2017 Summer Course

Optical Oceanography and Ocean Color Remote Sensing

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Light and Radiometry

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July 2017

Light and Radiometry

Start with some comments about the nature of light. Then...

Review the basic knowledge needed for this course:

How do you describe how much light there is, where it is going, etc.?

How to specify directions

Radiance—the fundamental quantity for describing light

Irradiances—easier to measure than radiance and often more useful

A Brief History of Light

Is light a particle, a wave, both, or neither?

- ancient Greece, Democritus: Everything is made of particles (atoms)
- 11th century, Alhazen: Light is rays of particles
- 1630s, Descartes: light is waves
- 1670s, Newton: light is particles ("corpuscles")
- same time: Huygens, Fresnel: light is waves
- 1803 Young: light is waves (double slit interference)
- late 1800's, Maxwell: light is propagating electric and magnetic fields; a wave
- 1900: Planck, emission of light is quantized (black body radiation)
- 1905: Einstein: light is absorbed as discrete quanta (photolectric effect)
- early-mid 1900's: quantum mechanics: both light and matter have both particle and wave properties ("wave-particle duality")
- 1926: "photon" invented in a different context
- mid-late 1900s: quantum electrodynamics (QED): light is photon "particles", but the photons cannot be localized; they take all possible paths from source to detector; they fill all of space between the source and detector, a single photon can interfere with itself (single-photon double-slit experiment)
- today, elementary particle theory: everything is particles, but all particles have wave properties

Photon Properties

A photon is defined by its

- energy (or frequency or wavelength or linear momentum)
- angular momentum
- state of polarization

“position” and “time” and “path” are not defined and have no meaning for photons

Photons can NOT be “localized” like electrons or basketballs or other particles with a non-zero rest mass. You can say “there is an electron in the left half of this box.” You can not say that for a photon. In quantum mechanics, there is no “position operator” for photons, which would give the probability of finding a photon at a certain location at a particular time.

“particle” and “wave” are idealized classical physics models for nature, but light is more complicated and behaves very, very strangely by human terms.

What Nobel Prize Winners for Work in Optics Have Said about Photons

Einstein (photoelectric effect): “All the fifty years of conscious brooding have brought me no closer to answer the question, “What are light quanta?” and “These days, every Tom, Dick and Harry thinks he knows what a photon is, but he is wrong.”

Feynman (development of QED): “Nobody knows [what photons are], and it’s best if you try not to think about it.”

Glauber (quantum optics): “I don’t know anything about photons, but I know one when I seen one.” and “A photon is what a photodetector detects.”

Lamb (the Lamb shift in H): “There is no such thing as a photon. Only a comedy of errors and historical accidents led to its popularity amoung physicists and optical scientists.” and “It is high time to give up the use of the word ‘photon’, and of a bad concept which will shortly be a century old.”

Thinking About Light

In spite of Lamb's opinion, most physicists seem happy to regard photons as real, but they are very careful not to view them as classical particles or waves. They have features of both, depending on what is measured, but they are neither.

You can say a photon was created at point A (e.g, emitted by an atom in a light bulb filament) and that it was absorbed at point B (e.g., in a particular pixel of a CCD array), but you can say nothing about how it got from A to B.

Feynman's view is that a single photon simultaneous takes all possible paths from A to B. Others take the view that a single photon fills all of space between A and B. Either way, the photon can pass through both slits of an interference filter and interferes with itself, and create an interference pattern.

Thinking About Light

However, if you do want to think more deeply about photons and light:

- Start by reading *QED: The Strange Story of Light and Matter* by Feynman
- Study the articles in “What is a Photon” in the Library
- Watch the video single-photon-interference.mp4 in the Library (from https://youtu.be/I9Ab8BLW3kA)
- Watch the video at https://phys.org/news/2015-03-particle.html

Remember that much (perhaps most) of what is said about photons on websites and even in some physics textbooks (and here!) is overly simplfied, outdated, or just simply wrong.

Photons are defined by what they ***do***, not by what they ***are***.

All You Need to Know about Photons

q photon energy [J]

ν frequency $[\mathrm{s}^{-1}]$

λ wavelength [m]

$h = 6.626 \cdot 10^{-34}$ J s Planck's constant

$c = 2.998 \cdot 10^{8}$ m s^{-1} speed of light (in a vacuum)

Photon energy is related to frequency and wavelength by

$$\boxed{q = h\nu = \frac{hc}{\lambda} \quad [J]}$$

The linear momentum is related to wavelength, energy, and frequency by

$$p = \frac{h}{\lambda} = \frac{q}{c} = \frac{h\nu}{c} \quad [\mathrm{kg\,m\,s^{-1}}]$$

The angular momentum is

$$\ell = \frac{h}{2\pi} \quad [\mathrm{kg\,m^2\,s^{-1}}]$$

Energy and linear momentum depend on frequency, but all photons have the same angular momentum ("spin 1 particles")

Example Calculations

How many photons of visible light are there on a typical day at sea level?

From *Light and Water*, Table 1.4, typical day, 400-700 nm: 400 $\mathrm{W\,m^{-2}}$, so for $\lambda = 550\ \mathrm{nm} = 550 \cdot 10^{-9}\ \mathrm{m}$ (green light)

$$\frac{400\ \mathrm{J\,s^{-1}\,m^{-2}}}{\frac{(6.63\cdot 10^{-34}\ \mathrm{J\,s})\,(3\cdot 10^{8}\ \mathrm{m\,s^{-1}})}{550\cdot 10^{-9}\ \mathrm{m}}} \approx 10^{21}\ \text{photons}\ \mathrm{m^{-2}\,s^{-1}}$$

How many photons are there per cubic meter in the water?

The speed of light in water is *c*/(index of refraction) ≈ *c*/1.34, so

$$\frac{10^{21}\ \text{photons}\ \mathrm{m^{-2}\,s^{-1}}}{\frac{3\cdot 10^{8}\ \mathrm{m\,s^{-1}}}{1.34}} \approx 4\cdot 10^{12}\ \frac{\text{photons}}{\mathrm{m^3}} \approx \frac{\text{number of phytoplankton}}{\mathrm{m^3}}$$

Each phytoplankton is being hit by photons many times per second.

We will discuss polarization later….

Radiometry

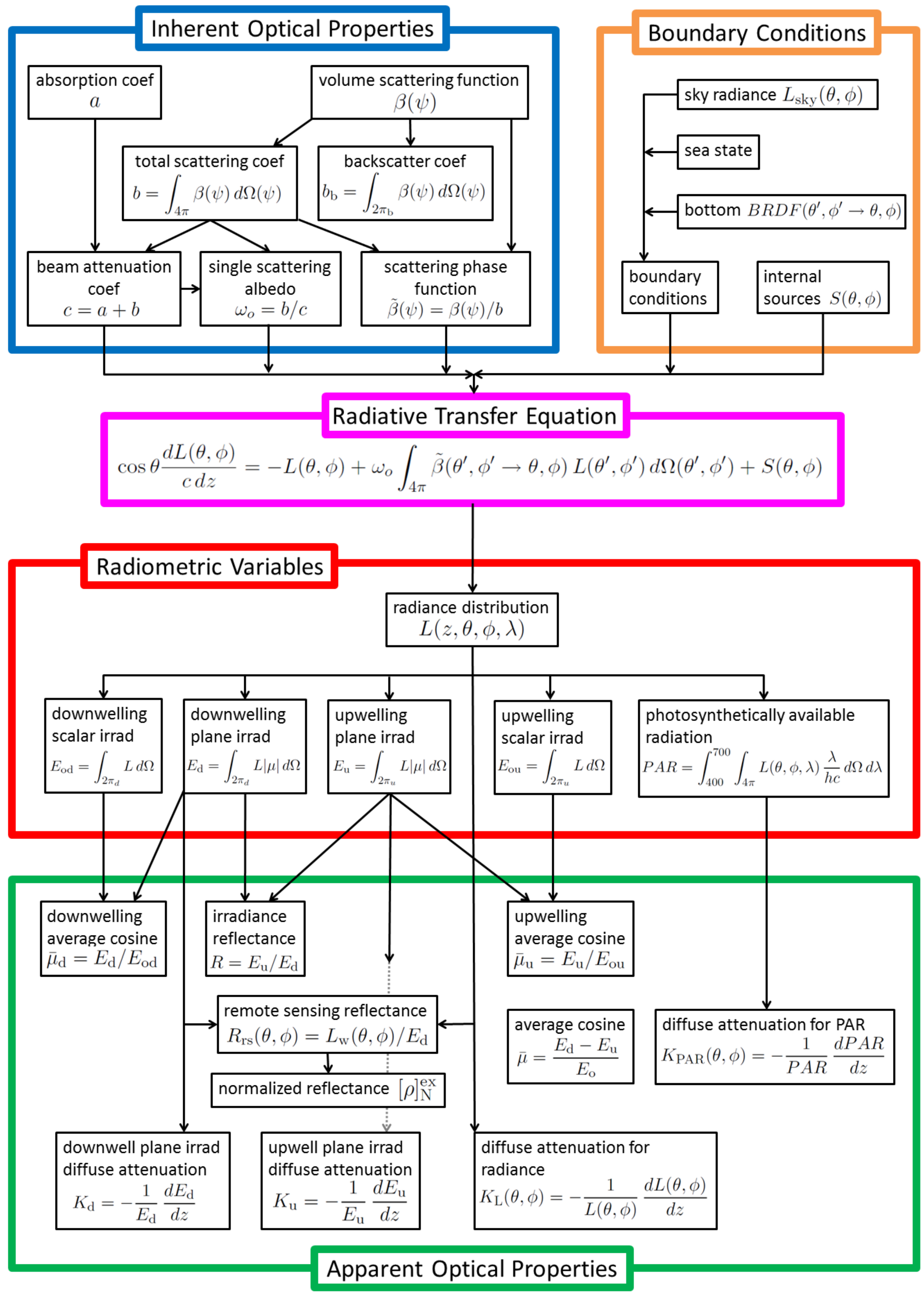
Radiometry is the science of measuring electromagnetic (radiant) energy

Two types of detectors:

• thermal—instrument response is proportional to the *energy* (absorbed and converted to heat)

• quantum—instrument response is proportional to the *number of photons* absorbed

Calibration of radiometric instruments is very difficult (~2% accuracy)



How to specify directions

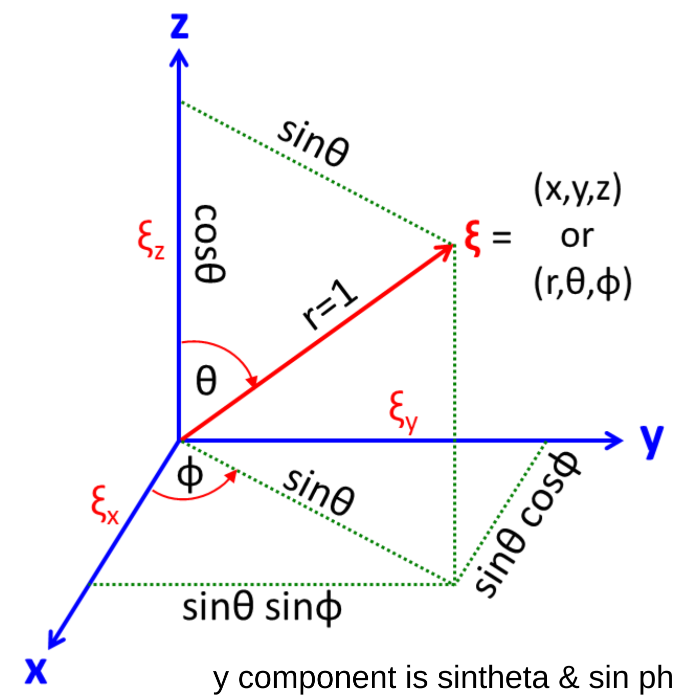
This is the math of specifying the direction that light is going

Warning on directions:

In radiative transfer theory (i.e., in the radiative transfer equation, in *Light and Water*, and in HydroLight), θ and ϕ always refer to the direction the light is going.

Experimentalists often let θ and ϕ refer to the direction the instrument was pointed to measure the radiance.

I call the instrument direction the viewing direction, θ_v and ϕ_v, where $\theta_v = \pi - \theta$ and $\phi_v = \phi + \pi$.



y component is sintheta & sin phi

$\hat{\xi}$ is a unit vector specifying direction (θ, ϕ)

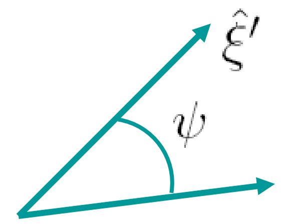
$$|\hat{\xi}| = 1 = \hat{\xi} \cdot \hat{\xi} = \xi_x^2 + \xi_y^2 + \xi_z^2$$

$$\begin{aligned}\hat{\xi} &= \xi_x \hat{x} + \xi_y \hat{y} + \xi_z \hat{z} \\ &= (\sin\theta\cos\phi)\hat{x} + (\sin\theta\sin\phi)\hat{y} + (\cos\theta)\hat{z}\end{aligned}$$

$$\theta = \cos^{-1}(\xi_z) \qquad \mu \equiv \cos\theta$$

$$\phi = \tan^{-1}\left(\frac{\xi_y}{\xi_x}\right)$$

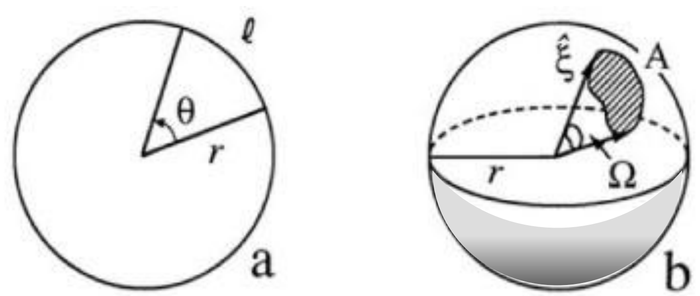
Computing the (scattering) angle between two directions



$$\hat{\xi}' \cdot \hat{\xi} \equiv |\,\hat{\xi}'\,||\,\hat{\xi}\,| \cos\psi = \cos\psi.$$

$$\begin{aligned}\cos\psi &= \xi'_x \xi_x + \xi'_y \xi_y + \xi'_z \xi_z \\ &= \cos\theta' \cos\theta + \sin\theta' \sin\theta \cos(\phi' - \phi) \\ &= \mu'\mu + \sqrt{1 - \mu'^2}\sqrt{1 - \mu^2}\cos(\phi' - \phi)\end{aligned}$$

Defining solid angles

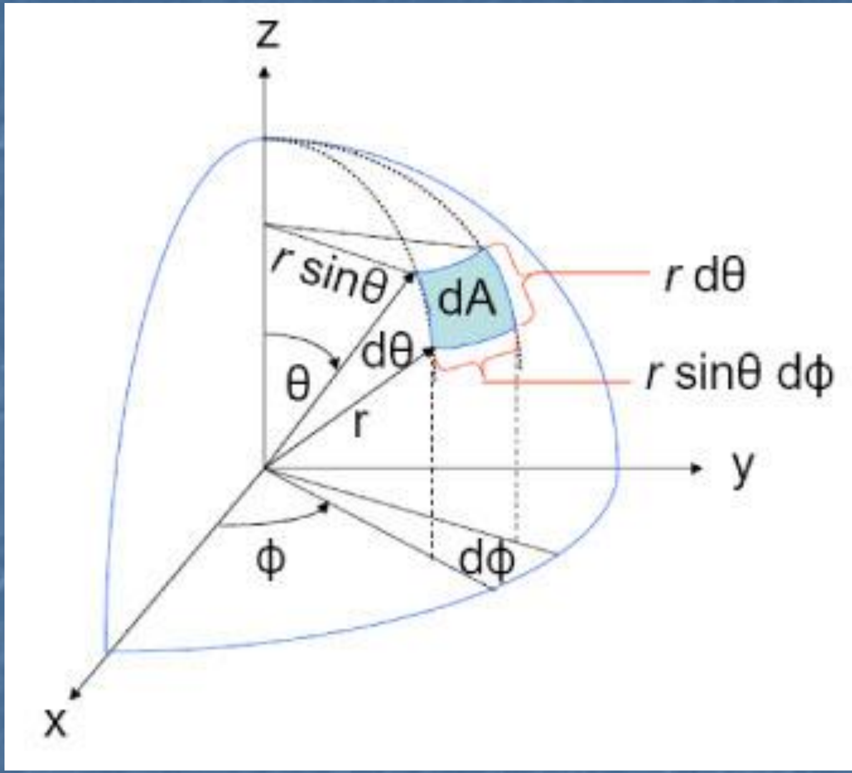


$$\text{angle} \equiv \frac{\text{arc length}}{\text{radius}} \qquad \text{solid angle} \equiv \frac{\text{area}}{\text{radius squared}}$$

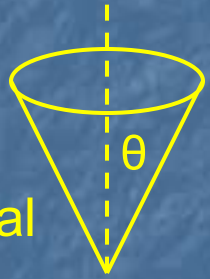
$$\theta = \frac{\ell}{r} \ (\text{radian}) \qquad \Omega = \frac{A}{r^2} \ (\text{steradian})$$

$$\text{circle} = 2\pi \text{ rad} \qquad \text{sphere} = 4\pi \text{ sr}$$

Computing Solid Angles



Example: What is the solid angle of a cone with half-angle θ?

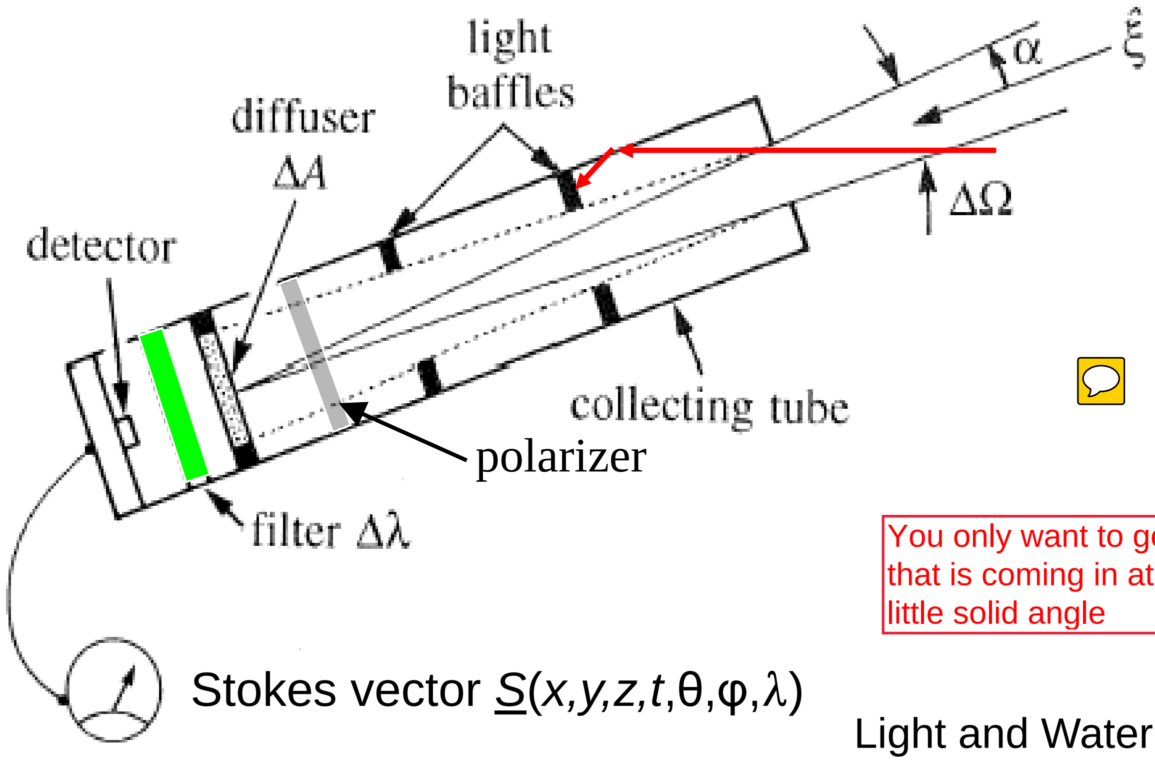


Place the cone pointing to the "north pole" of a spherical coordinate system.

$$\begin{aligned}\Omega &= \int_{\phi'=0}^{2\pi} \int_{\theta'=0}^{\theta} \sin\theta' d\theta' d\phi' = 2\pi(1-\cos\theta) \\ &= \int_{\phi'=0}^{2\pi} \int_{\mu'=\mu}^{1} d\mu' d\phi' = 2\pi(1-\mu)\end{aligned}$$

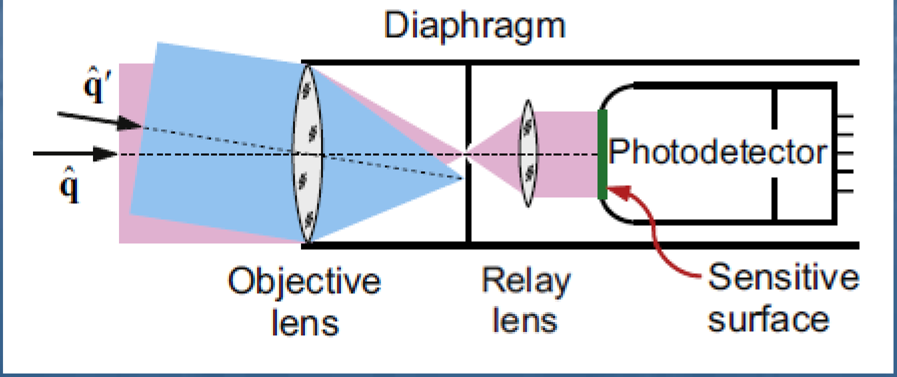
$$\begin{aligned}d\Omega &= \frac{dA}{r^2} = \frac{(r sin\theta\, d\phi)(r d\theta)}{r^2} = \sin\theta\, d\theta\, d\phi \\ &= d\mu d\phi\end{aligned}$$

Gershun Tube Radiometer



Light and Water

You only want to get the light that is coming in at your little little solid angle



This is the fundamental concept of how to measure radiance

Mishchenko (2014)

Well Collimated Radiometers

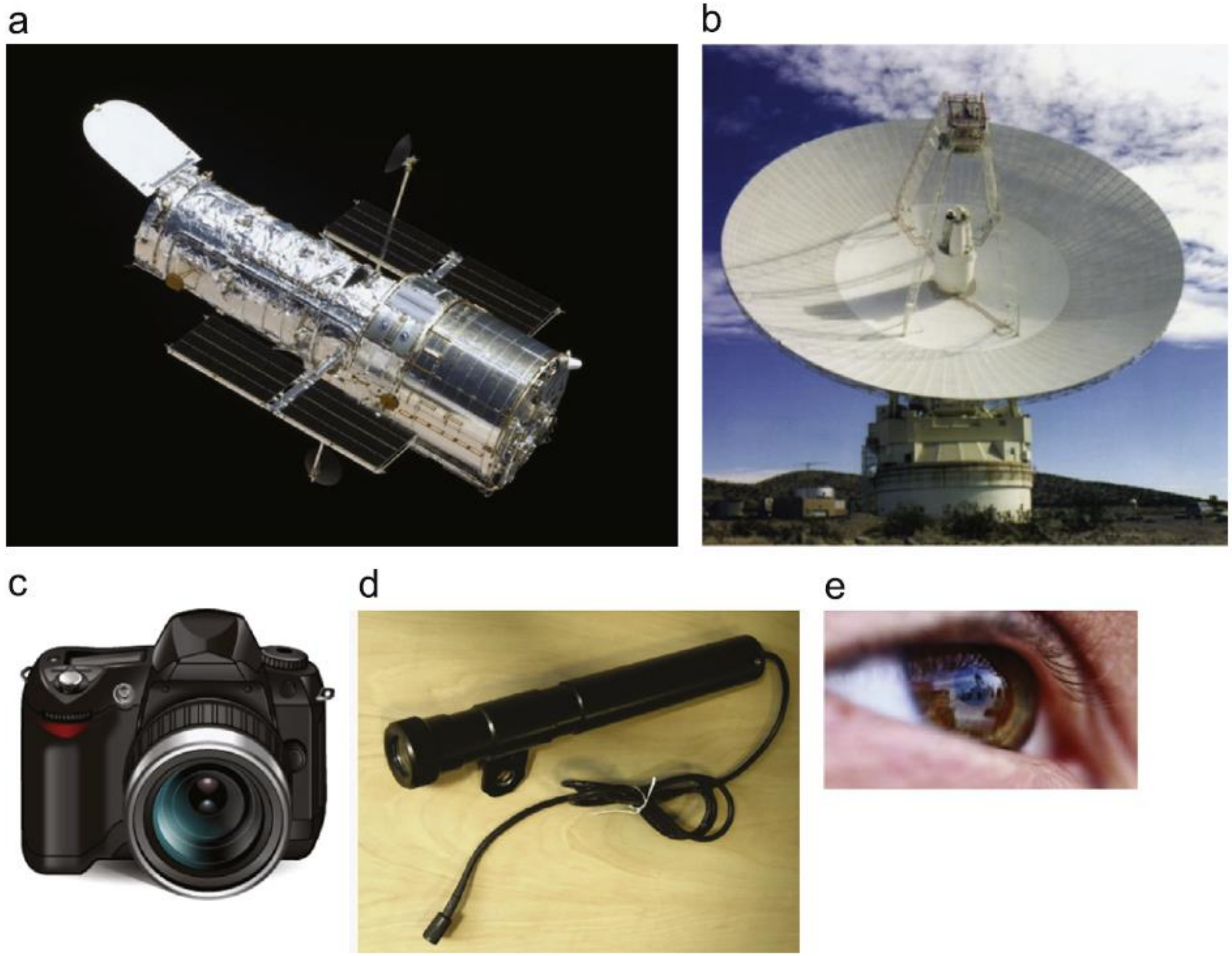


Fig. 15. (a) NASA's Hubble Space Telescope. (b) NASA's 64-m Goldstone radio telescope. (c) Digital photographic camera. (d) Gershun tube [120]. (e) Human eye.

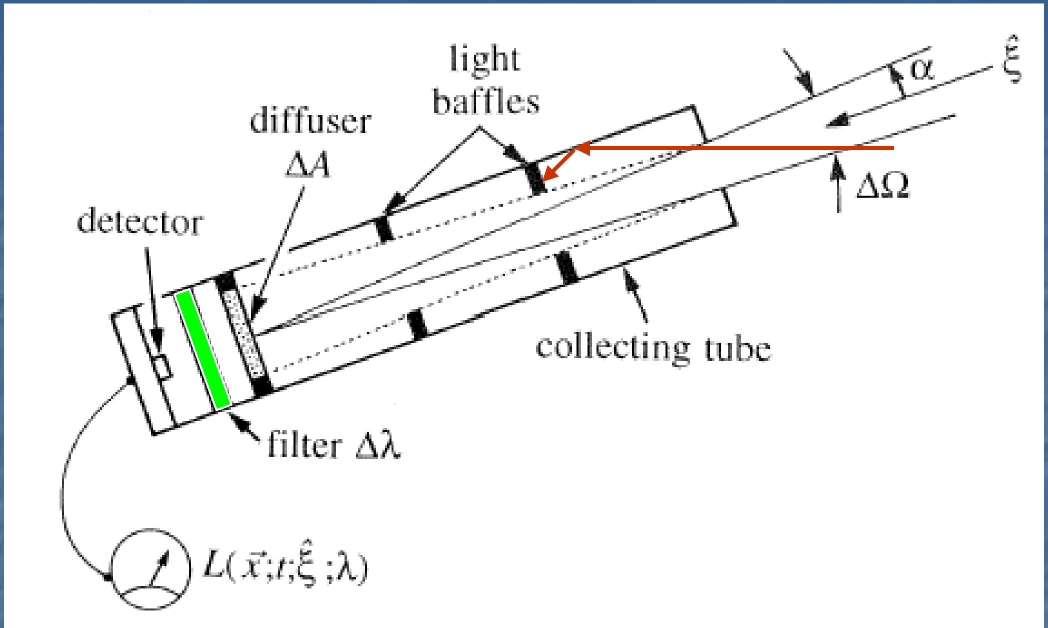
Mishchenko (2014)

Spectral Radiance

If you know the spectral radiance *L*, you know everything there is to know about the total light field (except for polarization)

Full specification of the radiance at a given location and time includes its state of polarization, wavelength, and direction of propagation

"spectral" can mean either "per unit of wavelength or frequency" or "as a function of wavelength"



$$L(\vec{x}, t, \hat{\xi}, \lambda) \equiv \frac{\Delta Q}{\Delta t\, \Delta A\, \Delta\Omega\, \Delta\lambda}$$

$$(\mathrm{J\ s^{-1}\ m^{-2}\ sr^{-1}\ nm^{-1}})$$

$$(\mathrm{W\ m^{-2}\ sr^{-1}\ nm^{-1}})$$

HydroLight computes $L(z,\theta,\varphi,\lambda)$

Polarization

To specify the polarization state of the radiance requires four numbers: the elements of the Stokes vector $\underline{S} = [I, Q, U, V]^T$

I is the total radiance, without regard for the state of polarizaiton. *I* is usually called the radiance *L* in oceanography.

Q, U, V describe the linear and circular polarization of the light. We will see how this is done in later lectures. Meanwhile, see

http://www.oceanopticsbook.info/view/light_and_radiometry/polarization_stokes_vectors

The state of polarization of the radiance contains information about the environment (affected by the size distribution, shape, and index of refraction of particles in the water)

However, oceanographers usually measure only the total radiance because

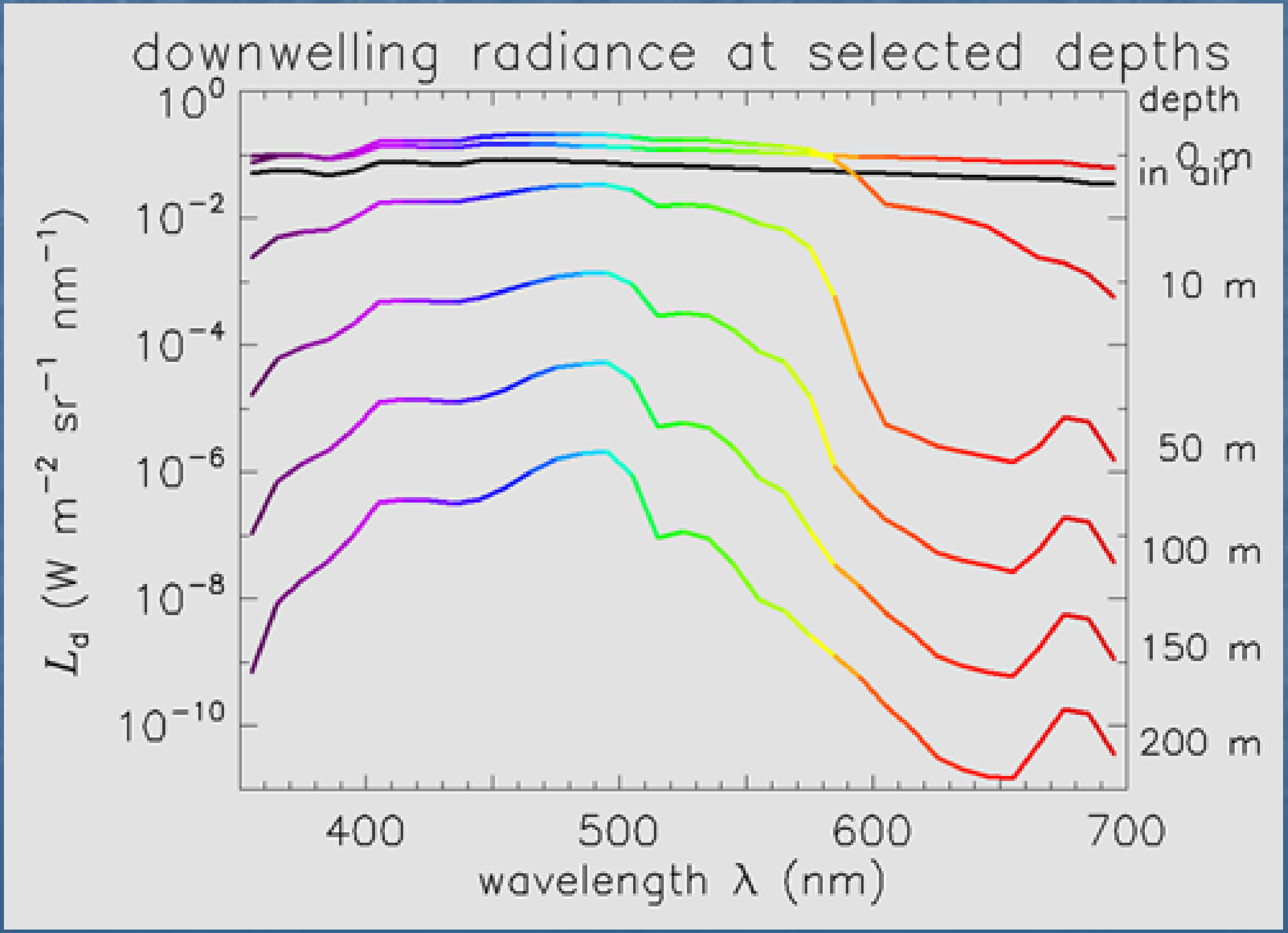
- The 4x1 Stokes vector (and corresponding 4x4 scattering matrix, which describes scattering of polarized light) is much harder to measure than just *L*
- The state of polarization is believed to have little effect on processes like phytoplankton photosynthesis or water heating
- The different polarizations of the radiance in different directions tend to average out when the radiance is integrated to get irradiance
- We do not have good models or data for the inputs needed to compute polarization in the ocean

Therefore, we will usually ignore polarization in this introductory class.

Keep in mind, however, that ignoring polarization (e.g., in HydroLight) causes some error (~10% in radiance, ~1% in irradiance) and that use of polarization will probably become more important in future years, as instruments and models improve.

Radiance is always hard to plot because of so many variables

Example plot: Radiance $L(z, \theta, \phi, \lambda)$ as a function of z and λ for the zenith-viewing direction (the downwelling radiance L_d: light traveling straight down, detector pointed straight up)



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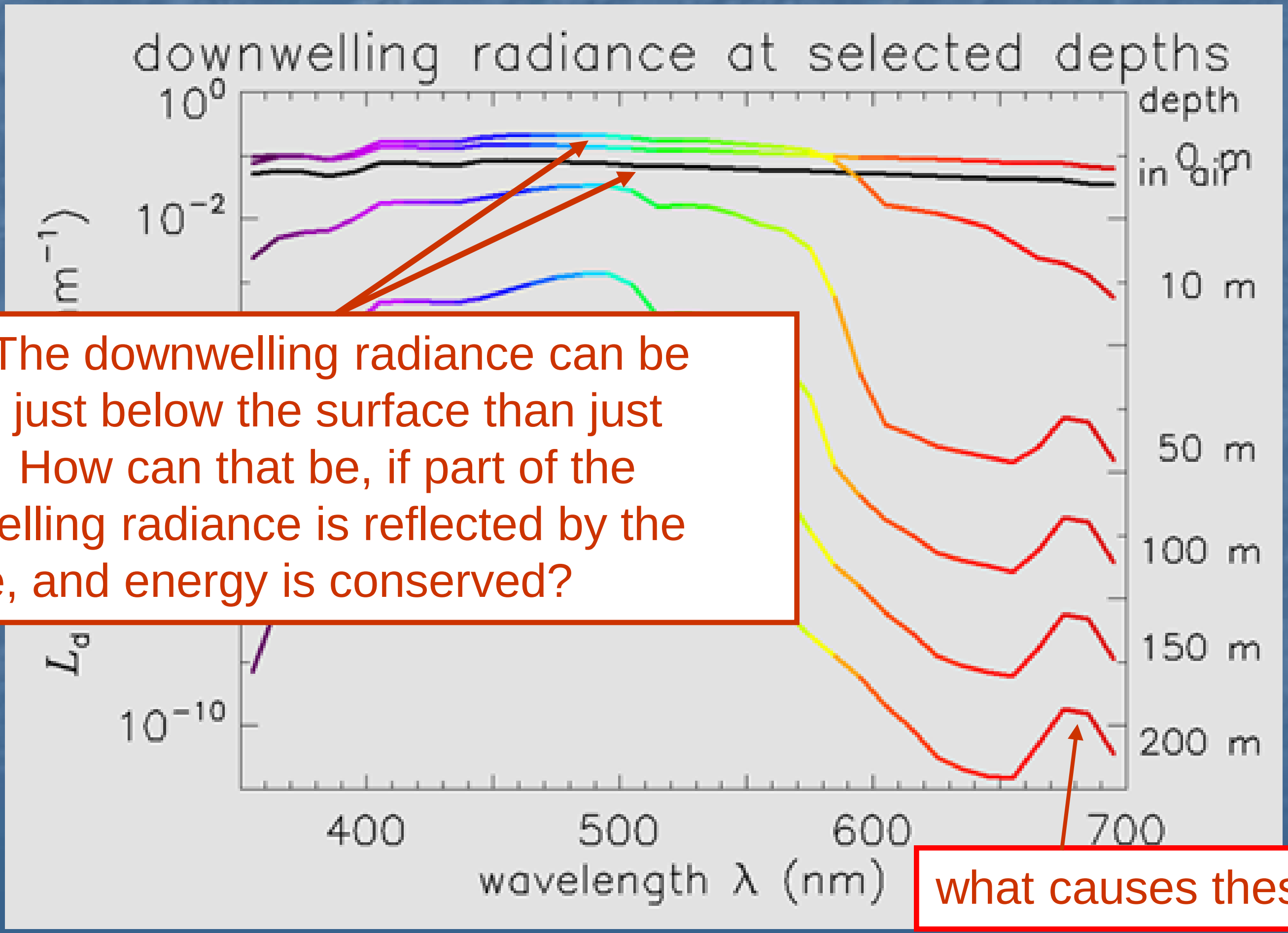
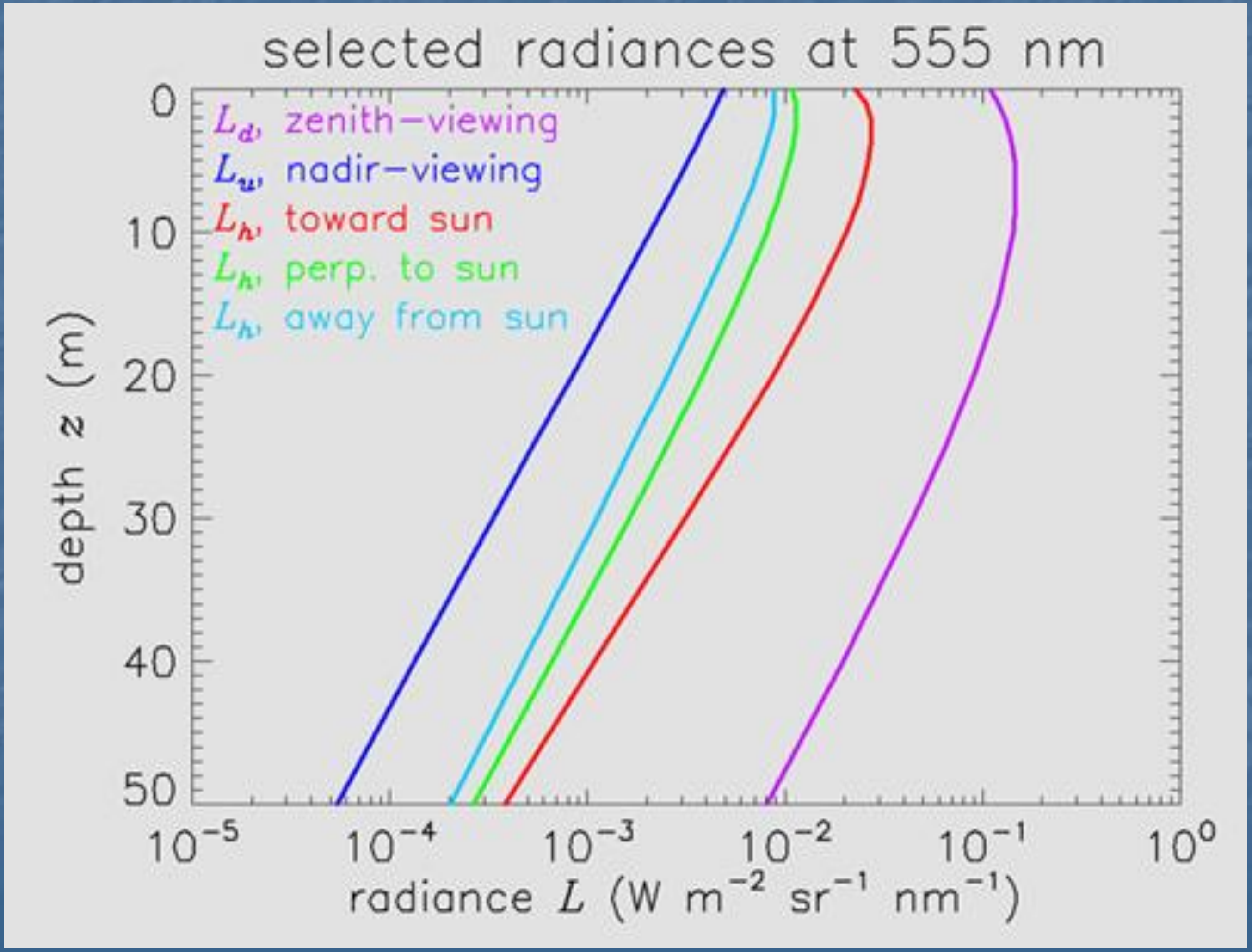


Note: The downwelling radiance can be greater just below the surface than just above. How can that be, if part of the downwelling radiance is reflected by the surface, and energy is conserved?

what causes these bumps?

Example plot: Radiance $L(z, \theta, \phi, \lambda)$ as a function of z and selected directions for one wavelength, λ = 555 nm.



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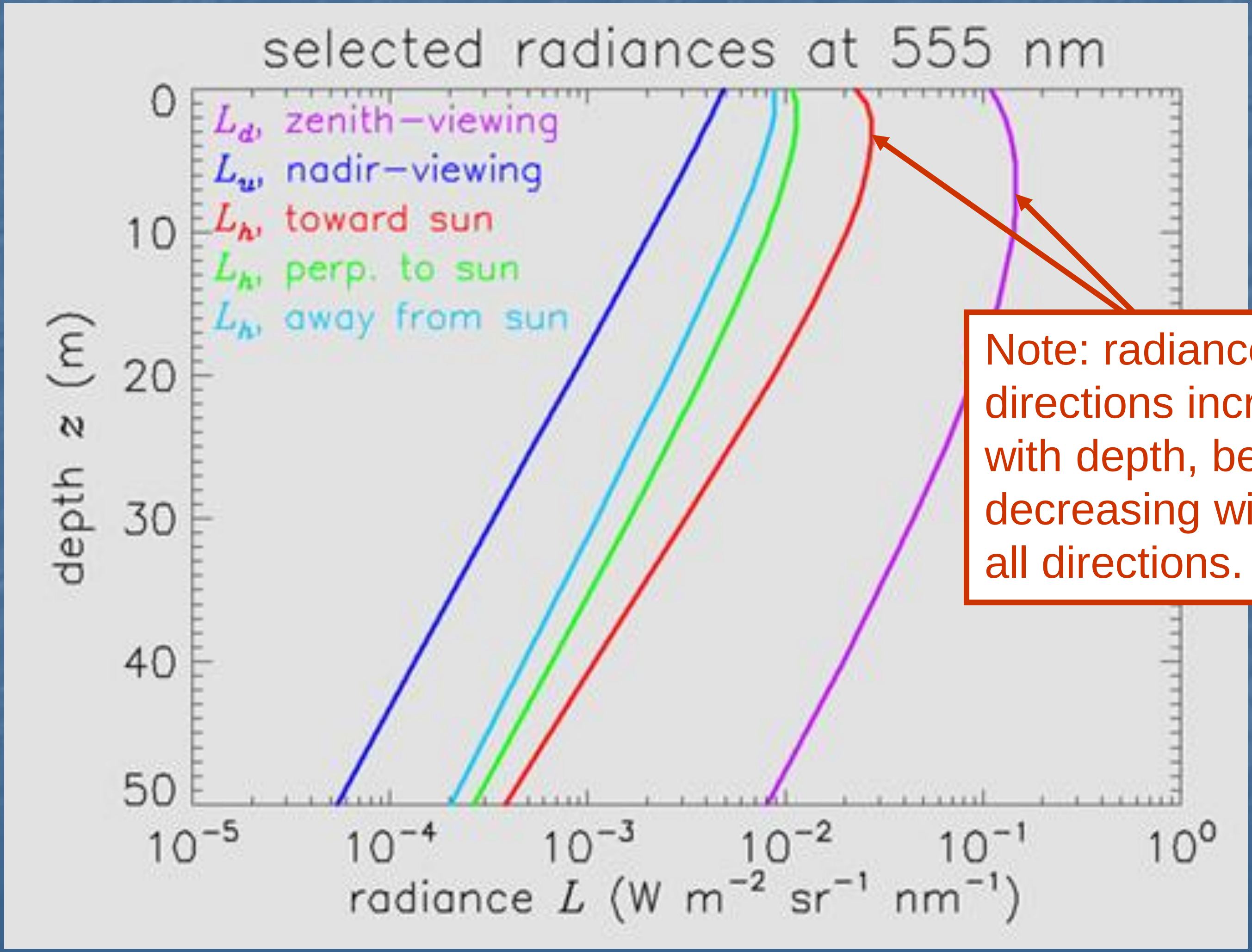
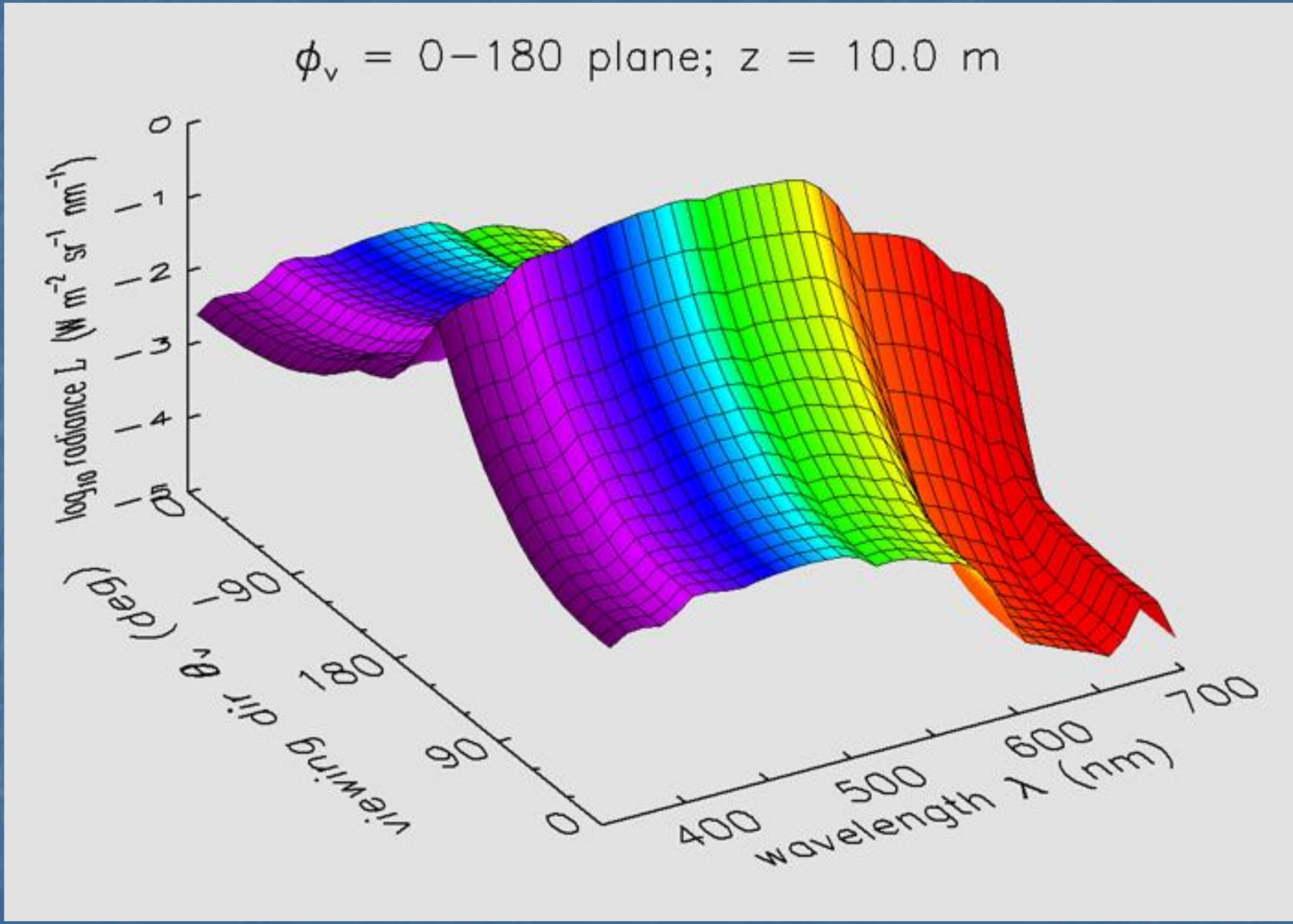


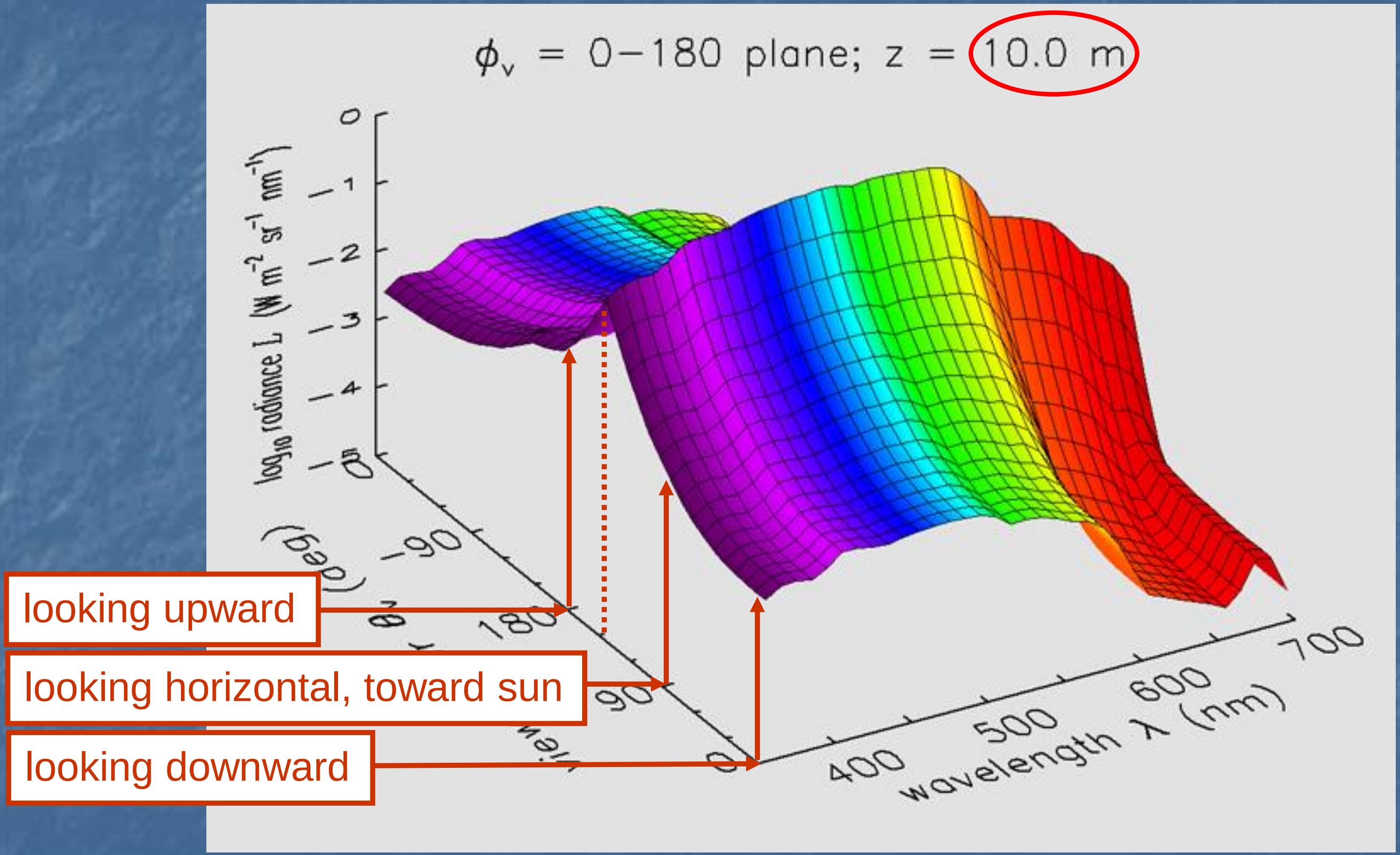
Note: radiance in some directions increases with depth, before decreasing with depth in all directions. Why?

Example plot: Radiance $L(z, \theta, \phi, \lambda)$ as a function of polar angle θ and wavelength λ, for depth z = 10 m and ϕ in the plane of the sun



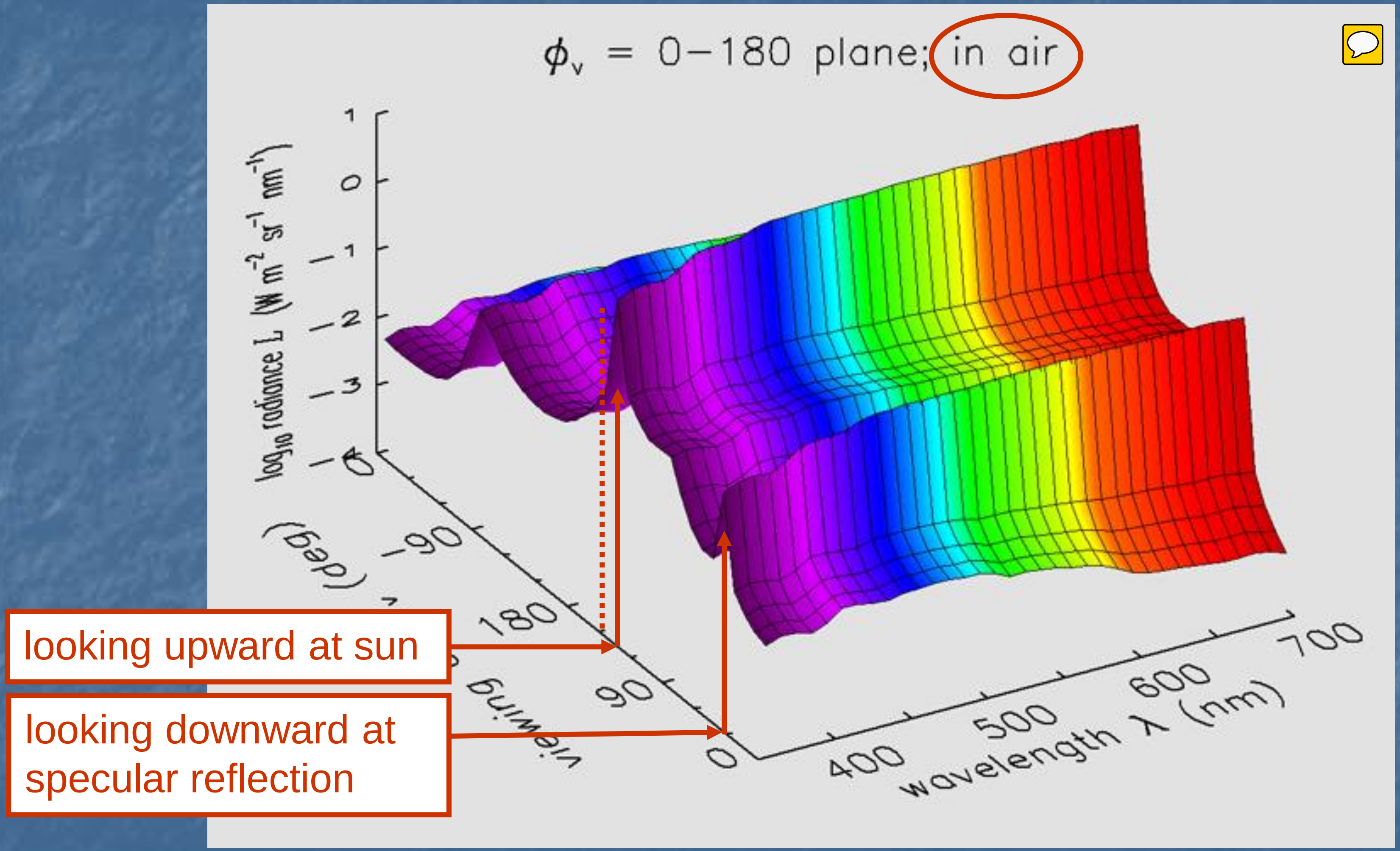
Note: $+z$ is downward, so θ = 0 is light heading straight down, viewed by looking straight up in the θ_v = 180 deg direction.

Example plot: Radiance $L(z, \theta, \phi, \lambda)$ as a function of polar angle θ and wavelength λ, for depth z = 10 m and ϕ in the plane of the sun



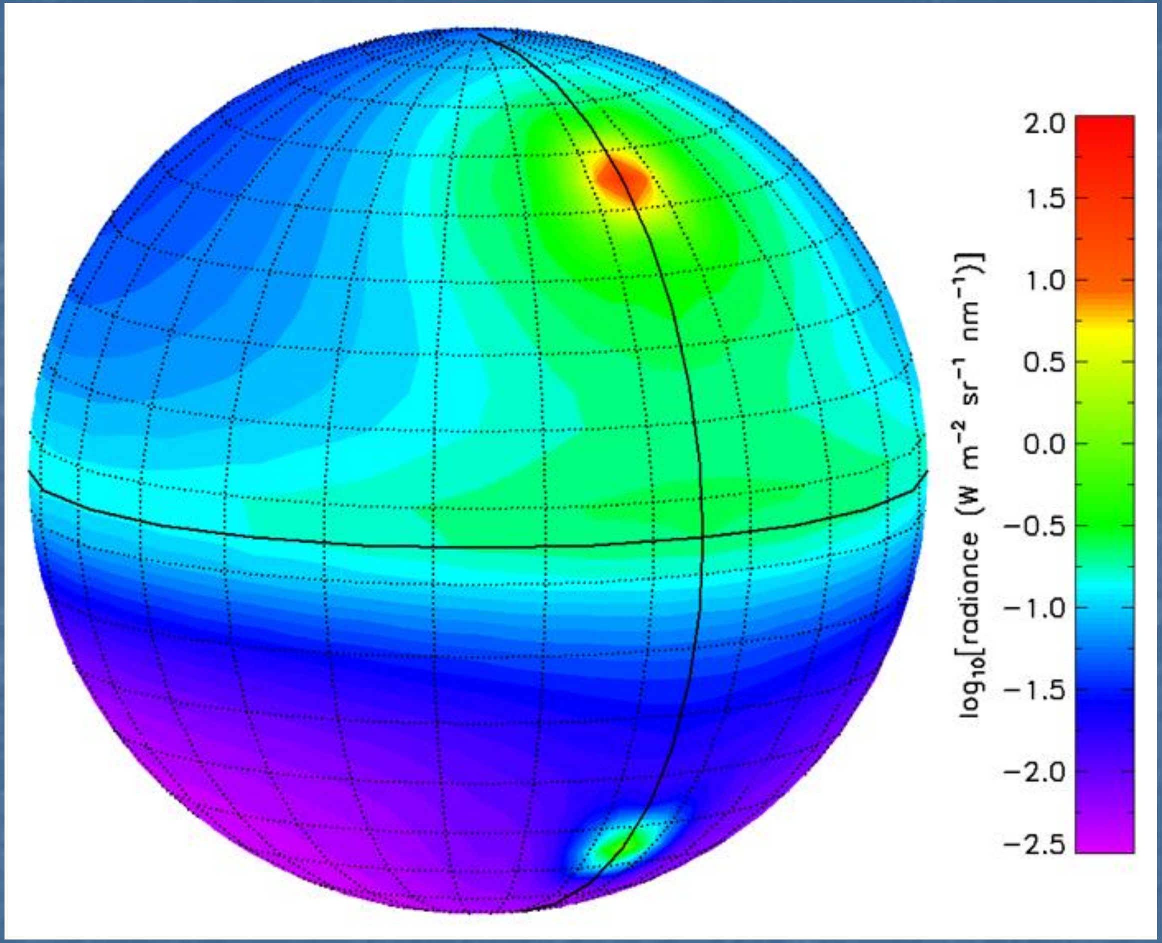
Note: $+z$ is downward, so $\theta = 0$ is light heading straight down, viewed by looking straight up in the θ_v = 180 deg direction.

Example plot: Radiance $L(z, \theta, \phi, \lambda)$ as a function of polar angle θ and wavelength λ, just above the sea surface and ϕ in the plane of the sun



Note: $+z$ is downward, so $\theta = 0$ is light heading straight down, viewed by looking straight up in the θ_v = 180 deg direction.

Example plot: Radiance $L(z, \theta, \phi, \lambda)$ just above the sea surface as a function of θ and ϕ for λ = 555 nm.



See www.oceanopticsbook.info/view/light_and_radiometry/visualizing_radiances for more discussion of these plots.

I don't understand this

Spectral Plane Irradiance

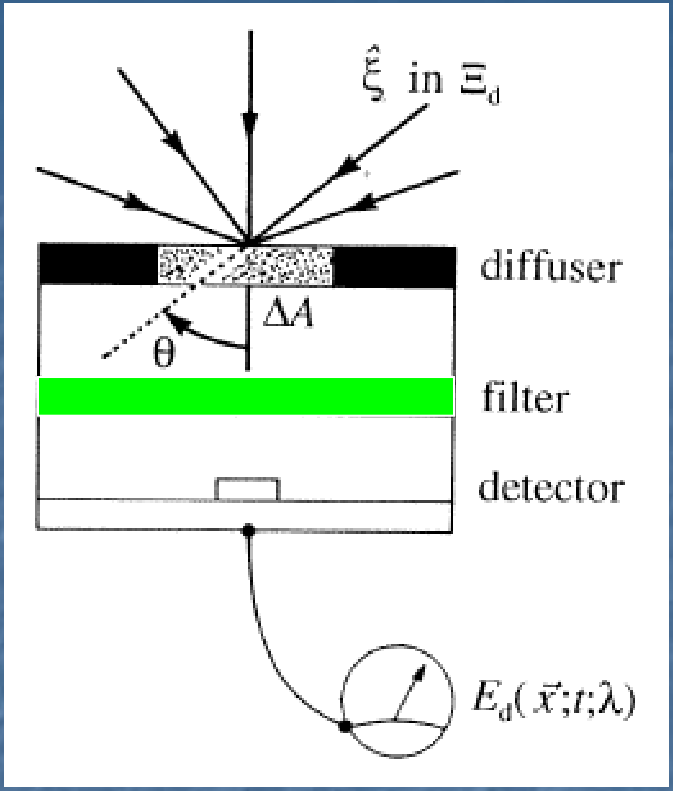
The most commonly measured radiometric variable

The collector *surface* is equally sensitive to light from any direction.

However, the effective (projected) area of the detector as “seen” by light in direction θ is ΔA cos(θ).

So must weight the radiance by cos(θ) when computed from *L*

this cosine correction accounts for the angle the light is coming in at

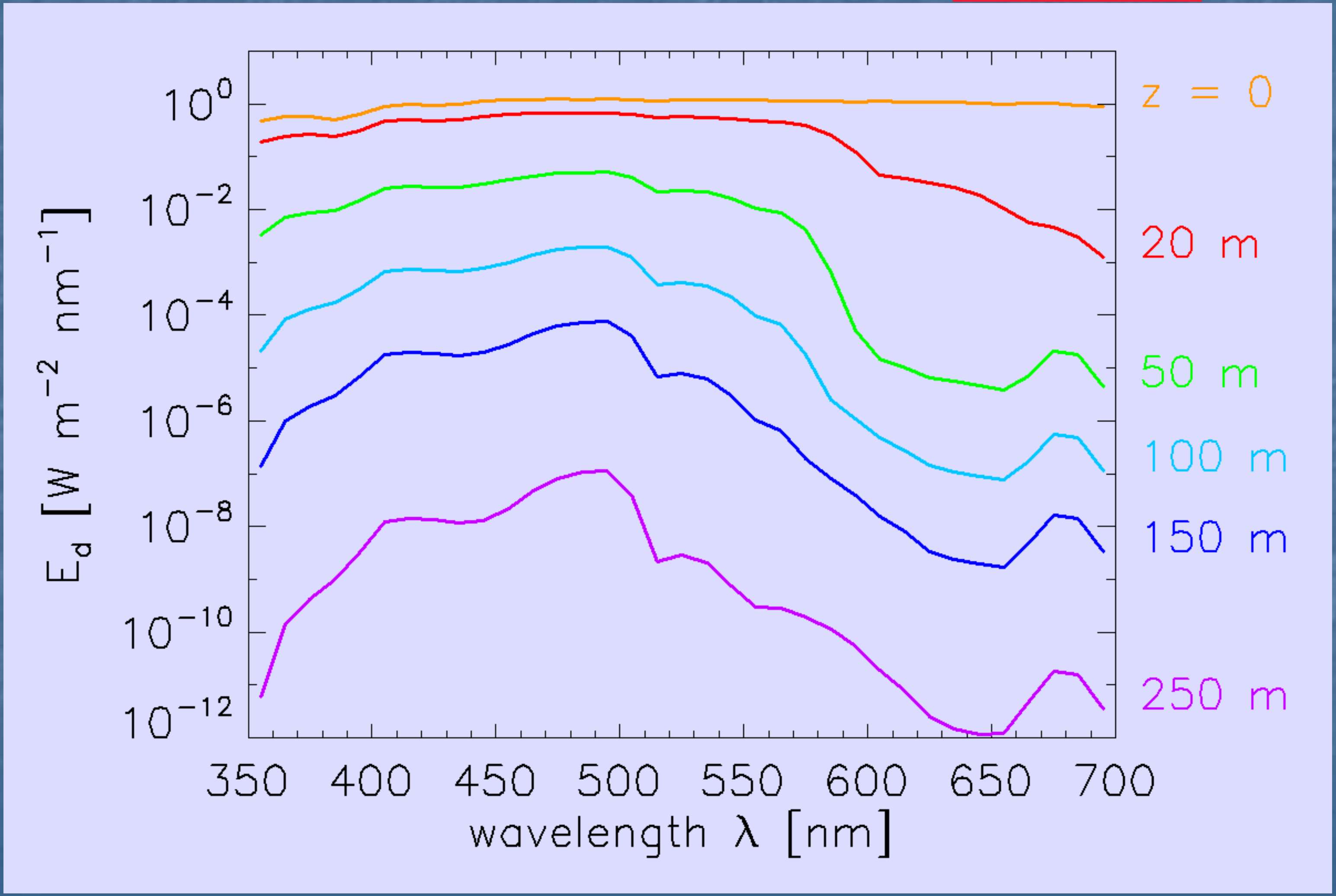


$$E_d(\vec{x}, t, \lambda) \equiv \frac{\Delta Q}{\Delta t\, \Delta A\, \Delta \lambda} \quad (\mathrm{W\ m^{-2}\ nm^{-1}})$$

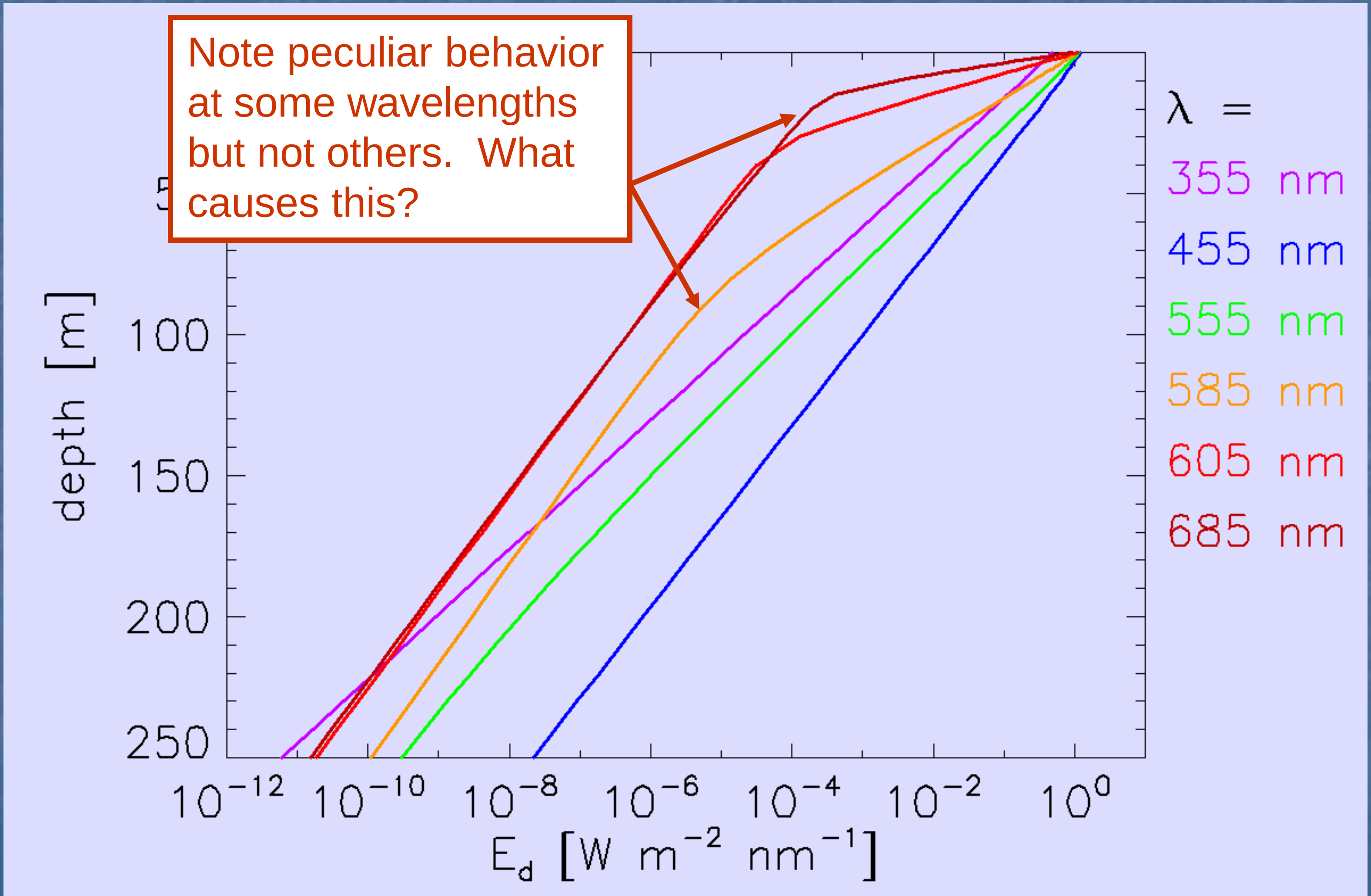
$$E_d(\vec{x}, t, \lambda) = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi/2} L(\vec{x}, t, \theta, \phi, \lambda) |\cos\theta| \sin\theta d\theta\, d\phi$$

Example plot: E_d as a function of wavelength for selected depths

ED - spectral plane irradiance

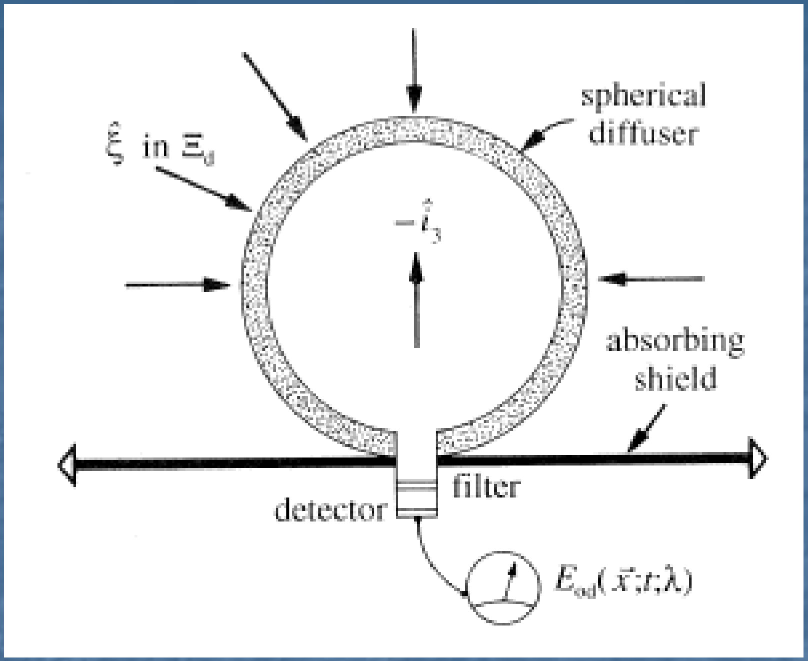


Example plot: E_d as a function of depth for selected wavelengths



Spectral Scalar Irradiance

The radiometric variable that is most relevant to photosynthesis and water heating because those processes are independent of the direction the light is traveling



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

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

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

The detector has the same effective area for radiance in any downward direction, so no cos(θ) factor on *L*

Downwelling scalar irradiance

Spectral Vector Irradiance

can be related to absorption by Gershun's law (derived later):

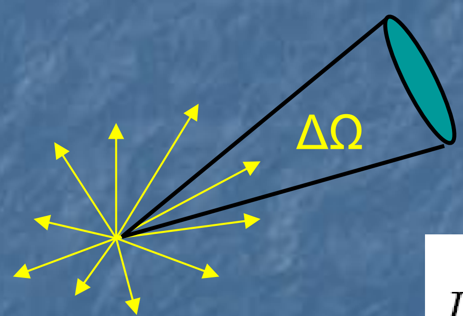
$a = -(1/E_o)\, d(E_d - E_u)/dz$

$E_z = E_{net} = E_d - E_u$ is the *net downward irradiance*

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

Spectral Intensity

useful for describing *point* light sources



$$
I(\vec{x}, t, \hat{\xi}, \lambda) \; = \; \frac{\Delta Q}{\Delta t \, \Delta\Omega \, \Delta\lambda} \quad (\mathrm{W\ sr^{-1}\ nm^{-1}})
$$

Photosynthetically Available Radiation (PAR)

Historically used in simple models for phytoplankton growth

More sophisticated ecosystem models today use the spectra scalar irradiance $E_o(\lambda)$ because different phytoplankton pigments absorb light differently at different wavelengths.

RADIOMETRY uses ENERGY units

PHOTOSYNTHESIS depends on the NUMBER on photons absorbed. The convenient measure of how many photons are available for photosynthesis is

$$PAR \equiv \int_{400\,\mathrm{nm}}^{700\,\mathrm{nm}} E_o(\lambda)\,\frac{\lambda}{hc}\,d\lambda$$
$$(\mathrm{photons\ s^{-1}\ m^{-2}})$$

PAR is often expressed as Einsteins s^{-1} m^{-2}

1 Einstein = 1 mole of photons
= 6.023×10^{23} photons

Warnings on Terminology

In atmospheric optics, spectral radiance is called “specific intensity” and irradiance is called “flux”. Some people call irradiance “flux” and some call irradiance “flux density”. Other fields (medical optics, astrophysics, etc.) have their own terminiolgy and notation. It is very confusing.

Spectral vs band-integrated radiance and irradiance:

hydrolight is spectral not band-integrated

Spectral downwelling plane irradiance $E_d(\lambda)$ is per unit wavelength interval, with units of W m^{-2} nm^{-1}

Band-integrated downwelling plane irradiance is the spectral irradiance integrated over some finite wavelength band, with units of W m^{-2}, e.g.,

$$E_d = \int_{410}^{420} E_d(\lambda)\, d\lambda$$

It is often not easy to figure out exactly what is being measured or discussed in a paper. Units and magnitudes matter! I reject papers that are not clear or have inconsistent or wrong units.

Sea Kayaking in Panama, Feb 2012