Light and Radiometry

How to quantitatively describe "how much" light there is, where it is going, etc.?

Different ways to quantify light:

•Energy [W m^{-2}]. Useful when we are interested in heating rates.

•Number of photons [Einstein= Mol ($6.023 \cdot 10^{23}$) photons m^{-2} s^{-1}]. Useful for photosynthesis.

•At what wavelength?

Depends on the specific application

*Based on lectures by Mobley, Roesler & Lewis

Radiometry

The science of measuring electromagnetic energy.

Detectors:
Thermal-instrument response is proportional to energy (absorbed and converted to heat)

Quatum-response is proportional to number of photons (photoelectric devices).

Calibration of radiometric instrument is non trivial (~1% accuracy, precision ~0.1%).

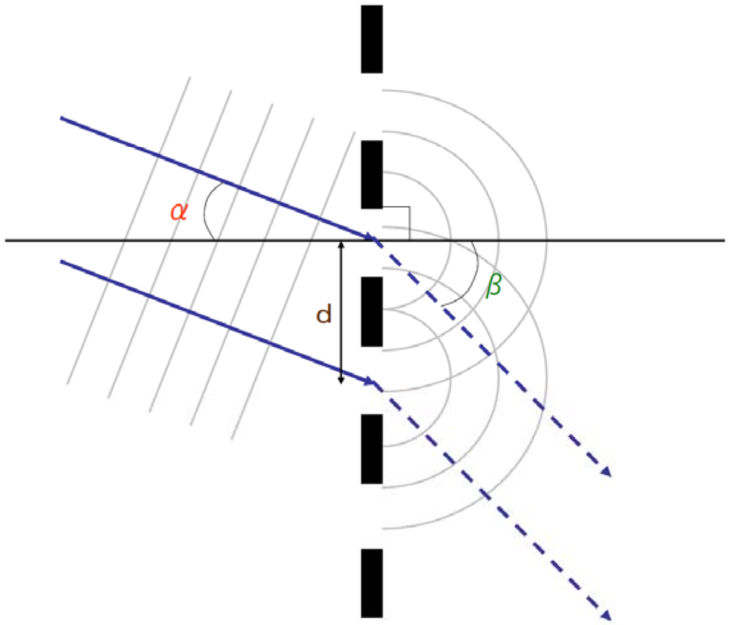
How do we measure spectrally resolved radiation?

→ For years it was easier to define the *euphotic depth* by a % of surface light rather than a constant *isolume*. Why does it matter?

Separating light into its spectral components:

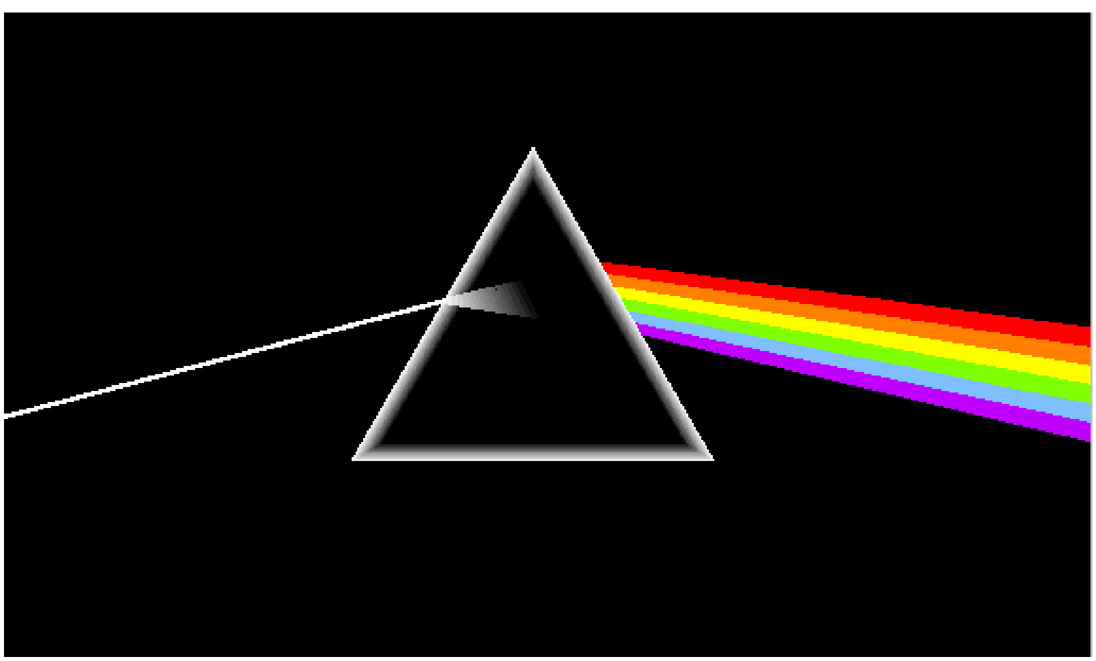
Spectrometers

Diffraction grating:



http://commons.wikimedia.org/wiki/Image:Diffraction_grating_principle.png

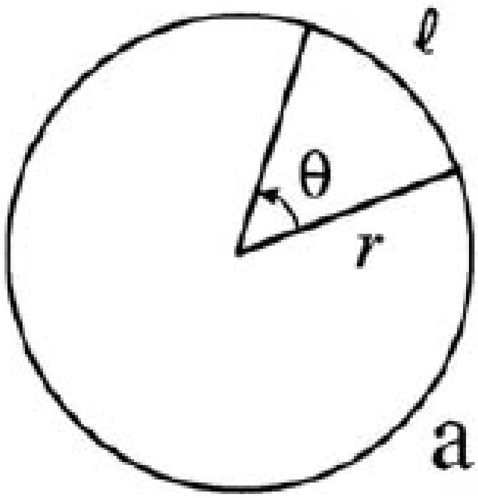
Prism:

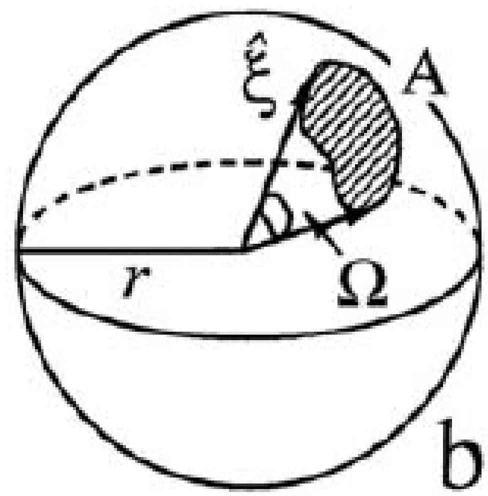


http://www.abdn.ac.uk/~u20lm5/px2013/app2.htm

Geometrical foundation

Solid angle review:

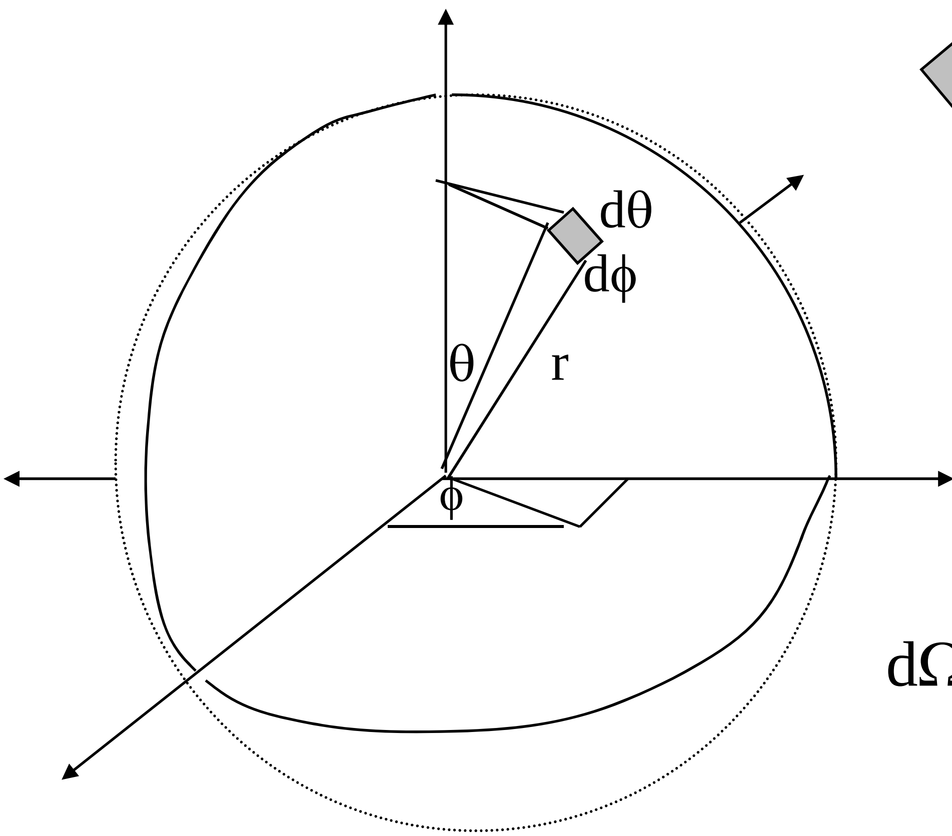


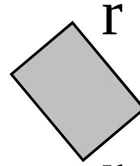


θ= arc-length/radius
or
$\ell = \theta r$

Ω= Area/radius^2
or
$A = \Omega r^2$

Computing solid angles:





$$d\Omega = dA/r^2$$

$$d\Omega = r^2 \sin\theta \, d\theta \, d\phi / r^2$$

θ-zenith angle
ϕ-azimuthal angle

Radiance:

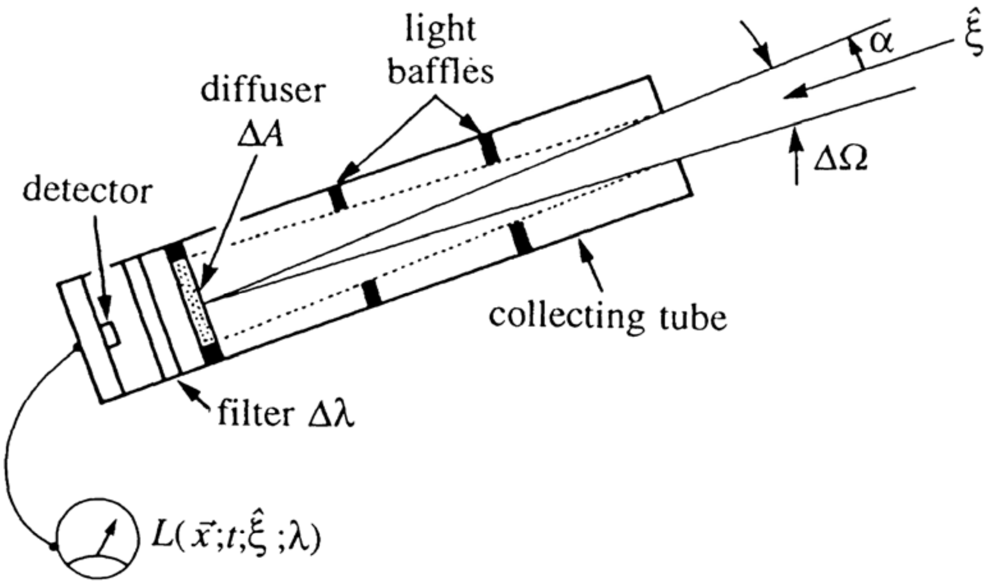


Fig. 1.5. Schematic design of an instrument for measuring unpolarized spectral radiance.

$$L(\vec{x},t,\phi,\theta,\lambda) \equiv \frac{\Delta Q}{\Delta t \Delta A \Delta \Omega \Delta \lambda} \left[\frac{\text{J}}{\text{s m}^2 \text{ sr nm}} = \frac{\text{W}}{\text{m}^2 \text{ sr nm}} \right]$$

[L]=(W m^{-2} sr^{-1} nm^{-1})

Note: we are in the geometric optics regime.

All other radiometric quantities can be derived from *L*.

Irradiance

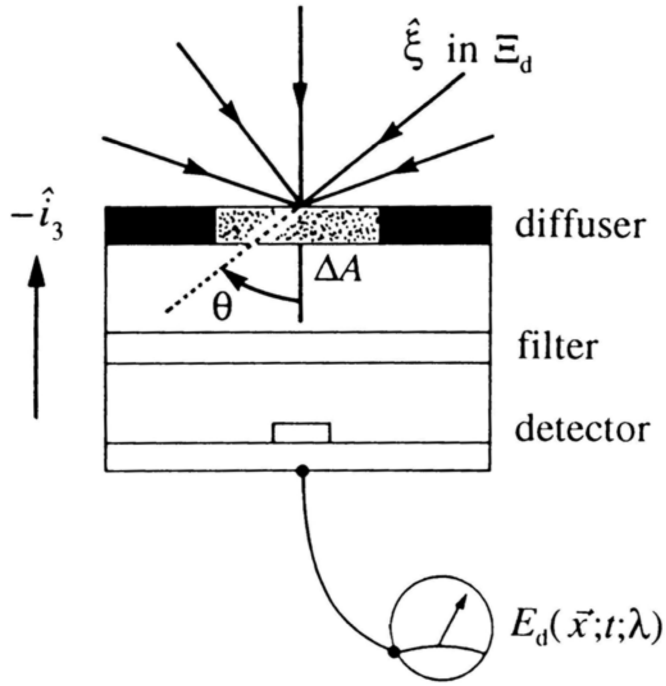


Fig. 1.6. Schematic design of an instrument for measuring spectral plane irradiance.

$$E_d \equiv \frac{\Delta Q}{\Delta t \Delta A \Delta \lambda}\left[\frac{\mathrm{W}}{\mathrm{m}^2\ \mathrm{nm}}\right]$$

$$E_d(\theta,\phi,\lambda) \equiv \int_{UH} L(\Omega,\lambda)\left|\cos\theta\right| d\Omega = \int_0^{2\pi}\int_0^{\pi/2} L(\theta,\phi,\lambda)\left|\cos\theta\right| \sin\theta d\theta d\phi$$

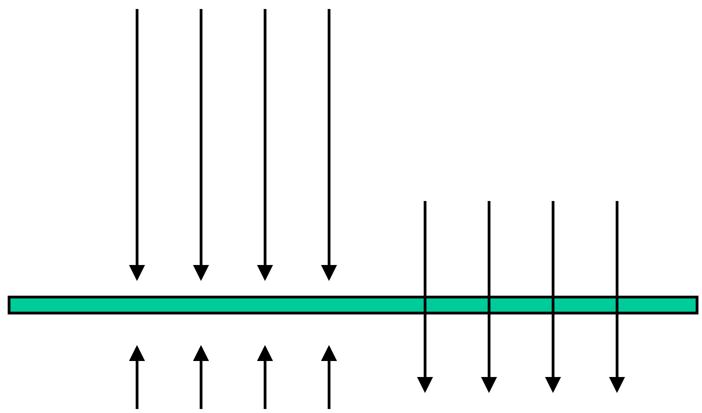
Downward irradiance is the downward component of the L vector, weighted by its angle to the detector (effective area over which the light is spread).

Cosine response to wide vs. narrow beams.

Net Downward Irradiance (vector)

$\vec{E} = E_d - E_u$

Describes net flux



$$\vec{E}(\theta,\phi,\lambda) \equiv \int_0^{4\pi} L(\Omega,\lambda)\left|\cos\theta\right| d\Omega = \int_0^{2\pi}\int_0^{\pi} L(\theta,\phi,\lambda)\left|\cos\theta\right| \sin\theta d\theta d\phi$$

When will we use it?

Scalar Irradiance

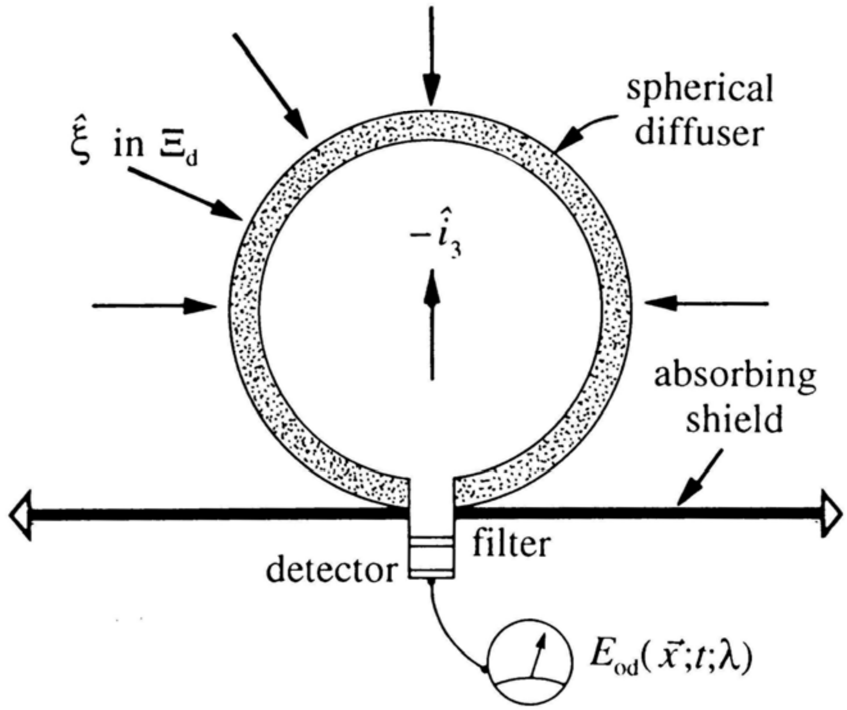


Fig. 1.7. Schematic design of an instrument for measuring spectral scalar irradiance.

$$E_{0d} \equiv \frac{\Delta Q}{\Delta t \Delta A \Delta \lambda}\left[\frac{\mathrm{W}}{\mathrm{m}^2\ \mathrm{nm}}\right]$$

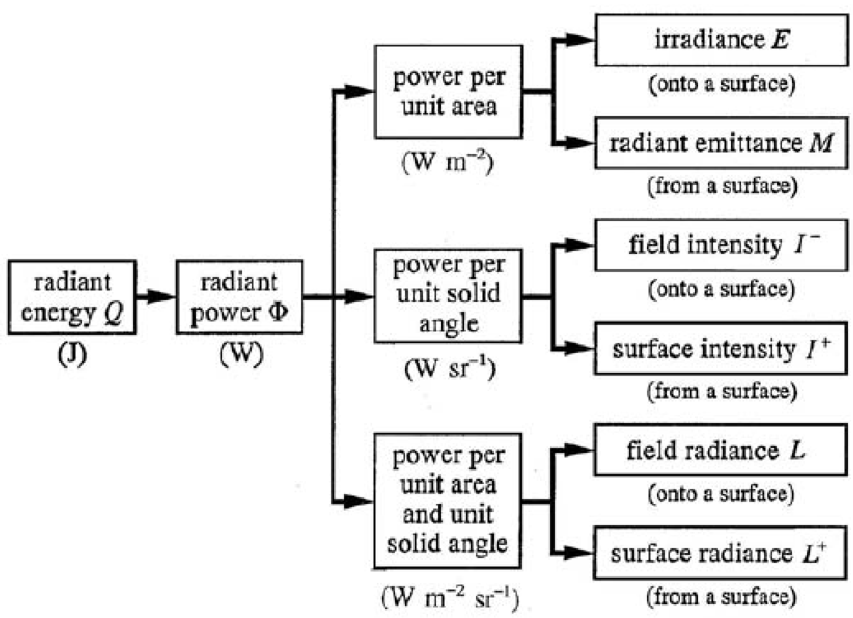
$$E_{0d}(\theta,\phi,\lambda) \equiv \int_{UH} L(\Omega,\lambda)d\Omega = \int_0^{2\pi}\int_0^{\pi/2} L(\theta,\phi,\lambda)\sin\theta d\theta d\phi$$

Downward scalar irradiance has the same effective area for *L* in any direction. No cosθ factor.

What science requires scalar irradiance?

Quantity	SI Units	Recommended symbol	Historic symbol
radiant energy	J	Q	U
radiant power	W	Φ	P
radiant intensity	$W\ sr^{-1}$	I	J
radiance (intensity)	$W\ m^{-2}\ sr^{-1}$	L (*I*)	N
plane irradiance (radiant flux)	$W\ m^{-2}$	E (*F*)	H
downward plane irradiance	$W\ m^{-2}$	E_d	$H(-)$
upward plane irradiance	W m−2	E_u	$H(+)$
scalar irradiance	$W\ m^{-2}$	$\mathring{E}$ or E_o	h
downward scalar irradiance	$W\ m^{-2}$	$\mathring{E}_d$ or E_{od}	$h(-)$
upward scalar irradiance	$W\ m^{-2}$	$\mathring{E}_u$ or E_{ou}	$h(+)$
vector irradiance	$W\ m^{-2}$	$\vec{\boldsymbol{E}}$	$\vec{\boldsymbol{H}}$
(vertical) net irradiance	$W\ m^{-2}$	$E_d - E_u$	—
radiant exitance	$W\ m^{-2}$	M	W
photosynthetically available radiation	$photons\ s^{-1}\ m^{-2}$	PAR or E_{PAR}	—

Table 1.5. Terms, units, and symbols for radiometric quantities commonly used in hydrologic optics. The quantities as shown represent broadband measurements. For narrow band (monochromatic) measurements, add the adjective "spectral" to the term, add nm^{-1} to the units, and add a wavelength index λ to the symbol, e.g. spectral radiance, L_λ or $L(\lambda)$, with units of $W\ m^{-2}\ sr^{-1}\ nm^{-1}$. PAR is always broadband.



Things to watch out for:

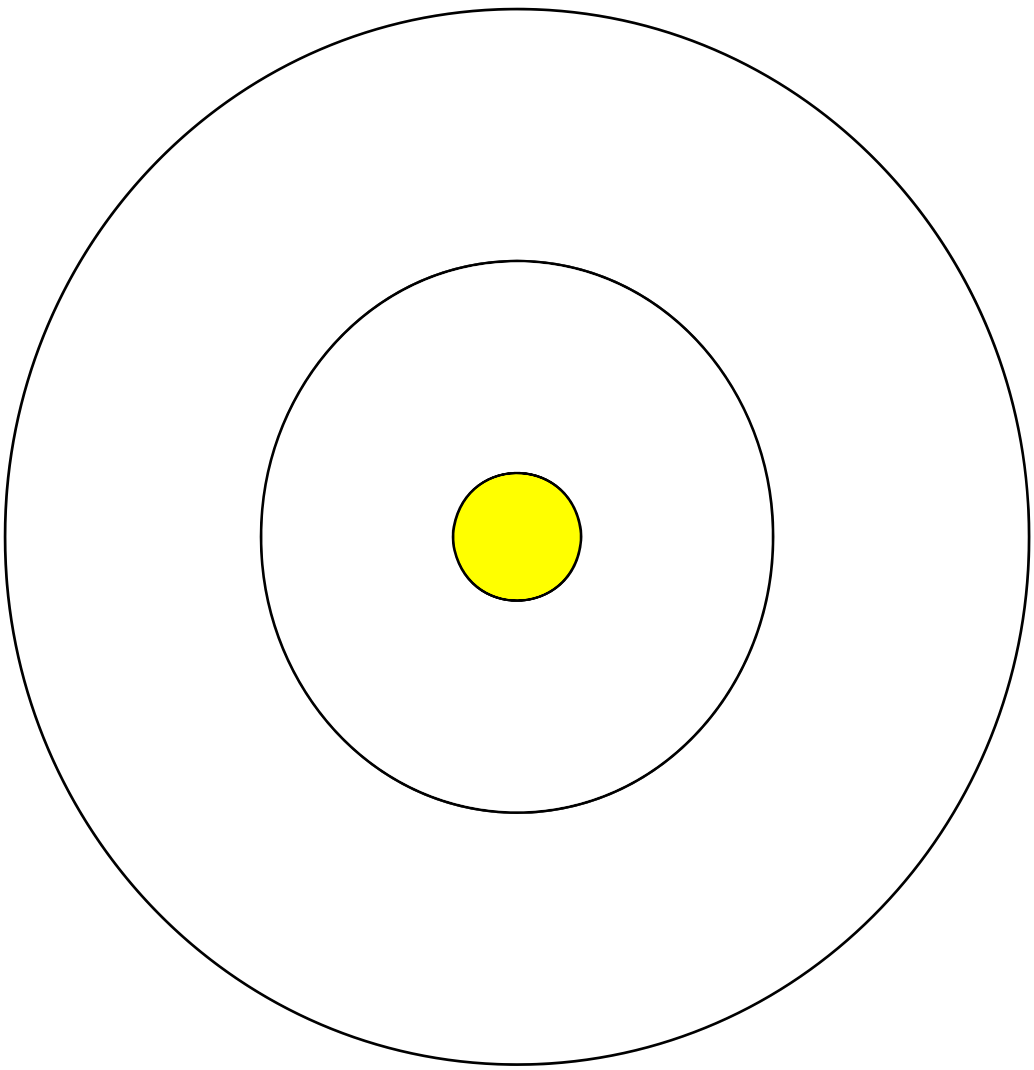
1. Spectral normalization are often done without change in notation. Hence E_d(PAR) , the integrated irradiance over the photosynthetic band had different units than spectral irradiance yet both are denoted by $E_d(\lambda)$.

2. Time for light field equilibration to a change in the environment is very rapid ($O(10^{-6}$s)). Hence most radiative problem omit time changes.

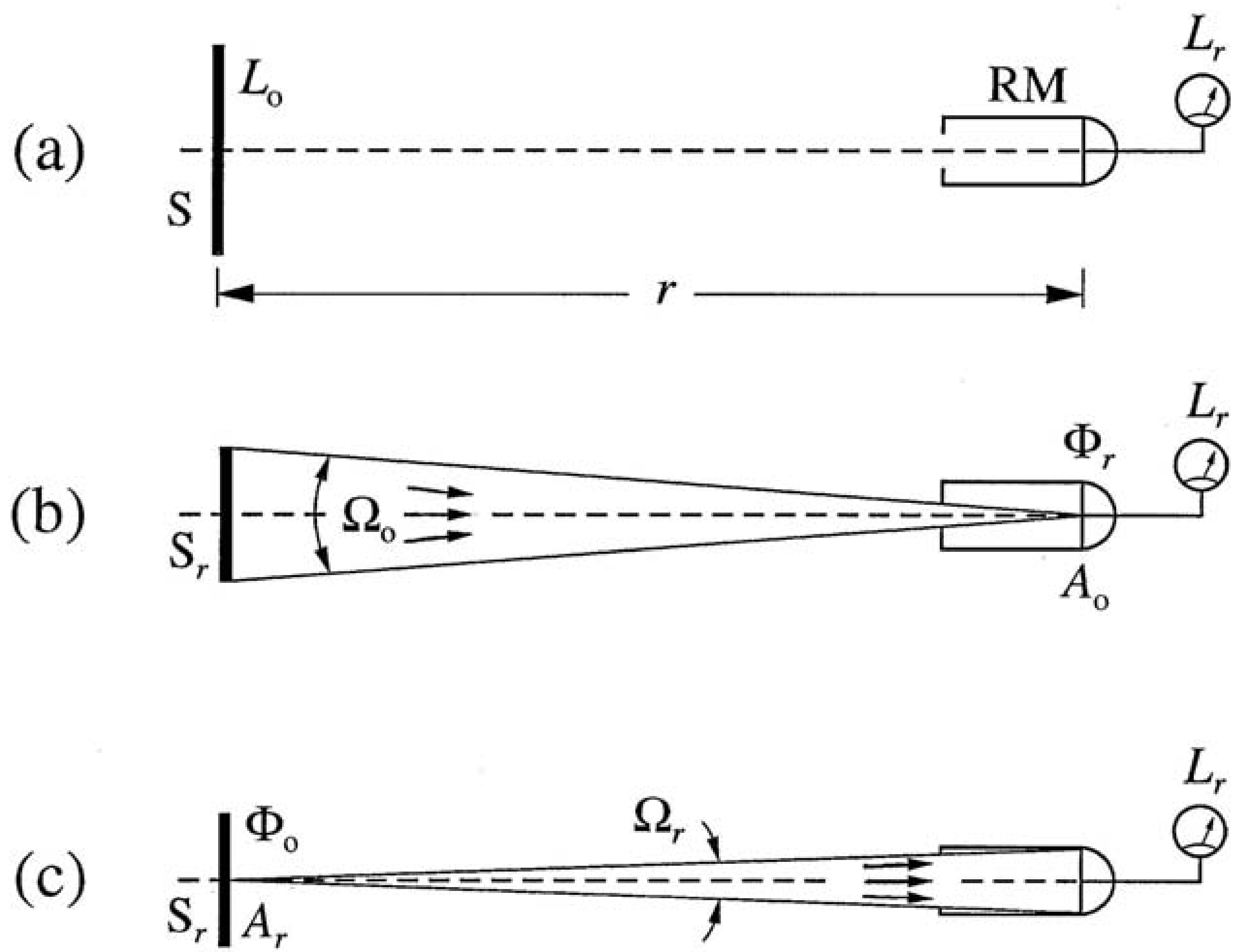
3. In most environment optical properties vary most in a single direction (e.g. vertical in the ocean and atmosphere). The radiative calculations and measurements are then limited to one direction. This is off course not true when dealing with patchy clouds and below gravity waves, and provide, at best, an average light field.

Inverse square law of for irradiance:

Energy per unit time per unit area (irradiance) decreases away from a point source as $1/R^2$.



Radiance invariance law – radiance does not change along a photon-path (ray) in vacuum, $L_o = L_r$ for all r:



Φ_r-arrives at detector in direction of source.
Φ_o- leaves the source (within field of view of detector)
Both fluxes are equal (conservation of energy).
Geometry: $\Omega_r = A_o/r^2$, $\Omega_o = A_r/r^2$

Since $\Phi_o = L_o A_r \Omega_r$ and $\Phi_r = L_r A_o \Omega_o$ → $L_o = L_r$

→ In absence of attenuation, provides for the radiance of a distant object.

The Physical foundation:

Light can be modeled as varying electrical ($\boldsymbol{E}(\mathbf{x},t)$) and magnetic ($\boldsymbol{B}(\mathbf{x},t)$) fields oscillating in time and space related to each other through Maxwell's equations.

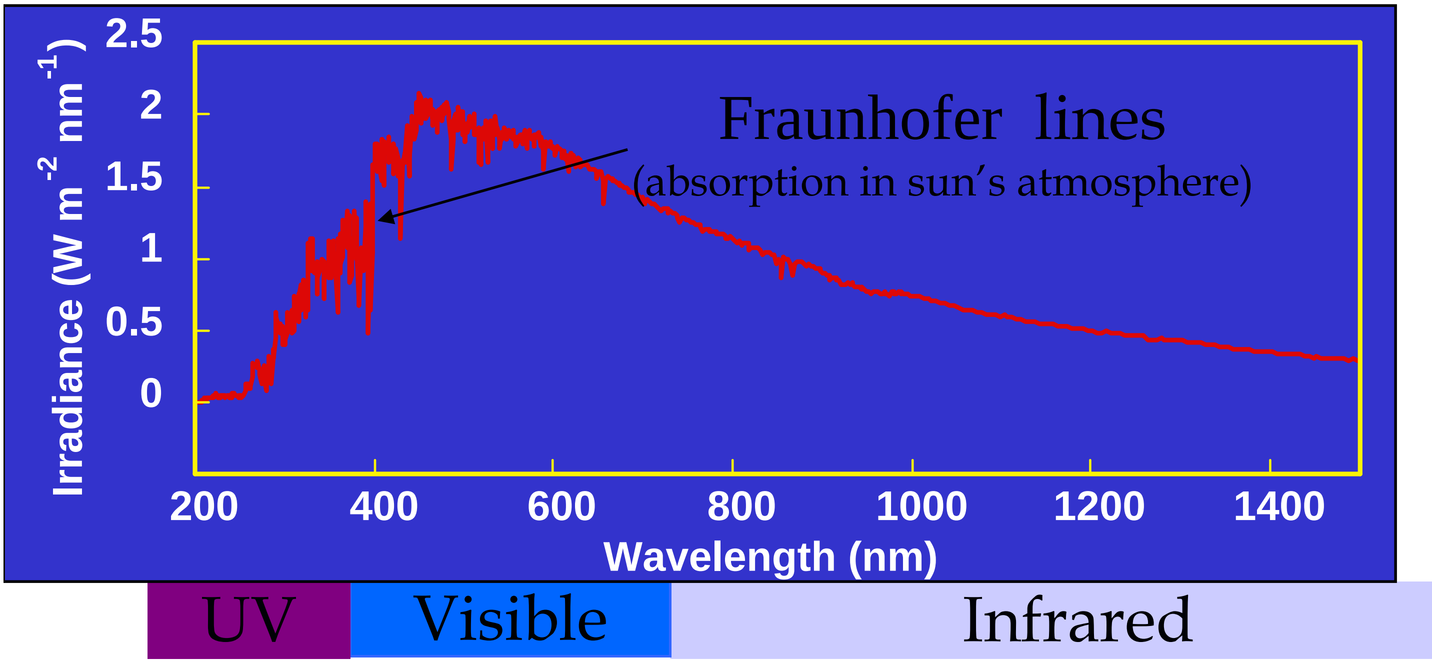
Defining a Poynting vector: $\boldsymbol{S}=\boldsymbol{E}\times\boldsymbol{B}/\mu_o$

provide the instantaneous power per unit area perpendicular to $\boldsymbol{S}$ (μ_o is the permeability).

This is the **irradiance**.

Light is polarized (what does it mean?).

Extraterrestrial Solar Radiation



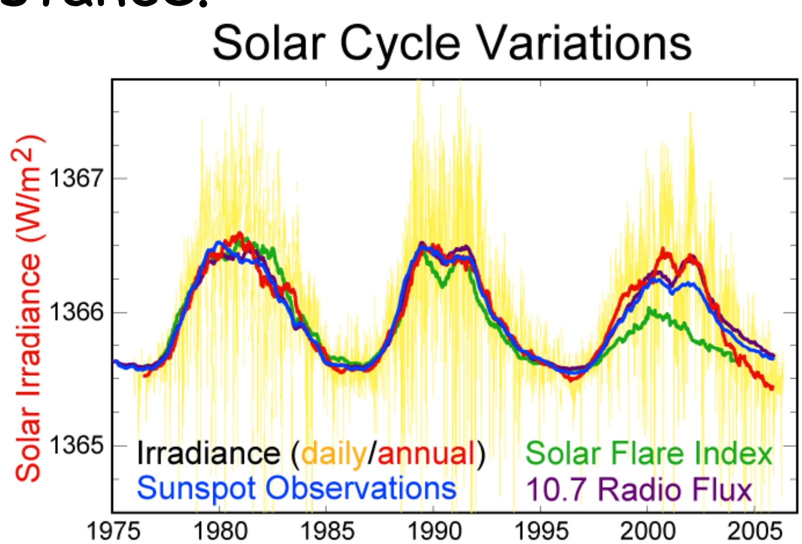
http://rredc.nrel.gov/solar/standards/am0/NewAM0.xls

The Solar 'Constant' is 1366.1 Wm^{-2}.

Amount of solar radiation on a surface perpendicular to the solar beam, at the outer limit of earth's atmosphere, at the mean sun-earth distance.

Yearly fluctuation

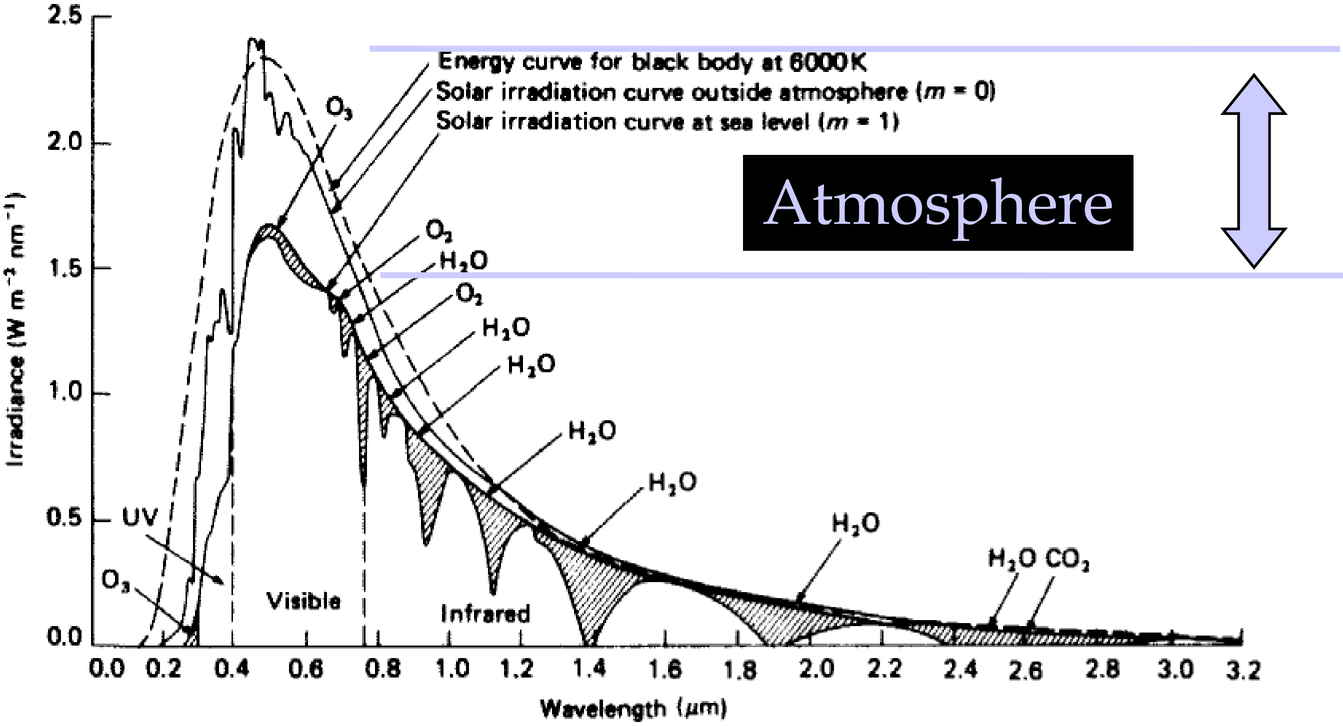
Sun spot cycle



http://en.wikipedia.org/wiki/Image:Solar-cycle-data.png

The atmosphere

The atmosphere attenuates the amount of radiation impinging on earth's surface.

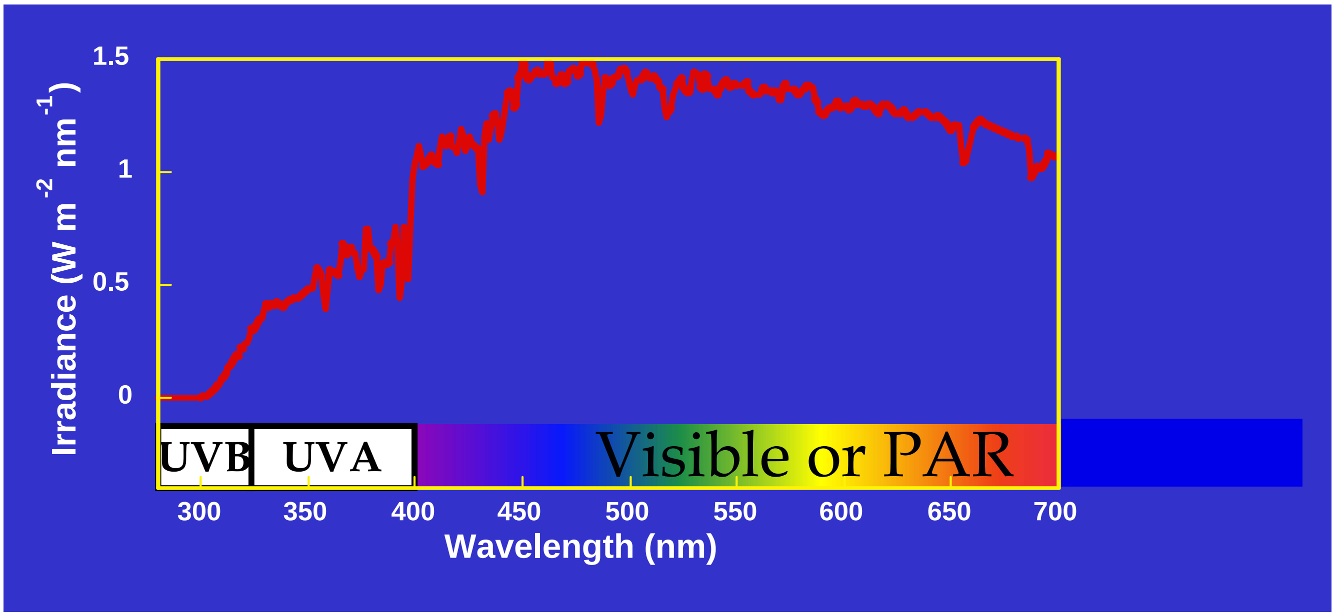


Kirk 1994, Fig. 2.1, p. 27

Solar Radiation Incident on the Ocean

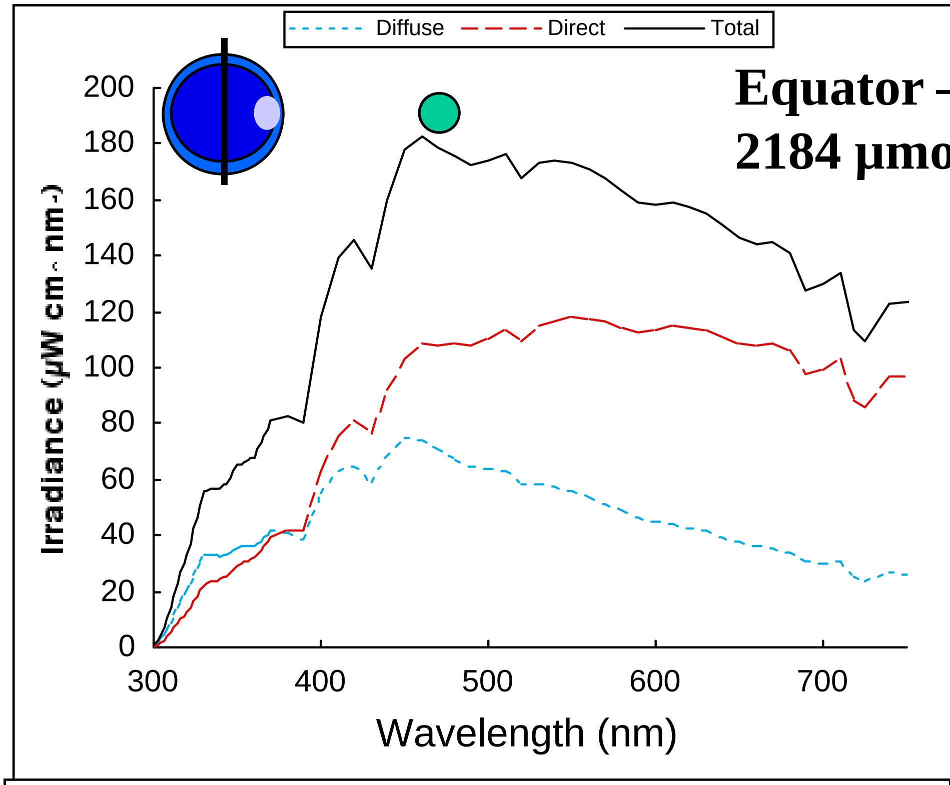
- Transmission through the atmosphere depends on:
    - **Solar zenith angle (latitude, season, time of day) ← why?**
    - **Cloud cover**
    - Atmospheric pressure (air mass)
    - Water vapor
    - Atmospheric turbidity
    - **Column ozone (important for UV-B)**
        - Ground albedo (how much light is reflected from the ground) also affects the incident irradiance.
- Midsummer Solar Irradiance at 45°N (midday)
    - about 400 W m^{-2} (PAR, energy units)
    - 1900 μmol m^{-2} s^{-1} (PAR, quanta)
- Midwinter Solar Irradiance at 45°N
    - about 130 W m^{-2}; 600 μmol m^{-2} s^{-1}

Visible and UV Irradiance Typical Spectrum for summer in Halifax

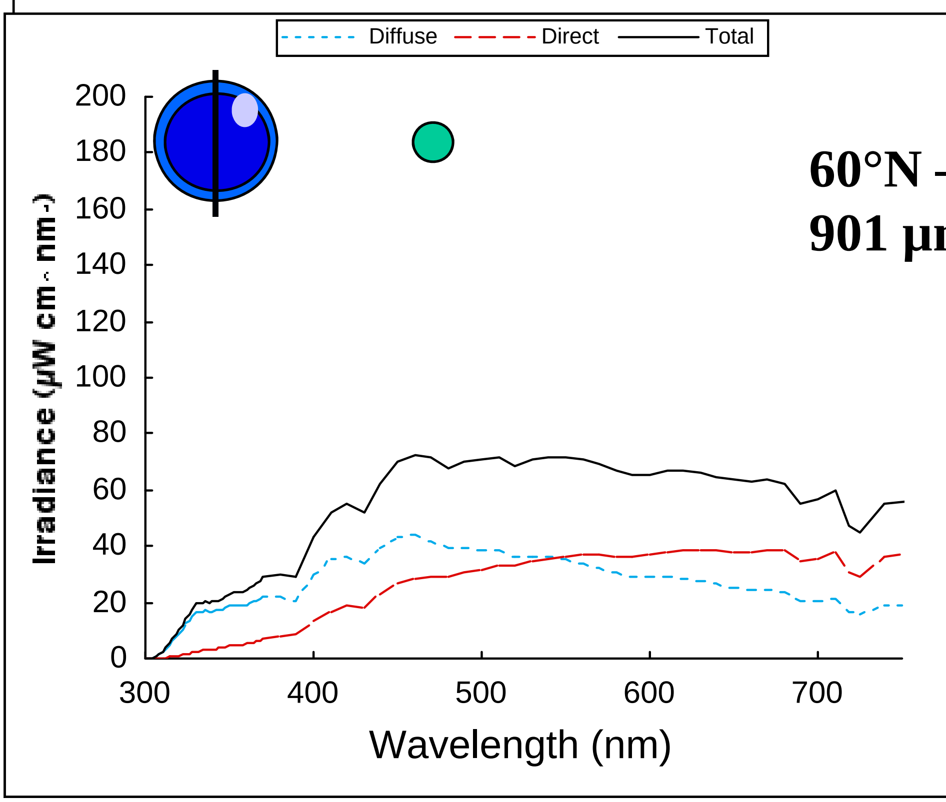


- -Visible: 400 to 700 nm
  - Also called Photosynthetically Available Radiation (PAR)
    - ABOUT 45% OF INCIDENT SOLAR RADIATION IS PAR
- -Ultraviolet
  - UVA 315 (or 320) to 400 nm, UVB 280 to 320 nm, UVC 200 to 280 nm

Examples: Vernal Equinox



Equator — March 21 – noon
2184 μmol m^{-2} s^{-1} PAR



60°N — March 21 — noon
901 μmol m^{-2} s^{-1} PAR

Sun angle accounts for a 50% reduction. Atmospheric pathlength is longer. Diffuse irradiance is enriched in the shorter, scattered wavelengths.

Some relations to **phytoplankton**:

- What type of irradiance do phytoplankton experience?
- How should the euphotic depth be defined?
- How is PAR computed?

Irradiance is often measured in units of energy [w/m^2]. Phytoplankton care about number of photons in wavelength they absorb:

$$PAR = \int_{350}^{700} E_0(\lambda)\frac{\lambda}{hc}d\lambda \left[\frac{\text{photons}}{\text{m}^2\ \text{s}}\right]$$

h is Plank's constant, 6.026x10^{-34} m^2 Kg s^{-1}.

But not all photons are equal. Phytoplankton absorb certain wavelength preferably.

Example: light and waves

Influence of surface waves on measured and modeled irradiance profiles

J. Ronald V. Zaneveld, Emmanuel Boss, and Andrew Barnard

Applied Optics, 2001

Observations:

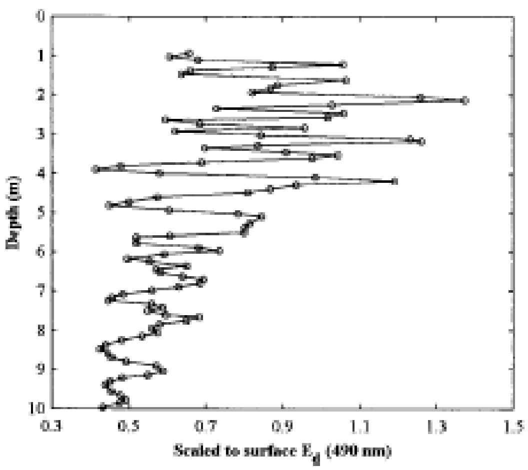


Fig. 1. Irradiance profile taken off the Oregon coast, September 1997, with a Satlantic irradiance profiler. The profiler drops at approximately 0.8 m/s and samples at 8 Hz. Conditions were calm.

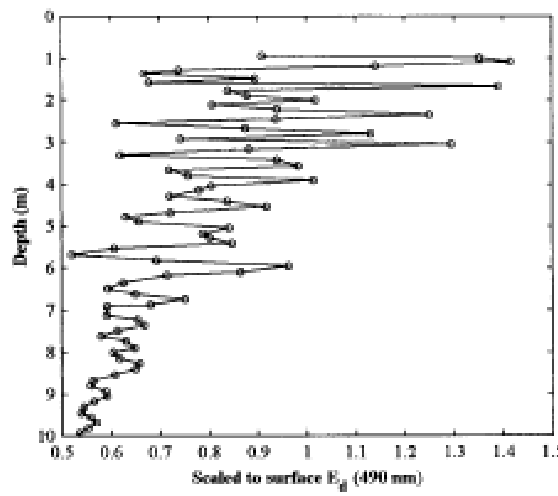


Fig. 2. Irradiance profile taken in the Gulf of California, October 1998, with the same profiler as used in Fig. 1. Conditions were calm.

Monte-Carlo modeling (Ron's 1st Matlab project):

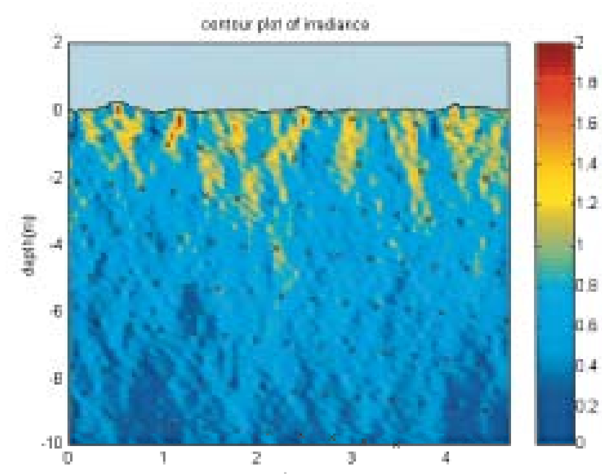


Fig. 3. Irradiance pattern beneath a random wave surface with a 1.1-m dominant wave: $a = 0.06\ m^{-1}$ and $b = 0.15\ m^{-1}$. A Petzold volume-scattering function was used (see text). Crosses are sampling points of an irradiance sensor dropping at 0.8 m/s with a sampling rate of 8 Hz.

Summary:

- Light is measured in different ways depending on application (e.g. heating rate vs. photosynthesis).

- Definitions, nomenclature, and units insure we compare similar quantities.

- Measuring ambient light is not trivial.