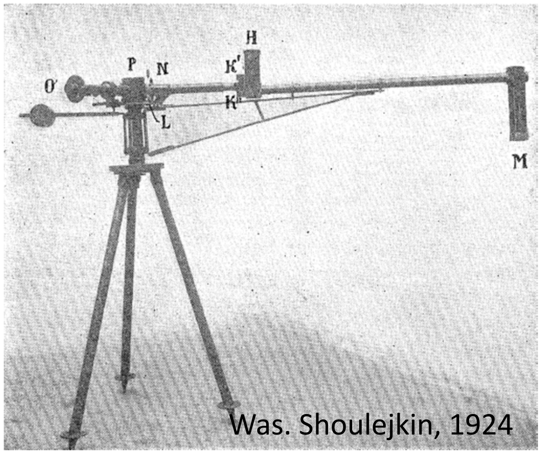
Workshop on Ocean Optics Protocols
October 25, 2014, Portland, ME

Above-Water Radiometry Protocols: elements for discussion



Was. Shoulejkin, 1924

Prepared by G. Zibordi with contributions from Tristan Harmel, Zhongping Lee, and Kevin Ruddick

Lexicon

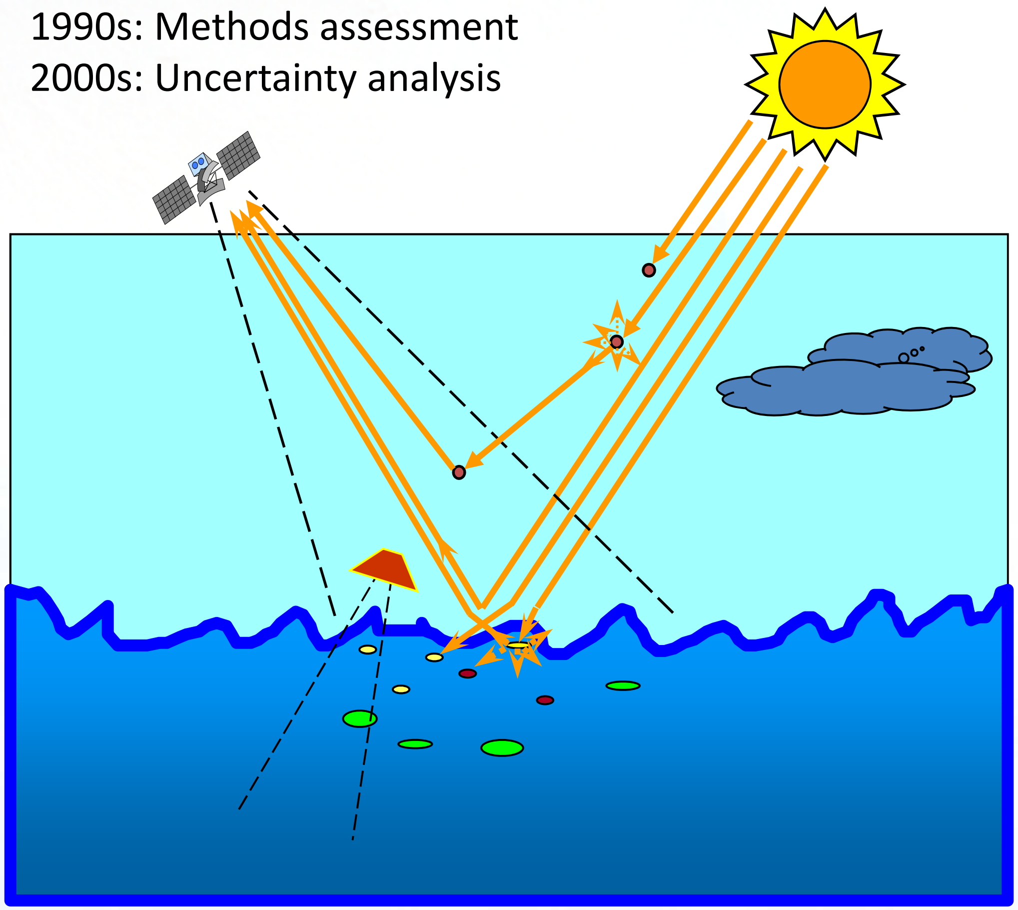
Scientific Method: a group of techniques for investigating phenomena and acquiring new knowledge.

Protocol: a written procedure for the design and implementation of experiments, that leads to *standardization* ensuring replication of results (*it should document in detail and unambiguously an implementation scheme even relying on approximations when exact solutions do not exist*).

Above-Water Radiometry

Historical dates

1930s: First observations
1980s: Documented methods
1990s: Methods assessment
2000s: Uncertainty analysis



Advantages

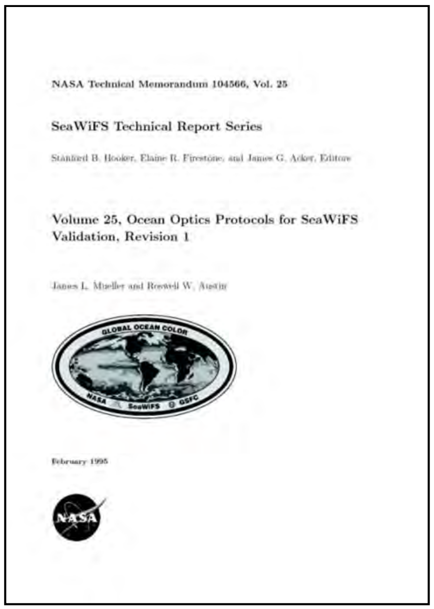
1. Long-term deployments are insensitive to bio-fouling
2. Insensitive to coastal water optical stratifications
3. Not affected by self-shading
4. …

Drawbacks

1. Cannot produce profiles of radiometric quantities
2. Restricted to a few radiometric quantities (i.e., L_w)
3. Highly sensitive to wave perturbations, which challenge correction for sky-glint
4. Requires care on superstructure perturbations
5. …

Existing Above-Water Radiometry Protocols

The **Ocean Optics Protocols for Satellite Ocean Color Validation (2004)** edited by J.L. Mueller, G.S. Fargion and C.R. McClain (5th revision of the original **Ocean Optics Protocols for SeaWiFS Validation** by J.L Mueller and R.W. Austin (1992)) is the most comprehensive compilation of Protocols for AOP Measurements.


NASA Technical Memorandum 104566, Vol. 25

SeaWiFS Technical Report Series

Stanford B. Hooker, Elaine R. Firestone, and James G. Acker, Editors

Volume 25, Ocean Optics Protocols for SeaWiFS Validation, Revision 1

James L. Mueller and Roswell W. Austin

February 1995

References stop at 2000!

Methods (measurement concepts) included in OOP (2004):

1. *Calibrated radiance and irradiance measurements:*

$$L_w(\lambda,\theta,\phi,\theta_0)=L_T(\lambda,\theta,\phi,\theta_0)-\rho(W,\theta,\phi,\theta_0)L_i(\lambda,\theta',\phi,\theta_0)$$

$$R_{rs}(\lambda,\theta,\phi,\theta_0)=L_w(\lambda,\theta,\phi,\theta_0)/E_s(\lambda,\theta_0).$$

2. *Un-calibrated radiance and reflectance plaque measurements*:

$$R_{rs}(\lambda,\theta,\phi,\theta_0)=[DN_T(\lambda,\theta,\phi,\theta_0)-\rho(W,\theta,\phi,\theta_0)DN_i(\lambda,\theta',\phi,\theta_0)]$$

$$/[DN_s(\lambda,\theta_P,\phi_P,\theta_0)/\rho_p(\lambda,\theta_P,\phi_P,\theta_0)].$$

3. *Calibrated surface-polarized radiance measurements with modeled irradiance and sky radiance:*

$L_T(\lambda,\theta,\phi,\theta_0)$ *and* $\tau_a(\lambda)$ *are measured and*

$E_s(\lambda,\theta_0)$ *and* $L_i(\lambda,\theta',\phi,\theta_0)$ *are computed using* $\tau_a(\lambda)$.

Weakness of Current OOP Protocols

Weakness of current OOP is mostly due to a decade+ of missing updates on findings (but not restricted to):

optics characterization, measurement techniques, deployment requirements, quality assurance and control, filtering of sun-glint contributions, spectral dependence of sea-surface reflectance, viewing-angle correction, polarization effects, turbid water applications, quantification of uncertainties.

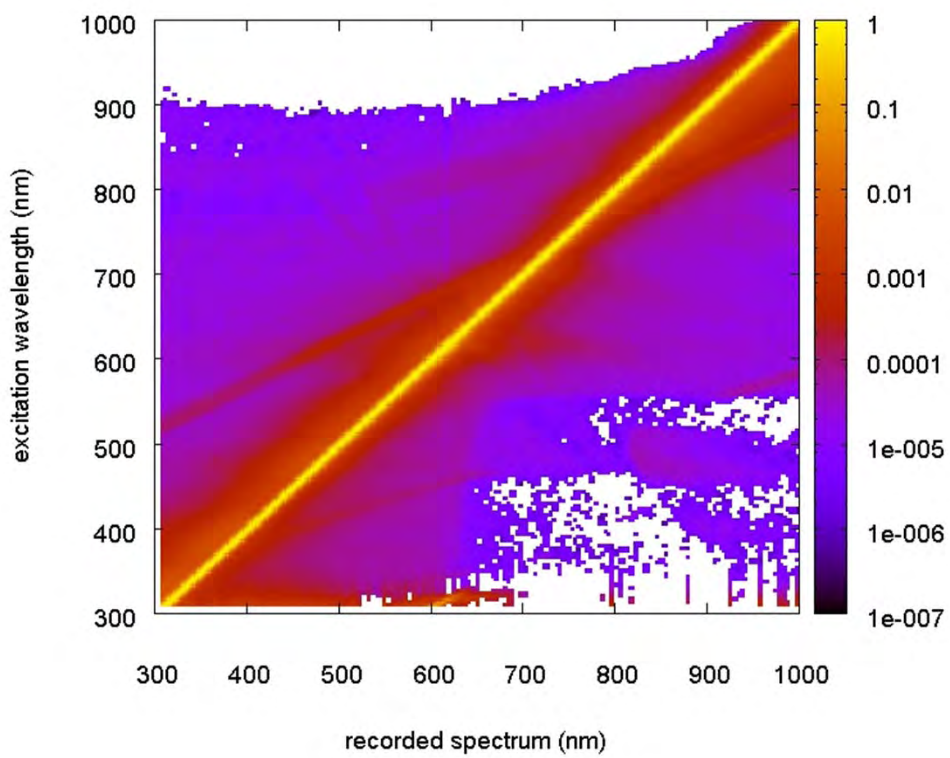
References (just a few starting in 2001):

- R. W. Gould, R. A. Arnone, and M. Sydor, “Absorption, scattering and remote-sensing reflectance relationships in coastal waters: Testing a new inversion algorithm,” J. Coastal Res. **17**, 328–341 (2001).
- S. B. Hooker, G. Lazin, G. Zibordi, and S. McClean, “An evaluation of above and in–water methods for determining water leaving radiances,” J. Atmos. Oceanic Technol. **19**, 486–515 (2002).
- G. Zibordi, F. Mélin, S. B. Hooker, D. D’Alimonte and B. Holben, “An autonomous above–water system for the validation of ocean color radiance data”, IEEE Trans. Geosci. Remote Sensing **42**, 401–415 (2004).
- S. B. Hooker and G. Zibordi, “Platform perturbation in above–water radiometry,” Appl. Opt. **44**, 553–567 (2005).
- D. D'Alimonte and G. Zibordi, "Statistical assessment of radiometric measurements from autonomous systems." *IEEE Transactions on Geoscience and Remote Sensing,* **44**, 719-728 (2006).
- K. G. Ruddick, V. De Cauwer and Y. J. Park, “Seaborne measurements of near infrared water-leaving reflectance: The similiarity spectrum for turbid waters,” Limnol. Oceanogr. **51**, 1167-1179 (2006).
- A. Tanaka, H. Sasaki, and J. Ishizaka. "Alternative measuring method for water-leaving radiance using a radiance sensor with a domed cover." *Optics express* 14, 3099-3105 (2006).
- M. E. Feinholz, S. J. Flora, M. A. Yarbrough, K. R. Lykke, S. W. Brown, and B. C. Johnson, “Stray Light Correction of the Marine Optical System,” J. Atmos. Ocean. Technol. **26**, 57–73 (2009).
- Z. P. Lee, Y.-H. Ahn, C. Mobley, and R. Arnone, “Removal of surface-reflected light for the measurement of remote-sensing reflectance from an above-surface platform,” Opt. Express **18**, 26313–26324 (2010).
- Z. Lee, K. Du, K. J. Voss, G. Zibordi, B. Lubac, R. Arnone, and A. Weidemann, “An IOP-centered approach to correct the angular effects in water-leaving radiance,” Appl. Opt. **50**, 3155–3167 (2011).
- T. Harmel, A. Gilerson, A. Tonizzo, J. Chowdhary, A. Weidemann, R. Arnone, and S. Ahmed, “Polarization impacts on the water-leaving radiance retrieval from above-water radiometric measurements,” Appl. Opt. **51**, 8324–8340 (2012).
- S.G.H. Simis and J. Olsson, "Unattended processing of shipborne hyperspectral reflectance measurements," *Remote Sens. Environ.* **135**, 202–212 (2013).
- Z.P. Lee, N. Pahlevan, Y.-H. Ahn, S. Greb, and D. O’Donnell, “Robust approach to directly measuring water-leaving radiance in the field”, *Applied Optics*, 52, 1693-1701 (2013).
- M. Gergely and G. Zibordi, “Assessment of AERONET L_{WN} uncertainties,” Metrologia **51**, 40–47 (2014).

Instrument characterization: stray light

Stray light is light that has been scattered or reflected inside the radiometer, and interferes with the measurement. It can be the result of spatial, angular and spectral effects.

Spectral stray light in hyperspectral instruments may cause the mixing of light from other regions of the spectrum. Its characterization requires the illumination of the optics with a sequence of sources having well resolved spectral characteristics.



Spectral stray light characterization of an hyperspectral radiometer (Courtesy of Ilmar Hansko, Tartu Observatory, Estonia)

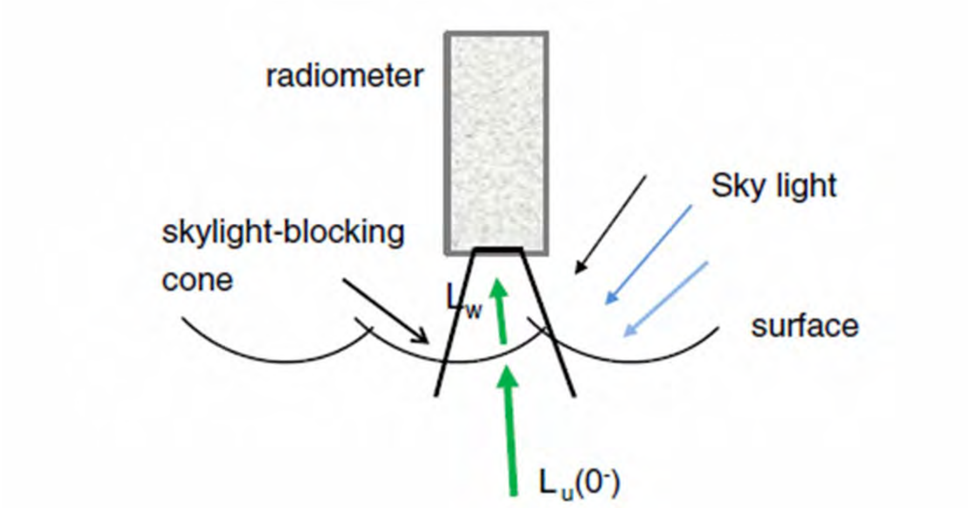
Stray light perturbations could be of the order of several percent, and spectrally change as a function of the shape and intensity of the incoming light.

M. E. Feinholz, S. J. Flora, M. A. Yarbrough, K. R. Lykke, S. W. Brown, and B. C. Johnson, "Stray Light Correction of the Marine Optical System," J. Atmos. Ocean. Technol. **26**, 57–73 (2009).

Measurement techniques: sky-blocked method

The Sky-Blocked method allows the collection of upwelling radiance from above the sea surface while blocking surface-reflected light with a screen.

The method leads to the direct measurement of L_w and provides the major advantage of not requiring corrections for glint-contributions, even though it requires self-shading corrections.



Schematic of the Sky-Blocked approach

Y.-H. Ahn, "Development of red tide & water turbidity algorithms using ocean color satellite," KORDI Seoul, Korea, p. 287 (1999).

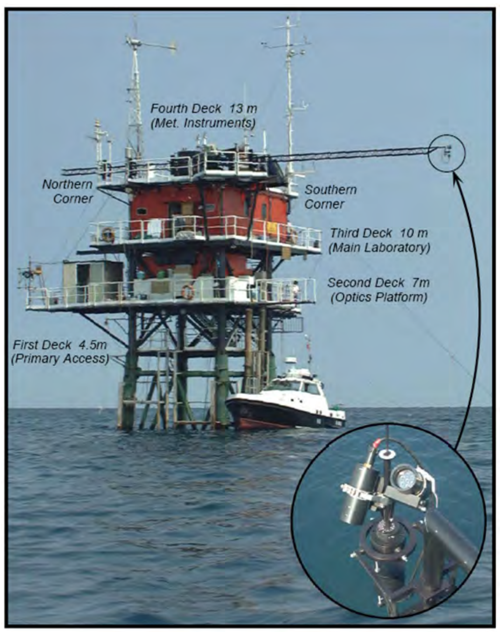
A. Tanaka, H. Sasaki, and J. Ishizaka. "Alternative measuring method for water-leaving radiance using a radiance sensor with a domed cover." *Optics express* 14, 3099-3105 (2006).

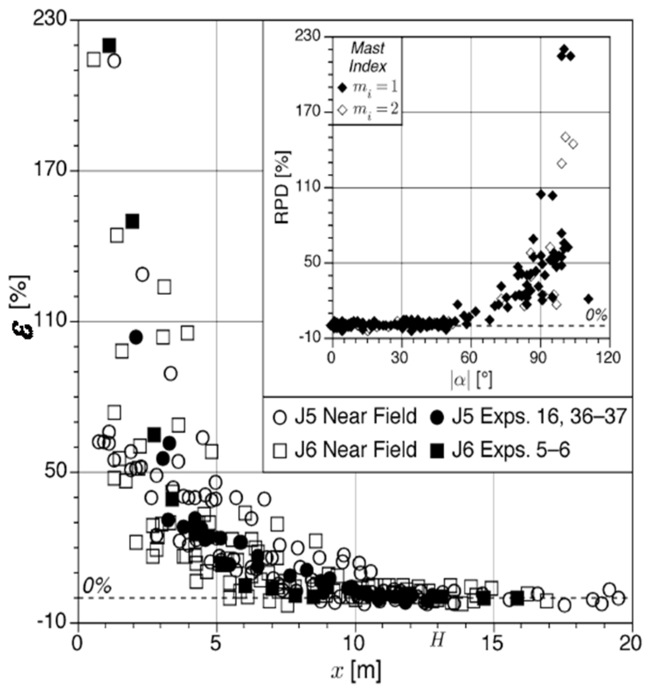
Z.P. Lee, N. Pahlevan, Y.-H. Ahn, S. Greb, and D. O'Donnell, "Robust approach to directly measuring water-leaving radiance in the field", *Applied Optics*, 52, 1693-1701 (2013).

Deployment requirements: instrument location

A comprehensive quantification of the measurement uncertainties related to platform shading and reflections, entails 3-D radiative transfer simulations specific for each deployment structure, radiometer type, and site.

Considering that each deployment platform is an individual case and generalizations are difficult, the location of above-water radiometers onboard deployment structures are often guided by common sense and by a limited number of focused investigations. The application of "empirical" rules, however, cannot assure perturbations are always negligible or spectrally independent.





Error ε in L_T/L_i with distance x from the superstructure at 865 nm

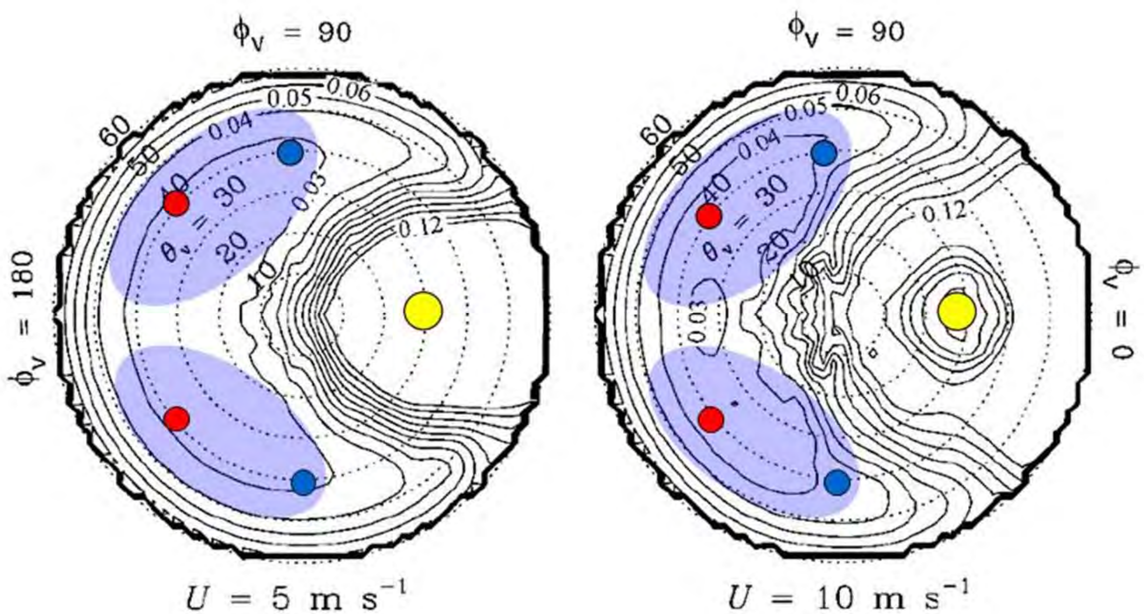
S. B. Hooker and G. Zibordi. Platform perturbation in Above-Water Radiometry. *Applied Optics*, 44, 553-567, 2005.

Data Reduction: sea surface reflectance

The sea surface reflectance ρ is an essential quantity required for the determination of $L_w(\lambda)$. It is generally quantified as a function of sea state and observation/illumination geometry.

Sky-glint contains sky radiance contributions from a variety of zenith and azimuth angles, and not only from the specular reflection of an ideal flat sea surface. 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.

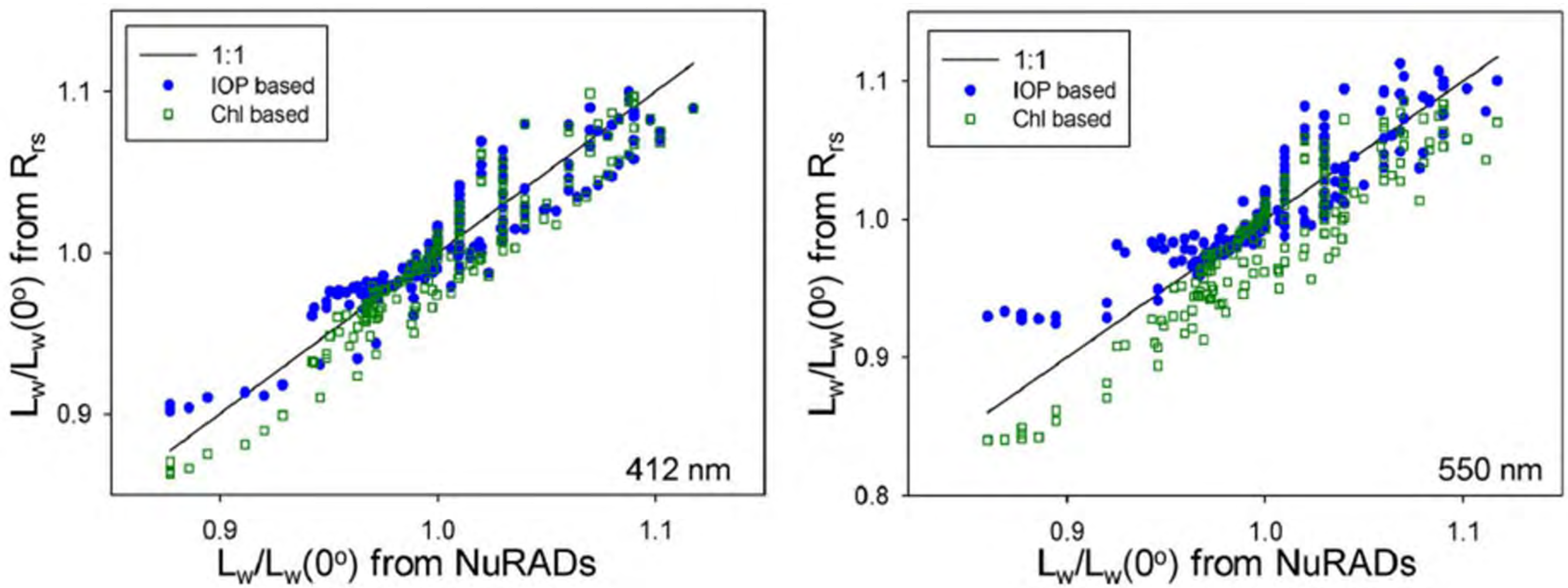


Sea-surface reflectance

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

Data Reduction: removal of viewing angle dependence

L_w varies not only with wavelength and water constituents, but also with angular geometry: θ_0, θ, ϕ

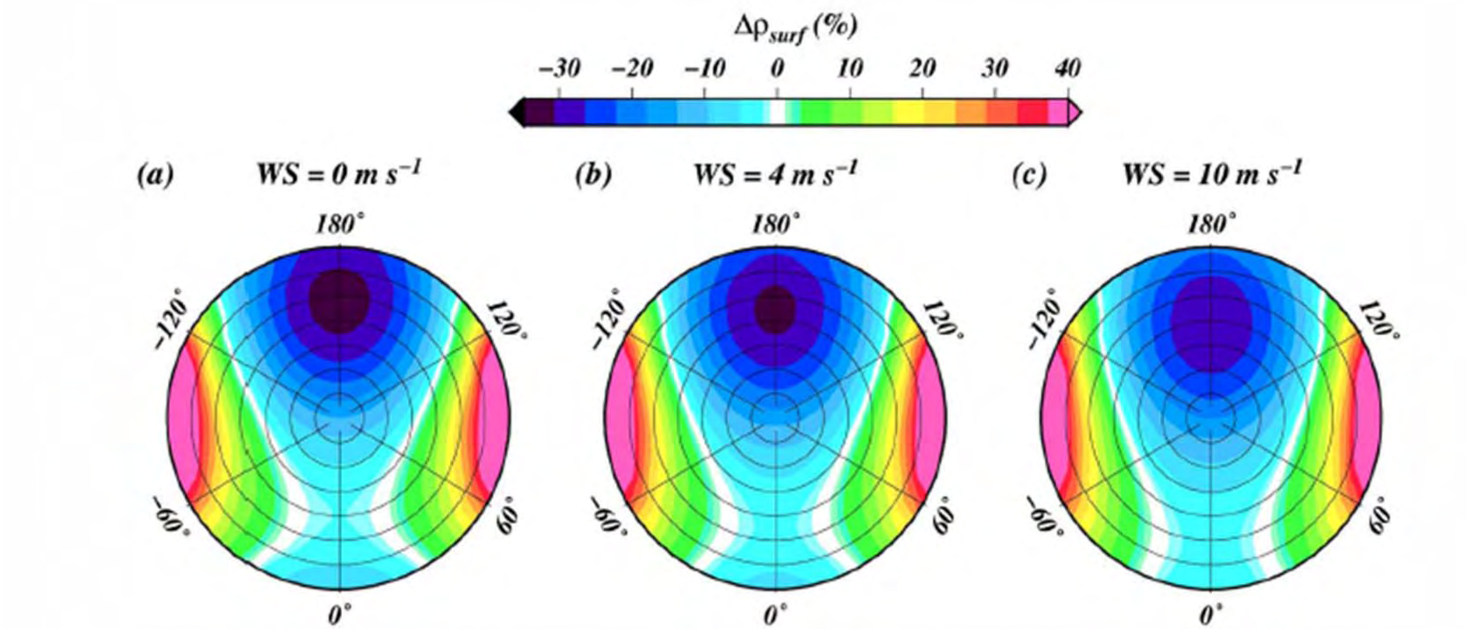


Comparison between measured and derived $L_w(\lambda,\theta,\theta_0,\phi)/L_w(\lambda,0,\theta_0,\phi)$ ratios for selected wavelength and viewing angle of measurements made in the Mediterranean Sea (blue circles indicate IOPs-centered approach; green squares indicate *Chla*-centered approach).

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

Data Reduction: polarization effects

The L_T and L_i radiance values are polarized as a result of the effects of the atmospheric scattering and reflectance of the sea surface. Consequently, polarization affects the determination of L_w when using above-water radiometry.



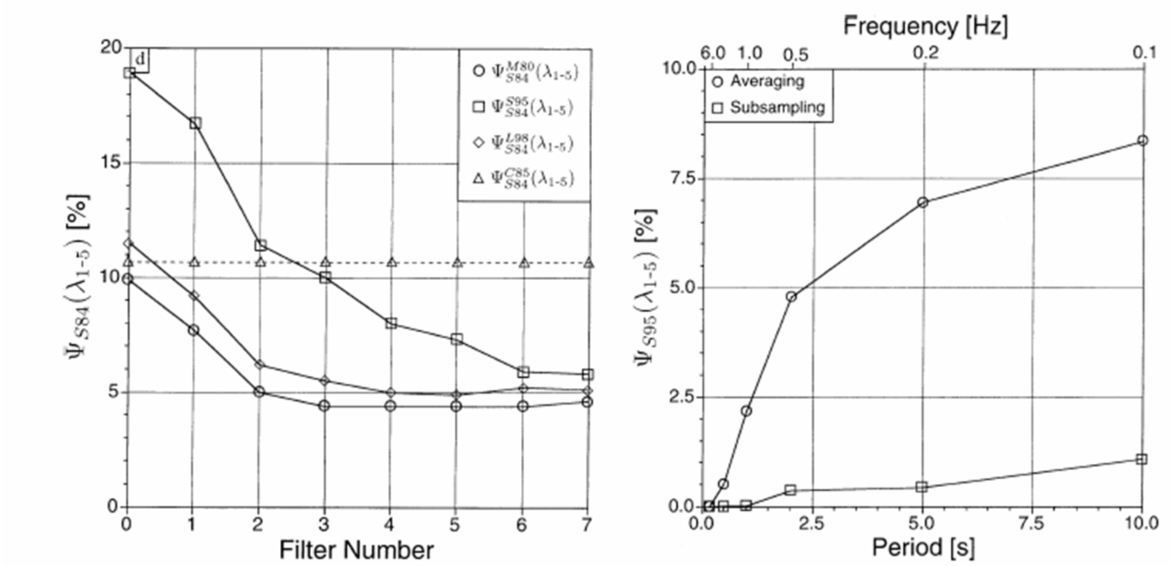
Relative difference $\Delta\rho_{surf}$ at 550 nm and an aerosol optical thickness of 0.1 for different wind speed conditions: (a) 0, (b) 4, and (c) 10 ms^{-1}. The polar diagrams account for all the azimuth and solar angles for a given viewing angle of 40°. The concentric circles represent the solar zenith angles by a step of 10° (from 0° to 70°), and angles in the polar diagrams represent the relative azimuth with the Sun.

T. Harmel, A. Gilerson, A. Tonizzo, J. Chowdhary, A. Weidemann, R. Arnone, and S. Ahmed, "Polarization impacts on the water-leaving radiance retrieval from above-water radiometric measurements," Appl. Opt. **51**, 8324–8340 (2012).

Data Reduction: minimization of glint contributions

The determination of above–water radiometric data products is perturbed by wave effects, which affect the accurate determination of ρ and thus challenge the removal of the glint component from $L_T(\lambda)$.

A practical solution for the minimization of wave effects is provided by the application of filtering techniques, which remove those measurements most likely affected by significant glint perturbation and additionally by whitecaps or foam. Still, the capability of minimizing glint perturbations through data filtering, decreases with an increase of the field-of-view and integration time. Additionally, this scheme is simply based on empirical thresholds.

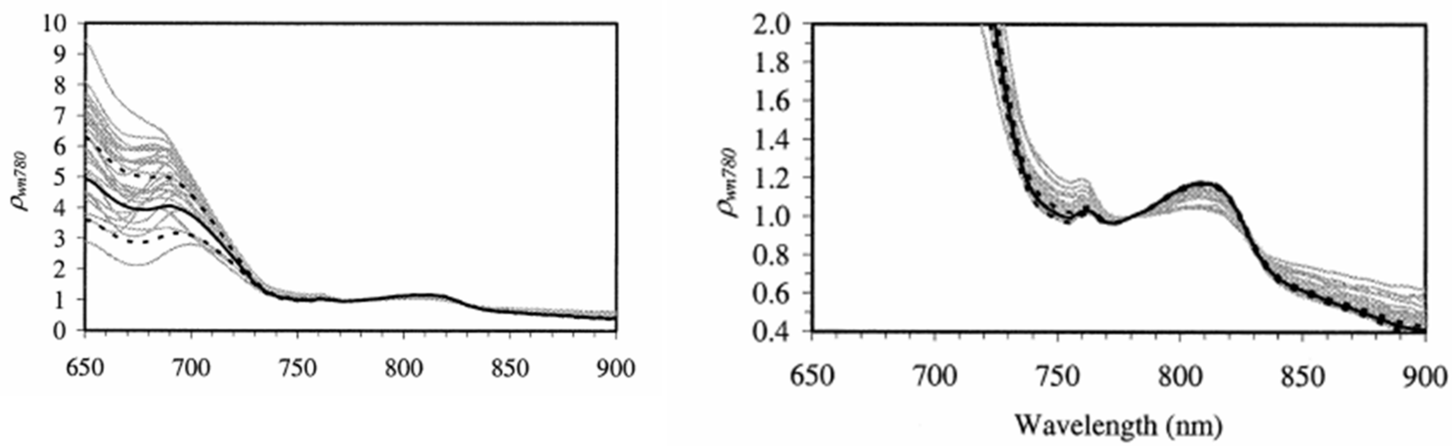


Filtering (i.e., decreasing the percentage of applied measurements) and averaging effects

S. B. Hooker, G. Lazin, G. Zibordi, and S. McClean, “An evaluation of above and in–water methods for determining water leaving radiances,” J. Atmos. Oceanic Technol. **19**, 486–515 (2002).

Data Reduction: turbid waters

Minimization of perturbations due to wave effects (mostly) in turbid waters can be achieved through the so-called *turbid water near-infrared (NIR) similarity correction* by determining the departure from the NIR spectrum (determined at two wavelengths) assuming ρ is spectrally invariant.



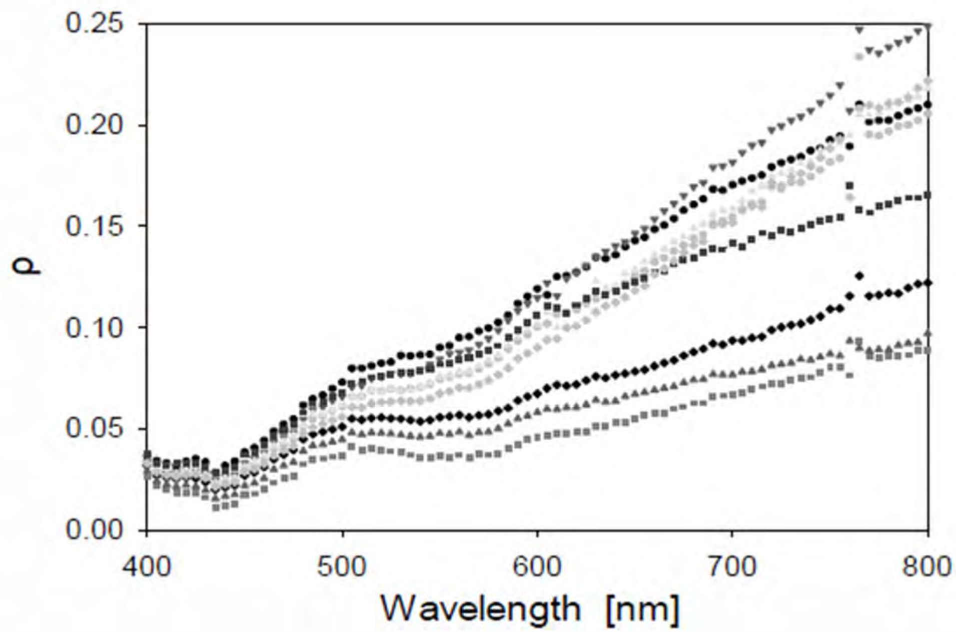
Measured water-leaving reflectance spectra normalized by reflectance at 780 nm (using different scales for axes).

K. G. Ruddick, V. De Cauwer and Y. J. Park, "Seaborne measurements of near infrared water-leaving reflectance: The similiarity spectrum for turbid waters," Limnol. Oceanogr. **51**, 1167-1179 (2006).

R. W. Gould, R. A. Arnone, and M. Sydor, "Absorption, scattering and remote-sensing reflectance relationships in coastal waters: Testing a new inversion algorithm," J. Coastal Res. **17**, 328–341 (2001).

Data Reduction: spectral dependence of ρ

The glint contributions in L_T may lead to spectrally dependent values of surface reflectance ρ increasing with wavelength (because of L_i contributions in L_T from directions including bright portions of the sky or even the sun).

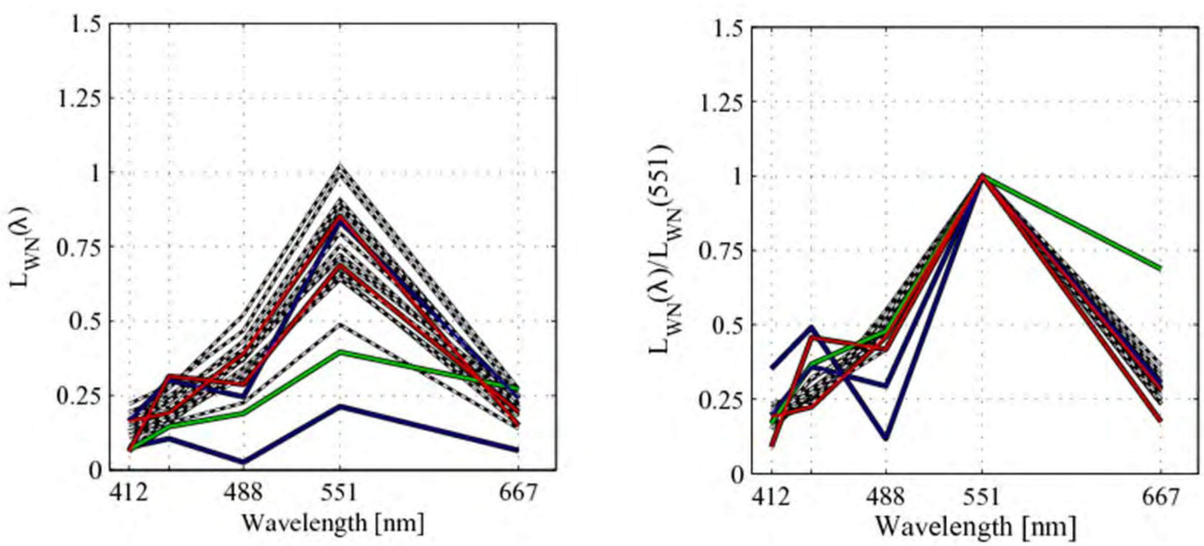


Values of ρ calculated from L_T an L_i measurements using simulated L_w assuming *Chla* = 0.05 mg m^{-3}.
The ρ values differ among the different L_T measurements and additionally largely vary spectrally.

Z. P. Lee, Y.-H. Ahn, C. Mobley, and R. Arnone, "Removal of surface-reflected light for the measurement of remote-sensing reflectance from an above-surface platform," Opt. Express **18**, 26313–26324 (2010).

Data Reduction: quality assurance and control

Quality assurance and control, need to be applied to remove data products affected by artifacts or having a non-physical meaning. The development of automatic procedures is of utmost importance for large data sets from major measurement programs or networks



Example offered by a statistical method applied for detecting artifacts in $L_{WN}(\lambda)$ and to reject spectra exhibiting:

i. low statistical representativeness within the data set itself (*self-consistency*);
ii. anomalous features with respect to a reference set of quality-assured data (*relative-consistency*).

D.D'Alimonte and G.Zibordi. Statistical assessment of radiometric measurements from autonomous systems. *IEEE Transactions in Geoscience and Remote Sensing*, 44, 1-11, 2006.

Data Reduction: quantification of uncertainties

Given the measurement equation

$$L_{WN} = L_W\, C_A\, C_Q \ \ \textit{with}\ \ L_W = L_T - \rho\, L_i$$

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;

following the *Guide to the Expression of Uncertainty in Measurement (GUM), w*ithout considering correlations among input quantities and non-linearity of the measurement model, the combined standard uncertainty of the normalized water-leaving radiance $\tilde{u}_c(L_{WN})$ is given by

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

with

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

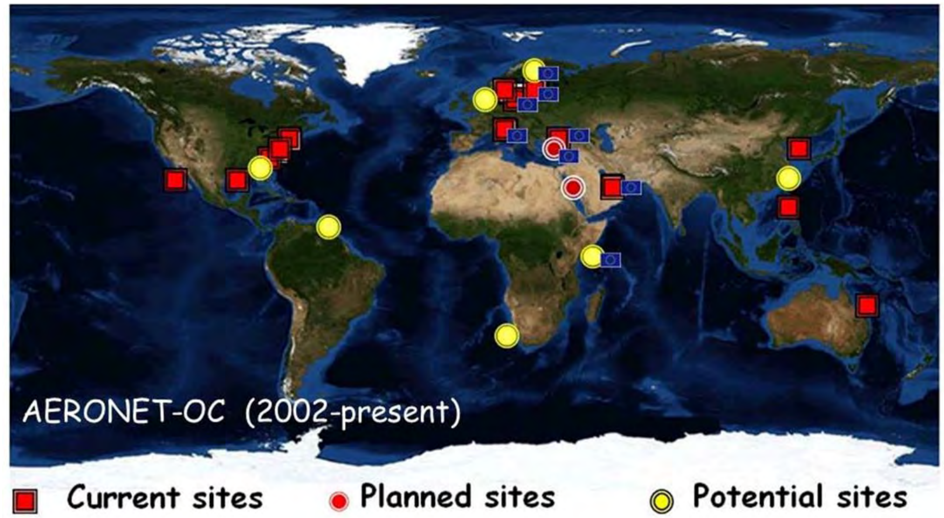
The uncertainties $u(L_{T,i})$, indicating either $u(L_T)$ or $u(L_i)$, should include contributions related to absolute calibration, sensitivity change during the deployment period of the measuring system, and environmental perturbations mostly caused by sea surface roughness and environmental changes during measurement sequences.

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

Networking and Protocols

One of the benefits of protocols is the capability of favoring networking (e.g., *AERONET – Ocean Color* sub-network supporting ocean color validation activities with cross-site consistent time-series of L_{WN} and τ_a).

In fact measurement networks generally require standardization of: instrumentation; calibration schemes; measurement techniques; and, data reduction, control and handling.



Considering that most of the commercial radiometers are from a few manufactures, a fact that already enforces some standardization on instrumentation, protocols should become the way to implement standardization for any other component of the *in situ* data production chain with large community benefits.

Because of this, protocols should be comprehensive and not leave space for interpretation.

Strategy for Protocols Revision and Update

What could be an efficient strategy for revising and updating protocols on Above-Water Radiometry?

1. **Identify** consolidated methods and techniques for which detailed protocols should be provided(?)
   The protocols need to have large shared consensus, still, they are not expected to have unanimous acceptance.

2. **Feed** protocols with consolidated and detailed techniques for: *i*. instrument calibration and characterization; *ii*. field deployment; *iii*. data reduction; *iv*. quality assurance and control of measurements and data products; *v*. quantification of uncertainties through techniques hopefully relying on the measurement equation (?)
   Elements related to quality assurance and control, and uncertainty analysis, are completely missing in the current version of the protocols. Data reduction requires detailed techniques for: an optimal determination of the surface reflectance, likely accounting for its spectral dependence; estimate of polarization effects; and additionally the determination of viewing angle corrections accounting for any water type.

3. **Adopt** a wiki-type solution allowing for continuous updates and immediate access (?)
   Obviously there should be Editor(s) in charge to keep focused the revision process, still envisaging discussions for advances and new findings.

Funding and Responsibilities

Funding: Space Agencies and/or National Programs ?

Responsibility: Space Agency or an international body (e.g., IOCCG) ?

Thanks