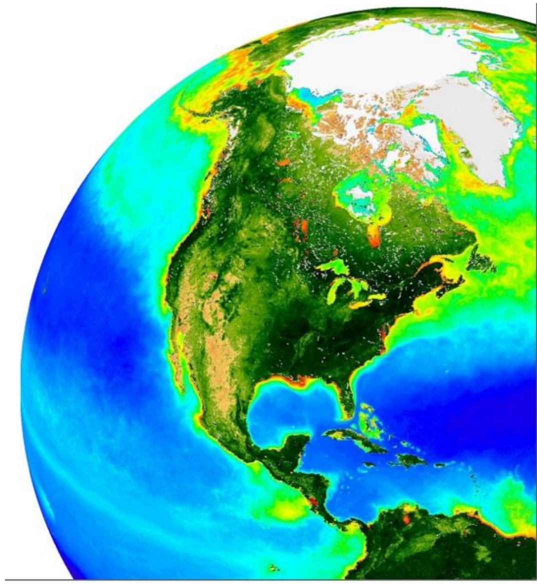
Light and Radiometry



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2025 Ocean Optics Course
Darling Marine Center, University of Maine
May 27, 2025

Oregon State University
College of Earth, Ocean, and Atmospheric Sciences

Lecture Content

- Light from the sun
- Radiometric terminology review
- Spherical coordinates, solid angles, and directions
- Radiance – the fundamental quantity in RTE, measuring radiance
- Irradiance – definitions and measurements
- Examples of radiometric Instruments

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

- *http://www.oceanopticsbook.info*
- Slides from Colin Roesler.
- 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*

The SUN – our ”point” source of LIGHT!

http://www.space.com/12934-brightness-sun.html

View of the sun and Earth’s horizon as seen from the International Space Station.

The image was taken using a fish-eye lens attached to an electronic still camera during the STS-134 mission's fourth spacewalk May 2011. *credit: NASA*

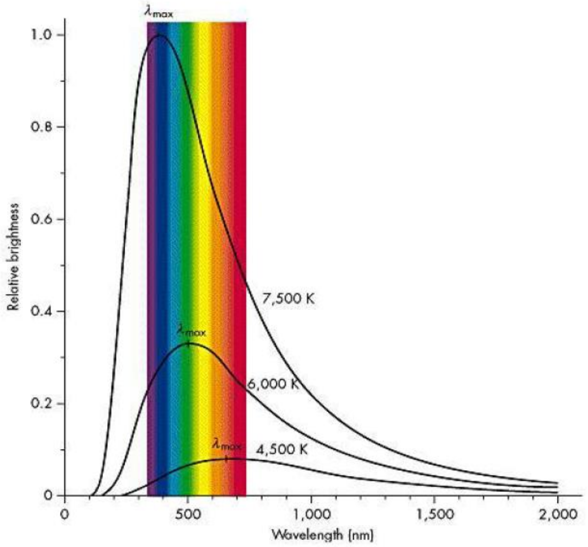
Courtesy of C. Roelser

A bit of physics…

Solar flux density at the top of Earth's atmosphere

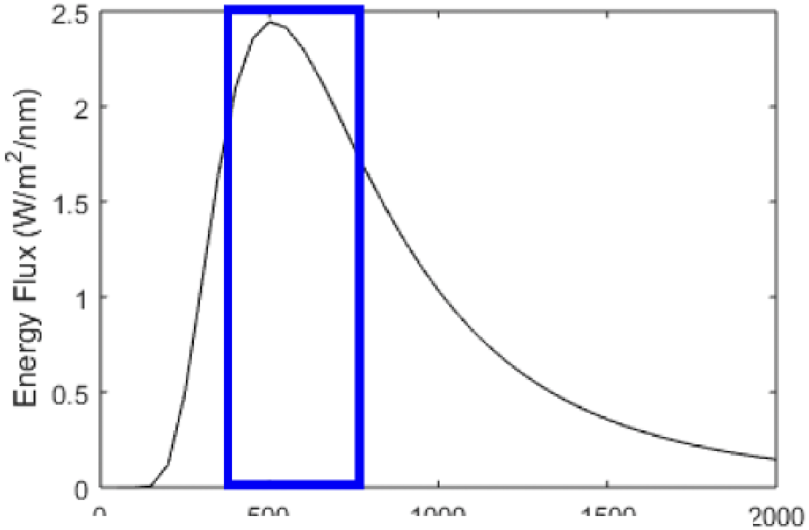
Black body radiation

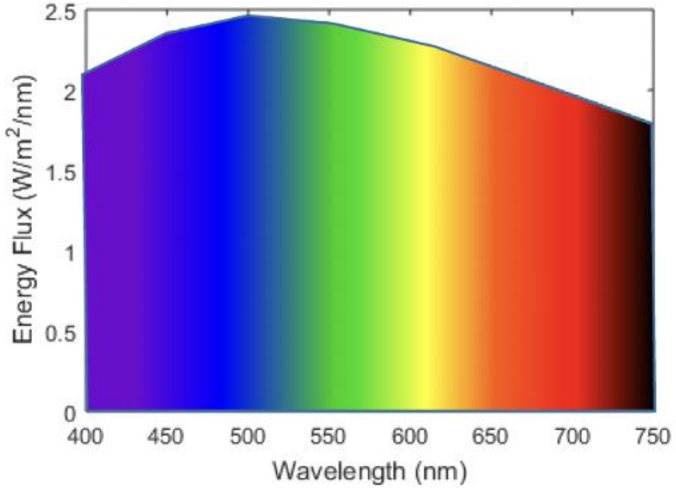
- Any object with a temperature >0K emits electromagnetic radiation (EMR)
- **Planck's Law** : The spectrum of emission depends upon the temperature (in a complex way)
- **Stefan-Boltzman Law**: The hotter the object, the more radiant power it emits, proportional to T^4(area under curve)
- **Wien's Displacement Law**: The hotter the object, the shorter the wavelength of maximal emission, $\lambda_{max} \sim T^{-1}$ (peak)
- **Sun *T*~ 5700 K**
  So it emits a spectrum of EMR that is maximal in the visible wavelengths



http://aeon.physics.weber.edu/jca/PHSX1030/Images/blackbody.jpg

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5\left(exp\left[\frac{hc}{\lambda kT}\right] - 1\right)}$$





Courtesy of C. Roelser

Compare the light fields: top of the atmosphere, Earth's surface, below ocean surface

http://www.space.com/12934-brightness-sun.html z

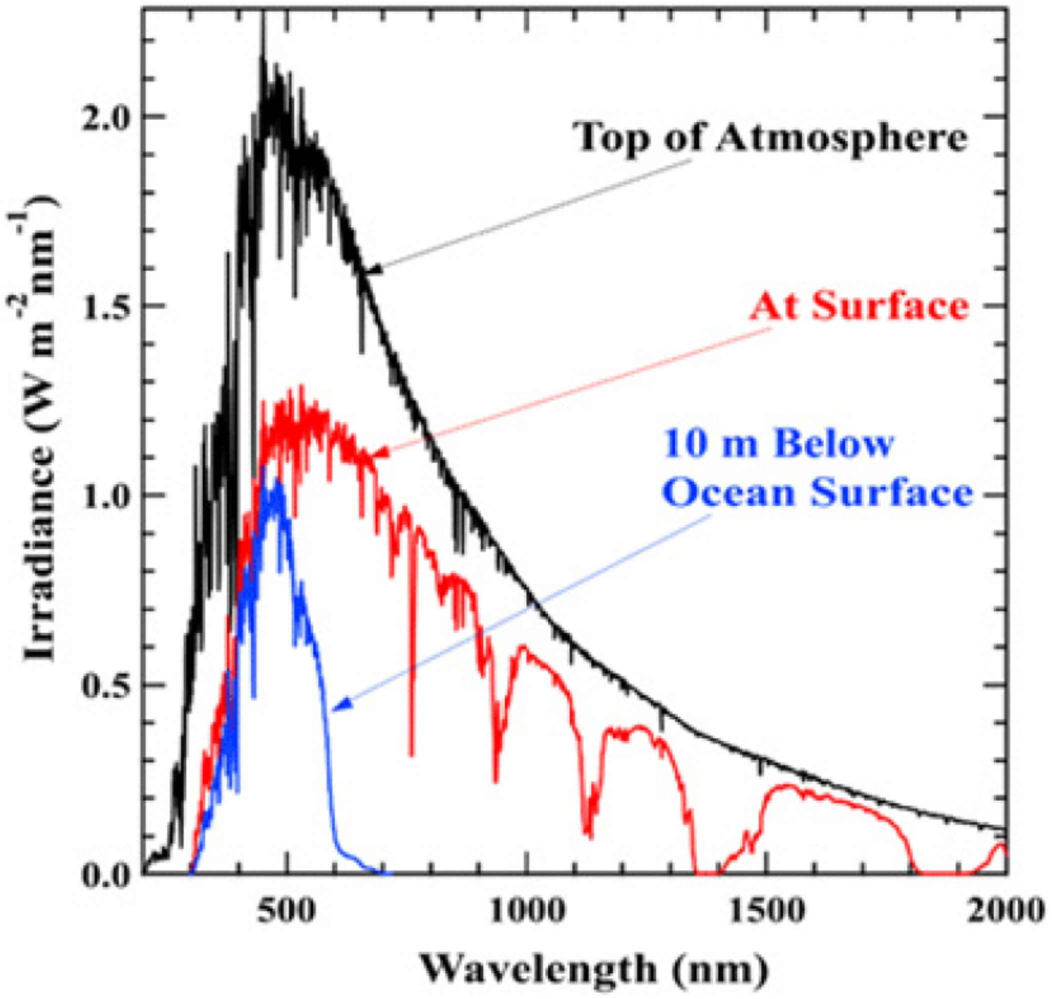
https://lsintspl3.wgbh.org/en-us/lesson/buac18-il-ilchangessky/1

https://www.shutterstock.com/nb/video/clip-1014907747-sun-underwater-sky-scenery

- Similarities
- Differences

Courtesy of C. Roelser

Spectrum of energy that we *measure* is different from Planck's Law predictions



http://lasp.colorado.edu/home/sorce/files/2011/09/fig01.gif

- Top of atmosphere
  - Fraunhofer lines
  - Absorption by gasses in *photosphere*
- At Earth surface
  - Atmosphere has attenuated
    - gases (O_3, O_2, H_2O, CO_2)
    - aerosols
- Beneath Ocean surface
  - Irradiance is attenuated
    - Water
    - Particulate and dissolved constituents

Courtesy of C. Roelser

Some Basic Radiometric Terminology

Radiometry is the science of measuring electromagnetic radiation.

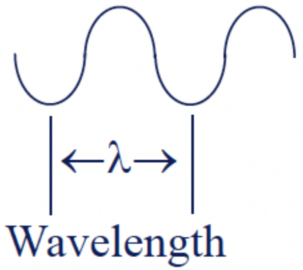
In Ocean Optics, Optical radiometry most often refers to UV, Visible, and Near Infrared regions of the spectrum

Note: many ocean color satellites measure in the ShortWave Infrared regions as well.

Electromagnetic Radiation

Name	Wavelength ranges
UV-C	100 nm to 280 nm
UV-B	280 nm to 315 nm
UV-A	315 nm to 400 nm
VIS	360 nm to 800 nm
NIR	800 nm to 1400 nm
SWIR	1.4 µm to 3 µm
MWIR	3 µm to 5 µm

$c = n\lambda\nu$



c = speed of light
λ = wavelength
n = index of refraction
ν = frequency

The wavelength is determined by the speed of light and measurements of the frequency by comparison to the atomic standards.

For example: $\lambda = 555$ nm, then $\nu = 540 \times 10^{12}$ Hz.

https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1001&context=calcon; *Howard W. Yoon, NIST; 2013*

Radiometric Quantities

Radiometry is the measurement of physical quantities like radiance and irradiance, performed through light-measuring instruments called radiometers.

Quantity	*Symbol*	*Unit*
Radiant Energy	Q	Joule
Radiant Flux	Φ	Watts (Joule/sec)
Irradiance	E 	Watts/m²
Radiance	L 	Watts/(m² sr)
Irradiance Reflectance	E_u/E_d	-
Remote Sensing Reflect.	L_u/E_d	sr^{-1}
Q-factor	E_u/L_u	sr

Radiant Flux → Energy per unit time.

Irradiance → Radiant flux incident on a surface

Radiance → Radiant flux per solid angle per unit projected source area

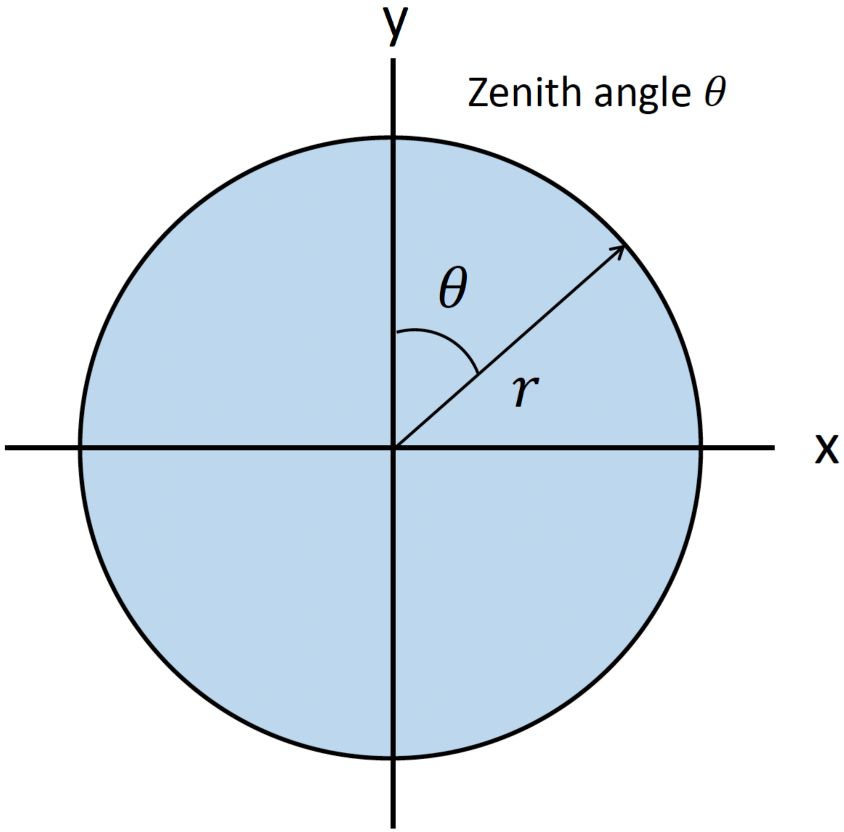
Irradiance Reflectance, Remote Sensing Reflect., Q-factor → A few Apparent Optical Properties

Courtesy of Giuseppe Zibordi, Joint Research Centre of European Commission

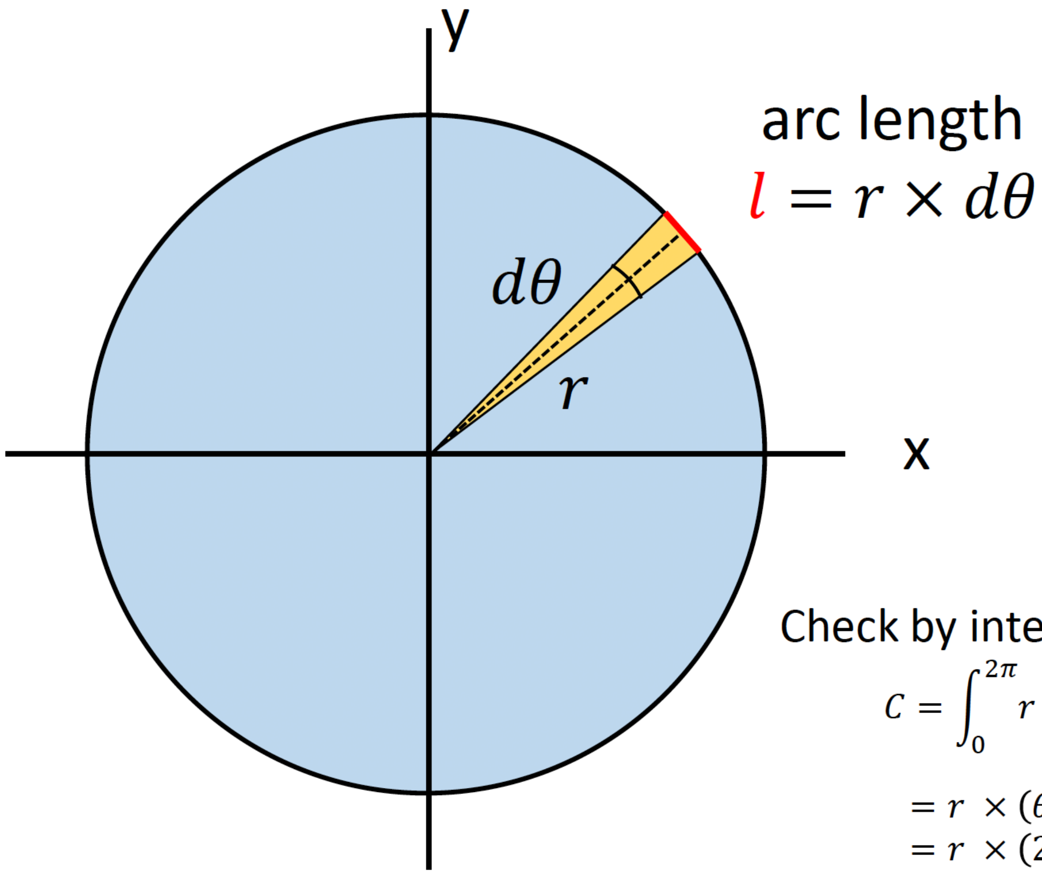
All of these quantities are measured over a spectral range, meaning that the units include a nm^{-1}

Geometry and coordinates

2d Geometry Review



2d Geometry Review



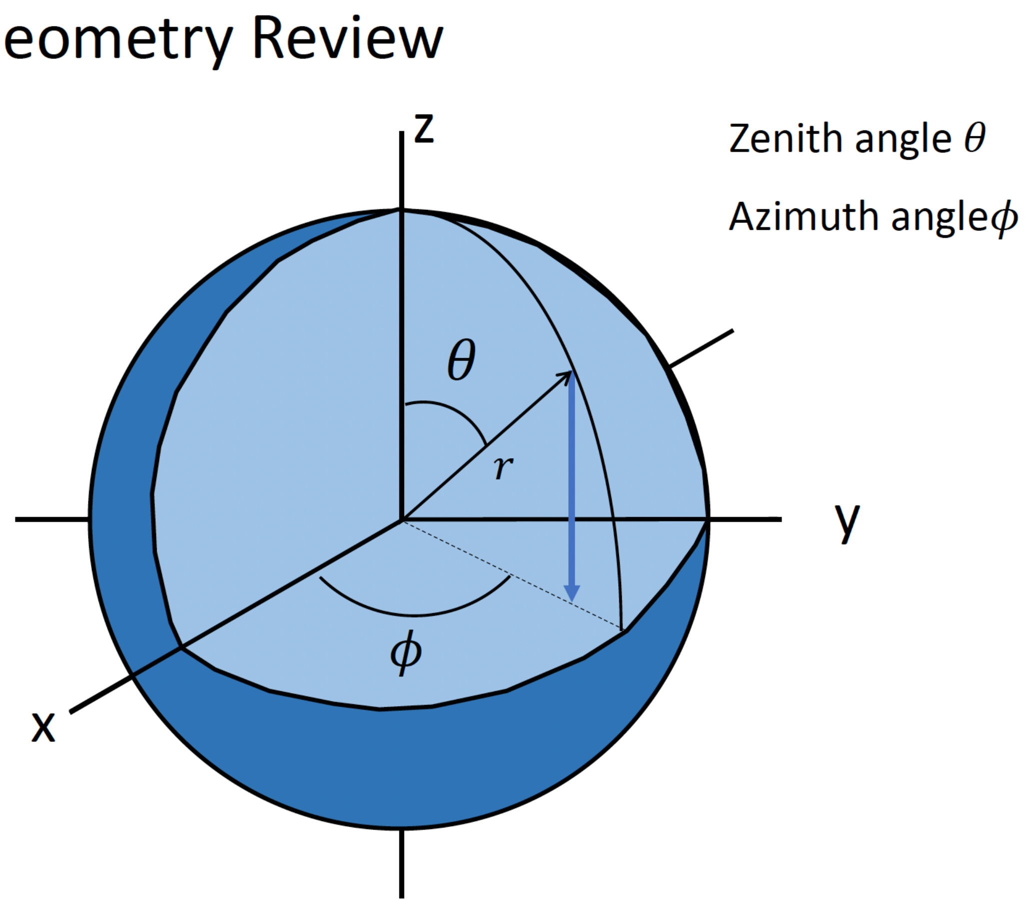
Check by integration

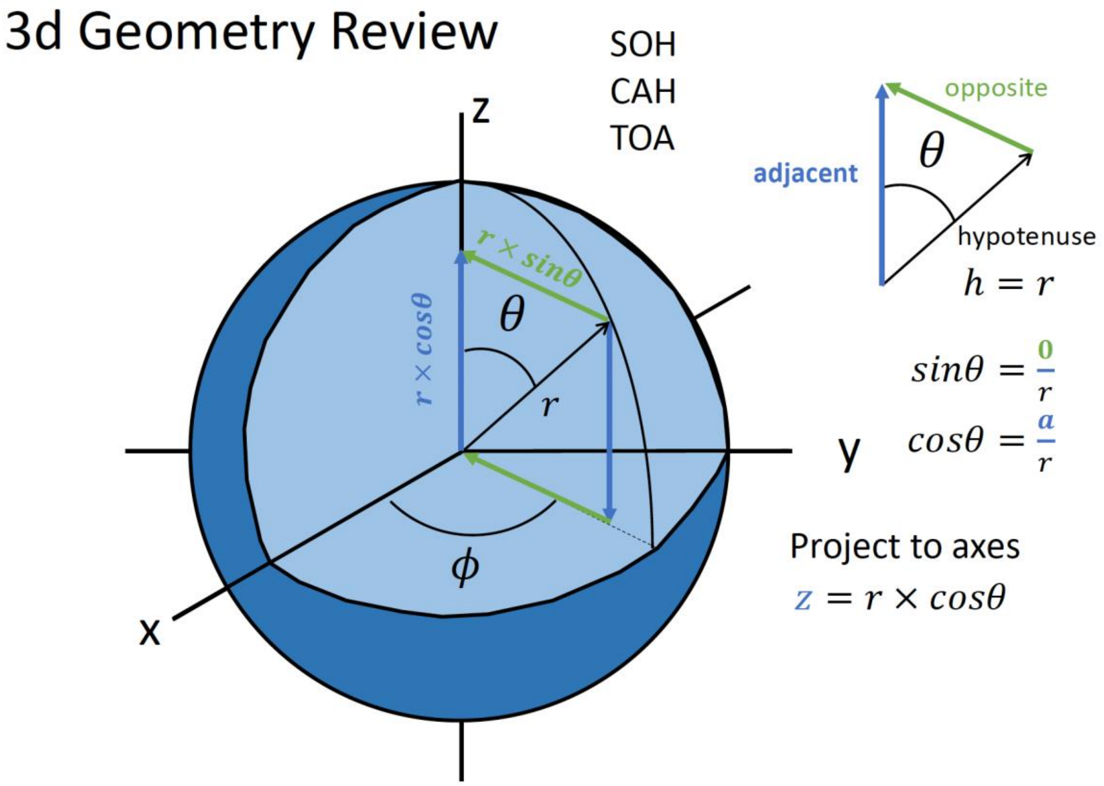
$$C = \int_0^{2\pi} r \, d\theta$$

$$= r \times (\theta_2 - \theta_1)$$
$$= r \times (2\pi - 0)$$
$$= 2\pi r$$

Courtesy of C. Roelser

Geometry and coordinates





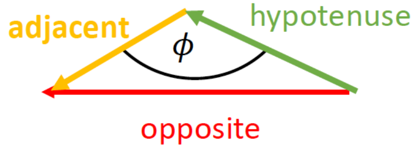
Courtesy of C. Roelser

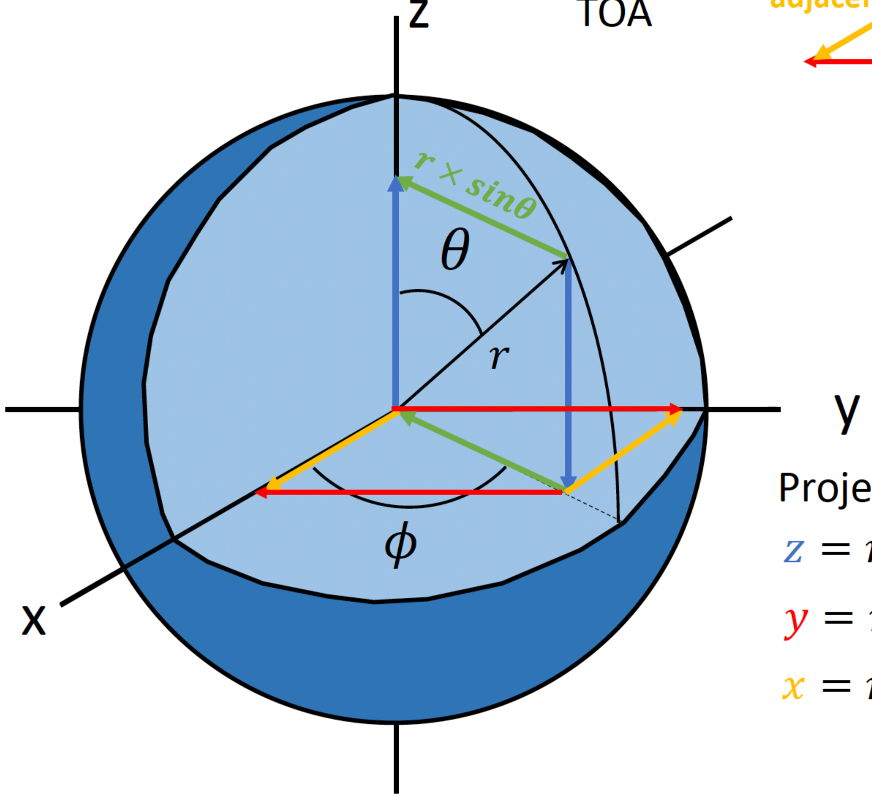
Geometry and coordinates

3d Geometry Review

SOH
CAH
TOA

$h = r \times sin\theta$





$$sin\phi = \frac{0}{r \times sin\theta}$$

$$cos\phi = \frac{a}{r \times sin\theta}$$

Project to axes

$z = r \times cos\theta$

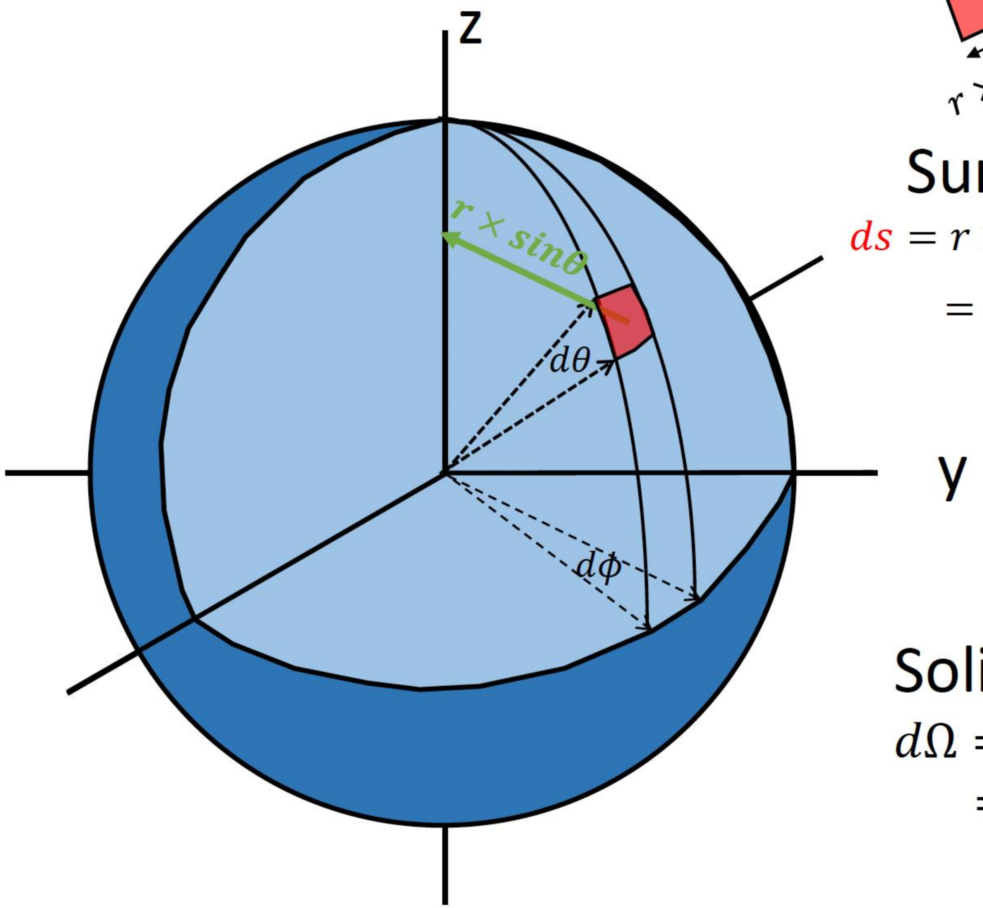
$y = r \times sin\theta sin\phi$

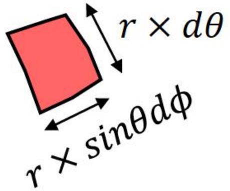
$x = r \times sin\theta cos\phi$

Courtesy of C. Roelser

Geometry and coordinates

3d Geometry Review





Surface area

$$ds = r \times d\theta \times r \times sin\theta d\phi$$
$$= r^2 \times sin\theta d\theta d\phi$$

Check by integration

$$S = \int_0^{2\pi}\int_0^{\pi} r^2 \times sin\theta d\theta d\phi$$
$$= r^2 \times \phi|_0^{2\pi} \times -cos\theta|_0^{\pi}$$
$$= r^2 \times (2\pi - 0) \times (-cos\pi - -cos0)$$
$$= 4\pi r^2$$

Solid Angle

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

Courtesy of C. Roelser

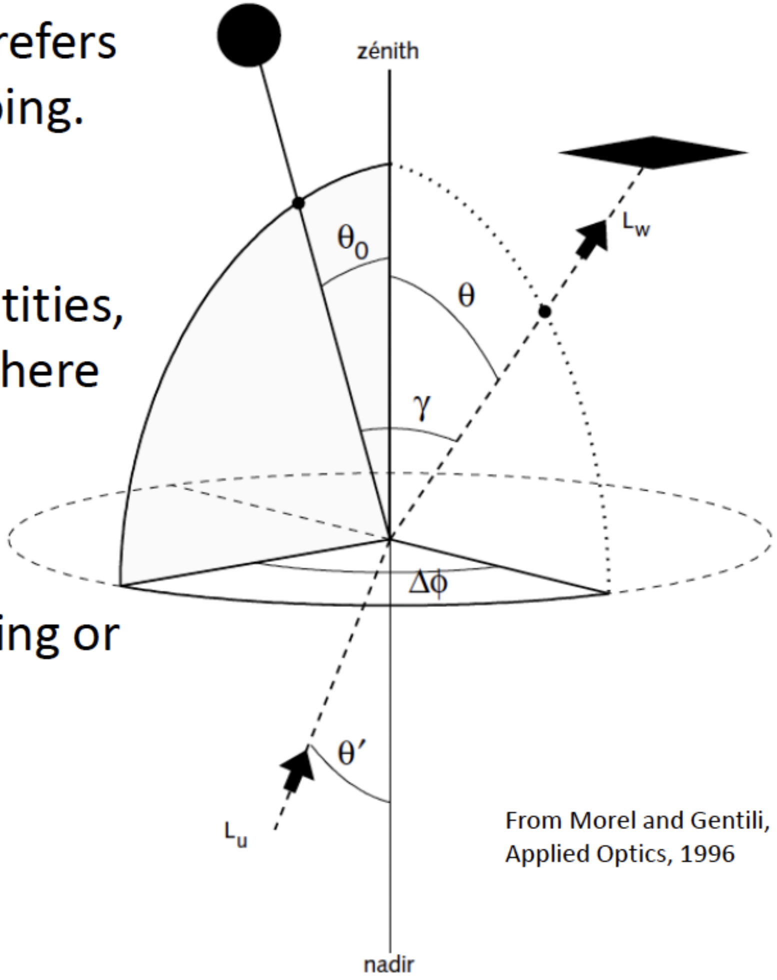
Terminology, units, angles (geometry)

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

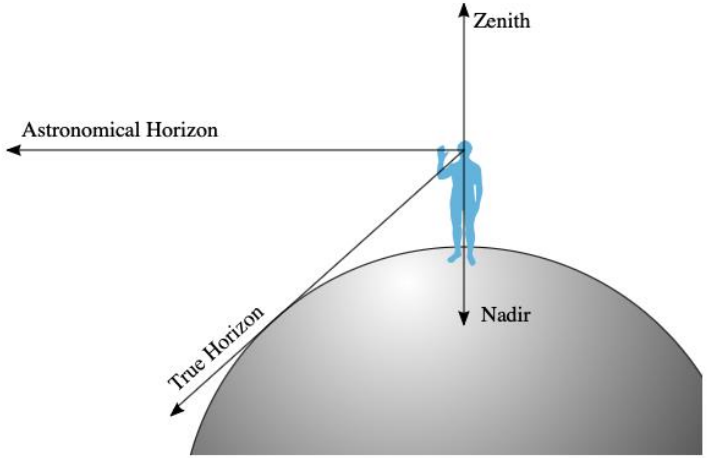
- When measuring radiometric quantities, the opposite is made: direction of where we point the instruments

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

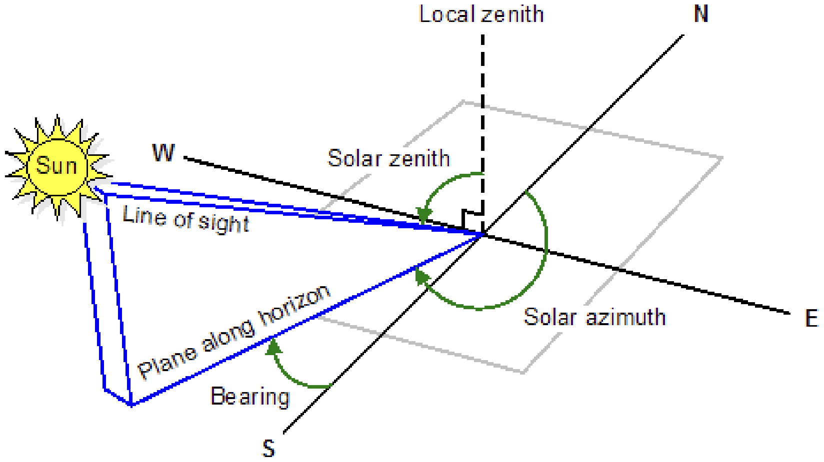
- Sun zenith angle: θ_s or θ_0
- View zenith angle: θ or θ_v
- Azimuth difference: $\Delta\phi$



From Morel and Gentili, Applied Optics, 1996



Zenith vs Nadir



Solar zenith & solar azimuth

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

Radiance (L): 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}

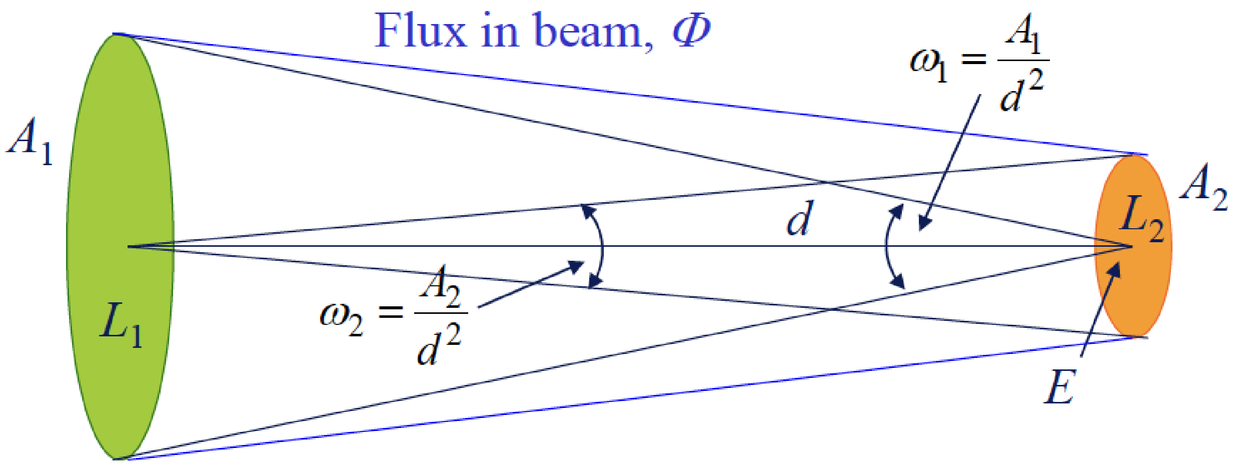
Radiant flux in a given direction per unit solid angle per unit projected area

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

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

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

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

$$A\omega = A_1 \omega_{1-2} = A_2 \omega_{2-1}$$

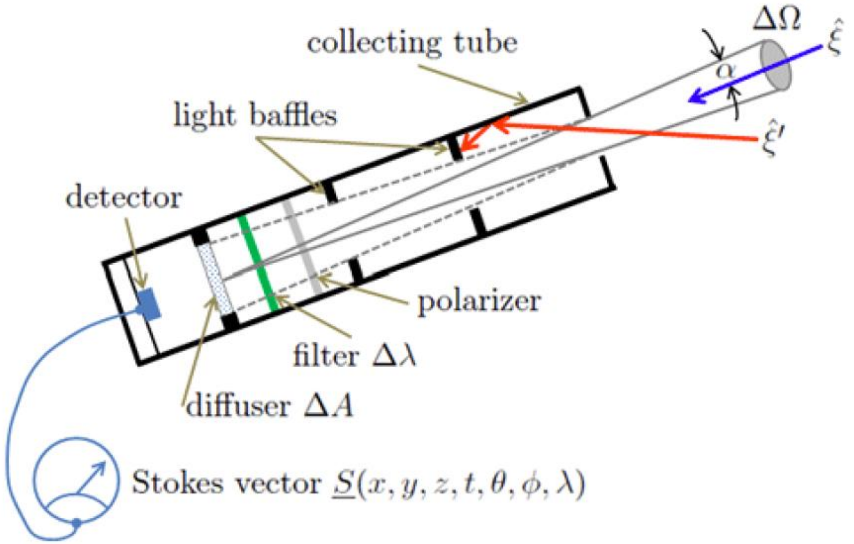
$$\left(\omega_{1-2} = \frac{A_2}{d^2}, \quad \omega_{2-1} = \frac{A_1}{d^2} \right)$$

Principle of "Radiance Invariance"

Radiance is independent of distance along a line of sight through a transparent optical medium (constant index of refraction).

Measuring Radiance

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

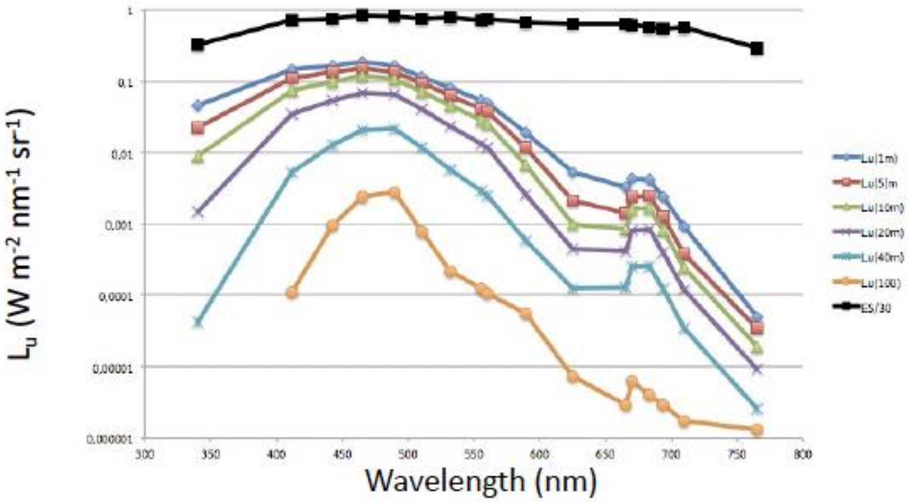


Often referred to as a Gershun tube

Produces “well” collimated light

- Radiance
- $L(\theta, \phi)$ (µmol photons m^{-2} s^{-1} sr^{-1})

Spectra and vertical profiles of underwater upwelling radiances

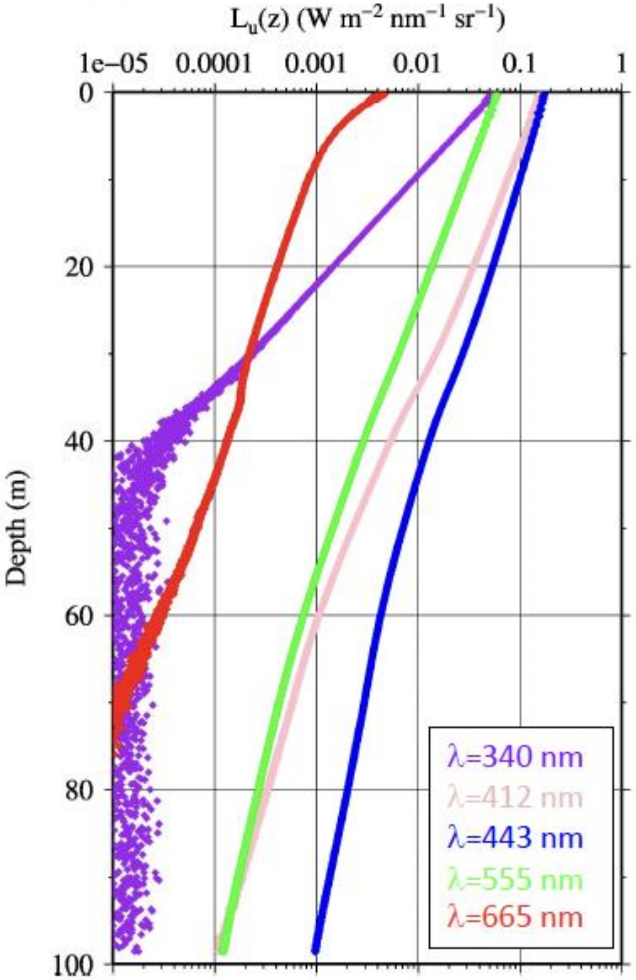


13th December 2015

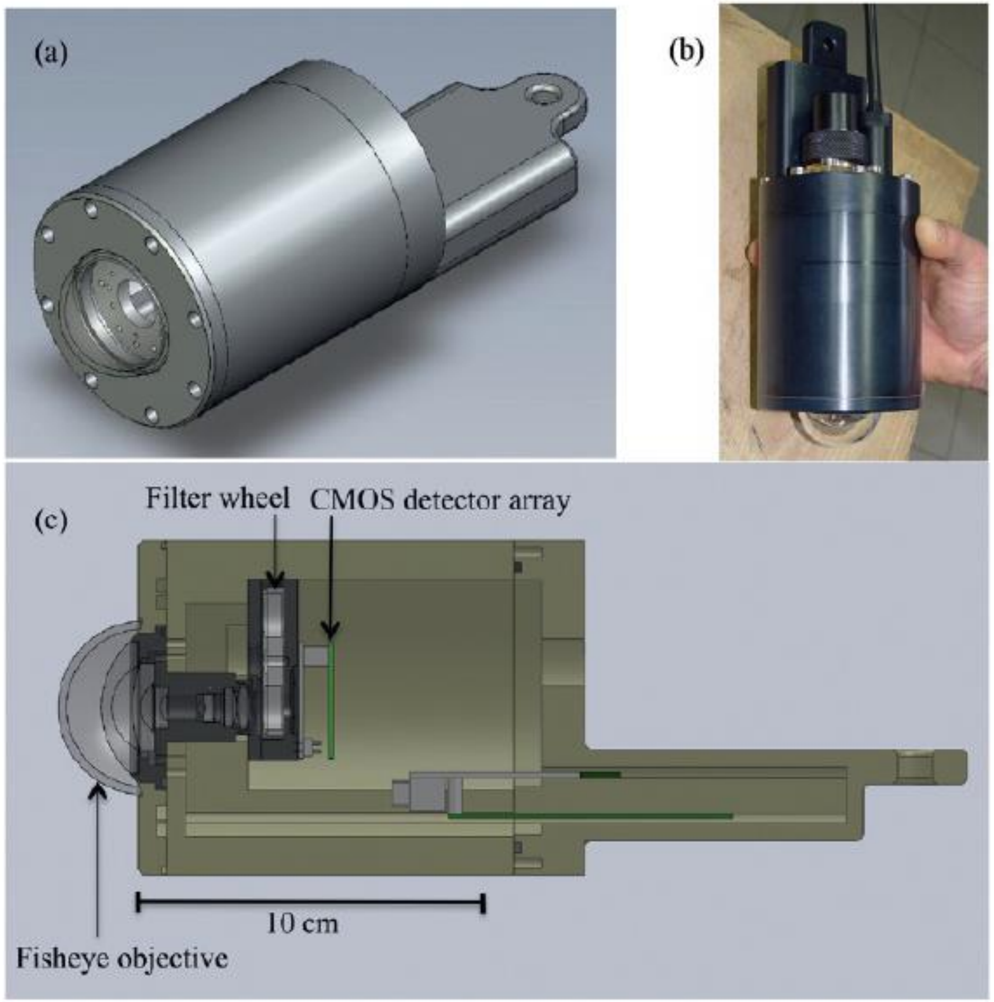
Chl ~0,24 mg m^{-3}

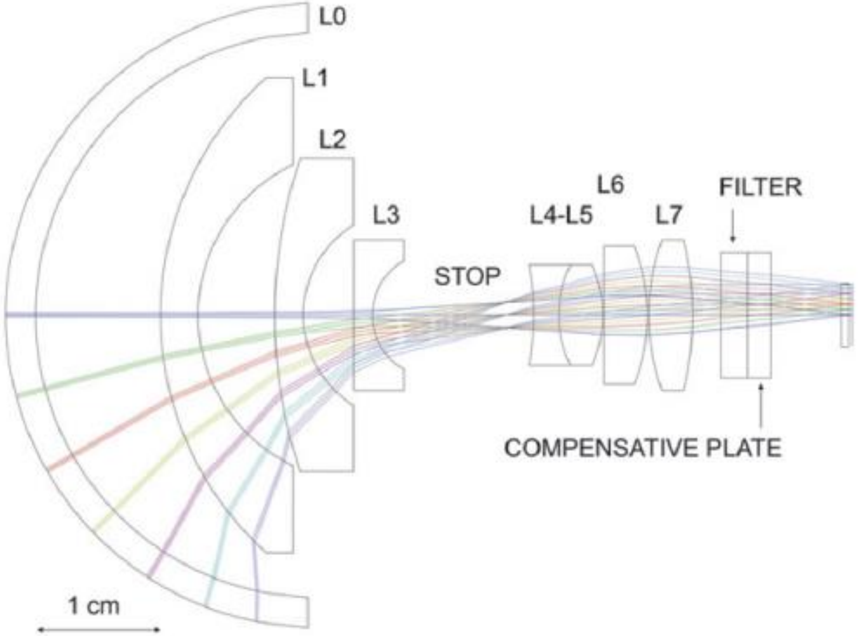
The water-leaving radiance

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



Measuring Radiance: fisheye radiance camera

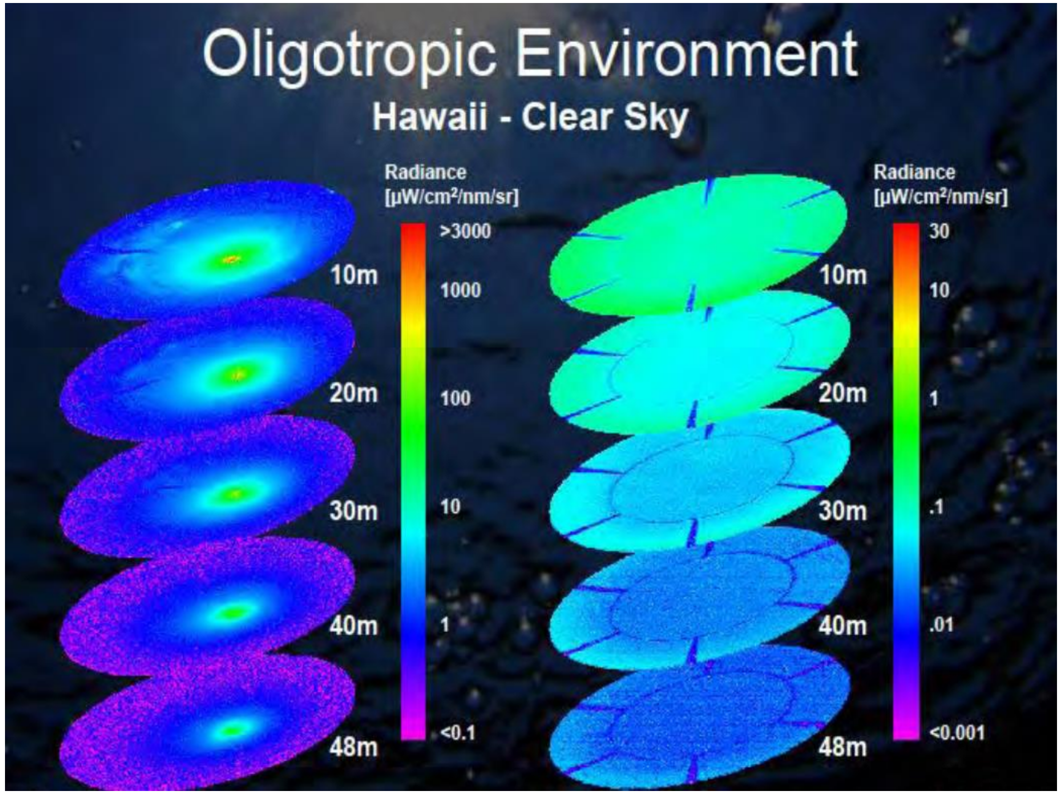




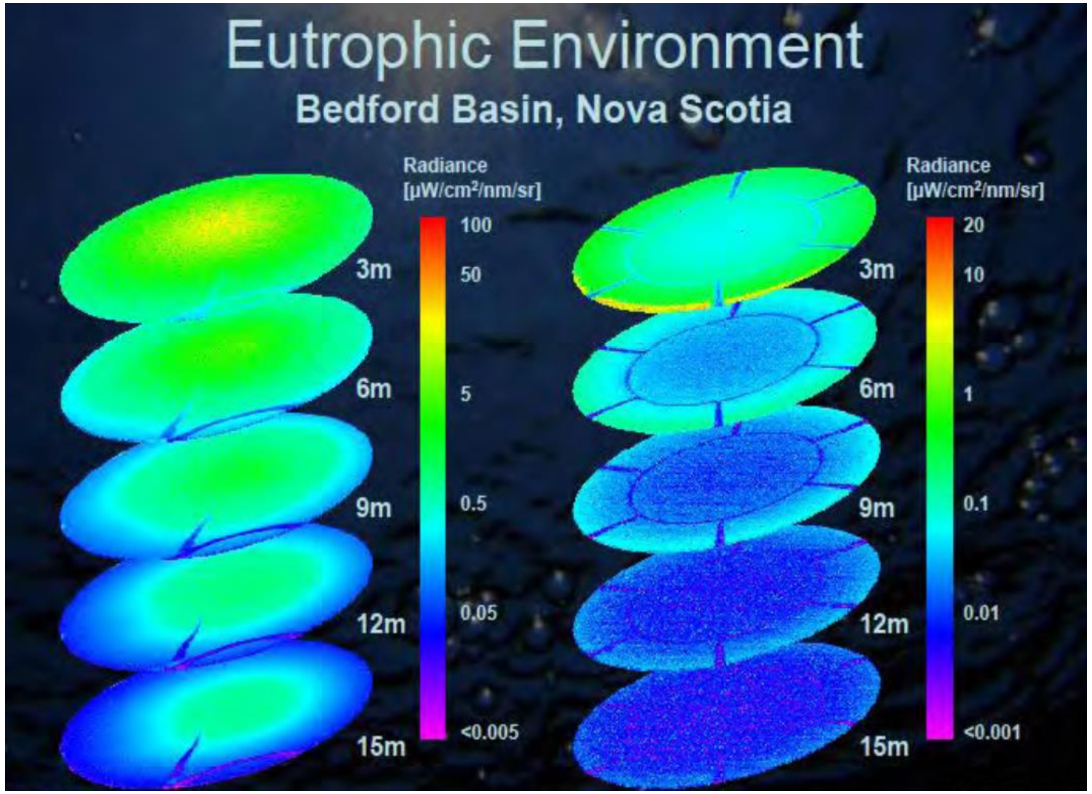
Radiance camera: getting simultaneously radiances in all directions of an hemisphere, at several wavelengths

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

Example: Hemispheric radiance distributions



downwelling upwelling



downwelling upwelling

n^2 Law of radiance

Radiance invariance between two media with different index of refractions

Snell's law

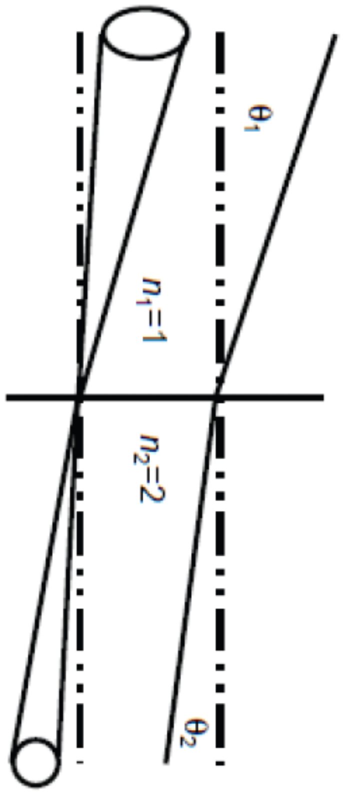
$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

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

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 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!

Irradiance (E): a useful & 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
- A measure of light available to phytoplankton for photosynthesis
- To derive various Apparent Optical Properties
- To derive/estimate the IOPs through inversion

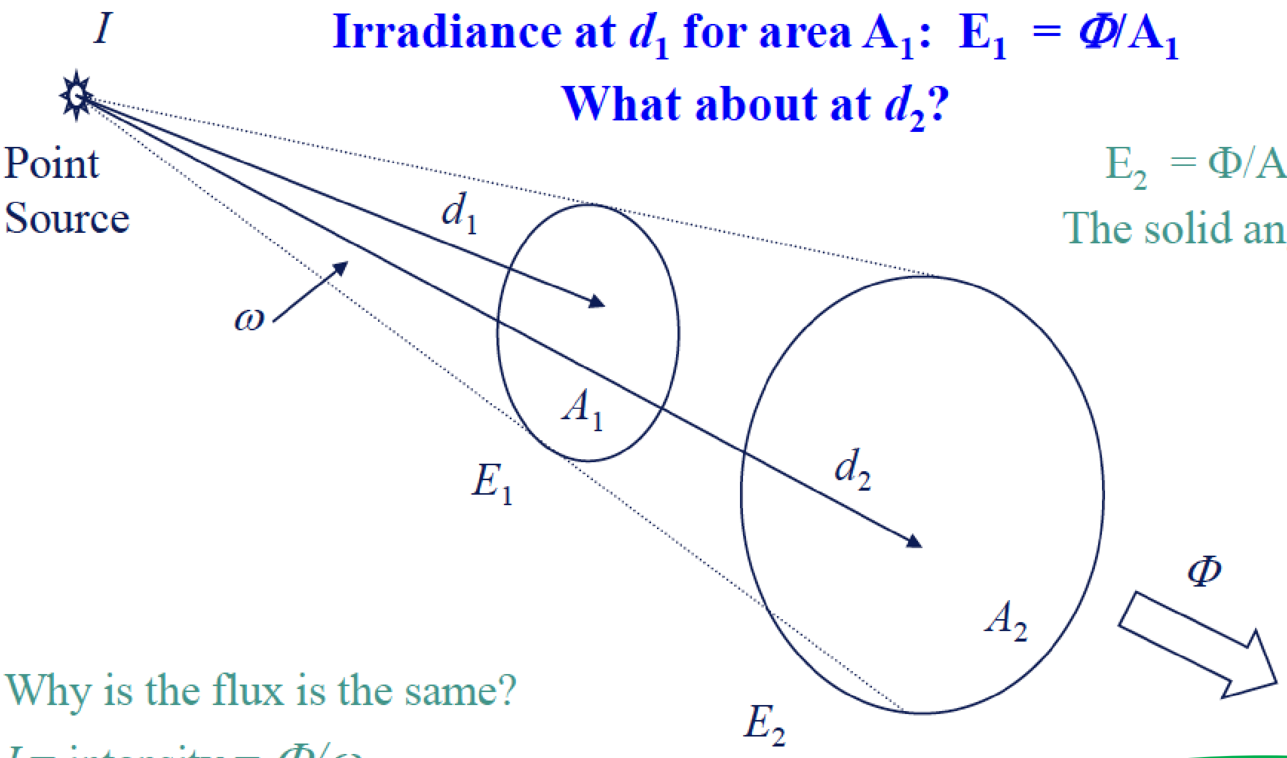
Quantity	**SI Units**	**Recommended Symbol**
radiant energy	J	Q
radiant power	W	Φ
radiant intensity	$\mathrm{W\,sr^{-1}}$	I
radiance	$\mathrm{W\,m^{-2}\,sr^{-1}}$	L
plane irradiance	$\mathrm{W\,m^{-2}}$	E
downward plane irradiance	$\mathrm{W\,m^{-2}}$	E_{d}
upward plane irradiance	$\mathrm{W\,m^{-2}}$	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)

Inverse square Law of Irradiance

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?

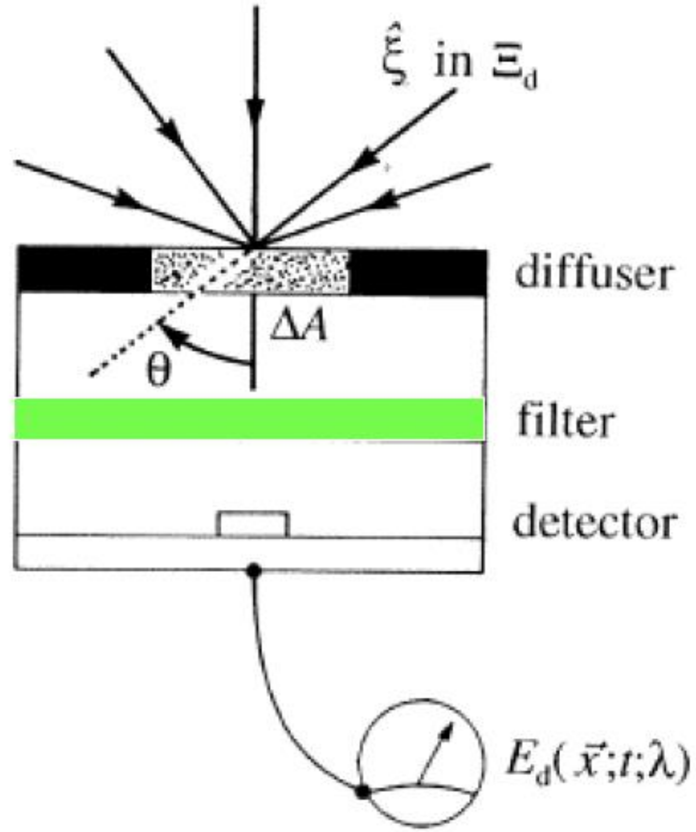
I = intensity = Φ/ω

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?

Spectral Plane Irradiance



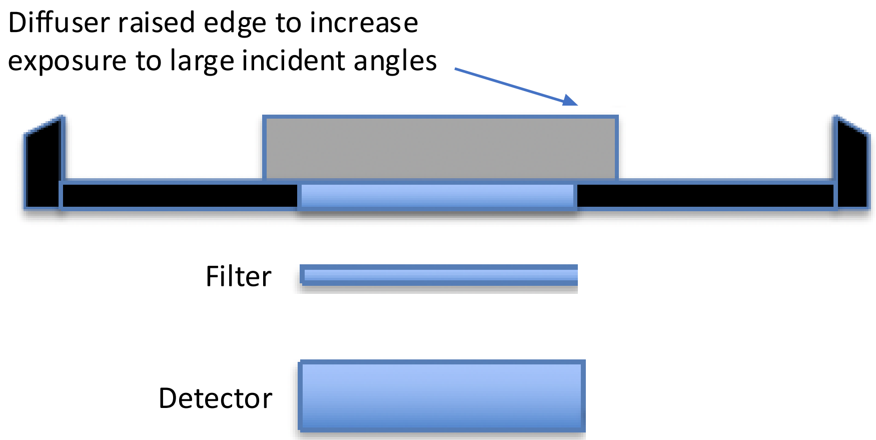
$$E_d(\vec{x}, t, \lambda) \equiv \frac{\Delta Q}{\Delta t\, \Delta A\, \Delta\lambda} \quad (\mathrm{W\ m^{-2}\ nm^{-1}})$$

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

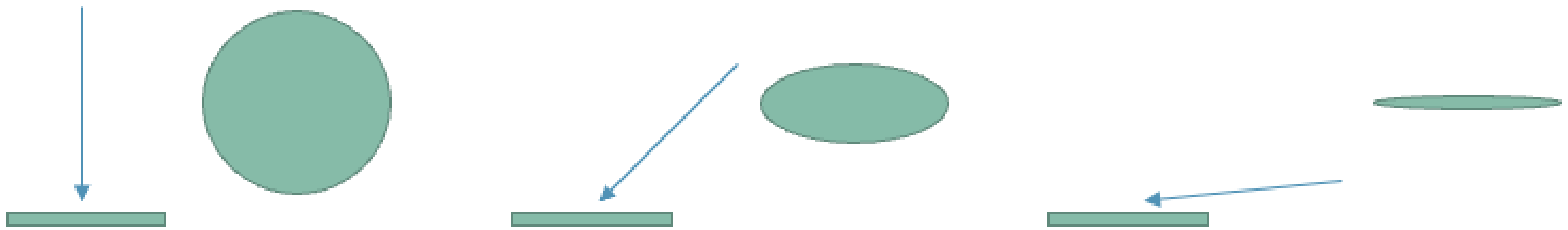
The most commonly measured radiometric parameter

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

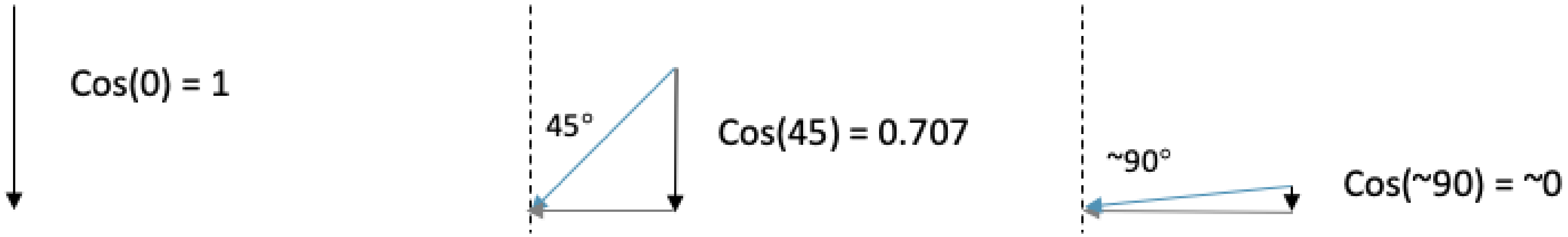
The projected area of the detector in the direction of θ is ΔA cos(θ). Diffuser is typically called a ”**cosine collector**”



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

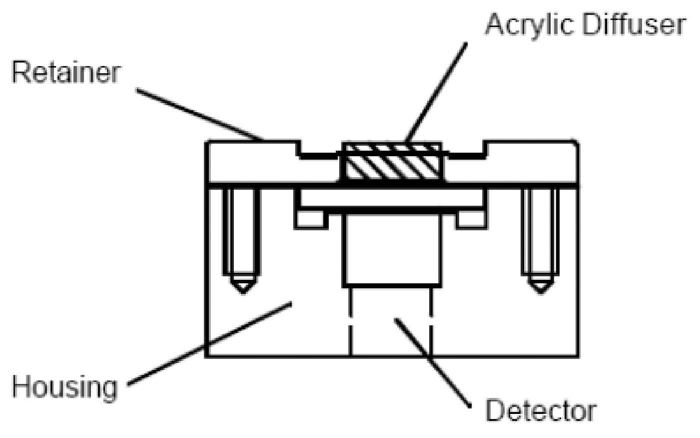


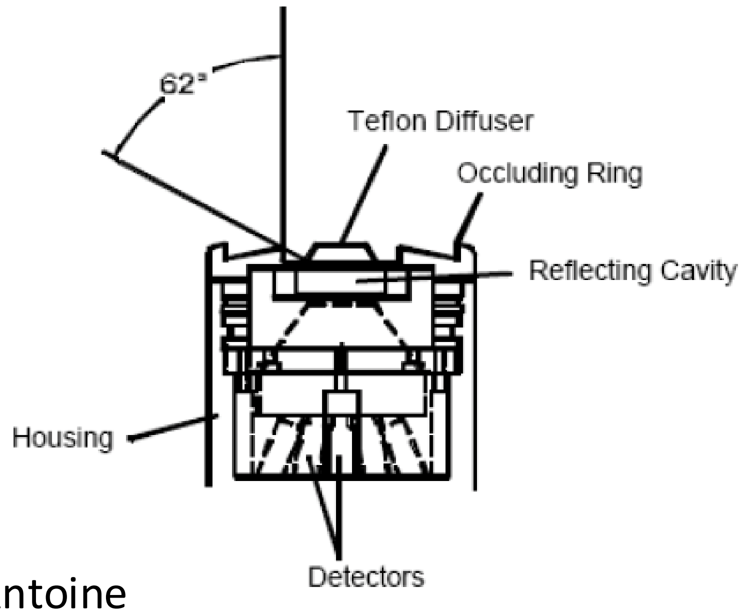
This is equivalent to weighting the incoming light by the vertical component of the incident light (i.e. the vertical *vector*).



Cosine Response

The process of quantifying the goodness of the angular response of a cosine collector to a collimated source.





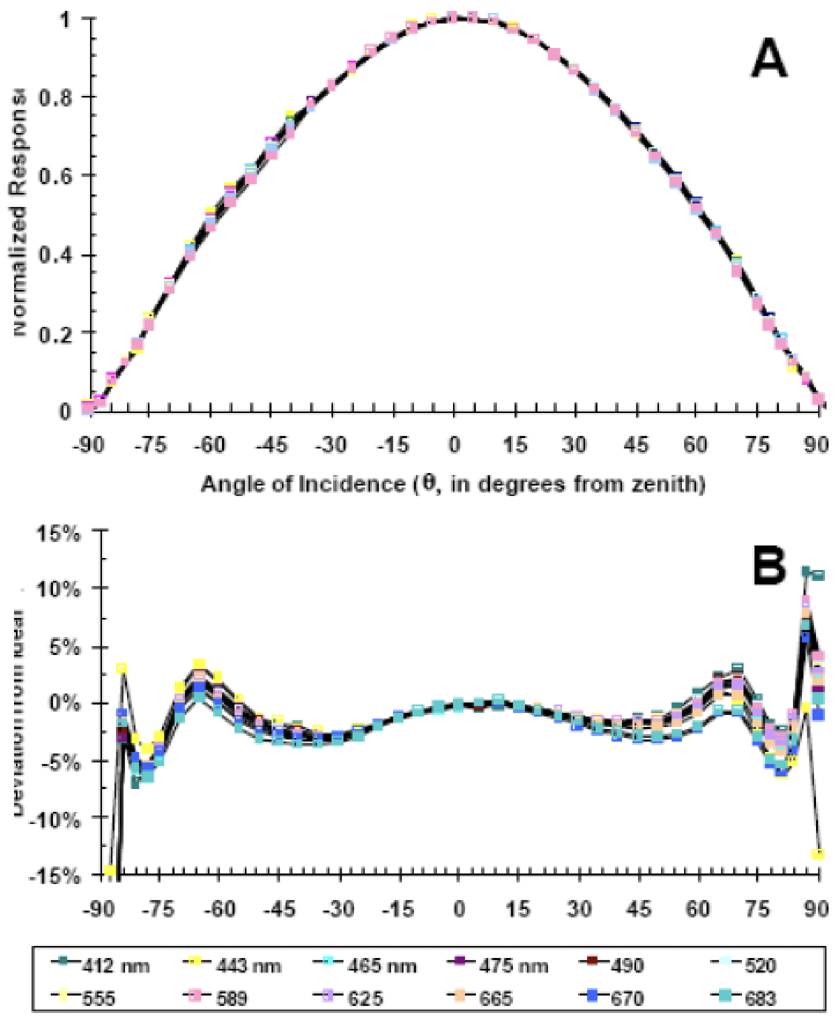
Antoine

Key consideration

Not all cosine collectors are created equal!

Many irradiance sensor manufacturers use different cosine collectors for in-air and in-water sensors.

Do not use an irradiance sensor that is designed to operate in-air in the water (and vice versa). Your cosine response will vary.



Morrow et al. 2000

Spectral Vector Irradiance

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

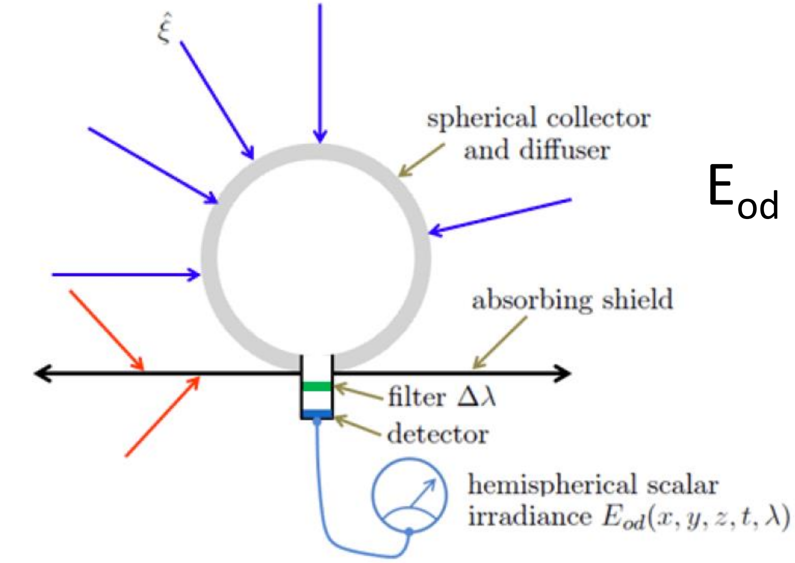
Vector Irradiance is simply the net difference of the downwelling plane irradiance and the upwelling place irradiance. Often described as the ***net downward irradiance***.

Gershun's Law

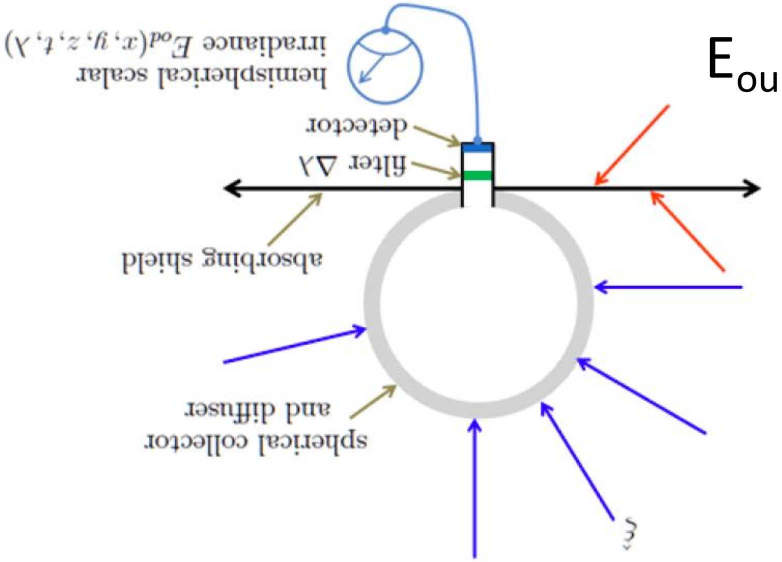
$$\frac{d}{dz}[E_\mathrm{d}(z,\lambda) - E_\mathrm{u}(z,\lambda)] = -a(z,\lambda)E_\mathrm{o}(z,\lambda) \quad (\mathrm{W\,m^{-3}\,nm^{-1}})$$

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

Spectral Scalar Irradiance



E_{od}



E_{ou}

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

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

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

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

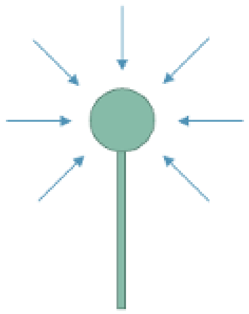
The detector has the same effective area for radiance in any downward direction, thus no $\cos(\theta)$ factor on L

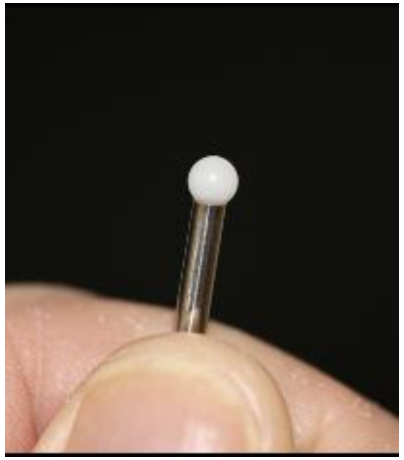
Relevant to photosynthesis/primary production as well as the heating of water.

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

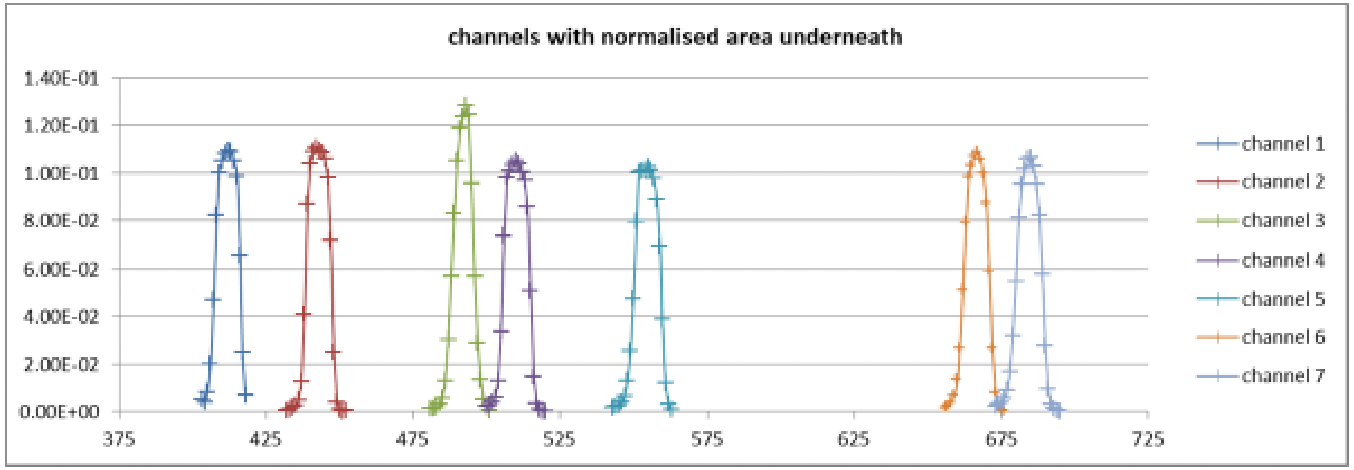
Typically used in simple models of phytoplankton growth. More ecosystem models are using spectral scalar irradiance measurements in to look at the phytoplankton pigment composition.

Most common radiometric Instrument types Defined by spectral resolution

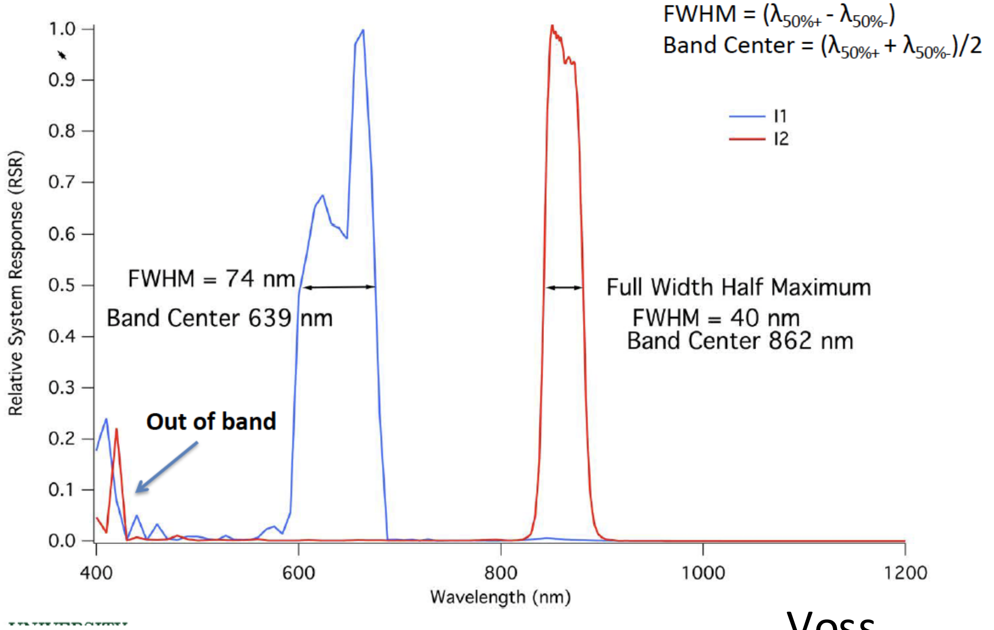
1. Broad band sensors: for example Photosynthetically Available Radiation (PAR), UV-A, photopic sensors
2. Multi-channel, discrete wavelength sensors: 4-19 individual bands, ~10nm in width
3. Hyperspectral instruments: continuous measurements, every 1-10 nm, across the visible/NIR spectrum.

Narrow band, multi wavelength/channel instruments

- Collection of several discrete wavelength bands (4-19 channels)
- Spectral channels defined by filters, typically an interference filter, ~10 nm width.
- Photodiode typically used, periodically sampled with A-D converter.
- Typically very stable and reliable.
- May try to match key spectral bands (e.g. VIIRS or MODIS bands)
- Low out-of-band effects, though do need consider depending on spectral bands used.



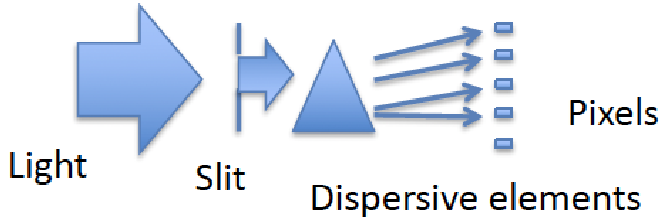
Bialek

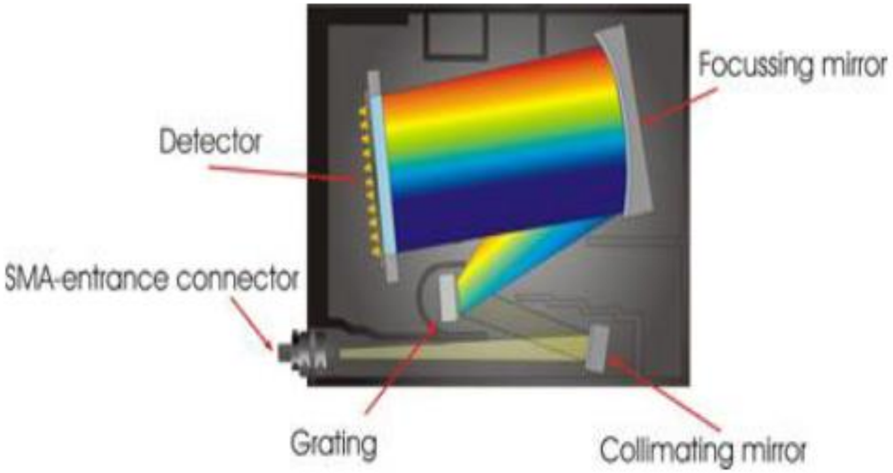


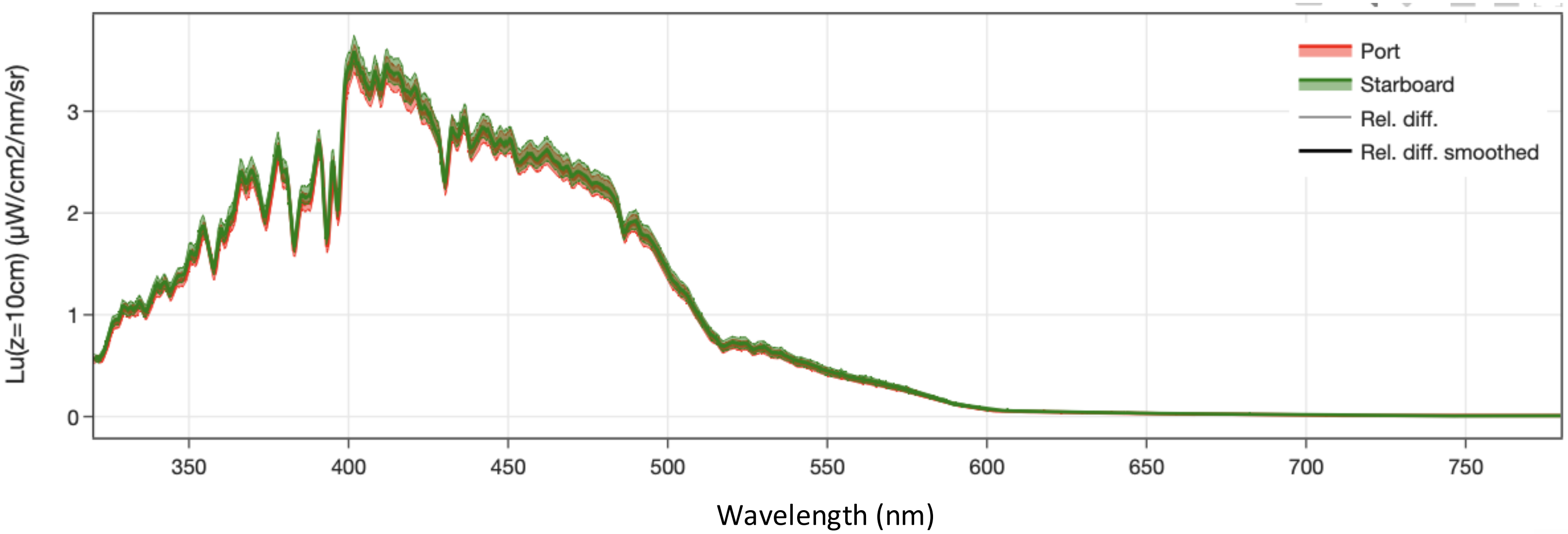
Voss

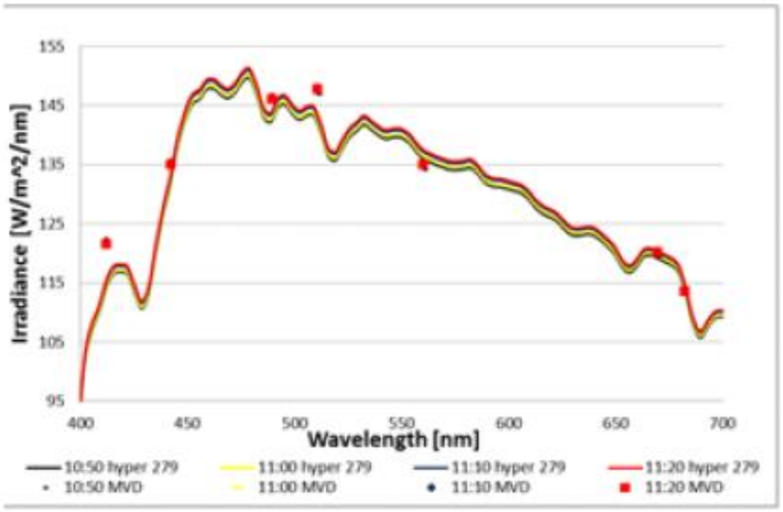
Hyperspectral wavelength instruments

- Continuous spectrum, ~1-10 nm, ~350-1000 nm
- Typically use small spectrometers, with grating / prism dispersive elements.
- Demanding instrument characterization necessary.
- Ability to build integrated channels, such as those on ocean color satellites (e.g. VIIRS or MODIS bands).









Examples of multi-channel sensors

Irradiance

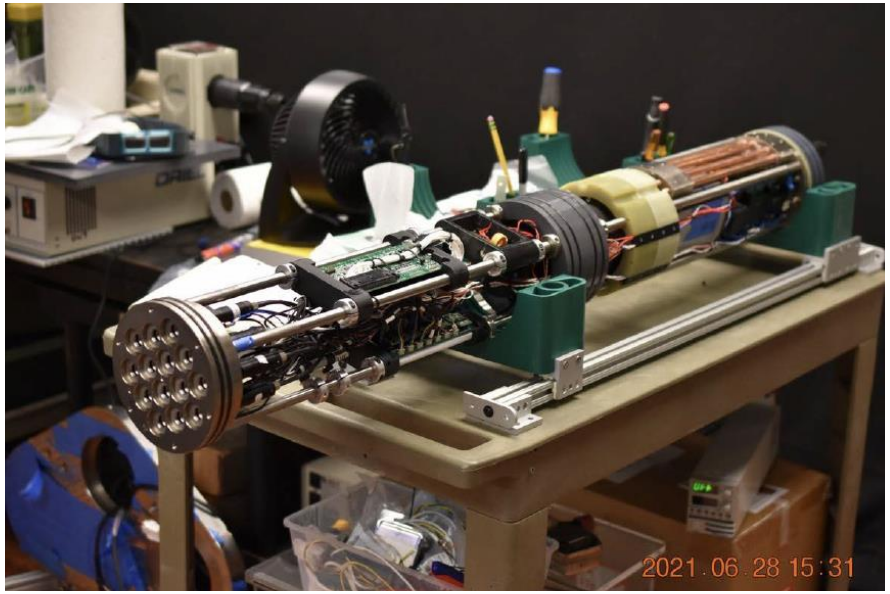
Radiance

Examples of Hyperspectral sensors

Irradiance
&
Radiance

HyperPro HyperNav

Moby irradiance & radiance



Examples of broad band sensors (PAR)

Both planar and scalar versions shown here.

Which is which?


Enjoy those photons!!

Radiometric Terms and Units

Radiometry

Vacuum UV	< 185 nm
Ultraviolet	~ 185 to ~ 380 nm
Visible	~ 350 to ~ 830 nm
NIR	~ 800 to ~ 1800 nm
SWIR	~ 1600 to ~ 2500 nm
MIR	~ 2 to 5 μm
LWIR	~ 5 to 12 μm
IR	> 12 μm

Radiance & Luminance

Sun	2 x 10⁷	W/m²-sr
Sun	2 x 10⁹	cd/m²
Frosted bulb	10,000	cd/m²
Fluorescent	5,000	cd/m²
Computer screen	100	cd/m²

Planck's Blackbody Equation

$$L_\lambda = \frac{2c^2h}{\lambda^5(e^{hc/\lambda kT}-1)} = W/(m^2\text{-sr-}\mu m)T{=}k$$

Useful Constants

h	6.63E-34 Planck Constant (J*s)
c	3.00E+08 Speed of Light (m/s)
k	1.38E-23 Boltzman Constant (J/K)
σ	5.67E-8 Stefan-Boltzman Constant

$$\sigma = \frac{2\pi^5k^4}{15c^2h^3} = W/(m^{\wedge2}*L^{\wedge4}) \text{ - "Sigma"}$$

Radiance of Sphere

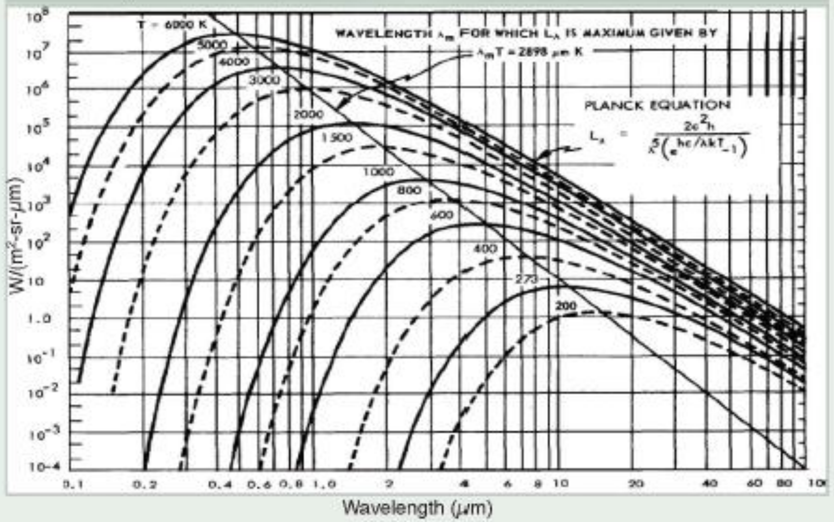
$$\text{Radiance of Sphere} = \frac{\Phi_i}{\pi A_S} * \frac{\rho}{1-\rho(1-f)}$$

Φ = Flux W/(m²-sr-μm)
ρ = Reflectance
A_S = Area of Sphere
f = Fractional port area

Approx. Calculation of Solid Angle

$\Omega = \pi \sin^2\theta$	(sr) FOV (θ= half angle)
$\Omega = \pi(NA)^2$	(sr) NA of Fiber
$\Omega = \frac{\pi}{2f(/\#)^2}$	(sr) F-Number

Blackbody Absolute Spectral Radiance Curves



Conversion Factors

ILLUMINATION

Multiply # > / To obtain #	Footcandles	Lux
Footcandles	1	0.0929
Lux	10.76	1

1 footlambert = 1 footcandle at sphere exit port

LUMINANCE

Multiply # > / To obtain#	Footlamberts	cd/m²
Footlamberts	1	0.2919
cd/m²	3.426	1

Sky Illumination Conditions

Condition	Approx. Lux
Clear, Peak Irradiance	1000W/m2
Clear, Peak Lux	100,000
Clear, in Shade	10,000
Overcast, Light	1,000
Overcast, Heavy	100
Overcast, Sunset	10
Clear, 0.25hr after Sunset	1
Clear, 0.5hr after Sunset	0.1000
Clear, Full Moon	0.0100
Clear, No Moon	0.0010
Overcast, No Moon	0.0001

Useful Conversion Calculations

Conversion Calculation of Spectral Radiance (W/m²-sr-μm) to Photons/Second

W/m²-sr-μm * (wavelength/(h*c)) = (photons/s)/m²-sr-μm

Conversion of Photons to Rayleighs

1 Rayleigh = 7.96E-08 photons/s*m²*sr

Plane Angle Conversions

Plane Angle Conversions (°/rad)	1 Degree (°)	1 Minute (')	1 Second (")	1 Radian (rad)	1 mRadian (mrad)
1 Degree (°)	1	60	3600	1.745E-02	17.453
1 Minute (')	1.667E-02	1	60	2.909E-04	0.29089
1 Second (")	2.778E-04	1.667E-02	1	4.848E-06	4.85E-03
1 Radian (rad)	57.2958	3437.75	2.06E+05	1	1000
1 mRadian (mrad)	5.730E-02	3.43775	206.265	1.00E-03	1

www.labsphere.com

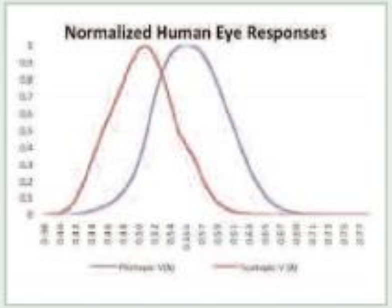
A handy summary of radiometric Terms and Units.

This is taken from www.labsphere.com

If you go on there website, you can request this as a laminated version!

Radiometric Terms and Units

	Radiometric	Spectroradiometric	Photopic
Flux	Power Watts	Power/wavelength interval Watts/nm	Luminous Flux Lumens
Flux/area	Irradiance Watts/m²	Spectral Irradiance Watts/m² nm	Illuminance Lumens/m² = Lux
Flux/solid angle	(Radiant) Intensity Watts/sr	Spectral Intensity Watts/sr nm	(Luminous) Intensity Lumens/sr = candela
Flux/area solid angle	Radiance Watts/m² sr	Spectral Radiance Watts/m² sr nm	Luminance Candela/m² = nit Lumens/m² sr = nit



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Conversion Factors Chart

Number of → multiplied by table factor equals number of ↓	W/m²·sr·µm	W/m2·sr·nm	mW/m²·sr·µm	mW/m²·sr·nm	µW/m²·sr·µm	µW/m²·sr·nm	W/cm²·sr·µm	W/cm²·sr·nm	mW/cm²·sr·µm	mW/cm²·sr·nm	µW/cm²·sr·µm	µW/cm²·sr·nm
W/m²·sr·µm	1	10^{3}	10^{-3}	1	10^{-6}	10^{-3}	10^{4}	10^{7}	10	10^{4}	10^{-2}	10
W/m²·sr·nm	10^{-3}	1	10^{-6}	10^{-3}	10^{-9}	10^{-6}	10	10^{4}	10^{-2}	10	10^{-5}	10^{-2}
mW/m²·sr·µm	10^{3}	10^{6}	1	10^{3}	10^{-3}	1	10^{7}	10^{10}	10^{4}	10^{7}	10	10^{4}
mW/m²·sr·nm	1	10^{3}	10^{-3}	1	10^{-6}	10^{-3}	10^{4}	10^{7}	10	10^{4}	10^{-2}	10
µW/m²·sr·µm	10^{6}	10^{9}	10^{3}	10^{6}	1	10^{3}	10^{10}	10^{13}	10^{7}	10^{10}	10^{4}	10^{7}
µW/m²·sr·nm	10^{3}	10^{6}	1	10^{3}	10^{-3}	1	10^{7}	10^{10}	10^{4}	10^{7}	10	10^{4}
W/cm²·sr·µm	10^{-4}	0.1	10^{-7}	10^{-4}	10^{-10}	10^{-7}	1	10^{3}	10^{-3}	1	10^{-6}	10^{-3}
W/cm²·sr·nm	10^{-7}	10^{-4}	10^{-10}	10^{-7}	10^{-13}	10^{-10}	10^{-3}	1	10^{-6}	10^{-3}	10^{-9}	10^{-6}
mW/cm²·sr·µm	0.1	10^{2}	10^{-4}	0.1	10^{-7}	10^{-4}	10^{3}	10^{6}	1	10^{3}	10^{-3}	1
mW/cm²·sr·nm	10^{-4}	0.1	10^{-7}	10^{-4}	10^{-10}	10^{-7}	1	10^{3}	10^{-3}	1	10^{-6}	10^{-3}
µW/cm²·sr·µm	10^{2}	10^{5}	0.1	10^{2}	10^{4}	0.1	10^{6}	10^{9}	10^{3}	10^{6}	1	10^{3}
µW/cm²·sr·nm	0.1	10^{2}	10^{-4}	0.1	10^{-7}	10^{-4}	10^{3}	10^{6}	1	10^{3}	10^{-3}	1

PB-13065-000

With all what I just went over on terminology and standard units.....

A conversion chart is really handy, as you may sometimes find a variety of units in the literature, manufacturers of radiometers, etc…

Radiometry

Measurement of optical energy

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

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

The Art of Radiometry, Palmer J.M. 2010

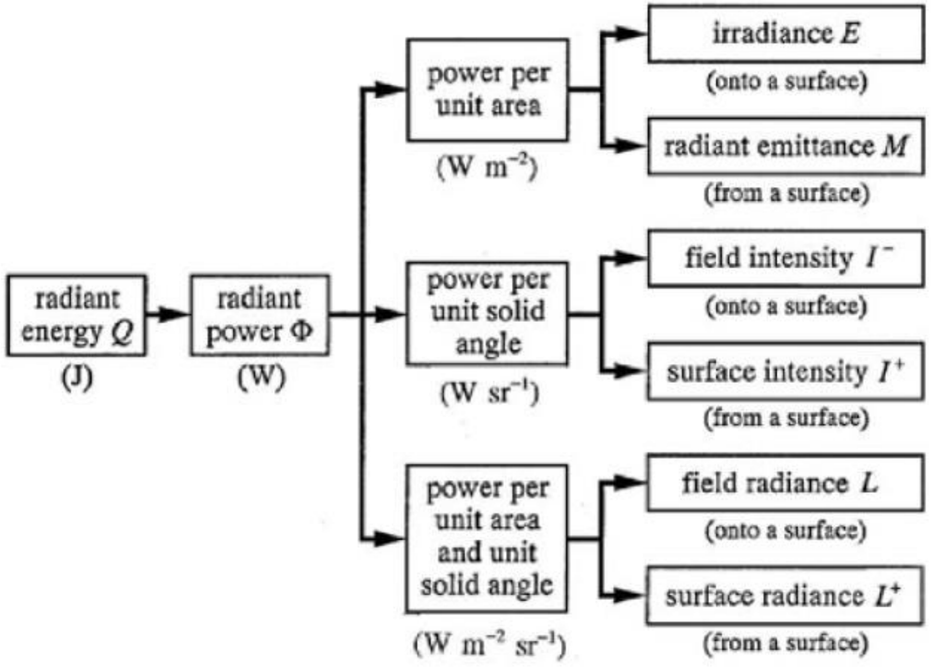

Figure 1.15: The hierarchy of radiometric concepts.

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