Joint Research Centre

Above- and in-water radiometry: Methods and Calibration

Giuseppe Zibordi

(giuseppe.zibordi@jrc.it)

Joint Research Centre of European Commission

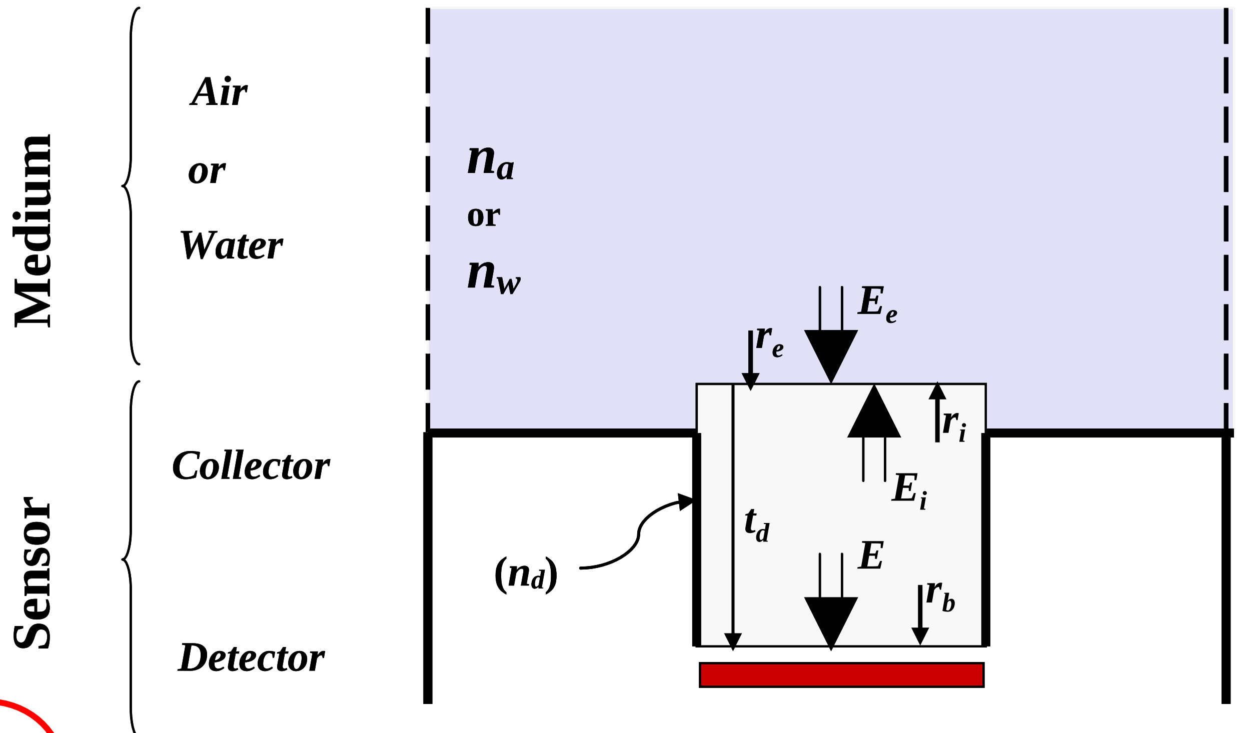
Joint Research Centre

Radiometric Calibration: Immersed

The process of quantifying 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.

I_f for E Sensors

The Immersion Factor for irradiance sensors accounts for the change in the reflectance and transmittance of the water-collector with respect to the air-collector interfaces.



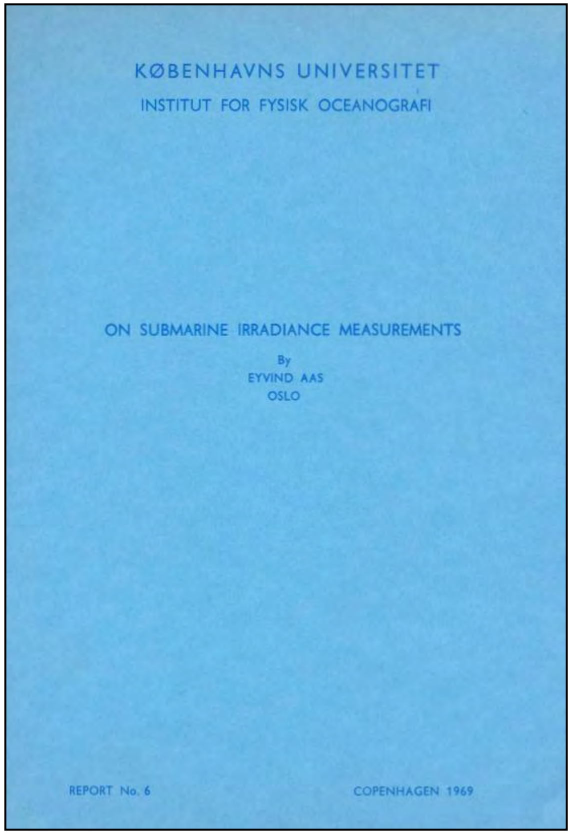
$$E(\lambda)=E_e(\lambda)\,[1-r_e(\lambda)]\,t_d(\lambda)\,[1-r_b(\lambda)]+E_i(\lambda)\,r_i(\lambda)$$

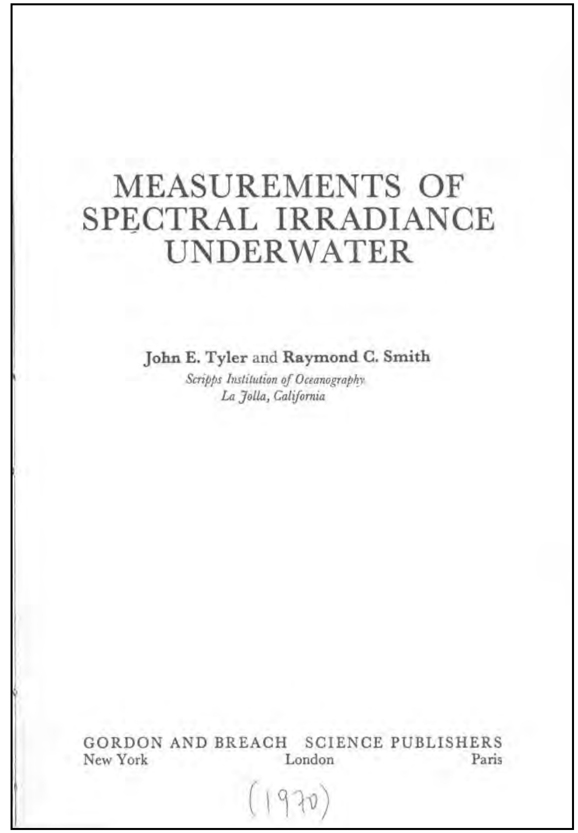
Its accurate theoretical determination is unfeasible

G.Zibordi et al. 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

Historical Background

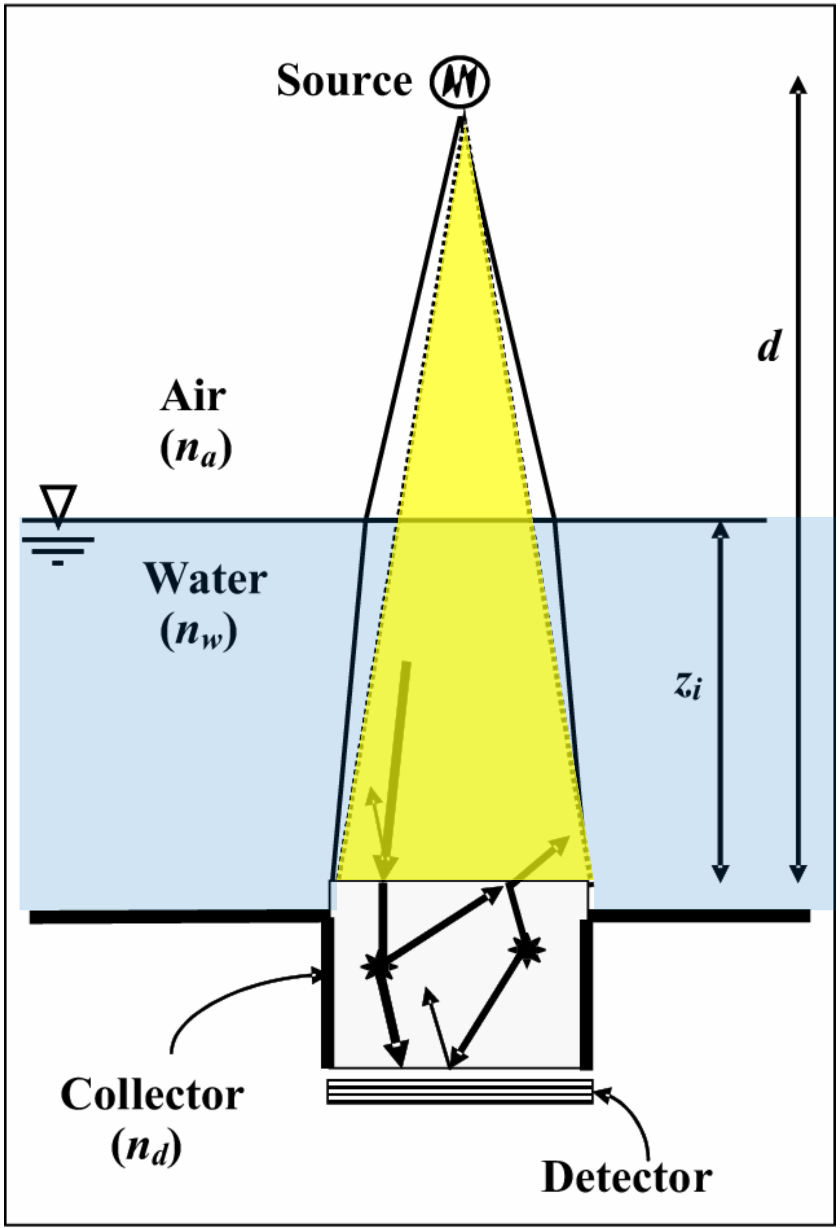




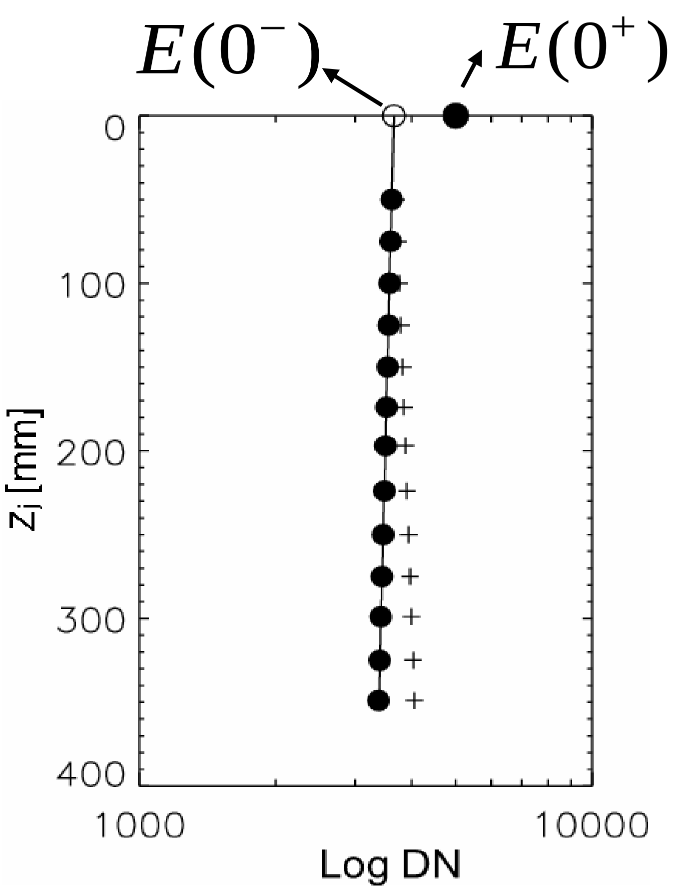
Aas, E., 1969: *On submarine irradiance measurements*. Institute of Physical Oceanography, University of Copenhagen, Denmark.

Tyler, J. E., and R. C. Smith, 1970: *Measurements of Spectral Irradiance Underwater.* Gordon and Breach.

Experimental determination of I_f for E sensors

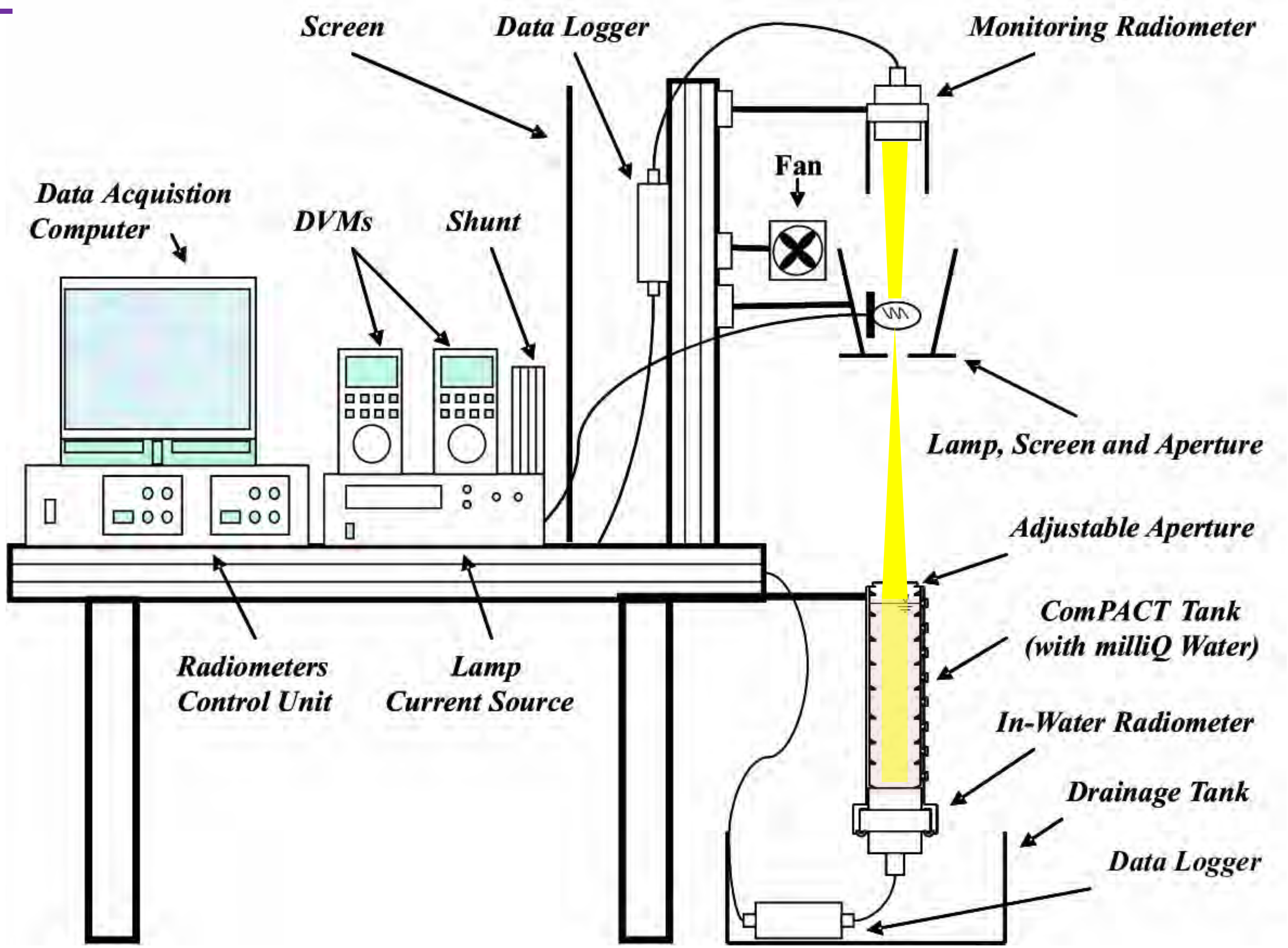


$$I_f = \frac{E(0^+)}{E(0^-)} t_{wa}$$



The Measuring Apparatus (I_f for E)

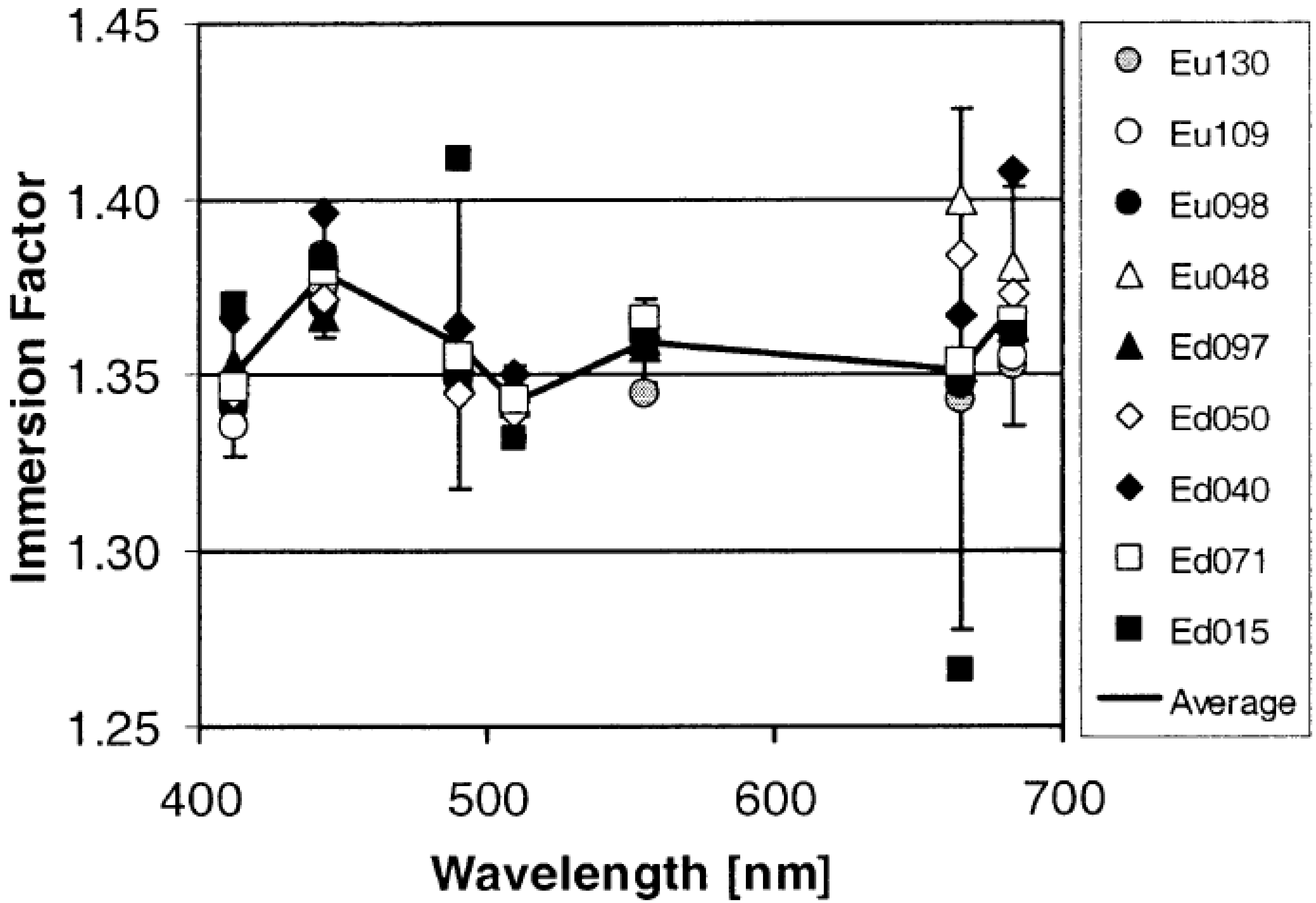
Joint Research Centre



G.Zibordi et al. 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

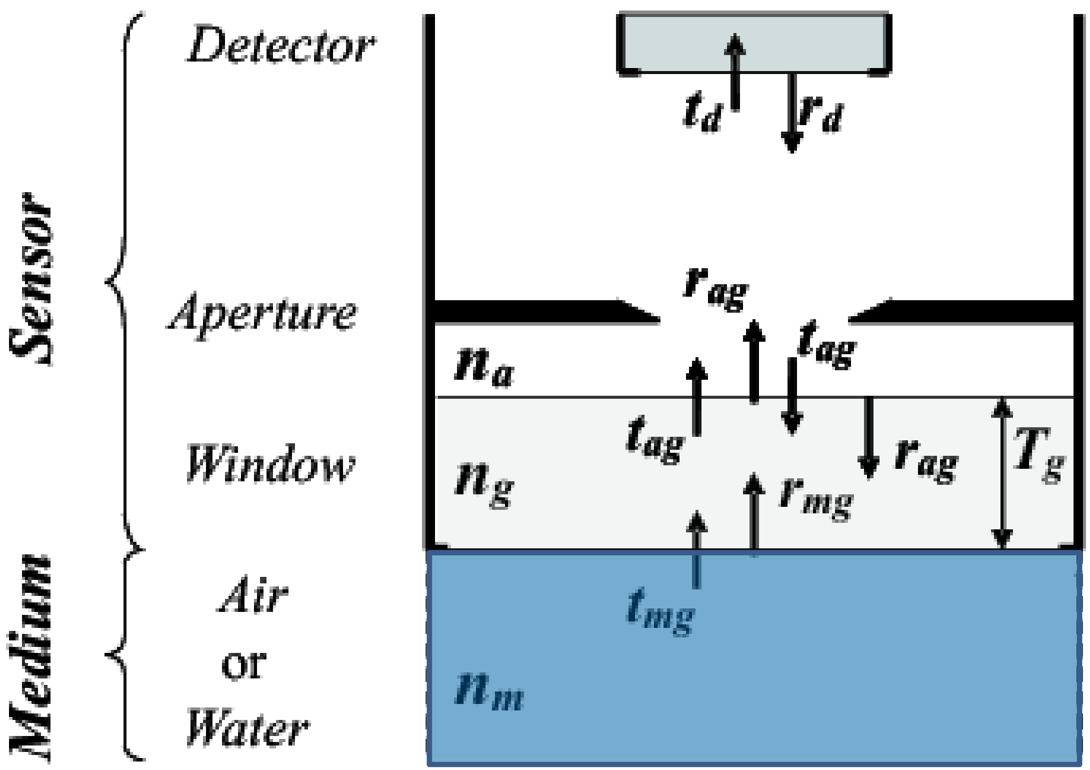
Results from I_f measurements (E)



G.Zibordi et al. Characterization of the immersion factor for a series of in–water optical radiometers. *Journal of Atmospheric and Oceanic Technology*, 21:501-514, 2004.

I_f for L Sensors

The Immersion Factor for radiance sensors accounts for the change in the solid angle fieldof-view and, in the reflectance and transmittance of the water-optics with respect to the air-optics interfaces.



$$I_f = \frac{\Omega_a}{\Omega_w}\frac{t_{ag}}{t_{wg}}$$

$$I_f = \frac{n_w(n_w + n_g)^2}{(1 + n_g)^2}$$

Theoretical (basic)

$$I_f = \frac{\Omega_a}{\Omega_w}\frac{t_{ag}}{t_{wg}}\frac{T_{ag}}{T_{wg}}\frac{T_{ad}}{T_{wd}}$$

Theoretical (expanded, and more difficult to determine)

G.Zibordi. Immersion factor of in-water radiance sensors: assessment for a class of radiometers. *Journal of Atmospheric and Oceanic Technology*, 2006.

Historical Background

LA JOLLA: SCRIPPS INSTITUTION OF OCEANOGRAPHY
VISIBILITY LABORATORY

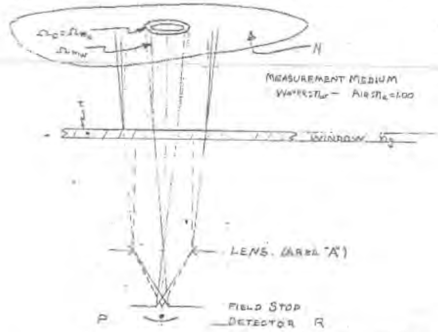
7 April 1976
ML-76-004t

TECHNICAL MEMORANDUM

Subject: Air-Water Radiance Calibration Factor

Instruments for the measurement of spectral radiance underwater may be calibrated by viewing a surface of known radiance in the laboratory, in air. This difference in environment must be accounted for when interpreting the readings from such instruments, i.e., in the data reduction process. The purpose of this memorandum is to provide the details of the logical derivation of the calibration factor for record, and to list values of the factor for wavelengths from 360 to 740 nanometers. Values will be presented for three-window materials, viz. Plexiglas, quartz; and Schott BK7 borosilicate crown glass. The seawater in which the measurements are made will be assumed to have a salinity of 35‰ and a temperature of 16°C. The sensitivity of the factor to changes in the index of refraction of the water and the window will be presented.

The radiometer may be schematically represented by the accompanying figure. Basically the instrument consists of a detector (e.g., a photomultiplier tube coupled to a monochromator); a field stop; a lens having an area A which, in conjunction with the field stop, determines Ω, the solid angle of the field-of-view of the instrument; and, lastly, a window with index of refraction n_g which separates the instrument from the environment in which the instrument is imbedded. The environment will be either air -- in the case of calibration or measurements in air -- or water -- in the normal underwater measurement situation.



NOV 13 2001 12:22 619 534 8670 PAGE.02

ML-76-004t

SIO/Vis Lab
DL-82-005t
23 September 1982

Technical Memorandum

Subject: Air-Water Radiance Calibration Factor - Gershun tube.

Ref. (a): Vis Lab Tech Memo ML-76-004t, 7 April 1976

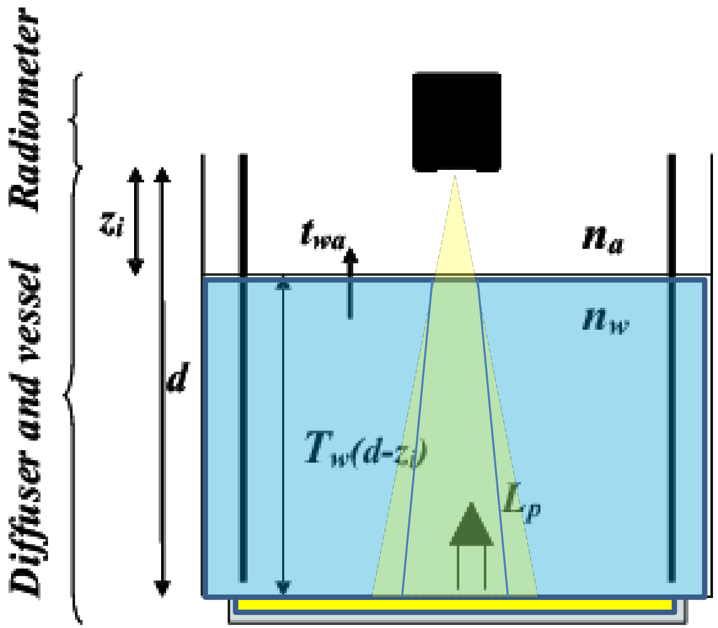
Background. The use of a Gershun Tube to determine the field of view of a radiance meter has the advantage of simplicity of design and construction as well as providing a simple means of converting an irradiance meter to a radiance meter in the field. Because it consists simply of a tube with two field-determining stops, the calibration factor for in-air use may be estimated fairly accurately from a simple calibration of the solid angle if, say, the angle is small, the irradiance meter has a proper cosine response function, and the radiance field is isotropic. In any event, once the system has been calibrated in the laboratory for radiance and irradiance and the factor for the Gershun tube is known, it is not necessary to perform both calibrations each time a recalibration is required. Furthermore, there need be little concern about changes in the transmission of the optical elements as there might be when an imaging telescopic system is used.

Some confusion has existed with respect to the necessity to apply an n^2 correction when using a Gershun tube radiance meter. Such a correction would be similar to that used to accomodate for the decreased solid angle which occurs at a plane window when an imaging radiance meter is immersed in water vice being in air as for calibration. (For example, Ref. (a) gives calibration factors for "imaging" systems.) Controlled measurements in an indoor tank were performed to confirm the nature of the behavior of the instrument in this respect and to determine the immersion factor which accounts for the change in behavior of the diffuser when it comes in contact with water. The following describes these tests and the rationale for the results.

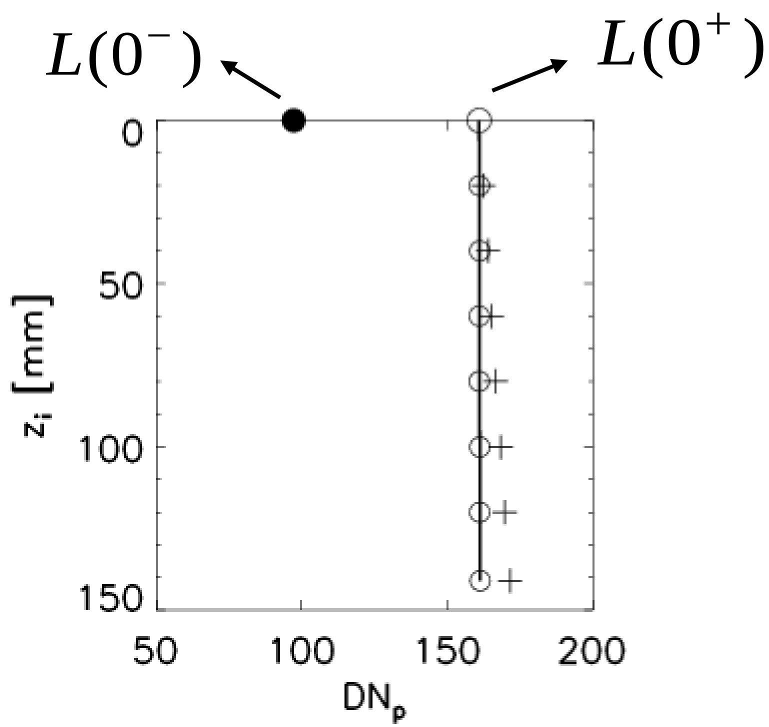
Austin, R., 1976: *Air-water radiance calibration factor*. Scripps Institution of Oceanography Tech. Memo. ML-76-004T.

Austin, R., & Petzold T.J., 1982: *Air-water radiance calibration facto- Gershun tube*. Scripps Institution of Oceanography Tech. Memo. DL-82-005T.

Experimental determination of I_f for L sensors

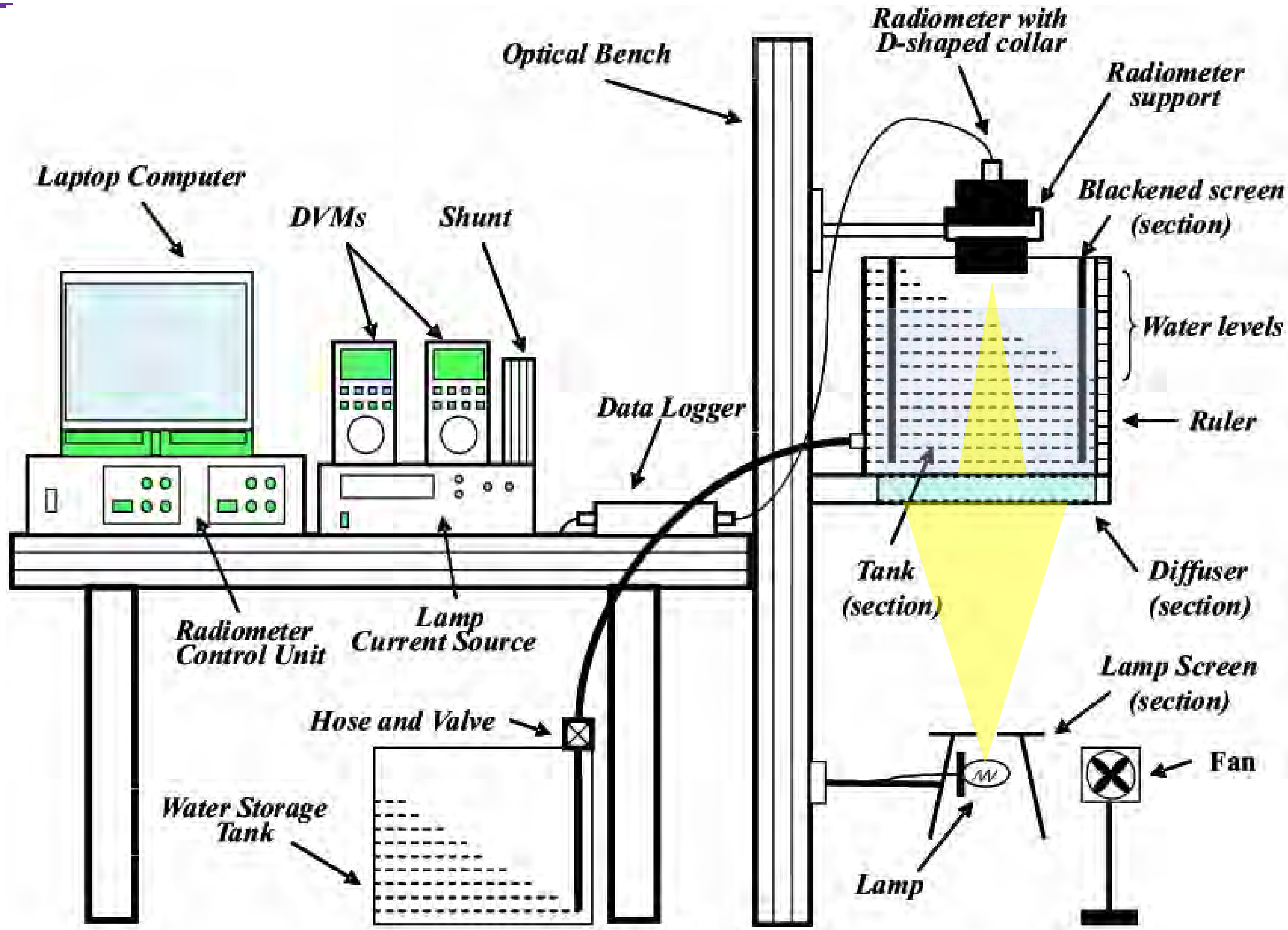


$$I_f = \frac{L(0^+)}{L(0^-)} \frac{\Omega_a}{\Omega_w} \frac{1}{t_{wa}}$$



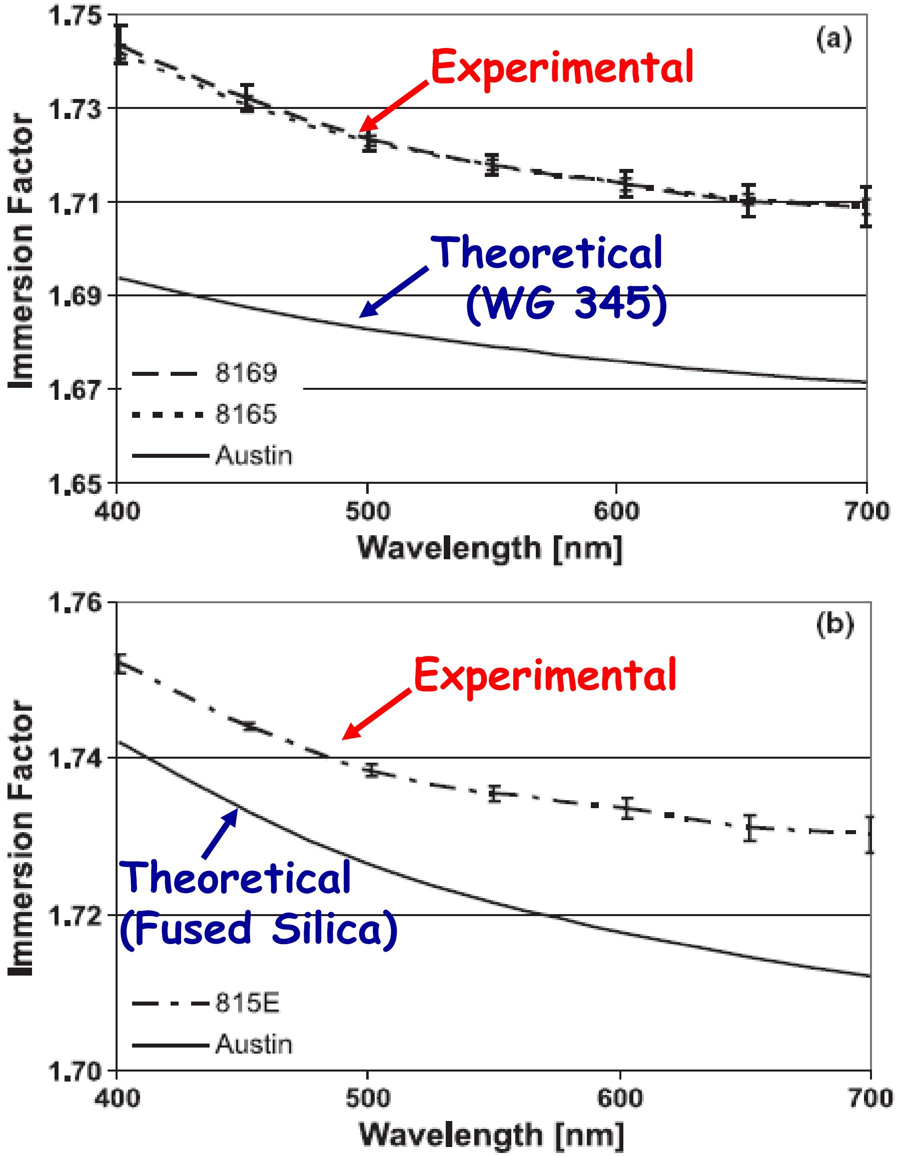
G.Zibordi. Immersion factor of in-water radiance sensors: assessment for a class of radiometers. *Journal of Atmospheric and Oceanic Technology*, 2006.

The Measuring Apparatus (I_f for L)



G.Zibordi. Immersion factor of in-water radiance sensors: assessment for a class of radiometers. *Journal of Atmospheric and Oceanic Technology*, 2006.

Results from I_f measurements (L)



G.Zibordi and M.Darecki. Immersion factor for the RAMSES series of hyper-spectral underwater radiometers. *Journal of Optics A – Pure and Applied*, 8: 252-258, 2006.

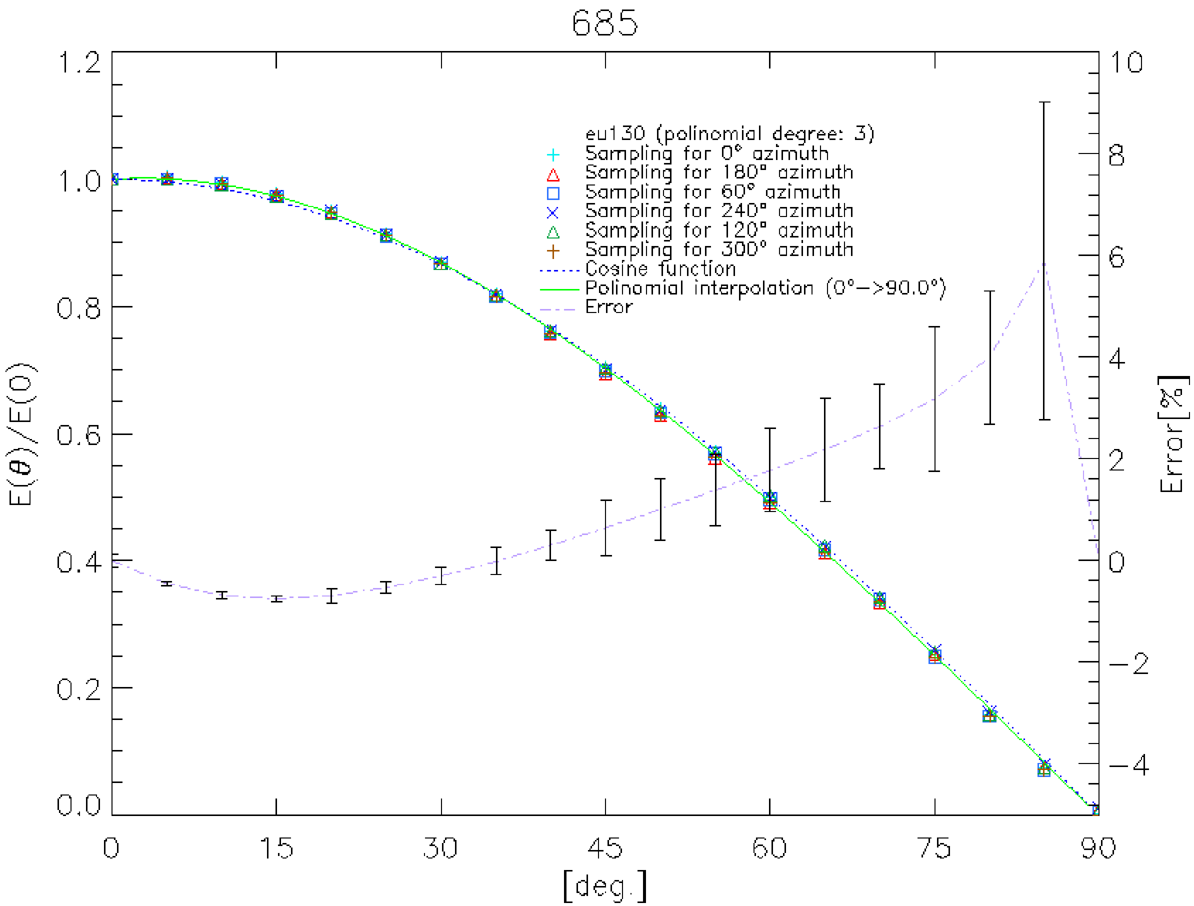
Joint Research Centre

Radiometric Calibration:

Geometric

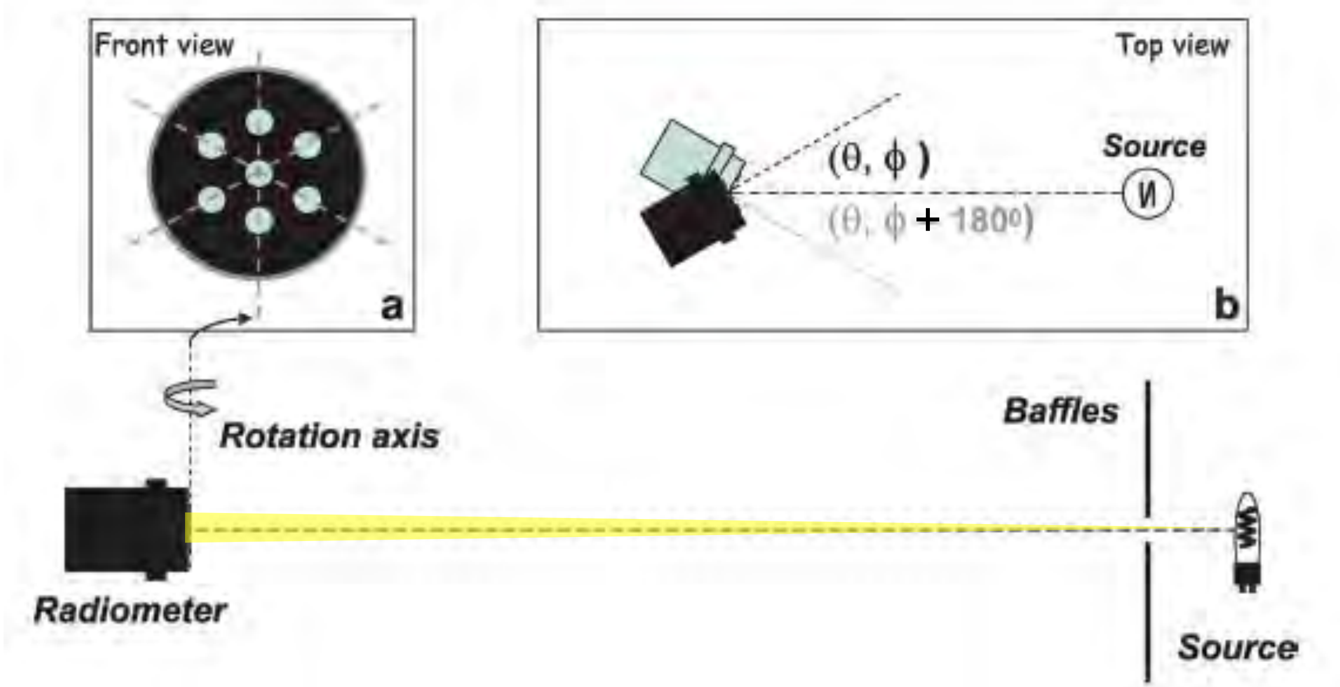
The process of quantifying the goodness of the angular response of a cosine collector to a collimated source.

Cosine response



G.Zibordi et al. 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 GSFC, Greenbelt, Maryland, 2002, 39 pp.

Determination of the Cosine Response

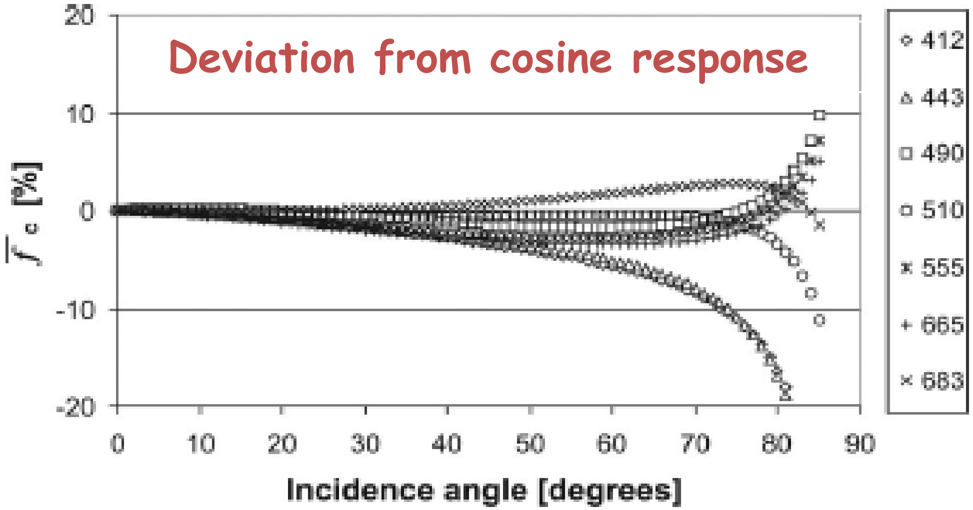


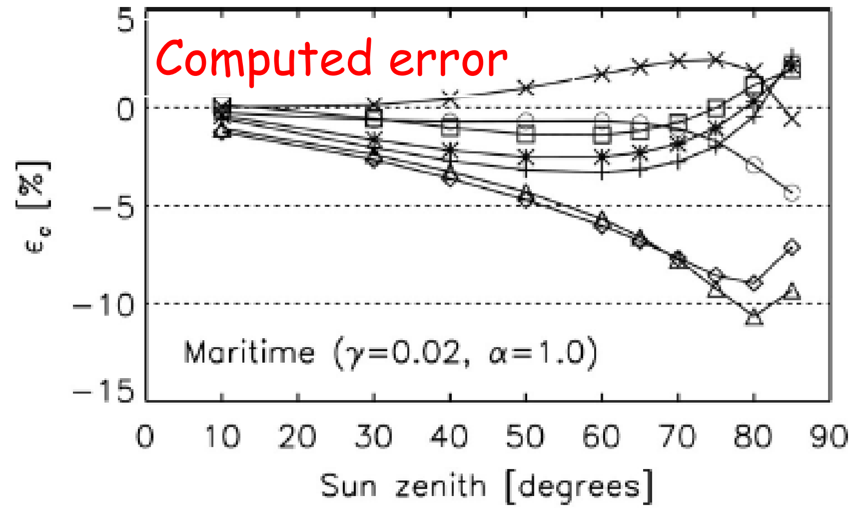
$$f_c(\lambda,\theta,\varphi) = 100[\frac{E(\theta,\varphi,\lambda)}{E(0,\varphi,\lambda)cos\theta} - 1]$$

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

Joint Research Centre

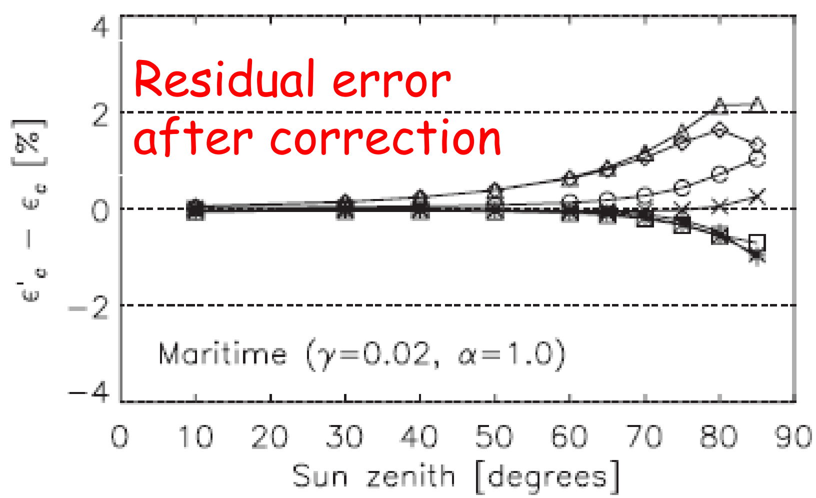
Error due to Non-Cosine Response





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

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



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.

Joint Research Centre

Concluding remark

In view of comprehensively supporting satellite ocean color, field radiometry needs to rely on:

a. Consolidated measurement protocols;
b. Comprehensive, accurate and traceable calibrations.

Joint Research Centre

In Situ Radiometric Products: Uncertainty Analysis and Applications

Giuseppe Zibordi

(giuseppe.zibordi@jrc.it)

Joint Research Centre of European Commission

Joint Research Centre

Uncertainties

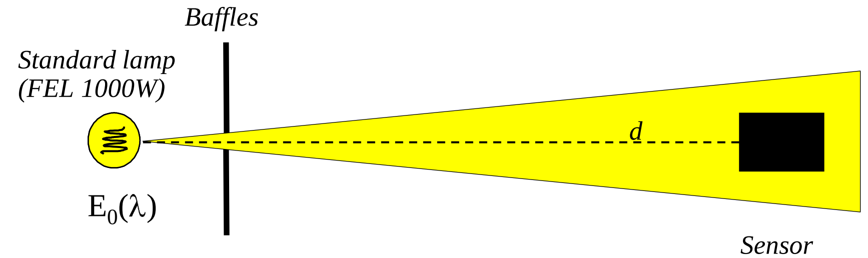
- Absolute radiometric calibration
- Sensor sensitivity decay
- Deployment perturbations
- Measurement methodology
- Environmental perturbations
- Data analysis and products retrieval

Joint Research Centre

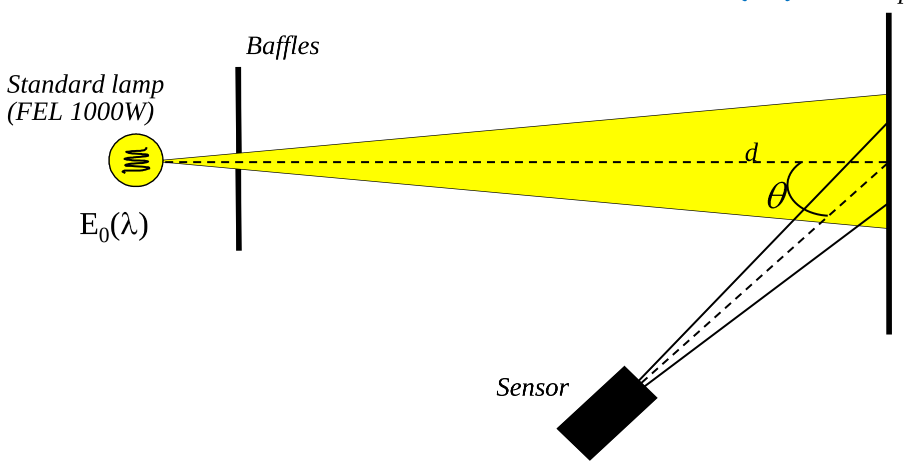
Absolute Calibration Uncertainties

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)



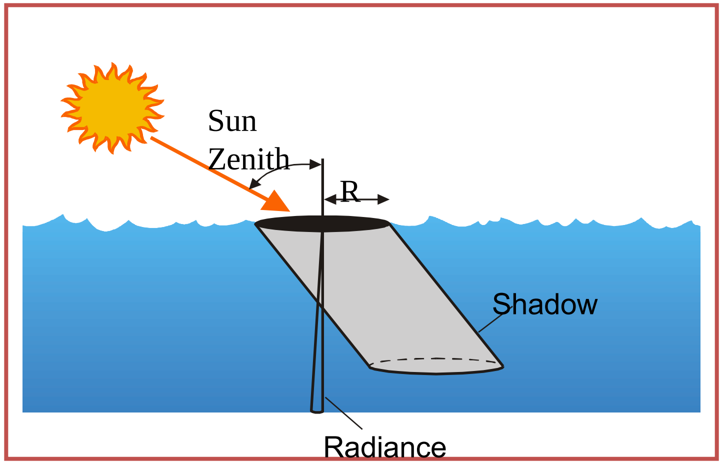
Radiance calibration (L)

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

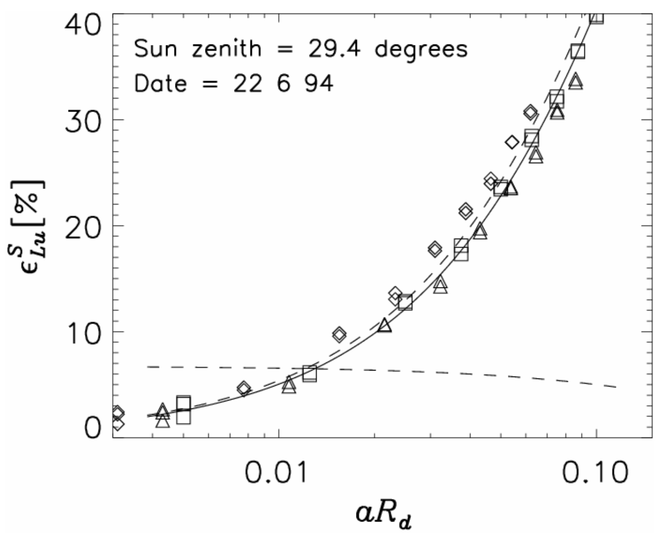
S.Hooker, et al,. The Seventh SeaWiFS Intercalibration Round-Robin Experiment (SIRREX-7), NASA/TM-2001-206892, v. 17, NASA SSFC, 2001 .

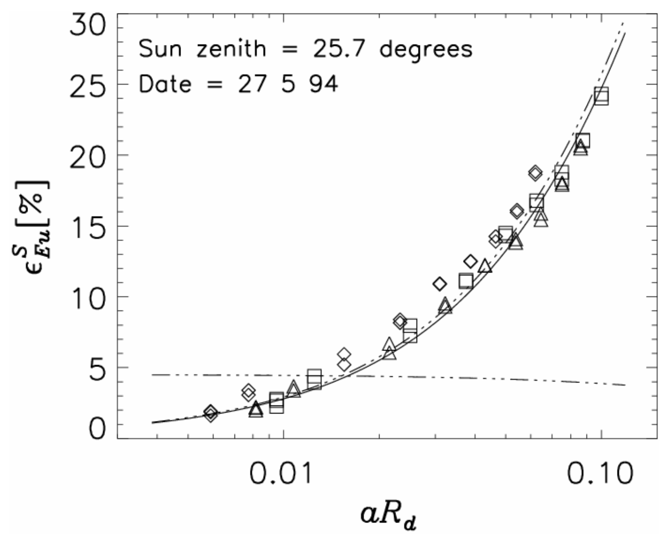
Joint Research Centre

Self-Shading



Self-shading perturbations can be estimated as a function of radiometer geometry (conveniently expressed by its radius) and seawater optical properties (conveniently expressed by the seawater absorption coefficient).





Gordon H R, Ding K (1992) Self-shading of in-water optical instruments. Limnol Oceanogr 37:491–500.

Zibordi G. and Ferrari G.M. (1995), Instrument self shading in underwater optical …. *Applied Optics*, 34: 2750-2754.

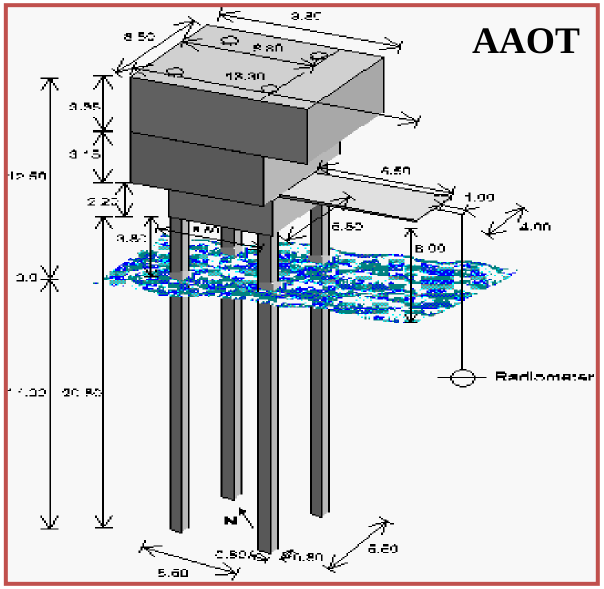
Aas E, Korsbø B (1997) Self–shading effect by radiance meters on upward radiance … Limnol Oceanogr 42: 968–974.

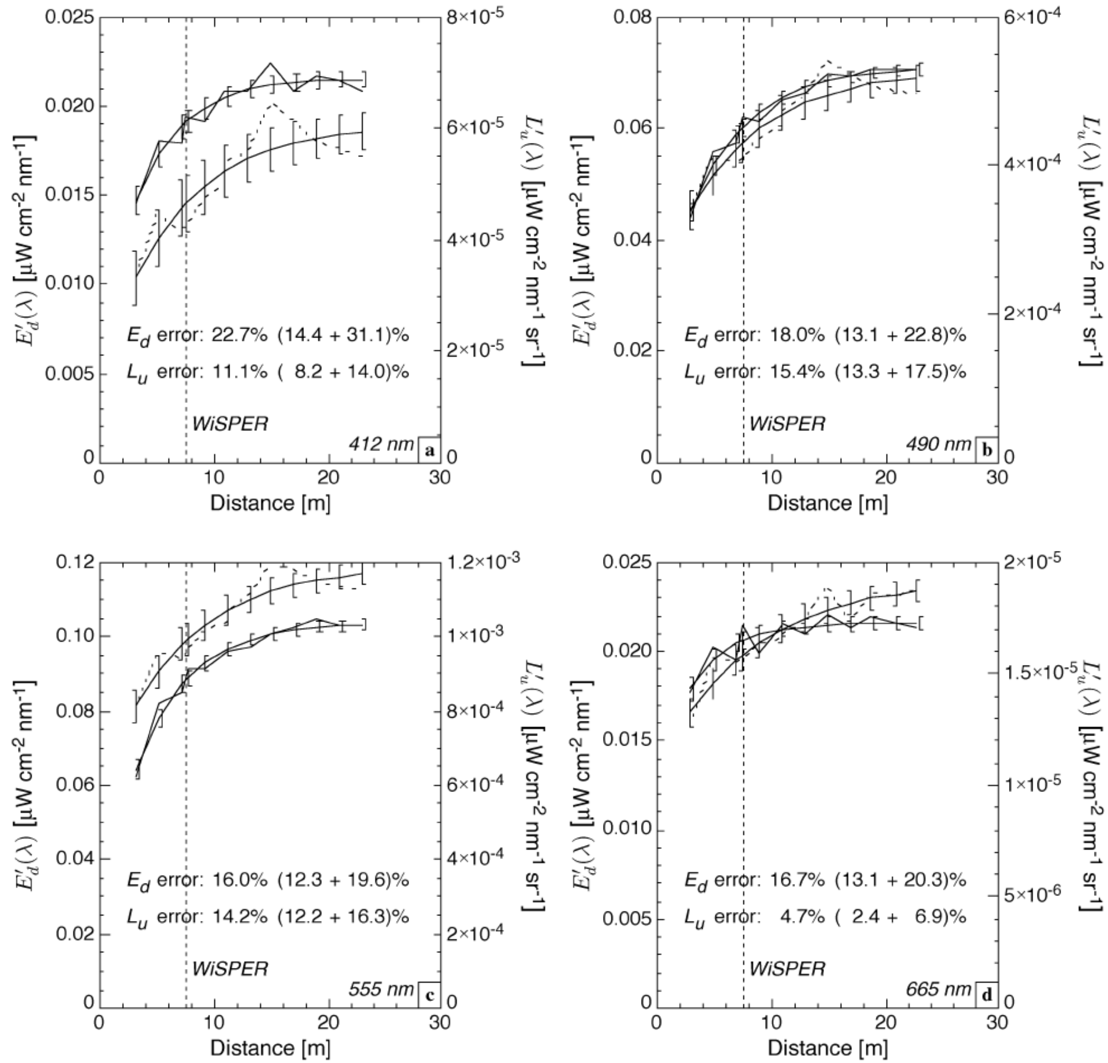
Piskozub J, Weeks A R, Schwarz JN, Robinson IS (2000) Self-shading of upwelling …. Appl Opt 39:1872–1878.

Leathers RA, Downes TV, Mobley CD (2001) Self–shading correction for upwelling …. Optics Express 8:561–570.

Joint Research Centre

Superstructure (in water)



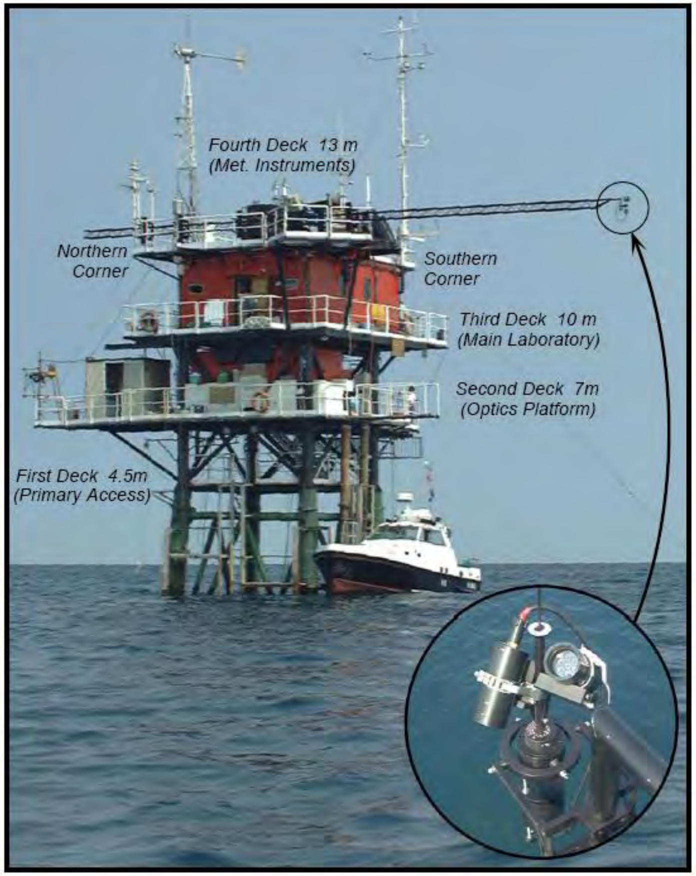


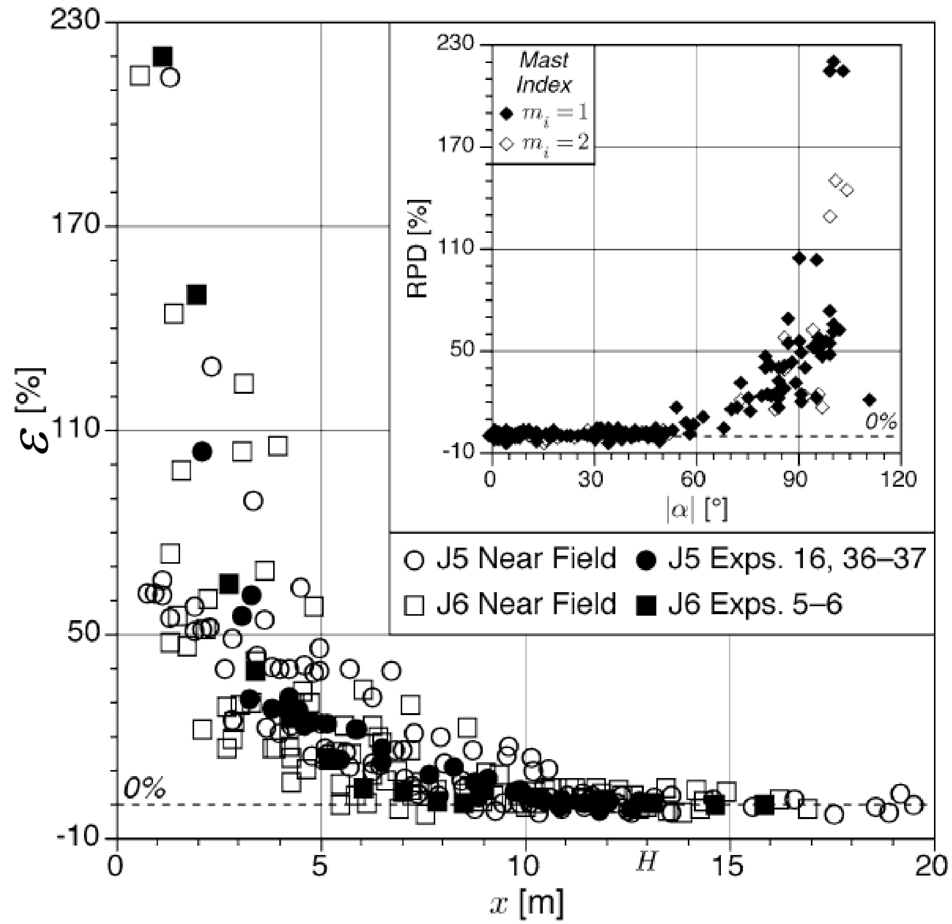
Superstructure perturbations depend on geometry of the deployment structure, deployment geometry and, seawater and atmosphere optical properties.

Gordon HR (1985) Ship perturbation of irradiance measurements at sea …. Appl Opt 24:4172–4182.

J.P.Doyle & G.Zibordi (2002) Optical propagation within a 3-dimensional shadowed …. *Applied Optics*, 41:4283-4306.

Superstructure (above water)





$$\varepsilon(x, x_0, \lambda_0) = 100\,\frac{\rho(x,\lambda_0) - \rho(x_0,\lambda_0)}{\rho(x_0,\lambda_0)} \quad \text{where} \quad \rho(x,\lambda_0) = L_T(x,\lambda_0)/L_i(\lambda_0)$$

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

Joint Research Centre

L_{WN} uncertainties

Uncertainty defines closeness between value of quantity obtained from measurements and its true value (it has a probabilistic basis and reflects incomplete knowledge of the measured value).

In water	L_{WN}		
	443	**551**	**667**
Absolute calibration	2.8	2.8	2.8
Sensitivity change	0.3	0.3	0.3
Corrections	1.0	1.1	2.6
$E_d(0^+)$ & E_0	3.4	2.8	2.8
Extrapolation	1.0	0.9	2.4
Environmental var.	1.1	1.3	2.8
Quadrature sum	**4.8**	**4.4**	**6.0**

Above water	L_{WN}		
	443	**551**	**667**
Absolute calibration	2.7	2.7	2.7
Sensitivity change	0.2	0.2	0.2
Corrections	2.0	2.9	1.9
t_d	1.5	1.5	1.5
ρ	1.5	0.6	2.5
Environmental var.	2.1	2.1	6.4
Quadrature sum	**4.5**	**4.7**	**7.8**

G.Zibordi and K.J.Voss, Field Radiometry and Ocean Color Remote Sensing. In *Oceanography from Space, revisited.* V.Barale, J.F.R.Gower and L.Alberotanza Ed.s, Springer, Dordrecht, pp. 365-398, 2010.

Joint Research Centre

Applications

- Vicarious Calibration
- Validation of satellite products
- Algorithms development

Joint Research Centre

Vicarious Calibration

Ocean bio-optical applications need uncertainties in primary remote sensing radiometric products lower than 5%, which require uncertainties roughly lower than 0.5 % at the satellite level.

This extremely high accuracy requirement can only be satisfied through vicarious calibration:

the adjustment of instrument calibration coefficients *forcing* convergence of top-of-atmosphere radiometric signal with that computed applying *in situ* measurements relying on mission specific atmospheric and radiative transfer models.

Clearly any bias in the *in situ* data is transferred to the remote sensing data.

Gordon,H R (1987) Calibration requirements and methodology for remote sensors viewing the oceans in the visible. Remote Sens.Environ.,22, 103-126.

Joint Research Centre

Vicarious Calibration Sites in the history of Ocean Color

YBOM (NASDA) (1996-1997)

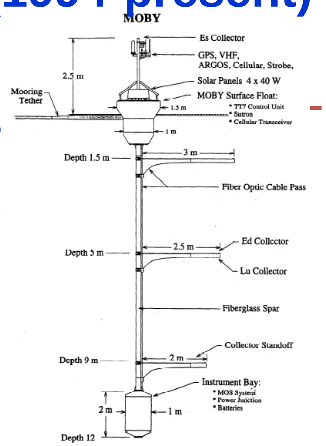
BOUSSOLE (LOV-CNES) (2004-present)

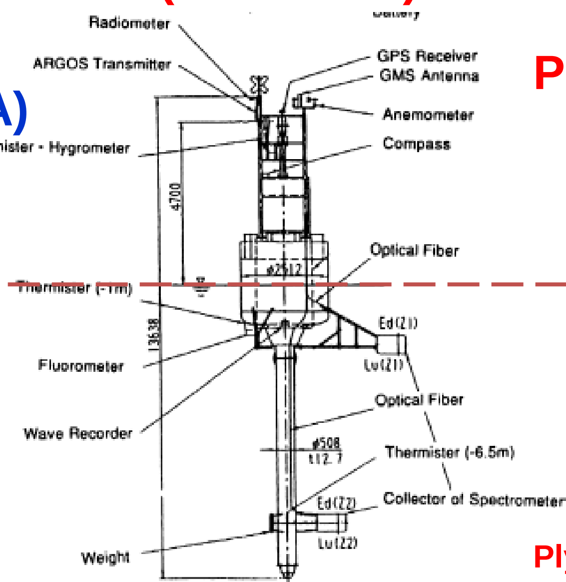
PlyMBODy (PML) (1997-1998)

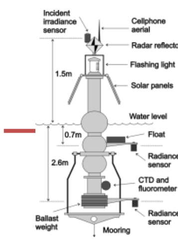
MOBY (NASA-NOAA) (1994-present)

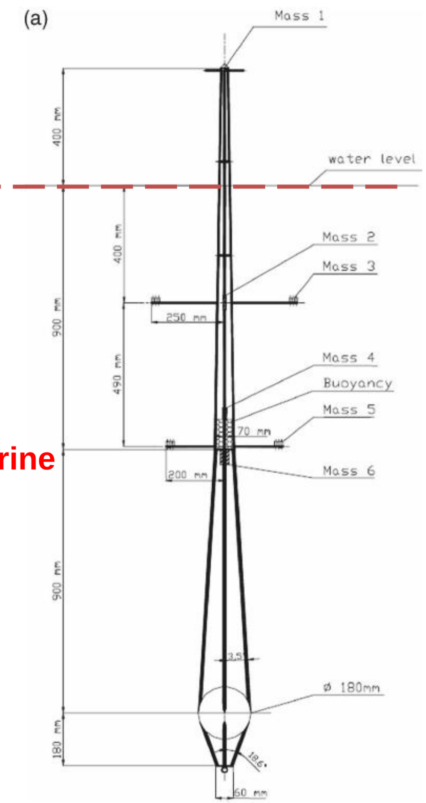
Air

Water









PlyMBODy: Plymouth Marine Bio-Optical Data Buoy

Site: English Channel

MOBY: Marine Bio-Optical Data Buoy

Site: Hawaiian Archipelago

YBOM: Yamato Bank Optical Mooring Buoy System

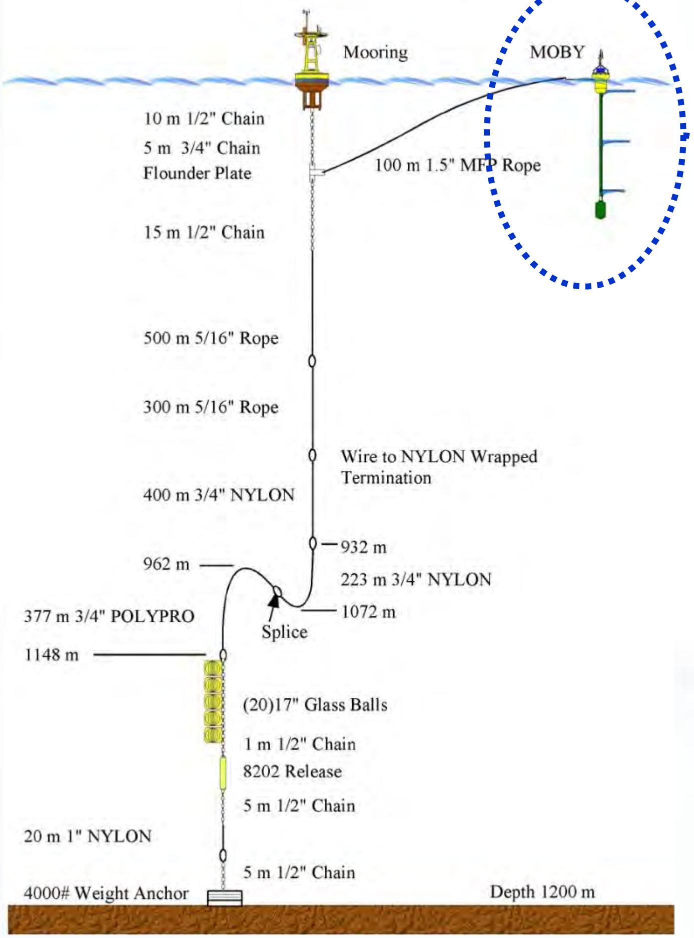
Site: Japan Sea

BOUSSOLE: Buoy for the Acquisition of a Long-Term Optical Time-Series

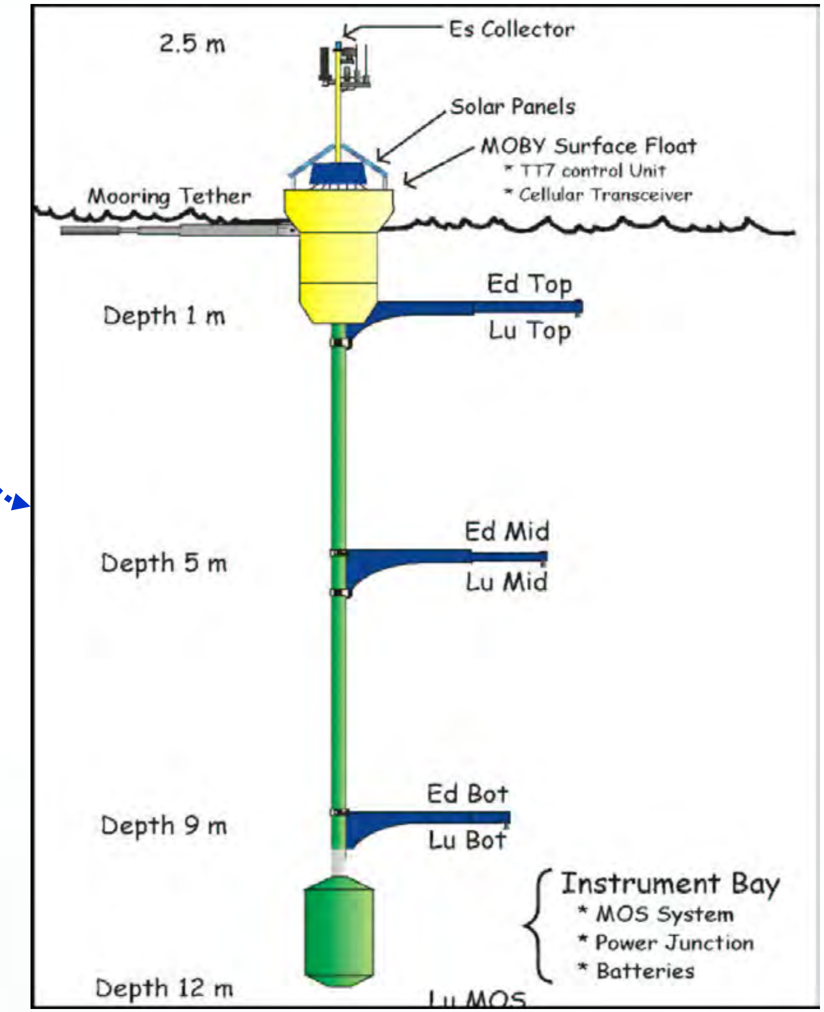
Site: Ligurian Sea

Joint Research Centre

MOBY: buoy



Lanai Mooring & MOBy



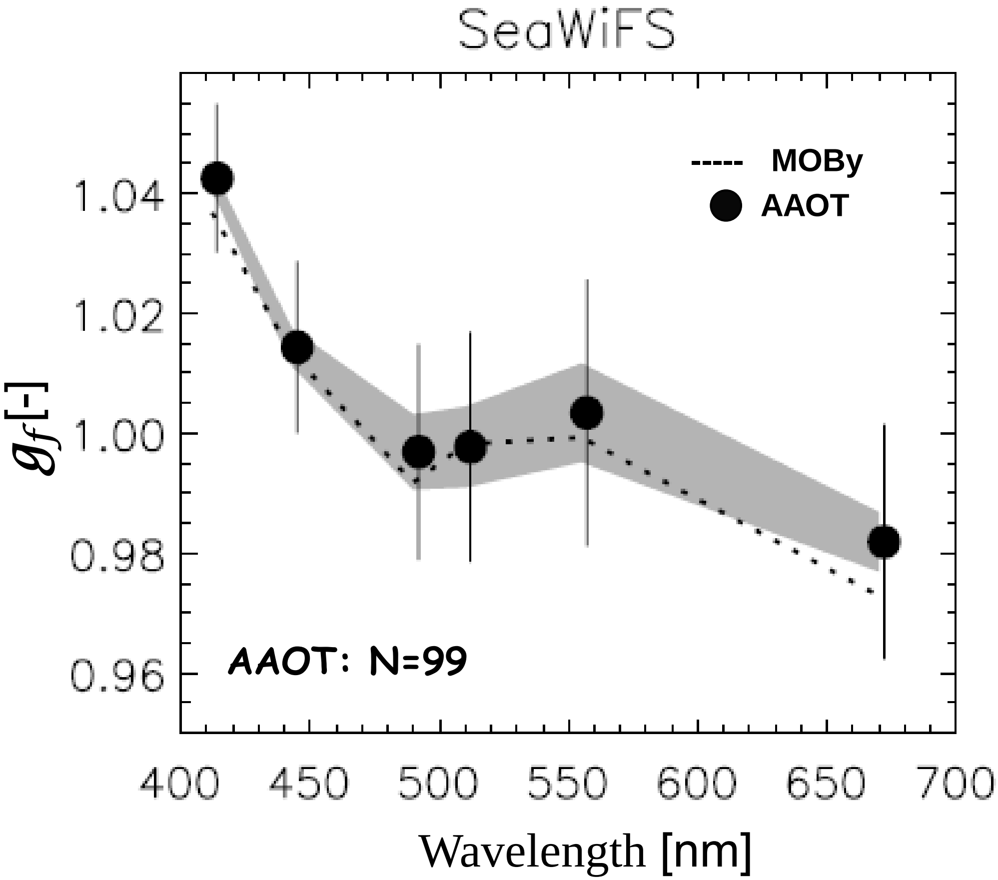
MOBY

Dera, J., W. Wensierski, and J. Olszewski (1972) A two-detector integrating system for optical measurements in the sea. Acta Geophys. Pol., 20, 3–159.

D. K. Clark, M. E. Feinholz, M.A.Yarbrough, B. C. Johnson, S. W. Brown, Y.S. Kim, and R. A. Barnes (2002). Overview of the radiometric calibration of MOBY. Earth Observing Systems VI, SPIE 4483, 64—76.

Joint Research Centre

Vicarious Calibration (SeaWiFS)



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

Principles

The correction factors g_f are determined by applying the methodology established by Bailey et al. 2008.

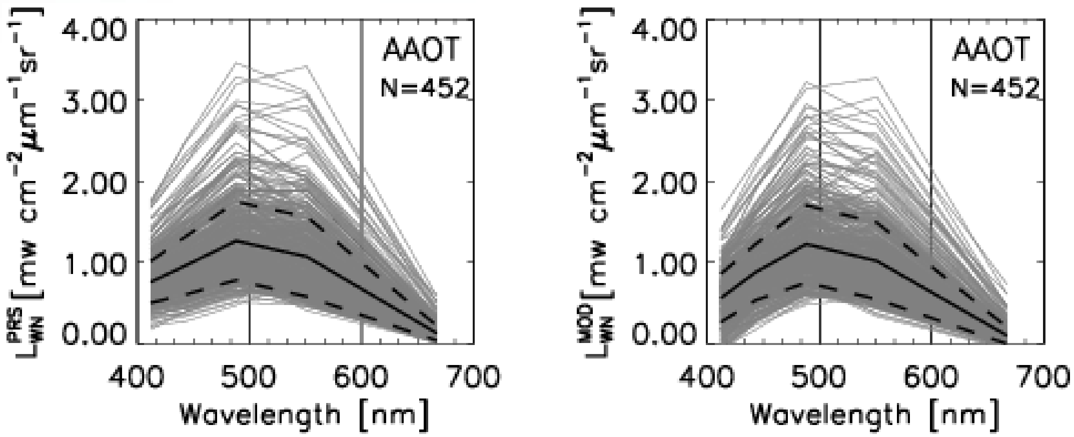
Bailey SW et al.. (2008). Sources and assumptions for the vicarious calibration …. *Appl Opt* 47:2035–2045.

F.Mélin and G.Zibordi (2010). Vicarious calibration of ocean color data using coastal sites. *Appl.Opt.,* 49:798-810.

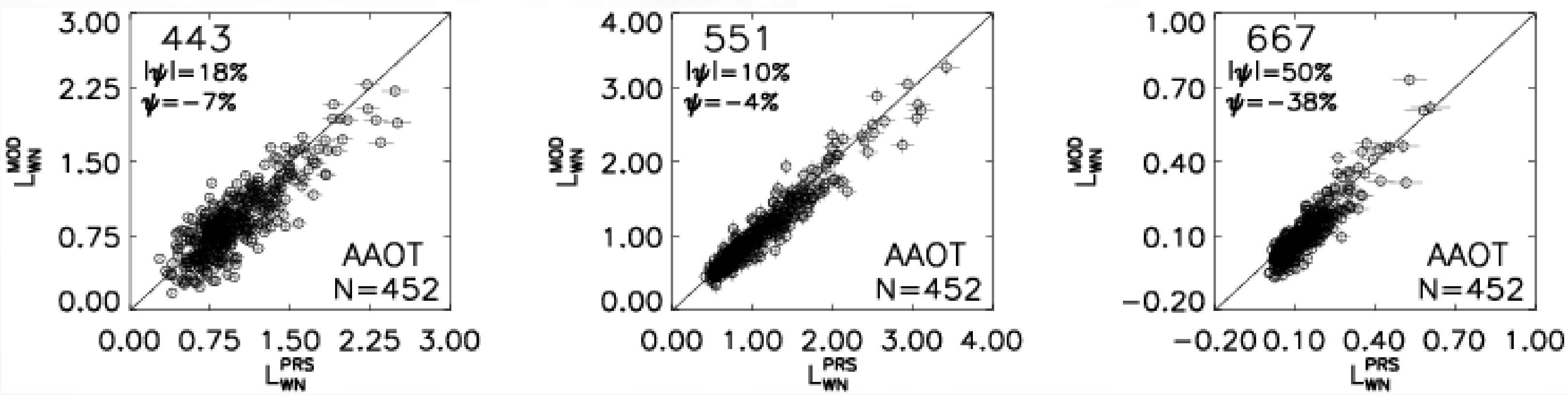
Joint Research Centre

Validation of radiometric products

Validation is the process of assessing by independent means, the quality of the data products derived from the system outputs (crudely, validation is an evaluation of the goodness of products different from verification that is an evaluation of the correctness of the process applied to generate products).



In situ **and satellite derived L_{WN} spectra**

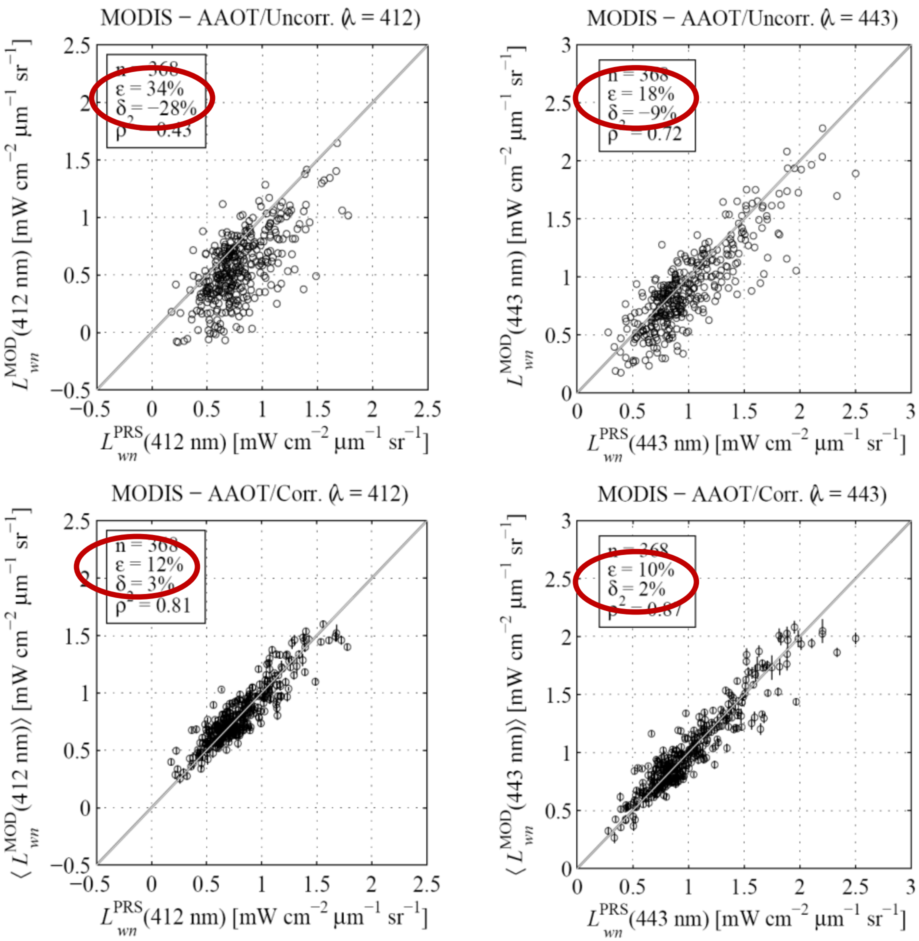


Satellite (MODIS) versus *in situ* (AERONET-OC) L_{WN} match-up analysis

G.Zibordi et al. (2009). Validation of satellite ocean color primary products. *Remote Sens. Env.*, 113, 2574-2591.

Joint Research Centre

Minimization of uncertainties in regional radiometric products



Match-ups with standard MODIS L_{WN}

Match-ups with corrected MODIS L_{WN}

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

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

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

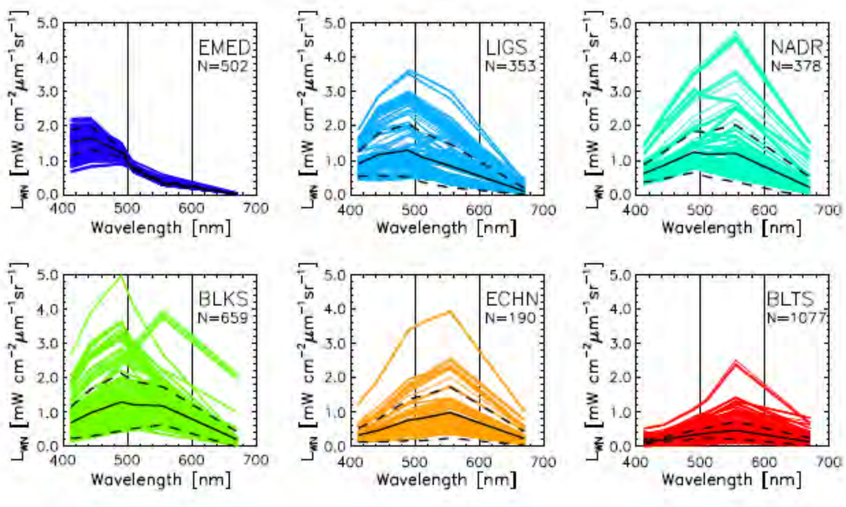
$$< \Delta L_{WN}^{MOD}(\lambda) >= a_0(\lambda) + \sum_{i=1}^{n} a_n(\lambda) X_n$$

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.

Mapping L_{WN}

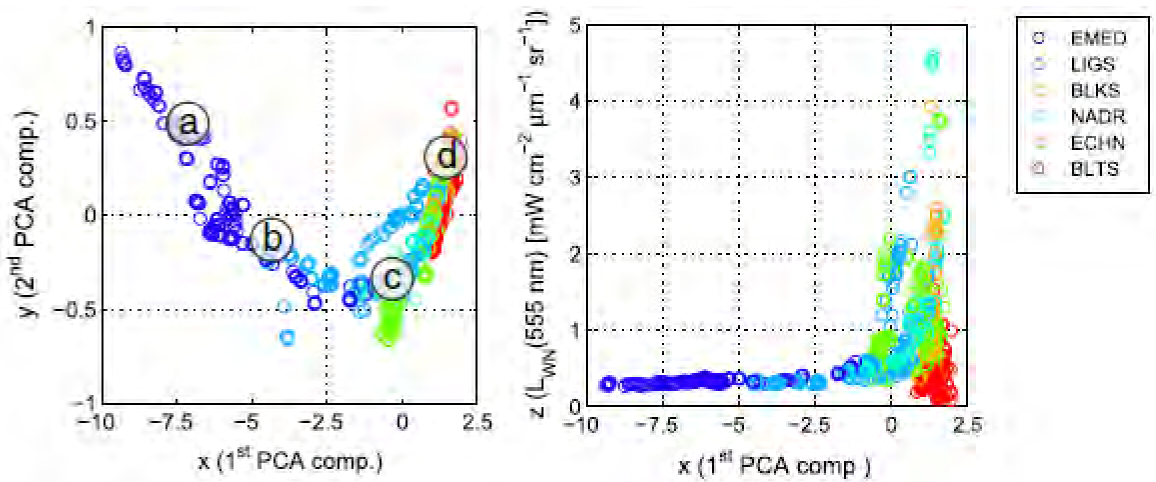


Spectra of L_{WN} from BiOMaP cruises

Feature maps of BiOMaP L_{WN} spectra from the first two components of PCA applied to $L_{WN}(\lambda)/L_{WN}(555)$

and

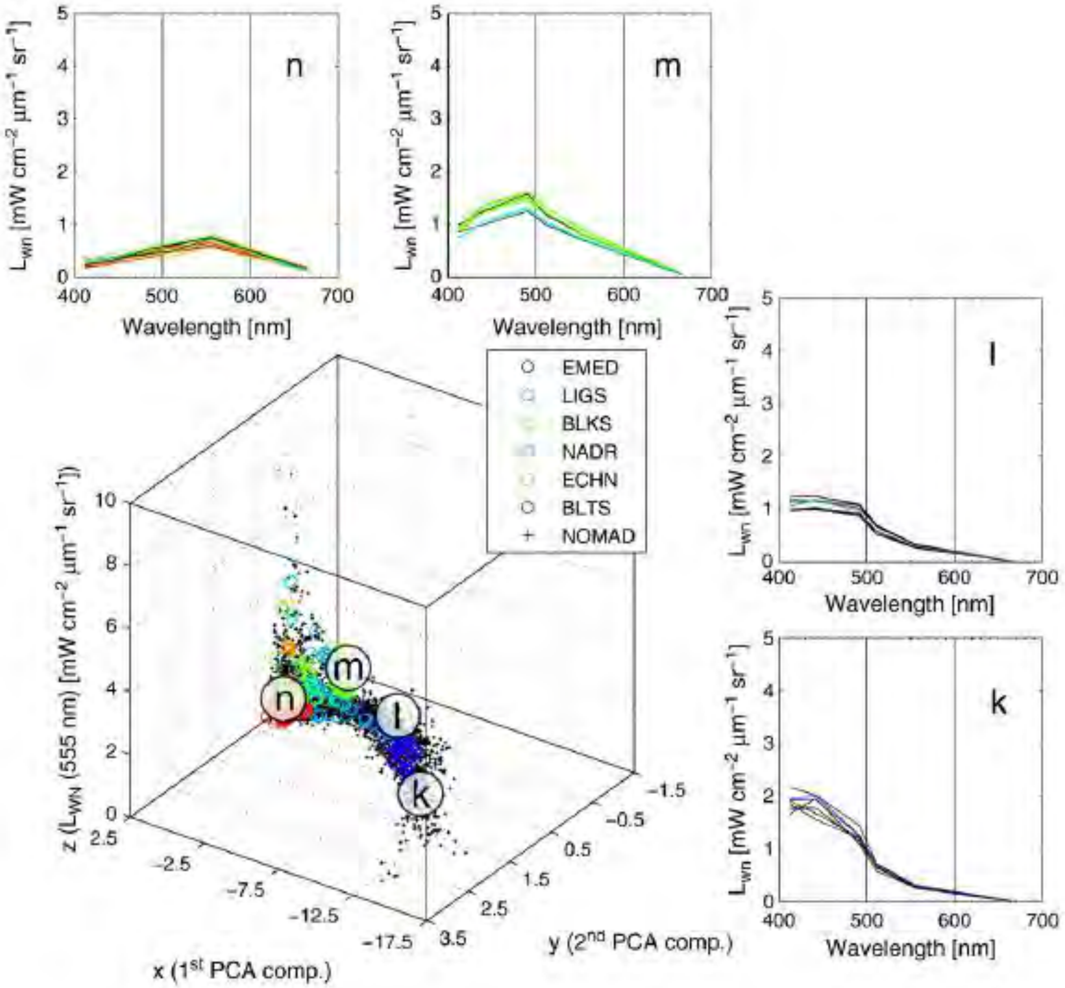
$L_{WN}(555)$ vs the first PCA component



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.

Joint Research Centre

De-Mapping L_{WN}

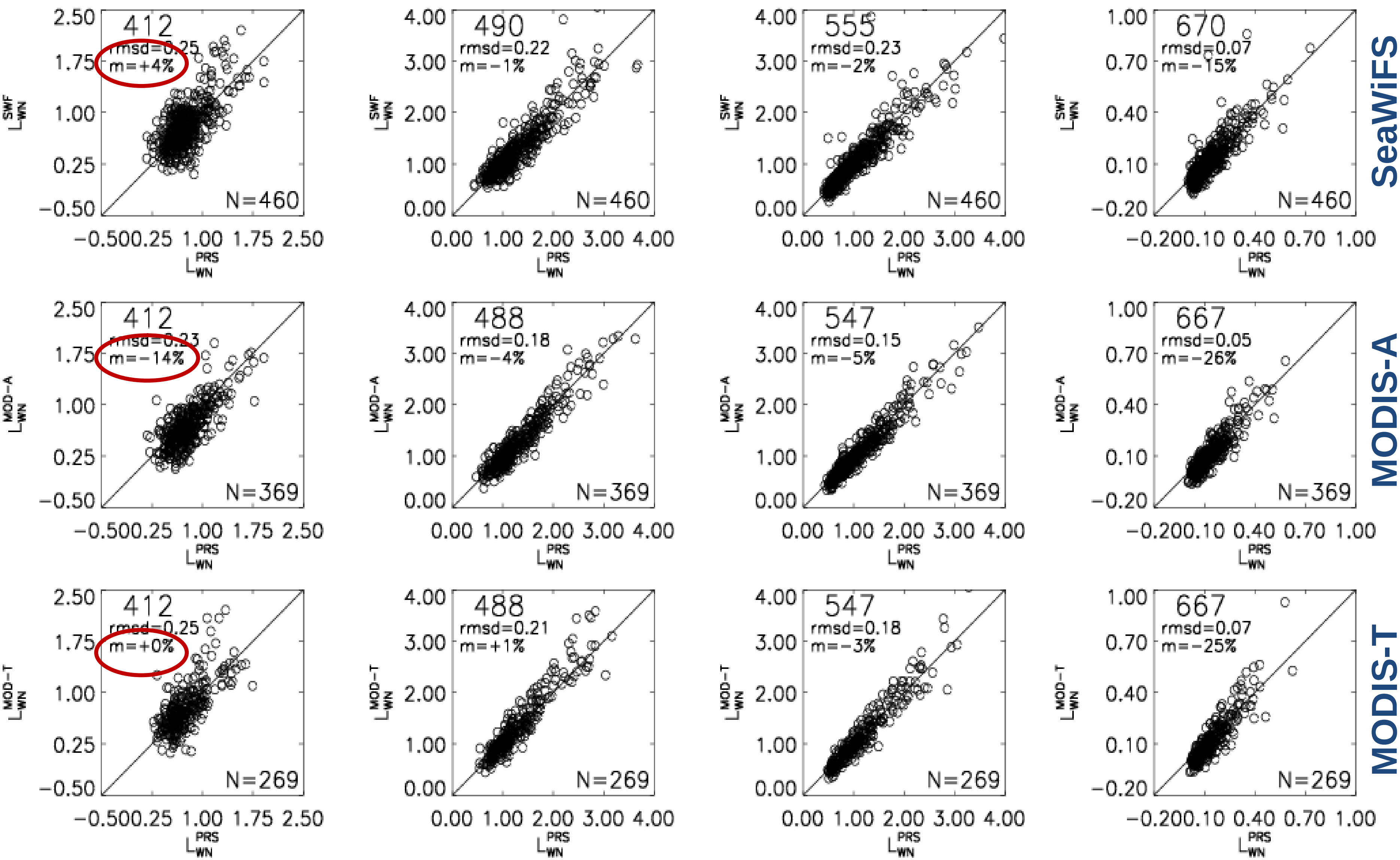


Three-dimensional representation of the BiOMaP L_{WN} features.
NOMAD (black points) data are added for comparison.

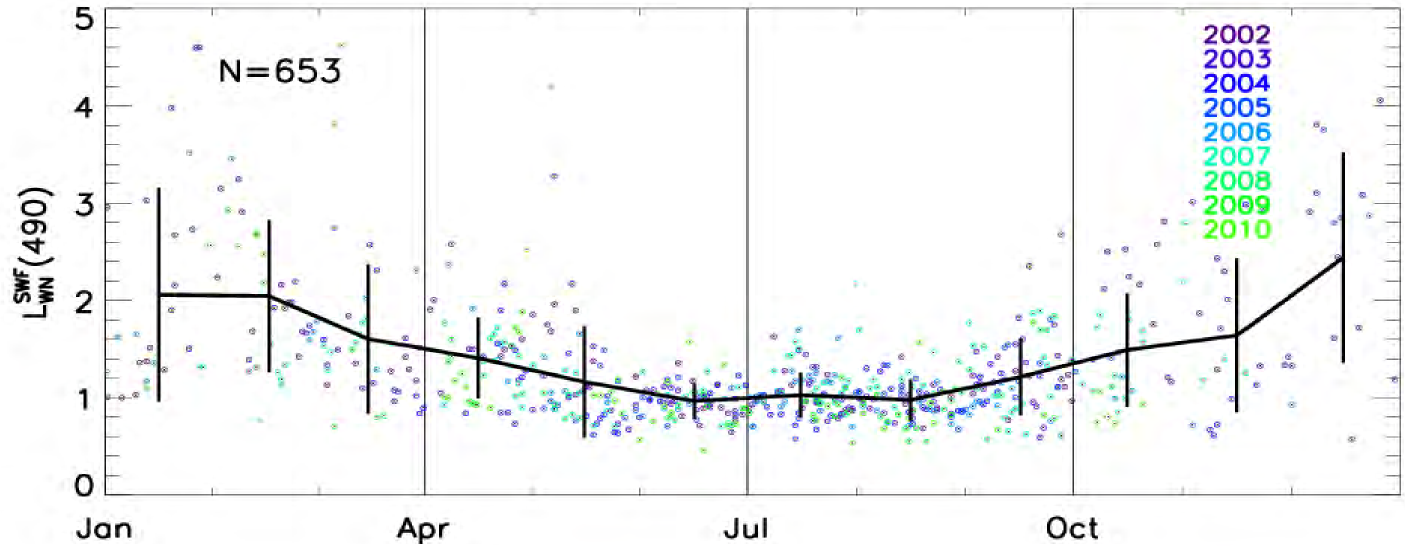
G. Zibordi, J.-F. Berthon, F. Mélin and D. D'Alimonte. Cross-site consistent in situ measurements for satellite ocean color applications: the BiOMaP radiometric dataset. *Remote Sensing of Environment*,115, 2104–2115, 2011.

Joint Research Centre

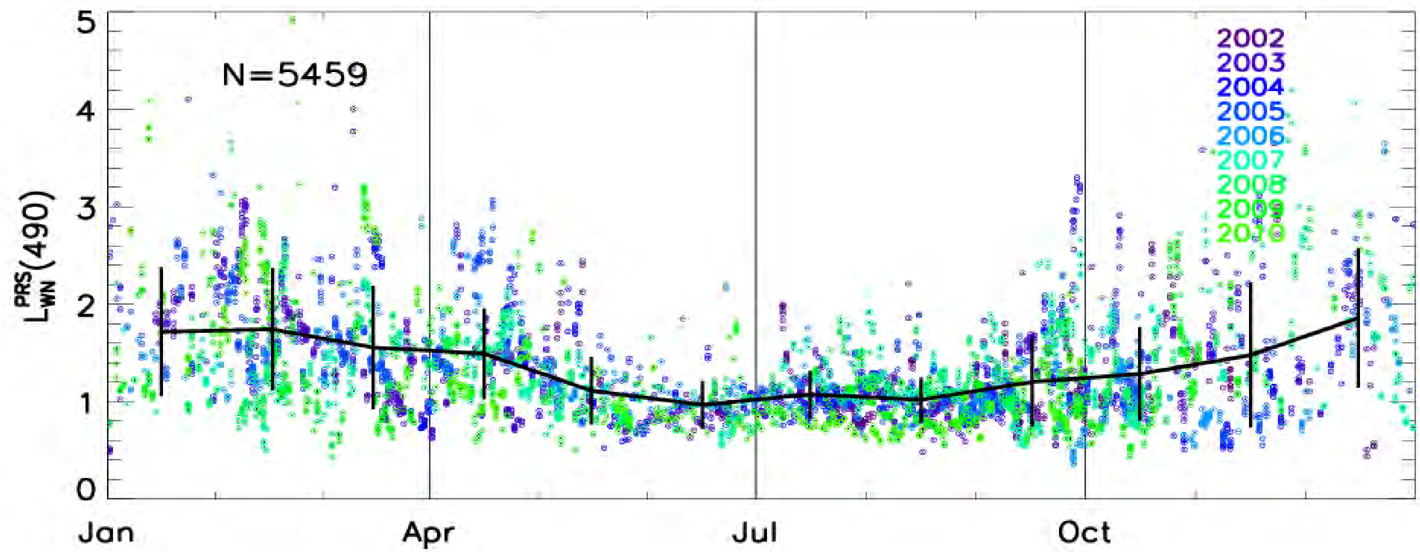
Cross-mission L_{WN} validation



Intra-annual climatology of L_{WN}



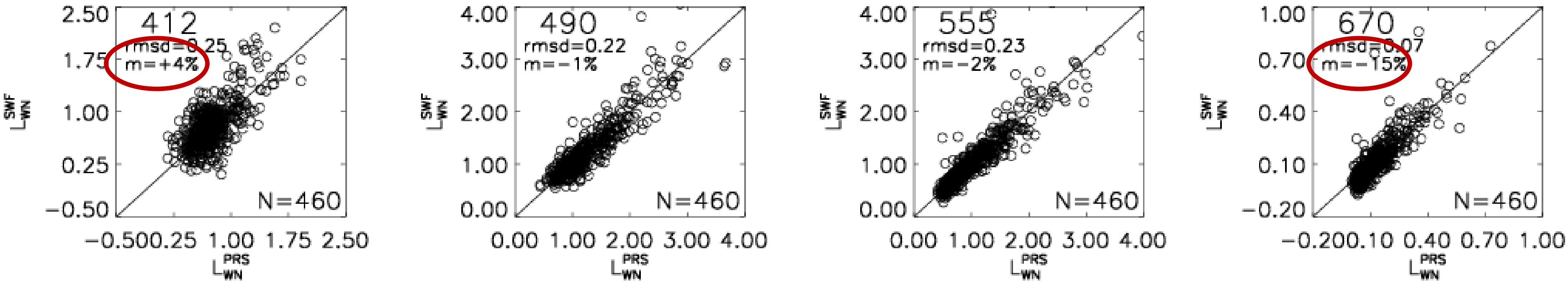
SeaWiFS SeaDAS (6.2)



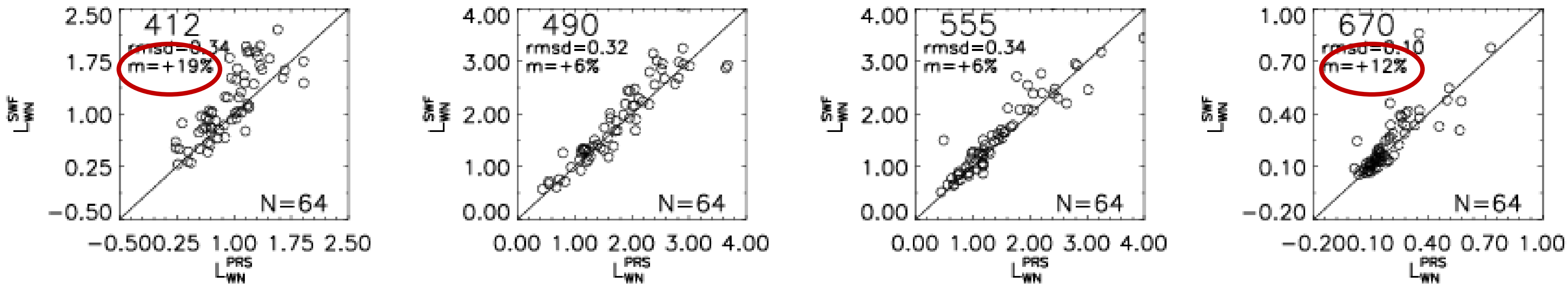
AERONET-OC

Intra-Annual Analysis

Overall Matchups (Jan-Dec)



Intra-Annual Matchups (Nov-Feb)



$$m = median\left[d_1,\ldots,d_i,\ldots,d_N\right] \quad d_i = 100\,\frac{\Re_i^C - \Re_i^R}{\Re_i^R}$$

and

$$rmsd = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\Re_i^C - \Re_i^R\right)^2}.$$

In the following analysis Δm and $\Delta rmsd$ will indicate the difference between intra-annual and annual values of m and $rmsd$.

Inter-annual variability (L_{WN})

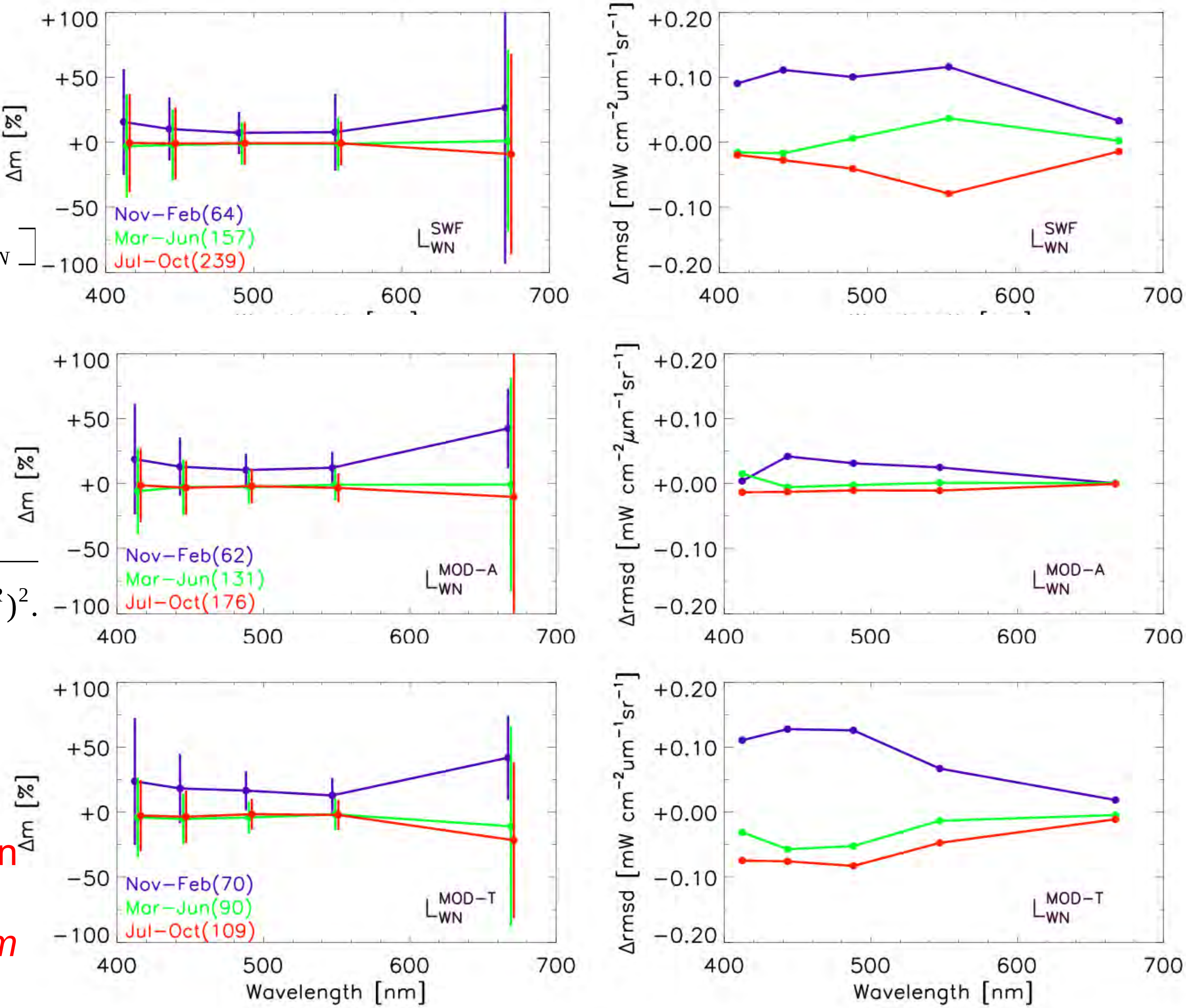
Joint Research Centre

$$m = median\left[d_1,\ldots,d_i,\ldots,d_N\right]$$

with

$$d_i = 100\,\frac{\Re_i^C - \Re_i^R}{\Re_i^R}$$

$$rmsd = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\Re_i^C - \Re_i^R)^2}.$$



Δ indicates the difference between intra-annual and annual values of *m* and *rmsd*.

Sun-zenith dependence (L_{WN})

Joint Research Centre

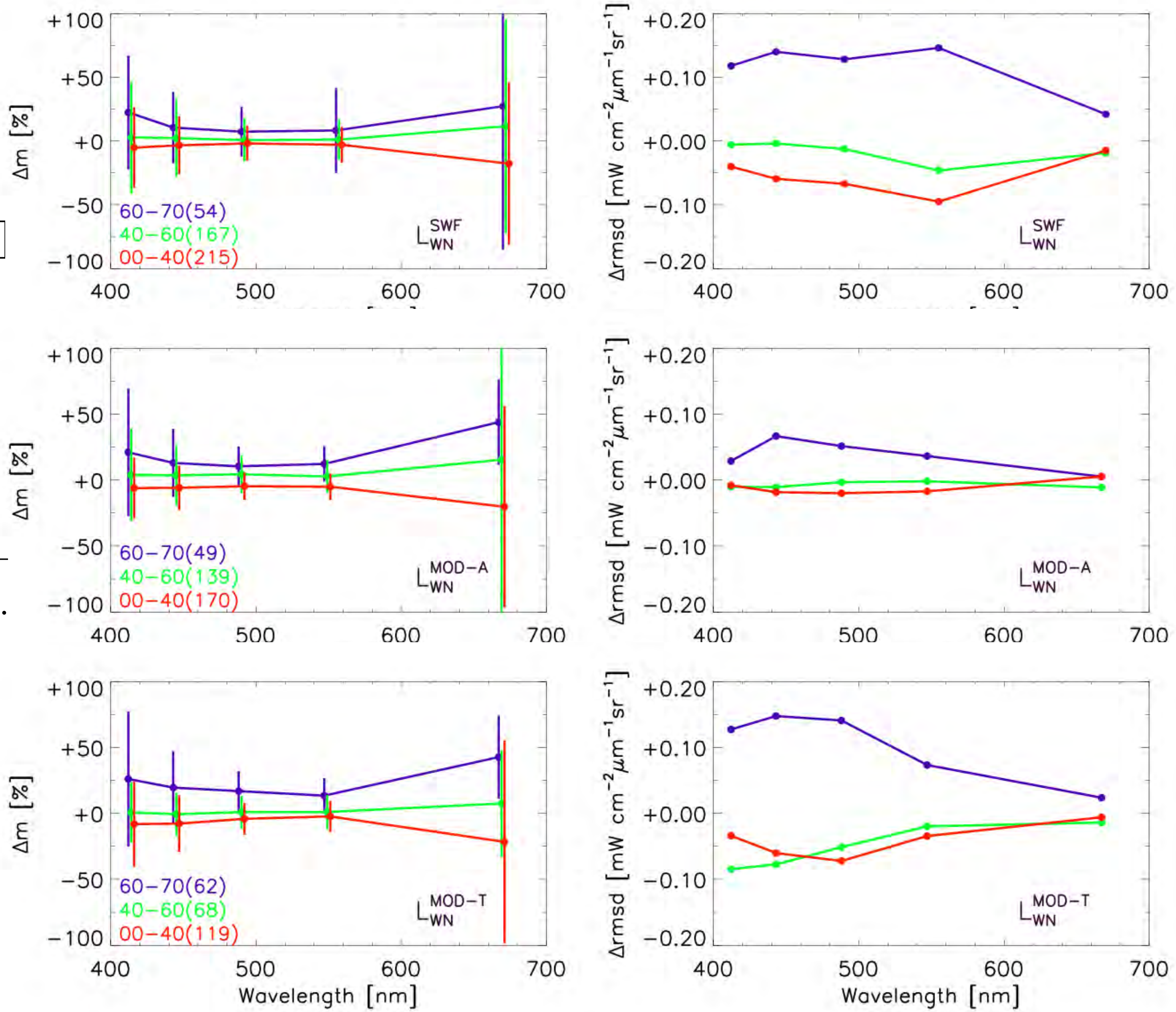
$$m = median\left[d_1,\ldots,d_i,\ldots,d_N\right]$$

with

$$d_i = 100\,\frac{\Re_i^C - \Re_i^R}{\Re_i^R}$$

$$rmsd = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\Re_i^C - \Re_i^R)^2}.$$

Δ indicates the difference between intra-annual and annual values of *m* and *rmsd*.



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;

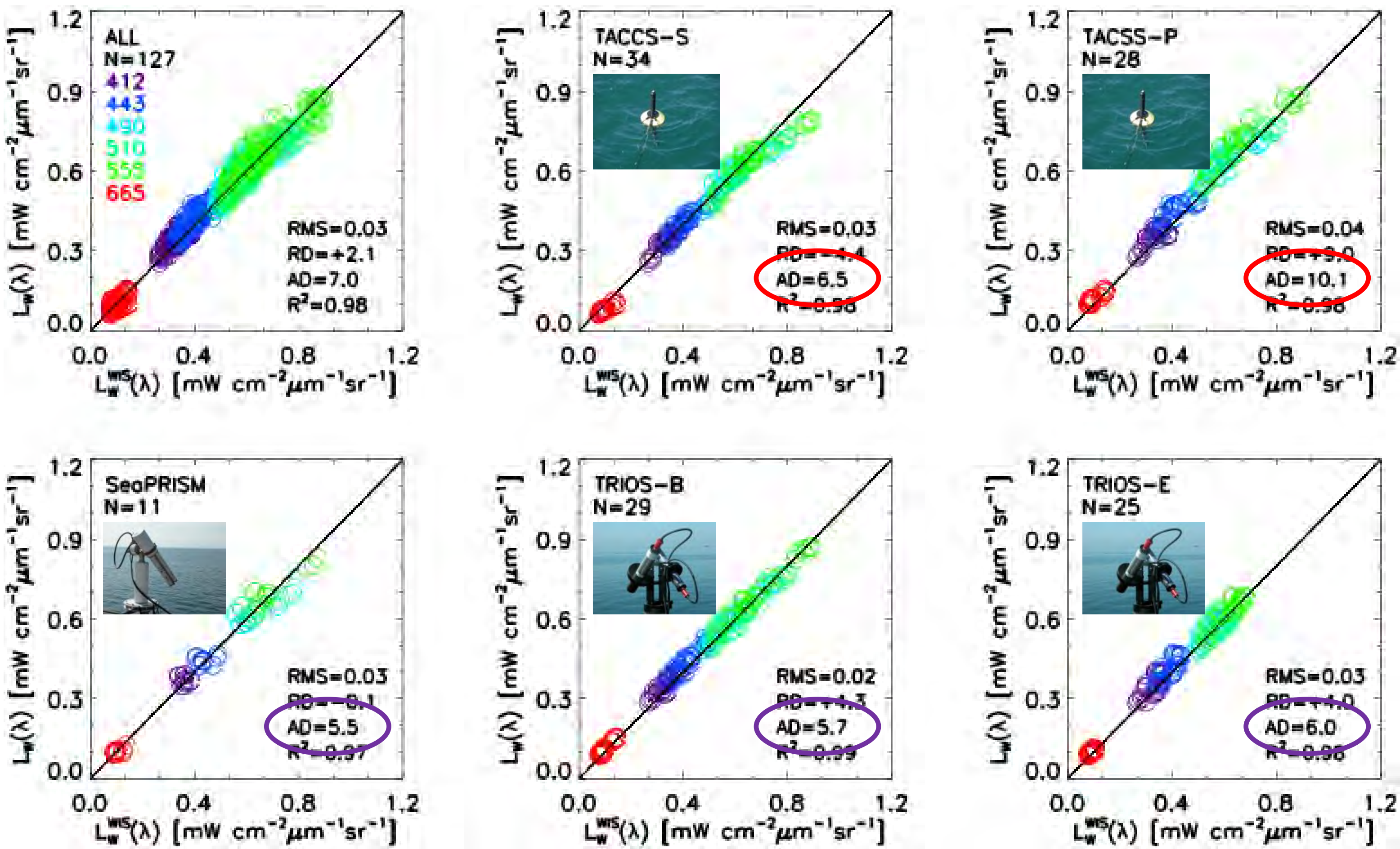
ii. standardizing measurements.

Back-up

Joint Research Centre

Inter-Comparison of *In Situ* Radiometric Methods

ARC inter-comparison (L_w)



$$RD = 100\frac{1}{N}\sum_{n=1}^{N}\frac{\Re^{C}(n)-\Re^{R}(n)}{\Re^{R}(n)}$$

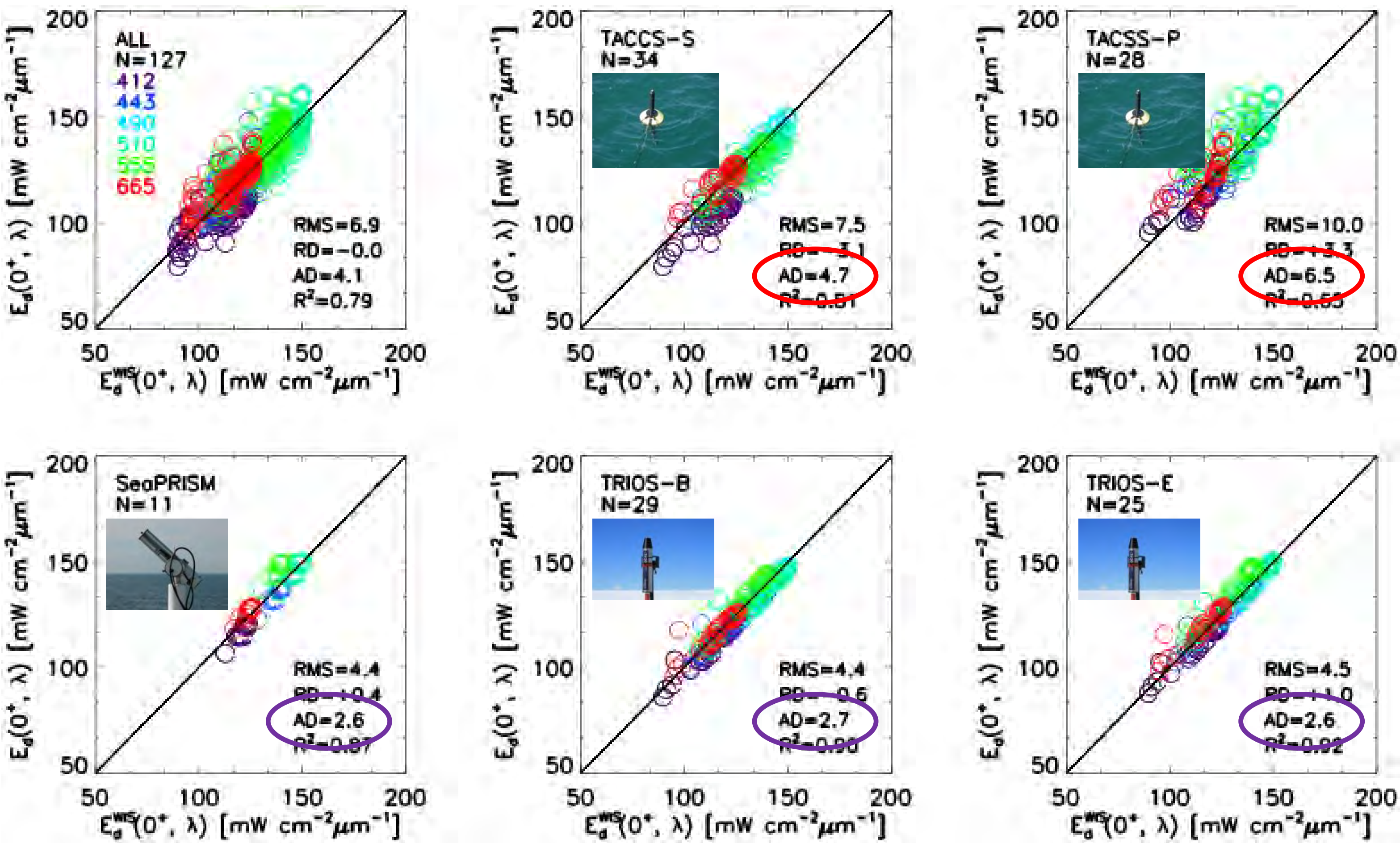
$$AD = 100\frac{1}{N}\sum_{n=1}^{N}\frac{\left|\Re^{C}(n)-\Re^{R}(n)\right|}{\Re^{R}(n)}$$

$$RMS = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(\Re^{C}(n)-\Re^{R}(n))^{2}}.$$

G.Zibordi et al. *In situ* determination of the remote sensing reflectance: an inter-comparison. *Ocean Science* D, 2012.

Joint Research Centre

ARC inter-comparison ($E_d(0^+)$)



$$RD = 100\frac{1}{N}\sum_{n=1}^{N}\frac{\Re^{C}(n)-\Re^{R}(n)}{\Re^{R}(n)}$$

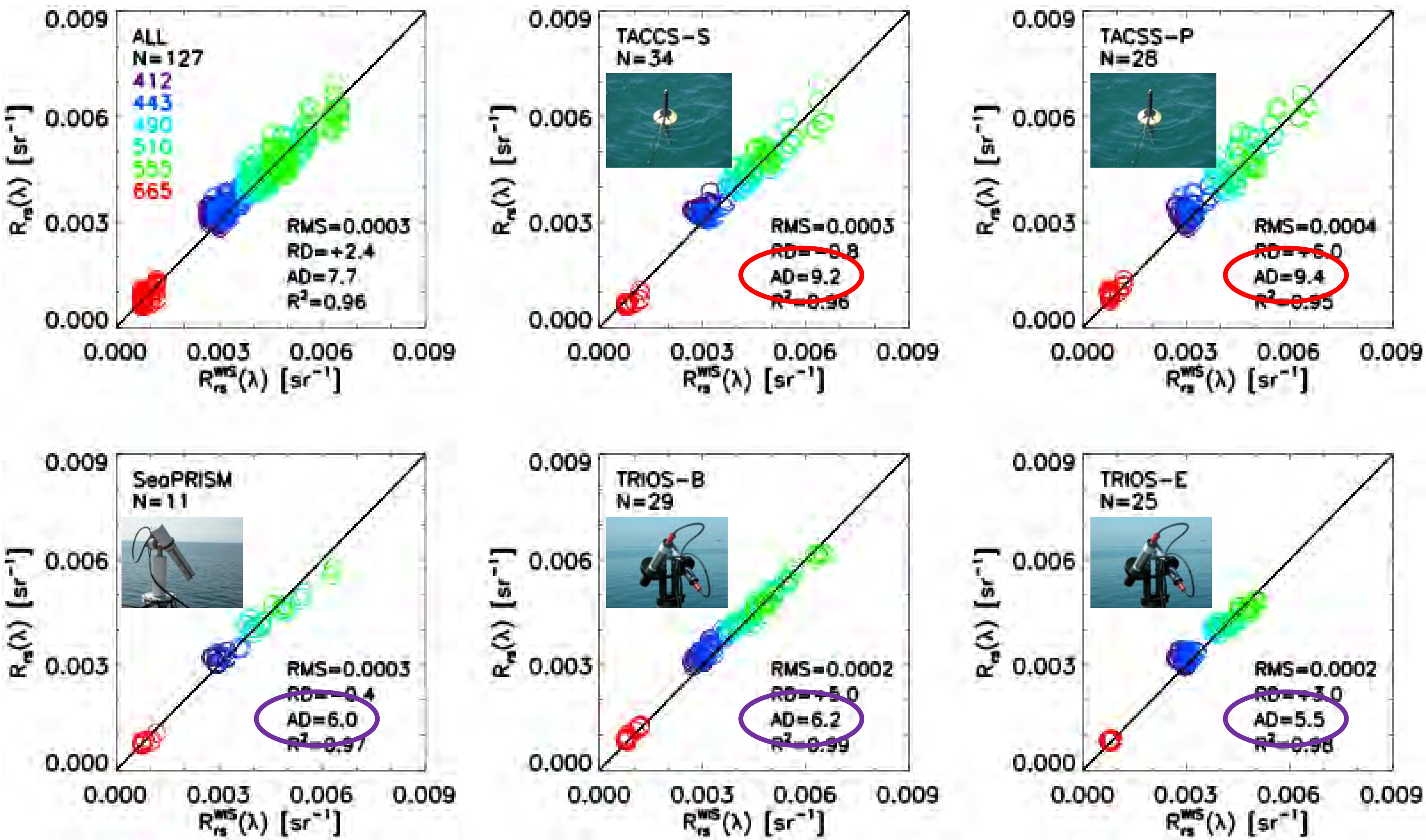
$$AD = 100\frac{1}{N}\sum_{n=1}^{N}\frac{\left|\Re^{C}(n)-\Re^{R}(n)\right|}{\Re^{R}(n)}$$

$$RMS = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(\Re^{C}(n)-\Re^{R}(n))^{2}}.$$

G.Zibordi et al. *In situ* determination of the remote sensing reflectance: an inter-comparison. *Ocean Science* D, 2012.

Joint Research Centre

ARC inter-comparison (R_{rs})



$$L_{wn}(\lambda) = R_{rs}(\lambda) E_0(\lambda)$$

G.Zibordi et al. *In situ* determination of the remote sensing reflectance: an inter-comparison. *Ocean Science* D, 2012.