Copernicus FRM4SOC FICE 2025

Training on
In Situ Ocean Colour Radiometry

Above-water radiometry procedures

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FRM4SOC Phase-2 | fiducial reference measurements for satellite ocean colour

CNR ISMAR ISTITUTO DI SCIENZE MARINE

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Quality assurance

Quality assurance (QA) entails actions leading to the correct execution of measurements.

Quality assurance practices imply:
i. ensuring pre- and post-field calibration to any component of the measurement system,
ii. putting efforts into proper installing the equipment,
iii. correctly implementing measurement protocols, and in general
iv. taking any action leading to the execution of measurements free from operational mistakes and only marginally affected by environmental perturbations (*e.g.*, wave and cloud perturbations, changes in illumination conditions and optical properties of water).

Quality assurance hints

Field radiometers must have been calibrated and ideally characterized

- *Pre- and post deployment calibrations are performed*

Accurate control of the measurement geometry

- *Appropriate viewing and azimuth angles are applied to avoid vanishing measurement efforts (e.g., the 135° relative azimuth angle may increase shading perturbations)*

Minimization of perturbations by the deployment structure

- *L_T measurements must not be affected by ship wakes*
- *L_T measurements must be collected well away from the superstructure*

Avoidance of critical environmental conditions

- *Cloudiness and extreme sea state vanish measurement efforts*

Dark signal recording

- *Allowing for the verification of the instrument performance and essential for dark signal corrections, which depend on temperature.*

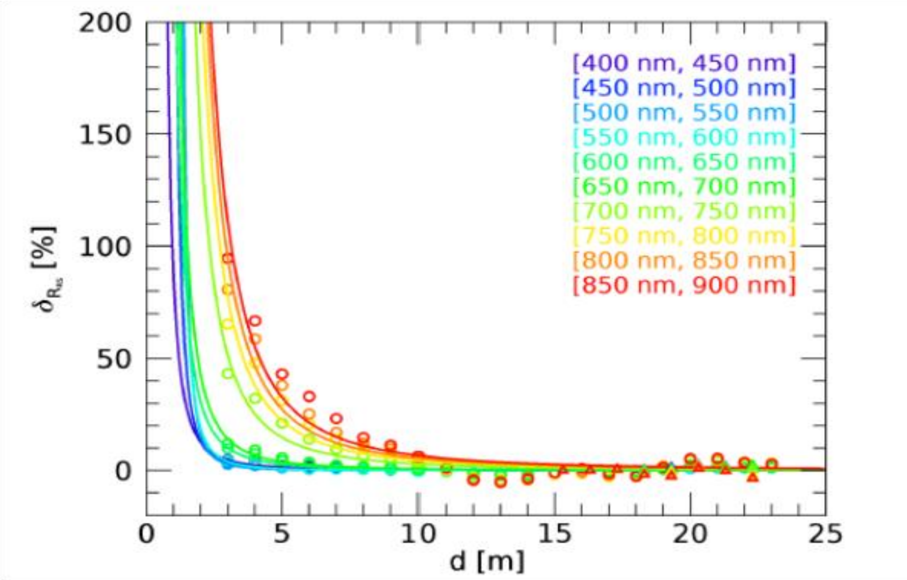
On the deployment geometry

The location of L_i and L_T radiometers must be chosen to *ensure measurements from a position that minimizes the impact of shading, reflection and surface perturbations by the superstructure*. On ships, there should be an attempt to profit of a pole allowing to deploy L_i and L_T radiometers at some height or distance. A favourable measurement location is generally offered by the bow.

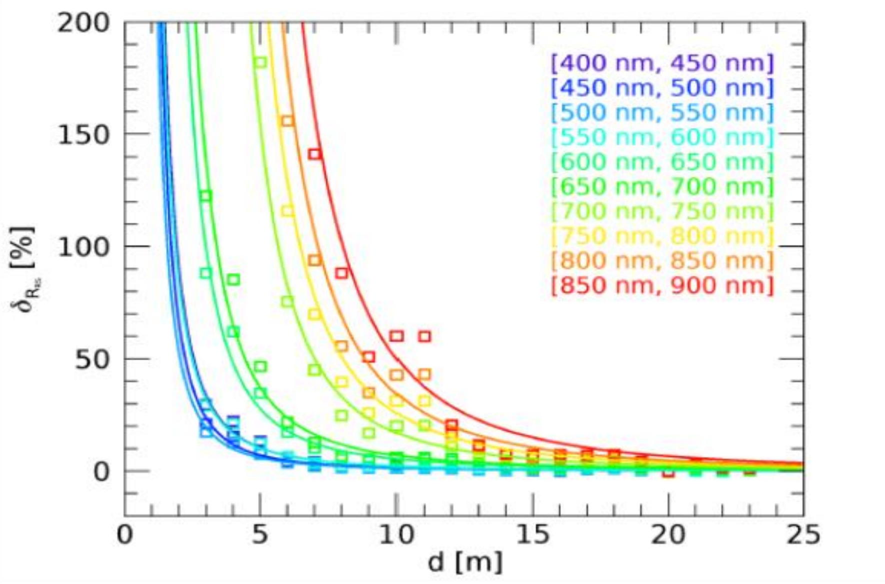
Assuming a suitable measurement geometry obtained with the sun azimuth normal to the port or starboard sides, *the L_T radiometer should look at portions of the sea undisturbed by ship wakes*. Still allowing for some flexibility in the measurement geometry, *it is essential that the heading direction of the ship allows for the L_T radiometer to view the sea surface at a distance at least larger than the superstructure height* (Hooker *and* Morel 2003, Hooker *and* Zibordi 2005, Talone and Zibordi 2019). This requirement often implies restricting the data collection to within specific azimuth limits with respect to the ship heading.

Superstructure perturbations affecting above-water radiometric data may naturally exhibit a spectral dependence with relative effects more pronounced in the red and near-infrared.

Perturbations by deployment structures



Impact of actual reflectance of the superstructure



Impact of an enhanced reflectance

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

Acquisition protocols

Measurement geometry

- *Must be supported by community shared consensus (see also QA requirements)*

Measurement sequence

- *Simultaneous measurements of E_S, L_T and L_i are desirable, but not a firm requirement during clear sky*

Requirements on data records

- *The number of E_S, L_T and L_i measurements must satisfy processing needs*

Requirements for quality control

- *Replicated measurement sequences are often the best support to quality control (see QC)*

On data reduction and processing

Above-water measurement sequences, performed during clear sky conditions, comprise:

N_T sea-radiance measurements for determining $L_T(\theta,\phi,\lambda)$;

N_i sky-radiance measurements for determining $L_i(\theta',\phi,\lambda)$; and

(simultaneous) measurements of the downward irradiance $E_s(\lambda)$.

N_i and N_T do not need to be identical when assuming stability of the sky-radiance during the execution of each sequence.

A relatively large number of N_T measurements (i.e., tentatively a few tens) is important to statistically address environmental perturbations.

Raw data are converted to physical units accounting for absolute radiometric calibration coefficients and any additional characterization factor. *Substantial differences in successive absolute radiometric calibration coefficients, such as those determined before and after deployments lasting more than a few weeks, must be carefully evaluated. Justified and significant differences, (e.g., larger than 2%) should lead to their interpolation as a function of time.*

For each measurement sequence performed during ideal illumination conditions, $L_i(\theta',\phi,\lambda)$ can be determined by the average of the N_i sky-radiance data. Conversely, $L_T(\theta,\phi,\lambda)$ should be subject to quality control tests aiming at minimizing the impact of environmental perturbations.

Ancillary data

Latitude/longitude/time

- *Time must be in GMT*

Instrument roll/pitch and ship heading

- *Required to flag poor measurement conditions*

E_S and E_i contributions

- *Required to correct for non-cosine response of E_S sensors*

Wind speed and likely direction

- *Required to determine most appropriate ρ-values*

Aerosol optical depth

- *For a better exploitation of most advanced ρ-tables*

Instrument working (ambient) temperature

- *When not directly available from the radiometers themselves*

Sea/sky conditions

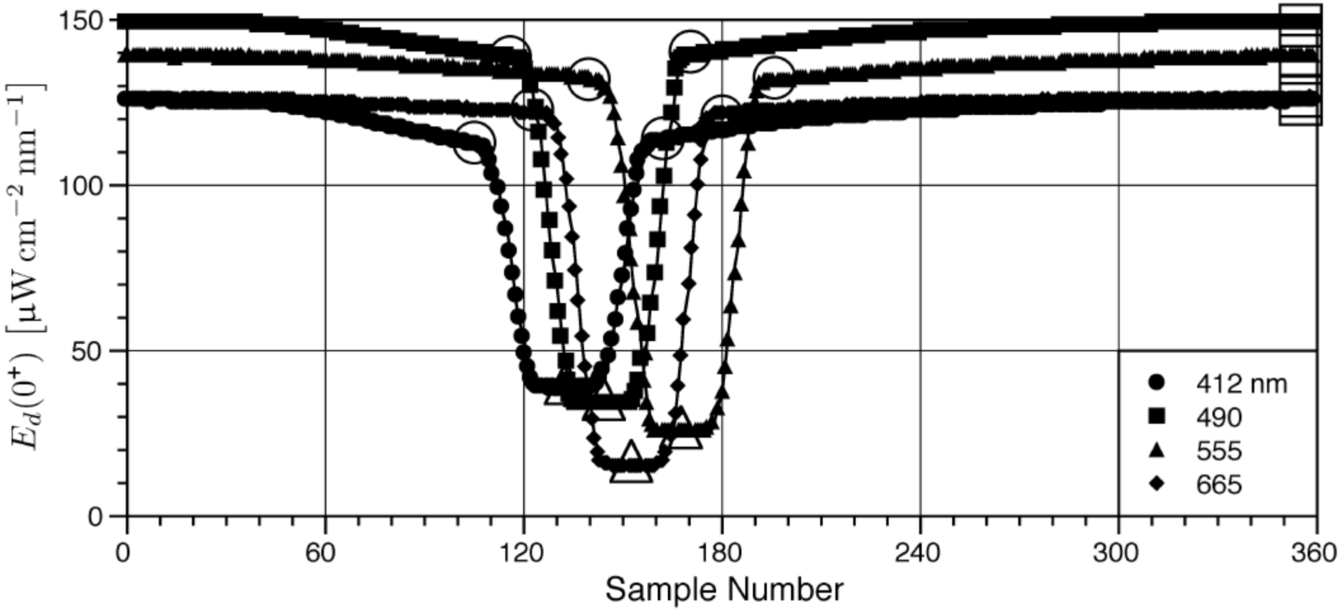
- *To qualitatively support analysis of dubious cases*

Salinity

- *To determine the refractive index of water*

On E_S and E_i measurement and application

E_s irradiance sensors operated in conjunction with a rotating shadow-band.

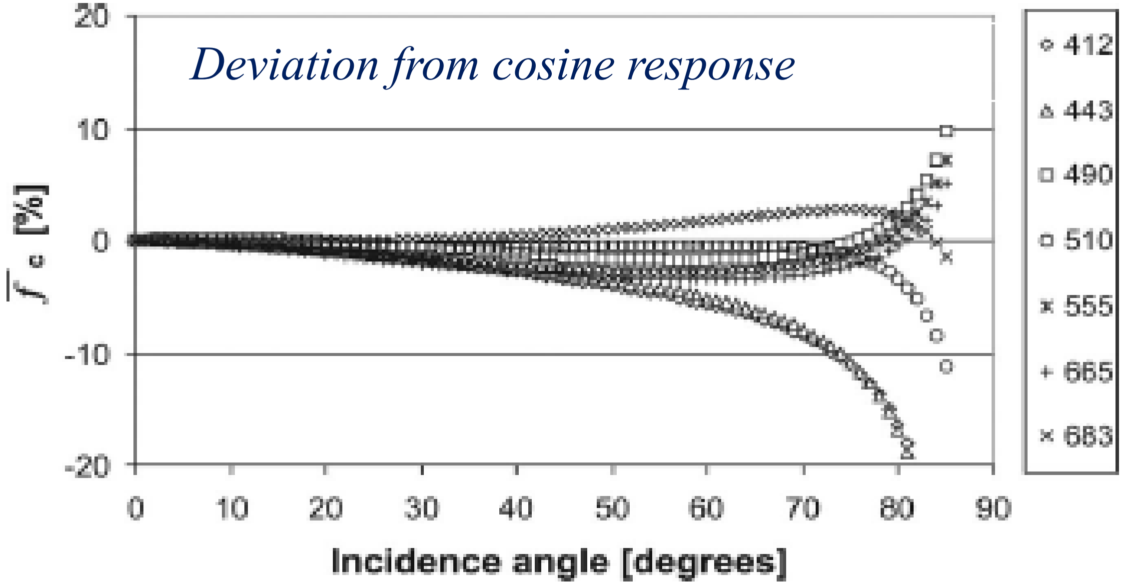


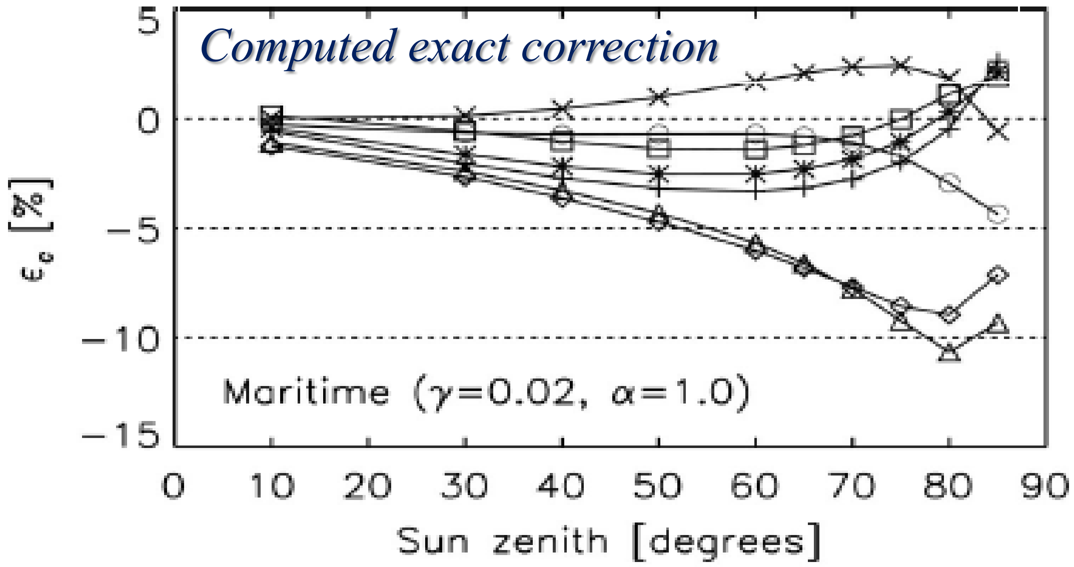
E_s and E_i irradiance measurements performed during a rotation cycle of the shadow-band.

Zibordi G., Berthon J-F., Doyle J.P., Grossi S., van der Linde D., Targa C. and Alberotanza L., 2002: Coastal Atmosphere and Sea Time Series (CoASTS), Part 1: A Tower-Based Long-Term Measurement Program. NASA Tech. Memo. 2002–206892, Vol. 19, S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 29 pp.

Hooker S.B., G. Zibordi, J-F. Berthon, D. D'Alimonte, D. van der Linde and J.W. Brown, 2003: Tower-Perturbation Measurements in Above-Water Radiometry. NASA Tech. Memo. 2003–206892, Vol. 23, S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space Flight Center, Greenbelt, Maryland, 35 pp.

Correcting for the non-cosine response



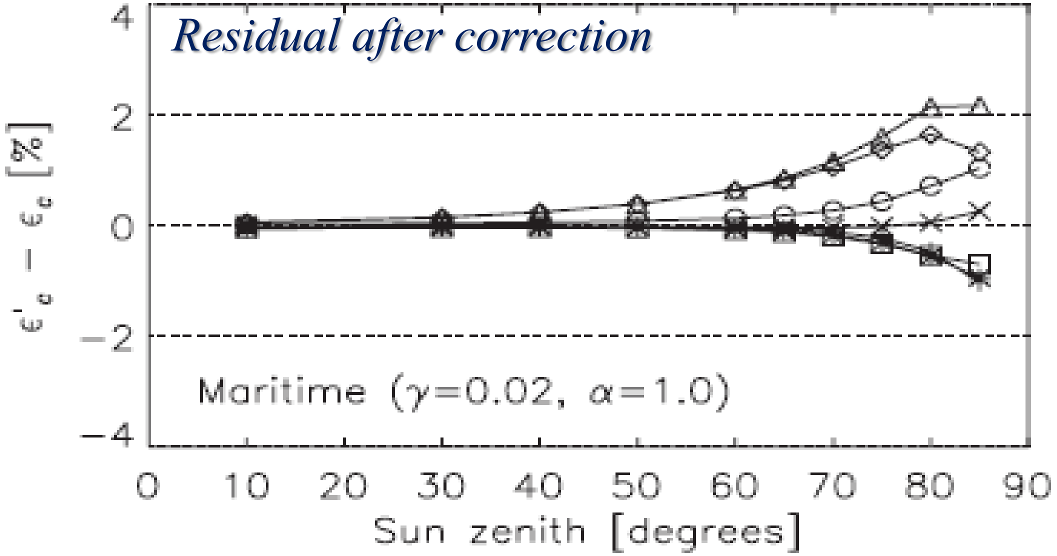


Diffuse isotropic component

Direct component

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

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

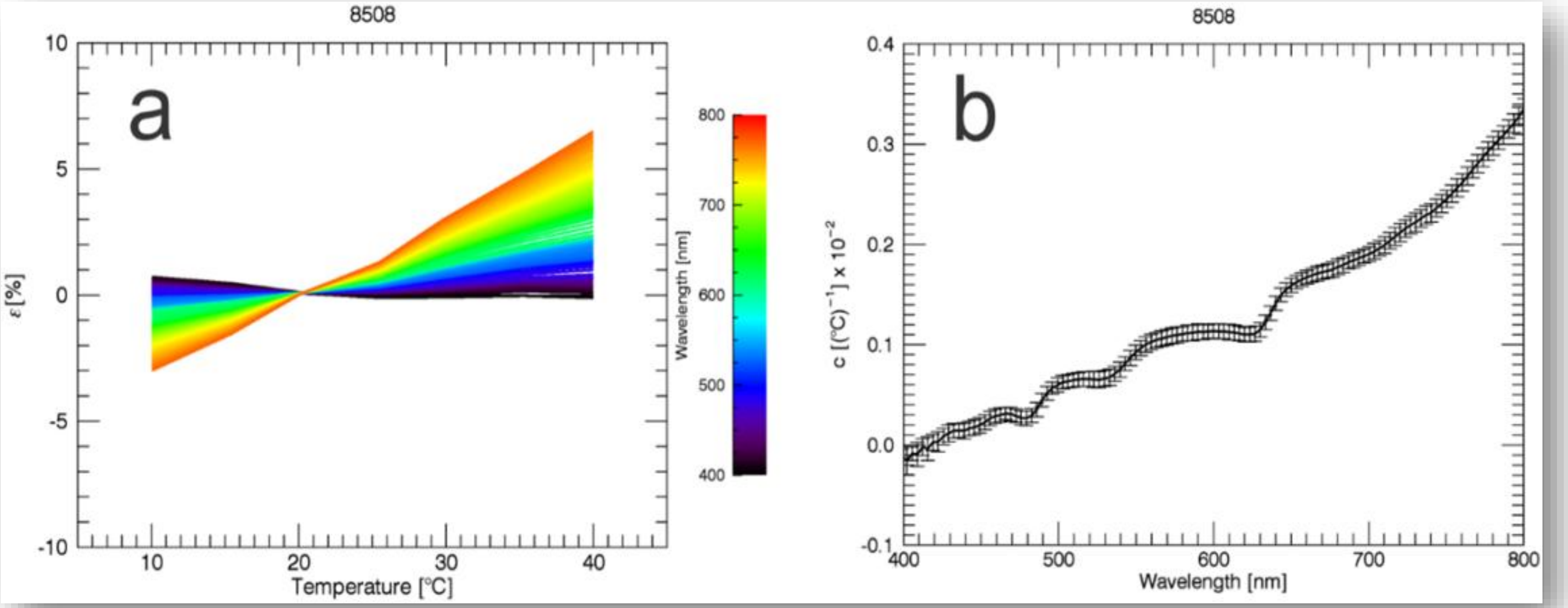


ε'_c= estimated error due to non-cosine response

I_r= diffuse to direct irradiance ratio $E_i/(E_s-E_i)$

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

How to practically address changes in ambient temperature



(a) Relative change in spectral response ε in % as a function of temperature determined with respect to the reference response at temperature T=20°C

(a) Temperature coefficient $c(\lambda)$ in units of $(°C)^{-1}$ for an hyperspectral radiometer

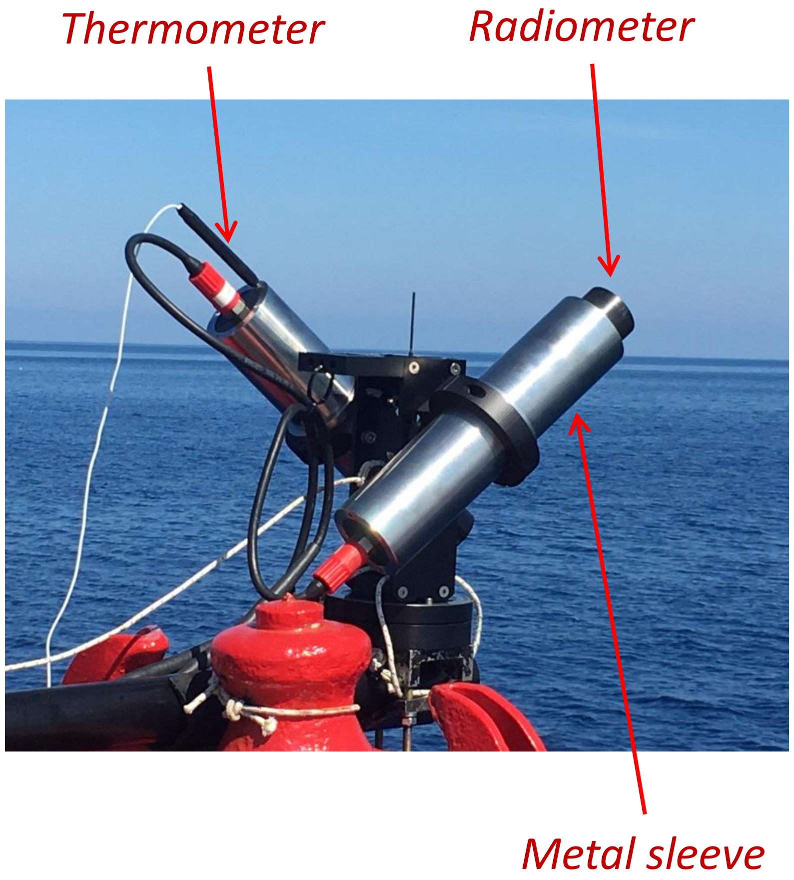
Zibordi, G., Talone, M., & Jankowski, L. (2017). Response to temperature of a class of in situ hyperspectral radiometers. Journal of Atmospheric and Oceanic Technology, 34(8), 1795-1805.

On ambient temperature

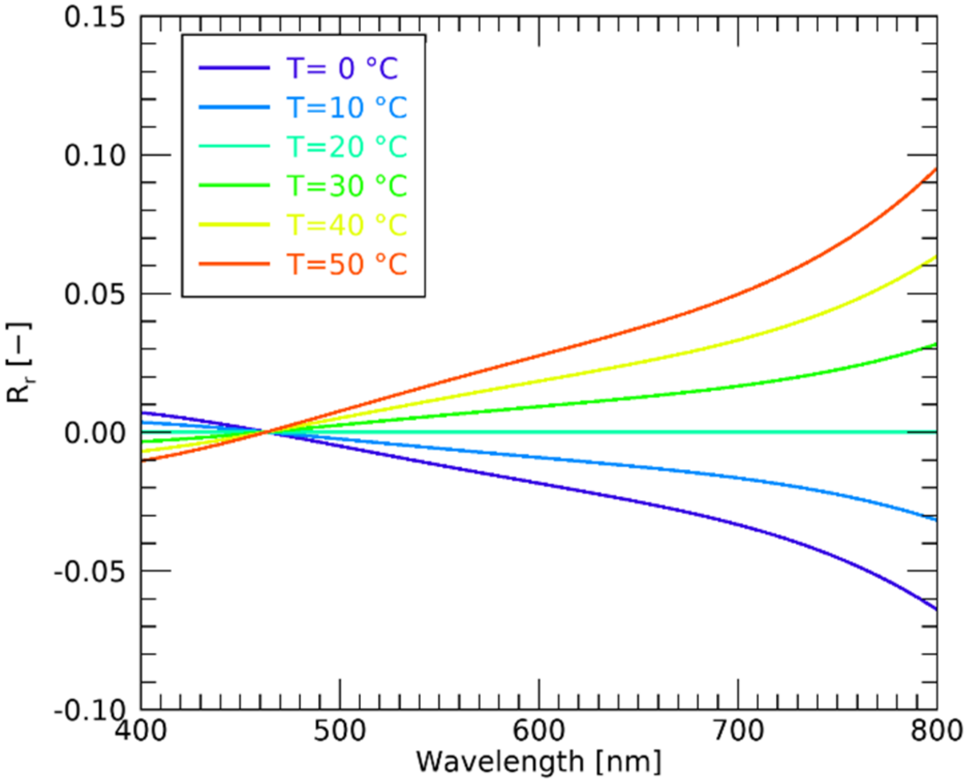
Ambient temperatures representative of the radiometer working temperature (i.e., the external temperature at which the radiometer is in thermal equilibrium), cannot be generically assumed equal to the air temperature. In fact the direct sun-light hitting the radiometer would definitively impact its working temperature, which may vary across each radiometer of the same system.

Ambient temperature may largely affect the response of optical sensors. When sensors do not allow for an automatic determination of the internal working temperature (*i.e.*, in the absence of an internal thermistor), still dedicated corrections should be envisaged.

A practical solution allowing to reliably correct for temperature response is achievable by increasing the thermal capacity of the radiometer through an external sleeve made of material having the same thermal coefficient of the radiometer case, and then considering as ambient temperature that measured inside the sleeve in the proximity of the radiometer case.

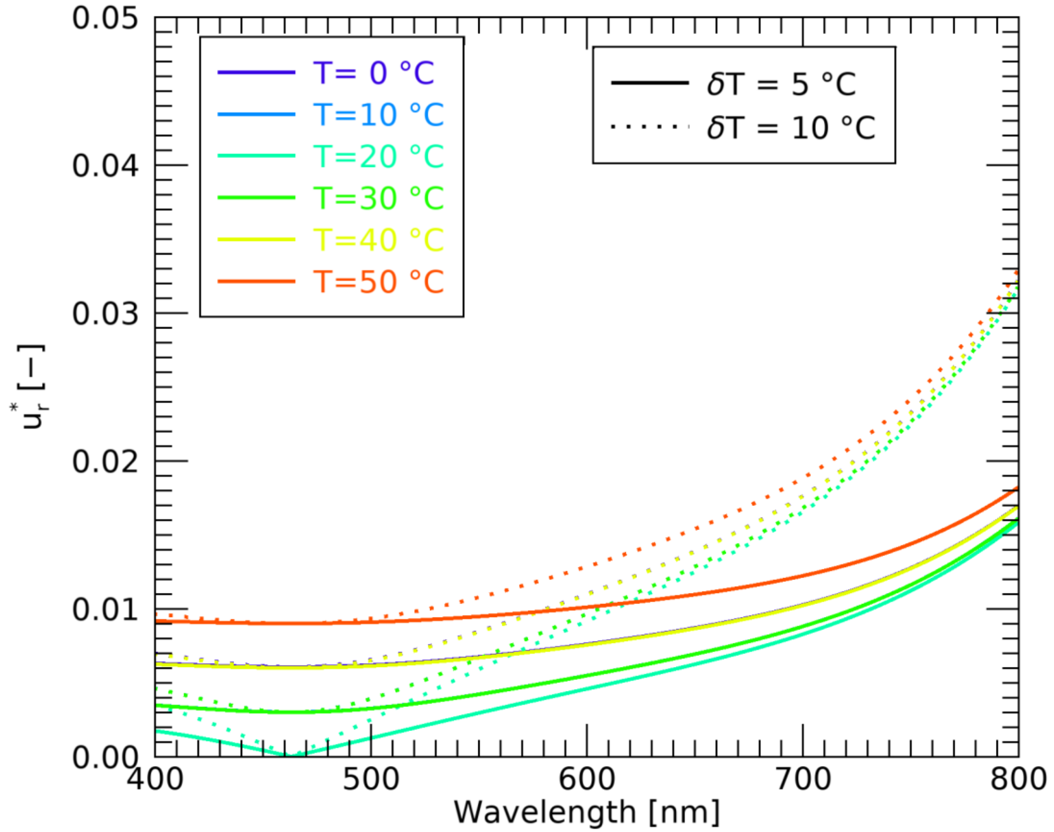


Corrections for temperature dependence



The relative spectral change affecting radiometric values due to the difference ΔT between the working temperature T and the laboratory one $T_0 = 20$°C (with $\Delta T = T - T_0$):

$$R_r(\lambda, \Delta T) = c(\lambda) \times \Delta T$$

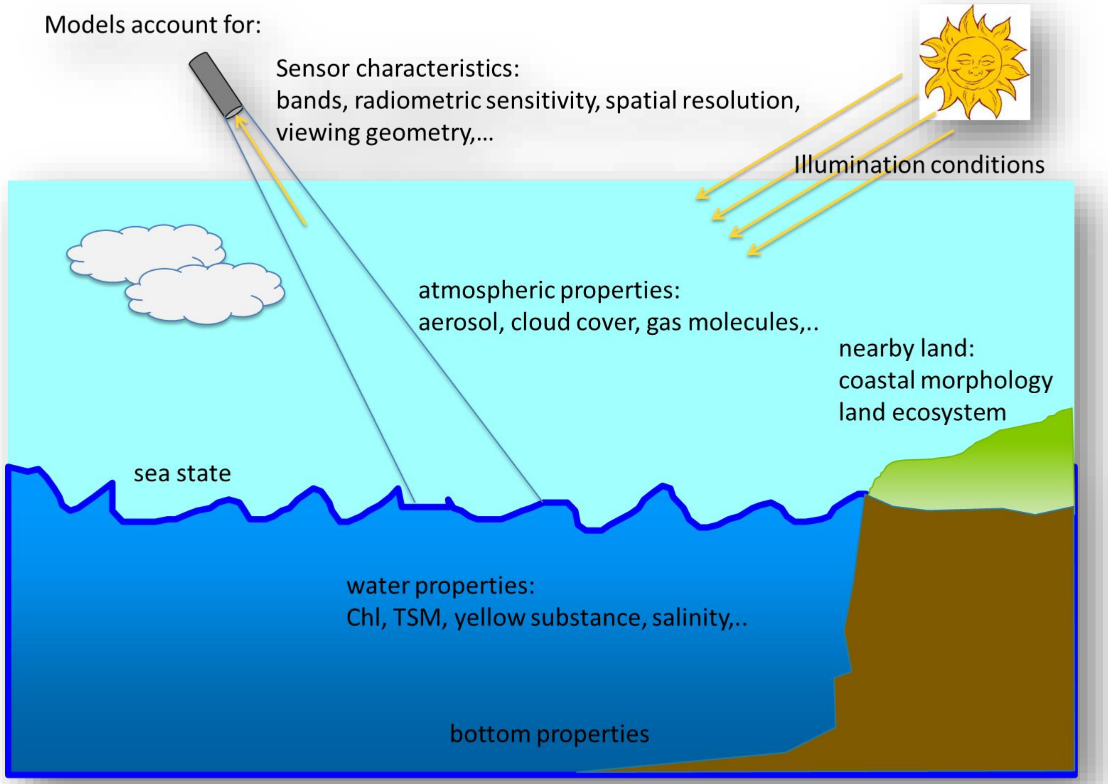


Combined uncertainty for $R_r(\lambda, \Delta T)$:

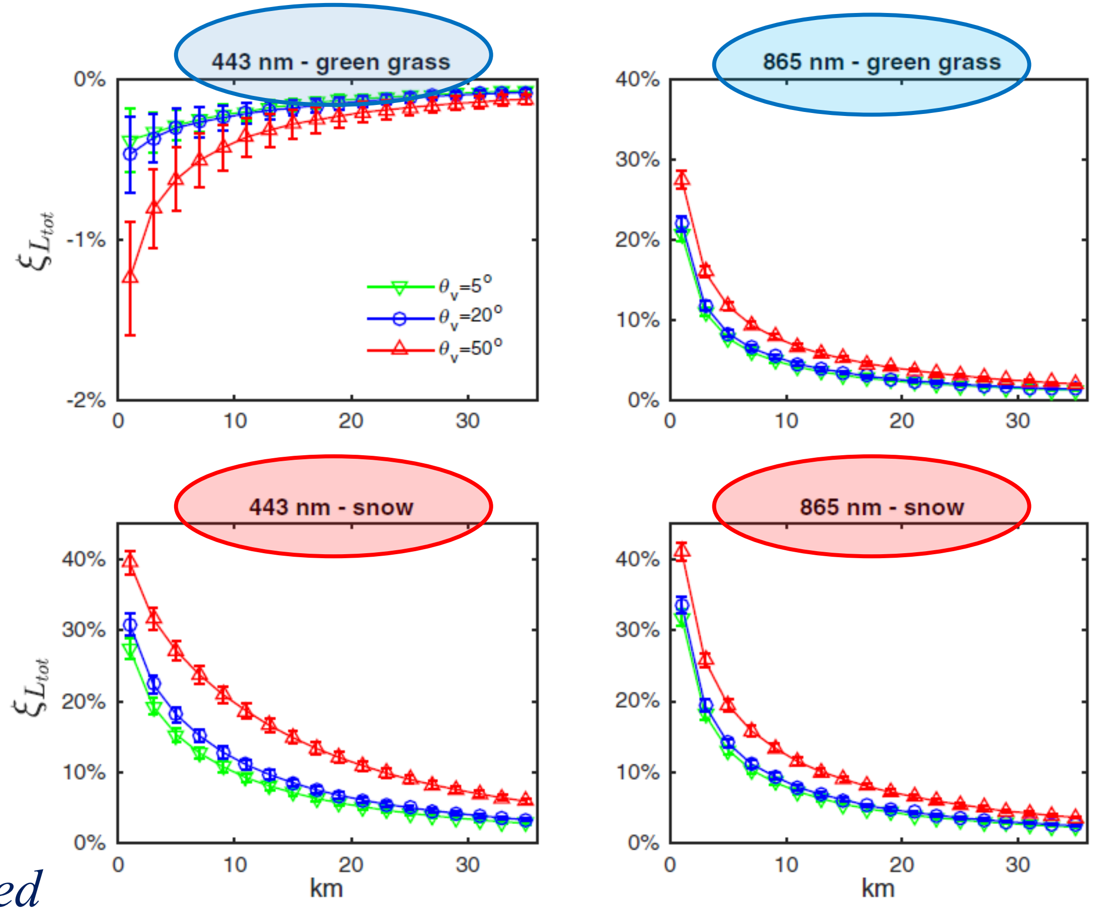
$$u_r^*(\lambda, \Delta T, \delta T) = [\varepsilon_c(\lambda, \Delta T)^2 + \varepsilon_T^*(\lambda, \delta T)^2]^{1/2}$$

Zibordi, G. & Talone, M. (2017). Operational correction for the temperature dependence of a class of hyperspectral radiometers . Journal of Atmospheric and Oceanic Technology, submitted.

Avoiding adjacency perturbations (when possible)



In situ reference measurements should be ideally collected at tens of nautical miles from the coast to ensure match-ups analysis not significantly affected by adjacency perturbations.



Adjacency perturbations at the satellite sensor as a function of the distance from the coast.

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.

Quality control

Quality control (QC) practices include all post-measurement actions supporting the provision of high-quality data (where the quality of data must satisfy application needs).

Quality control entails any step aiming at flagging questionable data products such as those exhibiting:
i. measurement geometry not fulfilling protocol requirements,
ii. appreciable negative values in the blue and/or red spectral regions,
iii. large positive values in the near-infrared,
iv. unexplained spectral inconsistencies.

Logically, automated procedures embedded in data processing are quite essential for the quality control of datasets resulting from a large number of field measurements such as time-series from a variety of sites or multiple oceanographic campaigns.

Something more on quality control

A first QC test should exclude from processing all those measurement sequences not satisfying constrains on instrument performance, viewing geometry, environmental conditions and superstructure perturbations. This implies verifying that:

i. tilts affecting L_T, L_i and E_s sensors do not exceed predefined thresholds (tentatively 5° for $L_T(\theta,\phi,\lambda)$ and $L_i(\theta',\phi,\lambda)$ measurements, and ideally 1-2° for $E_s(\lambda)$, still allowing larger values for this latter when the sun zenith angles are low;

ii. the values of ϕ_0 are within limits minimizing superstructure perturbations in $L_T(\theta,\phi,\lambda)$;

iii. the wind speed W does not exceed 15 m s^{-1} (and more strictly 7 m s^{-1}) for meaningful ρ–factors.

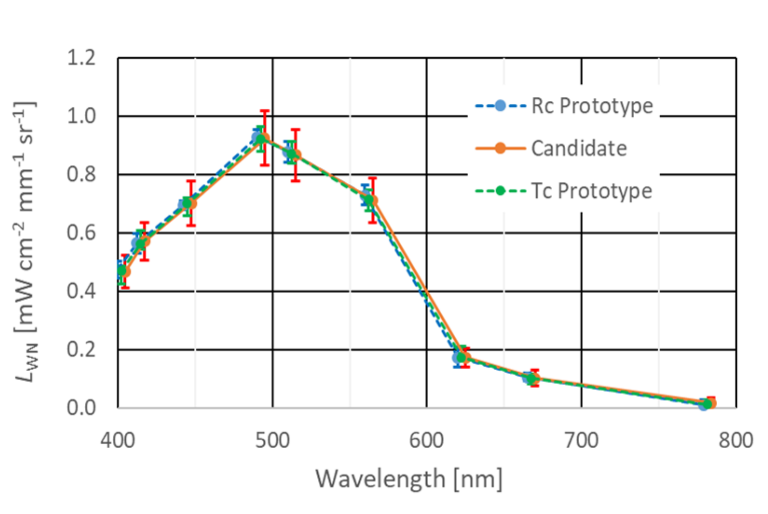
The N_T sea-radiance and N_i sky-radiance measurements should not exhibit high variability across individual measurement sequences, where:

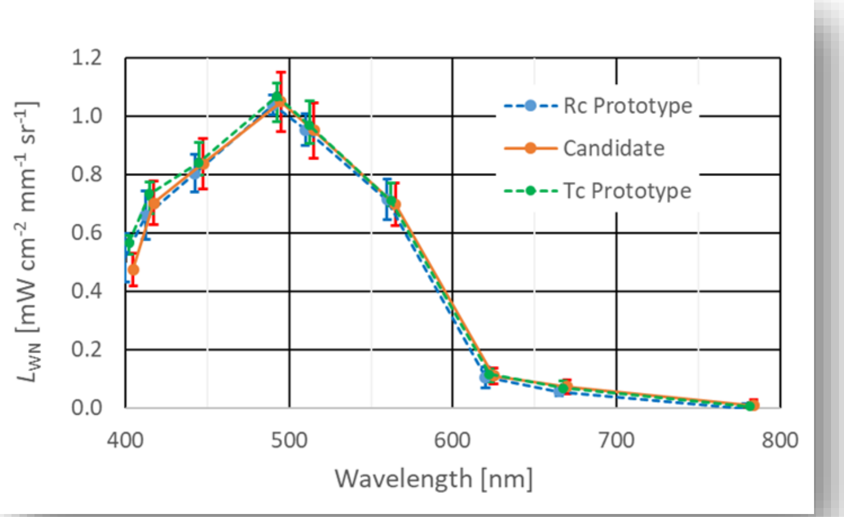
i. a high variability of sea-radiance measurements is generally explained by relatively high sea state, and additionally by low sun zenith angles and potential cloud perturbations; while

ii. a high variability of sky-radiance measurements is explained by cloudiness.

In view of minimizing the perturbing effects due to sun-glint or even foam contamination or clouds in $L_T(\theta,\phi,\lambda)$, and similarly exclude the potential for cloud perturbations in $L_i(\theta',\phi,\lambda)$, *data pre-processing should include quality control tests to remove measurement sequences exhibiting standard deviations above a given threshold for the N_T and N_i measurements.*

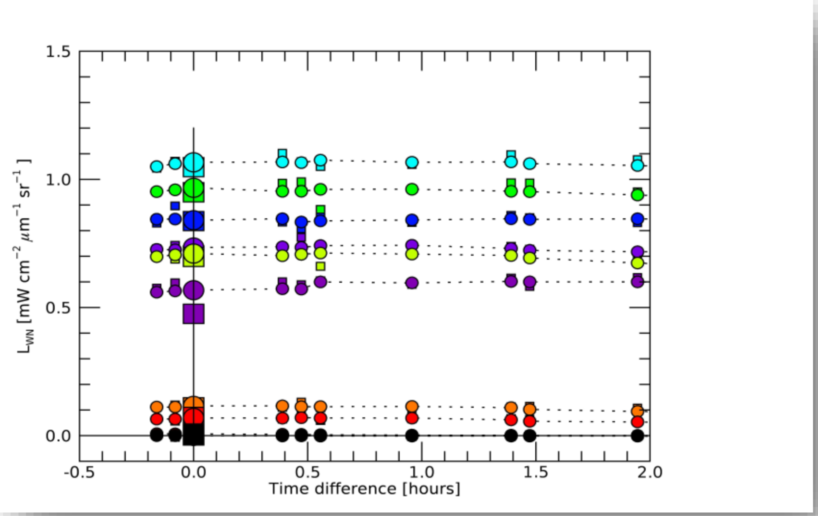
On the consistency of L_{WN} spectra





Rc: relative consistency evaluates the agreement within expected uncertainties between candidate and prototype spectra

Tc: temporal consistency evaluates the agreement within expected uncertainties between spectra within a given time interval



All comparisons rely on standard deviations or alternatively on uncertainties defined by confidence level k=1.

Zibordi, G., D'Alimonte, D., & Kajiyama, T. (2022). Automated quality control of AERONET-OC L WN data. *Journal of Atmospheric and Oceanic Technology*, *39*(12), 1961-1972.

On data processing, reprocessing and archival

Reprocessing of data often suggested by advances in methods and instruments re-calibration, is a fundamental need for any relevant measurement program.

This often overlooked need, requires an effective organization of
i. measurements,
ii. ancillary data and
iii. details on instruments absolute radiometric calibration and characterizations.

It is emphasized the importance of throughout assessments of processing codes through benchmarking. In fact, equivalent to the need for verifying the performance of calibration facilities through the inter-calibration of instruments, also code inter-comparisons are essential exercises to identify issues in protocol implementations.

The adoption of centralized data processors would help minimizing inconsistencies intrinsic of the application of independent data reduction solutions.

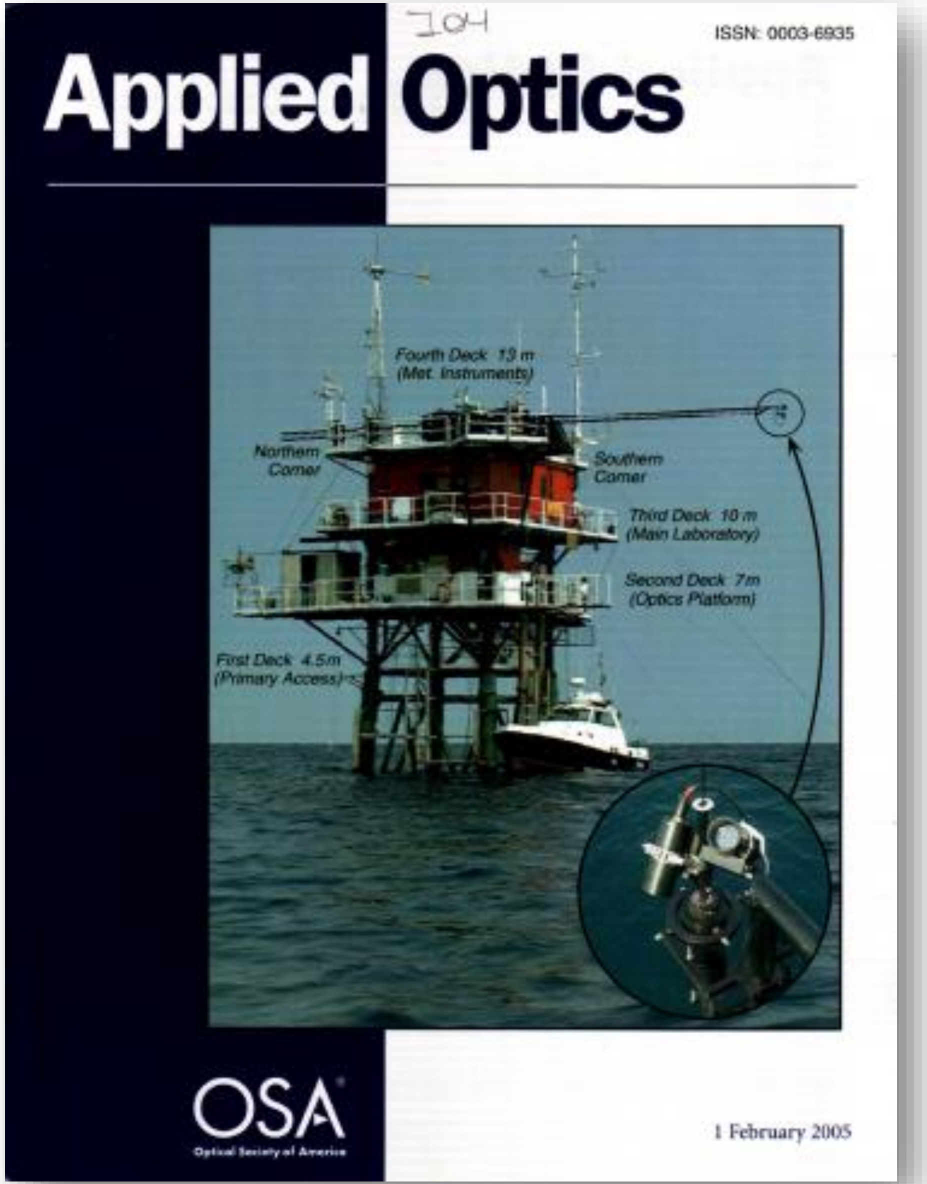
Timely and open access to data products is ultimately a fundamental need for any validation program. Because of this, in addition to the need for establishing, maintaining and continuously expanding repositories beyond any specific mission life, care should be put in imposing fair data policies facilitating access to data, but also granting recognition to data providers.

End

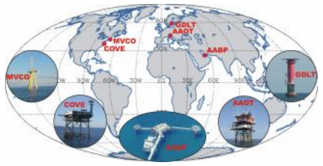
Above-water radiometry procedures

Outline

- Instruments configurations
  - One sensor
  - Three sensors
- Requirements for field sensors
  - Absolute radiometric calibration (for E_S, L_i and L_T)
  - Comprehensive radiometric characterization (cosine response, etc.)
- Quality assurance of field data
  - Minimization of perturbations by deployment structures
  - Accurate control of the viewing geometry
  - Avoidance of critical environmental/deployment conditions
  - Dark signal recording
- Acquisition protocols
  - Measurement sequence
  - Minimum requirements for data records
  - Requirements for quality control
- Ancillary data
  - Latitude/longitude/time(GMT)
  - Roll/pitch/heading
  - Sea/sky conditions
  - Es and Ei contributions



Validation Match-up Performance Matrix



Ranking (0-10) (0=lowest and 10 =highest)	*AERONET-OC (AAOT)*	*CoASTS (AAOT)*	*BiOMaP (ships)*
Measured Quantities	1	10	10
Matchups versus Deployment-Time	10	10	10
Accuracy	8	8	8
Temporal Representativity	10	2	1
Bio-optical Representativity	5	4	10
Matchups versus Funding	10	1	1
Overall mean	**6.8**	**6.0**	**6.7**

The cost per matchup:

less than 0.5 US K$

more than 10 US K$

more than 25 US K$

Instruments configurations and field requirements

One sensor

- More complex measurement sequence and the need to theoretically quantify E_s
- Minimum hardware requirements and simplified uncertainty analysis

$$L_{WN}(\lambda) = [L_T(\lambda, \theta, \varphi) - \rho(\theta, \varphi, \theta_0, W)\, L_i(\lambda, \theta', \varphi)] \cdot C_Q(\lambda, \theta, \varphi, \theta_0, W, \tau_a, IOP) \cdot C_A(\lambda, \theta, \tau_a, D)$$

$u(L_T)$: $u_{ac}(L_{T,i}), u_{sc}(L_{T,i}), u_{en}(L_T)$

$u(\rho)$

$u(L_i)$: $u_{ac}(L_{T,i}), u_{sc}(L_{T,i}), u_{en}(L_i)$

$u(C_Q)$

$u(C_A)$

Three sensors

- All quantities measured simultaneously
- Increased difficulty in handling uncertainties, however,

i. radiometers from the same production-series may benefit for class-based characterizations

ii. calibrations relying on the same reference sources would reduce uncertainties in the combined quantities

$$L_{WN}(\lambda) = [L_T(\lambda, \theta, \varphi) - \rho(\theta, \varphi, \theta_0, W)\, L_i(\lambda, \theta', \varphi)] \cdot C_Q(\lambda, \theta, \varphi, \theta_0, W, \tau_a, IOP) \cdot E_0(\lambda) / E_S(\lambda)$$

$u(L_T)$: $u_{ac}(L_T), u_{sc}(L_T), u_{en}(L_T)$

$u(\rho)$

$u(L_i)$: $u_{ac}(L_i), u_{sc}(L_i), u_{en}(L_i)$

$u(C_Q)$

$u(E_0)$

$u(E_s)$: $u_{ac}(E_s), u_{sc}(E_s), u_{en}(E_s)$