European Commission

In situ Requirements for Ocean Color System Vicarious Calibration: A Review

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Background literature

G.Zibordi, F. Mélin, K.J. Voss, B.C. Johnson, B.A. Franz, E. Kwiatkowska, J.P. Huot, M. Wang, D. Antoine. ***System Vicarious Calibration for Ocean Color Climate Change Applications: Requirements for In Situ Data***. *Remote Sensing of Environment*, 159, 361–69, 2015.

G. Zibordi and K.J.Voss, ***Requirements and Strategies for In Situ radiometry in Support of Satellite Ocean Color.*** In *Optical Radiometry for Oceans Climate Measurements, Experimental Methods in the Physical Sciences volume 47,* G. Zibordi, C.Donlon and A. Parr Ed.s, Elsevier - Academic Press, Amsterdam (December 2014).

G. Zibordi and K.J.Voss, ***In situ optical radiometry in the visible and near infrared***. In *Optical Radiometry for Oceans Climate Measurements, Experimental Methods in the Physical Sciences volume 47,* G. Zibordi, C. Donlon and A. Parr Ed.s, Elsevier - Academic Press, Amsterdam (December 2014).

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Uncertainty Requirements

5% uncertainty in satellite-derived L_W in the blue spectral region to allow for the determination of *Chla* concentration in oligotrophic waters with a standard uncertainty of 35% quantified through the work of Gordon and Clark (1981), Gordon et al. (1983) and Gordon (1987).

5% spectrally independent uncertainty in satellite-derived L_W across the blue-red bands set as an objective (not a science requirement) of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) mission (Hooker et al. 1992). This broad objective was later interpreted or set, as a science requirement for several missions.

5% radiometric uncertainty in satellite derived L_W in the blue-green spectral bands in oceanic waters and 0.5% radiometric stability over a decade for the creation of Climate Data Records (CDRs) of Essential Climate Variables (ECV) (WMO 2011, 2016).

Uncertainty and Stability

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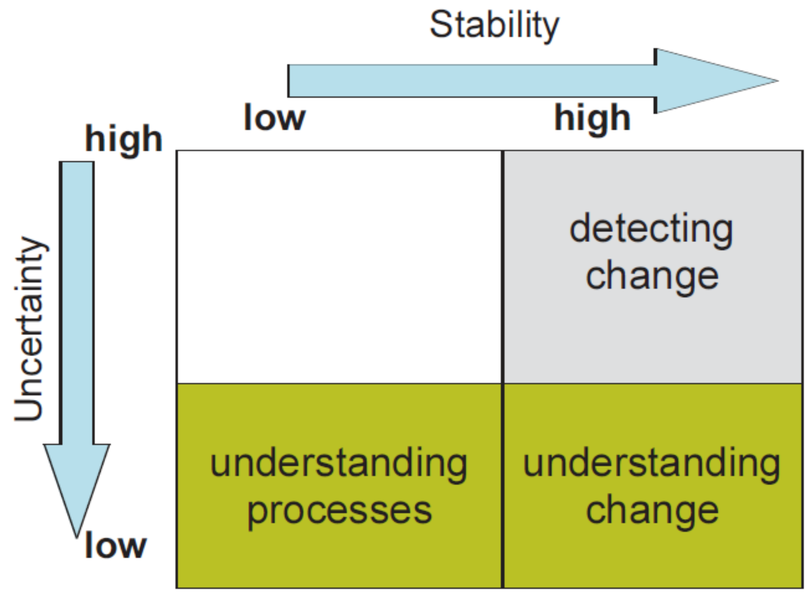
Requirements for satellite ocean color missions supporting climate change investigations (WMO 2011, 2016):

Radiometric uncertainty: less than 5% at blue-green bands

Stability: better than 0.5% per decade

Different from the 5% uncertainty requirement, which is commonly accepted by the satellite ocean colour community, the 0.5% stability requirement over a decade for the creation of CDRs through different missions, appears to be a more open issue.



Uncertainty and stability requirements for a climate observing system (Ohring et al. 2004)

Low uncertainties in the measurement of climate variables are essential for understanding climate processes and changes. However, it is not as necessary for determining long-term changes or trends as long as long as the data set has the required stability (Ohring et al. 2004).

Ohring, G. et al. "Satellite instrument calibration for measuring global climate change." B. Am. Meteorol. Soc. 86, 1303-1313 (2004). WMO, "Systematic Observation Requirements for Satellite-Based Data Products for Climate", GCOS (2016)

Legacy

Early indications on the appropriateness of *in situ* data/sites included

(extracted and interpreted with some freedom, from Gordon 1998):

1. Cloud free, very clear and maritime atmosphere (τ_a< 0.1 in the visible to increase performance of the atmospheric correction process);
2. Horizontally uniform L_w over spatial scales of a few kms (to increase comparability between satellite and in situ data at different geometrical resolutions);
3. Mesotrophic (oligotrophic) waters (to minimize the effects of in situ measurement errors of L_w in the blue);
4. Coincident aerosol measurements (expected to help in performing or assessing the atmospheric correction process).

Additional main indications suggested (extracted and interpreted with some freedom, from Clark et al. 2002):

5. Hyper-spectral measurements to cover any ocean color spectral band;
6. Fully characterized *in situ* radiometers to minimize / quantify uncertainties;
7. SI traceable measurements.

PACE Requirements

In situ data requirements *(extracted and interpreted with some freedom, from the PACE Mission Science Definition Team Report of October 16, 2012)*

1. Spectral range from 340-900 nm with ≤ 3 nm resolution
2. Radiometric uncertainties ≤ 5% including contributions from instrument calibration/characterization and data processing steps (NIST traceable)
3. Radiometric stability better than 1% per deployment (NIST traceable)
4. Data rate allowing for the reduction of the standard uncertainty of system vicarious coefficients to less than 0.2% within one year of launch (implying the need for multiple system simultaneously deployed)
5. …

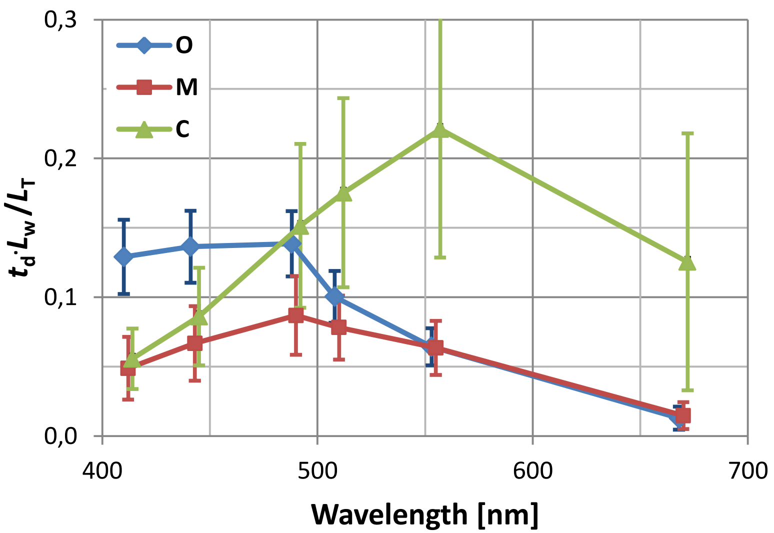
The previous requirements were closely applied to indicate specification for the ROSES-2014 call on "Ocean Color Remote Sensing Vicarious (*In Situ*) Calibration Instruments".

Uncertainty Equations

$$L_{\mathrm{T}} = L_{\mathrm{R}} + L_{\mathrm{A}} + L_{\mathrm{w}} t_{\mathrm{d}}$$

By assuming the values of L_R and L_A are exactly determined for any given observation condition, the relative uncertainties $u(L_T)/L_T$ are related to $u(L_w)/L_w$ with

$$\frac{u(L_T)}{L_T} = \frac{u(L_w)}{L_w} t_d \frac{L_w}{L_T}$$



Spectral values of $t_d \cdot L_w/L_T$ for oligotrophic (O), mesotrophic (M) and coastal (C) waters.

Mean values and standard deviations σ (indicated by the vertical error bars), result from the analysis of 814, 1487 and 1045 SeaWiFS data extractions, respectively.

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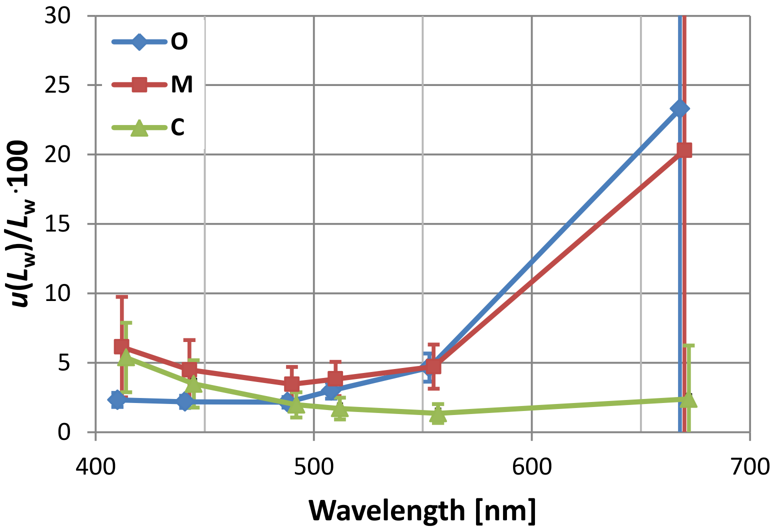
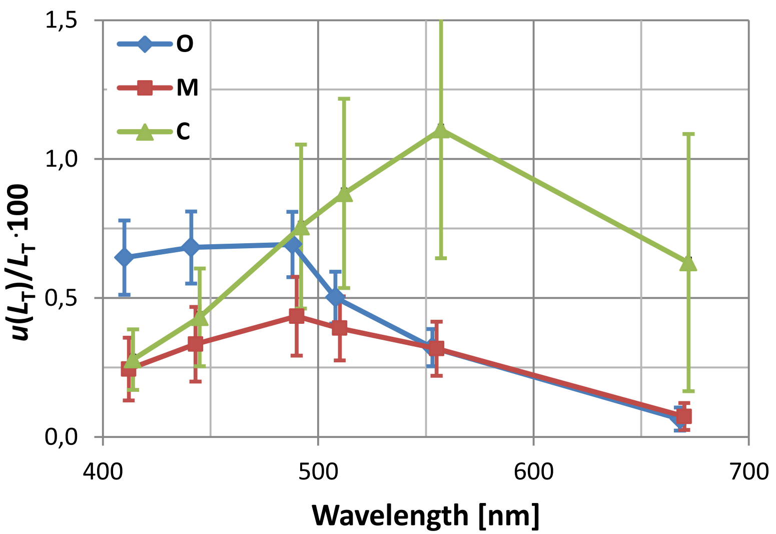
L_T and L_w Spectral Uncertainty Values



Relative uncertainties $u(L_w)/L_w$ determined assuming a spectrally independent 0.3% uncertainty value for L_T and the mean values of $t_d \cdot L_w/L_T$ for different water types.



Relative uncertainties $u(L_T)/L_T$ determined assuming a spectrally independent 5% uncertainty value for L_w and the mean values of $t_d \cdot L_w/L_T$ for different water types: oligotrophic (O), mesotrophic (M) and coastal (C).

The vertical bars refer to values determined with $t_d \cdot L_w/L_T \pm \sigma$.

Caution

If vicarious calibration factors determined from independent *in situ* data sets differ by as low as 0.3%, their application may introduce a **bias** of the order of the target uncertainty (~5%) on the derived radiometric products.

Thus, this bias can be a few times higher than the stability value per decade (expected to be lower than 0.5%) suggested for ocean color missions devoted to climate change investigations (WMO 2016), and may introduce unwanted inconsistencies in long-term data records from multiple missions.

This suggests that *in situ* data sources for vicarious calibration of satellite ocean color sensors need to be carefully evaluated accounting for the actual application of data products recognizing that the creation of CDRs imposes the most stringent conditions.
In particular, the need to merge data from multiple missions and the requirement to ensure a consistency over time much better than the uncertainty requirement, suggests caution in the application (and interchangeability) of system vicarious calibration coefficients determined from different *in situ* data sets.

Lesson learnt

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$$\Delta g = 100 \frac{g - g^{MOBY}}{g^{MOBY}}$$

Relative differences with respect to MOBY (SeaWiFS *SVC*)

N	Data - Source	Δg(412)	Δg443)	Δg(490)	Δg(510)	Δg(555)	Δg(670)	
166	MOBY	0	0	0	0	0	0	Reference, in-water, hyper-spectral, Hawaii
64	NOMAD	0.26	0.03	0.49	-0.20	-0.04	-0.37	Multiple sources and sites
46	BOUSSOLE	0.33	-0.03	0.43	0.33	0.14	-0.59	In-water, multispectral, Ligurian Sea
166	MOBY-MS	0.32	0.04	0.31	-0.45	-0.35	-0.39	Same as Ref. but reduced spectral resolution
99	AAOT-PRS	0.55	0.11	0.51	-0.05	0.41	0.93	Above-water, multi-spectral, Adriatic Sea
176	HOT-ORM	-0.66	-0.45	-0.39	-0.03	0.53	-0.11	Modeled Lw using *Chla*, Hawaii
241	BATS-ORM	-0.22	-1.11	-1.05	-0.41	0.23	0.02	Modeled Lw using *Chla*, Bermuda

MOBY: **166** matchups fulfilling defined SVC criteria from ~7-year data

NOMAD: **64** matchups fulfilling SVC criteria out of 1039 matchups identified in NOMAD, resulting from 3475 QC measurements out of 15400 included SeaBASS from 1350 field campaigns

BOUSSOLE: **46** matchups fulfilling SVC criteria from ~3-year data (with slightly relaxed exclusion criteria for *Chla* (0.25 instead of 0.20 mg l^{-1}) and only 5 matchups at 412 nm)

MOBY-MS: **166** matchups with reduced spectral resolution fulfilling SVC criteria from ~7-year data (same match-ups, and measurement conditions and *in situ* system as MOBY standard)

AAOT-PRS: **99** matchups from 5-year data fulfilling relaxed criteria (e.g., *Chla* less than 3 mg l^{-1})

Franz, B. A., Bailey, S. W., Werdell, P. J., & McClain, C. R. *(2007). Sensor-independent approach to the vicarious calibration of satellite ocean color radiometry. Applied Optics, 46, 5068–5082.*

Bailey, Sean W., Stanford B. Hooker, David Antoine, Bryan A. Franz, and P. Jeremy Werdell. *"Sources and assumptions for the vicarious calibration of ocean color satellite observations." Applied optics 47, 2035-2045, 2008.*

Werdell, P. Jeremy, Sean W. Bailey, Bryan A. Franz, André Morel, and Charles R. McClain. *"On-orbit vicarious calibration of ocean color sensors using an ocean surface reflectance model." Applied optics 46, 5649-5666, 2007.*

Mélin, Frédéric, and Giuseppe Zibordi. *"Vicarious calibration of satellite ocean color sensors at two coastal sites." Applied optics 49, 798-810, 2010*

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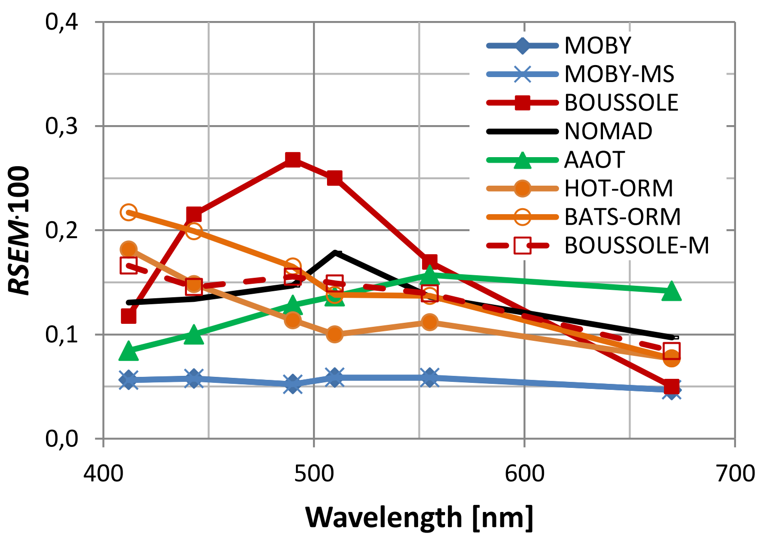
On radiometric stability

The relative standard error of the mean (*RSEM*) of *g*-factors *g* determined from

$$RSEM = (\sigma_g/g)/\sqrt{N_y}$$

with σ_g standard deviation of *g* assumed invariant with time for each considered data source, and N_y the scaled number of match-ups per decade (i.e., $N_y=10\cdot N/Y$ where *N* is the number of actual matchups and *Y* the number of measurement years scaled over a decade, to force the assumption of continuous availability of measurements for each *in situ* data source).



Plot of the standard percent error of the mean (RSEM) for the SeaWiFS g-factors and additionally for MERIS g-factors determined with BOUSSOLE data (i.e., BOUSSOLE-M).

The higher *RSEM* are likely explained by a number of factors including (but not restricted to):

i. measurement conditions perturbed by temporal changes in the marine and atmospheric optical properties or observation geometry;

ii. instability of the *in situ* measurement system when challenged by environmental perturbations during deployments (e.g., bio-fouling) or by variable performance of radiometer systems operated during successive deployments, or even by different measurement methods when considering a combined data set;

iii. or a relatively small of number of matchups.

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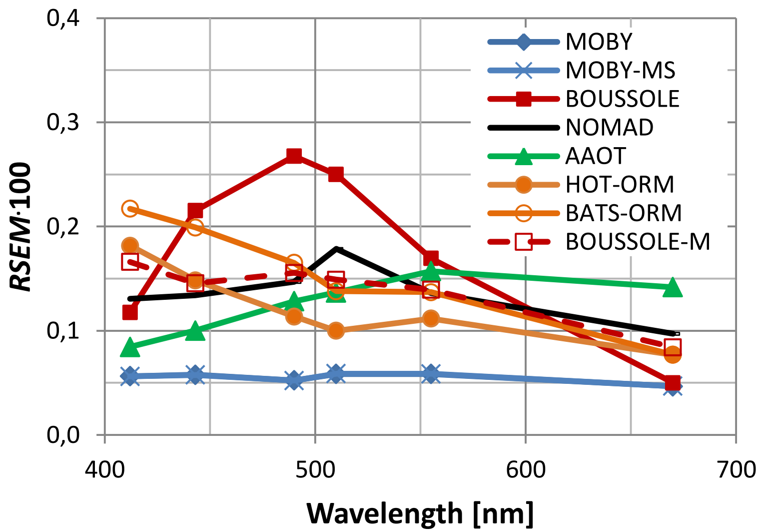
Conclusions from *RSEM*



The RSEM spectra exhibit large differences across the various data sources. The relevance of these differences can be discussed through the 0.5% stability requirement over a decade. This requirement implies (standard) uncertainties lower than 0.05 and 0.025 for *g*-factors determined in oligotrophic/mesotrophic waters in the blue and green spectral regions, respectively.

The previous standard uncertainties are comparable to the *RSEM* values determined for MOBY in the blue-green spectral regions during approximately 10 years. Conversely, they are significantly lower than those determined from the other *in situ* data sources included in the analysis.

These results suggest:

i. the use of long-term highly consistent *in situ* data for SVC to minimize uncertainties in *g*-factors determined for different satellite missions; and

ii. the inappropriateness of sole or multiple data sources referred to measurement conditions difficult to reproduce during the time frame of different missions.

General requirements

Overall, accounting Zibordi et al. (2015) concluded that *the creation of ocean colour CDRs should ideally rely on:*

- ***One main long-term in situ calibration system (site and radiometry)*** *established and sustained with the objective to maximize accuracy and precision over time of g-factors and thus minimize possible biases among satellite data products from different missions;*
- *and **unique (i.e., standardized) atmospheric models and algorithms for atmospheric corrections** to maximize cross-mission consistency of data products at locations different from that supporting SVC.*

Additionally, accounting for Zibordi et al. (2015) and previous literature, *an ideal ocean colour SVC site should meet the following general requirements:*

- *Located in a region chosen to maximize the number of high-quality matchups by trading off factors such as best viewing geometry, sun-glint avoidance, low cloudiness, and additionally set away from any continental contamination and at a distance from the mainland to safely exclude any adjacency effect in satellite data;*
- *Exhibiting known or accurately modelled optical properties coinciding with maritime atmosphere and oligotrophic/mesotrophic waters, to represent the majority of world oceans and minimize relative uncertainties in computed g-factors;*
- *Characterized by high spatial homogeneity and small environmental variability, of both atmosphere and ocean, to increase precision of computed g-factors.*

Further Requirements

Deployment structure: Highly stable with minimum impact on field measurements (including the capability of avoiding bio-fouling perturbations on in-water systems)

In situ radiometer: Hyper-spectral, fully characterized (in terms of linearity, temperature dependence, polarization sensitivity, straylights, …), exceptionally calibrated (with standard uncertainty lower than 2% traceable to a National Metrology Institute and determined accounting for uncertainty in the source, its transfer and error corrections), highly radiometrically stable (better than 1% per deployment, with target of 0.5%), regularly checked and frequently swapped

In situ radiometric data products: overall target combined standard uncertainty of 3% for L_W in the blue-green spectral regions and 4% in the red (benefitting of state-of-the-art data reduction and quality control schemes); data rate ensuring close matchups with any satellite ocean color mission (…)

In situ complementary measurements: water and atmospheric optical properties

Time frame: continuous and beyond the lifetime of any specific mission