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Above- and in-water radiometry: Methods and Calibration

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Joint Research Centre of European Commission

Satellite and *In Situ* Observations

The Global Climate Observing System (GCOS) requires calibration and validation actions to ensure a confident application of remote sensing products to long-term monitoring of the Earth's surface.

Most of the actions satisfying the former requirement for satellite ocean color products, need accurate and globally distributed *in situ* radiometric measurements.

Such a need, motivated by the production of highly accurate Ocean Color Essential Climate Variables for the creation of Climate Data Records, has become the rationale for advanced research in marine radiometry during the last two decades.

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Background on Quantitative Radiometry

Fully recognizing the effort that since early 1920s generated know-how in marine optical radiometry, quantitative optical radiometry started only in the mid 1960's thanks to development of spectral radiometers (Jerlov 1965, Tyler et al 1970) and highly accurate secondary standards of spectral irradiance (Slater 1980).

Major advances in the assessment and implementation of *in situ* optical radiometry methods were driven by satellite missions aiming at mapping the phytoplankton biomass at global scale.

The SeaWiFS program played a major role in such a development and assessment for more than a decade by supporting SIRREXs (e.g., Mueller 1992, Johnson et al. 1995, Johnson et al. 1999, Hooker et al. 2002, Zibordi et al. 2002) and finalizing the ocean optics protocols (e.g., Mueller and Austin 1992, Mueller et al. 2003).

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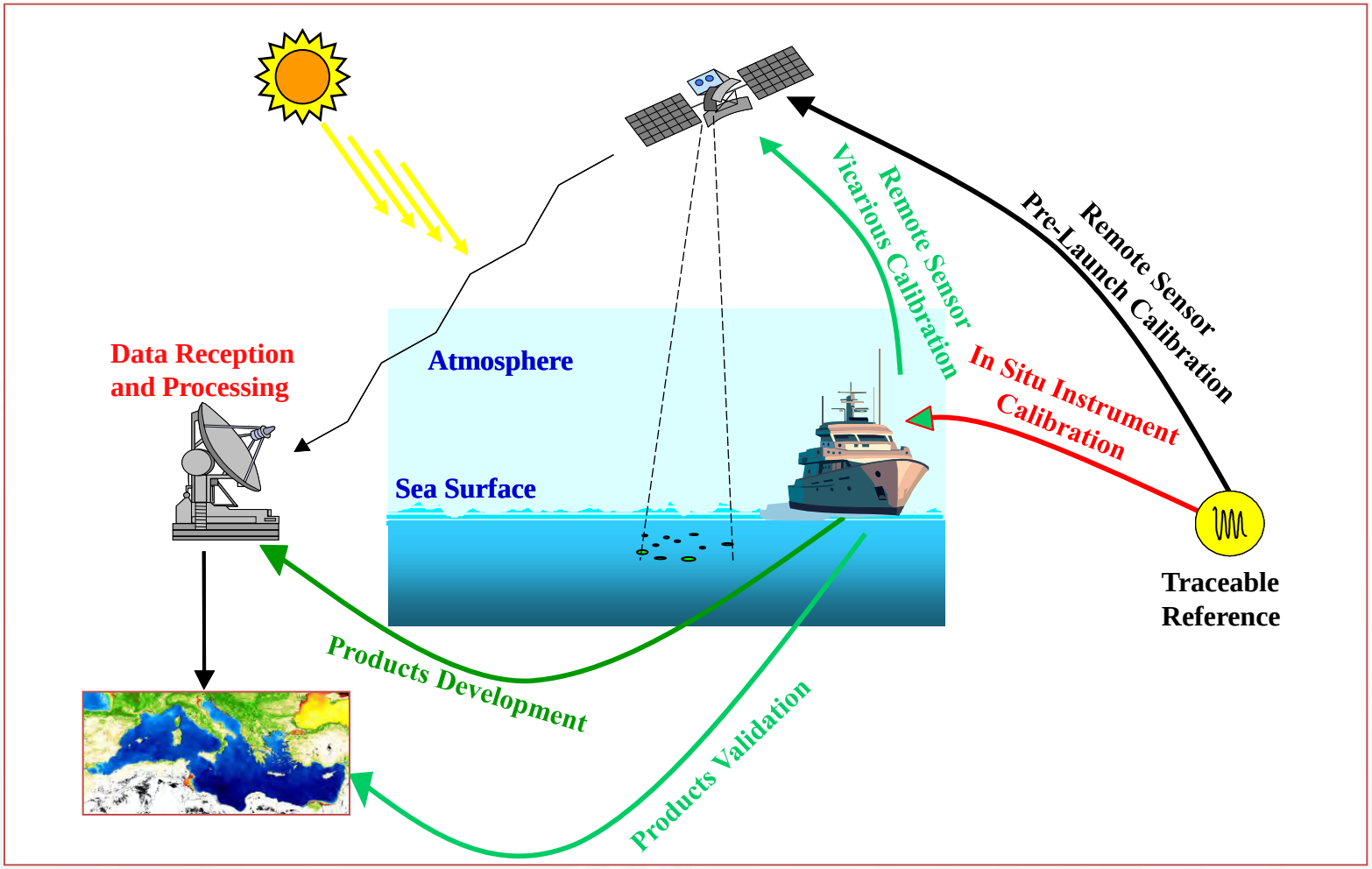
In Situ Data and Satellite Ocean Color



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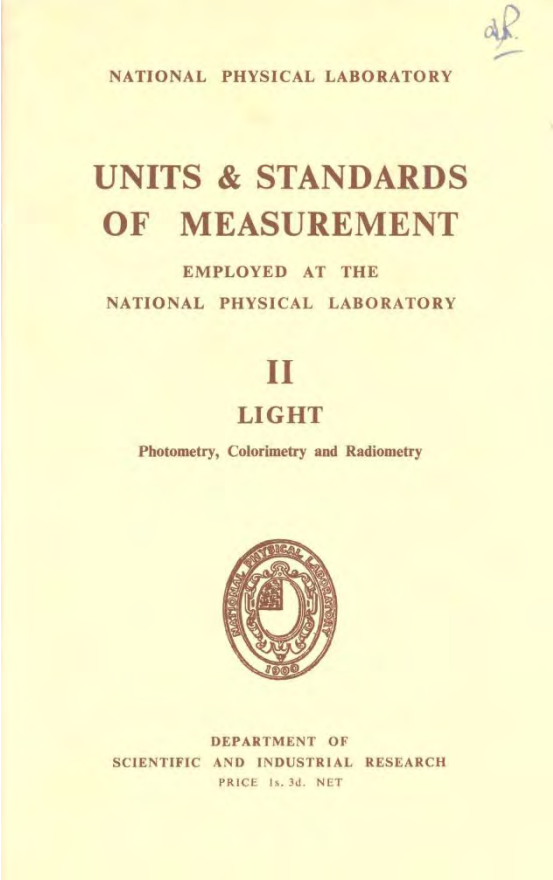
Requirements for field data supporting cal/val programs

1. Traceable (measurements should have well defined uncertainties quantified, when possible and appropriate, through standards);
2. Globally distributed (measurements should represent the wide range of geophysical conditions that remote sensing systems are expected to observe);
3. Continuous (time-series of quality assured data are fundamental for assessing remote sensing products from individual and mostly successive space missions);
4. Cross-site consistent (measurement uncertainties should be likely the same for all measurement sites and measurement conditions);
5. Accessible (measurement availability, through suitable data policy, is a key element for any actual cal/val program).

Radiometric Definitions



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II

LIGHT

Photometry, Colorimetry and Radiometry

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

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National Physical Laboratory. *Units and Standards of Measurements employed at the National Physical Laboratory*: II Light. *5, 1-8,* 1952.

Morel, A. and R. C. Smith. Terminology and units in optical oceanography. *Marine Geodesy 5, 335-350,* 1982.

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Radiometric Quantities

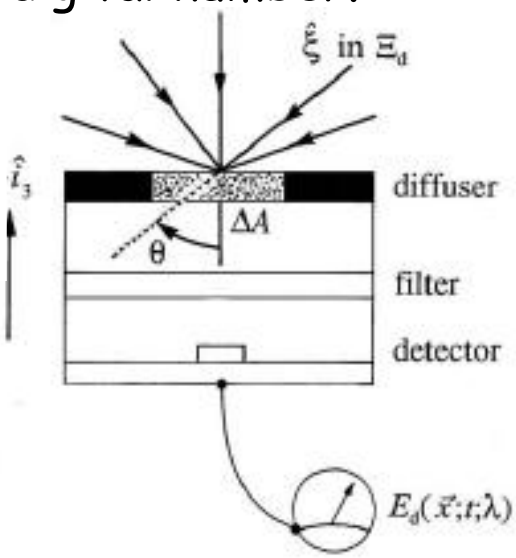
Radiometry is the measurement of physical quantities like radiance and irradiance, performed through light-measuring instruments called radiometers.

Quantity	*Symbol*	*Unit*
Radiant Energy	Q	Joule
Radiant Flux	Φ	Watts (Joule/sec)
Irradiance	E 	Watts/m^2
Radiance	L 	Watts/(m^2 sr)
Irradiance Reflectance	E_u/E_d	-
Remote Sensing Reflect.	L_u/E_d	sr^{-1}
Q-factor	E_u/L_u	sr

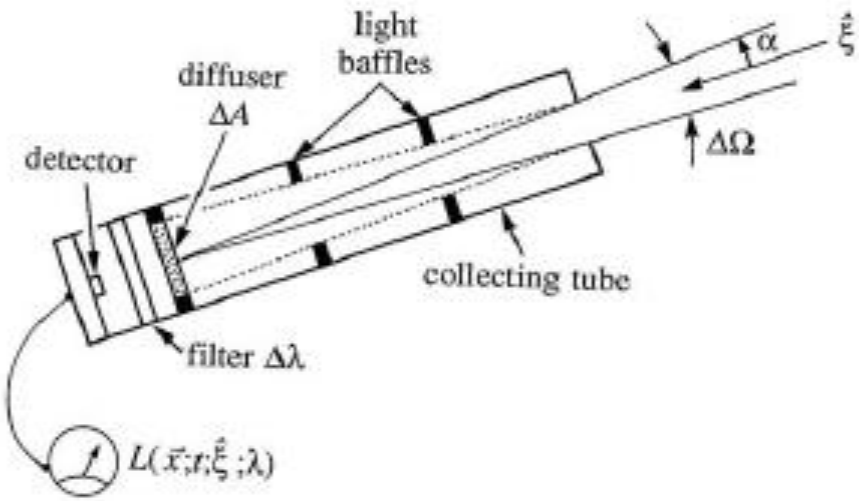
Radiometers

A radiometer is composed of at least three basic components:

1. the optics which collect the input radiant flux through an aperture, decompose it through spectral filters (or alternatively disperse it through prisms or gratings), and focus it on a field stop;
2. the detector which transduces the input radiant flux received through the field stop into an electrical signal;
3. the analog to digital converter which translates the analog output of the detector (typically a voltage or a current) into a digital number.



Irradiance (vector) sensor

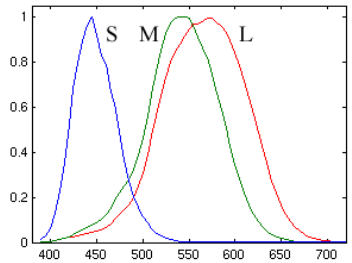


Radiance sensor

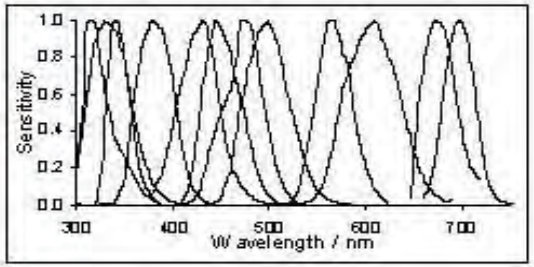
Optical Sensing Systems

Of all the techniques used in remote sensing, the observation of the Earth from optical sensors is perhaps the most easily understood in concept, because it is the most similar to our own personal remote sensing device – the human eye.

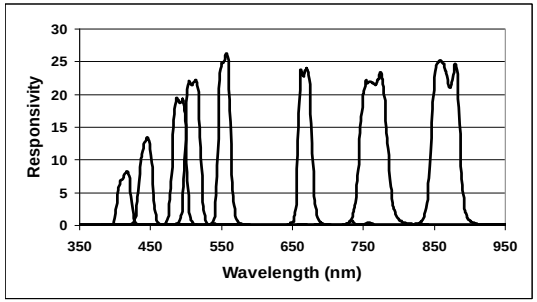
Ian Robinson (2004)



Human eye (tri-chromatic)



Mantis shrimp eye (multi-spectral with UV and polarization sensitivity)



SeaWiFS remote sensor (multi-spectral with NIR sensitivity)

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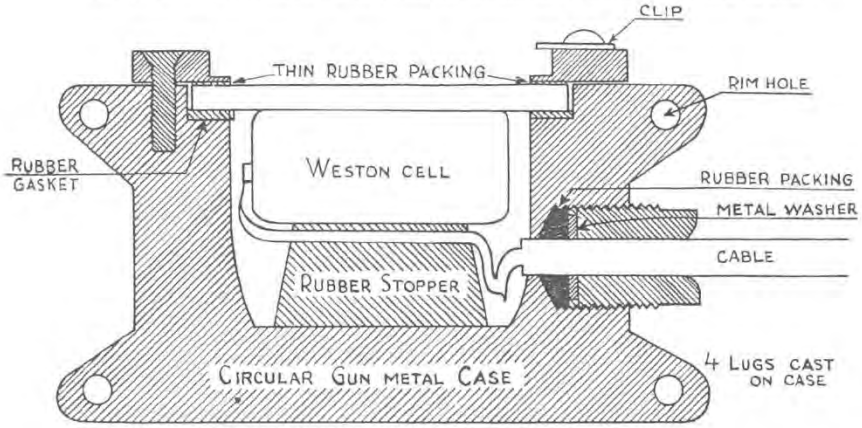
In-water Radiometry

Marine Equipment.

Photometer Case. This must evidently be absolutely watertight under all conditions of use, and strong enough to withstand the rough treatment that it is likely to receive in bad weather. It should be as compact as possible, so as to offer the minimum resistance to the lateral



Scale 2:3.

Fig. 1.
Section through suggested photometer-case

motion through the water that is often unavoidable. It must be readily capable of suspension with the window horizontal, and to ensure this, when the ship is drifting or anchored in a current, should have provision for the attachment of a lead sinker. It is also highly desirable that the bottom should be flat, so that the case can be placed on the deck when it is swung aboard, and comparisons with the deck photometer readily carried out on shore, or in smooth water, by placing both side by side on a level surface.

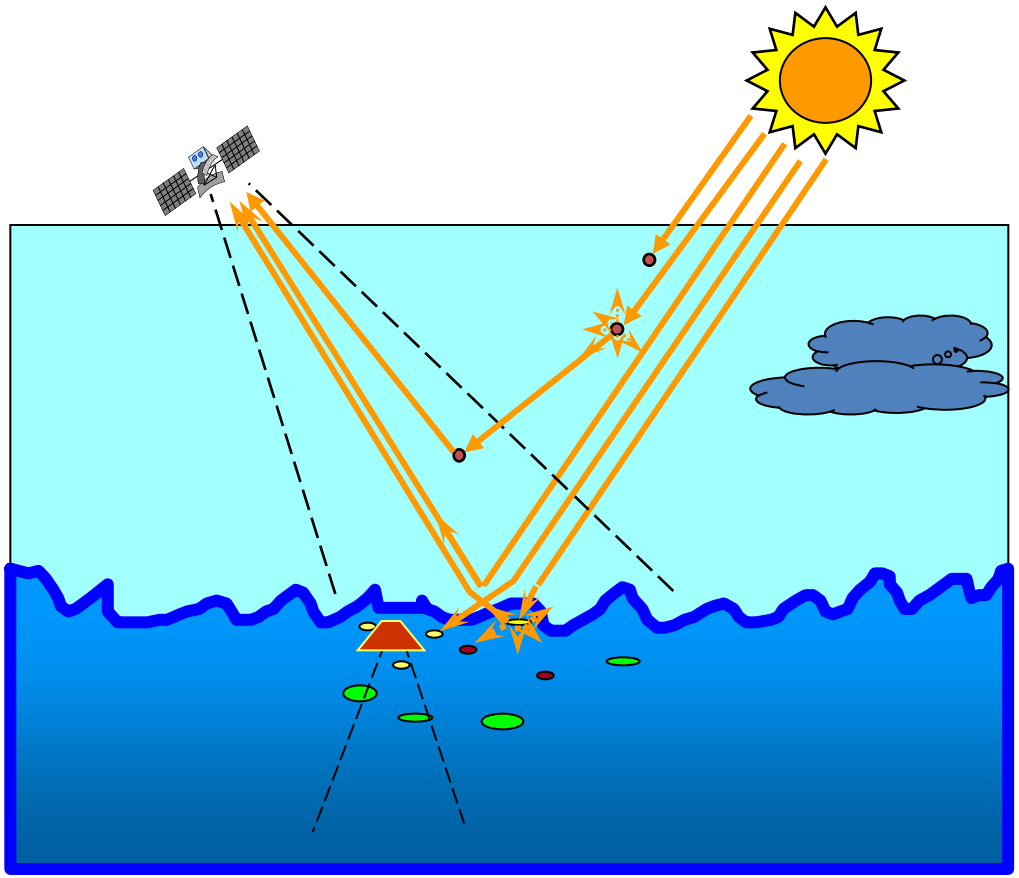
The metal rim surrounding the window should be deep enough to hold the filter and opal glass, and, to prevent appreciable shading of low-angle light by this rim, it is well to make the window somewhat larger than the cell. This window must, of course, be strong enough to withstand the hydrostatic pressure at the greatest depth reached.

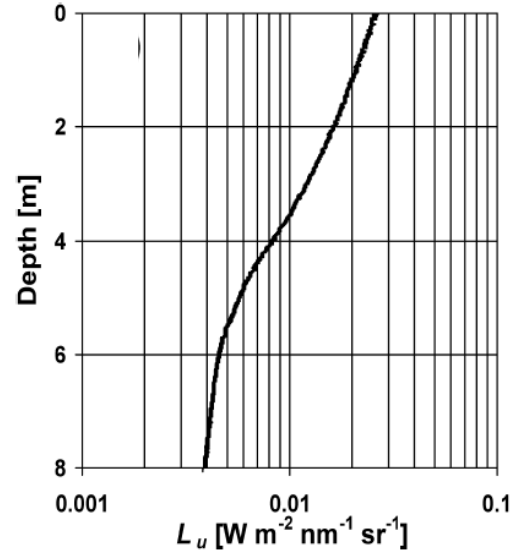
Atkins, W. R. G. and H. H. Poole. The photo-electric measurement of the penetration of light of various wave lengths into the sea and the physiological bearing of results. *T. Phil. Trans. Roy. Soc. London*, (B) 222, 129-164, 1933.

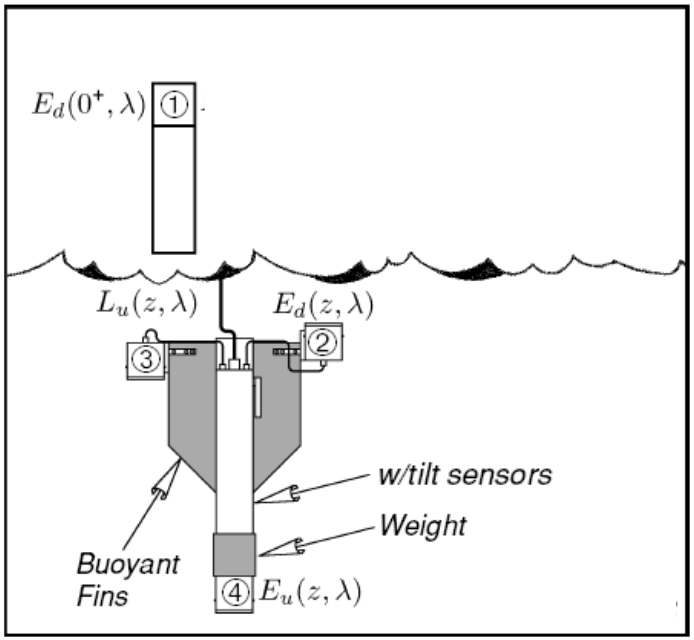
In-Water Radiometry

Historical dates

1920s: First successful measurements
1960s: Accurate absolute calibrations
1990s: Methods assessment
2000s: Accurate uncertainty analysis







In-Water Radiometry

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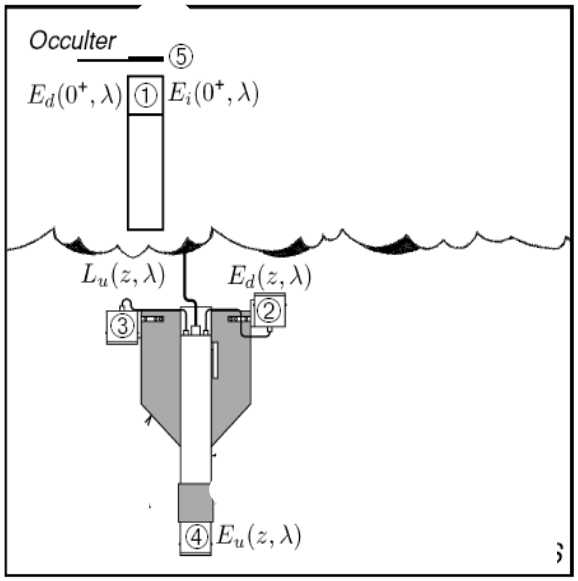

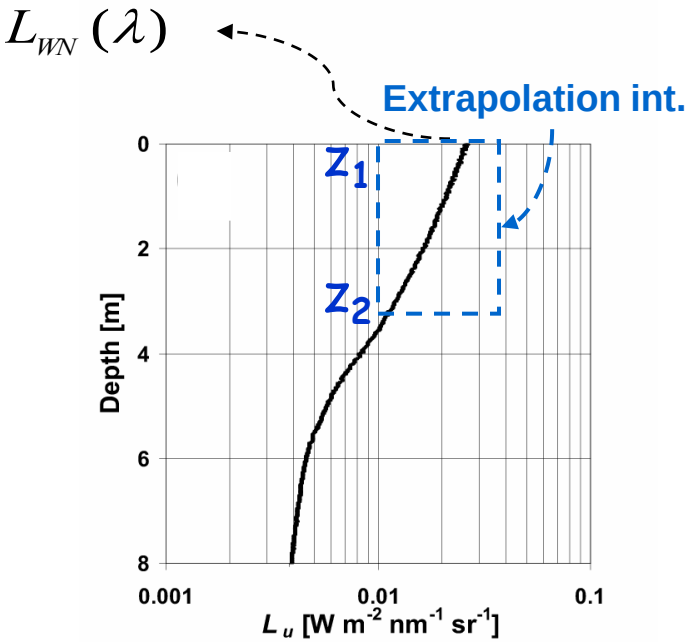

$$L_u(z,\lambda,t_0) = \frac{L_u(z,\lambda,t)}{E_d(0^+,\lambda,t)} E_d(0^+,\lambda,t_0)$$

Normalization to account for fluctuations in illumination

$$L_u(0^-,\lambda) = L_u(z_0,\lambda,t_0)\, e^{-K_l(\lambda,z_1,z_2)z_0}$$

Extrapolation just below the surface

$$L_w(\lambda) = L_u(0^-,\lambda)\frac{t_{aw}(\lambda)}{n_w^2(\lambda)}$$

Propagation through the surface

$$L_{WN}(\lambda) = L_w(\lambda)\frac{E_0(\lambda)}{E_d(0^+,\lambda)} C_{wind}(\lambda,\theta_0,\tau_a,IOP)$$

Transformation to exact normalized water-leaving radiance

Tyler JE, Smith RC, Gordon and Breach Science Publishers (1970); **Smith RC, Baker KS** SPIE vol 478, p 119–126 (1984).

Lewis MR, et al. Science 234:870–873 (1986). **Waters KJ et al.,** Oceanography, November-1990, 18–21.

Gordon HR, Clark DK, *Appl. Opt.* 20 4175-4180 (1981); **Morel A et al.** *Appl. Opt.*, 41, 6289–6306 (2002).

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Fixed-depth v.s. Continuous Profile: Is there any need for comparisons?

Assigning vertical profiles of the downward irradiance E_d and its diffuse attenuation coefficient K_d on the basis of the data measured during vertical movement of the probe in the most upper layer of the sea is improper, or at least extremely inaccurate.

The use of two integrating detectors working simultaneously at different depth appears to be much more accurate to calculate optical profiles in the most upper layer.

An (almost) Anonymous Reviewer, 2003

Fixed-depth v.s. Continuous Profile

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Comparisons have generally been made using **independent measuring systems**, without explicitly quantifying the uncertainties related to:

a. the measuring systems (e.g., absolute calibration, immersion factor, self-shading), and

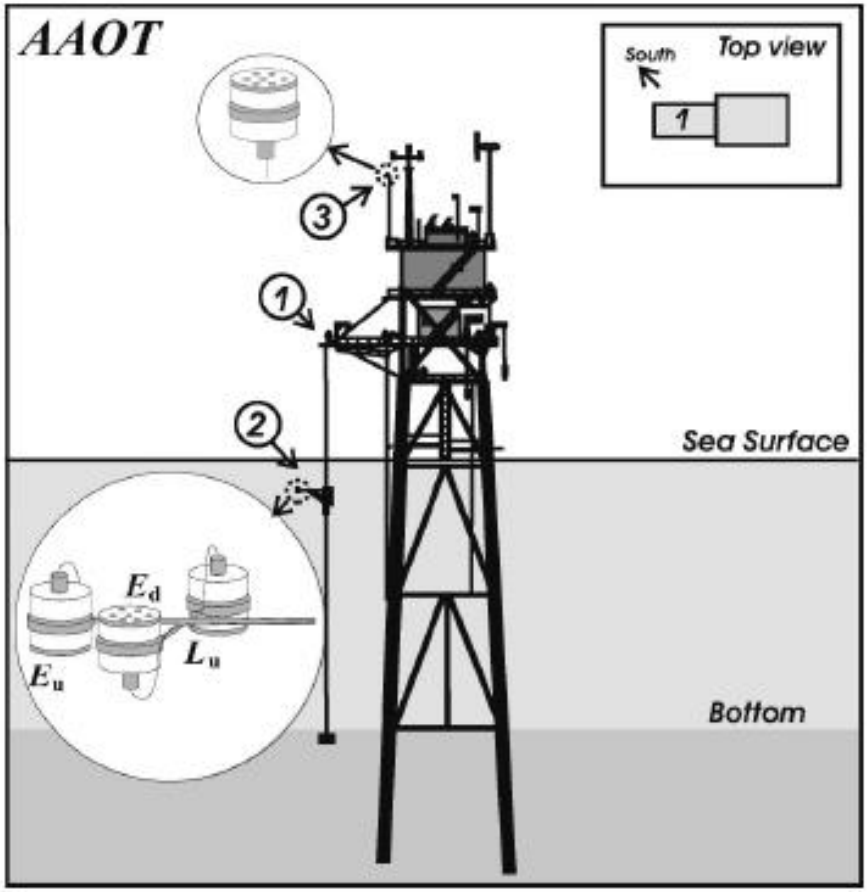
b. the measurement methods (i.e., fixed-depth and continuous profiling).

A specific comparison was performed utilizing identical:

i. instrumentation;

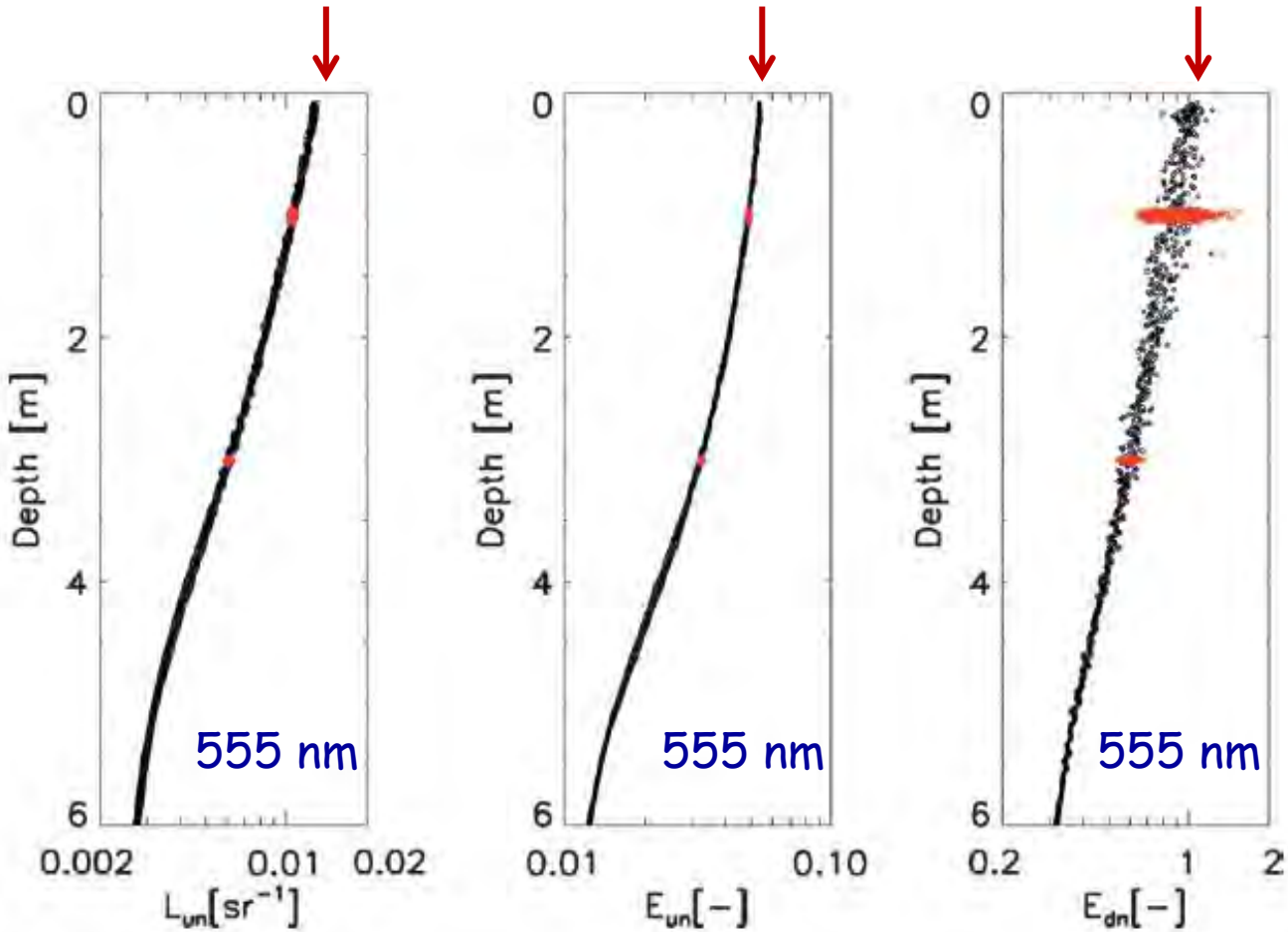
ii. deployment structure and

iii. processing code.



G.Zibordi et al.. An evaluation of radiometric products .... *JTECH*, 26, 91-106 2009.

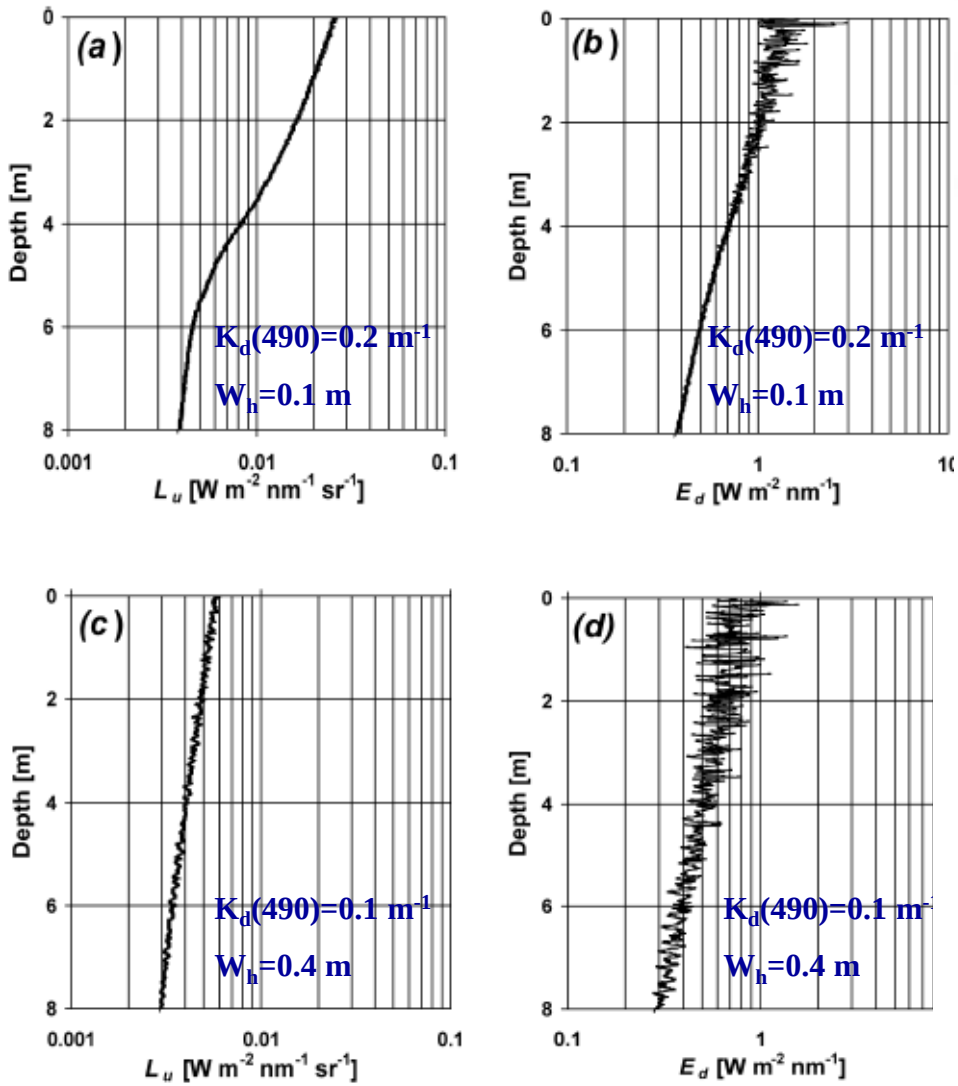
Fixed-depth and Continuous Profile Data

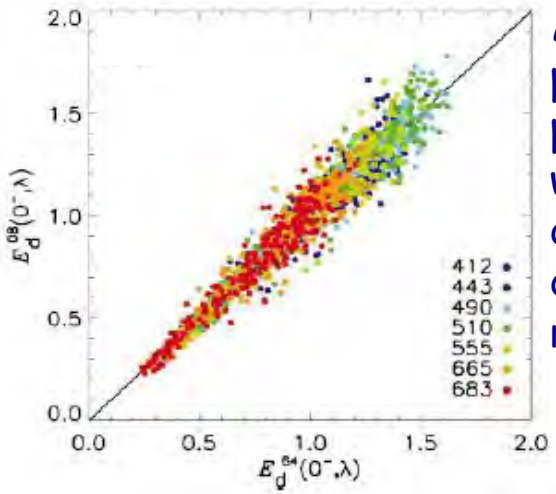


As long as discrete deployment depths are properly selected, fixed-depth and continuous profile data products are equivalent (i.e., inter-comparisons will exhibit statistical differences lower than the composition of the uncertainties from individual methods).

G.Zibordi et al.. An evaluation of radiometric products .... *JTECH*, 26, 91-106 2009.

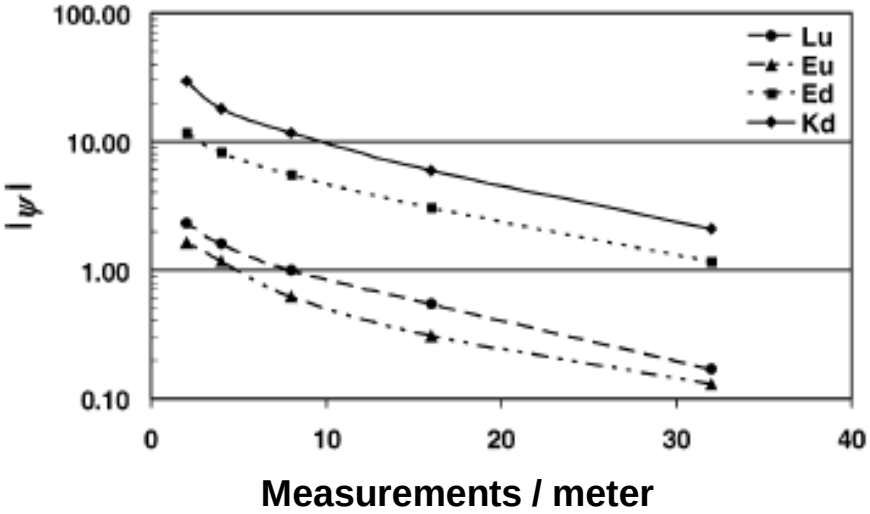
Depth resolution





E_d from profiles produced with different depth resolutions

Uncertainty in sub-surface values as function of depth resolution



G.Zibordi et al. An evaluation of depth resolution requirements for optical profiling …. *JTECH*, 21:1059-1073, 2004.

D.D'Alimonte et al. A Monte Carlo Code for High Spatial Resolution Ocean Color Simulations. *Appl.Opt.* 49:4936-4950, 2010.

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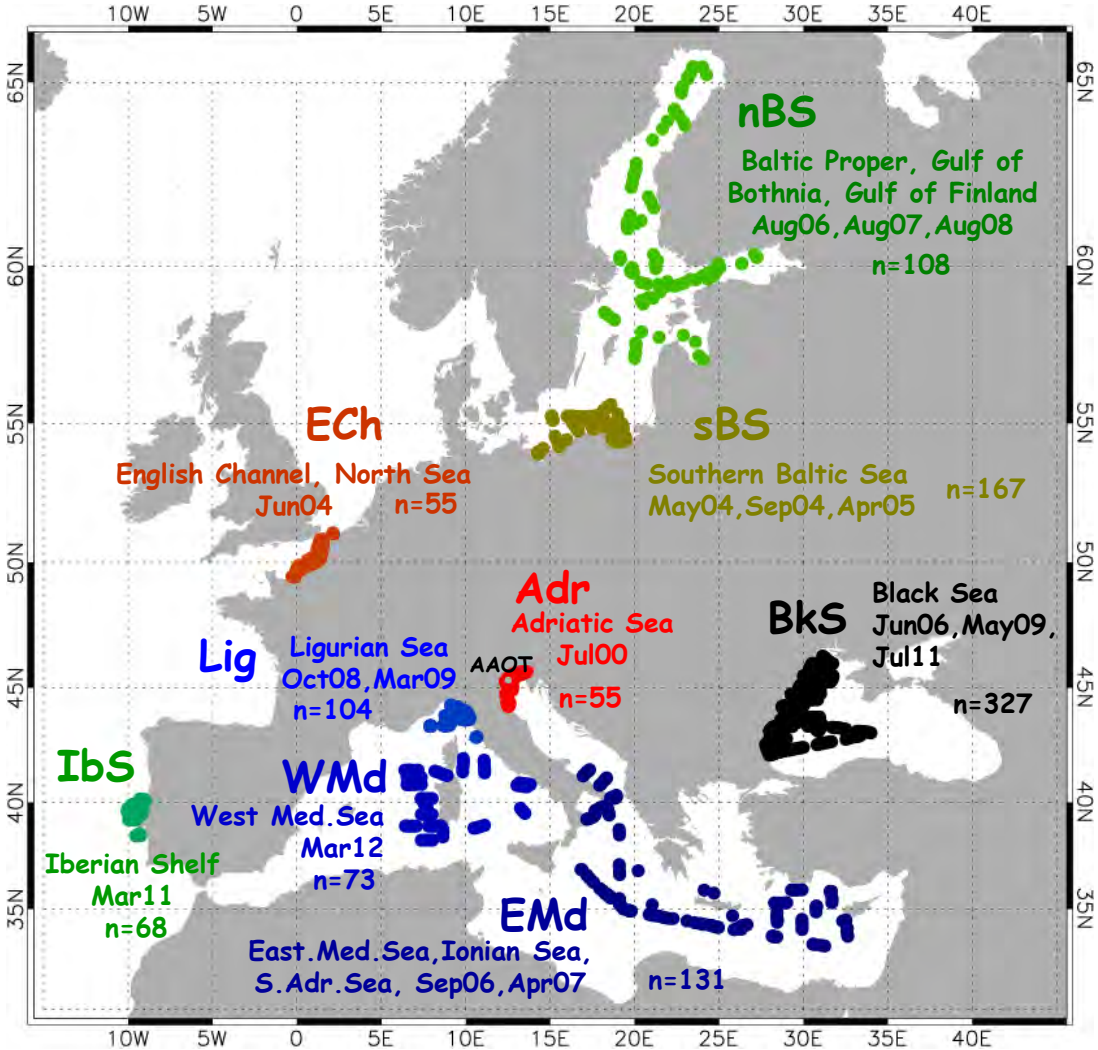
BiOMaP (Bio-Optical Marine Properties): a European Ocean Color Development Program

BiOMaP measurements are produced applying cross-site identical and consolidated: technology, measurement and calibration protocols, processing codes and quality assurance criteria.

G. Zibordi, J.-F. Berthon, F. Mélin and D. D'Alimonte Cross-site consistent in situ measurements for satellite ocean color applications: the BiOMaP radiometric dataset. *Remote Sensing of Environment*,115, 2104–2115, 2011.



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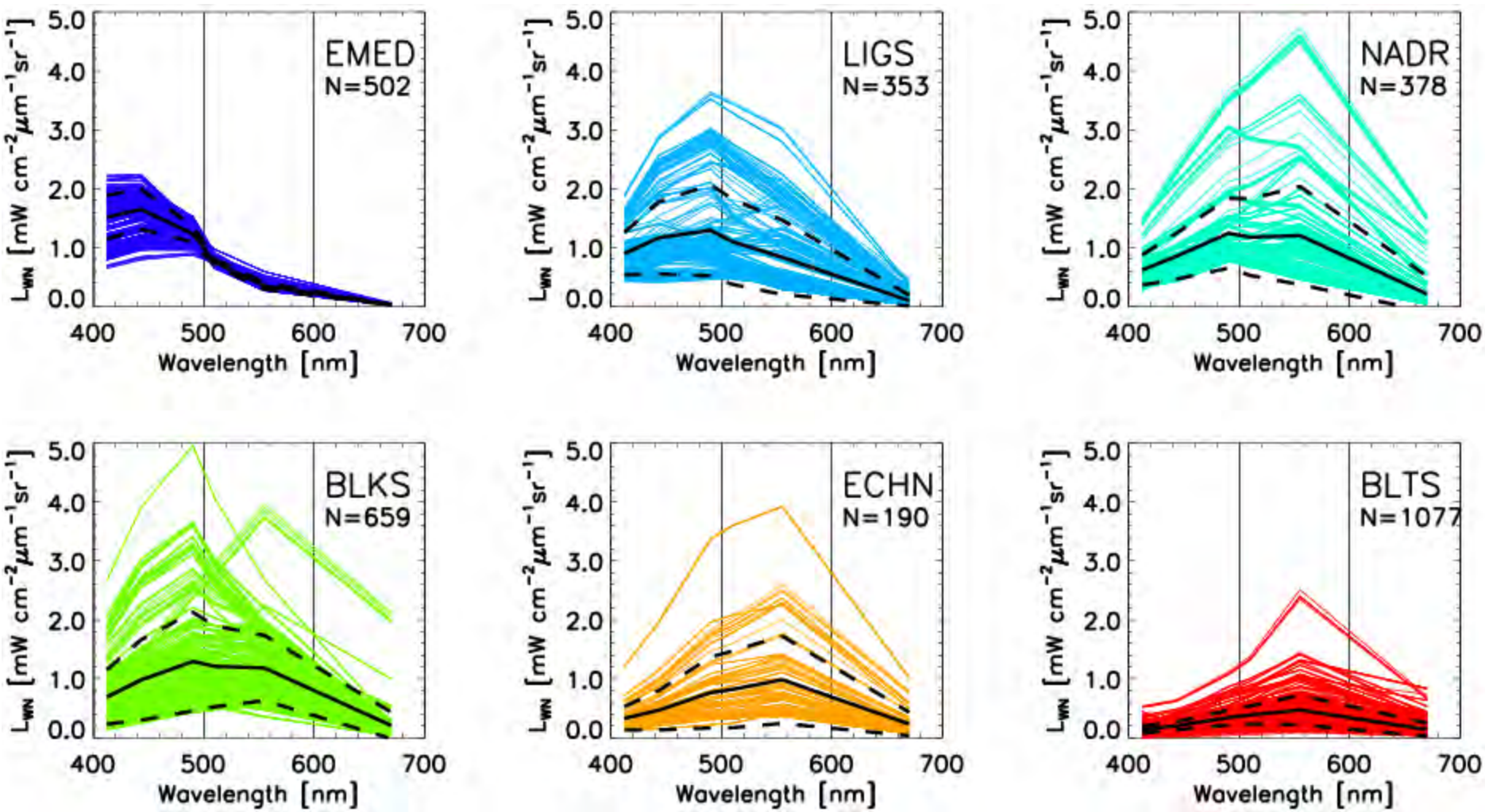
BiOMaP (Bio-Optical Marine Properties): L_{WN} spectra from the various European Seas



G. Zibordi, J.-F. Berthon, F. Mélin and D. D'Alimonte. Cross-site consistent in situ measurements for satellite ocean color applications: the BiOMaP radiometric dataset. *Remote Sensing of Environment*,115, 2104–2115, 2011.

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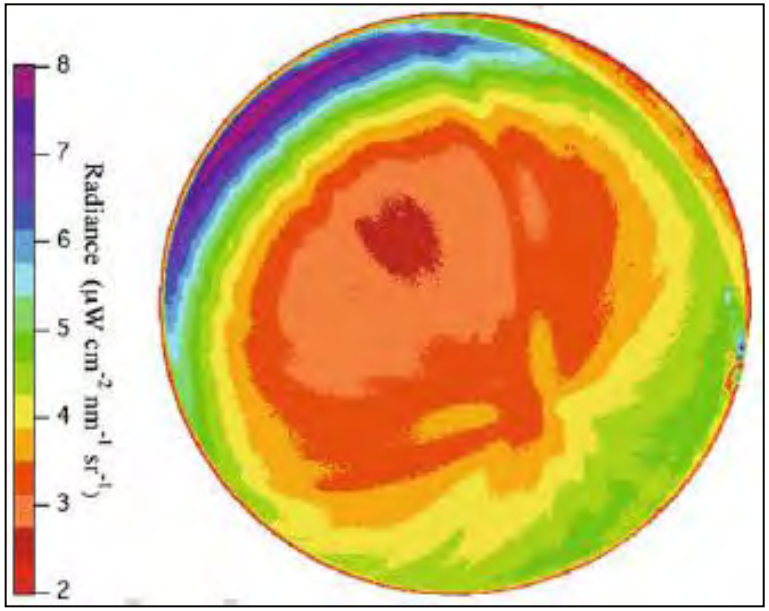
Radiance distribution (now)

NURADS
(Voss & Chapin 2005)

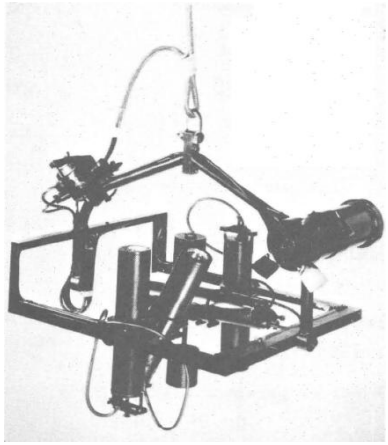


Upwelling radiance distribution
(MOBY site)

Voss KJ (1989) *Use of the radiance distribution to measure the optical absorption coefficient in the ocean. Limn Oceanogr 34:1614–1622.*

Voss KJ, Chapin AL (2005) *Upwelling radiance distribution camera system NURADS. Opt Express 13:4250–4262.*

Radiance distribution (past)



Angular Radiance Meter (Lundgren and Hojerslev 1971)

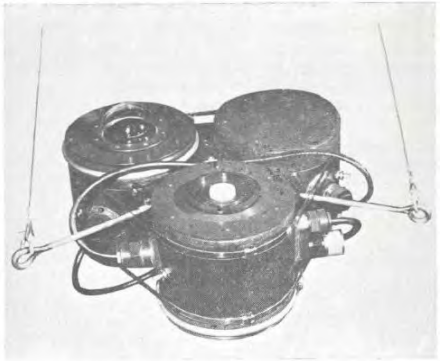
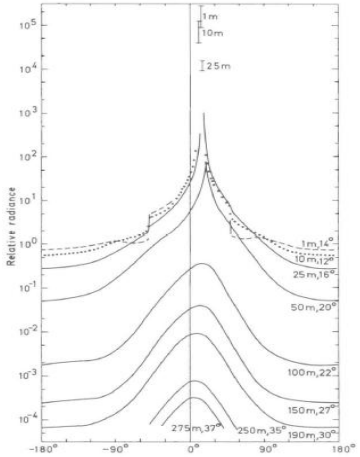
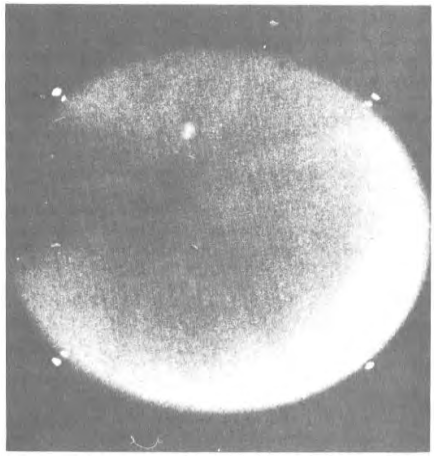


Fig. 4. Photograph of the underwater unit of the radiance distribution camera system.

Radiance Distribution Camera System (Smith et al. 1969)



Radiance change with depth in the sun vertical plane (Lundgren 1976)



Upwelling radiance distribution (Smith 1974)

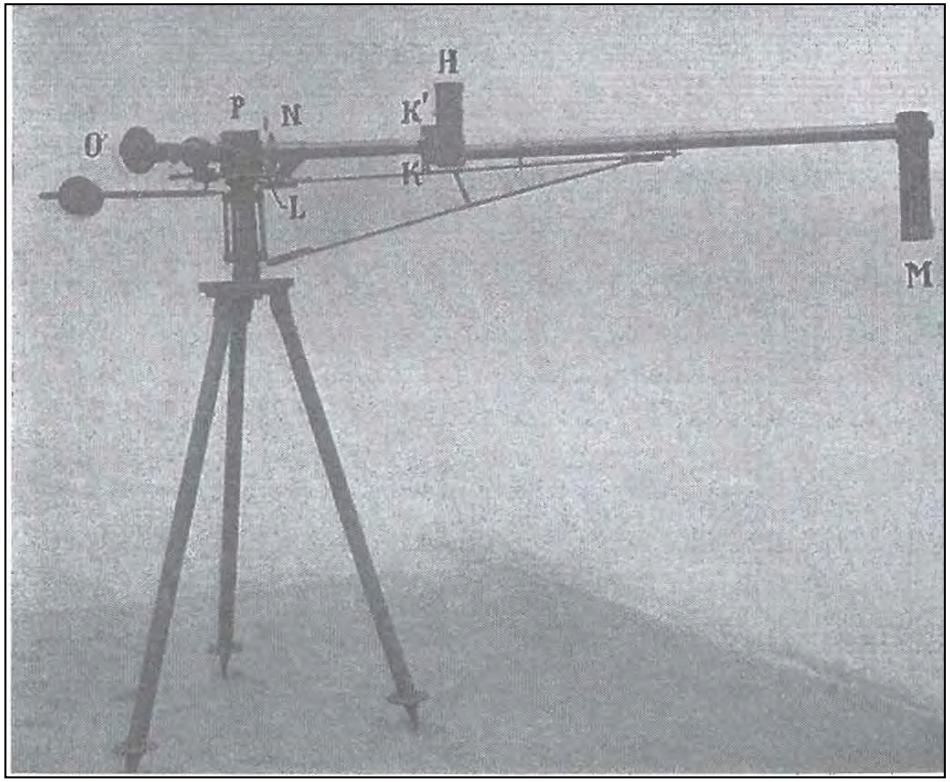
Tyler J.E . (1958) *Comparison of light distribution above and below water. J. Marine Res. 16:96-99.*

Sasaki et al. (1962) *On the instrument for measuring angular distribution … Bull. Japan Soc. Sci. Fisheries, 28:489-496.*

Lundgren B. and Hojerslev N. (1971) *Daylight measurements … Inst. Phys. Oceanography, Un. Copenhagen, Report n. 14.*

Smith R.C, Austin RW, Tyler J.E. (1969) *An oceanographic radiance distribution camera system. Appl Opt 27:341–351.*

Above-Water Radiometry

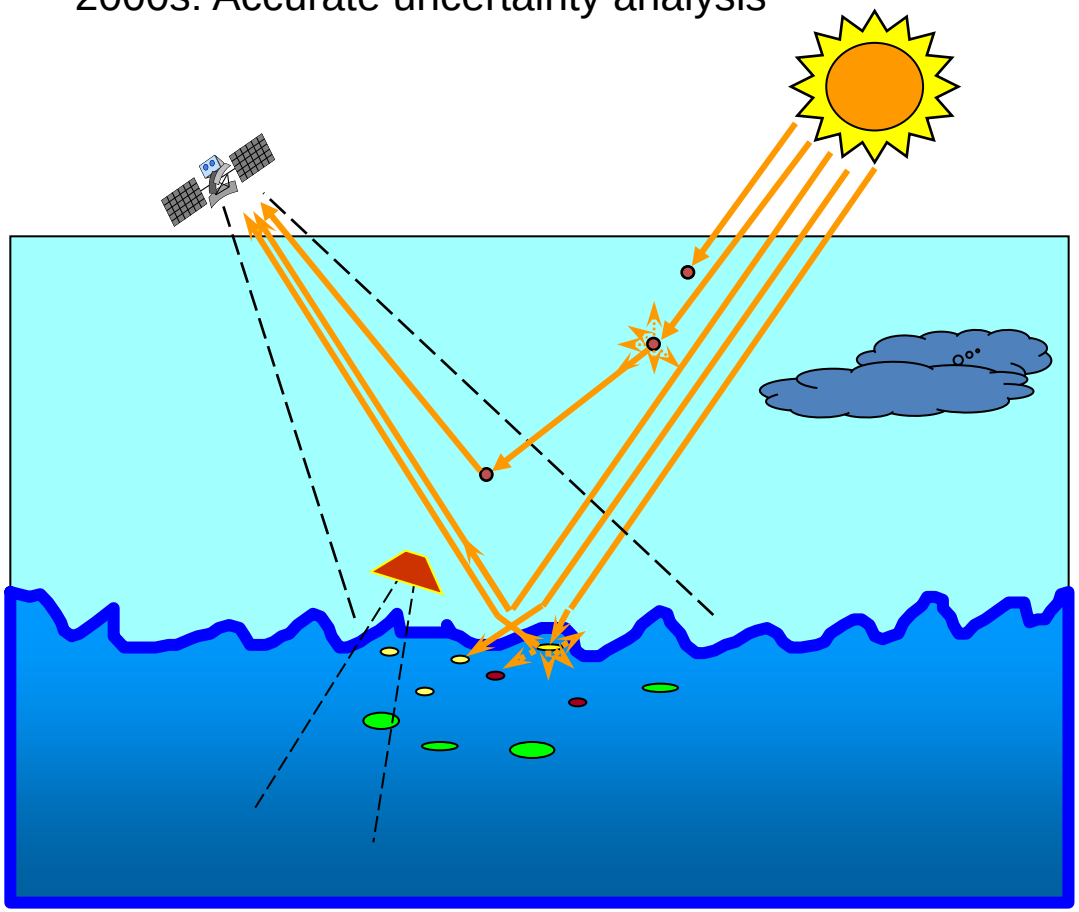


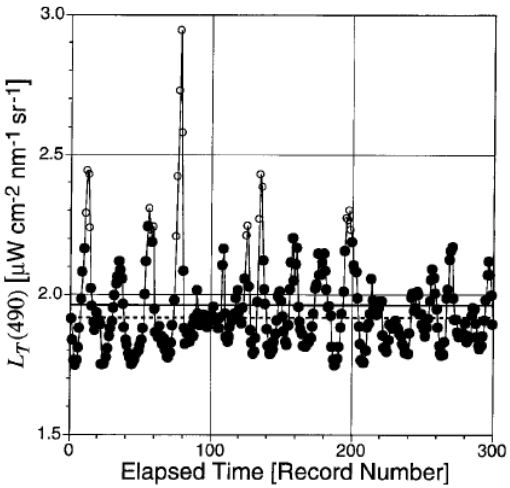
Shoulejkin W. On the Colour of the Sea: Part II. *The Physical Review: a journal of experimental and theoretical physics*. American Physical Society, 23: 744-751, 1924.

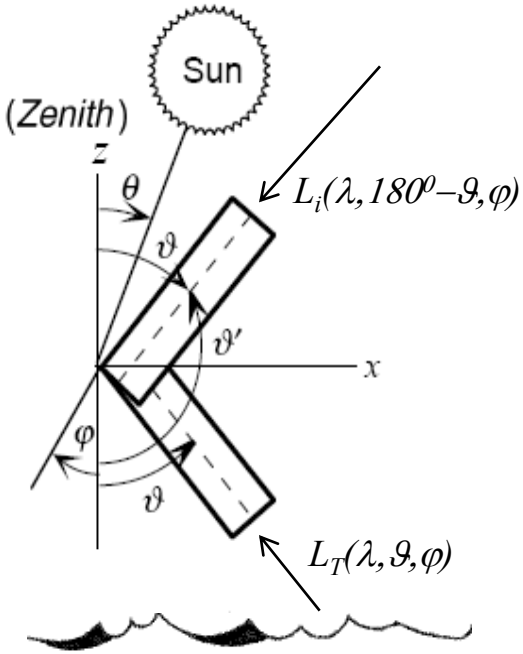
Above-Water Radiometry

Historical dates

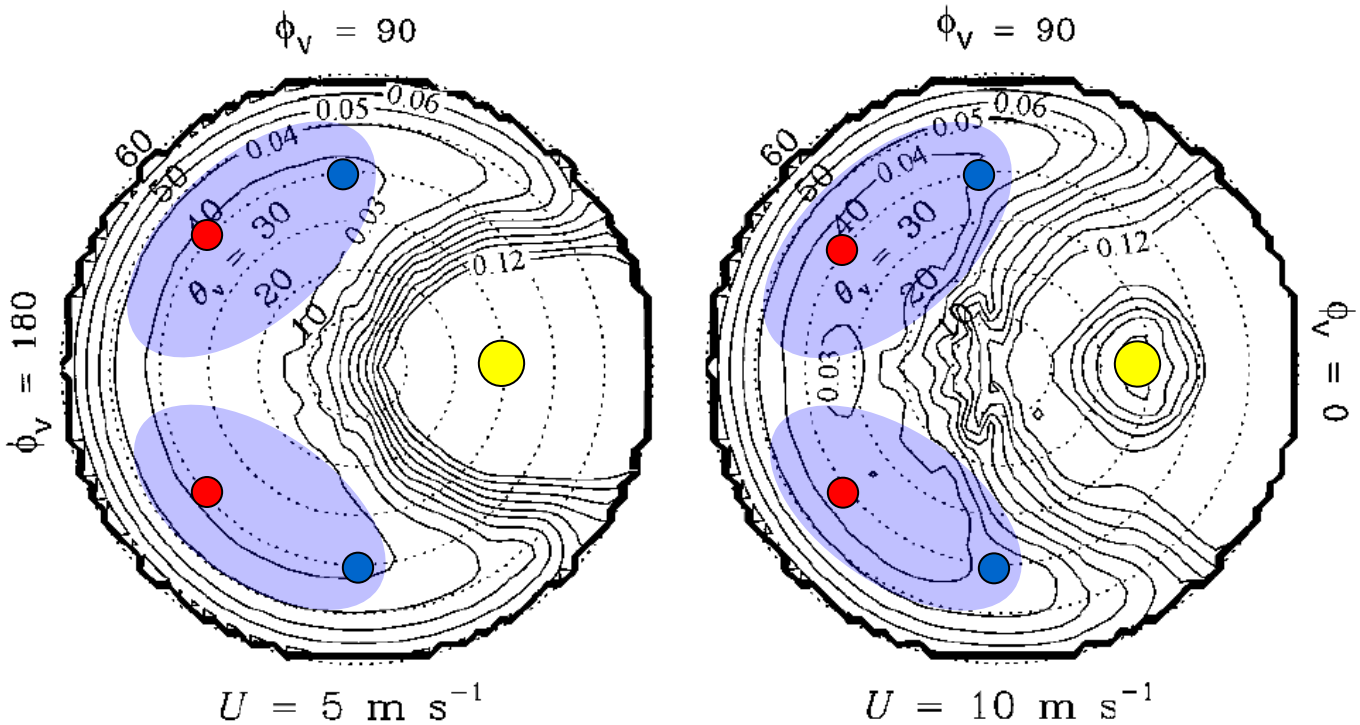
1920s: First observations
1980s: First documented methods
1990s: Methods assessment
2000s: Accurate uncertainty analysis







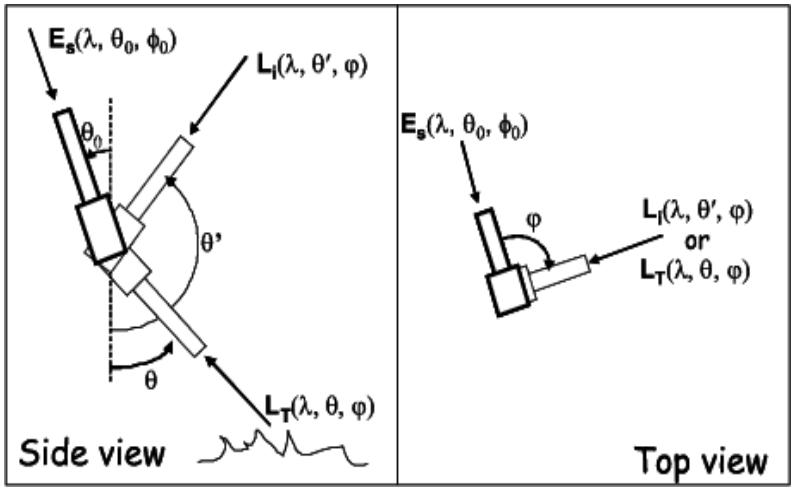
The viewing geometry: a key element for above-water radiometry.



Sea-surface reflectance

C.Mobley, Estimation of remote-sensing reflectance from above surface measurements. *Applied Optics*, 38: 7442-7455,1999.

Above-Water Radiometry



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

Sky-radiance: L_i

Sea-radiance: L_T

Removal of sky-light contribution

$$L_W(\varphi, \theta, \lambda) = L_T(\varphi, \theta, \lambda) - \rho(\varphi, \theta, \theta_0, W) L_i(\varphi, \theta', \lambda)$$

Correction for off-nadir view

$$L_W(\lambda) = L_W(\varphi, \theta, \lambda) C_{BQ}(\lambda, \theta, \varphi, \theta_0; \tau_a, IOP, W)$$

Transformation to exact normalized water-leaving radiance

$$L_{WN}(\lambda) = L_W(\lambda)\left(D^2 t_d(\lambda) \cos\theta_0\right)^{-1} C_{f/Q}(\lambda, \theta_0, \tau_a, IOP)$$

Morel, Bound Layer Meteorol, 18, 1980, **Carder & Steward**, Limnol Oceanogr, 30, 1985

Mobley, Appl Opt, 38, 1999, **Fougnie et al.**, Appl Opt, 38, 1999

Toole et al. Appl Opt, 39, 2000, **Hooker et al.** JAOT, 19, 2002, **Zibordi et al.**, JAOT, 19, 2002

Zibordi et al. TGARS, 43, 2004. **Hooker et al.** Appl. Opt. 21, 2004, 2004, **Deschamps et al.**, Appl Opt, 43, 2004

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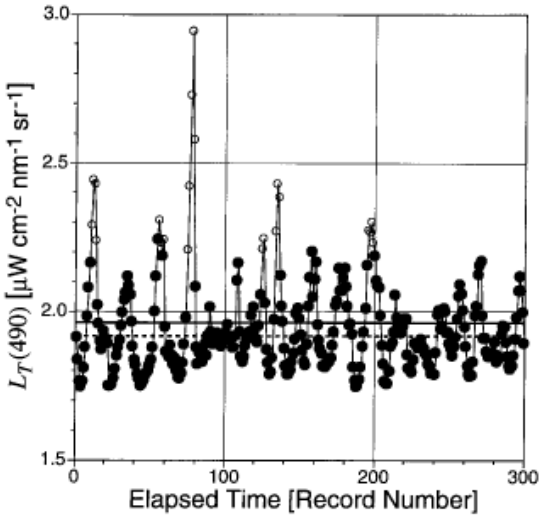
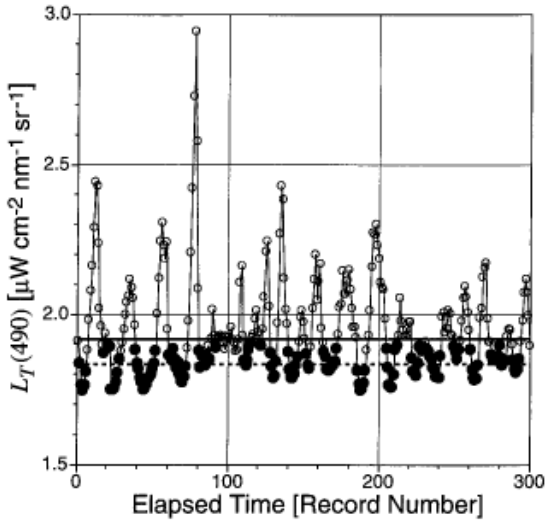
Wave-Perturbations

Dynamic Filtering



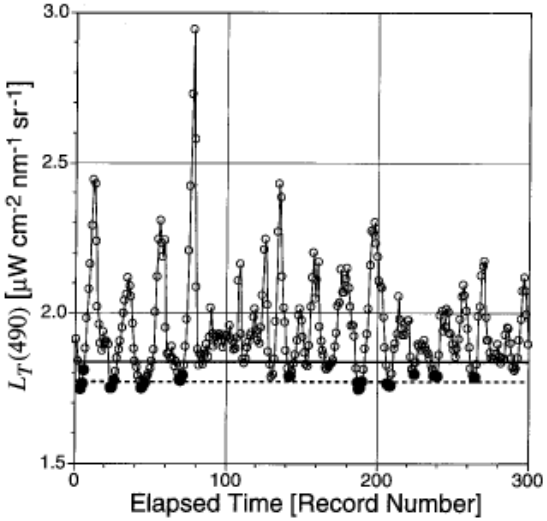
Data Rejection =10%, d=17%

Threshold Filtering



Data Rejection =50%, d=12%

Threshold Filtering



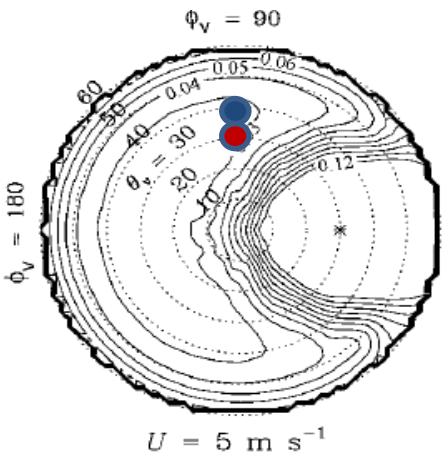
Data Rejection =95%, d=6%

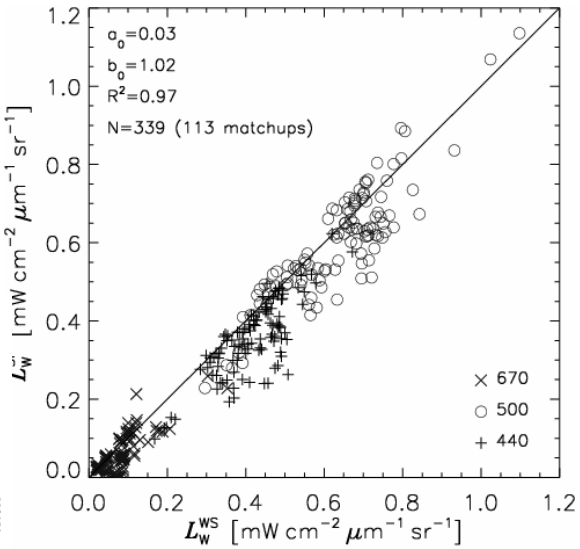
——————————— Average before data rejection

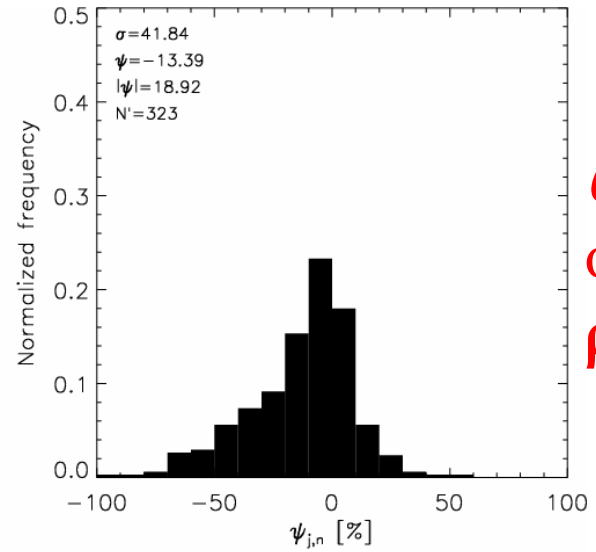
- Average after data rejection

S. Hooker, G. Lazin, G. Zibordi and S. McClean. An evaluation of above- and in-water methods for determining water leaving radiances. *Journal of Atmospheric and Oceanic Technology*, 19:486-515, 2002.

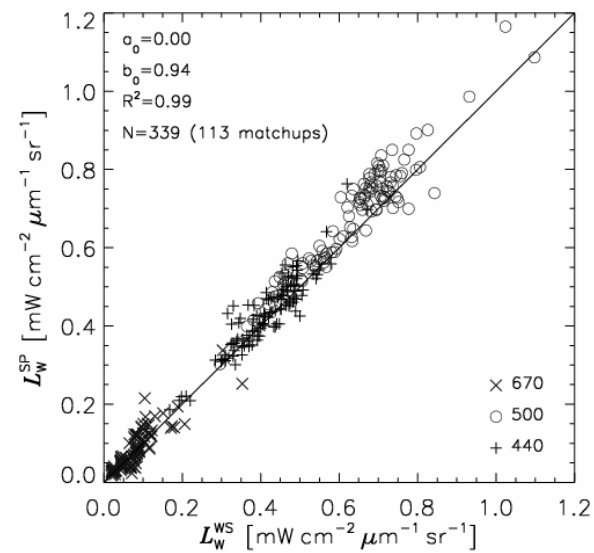
Viewing-angle dependence

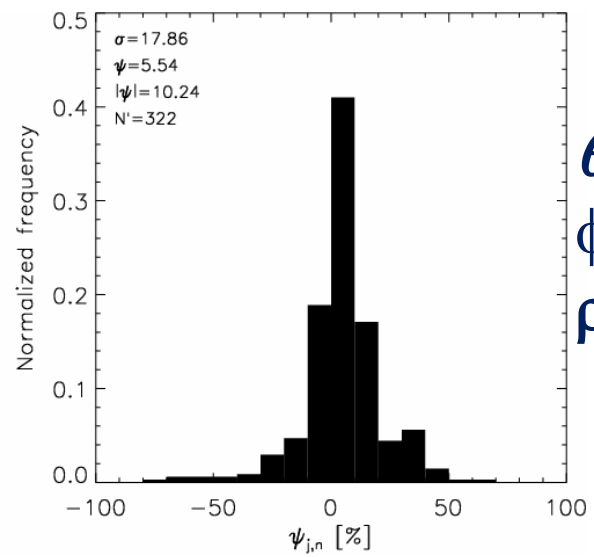






$\theta = 30^0$
$\phi = 90^0$
$\rho = 0.030$

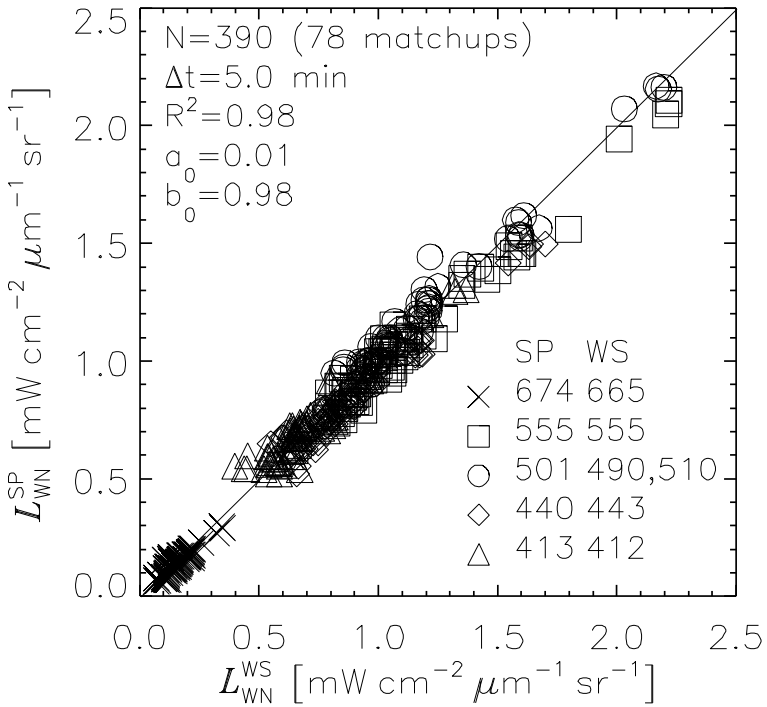


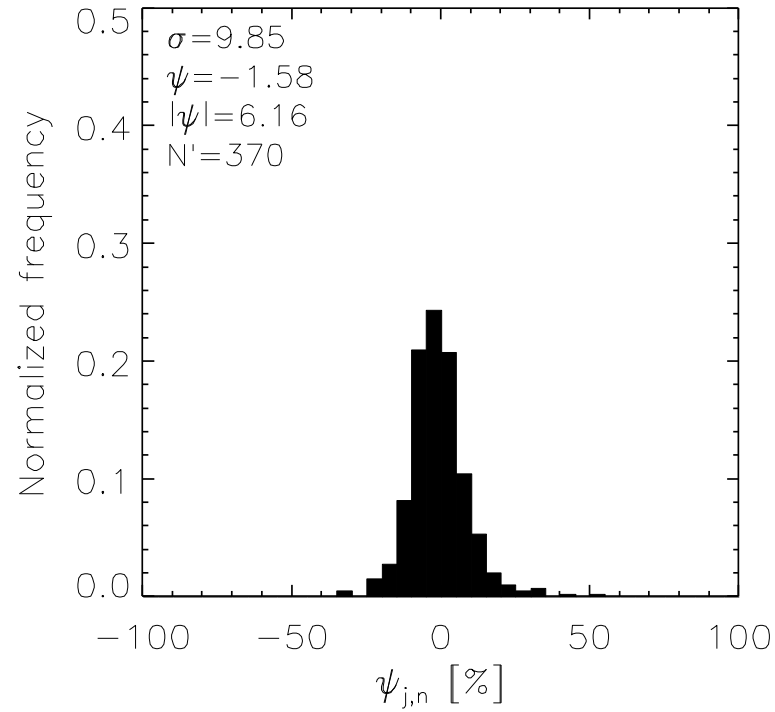


$\theta = 40^0$
$\phi = 90^0$
$\rho = 0.028$

G. Zibordi, S. Hooker, J-F. Berthon, D. D'Alimonte. Autonomous above water radiance measurements from stable platforms. *Journal of Atmospheric and Oceanic Technology, 19: 808-819, 2002.*

The Convergence of In- and Above-Water L_{WN}



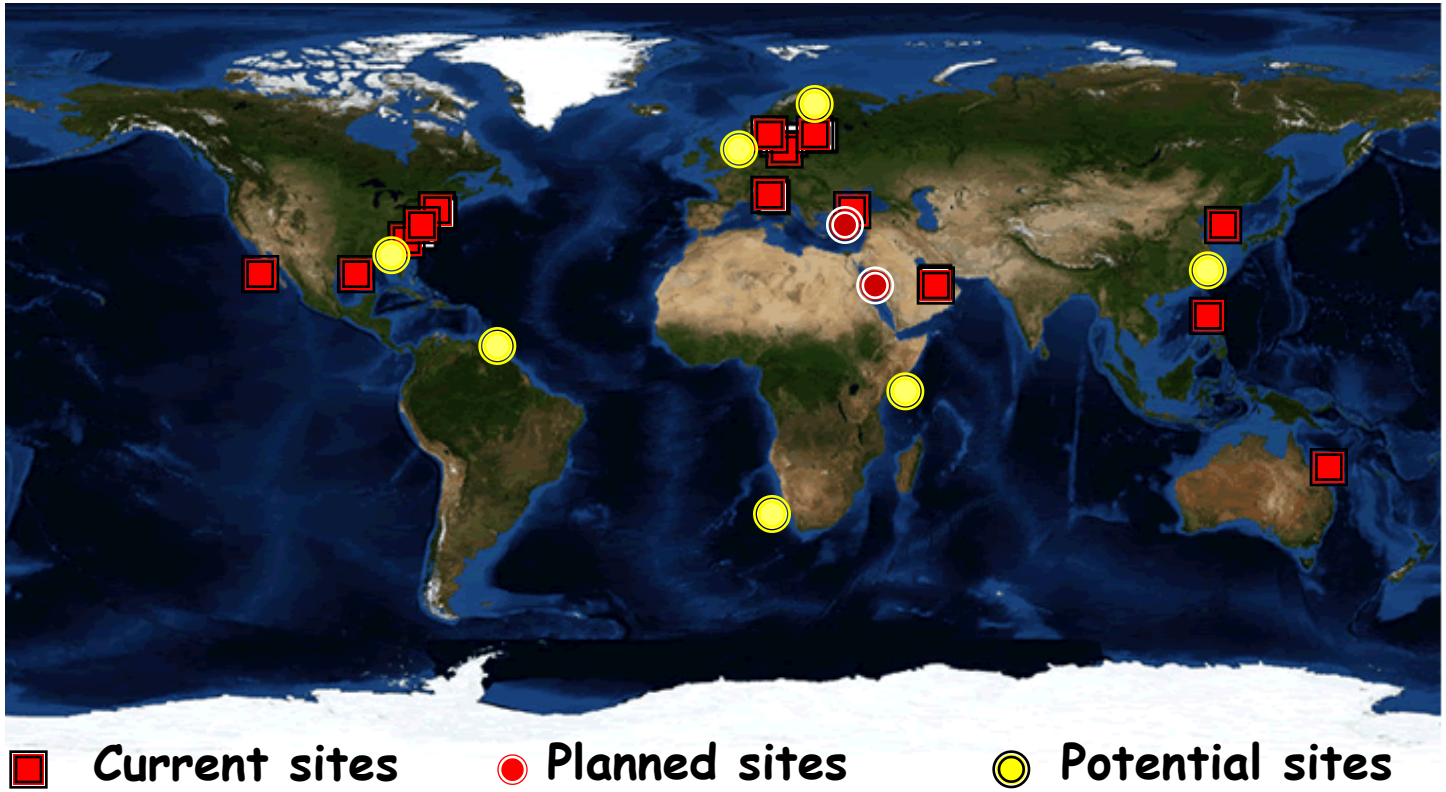


$$L_{WN}^{WS}(\lambda) = L_{W}^{WS}(\lambda)\frac{E_0(\lambda)}{E_d(0^+,\lambda)}C_{f/Q}(\lambda,\theta_0,\tau_a,Chla)$$

$$L_{WN}^{SP}(\lambda) = L_{W}^{SP}(\lambda,\theta,\varphi)C_{\Im Q}(\lambda,\theta,\varphi,\theta_0,\tau_a,Chla,W)\left(D^2 t_d(\lambda)\cos\theta_0\right)^{-1}C_{f/Q}(\lambda,\theta_0,\tau_a,Chla)$$

G.Zibordi, F. Mélin, S. B. Hooker, D. D'Alimonte and B. Holben. An autonomous above-water system for the validation of ocean color radiance data. *IEEE Transactions in Geoscience and Remote Sensing*, 42:401-415, 2004.

AERONET-OC (2002-present)



Current management and responsibilities

- **NASA** manages the network infrastructure (i.e., handles the instruments calibration and, data collection, processing and distribution within AERONET).
- **JRC** has the scientific responsibility of the processing algorithms and performs the quality assurance of data products.
- **PIs** establish and maintain individual AERONET-OC sites.

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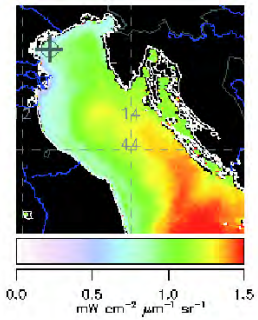
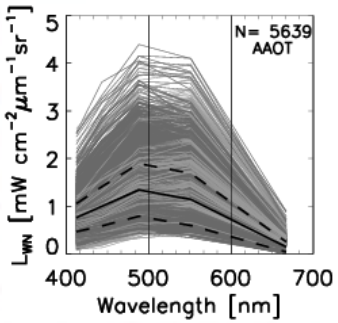
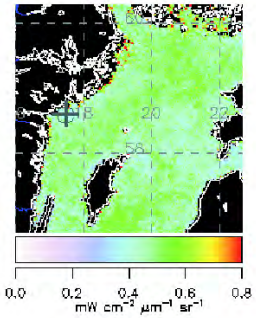
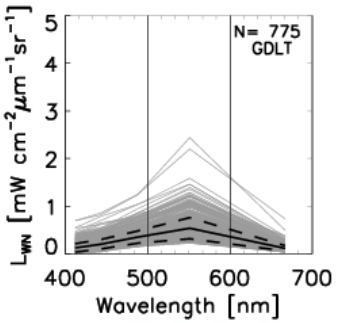
Examples of AERONET-OC Sites



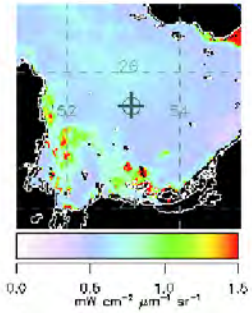


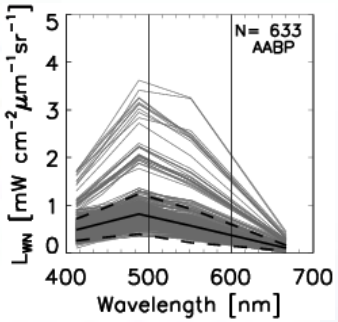
Site: AAOT
Location: Northern Adriatic Sea
Water type: Case-1/Case-2
Period: 2002-present





Site: GDLT
Location: Northern Baltic Proper
Water type: Case-2
Period: 2005-present (summer)





Site: AABT
Location: Persian Gulf
Water type: Case-1 (?)
Period: 2005-2008

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Above- v.s. In-Water

Above-Water

Advantages

1. Long-term deployments are insensitive to bio-fouling
2. Insensitive to coastal water optical stratifications
3. Relatively fast deployment time during short-term activities

Drawbacks

1. Cannot produce profiles of radiometric quantities
2. Restricted to a few radiometric quantities (i.e., L_w)
3. Highly sensitive to wave perturbations

In-Water

Advantages

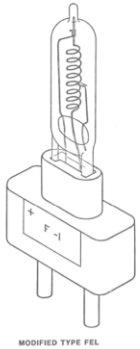
1. Produces comprehensive (fixed depths or continuous) profiles of radiometric quantities
2. Open to several radiometric quantities (i.e., L_u, E_d, E_u)
3. Upward radiometric quantities are almost not affected by wave perturbations

Drawbacks

1. Long-term deployments can be very sensitive to bio-fouling
2. Relatively slow deployment time during short-term activities
3. Sensitive to coastal water optical stratifications

Radiometric Calibration: Absolute

The process of quantitatively defining the system response to known and controlled signal inputs (in the specific case of radiometry this is achieved with a "(working) reference standard" that provides a direct realization of a radiometric SI quantity).



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Calibration Equation for a Field Radiometer

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

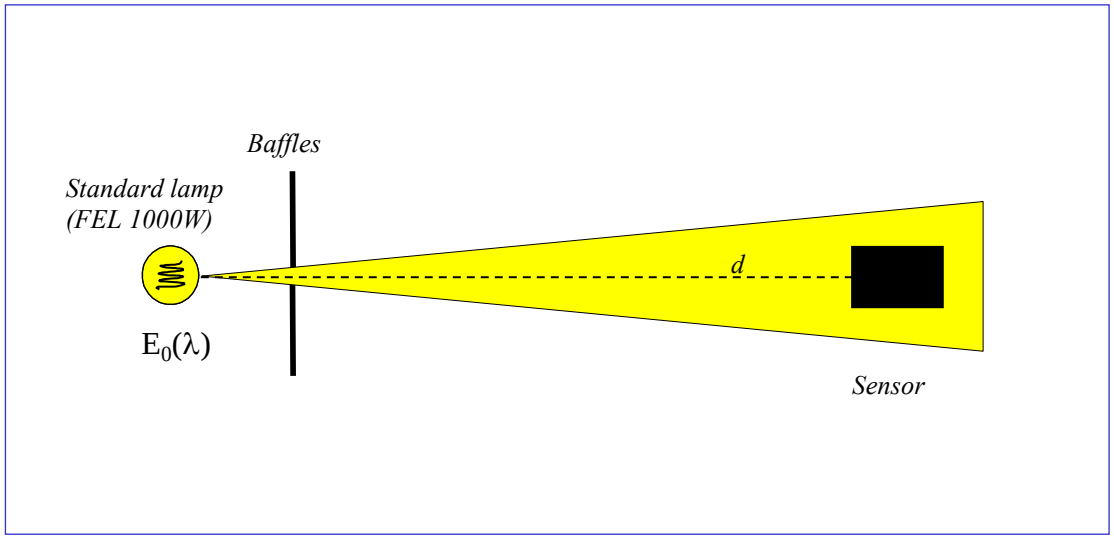
$\Re(\lambda)$ → Radiometric Quantity, *E* or *L*

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

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

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

In-Air Absolute Irradiance Calibration



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

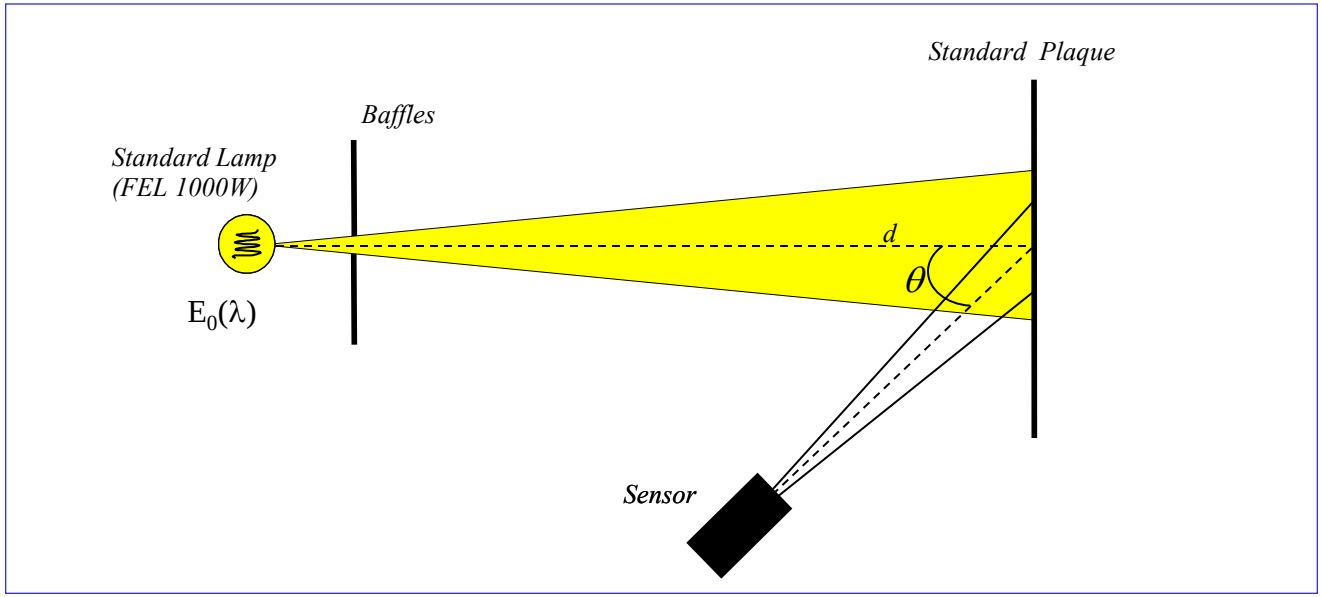
C_E: Calibration coefficient

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)

In-Air Absolute Radiance Calibration



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

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