Joint Research Centre

Water Quality Validation
7-9 June 2022, University of Wisconsin-Madison

Workshop on the Validation of Satellite-derived Optical and Water Quality Parameters for Coastal and Inland Waters

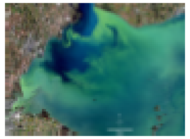
Field Measurements

Good (practically useful) data do not collect themselves. Neither do they magically appear on one's desk, ready for analysis and lending insight into how to improve processes (S.B. Vardemann and J.M. Jobe 2016)

A measurement of any kind is incomplete unless accompanied with an estimate of the uncertainty associated with that measurement. (J.M. Palmer and B.G. Grant 2009).

… adequately sampled, carefully calibrated, quality controlled, and archived data for key elements of the climate system will be useful indefinitely (Wunsch, R.W. Schmitt, and D.J. Baker 2013)

Prepared by G. Zibordi (2022)



Workshop on the Validation of Satellite-derived Optical and Water Quality Parameters for Coastal and Inland Waters

Validation and uncertainty assessment are crucial to the successful acceptance of satellite-derived data products. Only through confidence in parameter uncertainty will there be increased uptake of these data products by the end-user community. This workshop will focus on the validation of water quality products derived from satellite ocean color sensors within optically complex nearshore-coastal and inland waters with the goal of constructing a global validation network. The workshop will summarize and evaluate the state of current validation assets globally, identify gaps in validation coverage and begin to design a framework to construct a global validation network for these critical waters. Workshop objectives include:

- Review and evaluation of current and planned validation-related activities.
- Identifying validation gaps in spatial coverage as well as water types.
- Review and evaluation of current *in situ* and laboratory optical measurements and data acquisition protocols including instrument characterization and absolute radiometric calibration.
- Review and evaluation of satellite measurements in terms of representativeness for coastal and inland systems (e.g. pixel window, match up timing).
- Assessing current optical and water quality database resources including repository archive, preservation, stewardship, and access.
- Building global coordination through international partnerships for validation activities.

The workshop will cover a number of aspects related to validation including standardization of protocols, instrumentation needs, current validation research and operational efforts, validation metrics, interoperability, and documenting and formatting validation data.

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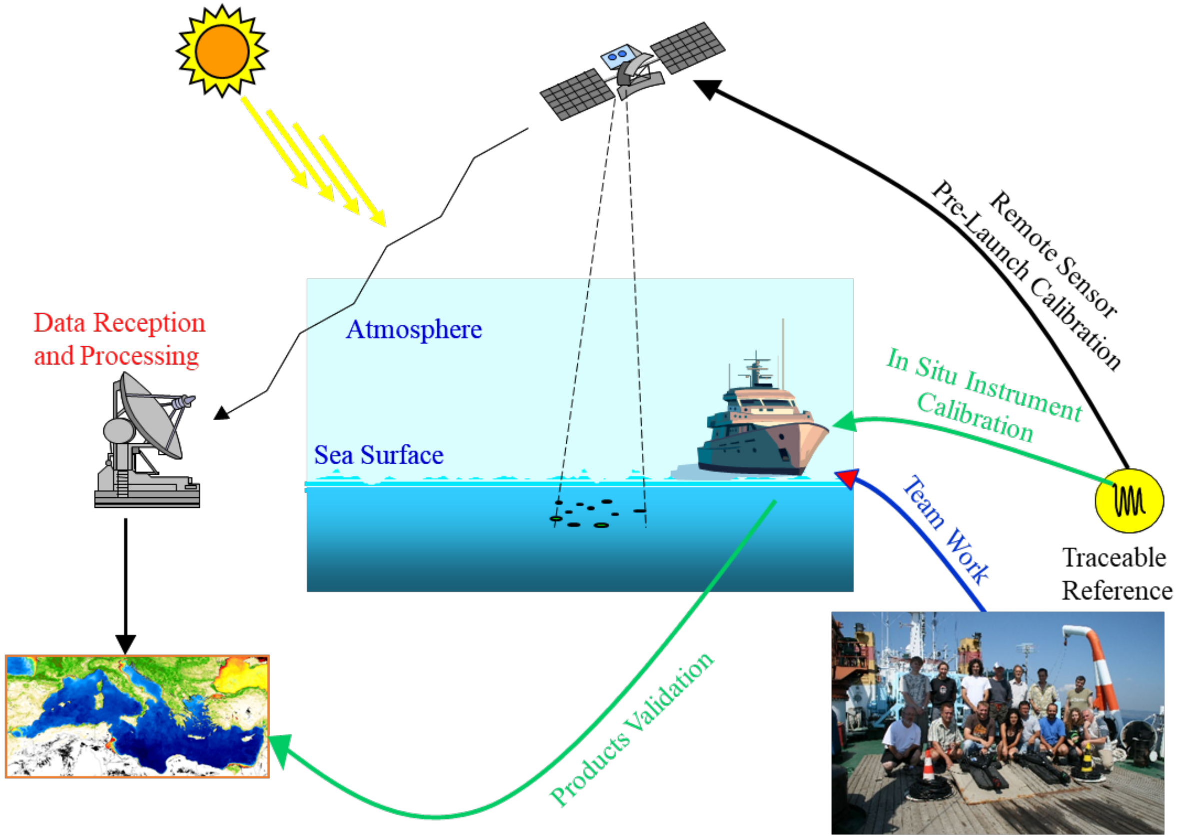
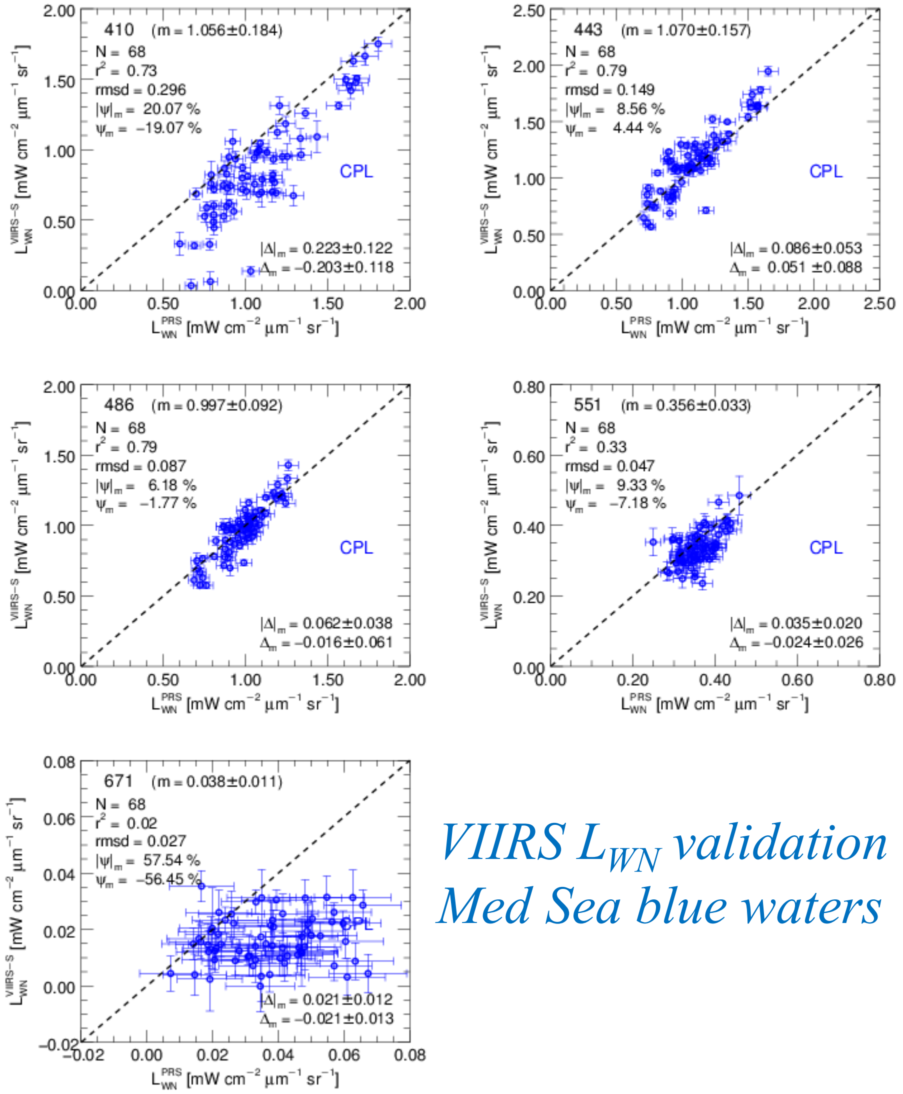
Validation of satellite data products

Validation is the process of assessing, by independent means, the quality of the data products derived from the system outputs





VIIRS L_{WN} validation in Med Sea blue waters

Field Measurements: topics and objectives

- Priority optical, biogeochemical & ancillary quantities
  - Instrumentation
  - Radiometry protocols
  - Calibration (implying traceability) & characterization
  - Quality assurance & quality control
  - Uncertainties

Considering current technology and know-how, would it be possible to recommend (or enforce) best-practices for in situ measurements supporting the validation of satellite derived data products for inland and coastal waters?

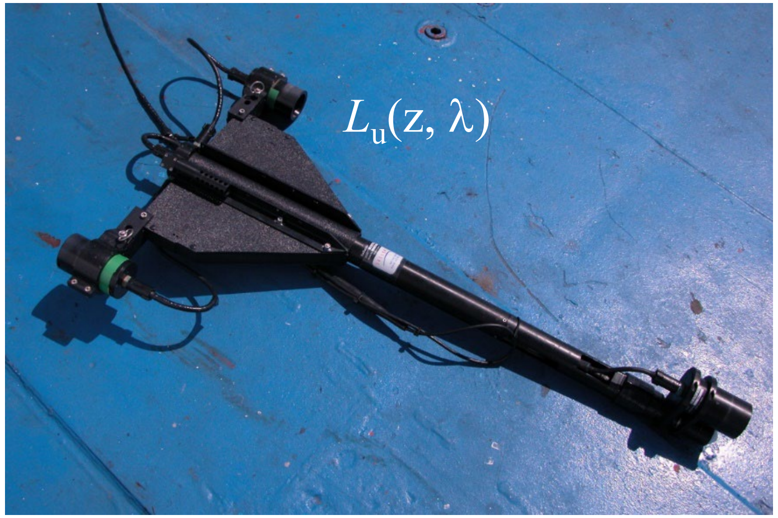
Priority optical, biogeochemical & ancillary quantities

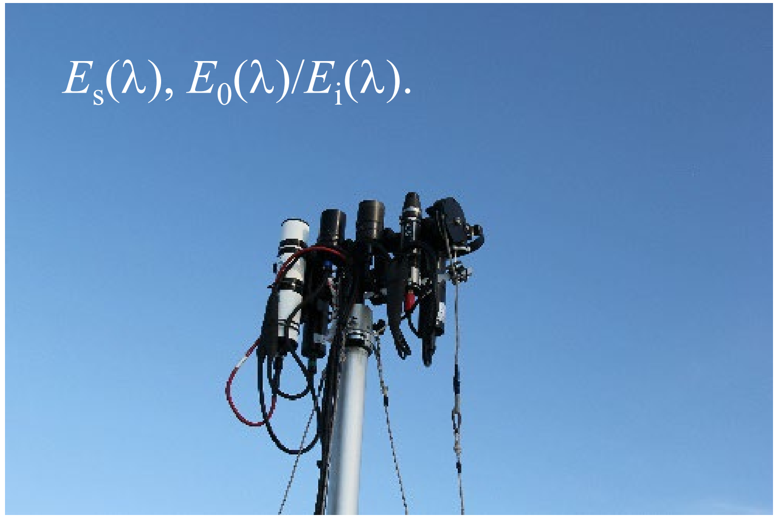
Field-Radiometric: $L_{WN}(\lambda)$ or $R_{RS}(\lambda)$, which implies determining/ measuring $L_w(\lambda)$, or alternatively $L_u(\lambda)$, or $L_u(z, \lambda)$, and additionally $E_s(\lambda)$, $E_0(\lambda)/E_i(\lambda)$).

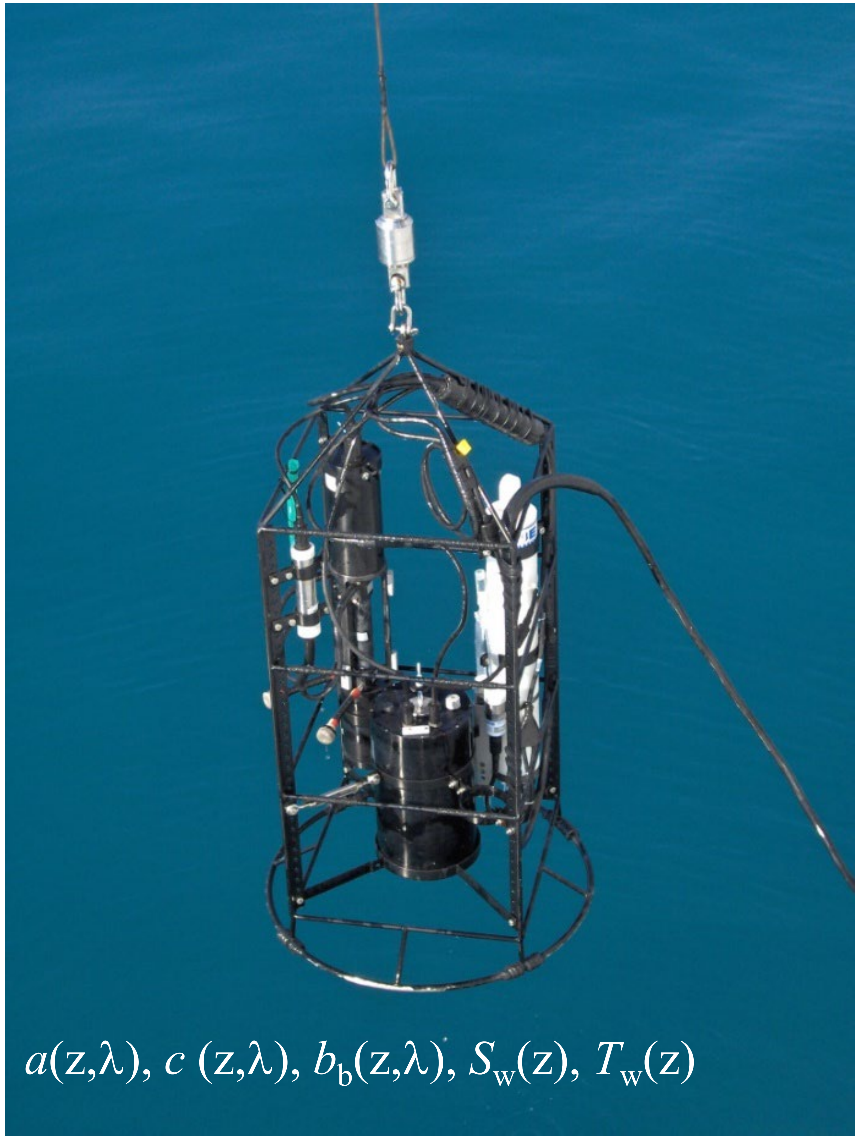
Field-IOPs: $a(\lambda)$, $b_b(\lambda)$ but also $c(\lambda)$, S_w ,T_w

Field-Ancillary: *Date, T(GMT), Lon, Lat, Altitude, Depth &* $W_s, W_H, T_a, P_a, C_c, \tau_a$

Priority Quantities more related to water quality such as pigments, particulate organic carbon, colored dissolved organic matter, …) will be addressed in the Session on Laboratory Measurements

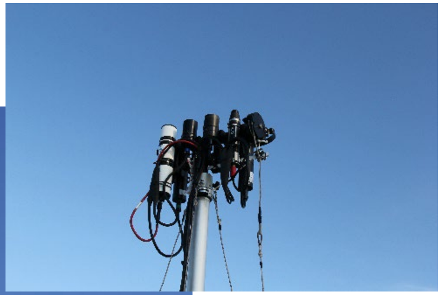


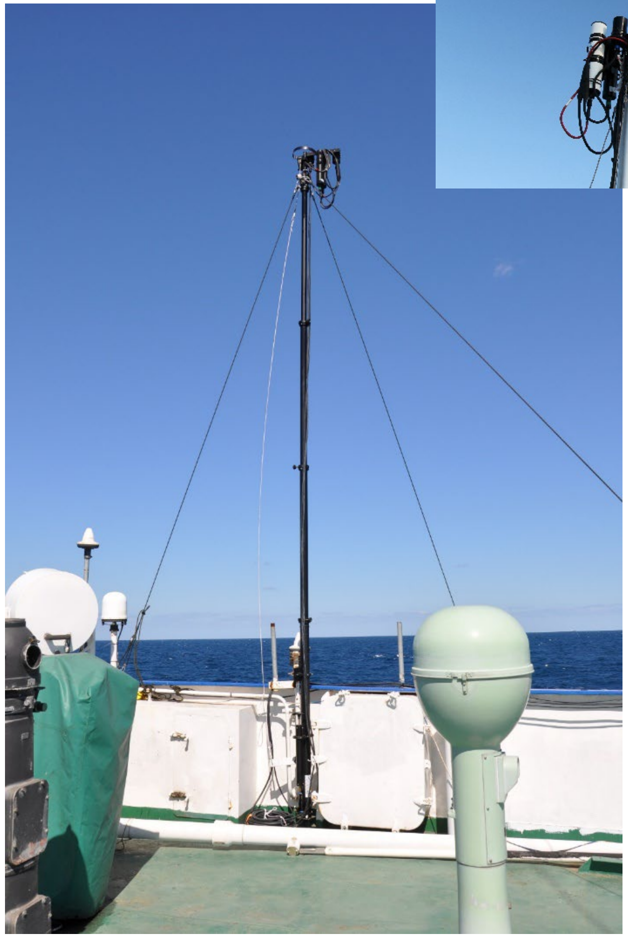


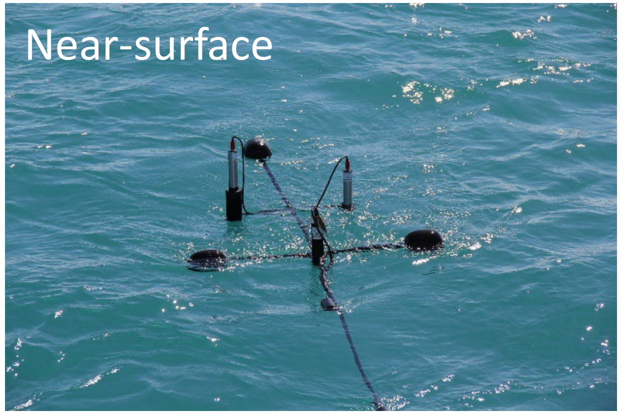


Instruments & Protocols (restricted to radiometry)

While keeping $L_{WN}(\lambda)$ or $R_{RS}(\lambda)$ as target quantities to be determined, various in-water, above-water and near-surface instruments and protocols are available







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Radiometers

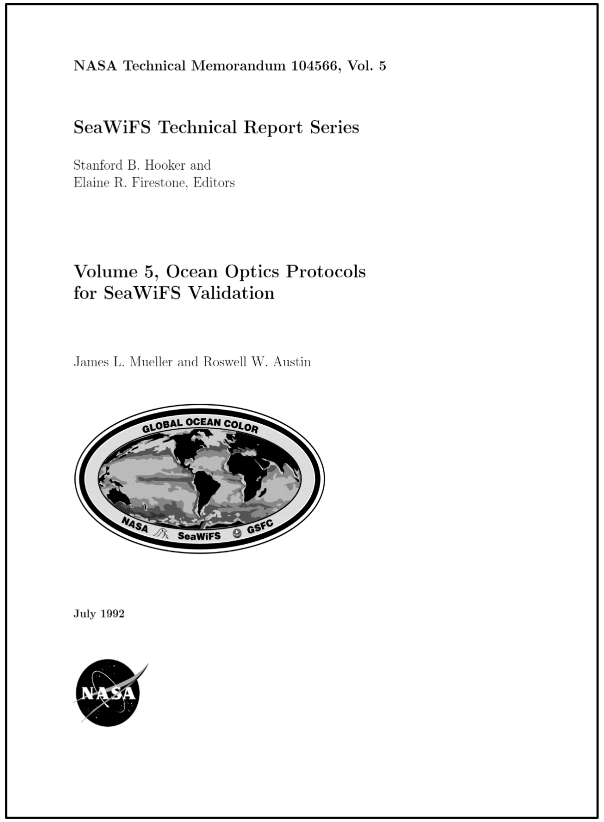
Hyperspectral radiometers have a high number of narrow spectral bands typically less than 10 nm wide distributed continuously through the spectrum. For these radiometers it is important to distinguish between the spectral resolution determined by the band-width, and the spectral sampling interval determined by the distance between center-wavelengths of adjacent bands (generally the spectral resolution is 2-3 times higher than the spectral sampling interval).
Stray lights due to scattering and reflections in the optical system, and also polarization sensitivity due to dispersive elements (i.e., diffraction grating or prism), must be determined.

Multi spectral radiometers measure the light field at a number of discrete spectral bands typically 10 nm wide.
The spectral responsivity of multispectral radiometers must be carefully characterized to identify possible spectral regions of response away from the central band (out-of-band response).

Recommended specifications for hyperspectral radiometers applied for validation activities.

Optical Sensors	
Spectral Range:	380 to 900 nm (an extension in the ultraviolet is desirable)
Spectral Resolution:	3-10 nm (FWHM)
Spectral Sampling:	1-3 nm (or at least 2 times the spectral resolution)
Wavelength Accuracy:	10 % FWHM resolution
Wavelength Stability:	5 % FWHM of resolution
Signal-to-Noise Ratio:	1000:1 (at minimum)
Stray Light Rejection:	10^{-5} (of the maximum radiometric signal at each spectral band)
FOV Maximum (full-angle):	5°, 20° (for above-water and in-water, respectively)
Temperature Stability:	Specified for 0–45°C
Linearity:	Correctable to 0.1 %

Radiometry Protocols



NASA Technical Memorandum 104566, Vol. 5

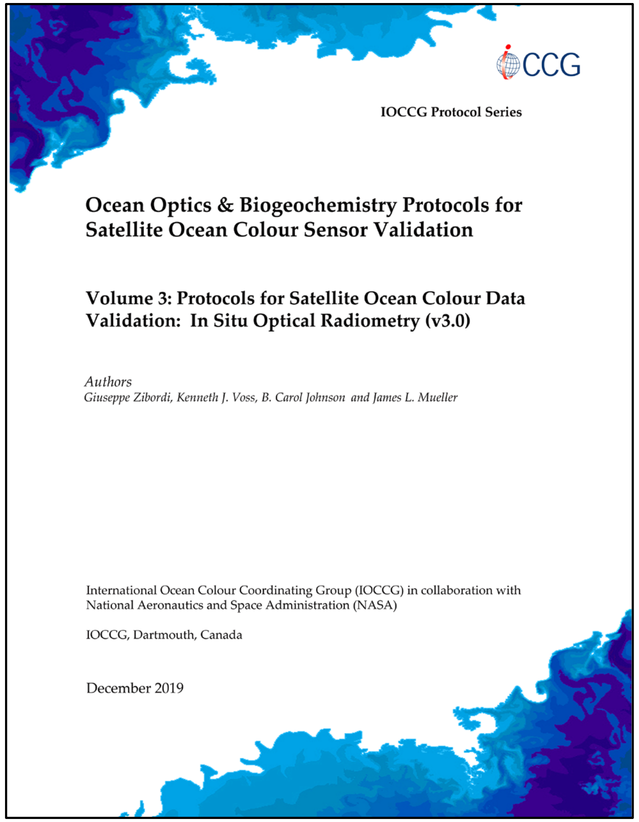
SeaWiFS Technical Report Series

Stanford B. Hooker and
Elaine R. Firestone, Editors

Volume 5, Ocean Optics Protocols
for SeaWiFS Validation

James L. Mueller and Roswell W. Austin

July 1992



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

A protocol is a set of rules. Protocols leave room for personal decisions, contrary to methods which enforce prescriptive rules commonly tied to classes of instruments.
Standardization implies the application of very prescriptive rules (often difficult to implement across a community).

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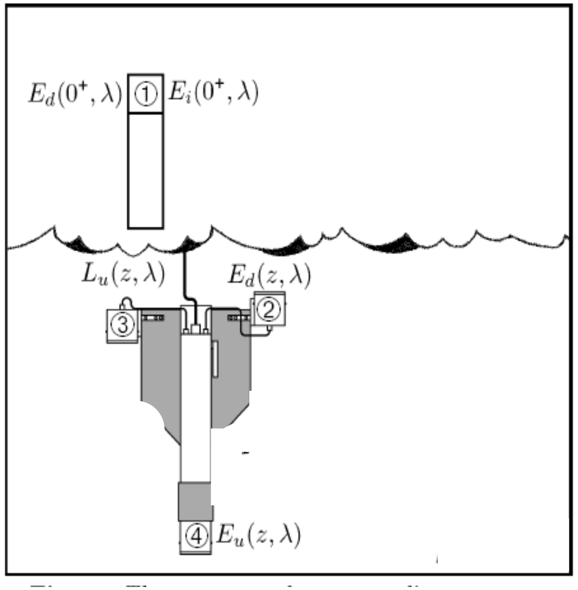
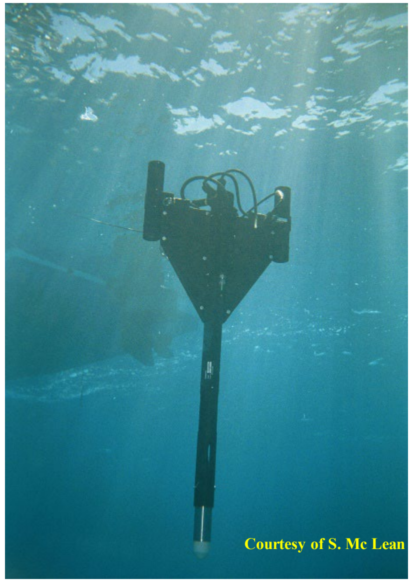
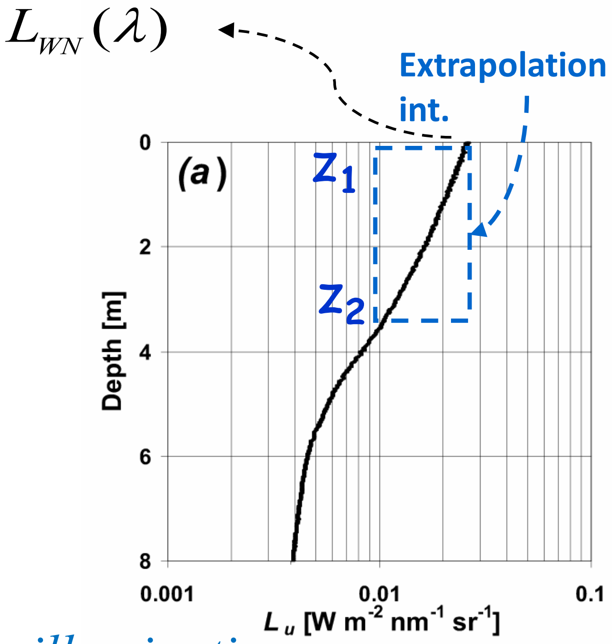
In-Water Radiometry







It is essential that the number of points per unit depth minimizes the impact of wave perturbations

Normalization to account for fluctuations in illumination

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

Extrapolation just below the surface

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

Propagation through the surface

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

Transformation to exact normalized water-leaving radiance

$$L_{WN}(\lambda) = L_W(\lambda) \frac{E_0(\lambda)}{E_d(0^+,\lambda)} C_{f/Q}(\lambda,\theta_0,\tau,IOP) S_s(\theta_0,r,IOP)$$

IOCCG Protocol Series (2019). Protocols for Satellite Ocean Colour Data Validation: In Situ Optical Radiometry. Zibordi, G., Voss, K. J., Johnson, B. C. and Mueller, J. L. IOCCG Ocean Optics and Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation, Volume 3.0, IOCCG, Dartmouth, NS, Canada.

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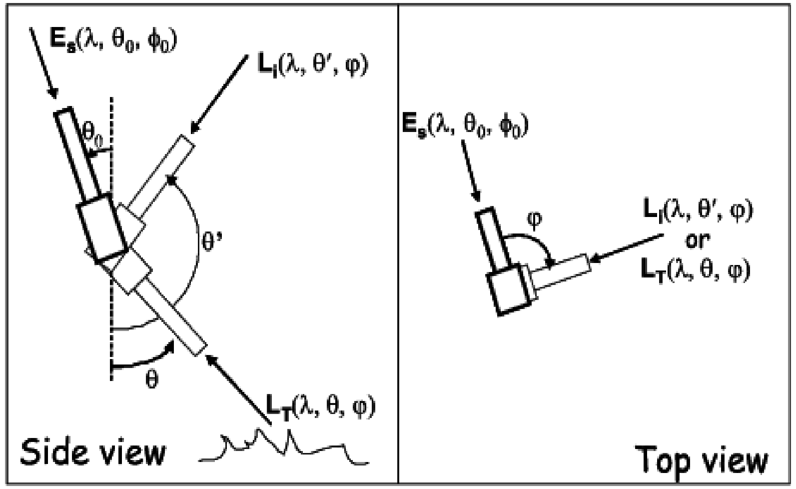
Above-Water Radiometry



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

Sky-radiance: L_i

Sea-radiance: L_T

Removal of sky-glint 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

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

Transformation to exact normalized water-leaving radiance

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

IOCCG Protocol Series (2019). Protocols for Satellite Ocean Colour Data Validation: In Situ Optical Radiometry. Zibordi, G., Voss, K. J., Johnson, B. C. and Mueller, J. L. IOCCG Ocean Optics and Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation, Volume 3.0, IOCCG, Dartmouth, NS, Canada.

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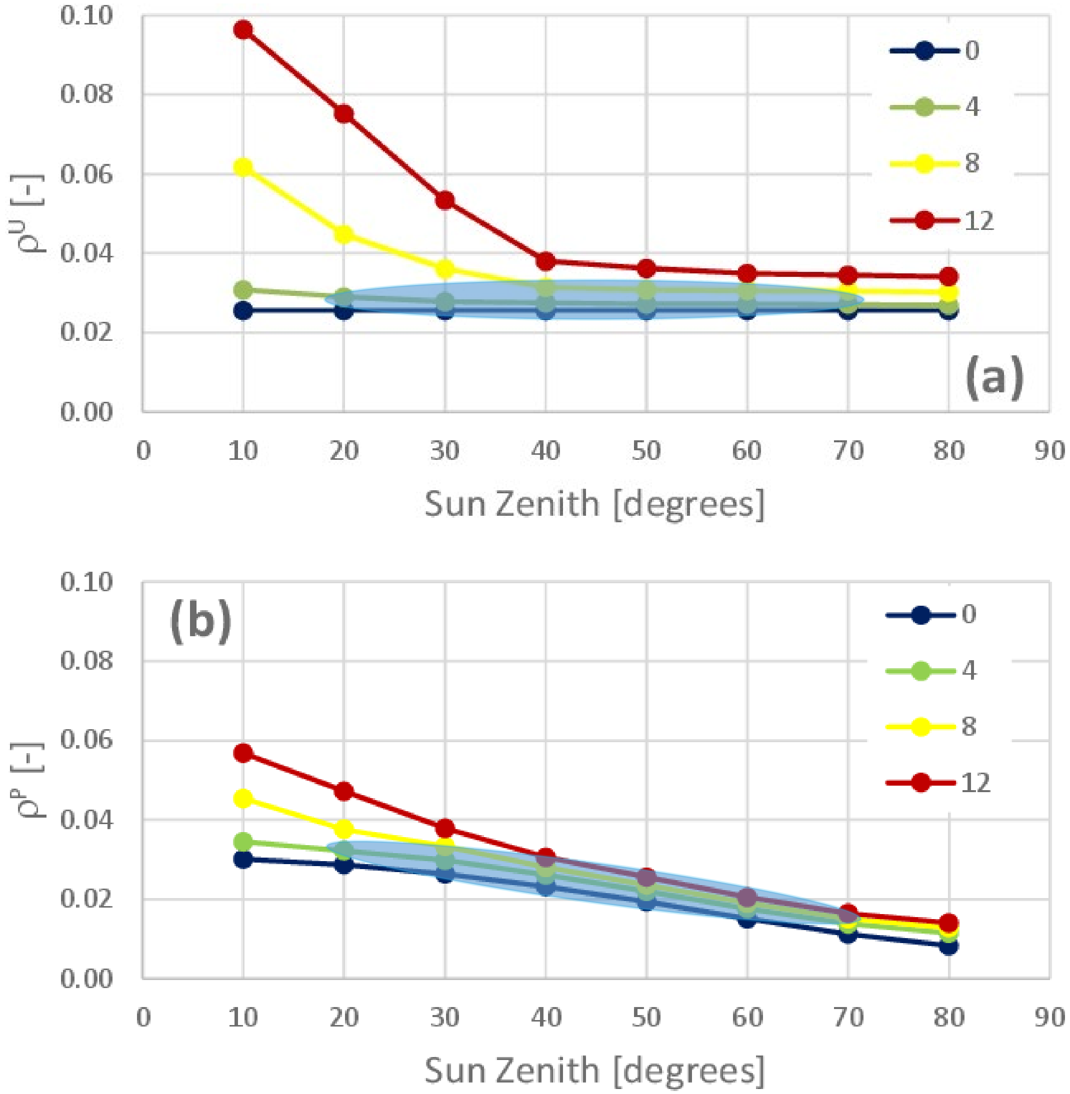
ρ^U and ρ^P

$\theta = 40°$

$\varphi = 90°$



The accuracy of any statistical modeling of ρ at low sun zenith angles and high wind speed, is decreased by: i. sky radiance contributions from a variety of zenith and azimuth angles; and ii. the time scale (tens milliseconds to seconds) and spatial extent of L_T measurements (varying from a few up to several hundreds of cm^2, depending on the field-of-view and height above the water).

Most favorable measurement conditions for above water radiometry created by $\theta_0 > 20°$ and $W_s < 5\ ms^{-1}$.

Mobley, C. D. (1999). Estimation of the remote-sensing reflectance from above-surface measurements. *Applied optics*, *38*(36), 7442-7455.
Mobley, C. D. (2015). Polarized reflectance and transmittance properties of windblown sea surfaces. *Applied optics*, *54*(15), 4828-4849

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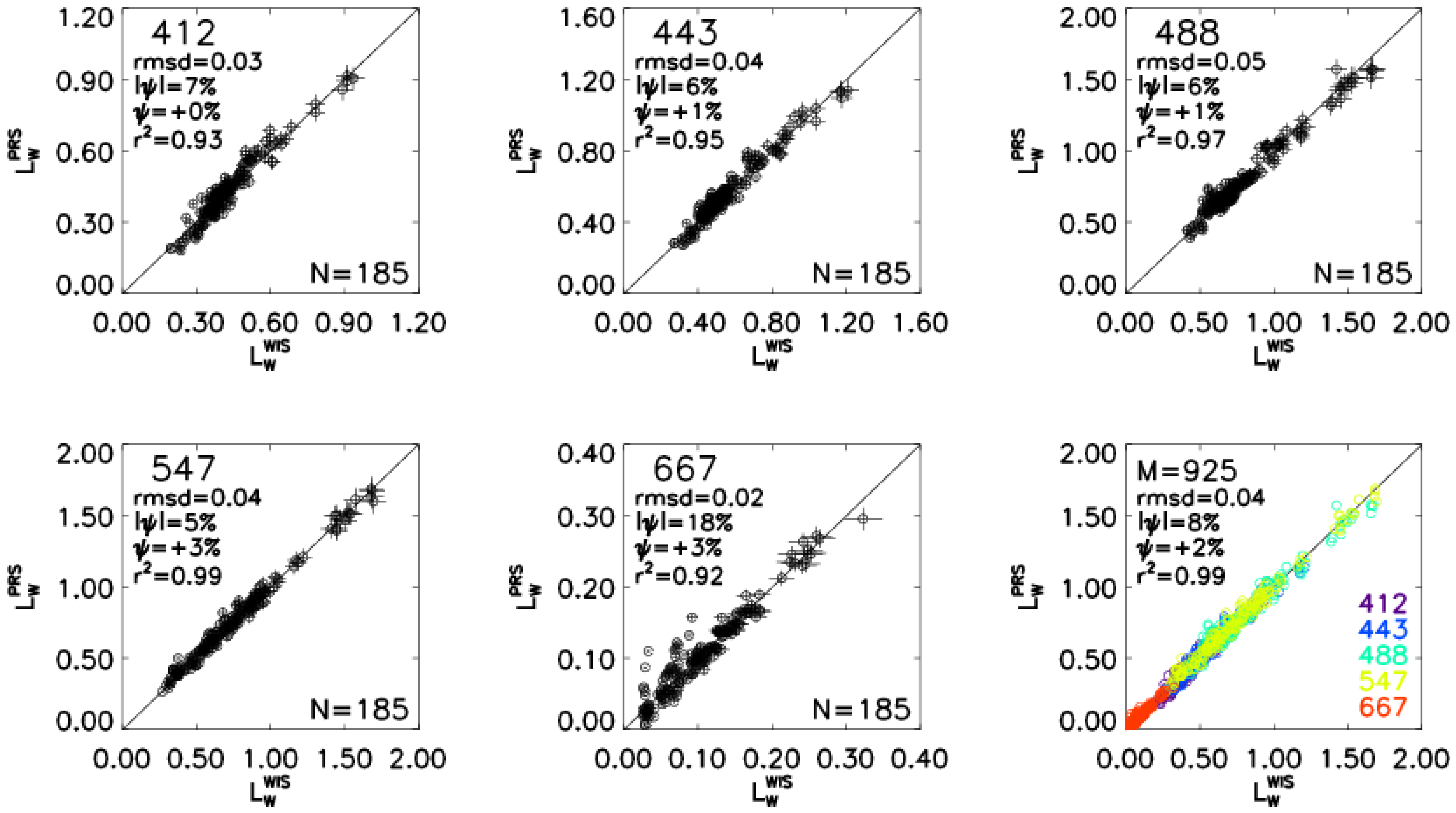
Assessment AERONET-OC L_W from ρ^U



G. Zibordi 2016. Experimental evaluation of theoretical sea surface reflectance factors relevant to above-water radiometry. *Optics Express*, *24*(6), A446-A459.

Assessment AERONET-OC L_W from ρ^P

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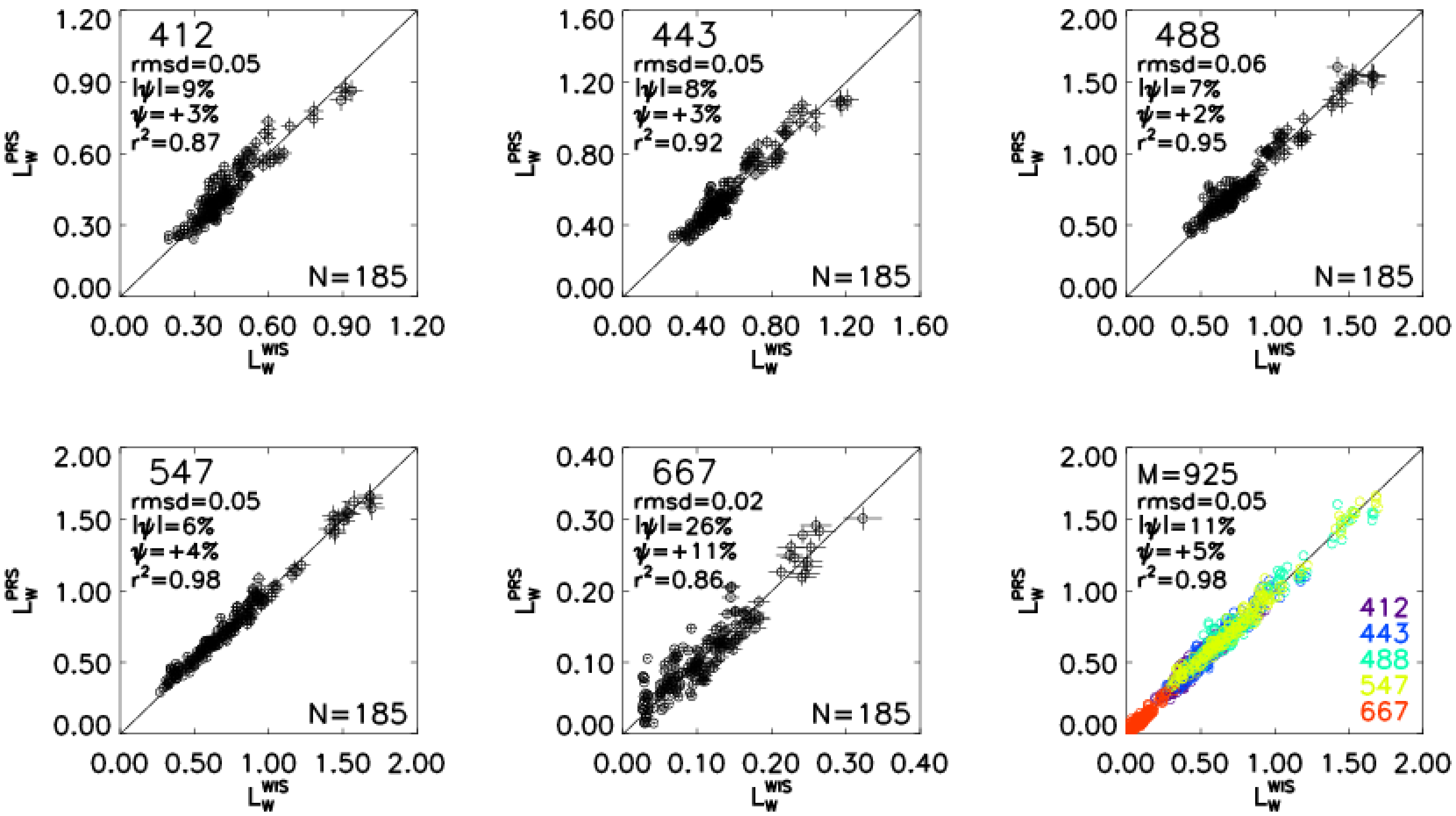

G. Zibordi 2016. Experimental evaluation of theoretical sea surface reflectance factors relevant to above-water radiometry. *Optics Express*, *24*(6), A446-A459.

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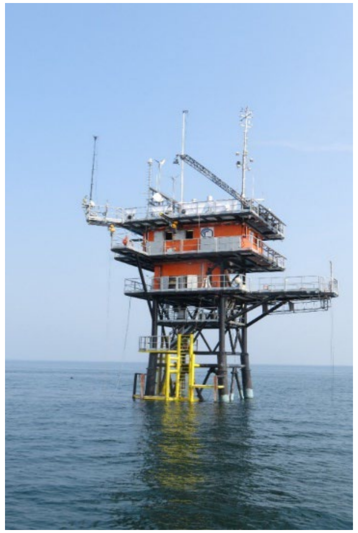
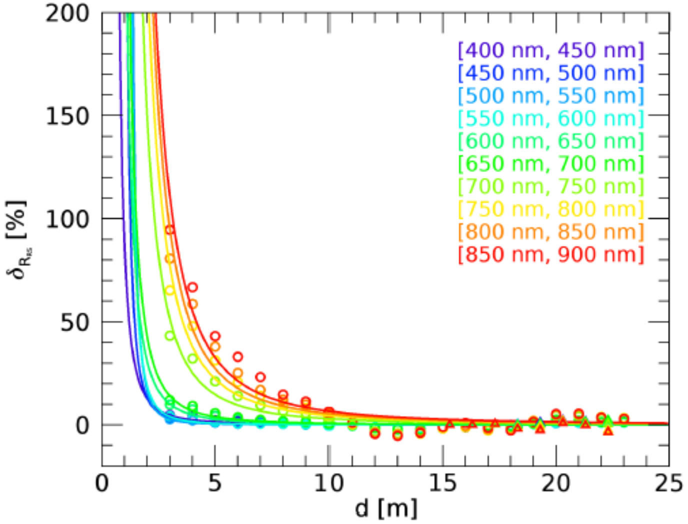
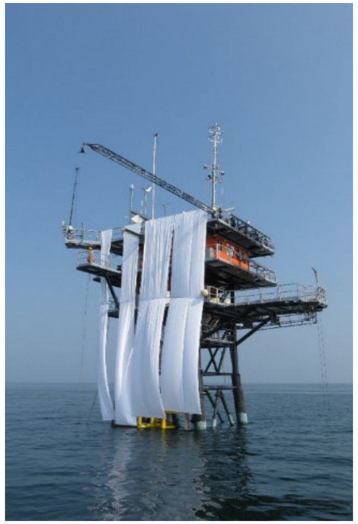
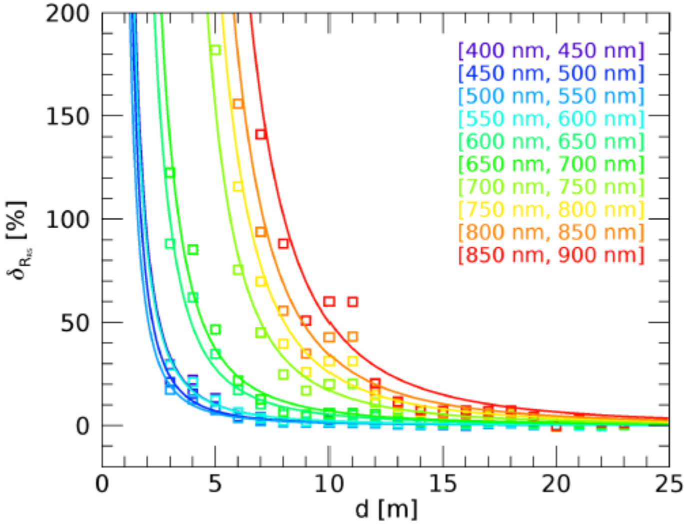
Superstructure perturbations (AAOT)





Perturbations as a function of the distance from the superstructure for actual measurement conditions.

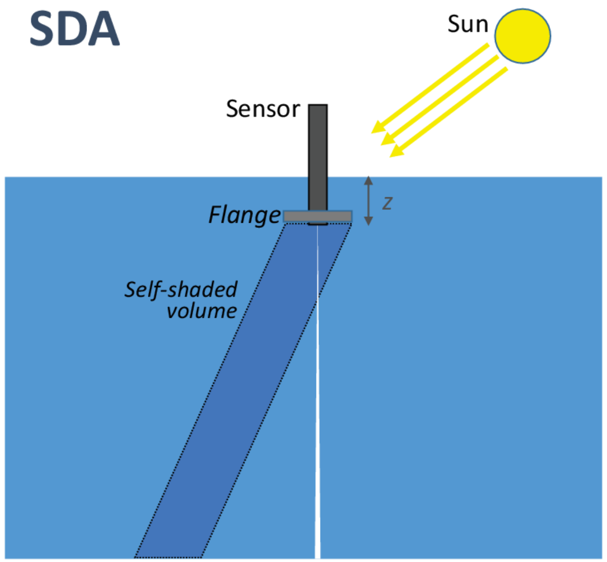


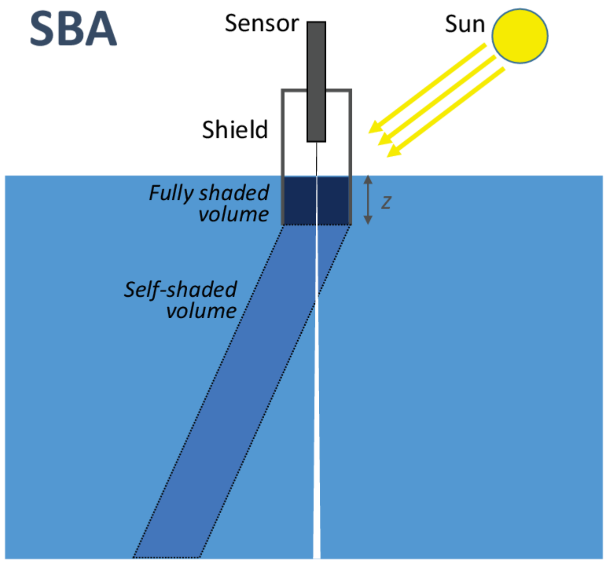


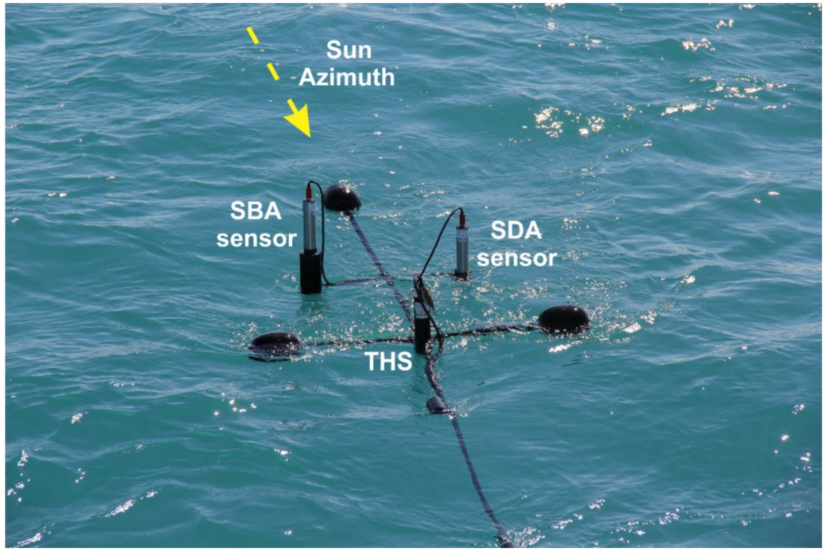
Perturbations as a function of the distance from the superstructure for measurement conditions worsened by the increased reflectance of superstructure components.

M. Talone and G. Zibordi, 2019. Spectral assessment of deployment platform perturbations in above-water radiometry. Optics Express, 27(12), A878-A889.

Single Depth Approach (SDA) & Sky-Blocked Approach (SBA)







SDA data processing

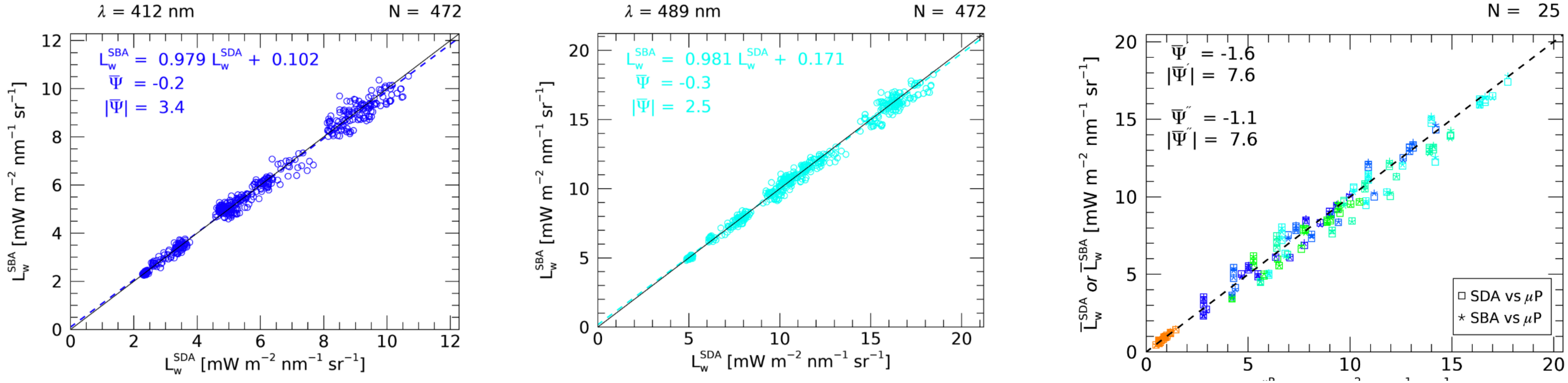
$$L_W^{SDA}(\lambda) = L_u(z,\lambda)\cdot C_{ss}^{SDA}(\lambda,a,I_r,\theta_0,R_d,f^{SDA})\cdot C_{K_L}(\lambda,K_L,z)\cdot\frac{t_{wa}(\lambda)}{n_w^2(\lambda)}$$

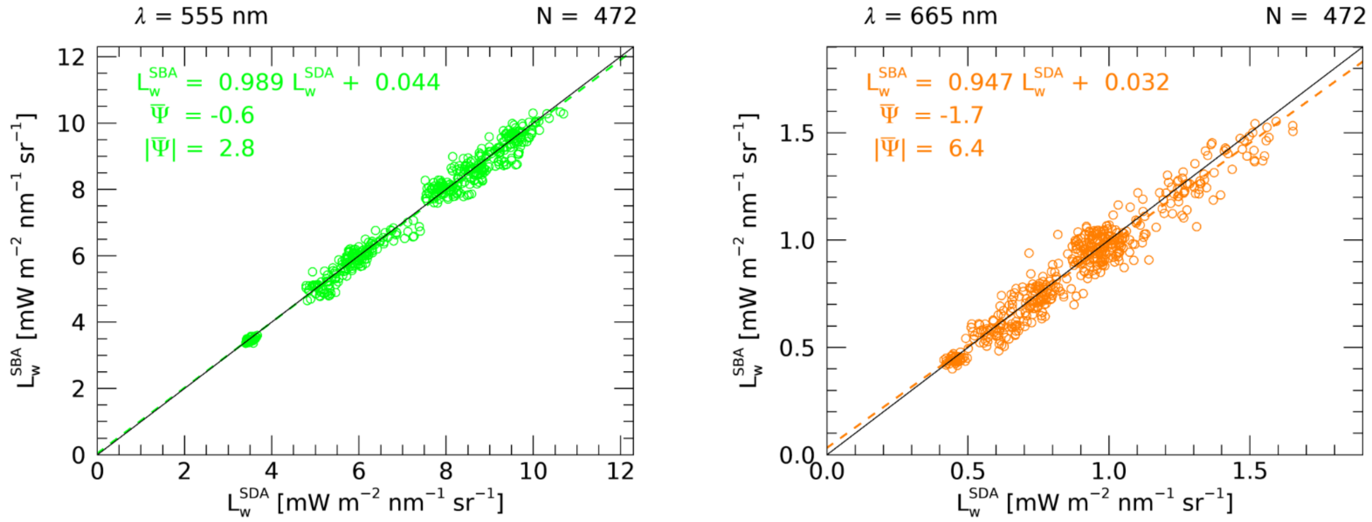
SBA data processing

$$L_W^{SBA}(\lambda) = L_W(z,\lambda)\cdot C_{ss}^{SBA}(\lambda,a,I_r,R_d,f^{SBA})\cdot C_{is}(\lambda,a,b_b,z)\cdot C_{K_L}(\lambda,K_L,z)\cdot C_{ww}(\lambda)$$

Zibordi, G., & Talone, M. (2020). On the equivalence of near-surface methods to determine the water-leaving radiance. *Optics Express*, *28*(3), 3200-3214.

SBA v.s. SDA derived L_W





Field inter-comparisons, duly supported by laboratory calibrations and characterizations, offer a unique solution for the verification of protocols implementation and instrument performance.
They also offer an excellent way for know-how transfer.

Zibordi, G., & Talone, M. (2020). On the equivalence of near-surface methods to determine the water-leaving radiance. *Optics Express*, *28*(3), 3200-3214.

BRDF corrections

Morel et al. (2002) look-up approach for Case-1 waters.
Input variables are: $\theta,\phi,\theta_0,\lambda,W,Chla$

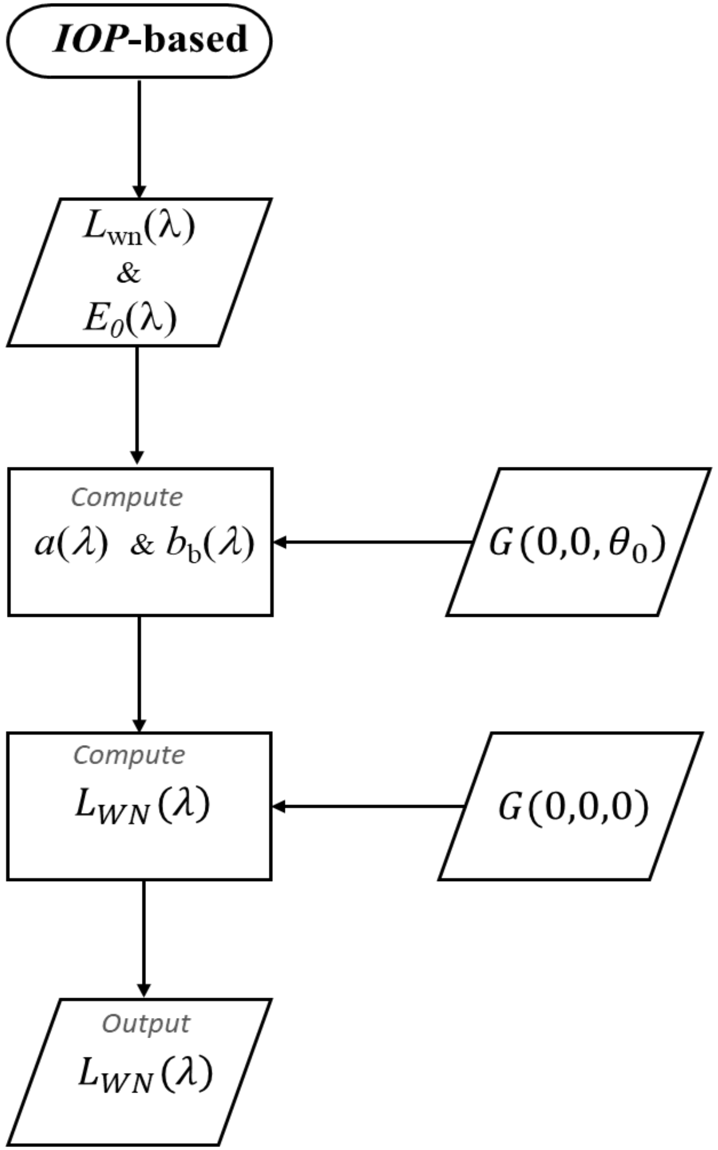
$$R_{RS}(\lambda)=R_{rs}(\theta,\phi,\theta_0,\lambda)\frac{\Re(0,W)}{\Re(\theta,W)}\frac{Q(\theta,\phi,\theta_0,\lambda,\tau_a,Chla)}{f(\theta_0,\lambda,\tau_a,Chla)}\frac{f(0,\lambda,\tau_a,Chla)}{Q(0,0,0,\lambda,\tau_a,Chla)}$$

Morel, D. Antoine, B. Gentili, B. "Bidirectional reflectance of oceanic waters…," Applied Optics **41**(30), 6289–6306 (2002).

Lee et al. (2011) semi-analytic approach for any water type.
Input variables are: $\theta,\phi,\theta_0,\lambda,G_0,G_1$

$$\begin{aligned}R_{rs}(\lambda,\Omega) \quad &= \left(G_0^w(\Omega)+G_1^w(\Omega)\frac{b_{bw}(\lambda)}{a(\lambda)+b_b(\lambda)}\right)\frac{b_{bw}(\lambda)}{a(\lambda)+b_b(\lambda)}\\ &+\left(G_0^p(\Omega)+G_1^p(\Omega)\frac{b_{bp}(\lambda)}{a(\lambda)+b_b(\lambda)}\right)\frac{b_{bp}(\lambda)}{a(\lambda)+b_b(\lambda)}\end{aligned}$$

Z. Lee, K. Du, K. J. Voss, G. Zibordi, B. Lubac, R. Arnone, and A. Weidemann, "An IOP-centered approach to correct …," Appl. Opt. **50**, 3155–3167 (2011).



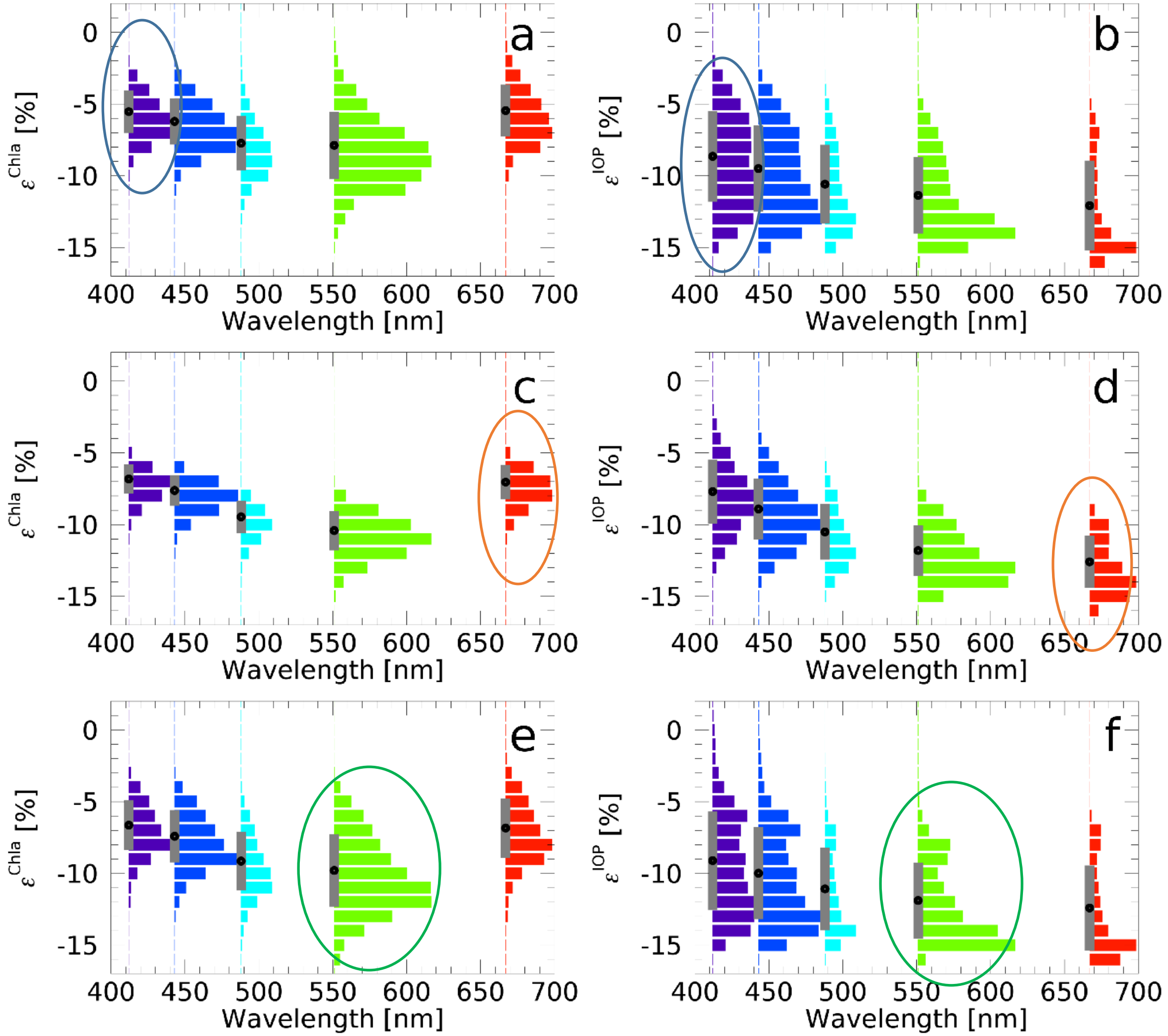
IOCCG Protocol Series (2019). Protocols for Satellite Ocean Colour Data Validation: In Situ Optical Radiometry. Zibordi, G., Voss, K. J., Johnson, B. C. and Mueller, J. L. IOCCG Ocean Optics and Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation, Volume 3.0, IOCCG, Dartmouth, NS, Canada.

Off-nadir corrections

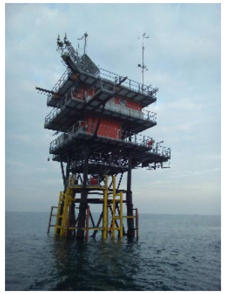
Percent corrections from the Chla- and IOP-based approaches applied to remove the off-nadir view in above water radiometric data.

Chla-Based Approach (Morel et al. 2002)

IOP-Based Approach (Lee et al. 2011)

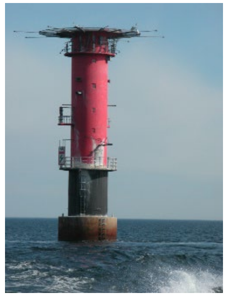


AAOT
(Adriatic Sea)



Gloria
(Black Sea)

Gustaf Dalen
(Baltic Sea)



Talone, M., Zibordi, G. and Lee, Z., 2018. Correction for the non-nadir viewing geometry … . Optics express, 26(10), pp.A541-A561.

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Above-water, In-Water & Near-Surface: pros & cons

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. Highly sensitive to wave perturbations
2. Restricted to a few radiometric quantities (i.e., L_w)

In-Water

Advantages

1. Open to several radiometric quantities (i.e., L_u, E_d, E_u)
2. Produces comprehensive (fixed depths or continuous) profiles of AOPs
3. Upward radiometric quantities are only slightly affected by wave focusing

Drawbacks

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

Near-Surface

Advantages

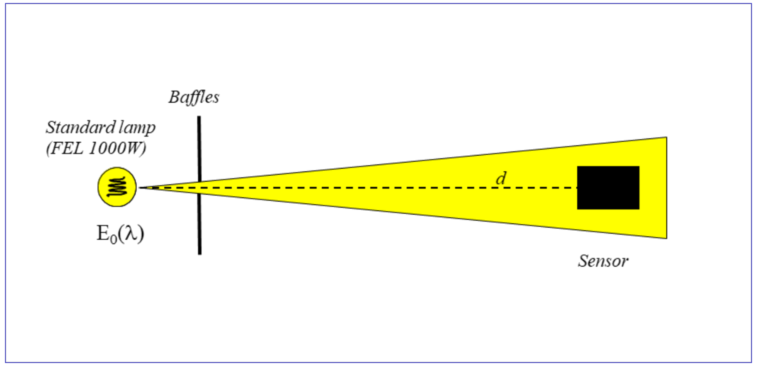
1. Insensitive to coastal water optical stratifications
2. Relatively fast deployment time during short-term activities

Drawbacks

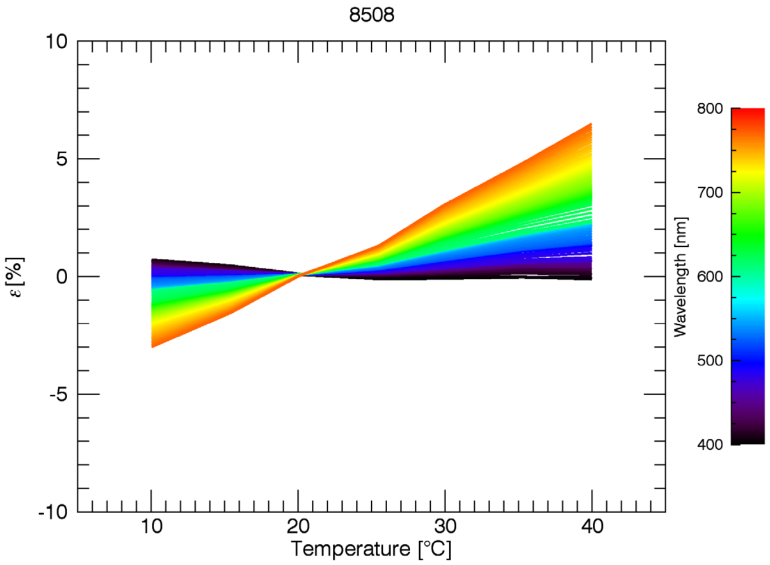
1. Sensitive to wave perturbations
2. Long-term deployments can be challenged by bio-fouling and/or deployment platforms

Calibration (implying traceability) and Characterization

Calibration is the comparison of the output from an instrument with that of a calibration standard with known accuracy. This process leads to establish a relationship allowing to obtain measurements with defined units and uncertainties from the output of an instrument.



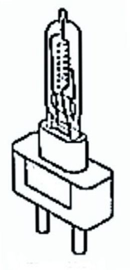
Characterization is the determination of the distinctive features of an instrument (e.g., temperature response).



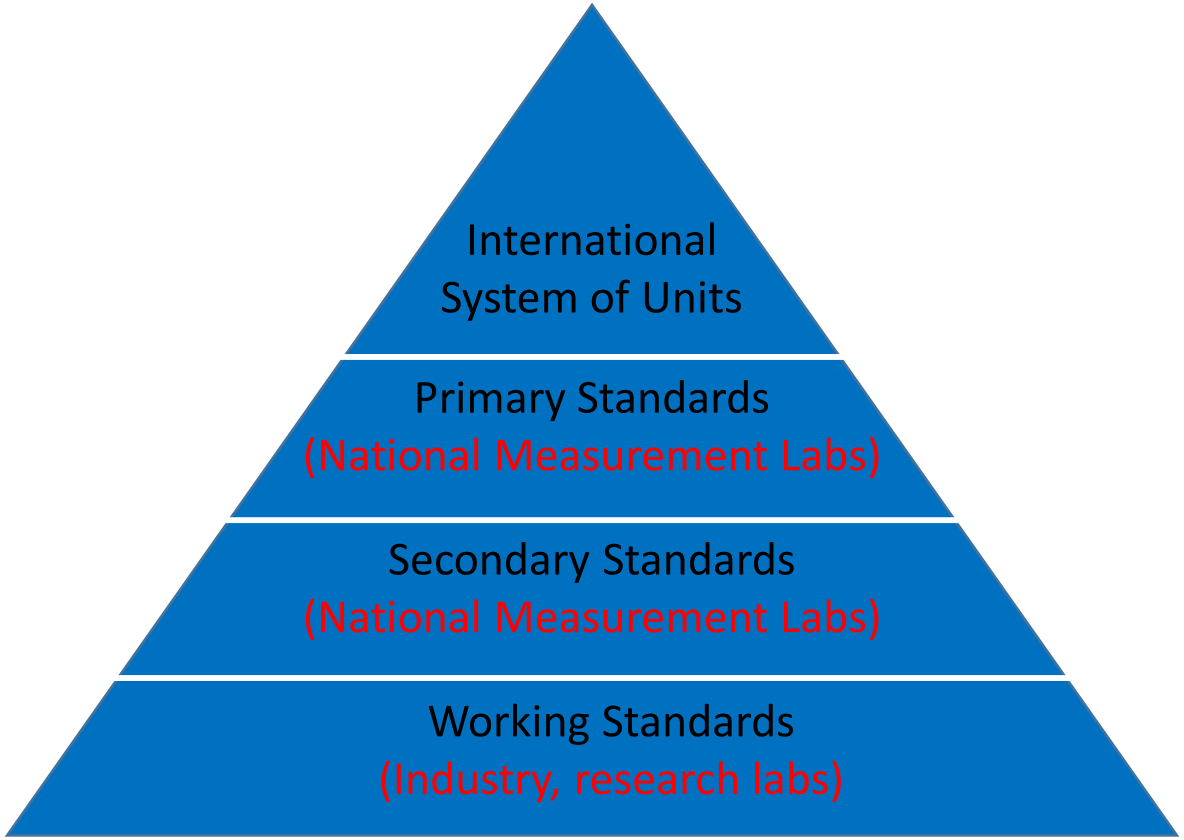
SI Traceability and Primary Standards

Metrological traceability implies a common origin of reference (for instance international reference systems) ensuring that measurements are comparable regardless of instrument, time, location and operator.

In the case of optical radiometers, traceability is provided by their calibration through a radiance and irradiance secondary source (commonly based on a 1000 W quartz-halogen FEL lamp with tungsten coiled filament, calibrated with respect to the freezing temperature of gold).



Traceability Pyramid



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Calibration Equation

The conversion from relative to physical units of the radiometric quantity $\Im(\lambda)$ (either $E(\lambda)$ or $L(\lambda)$) at wavelength λ is performed through

$$\Im(\lambda) = C_{\Im}(\lambda)\, I_f(\lambda)\, \aleph(\lambda)\, DN(\Im(\lambda))$$

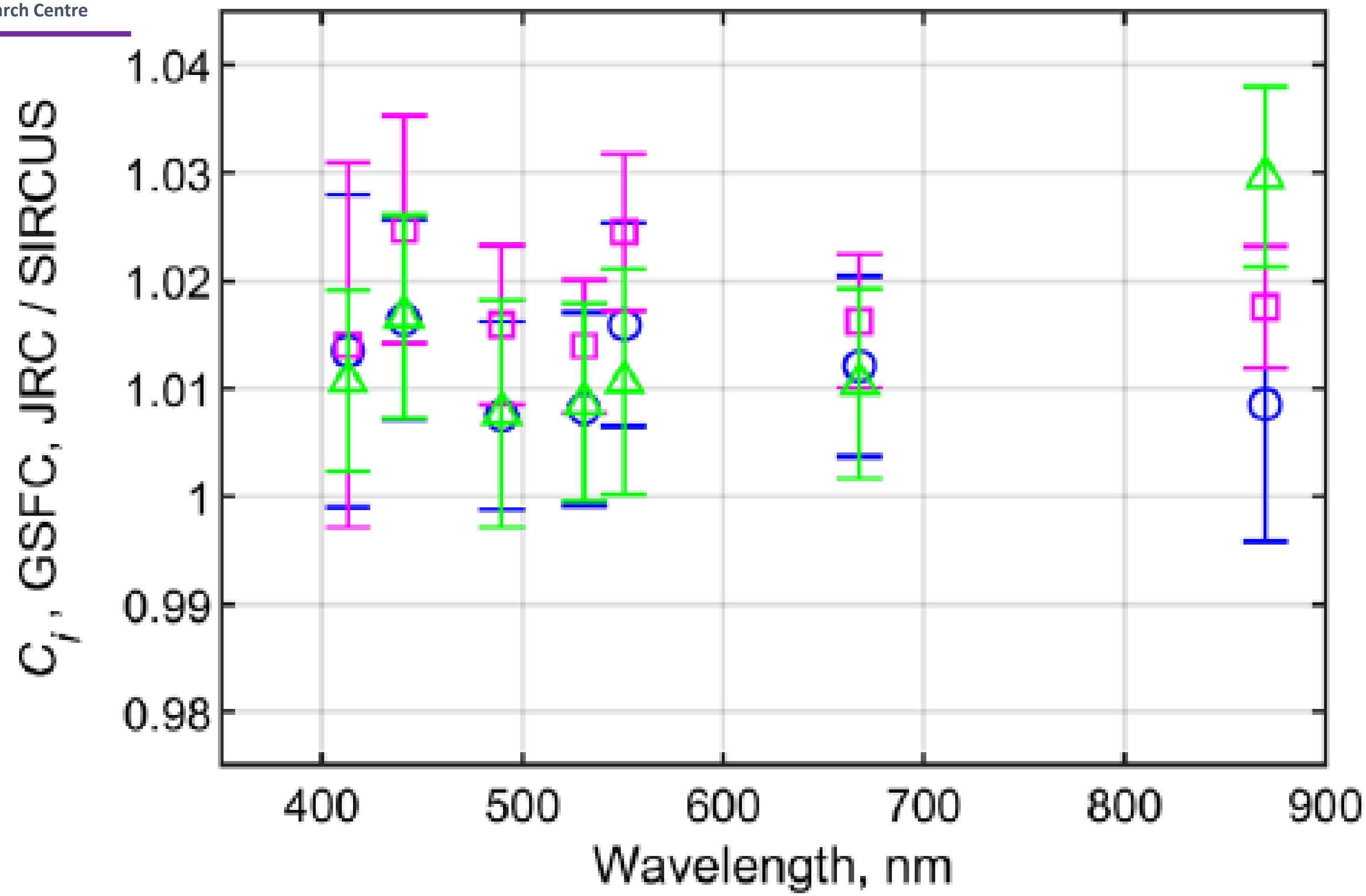
where $DN(\Im(\lambda))$ indicates the digital output corrected for the dark value, $C_{\Im}(\lambda)$ is the in–air absolute calibration coefficient (i.e., the absolute responsivity), $I_f(\lambda)$ is the immersion factor accounting for the change in responsivity of the sensor when immersed in water with respect to air, and $\aleph(\lambda)$ corrects for any deviation from the ideal performance of the measuring system.

In the case of an ideal radiometer $\aleph(\lambda)=1$, but in general

$$\aleph(\lambda)= \aleph_i(i(\lambda))\, \aleph_j(j(\lambda)) \ldots \aleph_k(k(\lambda))$$

where $\aleph_i(i(\lambda))$, $\aleph_j(j(\lambda))$, …, and $\aleph_k(k(\lambda))$ are correction terms for different factors affecting the performance of the considered radiometer (e.g., non-linearity, temperature response, polarization sensitivity, stray-light perturbations, spectral response, geometrical response, …).

Inter-Calibrations



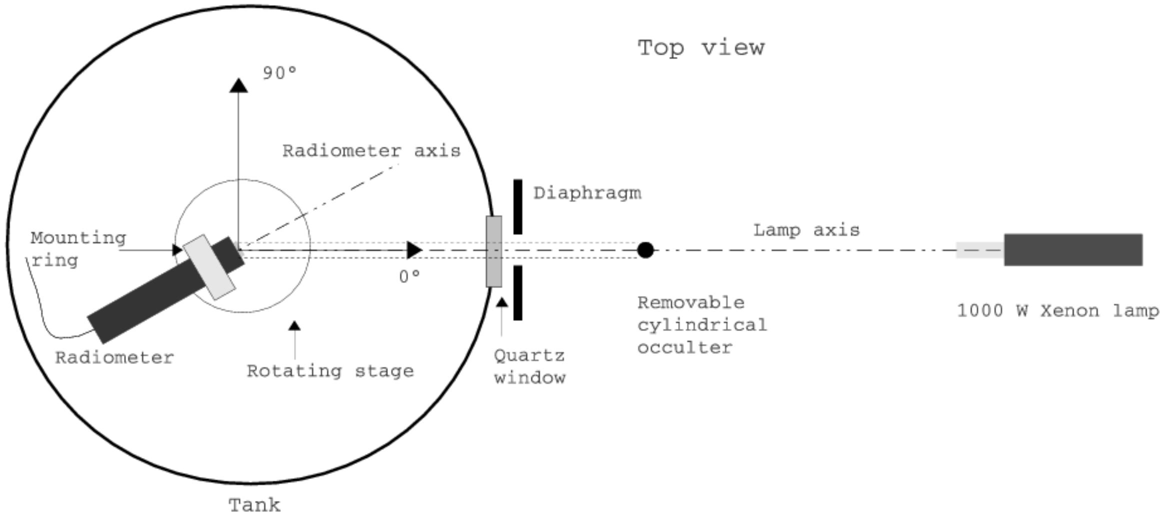
Ratio of NASA-GSFC ○ , □ and JRC △ to NIST radiance calibrations (note the use of error-bars and the adoption of absolute reference values.

Inter-calibrations among laboratories are essential to identify issues in calibration set-ups, sources, or even protocols implementation.

Best inter-calibration exercises exhibit values within 1% for irradiance and 2% for radiance (k=1).

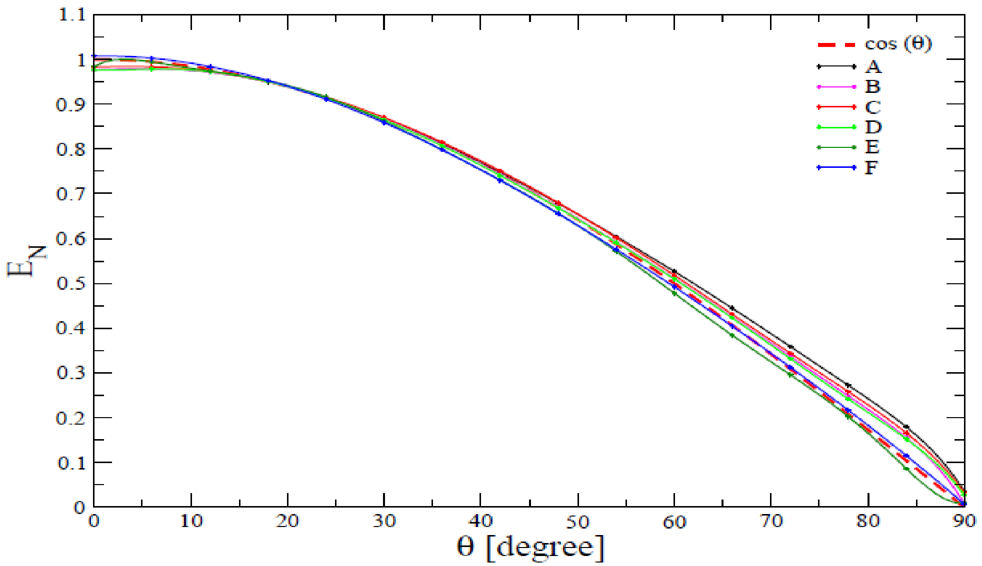
Johnson, B. C., Zibordi, G., Brown, S. W., Feinholz, M. E., Sorokin, M. G., Slutsker, I., ... & Yoon, H. W. (2021). Characterization and absolute calibration of an AERONET-OC radiometer. *Applied Optics*, *60*(12), 3380-3392.

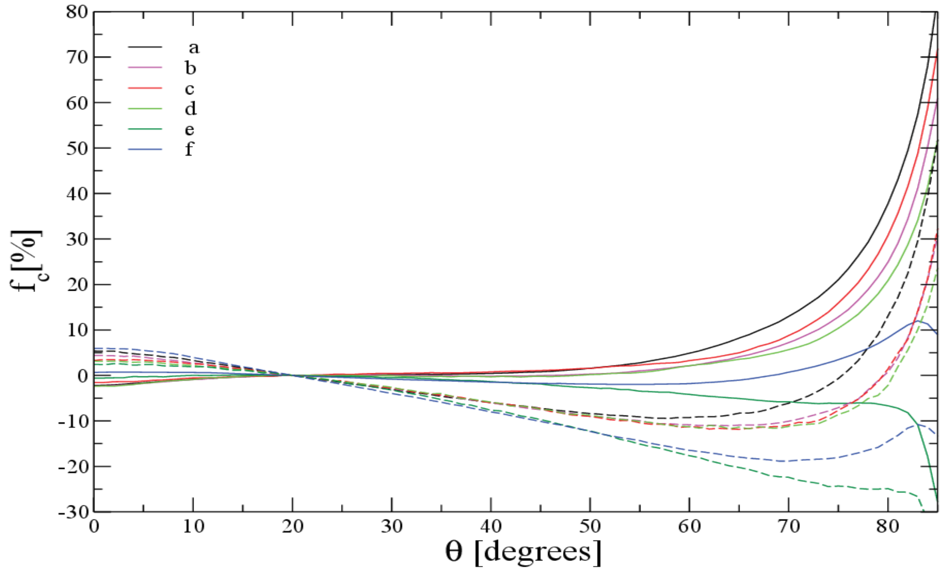
Cosine Response for Irradiance Sensors



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

The cosine response of irradiance sensors should be characterized for each unit because simple geometric differences of the collector may lead to appreciable differences.





S. Mekaoui and G. Zibordi. Cosine error for a class of hyperspectral irradiance sensors, *Metrologia 50 (2013).*

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On Calibration and Characterization Requirements

	Regular	Occasional	Initial	Class-based
Radiometric responsivity	X			
Spectral response		X		
Out-of-band & stray-light		X		
Immersion factor (irradiance)			X	
Immersion factor (radiance)				X
Angular response			X	
Linearity				X
Integration time				X
Temperature response				X
Polarization sensitivity				X
Dark signal	X			
Temporal response				X
Pressure effects				X

Very unlikely individual research teams may ensure comprehensive instrument characterizations. Because of this, occasional, initial and class-based characterizations should be taken over by major measurement programs in agreement with manufacturers and reference laboratories. This would imply a standardization of instrument models in use by the community.

IOCCG Protocol Series (2019). Protocols for Satellite Ocean Colour Data Validation: In Situ Optical Radiometry. Zibordi, G., Voss, K. J., Johnson, B. C. and Mueller, J. L. IOCCG Ocean Optics and Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation, Volume 3.0, IOCCG, Dartmouth, NS, Canada.

Quality assurance and quality control

Quality assurance entails process-oriented actions ensuring the correct execution of measurements.

1. *Instruments are calibrated & characterized*
2. *Measurement protocols are respected*
3. *…*

Quality control entails product-oriented actions embracing all post-generation steps supporting the provision of high-quality data (Bushnell et al. 2019, 2020)

1. *Post-field calibration are within expected thresholds with respect to pre-field calibration*
2. *Comply with basic QC thresholds (e.g., dark values, radiance values, ratios of specific radiometric quantities, …)*
3. *Relative consistency among data collected over similar regions*
4. *Spectral consistency (e.g., lack of any spectral artifact)*
5. *Temporal consistency (e.g., successive spectra do not exhibit unexplainable differences in shape and amplitude)*
6. *…*

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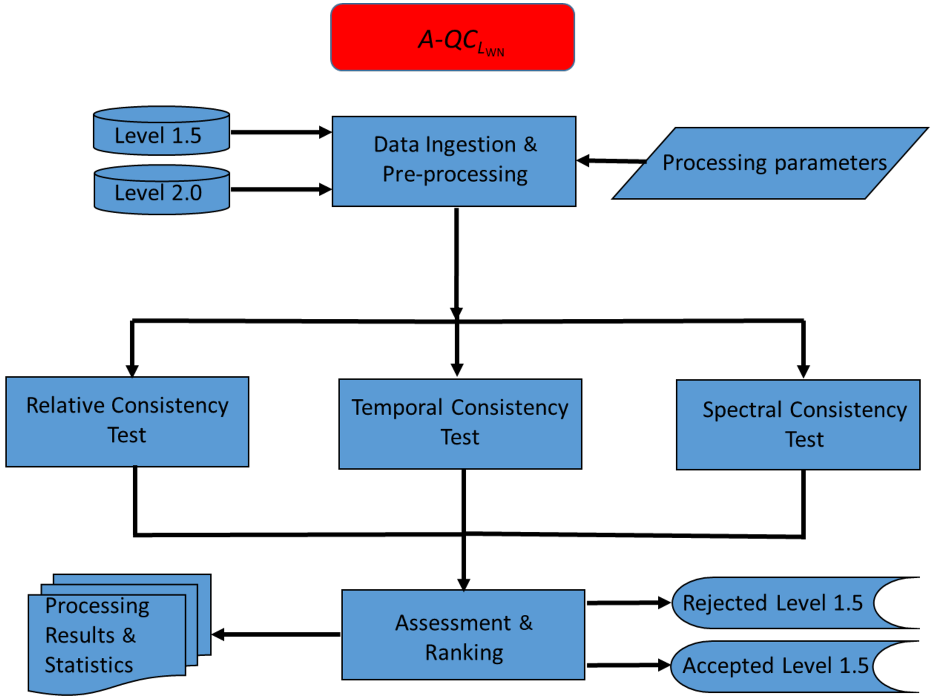
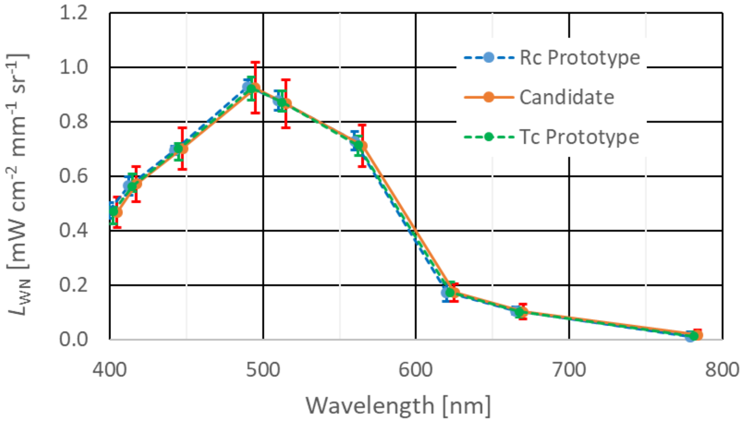
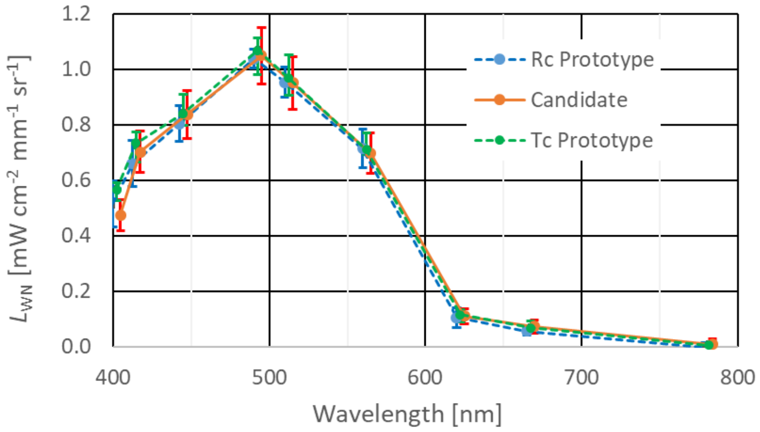
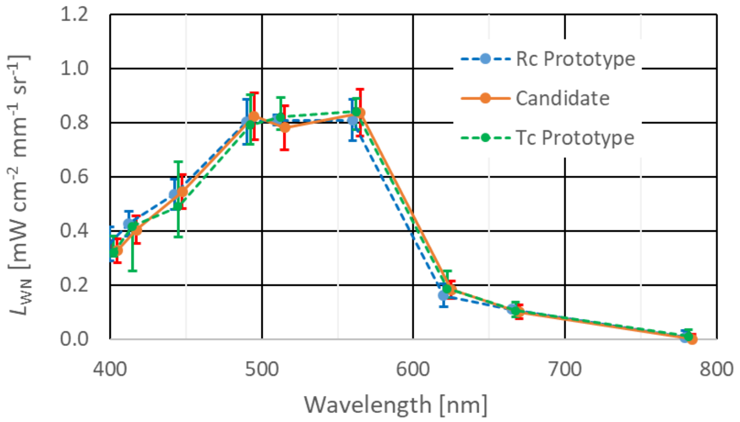
Automated QC

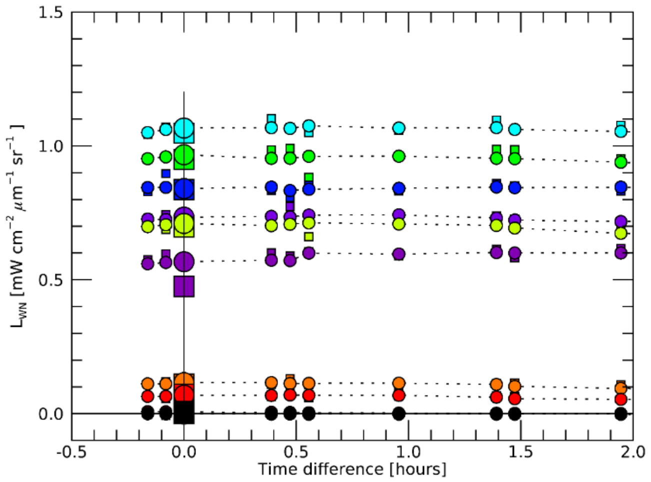


Flow-chart of an automated QC process









Error bars indicate: i. ±2σ of the spectral value for the reference spectra contributing to the determination of the "Prototype"; ii. ±2 u(Lwn) quantified for the "Candidate" spectrum.

G. Zibordi, D. D'Alimonte, T. Kajiyama (2022). Automated Quality Control of AERONET-OC L_{WN} data. *Journal of Atmospheric and Oceanic Technology*, *(submitted)*.

Errors and Uncertainties

Errors indicate differences between actual and measured values (often introduce biases). If identified, they should be corrected.

Uncertainty is a parameter associated with the result of a measurement characterizing the dispersion of the values that could be reasonably attributed to the measurand. Uncertainties indicate doubts and are an estimate of the range between actual and measured values (in other words, they express the "*reliability*" of the measurement).

Type A: Uncertainties evaluated by the statistical analysis of series of observations

Type B: Uncertainties evaluated by means other than the statistical analysis of series of observations

Standard uncertainty: uncertainty of a measurement expressed as a standard deviation (coverage factor k=1)

Combined standard uncertainty: standard uncertainty of the result of a measurement obtained from the composition of a number of other standard uncertainties (*i.e.*, individual uncertainty contributions).

Uncertainties (combined uncertainties for L_{WN} from in-water profiles)

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Uncertainty budget (in percent) for L_{WN} determined from in-water profile data

Uncertainty source	443	555	665
Absolute calibration of L_u	2.7	2.7	2.7
Immersion factor	0.2	0.2	0.2
Self-shading correction	0.5	0.3	1.3
Absolute calibration of E_s	2.3	2.3	2.3
Cosine response correction	0.5	0.5	0.5
Anisotropy correction	0.4	0.9	0.5
E_0 determination	1.9	0.8	0.2
Environmental effects	2.1	2.2	3.2
Quadrature sum	4.6	4.4	5.0

The various sources of uncertainty are all assumed independent, an added in quadrature as:

$$u(L_{WN})/\overline{L_{WN}} = \sqrt{\sum u_i^2/\overline{L_{WN}}}$$

The above table does not include contributions related to temperature response, polarization sensitivity, stray-lights, nonlinearity (i.e., the radiometers are assumed to exhibit ideal performance, except for cosine response).

Neglecting corrections may lead to an obvious underestimates of uncertainties. Noteworthy, compensation processes may minimize systematic effects for given measurement conditions or conversely lead to potential spectral effects (e.g., due to unaccounted self-shading perturbations).

IOCCG Protocol Series (2019). Protocols for Satellite Ocean Colour Data Validation: In Situ Optical Radiometry. Zibordi, G., Voss, K. J., Johnson, B. C. and Mueller, J. L. IOCCG Ocean Optics and Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation, Volume 3.0, IOCCG, Dartmouth, NS, Canada.

Quantification of uncertainties following GUM

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Given the measurement equation

$$L_{\mathrm{WN}} = L_{\mathrm{W}}\, C_A\, C_Q \qquad \textit{with} \qquad L_{\mathrm{W}} = L_{\mathrm{T}} - \rho\, L_{\mathrm{i}}$$

where the term C_Q is introduced to remove the dependence from the viewing geometry and the bidirectional effects, while the term C_A removes the basic dependence on sun zenith, atmosphere and sun-earth distance; *w*ithout considering correlations among input quantities and non-linearity of the measurement model, the application of the *Guide to the Expression of Uncertainty in Measurement (GUM)* would suggest that the combined standard uncertainty of the normalized water-leaving radiance $\tilde{u}_c(L_{\mathrm{WN}})$ is given by the first-order expansion of Taylor series of the measurement equation

$$\tilde{u}_c^2(L_{\mathrm{WN}}) = (C_Q C_A)^2\, \tilde{u}_c^2(L_{\mathrm{W}}) + (L_{\mathrm{W}} C_A)^2 u^2(C_Q) + (L_{\mathrm{W}} C_Q)^2 u^2(C_A)$$

with

$$\tilde{u}_c^2(L_{\mathrm{W}}) = u^2(L_{\mathrm{T}}) + L_{\mathrm{i}}^2 u^2(\rho) + \rho^2 u^2(L_{\mathrm{i}})\,.$$

The uncertainty $u(L_{\mathrm{T,i}})$, indicating either $u(L_{\mathrm{T}})$ or $u(L_{\mathrm{i}})$, neglecting instrument non-ideal performance, should include contributions related to absolute calibration, sensitivity change during the deployment period of the measuring system, and environmental perturbations mostly caused by sea surface roughness and environmental changes during measurement sequences.

M. Gergely and G. Zibordi, “Assessment of AERONET L_{WN} uncertainties,” Metrologia **51**, 40–47 (2014).

L_{WN} uncertainties from AW radiometry following GUM

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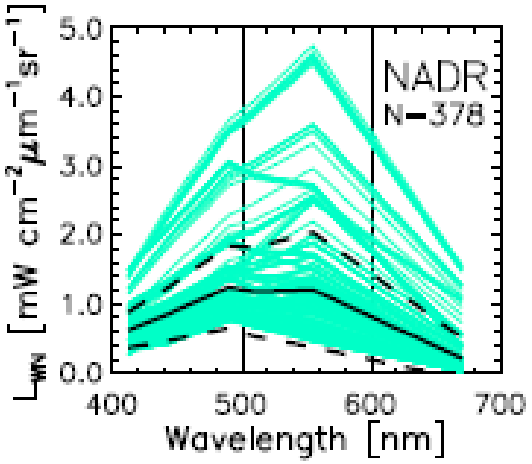
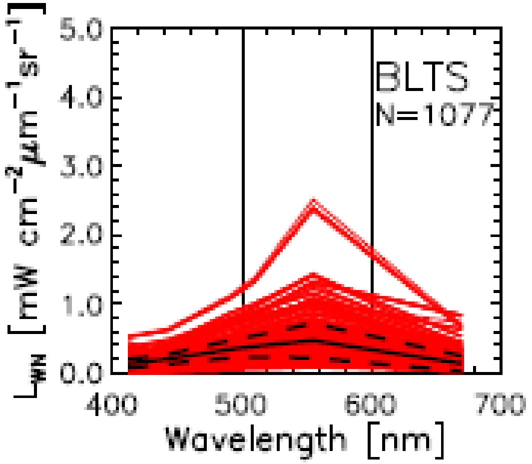
Target uncertainties for in situ data should reflect EO requirements. The generic 5% uncertainty requirement often stated in literature does not reflect actual requirements/capabilities when considering in land and costal waters.

λ	412	551	667
AAOT	5.3 [0.038; 0.71]	4.9 [0.049; 1.00]	7.3 [0.010; 0.13]
GLR	8.6 [0.027; 0.31]	5.6 [0.038; 0.67]	9.6 [0.011; 0.11]
AABP	11.1 [0.050; 0.44]	6.8 [0.033; 0.47]	9.5 [0.009; 0.08]
GDLT	16.3 [0.018; 0.11]	5.7 [0.027; 0.47]	6.4 [0.007; 0.10]
HLT	27.4 [0.016; 0.06]	6.7 [0.026; 0.39]	6.9 [0.008; 0.12]

$u(L_{WN})/L_{WN}$ $u(L_{WN})$ L_{WN}

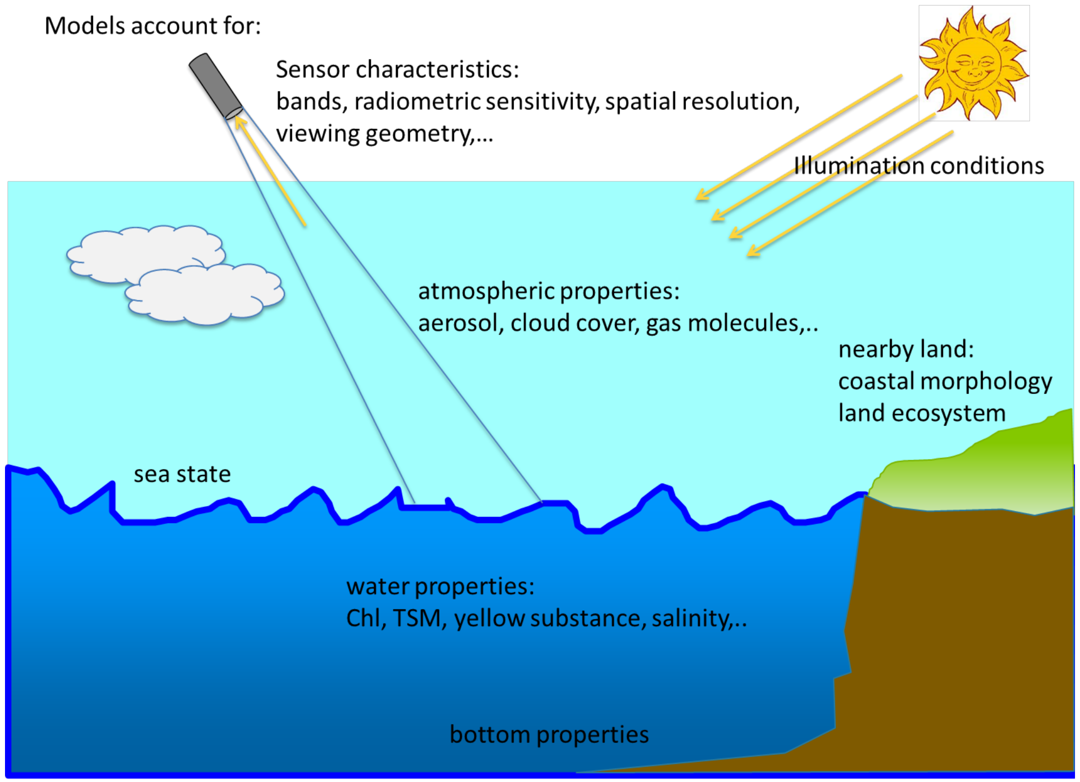
Relative combined uncertainties $u(L_{WN})/L_{WN}$ (%) and, in brackets, combined standard uncertainties $u(L_{WN})$ and median L_{WN} (mW cm^{-2} sr^{-1} µm^{-1}), respectively, at different λ (nm) for various AERONET-OC sites.

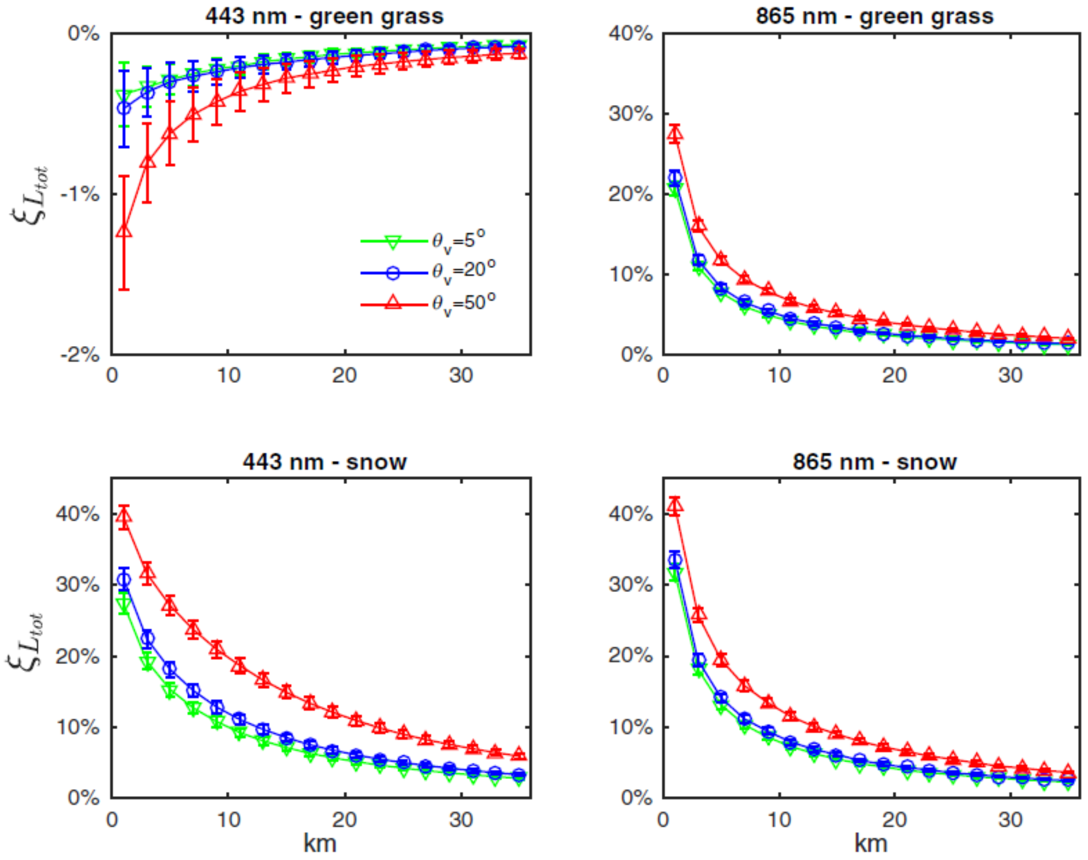




M. Gergely and G. Zibordi, "Assessment of AERONET L_{WN} uncertainties," *Metrologia* **51**, 40–47 (2014).

Adjacency perturbations





Adjacency perturbations at the satellite sensor as a function of the distance from the coast for representative center-wavelengths and surfaces.

Bulgarelli, B., & Zibordi, G. (2018). On the detectability of adjacency effects in ocean color remote sensing of mid-latitude coastal environments by SeaWiFS, MODIS-A, MERIS, OLCI, OLI and MSI. Remote sensing of Environment, 209, 423-438.

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Breakout Session I

Finalization of recommendations for minimum/compulsory:

- *Priority measurements*
- *Instruments specifications and requirements;*
- *Instruments calibration and characterization;*
- *Measurement protocols and data processing;*
- *Quality Assurance of measurements and Quality Control of products;*
- *Uncertainty estimate;*
- *Inter-calibrations and Inter-comparisons*

& time permitting on:

- *Generic field measurement requirements;*
- *Requirements for matchups construction;*
- *Revision/update and translation of current protocols.*

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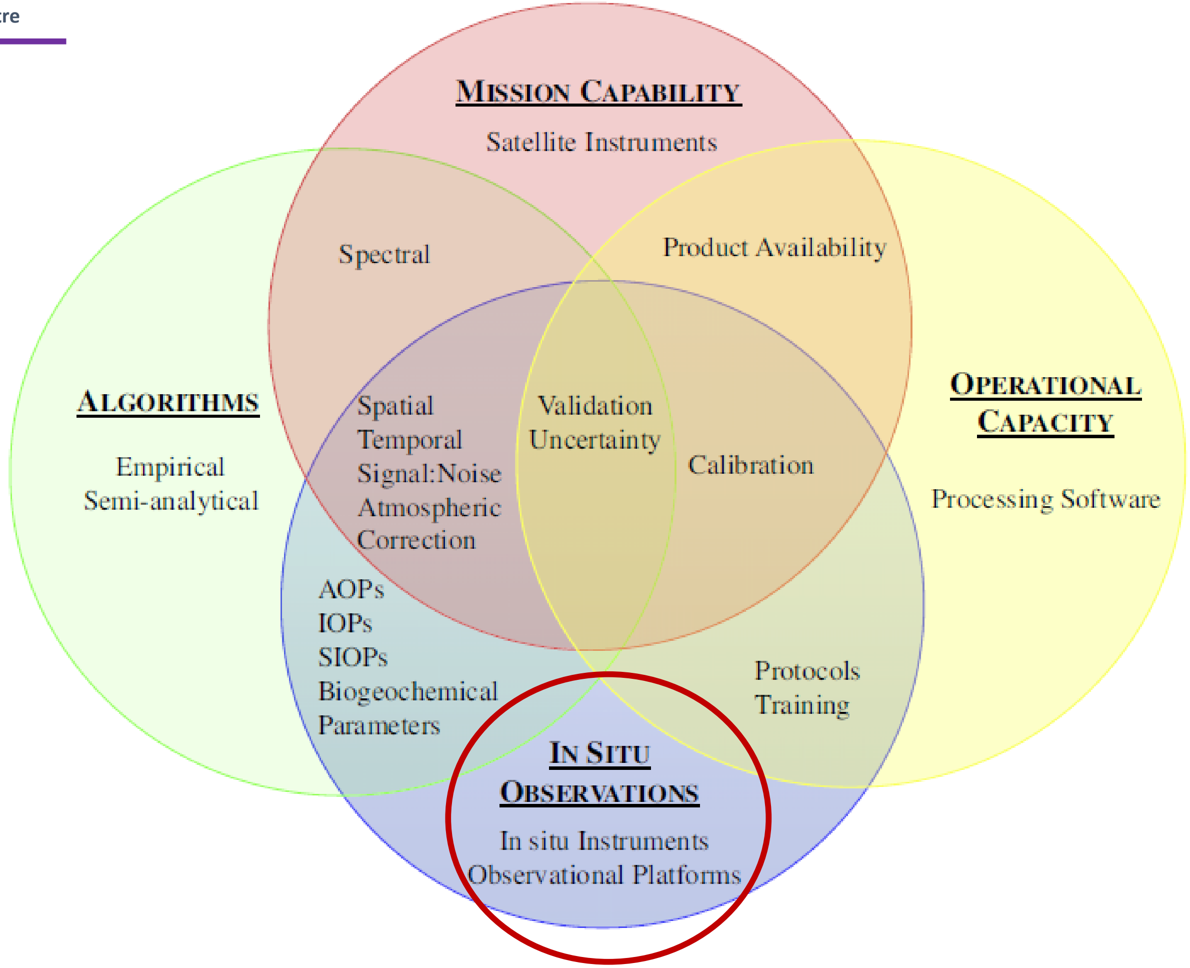
Generic in situ sampling requirements

1. Instruments calibrated/characterized
2. Protocols respected (e.g., viewing geometry)
3. Environmental conditions (e.g., clear sky)
4. Sampling fulfilling temporal/spatial needs (e.g., spatial variability)
5. Superstructure perturbations avoided/minimized
6. Adjacency effects avoided/minimized
7. …

Matchup-construction requirements

1. Number of pixels for the box centered at the measurement site
2. Illumination and viewing constrains (max sun zenith and viewing angle)
3. Minimization of the impact of noise and spatial variability (thresholds on VC)
4. Constrains imposed by adjacency perturbations (distance from coast)
5. Flags application (flags from data products)
6. …

Objective of the talk and following discussion

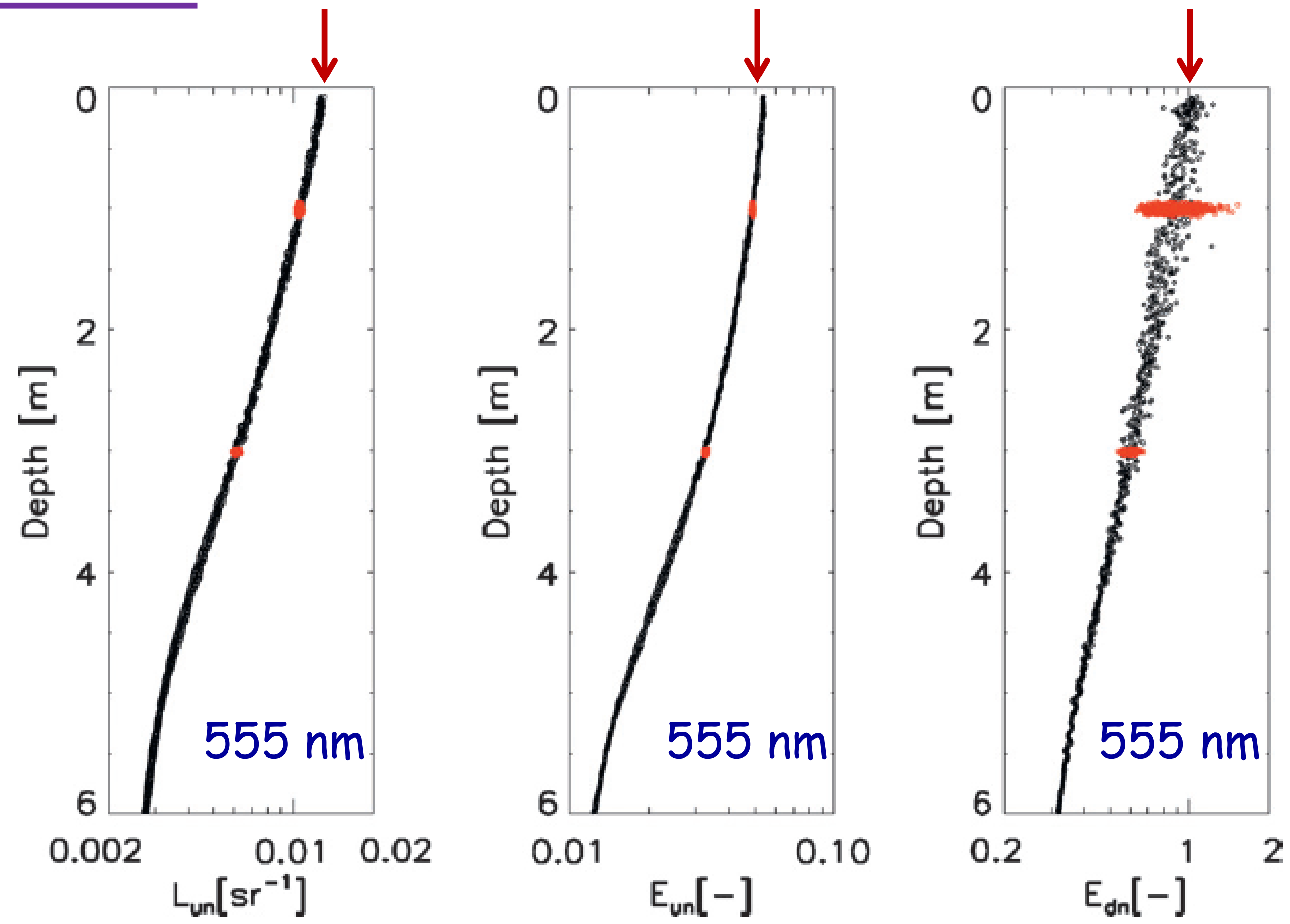


Considering current technology and know-how, would it be possible to recommend (or enforce) best-practices for in situ measurements supporting the validation of satellite derived data products for inland and coastal waters?

Integration schematic of the fundamental elements of aquatic color satellite remote sensing

Mouw, C. B., Greb, S., Aurin, D., DiGiacomo, P. M., Lee, Z., Twardowski, M., ... & Craig, S. E. (2015). Aquatic color radiometry remote sensing of coastal and inland waters: Challenges and recommendations for future satellite missions. *Remote sensing of environment*, *160*, 15-30.

Fixed-depth v.s. Continuous Profile Data



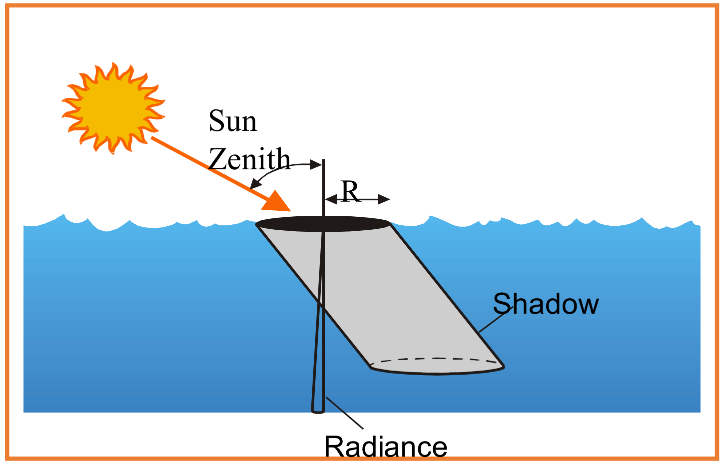
… the method of assigning vertical profiles of the downward irradiance E_d and its diffuse coefficient K_d, on the basis of the data measured during vertical movement of the probe in the most upper layer of the sea is improper, or at least extremely inaccurate *(an Anonymous Reviewer).*

The above statement is only true if the number of points per unit depth do not minimize the impact of wave perturbations

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

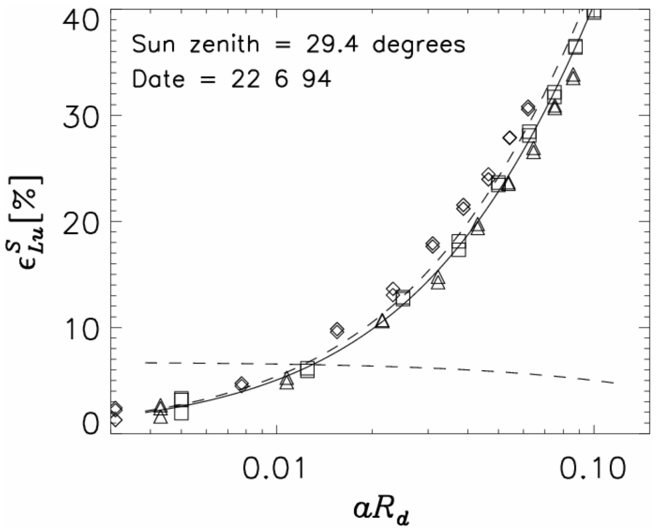
G.Zibordi et al. An evaluation of radiometric products from fixed-depth and continuous in-water profile data from moderately complex waters. *JTECH*, 26, 91-106 2009.

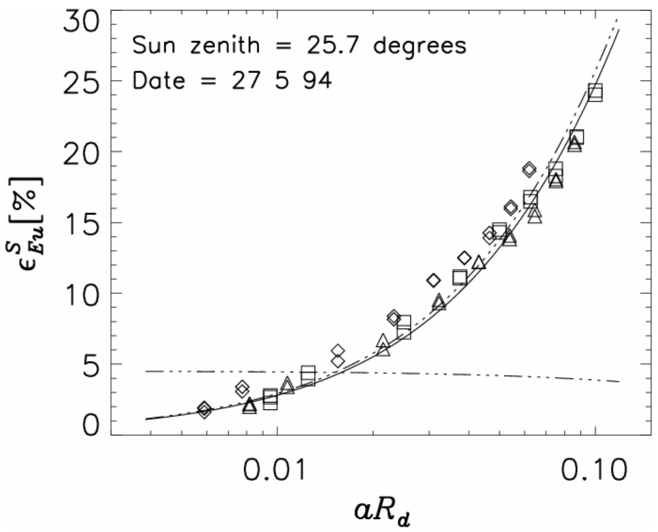
Self-Shading



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

Note the idealized instrument geometry relies on radiometers shaped as disks





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

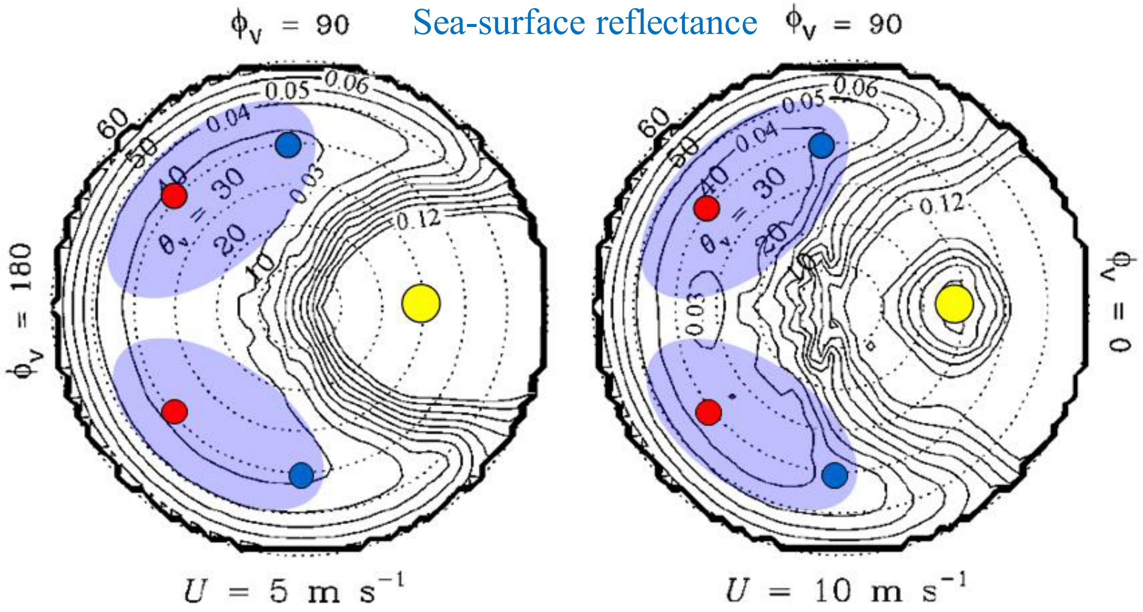
Zibordi G. and Ferrari G.M. (1995), Instrument self shading in underwater optical …. *Applied Optics*, 34: 2750-2754.

Sea surface reflectance

Sky-glint contains sky radiance contributions from a variety of zenith and azimuth angles, not only from the specular reflection of an ideal flat sea surface, which increases modelling complexity. In certain cases sun-glint and foam contributions may add to sky-glint, and lead to a significant spectral dependence of ρ.

The previous elements combined with the time scale (tens milliseconds to seconds) and spatial extent of L_T measurements (varying from a few up to several hundreds of cm^2, depending on the field-of-view and height above the water), reduce the effectiveness of any statistical modeling of ρ at low sun zenith angles and with increasing wind speed.

Sea-surface reflectance



The respect of recommended viewing geometries is essential. The minimization of the impact of high-glint contributions through filtering was also shown to be an essential pre-processing element.

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

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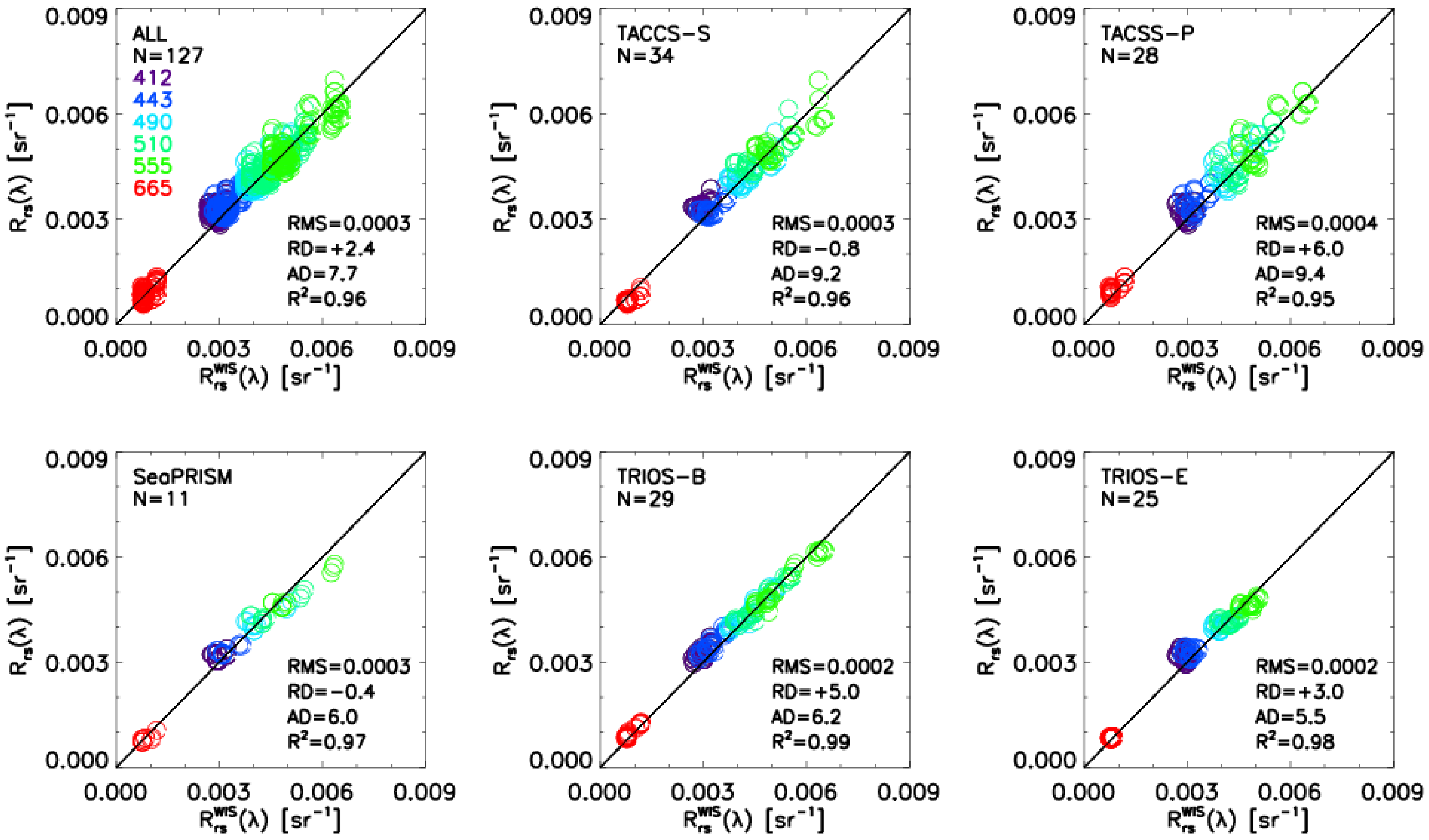
Field inter-comparisons

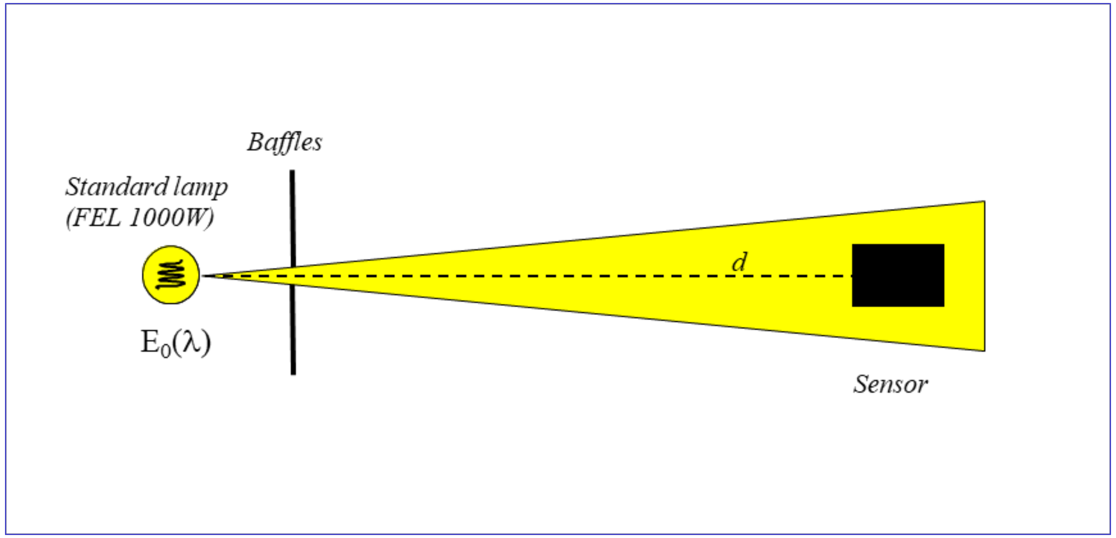


Field inter-comparisons, duly supported by laboratory calibrations and characterizations, offer a unique solution for the verification of protocols implementation and instrument performance.
They also offer an excellent way for know-how transfer.

Comparison of R_{RS} from a variety of above-water and in-water radiometer systems/methods with respect to the reference values determined with an in-water profiler system/method.

Zibordi, G., Ruddick, K., Ansko, I., Moore, G., Kratzer, S., Icely, J., & Reinart, A. (2012). In situ determination of the remote sensing reflectance: an inter-comparison. *Ocean Science*, *8*(4), 567-586

In-Air Absolute Irradiance & Radiance Calibrations



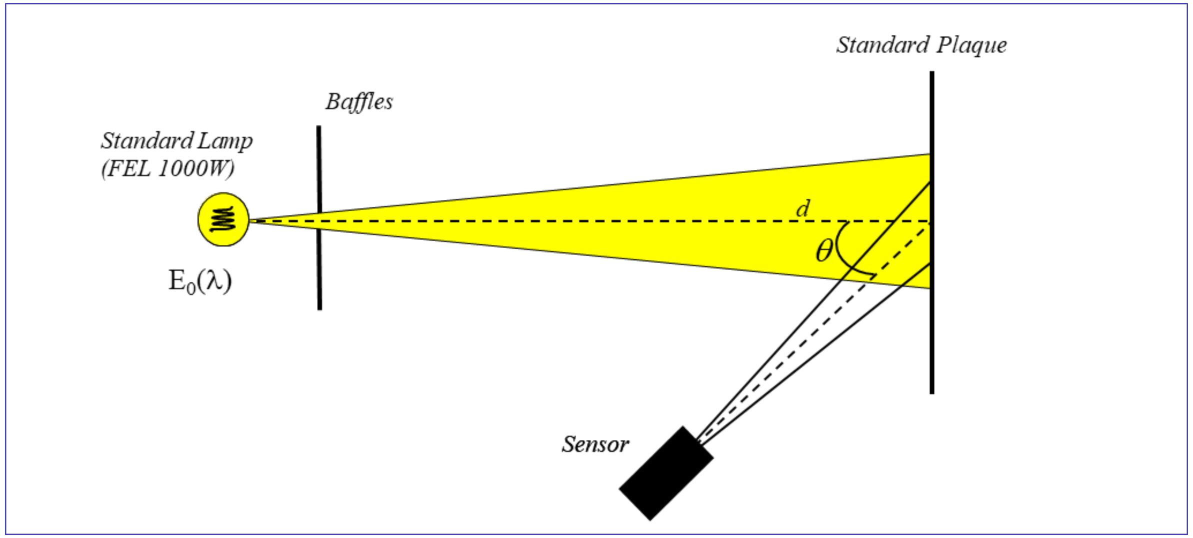
$$C_E(\lambda) = E_0(\lambda)\,(d_0/d)^2 \;/\; (D_N(\lambda)-D_0(\lambda))$$

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)*



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

C_L: *Calibration coefficient*

E_0: *Lamp Irradiance at distance d_0*

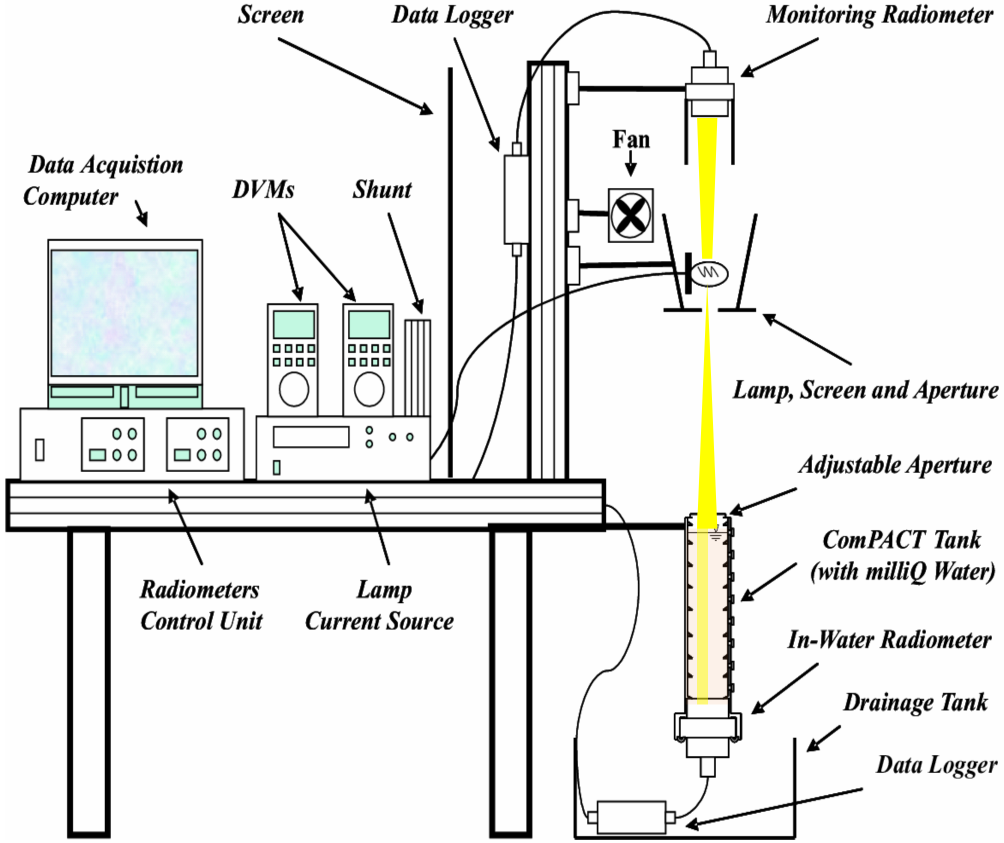
D_N: *Sensor output with the source at distance d from the Plaque*

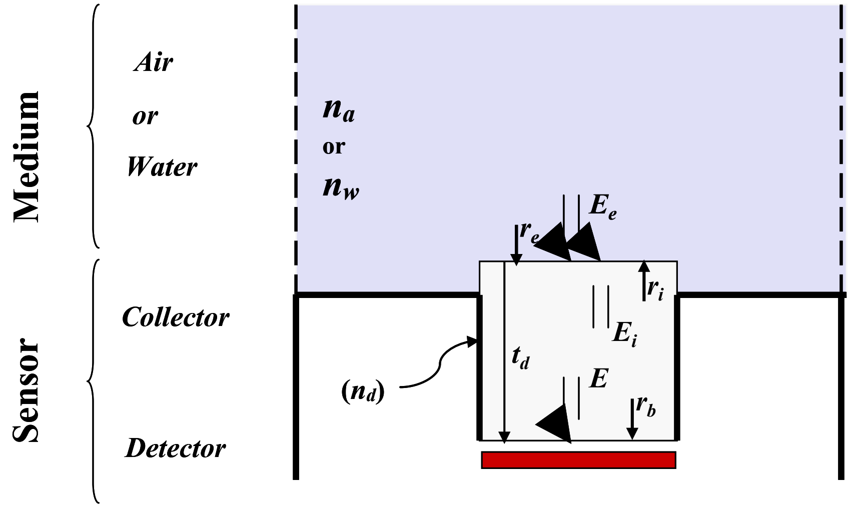
D_0: *Sensor output without any source (dark signal)*

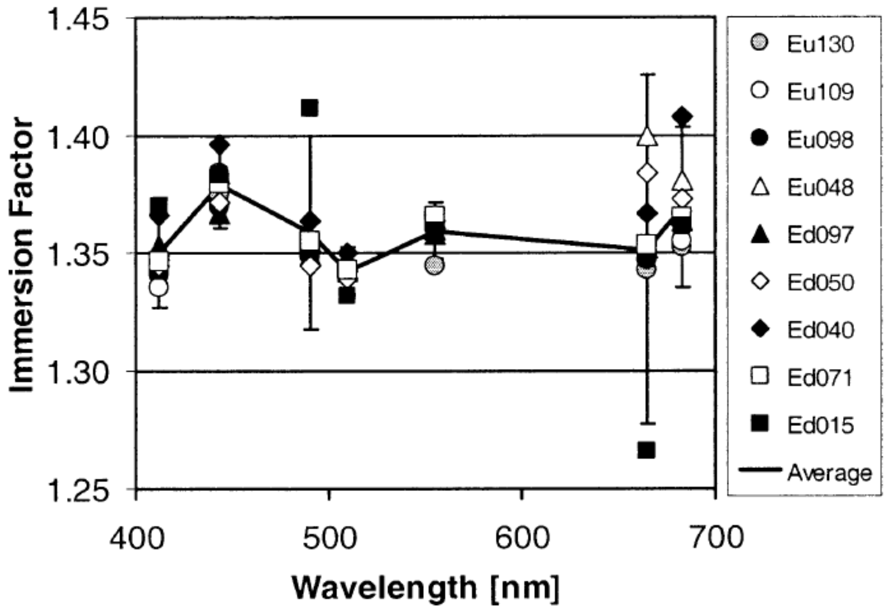
ρ : *Reflectance of the Standard Plaque*

c_p: *Correction factor for the Plaque (c_p=1 if lambertian)*

Immersion Factor I_f (irradiance)



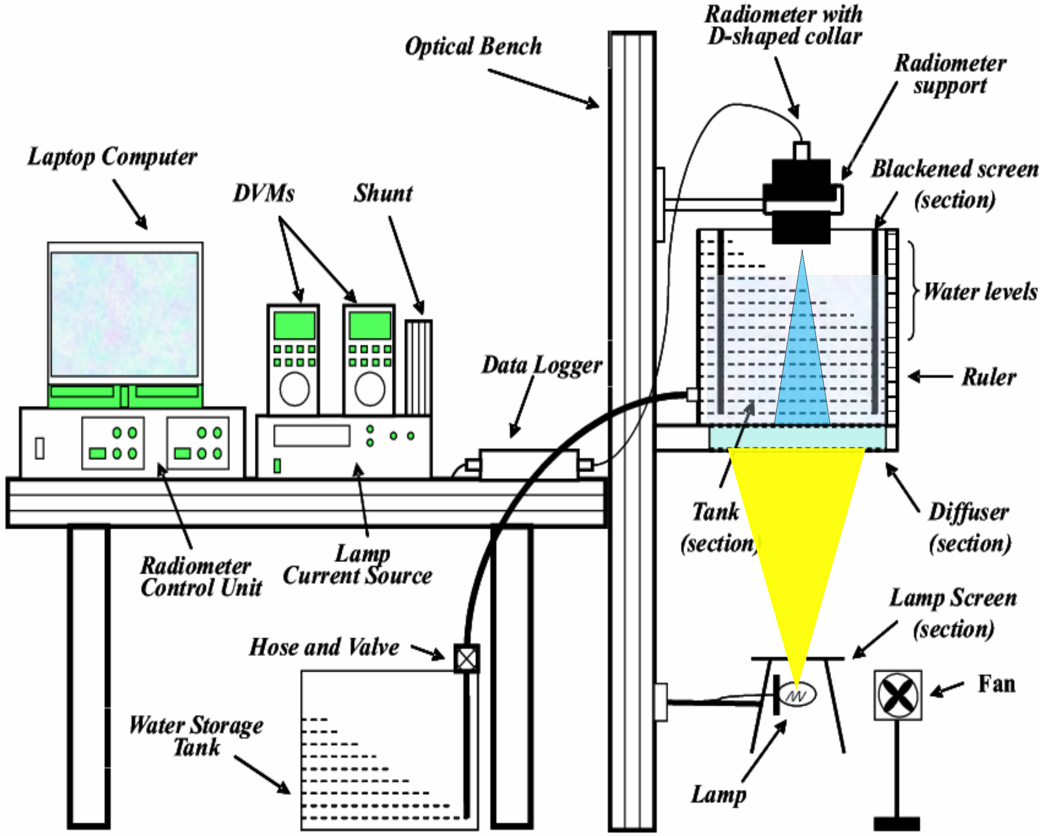


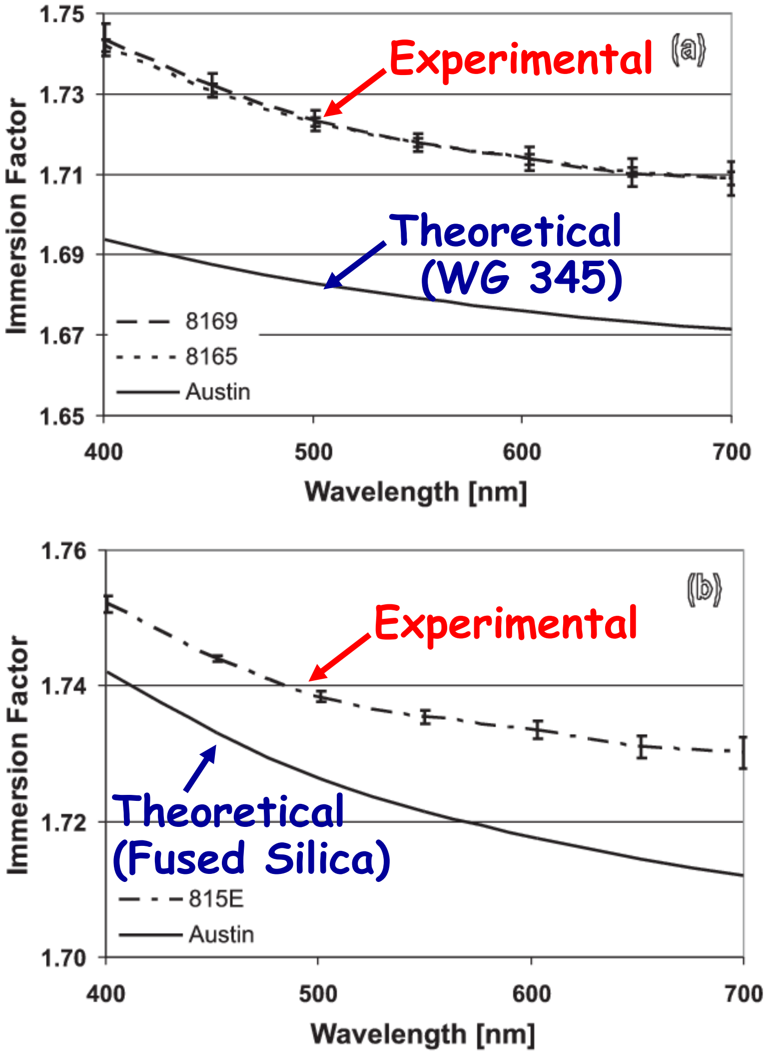


The immersion factor of irradiance sensors must be experimentally determined. It may vary by several percent from unit to unit because of mechanical/optical differences affecting collectors.

G.Zibordi et al. Characterization of the immersion factor … . Journal of Atmospheric and Oceanic Technology, 21:501-514, 2004.

Immersion Factor I_f (radiance)

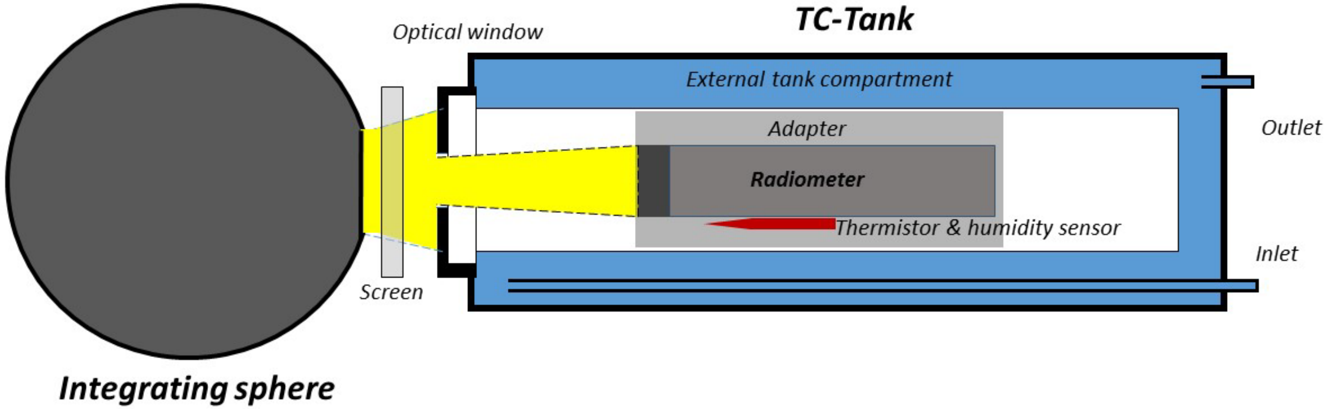




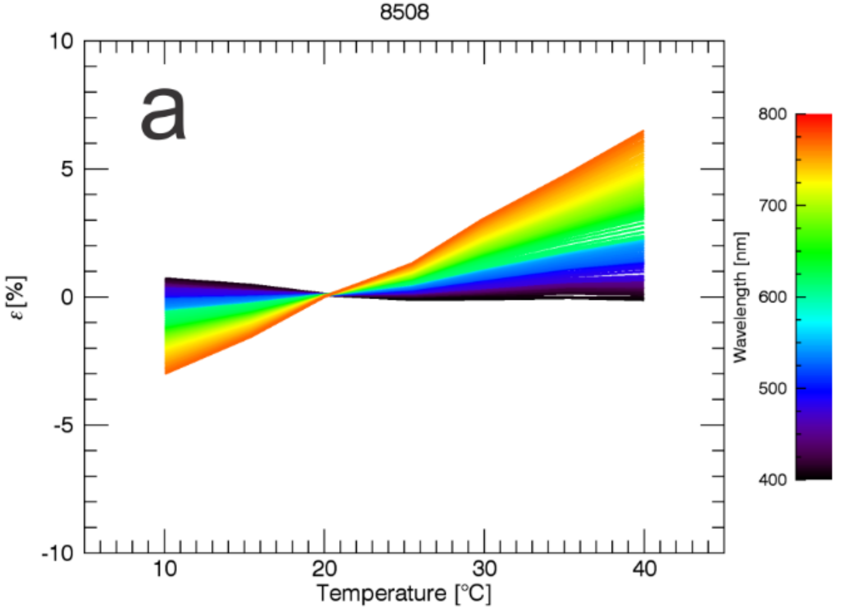
The immersion factor of radiance sensors can be computed. But class-based characterizations are strongly recommended for complex fore-optics.

G.Zibordi. Immersion factor of in-water radiance sensors … . *Journal of Atmospheric and Oceanic Technology*, 2006.

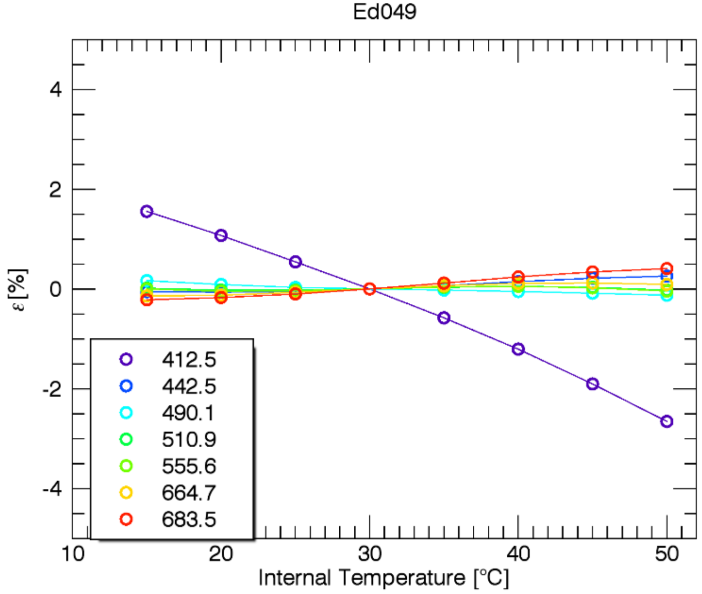
Temperature response



Change in response with temperature



RAMSES



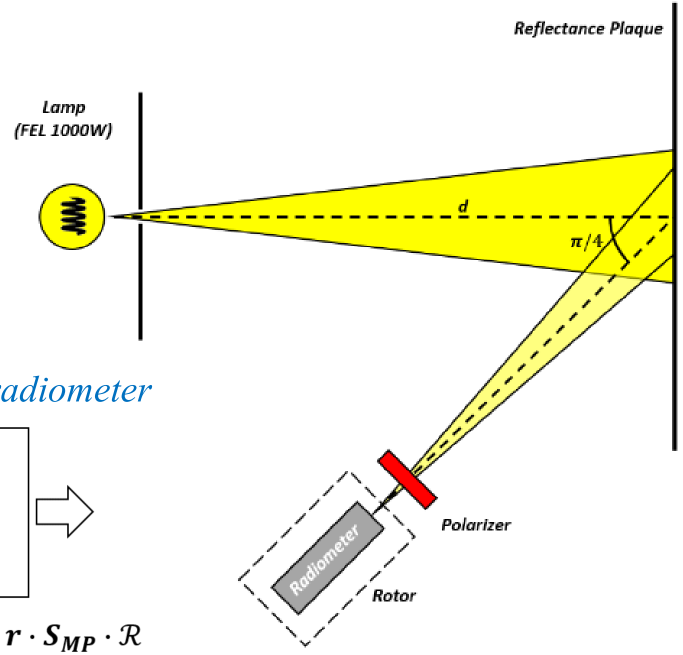
OCR-507

Temperature response is often overlooked. Unapplied corrections may become the source of intra-band inconsistencies.

Zibordi, G., et al., 2017. Response to Temperature of … . Journal of Atmospheric and Oceanic Technology, 34(8), pp.1795-1805.

Polarization sensitivity

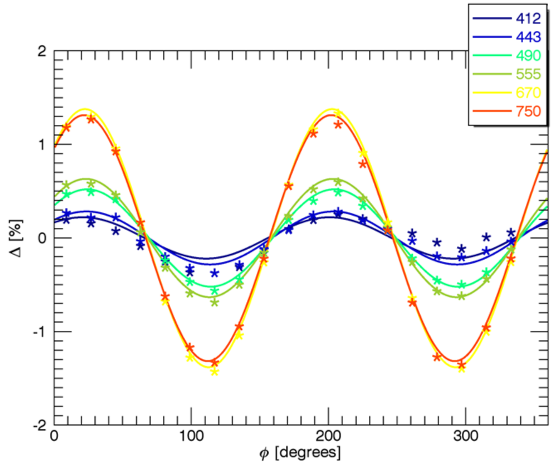
Measurement configurations applied for the determination the polarimetric characteristics of radiance sensors



Flow diagram for the determination of the polarimetric characteristics of a radiometer

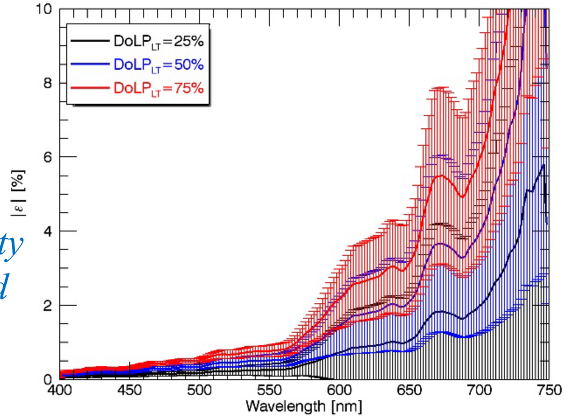
SOURCE → POLARIZER $\boldsymbol{P}(s,d,p,q)$ → ROTOR $\boldsymbol{M}(\phi)$ → RADIOMETER $\boldsymbol{r}(R_{00},r_1,r_2,r_3),\mathcal{R}$ →

$\boldsymbol{S}$ $\quad$ $\boldsymbol{S_P} = \boldsymbol{P}\cdot\boldsymbol{S}$ $\quad$ $\boldsymbol{S_{MP}} = \boldsymbol{M}\cdot\boldsymbol{S_P}$ $\quad$ $\boldsymbol{DN} = \boldsymbol{r}\cdot\boldsymbol{S_{MP}}\cdot\mathcal{R}$



Difference in polarization sensitivity across rotation planes of RAMSES hyperspectral radiometers

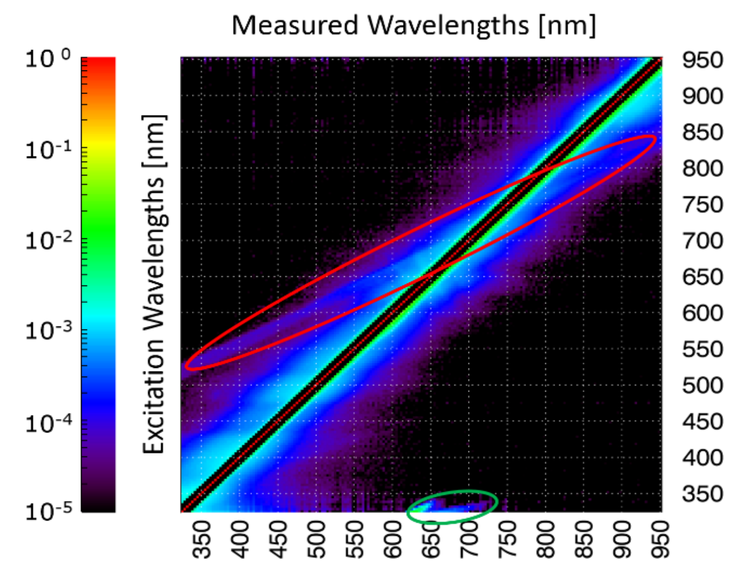
Impact of polarization sensitivity in R_{RS} measurements performed with RAMSES hyperspectral radiometers



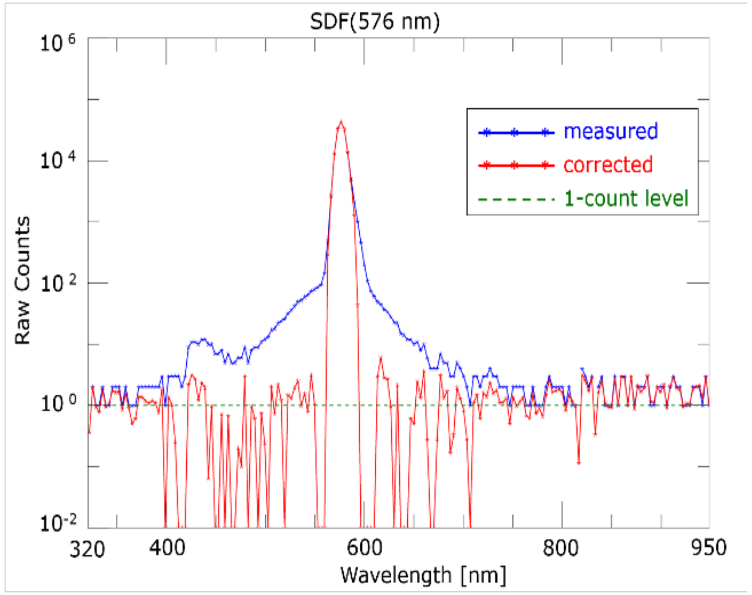
Light is polarized. Appreciable polarization sensitivity of radiometers due dispersive components (e.g., diffraction gratings) should be corrected.

Talone, M. and Zibordi, G., 2016. Polarimetric characteristics of … . Applied Optics, 55(35), 10092-10104.

Straylights perturbations

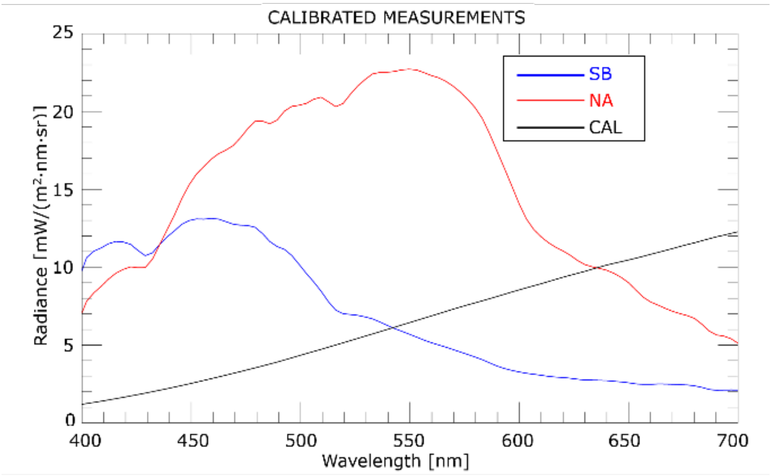


Stray light distribution matrix

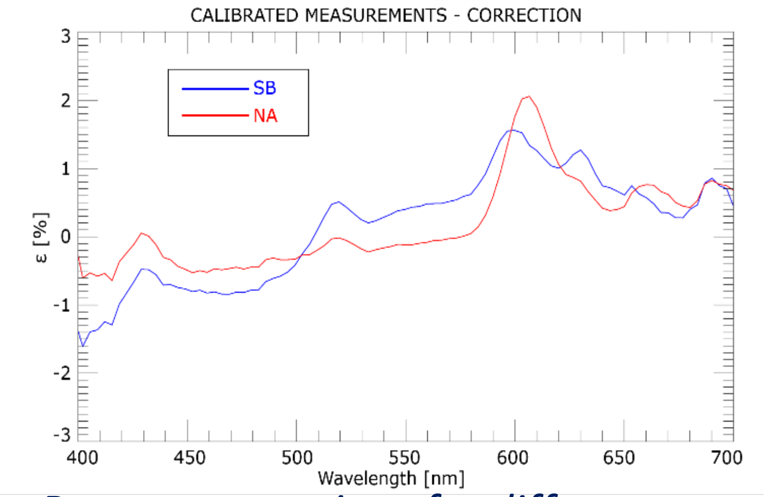


Line spread function

Internal instrument reflections or scattering, if not corrected, may lead to significant spectral artefacts.



L_T for different waters



Percent corrections for different waters

Talone, M., Zibordi, G., Ansko, I., Banks, A.C. and Kuusk, J., 2016. Stray light effects in above-water remote-sensing reflectance … . Applied optics, 55(15), pp.3966-3977.

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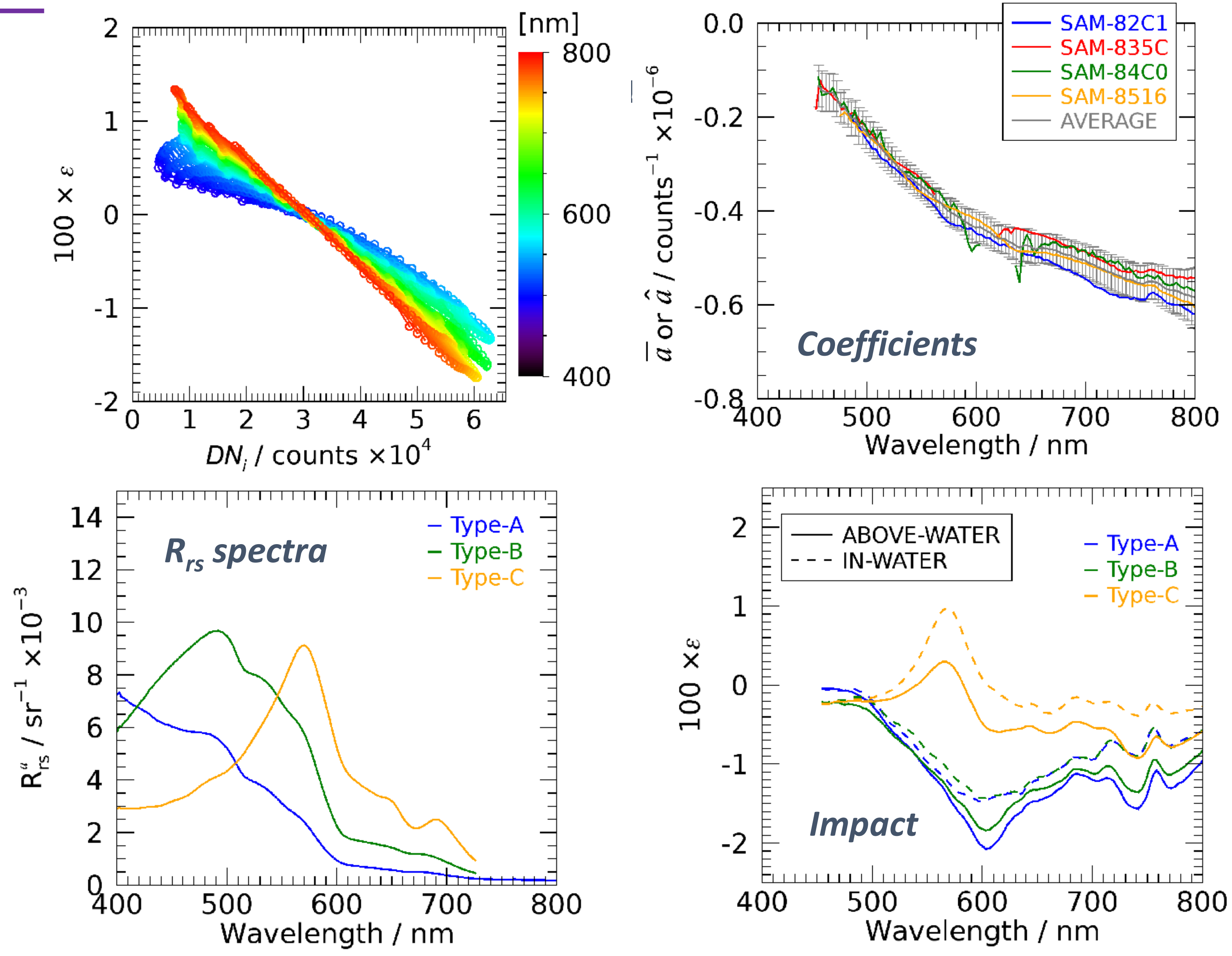
Nonlinearity of Response

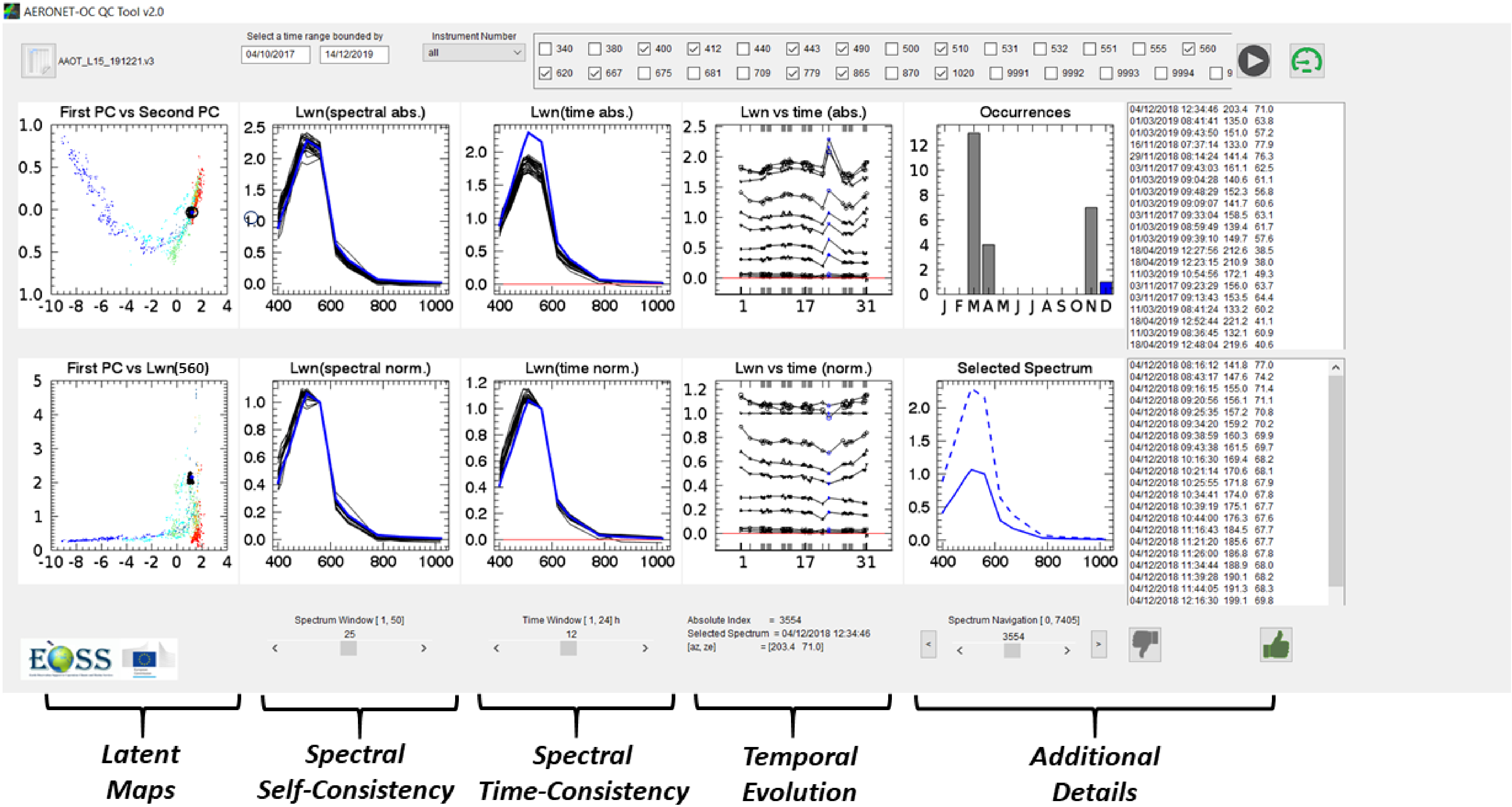


Finally, non-linearity of response may also become the source of measurement artefacts.

Talone, M. and Zibordi, G., 2018. Nonlinear response of a class of hyper-spectral radiometers. *Metrologia.*

Joint Research Centre

Expert Based QC



Zibordi, G., Holben, B. N., Talone, M., D'Alimonte, D., Slutsker, I., Giles, D. M., & Sorokin, M. G. (2021). Advances in the ocean color component of the aerosol robotic network (AERONET-OC). *Journal of Atmospheric and Oceanic Technology*, *38*(4), 725-746