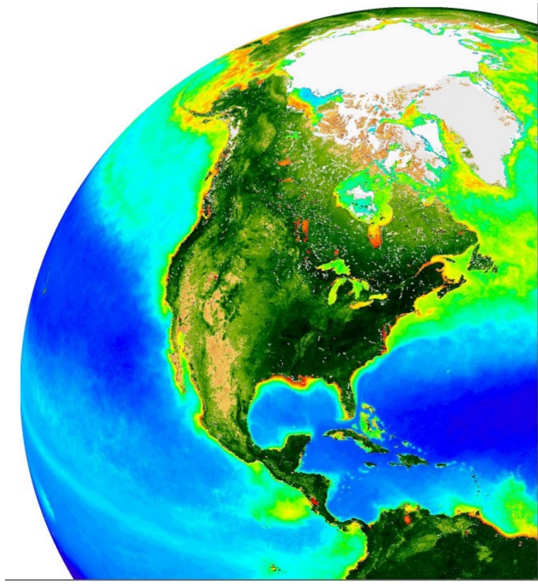
Calibration and Validation of Ocean Color Remote Sensing



Lecture 14: Light and Radiometry

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Lecture Content

- Radiometric terminology review
- Spherical coordinates, solid angles, and directions
- Radiance – the fundamental quantity in RTE, measuring radiance
- Irradiance – definitions and measurements
- Other Types of irradiance: plane, vector, scalar, PAR
- Uses of the radiometric measurements: Gershuns Law, hits to AOPs

Most of what is shown in this lecture was taken from the following sources:

- *http://www.oceanopticsbook.info*
- Mobley, C. D. (Editor), 2022. The Oceanic Optics Book, International Ocean Colour Coordinating Group (IOCCG), Dartmouth, NS, Canada, 924pp. DOI: 10.25607/OBP-1710
- *David Antoine; https://ioccg.org/wp-content/uploads/2022/09/radiometry-and-aops-d-antoine-sls2022.pdf*
- *Giuseppe Zibordi; https://ioccg.org/training/SLS-2012/Zibordi-2012_IOCCG_OC_Lectures_rev_part1.pdf*
- *Giuseppe Zibordi; https://ioccg.org/training/SLS-2012/Zibordi-2012_IOCCG_OC_Lectures_rev_part2.pdf*
- *Howard W. Yoon, 2013, NIST; https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1001&context=calcon*

Radiometry

Measurement of optical energy

Table 1-1. Radiometric quantities (Palmer J. M. 2010)

Radiometric quantity	Equation and units	Definition
Radiant Energy	$Q[\text{J}]$	
Radiant Power (radiant flux)	$\Phi = \frac{dQ}{dt}[\text{W}]$	Energy per unit time
Irradiance (radiant incidence)	$E = \frac{d\Phi}{dA_s}\left[\text{W}/\text{m}^2\right]$	Power per unit area that is incident on a surface. Irradiance is measured at the detector
Solid angle	$\Omega[\text{ sr }]$	The plane-angle concept extended to three-dimension
Radiance	$L = \frac{d^2\Phi}{dA_s d\Omega}\left[\text{W}/\text{m}^2\text{sr}\right]$	Power per unit area and per unit projected solid angle.

The Art of Radiometry, Palmer J.M. 2010

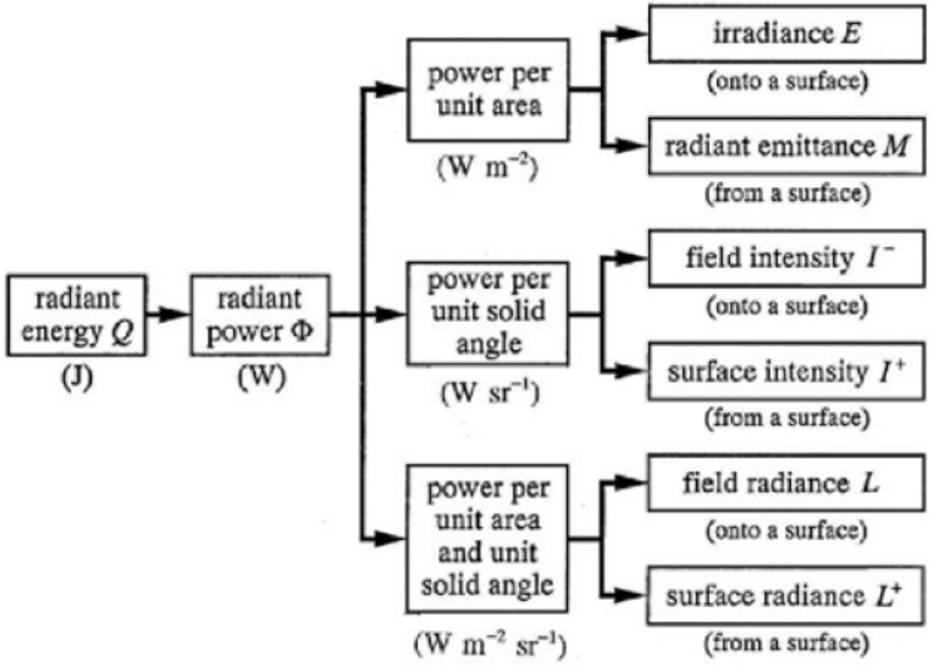


Figure 1.15: The hierarchy of radiometric concepts.

Mobley, C. D. (Editor), 2022. The Oceanic Optics Book, International Ocean Colour Coordinating Group (IOCCG), Dartmouth, NS, Canada, 924pp. DOI: 10.25607/OBP-1710

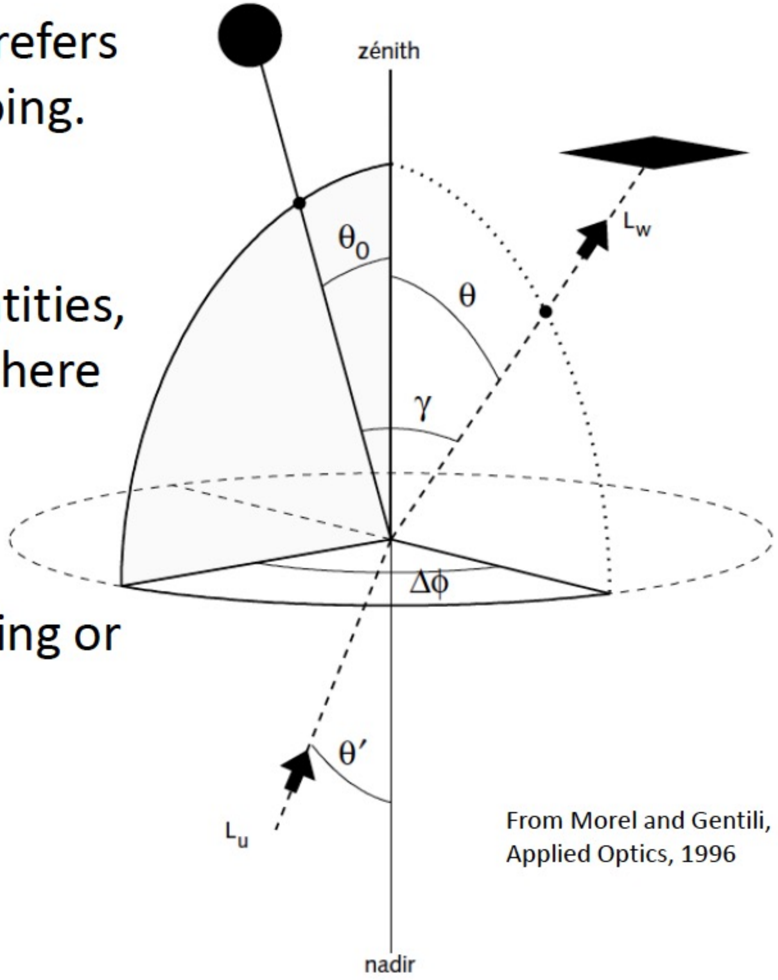
Terminology, units, angles (geometry)

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

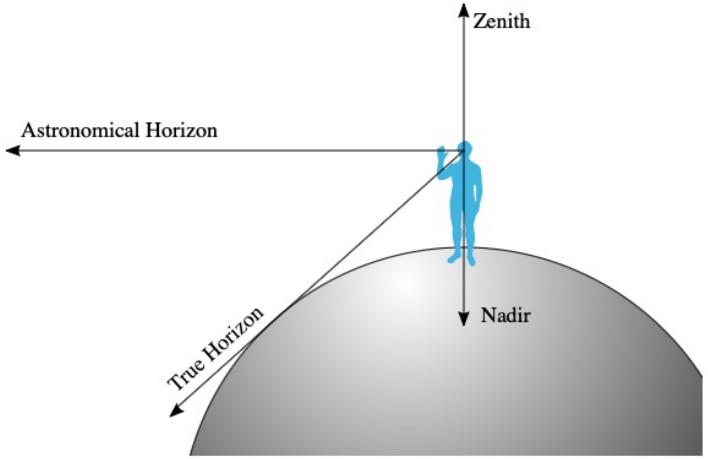
- When measuring radiometric quantities, the opposite is made: direction of where we point the instruments

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

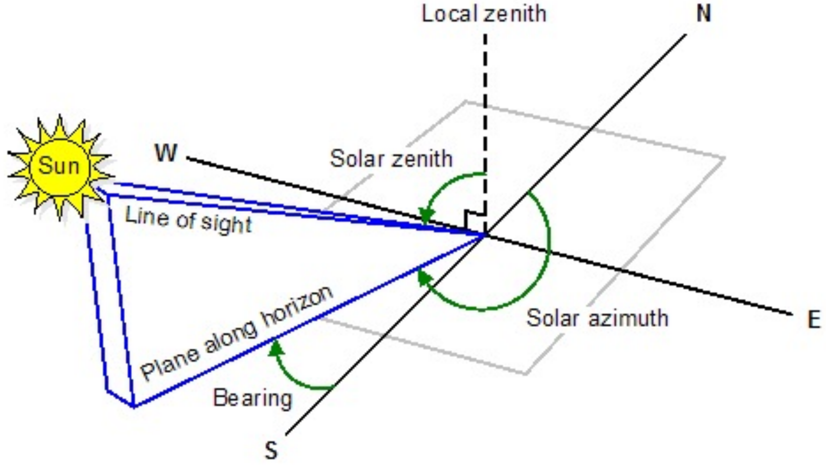
- Sun zenith angle: θ_s or θ_0
- View zenith angle: θ or θ_v
- Azimuth difference: $\Delta\phi$



From Morel and Gentili, Applied Optics, 1996



Zenith vs Nadir



Solar zenith & solar azimuth

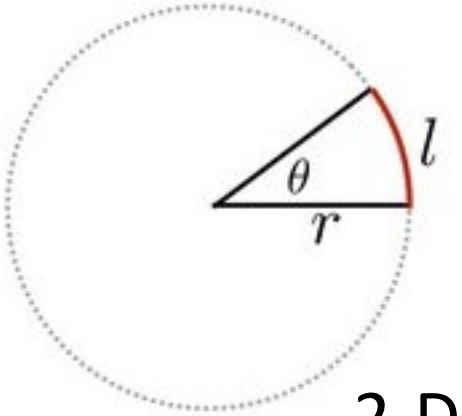
IOCCG Summer Lecture Series 2018. Lecture on *Radiometry and AOP*

Credit:David Antoine; https://ioccg.org/wp-content/uploads/2022/09/radiometry-and-aops-d-antoine-sls2022.pdf

Angles and Solid Angles

Angle: ratio of subtended arc length on circle to radius

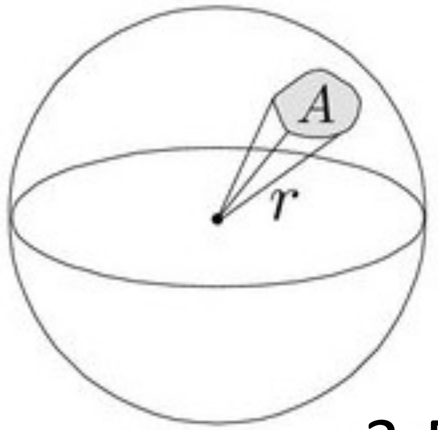
- $\theta = \frac{l}{r}$
- Circle has 2π radians



2-D

Solid angle: ratio of subtended area on sphere to radius squared

- $\Omega = \frac{A}{r^2}$
- Sphere has 4π steradians



3-D

Solid angle:

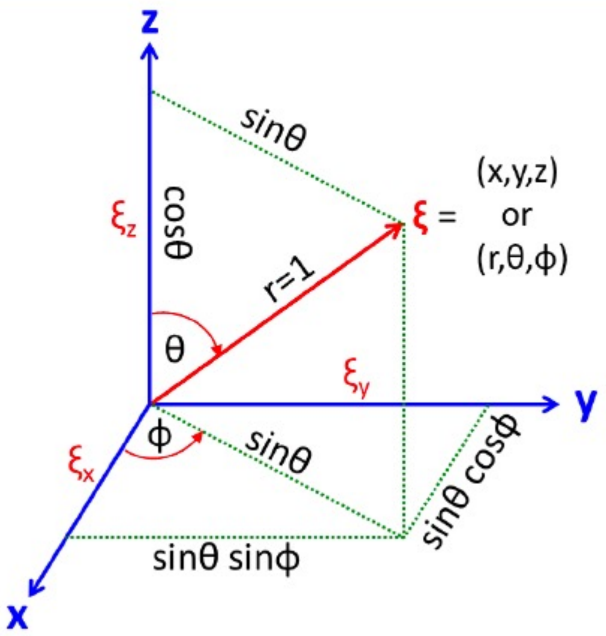
1. Defined as a 3-D angle
2. Is the angle subtended by any part of a spherical surface of unit radius at its center
3. Is represented by Ω
4. Is dimensionless, though we use steradian (sr) to indicate spherical angle

Example:
You are at the center of the Earth and want to know the solid angle of the 48 United State of the Earth's Surface.

Area of lower 48 = 8.08×10^6 km^2
Radius of the Earth = 6384 km

$\boldsymbol{\Omega} = 8.08 \times 10^6 \text{ km}^2 / (6384 \text{ km})^2 = 0.198$ sr

Spherical coordinates, angles, and computation of solid angles



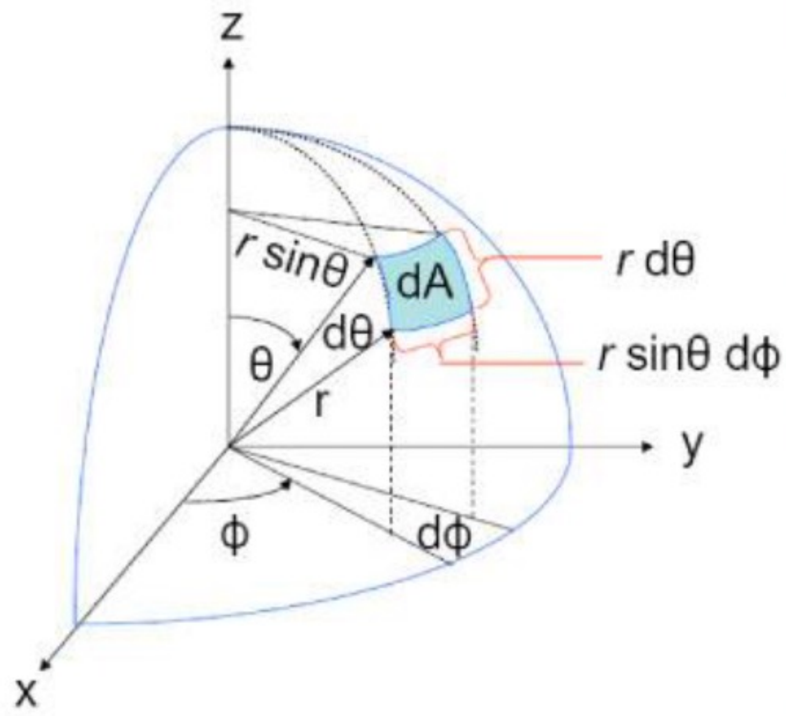
$\hat{\xi}$ is a unit vector specifying direction (θ, ϕ)

$$|\hat{\xi}| = 1 = \hat{\xi} \cdot \hat{\xi} = \xi_x^2 + \xi_y^2 + \xi_z^2$$

$$\begin{aligned} \hat{\xi} &= \xi_x \hat{x} + \xi_y \hat{y} + \xi_z \hat{z} \\ &= (\sin\theta\cos\phi)\hat{x} + (\sin\theta\sin\phi)\hat{y} + (\cos\theta)\hat{z} \end{aligned}$$

$$\theta = \cos^{-1}(\xi_z) \qquad \mu \equiv \cos\theta$$

$$\phi = \tan^{-1}\left(\frac{\xi_y}{\xi_x}\right)$$



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

The solid angle can also be defined by discretizing the area in terms changes in zenith and azimuth angles, which is needed in radiative transfer models (i.e. Hydrolight).

Radiance: the fundamental quantity

$$L(\vec{x}, t, \hat{\xi}, \lambda) \equiv \frac{\Delta Q}{\Delta t \Delta A \Delta \Omega \Delta \lambda}$$

$(\mathrm{J\ s^{-1}\ m^{-2}\ sr^{-1}\ nm^{-1}})$

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

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

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

Measuring radiance

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

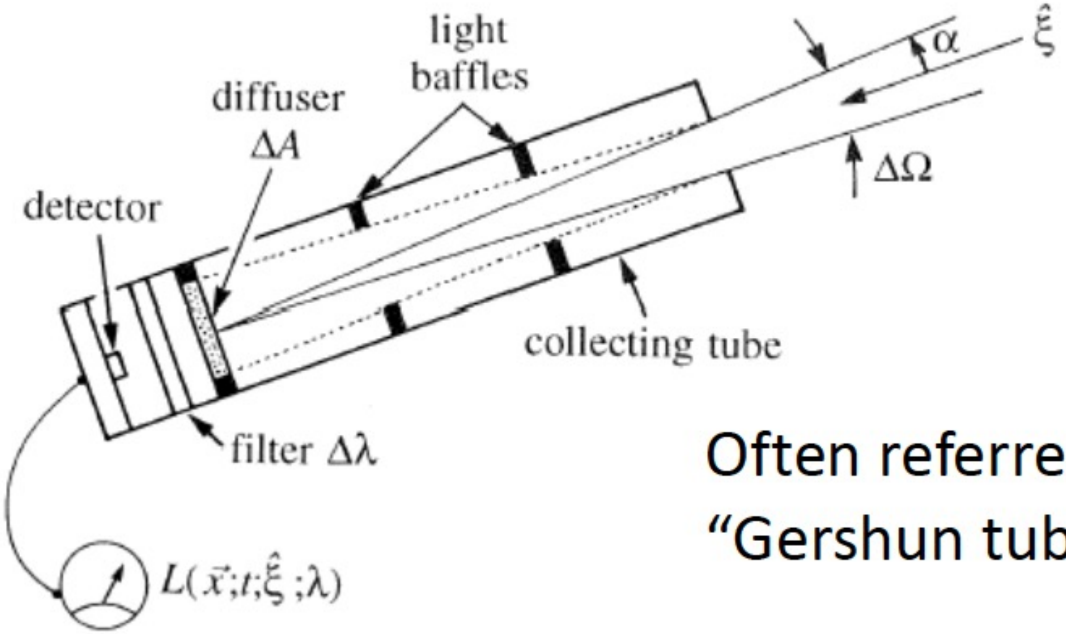


Figure: Schematic design of an instrument for measuring unpolarized spectral radiance.

Often referred to as a "Gershun tube"

Produces well collimated light

From: http://www.oceanopticsbook.info

Well Collimated Radiometers

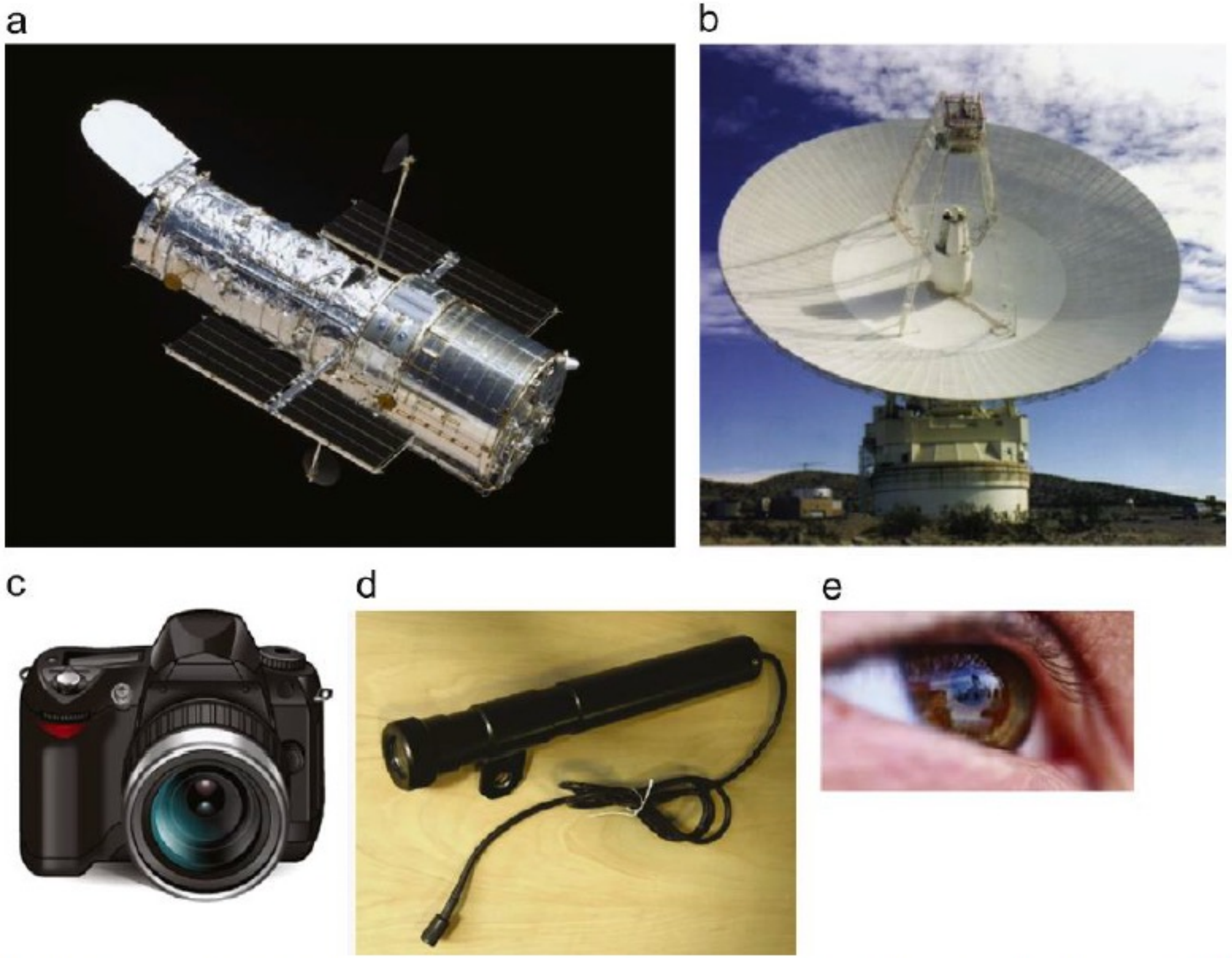
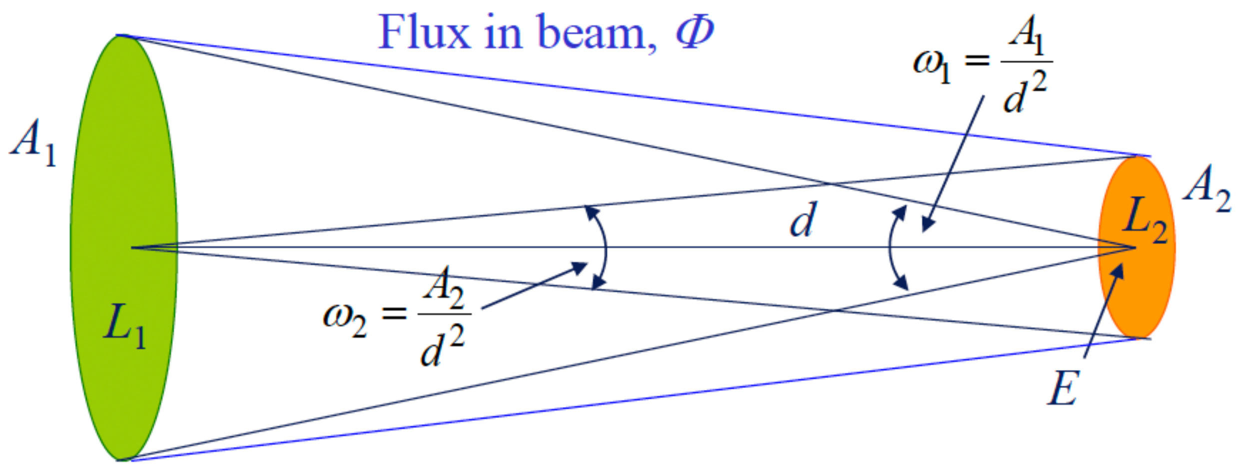


Fig. 15. (a) NASA's Hubble Space Telescope. (b) NASA's 64-m Goldstone radio telescope. (c) Digital photographic camera. (d) Gershun tube [120]. (e) Human eye.

Mishchenko (2014)

Invariance of radiance



From before,

$$E = L_1\,\omega_1$$
$$\Phi = E\,A_2$$
$$L_1 = \frac{E}{\omega_1} = \frac{\Phi}{A_2\,\omega_1}$$

It also must be true (from the definition of radiance)

$$L_2 = \frac{\Phi}{A_2\,\omega_1} = L_1$$

Invariance of Radiance

$$L_1 = L_2$$

Note we could also have said

$$L_1 = \frac{\Phi}{A_1\,\omega_2}$$

Throughput

$$A\,\omega = A_1\,\omega_{1-2} = A_2\,\omega_{2-1}$$
$$\left(\omega_{1-2} = \frac{A_2}{d^2}, \quad \omega_{2-1} = \frac{A_1}{d^2}\right)$$

n^2 Law of radiance

Radiance invariance between two media with different index of refractions

Snell's law

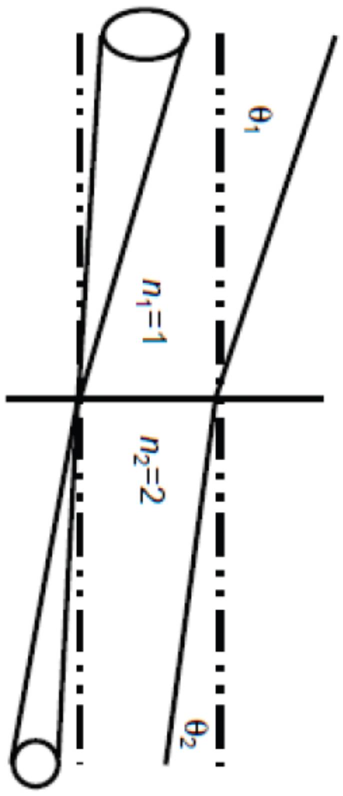
$n_1 \sin\theta_1 = n_2 \sin\theta_2$

$L_1 n_1^{-2} = L_2 n_2^{-2}$

Invariant across the lossless boundary

n^2 law of radiance

Zibordi &Voss, 2010



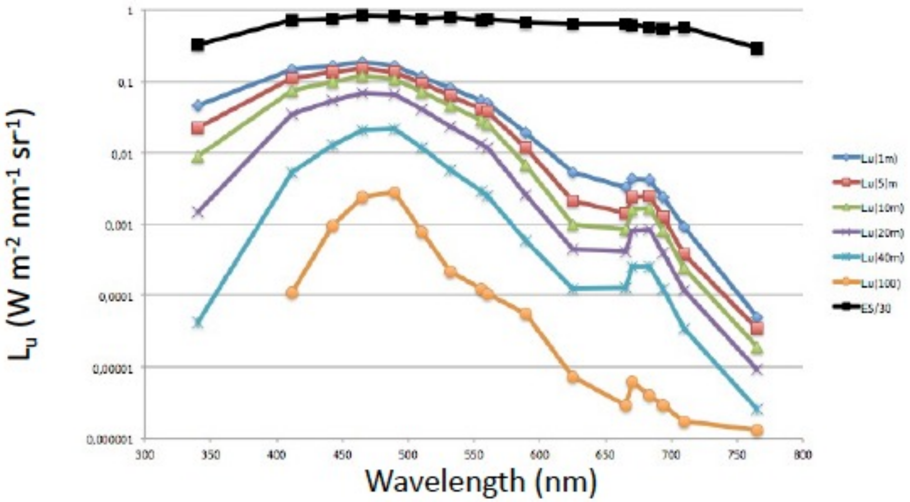
Palmer J.M, 2010

"For a light beam crossing the interface between two media with different refractive indices, the ratio of the radiance to the square of the the refractive index of the medium remains invariant when ignoring the reflective losses at the interface (i.e., ρ=0)"

$$L_2 = (1-\rho)\, L_1 \frac{n_2^2}{n_1^2}.$$

Note the changes in both the angle and the solid angle. In moving from a lower index of refraction to a higher index of refraction, both the angle and the solid angle decrease!

Spectra and vertical profiles of underwater upwelling radiances

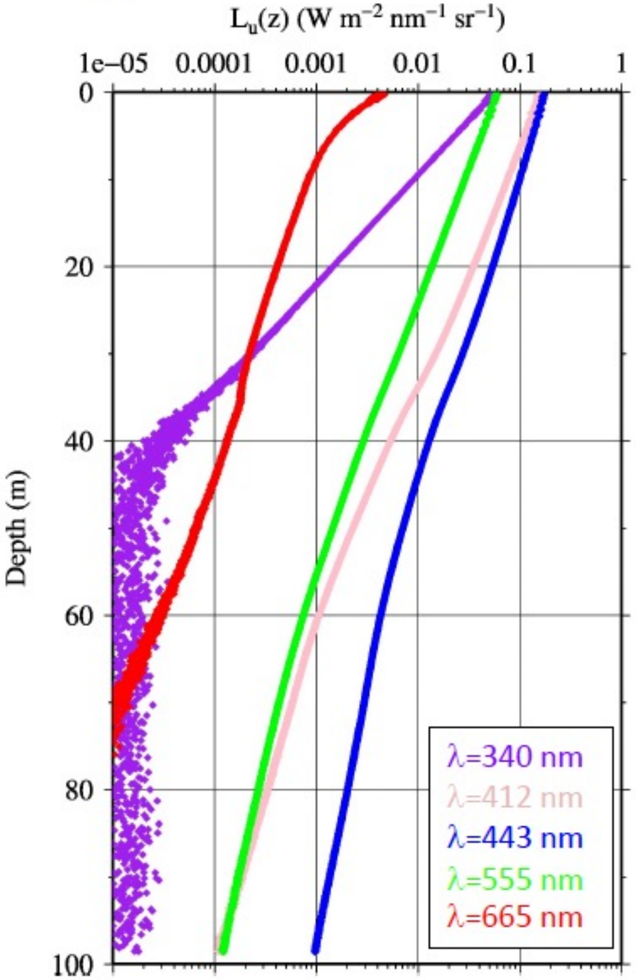


13th December 2015

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

The water-leaving radiance

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



If we measure the full **radiance distribution (all directions)** as a function of depth and spectrally, we have all we need for the RTE.

Radiance measurements depend on illumination conditions, such as sun elevation (solar zenith angle), cloudiness, atmospheric constituents, and air-sea surface properties.

The most common radiance sensors commercially available, typically use a Gershun tube design to measure radiance over a narrow field of view (solid angle).

Obtaining spectral measurements of the full radiance distribution is challenging! A few instruments have been created, but they are complex and expensive to create.

The most typical in-water radiance measurement made is the upwelling radiance at nadir, i.e. $L_u(z)$. Above water radiance measurements typically made are to look at the sky radiance and the above water radiance.

So WHY do we make radiance measurements

- For studies of optical closure of measurements
- For vicarious calibration of ocean color satellites – RADIANCE IT IS WHAT IS MEASURED BY THE SATELLITE SENSOR
- To validate satellite ocean color data products (derived from the satellite spectral radiance measurements)

A quick spin through radiance distribution measurements

Measuring radiance:
the 1st underwater radiance distribution

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

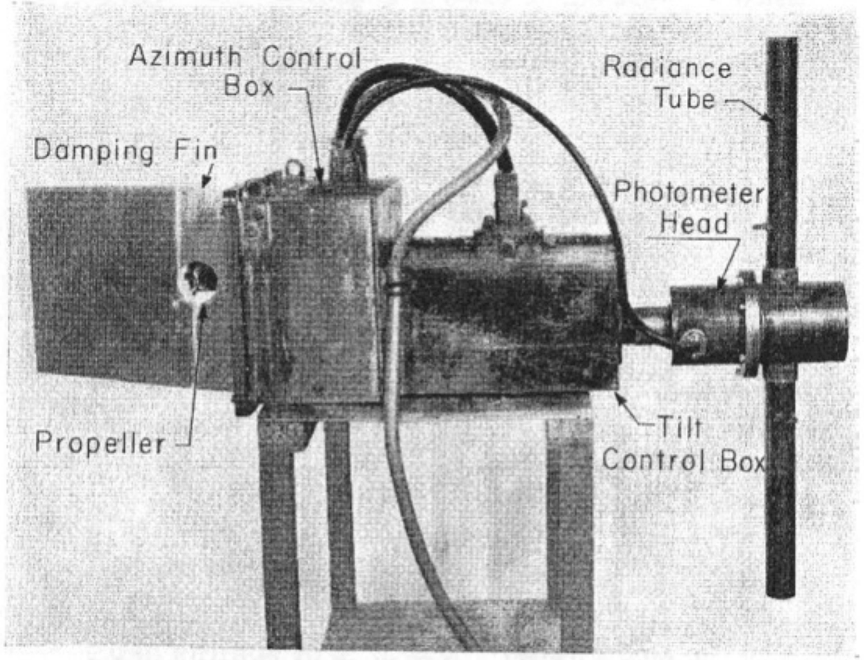
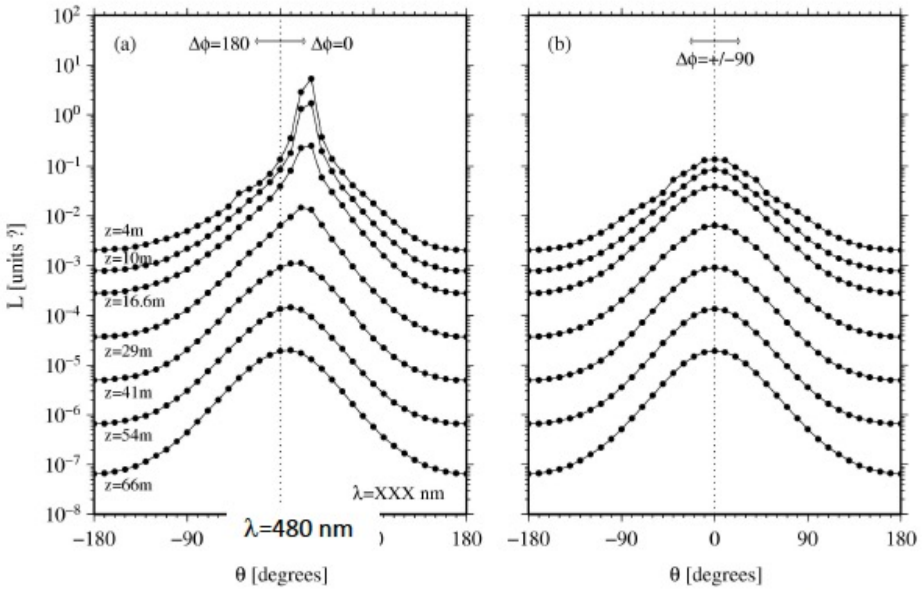


Fig. 8. Underwater radiance photometer (Tyler, 1960). The measuring head with its radiance tubes is on the right. The center box holds the tilt motor. The left box contains the gyrosyn compass and propeller-drive motor. The propeller can be seen through a hole in the damping fin on the left.

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

Unidirectional photometer with elevation scanning

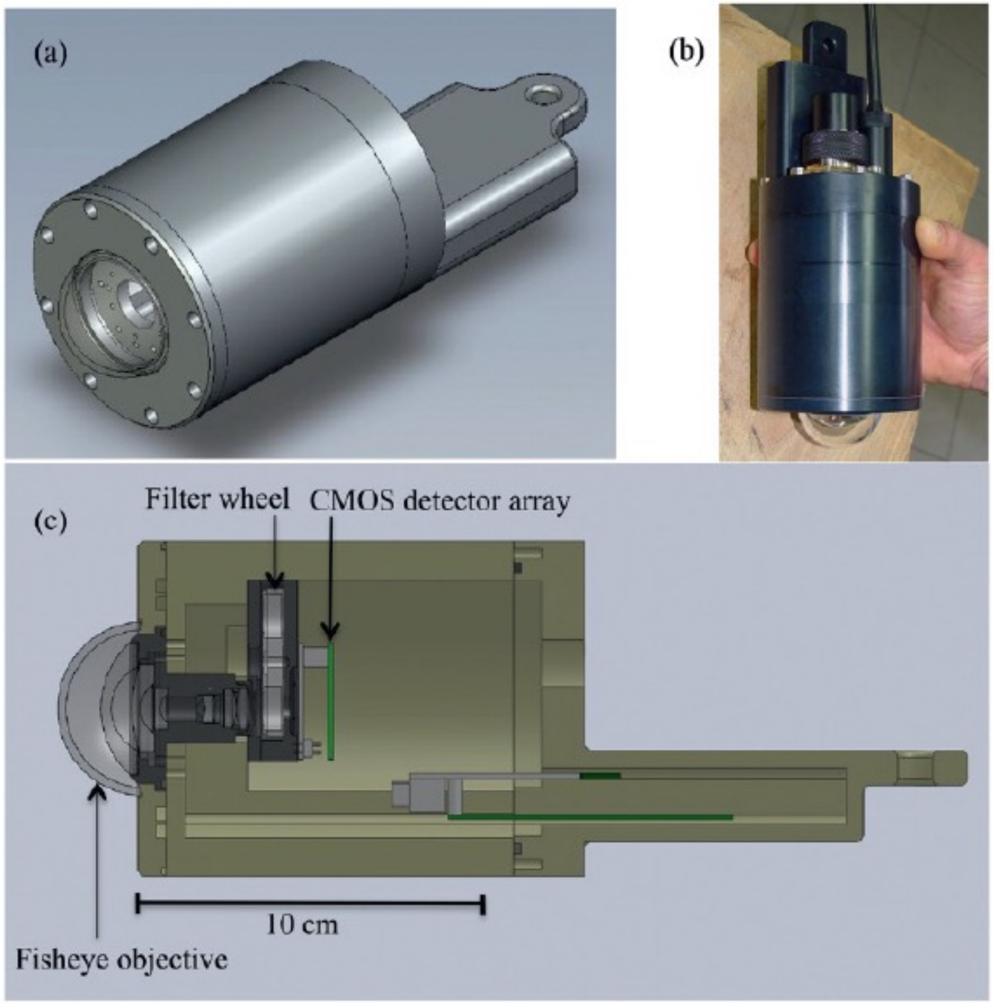
Radiances distribution in Lake Pend'Oreille
Redrawn from the data published by Tyler, 1960

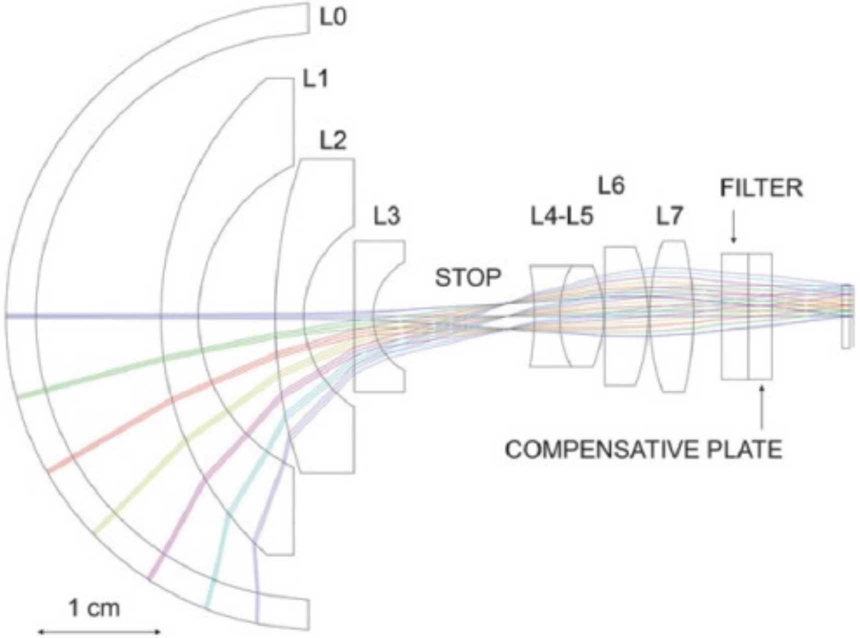


Principal plane

Perpendicular plane

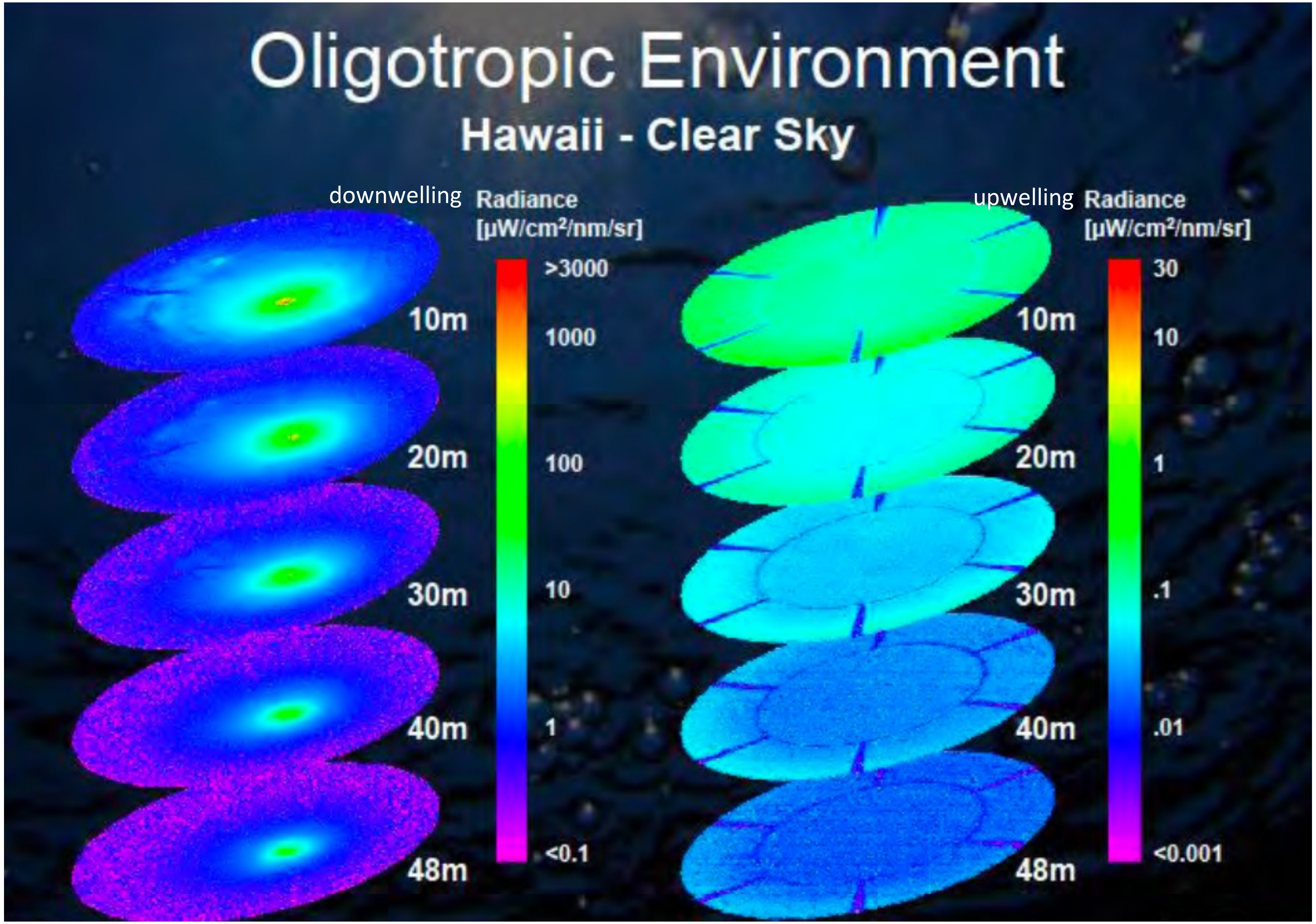
Measuring radiance



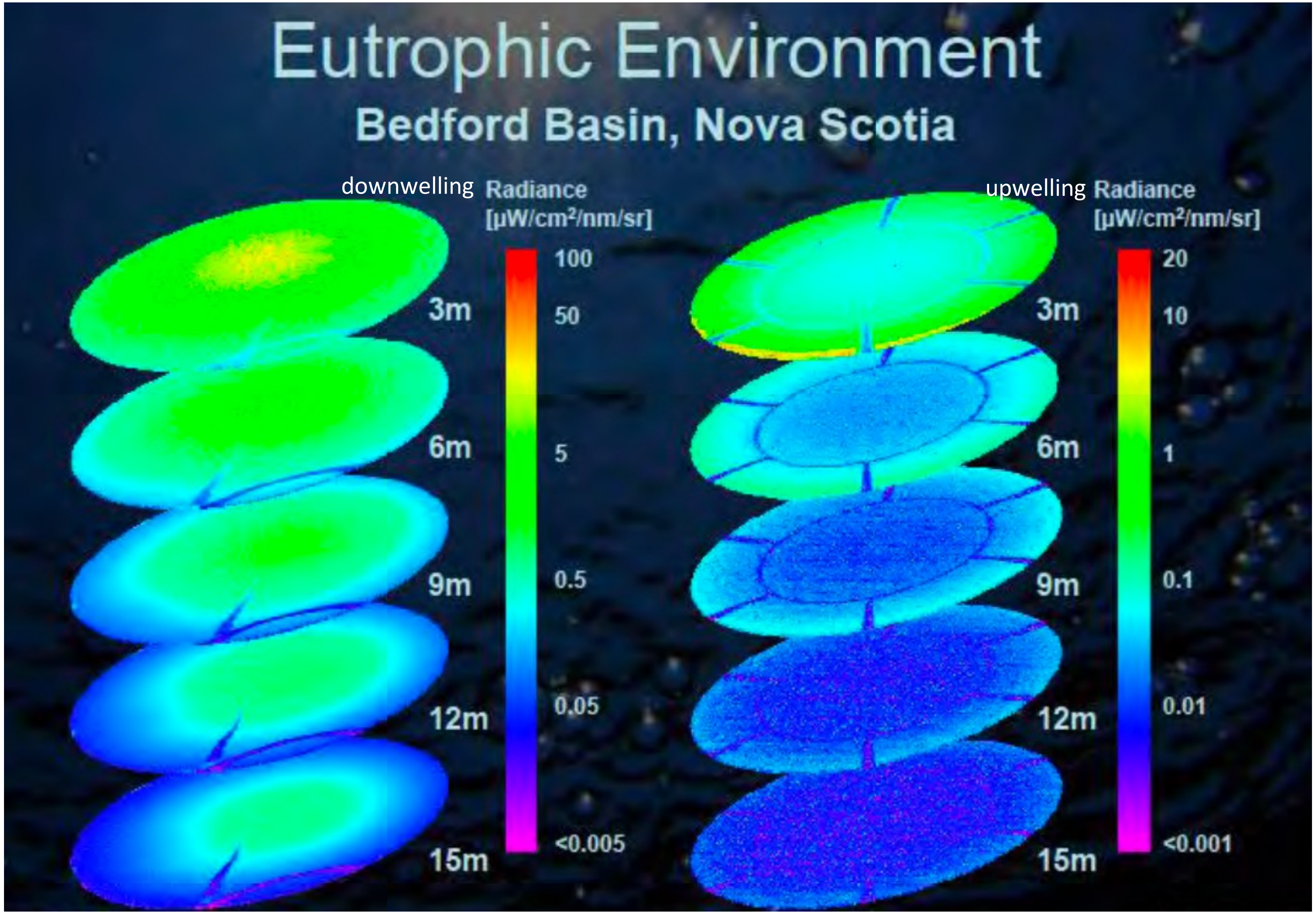


Radiance camera: getting simultaneously radiances in all directions of an hemisphere, at several wavelengths

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



Credit: Courtesy of Marlon Lewis and Satlantic



Credit: Courtesy of Marlon Lewis and Satlantic

Irradiance: a useful and common measurement

Spectral Irradiance is one of the more commonly made radiometric measurements in Ocean Optics, as they do not depend on the directionality of the light conditions, such as sun elevation (solar zenith angle) and azimuth direction.

There are several ways to measure Irradiance:

- Spectral Plane Irradiance
- Spectral Scalar Irradiance
- Spectral Vector Irradiance
- Photosynthetically Available Radiation (PAR)

The most common measurements are spectral plane and PAR.

So WHY do we make irradiance measurements

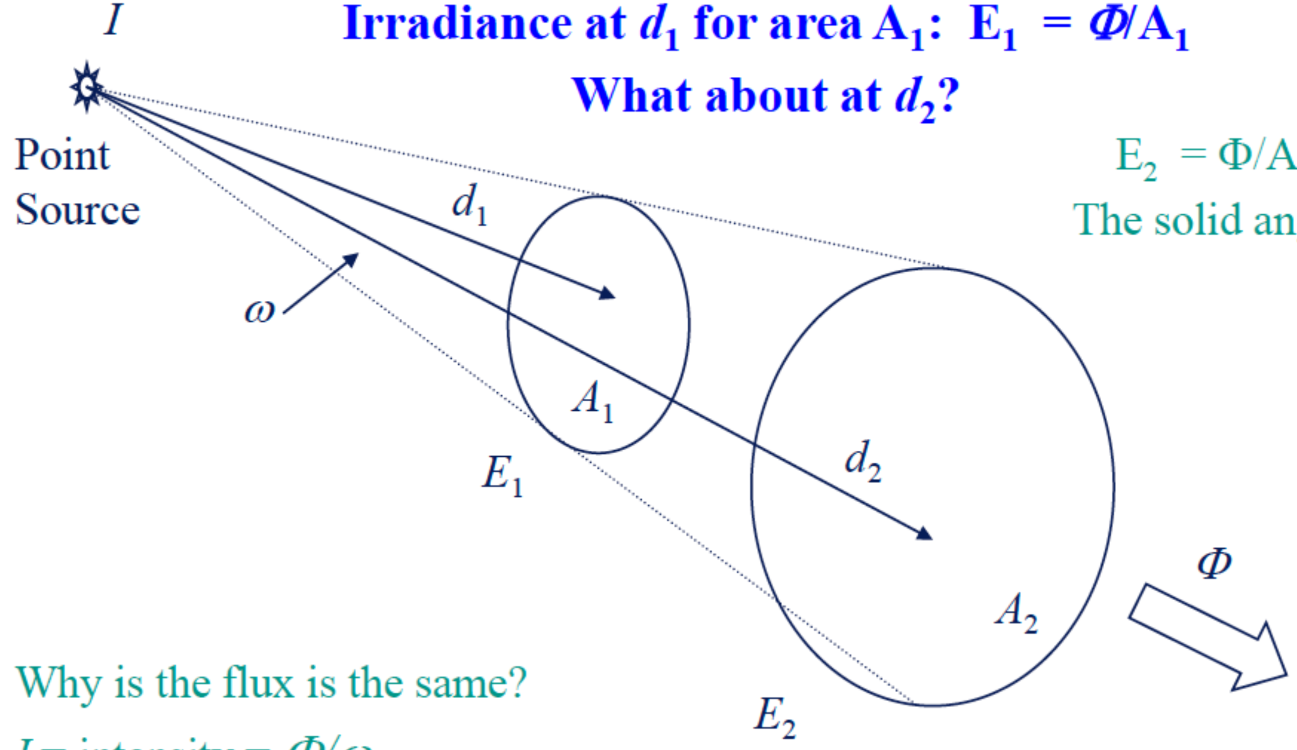
- To normalize radiance measurements to illumination conditions
- Ameasure of light available to phytoplankton for photosynthesis
- To derive various Apparent Optical Properties
- To compute remote sensing reflectance parameters
- To derive/estimate the IOPs through inversion

Quantity	SI Units	Recommended Symbol
radiant energy	J	Q
radiant power	W	Φ
radiant intensity	$\mathrm{W\,sr^{-1}}$	I
radiance	$\mathrm{W\,m^{-2}\,sr^{-1}}$	L
plane irradiance	$\mathrm{W\,m^{-2}}$	E
downward plane irradiance	$\mathrm{W\,m^{-2}}$	E_{d}
upward plane irradiance	$\mathrm{W\,m^{-2}}$	E_{u}
scalar irradiance	$\mathrm{W\,m^{-2}}$	E_{o}
downward scalar irradiance	$\mathrm{W\,m^{-2}}$	E_{od}
upward scalar irradiance	$\mathrm{W\,m^{-2}}$	E_{ou}
vector irradiance	$\mathrm{W\,m^{-2}}$	$\vec{E}$
vertical net irradiance	$\mathrm{W\,m^{-2}}$	$E_{\mathrm{d}} - E_{\mathrm{u}}$
emittance	$\mathrm{W\,m^{-2}}$	M
photosynthetically available radiation	$\mathrm{photons\,s^{-1}\,m^{-2}}$	PAR or E_{PAR}

Radiometry of point sources (Irradiance, E)

Irradiance at d_1 for area A_1: $E_1 = \Phi/A_1$

What about at d_2?



$E_2 = \Phi/A_2$ (flux is the same)

The solid angle is also constant (by geometry):

$$\omega = \frac{A_1}{d_1^2} = \frac{A_2}{d_2^2}$$

$$E_2 = E_1 \frac{d_1^2}{d_2^2}$$

Why is the flux is the same?

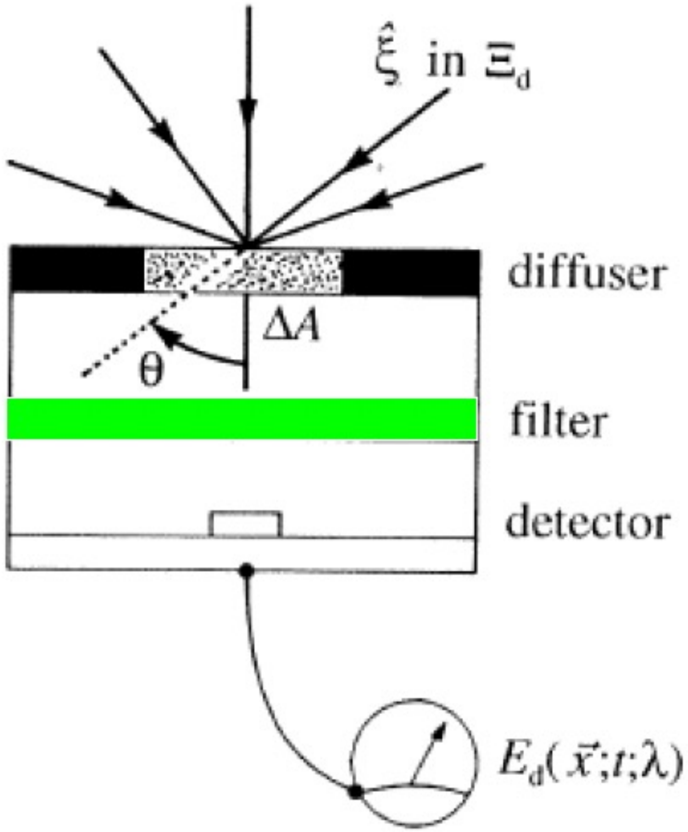
I = intensity = Φ/ω

For a point source, I is independent of direction (isotropic).

$$I = \frac{\Phi}{\omega} = \Phi\frac{d_1^2}{A_1} \text{ or } E_1 = \frac{I}{d_1^2}$$

The irradiance from an ideal point source falls off as $1/d^2$. How well must the distance be measured?

Inverse square Law of Irradiance



Spectral Plane Irradiance

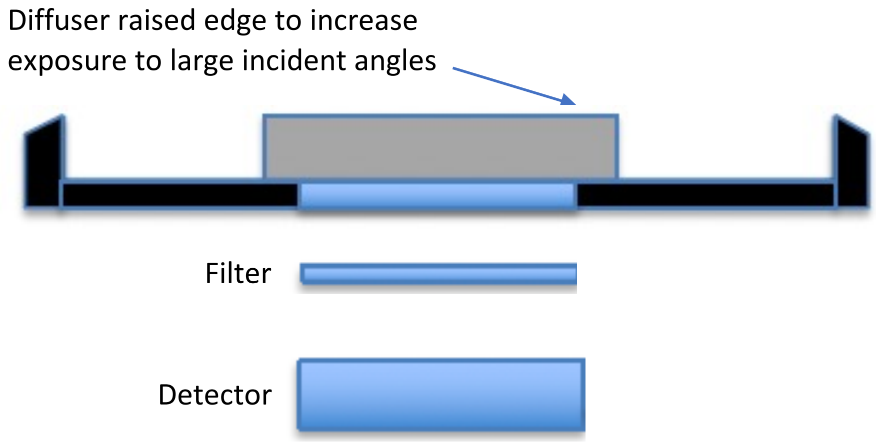
$$E_d(\vec{x}, t, \lambda) \equiv \frac{\Delta Q}{\Delta t \, \Delta A \, \Delta \lambda} \quad (\mathrm{W\ m^{-2}\ nm^{-1}})$$

$$E_d(\vec{x}, t, \lambda) = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi/2} L(\vec{x}, t, \theta, \phi, \lambda) |\cos\theta| \sin\theta \, d\theta \, d\phi$$

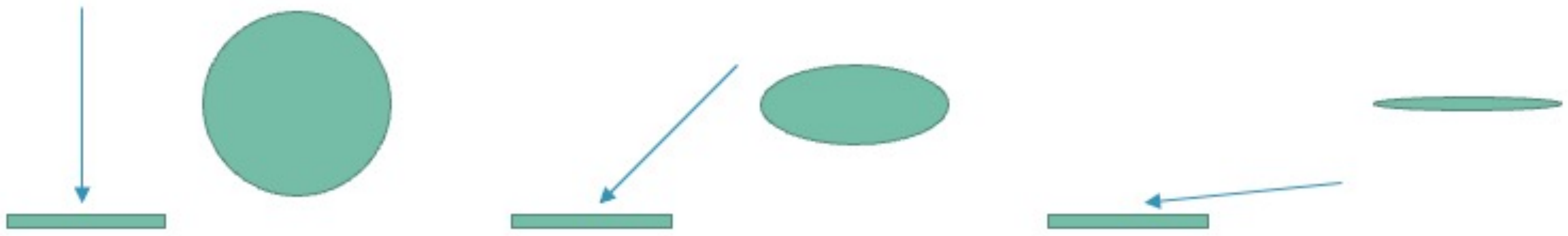
The most commonly measured radiometric parameter

The diffuser, i.e. the light collection surface, is equally sensitive to light from any direction.

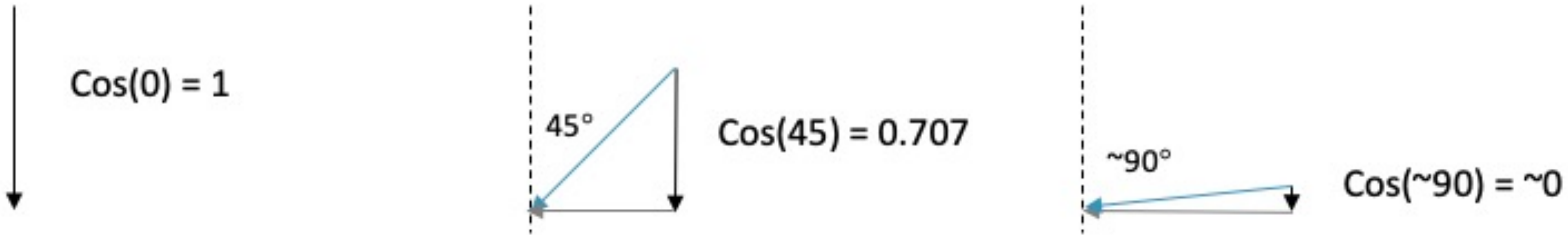
The projected area of the detector in the direction of θ is ΔA cos(θ). Diffuser is typically called a"cosine collector"

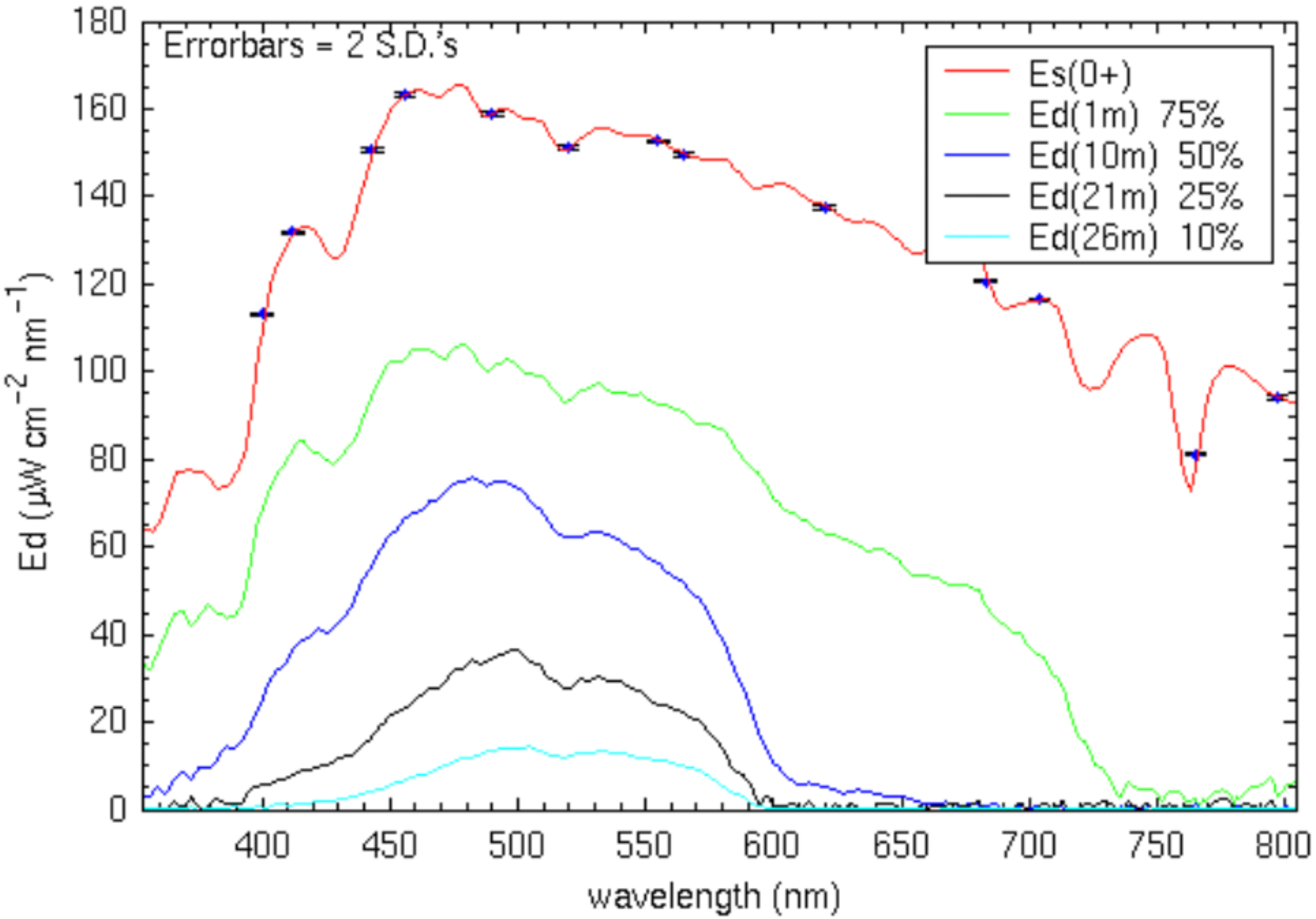


When you look at a flat surface, the apparent area depends on the cosine of the viewing angle.



This is equivalent to weighting the incoming light by the vertical component of the incident light (i.e. the vertical *vector*).





Blue water station (Data from Marlon Lewis, Satlantic)
Note…units 100 µW cm-2 nm-1 = W m-2 nm-1

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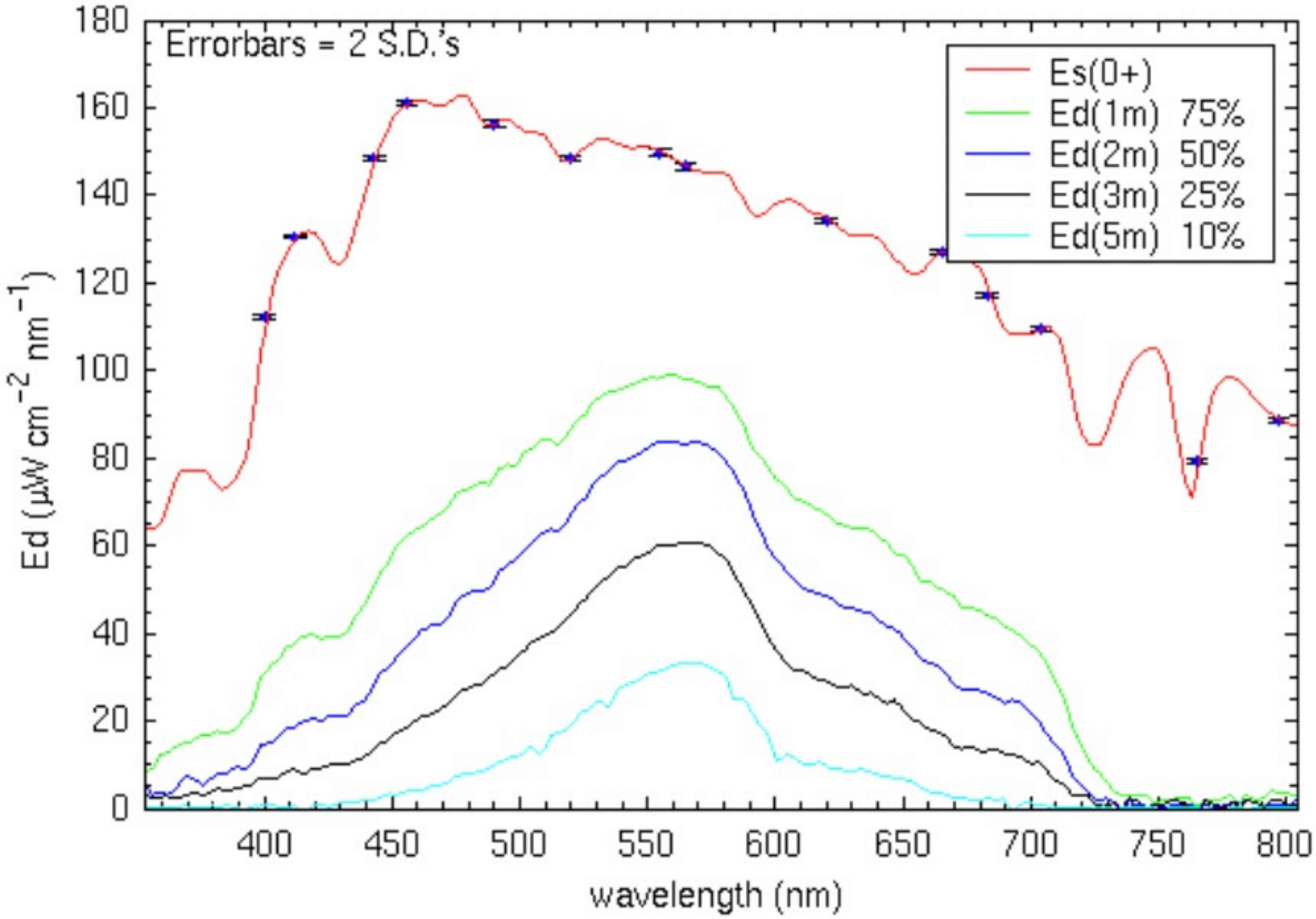

Green water station (Data from Marlon Lewis, Satlantic). Notice difference in depths in this plot and last one.

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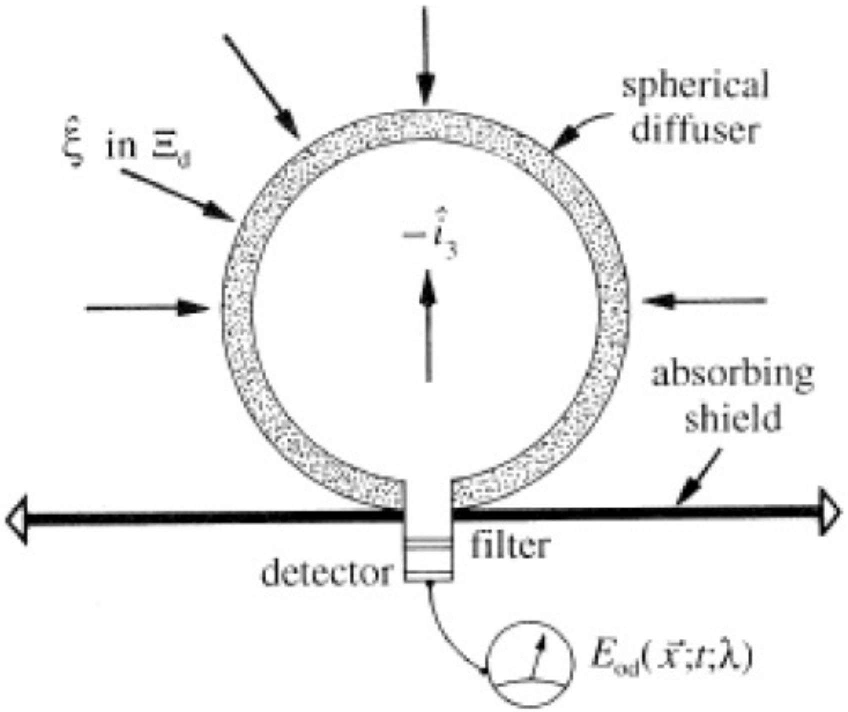
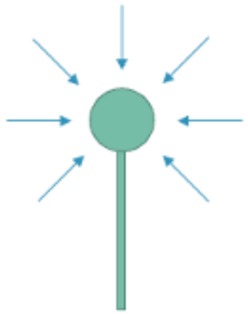
Spectral Scalar Irradiance

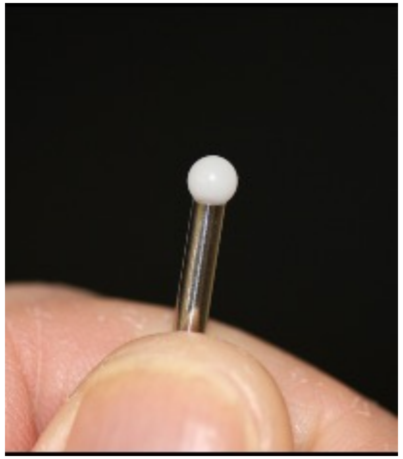


$$E_{od}(\vec{x},t,\lambda) \;\equiv\; \frac{\Delta Q}{\Delta t\,\Delta A\,\Delta\lambda} \quad (\mathrm{W\ m^{-2}\ nm^{-1}})$$

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

$$E_o(\vec{x},t,\lambda) = E_{od}(\vec{x},t,\lambda) + E_{ou}(\vec{x},t,\lambda)$$





Collection of light to a single point regardless of direction/angle.

Relevant to photosynthesis/primary production as well as the heating of water. Independent of light direction.

The detector has the same effective area for radiance in any downward direction, thus no cos(θ) factor on L

Spectral Vector Irradiance

$$
\begin{aligned}
(\vec{E})_z &= \hat{z} \cdot \vec{E} \\
&= \int_{\Xi} L(\vec{x}, t, \hat{\xi}, \lambda) \, \cos\theta \, d\Omega(\hat{\xi}) \\
&= \int_{\theta=0}^{90} L(\ldots\theta\ldots) \, \cos\theta \, d\Omega \; + \; \int_{\theta=90}^{180} L(\ldots\theta\ldots) \, \cos\theta \, d\Omega \\
&= E_d - E_u
\end{aligned}
$$

Vector Irradiance is simply the net difference of the downwelling plane irradiance and the upwelling place irradiance. Often described as the ***net downward irradiance***.

Gershun's Law

$$
\frac{d}{dz}\left[E_{\mathrm{d}}(z,\lambda) - E_{\mathrm{u}}(z,\lambda)\right] = -a(z,\lambda)E_{\mathrm{o}}(z,\lambda) \quad (\mathrm{W\,m^{-3}\,nm^{-1}})
$$

https://www.oceanopticsbook.info/view/radiative-transfer-theory/level-2/gershuns-law

Photosynthetically Available Radiation (PAR)

$$PAR \equiv \int_{400\,\mathrm{nm}}^{700\,\mathrm{nm}} E_o(\lambda)\,\frac{\lambda}{hc}\,d\lambda$$

$$(\mathrm{photons\ s^{-1}\ m^{-2}})$$

PAR most often expressed as micro Einstiens s^{-1} m^{-2}. As irradiance is in energy, must convert to how many photons are available (1 Einstein = 1 mole photons = 6.023 x 1023 photons)

Typically used in simple models of phytoplankton growth.

Typically uses a scalar irradiance design, though place irradiance versions exist (which come with a set of assumptions).

More ecosystem models are using spectral scalar irradiance measurements in to look at the phytoplankton pigment composition.

Dreaming of Gershun tubes and Snell's circles