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Radiometric quantities and their measurement

Ken Voss, Ocean Optics Class, Darling Center, Maine
Summer, 2013

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

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

1) Multi-channel instruments

2) Hyperspectral instruments

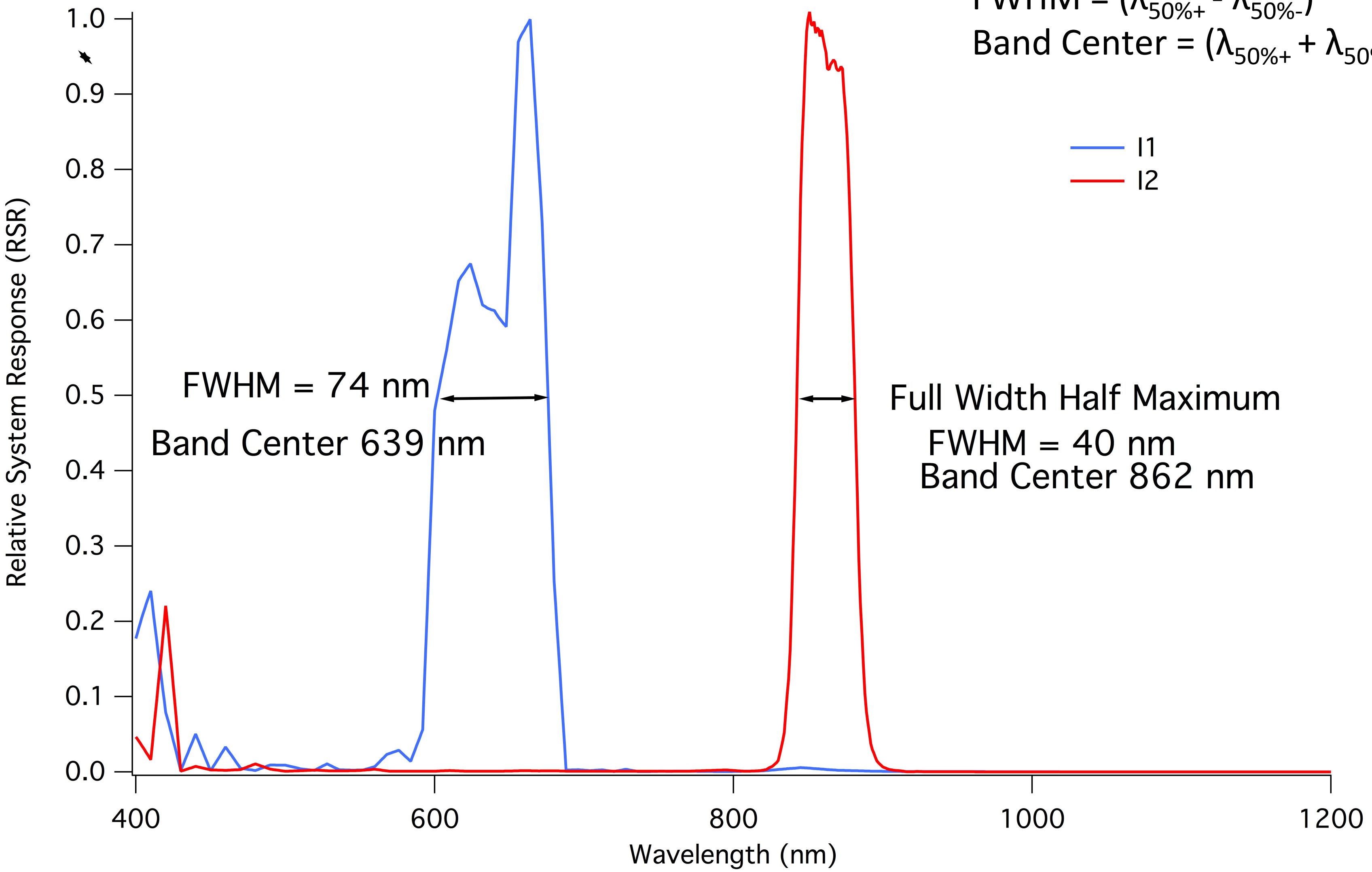
3) PAR (or other broadband for example UV-A) sensor

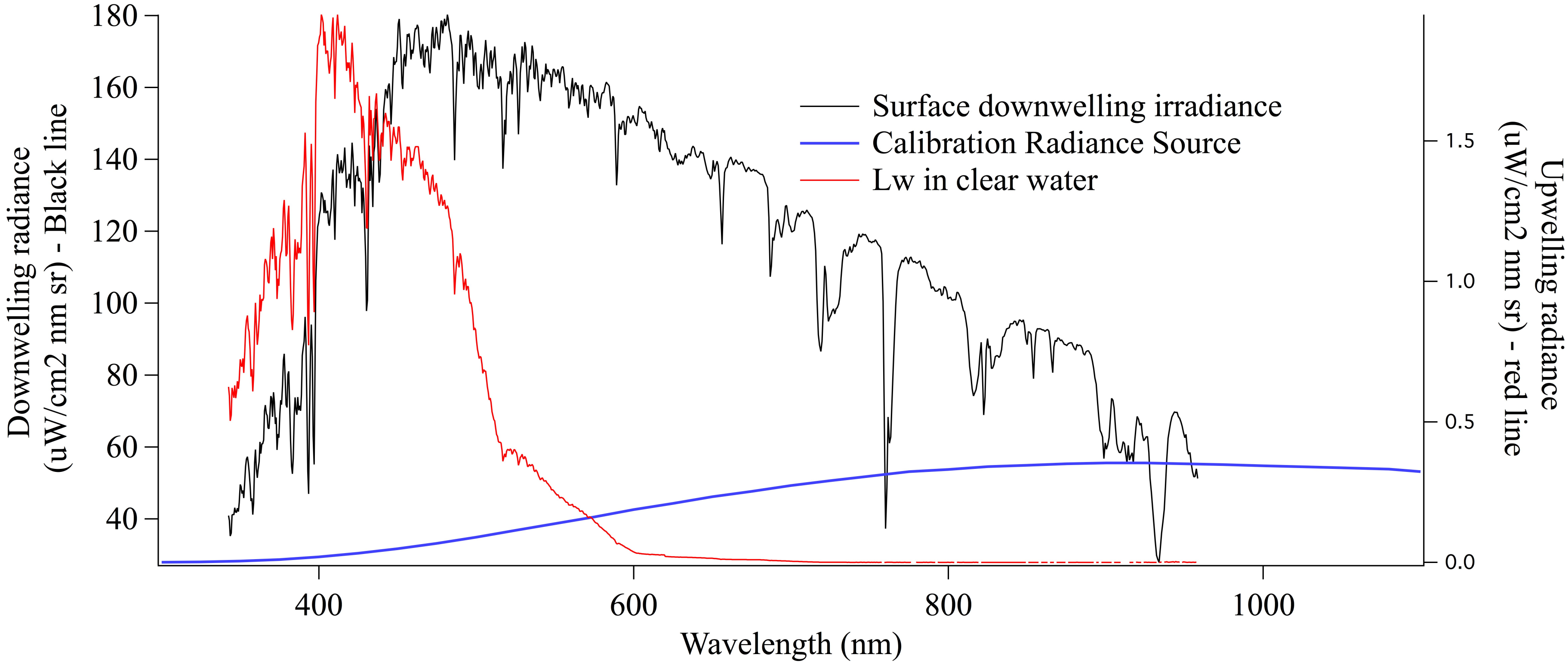
Narrow band, multi channel instruments

1) Typically channels have spectral bands of 10nm wide.
   a) Most ocean optics parameters do not have sharp features.
   b) May try to match some other spectral shape (SeaWiFS bands).

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 (looking at different "color" sources)

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





180
160
140
120
100
80
60
40
Downwelling radiance
(uW/cm2 nm sr) - Black line
400
600
800
1000
Wavelength (nm)
Surface downwelling irradiance
Calibration Radiance Source
Lw in clear water
1.5
1.0
0.5
0.0
Upwelling radiance
(uW/cm2 nm sr) - red line

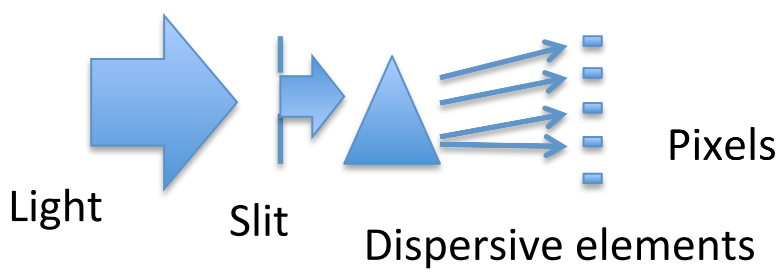
Hyperspectral Detectors

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

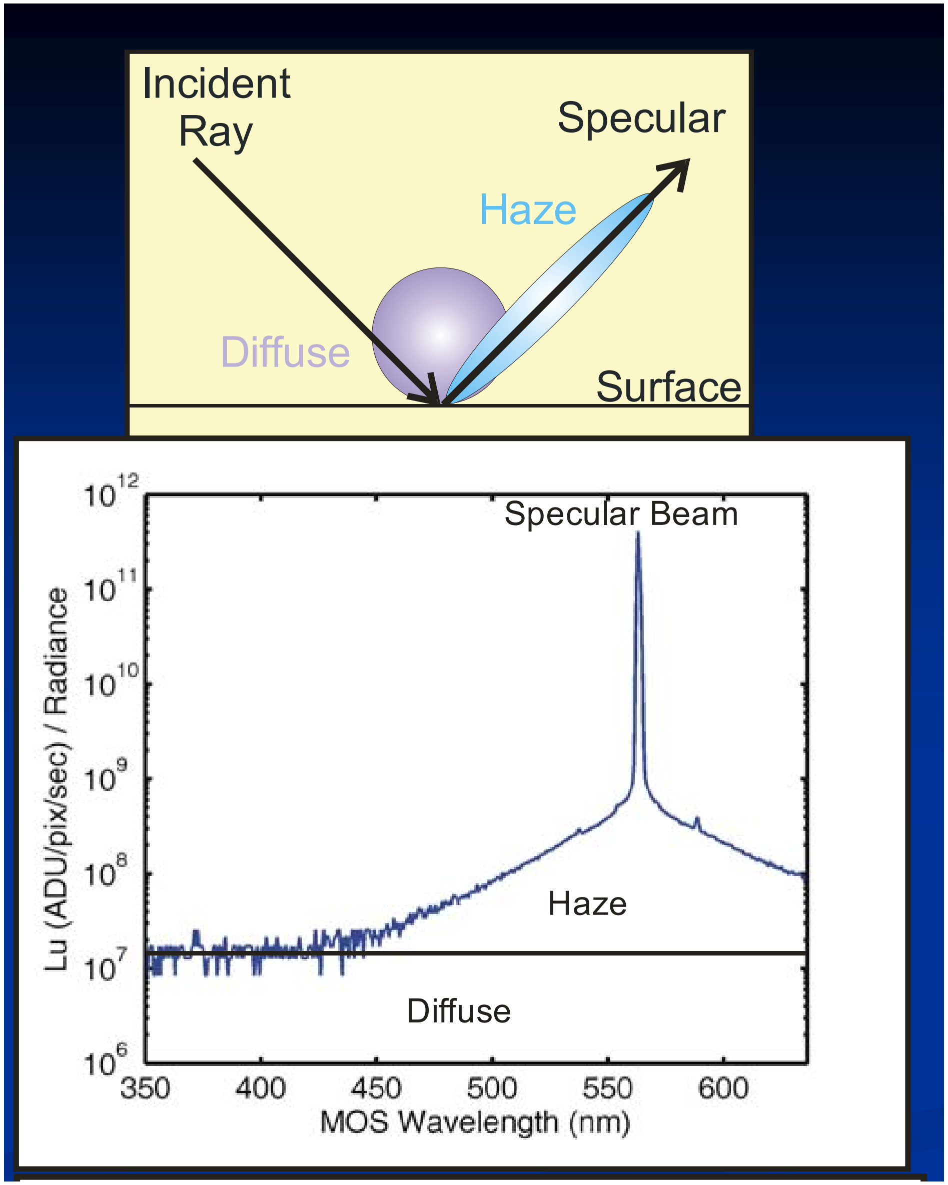
2) Typically grating or prism dispersive elements.

3) Can build integrated channels, match satellite sensor channels, etc.

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: WISP reports every 0.3 nm, BW 5 nm.

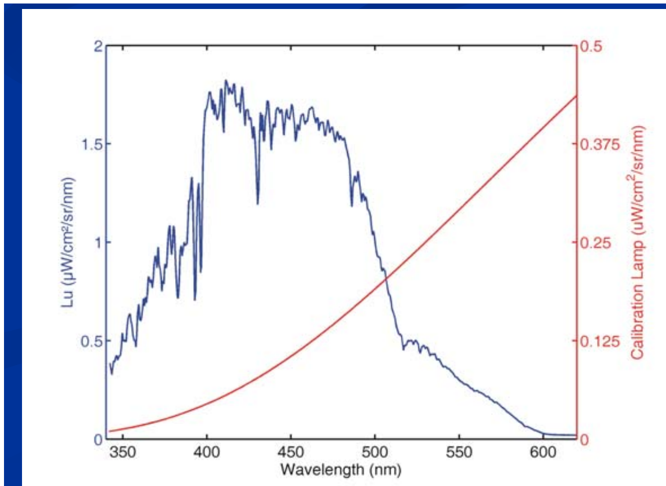


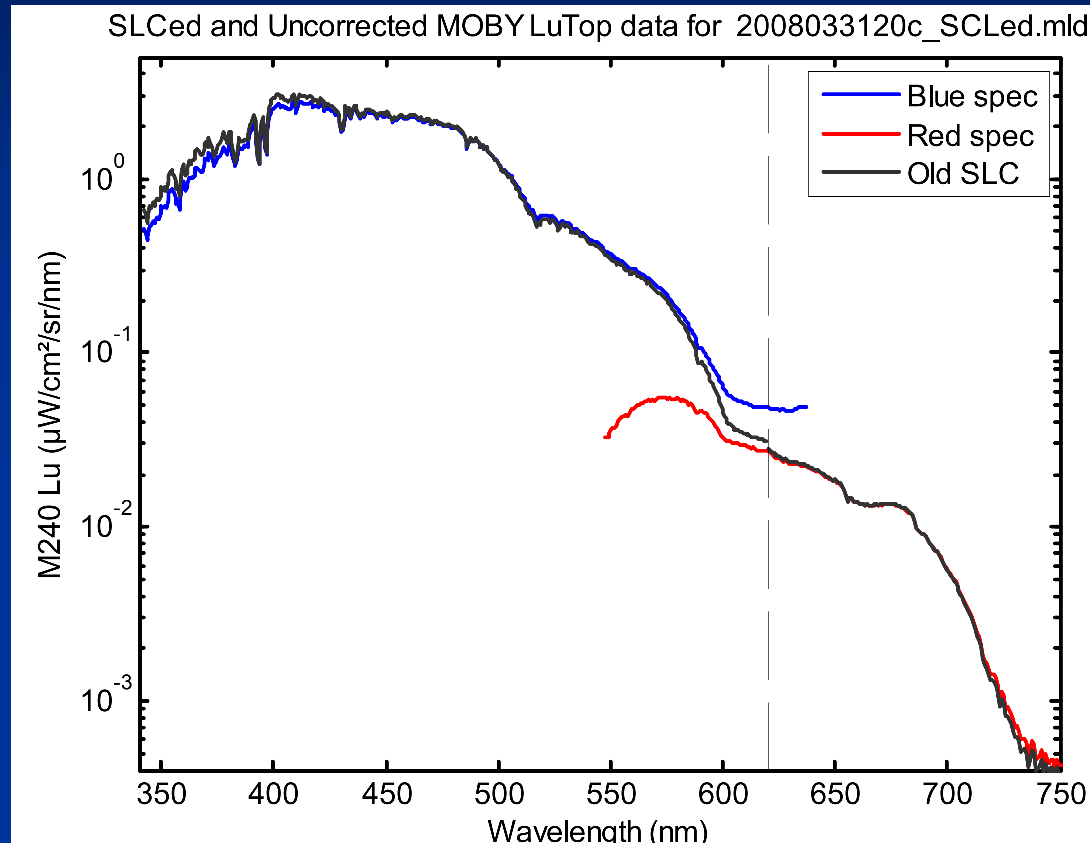
Dispersion: cm/nm



From Stephanie Flora
Moby project

Detectors





From Stephanie Flora, MOBY project

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.

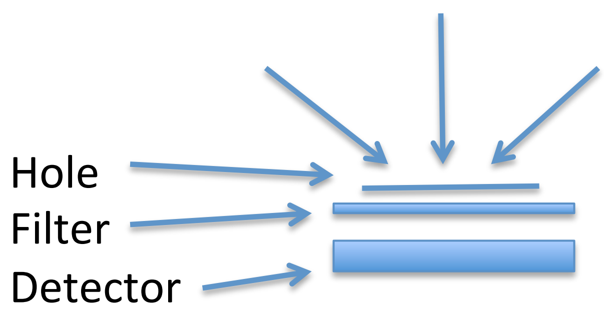
2) Silicon detector through photoelectric effect, should sort of do this:
   Each photon generates one photo-electron (perfect quantum efficiency)

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). Physically not a "nice" measurement, but easy.

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

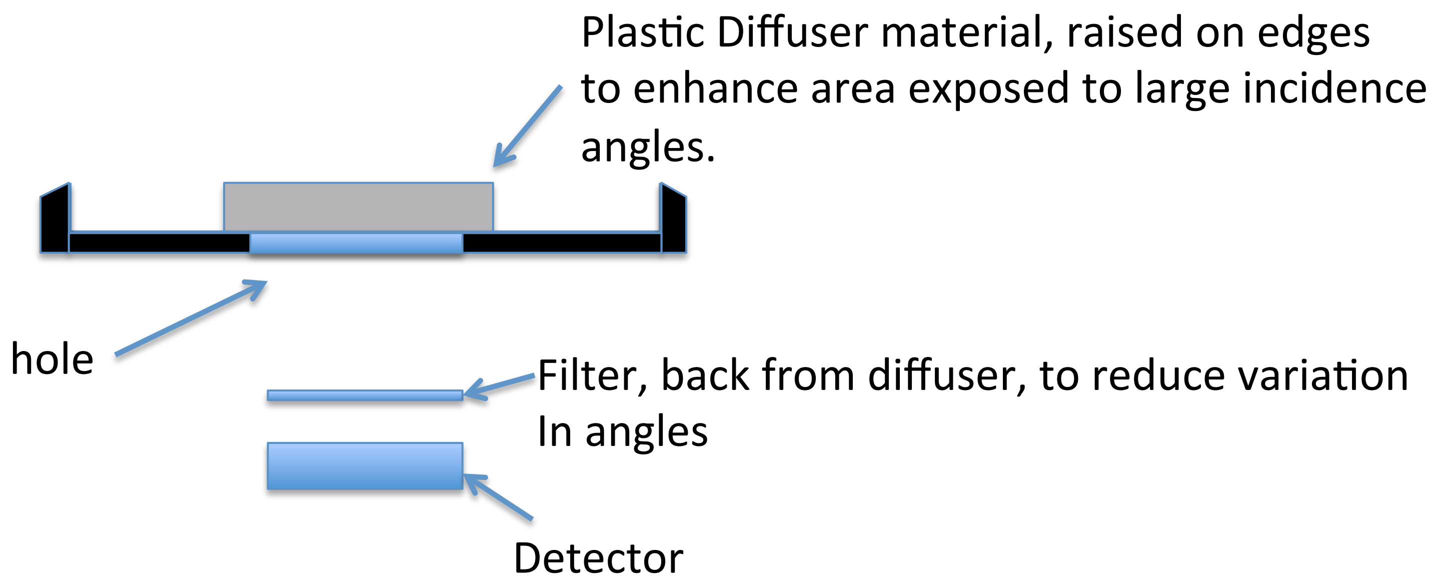
$$E_d(\theta,\phi,\lambda) \equiv \int_{UH} L(\Omega,\lambda)|\cos\theta| d\Omega = \int_0^{2\pi}\int_0^{\pi/2} L(\theta,\phi,\lambda)|\cos\theta|\sin\theta d\theta d\phi$$

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 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 2-3 decrease with increasing incidence angle.

Real Irradiance detectors try to enhance response to light at large incidence angles. Typical design shown below:



Note: this is in air, not water, but is typical

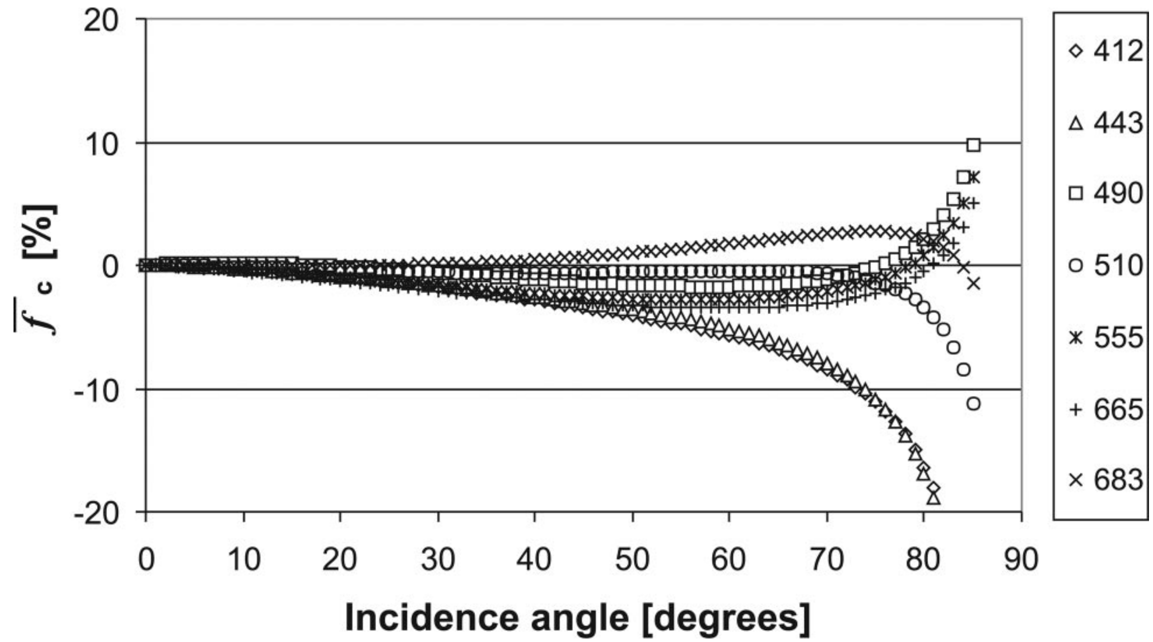
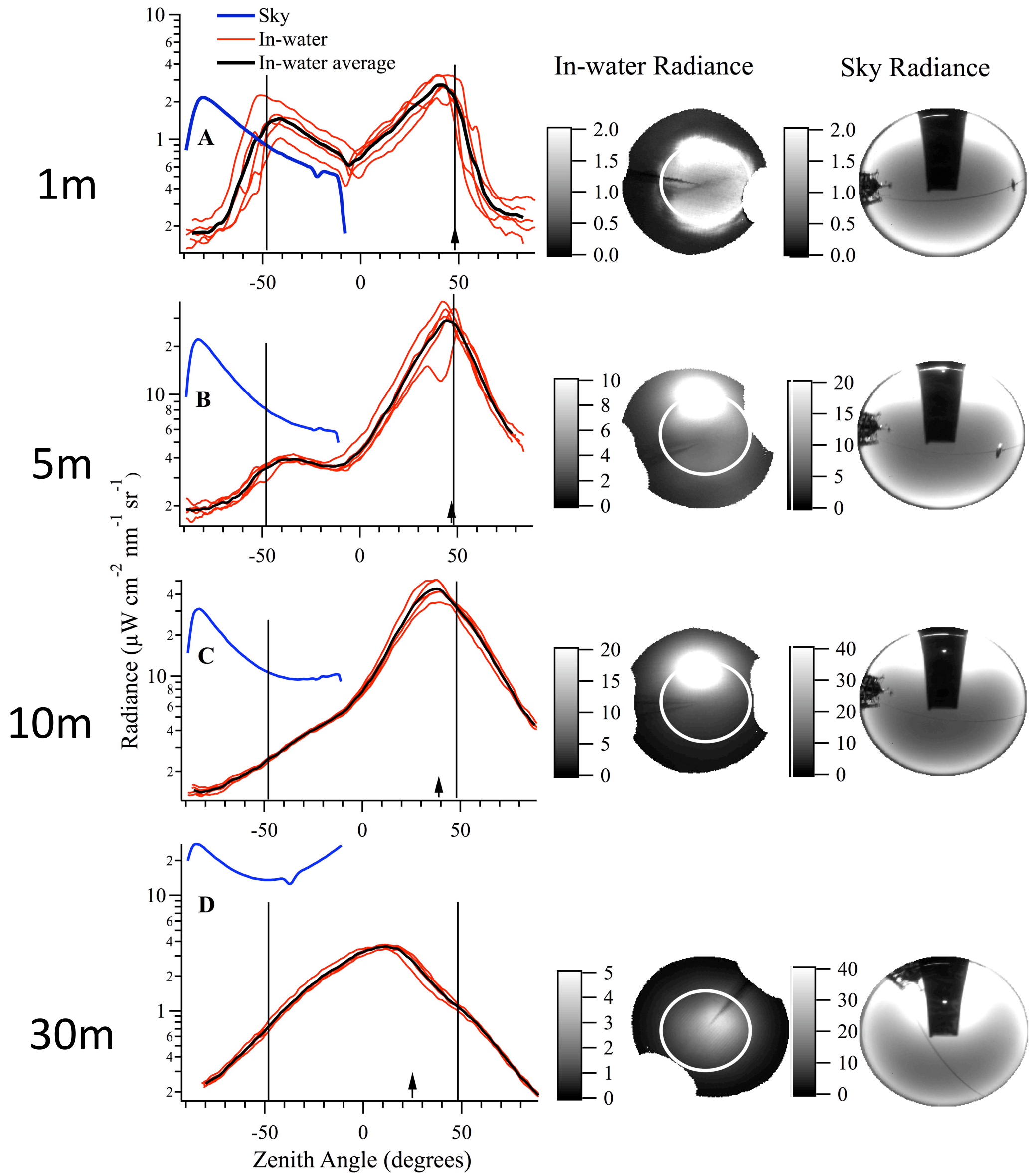


Fig. 3. Average cosine errors $\bar{f}_c(\theta, \lambda)$ determined at various center wavelengths.

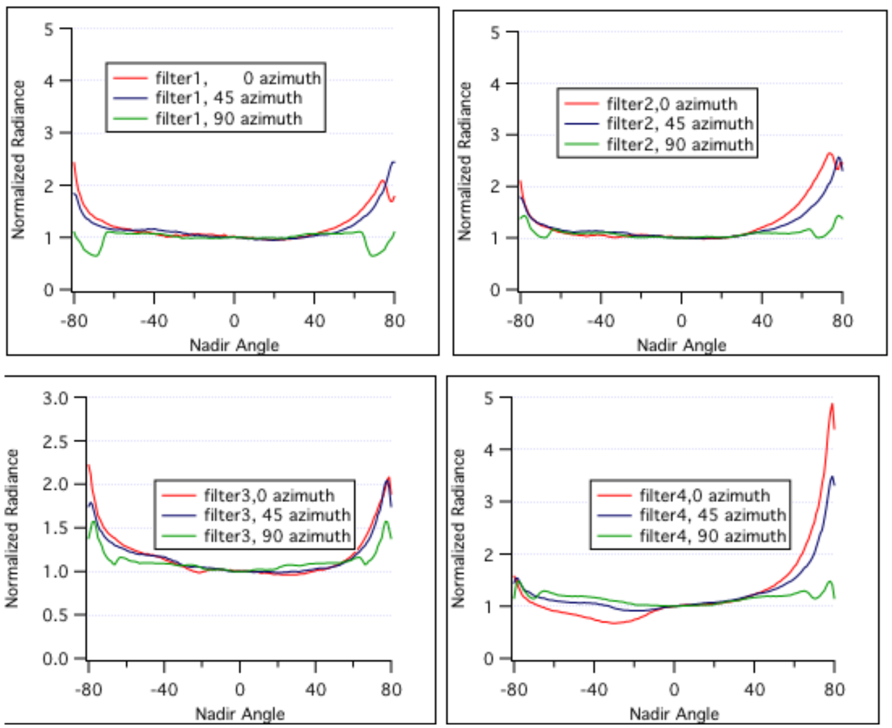
Zibordi and Bulgarelli, AO, pg:5529-5538 (2007)

Downwelling Radiance distribution

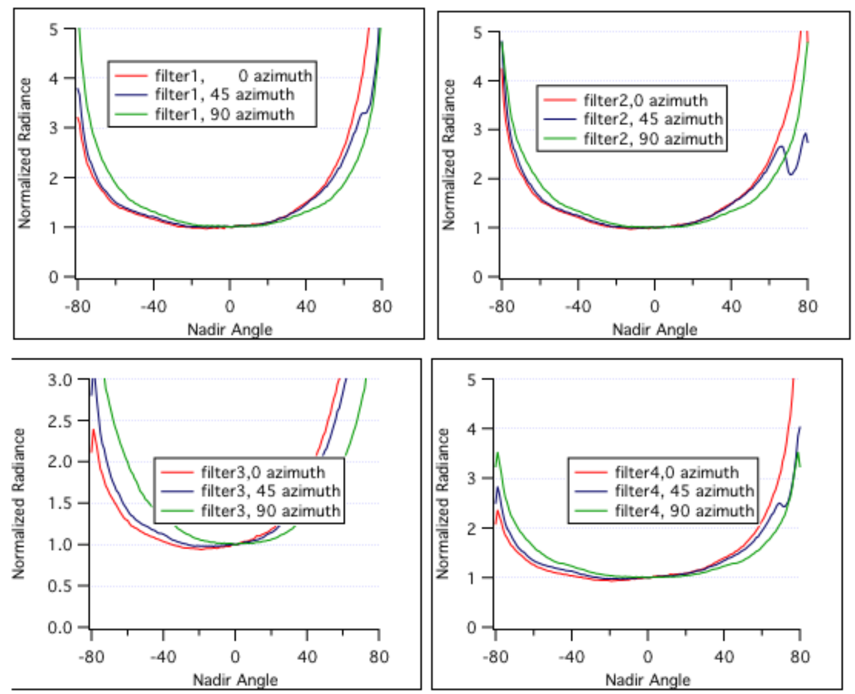


Upwelling Radiance distribution

Low Chl



High Chl

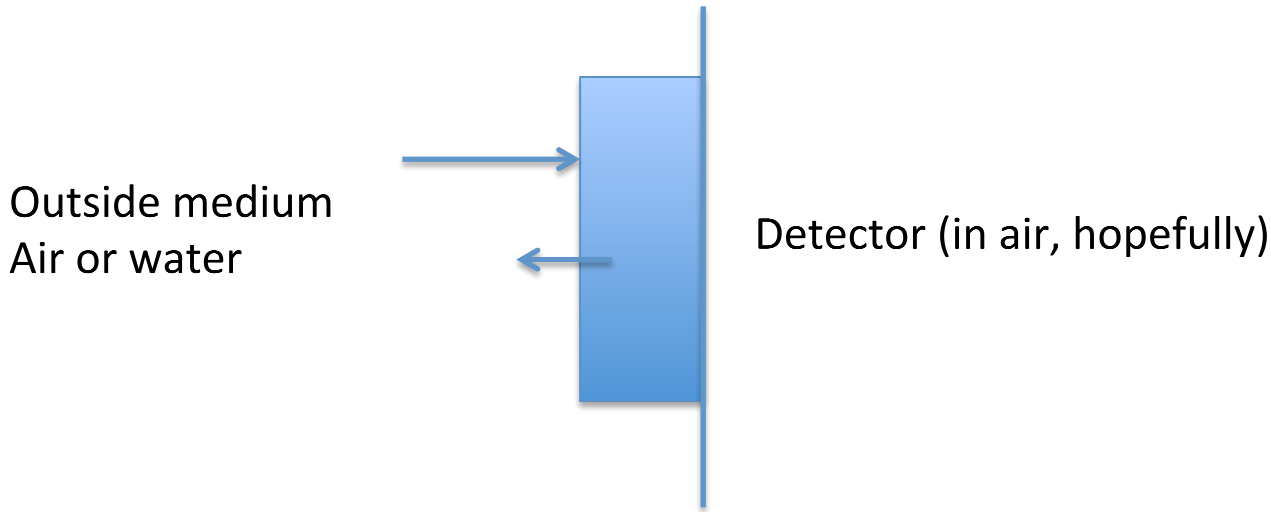


Error due to cosine collector much more significant

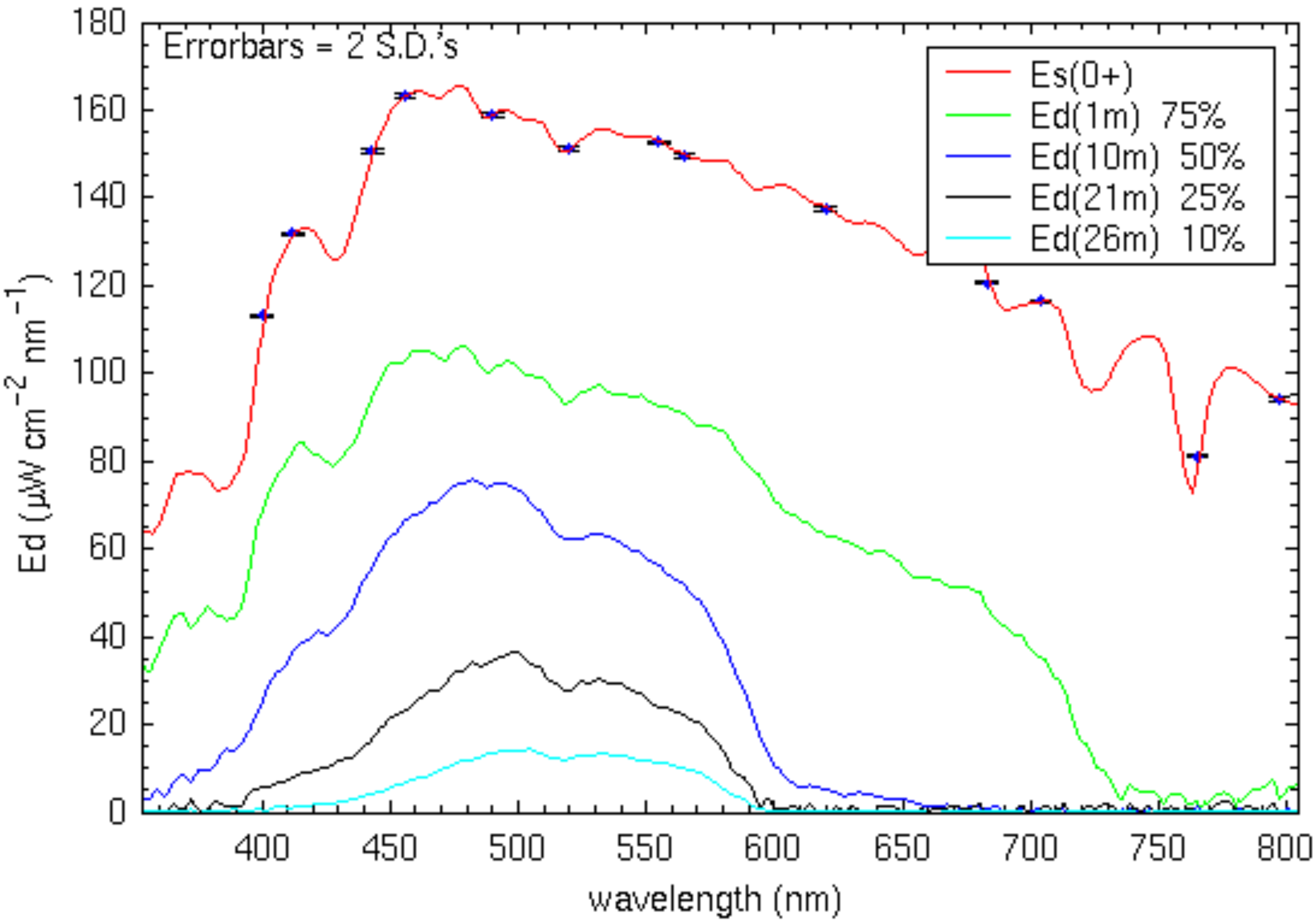
Irradiance

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

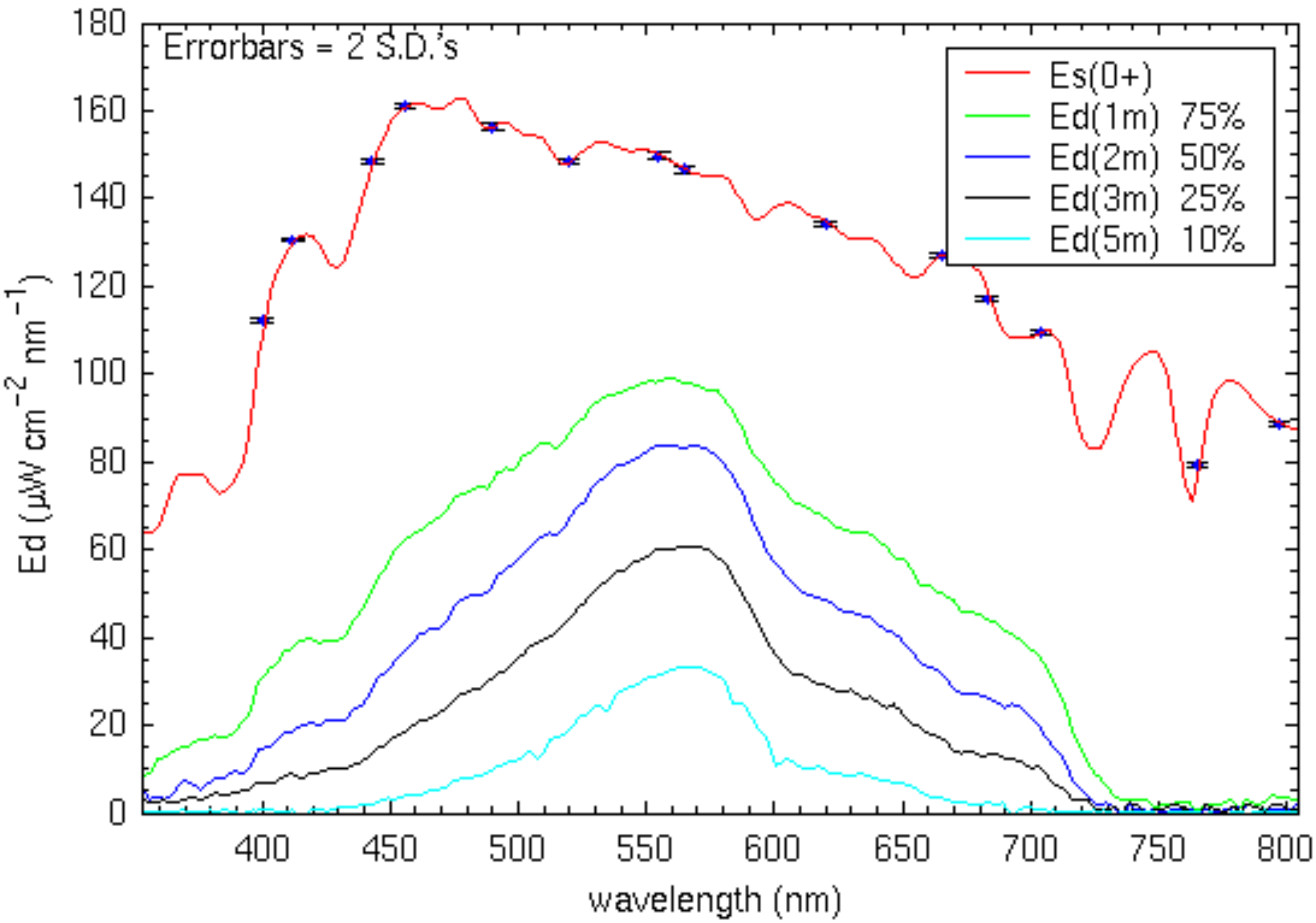
Cosine collector efficiency different when operating in air or water



Just drew normal incidence, really all over the place. 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.

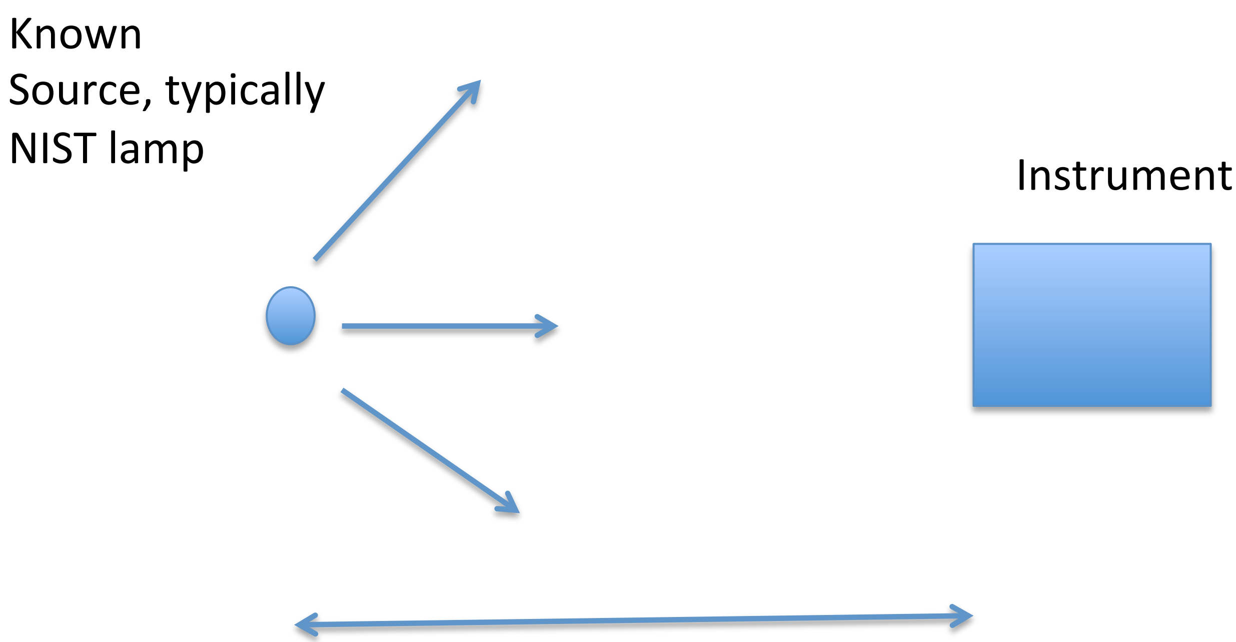


Blue water station (Data from Marlon Lewis, Satlantic)



Green water station (Data from Marlon Lewis, Satlantic)

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



Specified distance (typically 50 100 cm), note 1/r2 dependence

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)

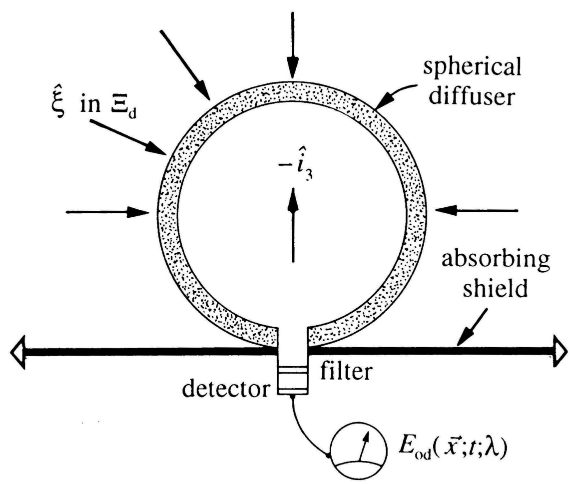


Fig. 1.7. Schematic design of an instrument for measuring spectral scalar irradiance.

Problems:

Would like 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?

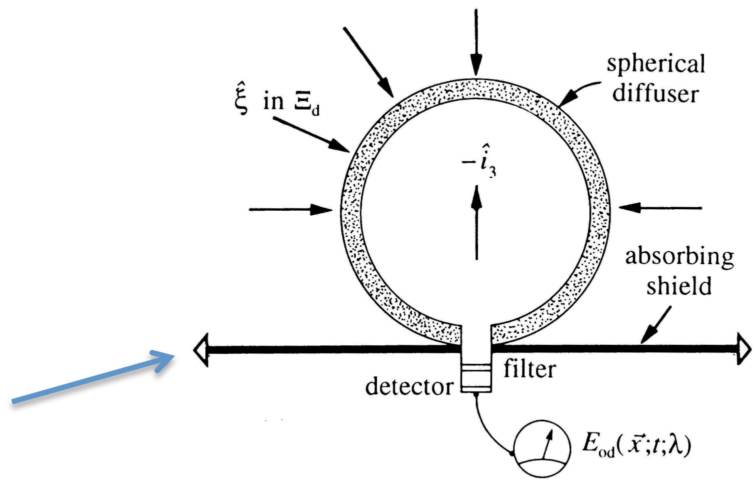


Fig. 1.7. Schematic design of an instrument for measuring spectral scalar irradiance.

$\mu = E_d / E_o$

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 of downwelling points to 44 deg, while upwelling is 67 deg

Definition of Radiance:

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

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

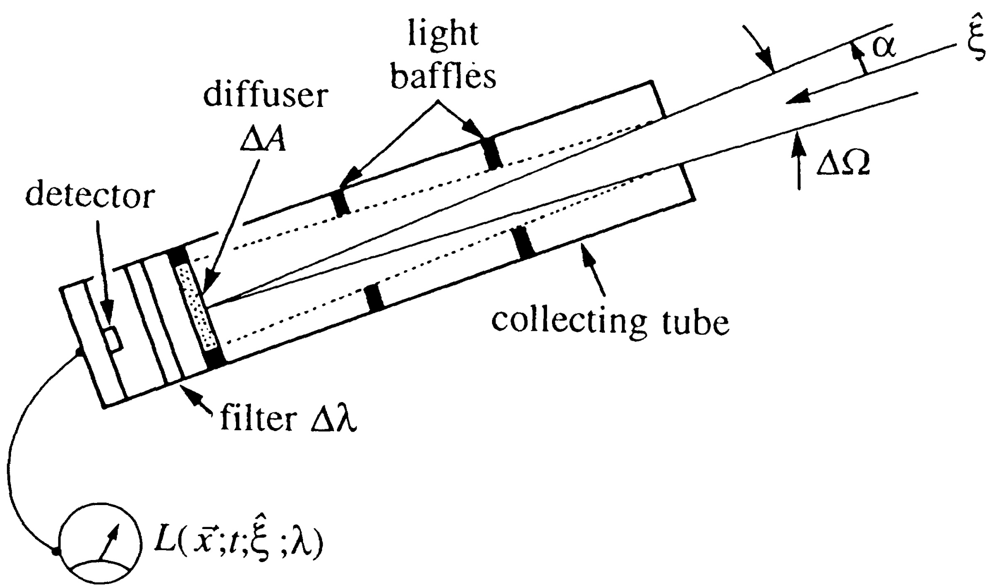
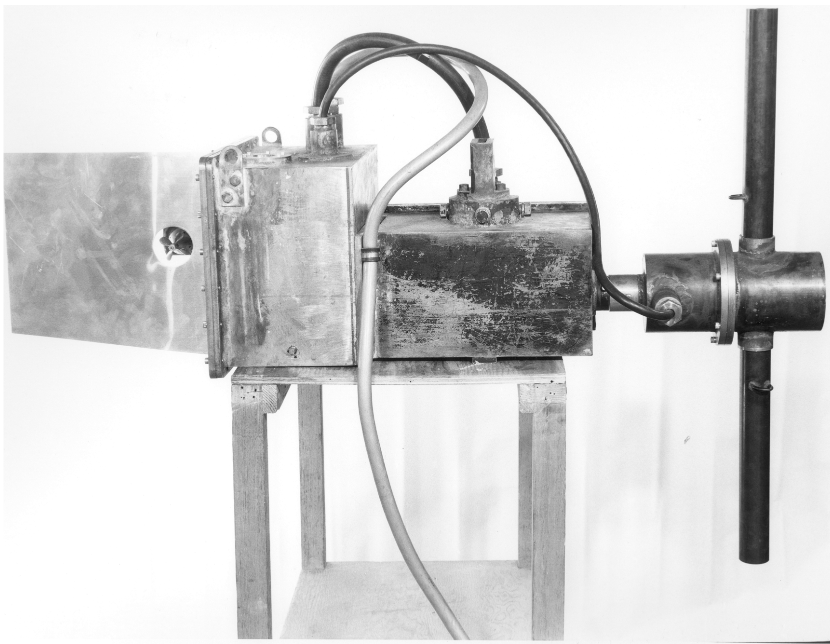


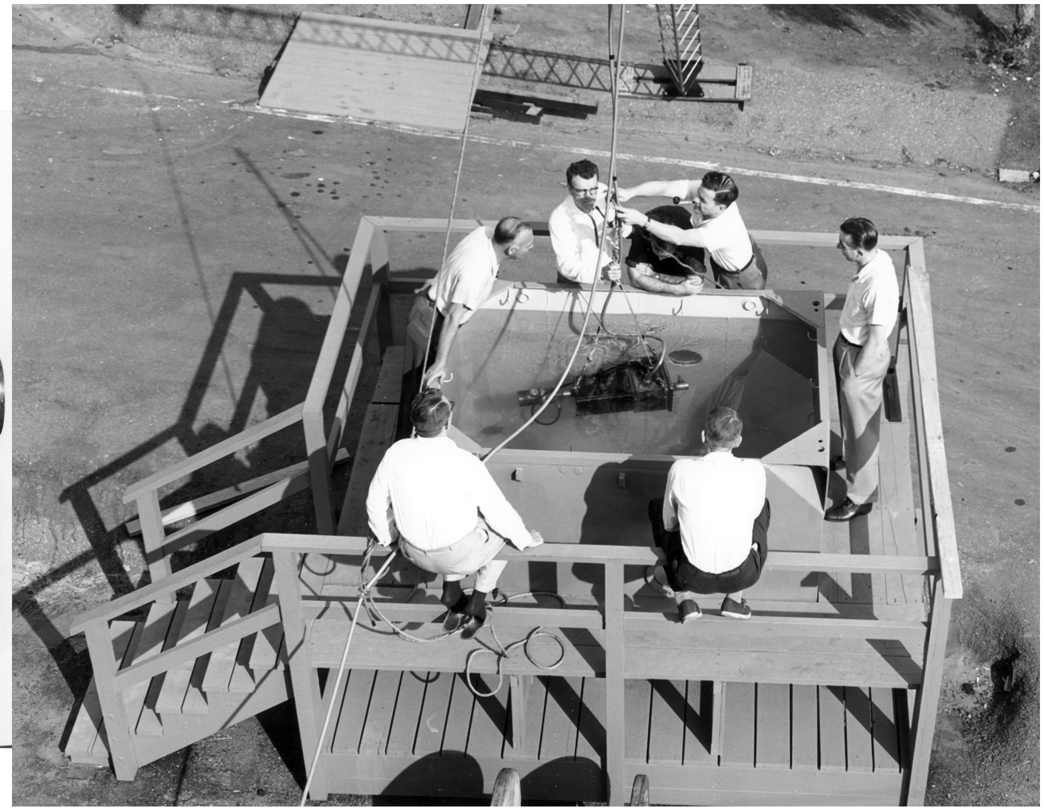
Fig. 1.5. Schematic design of an instrument for measuring unpolarized spectral radiance.

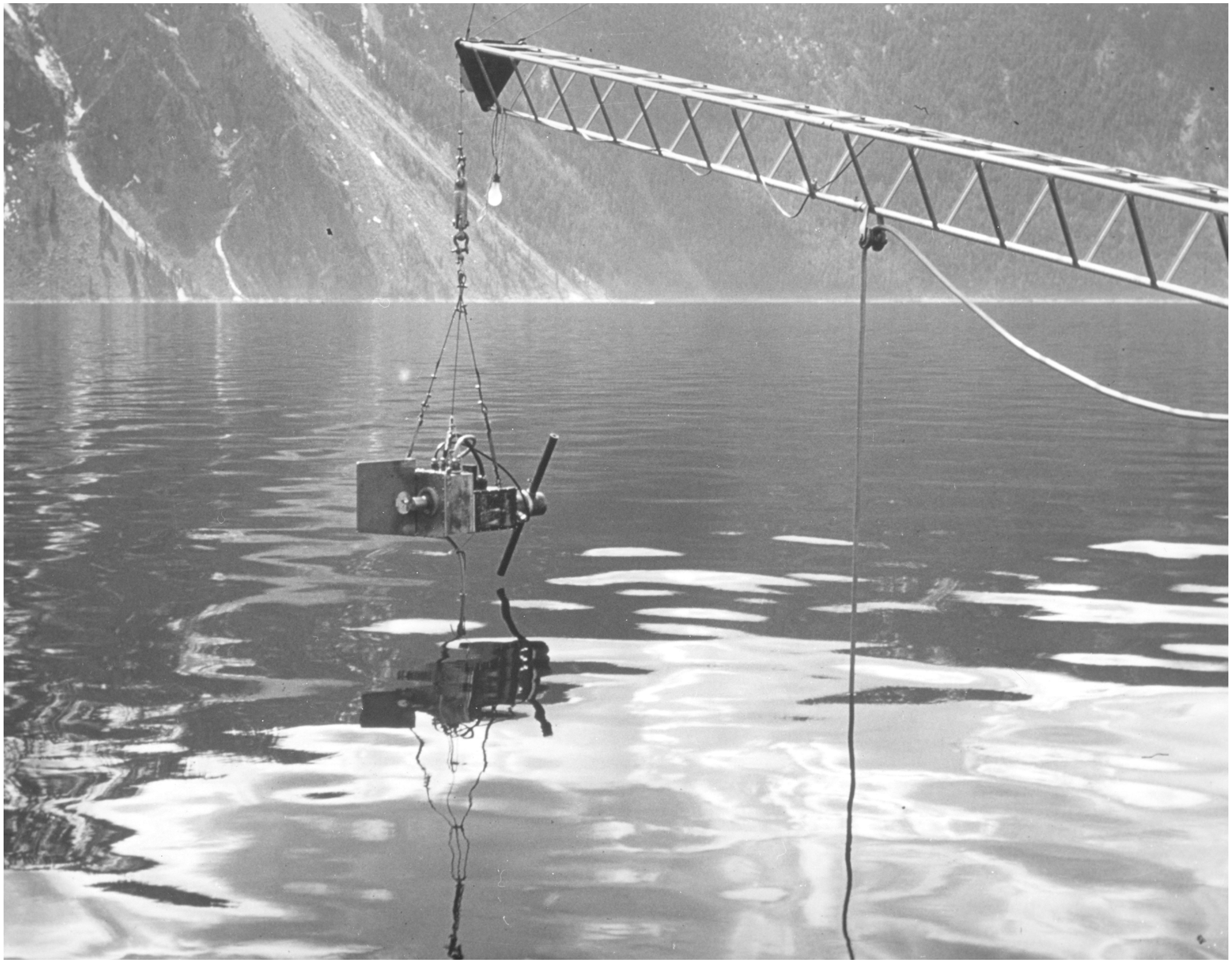
Most often Radiance measured with some sort of Gershun tube device in a single direction (typically upwelling nadir).

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).

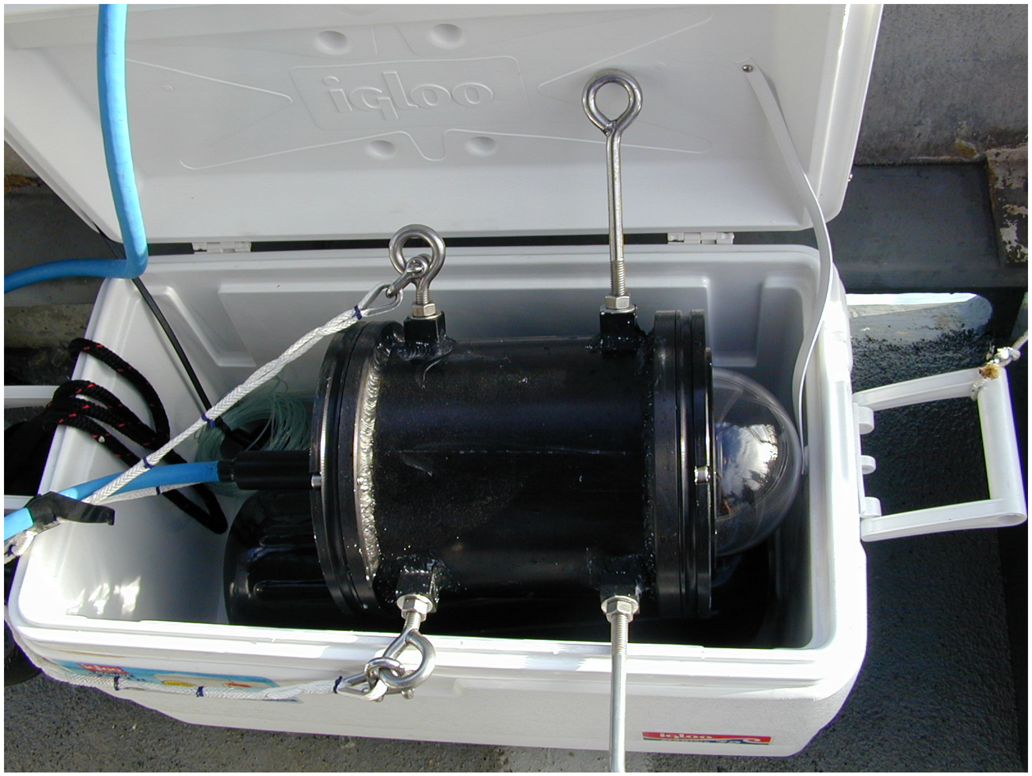
Example instruments, Tyler :

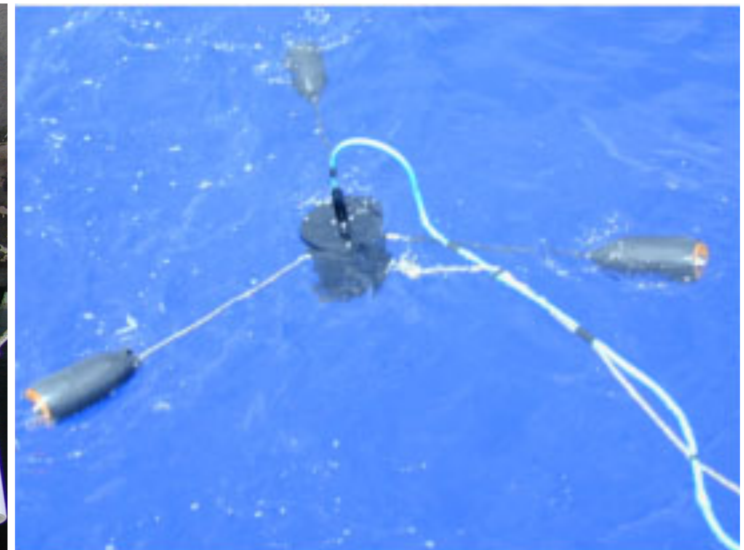






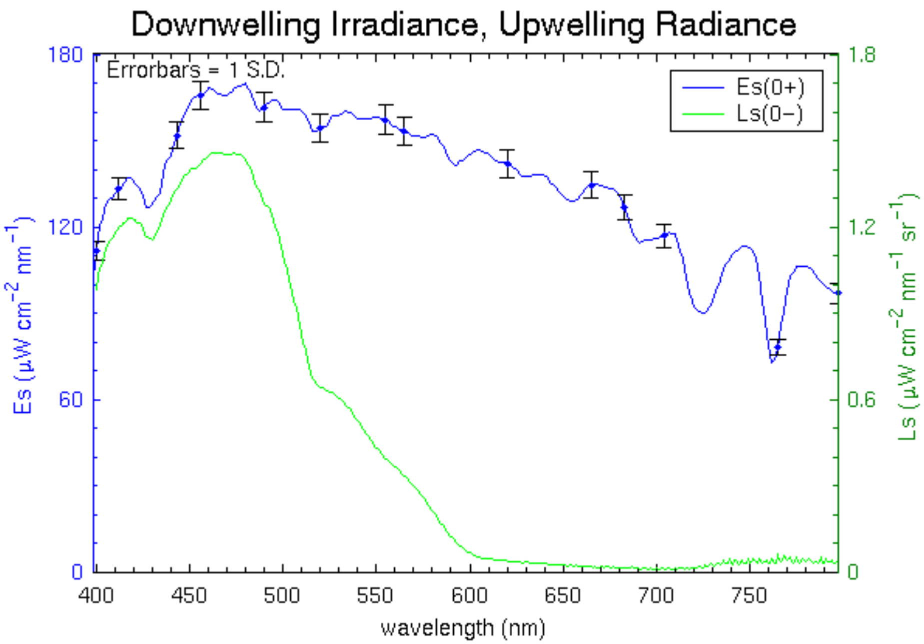
More modern instrument, NuRADS



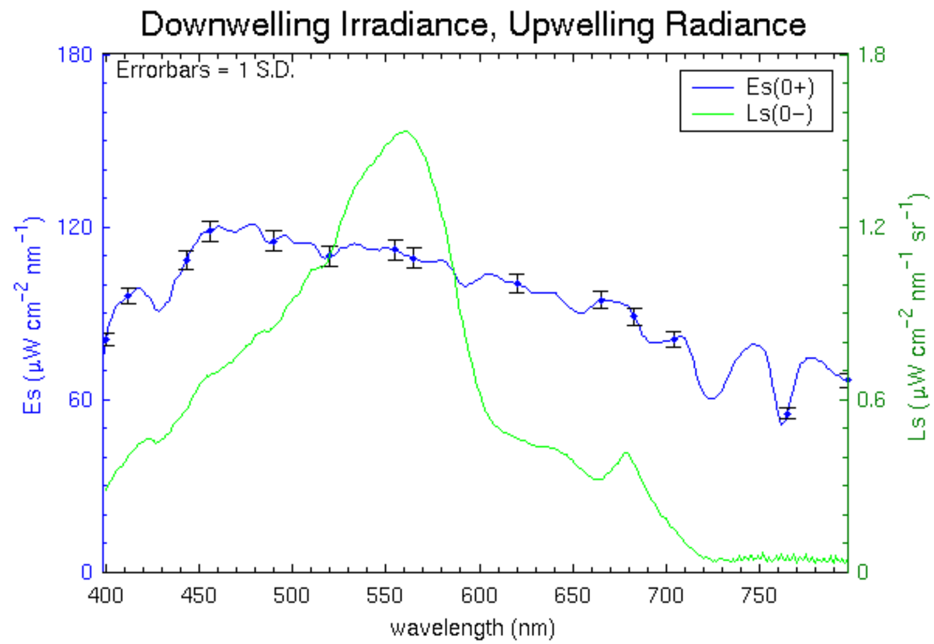


Example Nadir Radiance

Blue water station



Green water station



Data from Marlon Lewis

Downwelling Radiance Distribution (520 nm)

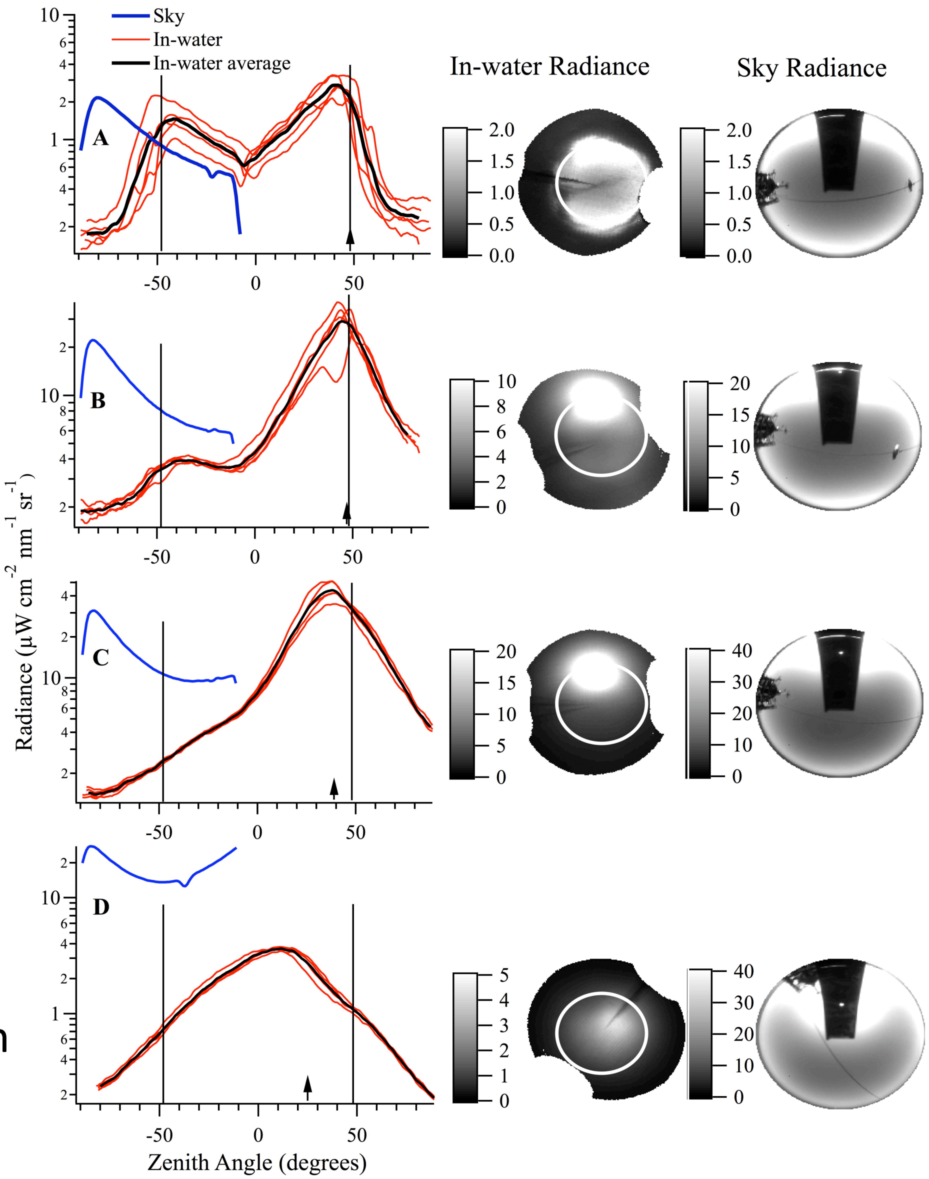
Santa Barbara channel

1m

5m

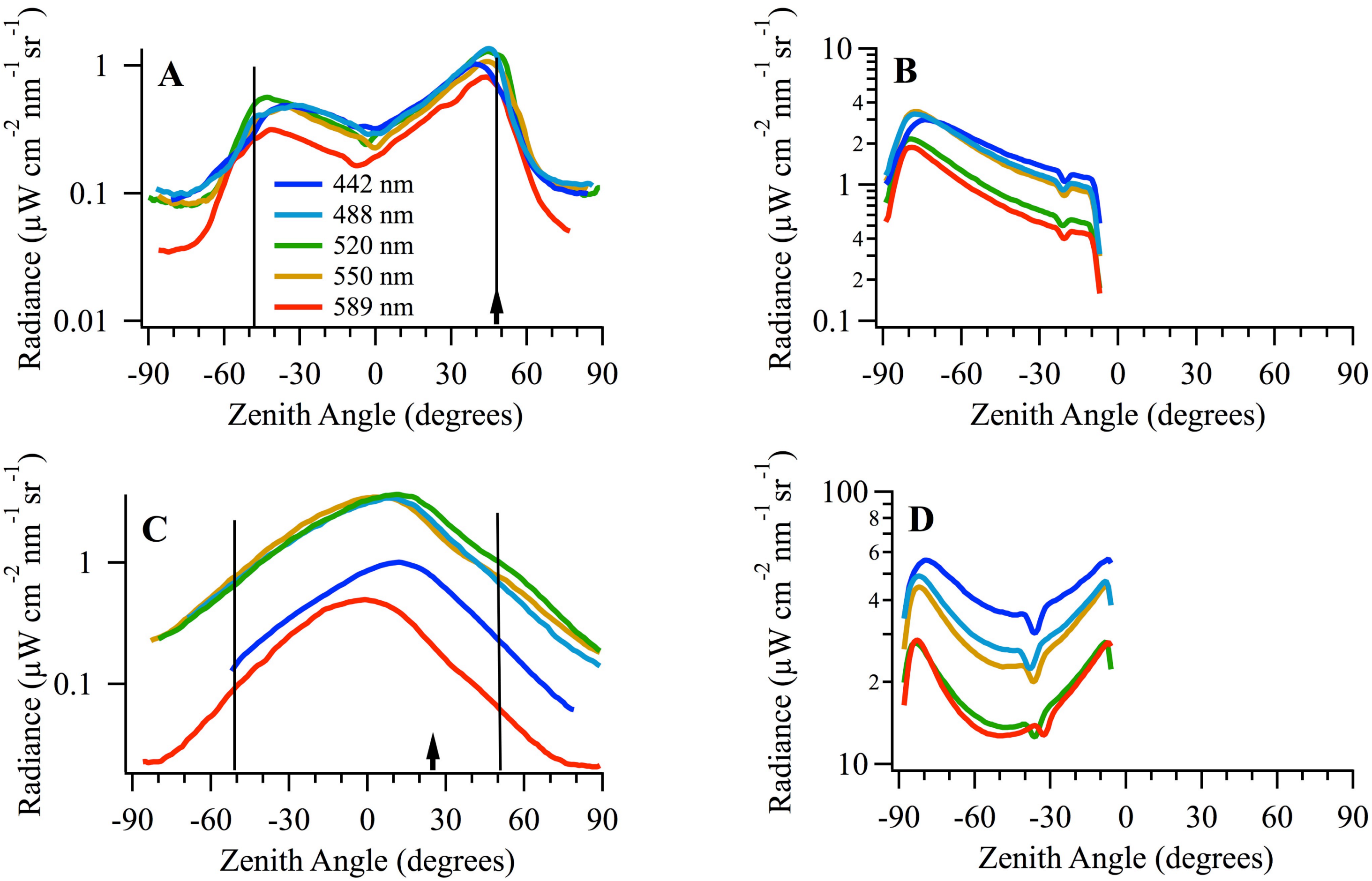
10m

30m

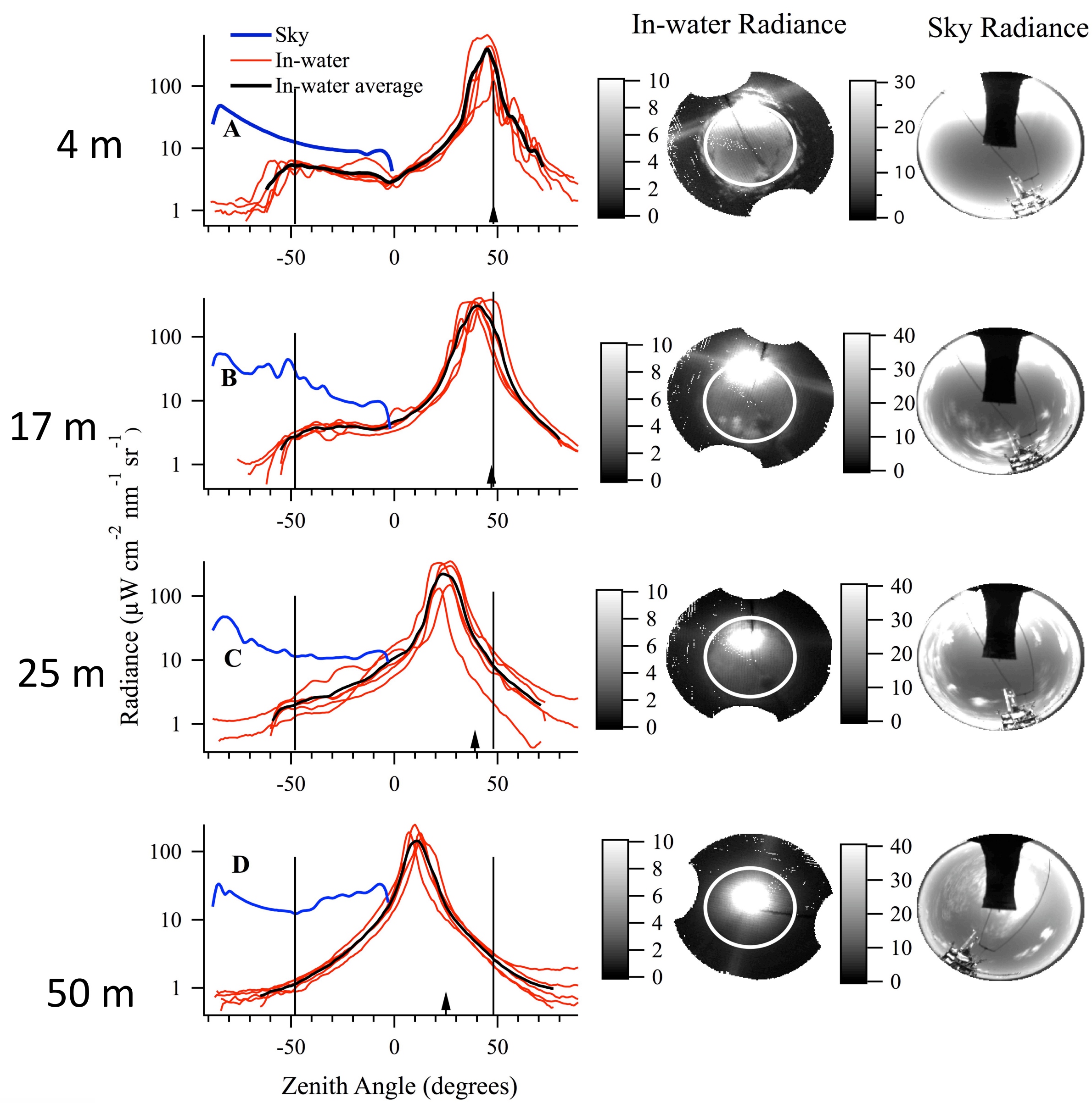


1 m

30 m

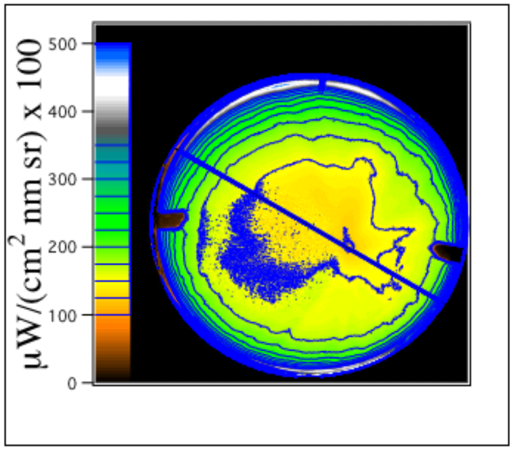

A
B
C
D
442 nm
488 nm
520 nm
550 nm
589 nm
Radiance (μW cm-2 nm-1 sr-1)
Zenith Angle (degrees)
1
0.1
0.01
10
4
2
100
8
6
-90 -60 -30 0 30 60 90

Clear water, Hawaii

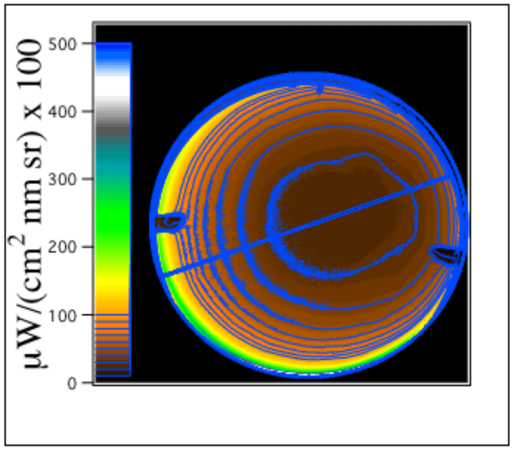


Example Radiance Distribution, 500nm

Low Chl (0.3 mg/m^3)

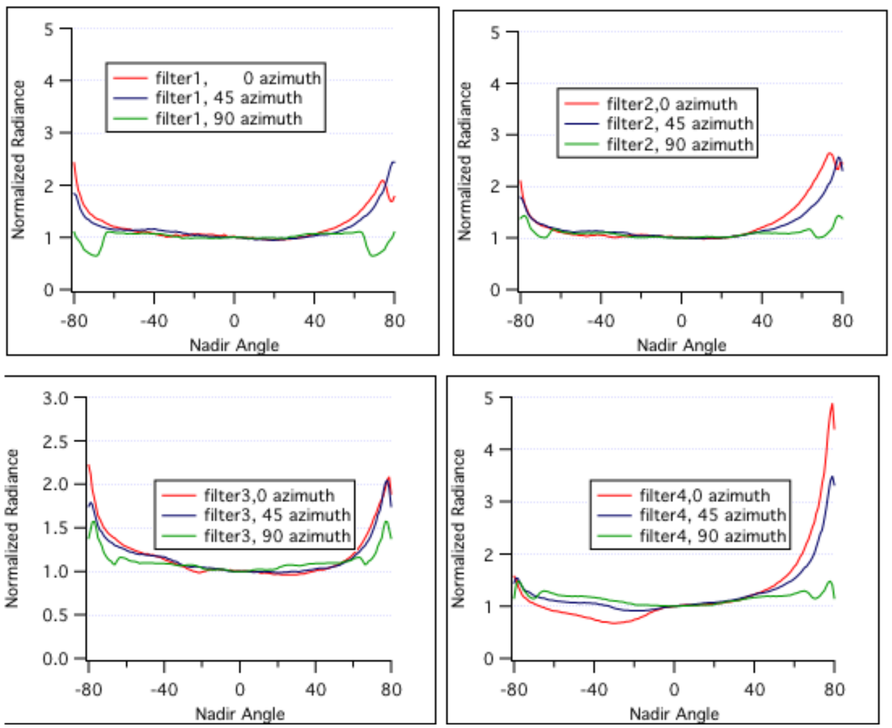


High Chl (5 mg/m^3)

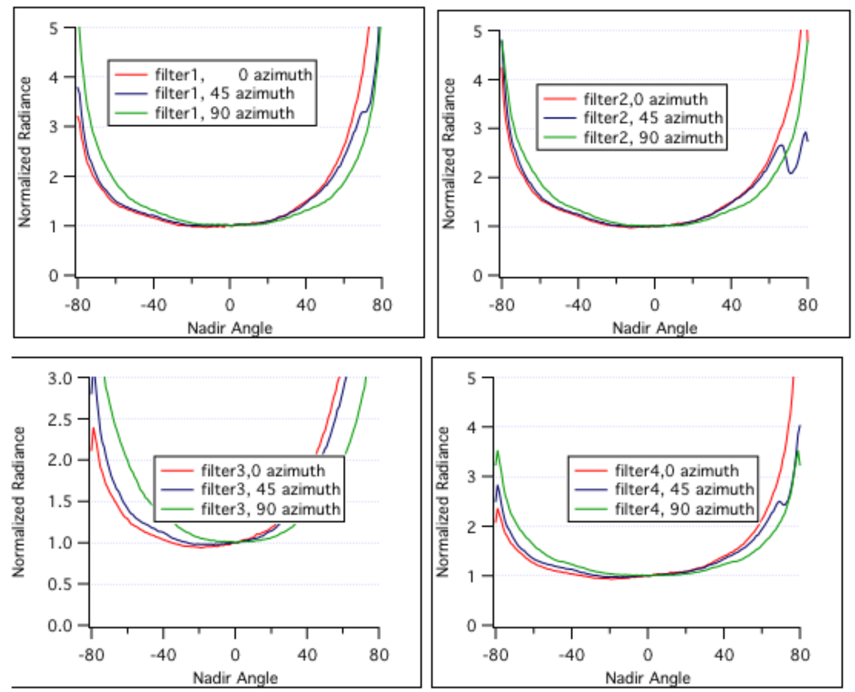


Upwelling Radiance distribution

Low Chl



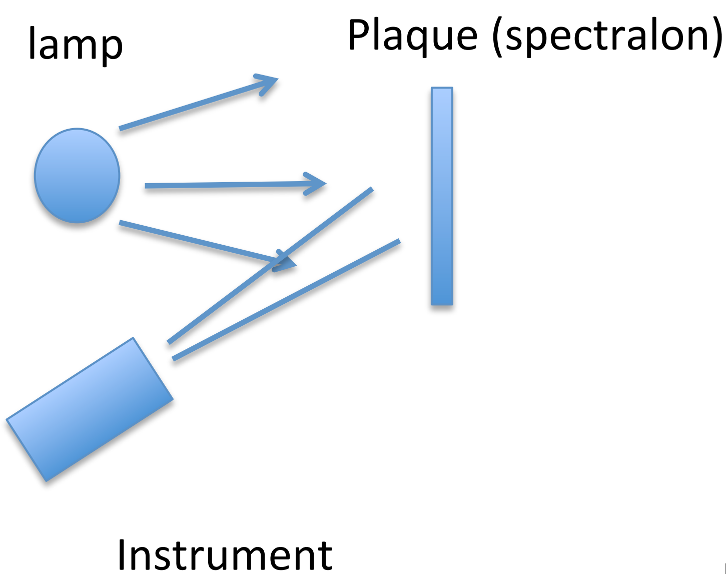
High Chl

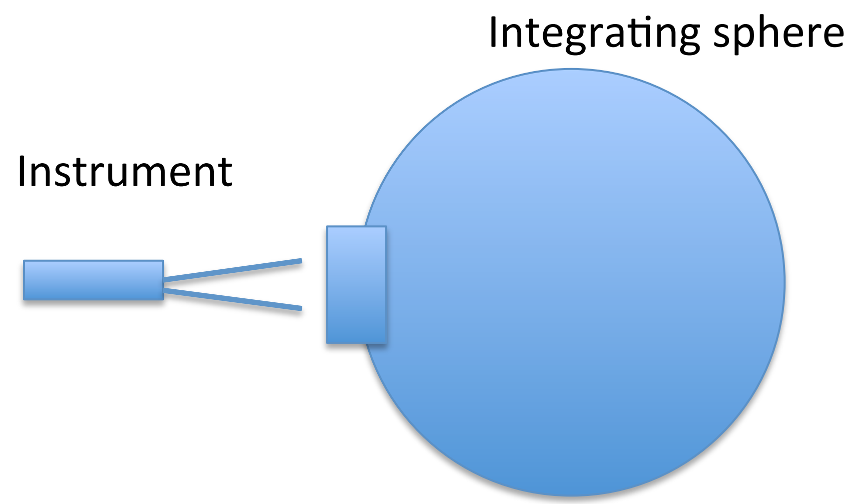


Radiance

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, $L = E/\pi$

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…..

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 = Lu(z) Taw /(Es*T(z))

Measure upwelling radiance at some depth (Lu(z))

Propogate to the surface T(z) = exp(-KL(z))

Propogate through the air-water interface, Taw (0.975/n2 = 0.543)

Measure Es 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 protocols

New Lee technique

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

nLw = Lw/Es * Eo/r^2

Eo 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).