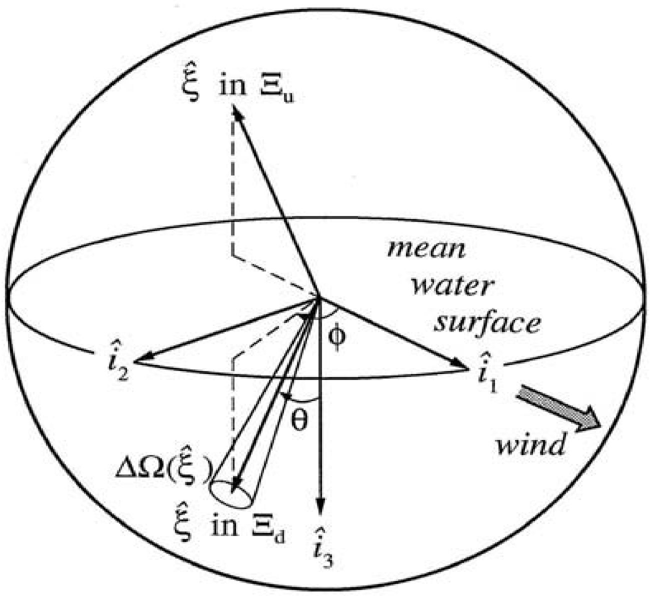
Chapter II - Radiometry and IOPs

1) <u>Some notes and reminders about the angles and derived measurements</u>

The figure below shows the spherical coordinate system typically used in optical modelling. The light ray is indicated by the vector ξ . The first unit vector typically points in the direction of the wind, the second in a direction orthogonal to the first (in the horizontal plane), and the third points towards the nadir. For better understanding, we can associate the azimuthal angle ϕ with the "longitude" and the polar angle θ with the "colatitude" (with respect to the nadir; example in the figure for a descending vector ξ).



(Courtesy Mobley, Light and Water, 1994, Fig 1.3: the ascending vector ξ example is not linked to the descending vector ξ).

The reference vector is oriented towards the nadir, i.e., when the sun is at the zenith and the light is shining down vertically, we have $\theta=0°$. We can divide the spherical coordinate system into a downwelling hemisphere Ξ_d and an upwelling hemisphere Ξ_u . $\Delta\Omega(\xi)$ represents the solid angle around the vector ξ .

We have: $\xi_1=\sin\theta\cos\phi$

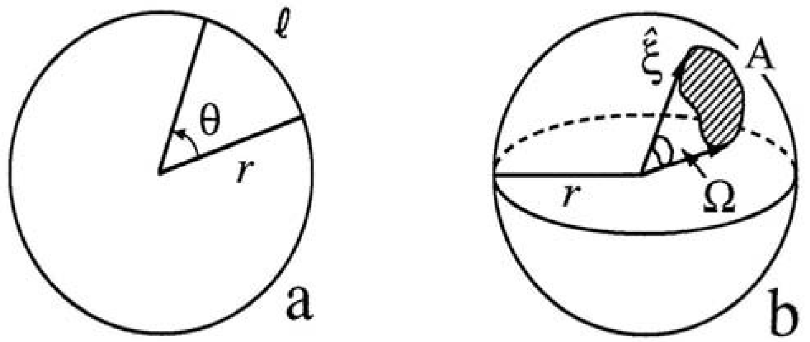
$\xi_2=\sin\theta\sin\phi$

$\xi_3=\cos\theta$

with $0>\theta>\pi$ and $0>\phi>2\pi$

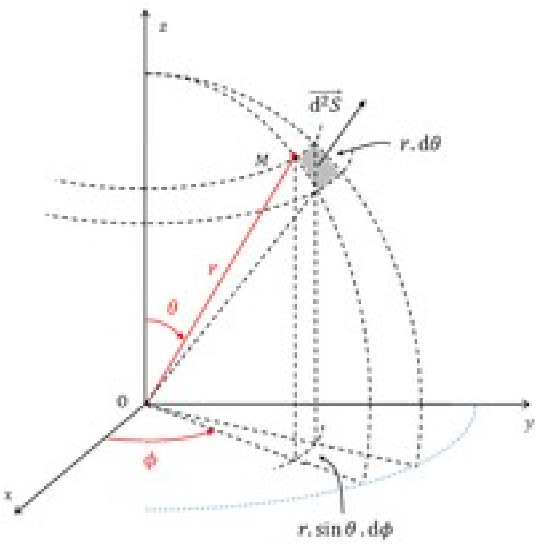
Note: when we speak of "direction" in this course, we always mean the direction of light propagation, i.e., the direction in which the light travels. Experimentalists often use angles that correspond to the direction in which the instrument is looking (direction of sight). $\theta_{instr}=\pi-\theta$ and $\theta_{instr}=\pi+\theta$

<u>Calculating the solid angle</u>



(Courtesy, Mobley, Light and Water, 1994, Fig 1.4)

$angle = \frac{(length\ of\ arc)}{(radius)}$	$solid\ angle = \frac{(area)}{(radius^2)}$
$\theta = \frac{l}{r}[radian]$	$\Omega = \frac{A}{r^2}[steradian]$



(Figure: Alasjourn; Wikipedia)

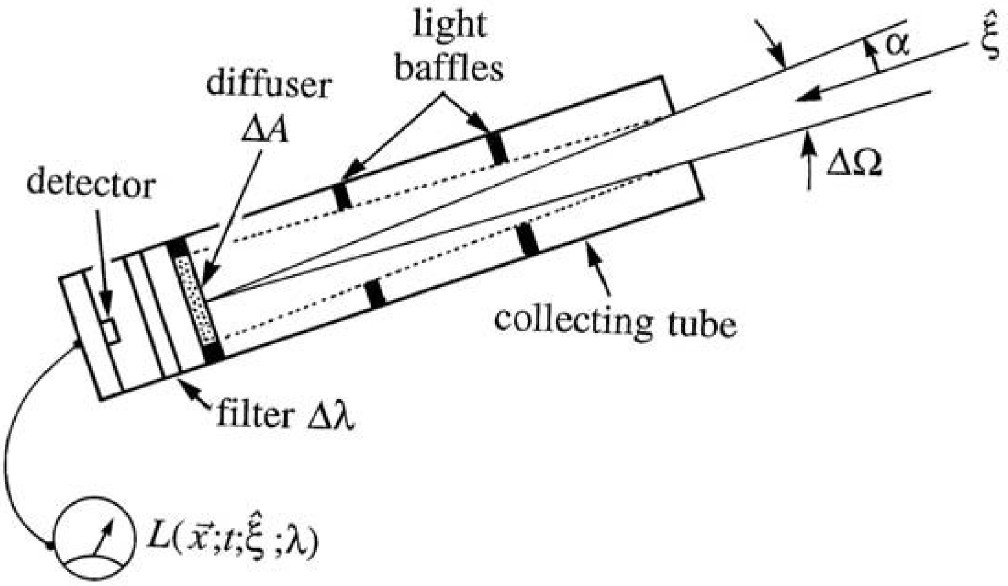
element of solid angle $d\Omega = \frac{dA}{r^2}$

$$\boxed{d\Omega} = \frac{r\sin\theta d\phi\, r d\theta}{r^2} = \boxed{\sin\theta d\theta d\phi}$$

The solid angle that corresponds to the entire sphere is 4π sr.
One hemisphere thus corresponds to a solid angle of 2π sr

2) Light measurements

* The **radiance L** denotes the amount of **spectral** energy (per unit wavelength) that is emitted into a certain direction, or rather a given solid angle, during a fixed time interval; its units are: J/s/m^2/nm/sr.



(Courtesy, Mobley, Light and Water, 1994, Fig 1.5)

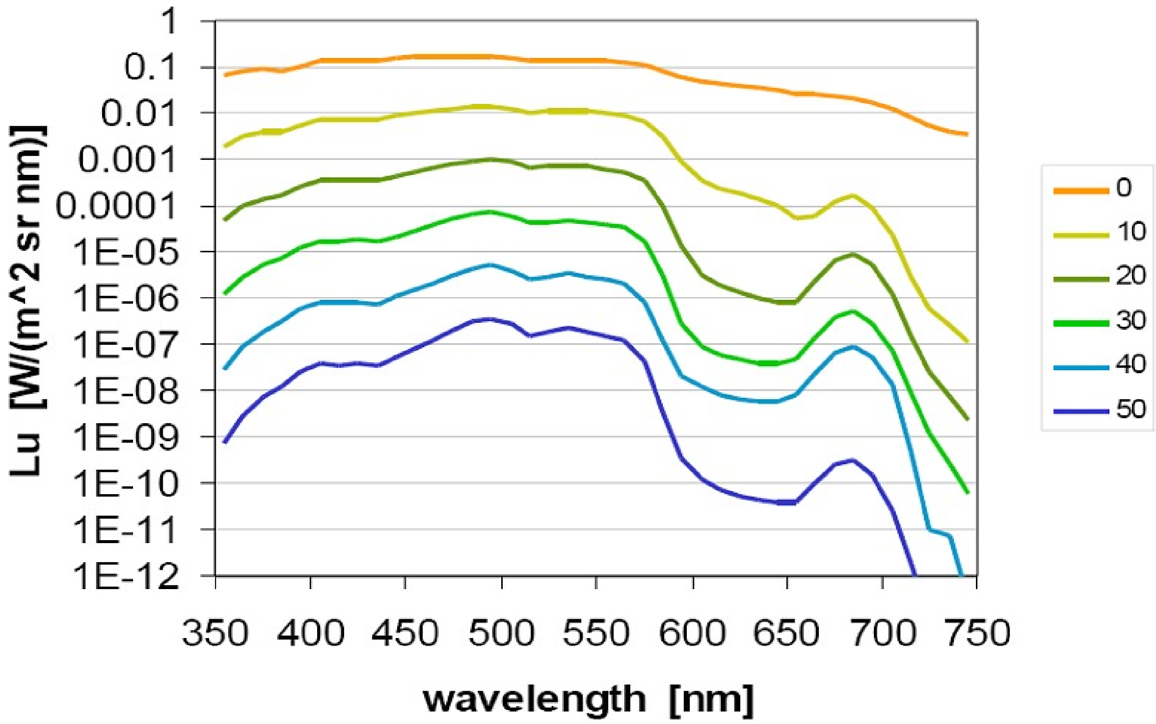
$$L(\vec{x},t,\vec{\xi},\lambda)=\frac{(\Delta Q)}{(\Delta t \Delta A \Delta\Omega \Delta\lambda)}(J\,s^{-1}\,m^{-2}\,sr^{-1}\,nm^{-1}=W\,m^{-2}\,sr^{-1}\,nm^{-1})$$

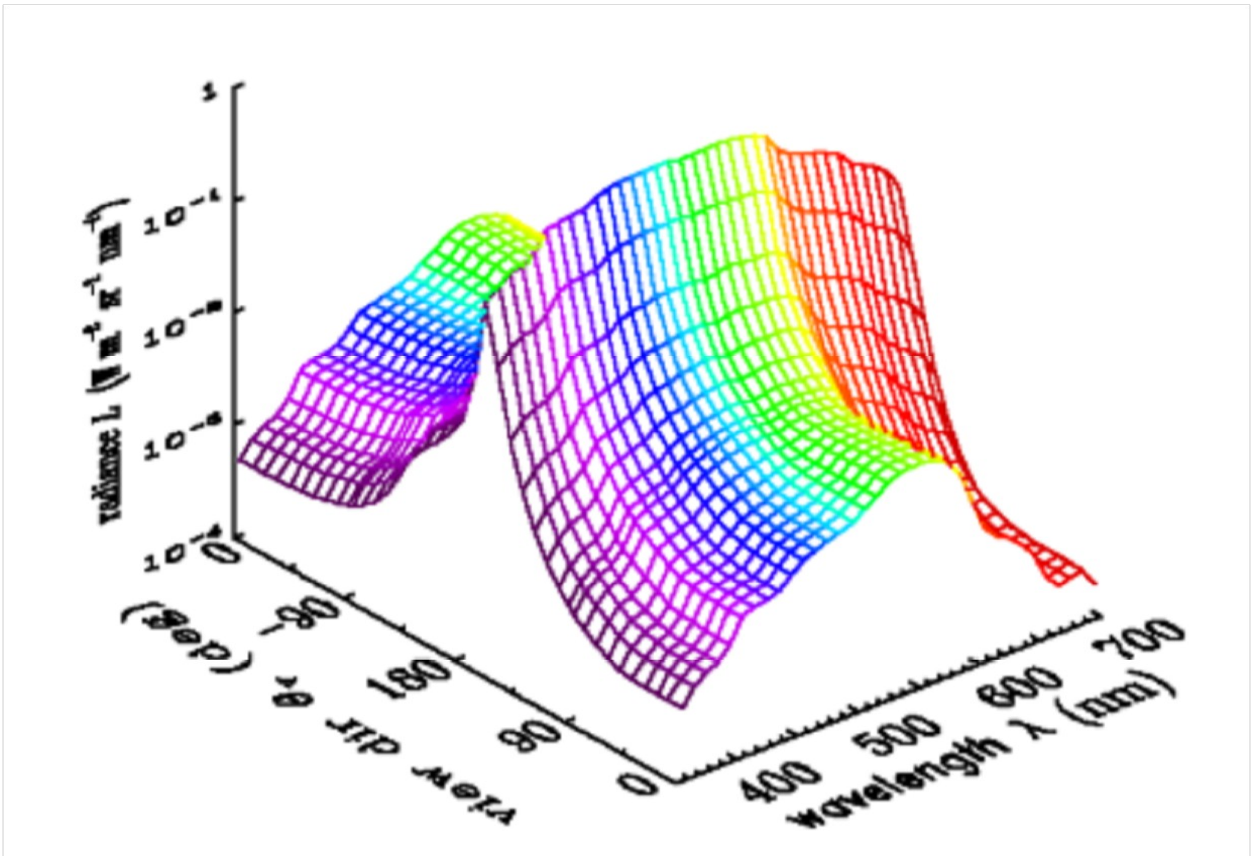
Reminder: 1 Watt = 1 J/s = 1 N m/s and $\vec{x}=\overrightarrow{OM}=(x,y,z)$

Radiance is difficult to represent graphically as it contains many variables. At a time, *t*, if we reduce the problem to one dimension (the vertical), we have $L(z,\theta,\phi,\lambda)$.

Example on following page (top): $Lu(z,\theta,\phi,\lambda)$ for different wavelengths and water depths (0, 10, 20, 30, 40, and 50 m), for a nadir of $\theta=180°$ (i.e., it is upwelling light that arrives from below with the detector pointed downward $\theta_{inst}=0°$) and ϕ in the plane of the sun.

Following page (bottom): radiance in the plane of the sun ϕ as a function of the viewing direction θ_{inst} ; when $\theta_{inst}=180°$ (looking toward the zenith) the light comes from above; when $\theta_{inst}=90°$ we are looking toward the horizon; when $\theta_{inst}=0°$ we are looking toward the nadir.

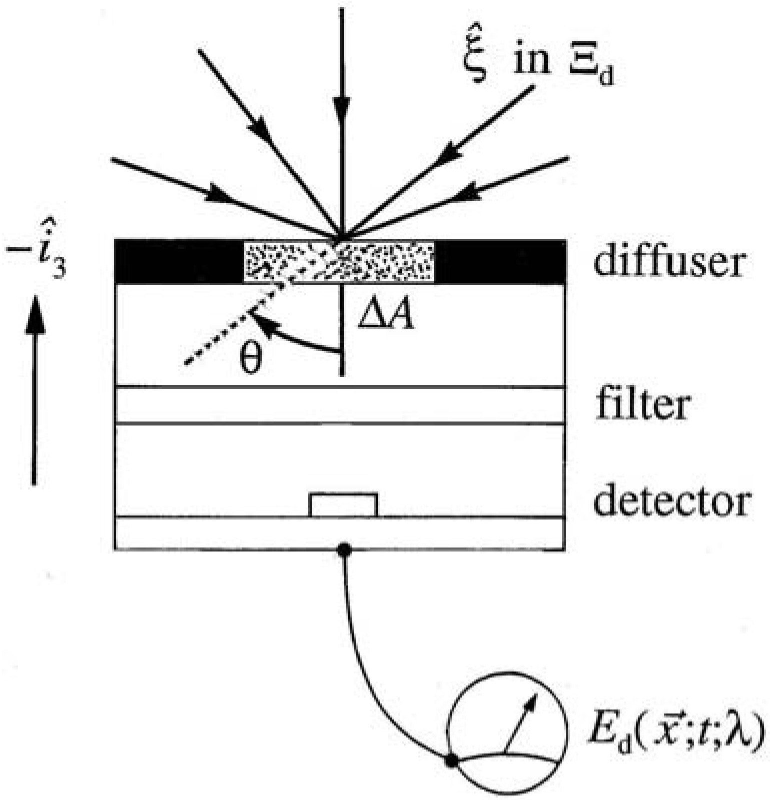




à

the depth Z = 5m, in the plane of the sun, by varying “view dir” = θ_{inst}

* **Downwelling and upwelling irradiance (**also known as spectral downward/upward plane irradiance, **Ed and Eu**) are defined as the amount of spectral (i.e., wavelength-specific) energy arriving at an upward (downward) facing detector from the corresponding hemisphere during a certain time interval. The unit of measurement is J/s/m^2/nm which is equivalent to W/m^2/nm.



Courtesy, Mobley, Light and Water, 1994, Fig 1.6

$$E_d(\vec{x},t,\lambda)=\frac{(\Delta Q)}{(\Delta t\,\Delta A\,\Delta\Delta\lambda)}(J\,s^{-1}m^{-2}nm^{-1}=W\,m^{-2}nm^{-1})$$

Such detectors are often called "cosine collectors" as they measure the irradiance based on the following formula:

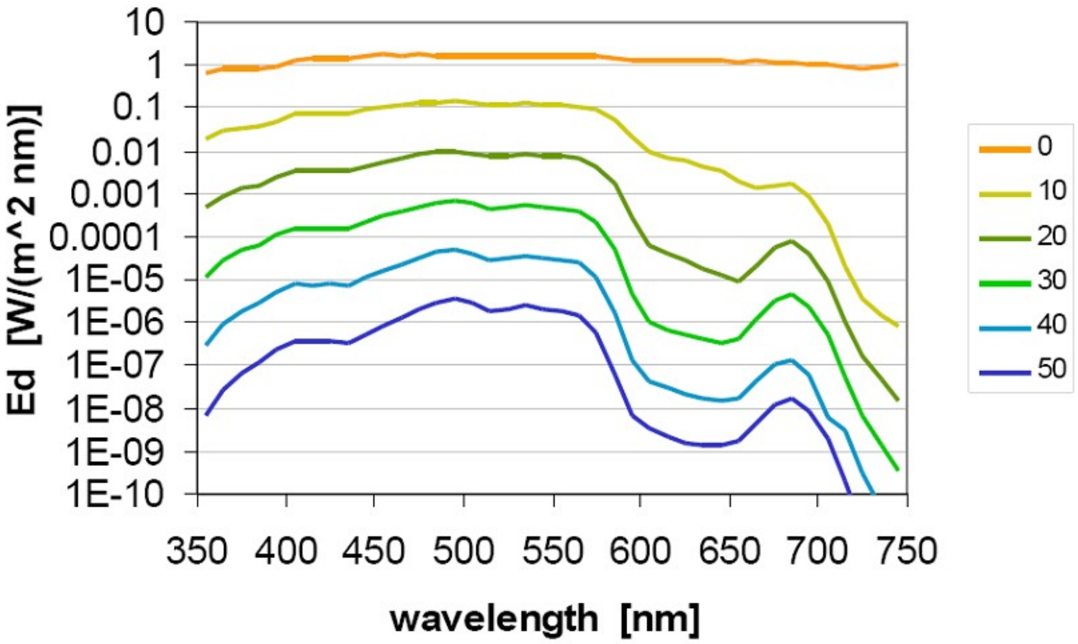
$$E_d(\vec{x},t,\lambda)=\int_{\xi\in\Xi_d} L(\vec{x},t,\vec{\xi},\lambda)|\cos\theta|\,d\,\Omega(\xi)$$

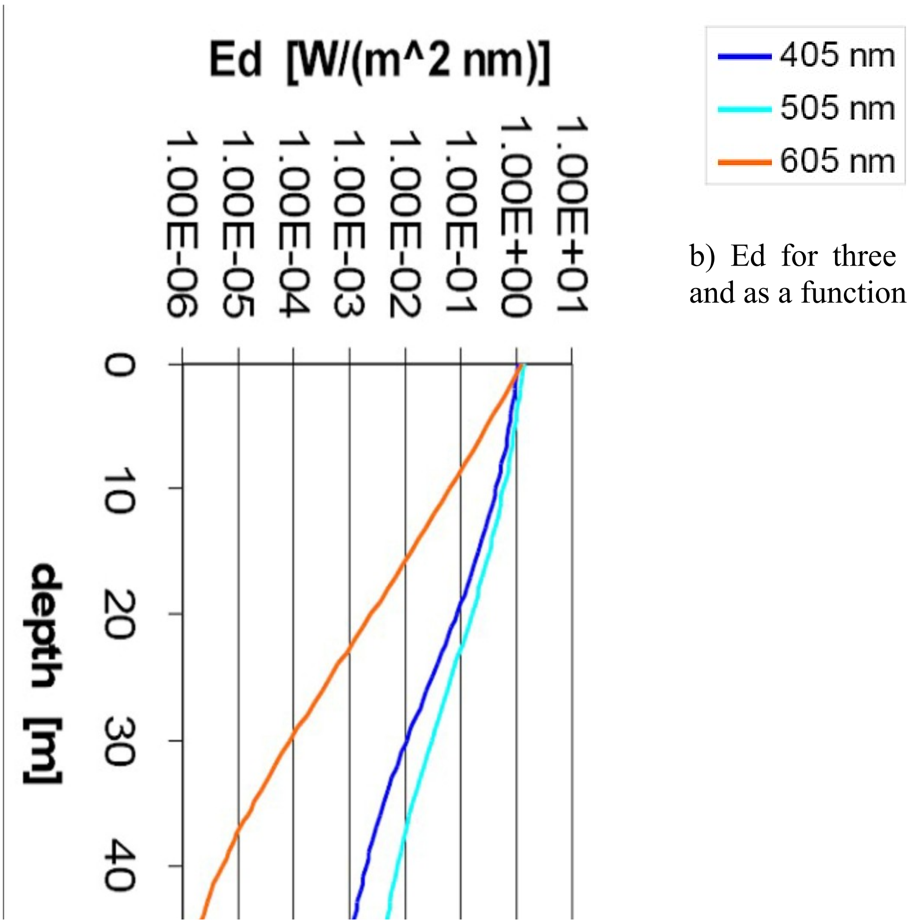
hence a beam travelling toward the collector from direction θ does not see the area A but the effective (projected) area $A|\cos\theta|$.

$$E_d(\vec{x},t,\lambda)=\int_0^{2\pi}\int_0^{\pi/2} L(\vec{x},t,\theta,\phi,\lambda)|\cos\theta|\sin\theta\,d\,\theta\,d\,\phi$$

Since Ed depends on fewer variables, it is easier to represent graphically compared to L. At a given time, we can simplify and measure Ed (z, λ).

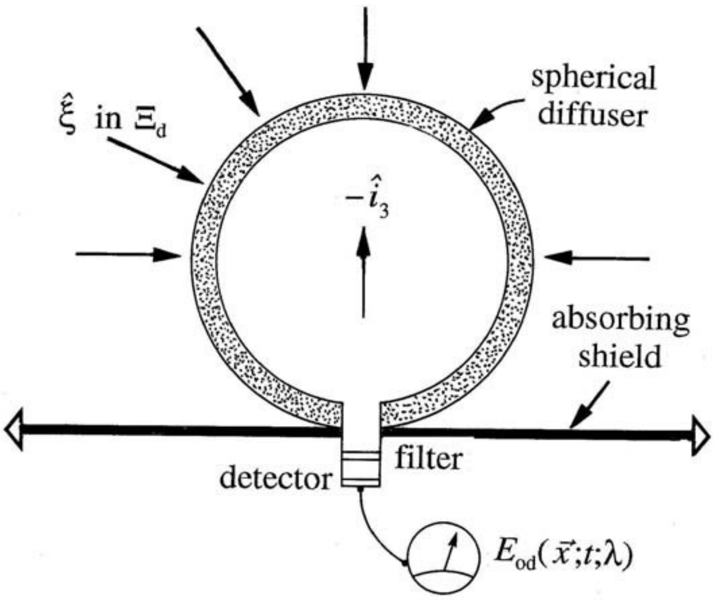
a) Ed as a function of the wavelength λ at different depths (0, 10, 20, 30, 40 and 50 m).





b) Ed for three distinct wavelengths and as a function of depth.

* **Spectral scalar irradiance** is the irradiance seen in all directions, measured by a spherical detector (without the need for the cosine term).



Courtesy, Mobley, Light and Water, 1994, Fig 1.7

We can have Eo, Eod, and Eou.
The equations below describe the spectral downward scalar irradiance:

$$E_{od}(\vec{x},t,\lambda)=\frac{(\Delta Q)}{(\Delta t \Delta A \Delta \lambda)}(J\,s^{-1}\,m^{-2}\,nm^{-1}=W\,m^{-2}\,nm^{-1})$$

or:

$$E_{od}(\vec{x},t,\lambda)=\int_0^{2\pi}\int_0^{\pi/2} L(\vec{x},t,\theta,\phi,\lambda)\sin\theta\, d\theta\, d\phi$$

Note the absence of the cosine.

* **Photosynthetically Available Radiation (PAR)** refers to the number of photons with a wavelength between 400 and 700 nm (it is therefore not a spectral quantity) received by a given surface during a given time interval and coming from all directions (unit: photons/s/m^2 or Einstein/s/m^2; with 1 Einstein = 1 Na photons = 6,023 10^{23} photons; Na being the Avogadro number).

$$PAR=\int_{400}^{700} E_o \frac{\lambda}{hc}\, d\lambda \quad \text{often given in units of} \quad \mu E\, m^{-2}\, s^{-1}$$

Note: PAR is neither a spectral measure nor a measure of energy. PAR measures the number of quanta and not the amount of irradiance. Be vary of PAR values given in Watts. They are based on certain assumptions regarding the composition of the water and thus its absorption characteristics of photons. Often, these assumptions are based on the work by Morel and Smith (1974, Limnol, 19 (4), Relation between total quanta and total energy for aquatic

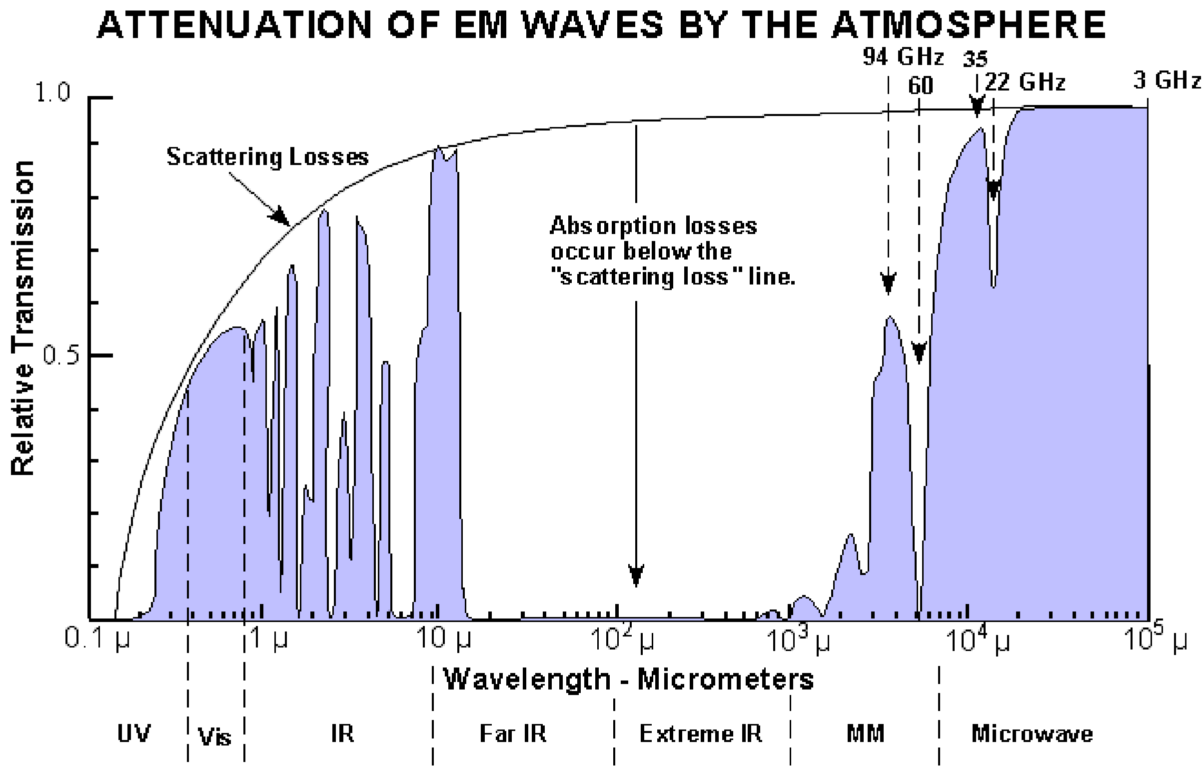
photosynthesis); where the following conversion factor is used:
$1\,Watt \approx 2{,}5\,10^{18}\,quanta\,s^{-1} \approx 2{,}5\,10^{18}\,photons\,s^{-1} \approx 4{,}2\,\mu E\,s^{-1}$. This relationship may not be suitable for non-oligotrophic coastal environments.

Reminder: 1 Watt = 1 J/s = 1 N m/s = 1 kg m²/s³

3) Solar radiation

The light that arrives from the sun at the Earth's surface does not contain all EM wavelengths emitted by the sun. Some are absorbed by the sun's atmosphere (Fraunhofer lines, $\Delta\lambda$ <0.1 nm) while others are absorbed by the Earth's atmosphere.

The EM transmission spectrum for the Earth's atmosphere (Figure below) show that the losses in the visible part of the spectrum mostly arise from Rayleigh scattering while losses in the IR part are mostly due to absorption.



Only 50% of the energy contained in the visible part of the spectrum passes through the atmosphere.

The radiation curve from the sun was provided in paragraph 3 of the first chapter. It is shown again below giving the amount of solar radiation arriving at the top of the Earth's atmosphere and at the level of the ocean surface.

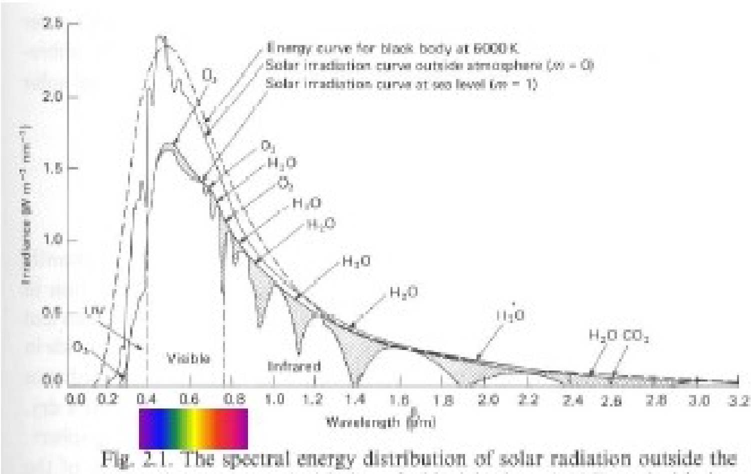
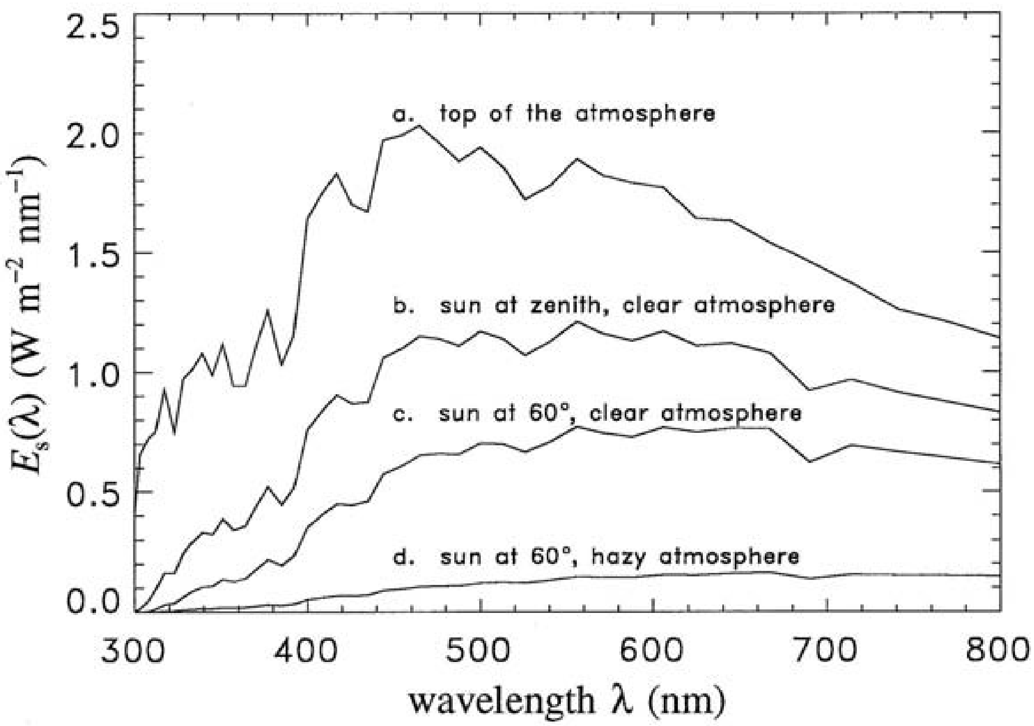


Fig. 2.1. The spectral energy distribution of solar radiation outside the atmosphere compared with that of a black body at 6000 K, and with that at sea level (zenith Sun). (By permission, from *Handbook of geophysics*, revised edition, U.S. Air Force, Macmillan, New York, 1960.)

Values have been averaged across $\Delta\lambda = 2$ nm intervals which produces smoother Fraunhofer lines.

The x-axis extends from 0 to 3.2μm.

Below: spectral irradiance of the sun's direct beam for different altitudes/environmental conditions.



(Courtesy, Mobley, Light and Water, 1994, Fig 1.2)

Irradiance is sometimes integrated over all wavelengths to obtain a value in W/m². For example, the average amount of solar energy arriving at the top of the atmosphere is Es = 1367 W/m² [Frolich, 1983], +/- 50 W/m² depending on the ellipticity of the Earth's orbit around the sun. This is also called the solar constant (see the box below for the method of calculation).

Note 1: The solar constant is the amount of solar energy received on a surface of 1 m² located at a distance of 1 au (average Earth-Sun distance) and oriented perpendicular to the incident rays from the Sun in the absence of an atmosphere. For the Earth, it is therefore the density of energy flow at the top of the atmosphere.

F = 1360.8 ± 0.5 W/m².

The amount of energy received by the Earth corresponds to F×Sdisk (Sdisk=the cross-sectional area of the Earth as seen from the sun). This energy is distributed across an entire hemisphere which corresponds to four times the cross-sectional area (4×Sdisc). The average amount of incident radiation is thus:

$\bar{F}=\frac{F\,Sdisc}{4\,Sdisc}=\frac{F}{4}\simeq 340$ W/m². This mean value is important for calculating the Earth's radiative budget.

Note 2: To obtain F, we can use the Stefan-Boltzmann law with the sun as a black body with a temperature T of about 5780 K. This black body then emits a surface energy flux, Fs, of:

$$F_s=\sigma T=6.45\times 10^7 \quad \text{W/m}^2$$

At a distance R, assuming perfect conservation of radiative energy as it travels through space, we obtain:

$4\pi R_s^2 F_s=4\pi R^2 F$ and thus $F=F_s\left(\frac{Rs}{R}\right)^2$ where Rs is the sun's radius of 695,600 km.

Inserting the numbers yields:

$F=\left(\frac{5535}{R}\right)^2$ where R is in millions of kilometres and F in Watts per square metre.

For Earth, where R = 1 au = 150 million km, we obtain: F = 1362 W m^{-2}

(adapted from https://fr.wikipedia.org/wiki/Constante_solaire)

The distribution of the solar constant in various wavelength bands is as follows (Mobley p9 and references therein):

Lambda (nm)	< 350 nm	350 à 400	**400 à 700**	700 à 1000	> 1000 nm	Total
Distribution (%)	4.5	4,2	**38.2**	22.6	30.5	100
Energy (W/m^2)	62	57	**522**	309	417	1367

The energy density contained in the visible part of the spectrum (400 to 700 nm) after crossing the atmosphere as a function of environmental conditions:

E= 500 W/m^2	clear sky; sun at zenith
E= 450 W/m^2	clear sky; sun at 60° from zenith
E= 300 W/m^2	cloudy; sun at 60° from zenith
E= 100 W/m^2	cloudy; sun at horizon
E= 10^{-3} W/m^2	clear sky; full moon
E= 3×10^{-6} W/m^2	clear sky; starlight only

Le rayonnement solaire qui arrive à la surface dépend de la latitude et de la teneur en vapeur d'eau de l'atmosphère

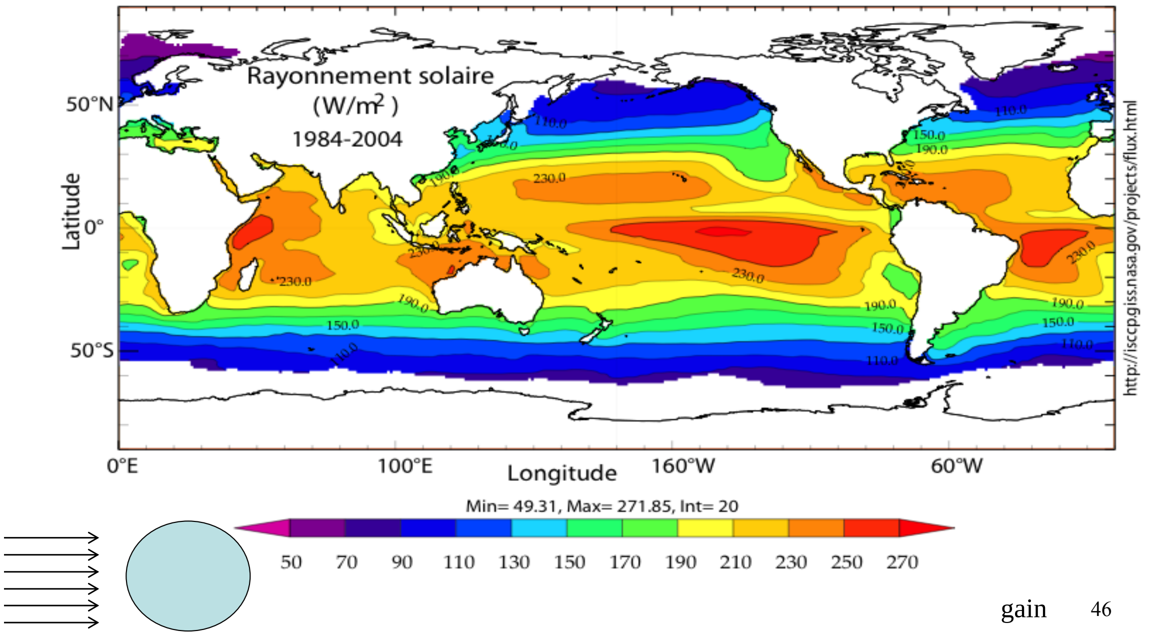


Figure courtesy M. FIEUX L'océan planétaire, Fig 1.8 (measurements from: CAMPBELL G.G., VONDER HAAR T.H. *Climatology of radiation budget measurements from satellites*. Colorado State University: Department. of Atmospheric Sciences, Atmospheric Science Paper no. 323, 1980, 74p).

4) Optical properties of water

A property is, by definition, a particular quality of the environment under consideration, here seawater. Parameters that are sufficiently stable to be considered characteristic of the marine environment can therefore be called properties. Moreover, if these properties do not depend on the light itself but only on the medium or, more precisely, on the components of the medium, they are called **inherent optical properties**. If the properties depend on both the medium and the light, they are called **apparent optical properties**. These definitions were introduced by Preisendorfer in 1976.

The following acronyms are used:

IOP = Inherent Optical Property
AOP = Apparent Optical Property

a) *IOPs of water*

Absorption

When light $\Phi_o(\lambda)$ enters a volume of water, a fraction $\Phi_a(\lambda)$ is absorbed and another fraction $\Phi_b(\lambda)$ is scattered while the remainder is transmitted $\Phi_t(\lambda)$ (Figure). The spectral absorbtance is defined as $A=\frac{\Phi_a(\lambda)}{\Phi_o(\lambda)}$.

Attention biogeochemists: this absorbtance should not be confused with the absorbance or optical density that is measured by spectrophotometers (in the lab) which is

$$D(\lambda)=\log_{10}\frac{\Phi_o(\lambda)}{(\Phi_b(\lambda)+\Phi_t(\lambda))}=-\log_{10}(1-A(\lambda))$$ [Kirk, 1983, 1994].

If a beam of monochromatic light rays crosses a volume of thickness, *l*, the spectral **absorption coefficient**, $a(\lambda)$, with unit m^{-1} is defined as the limit:

$$a(\lambda)=\lim_{l-0}\left(\frac{1}{l}\frac{\Phi_a(\lambda)}{\Phi_o(\lambda)}\right)$$

The spectral **scattering coefficient**, $b(\lambda)$, with unit m^{-1} is defined in a similar fashion by replacing $\Phi_a(\lambda)$ with $\Phi_b(\lambda)$.

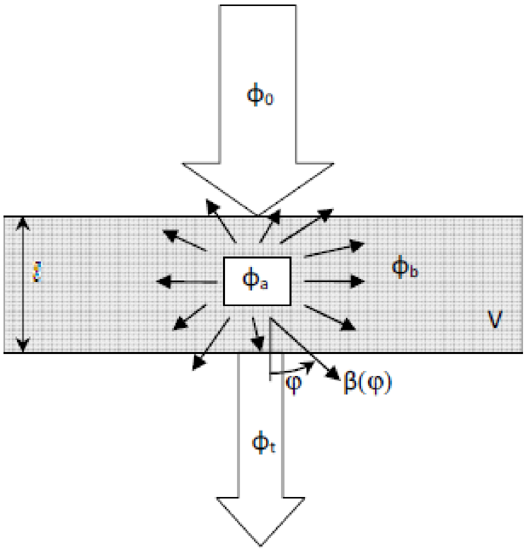


Figure 1-1 : D'après Morel (2008). Un faisceau monochromatique de rayons lumineux d'intensité φ_0 traverse un volume V d'eau de mer de longueur l. Une partie de la lumière est absorbée (φ_a), une autre diffusée (φ_b) et une autre transmise (φ_t). La partie diffusée est la somme des diffusions β(φ) à chaque angle φ.

Reminder: For most substances, the absorption is wavelength dependent which leads to the appearance of colour as some wavelengths are absorbed more than others. For example, white light that is incident on an object that predominantly absorbs blue, green, and yellow wavelengths will make the object appear as red. A material that appears black thus absorbs all wavelengths (converting the incident radiation into heat), while a white body reflects them all.

Supplements:
 - Researchers at the Rensselaer Polytechnic Institute created a material from carbon nanotubes that can absorb 99.955% of light (January 2008).
http://www.rpi.edu/about/inside/issue/v2n2/darkest.html

- Other research on "invisibility" by Ulf Leonhardt, student of Stephen Hawking, and Janos Perczel in the New Journal of Physics (August 9, 11) - Theory: a metamaterial with a negative refractive index could deflect light rendering the material effectively invisible (but with photons faster than light ...); in 'practice' they are working on a type of "fish eye" lens (invented by Maxwell) with varying refractive index which effectively creates an invisible spot (effect // consequence of the projection -ex Mercator- of a world map on a plane would get rid of the pole or the light would have to become infinite ! ...).

Scattering

As previously mentioned, the **scattering coefficient**, $b(\lambda)$, with unit m^{-1}, is defined as:

$$b(\lambda)=\lim_{l-0}\left(\frac{1}{l}\frac{\Phi_b(\lambda)}{\Phi_o(\lambda)}\right)$$

Due to scattering, a unit volume observed from a sufficiently large distance can be considered as a point source from which light emanates in all directions. The light scattered in the direction (α,ψ), where ψ is the polar angle to the direction of propagation (i_3) and α is the azimuth angle, is characterized by the **angular scatterance per unit distance and unit solid angle** $\beta(\lambda,\alpha,\psi)$ in m^{-1} sr^{-1} usually also referred to as "volume scattering function" (VSF).

This VSF can be simplified by assuming that the scattering is symmetrical around the light direction of propagation (i.e., we can integrate over α from 0 to 2π which simply adds a constant factor of 2π).

The scattering coefficient, *b*, can easily be expressed in terms of the VSF:

$$b(\lambda)=2\pi\int_0^{\pi}\beta(\lambda,\psi)\sin\psi\, d\psi$$

This integral can be split into two, for the **forward scattering coefficient:**

$$b_f(\lambda)=2\pi\int_0^{\pi/2}\beta(\lambda,\psi)\sin\psi\, d\psi$$

and the **backscattering coefficient:**

$$b_b(\lambda)=2\pi\int_{\pi/2}^{\pi}\beta(\lambda,\psi)\sin\psi\, d\psi$$

The **spectral volume scattering phase function** is defined as:

$$\beta'(\lambda,\psi)=\frac{\beta(\lambda,\psi)}{b(\lambda)} \quad \text{in} \quad sr^{-1} .$$

This is equivalent to the normalised VSF, i.e., it gives a value of one for the integration over a complete sphere.

Attenuation

The sum of the two quantities $a(\lambda)$ and $b(\lambda)$ is the attenuation coefficient $c(\lambda)$ in m^{-1}:

$$c(\lambda)=a(\lambda)+b(\lambda)$$

<u>Summary of IOPs</u>

The absorption, *a,* and scattering coefficient, *b,* are inherent optical properties (IOPs) of the environment. Strictly speaking, it is the scattering indicator $\beta(\lambda,\psi)$ that is an IOP; while *b* is a derived quantity that is also considered an IOP, as are the VSF and $\beta'(\lambda,\psi)$.

Similarly, attenuation, being the sum of *a* and *b*, is also an IOP.

Other IOPs include the refractive index *m* (and *n*) and a property that is called **albedo** (more precisely: single spectral scattering albedo) $\omega(\lambda)=\frac{b(\lambda)}{c(\lambda)}$. The latter, is also called the **probability of photon survival** as it represents the probability that a photon is scattered rather than absorbed.

IOPs are additive quantities, i.e., we can break down the (total) absorption or scattering coefficients into components due to the individual environmental constituents (assumption of linearity).