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

<table>
<thead>
<tr>
<th>AOP name</th>
<th>Symbol</th>
<th>Definition</th>
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<td>diffuse attenuation coefficients</td>
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<td>(K functions)</td>
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<td>of radiance in any direction L(θ, φ)</td>
<td>K(θ, φ)</td>
<td>−d ln L(θ, φ)/dz</td>
<td>m⁻¹</td>
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<td>of upwelling radiance L_u</td>
<td>K_Lu</td>
<td>−d ln L_u/dz</td>
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<td>of scalar irradiance E_o</td>
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<td>of PAR</td>
<td>K_PAR</td>
<td>−d ln PAR/dz</td>
<td>m⁻¹</td>
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Ocean Optics Book
Why not use irradiance as an AOP?

- Relatively easy to measure
- Do they fit all the criterias?
- Highly variable depending on external conditions (ex: Cloud overpass)

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).
K-functions: much stronger contenders:

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

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

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

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) \implies 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 ...

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

How does $K_{d1}$ compare to $K_{d2}$?

$\Rightarrow c > K_d$ or $K_d < c$?

$$K_d(z, \lambda) \triangleq - \frac{1}{E_d(z, \lambda)} \frac{dE_d(z, \lambda)}{dz}$$
Convergence at depth

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, \( K_{\infty} \), which is an IOP (or at least depends solely on IOPs).
How do we measure it?

**In theory:**

\[ E_d(z) = E_d(0) e^{-\int K_d(z) \, dz} \]

\[ \Delta E_d = -E_d \, K_d \, \Delta z \]

\[ \int_0^z \frac{dE_d}{E_d} = \int_0^z K_d(z) \, dz \]

**In real life:**

- Wave focusing
- Bubbles
- Passing clouds

Figure from Collin Roesler

Assuming homogeneity: \( E_d(z) = E_d(0) \exp(-K_d(z)) \)
Correction for the first few meters

Knowing it is noisy in the first few meters

\[ E_d(490,z) \]
\[ \rightarrow \text{You extrapolate to } E_d(0) \]
\[ \rightarrow \text{Compute } z_{pd} = \text{depth at which } E_d(z_{pd}) = E(0-)/e. \]

\[ K_d(490)_{z_{pd}} \]

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

How accurate is the zpd?

\[ K(\lambda, z) = \frac{1}{z} \ln \left( \frac{E(\lambda, 0^{-})}{E(\lambda, z)} \right) \approx \frac{1}{z_{pd}} \]

- Dark values due to instrument
- Representative sample
- Passing clouds
- Wave focusing

Xing et al., 2020

Organelli et al., 2016
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 $K \rightarrow$ 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**

\[ K_d(i\text{PAR}, z) = \frac{1}{z} \ln \left( \frac{i\text{PAR}(0^-)}{i\text{PAR}(z)} \right) \]

\( \Rightarrow \) Is highly dependent on the layer in which you calculate it.

For a layer of 2 zpd (From Morel07):

\[ K_d(i\text{PAR}) = 0.0665 + 0.874 K_d(490) - 0.00121 / K_d(490). \]
Average (mean) cosine

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

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

\[
\begin{align*}
\mu_d &= \frac{E_d}{E_{od}} \\
\mu_u &= \frac{E_u}{E_{ou}} \\
\bar{\mu} &= \frac{\vec{E}}{E_o} = \frac{(E_d - E_u)}{(E_{od} + E_{ou})}
\end{align*}
\]

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

Figure 4.20: Illustration of average cosines as a measure of the directional nature of the radiance distribution.
What do they tell us?

The more scattering $\rightarrow$ the faster is asymptotic attained.

The more absorbing $\rightarrow$ the more collimated.

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

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

$\overline{\mu} = \frac{\bar{E}}{E_o}$

Mobley, 2004, Hydrolight with $b=a$ ($b/c=0.5$) & $b=4a$ ($b/c=0.8$).
AOPs are closely linked together and can be used in Inverse problem solving (more on that later ...)

\[ \mu_d = \cos(\theta_{sw}) \]

Effectively normalizing by the dependence on the sun.

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

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

\[ K_d \propto \frac{a + b_b}{\mu_d} \]
Explain these AOPs...

→ 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’.

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.
\[ R_{rs} = \frac{L_{wn}}{E_d(0+)} \]

\[ E_d(0+) \]

\[ L_{wn} \]

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

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

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

Figure 3: Schematic of fixed-depth underwater measurements.
\[
R_{rs} = \frac{L_{un}(0^-)}{E_d(0^+)}
\]

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

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

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

\[Z_1 \sim 10\, \text{cm}\]
Profiling radiometers

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

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

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

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

\[ Z_1 \approx 10 cm \]
\[ R_{rs} = \frac{L_{wn}}{E_d(0+)} \]

\[ E_d(0+) \]

\[ L_w(0+) \]

Lee et al., 2013
\[ R_{rs} = \frac{L_w(\theta_v, \Delta \varphi)}{E_d(0^+)} \]

\[ L_r(\theta_v, \Delta \varphi) = \rho_F L_d(0^+, 180^\circ - \theta_v, \Delta \varphi) \]

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

Mobley, 1999
Plaque should be horizontal and above the height of all other structures or objects (including humans).
Irradiance reflectance

\[ R_{rs} = \frac{E_u}{E_d} \]
Secchi disk depth: theory

Contrast reduction theory for detecting target for any direction:

\[
\frac{c_r(\theta, \phi, z)}{c_0(\theta, \phi, z_T)} = \exp[-cr + K(\theta, \phi, z) r \cos(\theta)]
\]

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.

Necessary to validate OCR measurements.