Copernicus FICE 2024

Training on
In situ Ocean Colour Above-Water Radiometry towards Satellite Validation

A practical view to above-water uncertainties

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Uncertainties: definition

The term uncertainty indicates the incomplete knowledge of the measurand through the available information.

Uncertainties are generally divided into type A when determined through statistical methods (*e.g.*, multiple measurements allowing to quantify standard deviations) and type B when determined by means other than statistical (*e.g.*, models, published data, calibration certificates).

Uncertainties can be additive (*i.e.*, independent of the measured value such as the inaccurate quantification of the dark signal) or multiplicative (*i.e.*, dependent on the measured value such as those related to the inaccurate determination of the responsivity of the radiometer).

Assuming individual uncertainty contributions are independent, multiplicative and normally distributed, the overall measurement uncertainty is given by their combined values (*i.e.*, the square root of the sum of their squared values). The so called *coverage factor* k determines the level of confidence on uncertainties: $k = 1$, 2 and 3 refer to confidence levels of approximately 68%, 95% and 99%.

Uncertainties, when possible, should be provided in both relative (*i.e.*, %) and physical units.
The range of values for which the uncertainties are proposed should also be reported together with details on environmental conditions. In fact, uncertainties determined for a specific range of values may not necessarily be the same for other ranges or different measurement conditions.

On uncertainties

The quantification of uncertainties of in situ measurements should comprehensively address 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, and possibly,
v. perturbations by deployment platforms.

Many publications mention a *"5%" uncertainty target* for both satellite and *in situ* radiometric data. The 5% uncertainty was originally defined for satellite derived $L_{WN}(\lambda)$ in the blue spectral region to satisfy the 35% uncertainty in chlorophyll-*a* concentration determined for a specific bio-optical algorithm proposed for oligotrophic waters (Gordon and Clark 1981). The 5% uncertainty value, was then set as the target for $L_{WN}(\lambda)$ for the majority of ocean colour missions, regardless of spectral region and application.

This uncertainty assigned to satellite derived $L_{WN}(\lambda)$ prompts the need for uncertainties better than 5% for *in situ* $L_{WN}(\lambda)$ (still, in oligotrophic and likely mesotrophic open sea waters in the blue-green spectral regions). This requires *constraining individual sources of uncertainty of in situ radiometric data to within 1-2 % (commonly referred as 1% radiometry).*

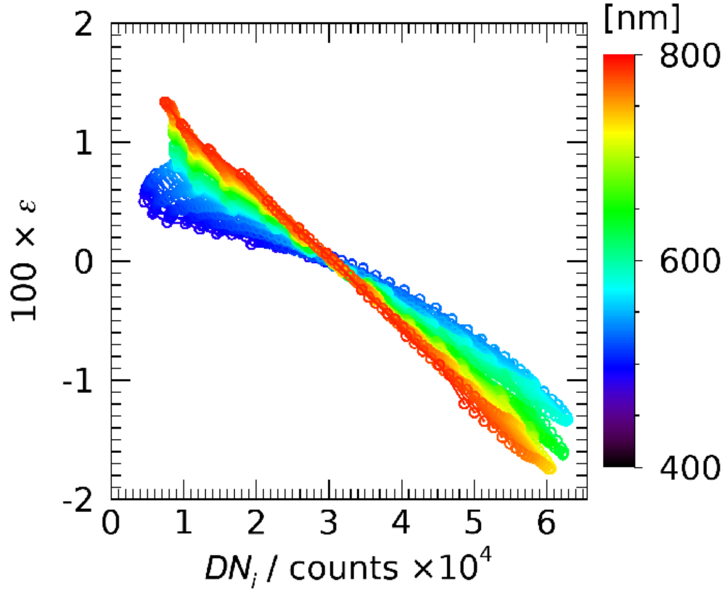
Sources of uncertainty from calibration and characterizations

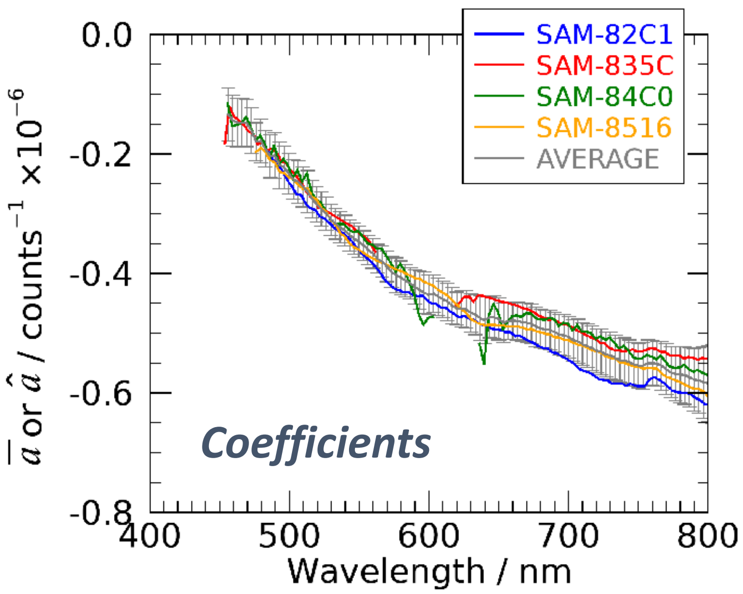
	Regular	Occasional	Initial	Class-based
Radiometric responsivity	X			
Spectral response		X		
Out-of-band & stray-light		X		
Immersion factor (irradiance)			X	
Immersion factor (radiance)				X
Angular response			X	
Linearity				X
Integration time				X
Temperature response				X
Polarization sensitivity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

Absolute calibration and characterizations expected for optical radiometers together with their envisaged temporal occurrence (reprinted from IOCCG 2019).

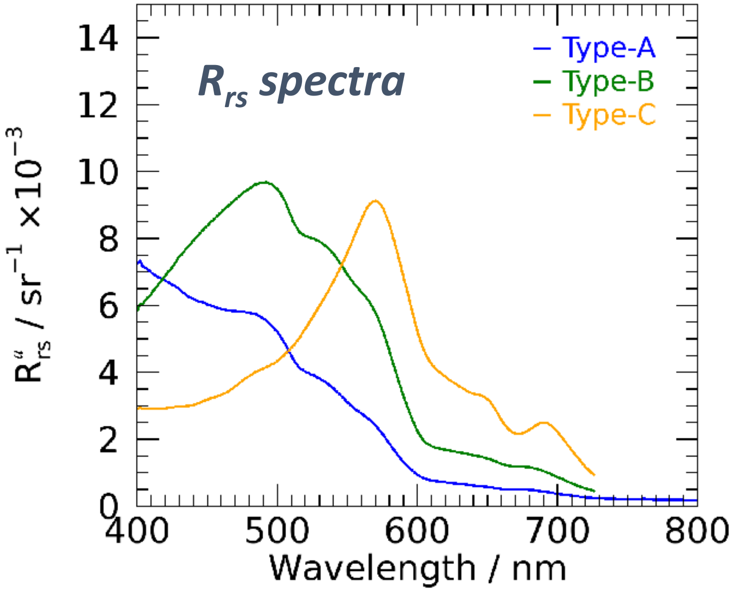
This table was built on the assumption that the characterizations and the the expected target uncertainties for data products obtained from specific radiometers or systems, allow for ideally considering a number of class based characterizations.

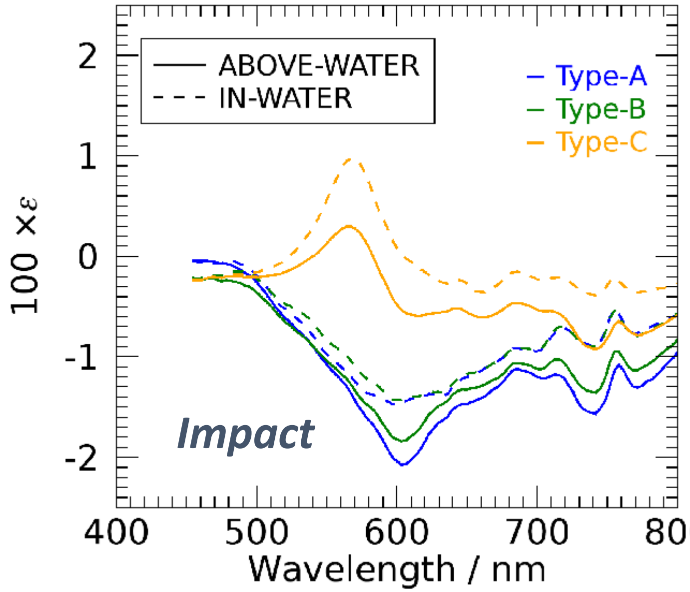
Nonlinearity of Response





Individual vs class-based characterizations





Impact of non-linearity on R_{rs}

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

Uncertainties: examples

$$u(L_{WN}) = \sqrt{[u_1(L_{WN})]^2 + [u_2(L_{WN})]^2 + \cdots + [u_j(L_{WN})]^2}$$

Source	412	443	488	551	667
Absolute calibration	2.1	2.1	2.1	2.1	2.1
Sensitivity change	0.4	0.2	0.2	0.2	0.2
Correction	1.6	2.0	2.8	2.9	1.9
t_d	1.5	1.5	1.5	1.5	1.5
ρ	1.8	1.3	0.7	0.6	2.5
W	1.1	0.8	0.4	0.4	0.4
Environmental effects	3.1	2.1	2.1	2.1	6.4
Combined values	4.8	4.2	4.4	4.5	7.6

Lamp, plaque, power supply, mechanical set-up, …
Responsivity change between successive cals
Corrections applied for viewing angle and brdf
Normalization to Es
Data reduction and determination of ρ
Wind speed
Wave and cloud perturbations

$$u(L_{WN}) = \sqrt{[\varepsilon_1(L_{WN}) + \varepsilon_2(L_{WN}) + \cdots + \varepsilon_i(L_{WN})]^2 + [u_1(L_{WN})]^2 + [u_2(L_{WN})]^2 + \cdots + [u_j(L_{WN})]^2}$$

Source	443	551	667
Absolute calibration	2.1	2.1	2.1
Sensitivity change	0.2	0.2	0.2
Correction	2.0	2.9	1.9
Temperature resp. (+10°C)	+0.4	–0.6	**–1.4**
Polarization Sensitivity	+0.1	+0.2	**+0.4**
Straylight effects	–1.0	+0.5	**+0.5**
Nonlinearity	–0.0	–1.0	**–1.2**
t_d	1.5	1.5	1.5
ρ	1.3	0.6	2.5
W	0.8	0.4	0.4
Environmental effects	2.1	2.1	6.4
Combined values	4.2	4.6	7.8

Results are explained by the relatively small values of the biases (considered with their sign) naturally leading to compensations.

Results indicate that the non-ideal radiometer performance, if confidently constrained to within tentative measurement errors (*i.e.*, biases) of ±1%, may still allow to have a first guess on the uncertainties affecting data products.

It is, however, essential that potential radiometer non-performances are investigated and estimated.

Uncertainties: GUM

The Guide on Measurement Uncertainties (GUM, JCGM 2008) provides a general metrological framework for the quantification of measurement uncertainties.

The standard uncertainty associated with a measurand indirectly determined by other quantities $x_1, \ldots, x_N$ through a measurement model $y = f\,(x_1, \ldots, x_N)$, can be obtained propagating the uncertainties of each (model input) quantity x_i through the first-order expansion of Taylor series:

$$\tilde{u}_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)\,.$$

The above equation may be further expanded to account for non-negligible correlations between pairs of input quantities x_i, x_j or non-linearity in the model function of the measurement model.

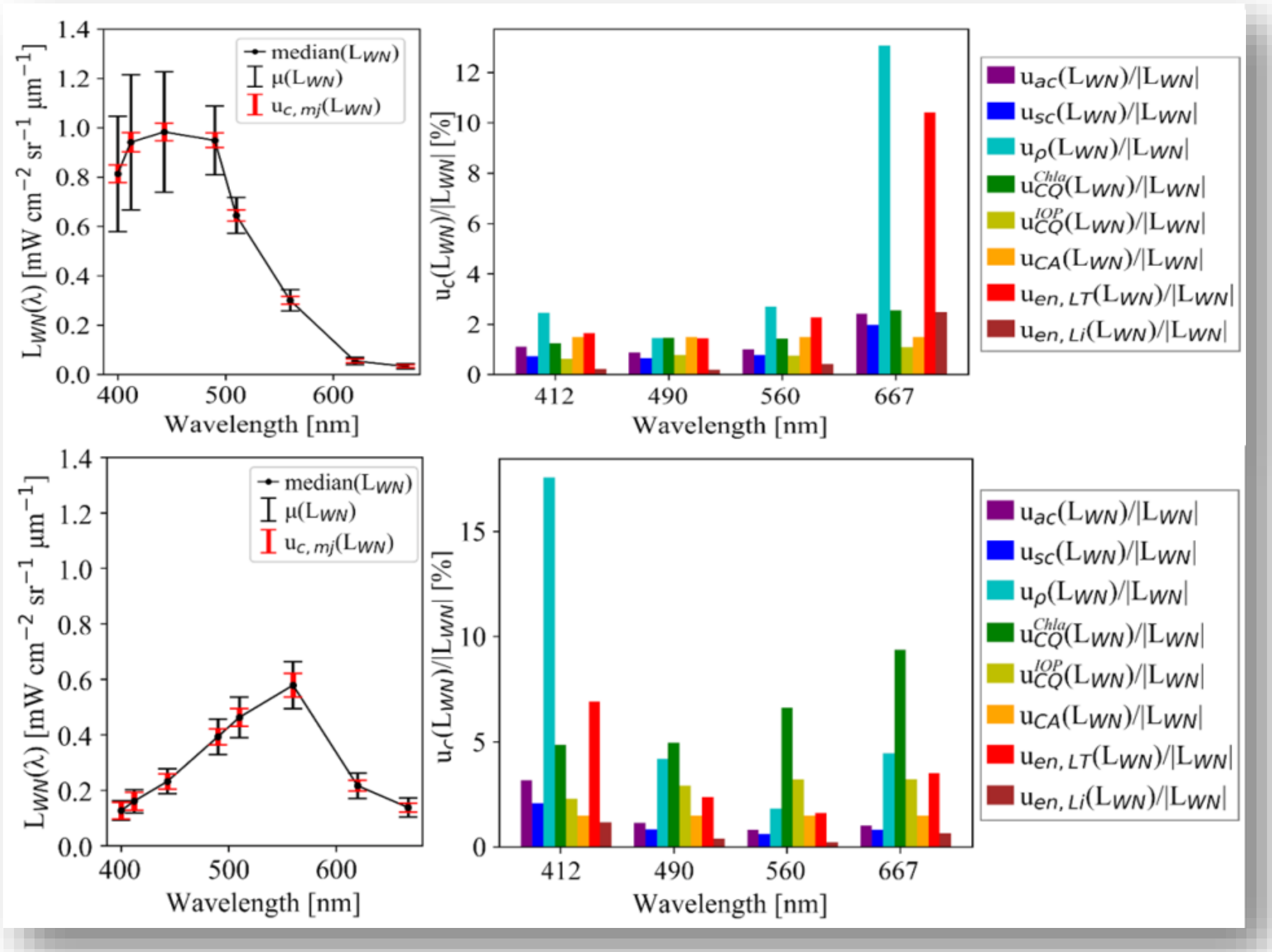
For simplicity, excluding correlations and non-linearity contributions, the combined uncertainty $\tilde{u}_c(L_W)$ for the spectral values of $L_W = L_T - \rho\, L_i$ are quantifiable from the individual uncertainties affecting L_T, L_i and ρ (hereafter indicated by $u(L_T)$, $u(L_i)$ and $u(\rho)$, respectively), according to

$$\tilde{u}_c^2(L_W) = u^2(L_T) + u^2(L_i)\rho^2 + u^2(\rho){L_i}^2\,.$$

Considering that $L_{WN} = L_W\, C_Q C_A$, the value of $u_c(L_{WN})$ is then quantifiable considering the additional uncertainties affecting C_Q and C_A, hereafter defined as $u\left(C_Q\right)$ and $u(C_A)$, respectively,

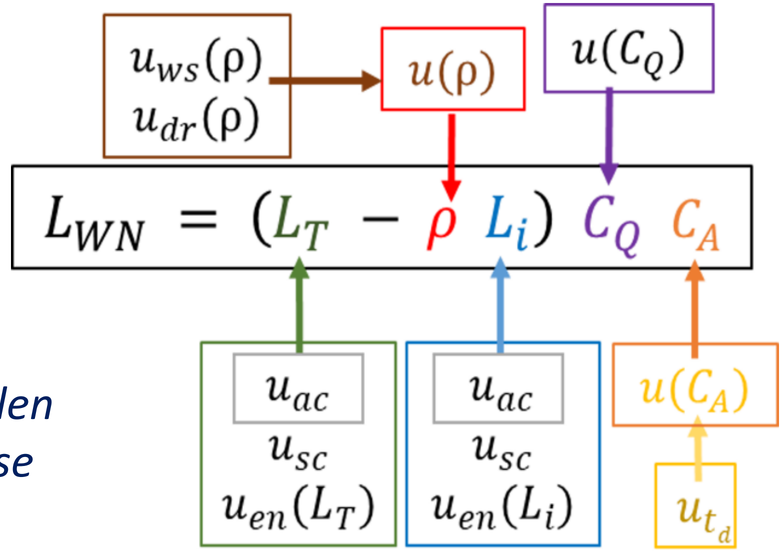
$$\tilde{u}_c^2(L_{WN}) = \left(C_Q C_A\right)^2 \tilde{u}_c^2(L_W) + (L_W C_A)^2\, u^2\left(C_Q\right) + \left(L_W C_Q\right)^2 u^2(C_A).$$

GUM application



Casablanca Platform

Gustaf Dalen Lighthouse



$u_{ws}(\rho)$
$u_{dr}(\rho)$

$u(\rho)$

$u(C_Q)$

$$L_{WN} = (L_T - \rho\ L_i)\ C_Q\ C_A$$

u_{ac}
u_{sc}
$u_{en}(L_T)$

u_{ac}
u_{sc}
$u_{en}(L_i)$

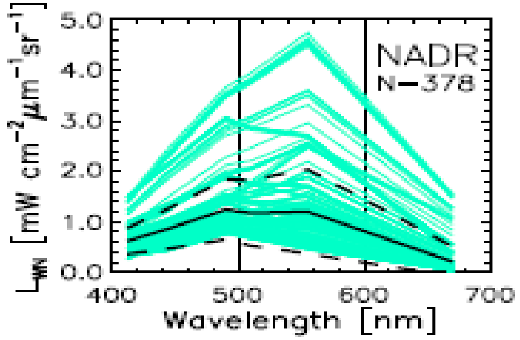
$u(C_A)$

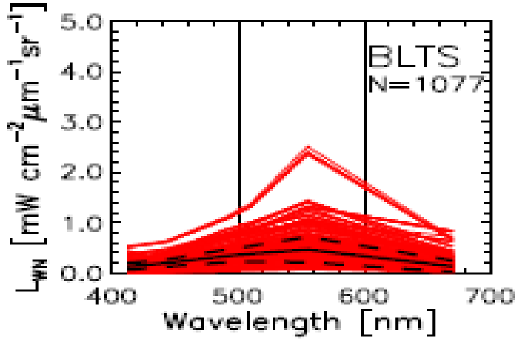
u_{t_d}

Relative uncertainty	**400**	**412**	**443**	**490**	**510**	**560**	**620**	**667**
$u^{IOP}_{c,mj}/L_{WN}$ **(oligotrophic waters)**	3.9	3.6	3.3	3.0	3.3	4.2	12.2	15.8
$u^{IOP}_{c,mj}/L_{WN}$ **(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.

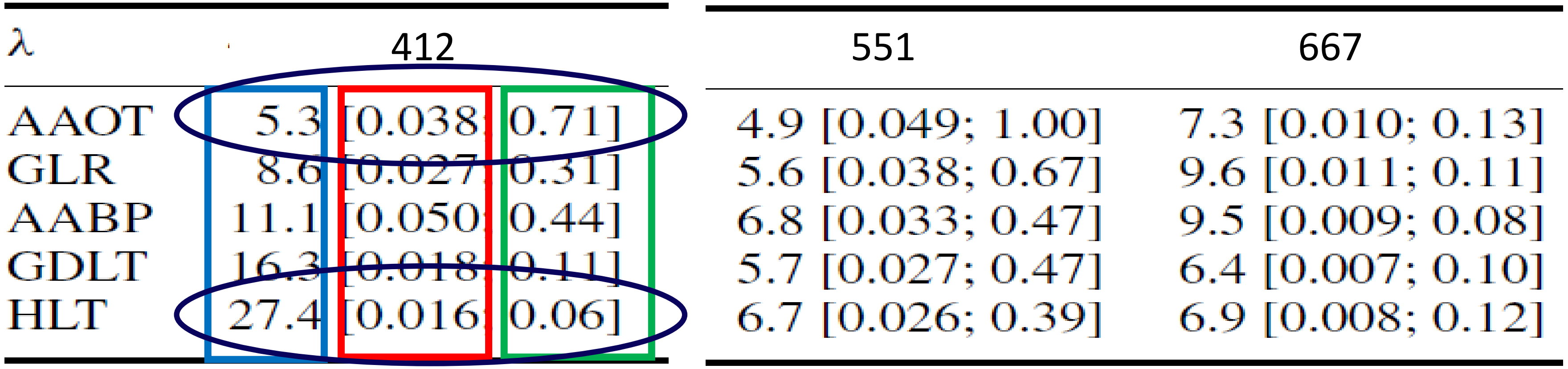
On reporting relative and absolute uncertainties





Relative combined uncertainties $u(L_{WN})/L_{WN}$ (%) and in square brackets the related 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.

The sole use of relative uncertainties may not comprehensively support cross-site or cross-study comparisons.

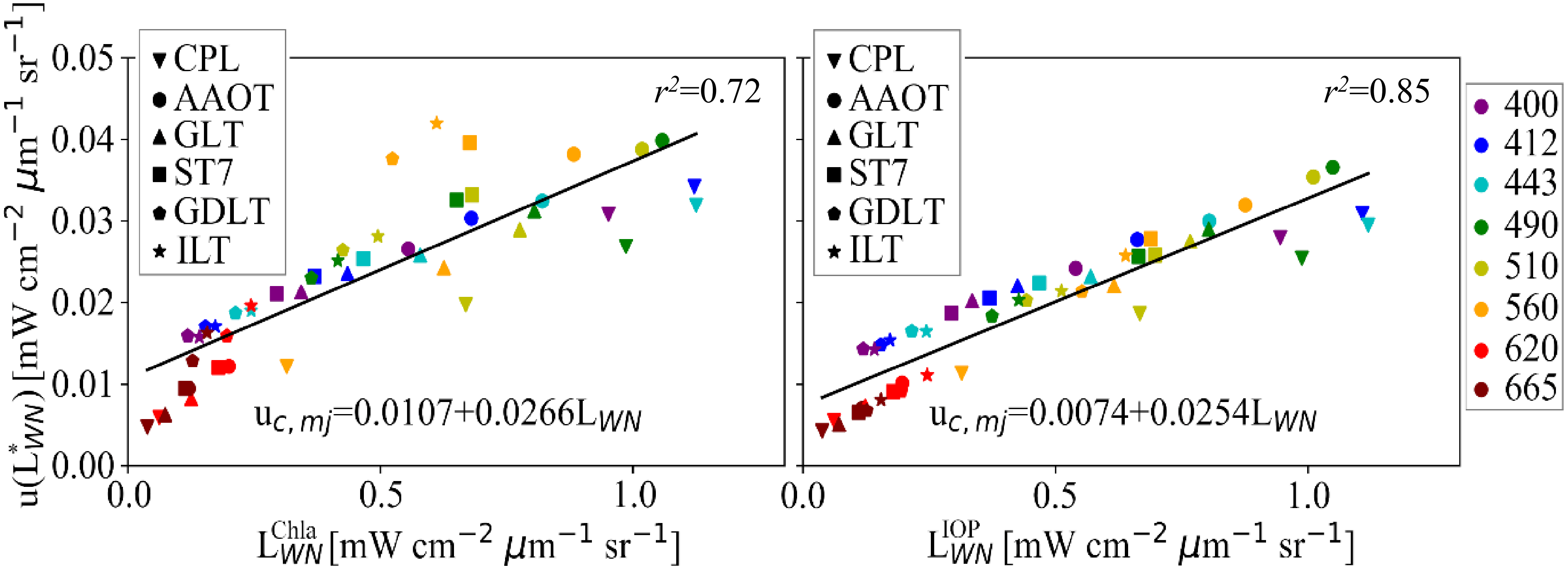


λ	412	551	667
AAOT	5.3 [0.038; 0.71]	4.9 [0.049; 1.00]	7.3 [0.010; 0.13]
GLR	8.6 [0.027; 0.31]	5.6 [0.038; 0.67]	9.6 [0.011; 0.11]
AABP	11.1 [0.050; 0.44]	6.8 [0.033; 0.47]	9.5 [0.009; 0.08]
GDLT	16.3 [0.018; 0.11]	5.7 [0.027; 0.47]	6.4 [0.007; 0.10]
HLT	27.4 [0.016; 0.06]	6.7 [0.026; 0.39]	6.9 [0.008;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

$u(L_{WN})/L_{WN}$ ***$u(L_{WN})$*** ***$<L_{WN}>$***

Gergely, M., & Zibordi, G. (2013). Assessment of AERONET-OC L $_{WN}$ uncertainties. *Metrologia*, *51*(1), 40.

Uncertainties: parameterization



Median L_{WN}^{Chla} (left) and L_{WN}^{IOP} (right) values versus the corresponding uncertainties $u_{c,mj}(L_{WN}^{Chla})$ and $u_{c,mj}(L_{WN}^{IOP})$ for data restricted to cases characterized by W<3 m s^{-1}.

The diverse symbols represent the various sites, whereas their color indicates the wavelength and the black solid line the linear regression.

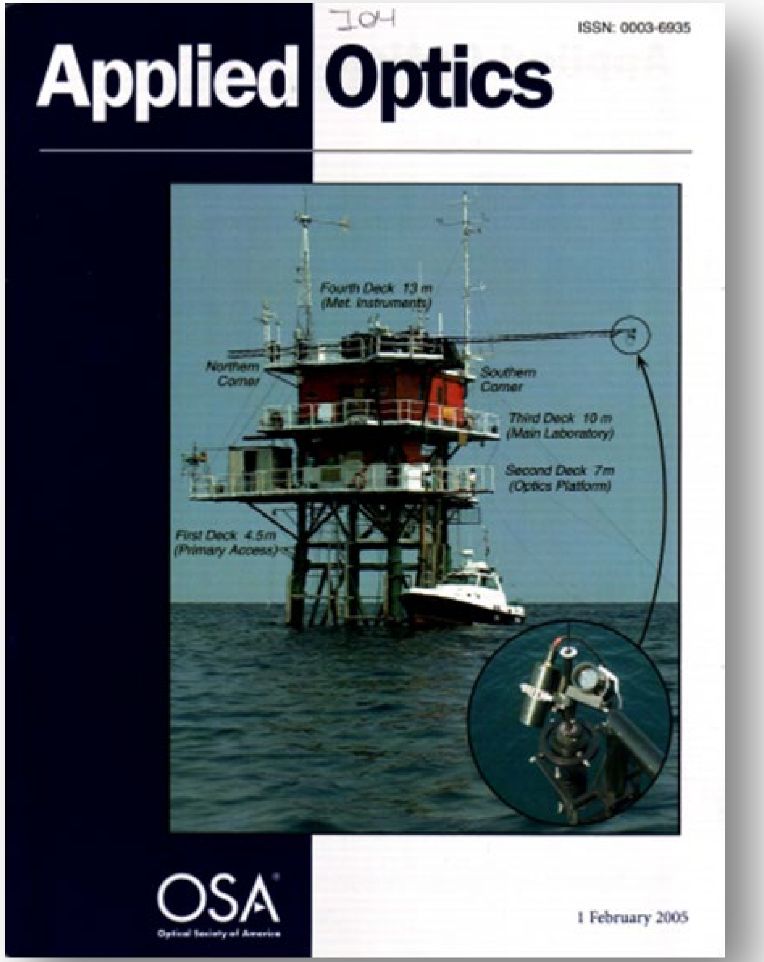
This is a practical approach used to assign statistical uncertainties to data sets for which it would be difficult to determine individual measurement uncertainties.

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

A practical view to above-water uncertainties

Outline

- Definition of uncertainty
- Uncertainty contributions
    - Absolute calibration
    - Characterizations
    - Temporal stability
    - ρ-factor
    - Environmental variability
    - Wind speed
    - Viewing angle and BRDF corrections
- Basic determination of uncertainty budgets
    - Quadrature sum
    - GUM benefits
- Sample spectra and evaluation of absolute *vs* relative uncertainties
- Parameterization of uncertainties



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