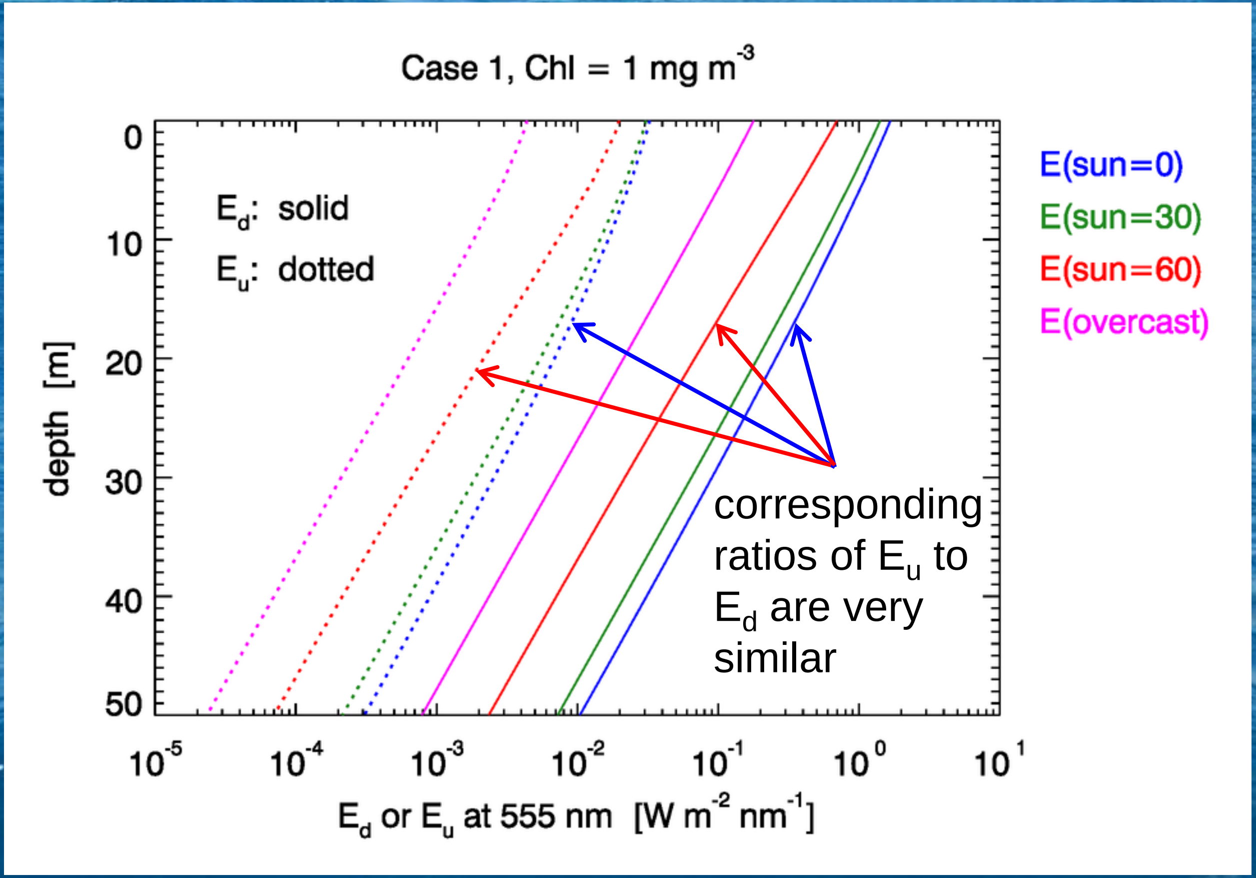
Virtues:

- K's are defined as rates of change with depth, so don't need absolutely calibrated instruments
- K_d is very strongly influenced by absorption, so correlates with chlorophyll concentration (in Case 1 water)
- about 90% of water-leaving radiance comes from a depth of $1/K_d$ (called the penetration depth by Gordon)
- radiative transfer theory provides connections between K's and IOPs and other AOPs (recall Gershun's equation: $a = K_{net}\,\mu$)

Vices:

- not constant with depth, even in homogeneous water
- greatest variation is near the surface
- difficult to compute derivatives with noisy data

E_d and E_u



corresponding ratios of E_u to E_d are very similar

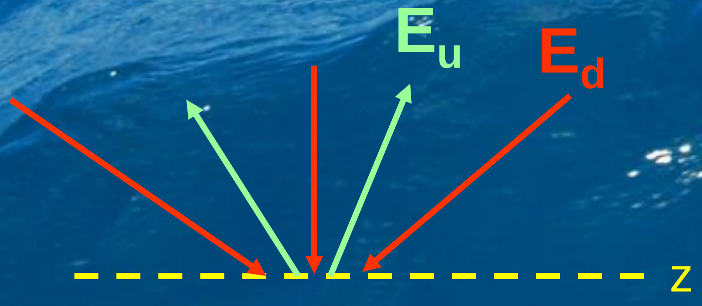
Magnitude changes are due to incident lighting (sun angle and sky condition); ratio of E_u/E_d is determined by water IOPs.

This suggests trying...

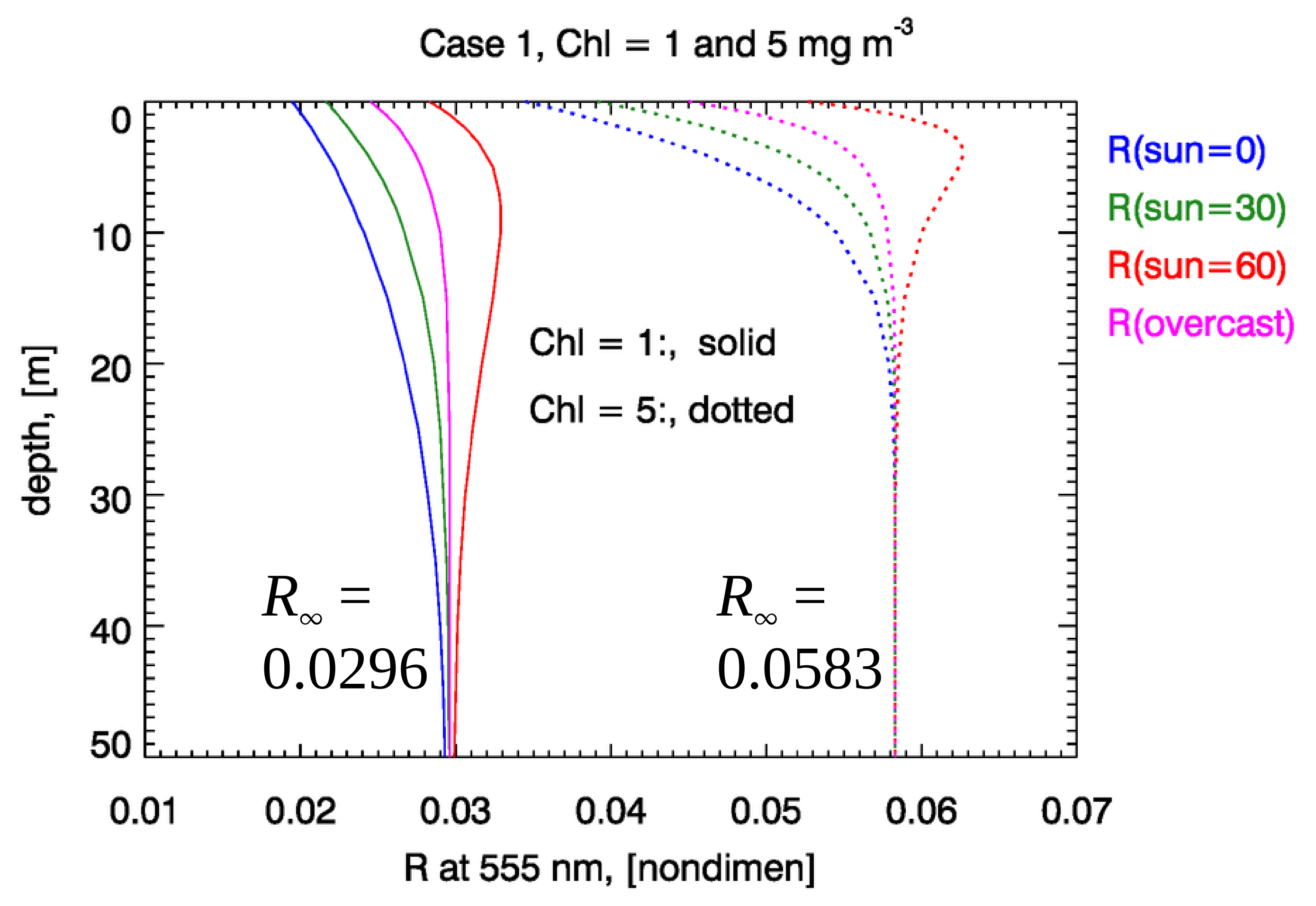
…the ratio of upwelling plane irradiance E_u to downwelling plane irradiance E_d as an AOP.

This is the irradiance reflectance R:

$$R(z, \lambda) = \frac{E_u(z, \lambda)}{E_d(z, \lambda)}$$



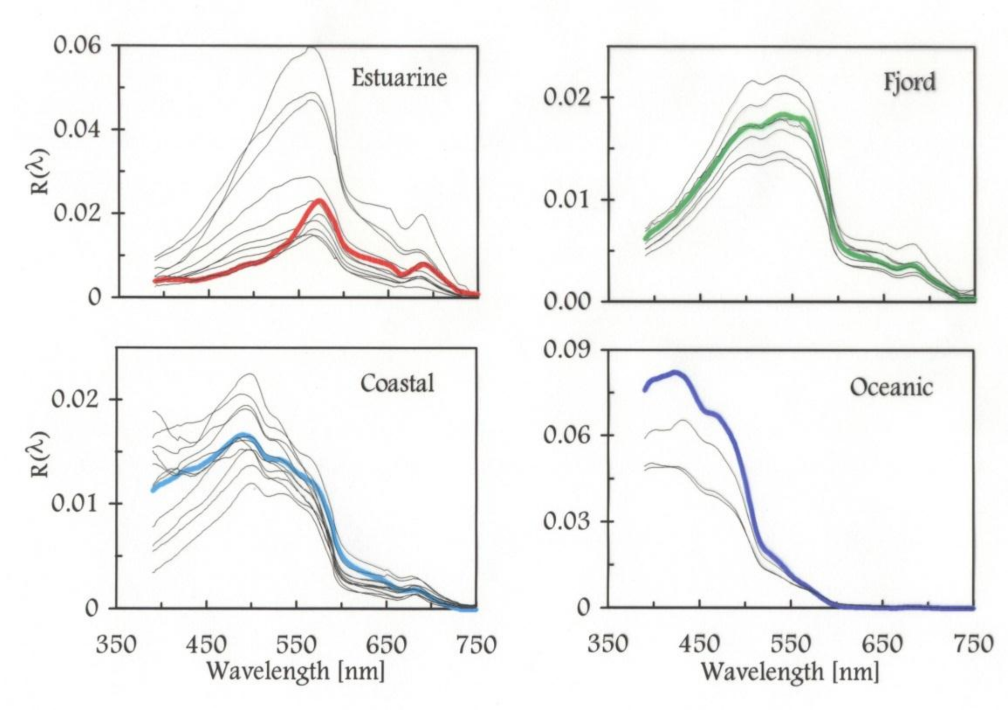
$R = E_u/E_d$



For given IOPs, the *R*’s all approach the same value as you go deeper: the asymptotic reflectance, R_∞, which is an IOP.

Examples of $R = E_u/E_d$

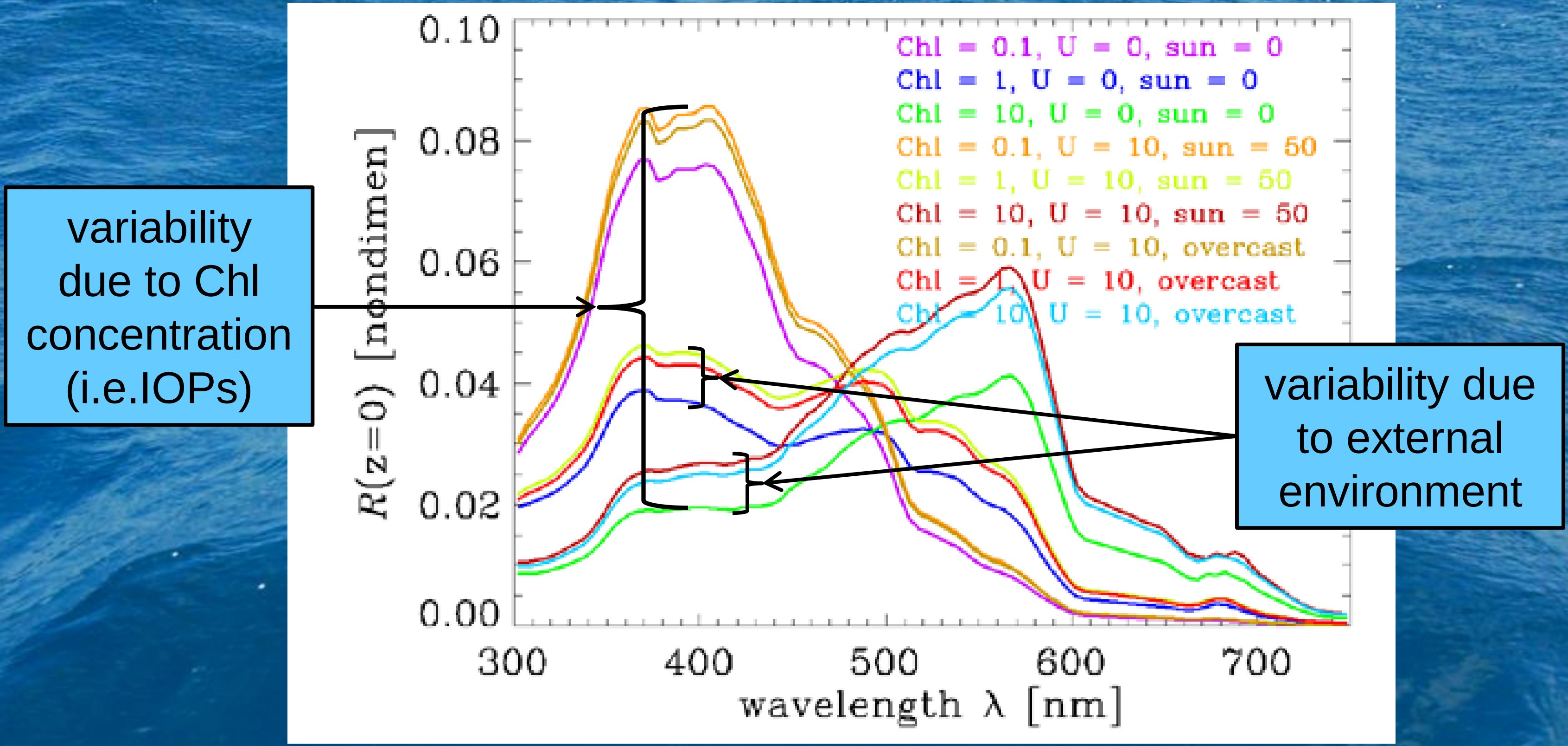
measurements from various ocean waters



Roesler and Perry 1995

$R = E_u / E_d$

HydroLight runs: Chl = 0.1,1, 10 mg/m^3
Sun at 0 and 50 deg in clear sky, and overcast



variability due to Chl concentration (i.e.IOPs)

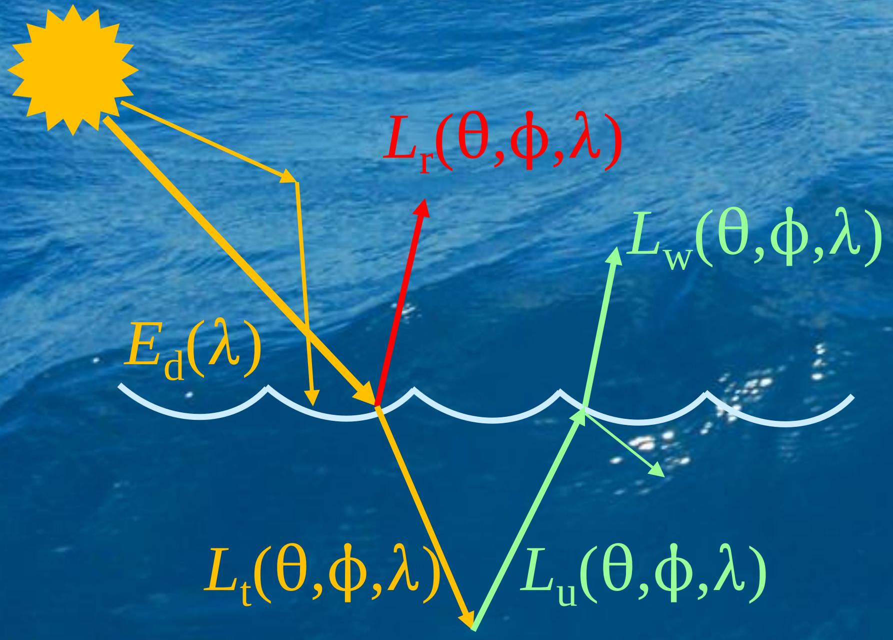
variability due to external environment

R depends weakly on the external environment and strongly on the water IOPs

Water-leaving Radiance, L_w

total upwelling radiance in air (above the surface) =
water-leaving radiance + surface-reflected radiance

$$L_u(\theta,\phi,\lambda) = L_w(\theta,\phi,\lambda) + L_r(\theta,\phi,\lambda)$$

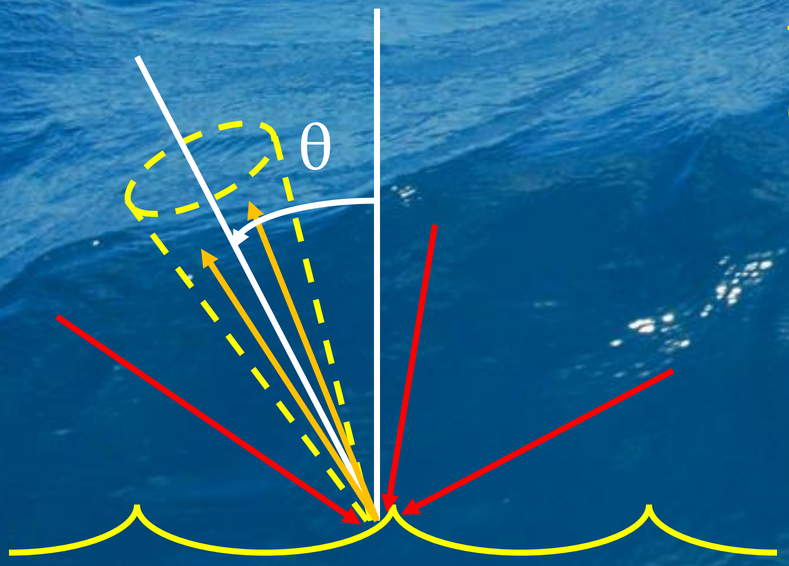


An instrument measures L_u (in air), but L_w is what tells us what is going on in the water. It isn't easy to figure out how much of L_u is due to L_w.

Remote-sensing Reflectance R_{rs}

$R_{rs}(\theta,\varphi,\lambda) = \dfrac{\text{upwelling water-leaving radiance}}{\text{downwelling plane irradiance}}$

$$R_{rs}(\text{in air},\theta,\varphi,\lambda) \equiv \frac{L_w(\text{in air},\theta,\varphi,\lambda)}{E_d(\text{in air},\lambda)} \qquad [\text{sr}^{-1}]$$

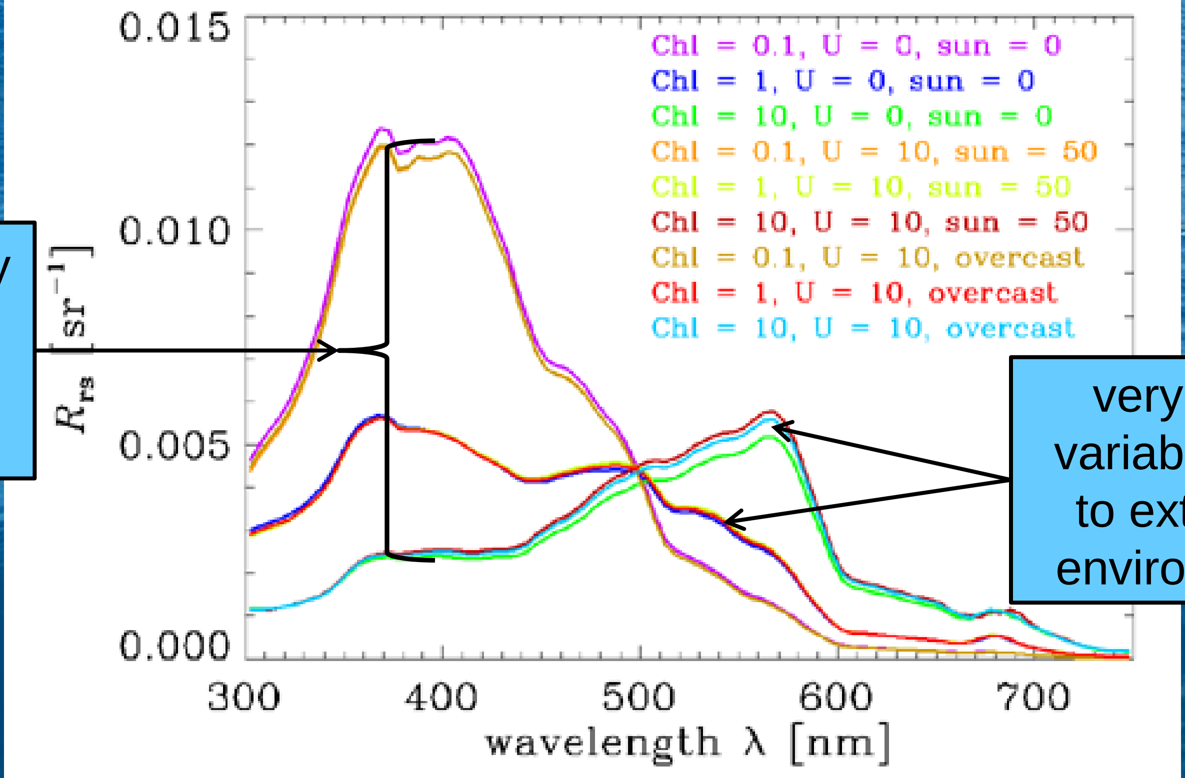


The fundamental quantity used in ocean color remote sensing

Often work with the nadir-viewing R_{rs}, i.e.,with the radiance that is heading straight up from the sea surface ($\theta = 0$)

Example R_{rs}

HydroLight runs: Chl = 0.1,1, 10 mg Chl/m^3
Sun at 0 and 50 deg in clear sky, overcast sky



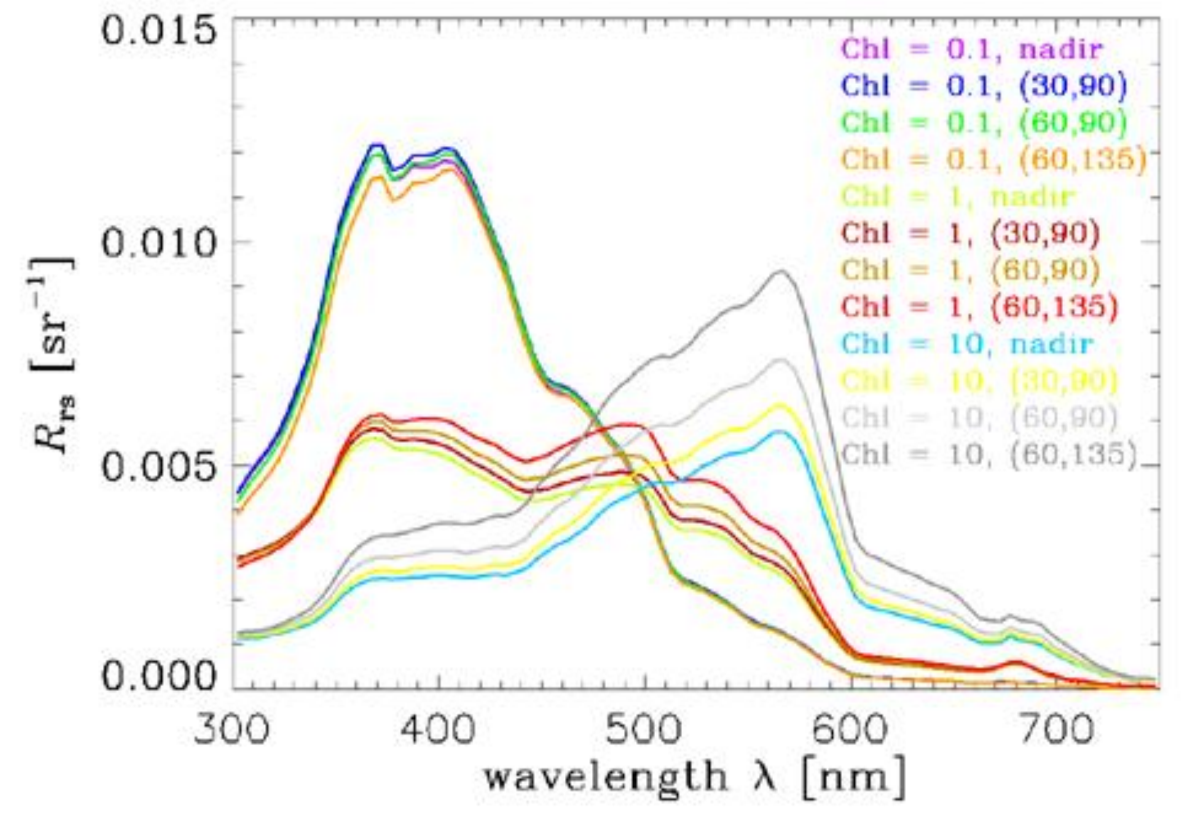
large variability do to Chl concentration (i.e.IOPs)

very little variability do to external environment

R_{rs} shows almost no dependence on sky conditions and strong dependence on the water IOPs—a very good AOP

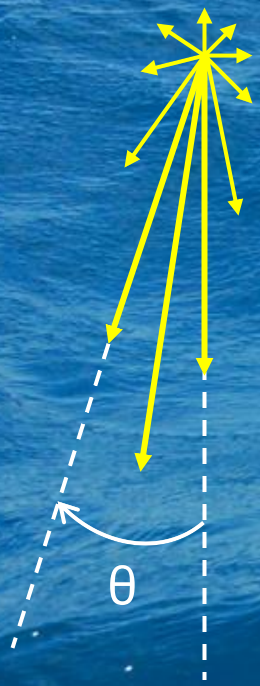
Example R_{rs}

HydroLight runs: Chl = 0.1,1, 10 mg Chl/m^3
Sun at 50 deg in clear sky
R_{rs} for nadir vs off-nadir viewing directions

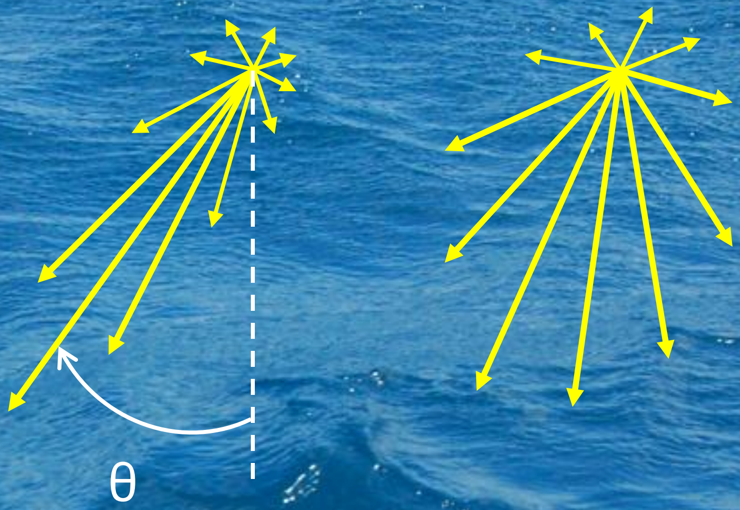


R_{rs} shows weak dependence on viewing direction and strong dependence on the water IOPs—still a good AOP

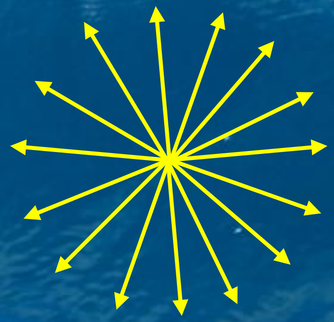
Average or Mean Cosines



most photons heading almost straight down: small average θ, large μ_d



most photons heading at a large angle, or a diffuse radiance: large average θ, small μ_d



isotropic radiance:
$\mu_d = \mu_u = 0.5$
$\mu = 0$

Average or Mean Cosines

The average or mean cosines give the average of the cosθ for all of the photons making up the radiance distribution. This tells you something about the directional pattern of the radiance. For the downwelling radiance we have

$$\bar{\mu}_d(z,\lambda) = \frac{\int_0^{2\pi}\int_0^{\pi/2} L(\theta,\phi)\,\cos\theta\,\sin\theta\,d\theta\,d\phi}{\int_0^{2\pi}\int_0^{\pi/2} L(\theta,\phi)\,\sin\theta\,d\theta\,d\phi} = \frac{E_d(z,\lambda)}{E_{od}(z,\lambda)}$$

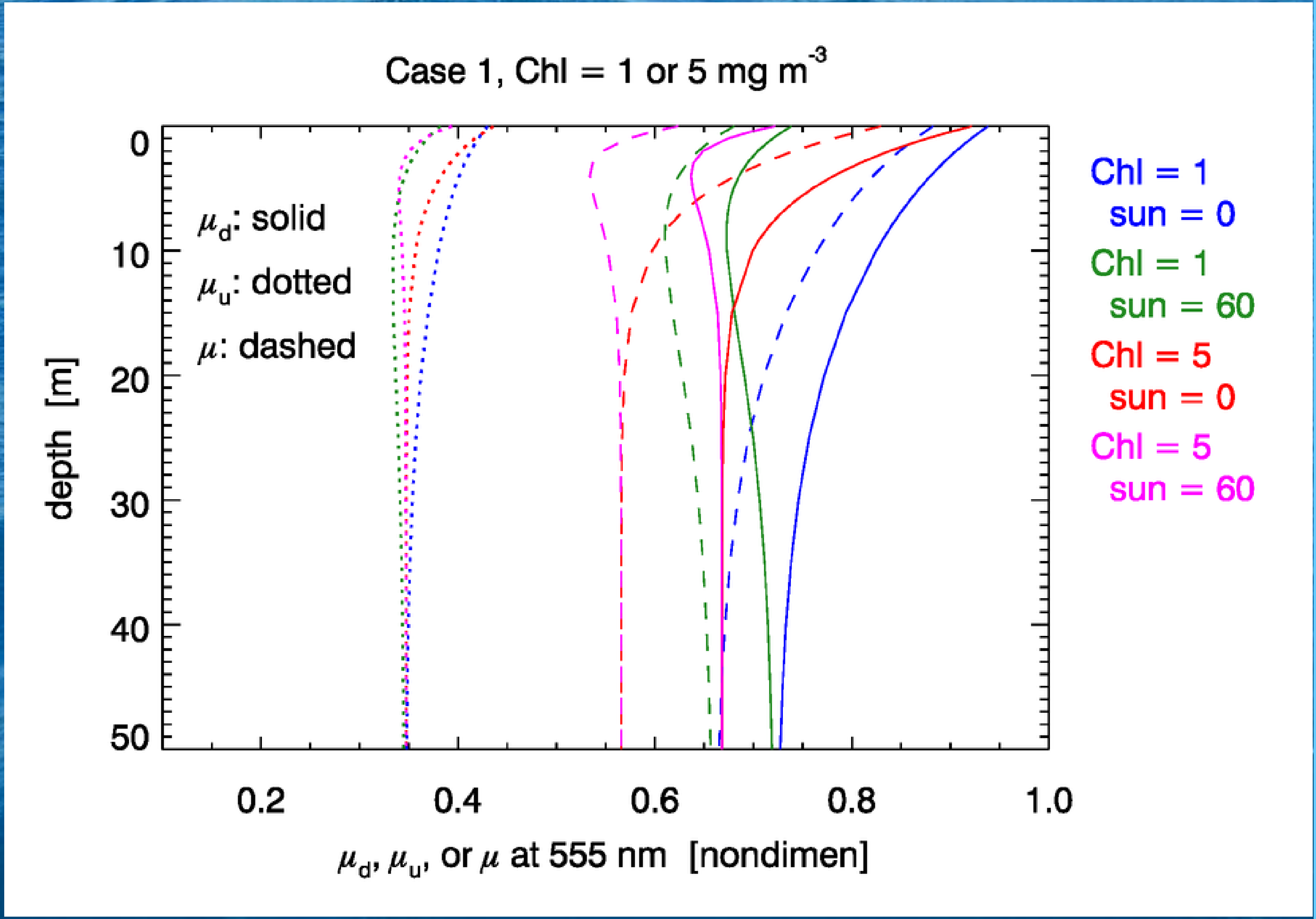
Likewise, for the upwelling radiance, $\overline{\mu}_u = E_u / E_{ou}$

For the entire radiance distribution,

$$\bar{\mu}(z,\lambda) = \frac{\int_0^{2\pi}\int_0^{\pi} L(\theta,\phi)\,\cos\theta\,\sin\theta\,d\theta\,d\phi}{\int_0^{2\pi}\int_0^{\pi} L(\theta,\phi)\,\sin\theta\,d\theta\,d\phi} = \frac{E_d(z,\lambda) - E_u(z,\lambda)}{E_o(z,\lambda)}$$

Note: $E_o = E_{od} + E_{ou}$, but $\overline{\mu} \neq \overline{\mu}_d + \overline{\mu}_u$

Mean Cosines



values at 555 nm:

Albedo of single scattering $\omega_o = b/c$:

$\omega_o(\text{Chl}=1) = 0.85$
$\omega_o(\text{Chl}=5) = 0.93$

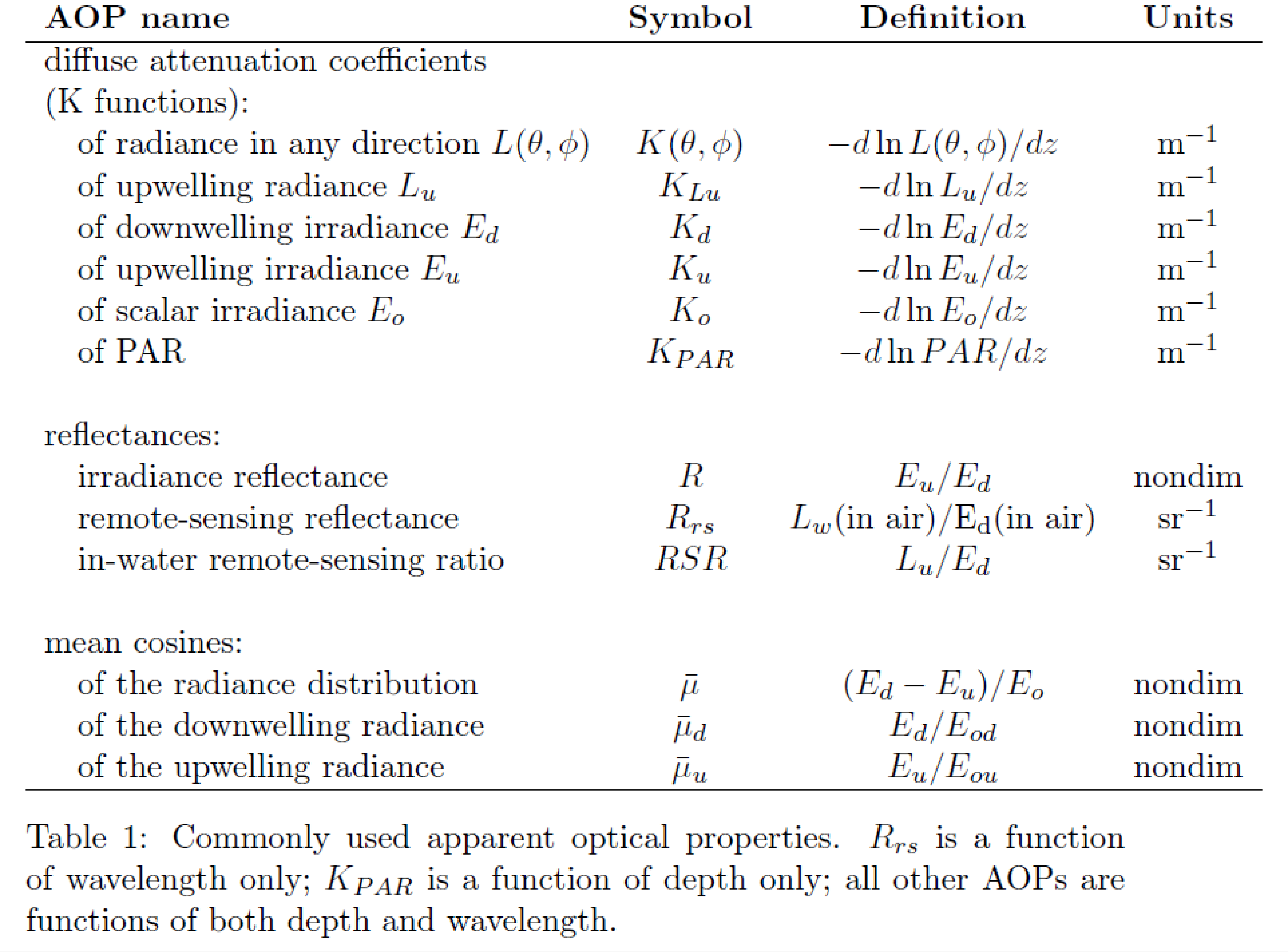
Asymptotic values:

Chl = 1:
$\mu_d(\infty) = 0.7222$
$\mu_u(\infty) = 0.3436$
$\mu(\infty) = 0.6600$

Chl = 5:
$\mu_d(\infty) = 0.6682$
$\mu_u(\infty) = 0.3473$
$\mu(\infty) = 0.5658$

Note: highly scattering water approaches asymptotic values quicker than highly absorbing water.

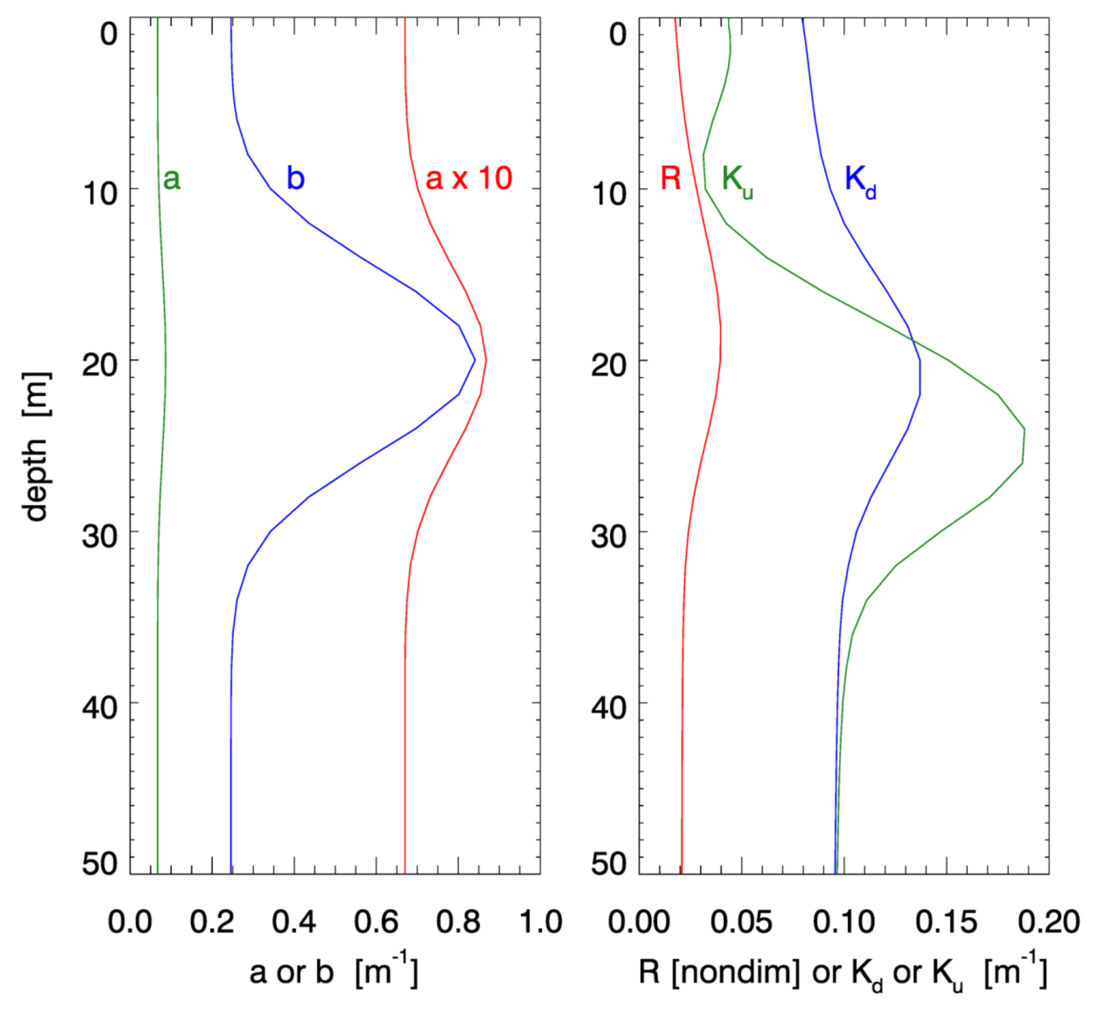
Summary of AOPs



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}
reflectances:			
irradiance reflectance	R	E_u/E_d	nondim
remote-sensing reflectance	R_{rs}	$L_w(\text{in air})/\mathrm{E_d}(\text{in air})$	sr^{-1}
in-water remote-sensing ratio	RSR	L_u/E_d	sr^{-1}
mean cosines:			
of the radiance distribution	$\bar{\mu}$	$(E_d - E_u)/E_o$	nondim
of the downwelling radiance	$\bar{\mu}_d$	E_d/E_{od}	nondim
of the upwelling radiance	$\bar{\mu}_u$	E_u/E_{ou}	nondim

Table 1: Commonly used apparent optical properties. R_{rs} is a function of wavelength only; K_{PAR} is a function of depth only; all other AOPs are functions of both depth and wavelength.

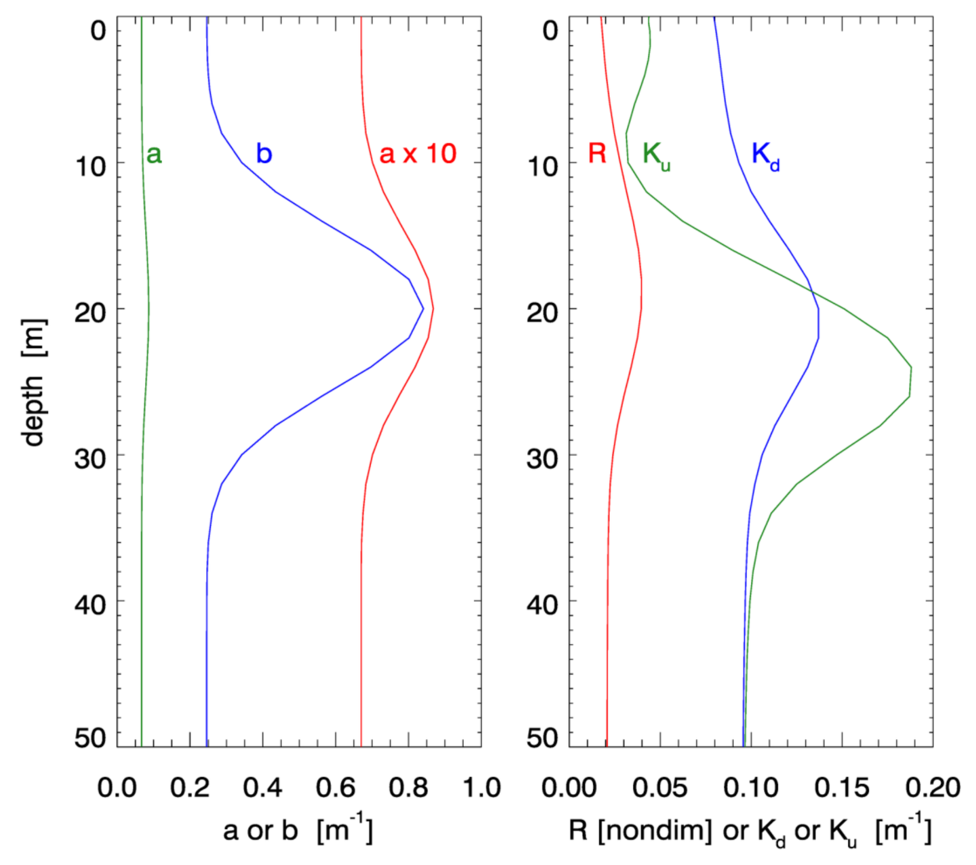
The Real World: Inhomogeneous Water



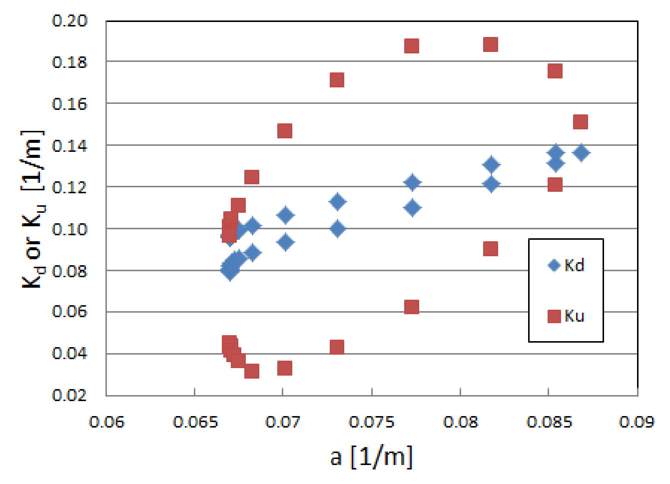
HydroLight run for Case 1 water with Chl = 0.5 mg/m^3 background and Chl = 2.5 mg/m^3 max at 20 m; sun at 30 deg in a clear sky, etc.

Note how well K_d correlates with the IOPs, but R is less affected. K_u is clearly affected by the IOPs, but in a more complicated way than K_d. Why?

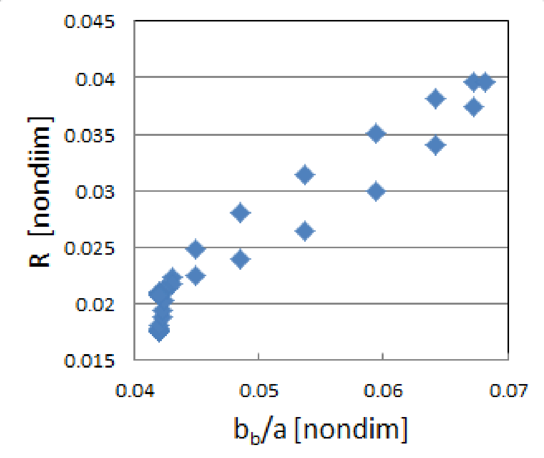
The Real World: Inhomogeneous Water



to first order, $K_d \propto a$
K_u is more compliated

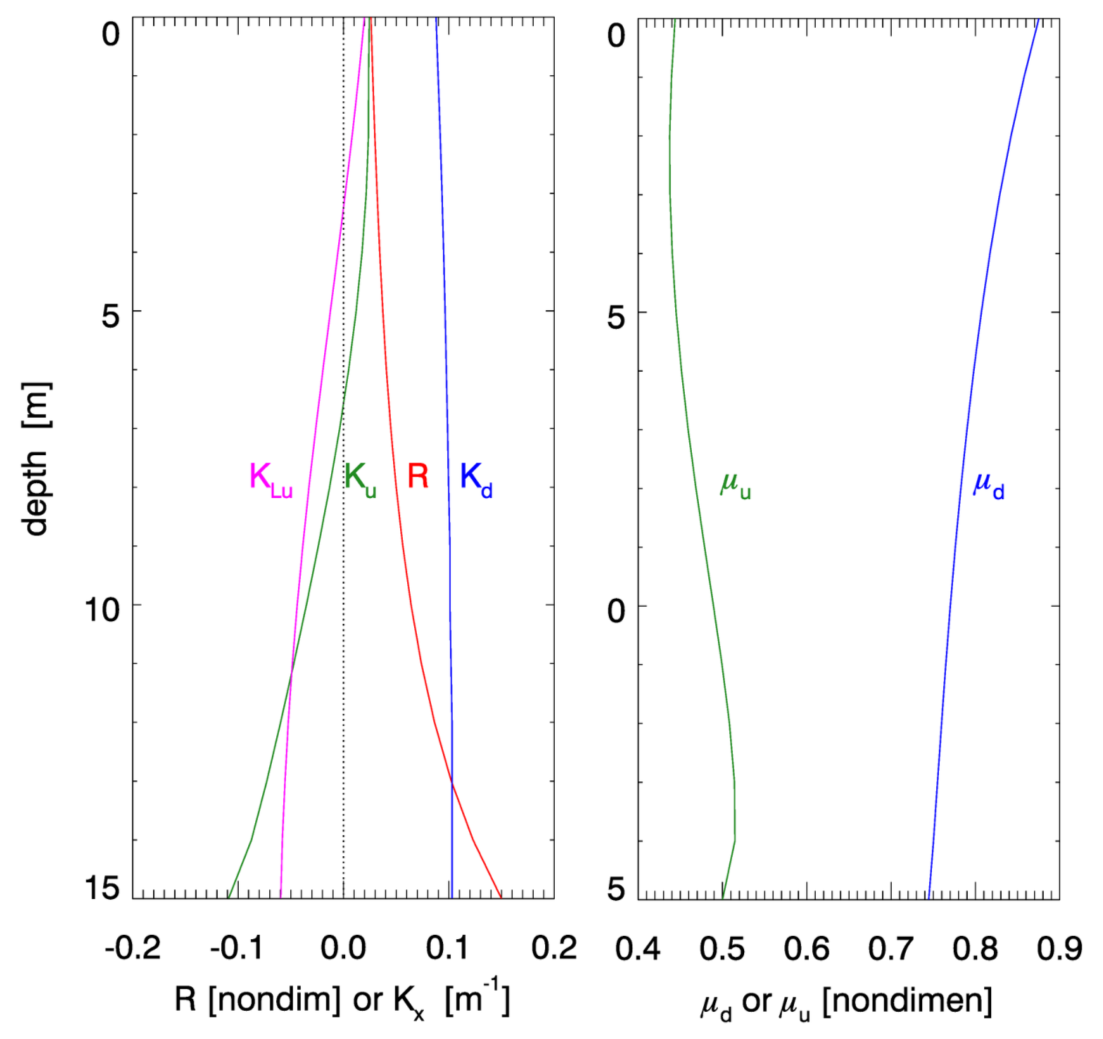


to first order, $R \propto b_b/a$



What would happen to K_d and R if there were a layer of highly scattering but non-absorbing particles in the water?

Explain These AOPs

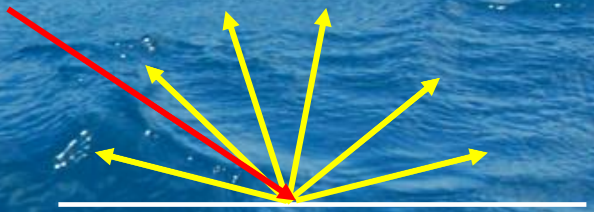


What does it mean for K_u and K_{Lu} to become negative?

What does $\mu_u = 0.5$ say about the upwelling radiance distribution at 15 m?

The Answer

The water was homogeneous (Case 1, Chl = 1 mg/m^3), but there was a Lambertian bottom at 15 m, which had a reflectance of $R_b = 0.15$

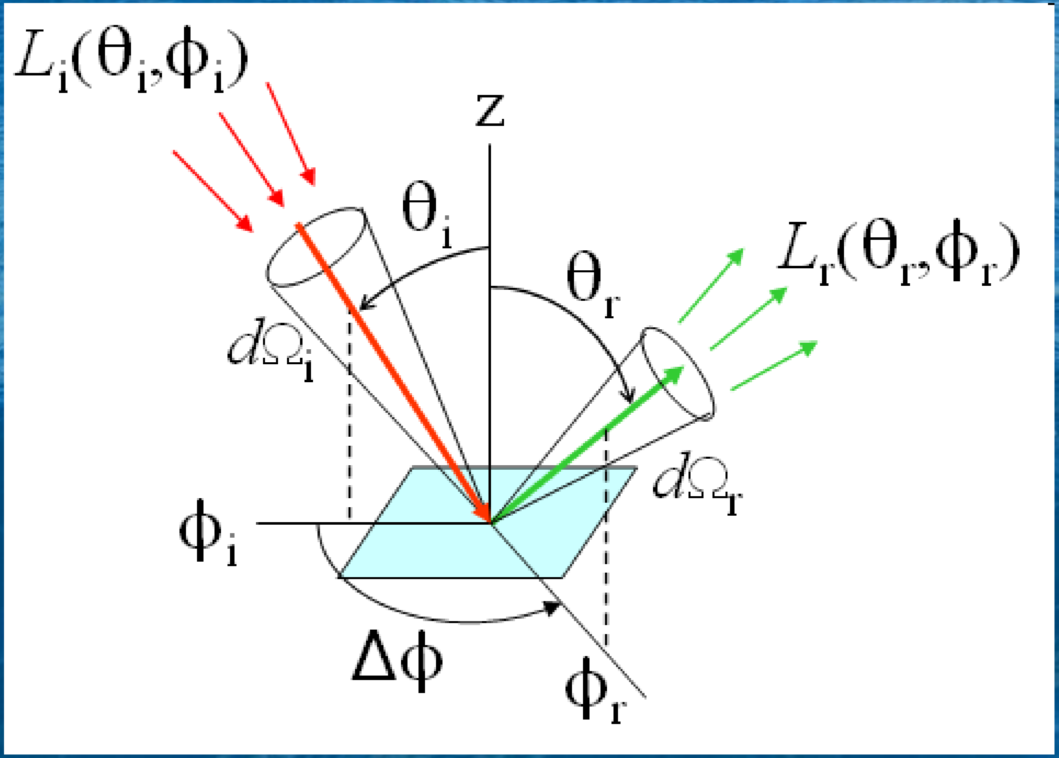


Lambertian means the reflected radiance is the same in all directions
(L_u is isotropic)

Exercise: compute μ_d, μ_u, and μ for an isotropic radiance distribution: $L(\theta,\phi) = L_o$ = a constant

The Bidirectional Reflectance Distribution Function (BRDF)

The BRDF is the IOP that describes how a surface reflects (scatters) radiance from any incident direction into any reflected direction: BRDF(θ_i, φ_i, θ_r, φ_r, λ)



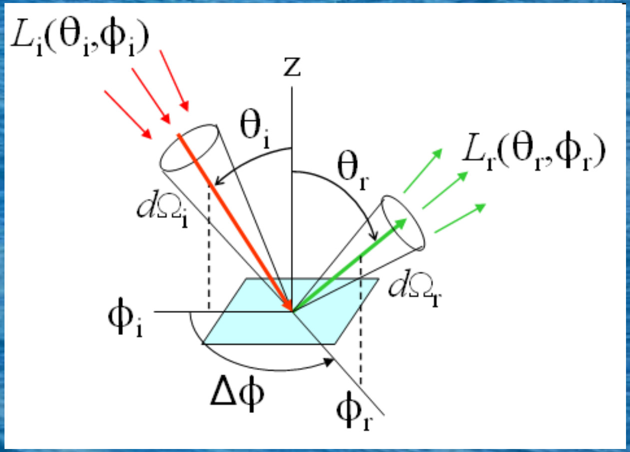
See www.oceanopticsbook.info/view/radiative_transfer_theory/level_2/the_brdf

The Bidirectional Reflectance Distribution Function (BRDF)

How the BRDF is defined:

$$BRDF(\theta_i,\phi_i,\theta_r,\phi_r) \equiv \frac{dL_r(\theta_r,\phi_r)}{L_i(\theta_i,\phi_i)\,\cos\theta_i\,d\Omega_i(\theta_i,\phi_i)}$$

How it's measured: $= \dfrac{L_r(\theta_r,\phi_r)}{E_d(\theta_i,\phi_i)} \qquad [\mathrm{sr}^{-1}]$



How the BRDF is used (e.g., in HydroLight):

$$\begin{aligned} L_r(\theta_r,\phi_r) &= \int_{2\pi_i} L_i(\theta_i,\phi_i)\,BRDF(\theta_i,\phi_i,\theta_r,\phi_r)\,\cos\theta_i\,d\Omega_i \\ &\equiv \int_{2\pi_i} L_i(\theta_i,\phi_i)\,r(\theta_i,\phi_i,\theta_r,\phi_r)\,d\Omega_i\ . \end{aligned}$$

in L&W

Radiance incident onto the surface from all directions is reflected into the direction of interest.

BRDF of Sand

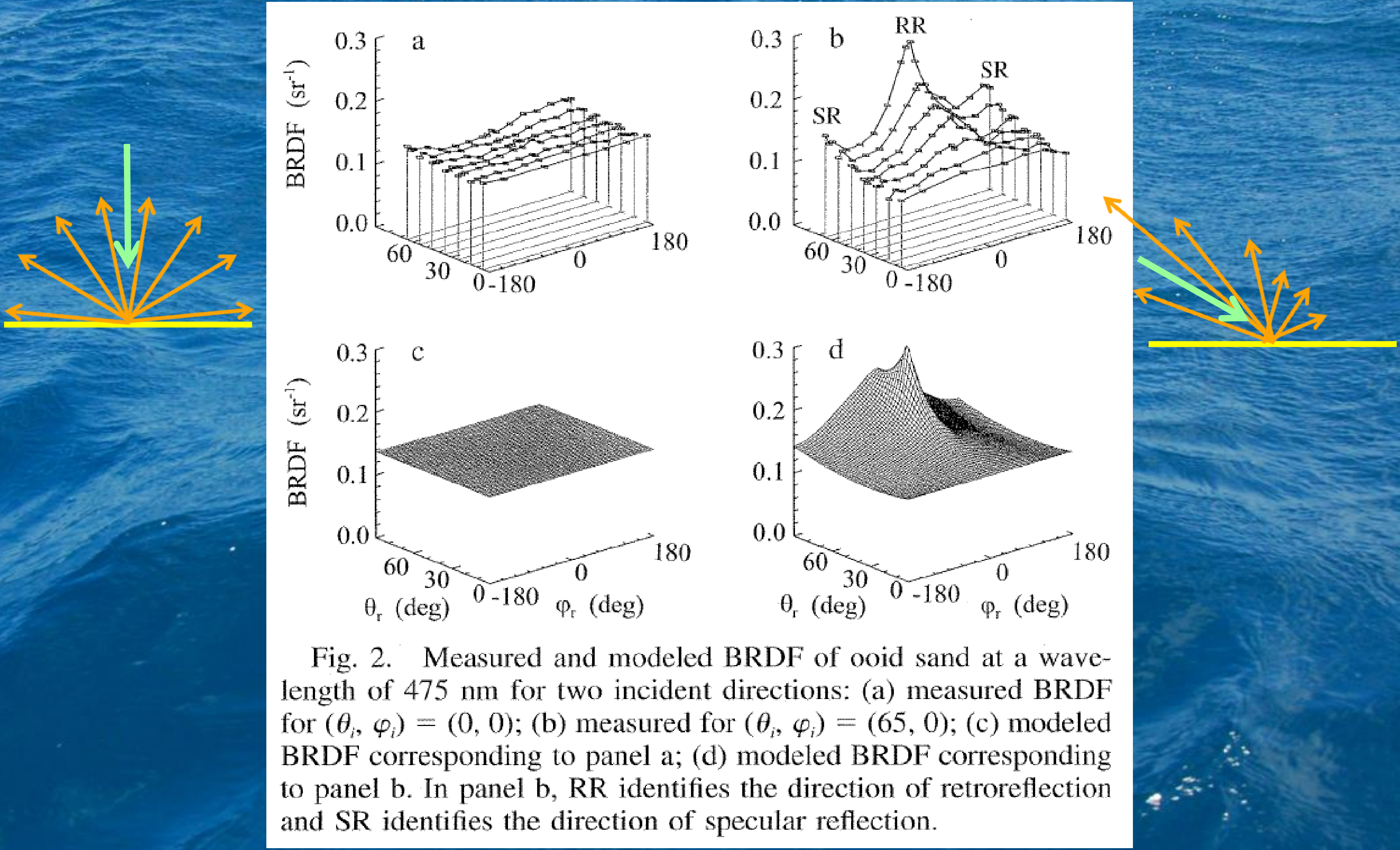
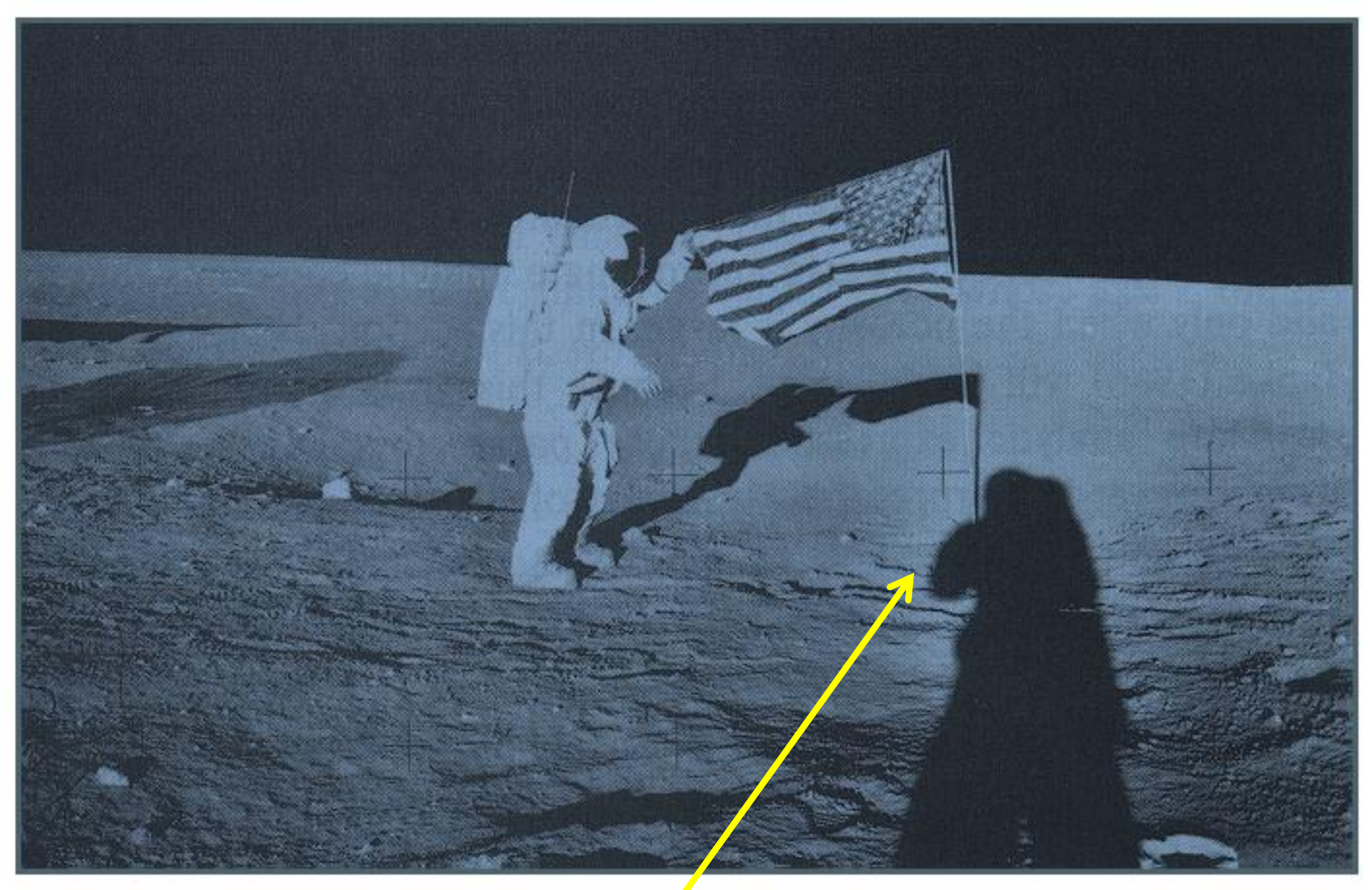


Fig. 2. Measured and modeled BRDF of ooid sand at a wavelength of 475 nm for two incident directions: (a) measured BRDF for $(\theta_i, \varphi_i) = (0, 0)$; (b) measured for $(\theta_i, \varphi_i) = (65, 0)$; (c) modeled BRDF corresponding to panel a; (d) modeled BRDF corresponding to panel b. In panel b, RR identifies the direction of retroreflection and SR identifies the direction of specular reflection.

Mobley, Zhang, & Voss, L&O, 2003

BRDF of the Lunar Surface



Note bright region around the photographer’s shadow: retroreflection or the “hot spot”

Is R_{rs} = BRDF?

R_{rs} is "all directions in, one direction out" for whatever input irradiance E_d nature gives you. It is an AOP that depends (weakly) on the ambient radiance distribution.

It is a "hemispherical-directional" reflectance

The BRDF is "one direction in, one direction out" for a collimated $E_d(\theta',\phi')$. It is an IOP that defines the scattering (reflectance) properties of a surface. It does not depend on ambient radiance.

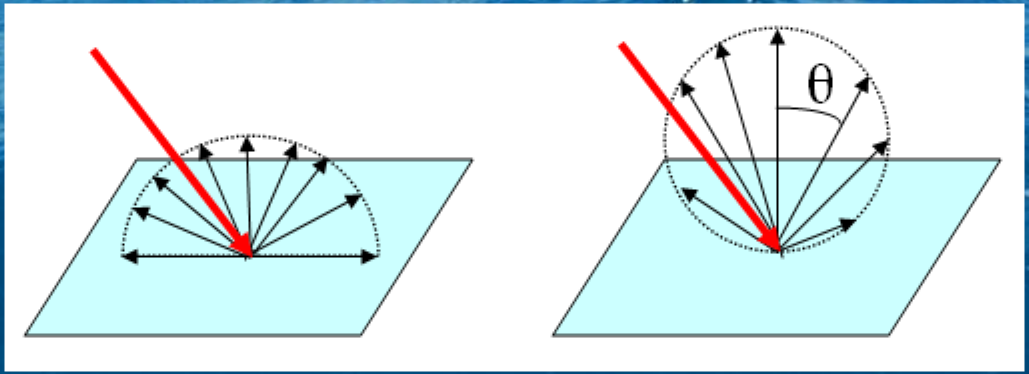
It is a "directional-directional" (i.e., bidirectional) reflectance

Lambertian BRDFs

You will sometimes see statements like

- A Lambertian surface reflects “light” equally into all directions. Lambertian surfaces are therefore also called isotropic/uniform/perfectly diffuse reflectors

- A Lambertian surface reflects “light” with a cosine angular distribution. Lambertian surfaces are therefore also called cosine reflectors.



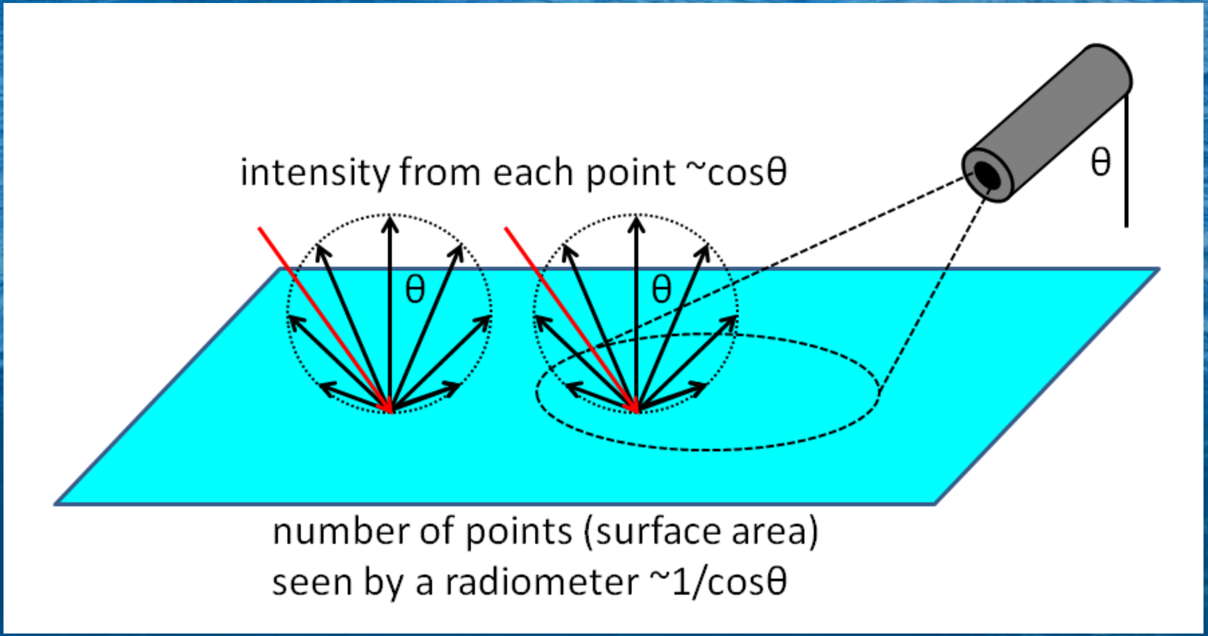
uniform reflectance   cosine reflectance

Which definition is correct?

Lambertian BRDFs

The correct statements are

- Each point of a Lamb surf reflects intensity in a cosine pattern
- A Lamb surf reflects radiance equally in all directions



See
www.oceanopticsbook.info/view/radiative_transfer_theory/level_2/the_lambertian_brdf

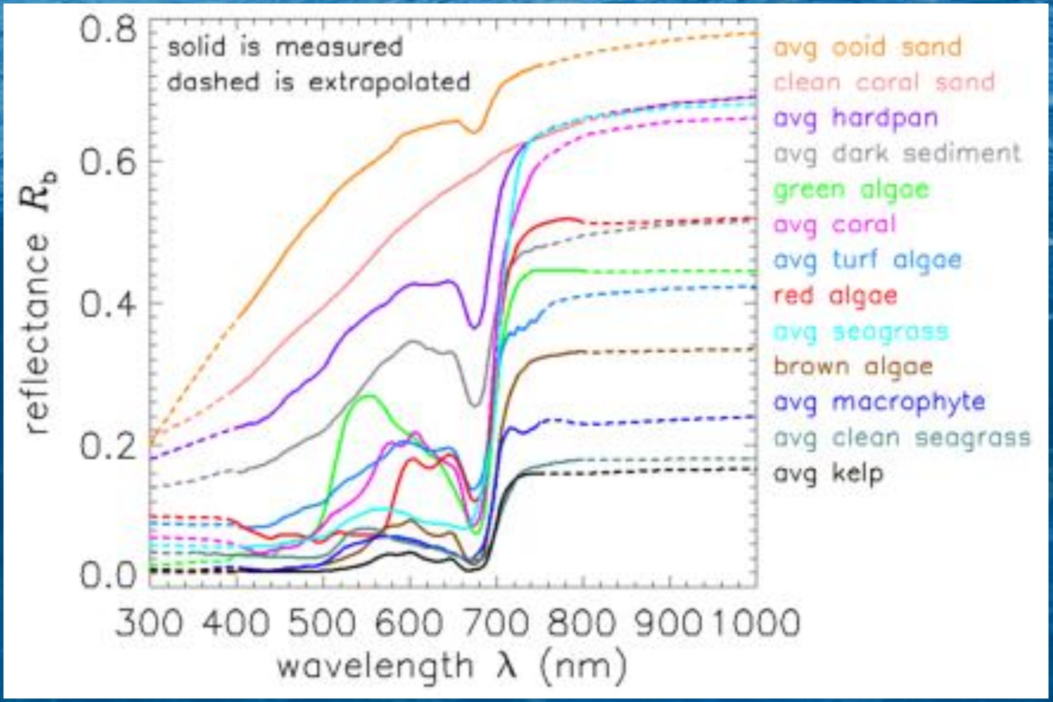
Lambertian BRDFs

The BRDF of a Lambertian reflector is fully specified by its *reflectivity* ρ, which equals the irradiance reflectance $R = E_u / E_d$ (see the web book for the math):

$$\mathrm{BRDF}_{\mathrm{Lamb}}(\theta_i, \varphi_i, \theta_r, \varphi_r, \lambda) = \rho(\lambda)/\pi = R(\lambda)/\pi$$

ρ = 0 for a "black" surface; ρ = 1 for a "white" surface

The default in HydroLight is to specifiy a bottom reflectance (really $\rho = E_u/E_d$), and H then assumes that the bottom is Lambertian.



Other Reflectances

We have now seen three reflectances:

- The irradiance reflectance $R = E_u / E_d$
  When R is measured above the sea surface, it is often called the albedo

- The remote-sensing reflectance $R_{\mathrm{rs}} = L_w(\text{in air}) / E_d(\text{in air})$
  $RSR = L_u / E_d$ is the in-water equivalent

- The BRDF, with the special case of a Lambertian reflector

There are many other reflectances: e.g., Hapke (1993) uses bolometric, Bond, geometric, hemispherical, normal, physical, plane, single-scattering, and spherical albedos, as well as an albedo factor. To add insult to injury, not a single one of these albedos corresponds to how "the" albedo is used in oceanography.

"I measured the reflectance" doesn't make it. As always, must be precise in terminology.

Sunrise on Annapurna, 8090 m (10th highest in the world)

Rhino

Chitwan
National
Park,
Nepal

2011