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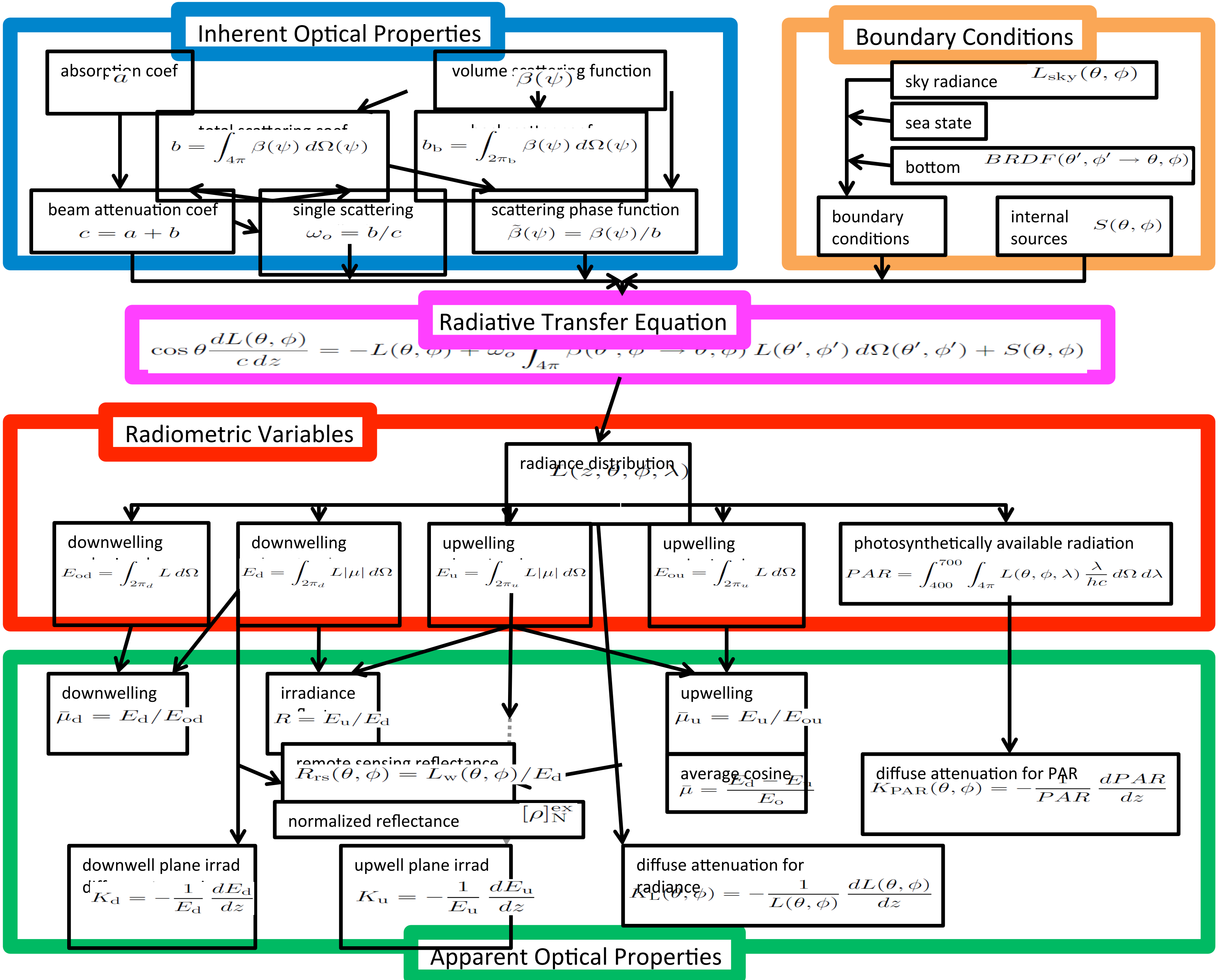
Radiometric quantities and their measurement

Ken Voss, Ocean Optics Class, Darling Center, Maine
Summer, 2015



Inherent Optical Properties

absorption coef a

volume scattering function $\beta(\psi)$

total scattering coef $b = \int_{4\pi} \beta(\psi)\, d\Omega(\psi)$

backscattering coef $b_{\rm b} = \int_{2\pi_{\rm b}} \beta(\psi)\, d\Omega(\psi)$

beam attenuation coef $c = a + b$

single scattering $\omega_o = b/c$

scattering phase function $\tilde\beta(\psi) = \beta(\psi)/b$

Boundary Conditions

sky radiance $L_{\rm sky}(\theta,\phi)$

sea state

bottom $BRDF(\theta',\phi' \rightarrow \theta,\phi)$

boundary conditions

internal sources $S(\theta,\phi)$

Radiative Transfer Equation

$$\cos\theta \frac{dL(\theta,\phi)}{c\,dz} = -L(\theta,\phi) + \omega_o \int_{4\pi} \tilde\beta(\theta',\phi' \rightarrow \theta,\phi)\, L(\theta',\phi')\, d\Omega(\theta',\phi') + S(\theta,\phi)$$

Radiometric Variables

radiance distribution $L(z,\theta,\phi,\lambda)$

downwelling $E_{\rm od} = \int_{2\pi_d} L\, d\Omega$

downwelling $E_{\rm d} = \int_{2\pi_d} L|\mu|\, d\Omega$

upwelling $E_{\rm u} = \int_{2\pi_u} L|\mu|\, d\Omega$

upwelling $E_{\rm ou} = \int_{2\pi_u} L\, d\Omega$

photosynthetically available radiation $PAR = \int_{400}^{700} \int_{4\pi} L(\theta,\phi,\lambda)\, \frac{\lambda}{hc}\, d\Omega\, d\lambda$

Apparent Optical Properties

downwelling $\bar\mu_{\rm d} = E_{\rm d}/E_{\rm od}$

irradiance $R = E_{\rm u}/E_{\rm d}$

remote sensing reflectance $R_{\rm rs}(\theta,\phi) = L_{\rm w}(\theta,\phi)/E_{\rm d}$

normalized reflectance $[\rho]_{\rm N}^{\rm ex}$

upwelling $\bar\mu_{\rm u} = E_{\rm u}/E_{\rm ou}$

average cosine $\bar\mu = \frac{E_{\rm d} - E_{\rm u}}{E_{\rm o}}$

diffuse attenuation for PAR $K_{\rm PAR}(\theta,\phi) = -\frac{1}{PAR}\frac{dPAR}{dz}$

downwell plane irrad diff $K_{\rm d} = -\frac{1}{E_{\rm d}}\frac{dE_{\rm d}}{dz}$

upwell plane irrad $K_{\rm u} = -\frac{1}{E_{\rm u}}\frac{dE_{\rm u}}{dz}$

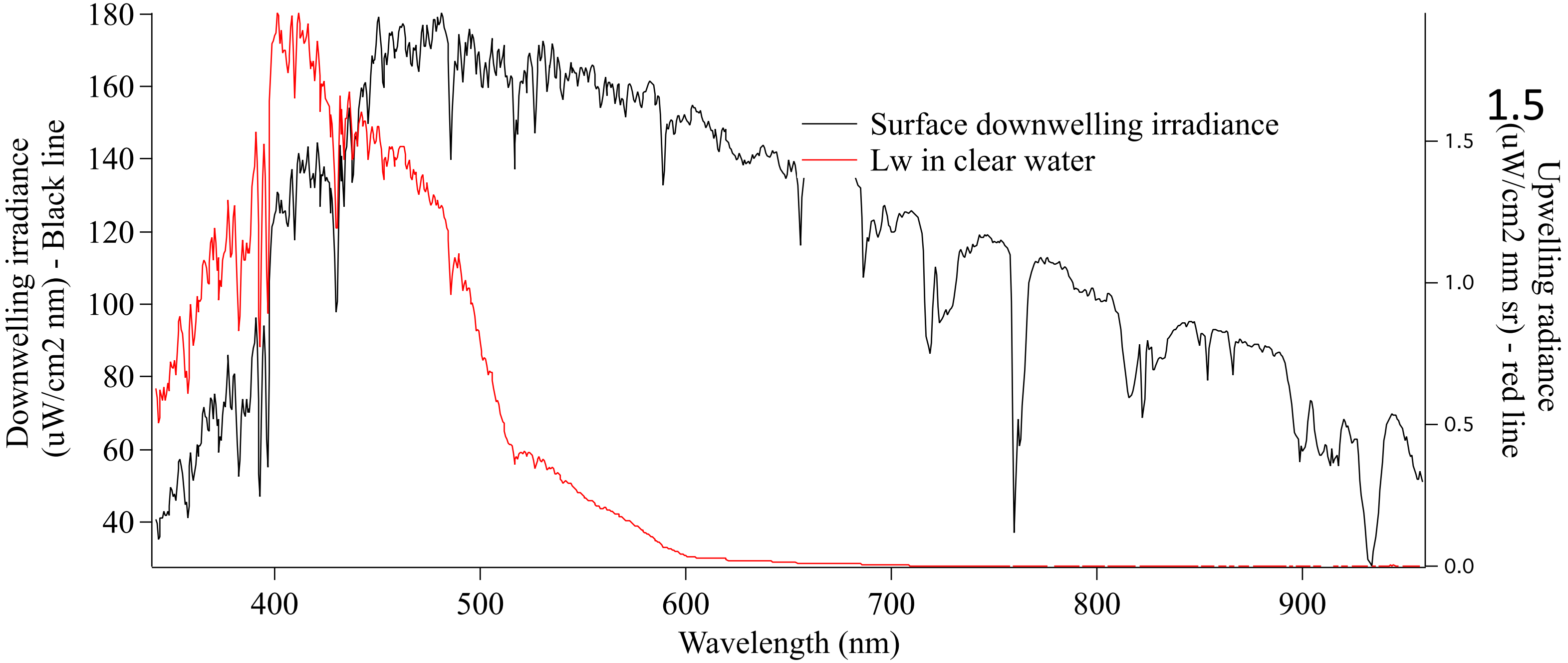
diffuse attenuation for radiance $K_{\rm L}(\theta,\phi) = -\frac{1}{L(\theta,\phi)}\frac{dL(\theta,\phi)}{dz}$

While radiance is the fundamental property, for measurements, an irradiance detector is easier to understand, so I will build from irradiance to radiance.

Outline

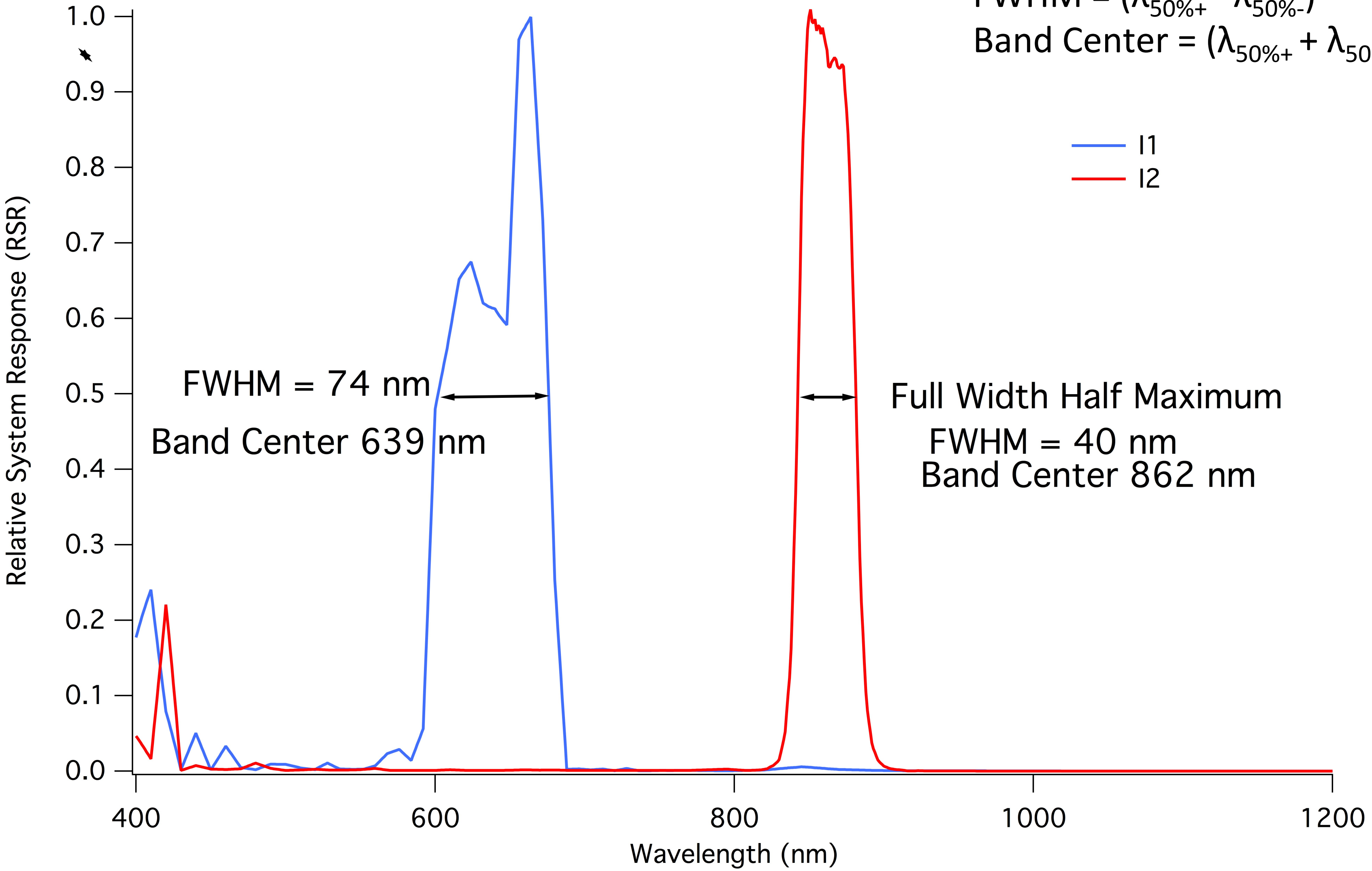
1) Spectral resolution of Detectors
2) Plane irradiance measurements
3) Scalar irradiance measurements
4) Radiance and Radiance Distribution measurements

What does the light field we are trying to measure look like?



NOTE: Many spectral features in downwelling light field. Also in upwelling light field large dynamic range across the visible spectrum (this is clear water).

Detectors, Define wavelength of filters or bands



FWHM = ($\lambda_{50\%+}$ - $\lambda_{50\%-}$)

Band Center = ($\lambda_{50\%+}$ + $\lambda_{50\%-}$)/2

FWHM = 74 nm

Band Center 639 nm

Full Width Half Maximum

FWHM = 40 nm

Band Center 862 nm

Two (maybe three) classes of detectors/ instruments if defined by spectral resolution

1) PAR (or other broadband for example UV-A, photopic) sensor

2) Multi-channel instruments..collection of individual bands (say 10 bands, 10nm wide)

3) Hyperspectral instruments..measurements every few nm through visible spectrum.

PAR or other broadband (UVA, UVB, etc.)

PAR:

1) photosynthetically available radiation, try to count photons in the range from 400-700 nm, equal weight to each photon.

2) Silicon detector through photoelectric effect, should sort of do this:
   Each photon generates one photo-electron (perfect quantum efficiency)

3) Problems due to scattering in detector, reabsorption of photo-electrons,
   spectrally dependent reflection…break down this relationship which then causes calibration to be difficult (different colored sources). PAR physically not a "nice" measurement, but easy.

Another broadband measurement is photopic which matches the eye response….centered at 550 nm, about 100 nm wide.

These instruments are very hard to calibrate accurately! Often get very different numbers for same energy of light depending on spectral composition of light field being measured (note this is often intentional).

Narrow band, multi channel instruments

1) Typically channels have spectral bands 10nm wide, used because:

    a) Most ocean optics parameters do not have sharp features.

    b) May try to match some other spectral shape (SeaWiFS bands for example).

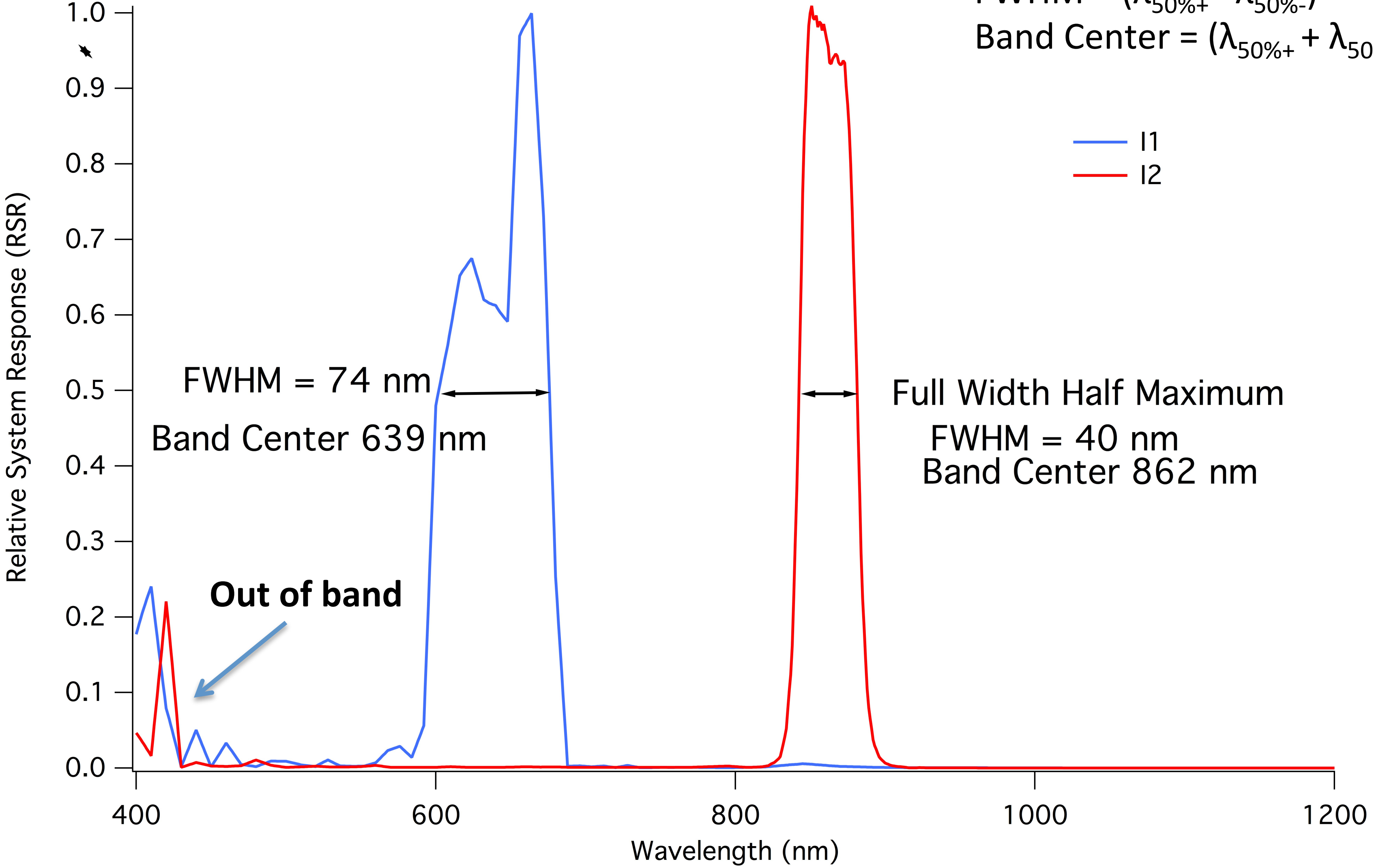
    c) when you look at reflectance, sharp atmospheric/solar features cancel out to some extent.

2) Spectral channels defined by filters, typically interference filters.

    a) Filters have some spectral shape, defined by band center and the width.

    b) Have to be careful of out-of-band effects (when looking at different "color" sources)

Detectors



$\text{FWHM} = (\lambda_{50\%+} - \lambda_{50\%-})$

$\text{Band Center} = (\lambda_{50\%+} + \lambda_{50\%-})/2$

FWHM = 74 nm

Band Center 639 nm

Full Width Half Maximum

FWHM = 40 nm

Band Center 862 nm

Out of band

Hyperspectral Detectors

1) “continuous spectrum”, really channels every 1-10nm.

2) Typically grating or prism dispersive elements.

3) Can build integrated channels, match satellite sensor channels, etc. with this extra spectral resolution

3) Be careful of various effects
    a) similar to out-of-band effects, have scattered light effects
    b) resolution limits (entrance slitwidth, dispersion, imaging ability)
        just because there is a detector every 1 nm, doesn’t mean it tells you anything. Example: Hyperpro reports every 2-3 nm, BW 10 nm.

Pixels

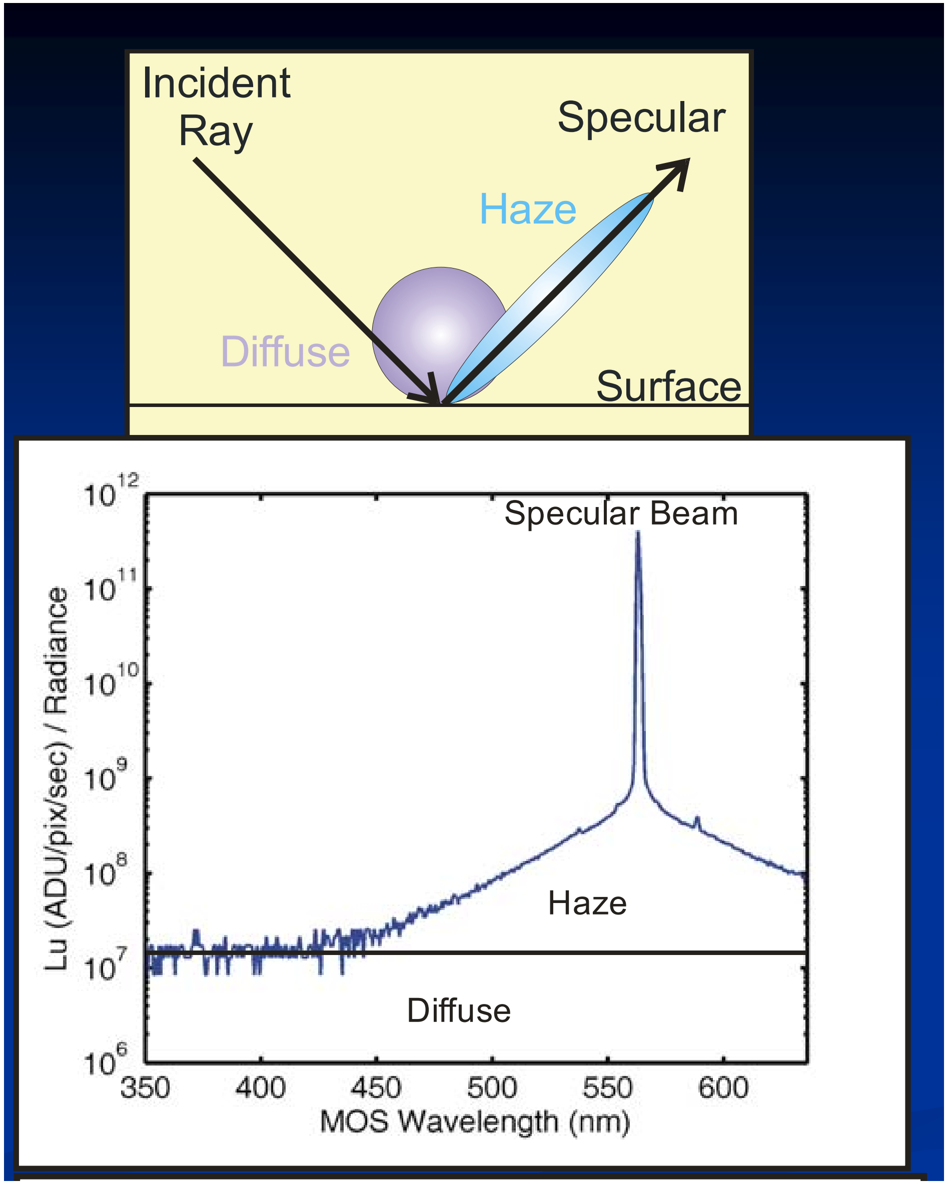
Dispersion: cm/nm

Light

Slit

Dispersive elements

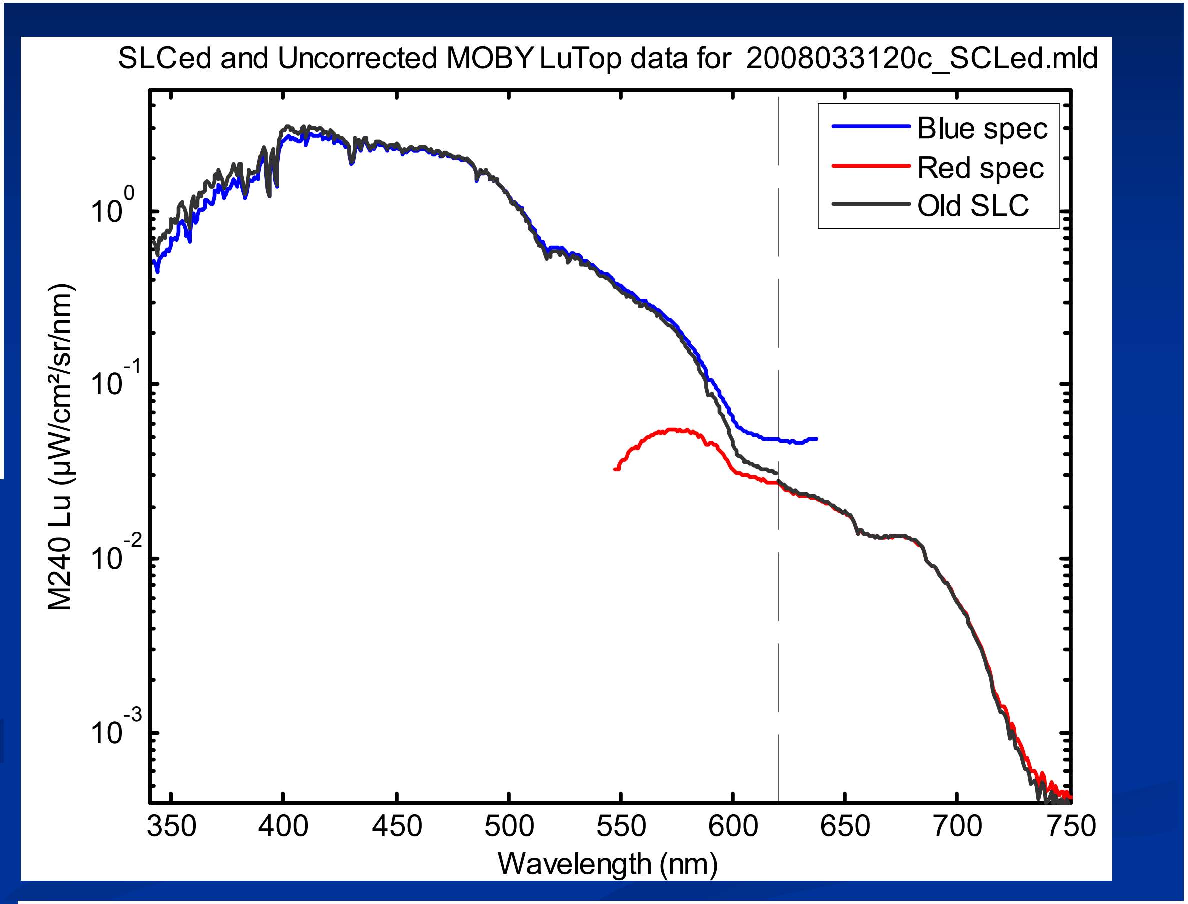
Detectors

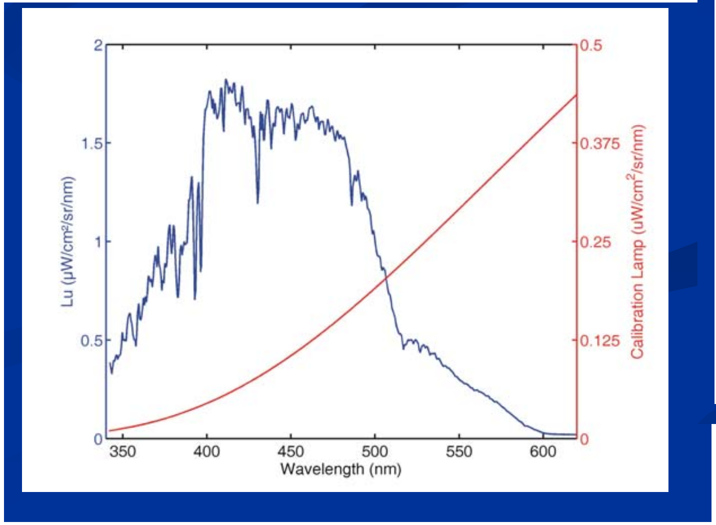


From Stephanie Flora Moby project,

Current MOBY system

Detectors





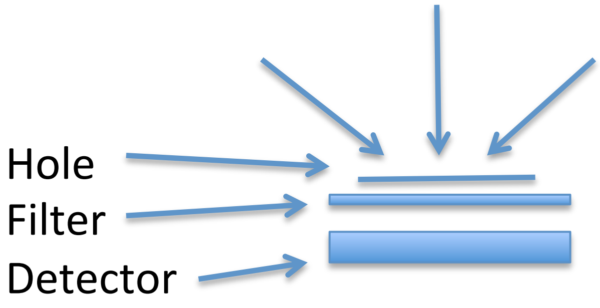
From Stephanie Flora, MOBY project

- Those are the three classes of instruments defined by their spectral characteristics…now look at the different instruments as defined by the parameter they measure.

Definition of plane Irradiance : $E_d \equiv \dfrac{\Delta Q}{\Delta t \Delta A \Delta \lambda} \left[\dfrac{\mathrm{W}}{\mathrm{m}^2\ \mathrm{nm}} \right]$

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

Perfect detector would be a hole, with a detector right behind that collects all the light which passed through the hole:



Problems:

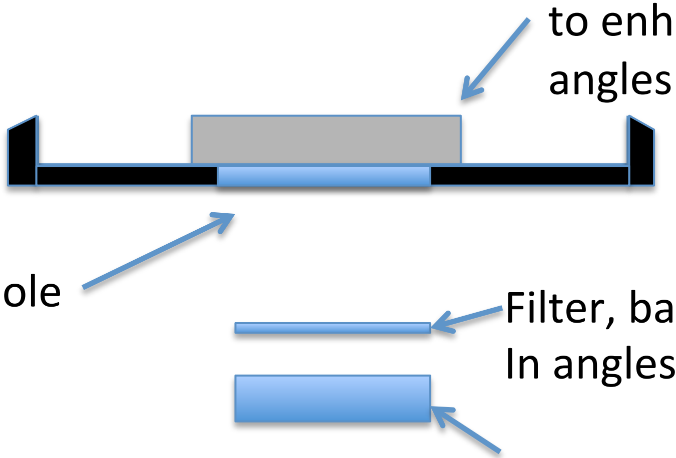
1) Filter, typically interference filter, has an angle dependence on spectral transmission

2) Detectors also have angular dependence on their response

3) Invariably need some sort of window in front of hole, which then has a reflection/transmission coefficient which varies with incident angle.

Typically because of 2-3 decrease with increasing incidence angle.

Real Irradiance detectors try to enhance response to light at large incidence angles. Typical design shown below: IMPORTANT…AIR SENSORS NOT THE SAME AS IN-WATER SENSORS!



Plastic Diffuser material, raised on edges to enhance area exposed to large incidence angles.

hole

Filter, back from diffuser, to reduce variation In angles

Detector

Irradiance

Note: this is in air, not water, but is typical. Collection efficiency good at small incidence angles and gets worse at large angles

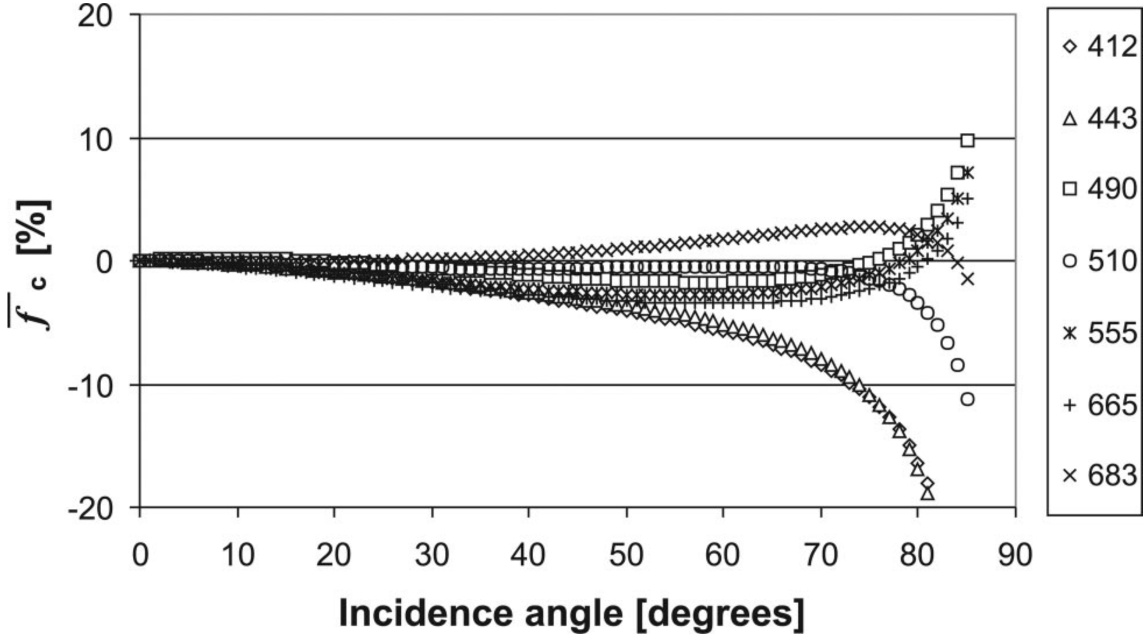


Fig. 3. Average cosine errors $\bar{f}_c(\theta, \lambda)$ determined at various center wavelengths.

Zibordi and Bulgarelli, AO, pg:5529-5538 (2007)

Irradiance

Downwelling Radiance Distribution

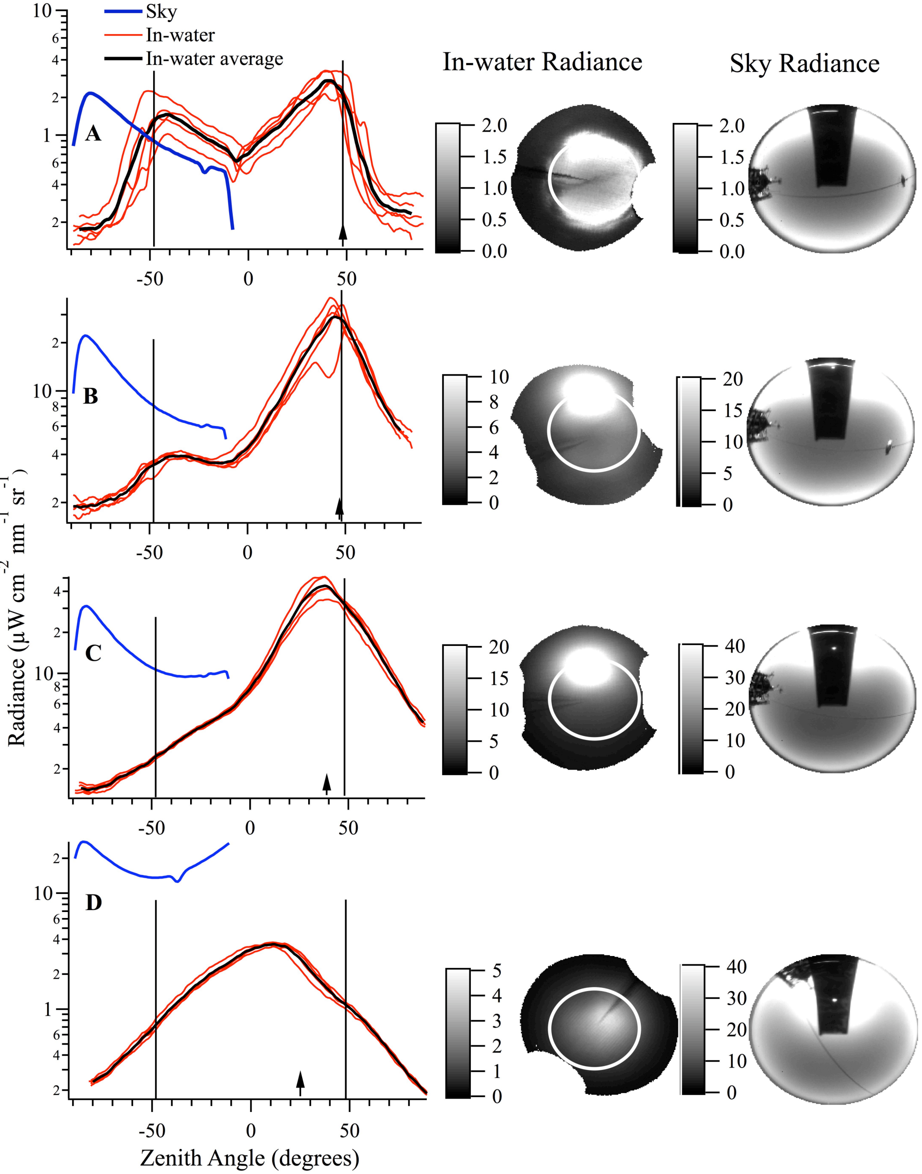
Look at black line. In downwelling light field, Radiance distribution is peaked and falls off towards large angles…cosine response not as big a problem.

1m

5m

10m

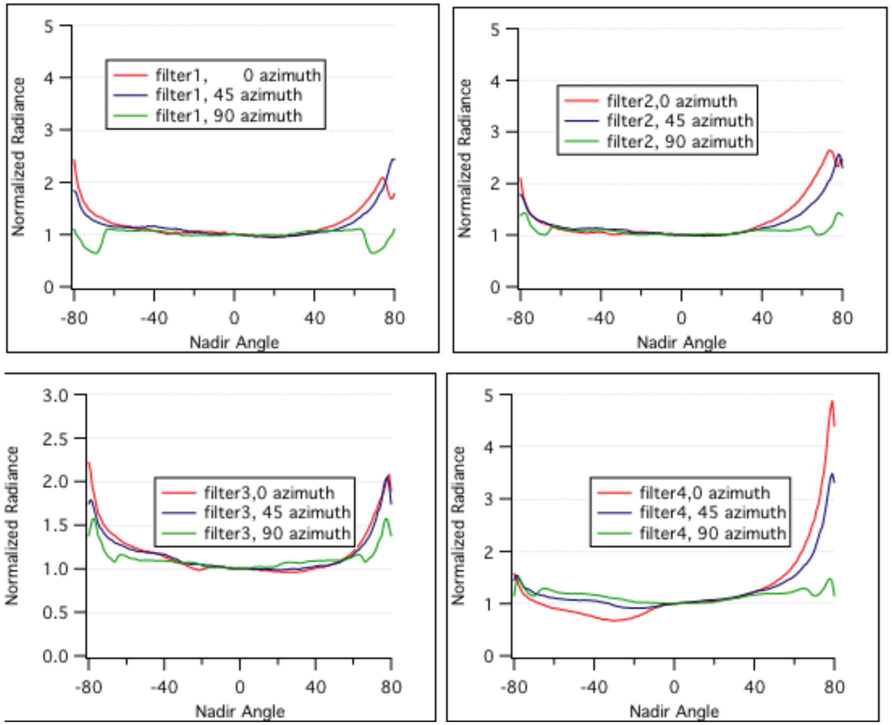
30m



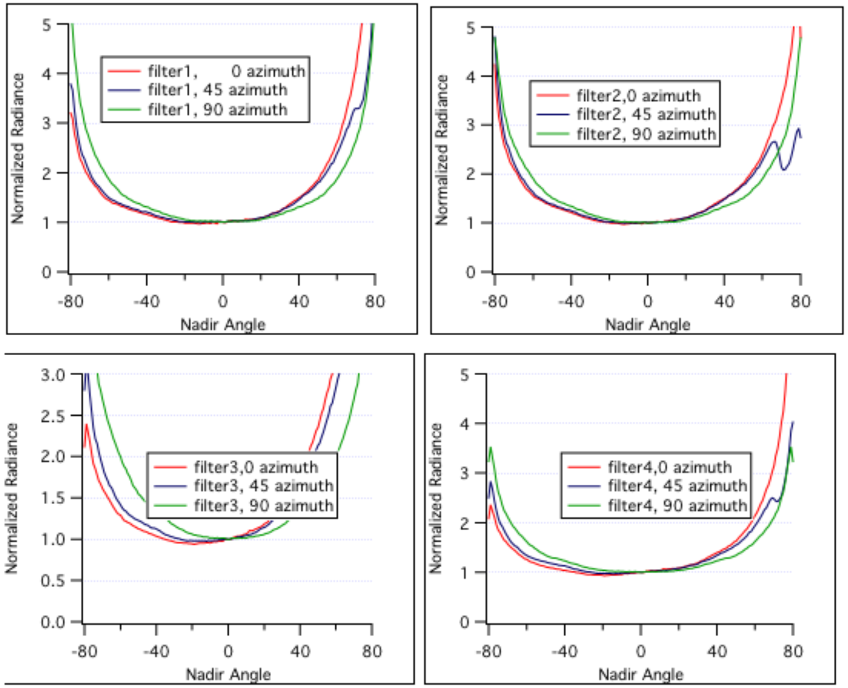
Upwelling Radiance distribution

All y axis 0-5 normalized radiance (except lower left in each set), all x axis -90-90 deg

Low Chl



High Chl

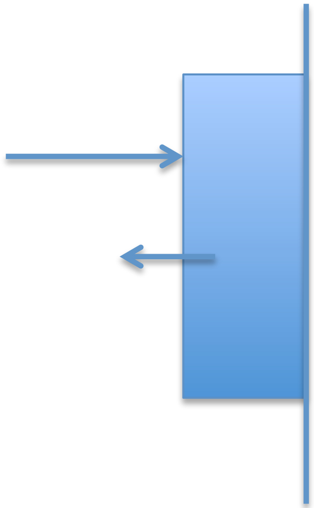


Error due to cosine collector much more significant, Radiance distribution goes higher on edges

Irradiance

Should mention one more factor: Immersion coefficient, 30-40% correction.

Cosine collector efficiency different when operating in air or water

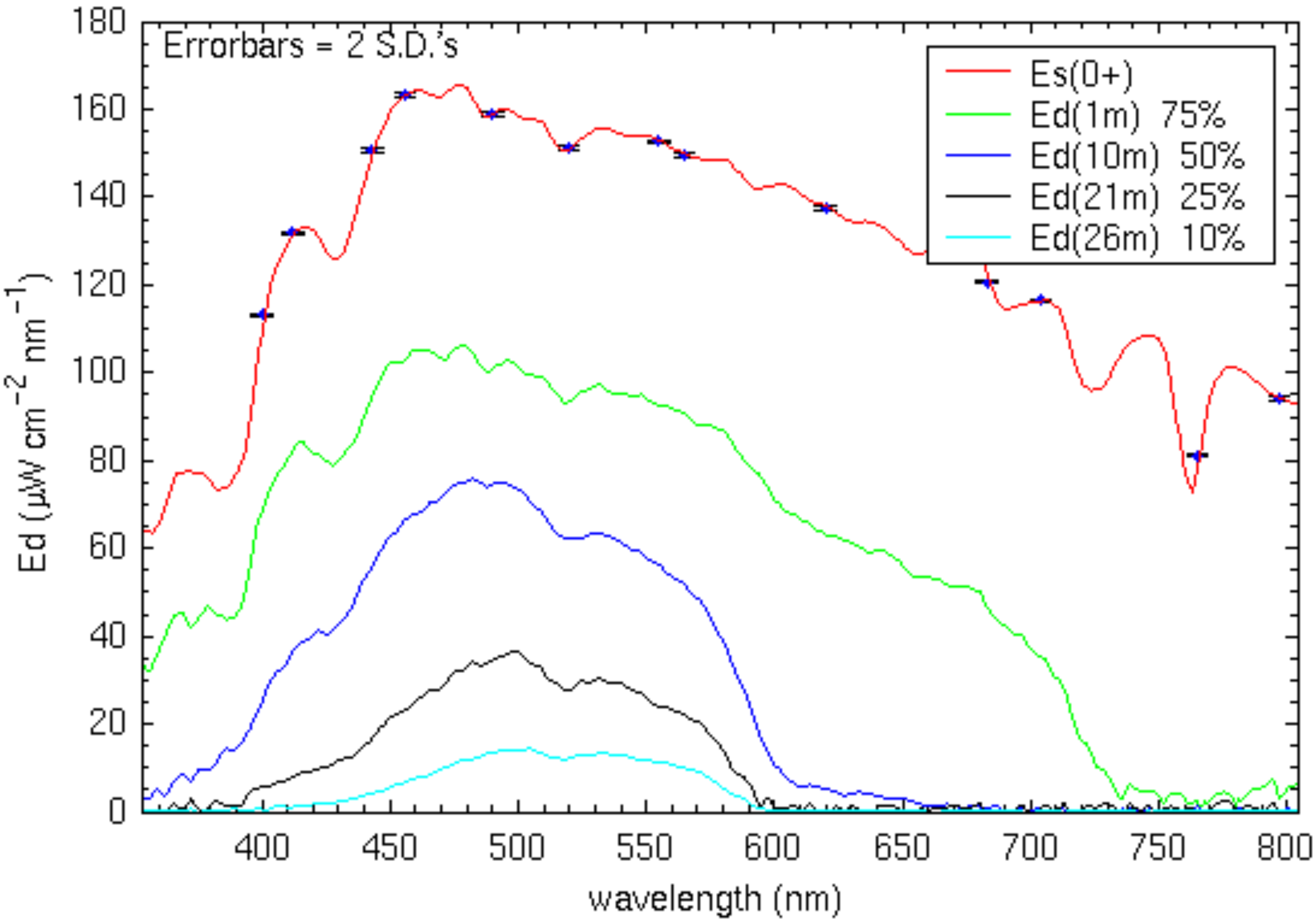


Outside medium
Air or water

Detector (in air, hopefully)

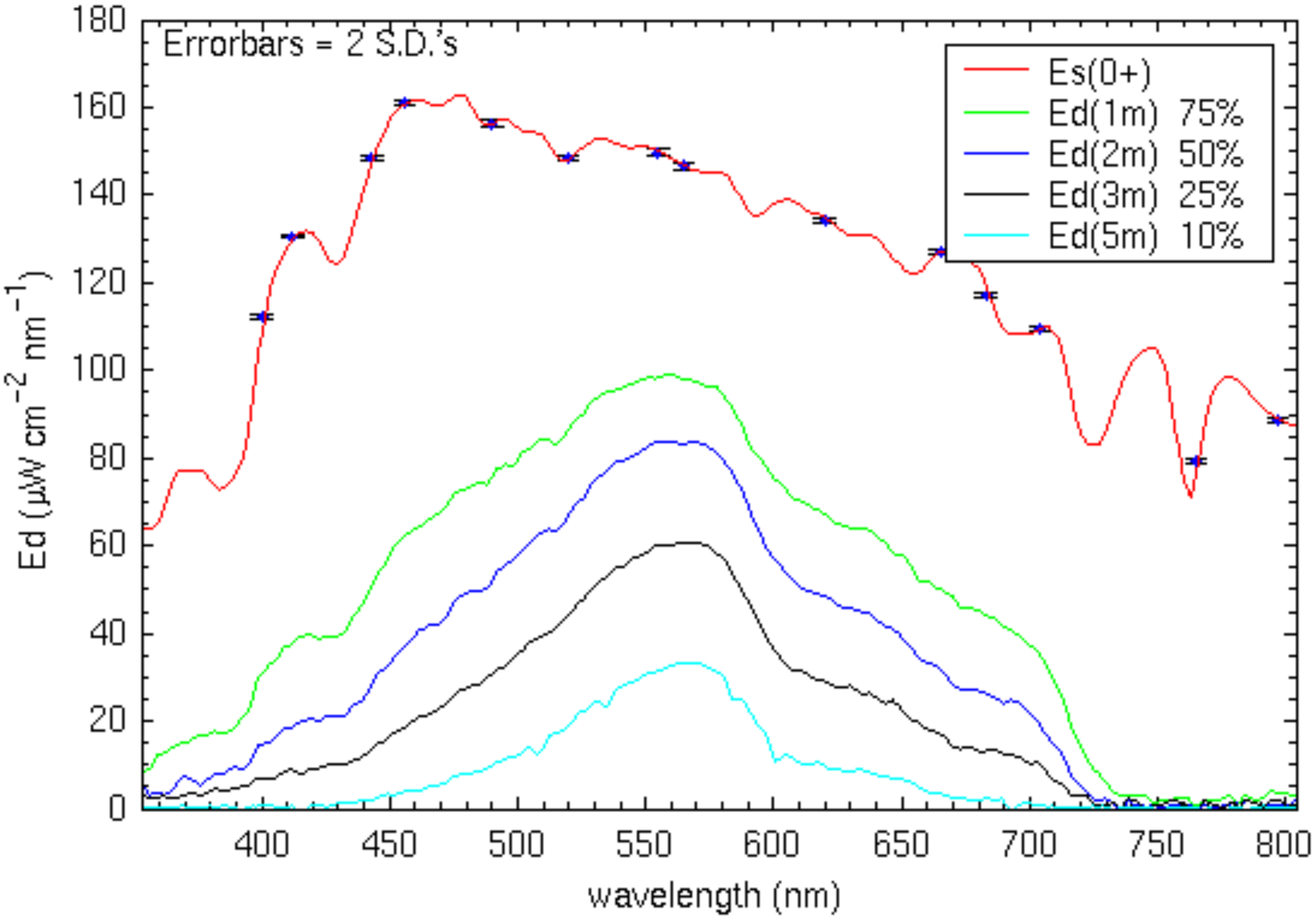
Just drew normal incidence, really large set of angles. When in air, larger index of refraction difference between medium and plastic, harder for light to escape. In water more light, after being diffused in detector, can escape....so collection efficiency is less. Immersion factor corrects for this. Is spectrally dependent, and collector design dependent (including plastic), so must be measured. Paper by Hooker and Zibordi 2005.

Irradiance



Blue water station (Data from Marlon Lewis, Satlantic)
Note…units 100 μW cm-2 nm-1 = W m-2 nm-1

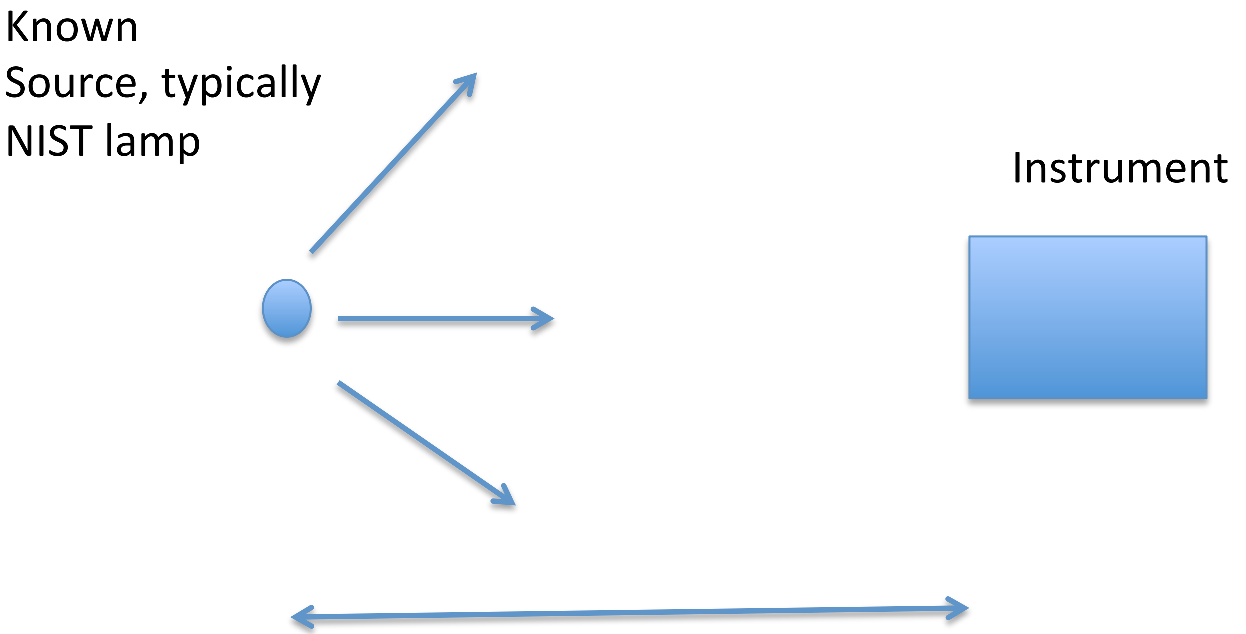
Irradiance



Green water station (Data from Marlon Lewis, Satlantic). Notice difference in depths in this plot and last one.

Irradiance

Greatly simplified, but to calibrate this sensor…set up in lab with known source of irradiance:



Specified distance (typically 50 or 100 cm), note roughly $1/r^2$ dependence (ignoring many subtleties)

Scalar Irradiance

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

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

Want to collect all light coming to a single point, regardless of angle. Perfect collector would be as shown earlier, with the limit of the radius going to zero:

(from Curt's Book)

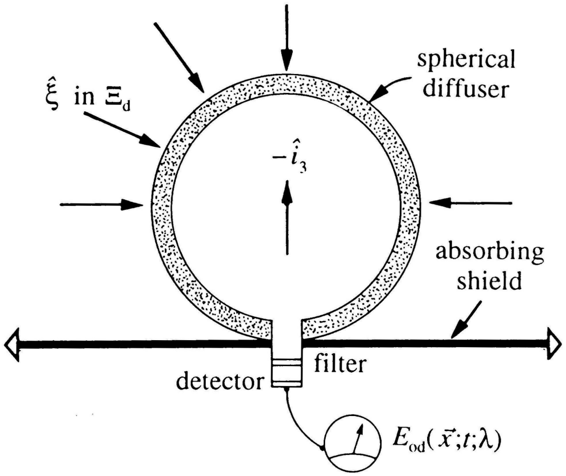


Fig. 1.7. Schematic design of an instrument for measuring spectral scalar irradiance.

Problems:

Would like to shield below the ball to be zero (to measure total), or infinity, to measure E_{od}. If you want total then how to handle horizon from a combination of E_{od} and E_{ou} in this case?

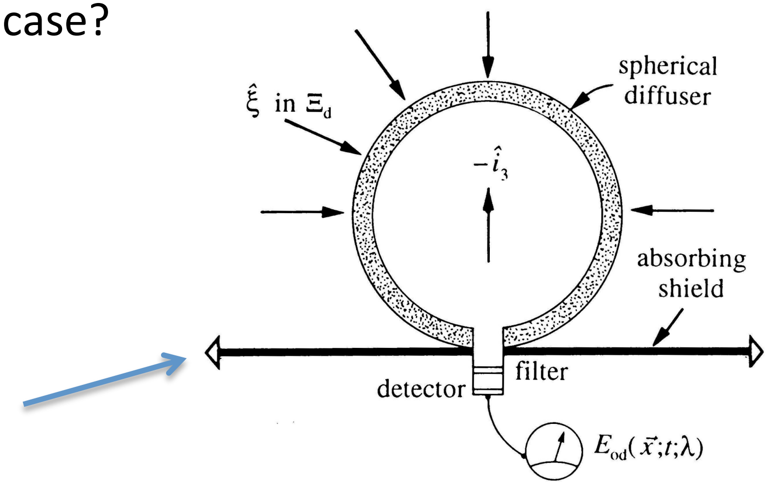


Fig. 1.7. Schematic design of an instrument for measuring spectral scalar irradiance.

Example numbers for scale.

Average cosine $\mu = E_d / E_{o=}$

Depth	$E_d(z)$	$E_{od}(z)$	$E_u(z)$	$E_{ou}(z)$	$\mu_d(z)$	$\mu_u(z)$
20.0 m	16.7	23.1	0.488	1.29	0.72	0.38
24.8m	9.34	13.0	0.330	0.852	0.72	0.39
29.9m	6.29	8.78	0.212	0.550	0.72	0.38
44.8m	1.73	2.31	0.0658	0.160	0.75	0.41
49.6	1.56	2.07	0.0512	0.129	0.75	0.40

E_d, E_{od}, E_u, E_{ou} all in units of $\mu W\ cm^{-2}\ nm^{-1}$

upwelling measurements at 505 nm
Downwelling measurements at 503 nm

Average cosine for downwelling points is 44 deg, while upwelling is 67 deg

Definition of Radiance:

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

As shown earlier, basic concept for radiometer is a Gershun tube:

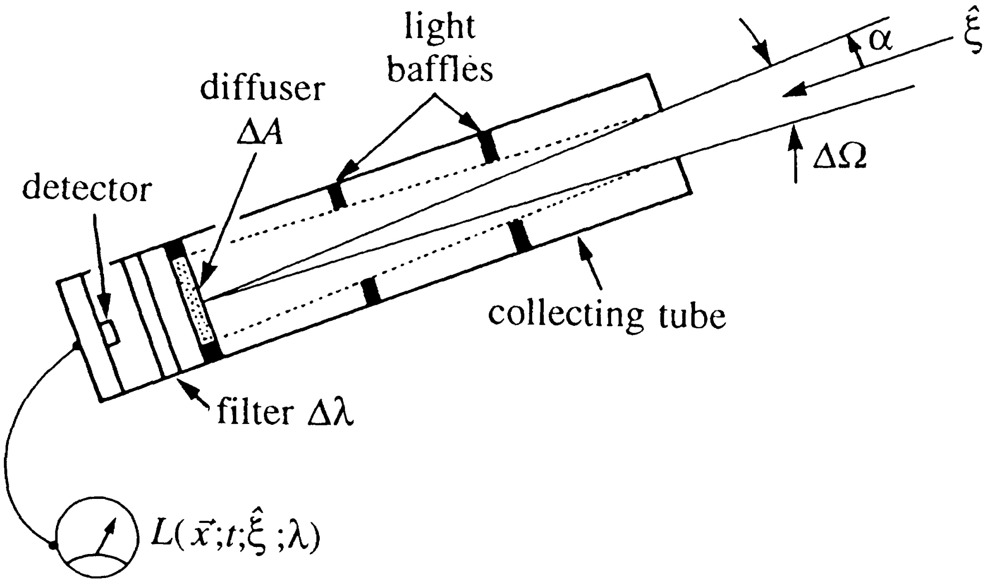
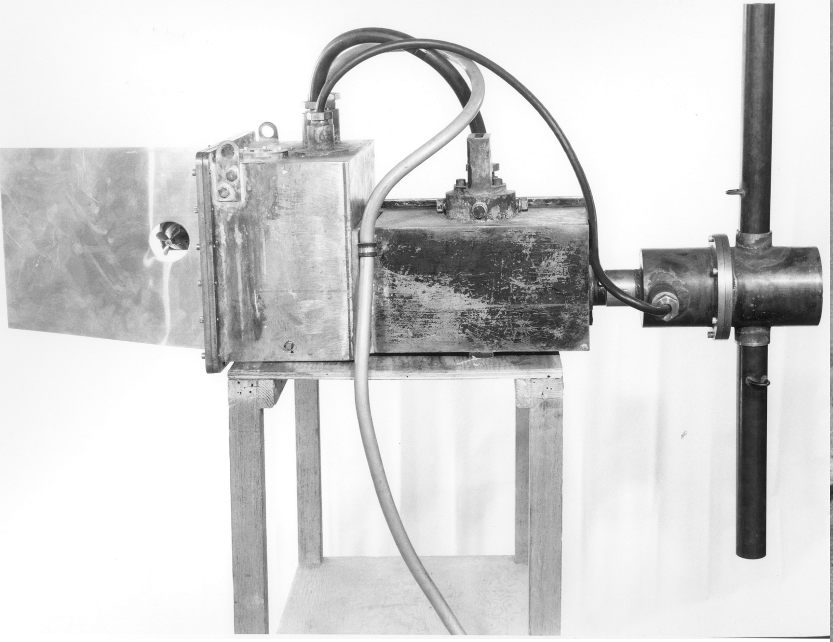


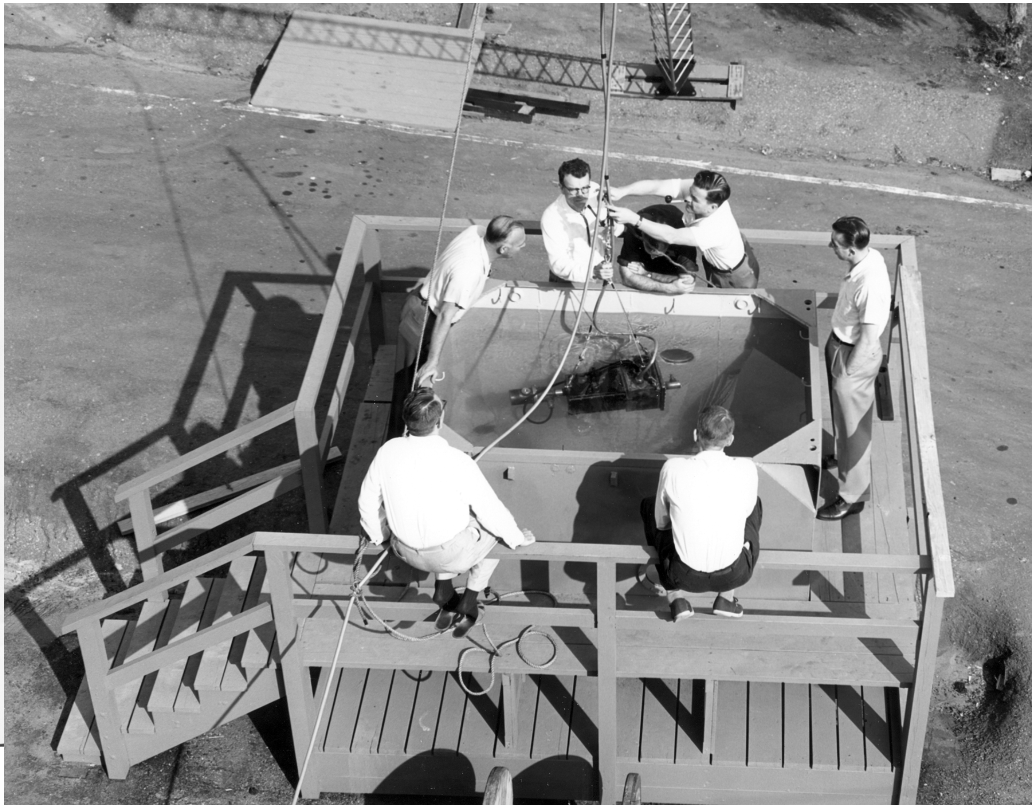
Fig. 1.5. Schematic design of an instrument for measuring unpolarized spectral radiance.

Most often Radiance measured with some sort of Gershun tube device in a single direction (typically upwelling nadir).

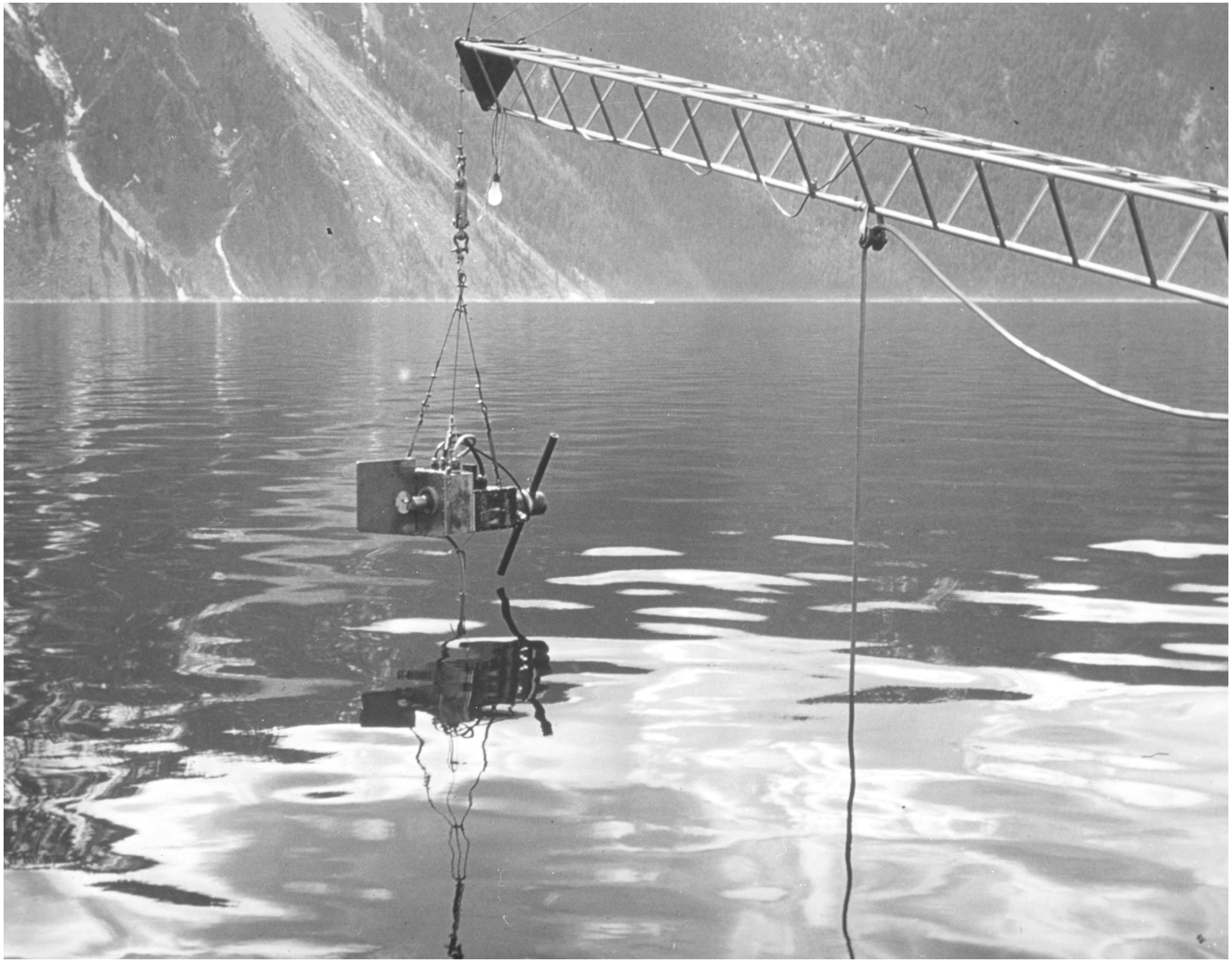
But to use radiance in all the other equations, need radiance distribution. Either measure many individual directions (such as Tyler, 1960) or many directions at once with a camera and lens of some sort (Fisheye, Smith et al. 1970).

Example instruments, Tyler :

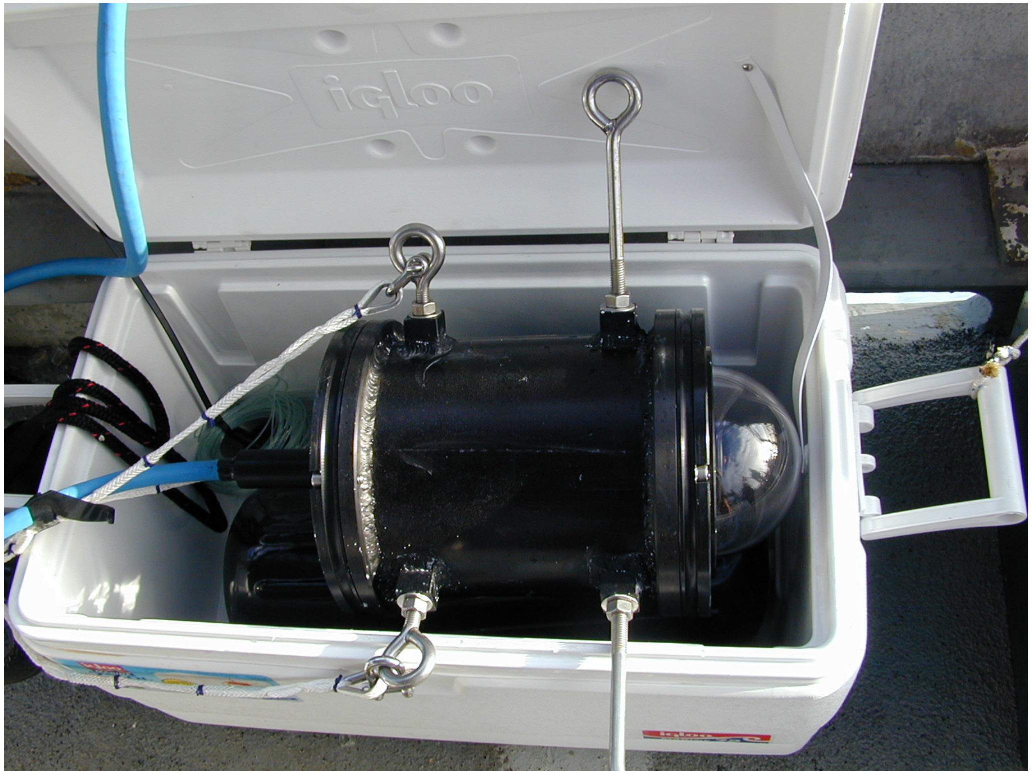


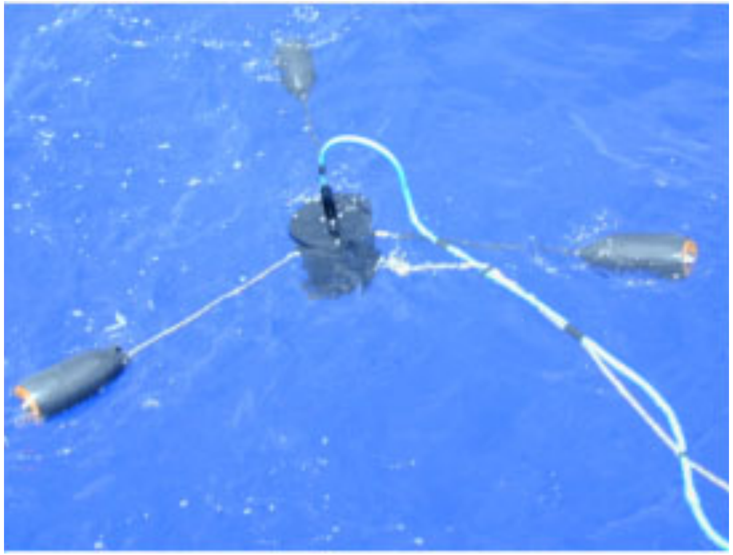


Radiance



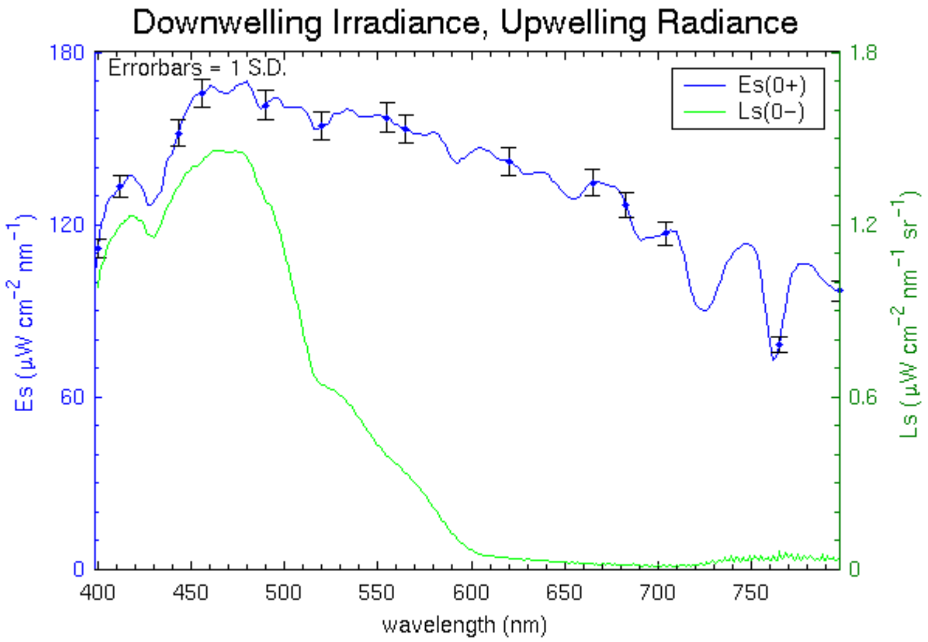
More modern instrument, NuRADS



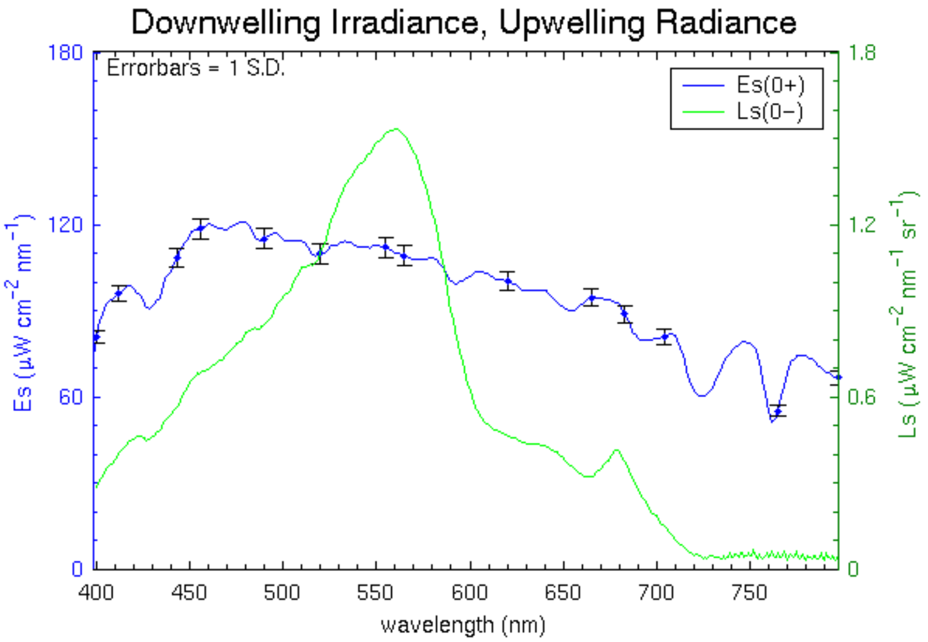


Example Nadir Radiance

Blue water station



Green water station



X-axis 400-800 nm, left y axis 0 – 180 μW cm^{-2} nm^{-1}, right y axis 0 – 1.8μW cm^{-2} sr^{-1} nm^{-1}

Data from Marlon Lewis

Radiance Distribution

Downwelling Radiance Distribution (520 nm)

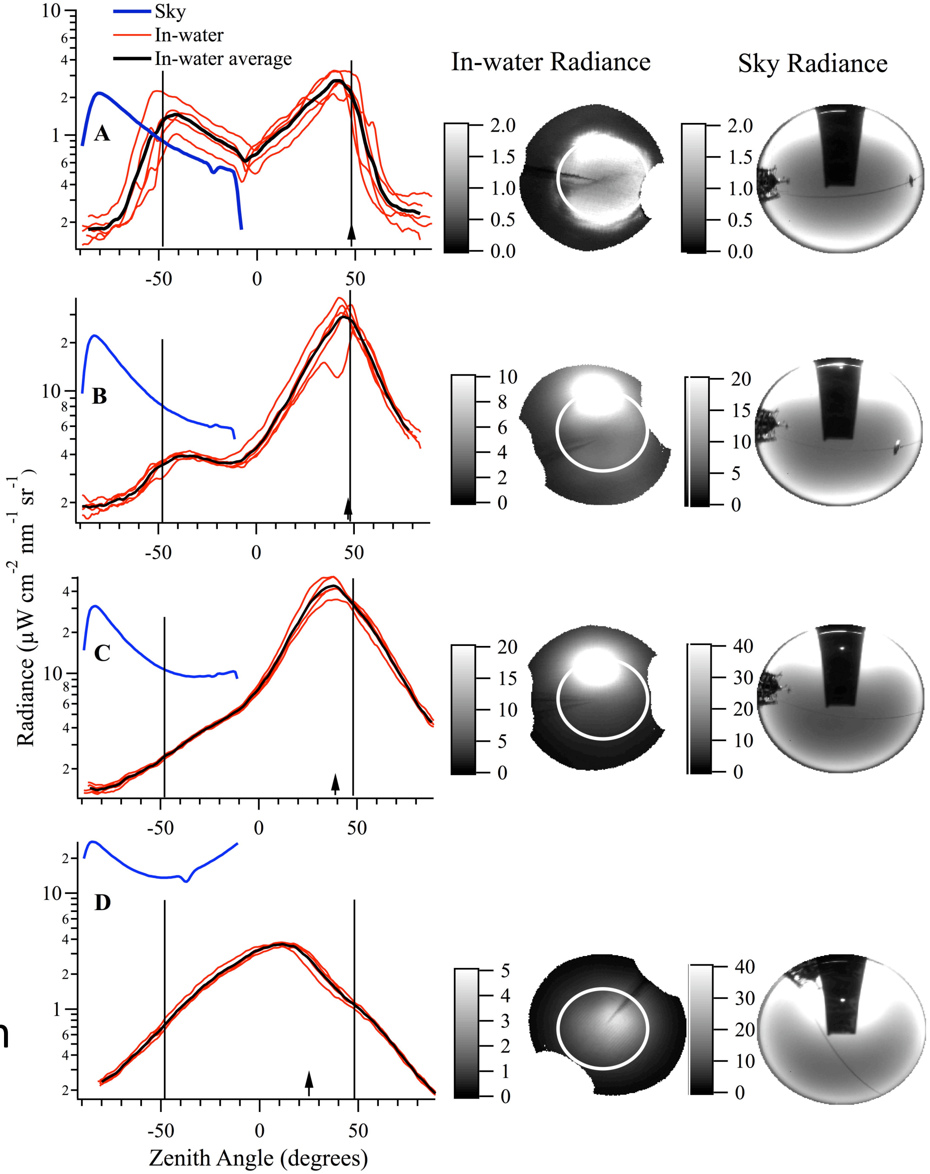
Santa Barbara channel

1m

5m

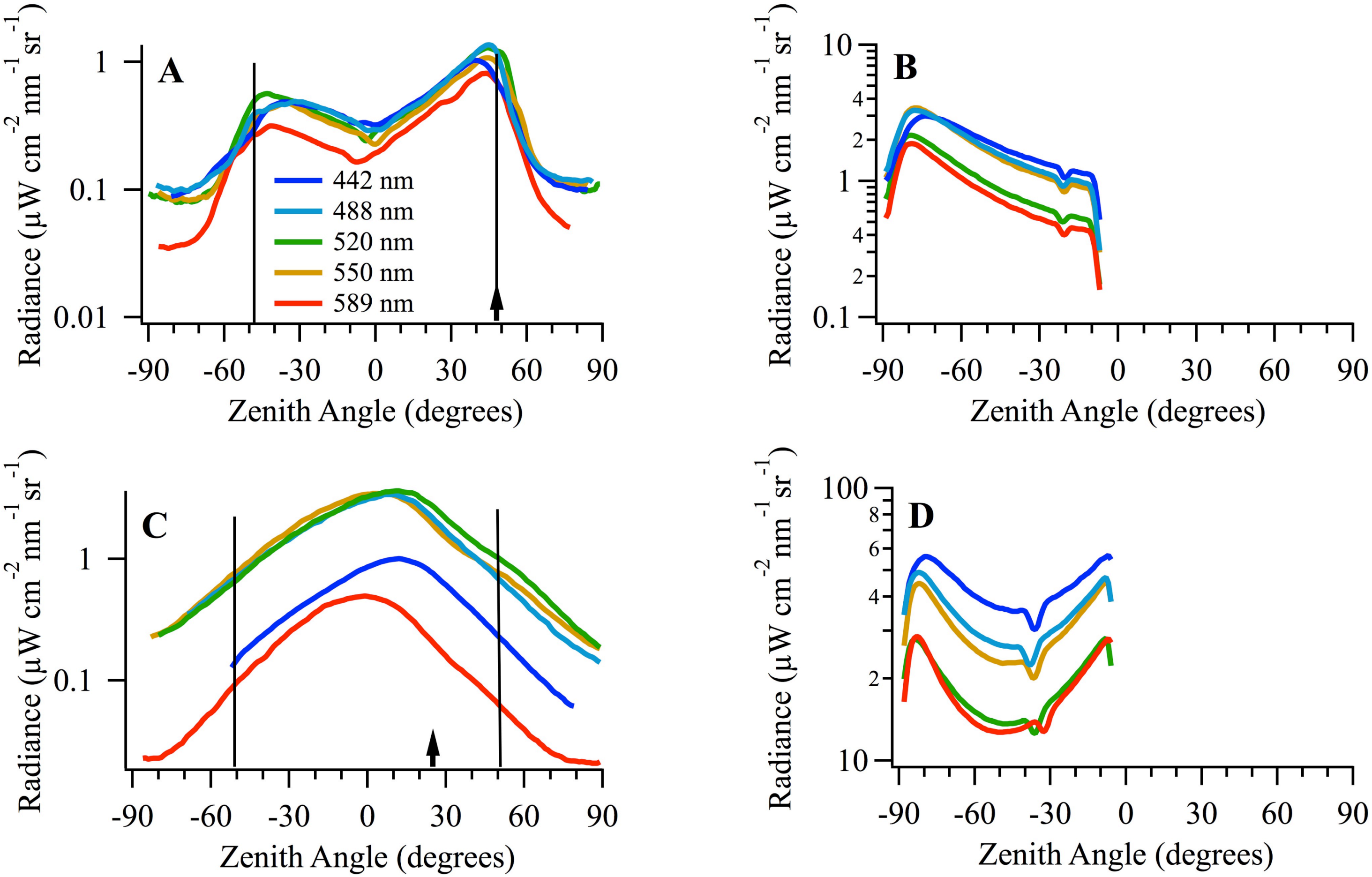
10m

30m



1 m

30 m



In water

Sky (note sun side is not shown)

Radiance Distribution

Clear water, Hawaii

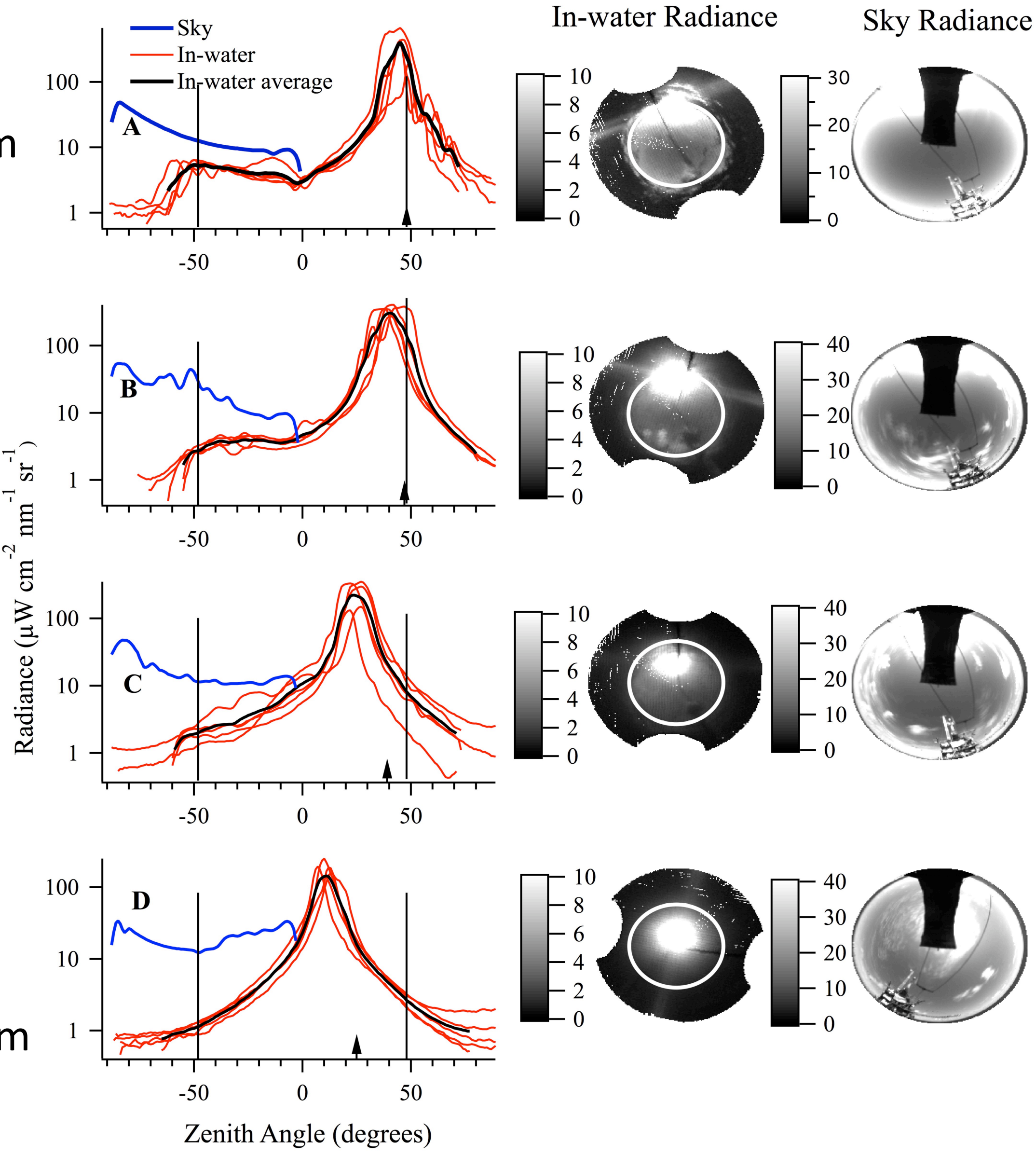
Note sunangle changed during the measurement period.

4 m

17 m

25 m

50 m



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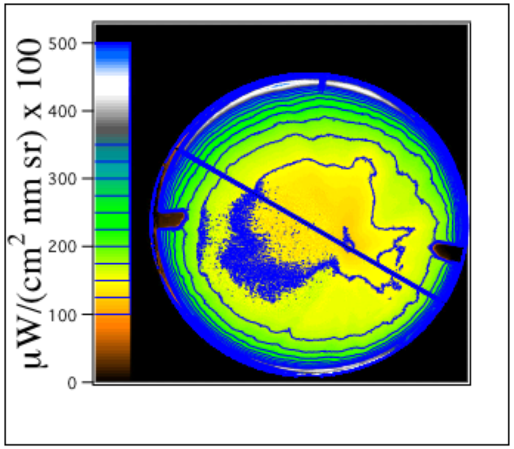
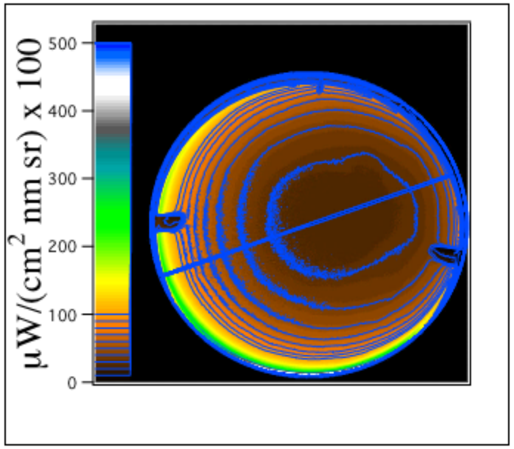
Upwelling Radiance Distribution

Example Radiance Distribution, 500nm

Low Chl (0.3 mg/m^3)



High Chl (5 mg/m^3)

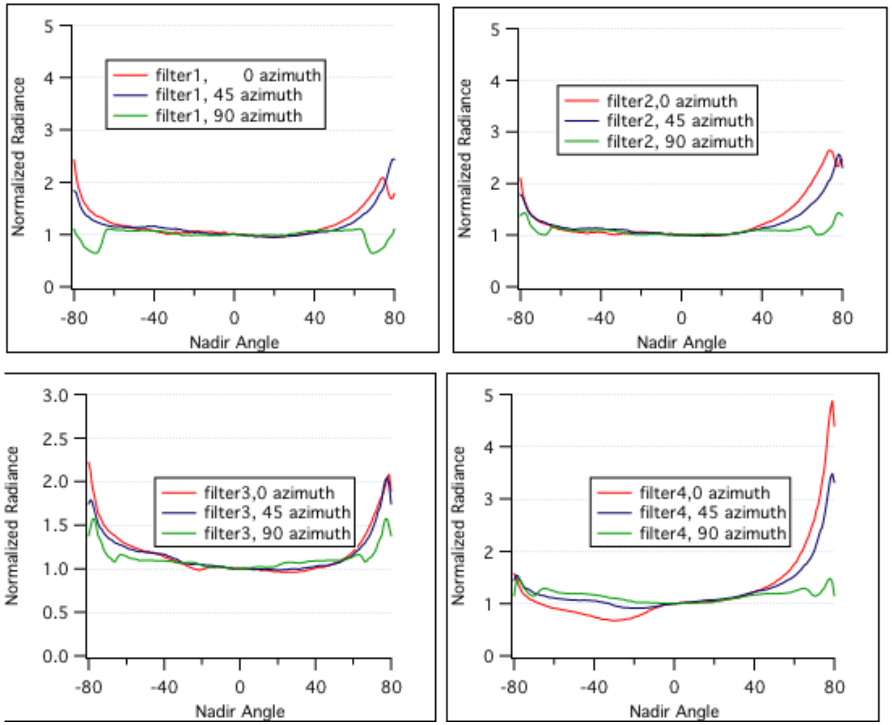


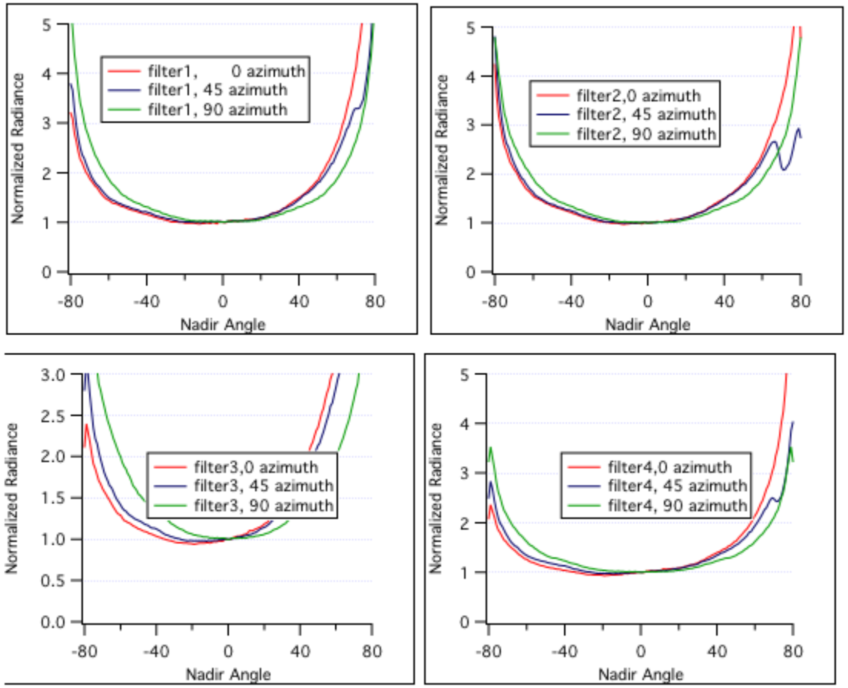
Upwelling Radiance distribution

All y axis 0-5 normalized radiance (except lower left in each set), all x axis -90-90 deg

Low Chl

High Chl





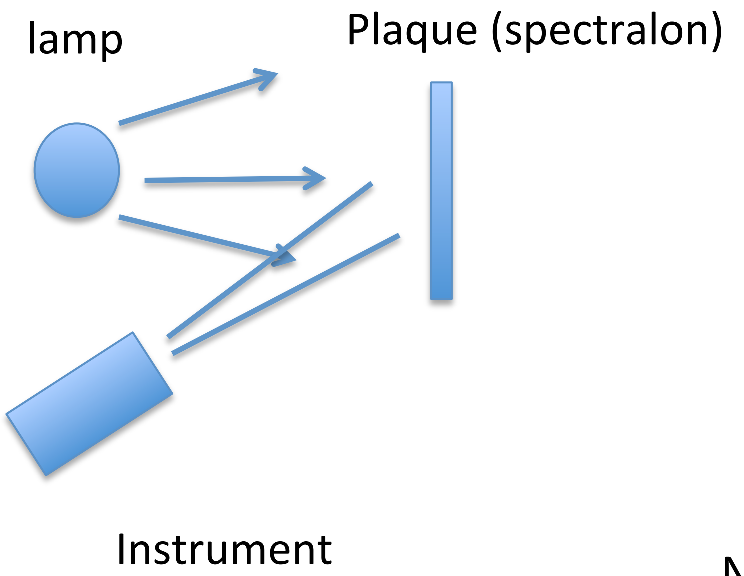
Filter 1:410, Filter 2: 440 nm, Filter 3: 490 nm, Filter 4: 530 nm)

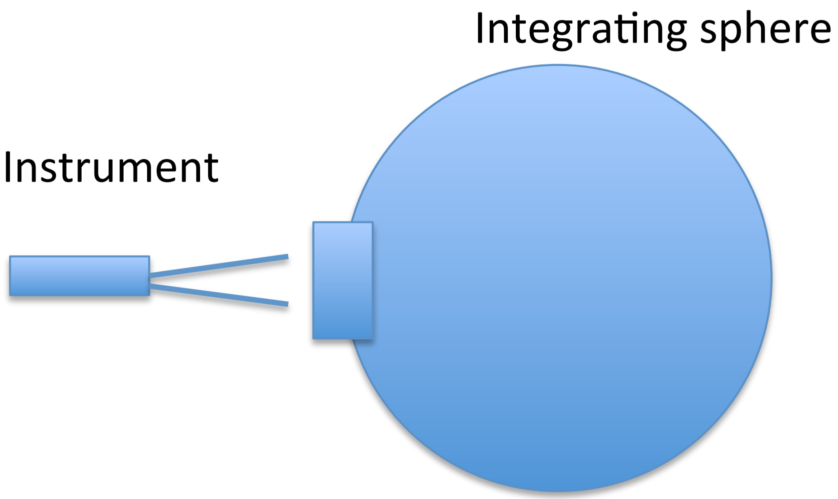
Upwelling light field becomes more “cupped” at high chl.

Radiance

Calibration: Look at a source of known Radiance

Either bounce light from a lamp off of a plaque, or look into an integrating sphere.



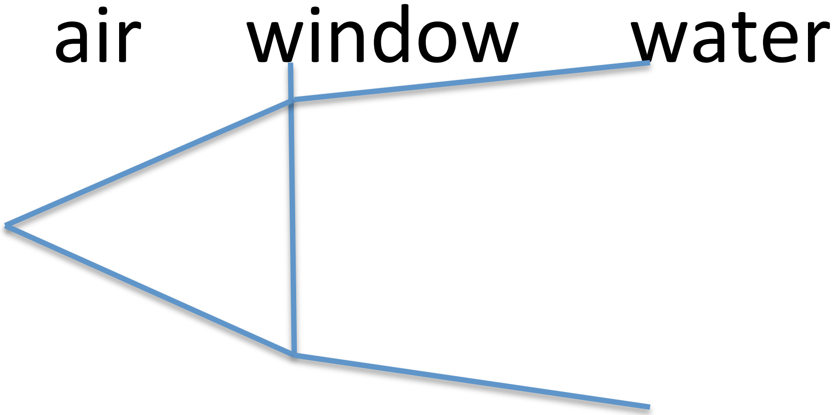


Note how radiance works from plaque, L= E/π

Radiance detectors also can have immersion factor

- Difference between calibration (Transmission from glass to air, vs glass to water).

- Flat window: n^2 factor



Different light levels between field and lab

Different colored sources between field and lab

Different temperatures in lab and field (variation in field temperatures)

Scattered light in lab

Geometrical setup in lab

Drifts in calibration sources

Etc.....

RRS techniques

Want something to relate to satellite measurements, and is an apparent optical property (relatively dependent on water properties, less on illumination conditions:

Remote sensing reflectance

Rrs = Lw/Es

Lw….water leaving radiance (above surface)

Es….downwelling irradiance

Above water techniques:
Rrs= Lw/Es

Rrs = (Lmeasured-Lg)/Es
Lg= Lsky *Reflectivity of surface

Reasonable Reflectivity is 0.028 of sky measurement with a geometry of nadir angle 40 deg, azimuth 135 from sun, wind <5 m/s (around 10 knts) (Mobley, 1999) :

References:

Mobley, **Estimation of the remote-sensing reflectance from above-surface measurements, Applied Optics, 7442-7455, 1999.**

Lee et al., Removal of surface-reflected light for the measurement of remote-sensing reflectance from an above-surface platform, Optics Express, 26313-26324, 2010.

Garaba et al., **Comparison of remote sensing reflectance from above-water and in-water measurements west of Greenland, Labrador Sea, Denmark Strait, and west of Iceland, Optics Express, 15938-15950, 2013**

In water techniques:

$Rrs = L_u(z)\ T_{aw} /(E_s{*}T(z))$

Measure upwelling radiance at some depth ($L_u(z)$)

Propagate to the surface $T(z) = \exp(-K_L{*}z)$

Propagate through the air-water interface, T_{aw} ($0.975/n^2 = 0.543$)

Measure E_s above the surface
Reference: many…one example Voss et al., *An Example Crossover Experiment for Testing New Vicarious Calibration Techniques for Satellite Ocean Color Radiometry*, JAOT, 2010.
Also Ocean Optics protocols

New Lee technique

Shade surface, measure above the water. Should be directly L_w/Es

Lee et al. Robust approach to directly measuring water-leaving radiance in the field, Applied Optics, 1693-1701 (2013).

Another factor: Normalized water leaving radiance

$nL_w = L_w/E_s * E_o/r^2$

E_o extra terrestrial solar irradiance

r = earth sun distance

Lee et al. Robust approach to directly measuring water-leaving radiance in the field, Applied Optics, 1693-1701 (2013).

Two other things we should mention..f/Q and shadowing

Remember we just saw that the radiance distribution for upwelling light is not isotropic…this led Morel (and Gentili and Antoine) to come up with a factor to relate measurements at one direction to the nadir direction the f/Q factor.

f comes from $R = Eu/Ed = f\, b_b/a$ f is factor which relates b_b/a to the irradiance reflectance. Actually a function of sun angle (and atmospheric parameters)

$Q = Eu/Lu$ (actually π if isotropic…generally between 3.5 and 6) or more generally $Q(\theta_o,\theta,\Phi) = L(\theta_o,\theta,\Phi)/Eu$ Also a factor of atmospheric parameters and optical properties of water.

So we have this factor $f/Q(\theta_o,\theta,\Phi)$. To relate measurements at one angle to another (say nadir):

$$\{f/Q(\theta_o,\theta,\Phi)\}/\{f/Q(\theta_o,0,0)\} = L(\theta_o,\theta,\Phi)/L(\theta_o,0,0)$$

References for f/Q Case 1

Voss, K., Morel, A. and D. Antoine Detailed validation of the bidirectional effect in various Case 1 waters for application to Ocean Color imagery. *Biogeosciences*, 4,   781-789.

Morel, A., Antoine, D. and B. Gentili (2002). Bidirectional reflectance of oceanic waters: Accounting for Raman emission and varying particle phase function, *Applied Optics*, **41**, 6289-6306.

Morel, A., and B. Gentili (1996). Diffuse reflectance of oceanic waters. 3. Implication of bidirectionality for the remote-sensing problem. *Applied Optics,* **35**, 4850-4862.

Morel, A., Voss, K.J. and B. Gentili (1995). Bidirectional reflectance of oceanic waters: A comparison of modeled and measured upward radiance fields, *Journal of Geophysical Research,* **100**, 13,143-13,150.

Morel, A. and B. Gentili (1993). Diffuse reflectance of oceanic waters. 2. Bidirectional aspects. *Applied Optics,* **32**, 6864-6872.

Morel, A., and B. Gentili (1991). Diffuse reflectance of oceanic waters: its dependence on sun angle as influenced by molecular scattering contribution. *Applied Optics,* **30**, 4427-4438.

f/Q case 2:

Z. Lee, K. Du, K. J. Voss, G. Zibordi, B. Lubac, R. Arnone, and A. Weidemann, "An IOP-centered approach to correct the angular effects in water-leaving radiance", Applied Optics, **50**, 3155-3167 (2011).

A.C.R. Gleason, K. J. Voss, H. R. Gordon, M. Twardowski, J. Sullivan, C. Trees, A. Weidemann, J-F. Berthon, D. Clark, and Z-P. Lee, "Detailed validation of the bidirectional effect in various Case I and Case II waters", Optics Express, 20, 7630 – 7645 (2012).

Others coming out.....

Put an instrument in the water (or stand on a ship in the sea, or a dock in a river)…and you are shadowing some volume of water.

Since in remote sensing applications we are always trying to measure upwelling light, how bad are we disturbing the light field?

Several studies into this…major results:
Avoid ship shadow..try to get make measurements 10m or more(dependent on water properties) from ship on sunny side of ship. (Gordon 1985, Voss et al. 1987….probably many others).

Instrument shadow, to first order is proportional to a*r…absorption coefficient times radius of instrument. Use as small of an instrument as possible, impossible in this river. (Gordon and Ding, 1992, L&O)

Various calculations of effects and correction schemes:

Leathers, Downes, and Mobley (2004) TSRB

Doyle and Zibordi, 2002, larger structures

Mueller,2007, MOBY (at least first generation shadowing correction)

Common feature, none of these have Raman…..where is shadowing most important?

Application of Beer's law….(all factors below function of wavelength)

$E = E_o \exp(-\tau m)$

E is direct irradiance (solar irradiance measured with reference plane perpendicular to sun) in instrument units

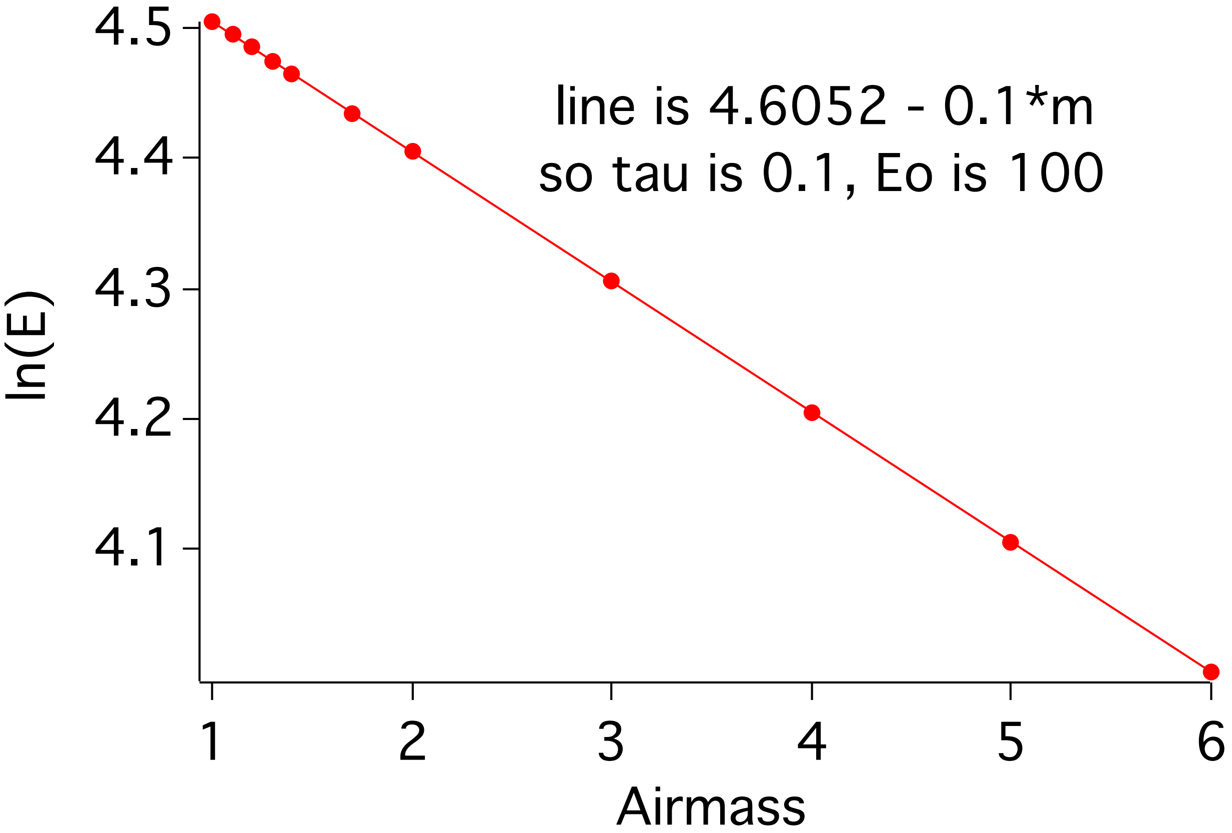
E_o is extra terrestrial solar irradiance, corrected for earth-sun distance in instrument units

m is airmass (approximately $1/\cos(\theta_o)$ for $\theta0<70$ degrees)

τ is optical depth of atmosphere..can be split into molecular scattering and absorption and aerosols scattering and absorption.

maybe we can have another lecture on atmosphere later…

If you know E_o, and m (calculate) then measure E, can calculate τ. But need to know Eo very accurately....cannot calibrate in lab well enough so use Langley technique



line is 4.6052 - 0.1*m
so tau is 0.1, Eo is 100