

UNIVERSITY
OF MIAMI



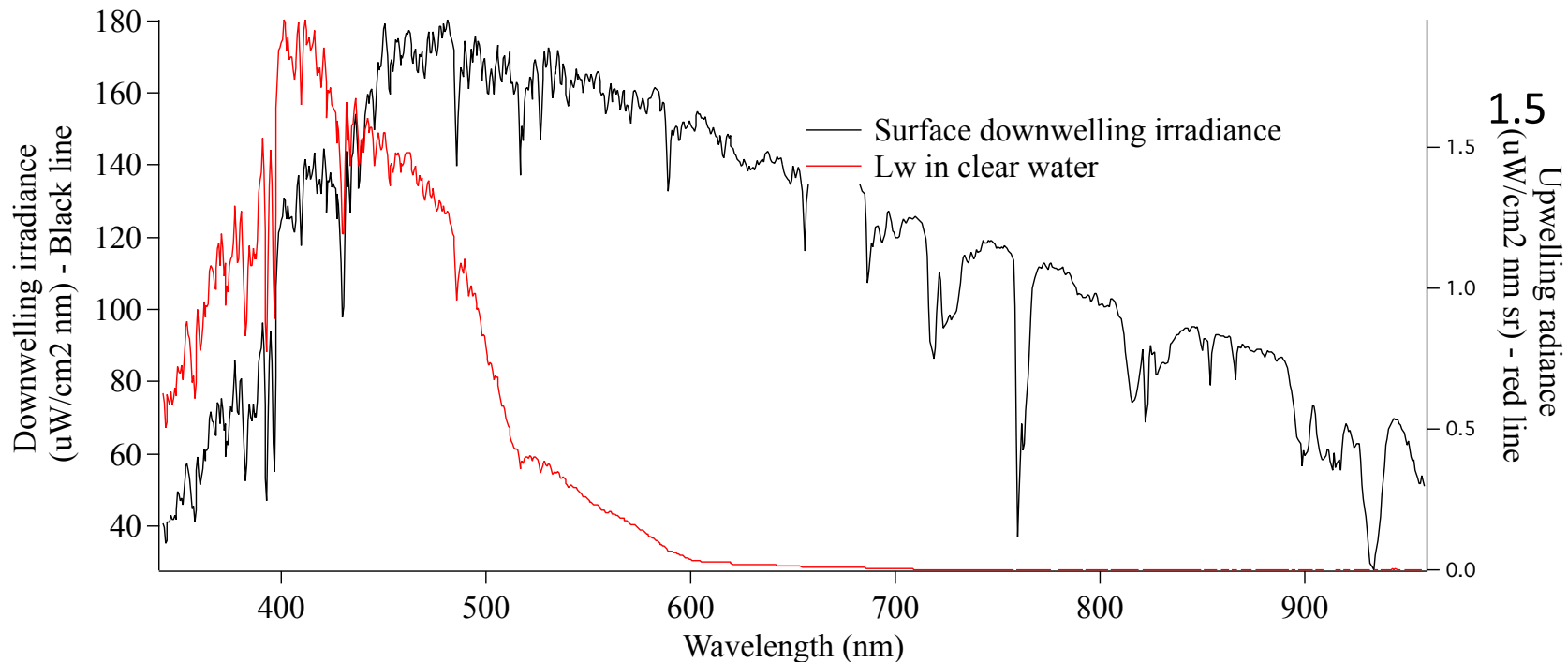
Radiometric quantities and their measurement

Ken Voss, Ocean Optics Class, Bowdin, Maine
Summer, 2019

Outline

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

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

- 1) photosynthetically available radiation (PAR) or other broadband for example UV-A, photopic sensors
- 2) Multi-channel instruments..collection of individual bands (say 10 bands, 10nm wide)
- 3) Hyperspectral instruments..measurements every 1-10 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 is an approximation:
Each photon generates one photo-electron (assume 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 and important.

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

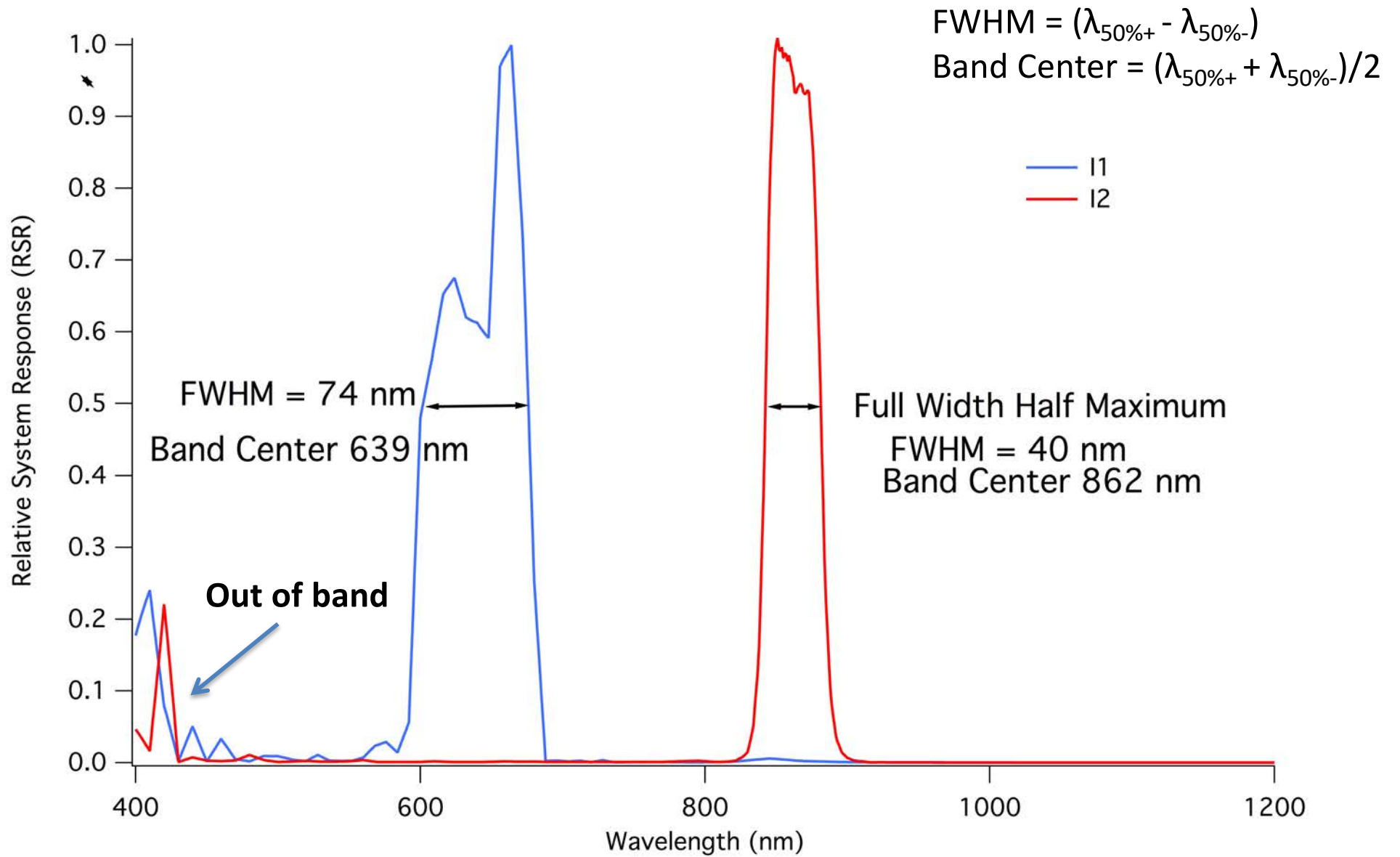
These instruments are very hard to calibrate accurately! Often get very different numbers for same energy of light depending on spectral composition of light field being measured (note for PAR this is intentional).

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 (VIIRS, MODIS bands for example).
 - c) when you look at reflectance, sharp atmospheric/solar features cancel out to some extent.

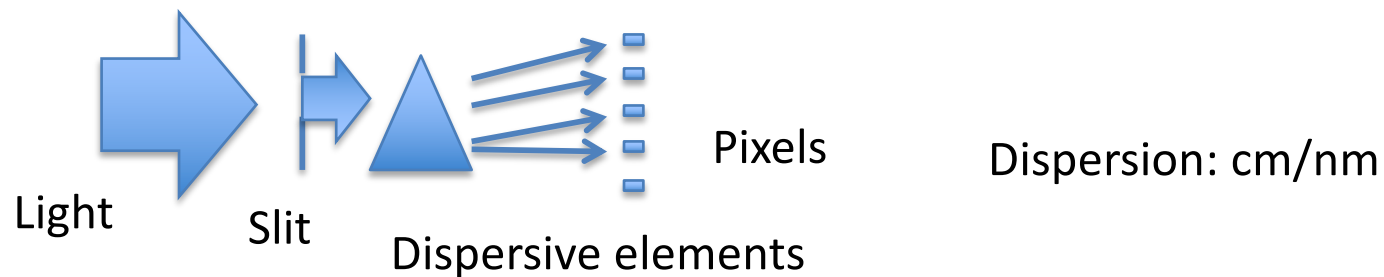
- 2) Spectral channels defined by filters, typically interference filters.
 - a) Filters have some spectral shape, defined by band center and the width.
 - b) Have to be careful of out-of-band effects (when looking at different “color” sources)

Detectors

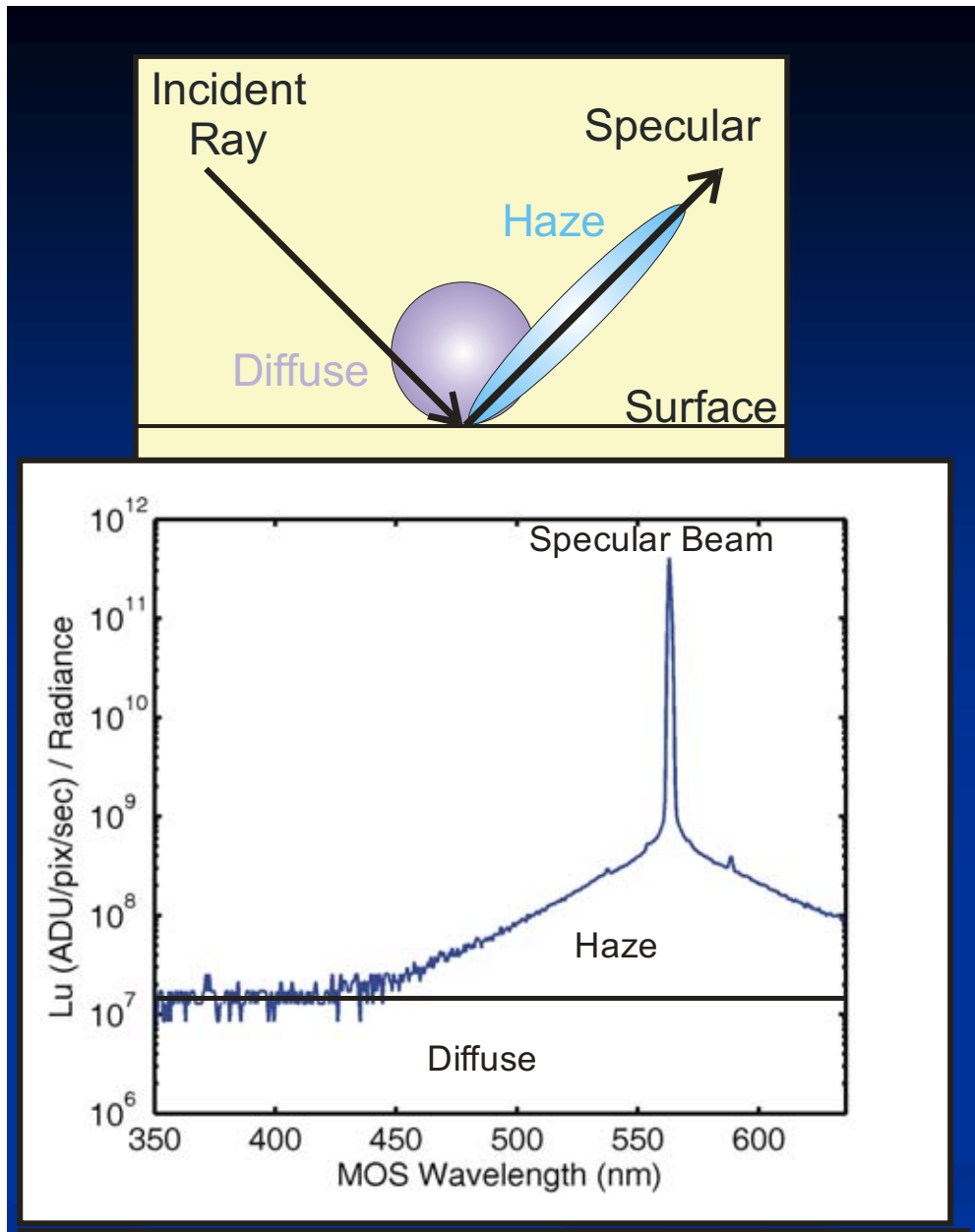


Hyperspectral Detectors

- 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.



Be aware of problems with hyperspectral sensors, Stray Light

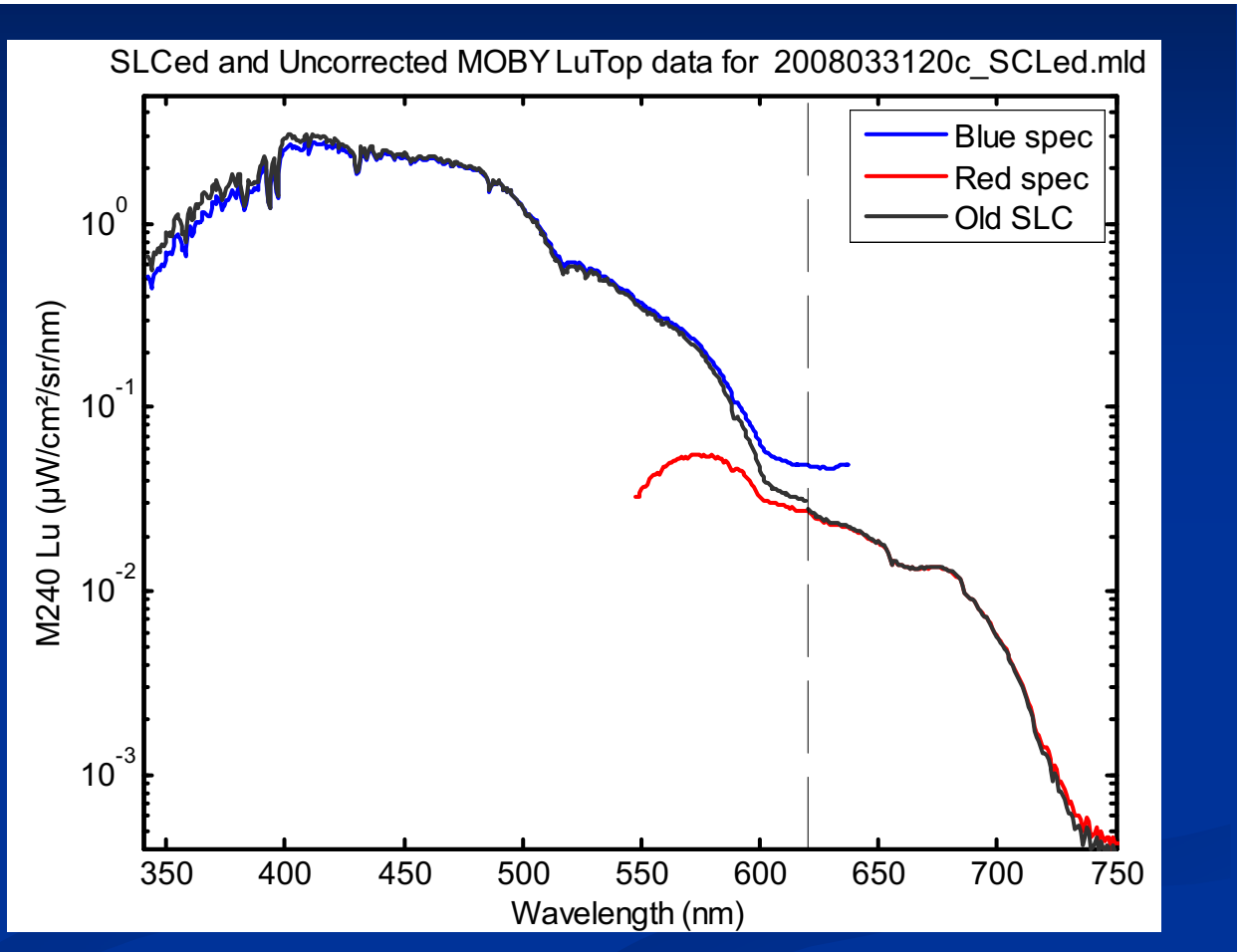
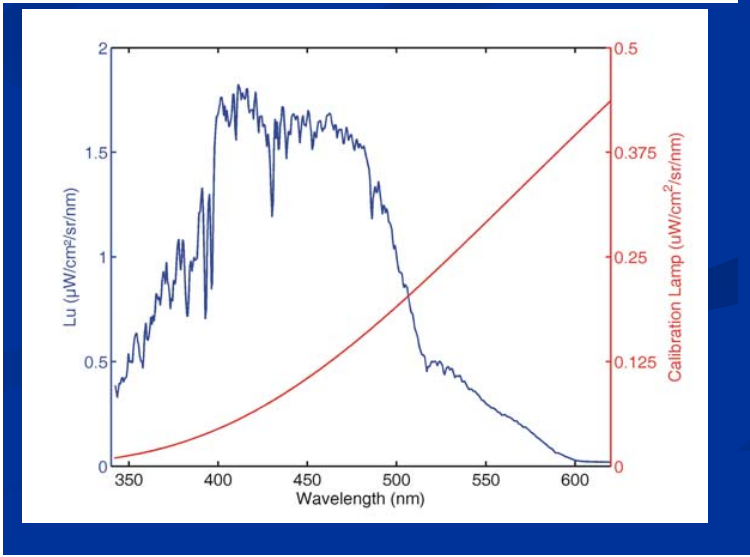


Stray Light effects

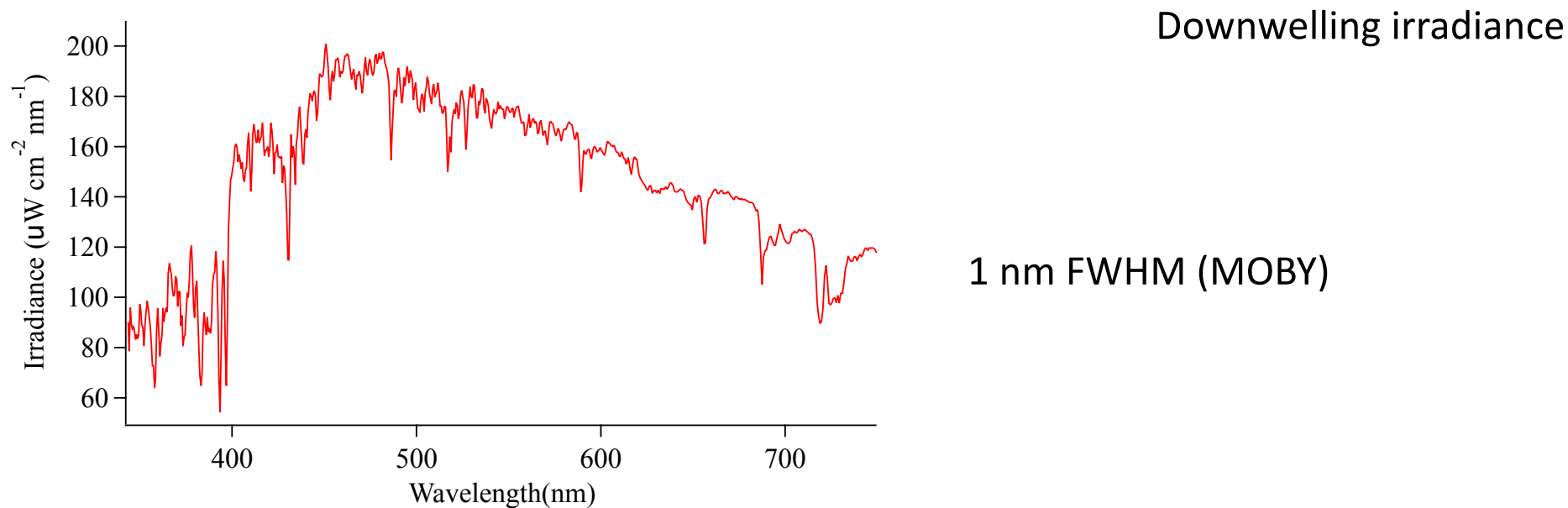
From Stephanie Flora
Moby project,

Current MOBY system

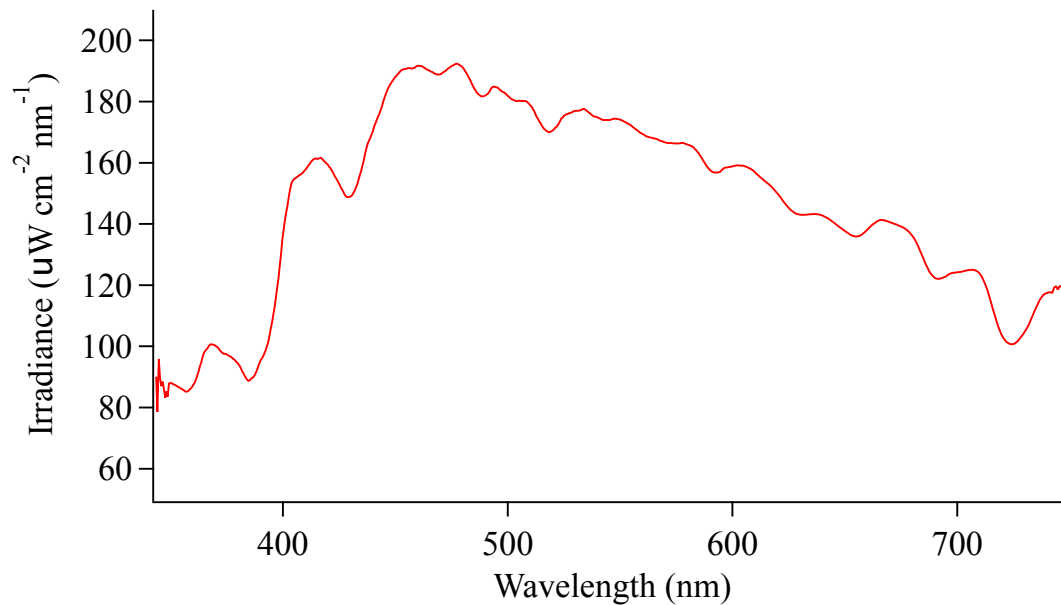
Be aware of problems with hyperspectral sensors, Stray Light



Be aware of problems with hyperspectral sensors, BandWidth



10 nm FWHM
Hyperpro



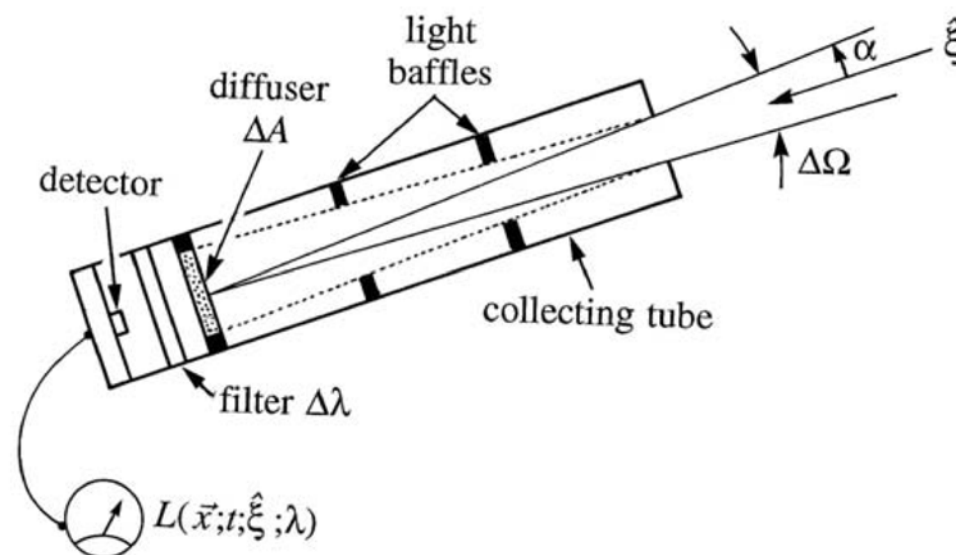
- Those are the three classes of instruments defined by their spectral characteristics...now look at the different instruments as defined by the parameter they measure.

Definition of Radiance:

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

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

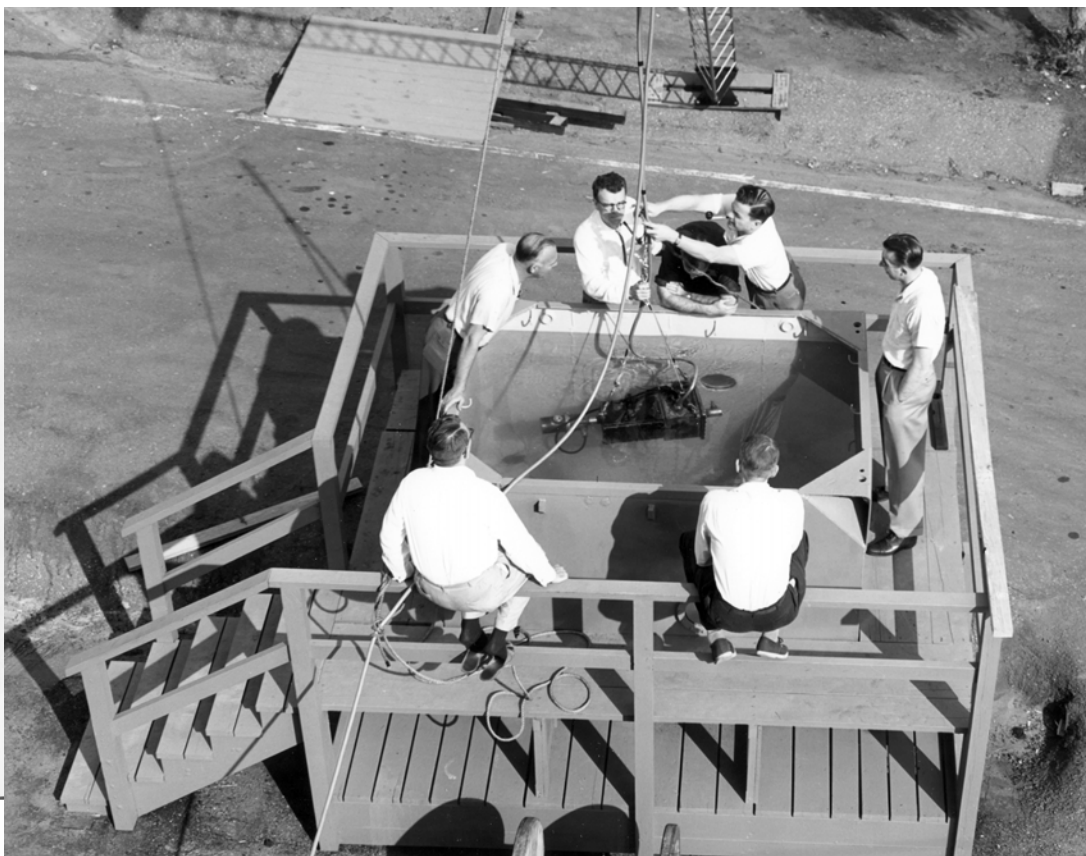
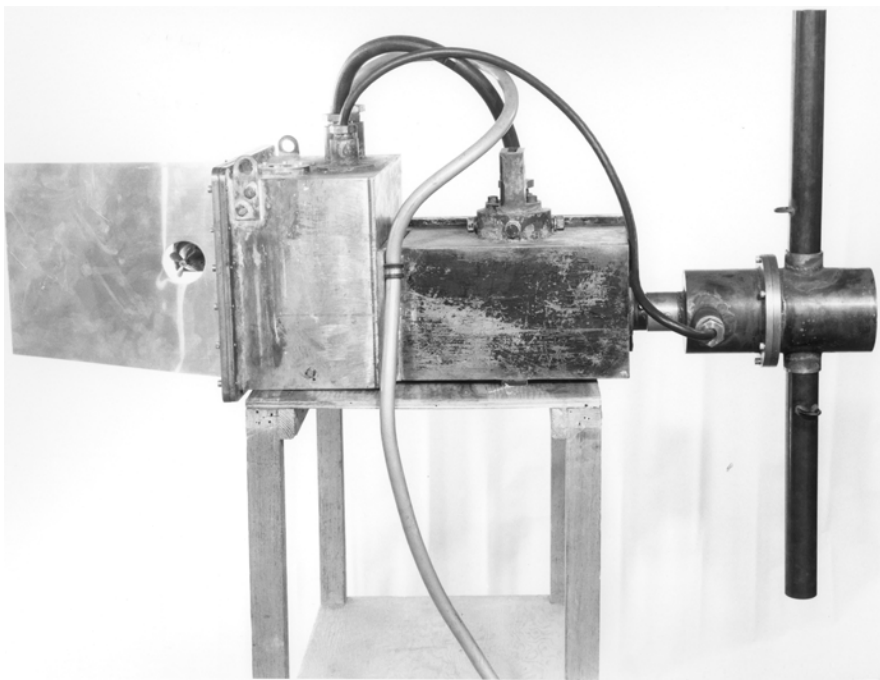
From Light
And Water, Mobley

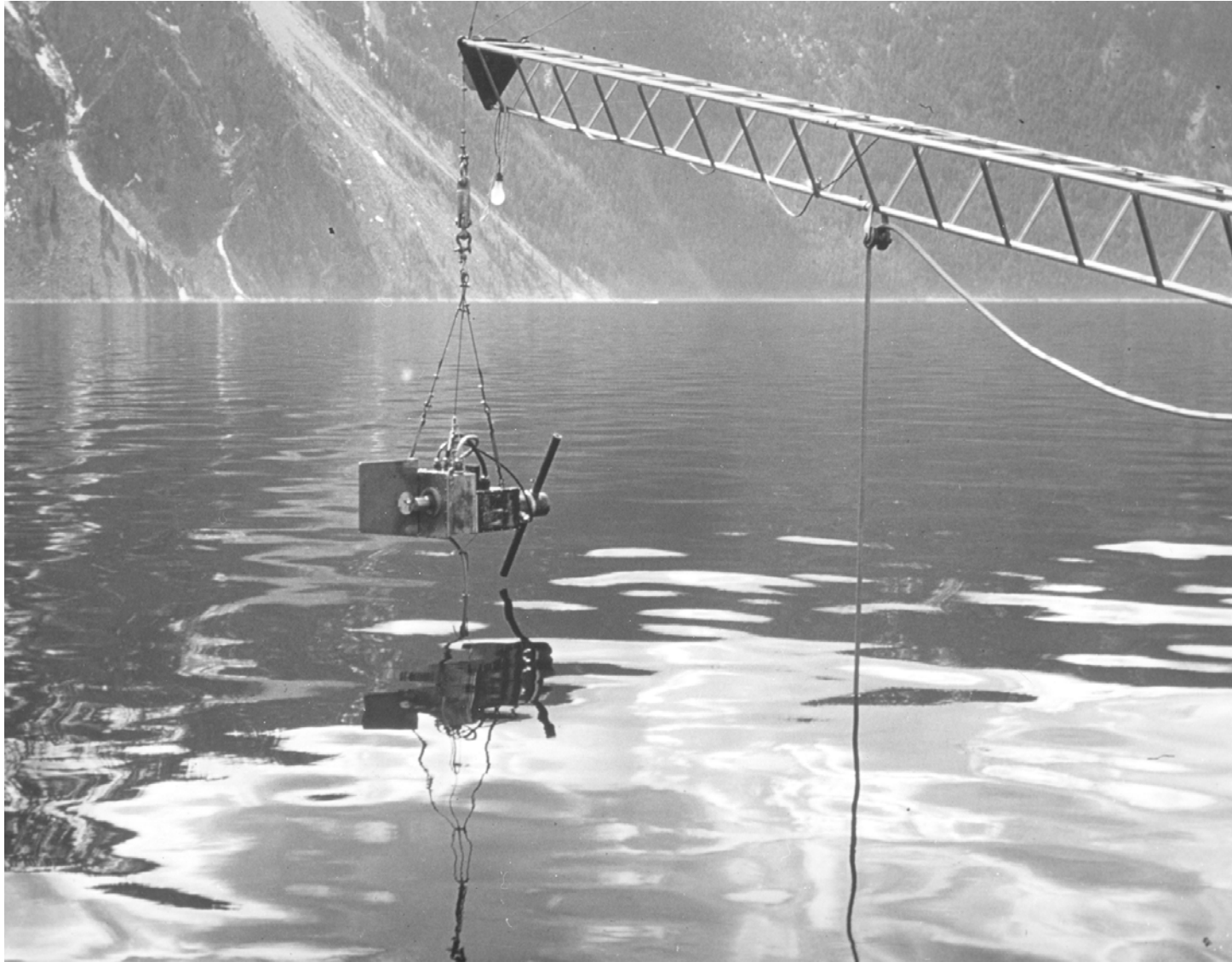


Most often radiance measured with some sort of Gershun tube or lens system device in a single direction (typically upwelling nadir).

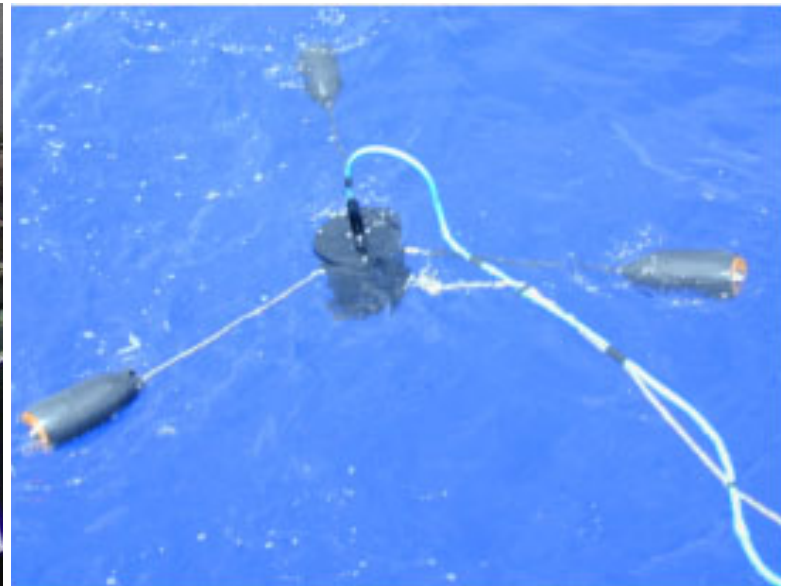
But to use radiance in all the other equations, need radiance distribution. Either measure many individual directions (such as Tyler, 1960) or many directions at once with a camera and lens of some sort (Fisheye, Smith et al. 1970).

Example instruments, Tyler :





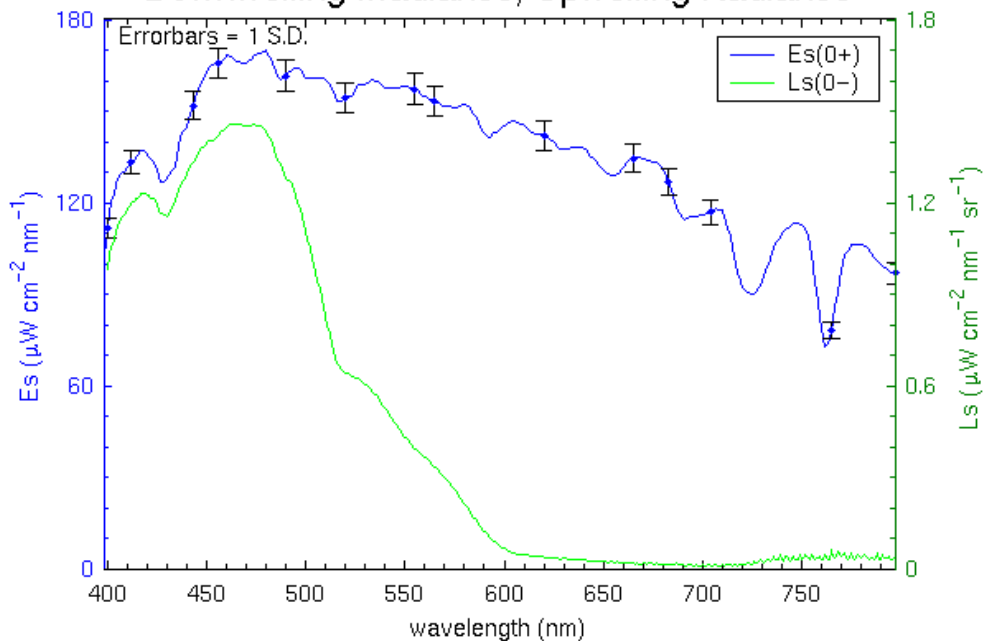
More modern instrument, NuRADS



Example Nadir Radiance

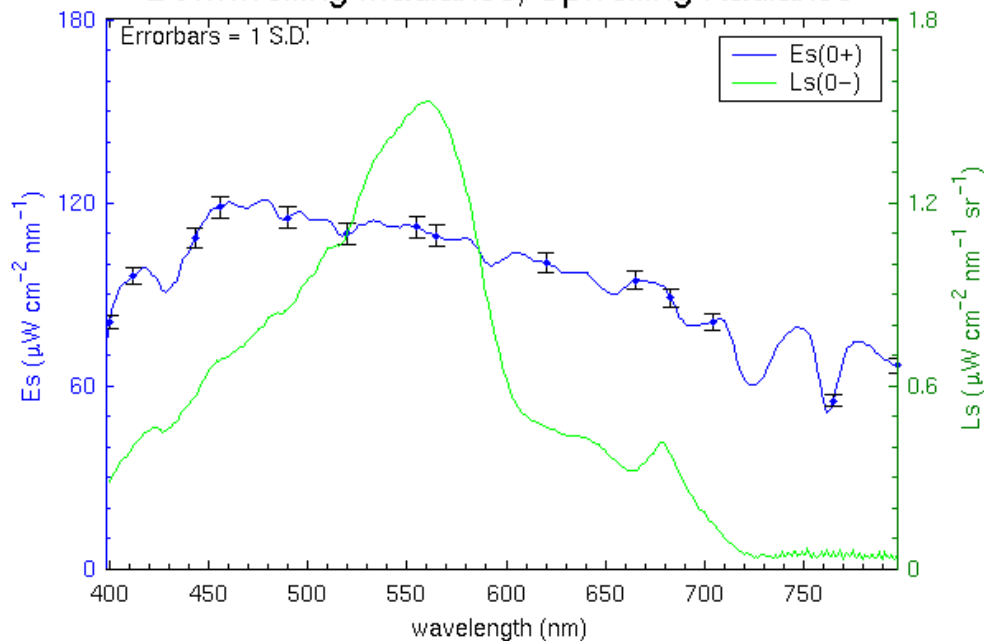
Blue water station

Downwelling Irradiance, Upwelling Radiance



Green water station

Downwelling Irradiance, Upwelling Radiance



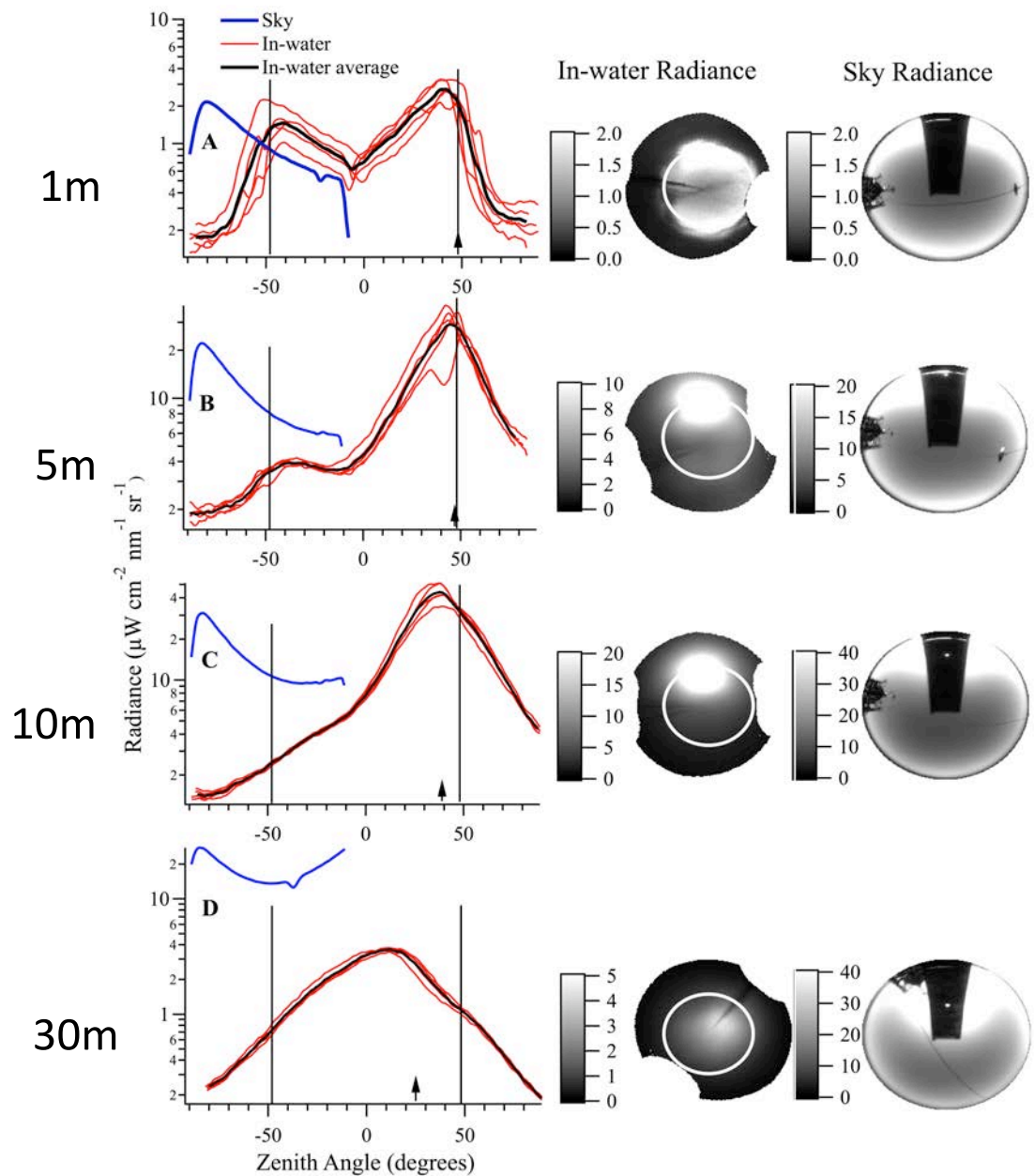
X-axis 400-800 nm, left y axis 0 – 180 $\mu\text{W cm}^{-2} \text{ nm}^{-1}$, right y axis 0 – 1.8 $\mu\text{W cm}^{-2} \text{ sr}^{-1} \text{ nm}^{-1}$

Data from Marlon Lewis

Radiance Distribution

Downwelling
Radiance
Distribution
(520 nm)

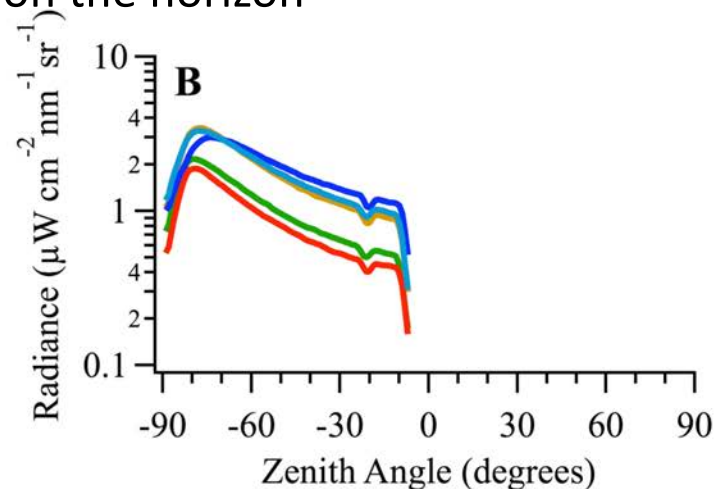
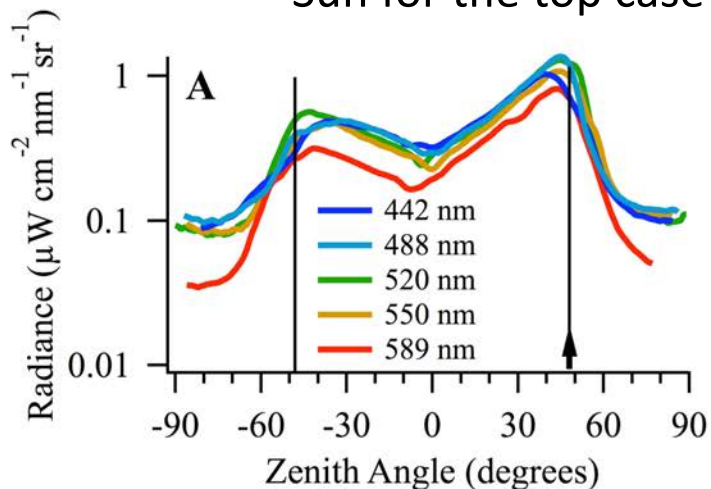
Santa Barbara channel



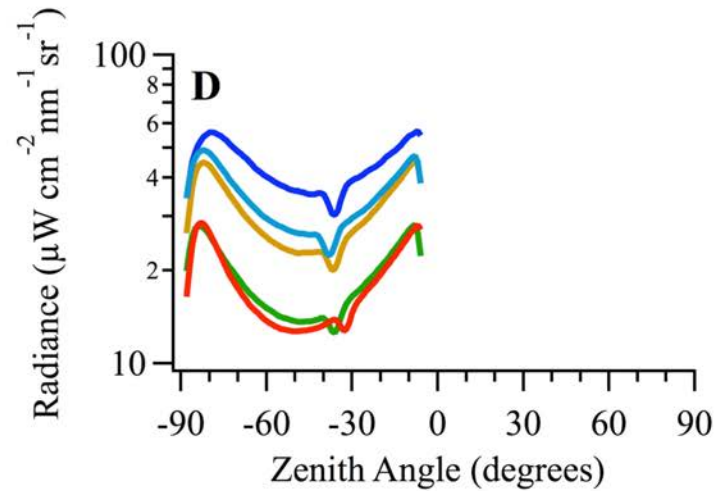
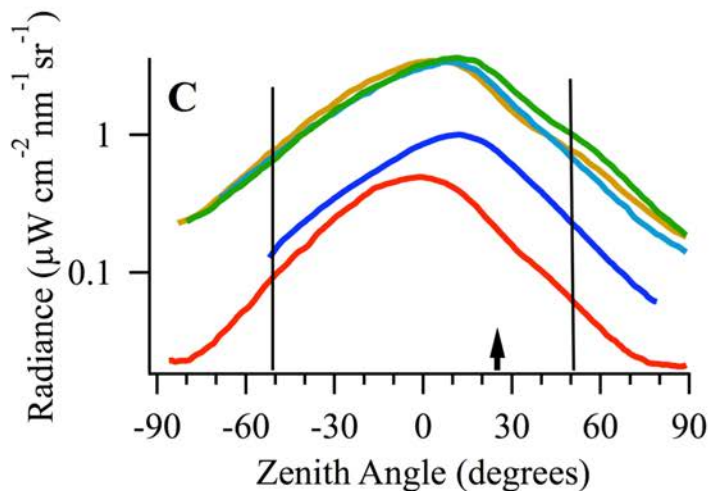
Radiance Distribution

Sun for the top case is just on the horizon

1 m



30 m



In water

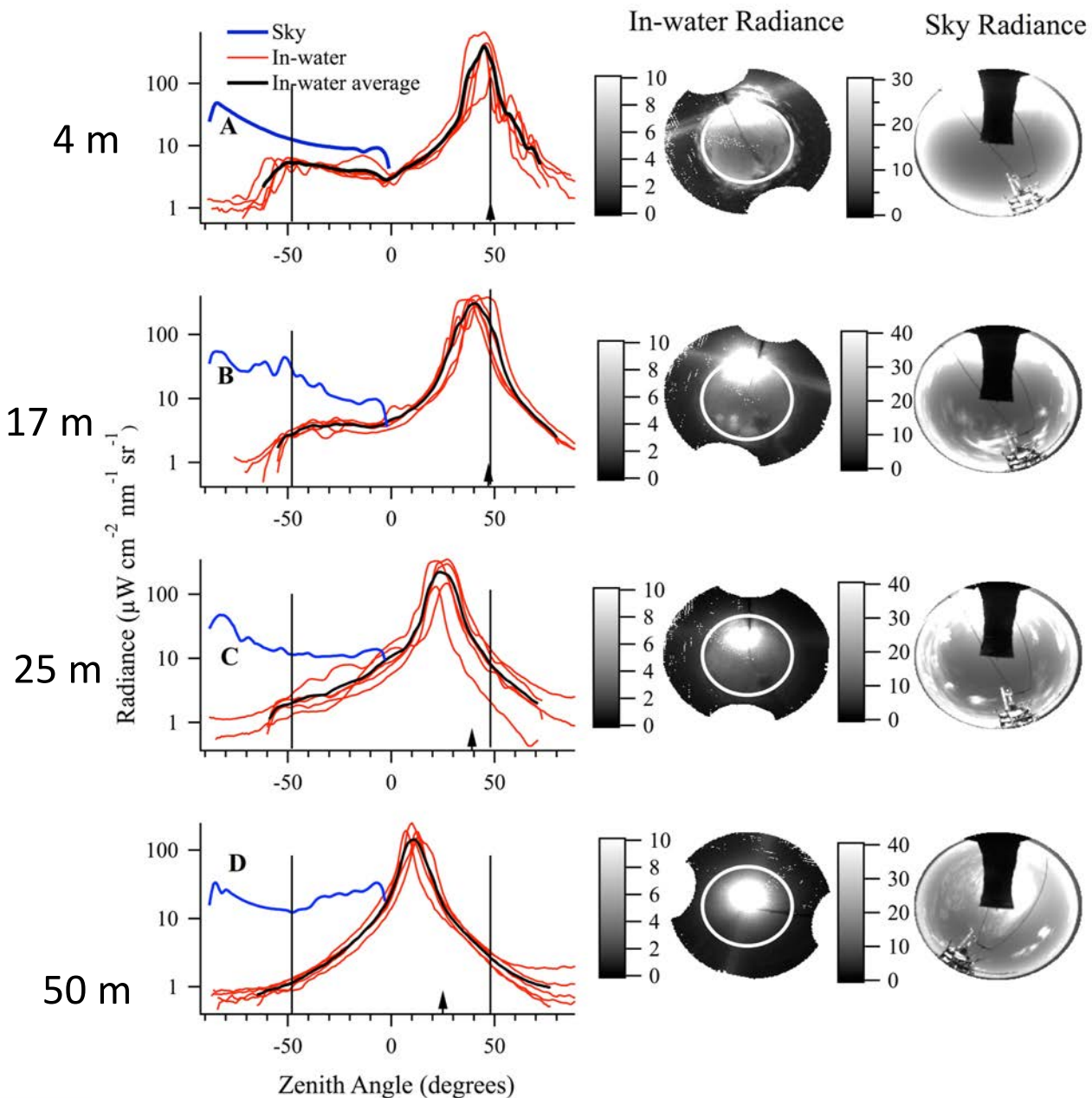
Sky (note sun side is not shown)



Radiance Distribution

Clear water, Hawaii

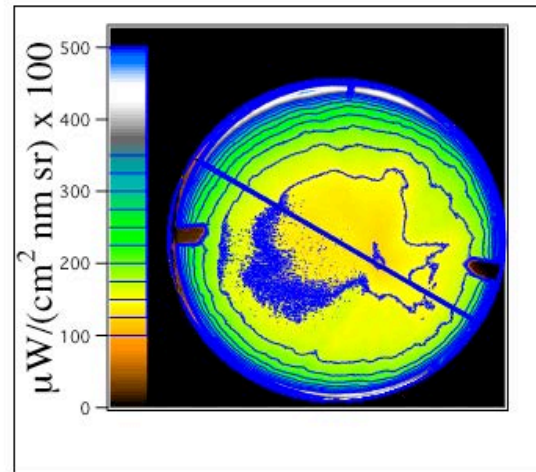
Note sun angle changed during the measurement period.



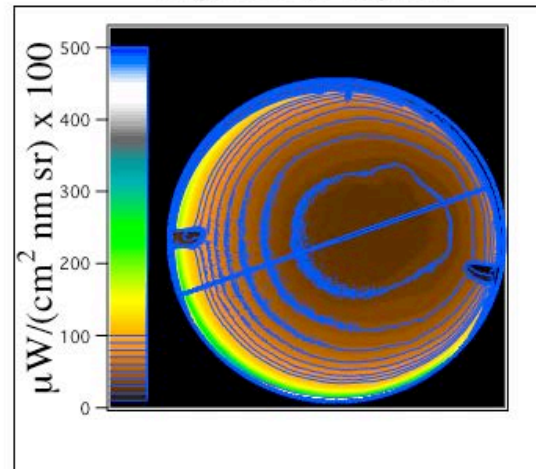
Upwelling Radiance Distribution

Example Radiance Distribution, 500nm

Low Chl (0.3 mg/m^3)



High Chl (5 mg/m^3)

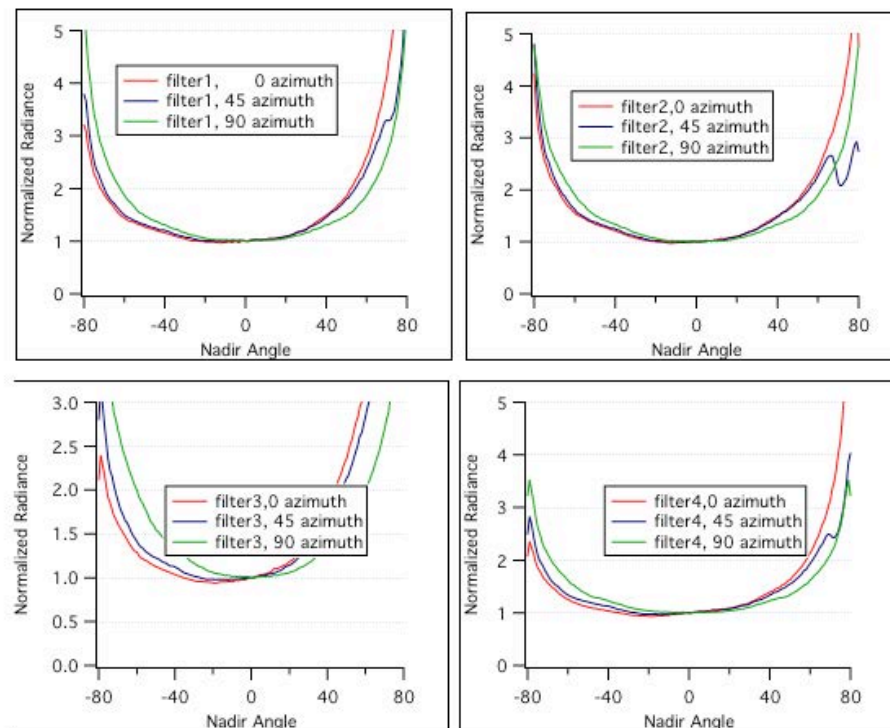
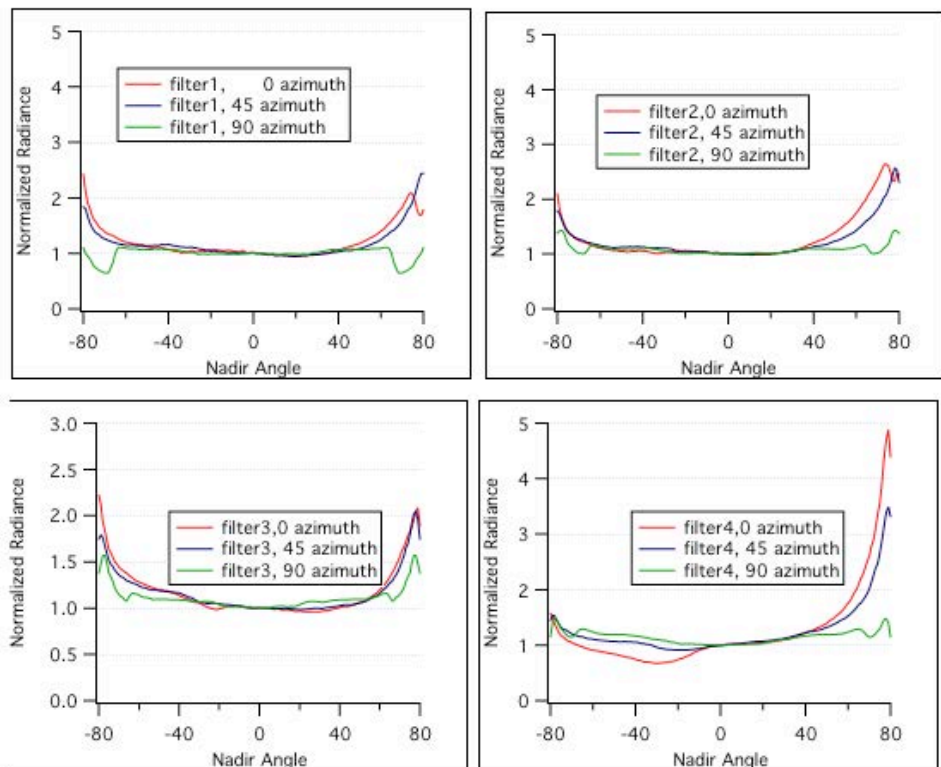


Radiance

Upwelling Radiance distribution

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

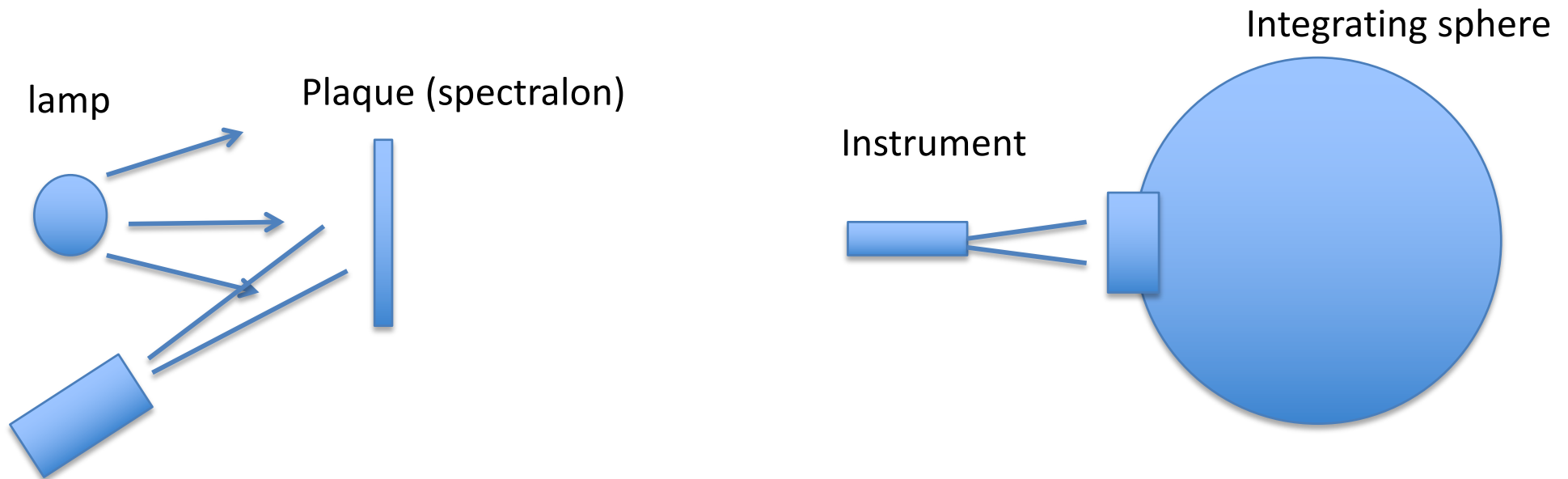
High Chl



Filter 1:410, Filter 2: 440 nm, Filter 3: 490 nm, Filter 4: 530 nm)
Upwelling light field becomes more "cupped" at high chl.

Calibration: Look at a source of known Radiance

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



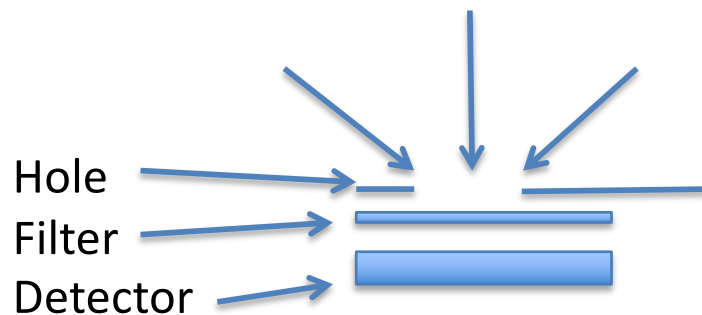
Instrument

Note how radiance works from plaque, $L = E/\pi$

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

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

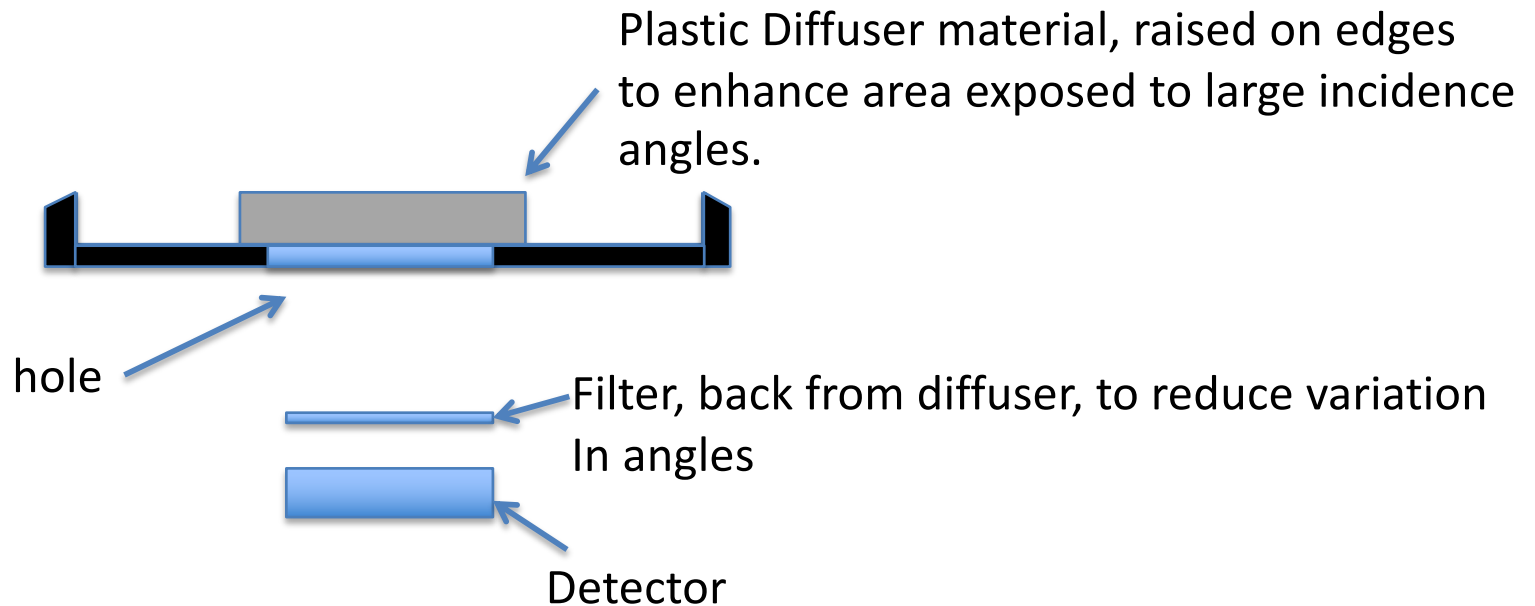
Perfect detector would be a hole, with a detector right behind that collects all the light which passed through the hole:



Problems:

- 1) Filter, typically interference filter, has an angular dependence of spectral transmission
- 2) Detectors also have angular dependence of 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.

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



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

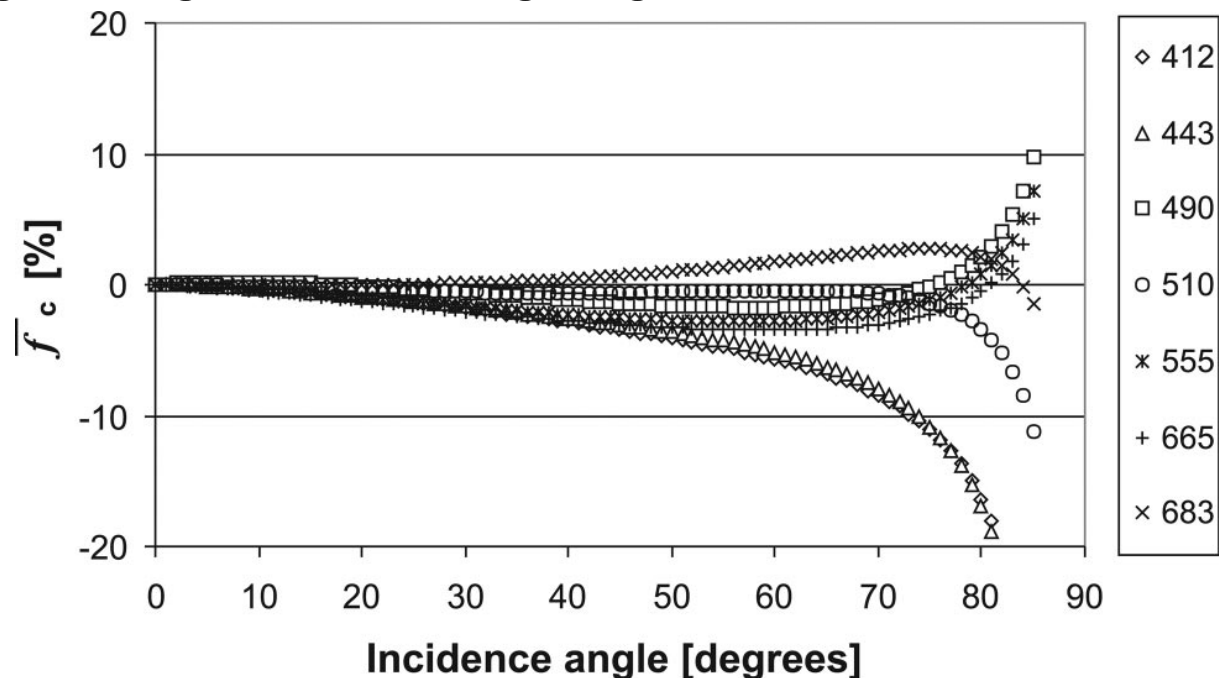
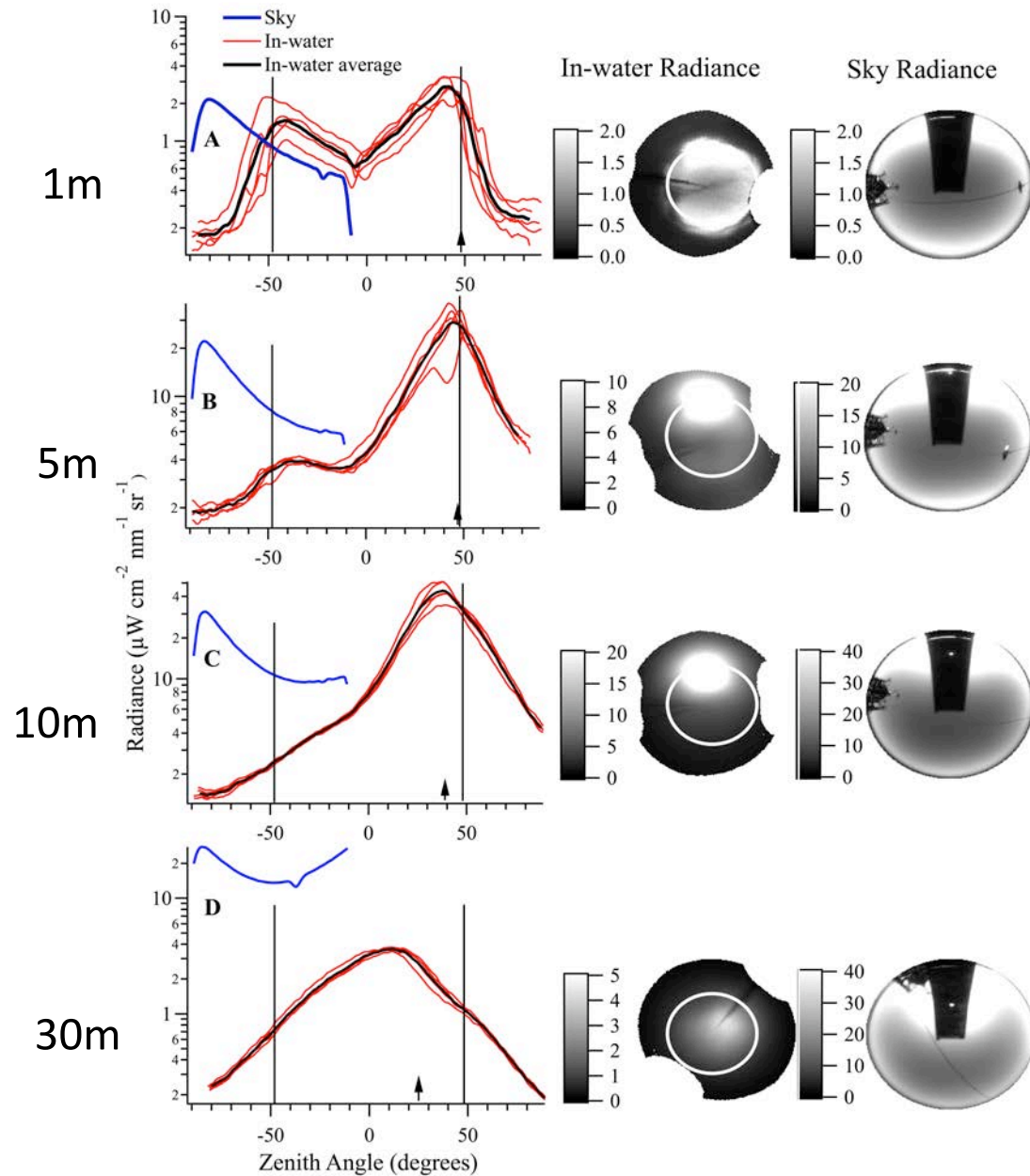


Fig. 3. Average cosine errors $\bar{f}_c(\theta, \lambda)$ determined at various center wavelengths.

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

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.

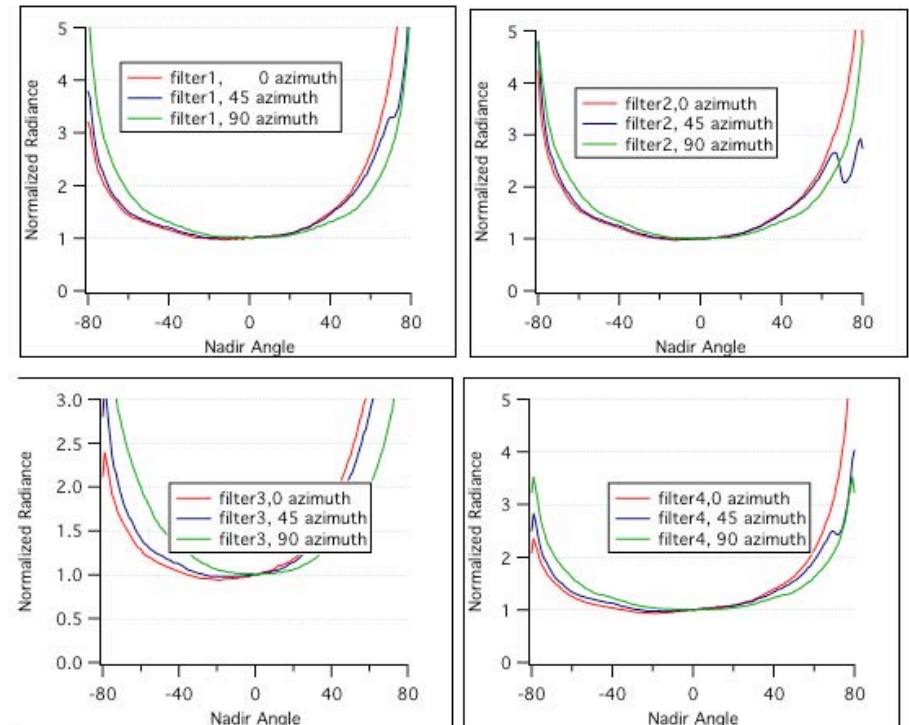
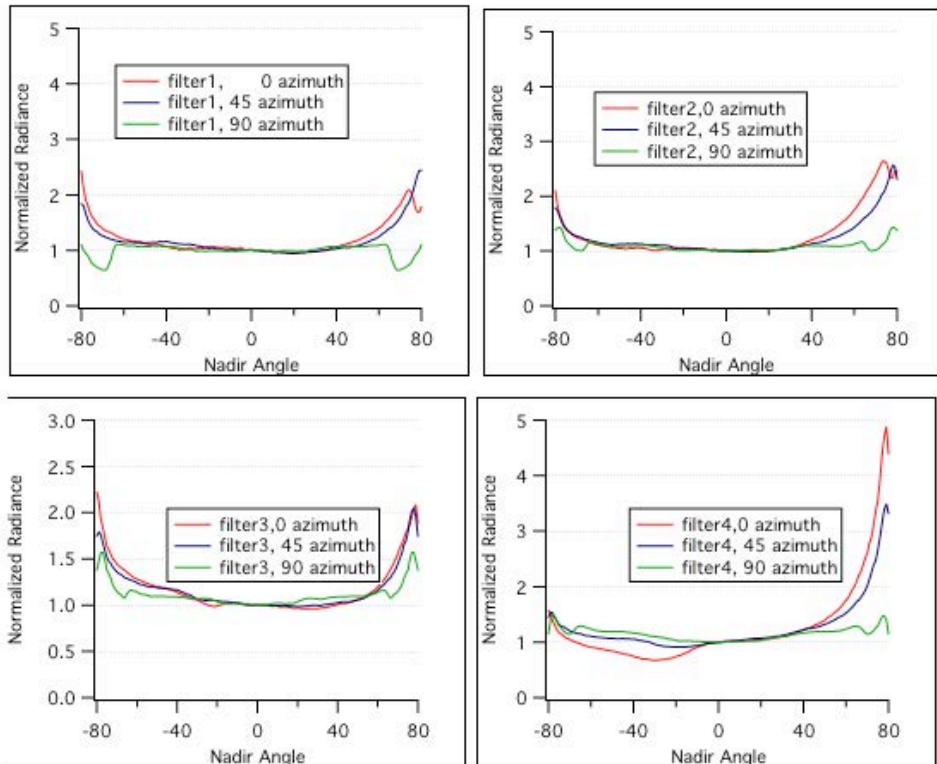


Upwelling Radiance distribution

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

Low Chl

High Chl

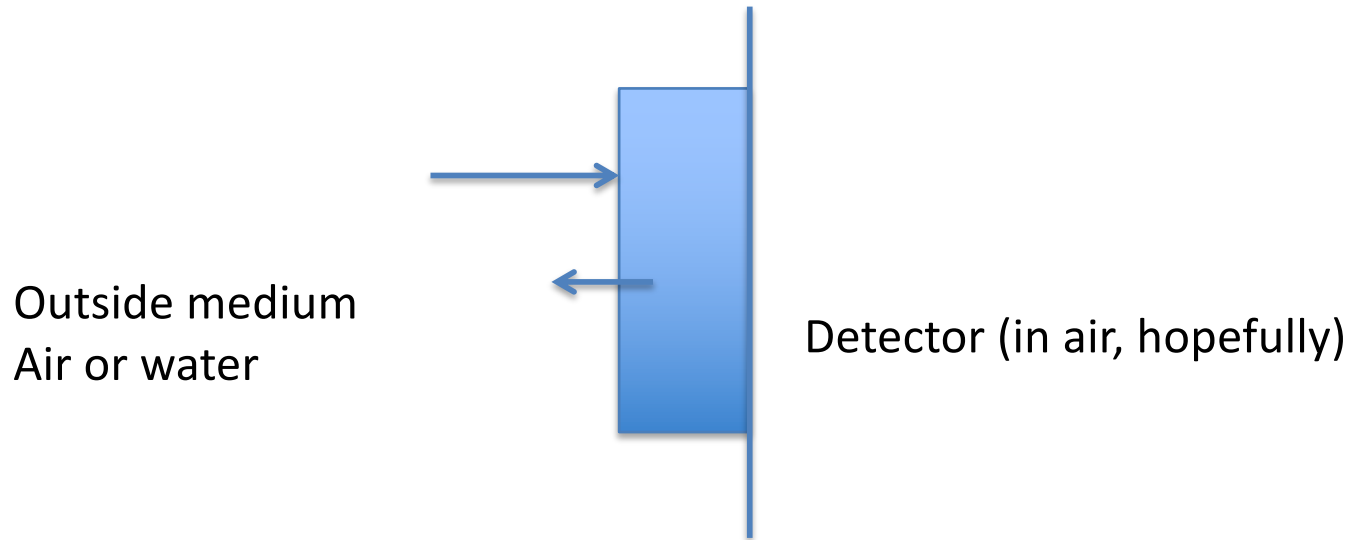


Error due to cosine collector much more significant, radiance is higher on edges

Irradiance

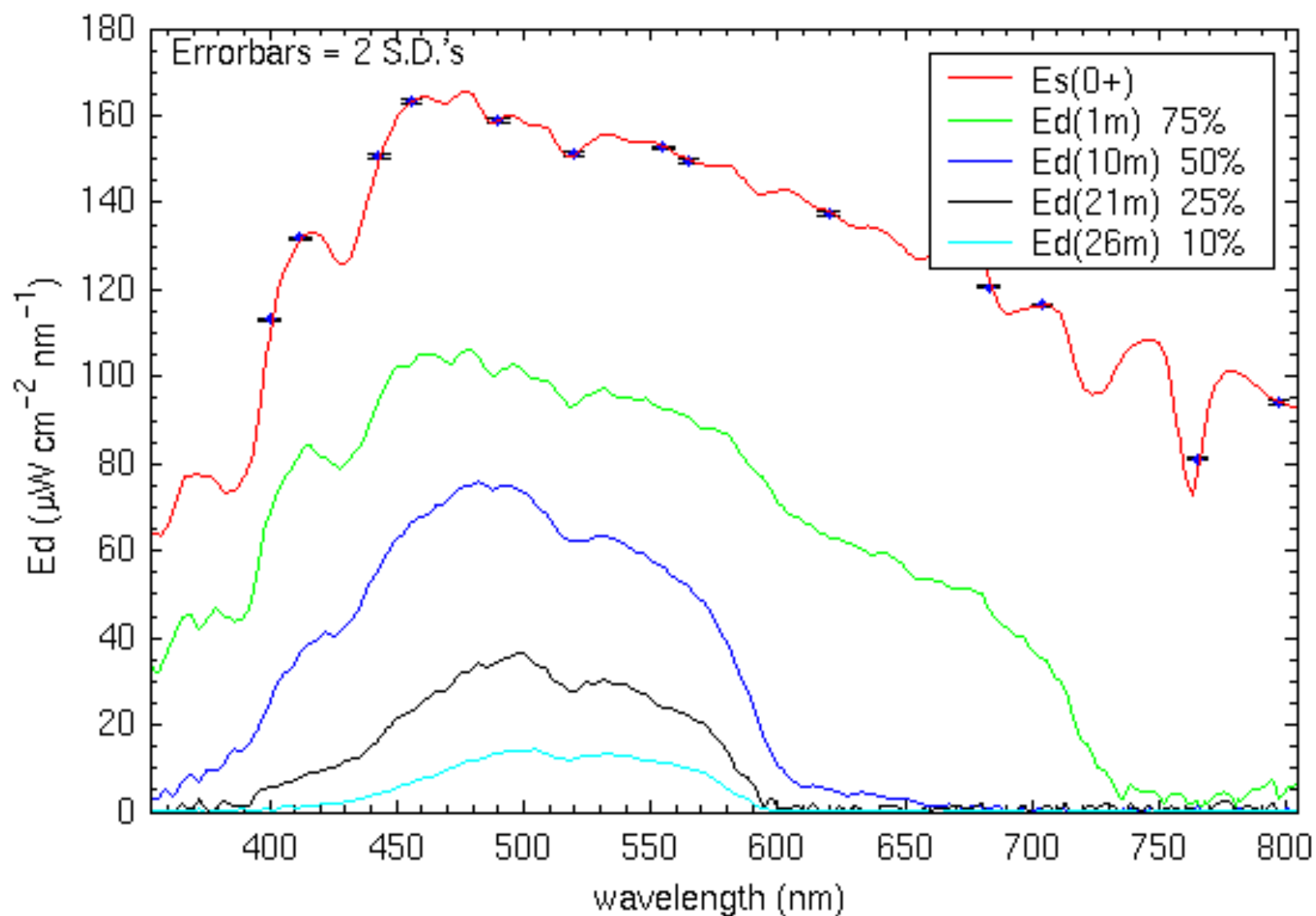
Should mention one more factor: Immersion coefficient, 30-40% correction.

Cosine collector efficiency different when operating in air or water



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 once it has gotten into collector. 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. IMPORTANT SWITCH IN SATLANTIC SOFTWARE!

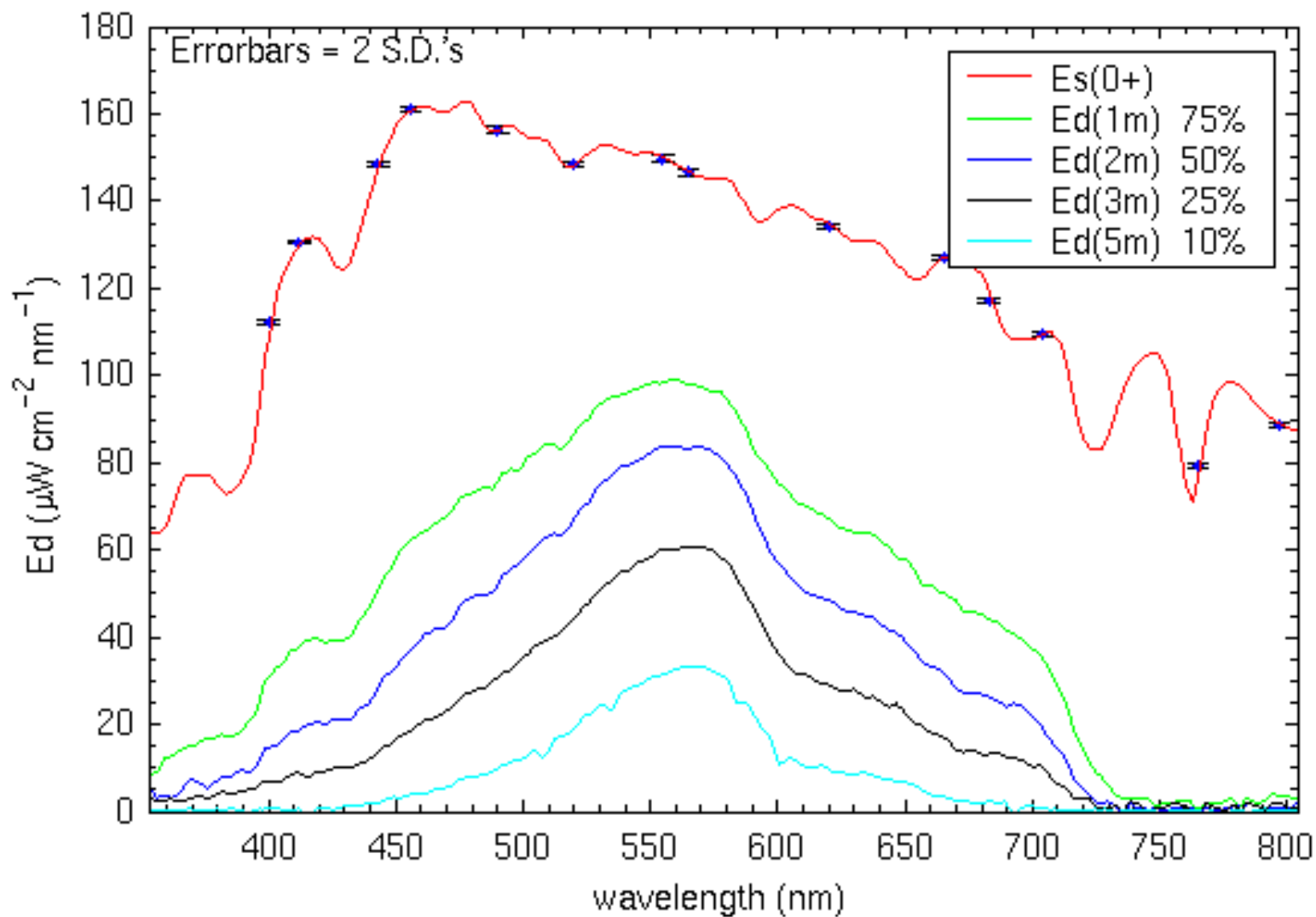
Irradiance



Blue water station (Data from Marlon Lewis, Satlantic)

Note...units $100 \mu\text{W cm}^{-2} \text{ nm}^{-1} = \text{W m}^{-2} \text{ nm}^{-1}$

Irradiance



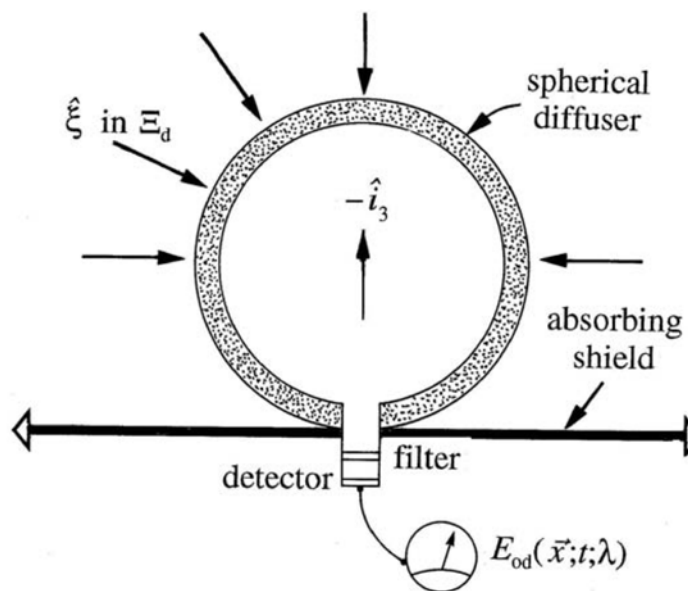
Green water station (Data from Marlon Lewis, Satlantic). Notice difference in depths in this plot and last one.

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

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

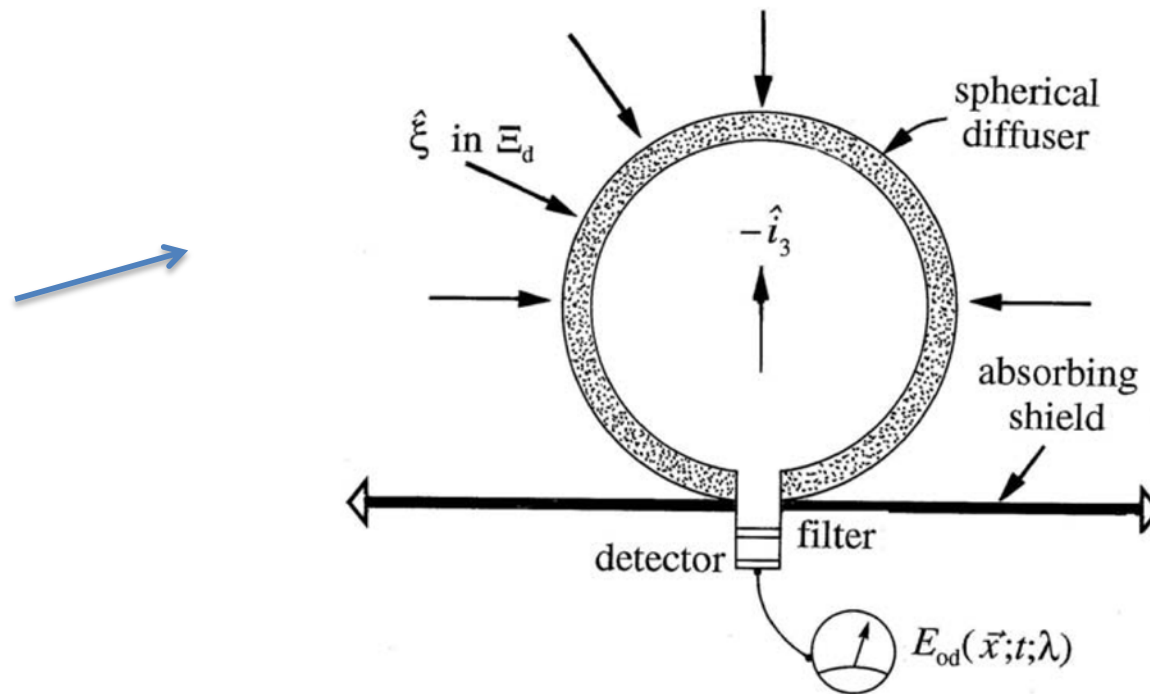
Want to collect all light coming to a single point, regardless of angle. Perfect collector would be as shown below, with the limit of the radius going to zero:

(from Curt's Book)



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?



Example numbers for scale.

Average cosine $\mu = E_d / E_{0=}$

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 $\mu\text{W cm}^{-2} \text{nm}^{-1}$

upwelling measurements at 505 nm

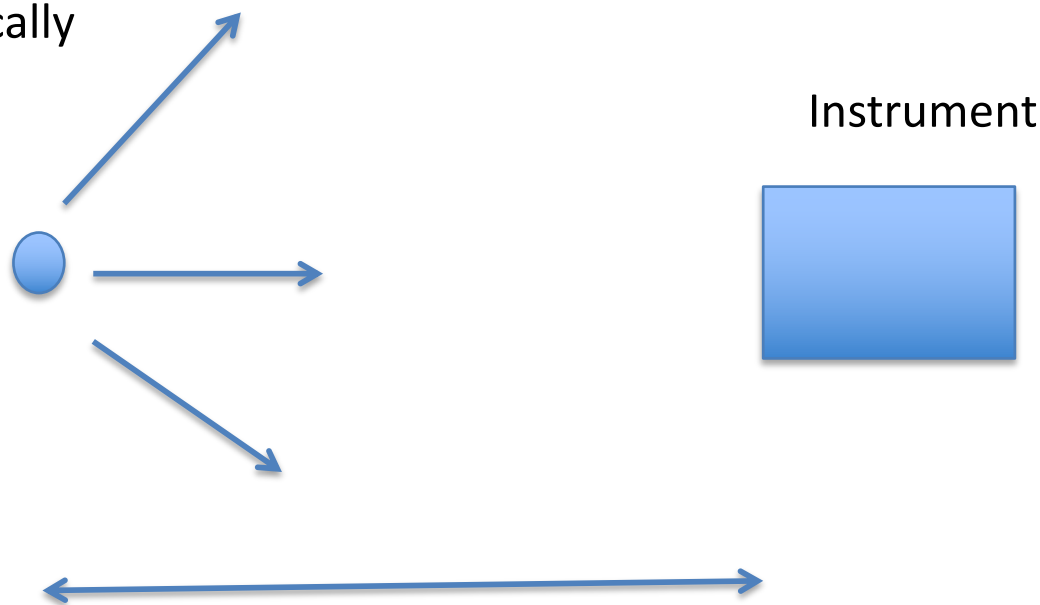
Downwelling measurements at 503 nm

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

Irradiance

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

Known
Source, typically
NIST lamp



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

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.....

Remote sensing reflectance

$$R_{rs} = L_w / E_s$$

L_wwater leaving radiance (above surface)

E_sdownwelling irradiance

Why remote sensing reflectance? Want something to relate to satellite measurements, and is an apparent optical property (relatively dependent on water properties, less on illumination conditions):

Above water techniques:

$$Rrs = Lw / Es$$

$$Rrs = (L_{\text{measured}} - L_g) / Es$$

$$L_g = L_{\text{sky}} * \text{Reflectivity of surface}$$

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, SBA...skylight blocked approach

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

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 (or L_{wn}) = $L_w/E_s * E_o$ (sometimes $/r^2$)

E_o extra terrestrial solar irradiance

r = earth sun distance

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. Will also account for differences in solar zenith angle.

f comes from $R = E_u/E_d = f b_b/a$ f is factor which relates b_b/a to the irradiance reflectance. Actually a function of sun angle (and atmospheric parameters). Note this R used to be really popular (especially with the French) as you could use one irradiance spectrometer and flip it over....

Earlier work (I think Gordon started it) reasonable approximation.... $R = 0.33 b_b/a$

Helpful to have these simple rules in your head....

$Q = E_u/L_u$ (actually π if isotropic...generally between 3.5 and 6) or more generally $Q(\theta_o, \theta, \Phi) = E_u/L(\theta_o, \theta, \Phi)$ 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):

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

Or full blown correction (to solar zenith angle =0):

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

Series of Morel et al papers culminating with:

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.

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.

Trying beyond Case 1:

Lee et al., “An IOP-centered approach to correct the angular effects in water-leaving radiance”, *Applied Optics*, **50**, 3155-3167 (2011).

Fan, et al., Neural network method to correct bidirectional effects in water leaving radiance, *Applied Optics*, 10-21, 2016.

Gleason et al., “Detailed validation of the bidirectional effect in various Case I and Case II waters”, *Optics Express*, 20, 7630 – 7645 (2012).

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 $a \cdot r$...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 (big effect in upwelling light field above 575 nm.....where is shadowing going to be largest?)

New results for MOBY using Simulo (Edouard Leymarie program)

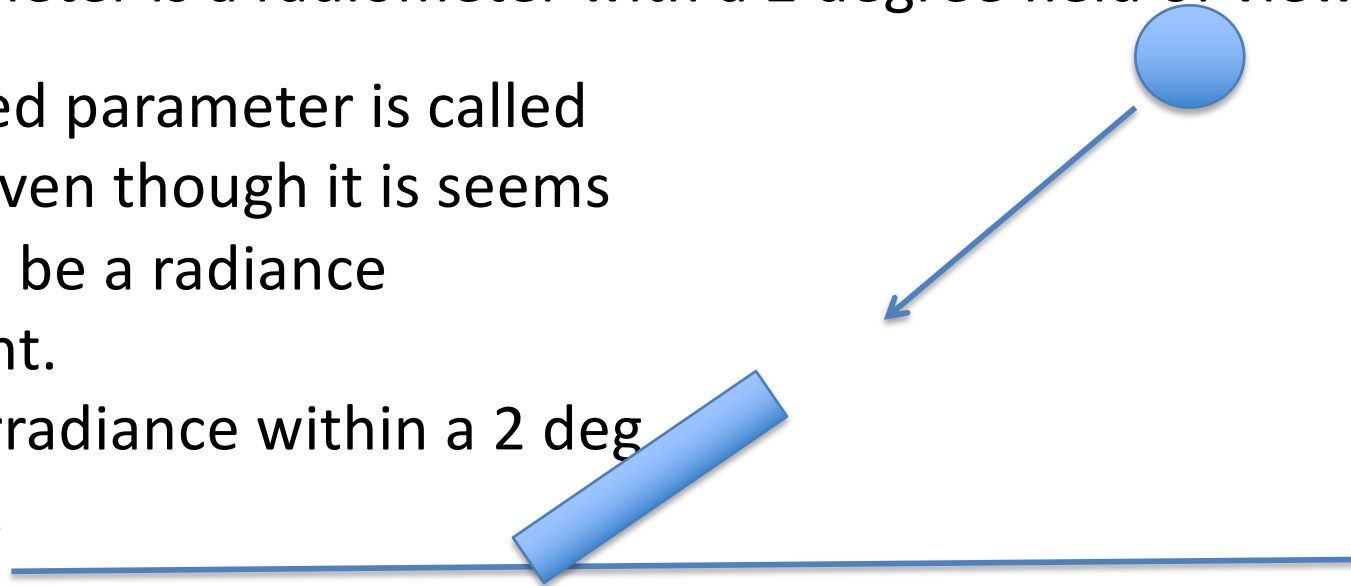
A very short atmospheric measurement technique

Sunphotometry to get at least one atmospheric parameter, aerosol optical depth.

Sunphotometer is a radiometer with a 2 degree field of view

The measured parameter is called irradiance, even though it seems like it should be a radiance measurement.

Measuring irradiance within a 2 deg field of view.



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

$$E = E_0 \exp(-\tau m)$$

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

E_0 is extra terrestrial solar irradiance, corrected for earth-sun distance in instrument units

m is airmass (approximately $1/\cos(\theta_0)$ for $\theta_0 < 70$ 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_0 , and sun angle (calculate) then measure E , can calculate τ . But need to know E_0 very accurately....cannot calibrate in lab well enough so to calibrate instrument must use Langley technique (or compare with known photometer).

