The Abdus Salam International Centre for Theoretical Physics

2018-2

Winter College on Optics in Environmental Science

2 - 18 February 2009

Field Radiometry: Application to ocean color remote sensing

Zibordi G.

European Commission Joint Research Centre
Italy

EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

Joint Research Centre

Field Radiometry:
Application to ocean color remote sensing

Giuseppe Zibordi

(giuseppe.zibordi@jrc.it)

Global Environment Monitoring Unit

Joint Research Centre of EC

Satellite and *In Situ* Observations

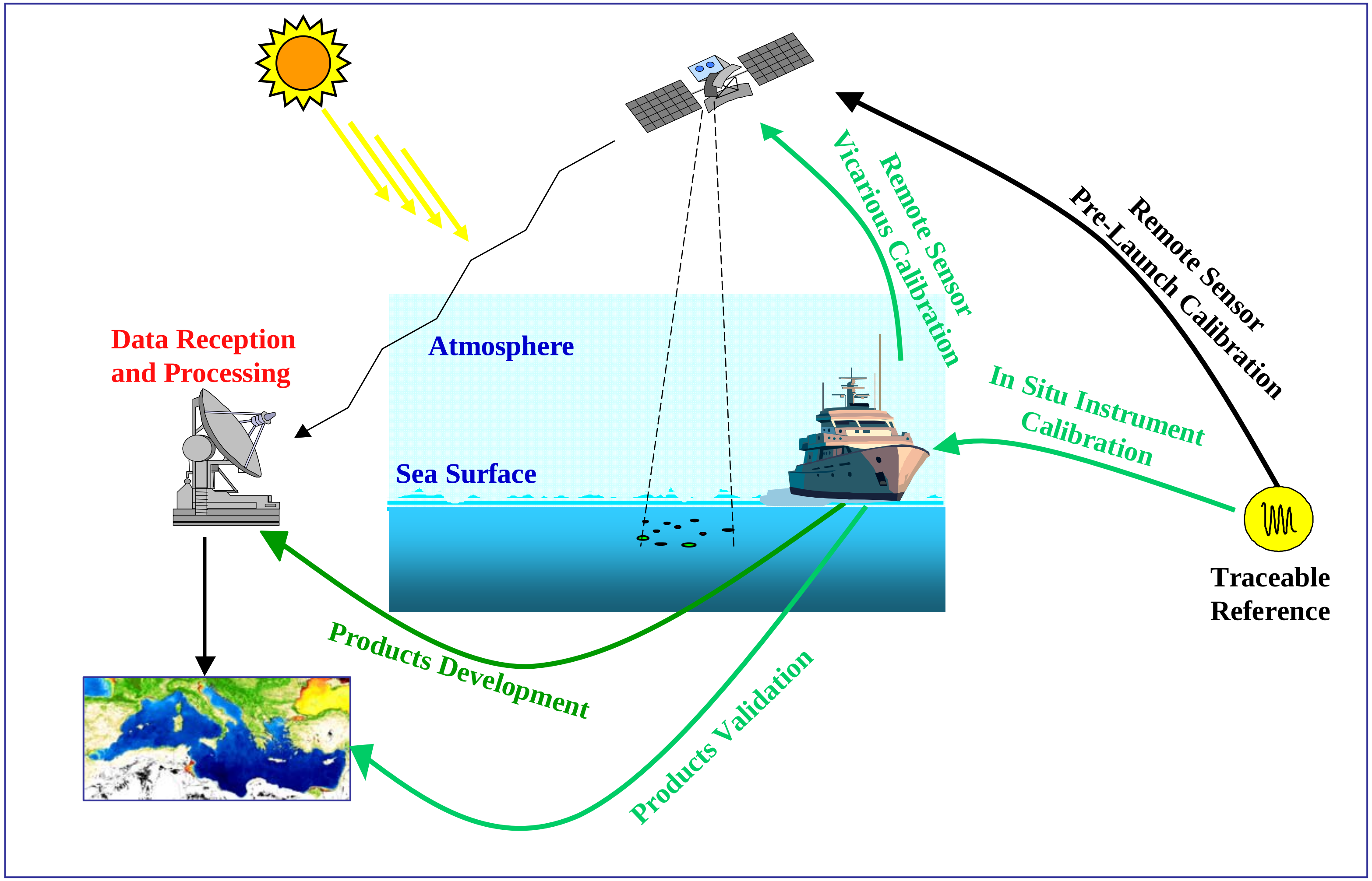
The Global Climate Observing System (GCOS) requires calibration and validation actions to ensure a confident application of remote sensing products to global and long-term monitoring of the Earth's surface.

Most of the actions satisfying the former requirement need accurate and globally distributed *in situ* (radiometric) measurements. During the last two decades, such a need has become the rationale for advanced research in marine radiometry.

EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

The Ocean Color Cal/Val Paradigm

Ocean Color indicates remote sensing of the sea in the visible and near infrared with the primary objective of determining *the radiance emerging from the sea* from top-of-atmosphere radiometric signal. The radiance emerging from the sea is then utilized to quantify the higher level products (e.g. Chla).



Joint Research Centre

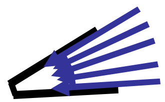
Joint Research Centre

In Situ Radiometry

Joint Research Centre

Radiometric Quantities

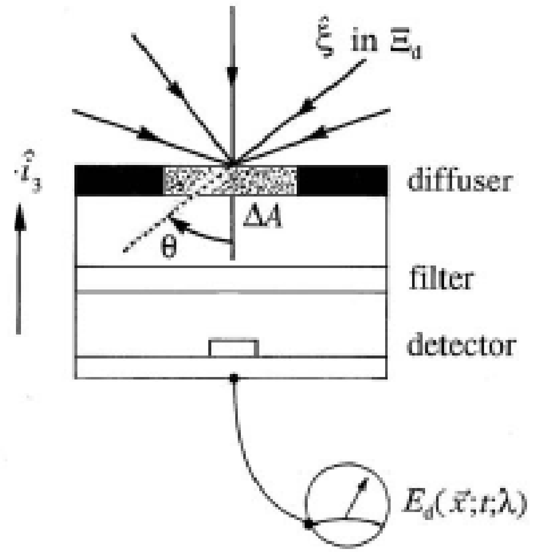
Radiometry is the he measurement of physical quantities like radiance and irradiance, through light-measuring instruments called radiometers.

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}

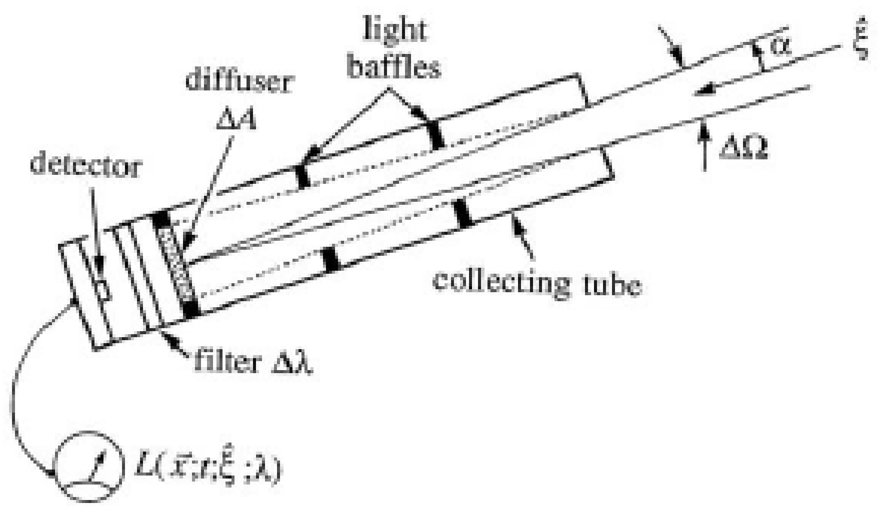
Radiometers

A radiometer is composed of at least three basic components:

1. the optics which collect the light through an aperture, spectrally disperse the light, and focus it on a field stop;
2. the detector which transduces the light 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

Calibration Equation for a Field Radiometer

Calibration: The process of quantitatively defining the system response to known, controlled signal inputs.

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

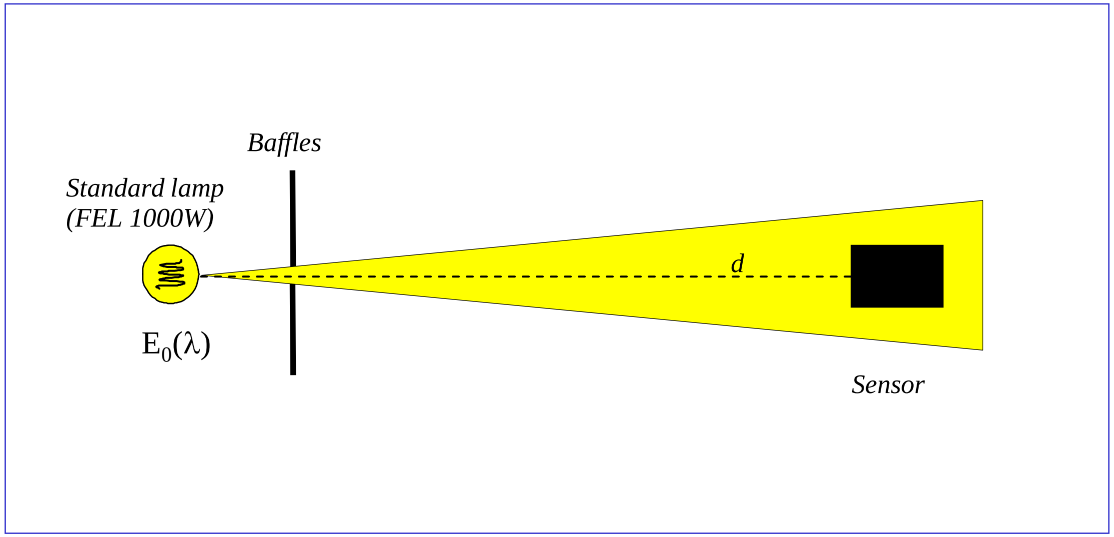
$\Re(\lambda)$ → Radiometric Quantity, *E* or *L*

$D_N(\lambda) - D_0(\lambda)$ → 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 (determined at distance d)

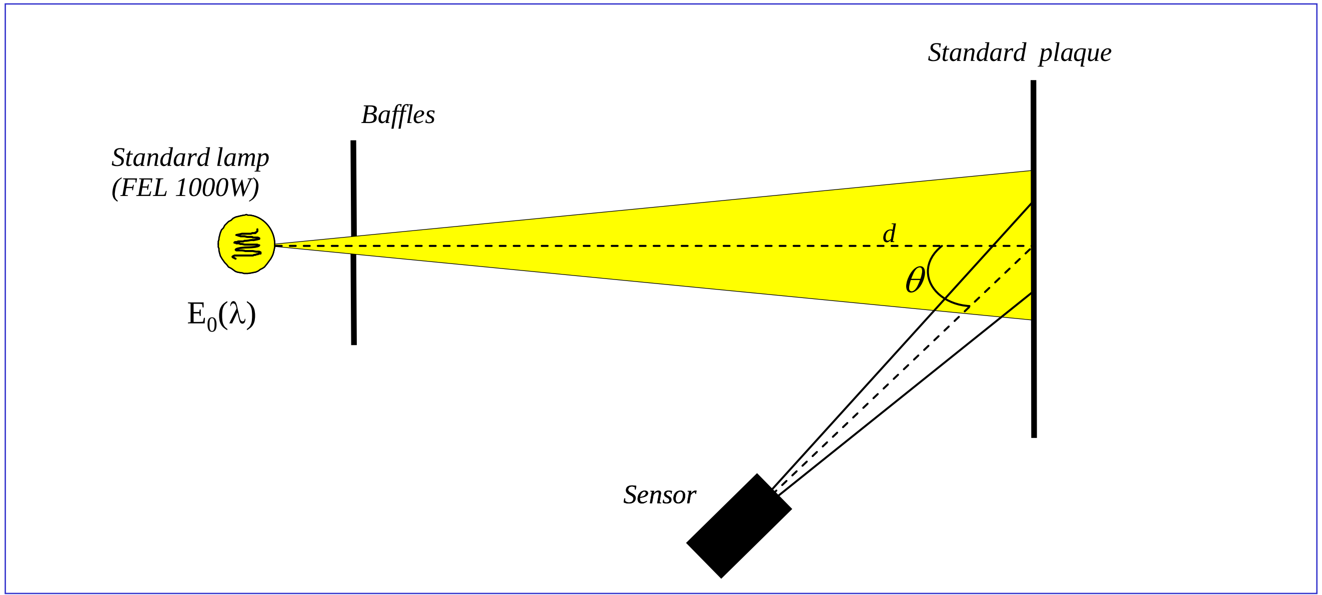
E_0: Lamp Irradiance at distance d0

D_N: Sensor output with the source at distance d

D_0: Sensor output without any source (dark signal)

S.Hooker, S.McLean, M.Small, G.Lazin, G.Zibordi, J.Brown. The Seventh SeaWiFS Intercalibration Round-Robin Experiment (SIRREX-7). *NASA Tech. Memo. 2002-206892,* v. 17, S.B.Hooker and E.R.Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 2001 .

In-Air Absolute Radiance Calibration



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

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

E_0: Lamp Irradiance at distance d_0

C_L: Calibration coefficient (determined using the distance *d* and angle θ)

D_N: Sensor output with the source at distance *d*

D_0: Sensor output without any source (dark signal)

ρ : Reflectance of the Standard Plaque

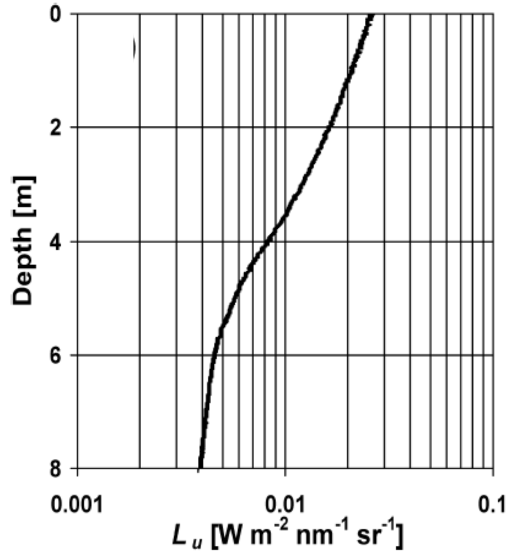
c_p: Correction factor for the plaque non-Lambertian response at angle θ

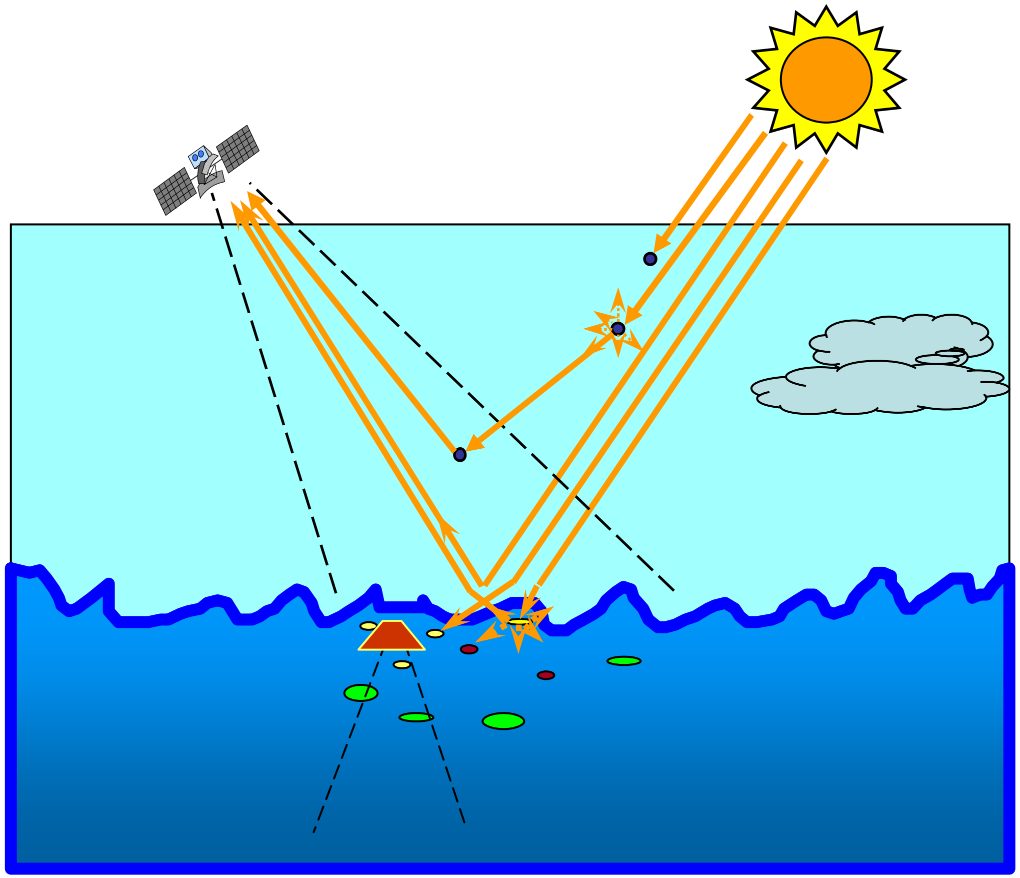
In Situ Radiometric Methods

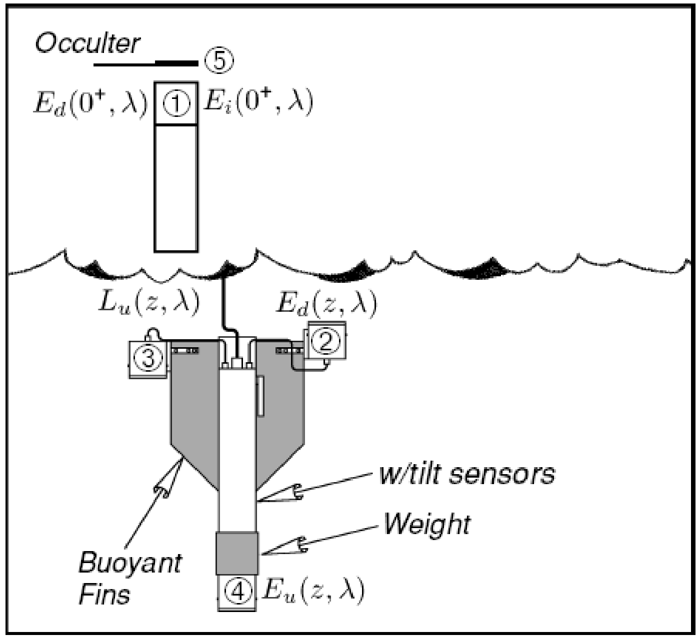
In-Water Radiometry

Historical dates

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

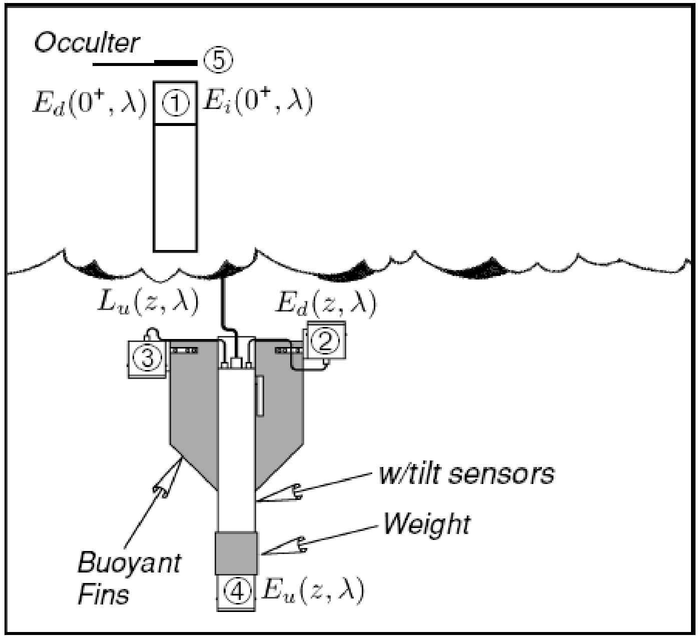


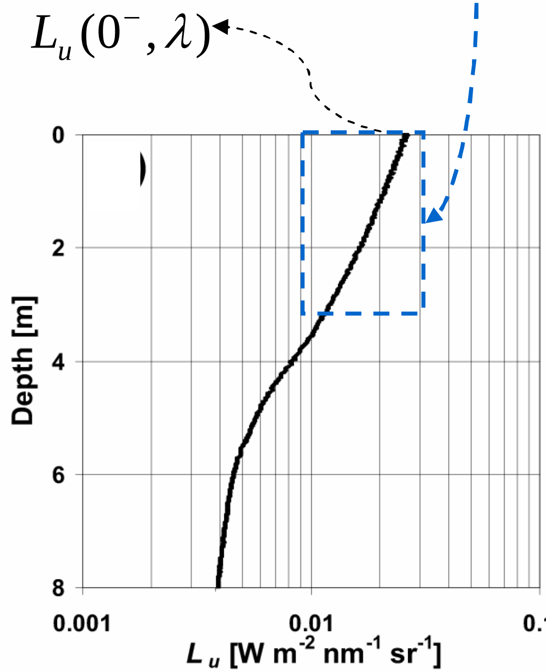




An In-Water Method

The determination of the extrapolation interval is one of the major sources of uncertainty





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

Minimization of the effects due to changes in illumination

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

~0.543

Determination of L_w after computing L_u

G.Zibordi, D.D'Alimonte and J.-F.Berthon. An evaluation of depth resolution requirements for optical profiling in coastal waters. *Journal of Atmospheric and Oceanic Technology* 21:1059-1073, 2004.

Joint Research Centre

In-Water Radiometry: Specific Investigations

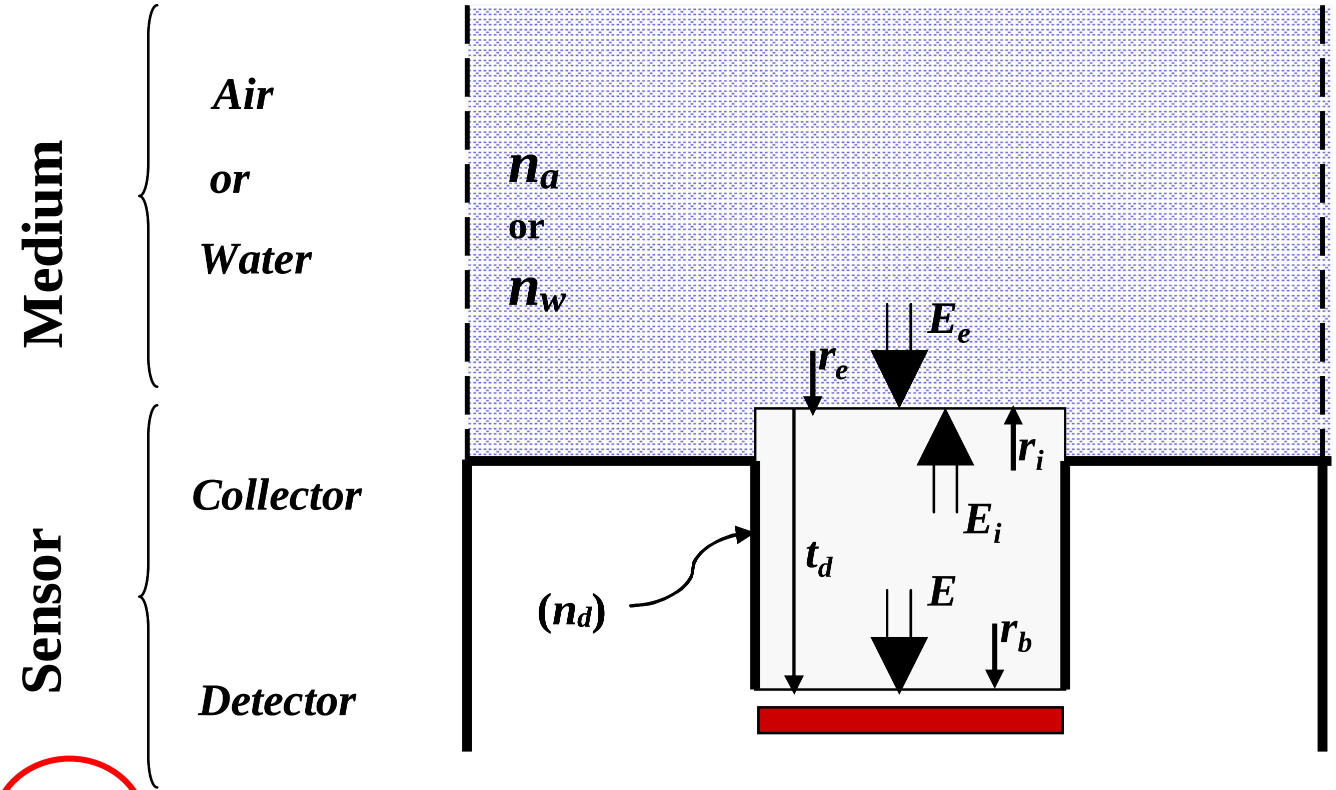
Immersion factor

Cosine response

Self-shading

I_f for E Sensors

Immersion Factor: The factor that multiplies the in-air calibration coefficient to account for the sensitivity decrease of the measuring system in-water, due to the an increase in the refractive index of the medium in contact with the collector.

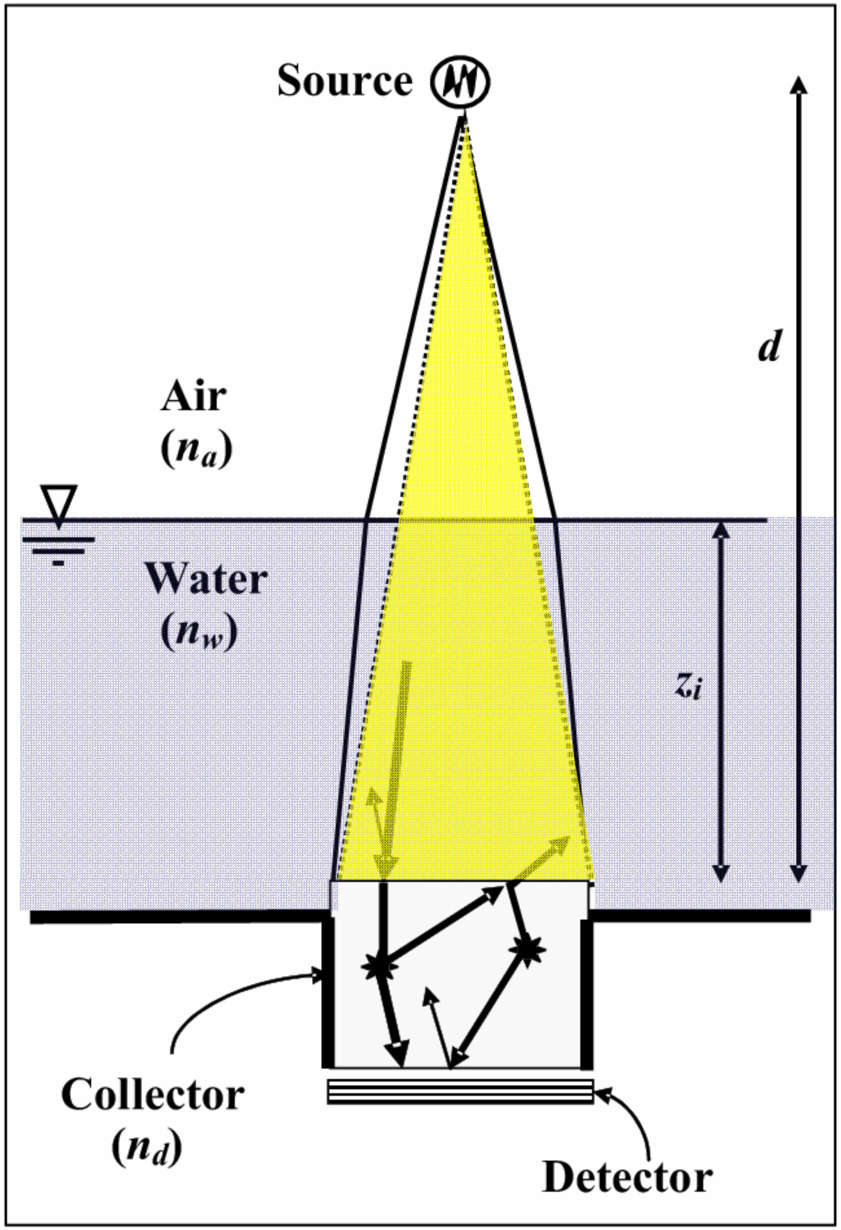


$$E(\lambda) = E_e(\lambda)\,[1-r_e(\lambda)]\,t_d(\lambda)\,[1-r_b(\lambda)] + E_i(\lambda)\,r_i(\lambda)$$

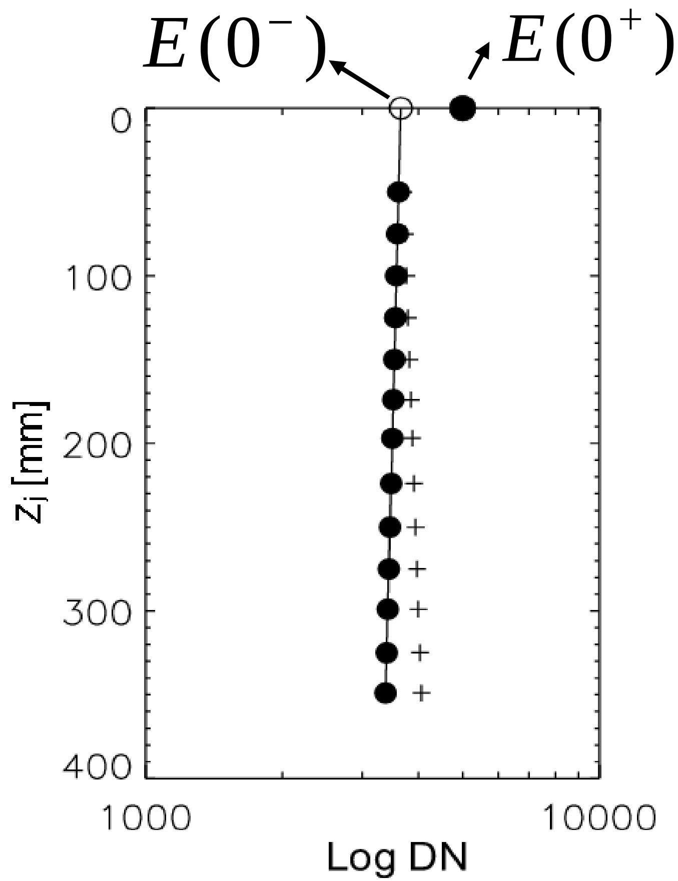
Its accurate theoretical determination is unfeasible

G.Zibordi, S.Hooker, J.Mueller, S.McLean, G.Lazin. Characterization of the immersion factor for a series of in–water optical radiometers. *Journal of Atmospheric and Oceanic Technology*, 21:501-514, 2004.

Experimental determination of I_f for E sensors

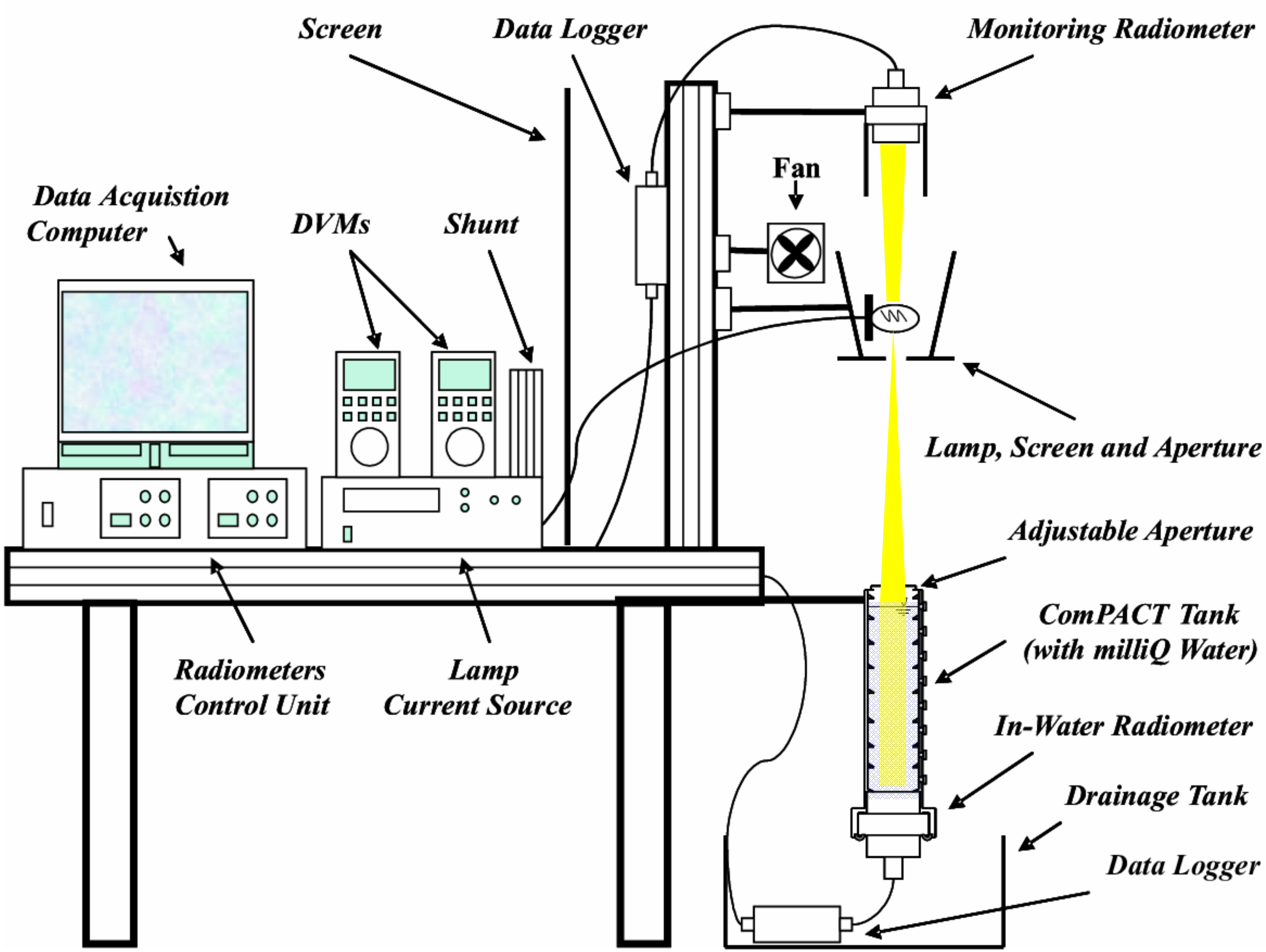


$$I_f = \frac{E(0^+)}{E(0^-)} t_{wa}$$



EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

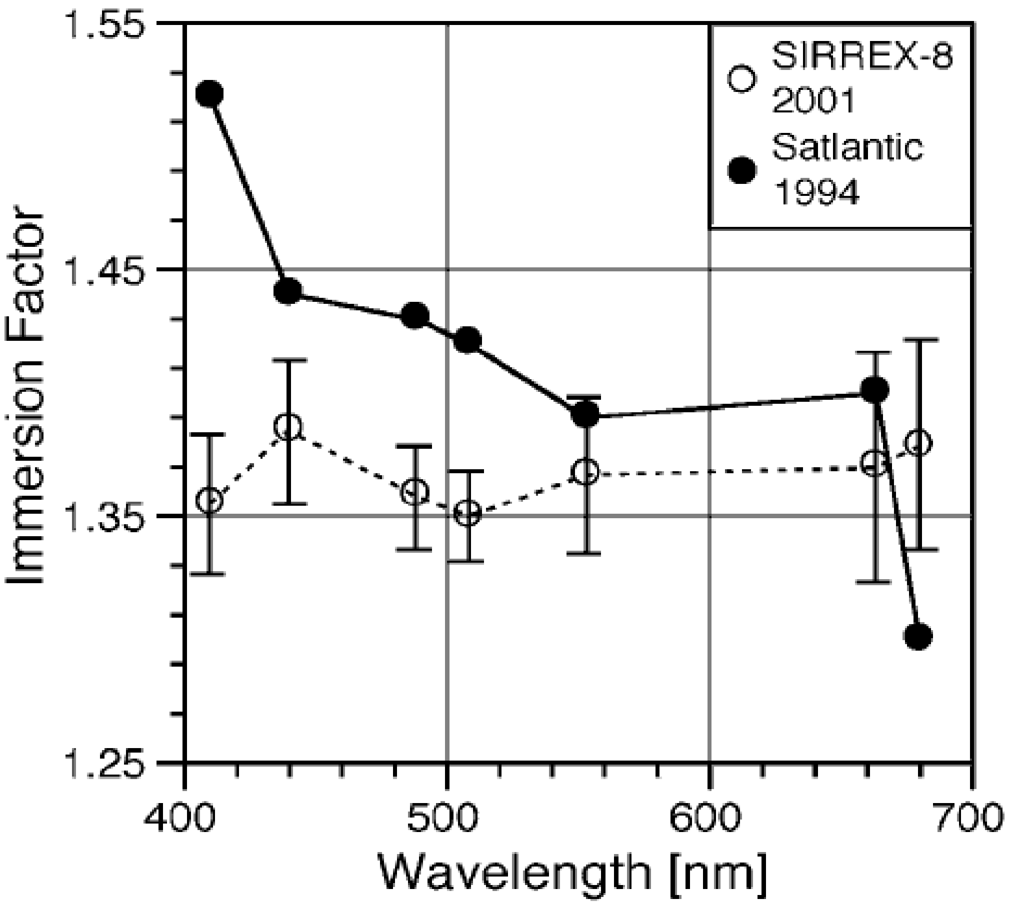
The Measuring Apparatus



G.Zibordi, S.Hooker, J.Mueller, S.McLean, G.Lazin. Characterization of the immersion factor for a series of in–water optical radiometers. *Journal of Atmospheric and Oceanic Technology*, 21:501-514, 2004.

Joint Research Centre

Results from I_f measurements

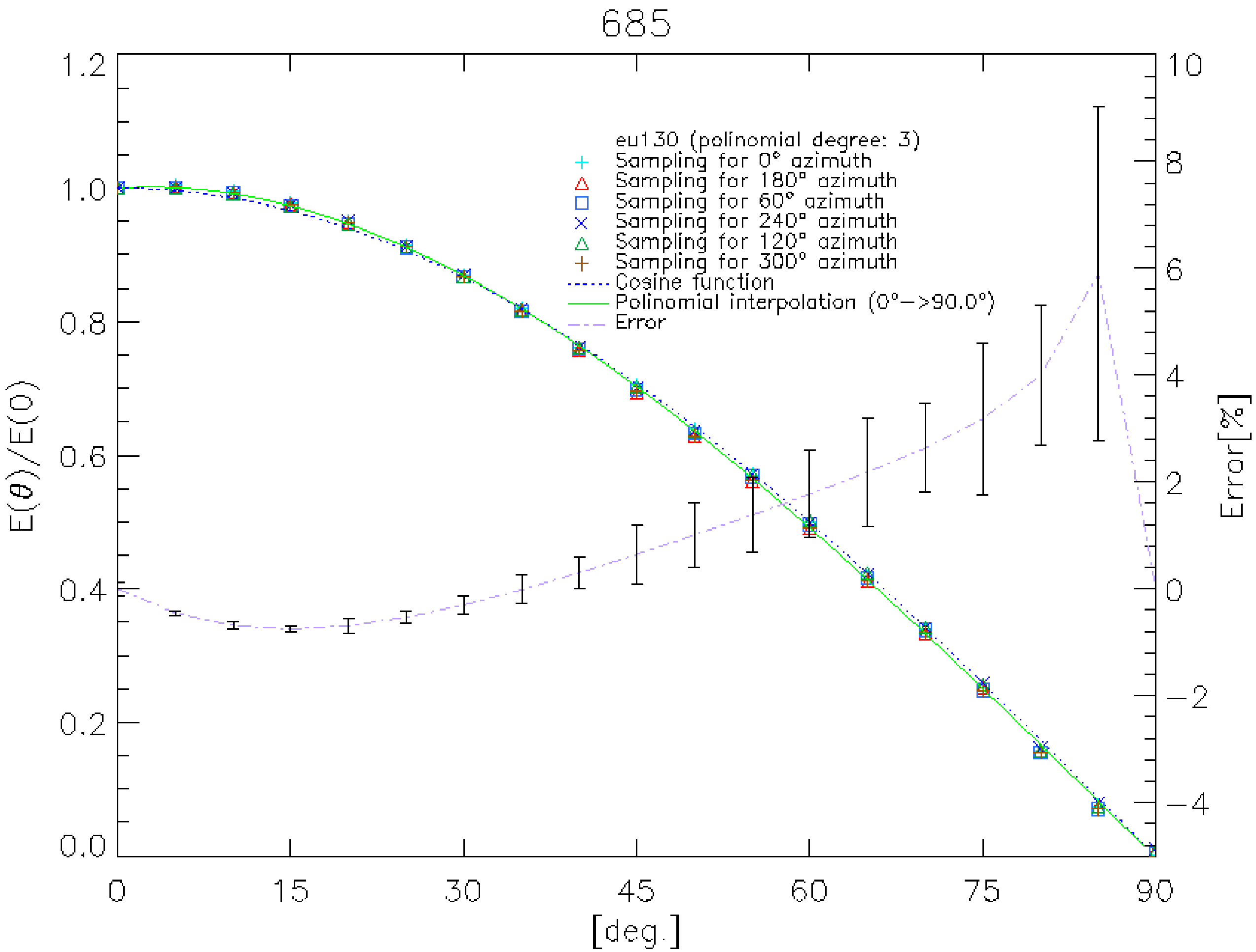


G.Zibordi, S.Hooker, J.Mueller, S.McLean, G.Lazin. Characterization of the immersion factor for a series of in–water optical radiometers. *Journal of Atmospheric and Oceanic Technology*, 21:501-514, 2004.

EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

Cosine response

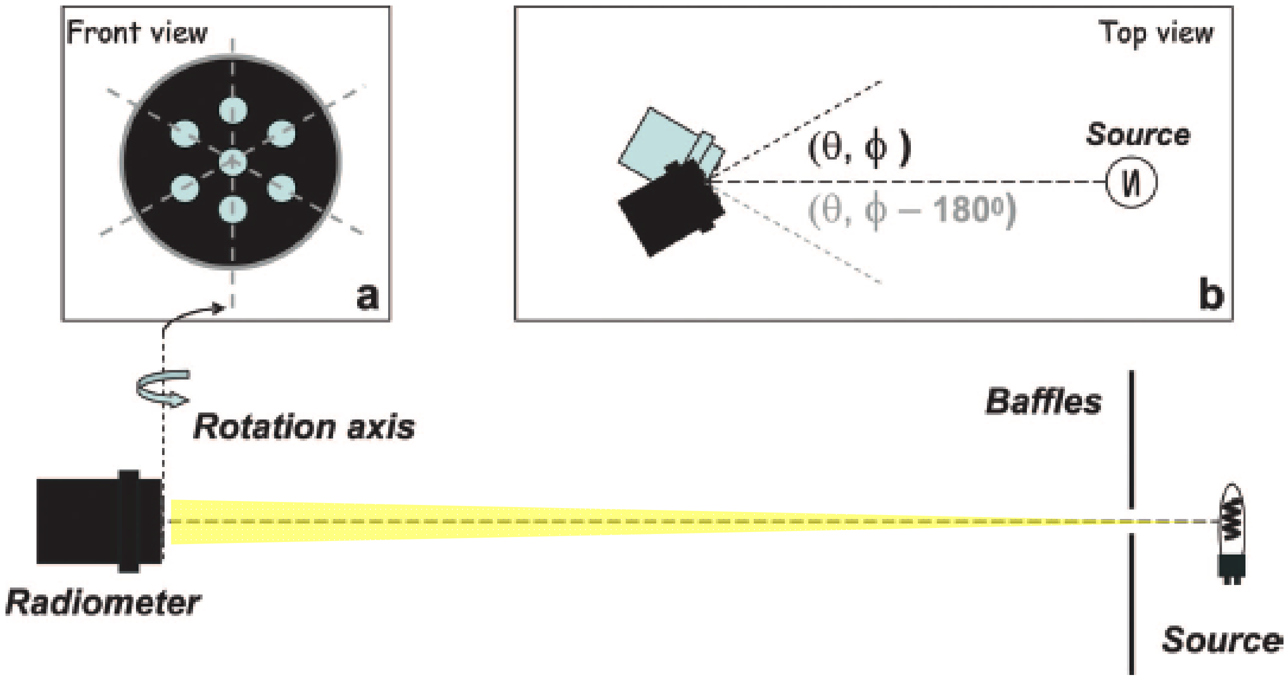
Cosine Response: The goodness of the angular response of a cosine collector to a collimated source.



G.Zibordi, D.D'Alimonte, D. van der Linde, J.F.Berthon, S.B.Hooker, J.L.Mueller, S.McLean and G.Lazin. The Eight SeaWiFS Intercomparison Round Robin Experiment (SIRREX-8). *NASA Tech. Memo. 2002-206892*, v. 21, S.B.Hooker and E.R.Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 2002, 39 pp.

Joint Research Centre

Determination of the Cosine Response

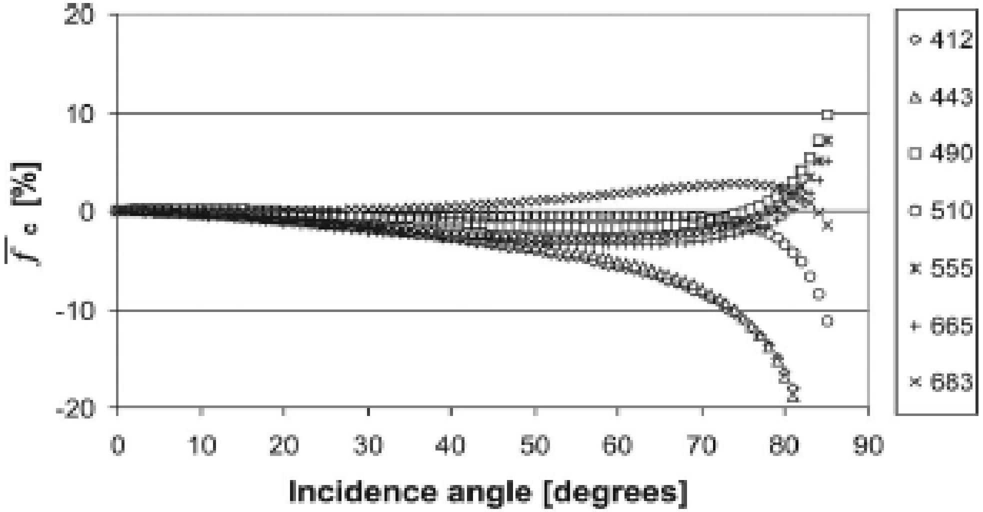


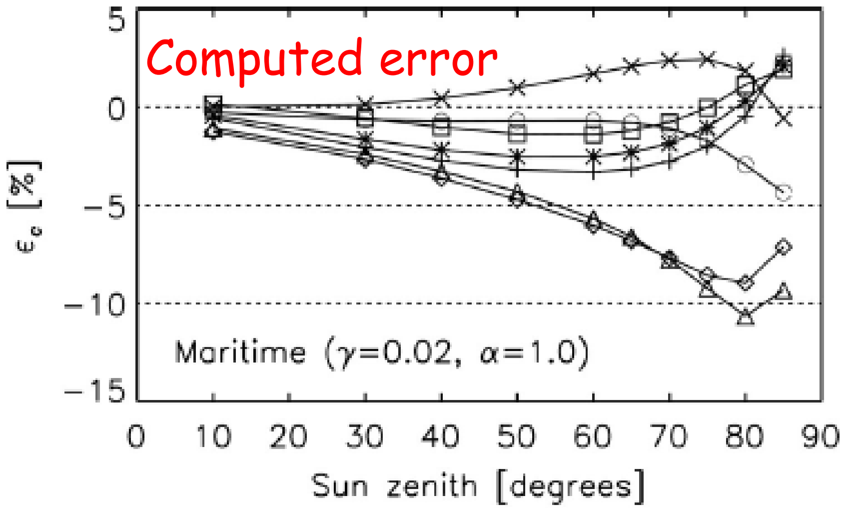
$$f_c(\lambda,\theta,\varphi) = 100[\frac{E(\theta,\varphi,\lambda)}{E(0,\varphi,\lambda)cos\theta} - 1]$$

G.Zibordi and B.Bulgarelli, Uncertainties in irradiance measurements from a class of radiometers: the cosine error. *Applied Optics*, 46, 5529-5538, 2007.

Error due to Non-Cosine Response

Deviation from cosine response



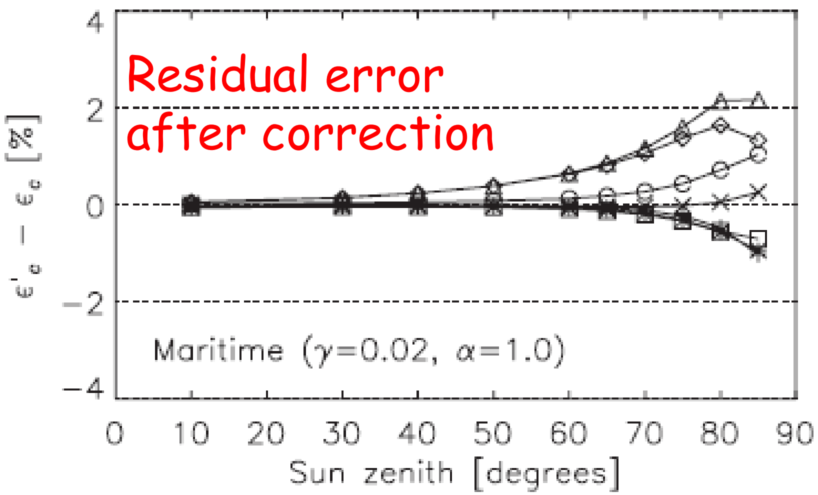


$$\varepsilon_c'(\theta_0, \lambda) = \langle \bar{f}_c(\lambda) \rangle \frac{I_r(\theta_0, \lambda)}{I_r(\theta_0, \lambda) + 1} + \bar{f}_c(\theta, \lambda) \frac{1}{I_r(\theta_0, \lambda) + 1}$$

$$\langle \bar{f}_c(\lambda) \rangle = \int_0^{0.5\pi} \bar{f}_c(\theta, \lambda) \sin(2\theta) d\theta.$$

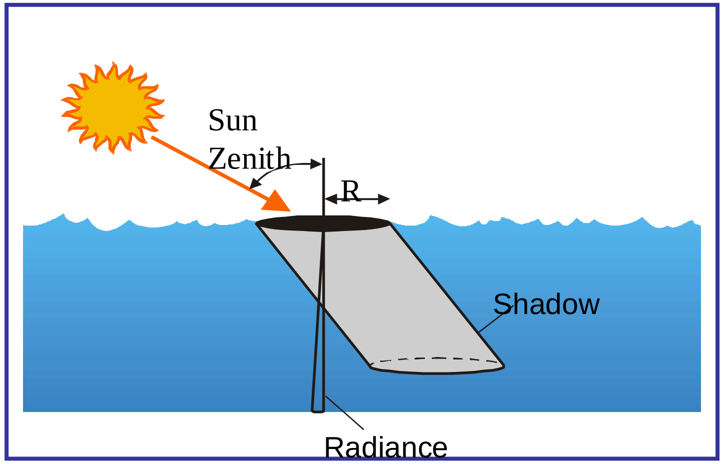
ε'_c=error

I_r= diffuse to direct irradiance ratio

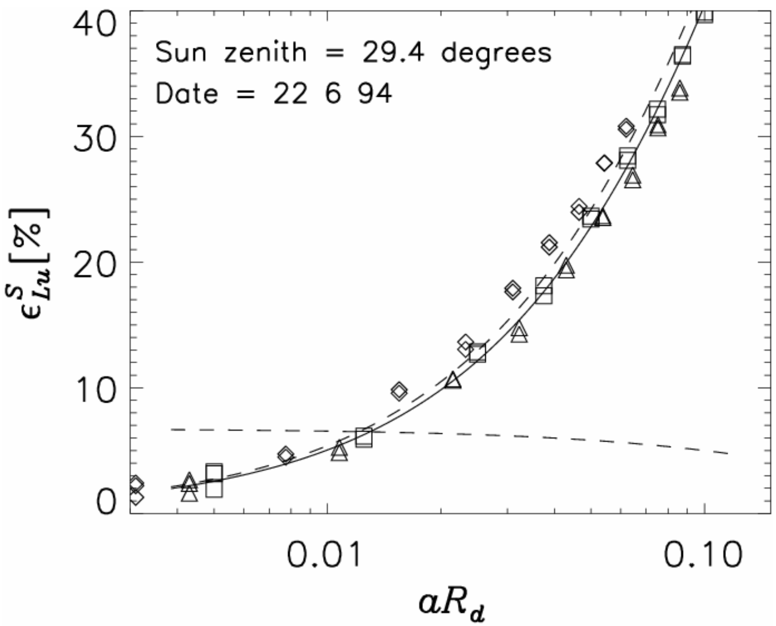


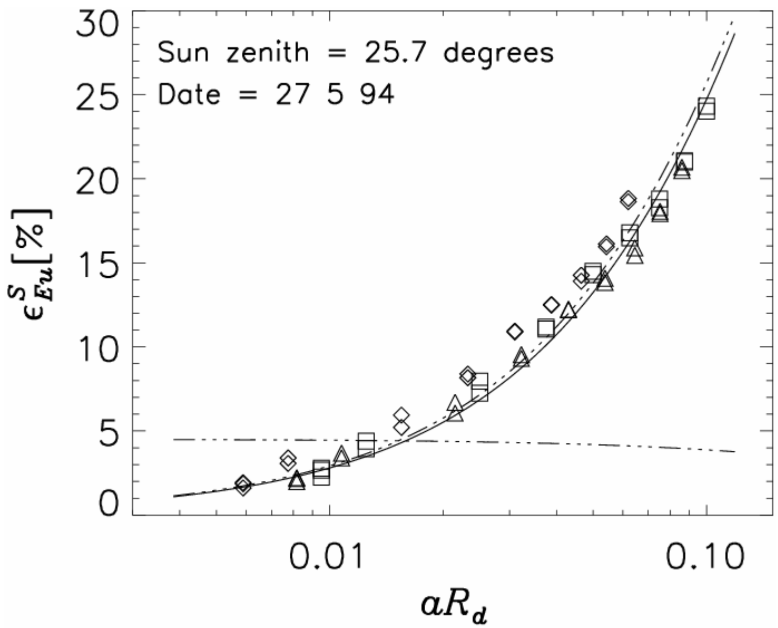
G.Zibordi and B.Bulgarelli, Uncertainties in irradiance measurements from a class of radiometers: the cosine error. *Applied Optics*, 46, 5529-5538, 2007.

Self-Shading



Self-Shading: The perturbation produced in the light field by the presence of the radiometer (it depends on the geometry of the radiometer and on the optical properties of the medium).





G.Zibordi and G.M.Ferrari, Instrument self shading in underwater optical measurements: experimental data. *Applied Optics*, 34: 2750-2754, 1995.

L_{WN} Uncertainties (in-water)

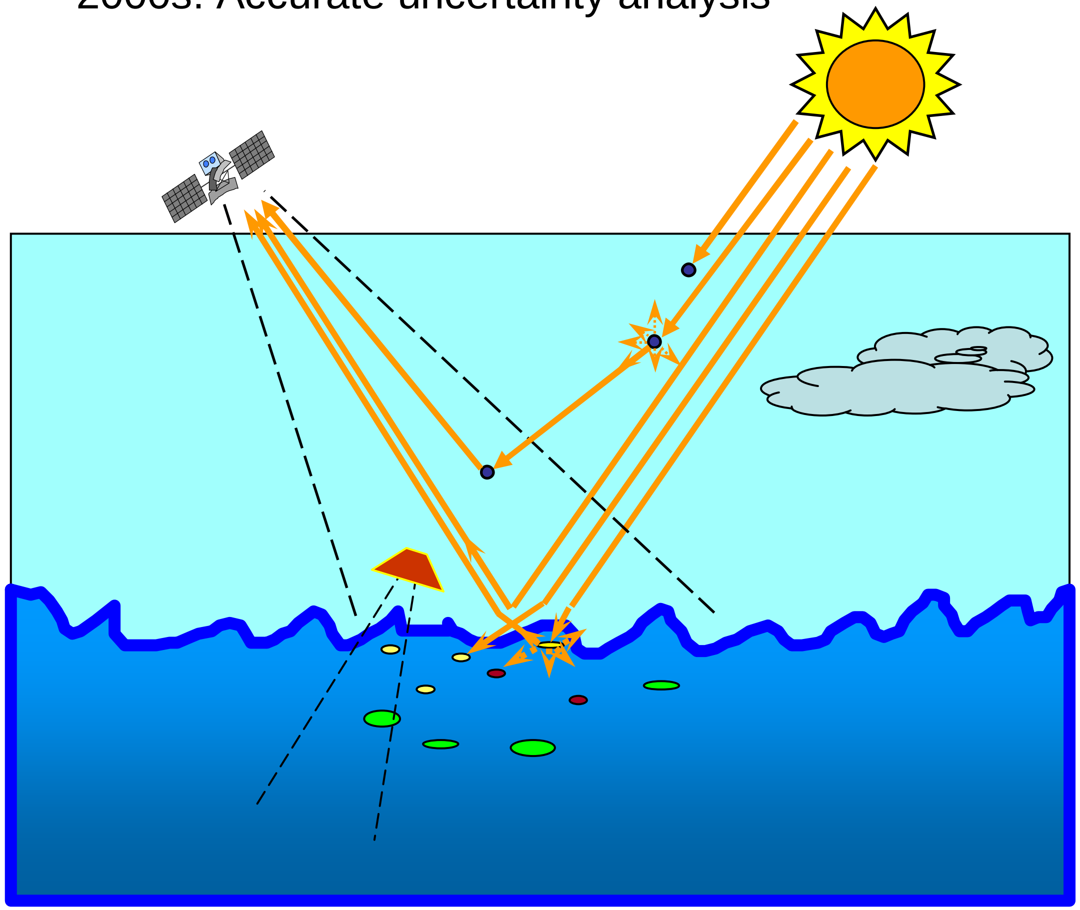
Source	L_{WN}				
	412	**443**	**488**	**551**	**667**
Absolute calibration	2.8	2.8	2.8	2.8	2.8
Sensitivity change	0.3	0.3	0.3	0.3	0.3
Correction	2.2	1.7	1.1	0.6	2.6
$C_{f/Q}$	0.3	0.4	0.8	0.9	0.5
$E_d(0^+)$	1.6	1.6	1.6	1.6	1.6
E_s	0.5	1.9	0.8	0.1	0.2
Environmental effects	1.5	1.1	1.2	1.3	2.8
Quadrature sum	**4.2**	**4.3**	**3.8**	**3.7**	**5.0**

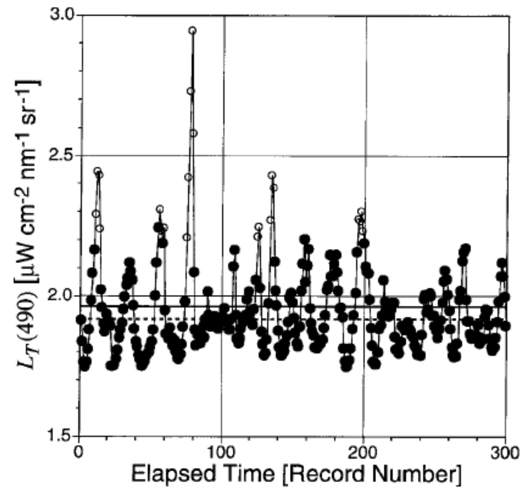
Above-Water Radiometry

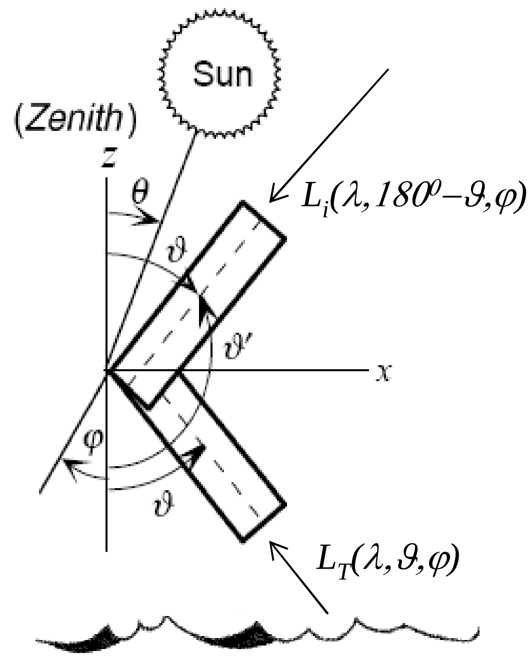
Joint Research Centre

Historical dates

1930s: First observations
1980s: First documented methods
1990s: Methods assessment
2000s: Accurate uncertainty analysis

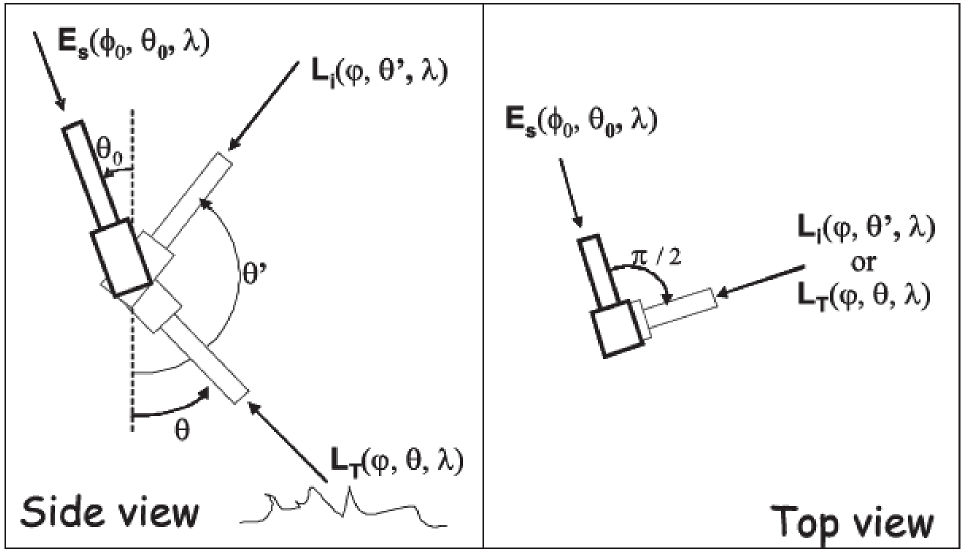


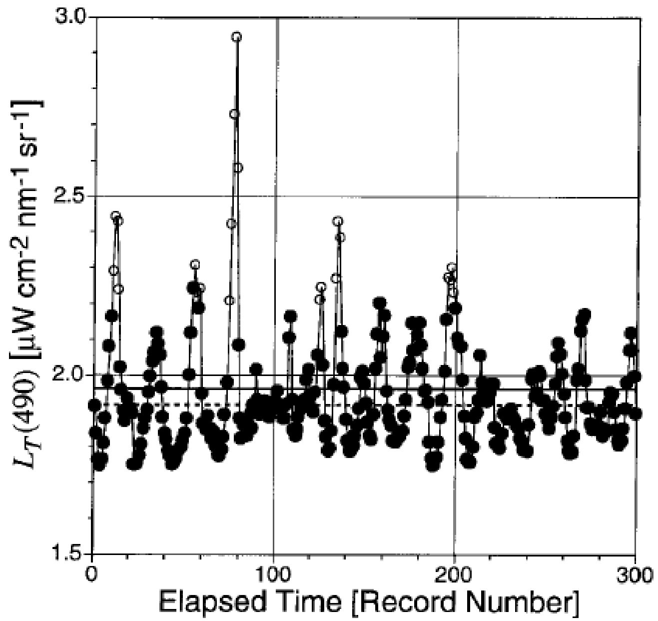




Joint Research Centre

An Above-Water Method





E_s: Direct solar irradiance

L_T: Total radiance from the sea

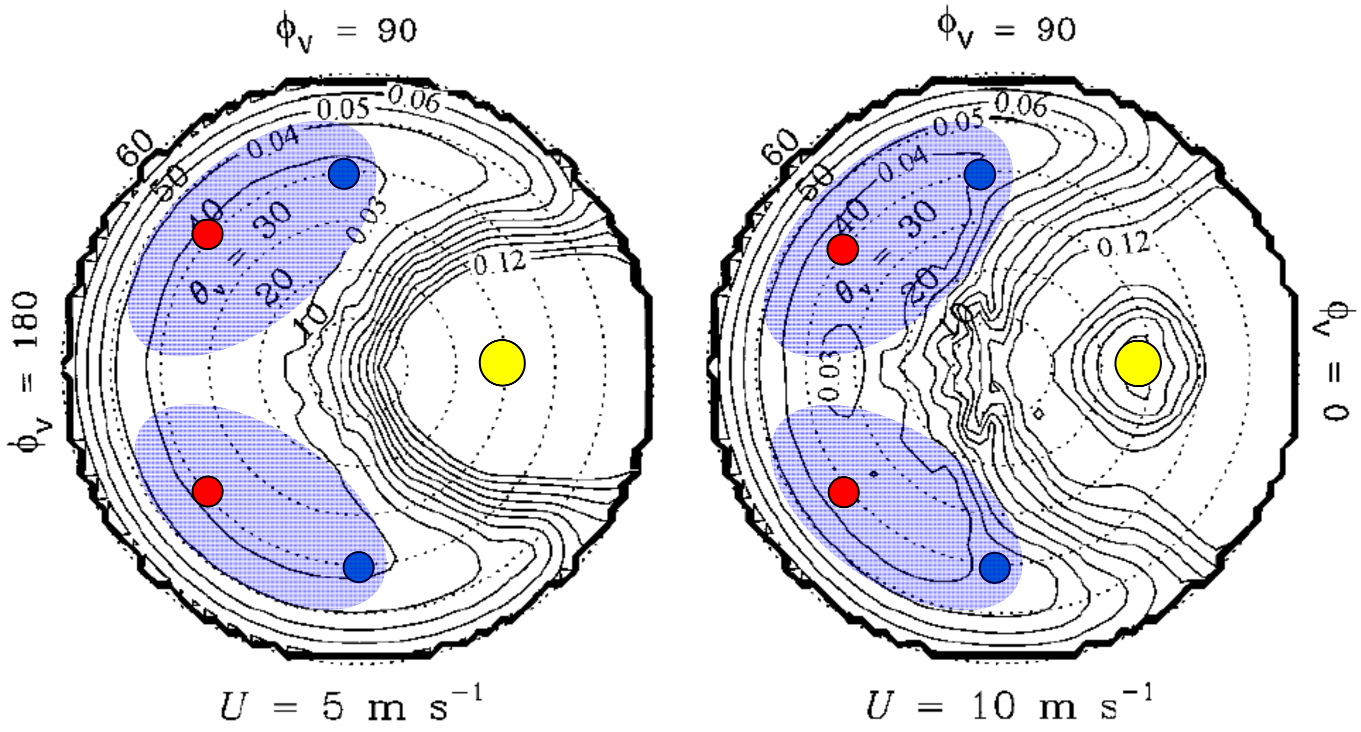
L_i: Sky-radiance

Average of measured L_i

$$L_W(\phi,\theta,\lambda) = L_T(\phi,\theta,\lambda) - \rho(\phi,\theta,\theta_0,W)\, L_i(\phi, 180^{o} - \theta, \lambda)$$

Relative minimum of measured L_T

The viewing geometry is 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.

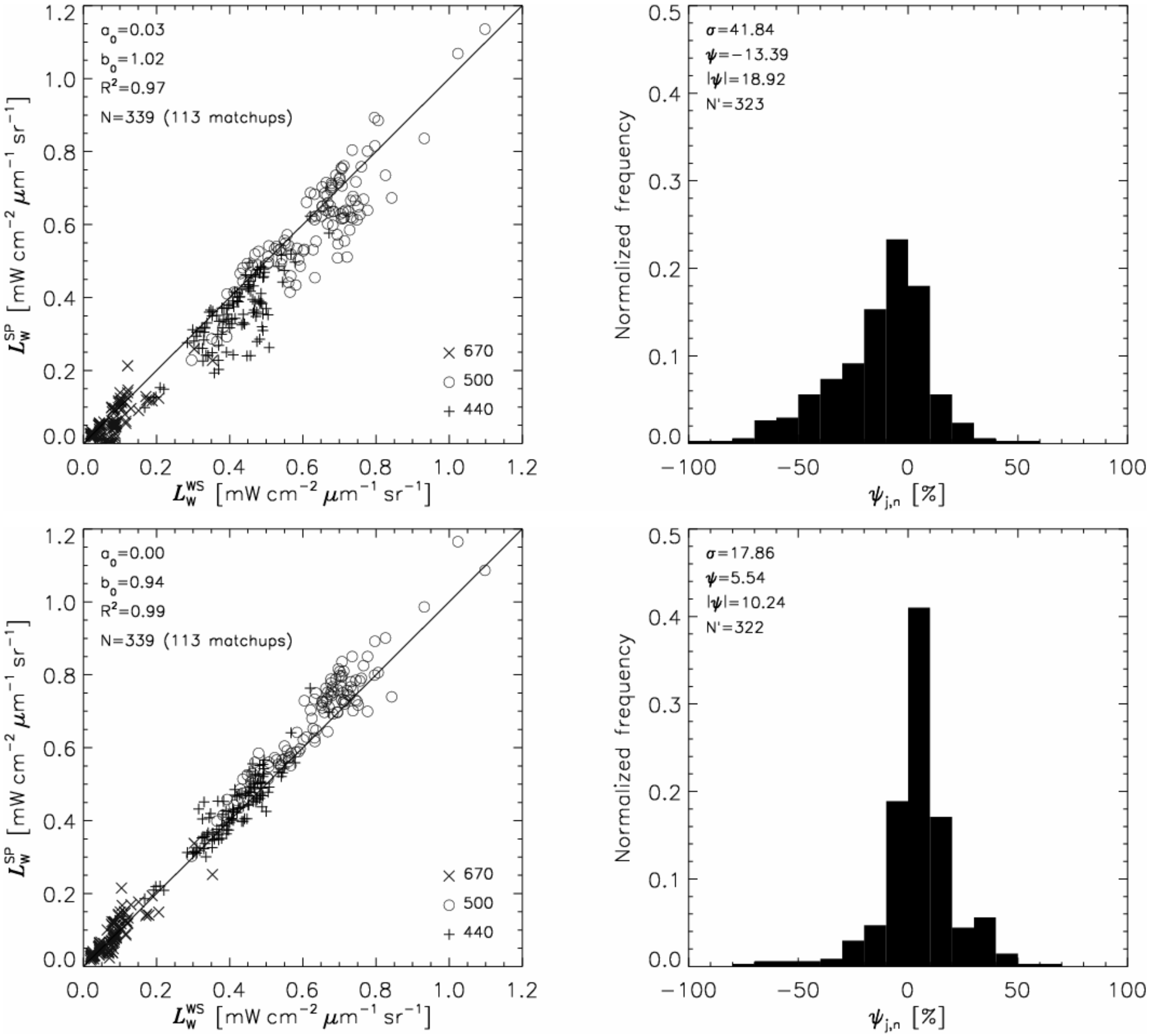
Joint Research Centre

Specific investigations for above-water radiometry

Viewing angle dependence

Superstructure perturbation

Viewing-angle dependence

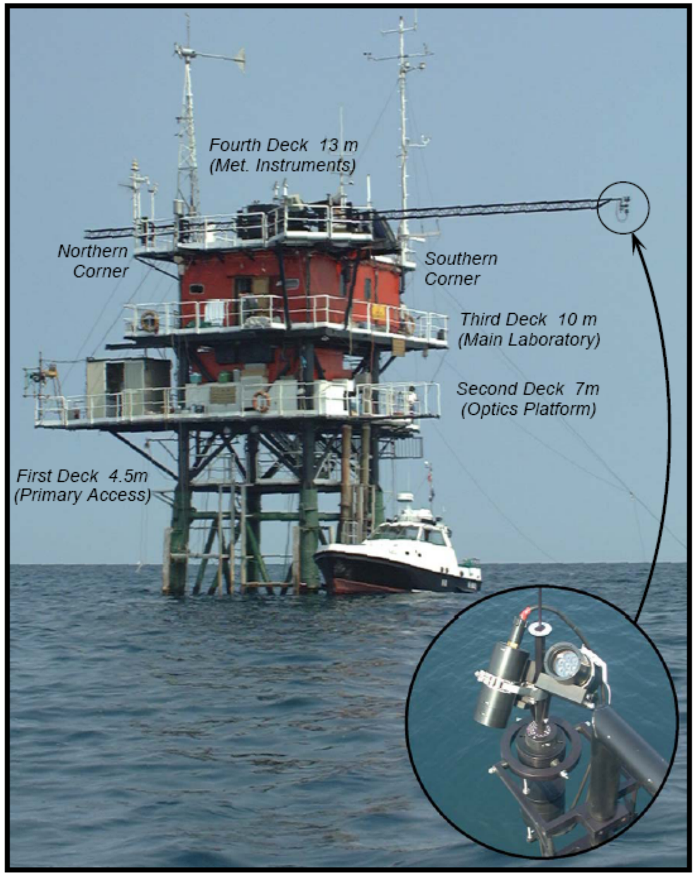


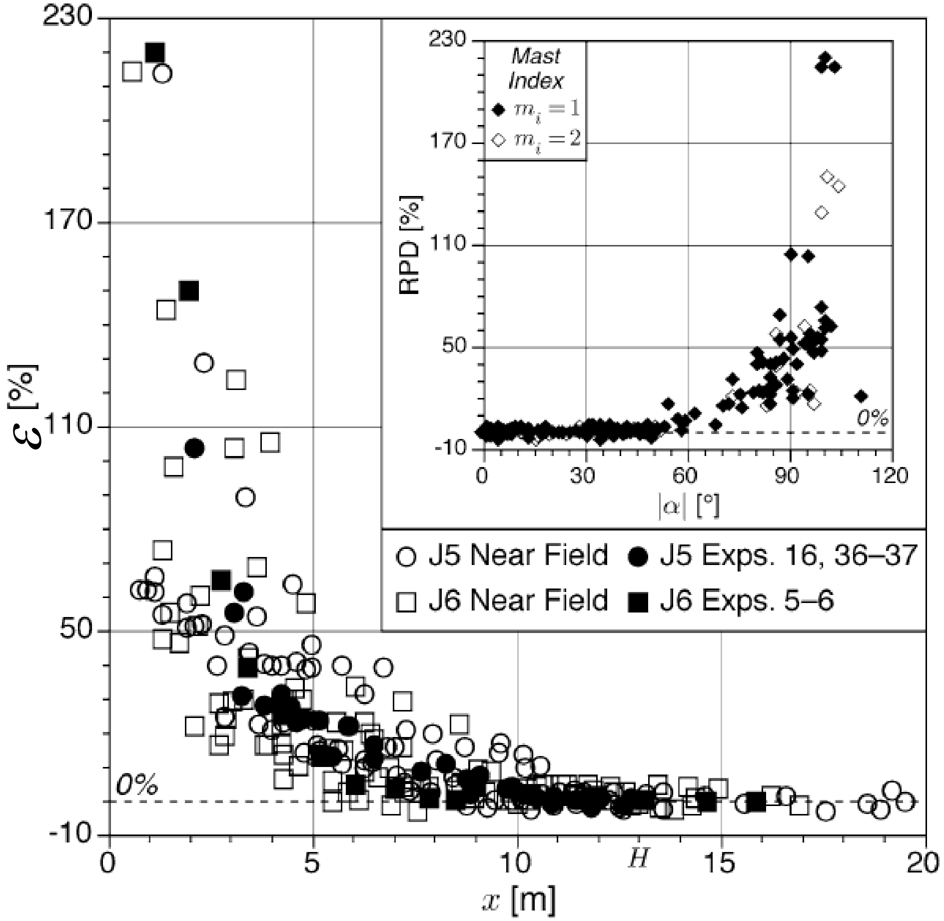
$\theta = 30^0$
$\phi = 90^0$
$\rho = 0.030$

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

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.*

Superstructure-Perturbations





$$\varepsilon(x, x_0, \lambda_0) = 100\,\frac{\rho(x,\lambda_0) - \rho(x_0,\lambda_0)}{\rho(x_0,\lambda_0)}$$

where

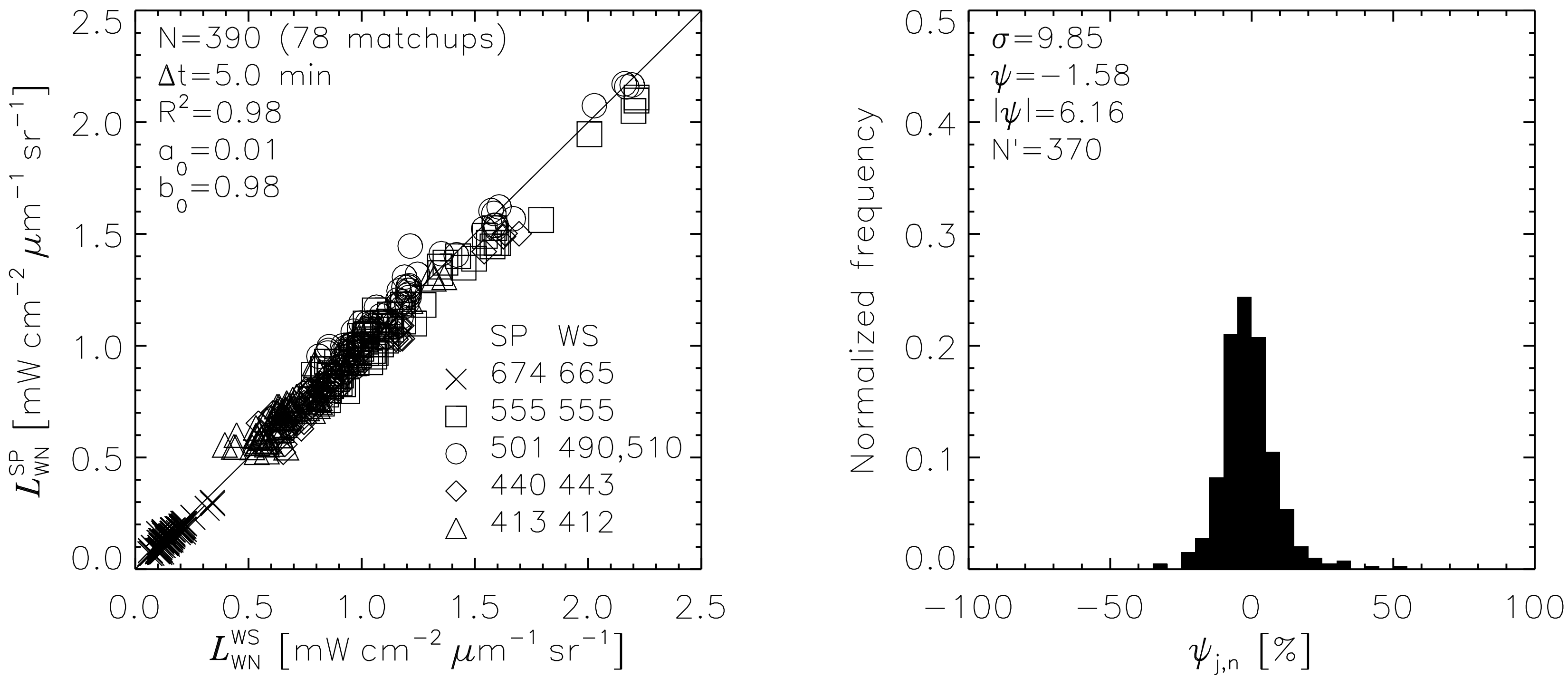
$$\rho(x,\lambda_0) = L_T(x,\lambda_0)/L_i(\lambda_0)$$

S. B. Hooker and G. Zibordi. Platform perturbation in Above-Water Radiometry. *Applied Optics*, 44, 553-567, 2005.

Uncertainties (above-water)

Source	L_{WN}				
	412	**443**	**488**	**551**	**667**
Absolute calibration	2.7	2.7	2.7	2.7	2.7
Sensitivity change	0.4	0.2	0.2	0.2	0.2
Correction	1.6	2.0	2.8	2.9	1.9
t_d	1.5	1.5	1.5	1.5	1.5
ρ	1.8	1.3	0.7	0.6	2.5
W	1.1	0.8	0.4	0.4	0.4
Environmental effects	3.1	2.1	2.1	2.1	6.4
Quadrature sum	**5.1**	**4.5**	**4.7**	**4.7**	**7.8**

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



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

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

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.

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

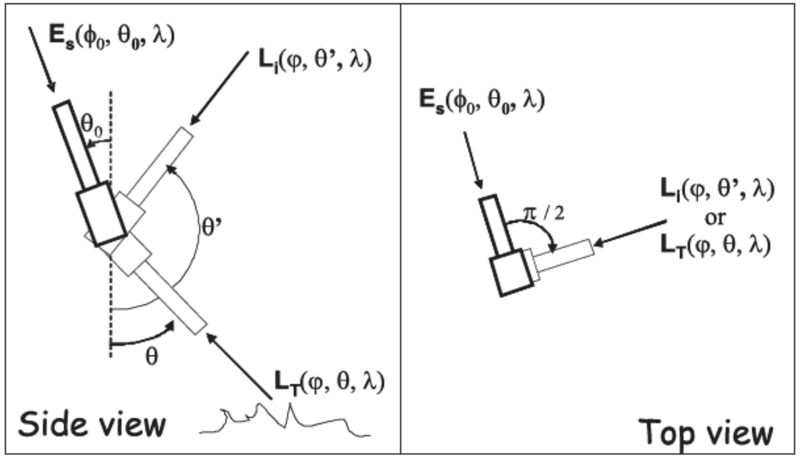
1. Produces comprehensive (fixed depths or continuous) profiles of radiometric quantities
2. Open to several radiometric quantities (i.e., L_u, E_d, E_u)
3. Upward radiometric quantities are almost not affected by wave perturbations

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

On the use of *in situ* data

An autonomous system



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

CE-318 (sky-viewing: L_i)

CE-318 (sea-viewing: L_T)

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

$$L_W^{SP}(\lambda) = L_W^{SP}(\varphi,\theta,\lambda)C_{\Im Q}(\lambda,\theta,\varphi,\theta_0,\tau_a,Chla,W)$$

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

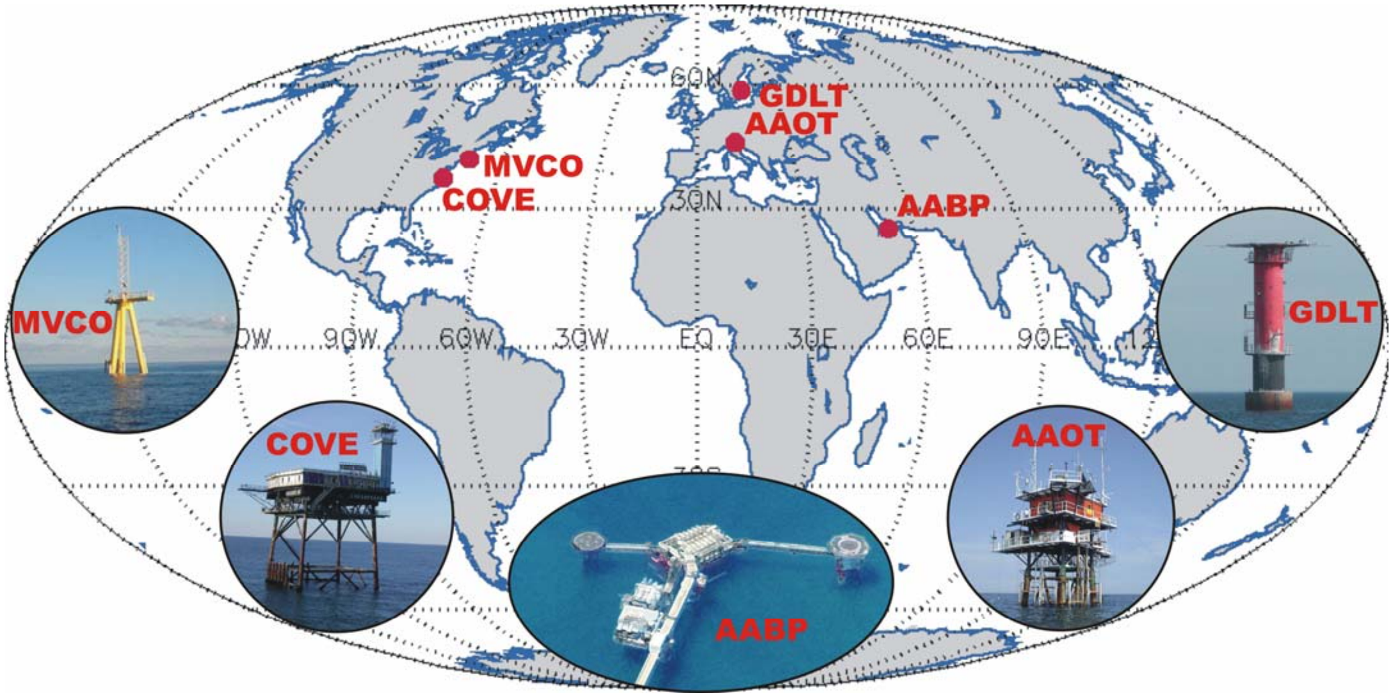
G.Zibordi, F. Mélin, S. B. Hooker, D. D'Alimonte and B. Holben. *IEEE Transactions in Geoscience and Remote Sensing* , 42:401-415, 2004 .

EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

AERONET – Ocean Color

AERONET-OC is an integrated network supporting ocean color validation with highly consistent time-series of standardized $L_{WN}(\lambda)$ measurements.

Autonomous system

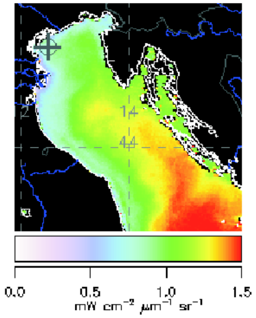


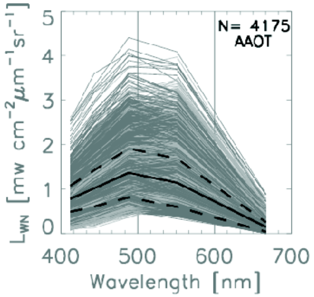
G.Zibordi et al. A Network for Standardized Ocean Color Validation Measurements. Eos Transactions, 87: 293, 297, 2006.

Joint Research Centre

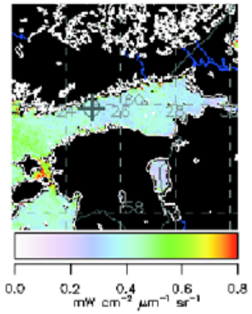
Joint Research Centre

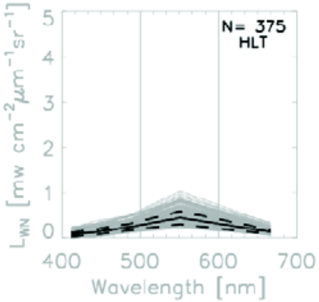
AERONET-OC Sample Sites



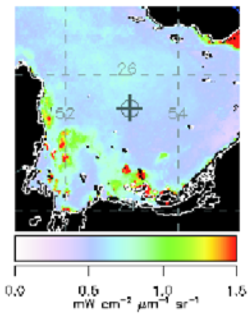


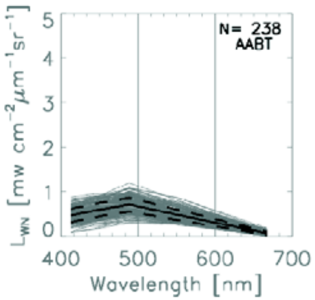
Site: AAOT
Location: Northern Adriatic Sea
Water type: Case-1/Case-2
Period: 2002-present





Site: HLT
Location: Gulf of Finland
Water type: Case-2
Period: 2006-present (summer)

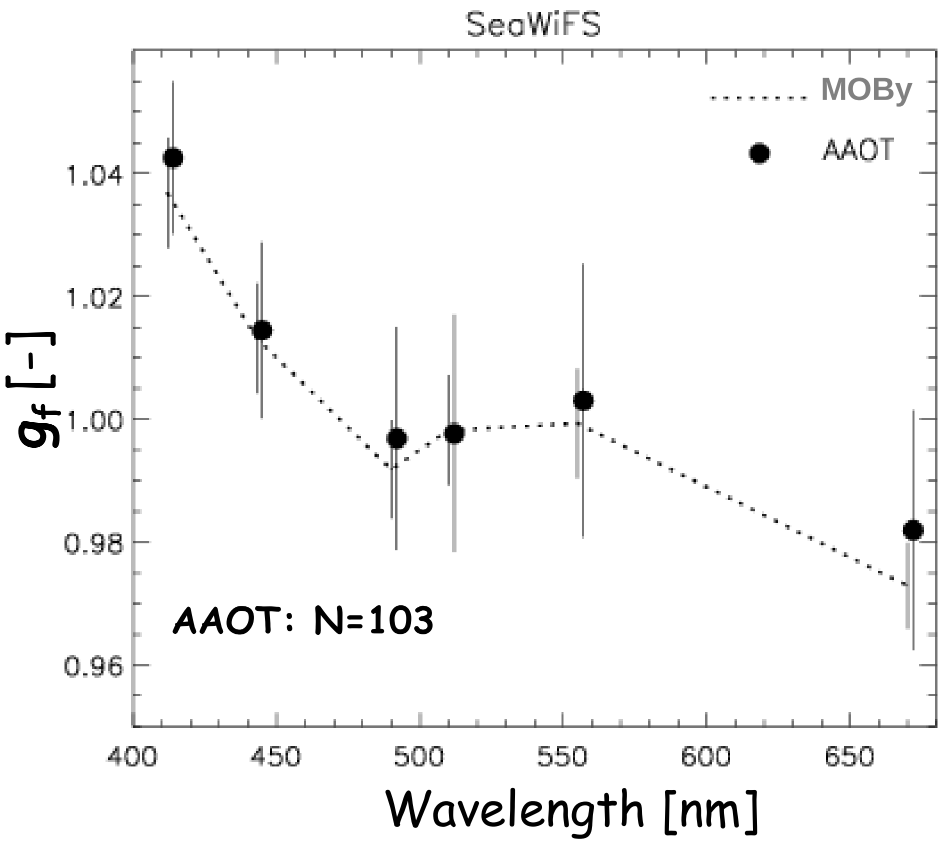




Site: AABT
Location: Persian Gulf
Water type: Case-1
Period: 2005-present

Vicarious calibration

Vicarious Calibration: Indirect calibration of the space sensor relying on in situ measurements and a radiative transfer code to propagate the *in situ* radiometric data to top-of-atmosphere.



$$g_f(\lambda) = \frac{L_T^{COMP}[L_{WN}(\lambda), \tau_a]}{L_T^{SAT}(\lambda)}$$

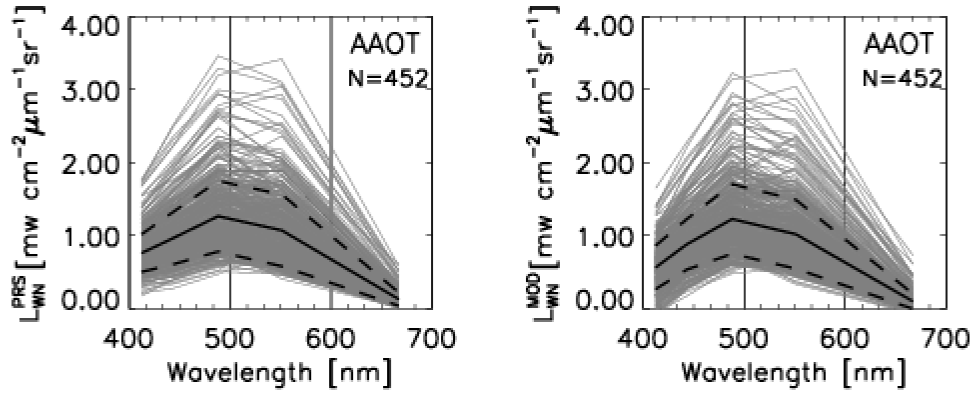
Principles

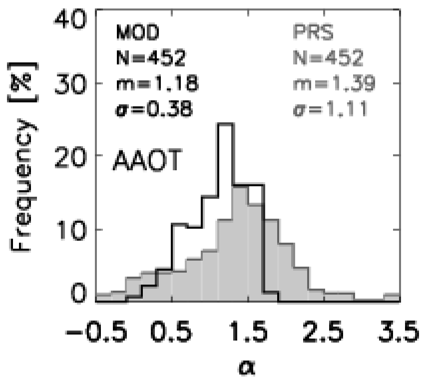
The correction factors g_f are determined using AERONET-OC data from AAOT by applying the methodology established for MOBY data (Bailey et al. 2008)

F.Mélin and G.Zibordi. Vicarious calibration of ocean color data using coastal sites. *IEEE Transactions in Geoscience and Remote Sensing,* in preparation, 2009.

Validation of satellite primary products in coastal regions

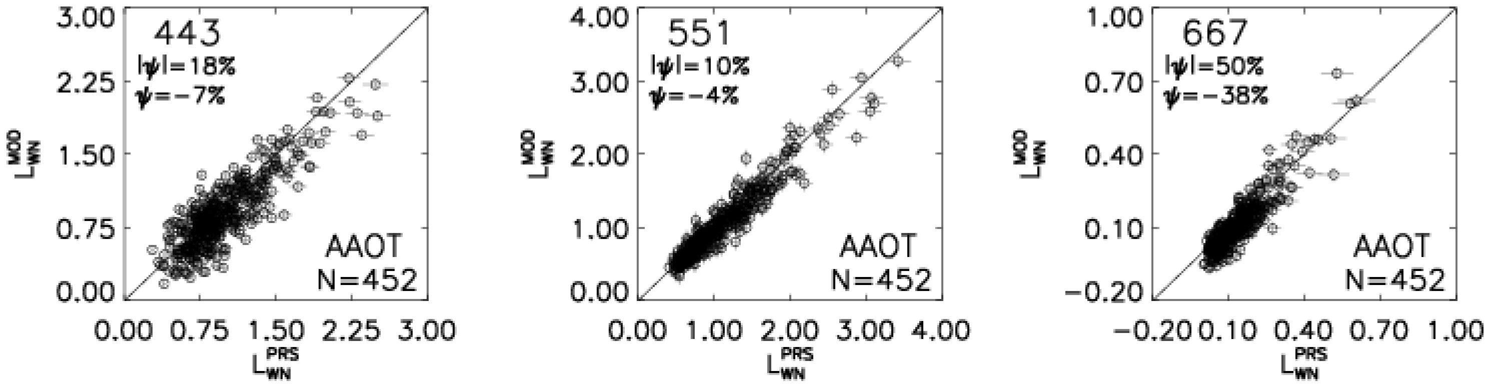
Validation: The process of assessing by independent means the quality of the data products derived from the system outputs.





In situ and satellite derived L_{WN} spectra

Ångström exponents

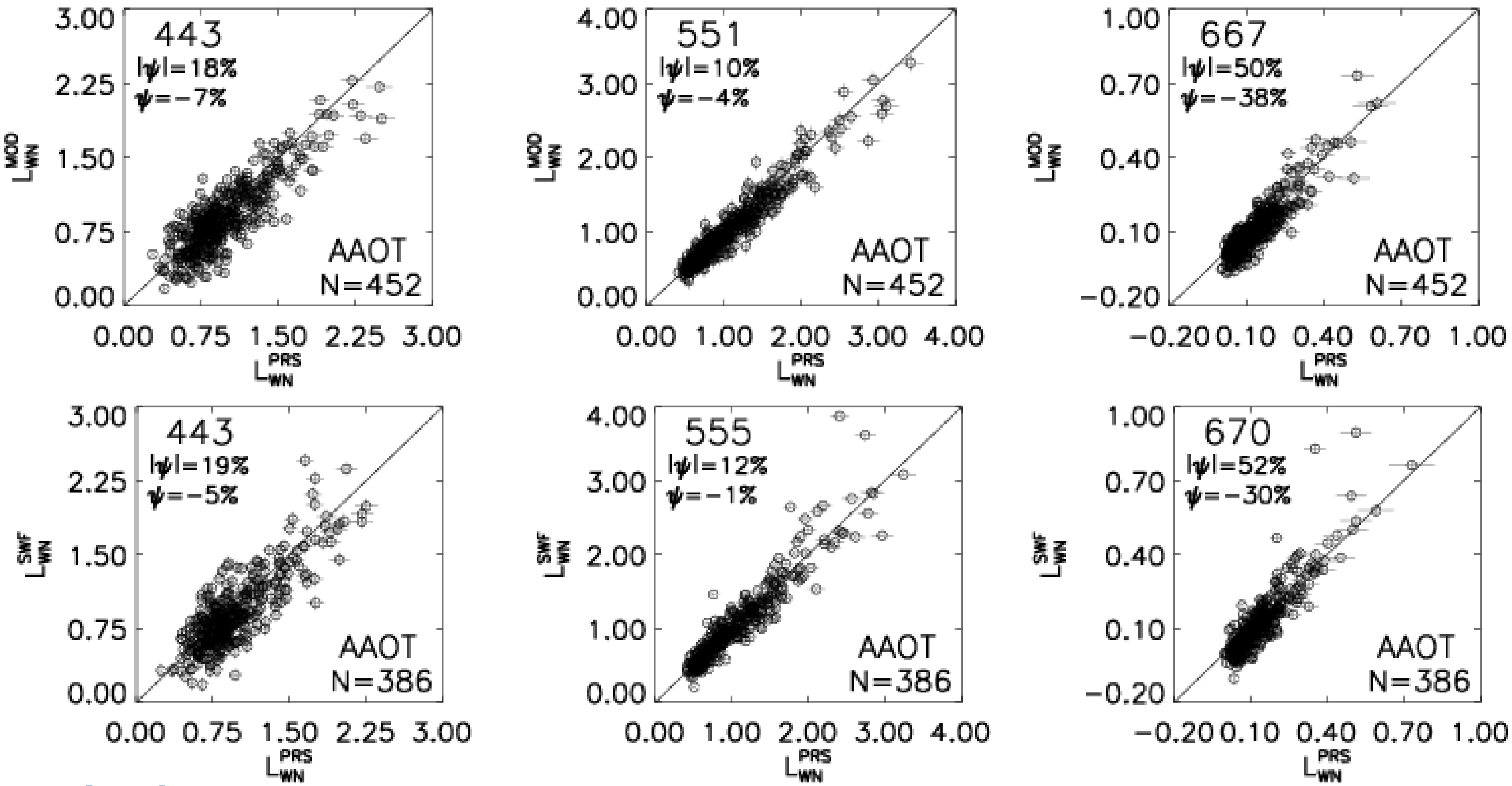


Satellite (MODIS) versus *in situ* (AERONET-OC) L_{WN} match-up analysis

G.Zibordi, J.-F. Berthon, F. Melin, D.D'Alimonte and S. Kaitala. Validation of satellite ocean color primary products at optically complex coastal sites: northern Adriatic Sea, northern Baltic Proper and Gulf of Finland. *Remote Sensing of Environmen* (submitted), 2009

Joint Research Centre

Ocean Color cross mission comparisons



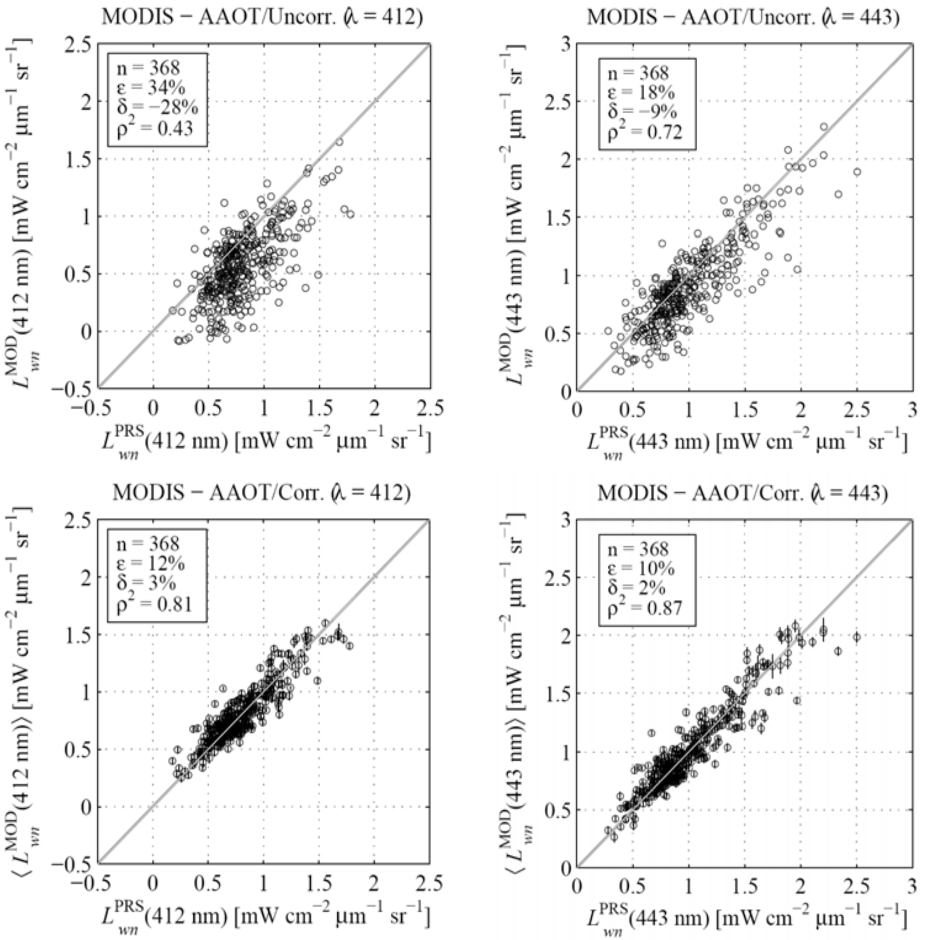
Criteria

i. satellite and *in situ* data collected within +/-2 h;
ii. satellite viewing angle lower than 56 and sun zenith lower than 70 degrees;
iv. variation coefficient of the 3x3 pixels centered at the site lower than 20%

Joint Research Centre

EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

Minimization of uncertainties in regional radiometric products



Match-up criteria

i. satellite and *in situ* data collected within +/-2 h;
ii. satellite viewing angle lower than 56 and sun zenith lower than 70 degrees;
iv. 3x3 pixels centered at the site free of cloud and glint contamination;
v. variation coefficient of the 3x3 pixels lower than 20%

Principles

$$< L_{WN}^{MOD}(\lambda) >= L_{WN}^{MOD}(\lambda) + < \Delta L_{WN}^{MOD}(\lambda) >$$

$$< \Delta L_{WN}^{MOD}(\lambda) >= L_{WN}^{PRS}(\lambda) - L_{WN}^{MOD}(\lambda)$$

$$< \Delta L_{WN}^{MOD}(\lambda) >= a_0(\lambda) + \sum_{i=1}^{n} a_n(\lambda) X_n$$

where X_n indicates:

$L_{WN}^{MOD}(\lambda)$, θ_0, φ_0, θ_V, ϕ_V

D.D'Alimonte, G.Zibordi and F.Mélin. A statistical method for generating cross-mission consistent normalized water-leaving radiances. *IEEE Transactions in Geoscience and Remote Sensing,* 46, 2008.

Joint Research Centre

Concluding remark

Field radiometry is a fundamental complement to satellite ocean color. In fact it is the means to support:

a. vicarious calibration of space sensors;

b. development of bio-optical algorithms;

c. assessment of primary satellite products.

Because of this, research and development in marine radiometry has seen a considerable raise during the last two decades aiming at:

i. reducing uncertainties;

ii. standardizing measurements;

iii. automating observations.

Any question?