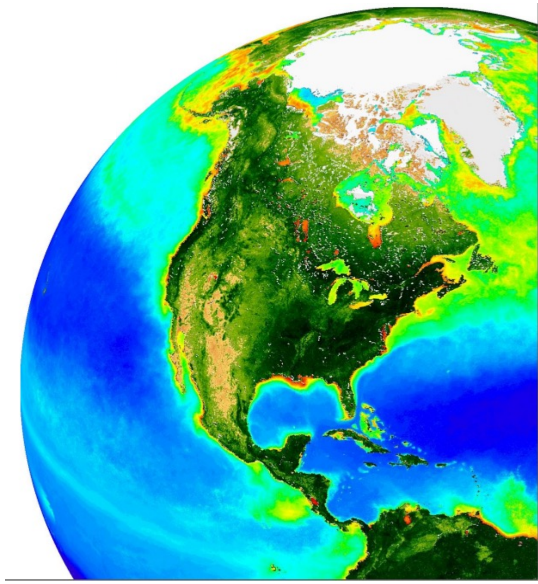
Calibration and Validation of Ocean Color Remote Sensing

Lecture 15: Radiometric quantities and their measurement



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June 20, 2023

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Lecture Content

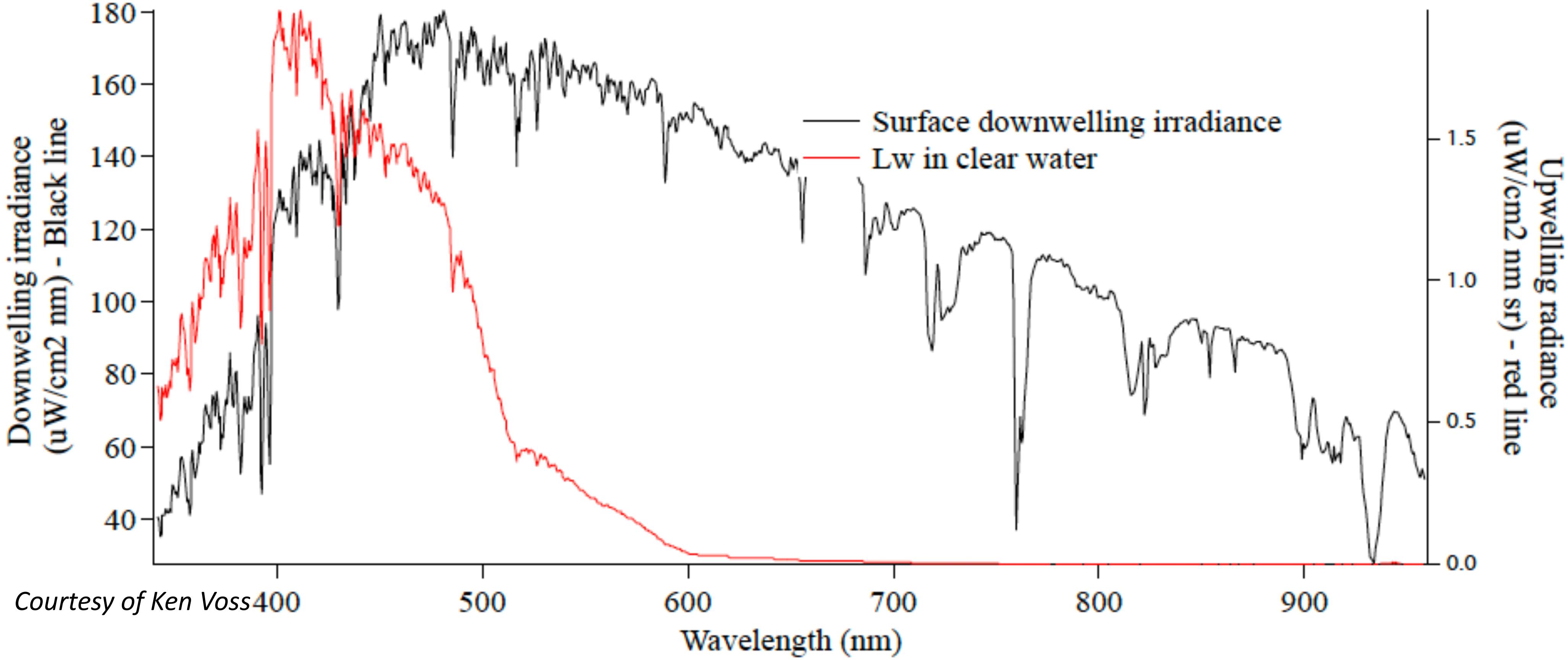
- Types of radiometers
- Radiometric calibration
- Measurement techniques
- Field sampling methods
- Sunphotometers

Most of what is shown in this lecture was taken from the following sources:

- *http://www.oceanopticsbook.info*
- *Mobley, C. D. (Editor), 2022. The Oceanic Optics Book, International Ocean Colour Coordinating Group (IOCCG), Dartmouth, NS, Canada, 924pp. DOI: 10.25607/OBP-1710*
- *David Antoine; https://ioccg.org/wp-content/uploads/2022/09/radiometry-and-aops-d-antoine-sls2022.pdf*
- *Giuseppe Zibordi; https://ioccg.org/training/SLS-2012/Zibordi-2012_IOCCG_OC_Lectures_rev_part1.pdf*
- *Giuseppe Zibordi; https://ioccg.org/training/SLS-2012/Zibordi-2012_IOCCG_OC_Lectures_rev_part2.pdf*
- *Howard W. Yoon, 2013, NIST; https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1001&context=calcon*
- *Ken Voss and his lectures from the Ocean Optics class, 2021;*
- *Agnieszka Bialek, 2016; https://www.ioccg.org/training/SLS-2016/Bialek-L1.pdf*

What does the *in situ* light we want to measure look like (e.g. clear water)?

$E_s(\lambda)$



Courtesy of Ken Voss

$L_w(\lambda)$

Figure shows the high spectral (~1 nm) features in radiance and irradiance.

This lecture will focus on the most common types of ocean radiometers, upwelling radiance and downwelling plane irradiance sensors, though we will dabble into a few others.

Most common radiometric Instrument types Defined by spectral resolution

1. Broad band sensors: for example Photosynthetically Available Radiation (PAR), UV-A, photopic sensors
2. Multi-channel, discrete wavelength sensors: 4-19 individual bands, ~10nm in width
3. Hyperspectral instruments: continuous measurements, every 1-10 nm, across the visible/NIR 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.

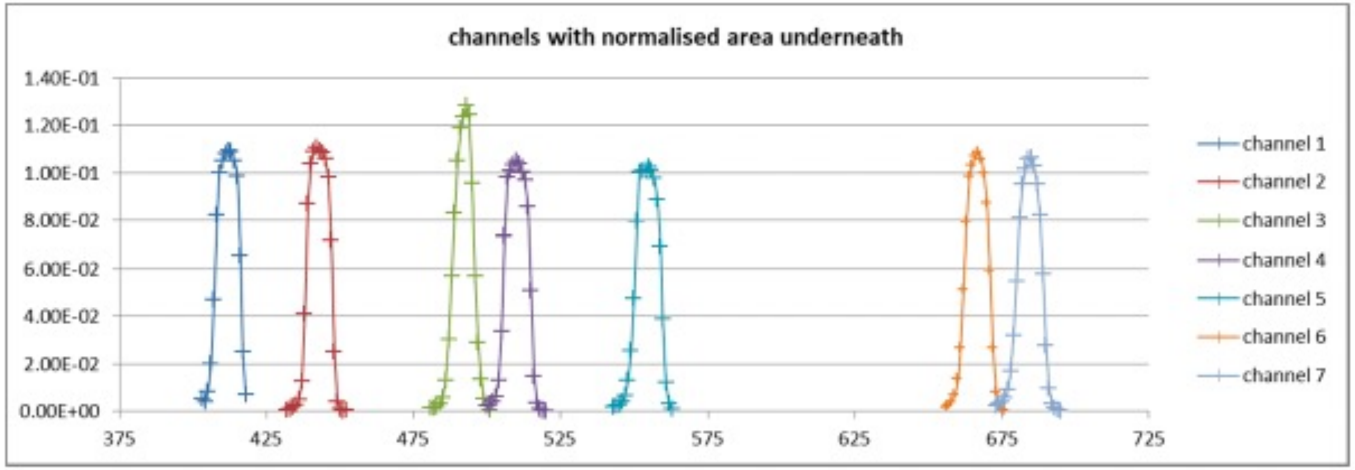
Another broadband measurement is photopic which matches the eye response….centered at 550 nm, about 100 nm wide.

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).

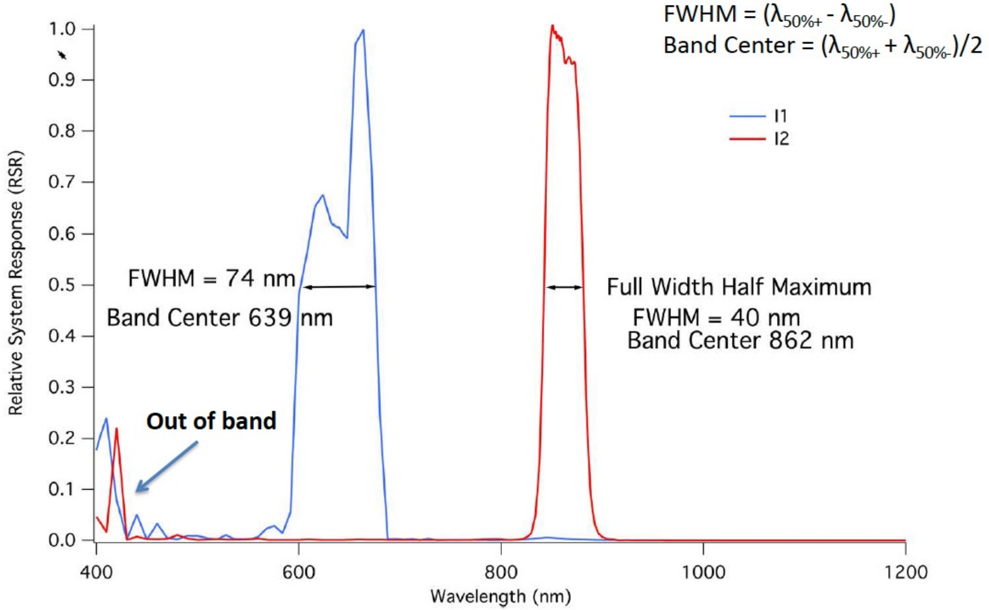
Examples of broad band sensors (PAR)

Narrow band, multi wavelength/channel instruments

- Collection of several discrete wavelength bands (4-19 channels)
- Spectral channels defined by filters, typically an interference filter, ~10 nm width.
- Photodiode typically used, periodically sampled with A-D converter.
- Typically very stable and reliable.
- May try to match key spectral bands (e.g. VIIRS or MODIS bands)
- Low out-of-band effects, though do need consider depending on spectral bands used.



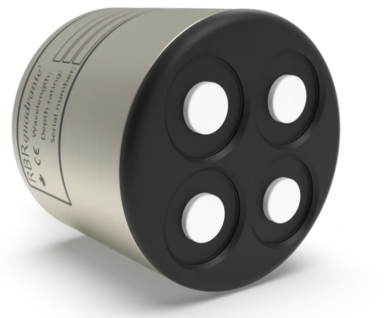
Bialek



Voss

Examples of multi-channel sensors

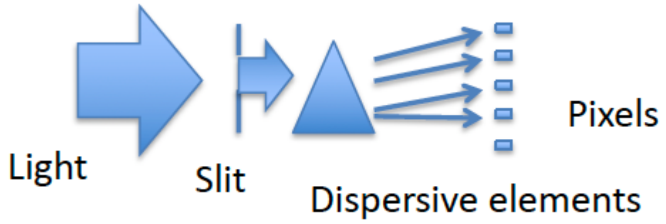
Irradiance

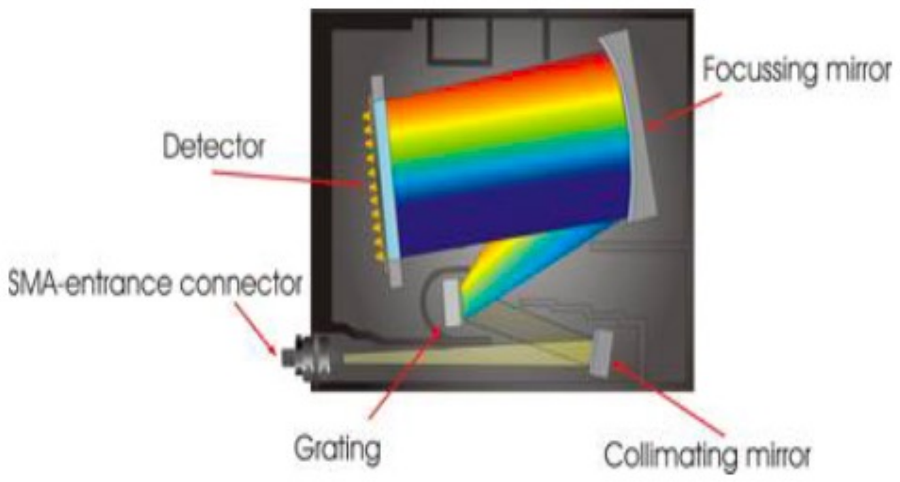


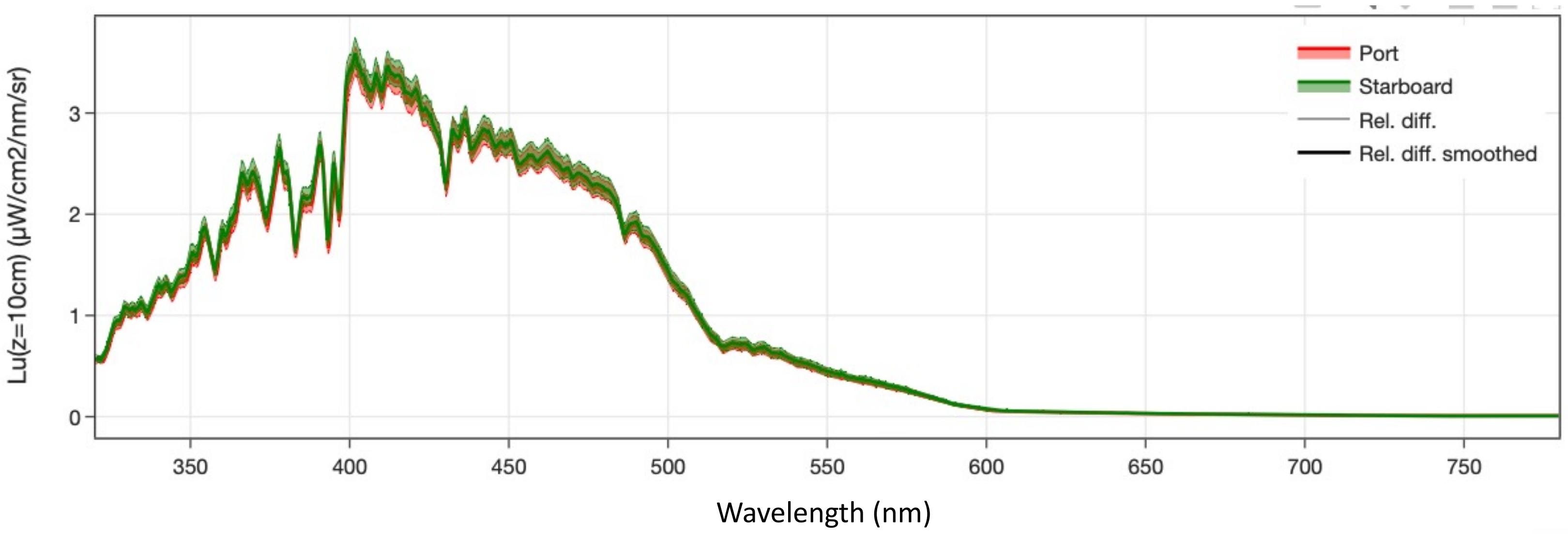
Radiance

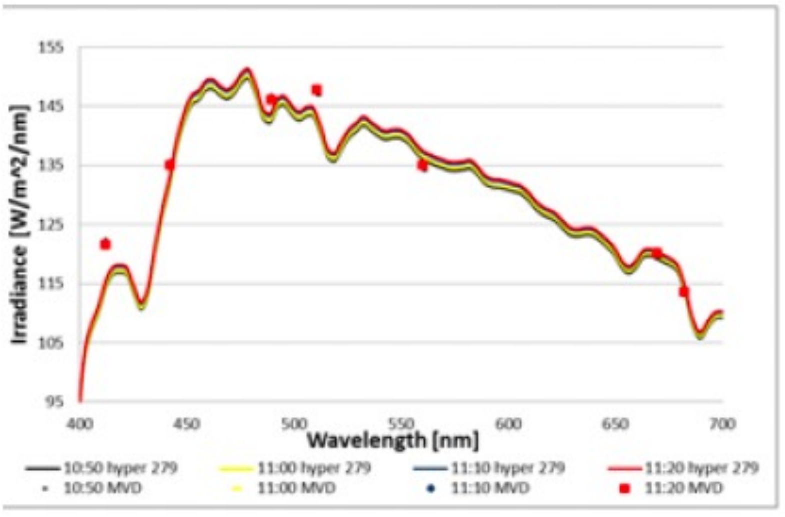
Hyperspectral wavelength instruments

- Continuous spectrum, ~1-10 nm, ~350-1000 nm
- Typically use small spectrometers, with grating / prism dispersive elements.
- Demanding instrument characterization necessary.
- Ability to build integrated channels, such as those on ocean color satellites (e.g. VIIRS or MODIS bands).







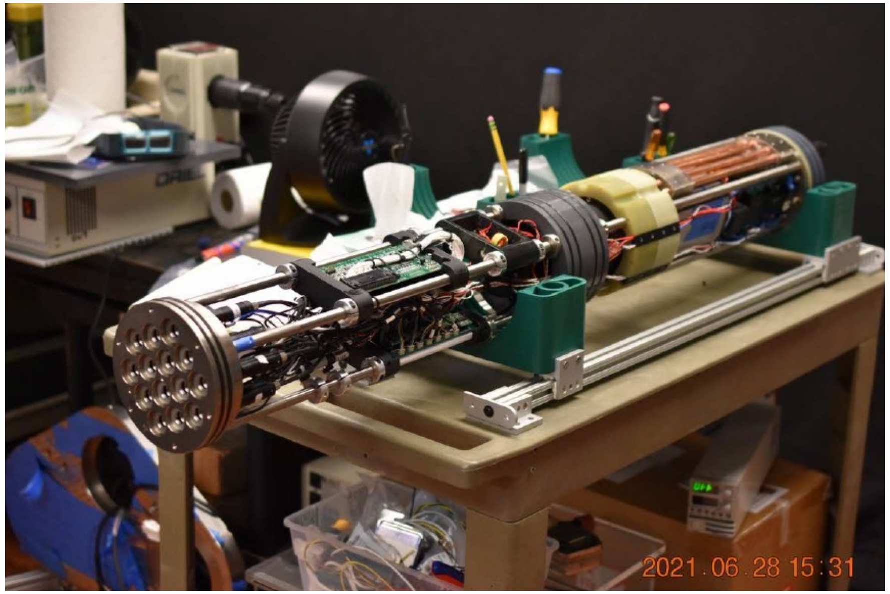


Examples of Hyperspectral sensors

Irradiance
&
Radiance

HyperNav
radiance

Moby
irradiance &
radiance

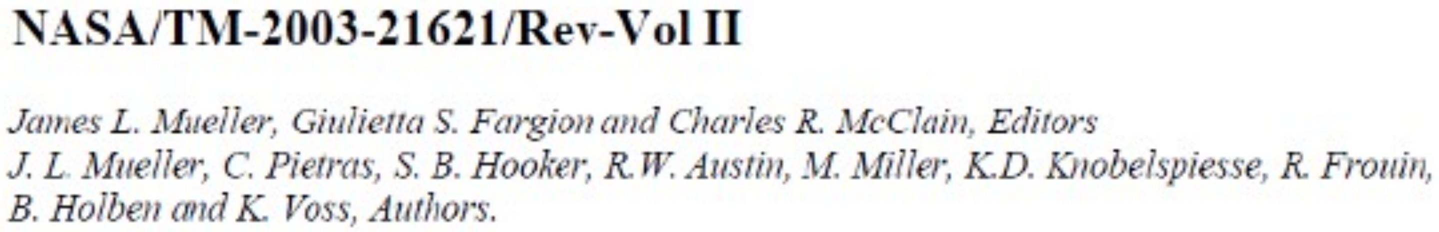


Absolute radiometric calibration

Calibration is the process of quantitatively defining the sensor system response to known and controlled signal inputs. For ocean color radiometers, this is accomplished using a reference standard(s) that provides a direct realization of a radiometric SI quantity.

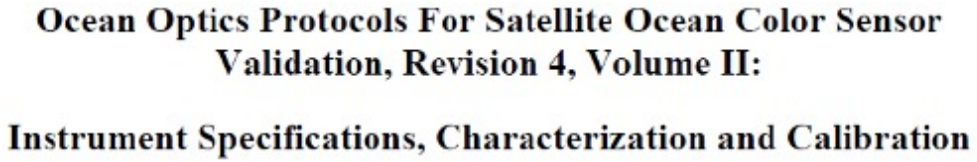
While most calibrations are done by the commercial vendors, its important to understand that even in the very best calibration labs, getting an absolute calibration is very difficult and typically can only achieve ~**2% accuracy** (uncertainty).

An excellent resource to learn more about radiometric sensor calibrations and characterizations is:



NASA/TM-2003-21621/Rev-Vol II

James L. Mueller, Giulietta S. Fargion and Charles R. McClain, Editors
J. L. Mueller, C. Pietras, S. B. Hooker, R.W. Austin, M. Miller, K.D. Knobelspiesse, R. Frouin, B. Holben and K. Voss, Authors.

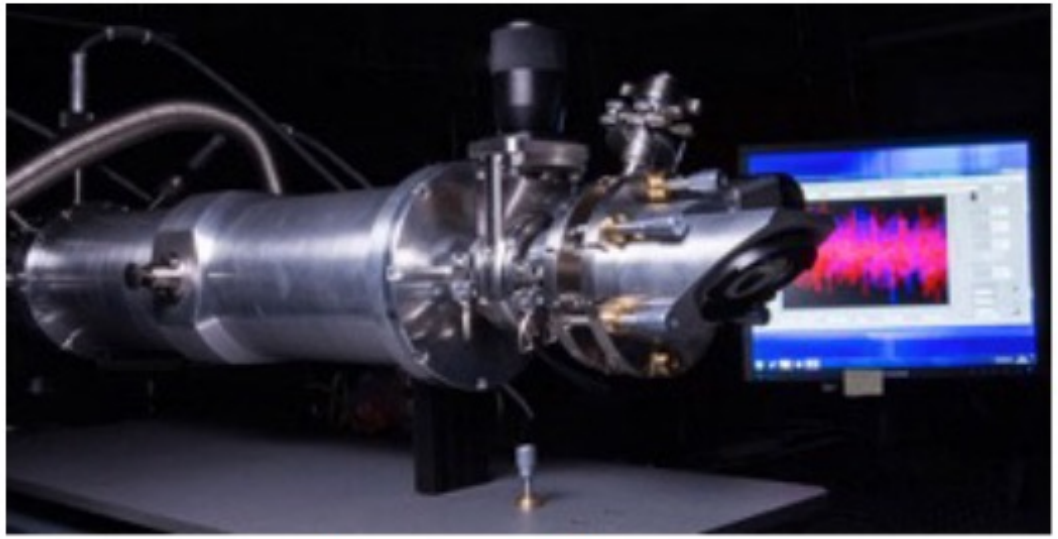


Ocean Optics Protocols For Satellite Ocean Color Sensor Validation, Revision 4, Volume II:

Instrument Specifications, Characterization and Calibration

The primary radiometry standard: Cryogenic radiometer

The cryogenic radiometer uses the electrical substitution technique, whereby the optical power incident on an absorbing cavity is compared with the electrical power required to heat the cavity to the same temperature.
"cryogenic" because it is forced to very low temperature in order to improve sensitivity



A cryogenic radiometer of the UK NPL

1987
New cryogenic radiometer paves way to improve climate records

https://www.npl.co.uk/12-decades/new-cryogenic-radiometer

Antoine

Calibration Equation for a Field Radiometer

$$\Re(\lambda) = C_{\Re}(\lambda) I_f(\lambda)[D_N(\lambda) - D_0(\lambda)]$$

$\Re(\lambda)$ → Radiometric Quantity, *E* or *L*

$D_N(\lambda) - D_0(\lambda)$ → Measurement in Relative Units

$C_{\Re}(\lambda)$ → In-Air Calibration Factor

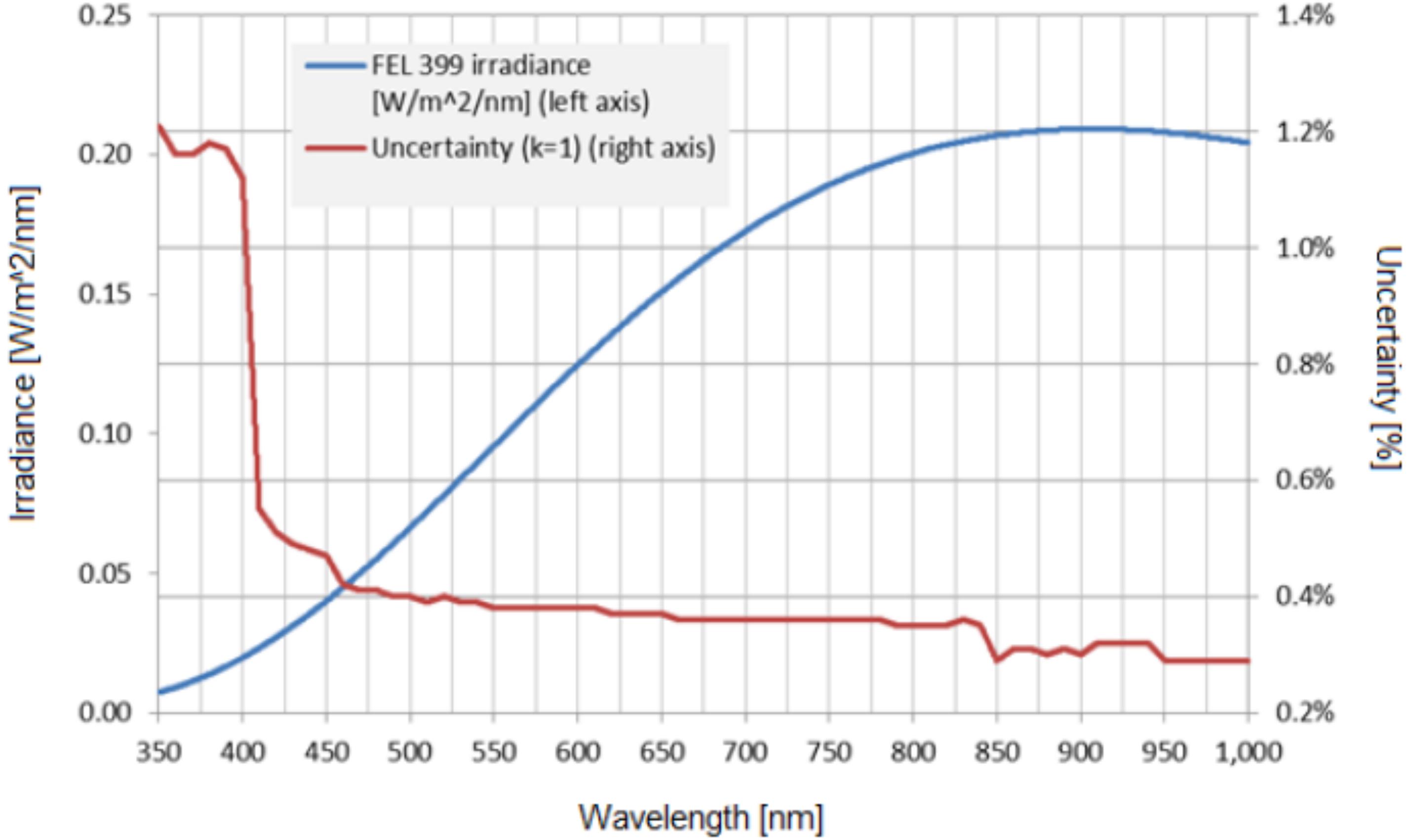
$I_f(\lambda)$ → Immersion Factor ($I_f \neq 1$ for in-water meas.)

Standard and Reference Surface

The common irradiance standard is a 1000W FEL-type lamp.

They have tungsten coiled-coil filaments and a bi-post base, as recommended by NIST.

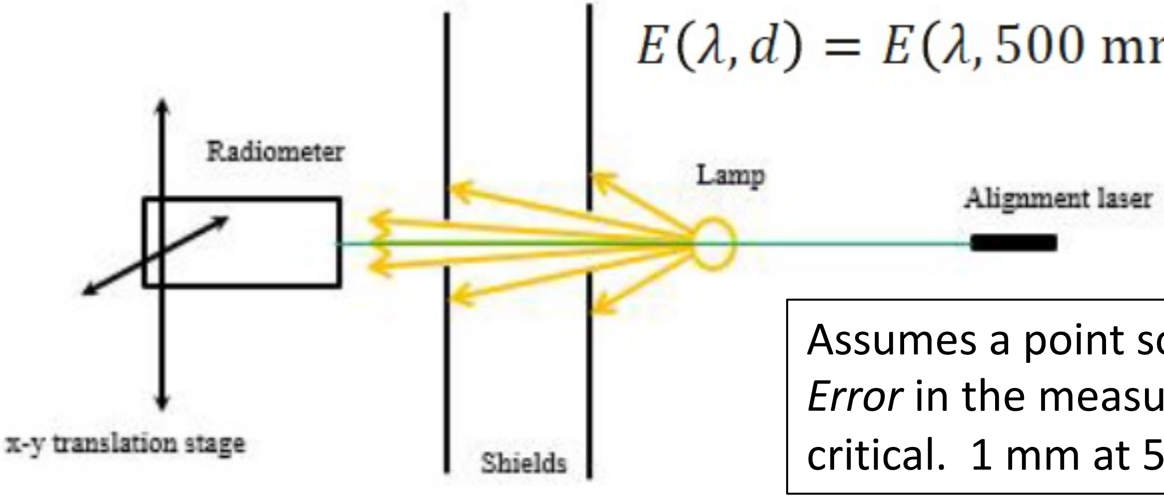
Note however, that the spectral lamp output is not very similar to the solar spectrum



1000W FEL lamp

Irradiance

$$E(\lambda, d) = \overset{\text{Lamp Cal Irradiance}}{E(\lambda, 500\text{ mm})}\boxed{\overset{\text{Lamp Cal Distance}}{\left(\frac{500\text{ mm}}{d}\right)^2}}$$



Assumes a point source.
Error in the measured distance is also critical. 1 mm at 50 cm is 0.4% error.

Bialek

$$C_E(\lambda) = E_0(\lambda)\,(d_0/d)^2 \,/\, (D_N(\lambda) - D_0(\lambda))$$

C_E: Calibration coefficient
E_0: Lamp Irradiance at distance d_0
D_N: Sensor output with the source at distance d
D_0: Sensor output without any source (dark signal)

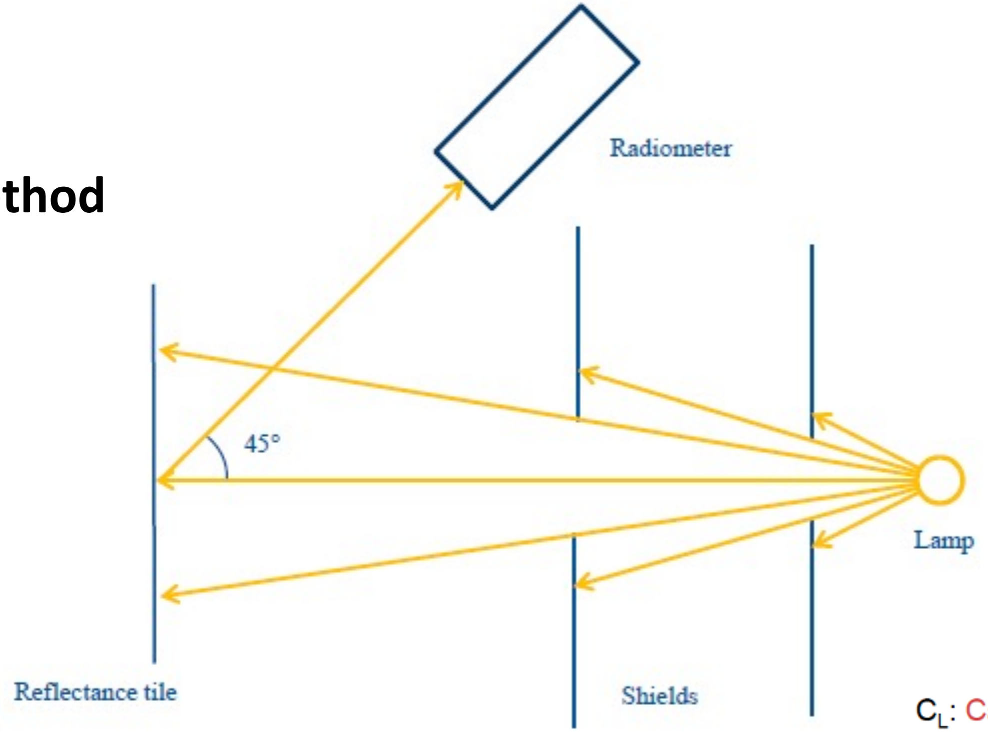
Zibordi

Radiance

Aka: Lamp - Plaque Method

Lamp - tile

Tile = Plaque = Target



$$C_L(\lambda)=E_0(\lambda)\,(d_0/d)^2\,(\rho(\lambda)/\pi)\,c_p(\theta)\,/\,(D_N(\lambda)-D_0(\lambda))$$

for a Lambertian source $L=E/\pi$

C_L: Calibration coefficient

E_0: Lamp Irradiance at distance d_0

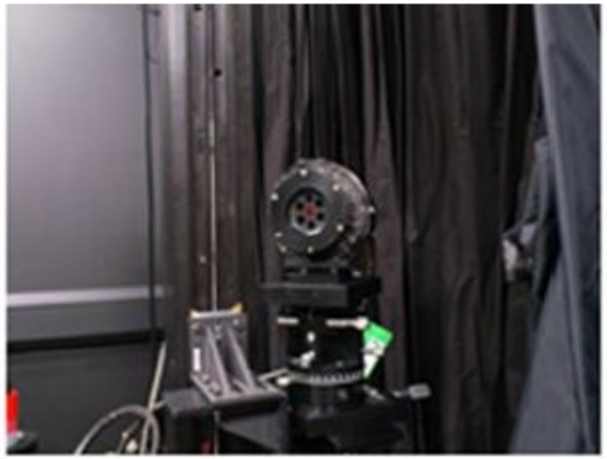
D_N: Sensor output with the source at distance d from the Standard Plaque

D_0: Sensor output without any source (dark signal)

ρ : Reflectance of the Standard Plaque

c_p: Correction factor for the non-Lambertian response of the Plaque at angle θ

Zibordi



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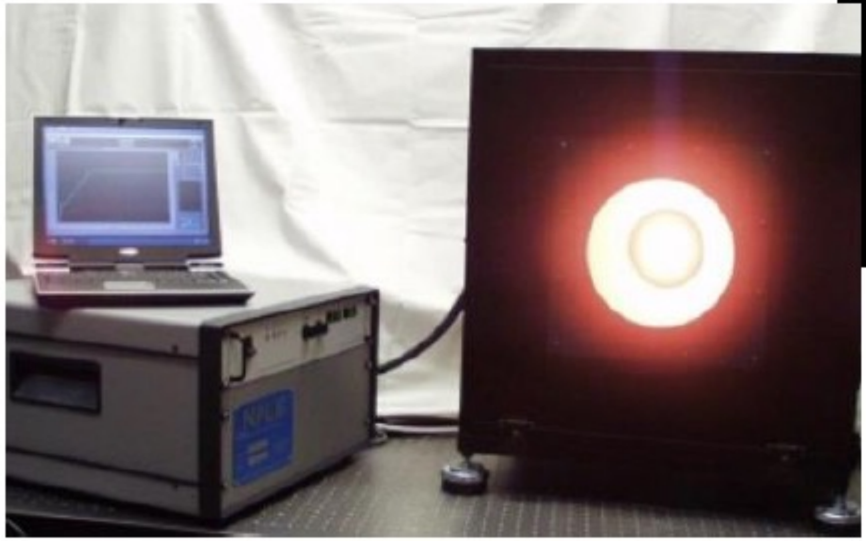
$$L_s = \frac{E_{FEL}\beta_{0:45}}{\pi}\,\frac{d^2_{cal}}{d^2_{use}}$$

Radiance standards

- Lamp –reflectance standard
- Integrating sphere

Lambertian reflectance
plaques



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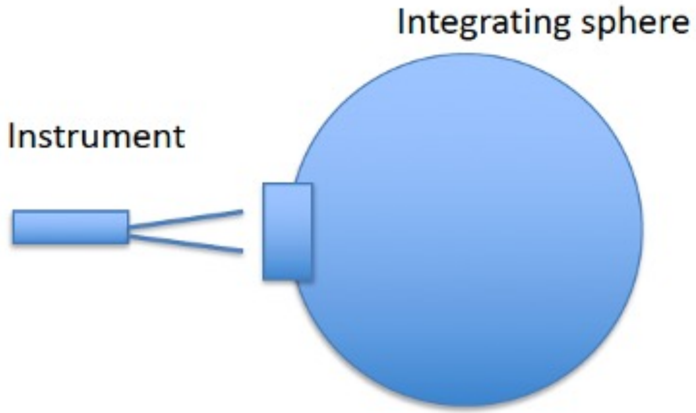


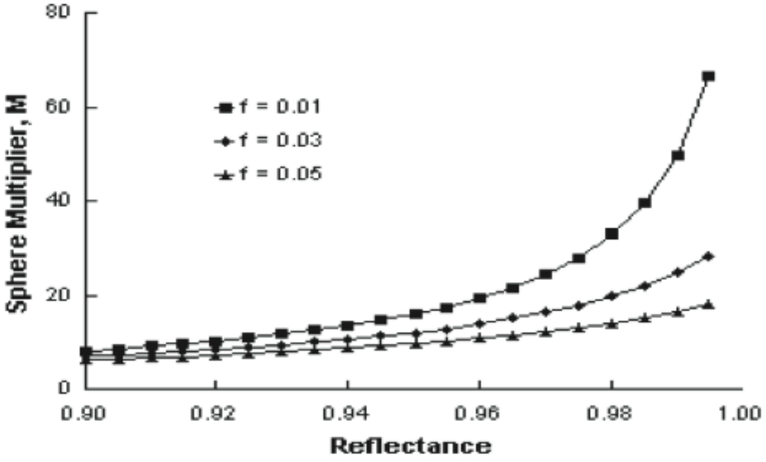
Voss

Radiance Calibrations using a Sphere

$$Ls = \frac{\Phi i}{\pi\ As} * M \quad where\ \ M = \frac{\rho}{1 - \rho\,(1 - f)}$$

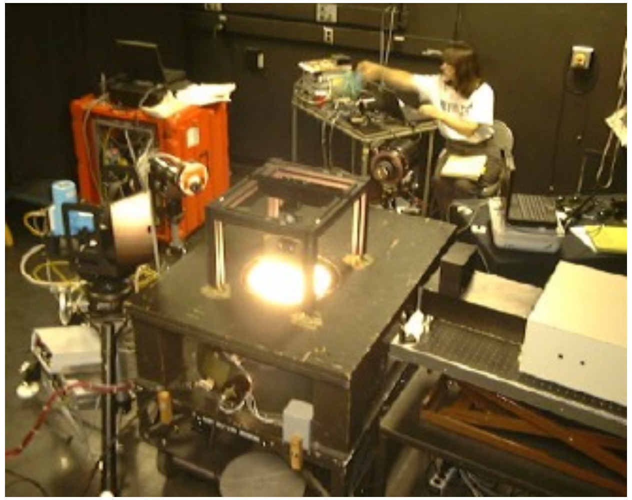
Where Ls is sphere radiance, Φi is input flux, As is sphere surface area, ρ is reflectance and f is port fraction. So a smaller sphere produces higher radiances.

Because of the sphere multiplier M, the sphere is very sensitive to changes in surface reflectance.

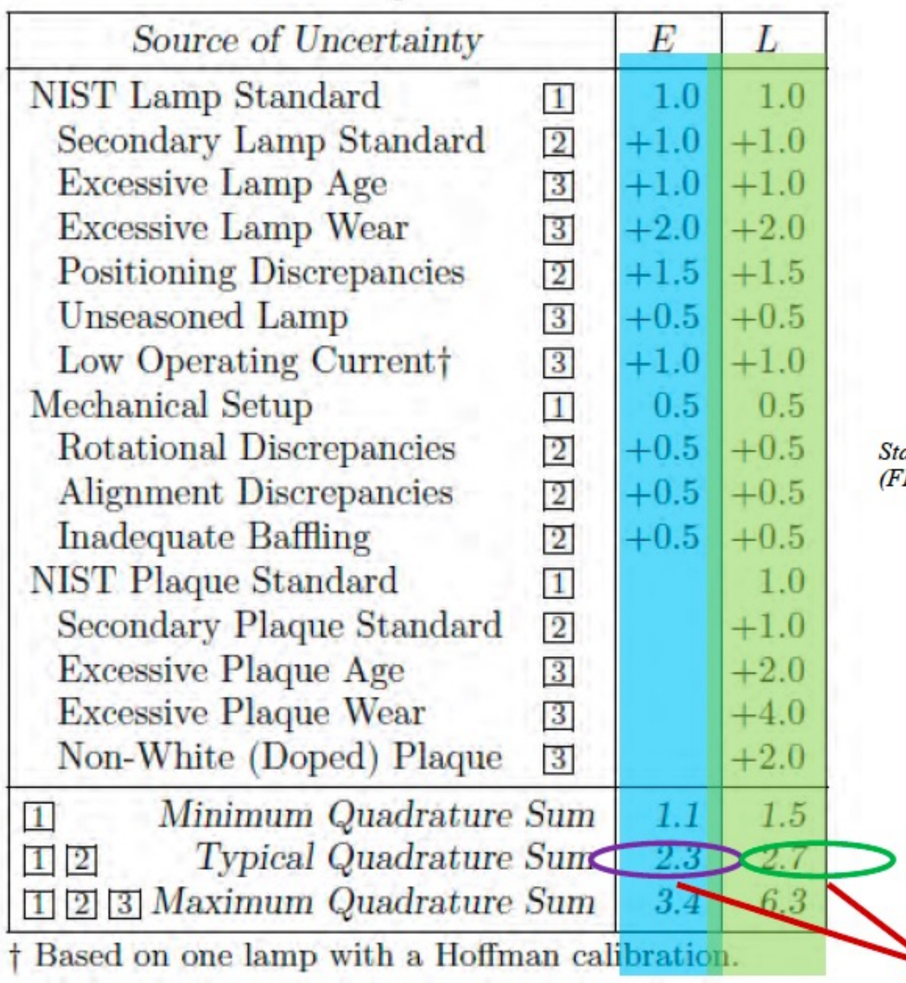


Consequences:

- Sphere aging
- Highly affected by light reflected back into output port by sensor

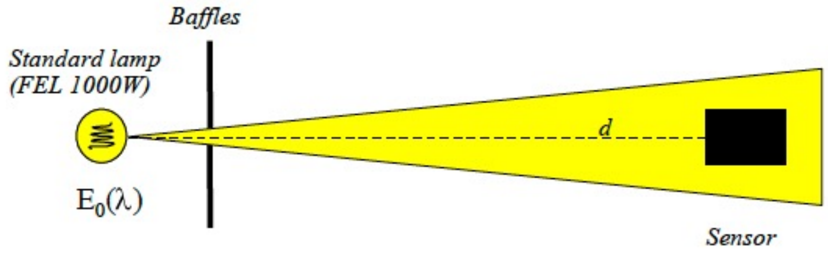


Absolute Calibration Uncertainties

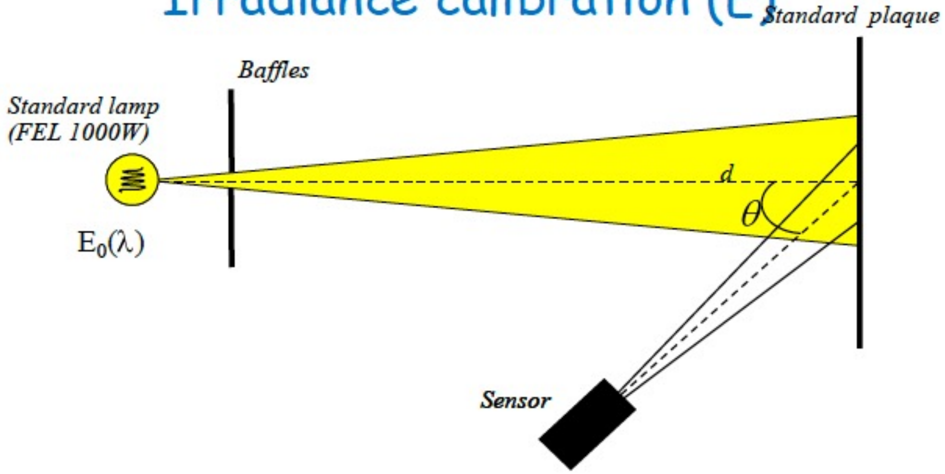


Source of Uncertainty		*E*	*L*
NIST Lamp Standard	1	1.0	1.0
Secondary Lamp Standard	2	+1.0	+1.0
Excessive Lamp Age	3	+1.0	+1.0
Excessive Lamp Wear	3	+2.0	+2.0
Positioning Discrepancies	2	+1.5	+1.5
Unseasoned Lamp	3	+0.5	+0.5
Low Operating Current†	3	+1.0	+1.0
Mechanical Setup	1	0.5	0.5
Rotational Discrepancies	2	+0.5	+0.5
Alignment Discrepancies	2	+0.5	+0.5
Inadequate Baffling	2	+0.5	+0.5
NIST Plaque Standard	1		1.0
Secondary Plaque Standard	2		+1.0
Excessive Plaque Age	3		+2.0
Excessive Plaque Wear	3		+4.0
Non-White (Doped) Plaque	3		+2.0
Minimum Quadrature Sum	1	*1.1*	*1.5*
Typical Quadrature Sum	1 2	*2.3*	*2.7*
Maximum Quadrature Sum	1 2 3	*3.4*	*6.3*

† Based on one lamp with a Hoffman calibration.



Irradiance calibration (E)



Radiance calibration (L)

Typical uncertainty values (question any lower number !!!)

S.Hooker, et al,. The Seventh SeaWiFS Intercalibration Round-Robin Experiment (SIRREX-7), NASA/TM-2001-206892, v. 17, NASA SSFC, 2001 .

Instrument Sources of Uncertainty/Error

Stray light effects
Wavelength accuracy
Linearity in response
Thermal effects
Polarization sensitivity
Immersion effects
Cosine diffuser
Aging (filters, spectrometer, electronics)

Immersion factor

Calibrating in air, then measuring in water

Need to apply “immersion factors”:

For radiance: $C_{\mathrm{im}} = \left[1 - \left(\frac{n_g - 1}{n_g + 1}\right)^2 \Big/ 1 - \left(\frac{n_g - n_w}{n_g + n_w}\right)^2\right] n_w^2$

n_g: refractive index of glass
n_w: refractive index of water

Has to account for the change of the solid angle

For irradiance:

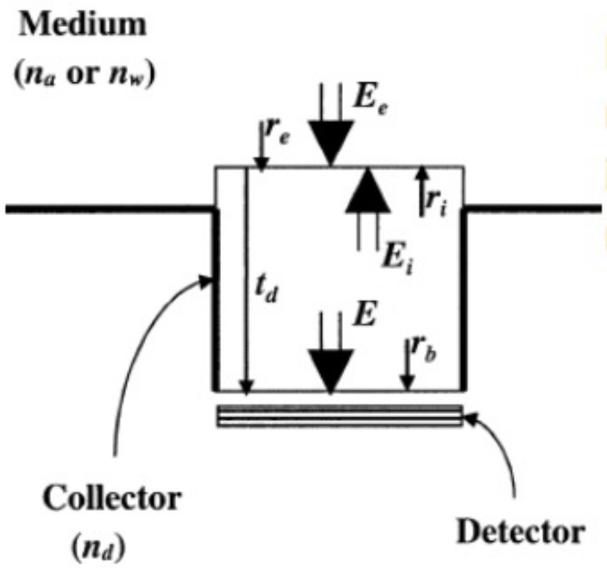


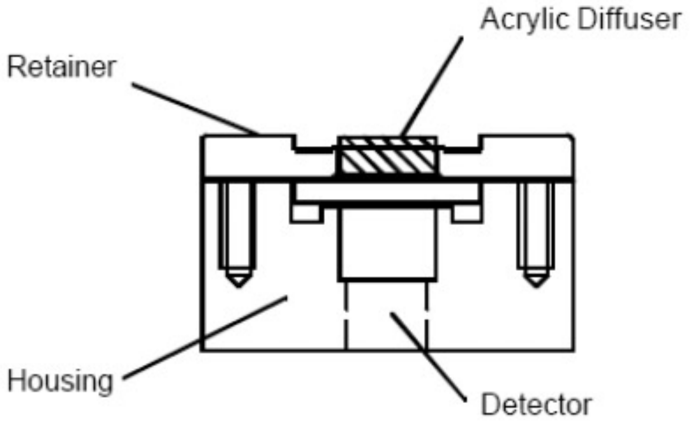
Fig 6 in Zibordi et al., 2004; J. Ocean. Atm. Tech., 21, 501-514

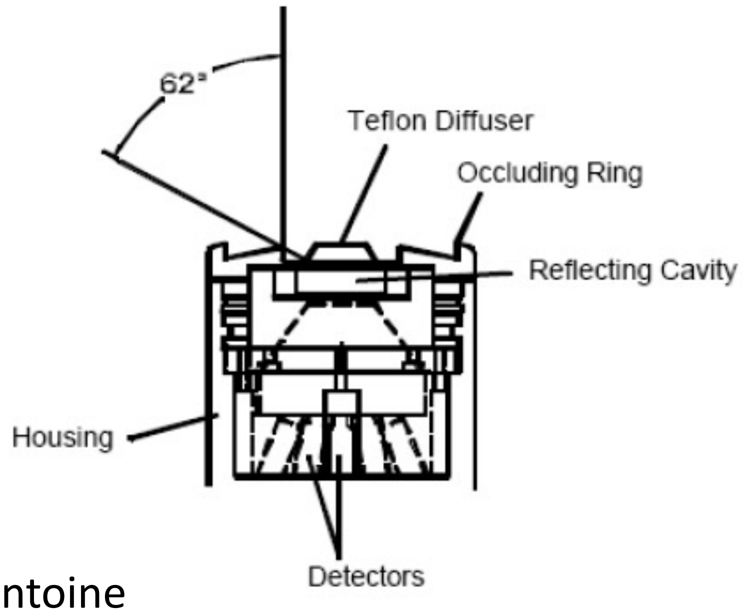
Has to account for the change of the reflections, transmissions effects at the interface between the collector and the medium

To be determined experimentally

Cosine Response

The process of quantifying the goodness of the angular response of a cosine collector to a collimated source.





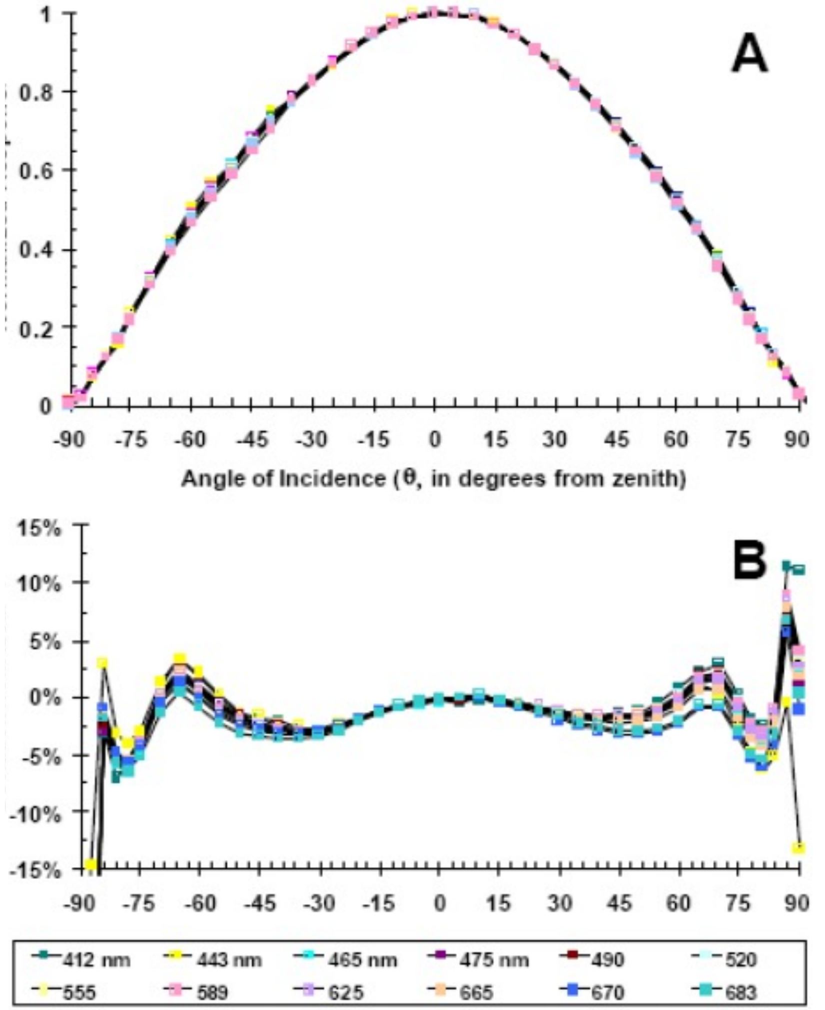
Antoine

Key consideration

Not all cosine collectors are created equal!

Many irradiance sensor manufacturers use different cosine collectors for in-air and in-water sensors.

Do not use an irradiance sensor that is designed to operate in-air in the water (and vice versa). Your cosine response will vary.



Morrow et al. 2000

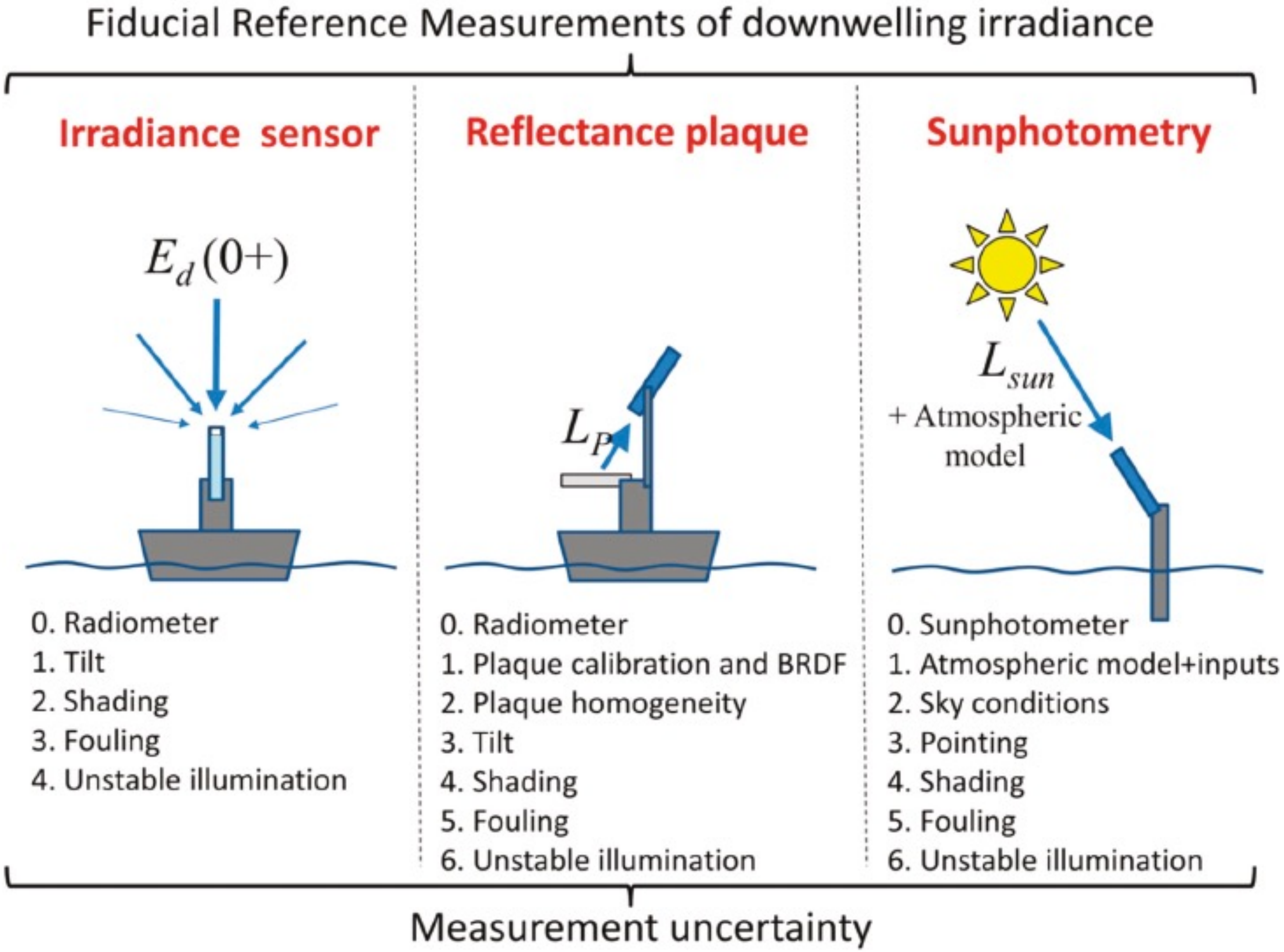
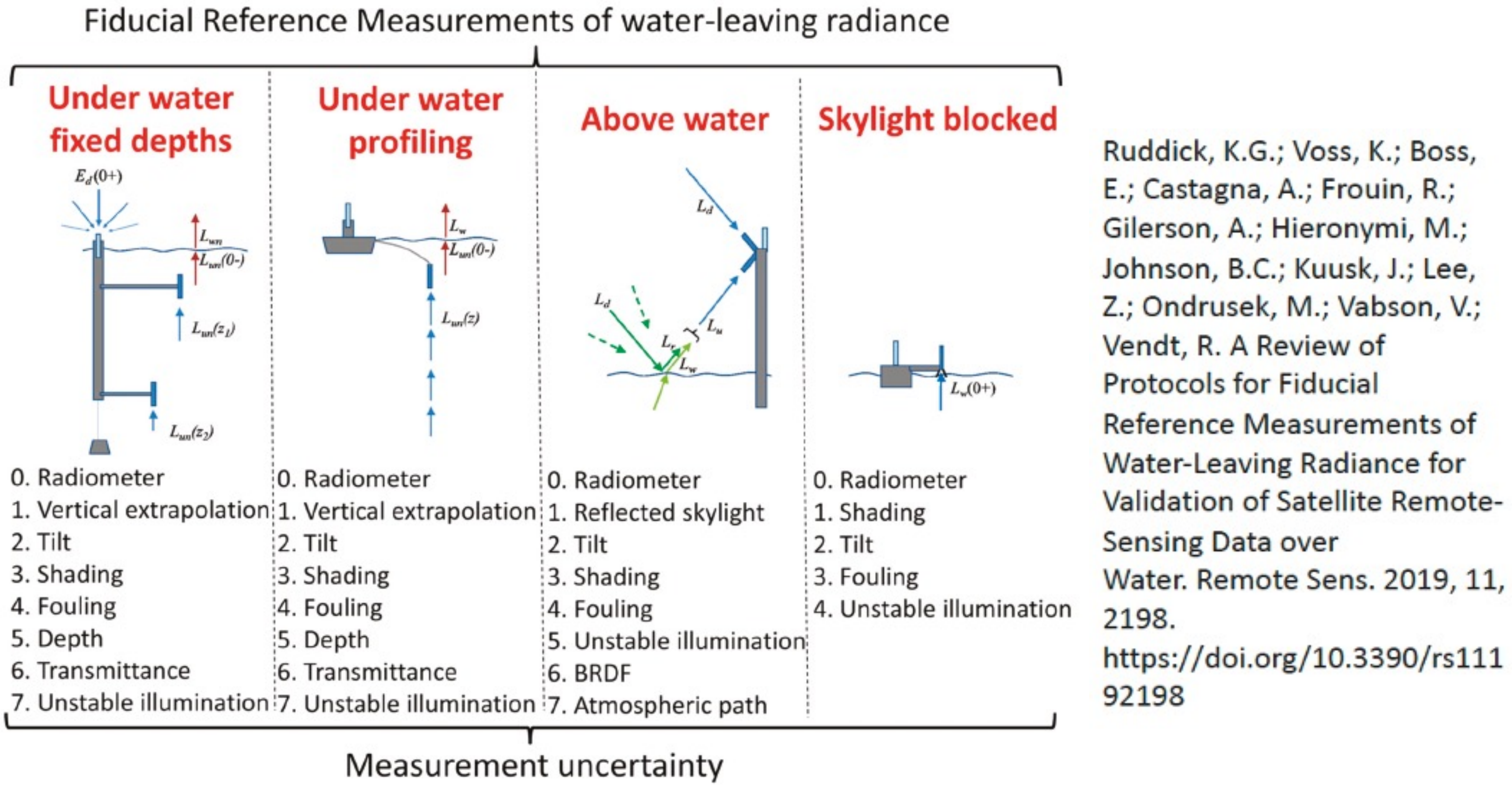


Figure 2. Summary of sources of uncertainty for the three generic families of method for measurement of downwelling irradiance. Reproduced with permission from [27].

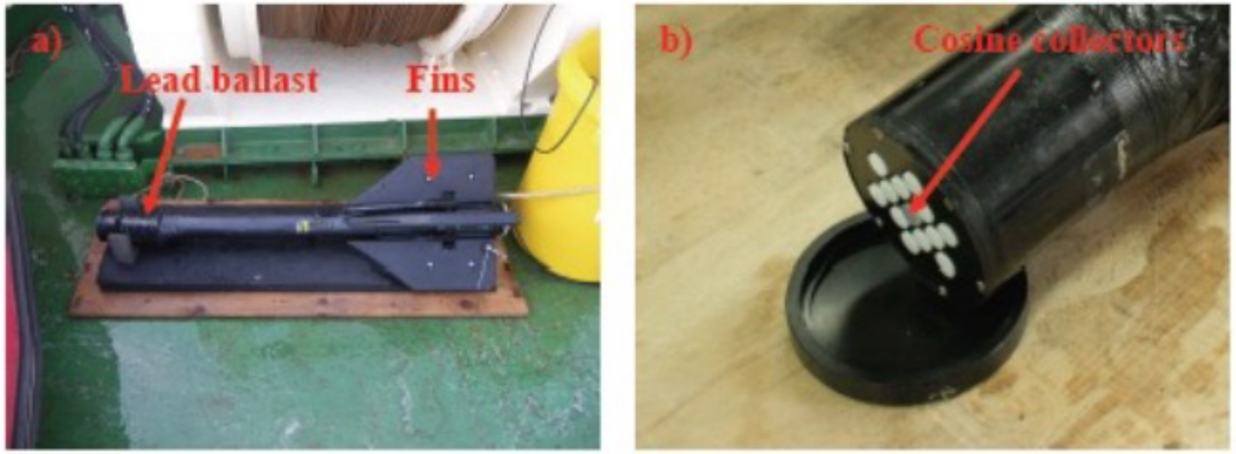
Ruddick, K.G.; Voss, K.; Boss, E.; Castagna, A.; Frouin, R.; Gilerson, A.; Hieronymi, M.; Johnson, B.C.; Kuusk, J.; Lee, Z.; Ondrusek, M.; Vabson, V.; Vendt, R. A Review of Protocols for Fiducial Reference Measurements of Water-Leaving Radiance for Validation of Satellite Remote-Sensing Data over Water. Remote Sens. 2019, 11, 2198. https://doi.org/10.3390/rs11192198



Ruddick, K.G.; Voss, K.; Boss, E.; Castagna, A.; Frouin, R.; Gilerson, A.; Hieronymi, M.; Johnson, B.C.; Kuusk, J.; Lee, Z.; Ondrusek, M.; Vabson, V.; Vendt, R. A Review of Protocols for Fiducial Reference Measurements of Water-Leaving Radiance for Validation of Satellite Remote-Sensing Data over Water. Remote Sens. 2019, 11, 2198. https://doi.org/10.3390/rs11192198

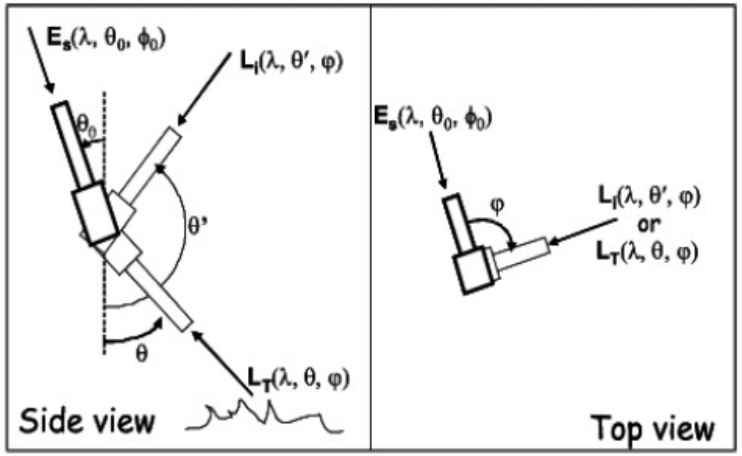
Figure 3. Summary of sources of uncertainty for the four generic families of method for measurement of water-leaving radiance. Reproduced with permission from [28].

Measuring irradiances



A typical “free-fall” profiling radiometer: the Satlantic “SeaWiFS Profiling Multichannel Radiometer”

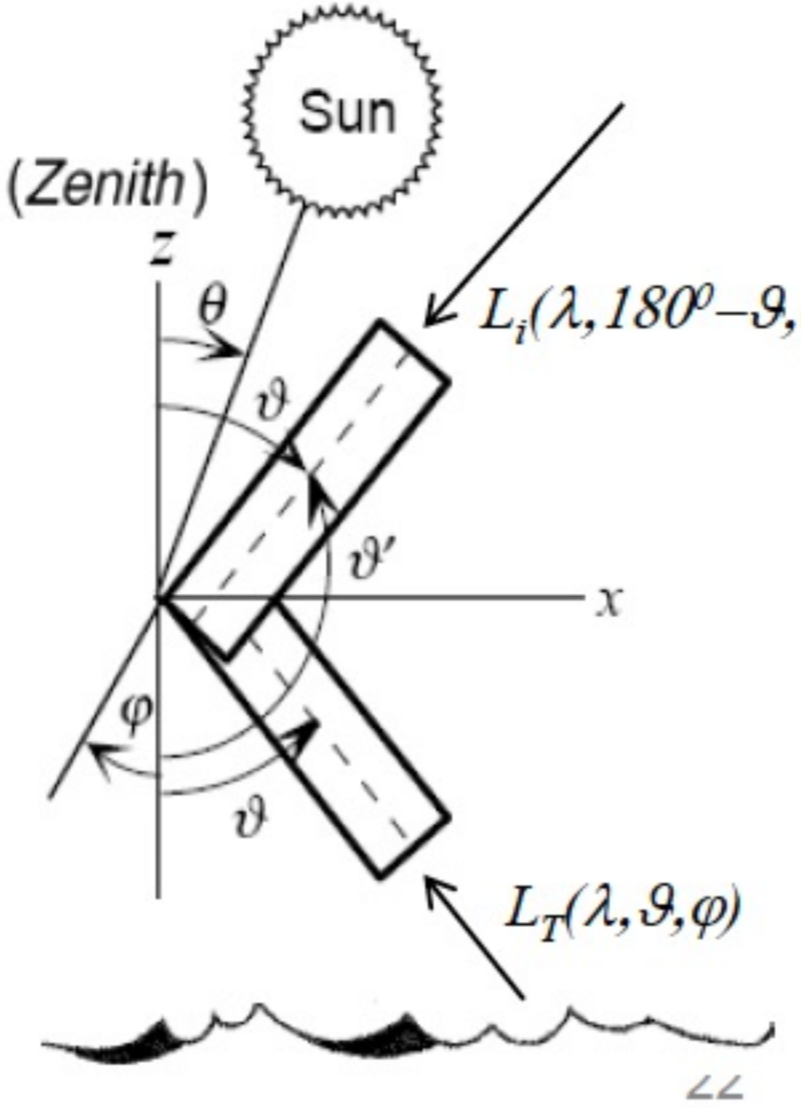
Hyperspectral Satlantic radiometers, as installed on the BOUSSOLE buoy

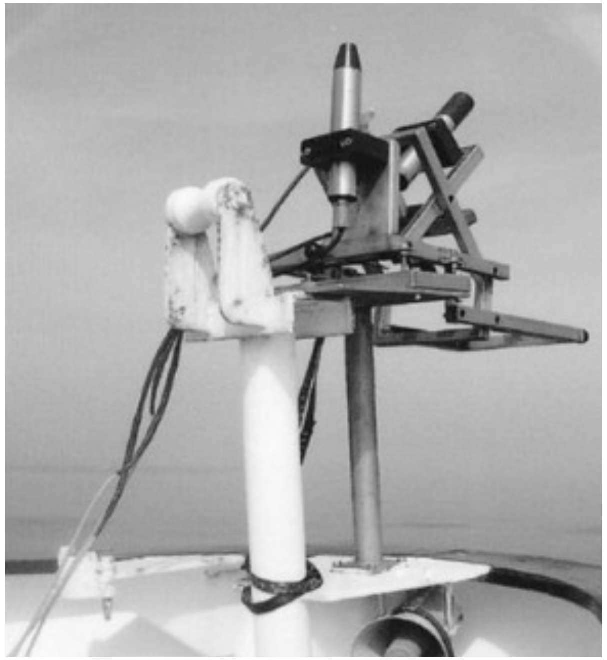


$$(\varphi = \varphi_0 + 90^0; \theta = 40^0; \theta' = 140^0)$$

Sky-radiance: L_i

Sea-radiance: L_T



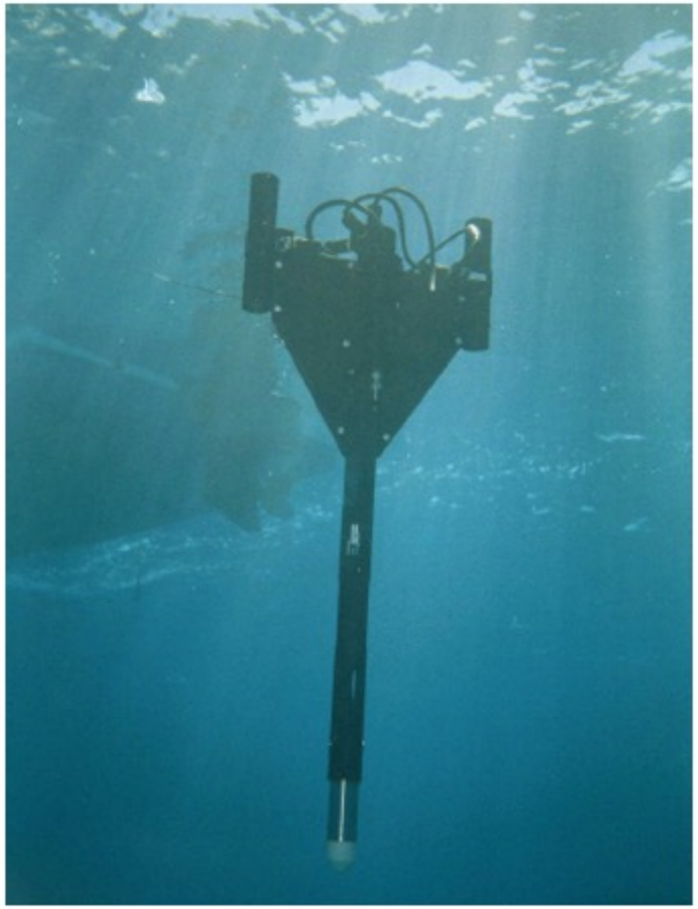


Neukermans, Griet. (2012

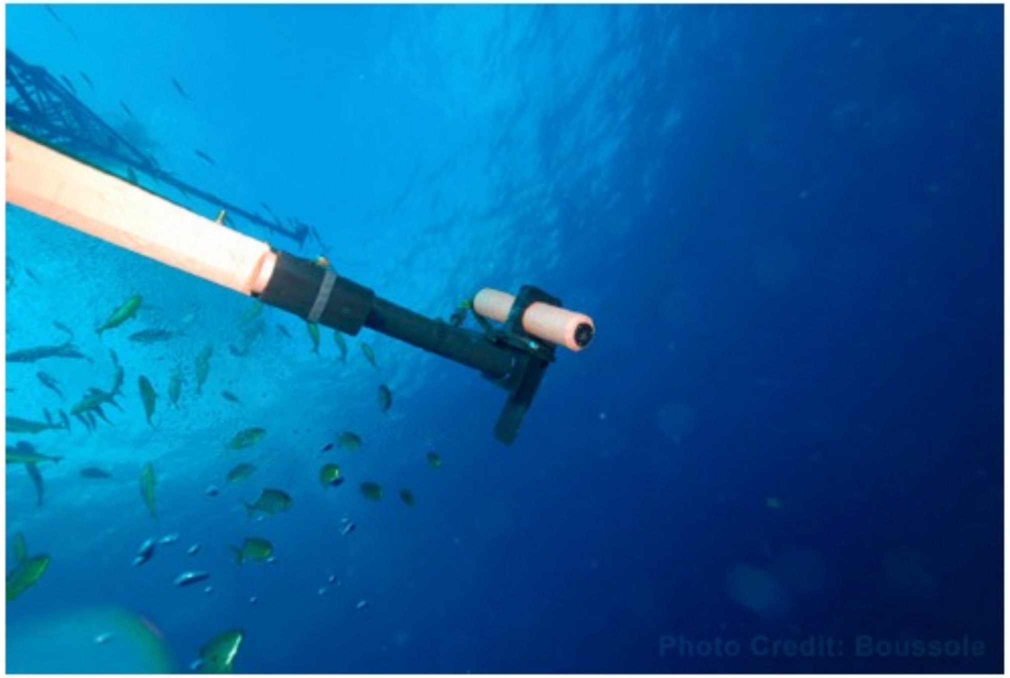
Measuring radiance: what we actually do most of the time

We measure L_u at nadir and E_d

vertical profiles (from ships) or fixed depths (moorings)



From: http://www.seabird.com/profiler



From BOUSSOLE

Field Sources of Uncertainty/Error

Self-Shading / platform shading

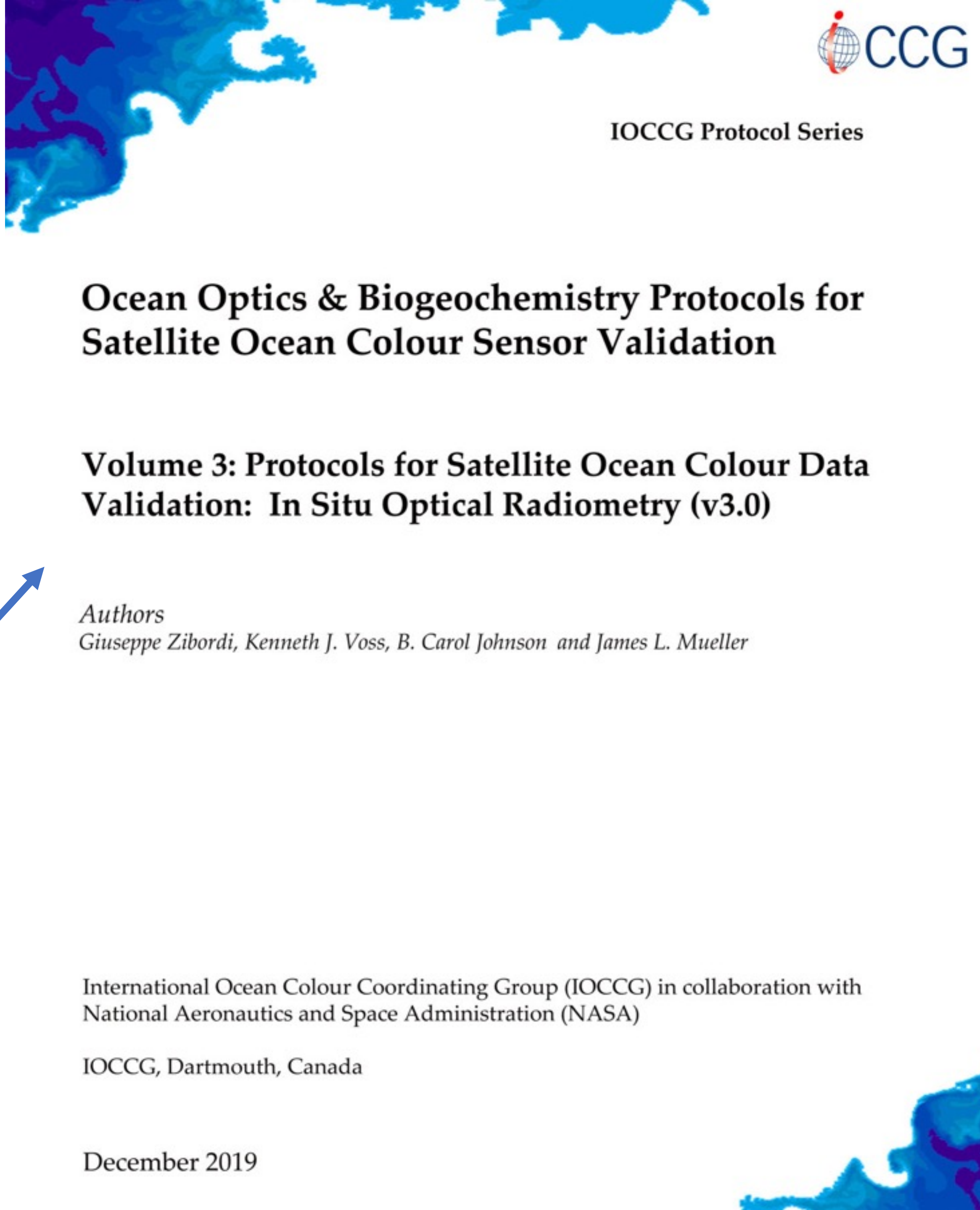
Tilt Effects

Wave Focusing

Depth Uncertainty/error

Surface Transmission

An excellent review of these effects and In situ radiometric protocols…



IOCCG Protocol Series

Ocean Optics & Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation

Volume 3: Protocols for Satellite Ocean Colour Data Validation: In Situ Optical Radiometry (v3.0)

Authors
Giuseppe Zibordi, Kenneth J. Voss, B. Carol Johnson and James L. Mueller

International Ocean Colour Coordinating Group (IOCCG) in collaboration with National Aeronautics and Space Administration (NASA)

IOCCG, Dartmouth, Canada

December 2019

Wave focusing effects on E_d

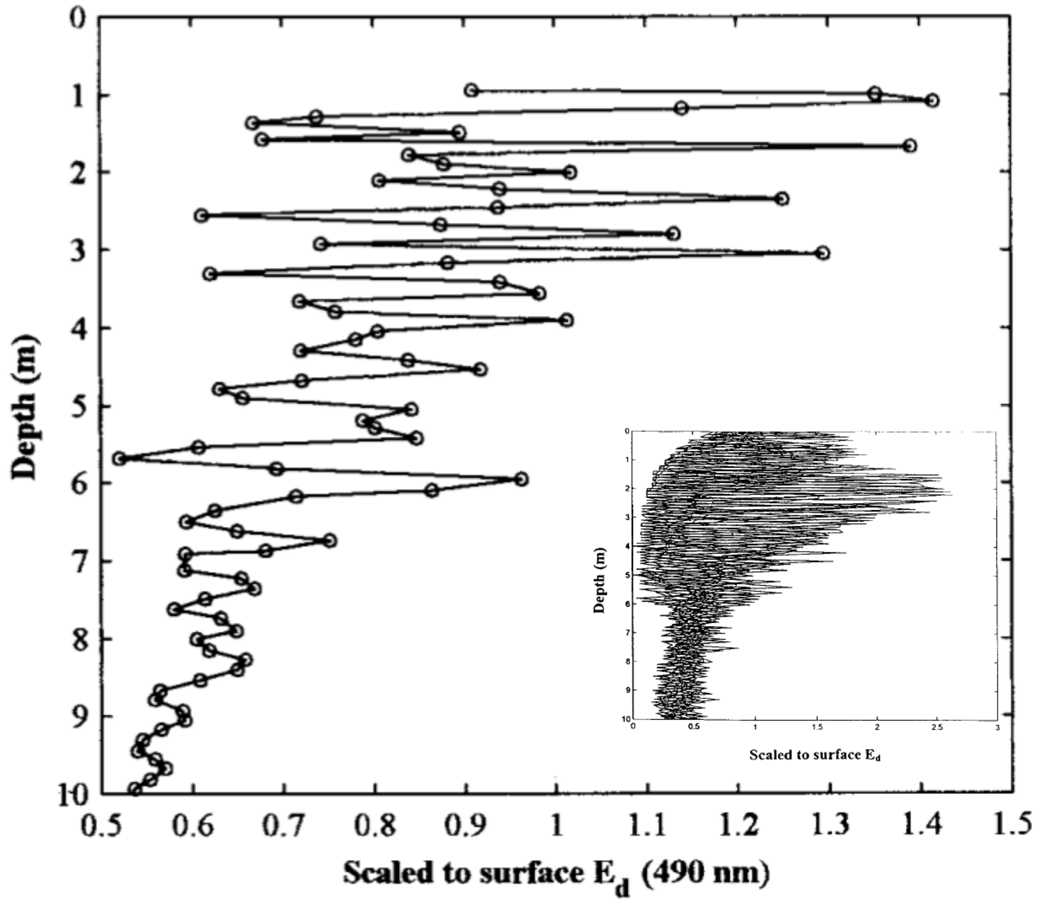


Fig. 2. Irradiance profile taken in the Gulf of California, October 1998, with the same profiler as used in Fig. 1. Conditions were calm.

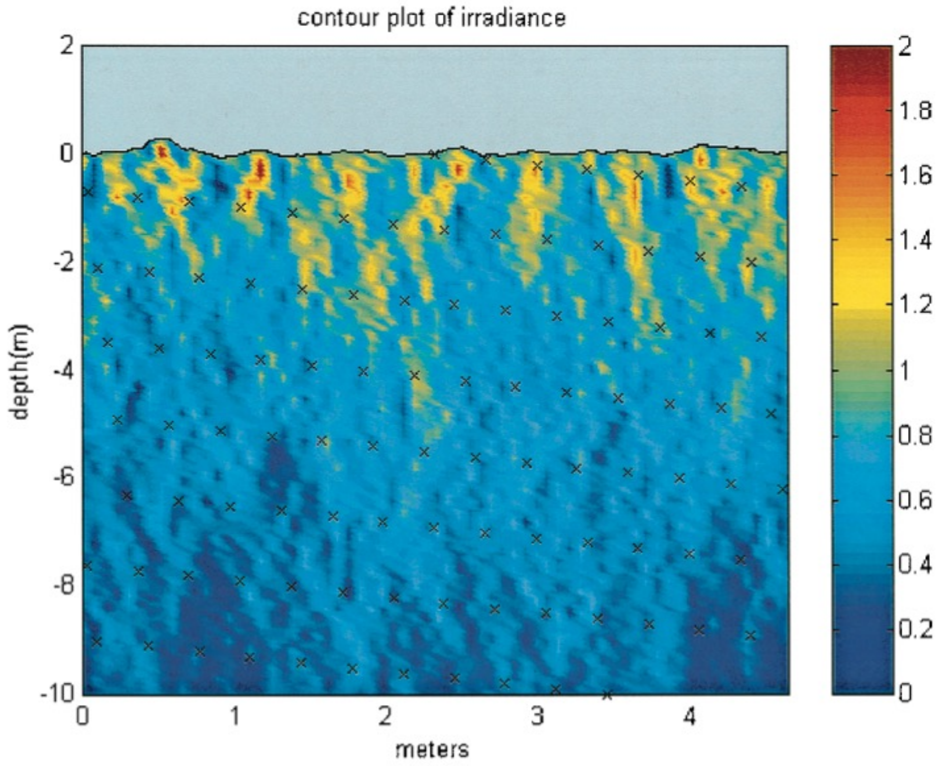


Fig. 3. Irradiance pattern beneath a random wave surface with a 1.1-m dominant wave: $a = 0.06\ \mathrm{m}^{-1}$ and $b = 0.15\ \mathrm{m}^{-1}$. A Petzold volume-scattering function was used (see text). Crosses are sampling points of an irradiance sensor dropping at 0.8 m/s with a sampling rate of 8 Hz.

Zaneveld, Boss, & Barnard, 2001, Influence of surface waves on measured and modeled irradiance profiles, App. Optc, 40(9): 1442-1449.

Sunphotometry – atmospheric aerosol optical depth

A sunphotometer is an irradiance with a 2 degree field of view. It is used to get at a key atmospheric parameter, the aerosol optical depth of the atmosphere.

The measurement is made by pointing the sunphotometer directly at the sun

Using Beer’s Law,

$E = Eo \exp(-\tau\, m)$

Where:
E = the direct irradiance
Eo = extra terrestrial solar irradiance (top of atmosphere) corrected for earth-sun distance
m = airmass
τ = optical depth of the atmosphere (can be split into molecular and aerosol scattering and absorption)

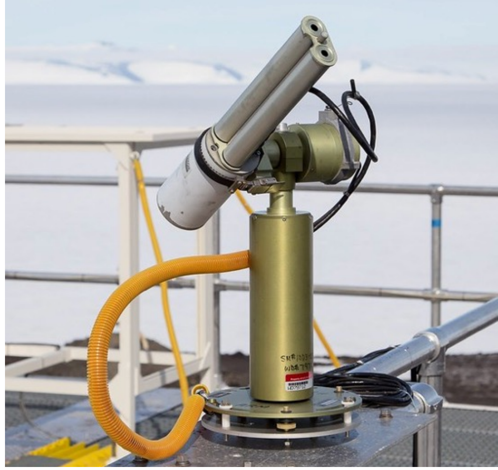


Image courtesy of the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility

If you know Eo and the sun angle, and measure E, you can calculate the aerosol optical depth at the wavelengths of measurement.

Im skipping lots of details on this method, but sunphotometers have been routinely used for many many years….

In fact they are a part of a global array of ground-based remote sensing aerosol network called AERONET

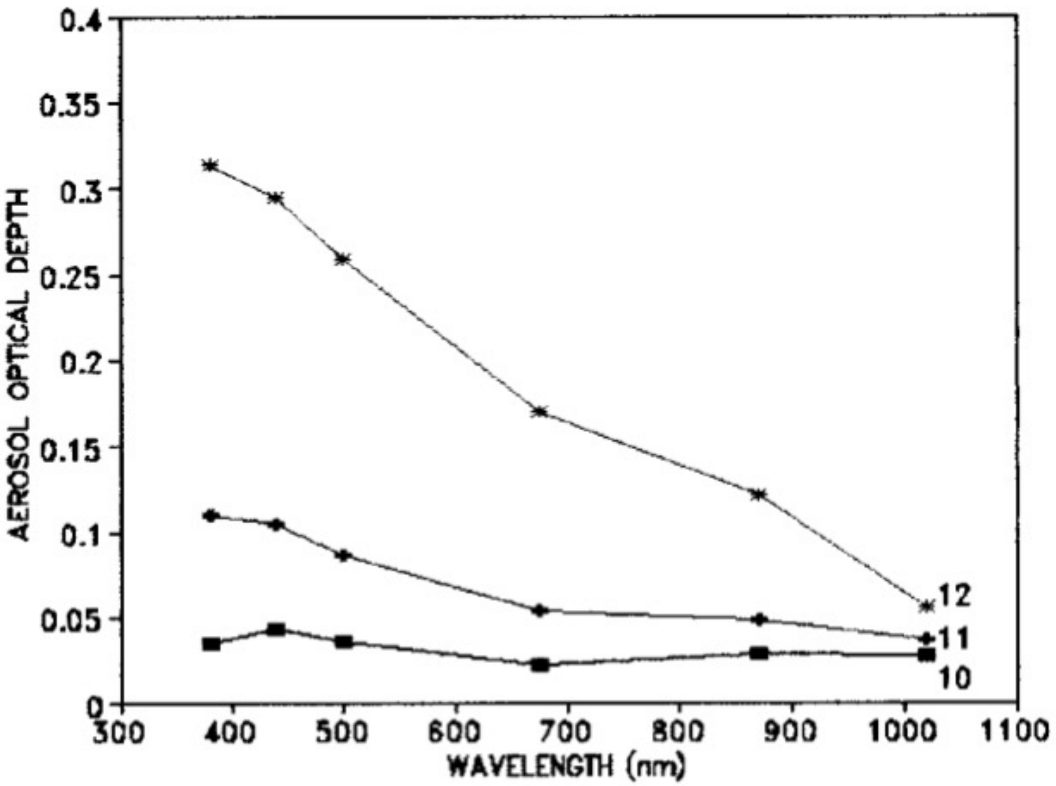


FIG. 7. Spectral dependence of aerosol optical depths measured on 10–12 Jan 1998 on HOT89 cruise.

Porter, et al., 2001.

Beautiful day for radiometry at the top of Mauna Loa