Optical radiometry requirements for drone systems supporting satellite ocean color applications

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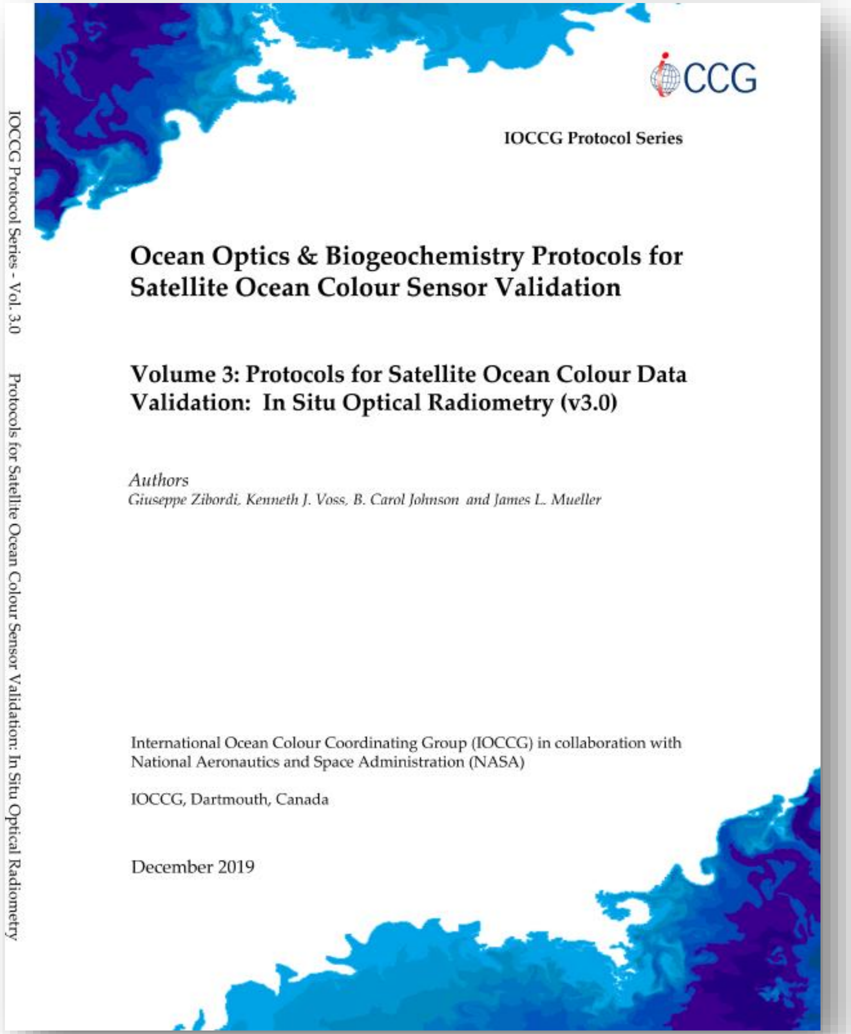
Second FRM4Drones-A Workshop, September 25, 2025

A revised definition of FRM

In situ radiometric measurements should be considered adhering to FRM requirements when:

- *Performed following*
  - *i*. published and verified, ideally community shared, measurement protocols and
  - *ii*. detailed quality assurance (QA) procedures.
- *Executed with instruments exhibiting*
  - *i*. features allowing to satisfy application needs and
  - *ii*. documented radiometric performance (*i.e.*, evidenced by absolute calibrations traceable to SI and characterizations determined for each potential instrument non-ideal performance).
- *Reduced and processed in agreement with community shared procedures supported by documented details on*
  - *i*. the flow leading to the determination of data products including the application of radiometric calibrations and corrections for the instrument non-ideal performance,
  - *ii*. the quality control procedures (QC), and
  - *iii*. the metrology principles applied for the determination of the uncertainty budget.
- *Accessible through consolidated data-bases supported by*
  - *i*. details on units and data formats, and
  - *ii*. ideally, community shared indices identifying the measurement method and the application fitness.

Protocols for in situ data supporting satellite ocean color validation


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)

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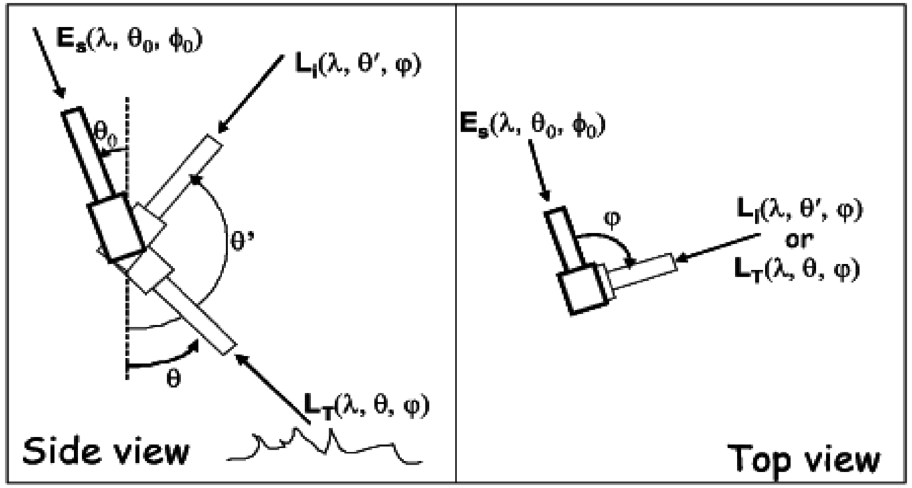
IOCCG, Dartmouth, Canada

December 2019

IOCCG Protocol Series - Vol. 3.0 Protocols for Satellite Ocean Colour Sensor Validation: In Situ Optical Radiometry

But limited to single field-of-view radiometry!

Above-water radiometry



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

Sky-radiance: L_i

Sea-radiance: L_T

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

Sea-surface reflectance factor
(the ρ-factor)

$$R_{RS}(\lambda) = L_W(\theta,\varphi,\lambda)/\,E_s(\lambda) \times C_Q\,(\theta,\varphi,\theta_0,\lambda,IOP,\tau_a)$$

Correction for bi-directional effects
(both off-nadir viewing angle
and off-zenith sun angle)

Mobley, C. D. (1999). Estimation of the remote-sensing reflectance from above-surface measurements. Applied optics, 38(36), 7442-7455.

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.

The ρ-factor

The sea-surface reflectance factors (*i.e., ρ-factors*) are computed quantities expected to provide a mean to quantify the radiance reflected by the water surface into the sensor field-of-view by benefitting of a single sky-radiance measurement L_i specular to L_T.

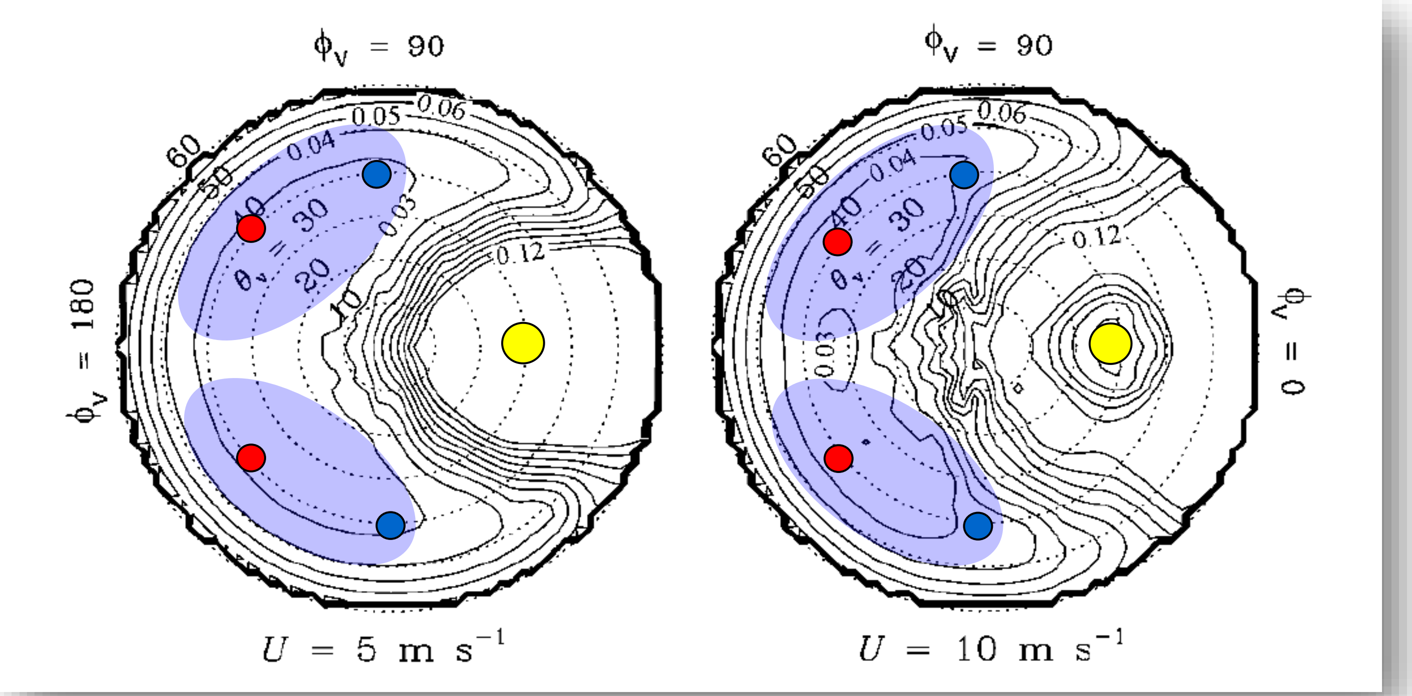
- This naturally implies accurate modelling of the *ρ-factors* for the specific measurement conditions (*e.g., the application of* wave statistics mirroring actual field conditions).

Assuming a viewing angle θ=40°, the relative azimuth angle with respect to the sun is illustrated for ϕ=90° ⟶ (blue) and ϕ=135° ⟶ (red)

The values between and nearby the above ones, suggest a lower dependence of ρ on sea state expressed as a function of wind speed.

However, large uncertainties are expected outside the above range of relative azimuths.

Thus restrictions would apply for imaging systems.



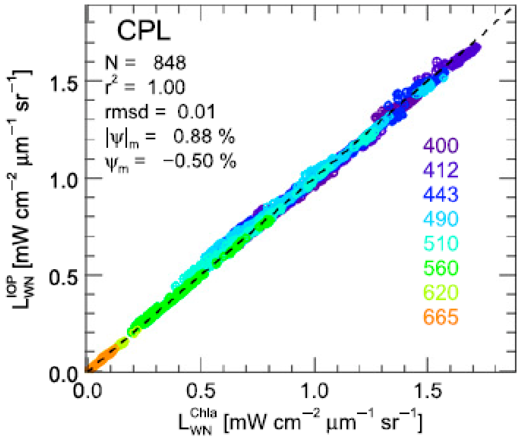
Distribution of *ρ-factors*

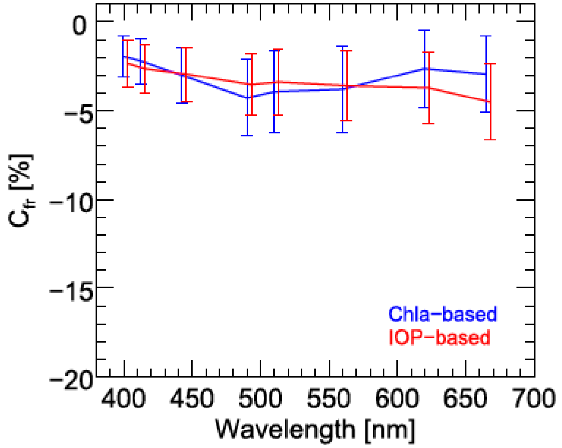
C.Mobley, Estimation of remote-sensing reflectance from above surface measurements. Applied Optics, 38: 7442-7455,1999.

Impact of corrections for bidirectional effects

Chla-based approach proposed for Case-1 waters (Morel et al., 2002. Bidirectional reflectance of oceanic waters: accounting for Raman emission and varying particle scattering phase function. Applied Optics, 41, 6289-6306).

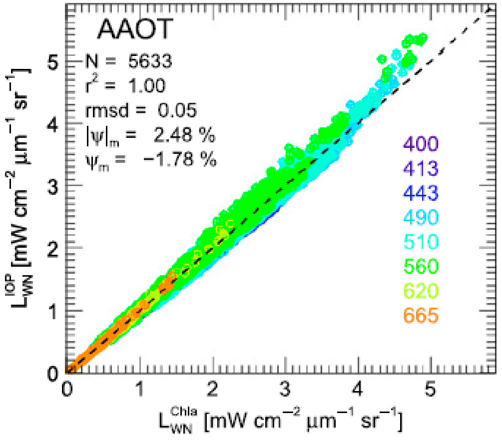
IOP-based approach tentatively proposed for any water type (Lee, et al., 2011. An inherent-optical-property-centered approach to correct the angular effects in water-leaving radiance. Applied Optics, 50, 3155-3167).

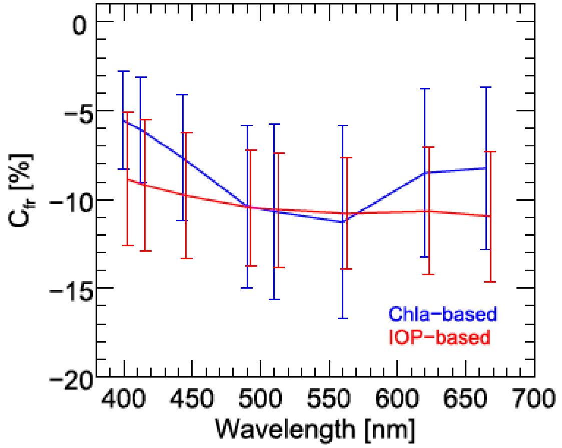




Open sea Case-1 water case:
The two correction approaches show convergence indicating they are both applicable.

Unapplied or inappropriate corrections for brdf effects may also lead to large uncertainties.





Moderate optically complex water case:
as expected, the two correction approaches do not show convergence.

Talone, M., Zibordi, G., & Lee, Z. (2018). Correction for the non-nadir viewing geometry of AERONET-OC above water radiometry data. *Optics Express*, *26*(10), A541-A561.

On Calibration and Characterization Requirements

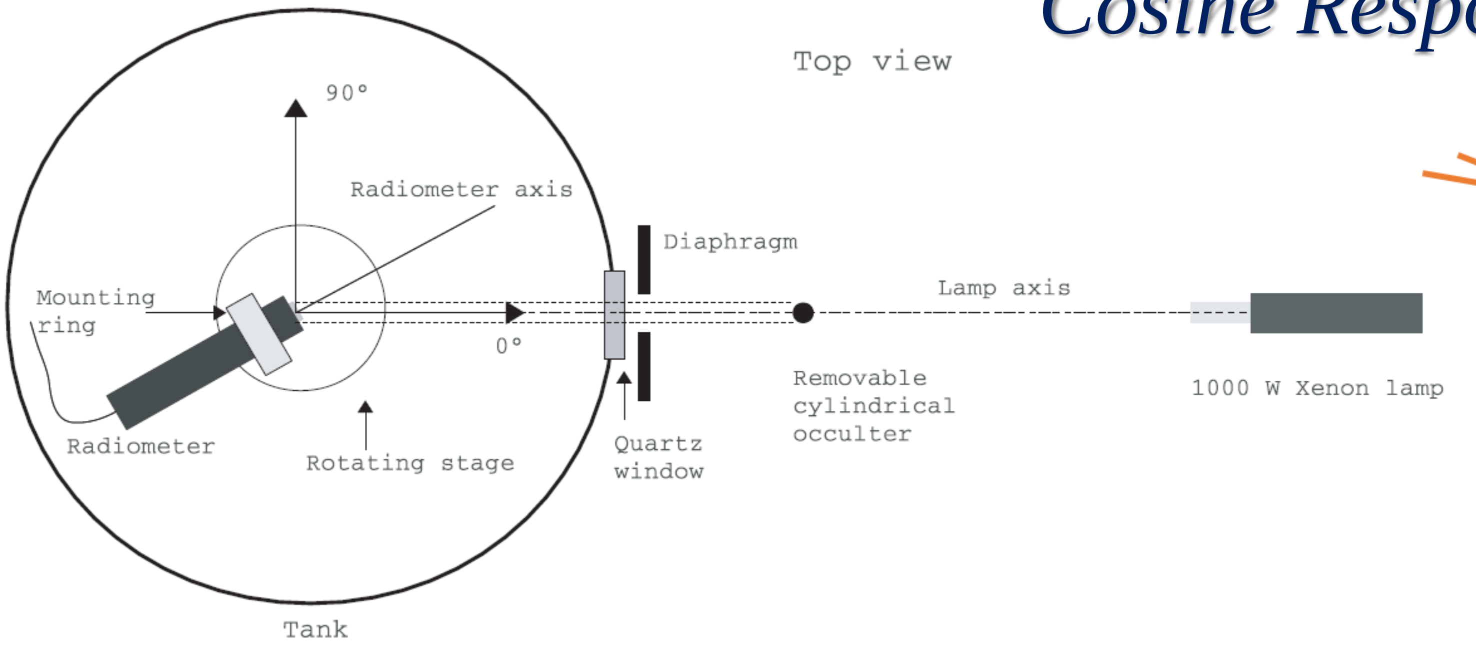
	Regular	Occasional	Initial	Class-based
Radiometric responsivity	X			
Spectral response		X		
Out-of-band & stray-light		X		
Immersion factor (irradiance)			X	
Immersion factor (radiance)				X
Angular response			X	
Linearity				X
Integration time				X
Temperature response				X
Polarization sensitivity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

Very unlikely individual research teams may ensure comprehensive instrument characterizations. Because of this, characterizations should be taken over by major measurement programs in agreement with manufacturers and reference laboratories.

This would necessarily imply a standardization of instrument models in use by the community.

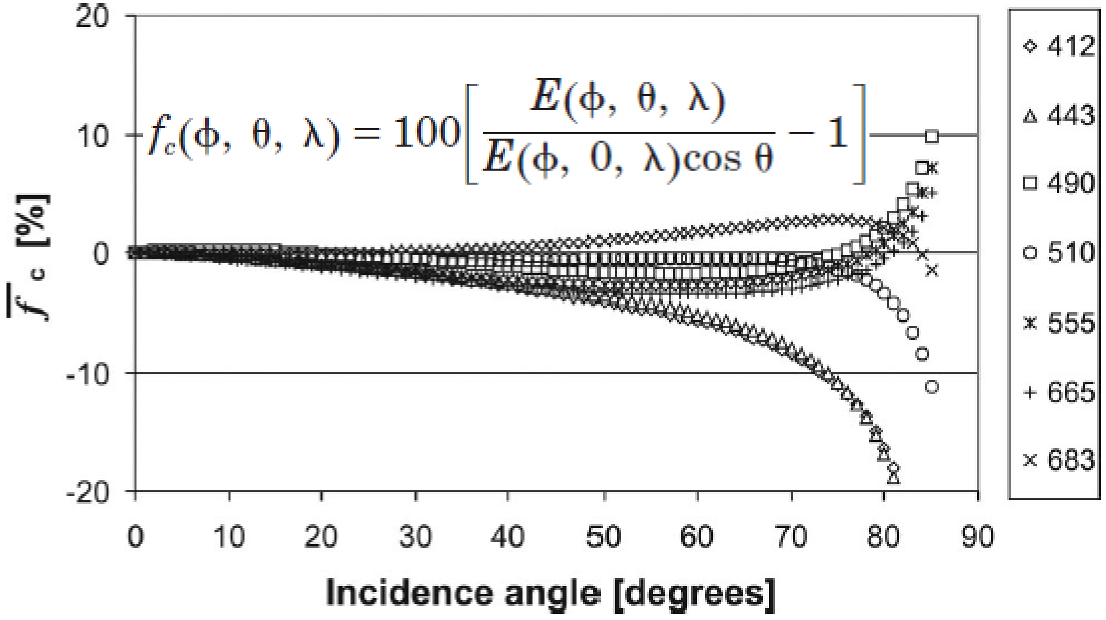
IOCCG Protocol Series (2019). Protocols for Satellite Ocean Colour Data Validation: In Situ Optical Radiometry. Zibordi, G., Voss, K. J., Johnson, B. C. and Mueller, J. L. IOCCG Ocean Optics and Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation, Volume 3.0, IOCCG, Dartmouth, NS,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

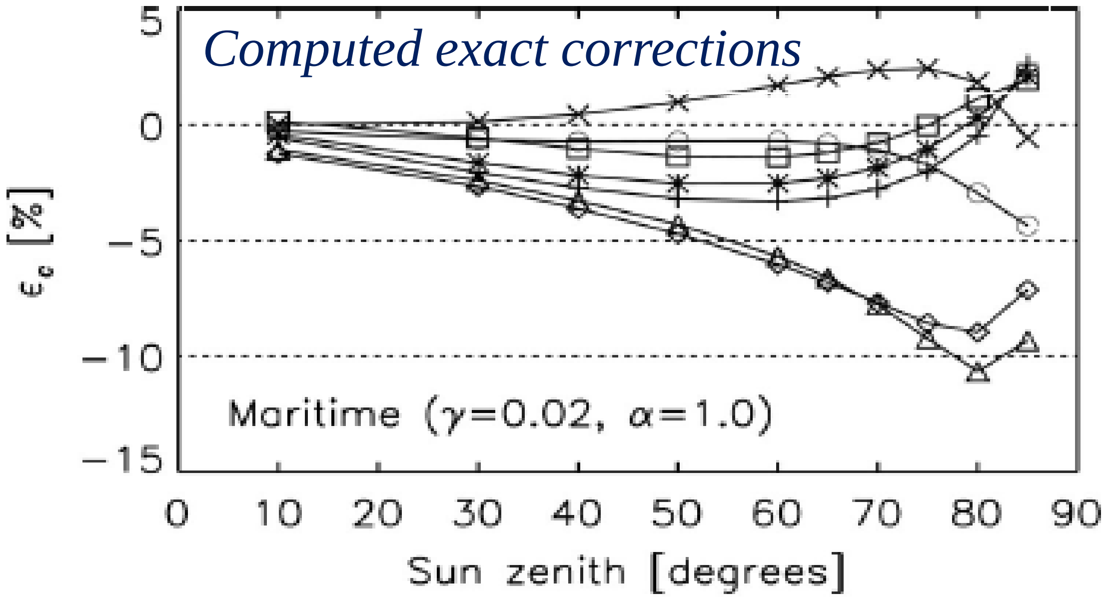
Cosine Response of Irradiance Sensors



Schematic of an irradiance collector

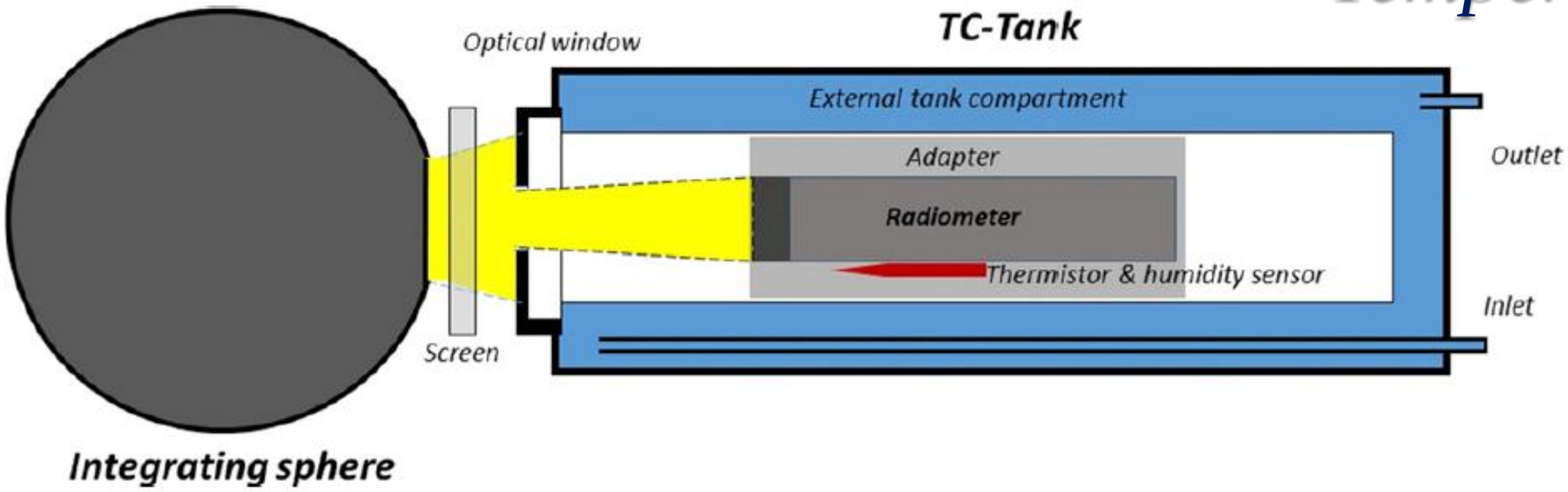
The cosine response of irradiance sensors should be characterized for each unit because simple geometric differences of the collector may lead to appreciable response differences.



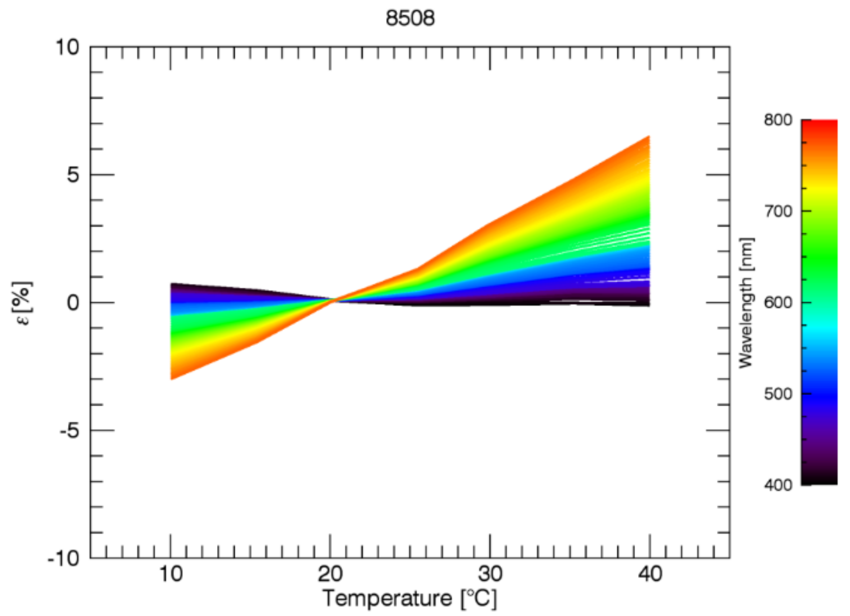


Zibordi, G., & Bulgarelli, B. (2007). Effects of cosine error in irradiance measurements from field ocean color radiometers. *Applied optics*, *46*(22), 5529-5538.

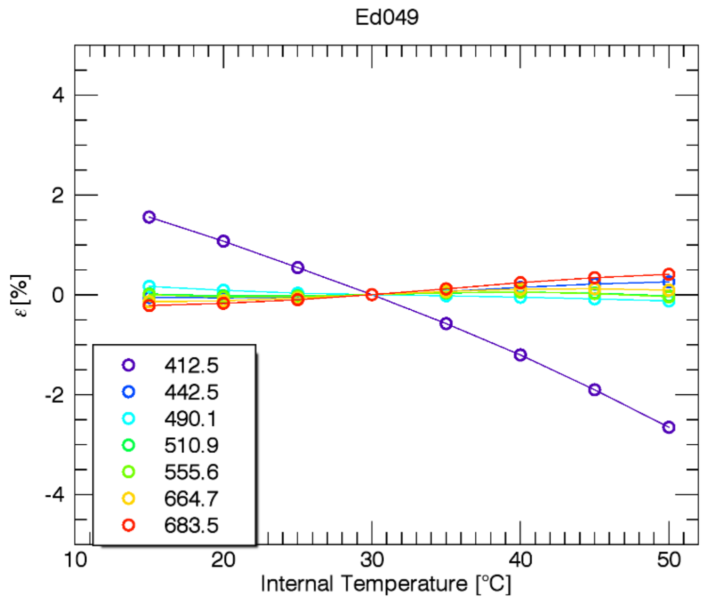
Temperature response



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., 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.

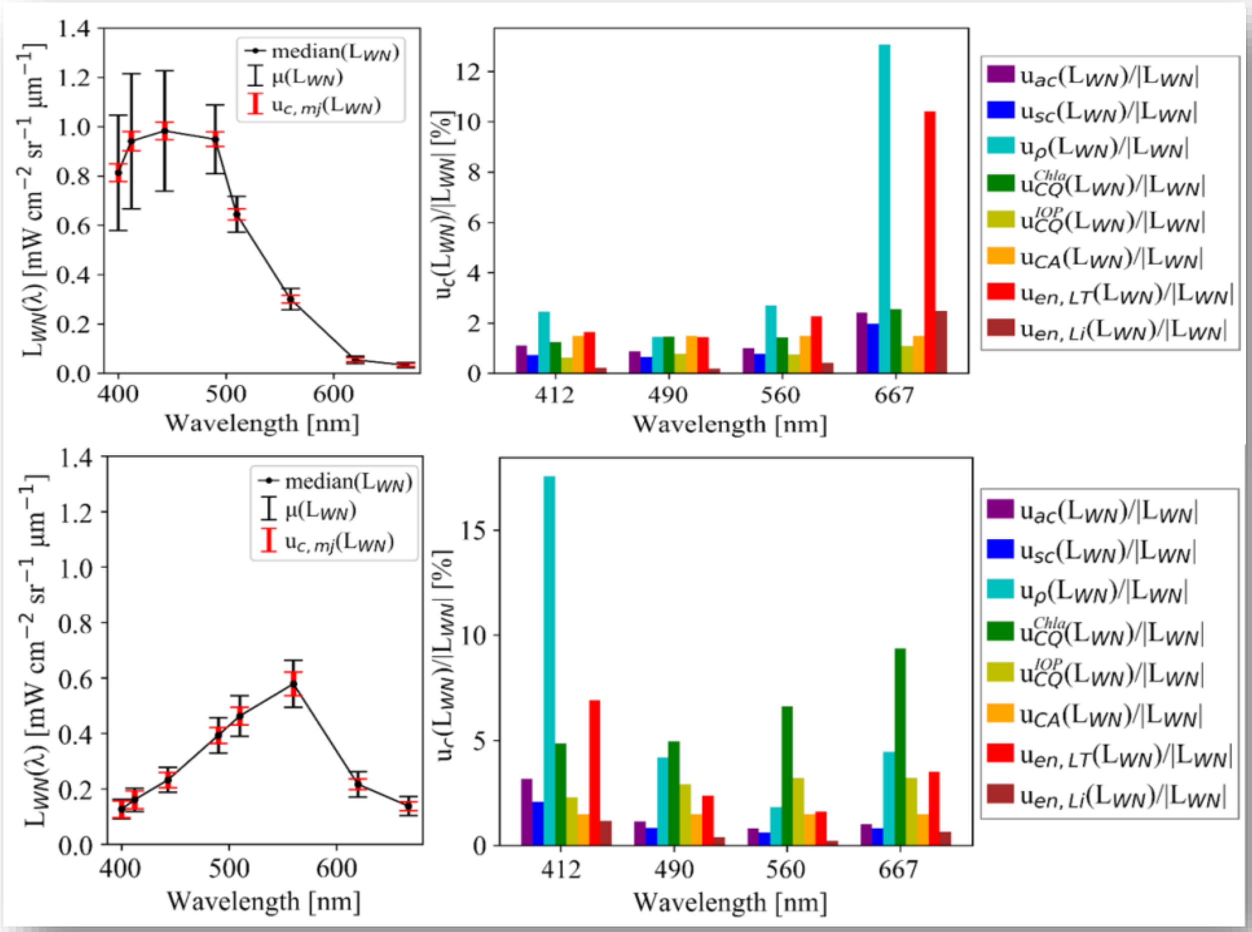
On uncertainties

Assuming that the uncertainty assigned to satellite derived $L_{WN}(\lambda)$ should be constrained within 5% for *in situ* $L_{WN}(\lambda)$ (still, in oligotrophic and likely mesotrophic open sea waters in the blue-green spectral regions), it would require *constraining individual sources of uncertainty of in situ radiometric data to within 1-2 % (commonly referred as 1% radiometry).*

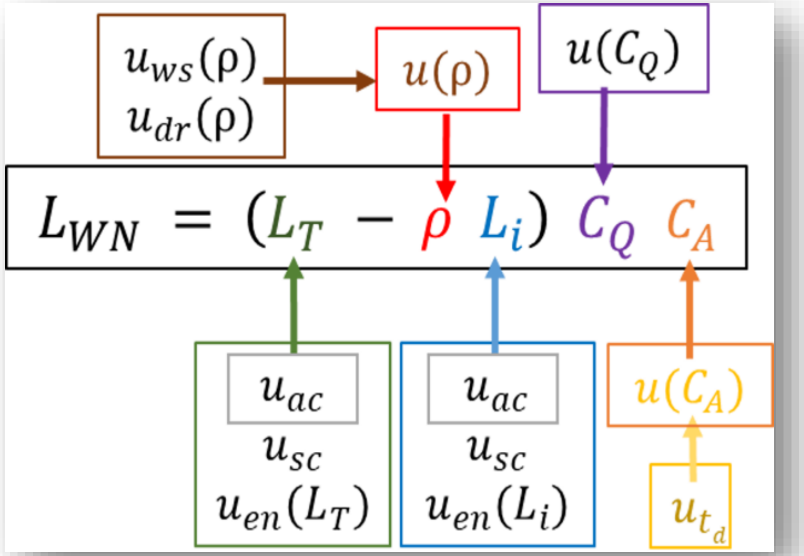
The quantification of uncertainties of in situ measurements should at least account for contributions from:

i. the calibration source and its transfer,
ii. the non-ideal performance of the radiometer,
iii. the inaccuracy of any model applied for data reduction,
iv. the impact of environmental variability.

GUM application



Casablanca Platform (blue waters)



Gustaf Dalen Lighthouse (CDOM dominated waters)

Relative uncertainty	400	412	443	490	510	560	620	667
$u_{c,mj}^{IOP}/L_{WN}$ **(oligotrophic waters)**	3.9	3.6	3.3	3.0	3.3	4.2	12.2	15.8
$u_{c,mj}^{IOP}/L_{WN}$ **(optically complex waters)**	22.3	18.7	11.1	5.9	5.1	4.5	5.8	6.7

Cazzaniga, I., & Zibordi, G. (2023). AERONET-OC L_{WN} Uncertainties: Revisited. Journal of Atmospheric and Oceanic Technology, 40(4), 411-425.

HYDRA: Hyperspectral Drone-based system for above-water Radiometric Acquisitions

HYDRA was conceived to support satellite ocean color validation activities benefitting from any element allowing to best adhere to metrology principles:

- *consolidated above-water methods;*
- *extensively characterized radiometers; and*
- *community efforts on data processing and uncertainty analysis.*

(a) Matrice 350

(c) Sun alignment jig

(b) Re-packed RAMSES-G2

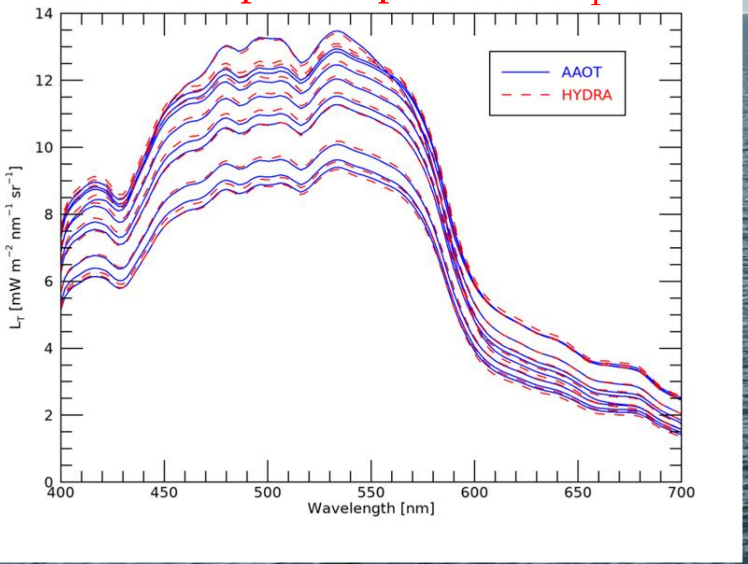
P.Sciuto, G.Zibordi, B.Bulgarelli, M.Talone, J.-F.Berthon, 2025. Drone-based system for hyperspectral above-water radiometry. Journal of Atmospheric and Oceanic Technology (submitted).

HYDRA assessment

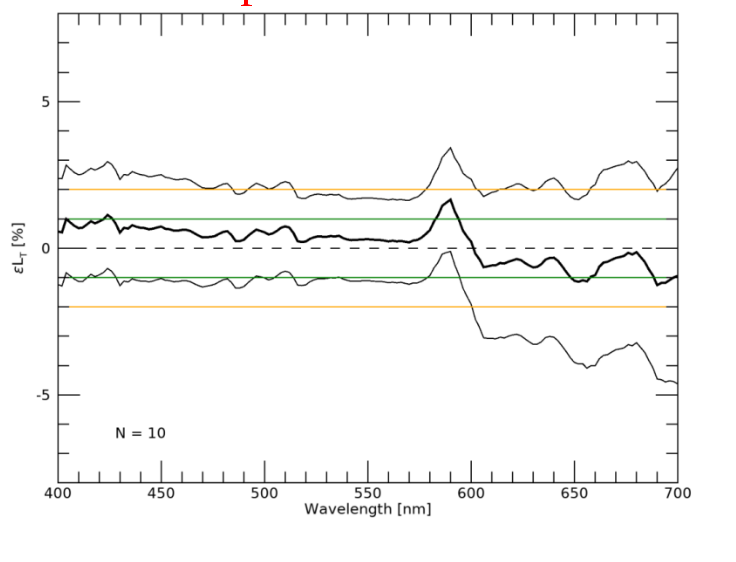
Location: AAOT (northern Adriatic Sea)
Sun zenith angle: 24-37°
Cloud cover: 0-1 Oktas
Wind speed: 1-3 m s^{-1}
Height: 20 m

Method: L_T HYDRA (RAMSES-G2) vs. L_T AAOT (RAMSES) applying consistent absolute radiometric calibration and identical processing

Compared spectra of L_T



Mean percent differences



P.Sciuto, G.Zibordi, B.Bulgarelli, M.Talone, J.-F.Berthon, 2025. Drone-based system for hyperspectral above-water radiometry. Journal of Atmospheric and Oceanic Technology (submitted).

Nevertheless …

While single field-of-view drone-based systems could be operated at a reasonable low altitude (tens of meters), the efficient use of imagers would suggest their operational use at much higher altitude (at least hundred of meters).

- *This may require the application of altitude-dependent atmospheric correction approaches rather than the existing above-water methods in view of ensuring a 'true' removal of path-radiance, sky-glint and sun-glint contributions at the drone height.*

Decadal investigations on applied radiometry indicate the fundamental importance of inter-comparisons to identify potential issues on:

- *The methods applied (the assessment of methods always requires extensive verifications);*
- *Instruments performance (including calibration and characterizations);*
- *Data reduction procedures (including quality control); or even*
- *Protocols implementation (assuming protocols exist).*

Thank you!