Radiometry
and
Apparent Optical properties (AOPs)

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Who am I?

- PhD in oceanography, January 1995, Université Pierre et Marie Curie, Paris 6. Carried out in the Villefranche optics group under supervision of Prof. André Morel
- Became CNRS research scientist at LOV in October 1996
- Was promoted to CNRS senior research scientist in 2008
- 1-year sabbatical at University of California at Santa Barbara (Dave Siegel's group)
- Professor at Curtin University, Perth, Western Australia, since 2013. Director of the "Remote Sensing and Satellite Research Group"
- Along the way, I did work and have published on primary production from satellite ocean colour (OCR), atmospheric corrections of satellite OCR, bio-optical relationships, long-term changes of global phytoplankton, …
- Have set up one of the longest oceanic time series of radiometry, optics and biogeochemical parameters (23 years) (the "BOUSSOLE" time series)
- Have been significantly involved into national and international bodies in charge of coordinating science, defining satellite missions etc… (e.g., IOCCG, ESAC)
- Otherwise, I'm 61, I am married (1990), have two children (27 and 32), and I am an occasional sailor, and now a regular cyclist

https://research.curtin.edu.au/remotesensing/ https://lov.imev-mer.fr/web/team-omtab/





Perth, 2020’s

Kimberley (NW Australia), 2021


Arctic, 2009


Falls creek, 2026

Nice, 2025

Lecture content

- The “grand scheme” linking IOPs, radiometric quantities, and AOPs
- Terminology, units, angles (geometry)
- Radiometry, calibration
- Radiance: the fundamental quantity, measuring radiances
- Irradiances, and measuring them
- Normalising radiances
- Bidirectionality of reflectance
- AOPs (K functions, R, R_{rs}, average cosines)
- From AOPs back to IOPs
- If time allows: polarization, asymptotic regime, light in the twilight zone

https://ioccg.org/wp-content/uploads/2022/01/mobley-oceanicopticsbook.pdf

http://www.oceanopticsbook.info

https://ioccg.org/wp-content/uploads/2020/09/gordon-book_nov_2019_with_doi.pdf

Lecture sources, further reading

- A lot of what is shown in this lecture has been taken from: http://www.oceanopticsbook.info
- Mobley C.D., 1994. *Light and Water: Radiative Transfer in Natural Waters*, Academic press.
- Jerlov, N.G., 1976. *Marine Optics*, Elsevier, 230pp.
- Morel, A. and R.C. Smith, 1982. *Terminology and units in optical oceanography*, Marine Geodesy, 5, 335-349.
- *Remote Sensing of Coastal Aquatic Environments, Technologies, Techniques and Applications*. Editors: Miller, Richard L., Del Castillo, Carlos E., McKee, Brent A. (Eds). Kluwer Publishing. A number of chapters in this book are relevant here
- https://lov.imev-mer.fr/web/all-publications (all papers from the Villefranche optics group since 1965)
- If you read French: Antoine D., 1998. Océanis 24, 81-150 (from the link above)
- https://licor.app.boxenterprise.net/s/liuswfuvtqn7e9loxaut (from the "Licor" manufacturer; "*Principles of radiation measurements*")
- Mishchenko, M.I., 2014. Directional radiometry and radiative transfer: *The convoluted path from centuries-old phenomenology to physical optics. Journal of Quantitative Spectroscopy & Radiative Transfer* 146, 4–33
- Mobley CD, 2024. *A Short History of Radiative Transfer Theory* https://www.amazon.com/Short-History-Radiative-Transfer-Theory/dp/B0D8GWJLW8.

The "Oceanic Optics Organization Chart"

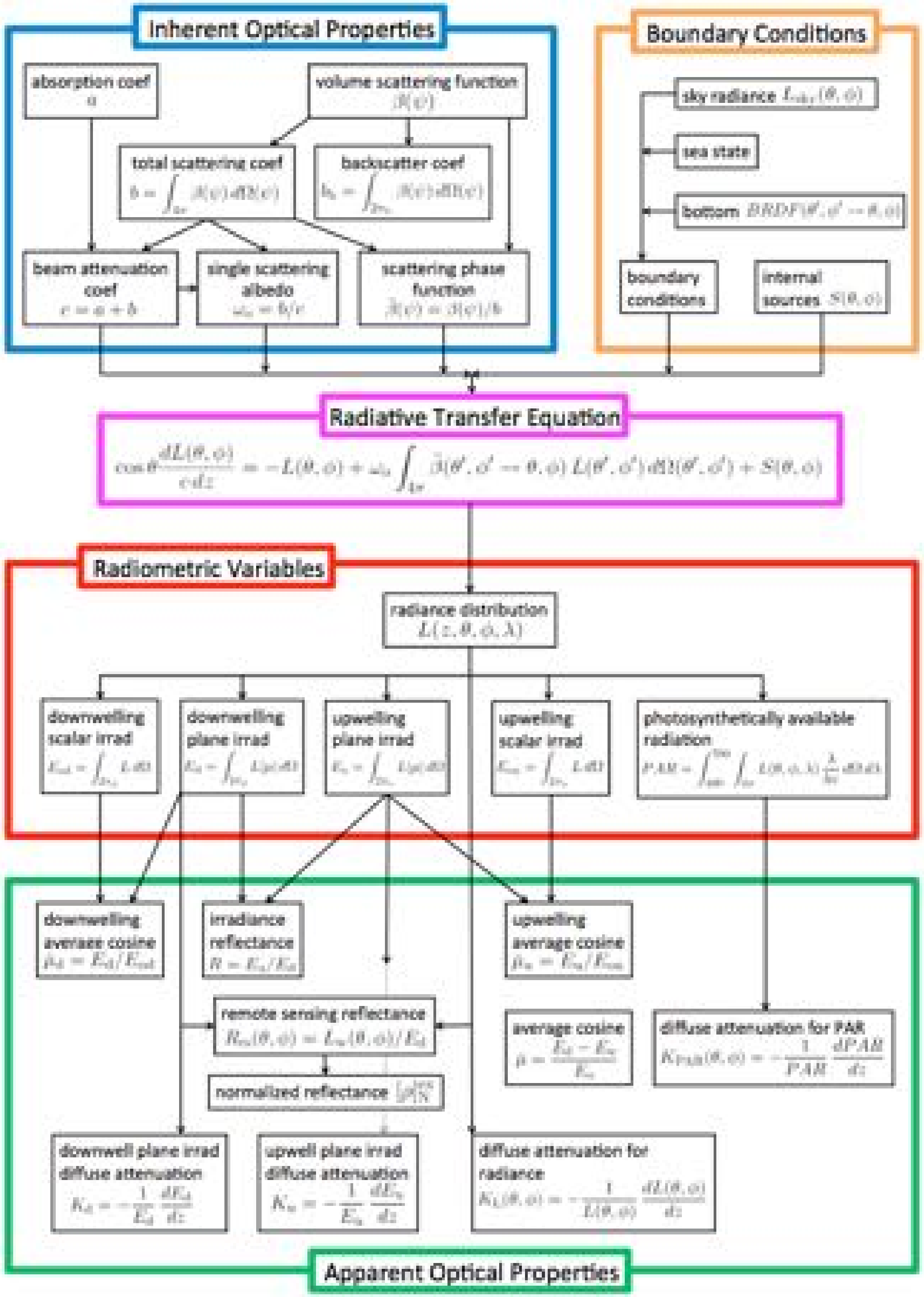
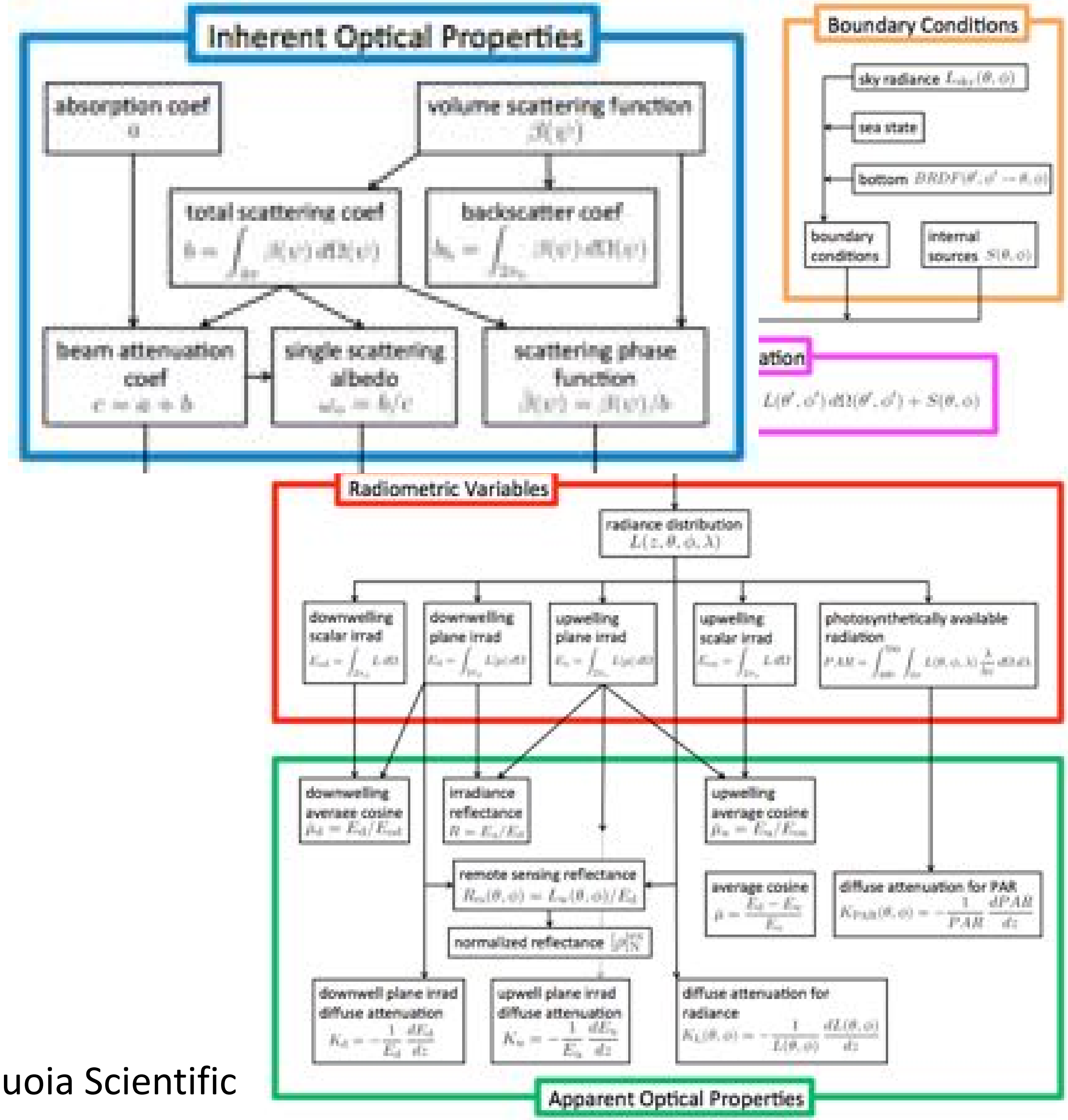


Figure courtesy:
Curt Mobley, Sequoia Scientific



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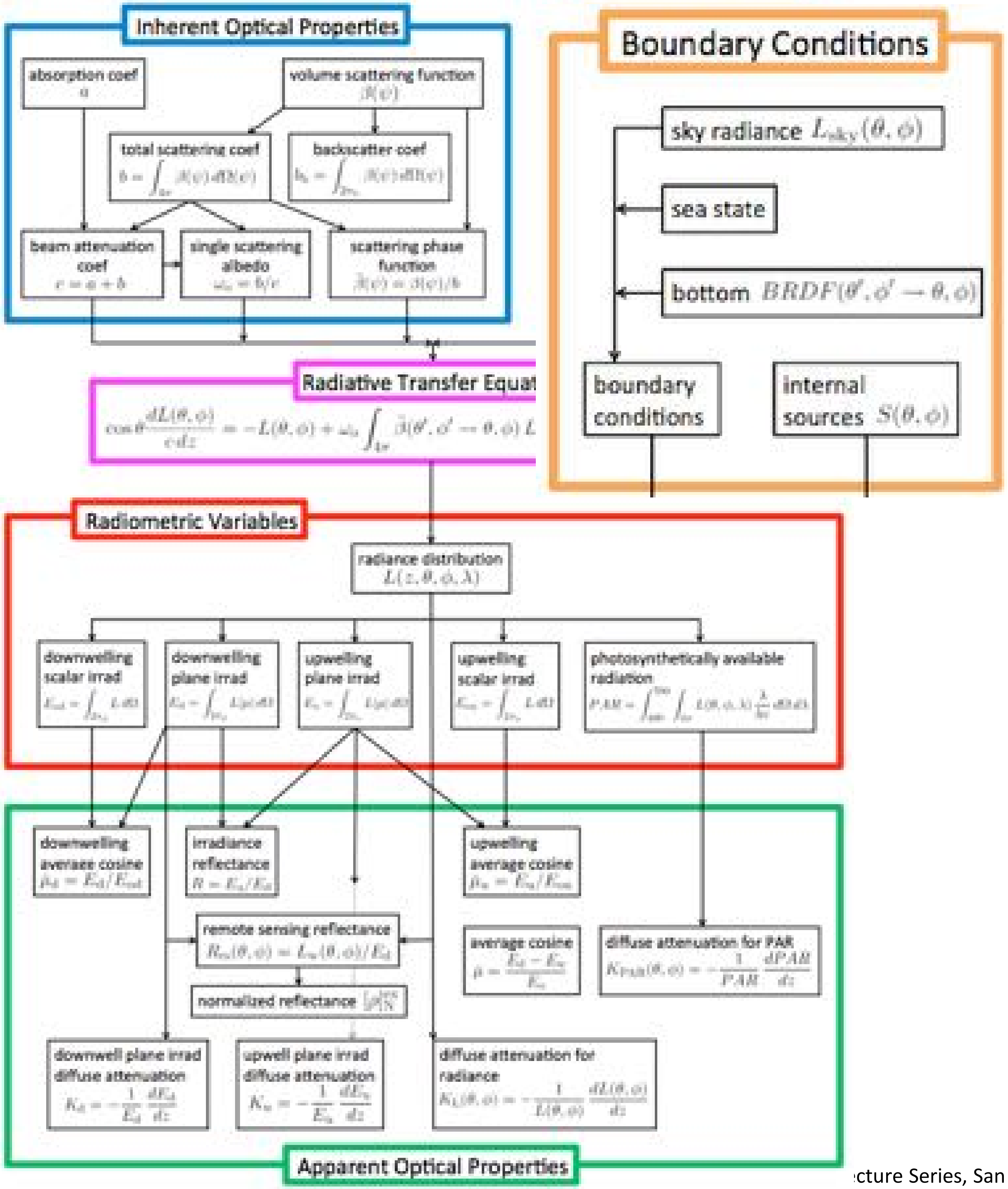

Figure courtesy:
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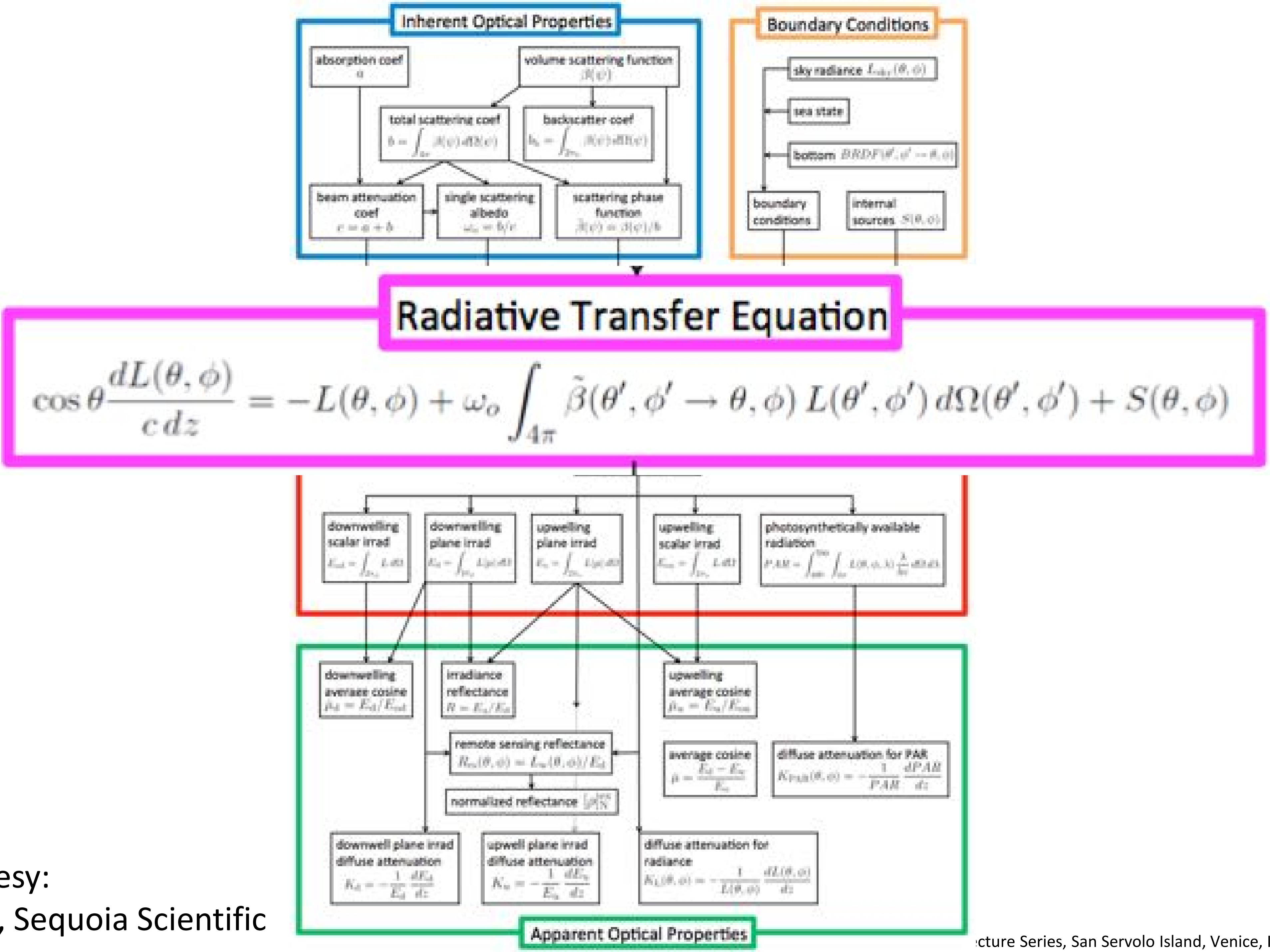


Figure courtesy:
Curt Mobley, Sequoia Scientific

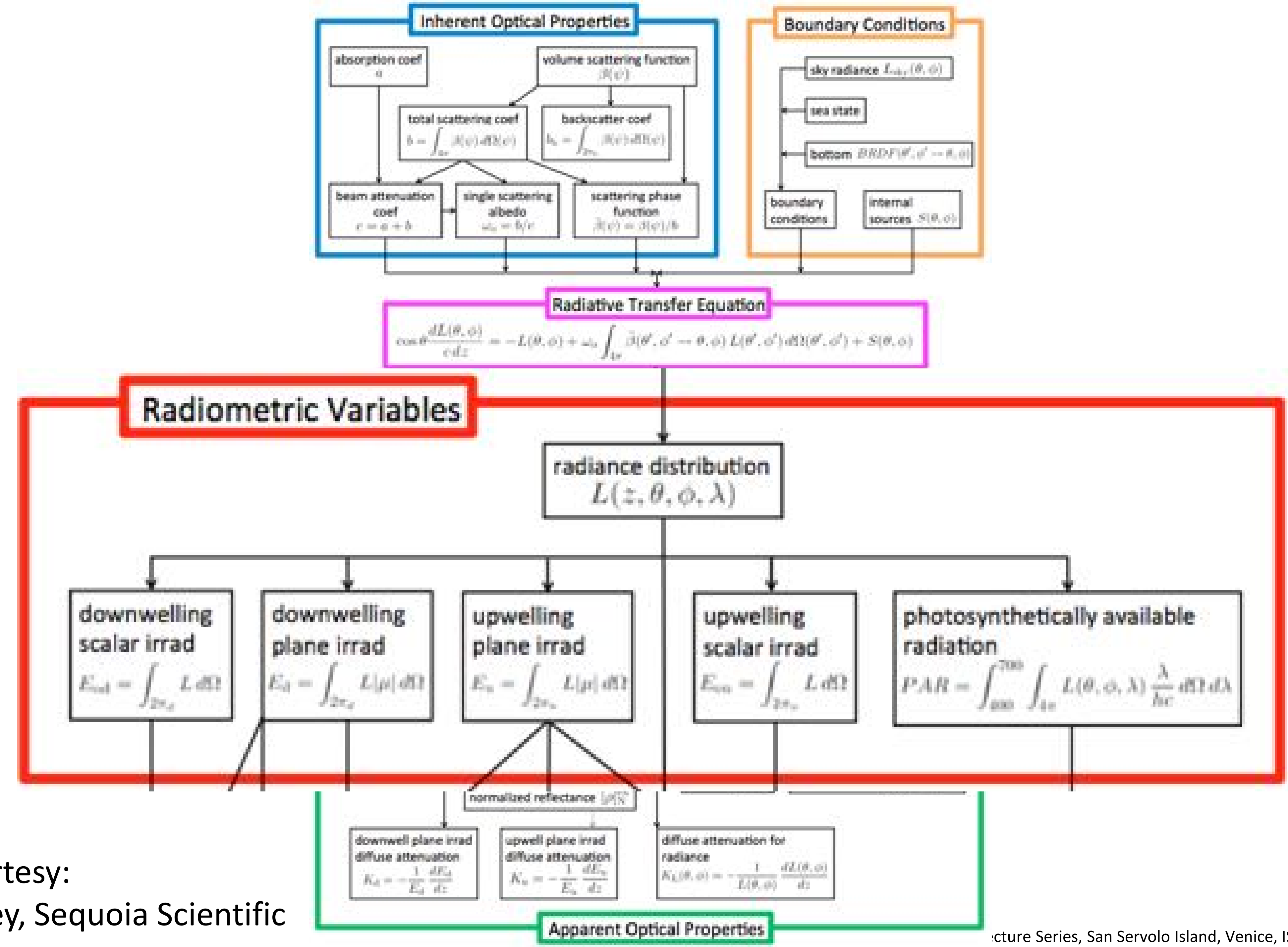


Figure courtesy:
Curt Mobley, Sequoia Scientific

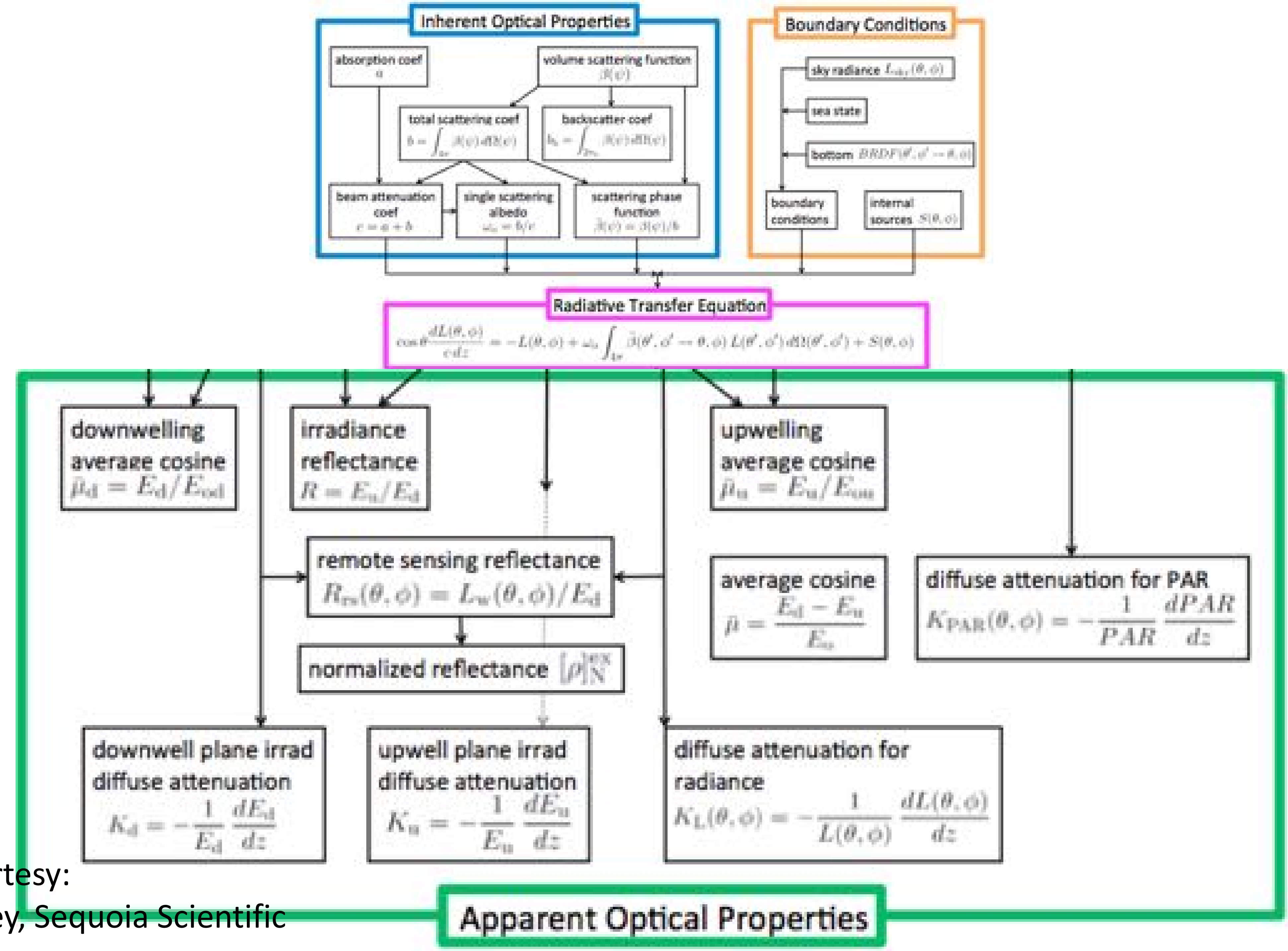


Figure courtesy:
Curt Mobley, Sequoia Scientific

Terminology, units, angles (geometry)

Morel, A. and R.C. Smith (1982) Terminology and units in optical oceanography, Marine Geodesy, 5, 335-349.

Photon		A photon is a quantum of electromagnetic radiation that has an energy equal to the product of the frequency of the radiation by the Plank's constant h (Quantum is entity of energy postulated in quantum theory). With : $h = (6.626\ 176 \pm 0.000\ 036) \times 10^{-34}$ J.Hz^{-1}	J
Quantity of radiant energy (F. Quantité d'énergie rayonnante)	W, Q	Energy emitted, transferred, or received as radiation	J
Radiant flux (F. flux énergétique).	Φ, F	The time rate of flow of radiant energy. Relation : $\Phi = dW / dt$ Note : The symbol Φ, rather than F recommended by IAPO has been adopted by the International Organization for Standardization (ISO) and by the International Association of Meteorology and Atmospheric Physics (IAMAP).	W

Terminology, units, angles (geometry)

Morel, A. and R.C. Smith (1982) Terminology and units in optical oceanography, Marine Geodesy, 5, 335-349.

Radiant intensity (of a source in a given direction) (F. intensité énergétique).	I	The radiant flux emitted by a point source, or by an element of an extended source, in an infinitesimal cone containing the given direction, divided by that element of solid angle. Relation : $I = d\Phi / d\omega$	$W.sr^{-1}$
Radiance (F. luminance énergétique)	L	Radiant flux in a given direction per unit solid angle per unit projected area. Relation : $L(\theta,\phi) = d^2\Phi / dA \cos\theta \, d\omega$	$W.m^{-2}.sr^{-1}$
Irradiance (at a point of a surface) (F. éclairement)	E	The radiant flux incident on an infinitesimal element of a surface containing the point under consideration, divided by the area of that element. Relation : $E = d\Phi / dA$	$W.m^{-2}$

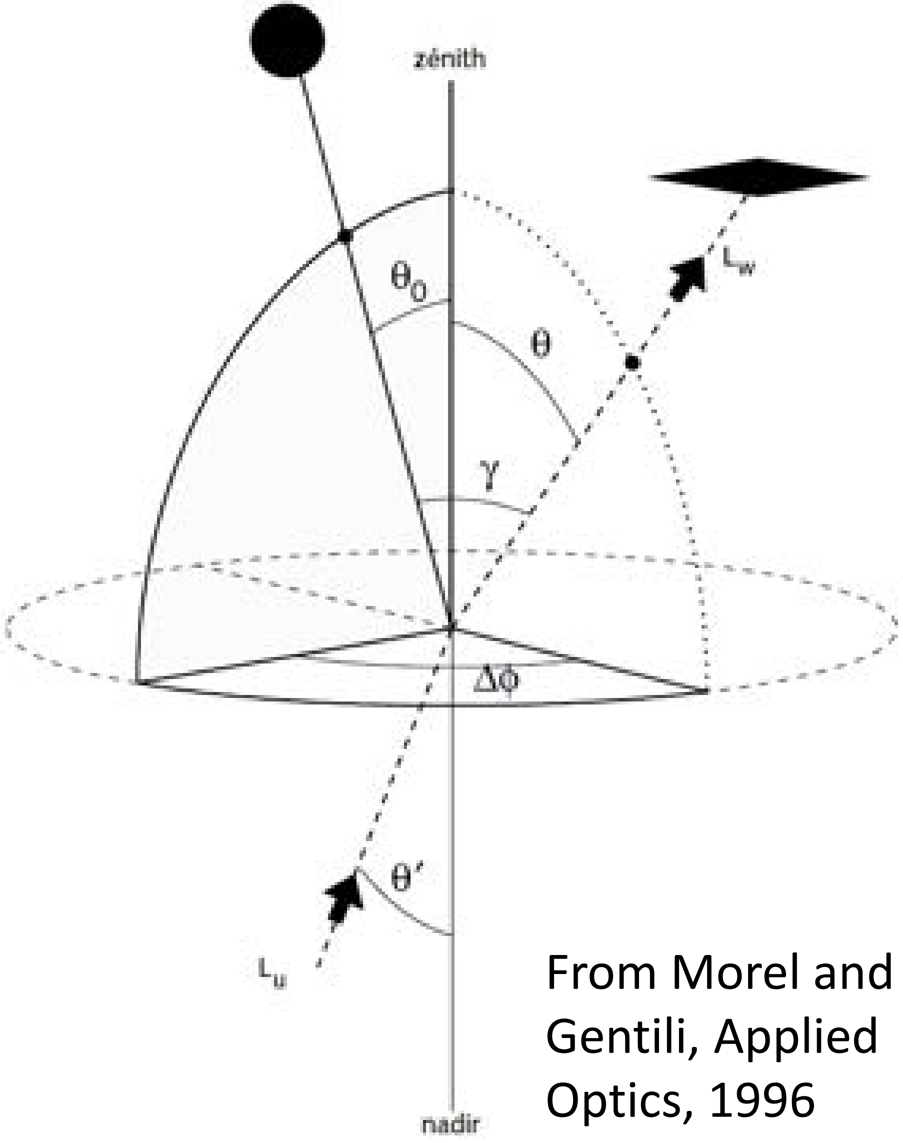
Terminology, units, angles (geometry)

- In radiative transfer, one normally refers to the direction where the light is going. Normally noted with θ and ϕ

- When measuring radiometric quantities, the opposite is made: direction of where we point the instruments

In an Earth frame (e.g., remote sensing or field measurements):

- Sun zenith angle: θ_s or θ_0
- View zenith angle: θ or θ_v
- Azimuth difference: $\Delta\phi$



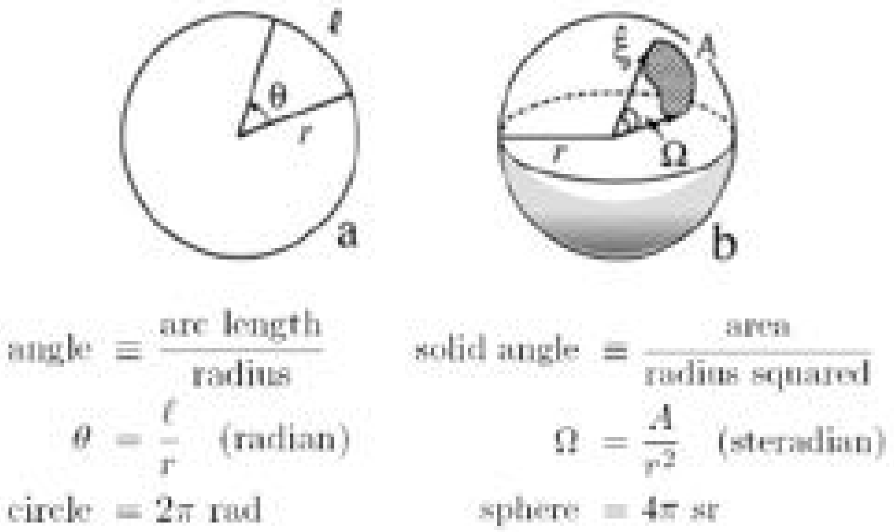
From Morel and Gentili, Applied Optics, 1996

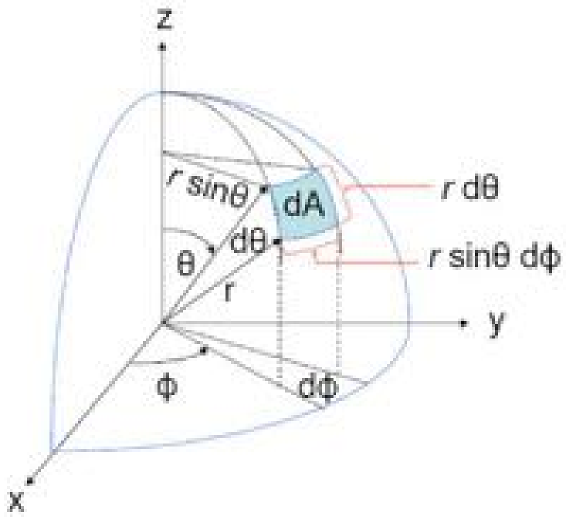
Terminology, units, angles (geometry)

The scattering angle:

$$\cos(\gamma) = \cos(\theta_v)\cos(\theta_s) + \sin(\theta_v)\sin(\theta_s)\cos(\Delta\phi)$$

Solid angles:





$$d\Omega = \sin(\theta)\, d\theta\, d\phi$$

Radiance: the fundamental quantity

$$L(\vec{x}, t, \hat{\xi}, \lambda) \equiv \frac{\Delta Q}{\Delta t \, \Delta A \, \Delta \Omega \, \Delta \lambda} \qquad (\mathrm{J\ s^{-1}\ m^{-2}\ sr^{-1}\ nm^{-1}})$$

W m^{-2} sr^{-1} nm^{-1}

Radiant flux in a given direction per unit solid angle per unit projected area

This is the quantity that appears in the radiative transfer equation, e.g., under the following form as a function of depth (z), and IOPs such as c and β

$$\cos\theta \frac{dL(z,\theta,\phi,\lambda)}{dz} = -c(z,\lambda)L(z,\theta,\phi,\lambda) + \int_0^{2\pi}\int_0^{\pi} L(z,\theta',\phi',\lambda)\beta(z;\theta',\phi' \rightarrow \theta,\phi;\lambda)\sin\theta' d\theta' d\phi'$$

Principle of “radiance invariance”:
independent of distance, if homogeneous target of large etendue

Radiometry

- Radiometry is the science of measuring electromagnetic energy (optical "radiant" energy)
- So, basically you need to collect energy and transform this into a signal that you can measure and quantify
- You need to have SI units attached to it → Calibration in reference to a standard.
- What are the units and standard for radiometry?

SI base units

The NIST Reference on Constants, Units, and Uncertainty

Return to Units home page

Units Topics: Base, Derived, Prefixes, Non-SI, Rules, Background

International System of Units (SI)

The following definitions of the SI base units are taken from NIST Special Publication 330 (SP 330), *The International System of Units (SI)*. See the Bibliography for a description of SP 330 and other NIST publications on the SI, and online access.

Definitions of the SI base units

Unit of length	**meter**	The meter is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second.
Unit of mass	**kilogram**	The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.
Unit of time	**second**	The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom.
Unit of electric current	**ampere**	The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length.
Unit of thermodynamic temperature	**kelvin**	The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
Unit of amount of substance	**mole**	1. The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12; its symbol is "mol." 2. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.
Unit of luminous intensity	**candela**	The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.

Taken from the US National Institute of Standards (NIST): https://physics.nist.gov/cuu/Units/current.html

SI derived units

Some of them

plane angle	radian [a]	rad	-	$m \cdot m^{-1} = 1$ [b]
solid angle	steradian [a]	sr [c]	-	$m^2 \cdot m^{-2} = 1$ [b]
energy, work, quantity of heat	joule	J	N·m	$m^2 \cdot kg \cdot s^{-2}$
power, radiant flux	watt	W	J/s	$m^2 \cdot kg \cdot s^{-3}$

$$L(\vec{x}, t, \hat{\xi}, \lambda) \equiv \frac{\Delta Q}{\Delta t \, \Delta A \, \Delta\Omega \, \Delta\lambda} \qquad (\mathrm{J\ s^{-1}\ m^{-2}\ sr^{-1}\ nm^{-1}})$$

$\mathrm{W\ m^{-2}\ sr^{-1}\ nm^{-1}}$

Radiant flux in a given direction per unit solid angle per unit projected area

Taken from the US National Institute of Standards (NIST):

https://physics.nist.gov/cuu/Units/current.html

SI standards (historical)

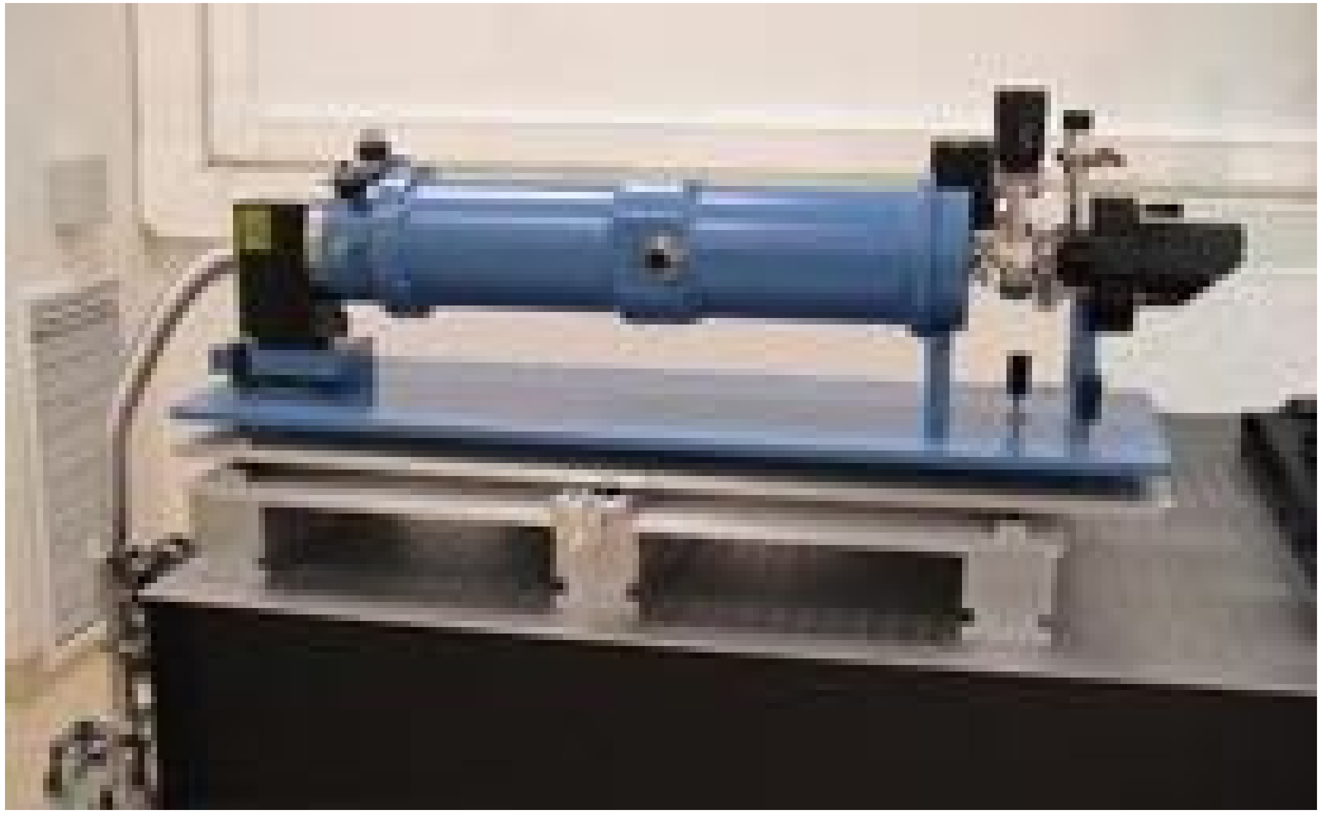
one ten-millionth (1/10,000,000) of the distance from the North Pole to the Equator along the meridian passing through Paris
Now based on the interferometry technique (light)

What about radiometry?

(which uses units of W / surface area / wavelength)

The primary radiometry standard: Cryogenic radiometer

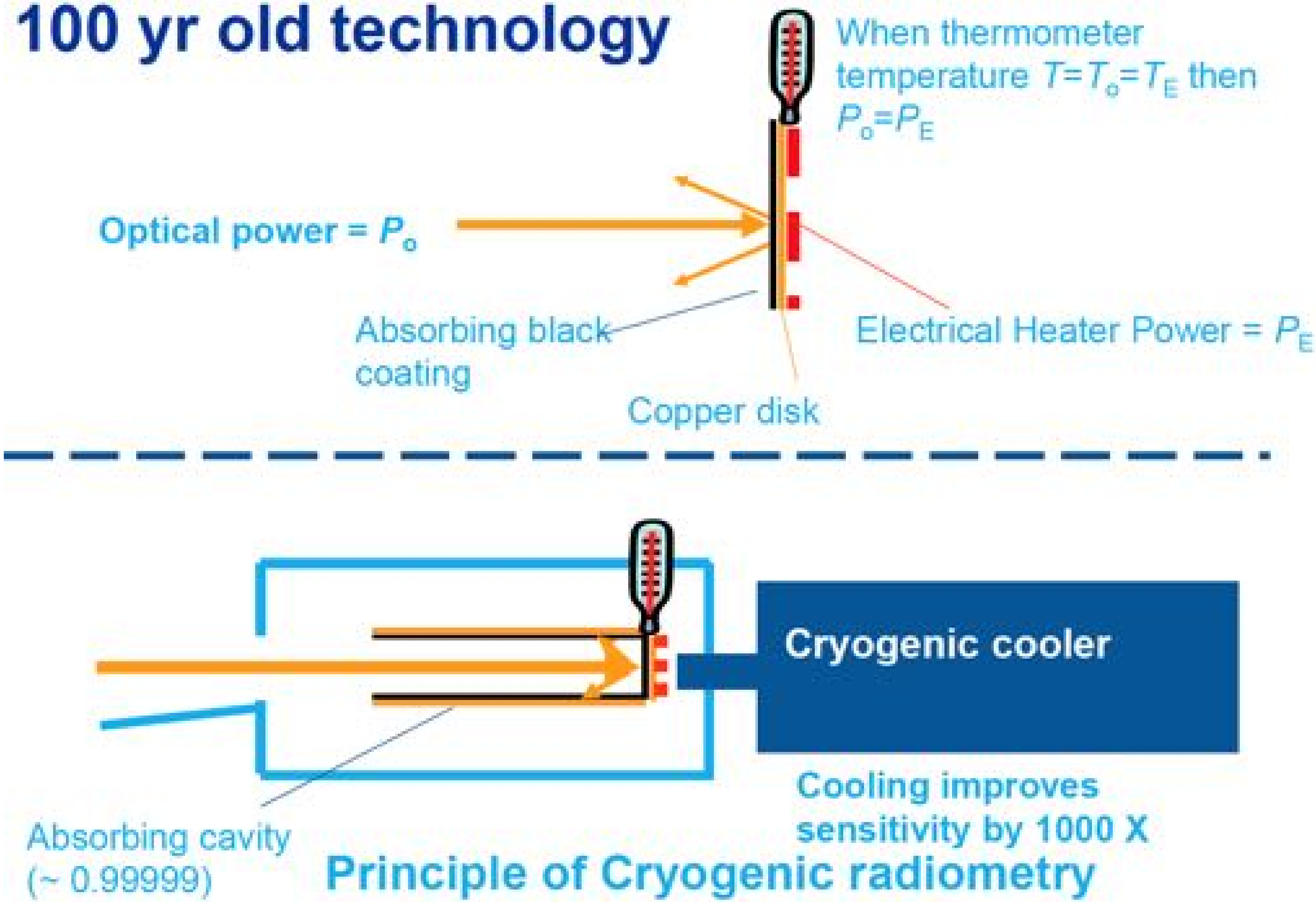
The cryogenic radiometer uses the electrical substitution technique, whereby the optical power incident on an absorbing cavity is compared with the electrical power required to heat the cavity to the same temperature. "cryogenic" because it is forced to very low temperature to improve sensitivity



UK National Physics Laboratories (NPL)
Primary Standard cryogenic radiometer

https://www.ukspacefacilities.stfc.ac.uk/Pages/National-Physical-Laboratory-(NPL)---Teddington---NPL's-Radiometric-Calibration-and-Characterisation-Facility-.aspx

Electrical Substitution Radiometry – a 100 yr old technology



Calibrating in air, then measuring in water

Need to apply "immersion factors":

For radiance:

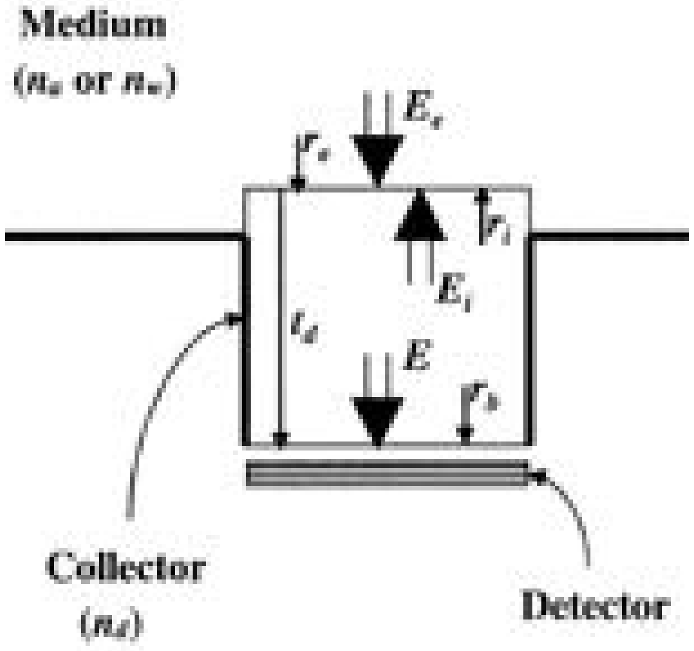
$$C_{\mathrm{im}} = \left[1 - \left(\frac{n_g - 1}{n_g + 1}\right)^2 \Big/ 1 - \left(\frac{n_g - n_w}{n_g + n_w}\right)^2\right] n_w^2$$

n_g: refractive index of glass
n_w: refractive index of water

Has to account for the change of the solid angle

For irradiance:

Fig 6 in Zibordi et al., 2004; J. Ocean. Atm. Tech., 21, 501-514



Has to account for the change of the reflections, transmissions effects at the interface between the collector and the medium

To be determined experimentally

Measuring radiance

$$L(\vec{x},t,\hat{\xi},\lambda) \equiv \frac{\Delta Q}{\Delta t\,\Delta A\,\Delta\Omega\,\Delta\lambda} \qquad (\mathrm{J\ s^{-1}\ m^{-2}\ sr^{-1}\ nm^{-1}}).$$

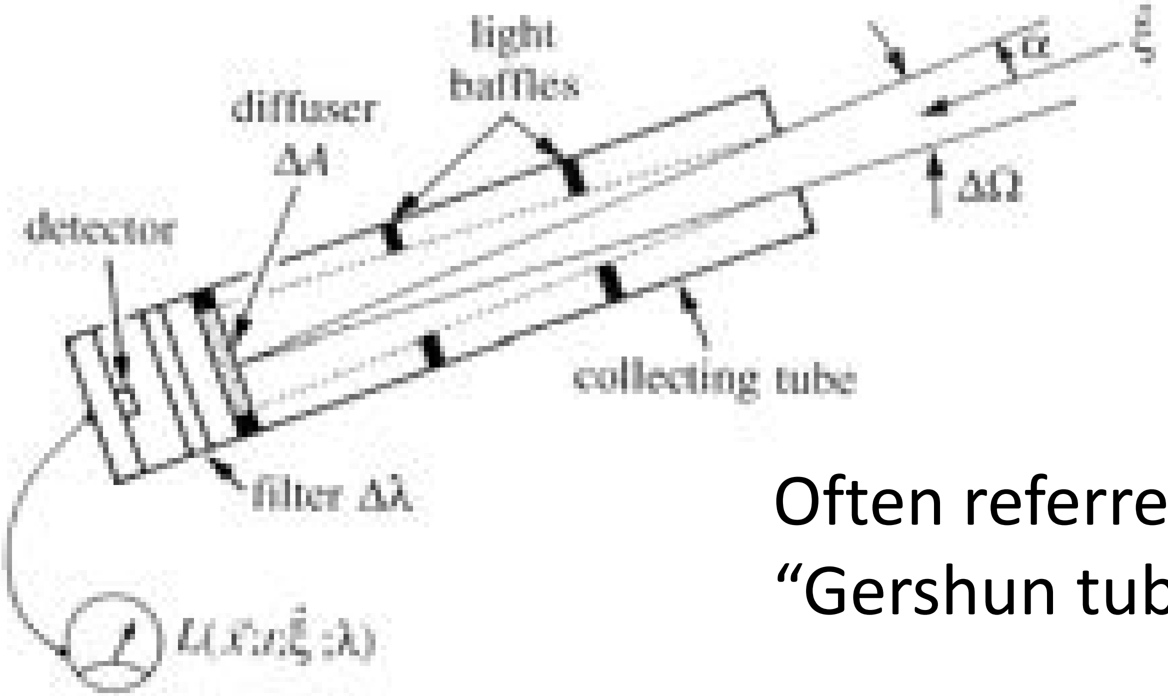


Figure: Schematic design of an instrument for measuring unpolarized spectral radiance.

Often referred to as a "Gershun tube"

From: http://www.oceanopticsbook.info

Measuring radiance: the 1st underwater radiance distribution

John E. Tyler, 1960, Bull. Scripps Inst. Oceanogr. 7, 363-412.

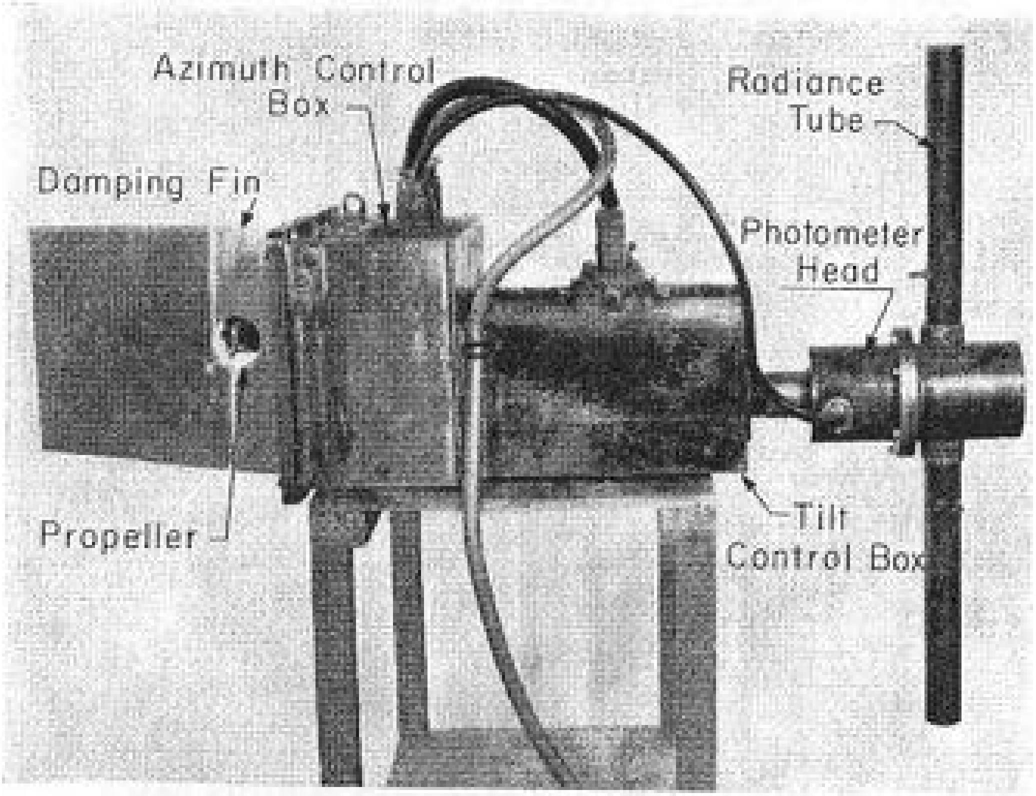
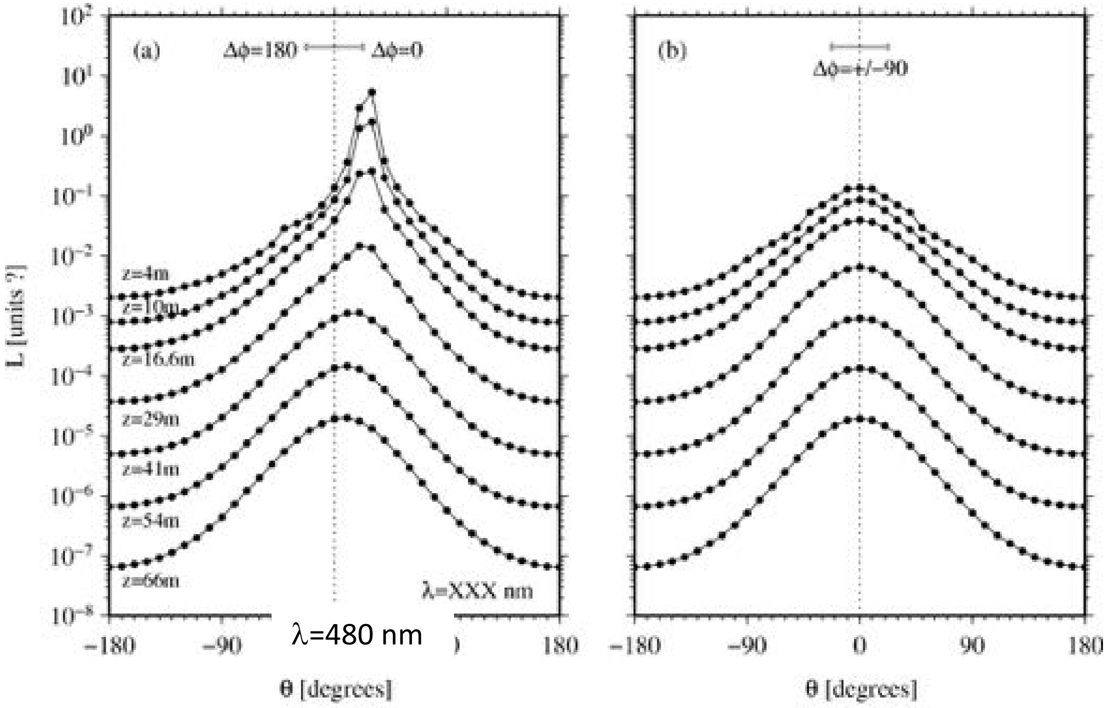


Fig. 8. Underwater radiance photometer (Tyler, 1960). The measuring head with its radiance tubes is on the right. The center box holds the tilt motor. The left box contains the gyrosyn compass and propeller-drive motor. The propeller can be seen through a hole in the damping fin on the left.

The Sea, Vol 1., M. N. Hill Ed., (1962)

Unidirectional photometer with elevation scanning

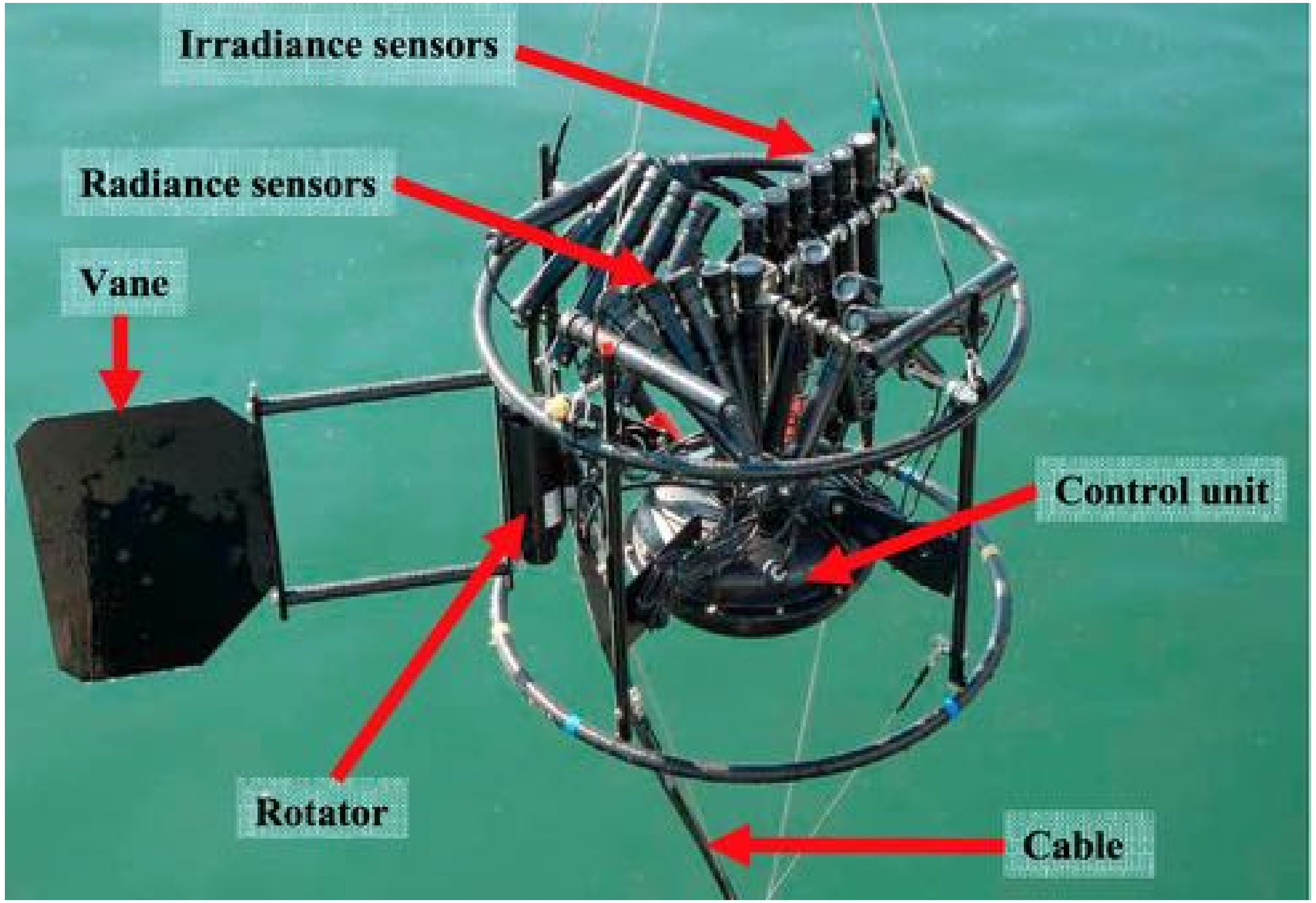
Radiances distribution in Lake Pend'Oreille
Redrawn from the data published by Tyler, 1960

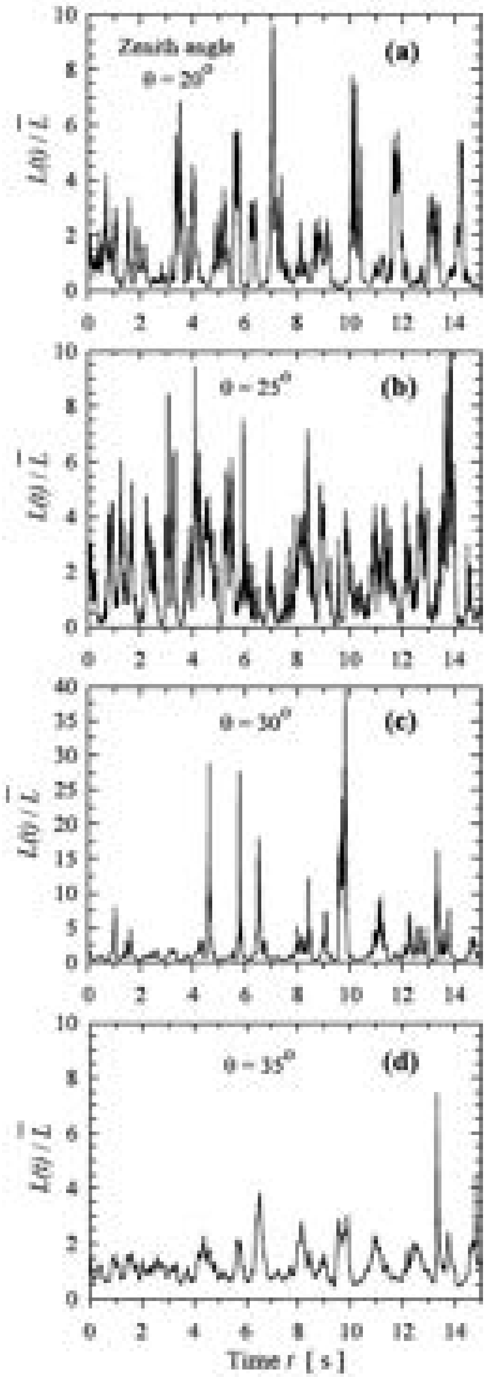


Principal plane

Perpendicular plane

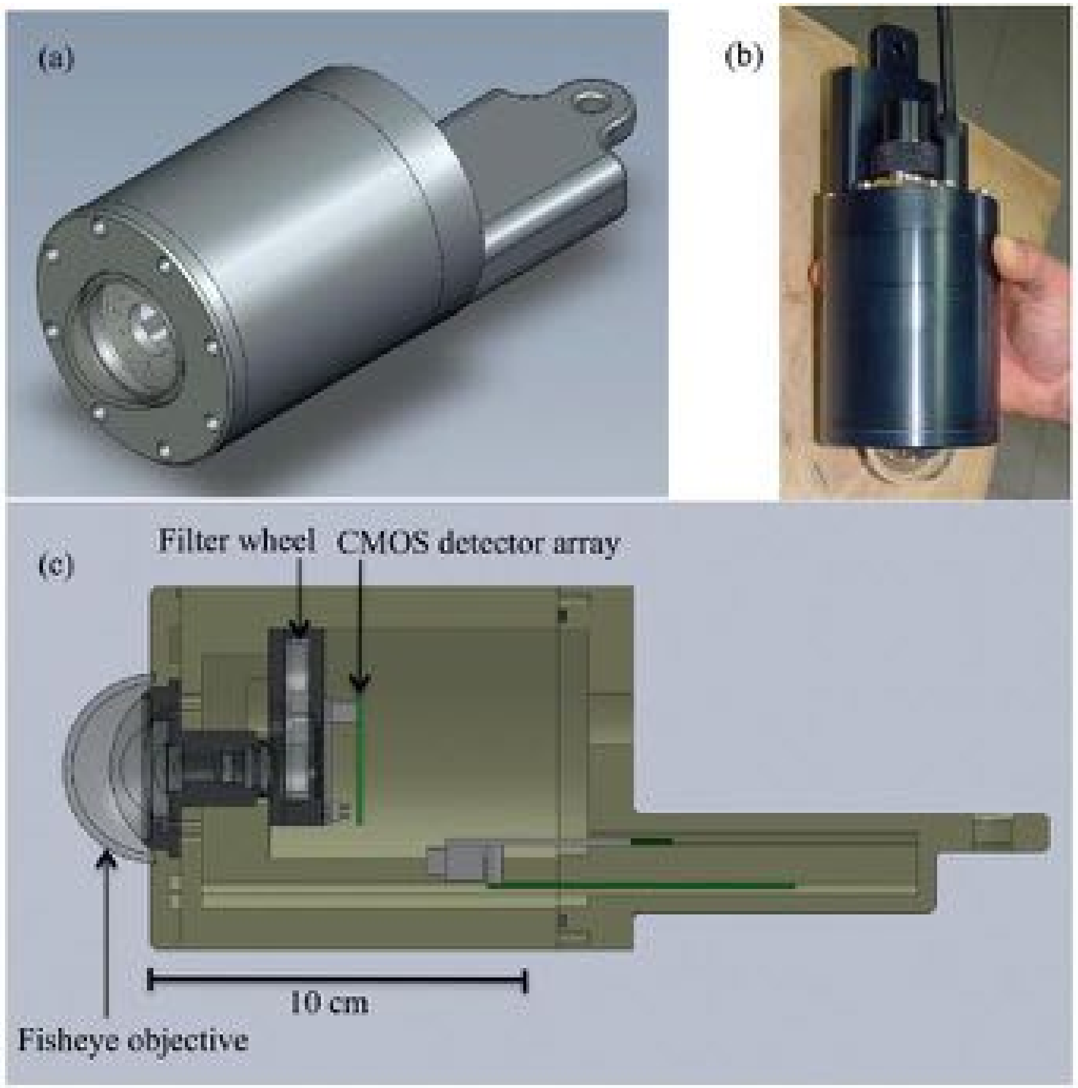
Measuring radiance

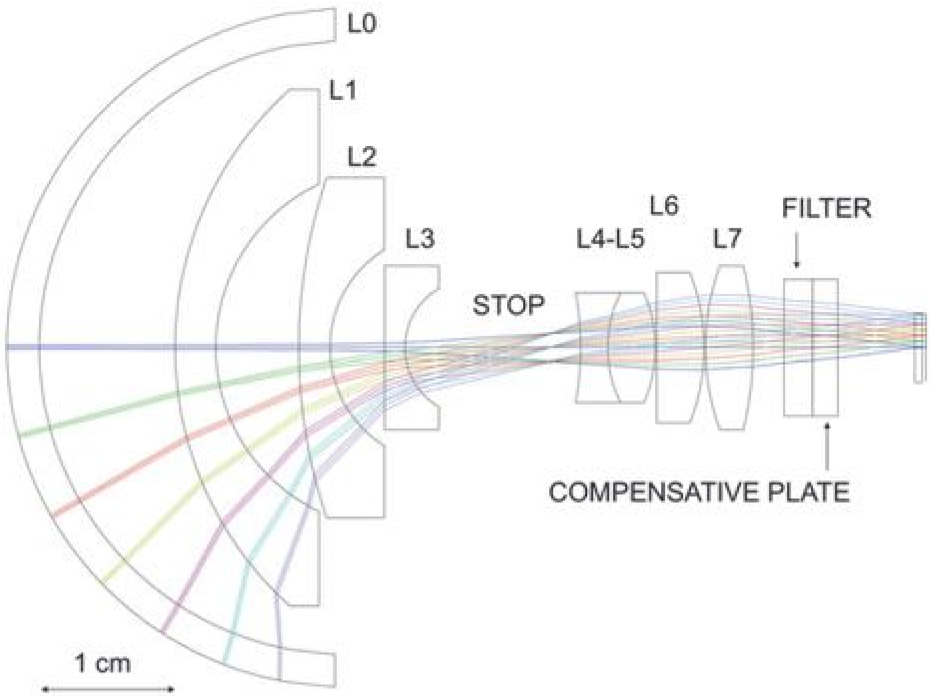




Figures 1 (above) and 14 (right) in: Darecki M, D Stramski, and M Sokolski, 2011, Journal of Geophysical Research, vol 116, C00H09, doi:10.1029/2011JC007338

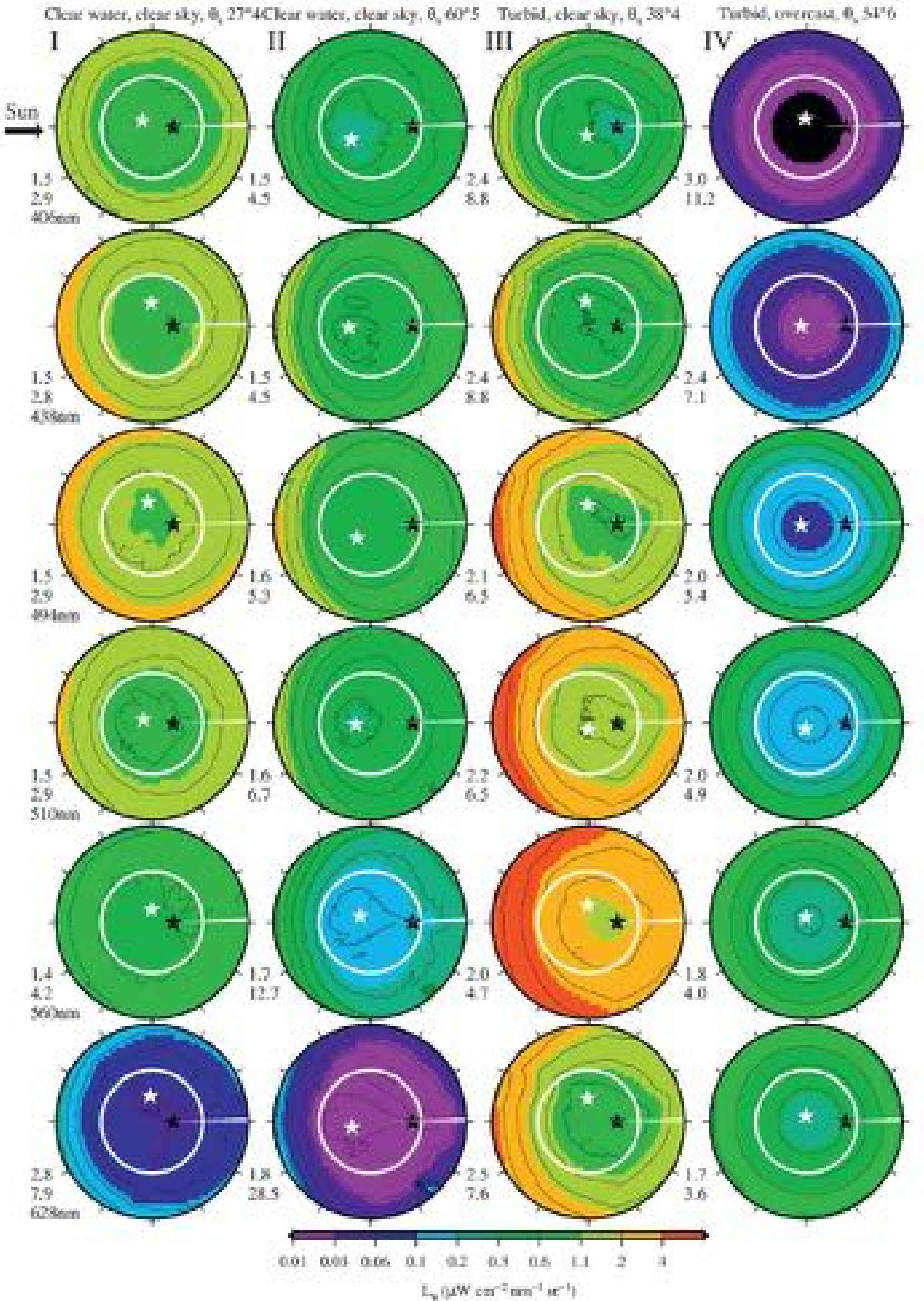
Measuring radiance





Radiance camera: getting simultaneously radiances in all directions of an hemisphere, at several wavelengths

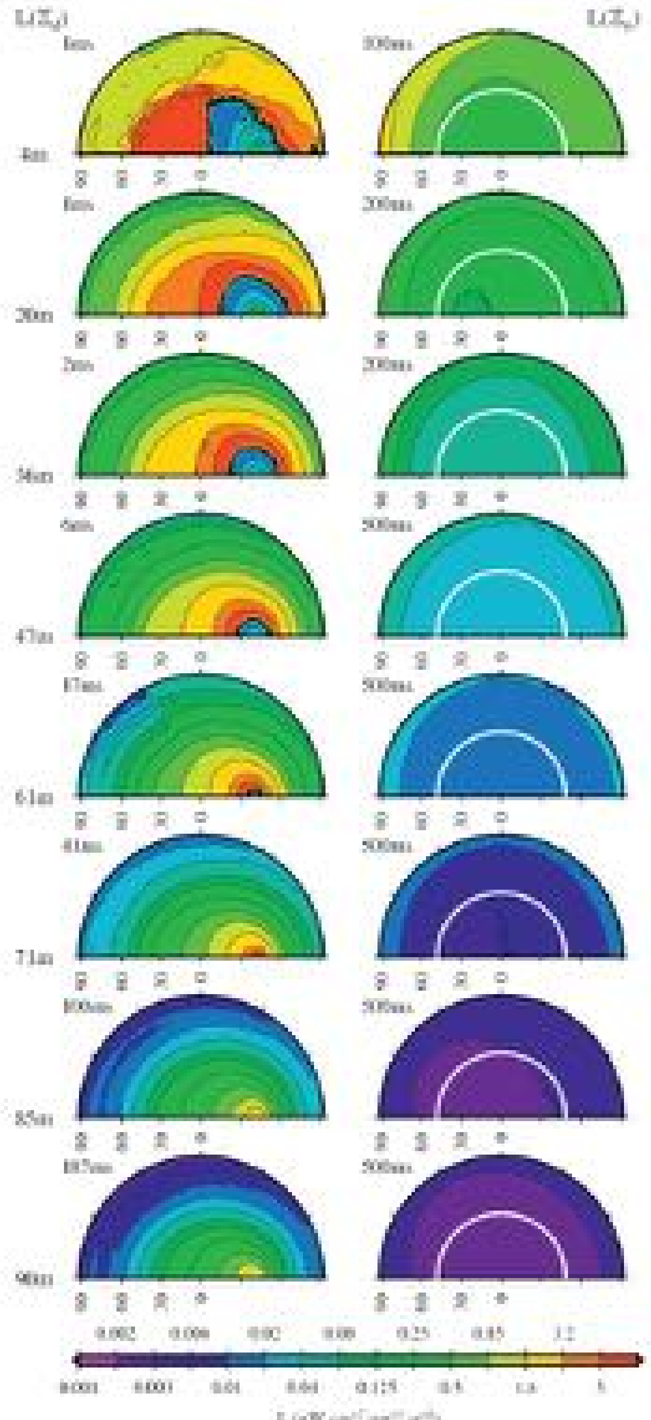
Figures 2 and 3 in: Antoine et al., 2013, Journal of Atmospheric and Oceanic technology, vol 30, doi: 10.1175/JTECH-D-11-00215.1



Measuring radiance: under water upwelling radiances distributions

	Water type	Sky	θ_s (°)	Chl (mg m^{-3})
I	Clear	Clear	27.4	0.3
II	Clear	Clear	60.5	0.1
III	Moderately turbid	Clear	38.4	0.3
IV	Highly turbid	Overcast	54.6	3

Figure 7 in: Antoine et al., 2013, Journal of Atmospheric and Oceanic technology, vol 30, doi: 10.1175/JTECH-D-11-00215.1



Measuring radiance: Underwater upwelling, L(Ξ_u), and downwelling, L(Ξ_d), radiances distributions

Figure 9 in: Antoine et al., 2013, Journal of Atmospheric and Oceanic technology, vol 30, doi: 10.1175/JTECH-D-11-00215.1

Do we need to go any further?

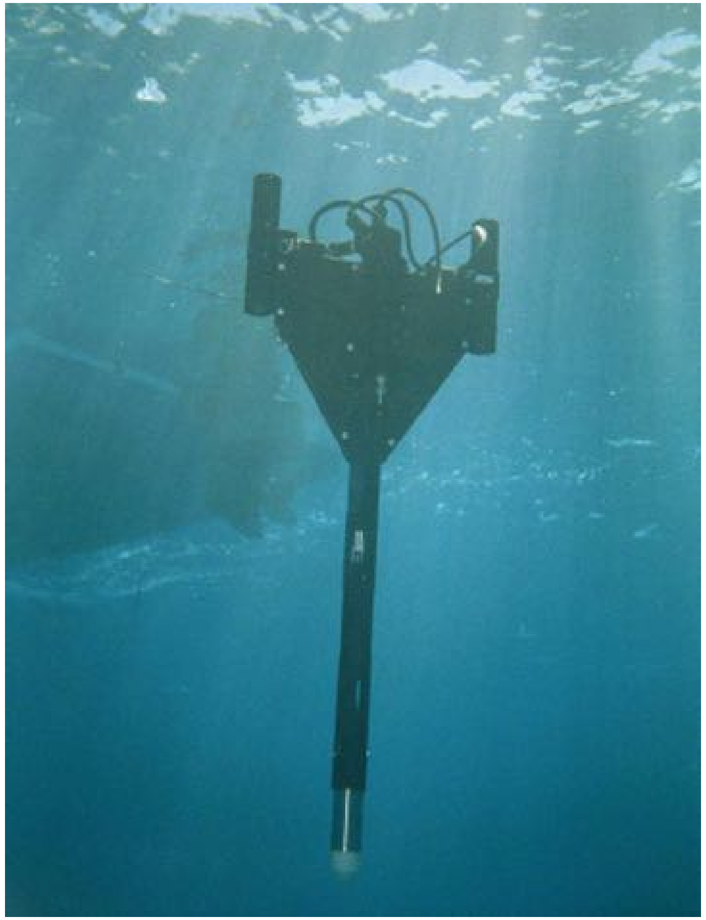
If we know radiances in all directions and all (or at least multiple) depths in the water column, plus maybe their distribution above the surface:
what else do we need?

In theory, nothing!

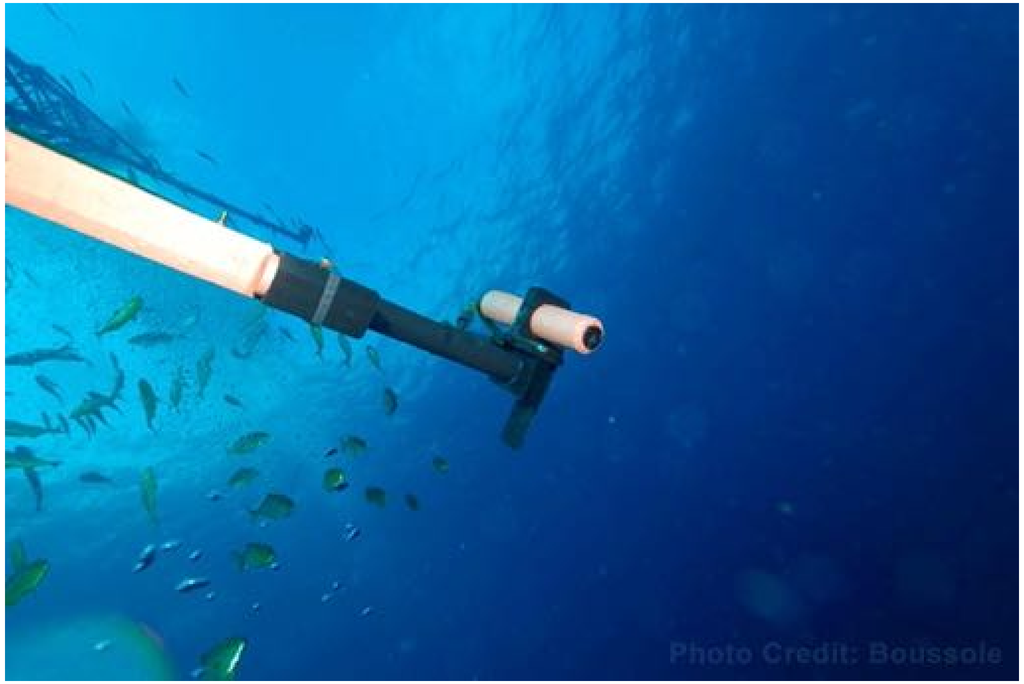
However, this is not what we get in the real world
(or really exceptionally)

Measuring radiance:
what we actually do most of the time

We measure L_u at nadir and E_d
vertical profiles (from ships) or fixed depths (moorings)



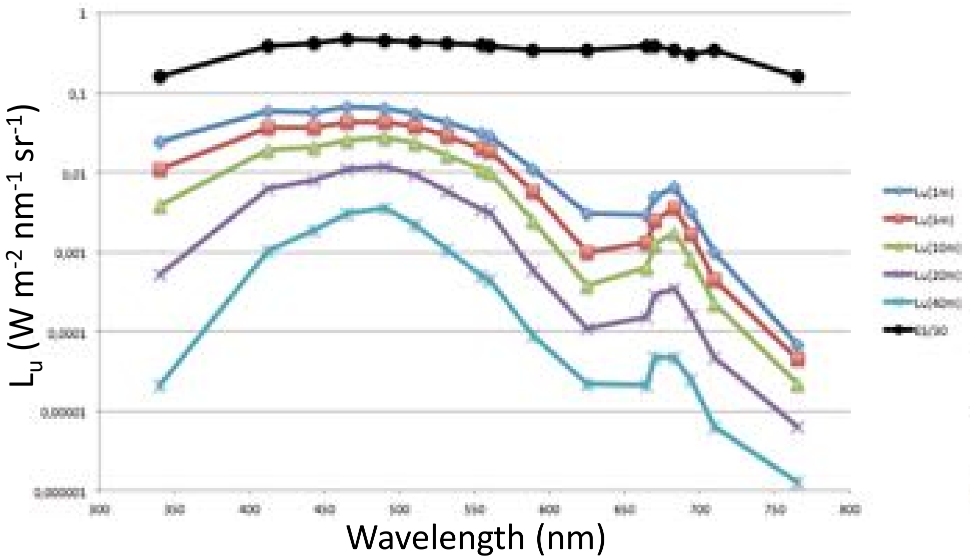
From: http://www.seabird.com/profiler



From BOUSSOLE

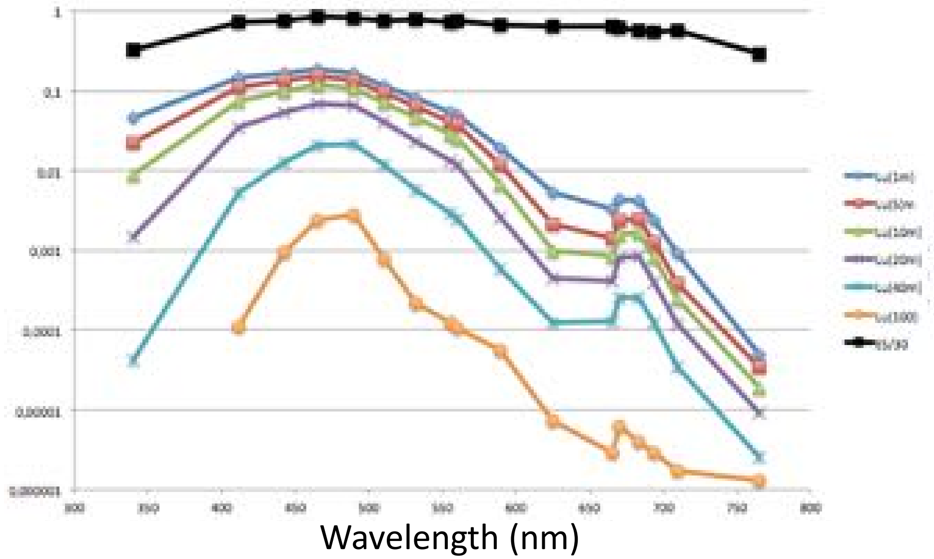
Spectra of underwater upwelling radiances

Example measurements taken 60km off Villefranche, at the “BOUSSOLE” site



18th January 2011

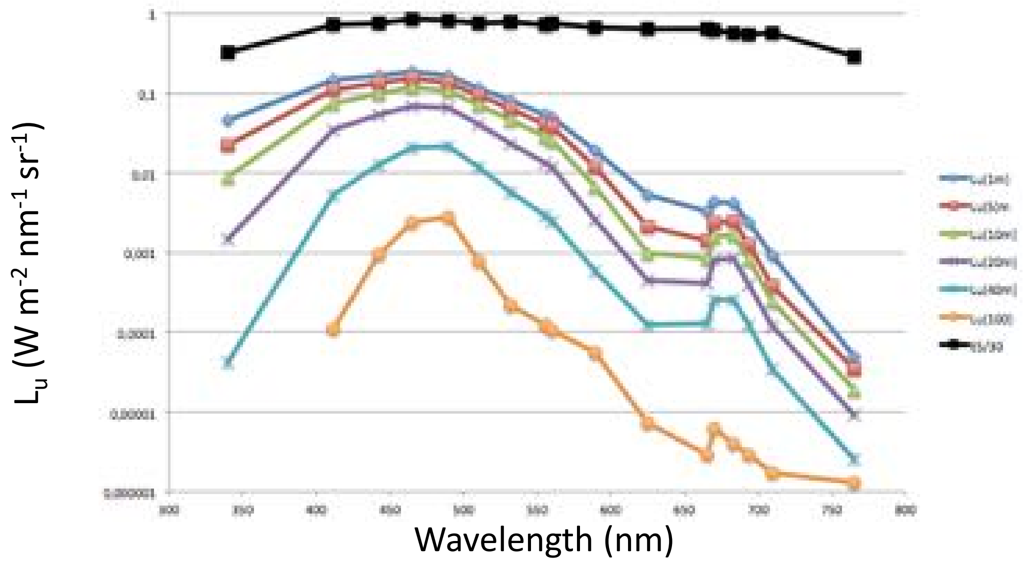
Chl ~1 mg m^{-3}



13th December 2015

Chl ~0,24 mg m^{-3}

Spectra and vertical profiles of underwater upwelling radiances

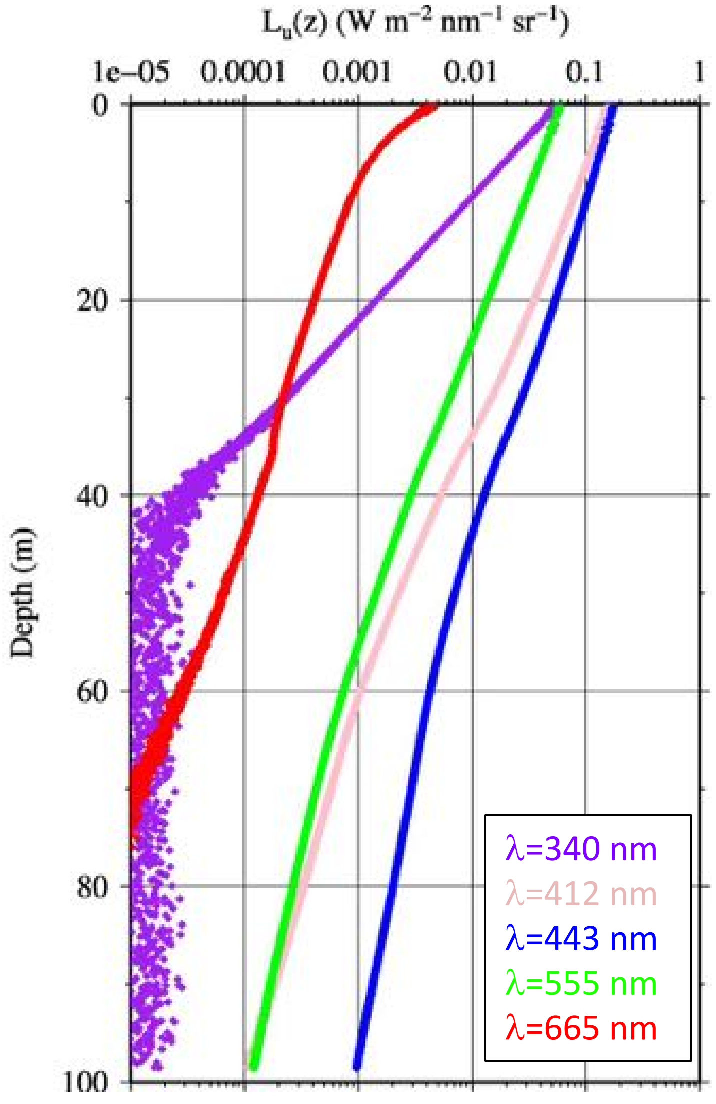


13th December 2015

Chl ~0,24 mg m^{-3}

The water-leaving radiance

$$L_w(\theta, \phi) = L_u(0^-, \theta', \phi)\,\frac{[1 - \rho(\theta', \theta)]}{n^2}$$



Irradiances

Scalar irradiance

$$\overset{o}{E} = \int_{\Xi} L(\theta, \phi)\, d\Omega$$

Downward plane irradiance

$$E_d = \int_{\Xi d} L(\theta, \phi) \cos\theta\, d\Omega$$

Upward plane irradiance

$$E_u = \int_{\Xi u} L(\theta, \phi) |\cos\theta|\, d\Omega$$

The irradiance falling on a plane surface varies as the cosine of the incident angle (Lambert's cosine law)

Irradiance also follows the "inverse square law"

Measuring irradiances

Plane irradiance
That's what enters the ocean through the air-sea interface

$$E_d(\vec{x},t,\lambda) \equiv \frac{\Delta Q}{\Delta t\, \Delta A\, \Delta\lambda} \quad (\mathrm{W\,m^{-2}\,nm^{-1}}).$$

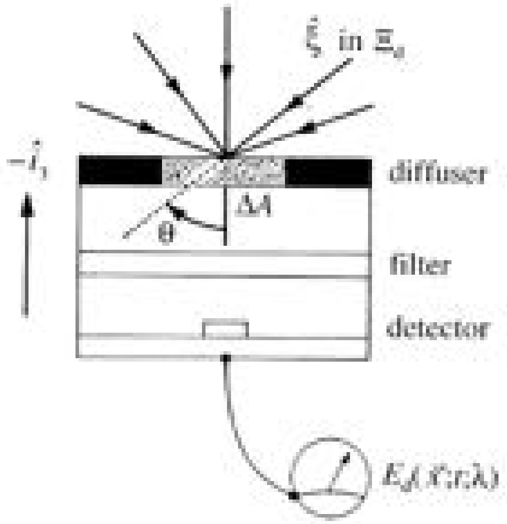


Figure: Schematic design of an instrument for measuring spectral plane irradiance.

Scalar irradiance
What provides energy for photosynthesis underwater

$$E_{od}(\vec{x},t,\lambda) = \int_{\hat{\xi}\in\Xi_d} L(\vec{x},t,\hat{\xi},\lambda)\, d\Omega(\hat{\xi})$$
$$= \int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi/2} L(\vec{x},t,\theta,\phi,\lambda)\sin\theta\, d\theta\, d\phi$$

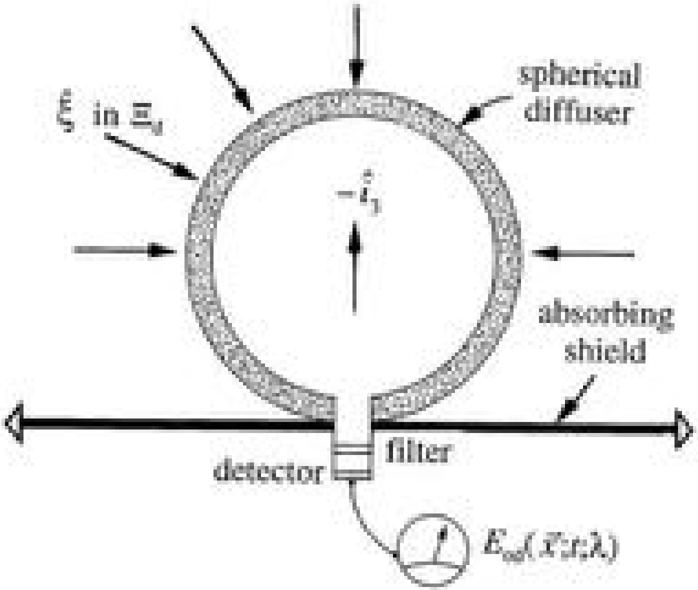
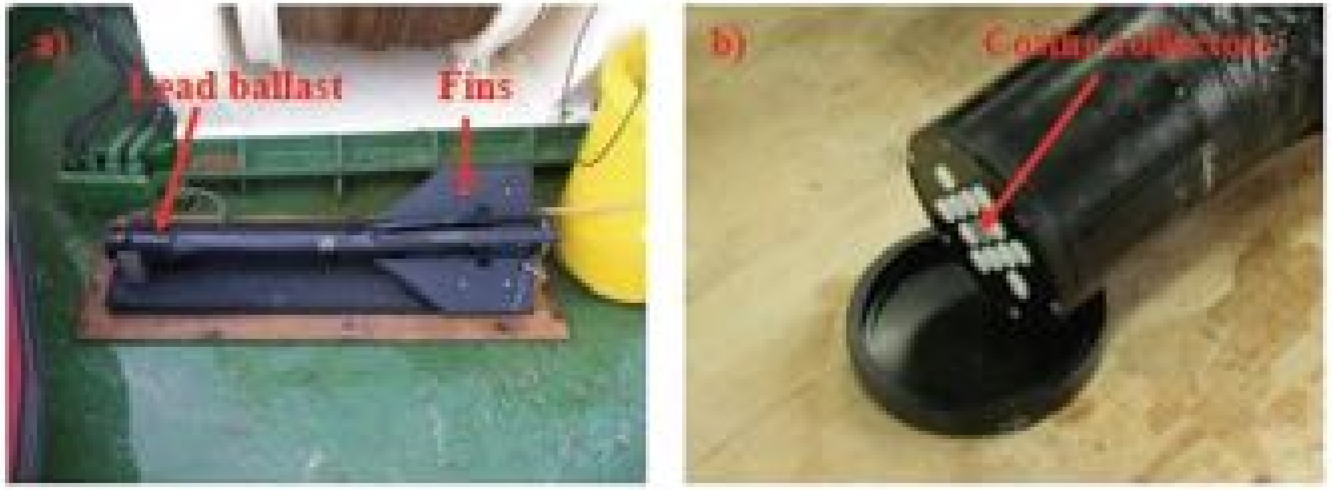


Figure: Schematic design of an instrument for measuring spectral scalar irradiance.

From: http://www.oceanopticsbook.info

Measuring irradiances



A typical “free-fall” profiling radiometer: the Satlantic “SeaWiFS Profiling Multichannel Radiometer”

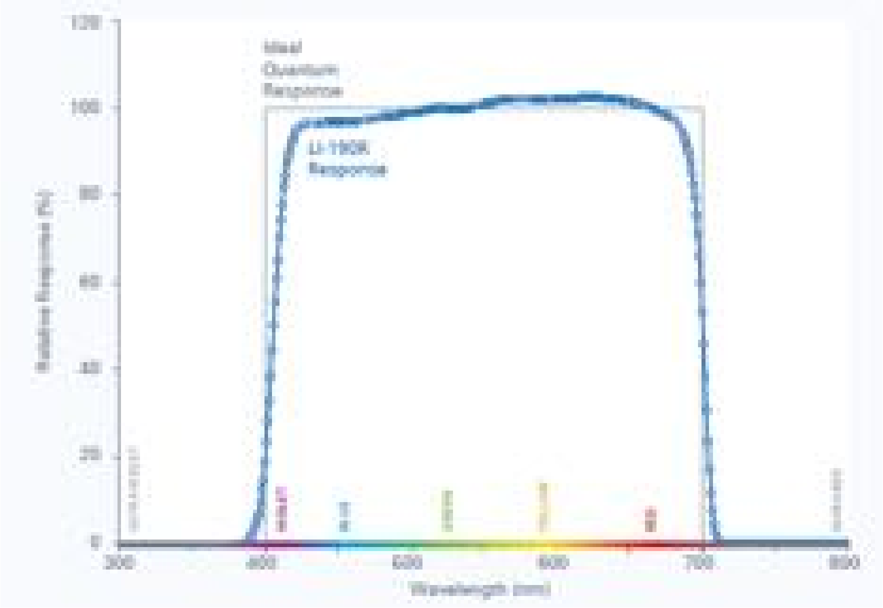
Hyperspectral Satlantic radiometers, as installed on the BOUSSOLE buoy

Photosynthetically Available Radiation (PAR)

PAR is the integrated radiation in the visible, from 400 to 700nm. Used in photosynhesis studies

This is the number of photons in the 400–700 nm waveband incident per unit time on a unit surface.
The ideal PAR sensor responds equally to all photons in the 400–700 nm waveband and has a cosine response.

As far as possible, PAR should not be used for anything else than photosynthesis studies. It is not a very good descriptor of the underwater light environment for other purposes



Typical response of a PAR sensor (basically the sensor response – sensitivity – has to be proportional to wavelength)

Figure 2 from “Principles of Radiation Measurement”, Li-COR.
See at: https://licor.app.boxenterprise.net/s/liuswfuvtqn7e9loxaut

What can we do with “unmodified”, direct measurements of radiances or irradiances?

A few things, actually:

1- Know how much light is available for photosynthesis

2- Directly use L_w for vicarious calibration of satellite OCR sensors

3- ??? Unsure actually

We are a bit limited, however, in using radiances of irradiances. Why?

Because they depend too much on illumination conditions (sun elevation, cloudiness, other atmospheric properties, air-sea interface properties)

Cannot compare different sets of measurements

Another reason (the major one actually) is that getting the full radiance distribution is a difficult task

Therefore, we will need to combine radiances and/or irradiances in different ways, to normalize them in some way, and to use depth derivatives

The normalized water leaving radiance: $L_{w,n}$ or $[L_w]_N$

A quantity that can be compared with a standard measurement made in situ, in the ocean, for whatever sun zenith angle, viewing direction, atmospheric conditions, and wave state occurred at the time of the satellite measurement

Basically (Gordon H. R. et al., 1988. J. Geophys. Res., 93:10909–10924):

$$L_w^n = \frac{L_w}{\varepsilon\, t_d \cos(\theta_s)} \quad \left(actually: L_w^n = L_w \frac{F_0}{E_d(0^+)} \right)$$

This normalisation is incomplete, however: it is for a particular viewing geometry. It does not account for the directionality of reflectance

"Bidirectionality" of the ocean reflectance

- Basically means that, for given IOPs and illumination conditions, the radiance exiting the ocean (the "water-leaving radiance, L_w) has not the same value for all directions.
- Depends on the shape of the VSF, and on how diffuse the underwater light regime is (e.g., ratios b/c and b_w/b_p), and how diffuse the incoming solar radiation is (so: θ_s and atmosphere optical thickness)
- This has to be taken into account for comparing measurements or using them in various algorithms or when using OCR remote sensing observations

Simple examples:

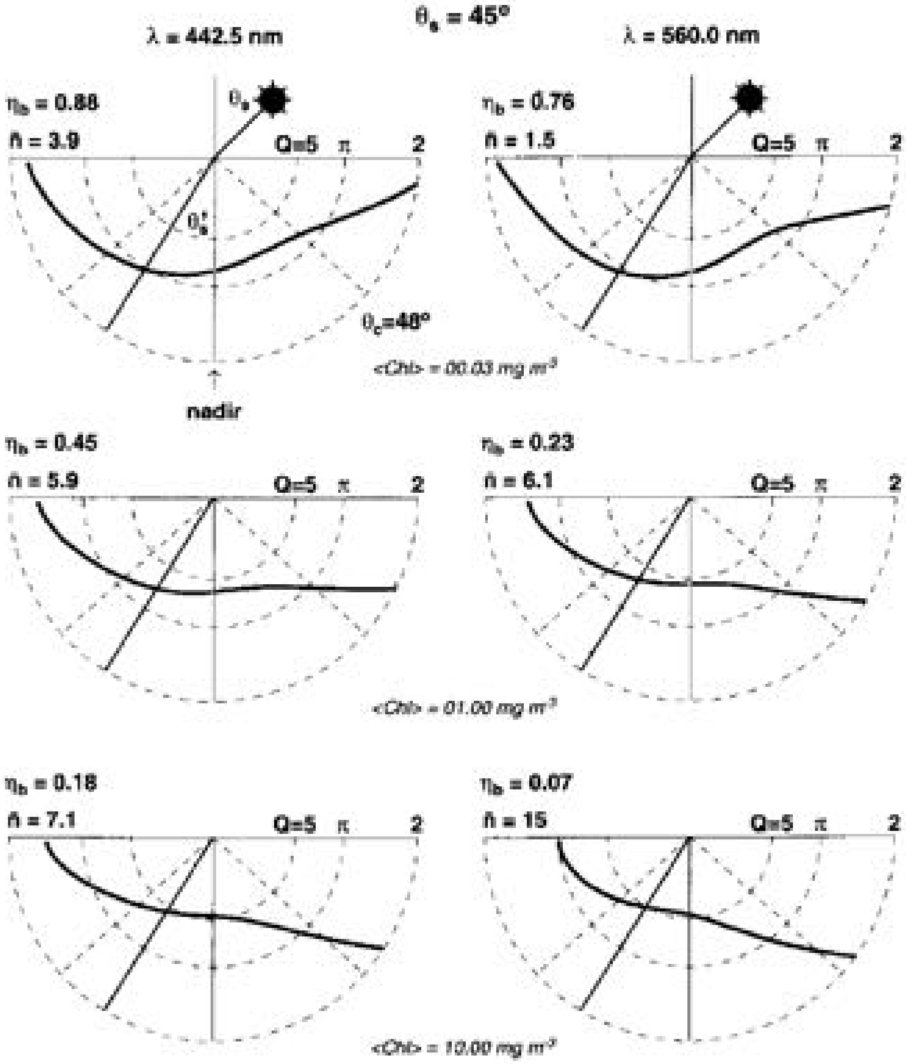
- Everything being equal in terms of IOPs:

  L_w at nadir and L_w at a viewing angle of 45° can be different by, say, about 10%.

  or

  L_w at nadir when the satellite crosses the equator and when it arrives above Villefranche will differ by, again, something like ~10% (change of solar zenith angle)

"Bidirectionality" of the ocean reflectance



$$\frac{L_u(0^-)}{E_u(0^-)}$$

Figure 10 in: Morel A. et al., 2002. Applied Optics 41(30), 6289-6306.

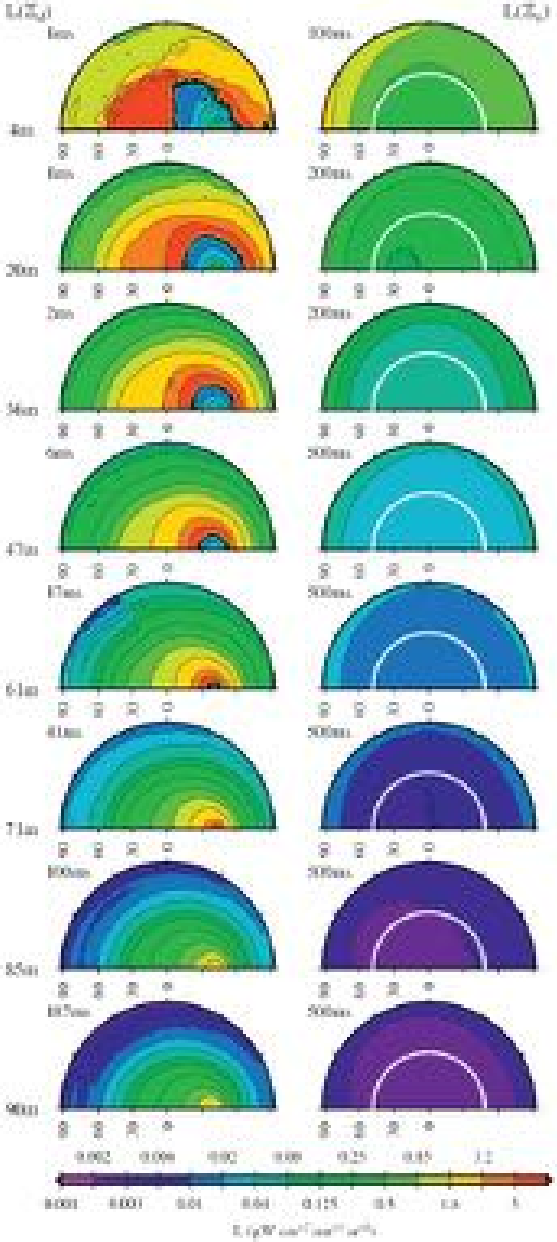


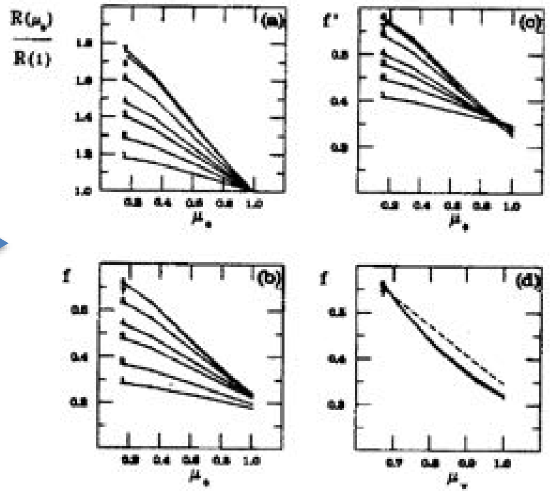
Figure 9 in: Antoine et al., 2013, Journal of Atmospheric and Oceanic technology, vol 30, doi: 10.1175/JTECH-D-11-00215.1

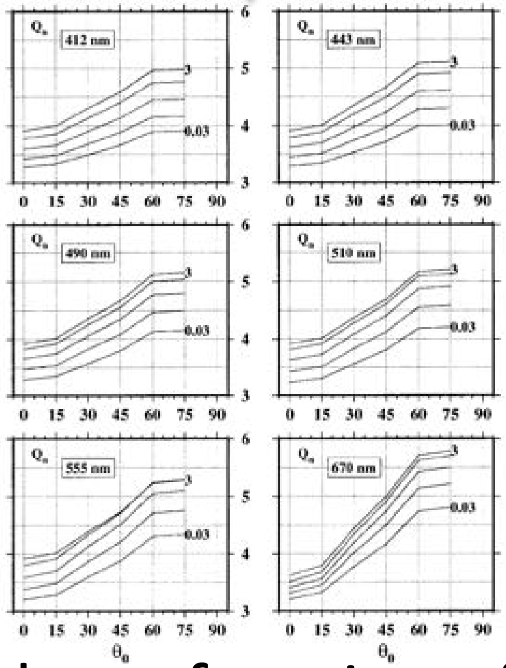
Full normalisation is needed

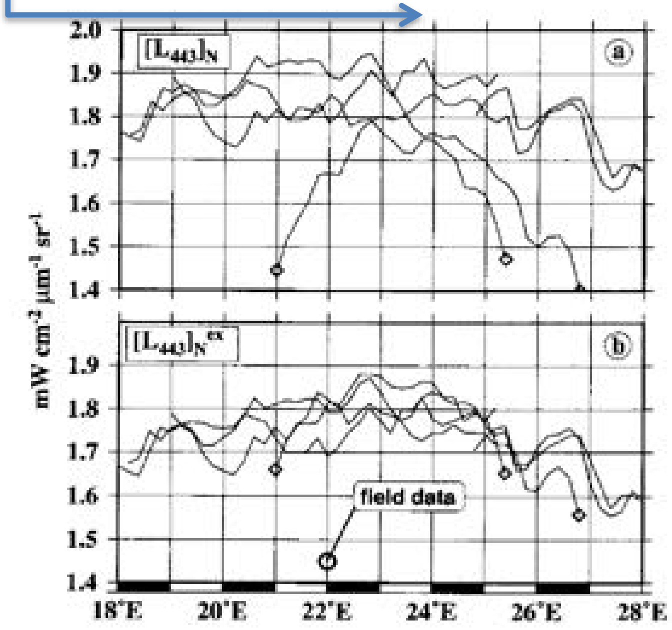
André Morel (Villefranche optics group) and coworkers developed a theoretical framework for the bidirectional aspects, and how to take it into account practically

Morel and Gentili, 1991, Applied Optics, 30, 4427-4438.
Morel and Gentili, 1993, Applied Optics, 32, 6864-6872.
Morel and Gentili, 1996, Applied Optics, 35, 4850-4862.
Morel, Antoine and Gentili, 2002, Applied Optics, 41, 6289-6306.
Voss, Morel, and Antoine. Biogeosciences, 4, 781-789.

$$Q = \frac{E_u(0^-)}{L_u(0^-)} \quad \text{and} \quad f = \frac{E_u(0^-)}{E_d(0^-)}\frac{a}{b_b}$$







f/Q described as a function of Chl and geometry

Apparent Optical Properties (AOPs)

The idea is to define quantities that:

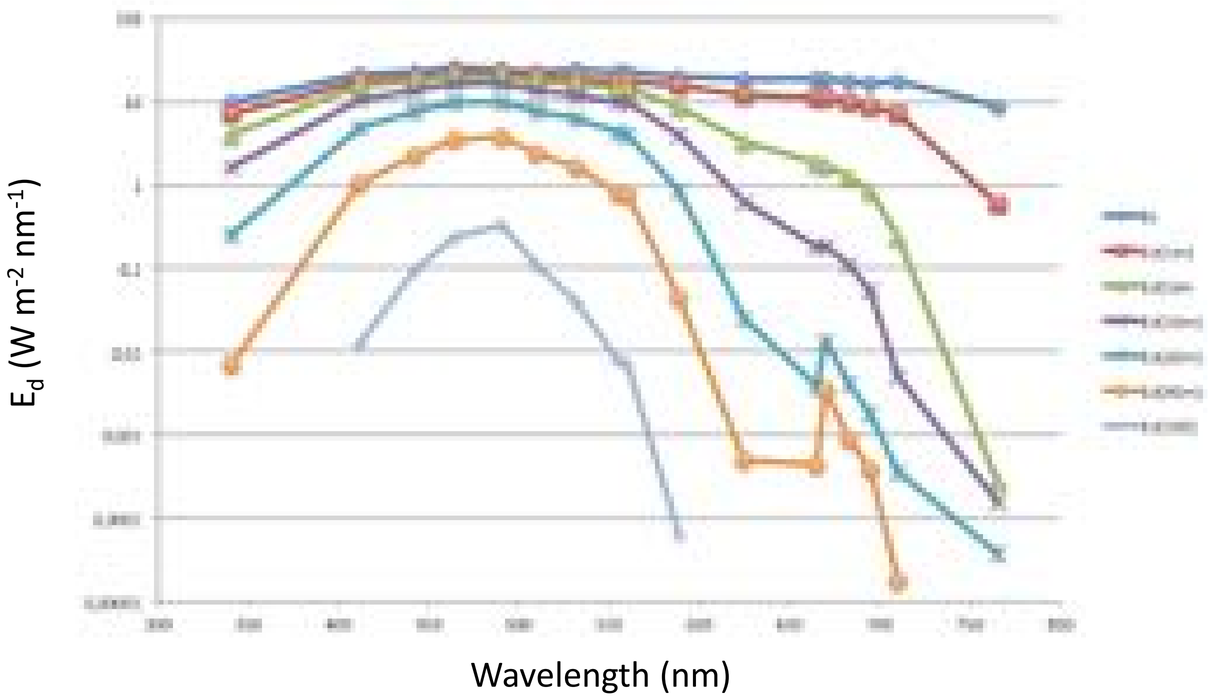
1) can be relatively easily determined from in situ measurements, without having to use overly sophisticated and difficult-to-handle instrumentation and,

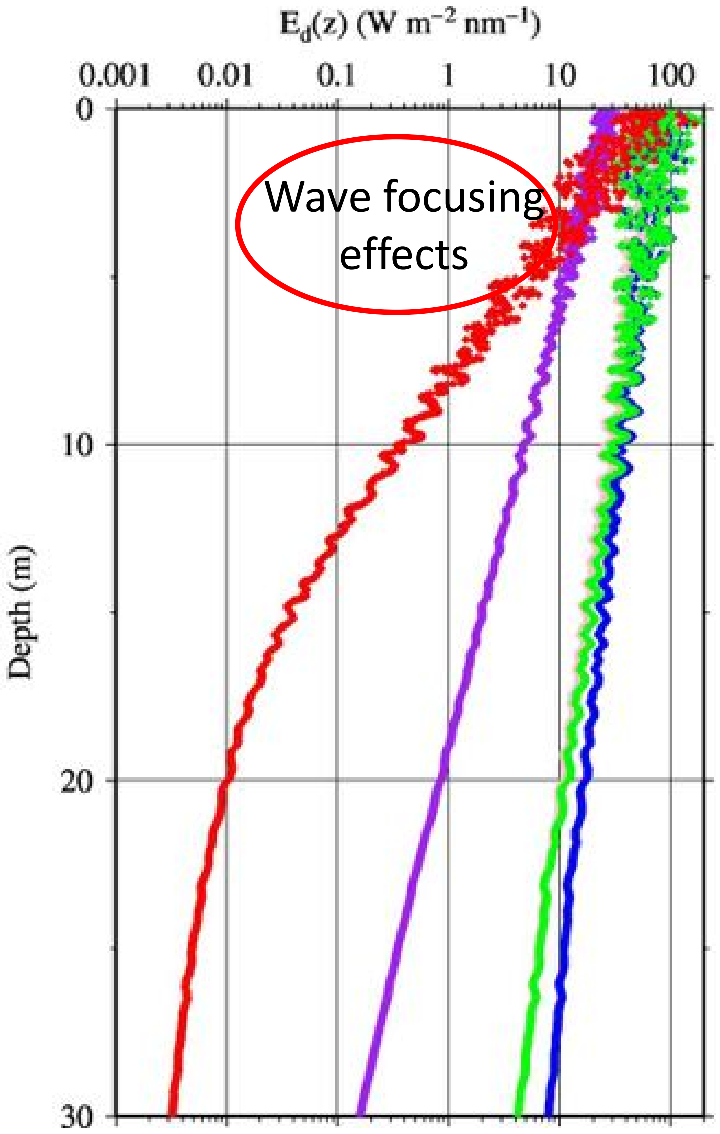
2) Are related to the quantities of interest, such as the chlorophyll concentration or the amount of particles

That's where the concept of "Apparent Optical Properties" (AOPs) comes into play

These quantities have to be related to the IOPs if we want them to be useful to determine "quantities of interest" (chlorophyll, particles…), and they have to be only weakly depending on environment conditions to be useful.

Apparent Optical Properties (AOPs)



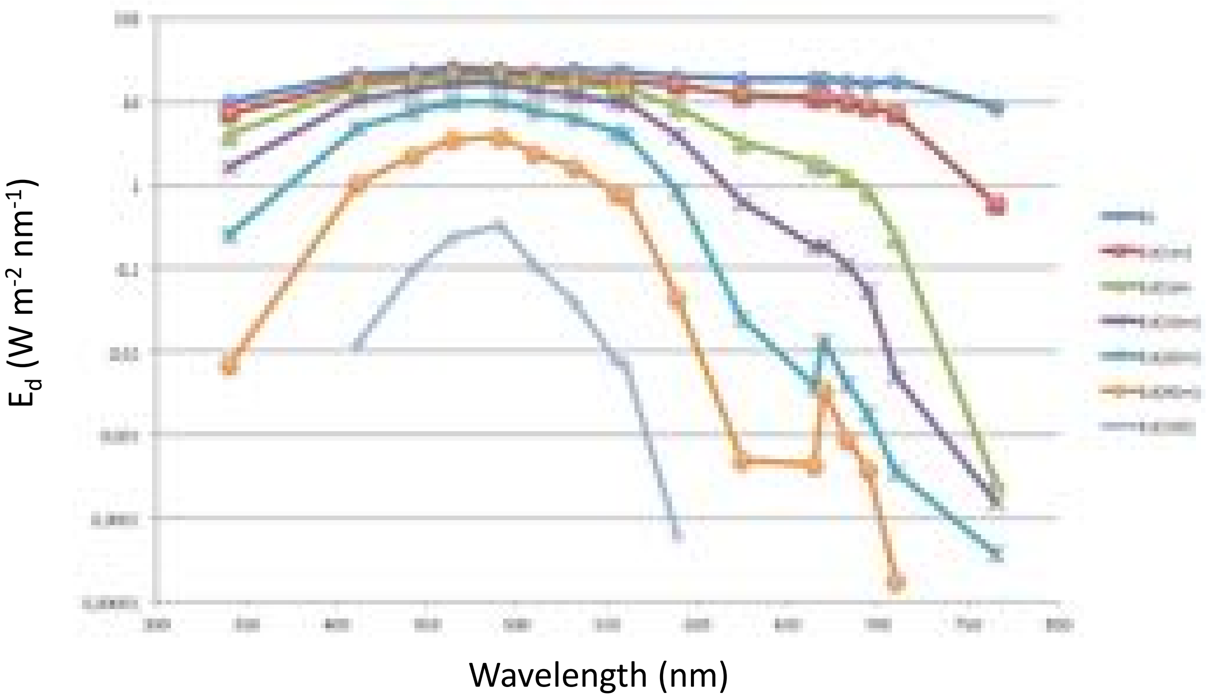


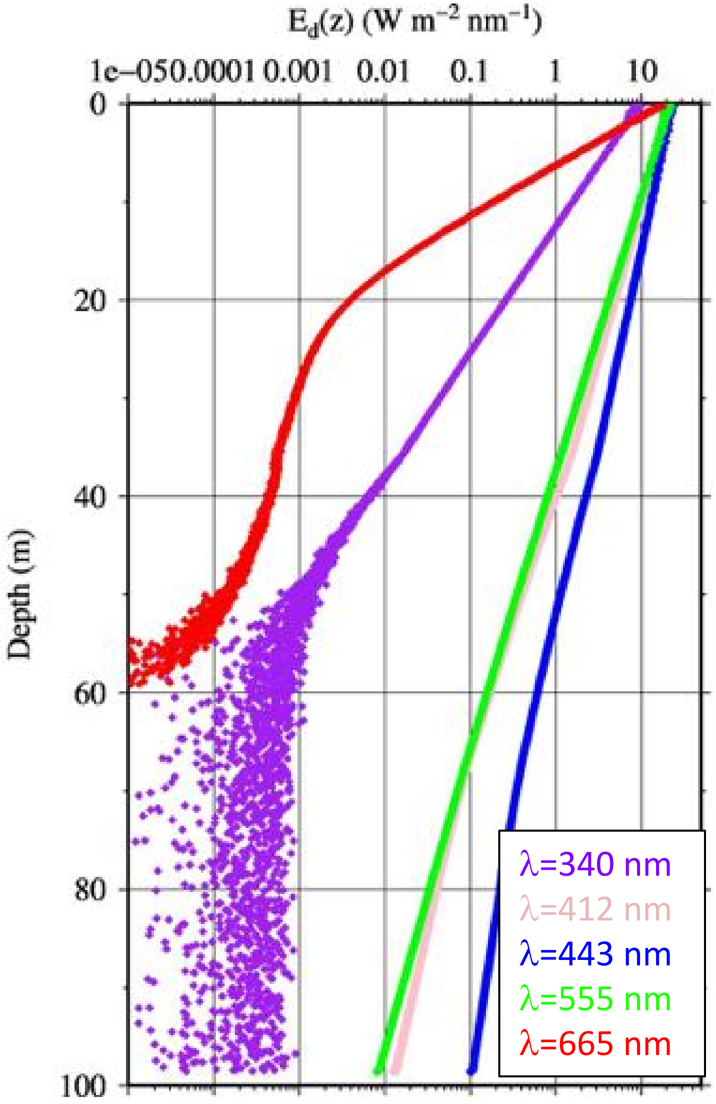
$$K_d(z,\lambda) \equiv -\frac{1}{E_d(z,\lambda)}\frac{dE_d(z,\lambda)}{dz}$$

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

m^{-1}

Apparent Optical Properties (AOPs)





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

m^{-1}

Apparent Optical Properties (AOPs)

Practically, K_d can be derived in a number of ways, e.g.:

$$K_d(\lambda) = -\frac{\log\left[E_d(z_1,\lambda) / E_d(z_2,\lambda)\right]}{z_2 - z_1}$$

Local K_d realisation at any given depth ($z_2=z_1+\Delta z$, with Δz small)

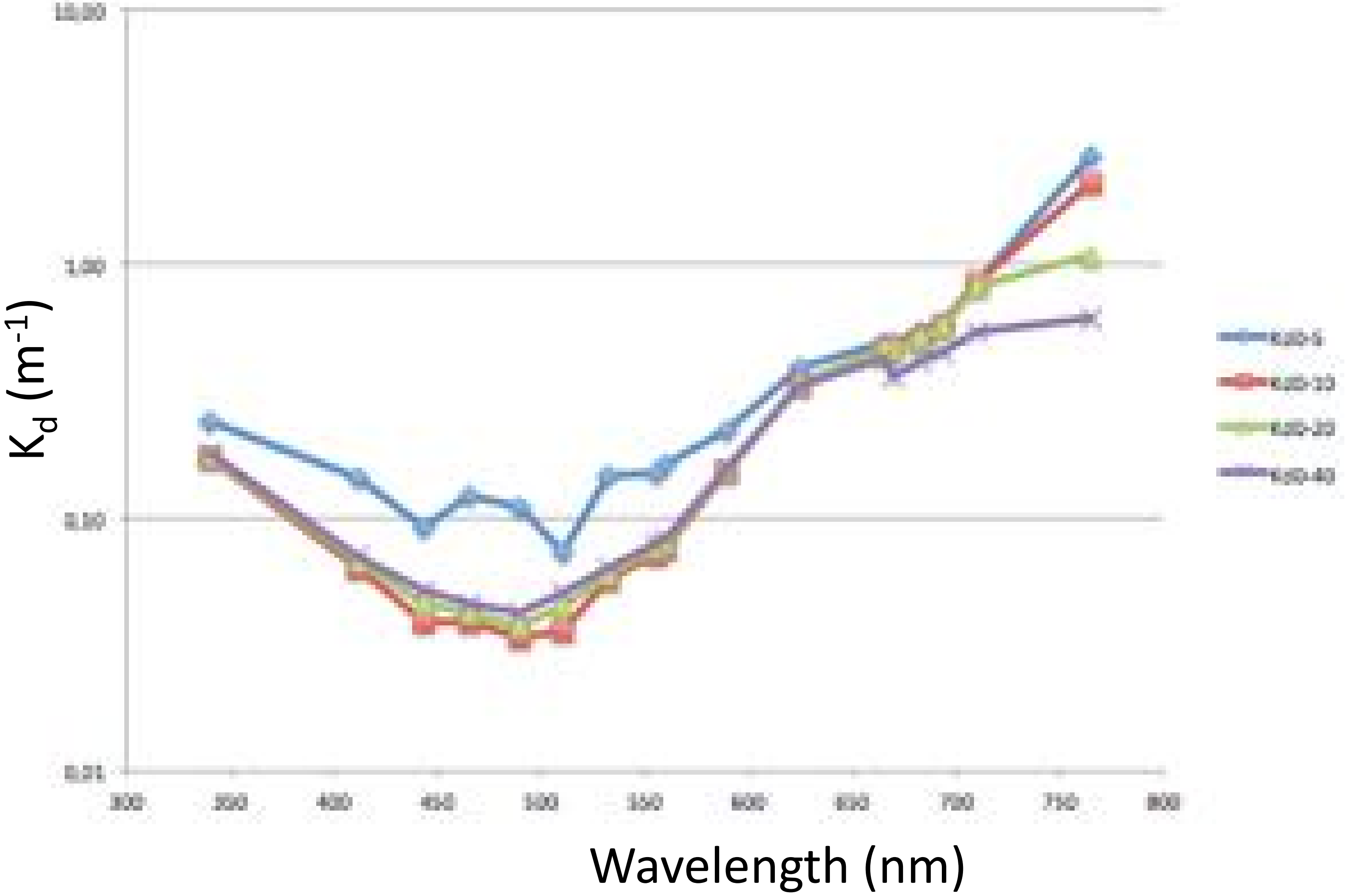
$$K_d = -\frac{\log\left[E_d(z) / E_d(0^-)\right]}{z}$$

K_d over layers of any depth from the surface ("0-" means just below the surface)

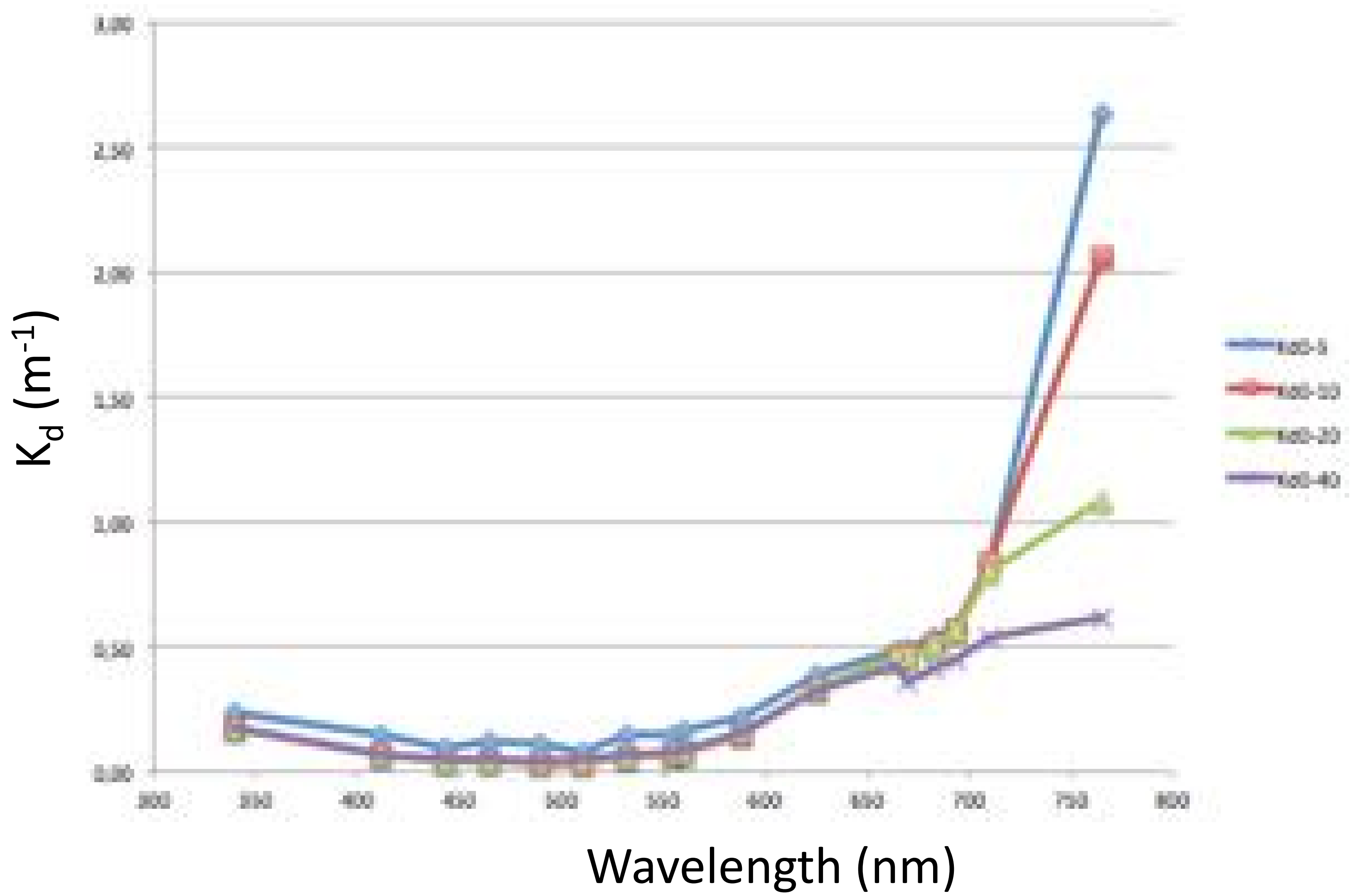
$$K_{d,av}(\lambda) = \frac{\int_0^z K_d(z,\lambda) E_d(z,\lambda) dz}{\int_0^z E_d(z,\lambda) dz}$$

An "irradiance-weighted K_d"
Kirk; J.T.O., 2003. Limnol. Oceanogr., 48(1), 2003, 9–17

Apparent Optical Properties (AOPs)



Apparent Optical Properties (AOPs)



Apparent Optical Properties (AOPs)

This slide is borrowed from Curt Mobley's IOCCG lecture in 2016

Pros and Cons of K_d's

Pros:
- 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 (e.g., Gershun's equation: $a = K_{net}\,\mu$)

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

Apparent Optical Properties (AOPs)

Other K functions

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

Replace E_d by:

L_u: often used to extrapolate L_u to the 0^- level

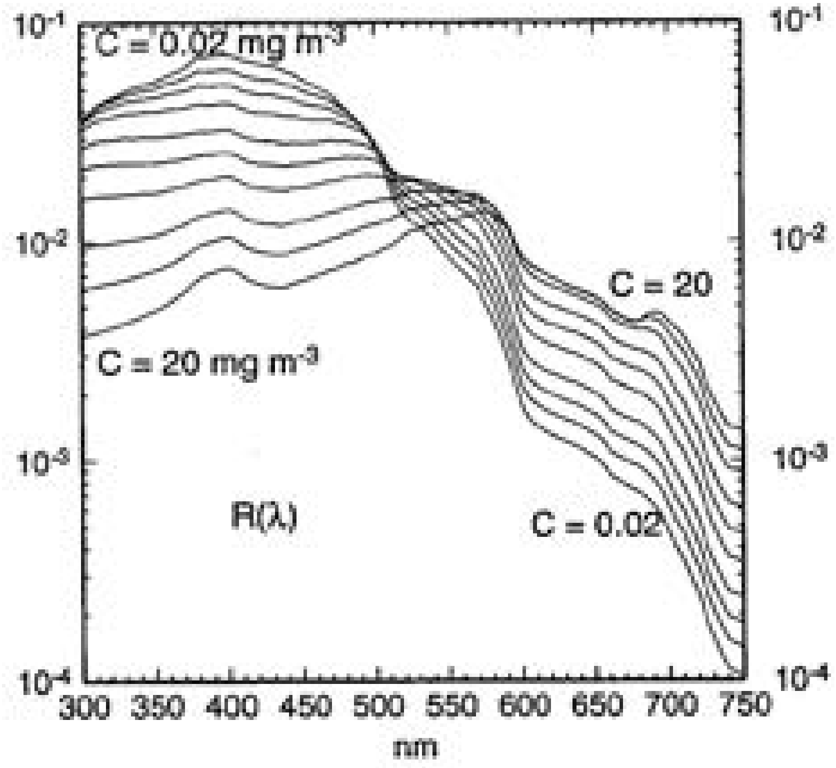
E_u: not commonly measured

$L(\theta,\phi)$: not commonly measured

Apparent Optical Properties (AOPs)

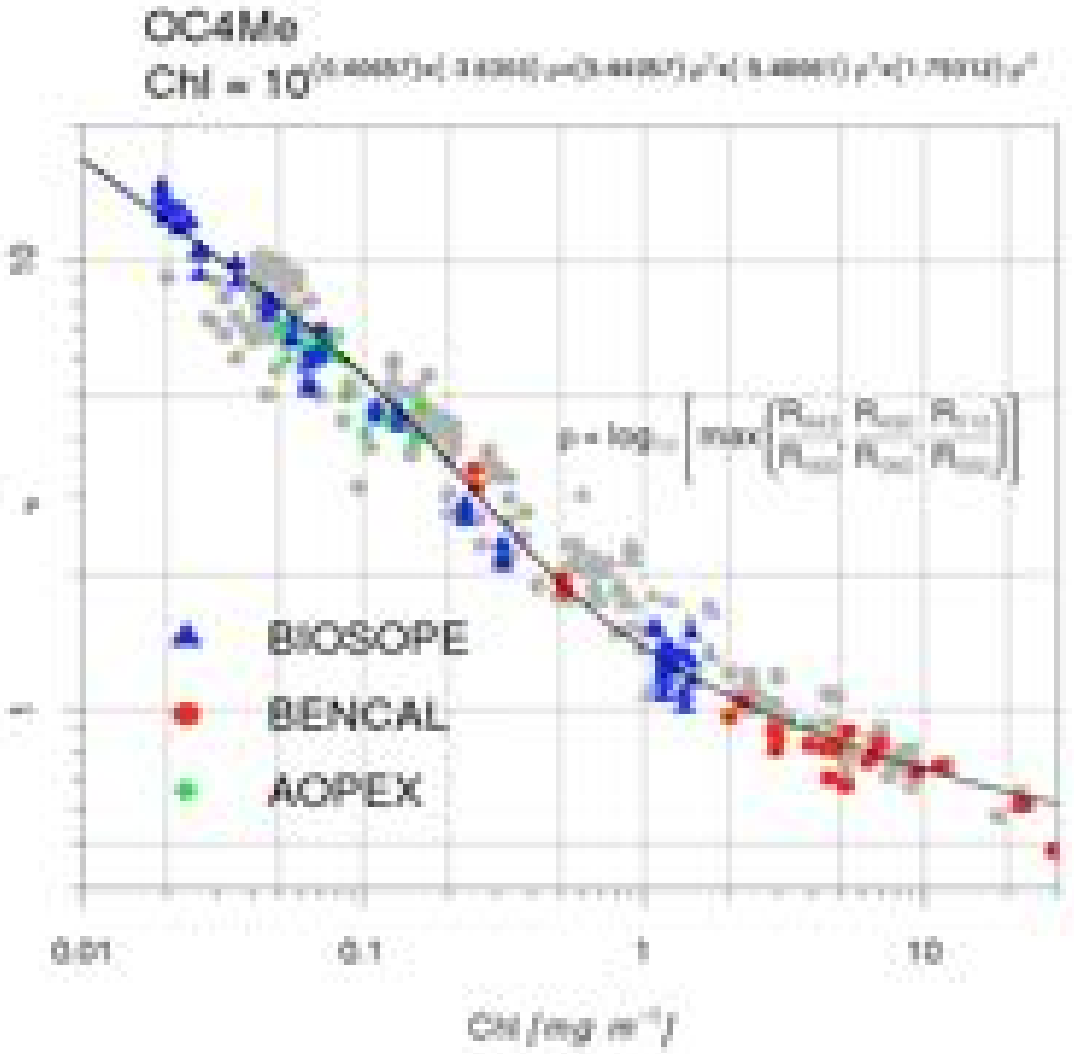
Irradiance reflectance

$$R(\lambda) = \frac{E_u(\lambda)}{E_d(\lambda)}, \quad \textit{often taken at } 0^-, \textit{ so } R(\lambda) = \frac{E_u(0^-, \lambda)}{E_d(0^-, \lambda)}$$



Morel, A., and D. Antoine, 1994. Heating rate within the upper ocean in relation to its bio-optical state, J. Phys. Oceanogr 24, 1652-1665.

Apparent Optical Properties (AOPs)



Band-ratio algorithms, using reflectance rations, have been the basis of satellite OCR for long

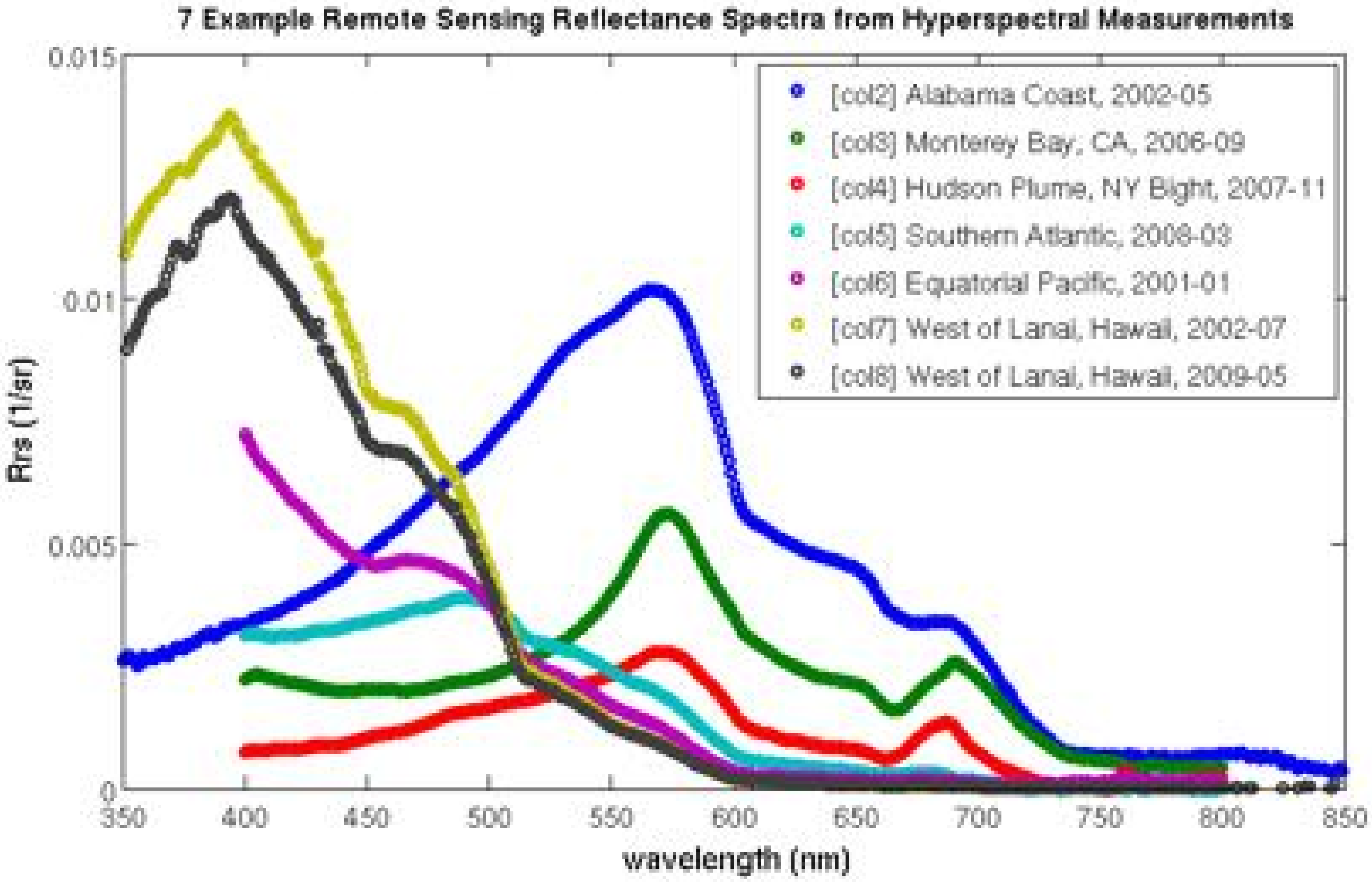
Apparent Optical Properties (AOPs)

Remote-sensing reflectance $R_{rs}(\lambda) = \frac{L_w(\lambda)}{E_S(\lambda)}$

Contrary to R, R_{rs} is defined above the surface

Similar behaviour and use than R

R_{rs}, however, is slightly less dependent on environment conditions than R is



https://seabass.gsfc.nasa.gov/wiki/Hyperspectral_Rrs_Examples

Apparent Optical Properties (AOPs)

Average (mean) cosines

For E_d (radiances over one hemisphere):

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

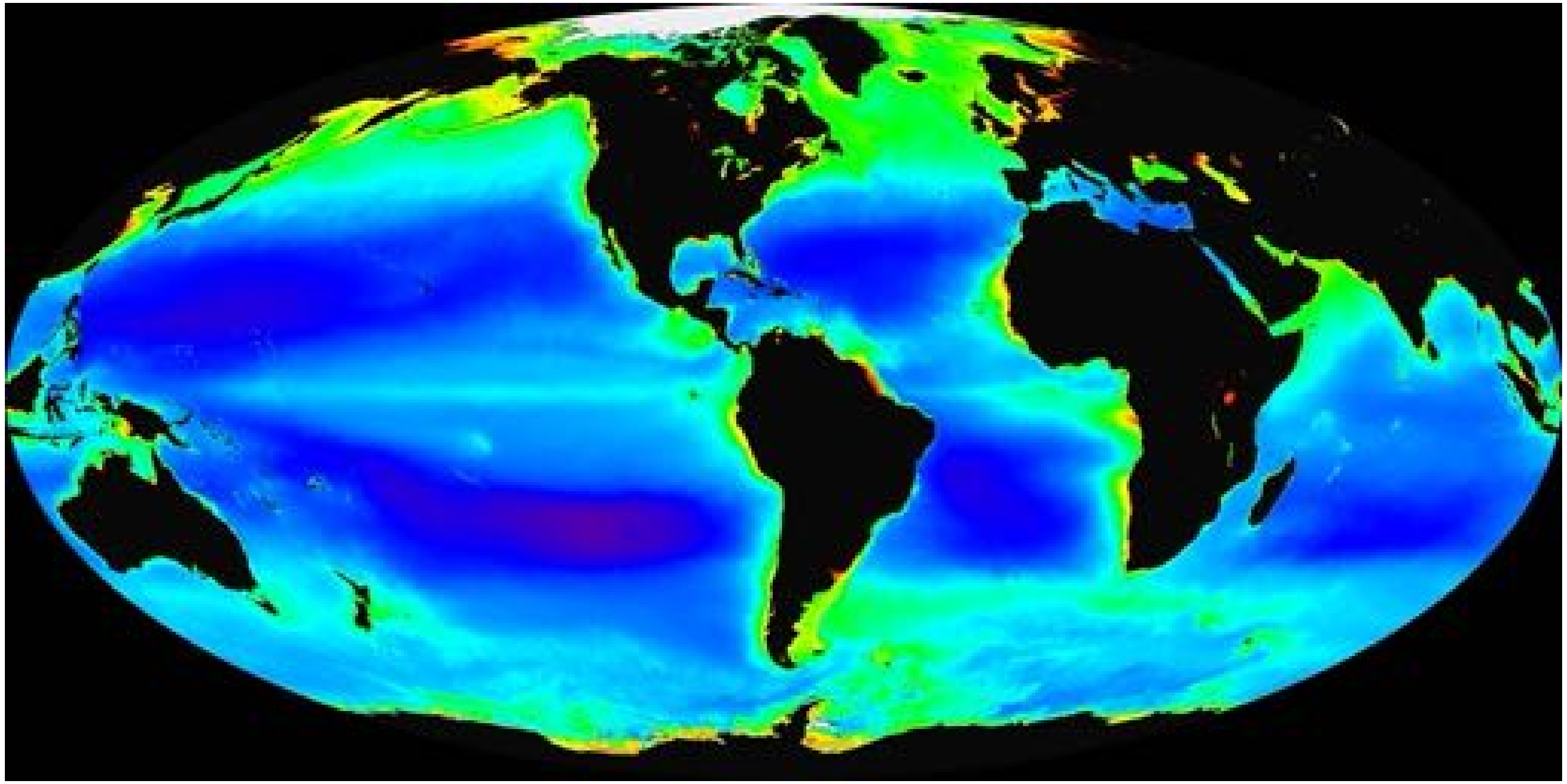
The more diffuse the radiance field, the smaller μ_d is.

For net irradiance E_d-E_u (full radiance distribution):

$$\bar{\mu} = \frac{\int_0^{2\pi} \int_0^{\pi} L(\theta,\phi) \cos\theta \, \sin\theta \, d\theta \, d\phi}{\int_0^{2\pi} \int_0^{\pi} L(\theta,\phi) \sin\theta \, d\theta \, d\phi} = \frac{E_\mathrm{d} - E_\mathrm{u}}{E_\mathrm{o}}$$

The use of AOPs

K_d's: how much light at what depth (photosynthesis)
K_d's: how much heat is absorbed along the vertical (physics)
R or R_{rs}: how much chlorophyll is in there? (e.g., satellite band ratio algorithms)



SeaWiFS global Chl composite

From AOPs back to IOPs

Examples:

Gershun's law (Gershun 1939). Valid without internal radiative sources such as Raman scattering or fluorescence (in other words without inelastic scattering)

$$a(z)\overset{o}{E}(z) = -\frac{d[E_d(z) - E_u(z)]}{dz}$$

Development by Zaneveld, R.J.V., 1989: An asymptotic closure theory for irradiance in the sea and its inversion to obtain the inherent optical properties. Limnol. Oceanogr., 34, 1442-1452

$$b_b(z) = \frac{\mathrm{RSR}(z)[K(\pi, z) + a(z)]}{(1/2\pi) - \mathrm{RSR}(z)}$$

Where:

$$\mathrm{RSR}(z) = \frac{L(\pi, z)}{\overset{o}{E}_d(z)} \quad \text{and} \quad K(\pi, z) = -\frac{1}{L(\pi, z)}\frac{dL(\pi, z)}{dz}.$$

From AOPs back to IOPs

Examples:

Gers
scat

Deve sea
and 52

Are we really using this ?

Sometimes, yes

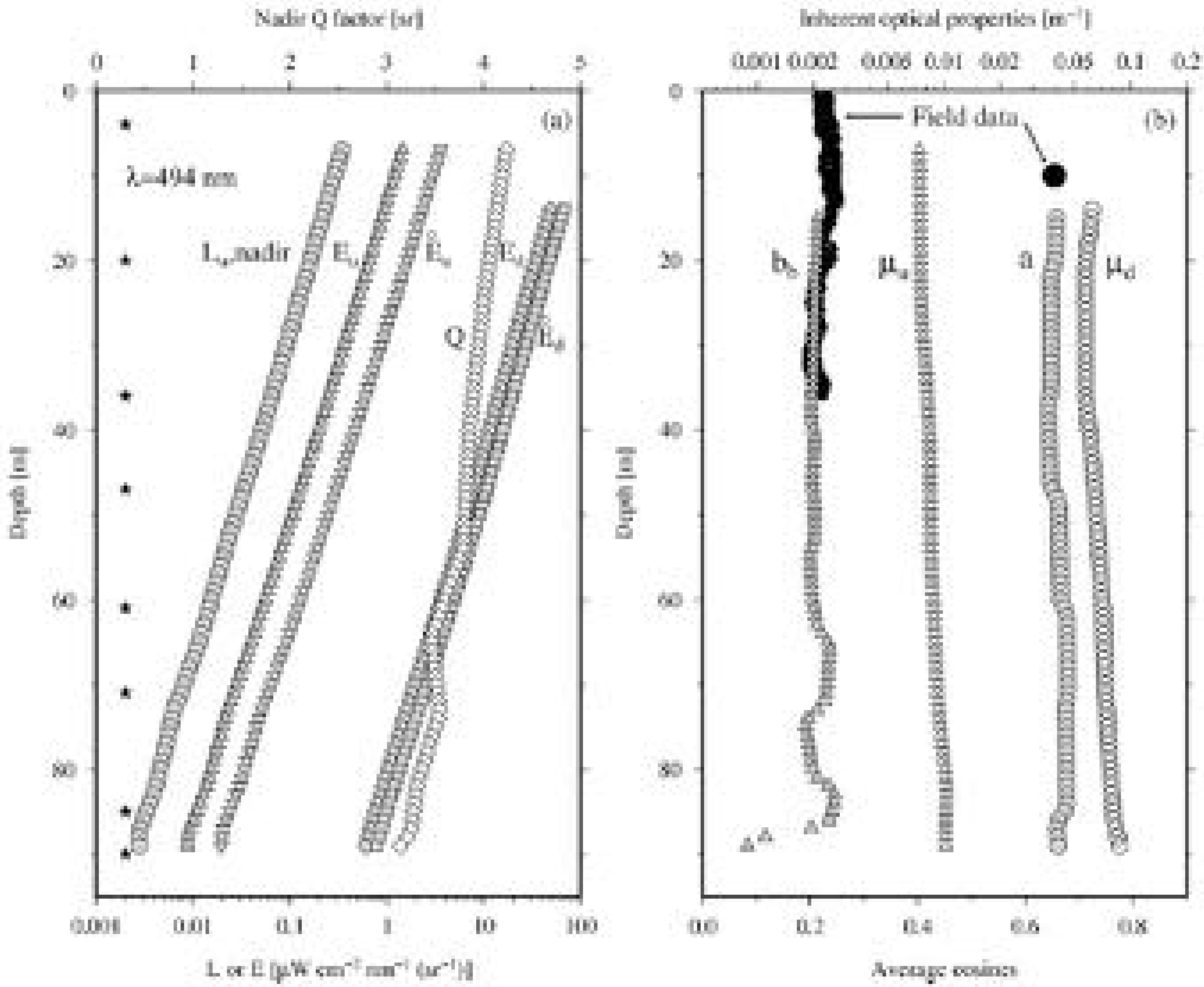


Figure 11 in: Antoine et al., 2013, Journal of Atmospheric and Oceanic technology, vol 30, doi: 10.1175/JTECH-D-11-00215.1

From AOPs back to IOPs

The real world is:

Most of the time, only L_u at nadir and E_d are measured, giving access to K functions only, and to R_{rs} after extrapolation

That is actually a rather poor description of the underwater environment

Therefore, to develop numerical inversion of AOPs into IOPs, one has to include a number of assumptions, introduce simplifications or some empiricism, and to rely on radiative transfer computations

From AOPs back to IOPs

The one you likely know:

$$R = f\,\frac{b_b}{a} \qquad or \qquad R = f'\,\frac{b_b}{a+b_b}$$

Can be combined with, e.g., (from Gordon, H.R., 1989. Limnol. Oceanogr. 34, 1389–1409)

$$K_d = \frac{1.0395\,(a+b_b)}{\mu_d}$$

So that (Morel et al., 2006, Deep-Sea Res, 53, 1439–1459):

$$a = 0.962\;K_d\,\mu_d\left(1-\frac{R}{f'}\right) \quad \text{and} \quad b_b = 0.962\;K_d\,\mu_d\left(\frac{R}{f'}\right)$$

If you measure R and K_d, you still have to know μ_d and f', or you have to "guess", i.e., to model them from chlorophyll

From AOPs back to IOPs

Another example: Gordon & Boynton, 1997, Applied Optics, 36(12), 2636-2641

Again, they used Gershun

$$a(z)\overset{o}{E}(z) = -\frac{d[E_d(z) - E_u(z)]}{dz}$$

And:

$$R = f\frac{b_b}{a} \qquad with\ f = 0.33, \quad or \quad b_b = 3Ra$$

Otherwise, you can enter into the real of semianalytical algorithms, e.g., the "GSM" (Garver and Siegel, 1997. J. Geophys. Res. 102, 18607–18625. Maritorena et al., 2002, Applied Optics, 41(15)):

$$\hat{L}_{wN}(\lambda) = \frac{tF_0(\lambda)}{n_w^2}\sum_{i=1}^{2} g_i\left\{\frac{b_{bw}(\lambda) + b_{bp}(\lambda_0)(\lambda/\lambda_0)^{-\eta}}{b_{bw}(\lambda) + b_{bp}(\lambda_0)(\lambda/\lambda_0)^{-\eta} + a_w(\lambda) + \mathrm{Chl}\, a_{\mathrm{ph}}{}^*(\lambda) + a_{\mathrm{cdm}}(\lambda_0)\exp[-S(\lambda - \lambda_0)]}\right\}^i.$$

A few last things

Polarisation

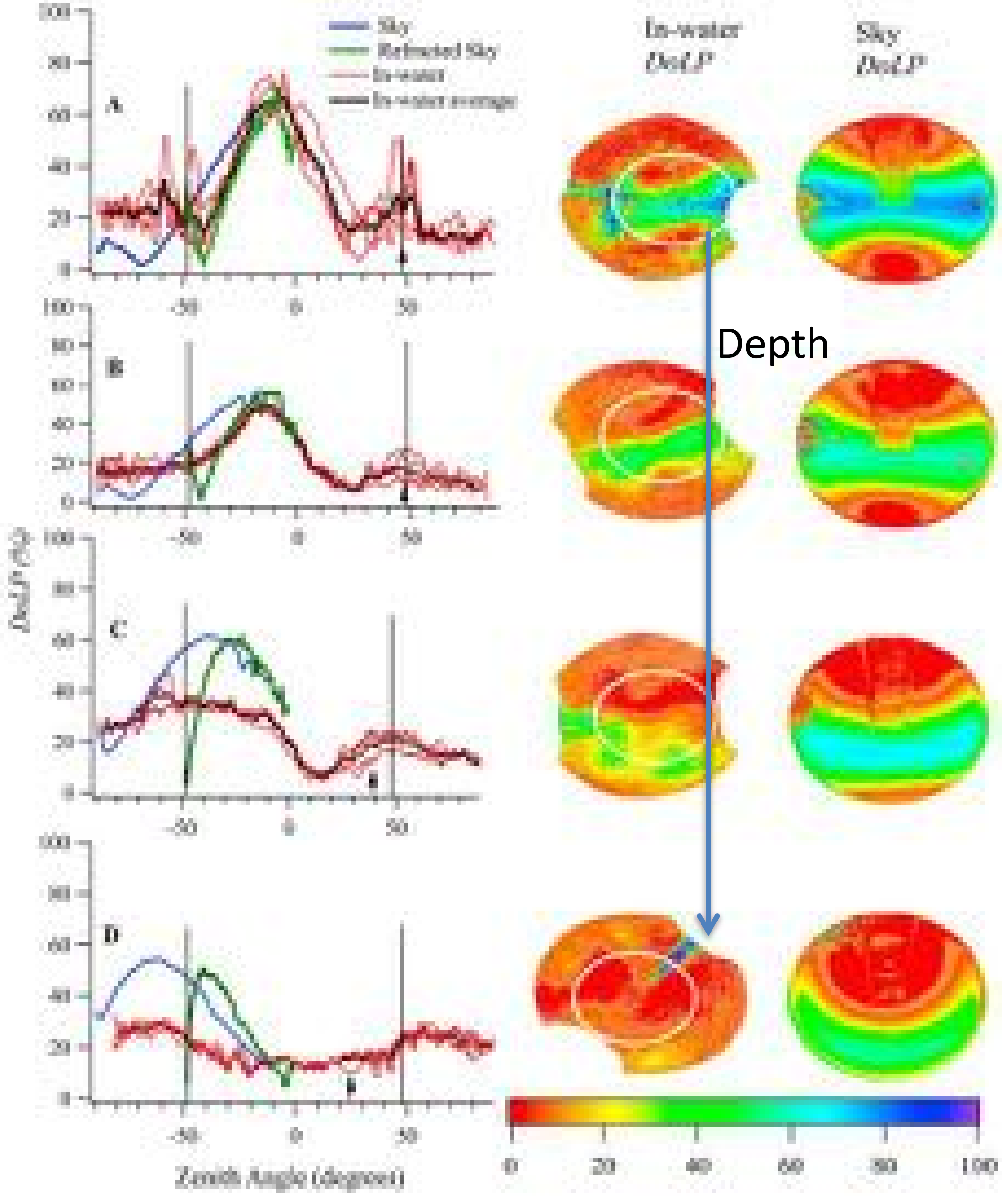
Quick summary:

- Related to the orientation of the Electric fields (see Dariusz Stramski's lecture)
- Linear or circular
- Described through the Stokes vector [I, Q, U, V]
- Why can this be of interest?

  - Because polarisation (degree of) depends on the size distribution, shape, and index of refraction of particles
  - Because reflected solar light at the air-sea interface is polarized so can be "eliminated" by using appropriately oriented polarized filters

- Note: radiative transfer (John Hedley's lectures) can be performed either by ignoring ("scalar") or by taking into account ("vector") polarisation. Remind that in the former case, radiances can be in error by a few % (up to about 10%)

Polarisation



Reproduced and quoted from Fig. 5 in Bhandari et al., J. Geophys. Res., 116, , C00H10, doi:10.1029/2011JC0073202011:

“Angular distribution of DoLP … Graphs show the DoLP along the solar principal plane. The (middle) in-water and (right) sky data are given. Also shown in graph is the DoLP of the refracted skylight, including polarization effects due to the surface”

Data from the Santa Barbara Channel, Sept. 2008, “DPOL” instrument by K. Voss

The asymptotic regime

When at multiple optical depths, the shape of the radiance distribution, in relative terms, becomes invariant (“constant azimuthally and dependent only on the absorption and scattering properties”)

This distribution then becomes an IOP (independent of illumination conditions, and only dependent on absorption and scattering)

Upwelling radiances ($90° < \theta < 180°$) would be between about 2 and 4 orders of magnitude lower than the downwelling radiances, depending on the proportion between molecular and particle scattering, and on the ratio k_∞ / c

As far as I’m aware, full radiance distributions under this regime have never been measured

Zaneveld J.R.V. and H. Pak, 1972. J. Geophys. Res., 77(15), 2677-2680

Twardowski M. and A. Tonizzo, 2017. Optics Express, 25(15), https://doi.org/10.1364/OE.25.018122

Light at great depths:
The twilight zone

- Essentially all field measurements of radiometric quantities are performed within the upper layers of the ocean.
- For instance, we often use the 1% light-level as the depth above which all light-driven phenomena (e.g., photosynthesis) occur. Sometimes the 0.1% level is used.
- In geometrical depths, this can be from just a few meters to nearly 200m in the clearest oceanic waters
- There is still light deeper, actually, and it maybe still significant for a number of processes there, and for certain marine life forms with highly sensitive "detectors".
- Therefore, there is some interest these days in trying to measure light at those great depths (200-500m).
- Need special prototypes, with highly sensitive detector.

  See, e.g., Haag J.M. et al., 2014. Optics Express, 22(24), DOI:10.1364/OE.22.030074
- They measured light down to 440m!

http://www.esa.int/Our_Activities/Observing_the_Earth/Satellites_help_understand_what_fuels_the_twilight_zone

Binocular fish, (Winteria telescopa)

Thanks for your attention