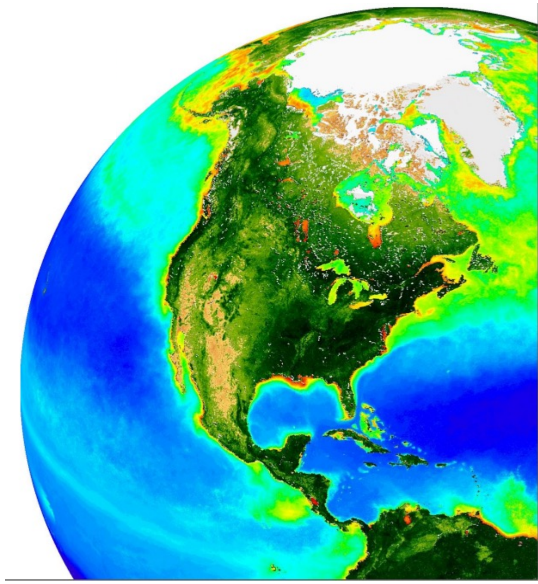
Calibration and Validation of Ocean Color Remote Sensing

Lecture 1: Basic Radiometric Terminology
“Introduction to what this class is about”



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Bowdoin College, Brunswick, ME
June 12, 2023

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"Light in the Sea: Man and Nature"
Paint by J. Ronald V. Zaneveld, 1998

A human eyes "view" of the surface ocean

A starting point to get you thinking

What do you see in this painting?

Why is the water blue?

Why does the intensity of light change with depth.

What causes the circular light pattern at the sea surface?

Why do you see light and dark patterns in the water?

What do you NOT see in this painting?

An Ocean Color satellites ”view” of the Earth.

What do you see in this image?

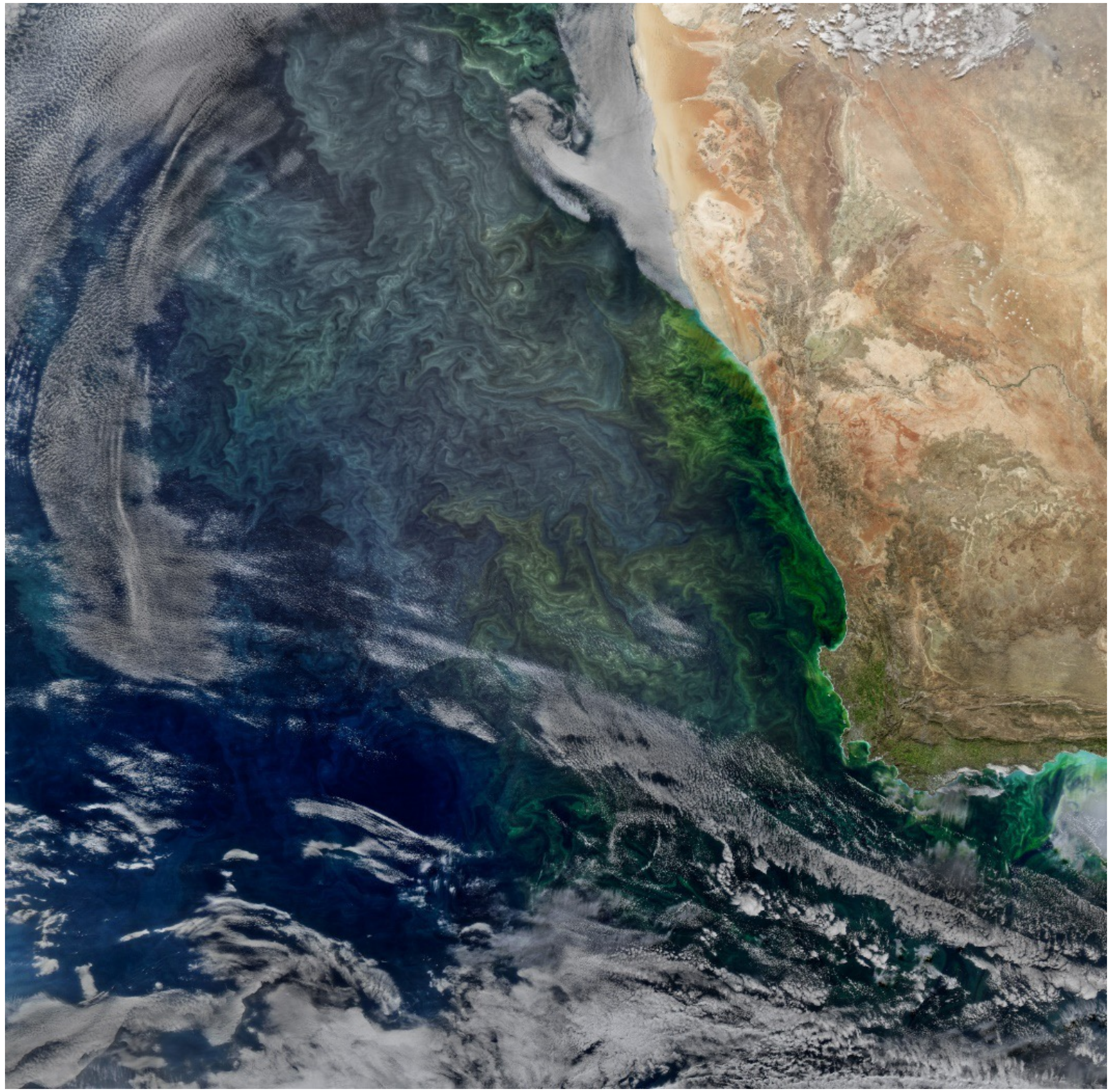
Why do the different colors tell you?

Why does the intensity of light (brighter in some areas in the image, darker in others)?

What do you NOT see in this image?

WHAT DOES THE IMAGER ON THE SATELLITE MEASURE?

LIGHT!!!!



Aqua/MODIS Ocean Color Satellite image collected on September 2, 2017 of Africa's Benguela upwelling ecosystem

Modeling Phytoplankton

Coupled with ship-based measurements and computer models, satellite data allow scientists to observe and study different characteristics about the ocean and how they have changed over time, as well as predict how they might change in the future. This false-color image [right], generated using the NASA Ocean Biogeochemical Model, shows the primary production by diatoms, a group that tends to be large and contributes heavily to the global carbon cycle. Primary production reflects the amount of carbon that is converted using sunlight from carbon dioxide into organic carbon through a process called photosynthesis. The organic carbon represents the carbon that will be usable by higher trophic levels. These data help to improve our understanding of the global ocean carbon and biogeochemical cycles.

Credit: Cecile Rousseaux/USRA/NASA

Spectral Coverage

Ocean Color Heritage Sensors compared with PACE

This graph compares the portions of the electromagnetic spectrum that the PACE Ocean Color Instrument will observe compared to previous NASA ocean color sensors. Human eyes are adapted to see a narrow band of this spectrum called visible light. Using satellite sensors to detect multiple spectral band combinations, scientists can study various aspects of ocean color in ways that they cannot from a photograph. Ocean color features, clouds, and aerosols each leave their signatures in the electromagnetic spectrum and scientists can observe and analyze these patterns to detect changes.

Find more information at *http://pace.gsfc.nasa.gov*.

Credit: NASA

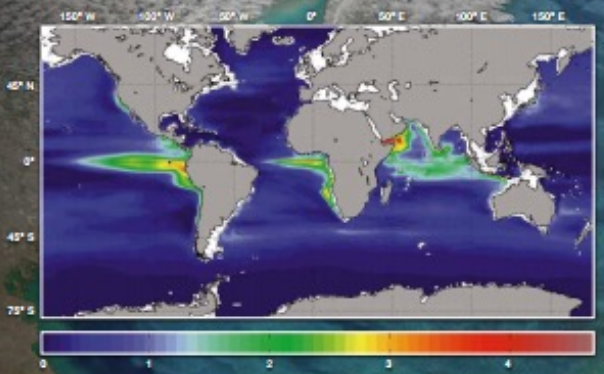
Cover image:

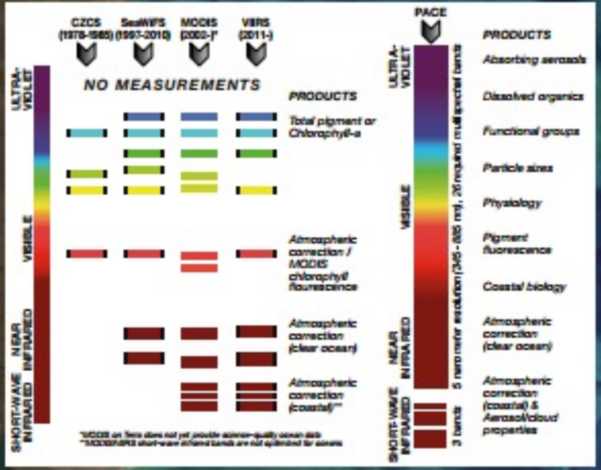
This true color image of the North Atlantic Ocean was created using data from the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi National Polar-orbiting Partnership satellite collected on April 12, 2015. Notice the swirling phytoplankton eddies and different color coastal waters associated with runoff from the eastern United States.

Credit: NASA

For more information, visit:
www.nasa.gov/earth

NASA Sets the PACE for Advanced Studies of Earth's Changing Climate
http://pace.gsfc.nasa.gov





The high spectral resolution of PACE will enable scientists to distinguish phytoplankton types, which will hopefully help to identify harmful algal blooms from space one day.

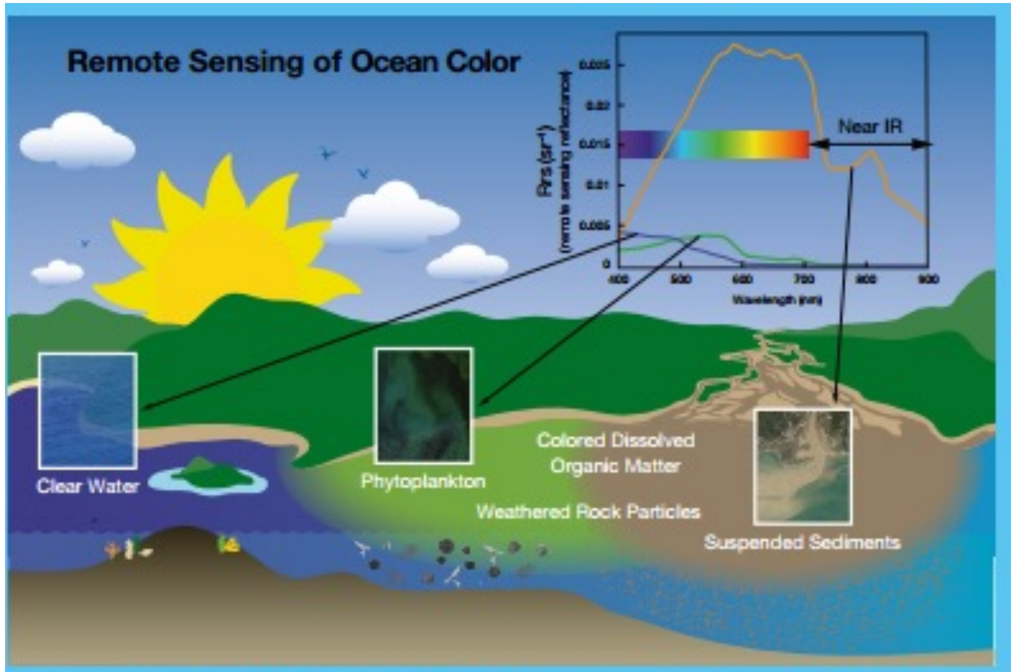
National Aeronautics and Space Administration

What Color is the Ocean?

Ocean Color

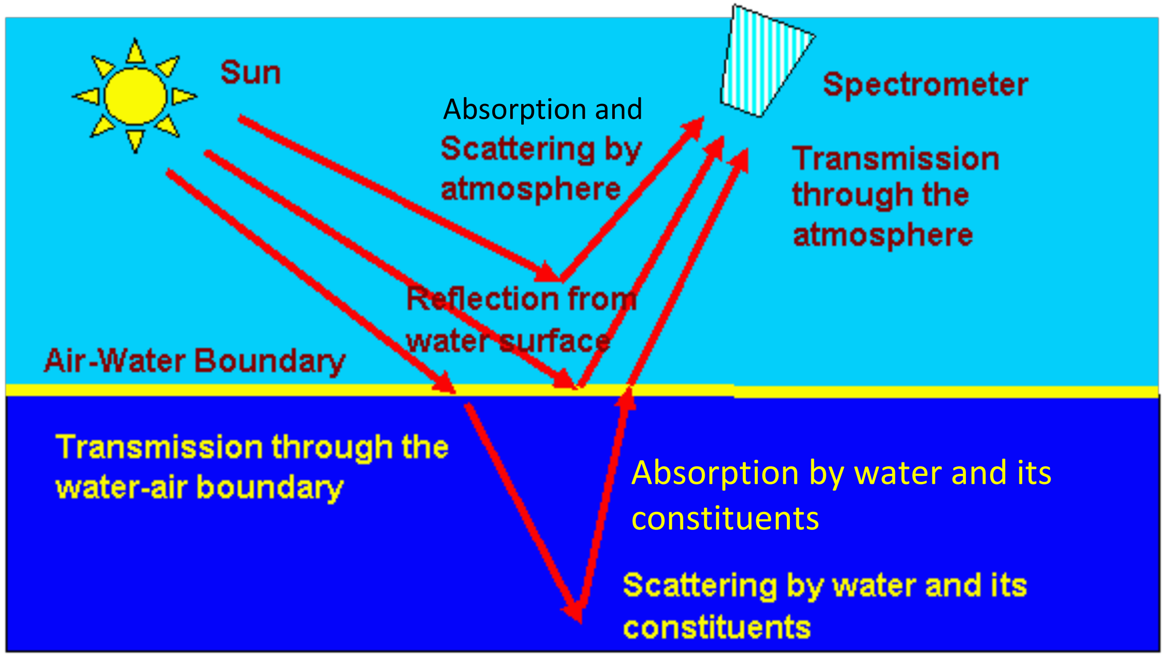
Some sunlight passes through the atmosphere, enters the ocean, gets scattered upwards, passes back up through the atmosphere and is detected by ocean color satellites.

By removing atmospheric effects and surface reflectance, you can isolate the light that interacted with the water column. The color of that light tells you about the constituents of within the water (e.g. plankton concentration, dissolved organics, sediments).

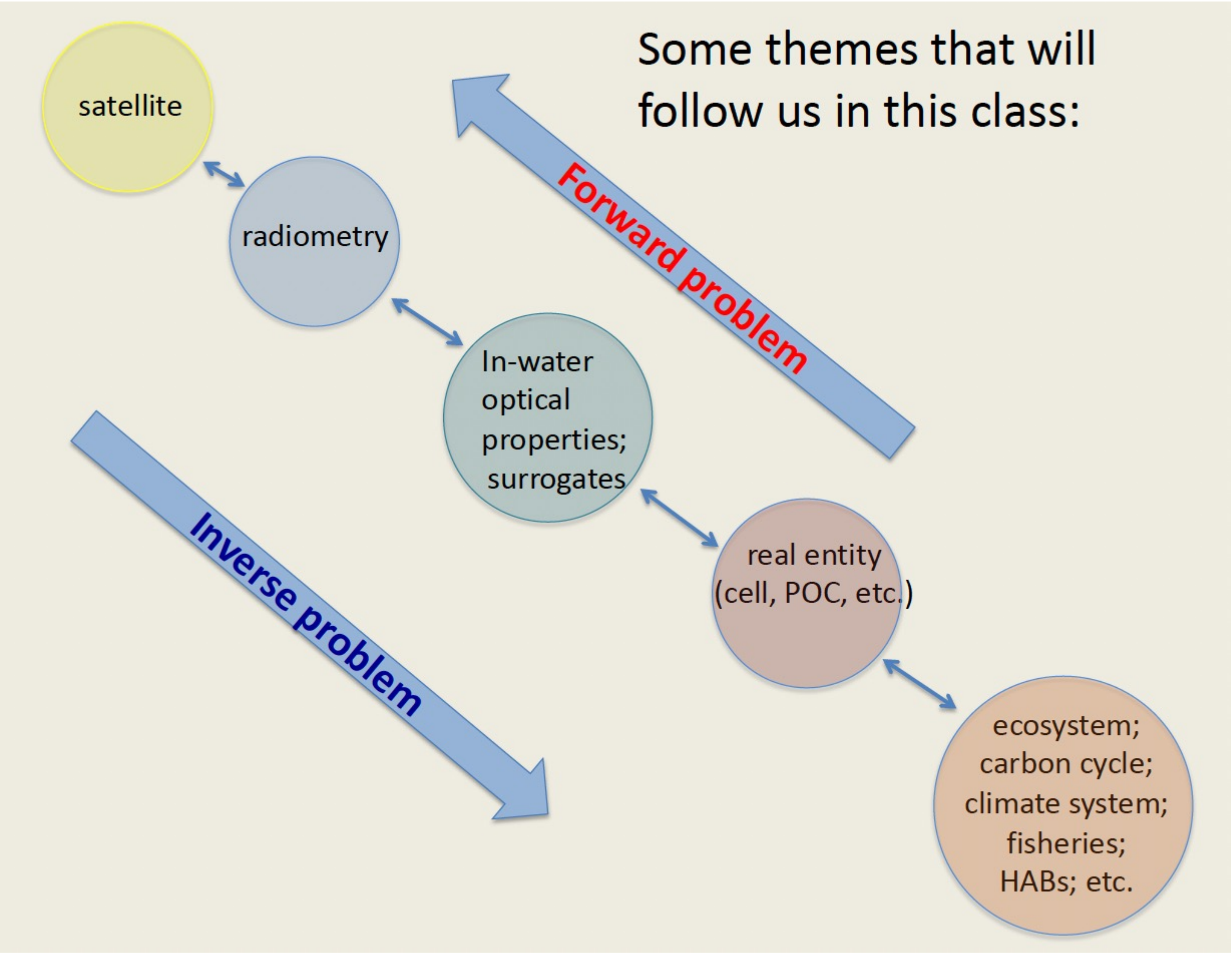


Scientists use a technique similar to spectrophotometry to quantify ocean color remotely. Satellite instruments (such as OCI) measure light reflected back to the satellite at different wavelengths and create emission spectra graphs [*inset, top right*]. Differences in the shape of the spectra can be used to determine what is in the water, such as sediments (orange line), chlorophyll (green line), or clear water (blue line). Brighter objects (e.g., sediments) reflect more light of all wavelengths while darker objects absorb more, thus the values are higher across the spectrum for sediment.

Credit: NASA



Two possible fates of a photon: absorption and scattering.



Pictogram by Collin Roesler

Week 1 – we will start at the middle, IOPs, and move a bit down the chain.

Week 2 – we will go up the chain from IOPs (including some radiometric surrogates) and dive more deeply into radiometric measurements, remote sensing.

Week 3 – Dive into Remote Sensing reflectance inversion methods, making optical measurements at sea, data processing, atmospheric corrections, QA/QC, uncertainties.

Week 4 – Synthesis: Working up cruise data results, Monte Carlo modelling methods, final presentations and CELEBRATE and PARTY!

Some Basic Radiometric Terminology

Radiometry is the science of measuring electromagnetic radiation.

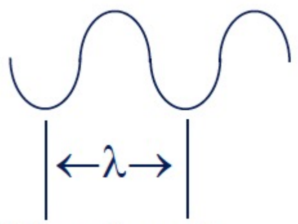
In Ocean Optics, Optical radiometry most often refers to UV, Visible, and Near Infrared regions of the spectrum

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

$c = n\lambda\nu$



Wavelength

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: λ = 555 nm, then ν = 540 x 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.

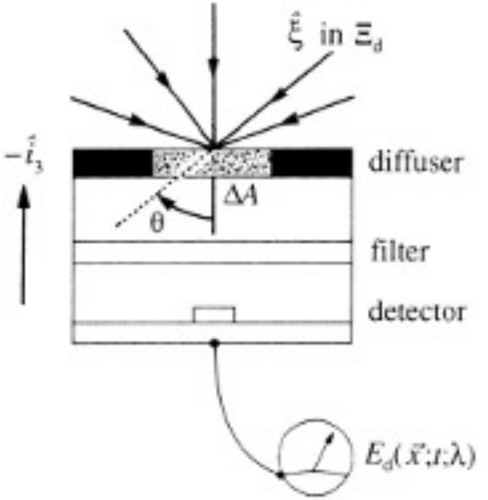
Quantity	*Symbol*		*Unit*
Radiant Energy	Q		Joule
Radiant Flux	Φ		Watts (Joule/sec)
Irradiance	E		Watts/m^2
Radiance	L		Watts/(m^2 sr)
Irradiance Reflectance	E_u/E_d		-
Remote Sensing Reflect.	L_u/E_d		sr^{-1}
Q-factor	E_u/L_u		sr

A few Apparent Optical Properties ← (Irradiance Reflectance, Remote Sensing Reflect., Q-factor)

Courtesy of Giuseppe Zibordi, Joint Research Centre of European Commission

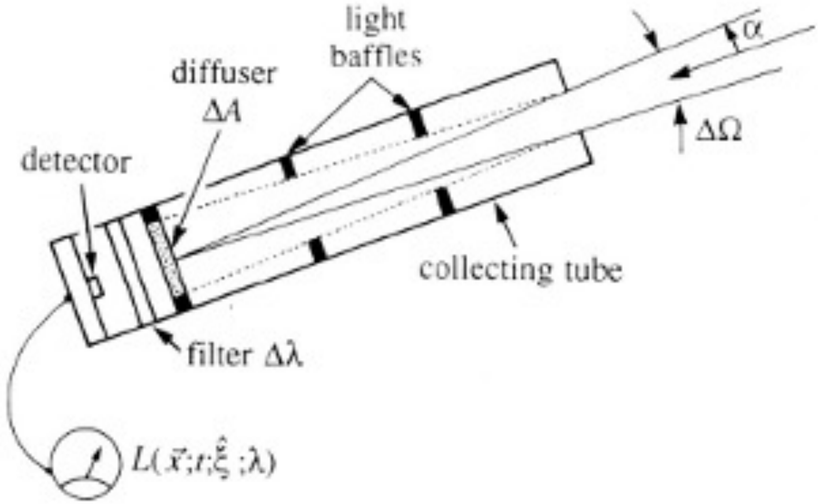
All of these quantities are measured over a spectral range, meaning that the units include a nm^{-1}

E



Radiant flux (power) incident on a surface

L



Radiant flux (power) per solid angle (steradian) per unit projected source area

Drawings from C. Mobley, http://www.oceanopticsbook.info

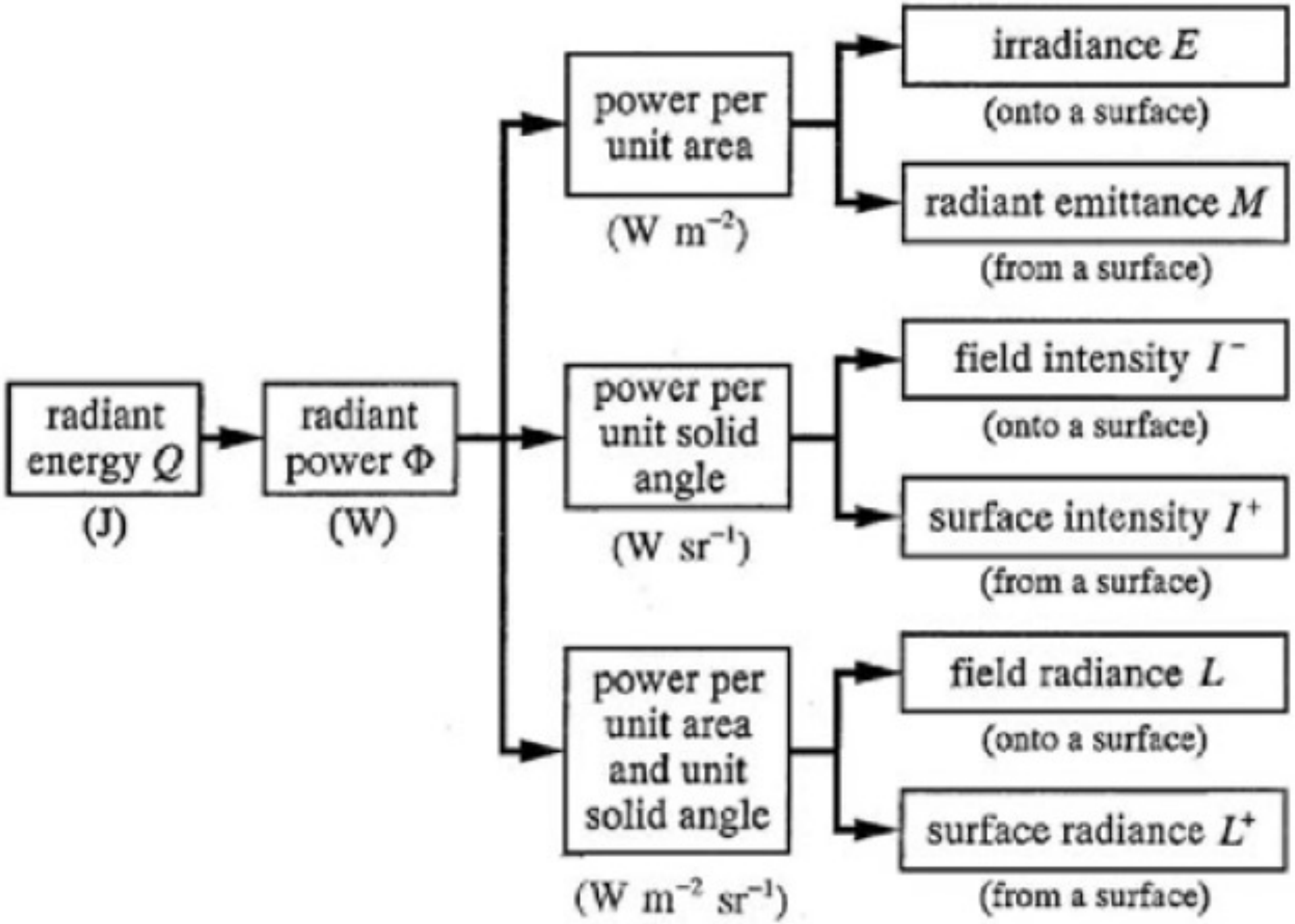


Figure 1.15: The hierarchy of radiometric concepts.

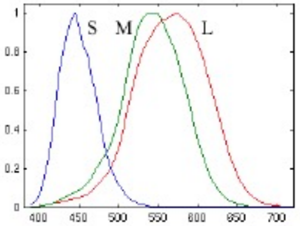
Mobley, C. D. (Editor), 2022. The Oceanic Optics Book, International Ocean Colour Coordinating Group (IOCCG), Dartmouth, NS, Canada, 924pp. DOI: 10.25607/OBP-1710

Joint Research Centre

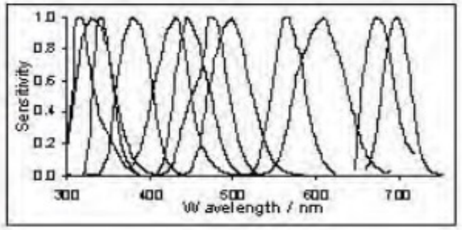
Optical Sensing Systems

Of all the techniques used in remote sensing, the observation of the Earth from optical sensors is perhaps the most easily understood in concept, because it is the most similar to our own personal remote sensing device – the human eye. *Ian Robinson (2004)*

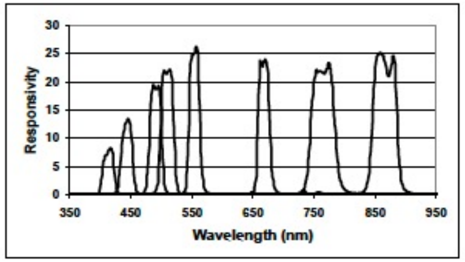
Photometry is special subset of radiometry weighted for the human eye



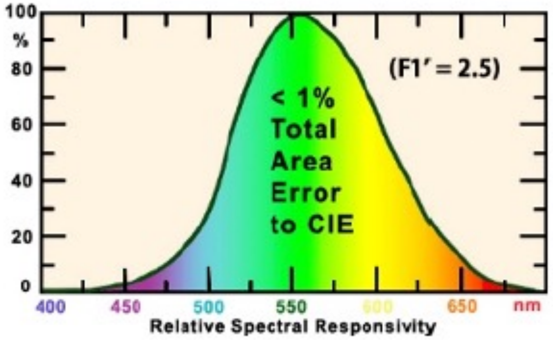
Human eye (tri-chromatic)



Mantis shrimp eye (multi-spectral with UV and polarization sensitivity)



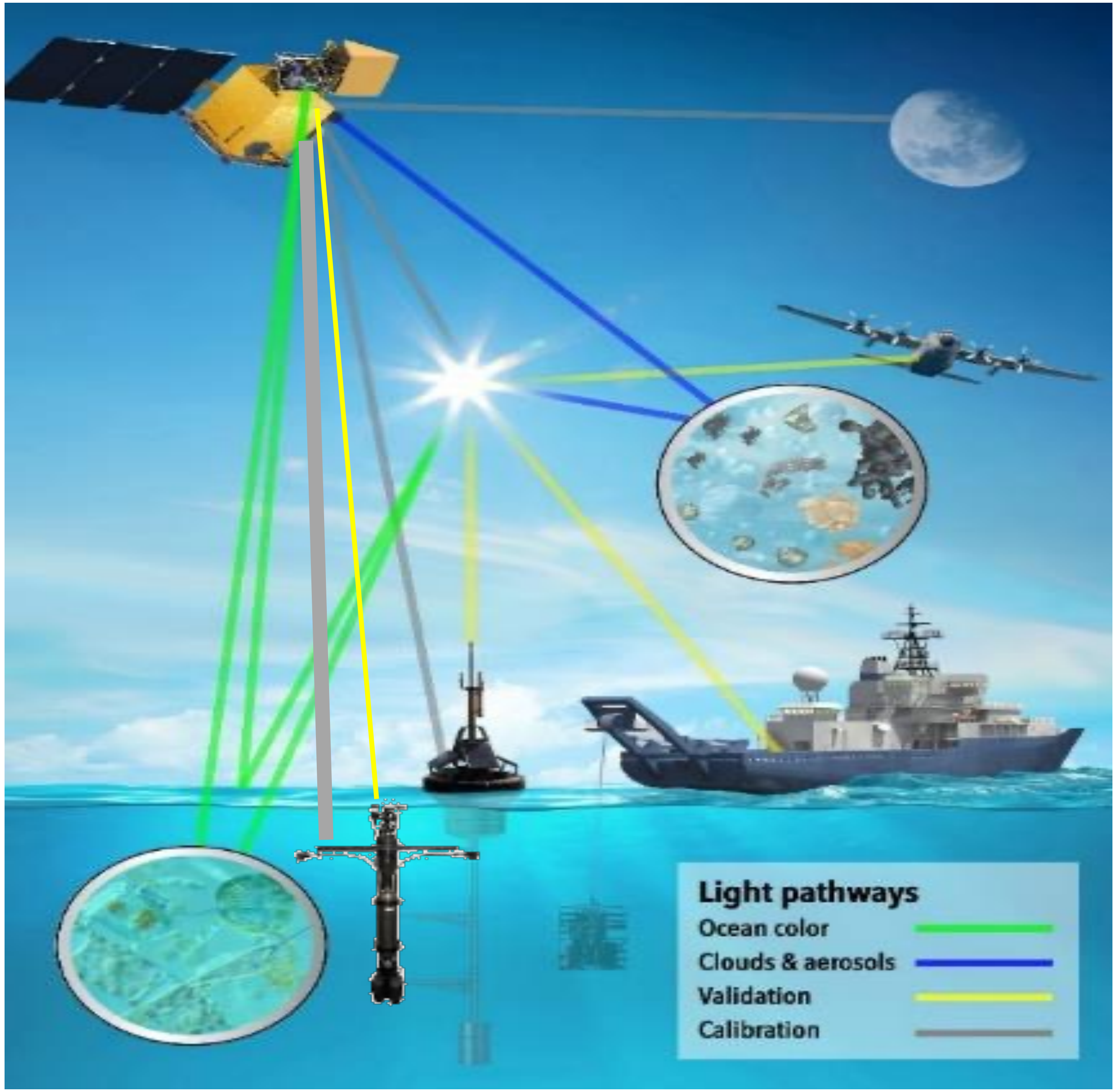
SeaWiFS remote sensor (multi-spectral with NIR sensitivity)



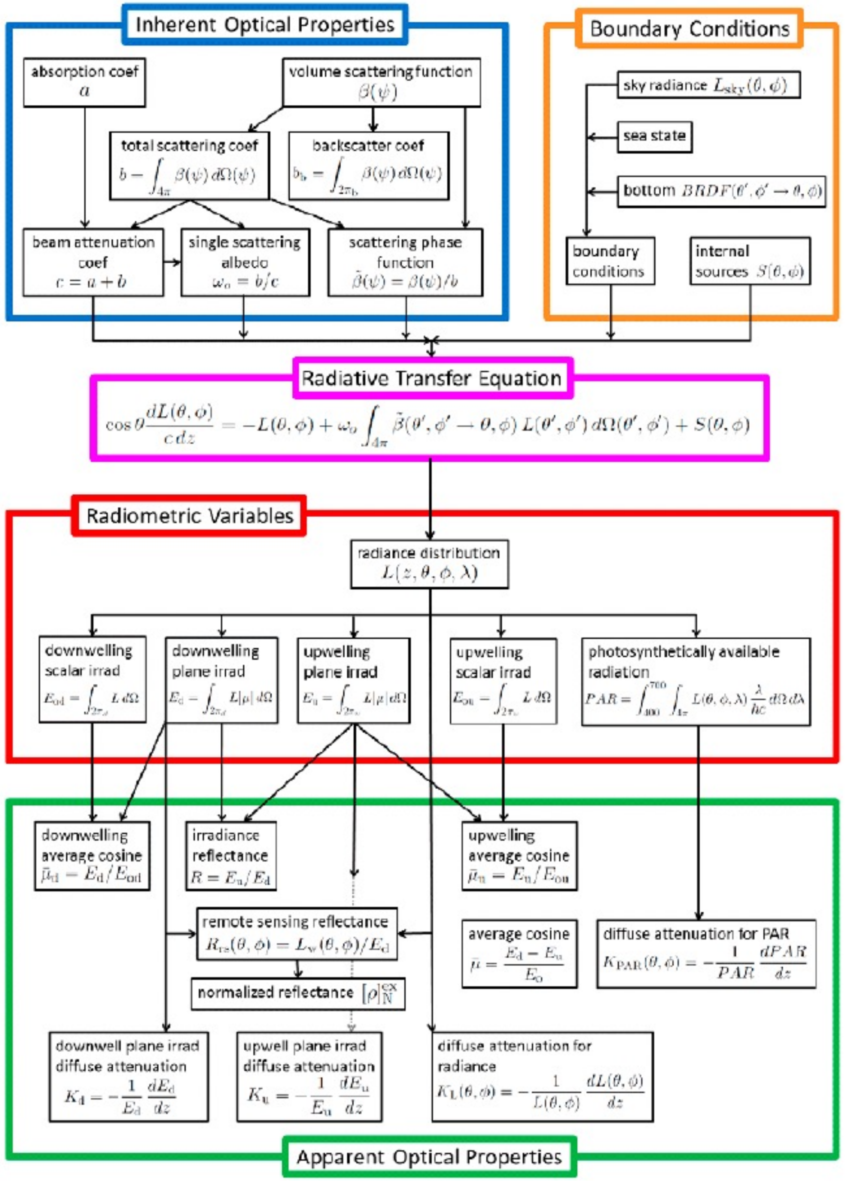
Example of a typical photometer

Courtesy of Giuseppe Zibordi, Joint Research Centre of European Commission

Light pathways to Satellites and Radiative Transfer



Credit: NASA PACE Program.



https://ioccg.org/wp-content/uploads/2022/01/mobley-oceanicopticsbook.pdf.

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	2×10^7	W/m²-sr
Sun	2×10^9	cd/m²
Frosted bulb	10,000	cd/m²
Fluorescent	5,000	cd/m²
Computer screen	100	cd/m²

Planck's Blackbody Equation

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

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

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

Radiance of Sphere

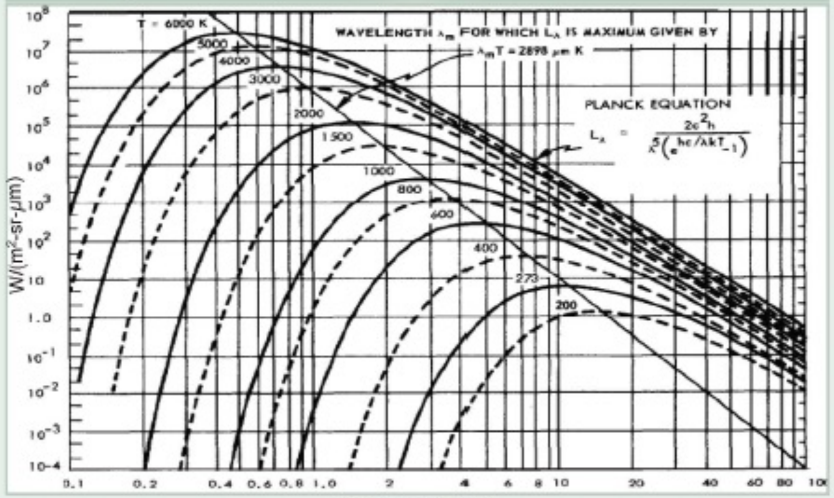
$$\text{Radiance of Sphere} = \frac{\Phi_i}{\pi A_S} * \frac{\rho}{1-\rho(1-f)}$$

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

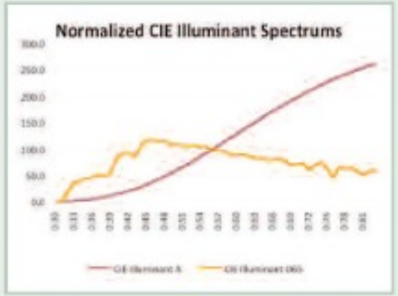
A handy summary of radiometric Terms and Units.

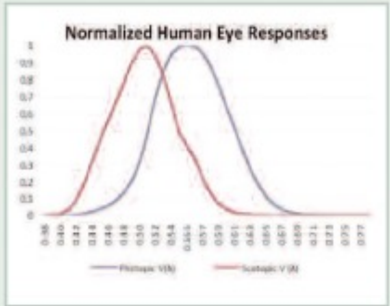
This is taken from www.labsphere.com

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





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/m²sr·µm	1	10^{3}	10^{-3}	1	10^{-6}	10^{-3}	10^{4}	10^{7}	10	10^{4}	10^{-2}	10
W/m²sr·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/m²sr·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

COURTESY OF

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

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

Welcome to Ocean Optics

Enjoy those photons!!