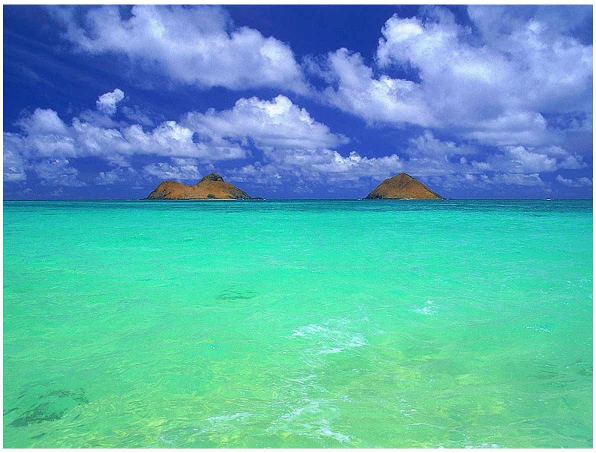
Chapter IV – Light through the water column

Introduction - **What is the colour of the sea, of the ocean?**

The first factor that comes into play is the reflection of light on the water (although this reflection is relatively weak). If the sky is blue, the sea will appear blue. If the sky is grey, the sea will appear grey; if the sky is red during sunset, a red shimmer will appear on the water, etc; the reverse is obviously not true. However, the sea can also have different colours depending on the light conditions, on the characteristics of the sea bed and coast, the sea state, and of course depending on the nature and concentration of substances and suspended particles in the water, etc. In effect, the second key factor is the **colour of the light that emerges from the water** which, if the bottom is not visible, depends on the absorption and scattering by H_2O molecules and the other sea water constituents.



A large body of water typically appears blue. Nevertheless, many different colour changes have been observed in the past and gave rise to the different names of water bodies, such as the Red Sea, the Rio Negro, the Black Lake, etc. To be interested in these colour changes means asking the question: what are the optical properties of water and how do they vary?

It is possible that the Red Sea got its name because of the presence of a particular alga, "Trichodesmium Erythraeum". After a Trichodesmium bloom, the blue-green colour of the sea seems to change to a reddish or brown colour. The Rio Negro is a tributary of the Amazon. Its black colour comes from a high degree of absorption due to high concentrations of iron and dissolved organic matter that originates from decomposing humus that is washed into the river by the frequent rains. In many mountain regions there are lakes called Black Lake. Here, the black colour is also due to high absorption coefficients due to high concentrations of dissolved substances. A red tide may be due to a bloom of specific dinoflagellates, absorbing all visible colours except red. Also "white blooms" of coccolithophorids have been observed, where the white "colour" was due to scattering from calcite.

Open ocean waters usually appear blue. The closer we look near the coast, the more they appear yellow.

A) Air/sea interface

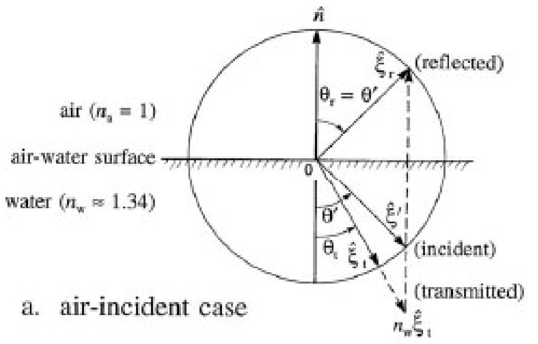
In the case of a flat surface, we can use Snell's law

$$n_i \sin\theta_i = n_t \sin\theta_t$$

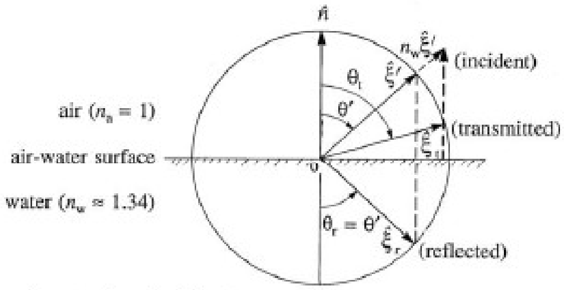
Considering the air/sea interface, a ray incident from the air will have a transmitted component that has its angle in the water reduced by θ_t compared to the angle of incidence because the refractive index is higher in water than in air. A ray that is incident on this surface from the air thus always "enters" the water.

In contrast, a ray hitting the air/sea interface from within the water will have an exit angle that is larger than the angle of incidence. There exists thus a critical angle above which the ray does not cross the interface but is totally internally reflected. This angle is $\theta_i = \arcsin\left(\frac{n_{air}}{n_w}\right)$ or about 48°. If a ray emerging from the water hits the air/sea interface at an angle of incidence greater than 48°, it does not leave the water.

Note: It is easier for light to enter the water than to leave it (for a photon!).



a. air-incident case



b. water-incident case

Left
Rays
a) incident from air
b) incident from water

Below
variation of the parameter r =Ar/Ai (see Section 6 of Chapter 1) using nw=1.367 for blue and nw=1.329 for red light (see section on refractive index) as a function of the angle of incidence

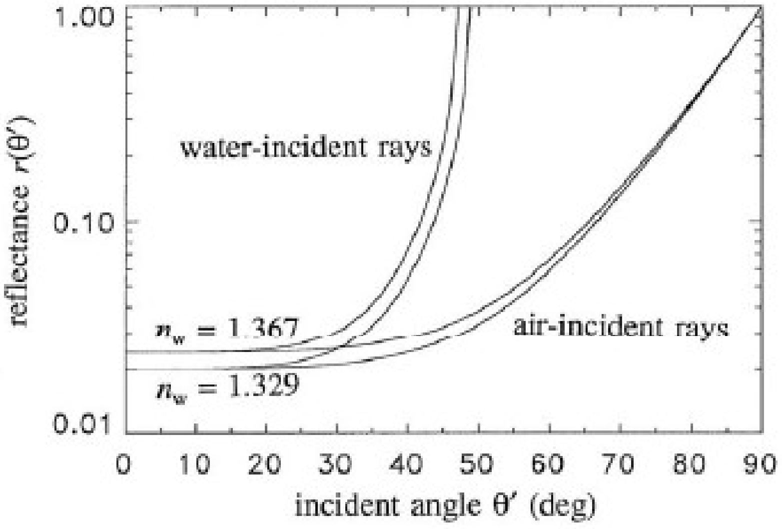


Fig. 4.3. Behavior of the Fresnel reflectance function of Eq. (4.14) for the extreme values of the real index of refraction n_w encountered in hydrologic optics.

Extra material: the n^2 Law for Radiance

Snell's law governs how unpolarized radiance changes when it crosses from one medium to another, for example when crossing the air/sea interface. The figure shows two beams of radiation, the one incident on an interface and the component that is transmitted. Let L1 be the incident radiance in medium 1, defined by the power $\Delta\,\Phi_1$ passing through an area $\Delta\,A_1$ normal to the direction of photon travel and contained in a solid angle $\Delta\,\Omega_1=\sin\theta_1\Delta\,\theta_1\,\Delta\,\phi_1$, where θ_1 is the polar angle measured relative to the surface normal and $\Delta\,\phi_1$ is the width of the solid angle in the azimuthal direction. Similarly, L2 is the transmitted radiance in medium 2, defined by the corresponding quantities as illustrated. The azimuthal angle does not change when crossing the surface, so $\Delta\,\Omega_2=\sin\theta_2\,\Delta\,\theta_2\,\Delta\,\phi_1$. The incident and transmitted energies pass through the same area $\Delta\,A$ at the interface.

http://www.oceanopticsbook.info/view/surfaces/the_level_sea_surface

with T_F the transmission coefficient defined as: $\Delta\,\Phi_2=T_F\,\Delta\,\Phi_1$,

it can be shown that: $\frac{L_2}{n_2^2}=T_F\frac{L_1}{n_1^2}$

Although energy is conserved when crossing a boundary, the radiance changes by a factor proportional to the change in the refractive index squared. This is a direct consequence of the change in solid angle resulting from the change in θ when crossing the boundary. Note that for normal incidence and $n_w=1{,}34\wedge T_F\approx 0{,}979$, the radiance just below the water surface is 0,979×$(1{,}34)^2$ or about 1.76 times the radiance in air. **Conversely, when going from water to air, the in-water radiance is reduced by a factor of 1.76**.

(see http://www.oceanopticsbook.info/view/surfaces/the_level_sea_surface for a demonstration)

Whenever losses due to absorption and scattering out of the beam can be ignored (this may sometimes be a good approximation for atmospheric transmission, but almost never in water), the radiance divided by the refractive index squared is constant along any path. This result has been called the **Fundamental Theorem of Radiometry**, which may appear a little grandiose considering that real-world light beams always lose radiance due to absorption and may lose or gain radiance as a result of scattering.

Finally, note that this n^2 law only applies to the transmission of radiance. When tracing photons in a Monte Carlo simulation (see Chapter 6) where radiance can be estimated by appropriate binning of the transmitted photons, no n^2 factor is applied to the energy of the transmitted photons or to the radiance estimated from the detected photons. This is because the n^2-effect is automatically accounted for when estimating the radiance from photons as the directions of the individual photons are computed by Snell's law.

To convert surface Ed and PAR to the corresponding values below the surface, refer to Mobley and Boss (2012). In short, they found:

The daily mean net downwelling irradiance $Ed(0\text{-})_{24}$ and $PAR(0\text{-})_{24}$ that enters the ocean is approximately 5% to 20% lower than the downwelling irradiance in air $Ed(air)_{24}$ incident on the ocean surface. The exact quantity that enters the water depends mainly on the latitude, the day of the year, the wind speed, and the cloud cover.

Easy-to-use function files have been developed to convert these daily means from just above the surface into values just below the surface: $Ed(0\text{-})_{24}$ and $PAR(0\text{-})_{24}$. These values can then be used to initialise optical models that calculate the light propagation to greater depths. The corresponding data files, used to create the figures in their article, can be downloaded from http://www.oceanopticsbook.info/view/radiative_transfer_theory/level3.

See figure on next page.

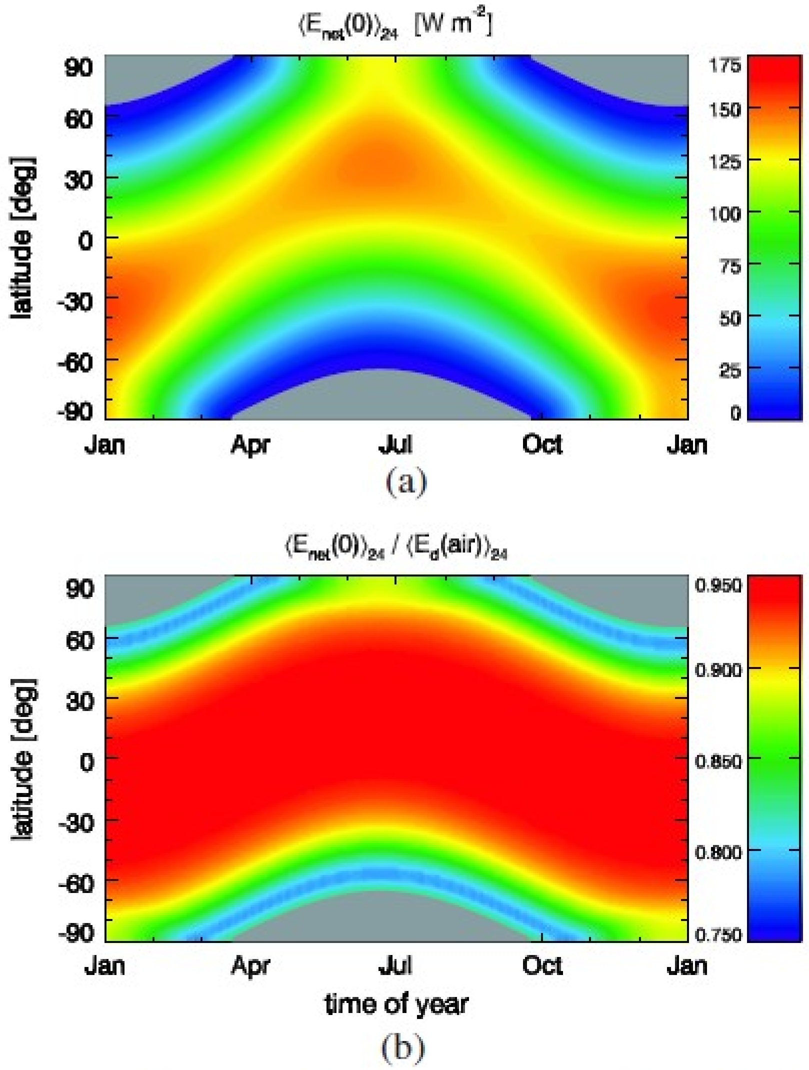


Fig. 10. (a) In-water $\langle E_{\mathrm{net}}(0)\rangle_{24}$ corresponding to Fig. 9(a). (b) Surface transmission factor that converts $\langle E_d(\mathrm{air})\rangle_{24}$ into $\langle E_{\mathrm{net}}(0)\rangle_{24}$.

It is thus important to know whether a given surface PAR value refers to an instantaneous or daily PAR (PAR_{24}); both are very different, see Lee (2009) and Wei and Lee (2013).

Non-planar interface

For a non-planar interface the situation becomes more complicated. Mobley (1994) chose to approach this problem using mini-spheres that could adapt to any rough surface. Theses spheres are divided into M zonal bands N meridional quads. The division into quads and bands can be irregular depending on the application.

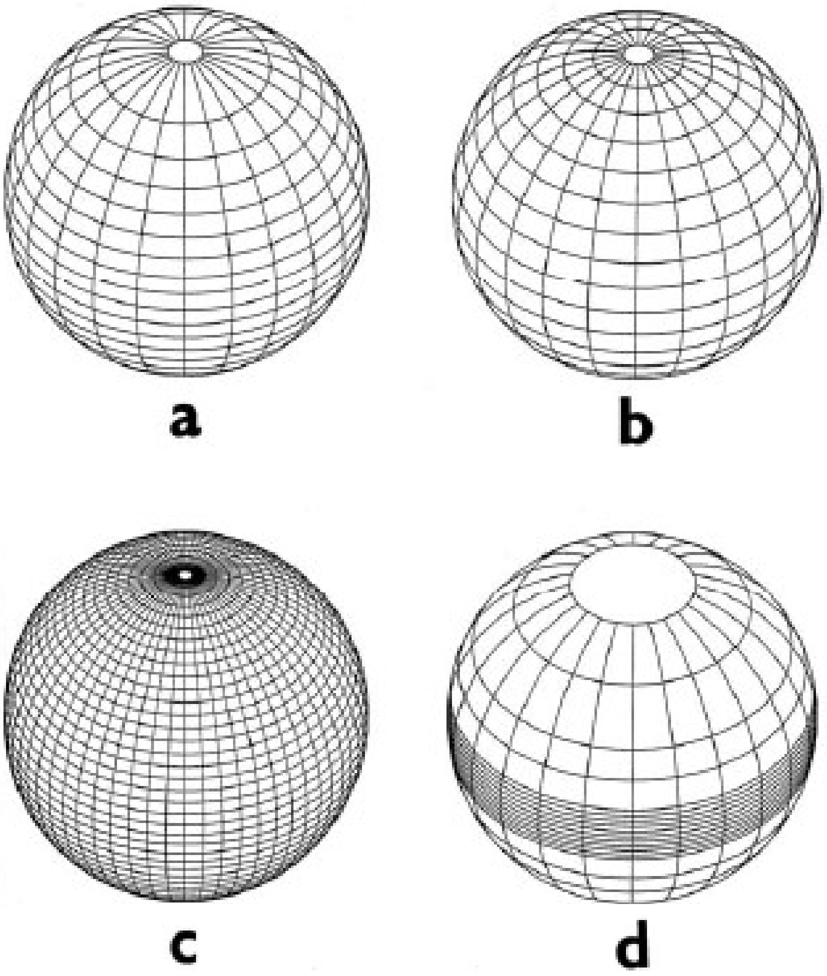


Fig. 4.19. Further examples of partitions of the unit sphere into quads. (a) $m = 10$ μ-bands and $n = 12$ ϕ-bands, with all solid angles Ω_{pq} and Ω_m equal. (b) $m = 10$ and $n = 12$, with all $\Delta\theta$ values equal. (c) $m = 23$, $n = 30$, with equal $\Delta\theta$ values, so that $\Delta\theta \approx 4°$, $\Delta\phi = 6°$. (d) $m = 10$, $n = 12$, with an *ad hoc* selection of the $\Delta\theta$ values. [redrawn from Mobley and Preisendorfer (1988)]

B) <u>The fate of light in water</u>

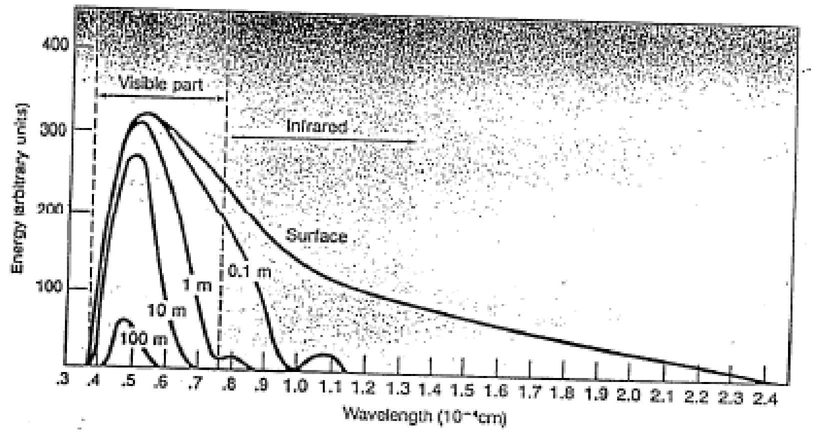
Two main rules constitute the B, A, BA of this domain:

a) the deeper we go, the longer the path travelled by light and thus the more feeble the light becomes (either through absorption or scattering). So the available electromagnetic energy from the sun decreases as depth increases.

b) this “disappearance” of light depends on the constituents in the water column (see Chapter 3). The more turbid the water, the faster the light is attenuated; the clearer the water, the deeper the light penetrates.

In any case, light has a tendency to become more monochromatic with depth.

Note: although water is considered “transparent” it does absorbs light. If it didn’t absorb as much as it does, it would be “cold and lifeless”.

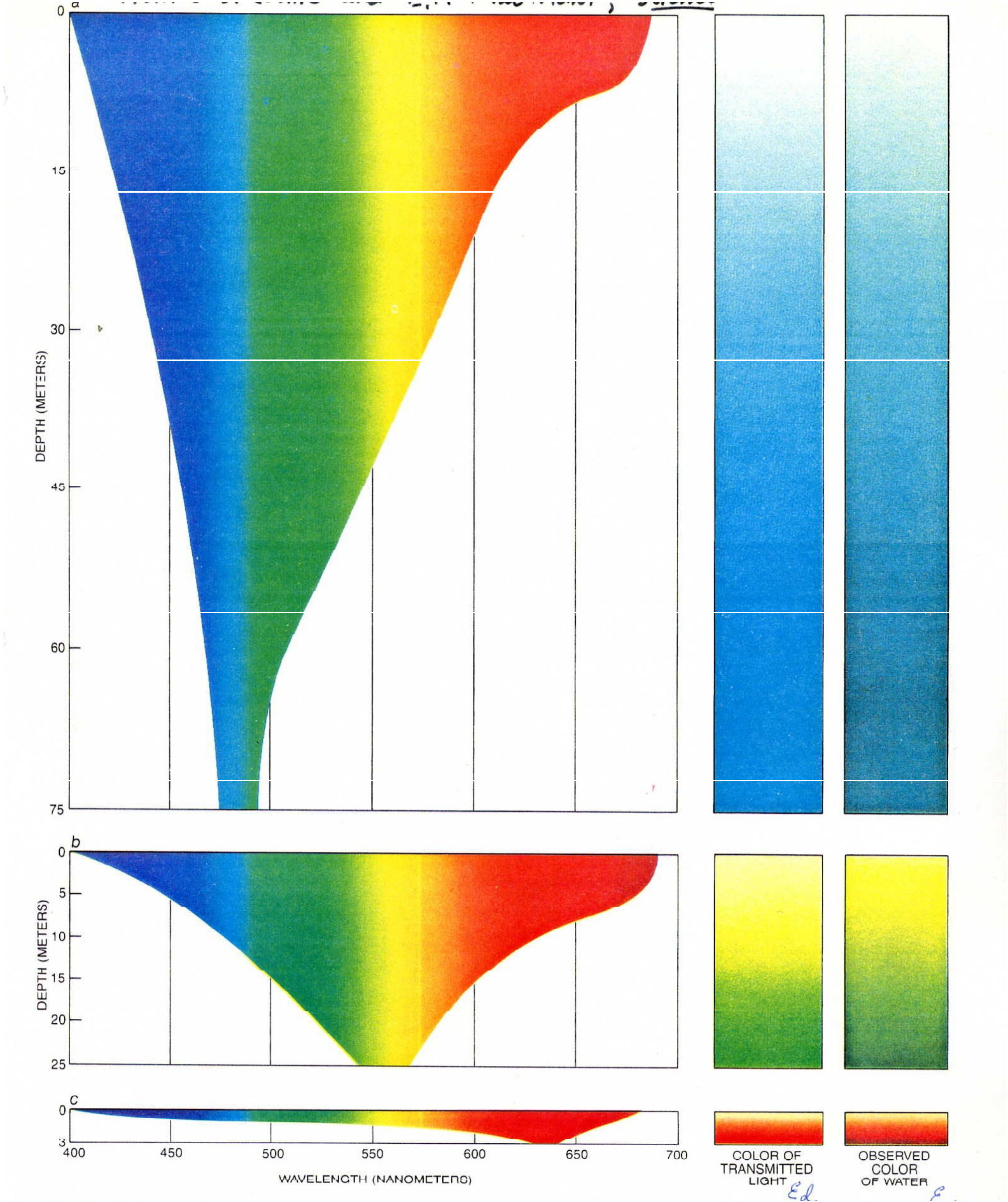


Total available solar energy in the sea (shown by the areas under the curves) decreases as depth increases. The longer, red wavelengths are absorbed first. The color peak shifts to the shorter, blue wavelengths as the depth increases.

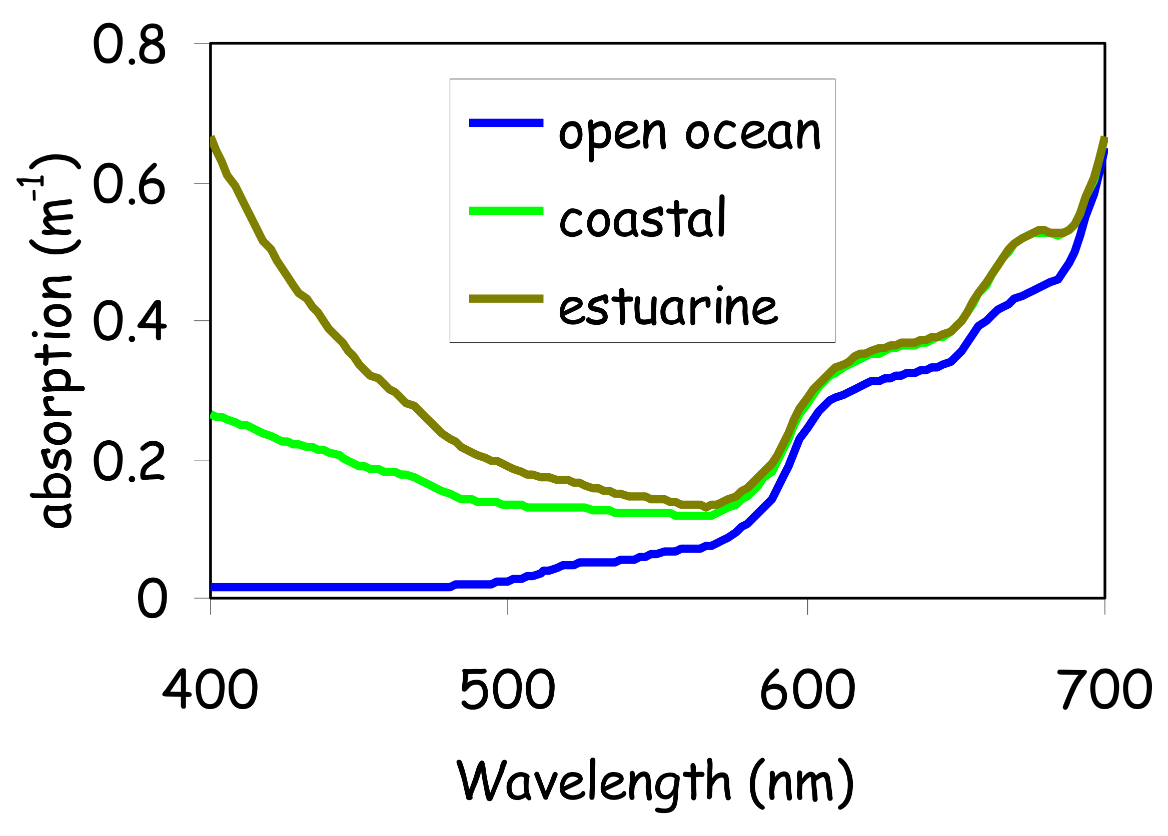
From Sverdrup/Johnson/Fleming, *The Oceans*, ©1942, renewed 1970, p. 105. Adapted by permission of Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

This light penetration is the “opposite” of the absorption spectra of the water constituents.

Light Penetration



TRANSMISSION OF LIGHT by water is dependent on the color or wavelength of the light. In clear oceans and lakes (*a*) the light becomes increasingly monochromatic and blue as its path length increases. In fresh water that carries green organic matter (*b*) light at all wavelengths is absorbed more quickly than it is in clear water, but the light becomes greener with path length. In rivers, swamps and marshes that carry large amounts of the products of plant and animal decay (*c*) absorption is rapid and the spectral distribution of the light shifts to the red. Such waters are called black because the human eye is relatively insensitive to light at long wavelengths; a less anthropomorphic name would be infrared water. The depths given for the maximum penetration of light are typical, but they vary widely.



Roesler, Handout, Ocean Optics class Summer 2007

C) Vertical profiles – the Beer-Lambert law
(Bouguer 1729, Lambert 1760, Beer 1862)

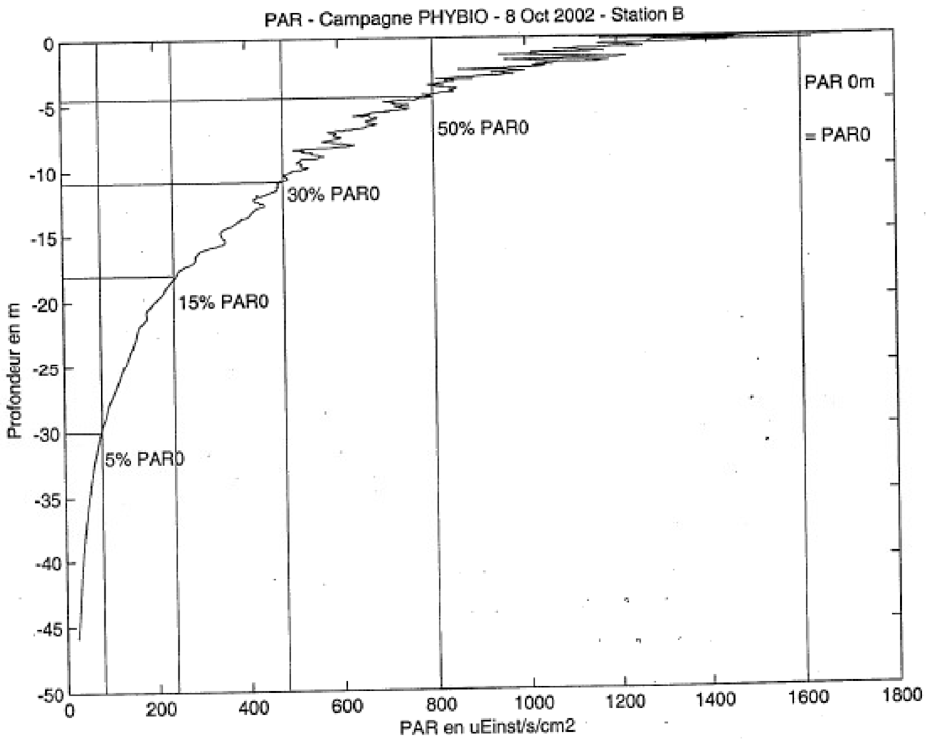
Vertical light profiles (Eo, Ed, Eu, PAR, etc.) can be approximated using the empirical Beer-Lambert law:

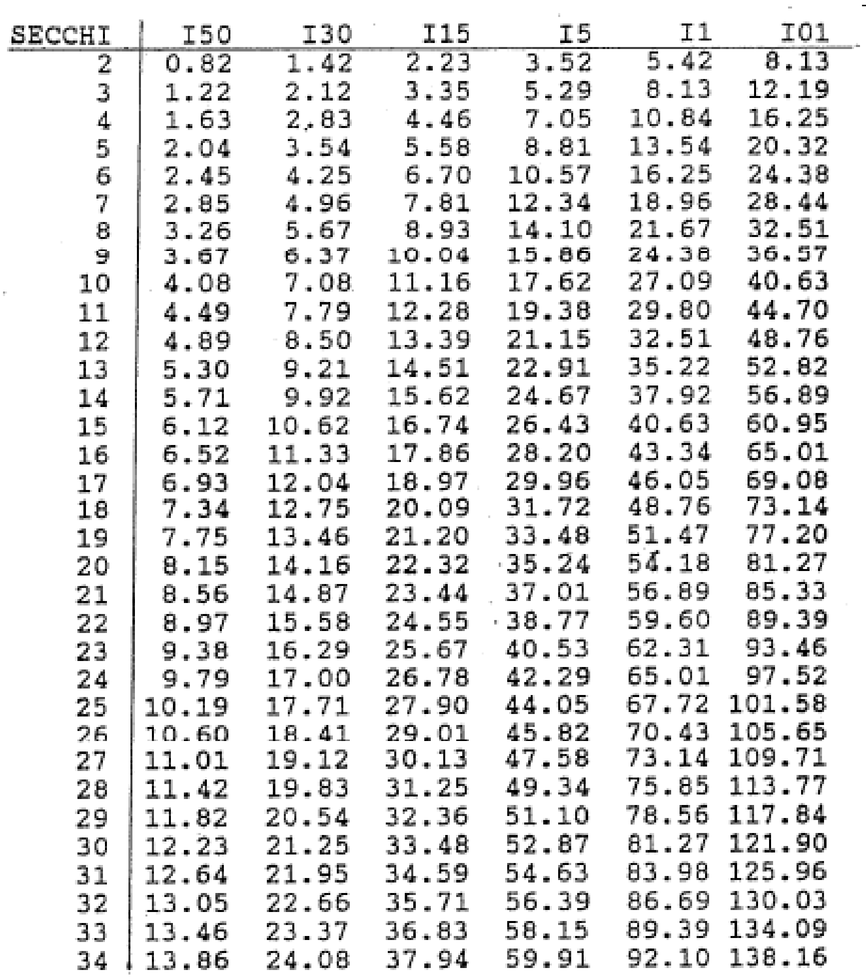
$E = E(z{=}0)\ e^{-kz}$

Note1: It is only an approximation!

Note 2: If we infuse a tea bag in a pot and then remove the bag, as counter-intuitive as it sounds, we will find that adding more water will not alter the colour of the liquid. The reason for this is that while the dilution with "clear" water will reduce the concentration (k) of tannins in the water, this reduction happens at exactly the same rate as the water depth (z) in the pot increases, thus light encounters the same amount of tannins along its path.
This law was discovered in 1729 by Pierre Bouguer and was published in a book entitled "Essai d'optique sur la gradation de la lumiere" (Claude Jombert, Paris, 1729), then taken up by Johann Heinrich Lambert in 1760 and eventually by August Beer in 1852 who introduced the concentration into the equation, giving it is current form.

Before the advent of instruments that could measure solar irradiance profiles in real time (a common example is PAR measurements, see figure below), oceanographers, and especially biogeochemists who needed to know the level of irradiance that existed at the depth from which they collected samples for incubation, used Secchi discs in combination with tabulated values (see following page and the explication in the course OPB201).





SECCHI	I50	I30	I15	I5	I1	I01
2	0.82	1.42	2.23	3.52	5.42	8.13
3	1.22	2.12	3.35	5.29	8.13	12.19
4	1.63	2.83	4.46	7.05	10.84	16.25
5	2.04	3.54	5.58	8.81	13.54	20.32
6	2.45	4.25	6.70	10.57	16.25	24.38
7	2.85	4.96	7.81	12.34	18.96	28.44
8	3.26	5.67	8.93	14.10	21.67	32.51
9	3.67	6.37	10.04	15.86	24.38	36.57
10	4.08	7.08	11.16	17.62	27.09	40.63
11	4.49	7.79	12.28	19.38	29.80	44.70
12	4.89	8.50	13.39	21.15	32.51	48.76
13	5.30	9.21	14.51	22.91	35.22	52.82
14	5.71	9.92	15.62	24.67	37.92	56.89
15	6.12	10.62	16.74	26.43	40.63	60.95
16	6.52	11.33	17.86	28.20	43.34	65.01
17	6.93	12.04	18.97	29.96	46.05	69.08
18	7.34	12.75	20.09	31.72	48.76	73.14
19	7.75	13.46	21.20	33.48	51.47	77.20
20	8.15	14.16	22.32	35.24	54.18	81.27
21	8.56	14.87	23.44	37.01	56.89	85.33
22	8.97	15.58	24.55	38.77	59.60	89.39
23	9.38	16.29	25.67	40.53	62.31	93.46
24	9.79	17.00	26.78	42.29	65.01	97.52
25	10.19	17.71	27.90	44.05	67.72	101.58
26	10.60	18.41	29.01	45.82	70.43	105.65
27	11.01	19.12	30.13	47.58	73.14	109.71
28	11.42	19.83	31.25	49.34	75.85	113.77
29	11.82	20.54	32.36	51.10	78.56	117.84
30	12.23	21.25	33.48	52.87	81.27	121.90
31	12.64	21.95	34.59	54.63	83.98	125.96
32	13.05	22.66	35.71	56.39	86.69	130.03
33	13.46	23.37	36.83	58.15	89.39	134.09
34	13.86	24.08	37.94	59.91	92.10	138.16

Table of depths (in metres) of illumination levels for different Secchi depths (in metres) given in the first column.