Ocean Color System Vicarious Calibration: requirements on in situ data and sites

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Several elements are taken from "*Requirements and Strategies for In Situ Radiometry in Support of Satellite Ocean Color*" by G. Zibordi et al., included in "*Optical Radiometry for Oceans Climate Measurements*", Elsevier, 2014.

System Vicarious Calibration
Accuracy tied to applications

Sample applications (not comprehensive)

1. Environment-Regional: e.g. *Chla* from band-ratio algorithms with uncertainty lower than 50% in regional seas . Radiometric uncertainty of L_{WN} can be of the order 10% (or even more depending on water type) in the blue-green (or green/red) spectral intervals. This requirement can be achieved without vicarious calibration or alternatively with regional vicarious calibration coefficients optimizing data products for regions exhibiting specific atmospheric and marine optical properties, or unique observation and illumination geometries.
2. Biology-Global: e.g. *Chla* from band-ratio algorithms with uncertainty lower than 30% in oligotrophic and mesotrophic world sea regions. Radiometric uncertainty of L_{WN} need to be lower than ~5% in the blue spectral bands. This requirement can be achieved with vicarious calibration coefficients optimizing data products for mesotrophic and oligotrophic regions.
3. Climate Change: Radiometric uncertainty of L_{WN} needs to be lower than 5% at all wavelengths[(*)], intra-channel uncertainties lower than 1%, decadal stability better 1%[(*)] (here is the real challenge).

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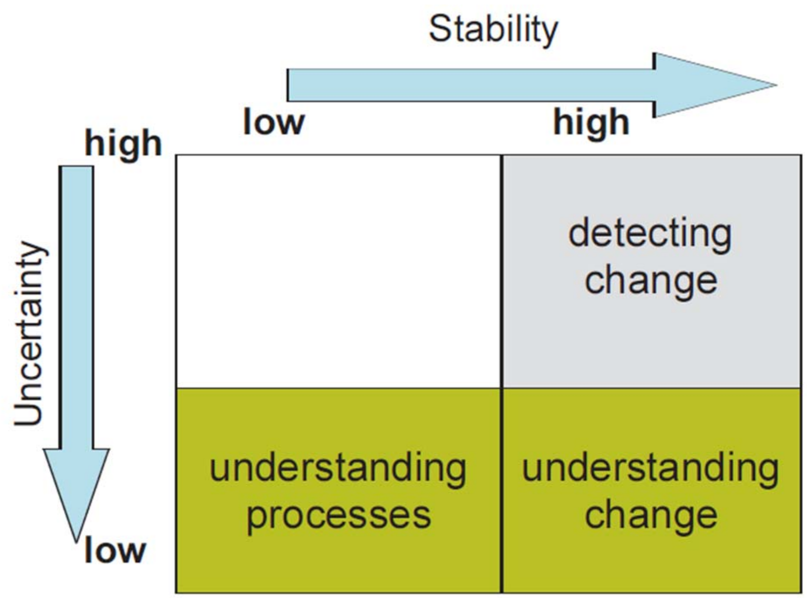
Uncertainty and Stability

Requirements for satellite ocean color missions supporting climate change investigations (Ohring et al. 2004):

Radiometric uncertainty: less than 5% at all λs
(in the blue & green spectral bands according to WMO (2011))

Inter-band uncertainty: less than 1%

Stability: higher than 1% per decade
(0.5% according to WMO (2011))



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-2011 Update", GCOS 154 (2011)

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Rationale

Accuracy specifications for the calibration of satellite ocean color sensors are set by target uncertainties expected for satellite-derived water leaving radiance L_w.

Specifically, by assuming a target uncertainty of 5% in L_w , with L_w approximately 10% of top-of-atmosphere radiance L_T , the uncertainty in L_T must be lower than 0.6% (=5% x 10/90)[1]. The target uncertainty in L_T decreases to approximately 0.3% when L_w is 5% of L_T.

This means that "system vicarious calibration[2]" is the only viable calibration for satellite ocean color sensors because of:

i. the 5% target uncertainty in L_w , and
ii. the approximately 2% standard uncertainty in absolute radiometric calibration currently achievable.

[1] It must be noted that the considered case is for blue wavelengths in oligotrophic/mesotrophic waters, thus much smaller uncertainty targets should be expected for the red spectral bands.

[2] System Vicarious calibration minimizes differences between target observations (assumed known with a given uncertainty) and, the combined effects of inaccurate atmospheric correction and error in sensor calibration. Because of this, "system vicarious calibration" is not absolute.

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Caution

If vicarious calibration factors determined from independent *in situ* data sets differ by as low as 0.6-0.3%, 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 1% with target of 0.5%) suggested for ocean color missions devoted to climate change investigations (Ohring et al. 2005, WMO 2011), 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 required for the creation of CDRs, suggests caution in the application (and interchangeability) of system vicarious calibration coefficients determined from different *in situ* data sets.

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Legacy Constrains

Early indications on the appropriateness of *in situ* data/sites included (extracted and interpreted with some freedom, from Gordon 1997):

1. Cloud free, very clear and maritime atmosphere ($\tau_a < 0.1$ 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.

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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 ≤ 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)

and additionally

5. Continuous deployment beginning one year pre-launch and extending throughout the life of the mission
6. Centralized service to maintain and deploy the field instruments
7. Routine field campaigns to the measurement site(s) to verify instrument radiometric quality and revise uncertainties.

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System Vicarious Calibration Lesson learnt

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

N	Data - Source	412	443	490	510	555	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 μg 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 μg l^{-1})

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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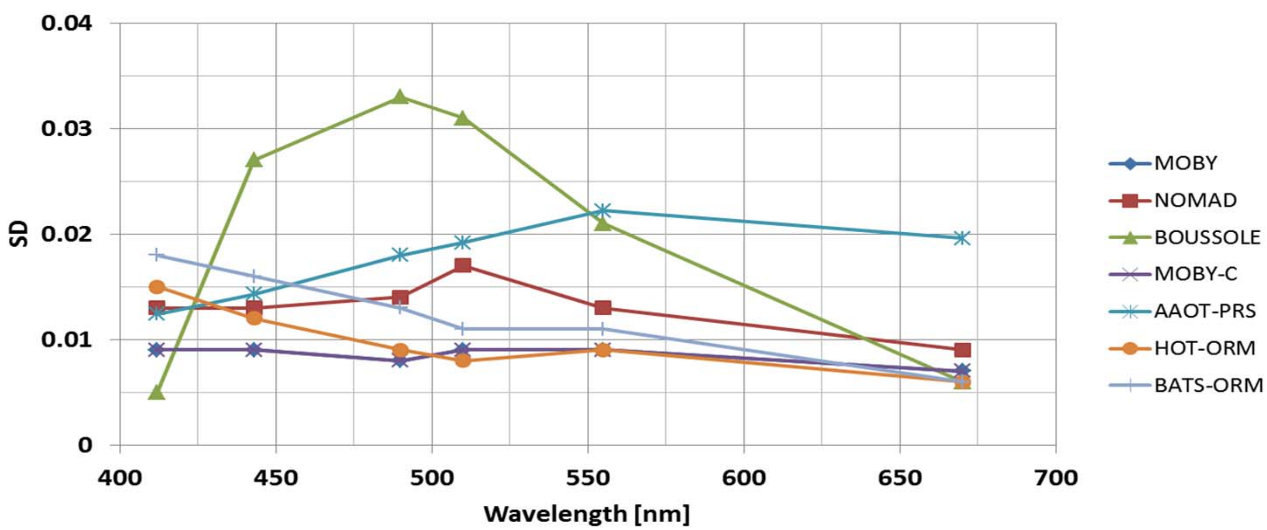
System Vicarious Calibration

Standard Deviation of SeaWiFS *SVC*

Standard deviation of SeaWiFS *SVC*

Data - Source	412	443	490	510	555	670
MOBY	0.009	0.009	0.008	0.009	0.009	0.007
NOMAD	0.013	0.013	0.014	0.017	0.013	0.009
BOUSSOLE	0.005	0.027	0.033	0.031	0.021	0.006
MOBY-MS	0.009	0.009	0.008	0.009	0.009	0.007
AAOT-PRS	0.012	0.014	0.018	0.019	0.022	0.020
HOT-ORM	0.015	0.012	0.009	0.008	0.009	0.006
BATS-ORM	0.018	0.016	0.013	0.011	0.011	0.006

- Reference, in-water, hyper-spectral, Hawaii
- Multiple sources and sites
- In-water, multispectral, Ligurian Sea
- Same as Ref. but reduced spectral resolution
- Above-water, multi-spectral, Adriatic Sea
- Modeled L_w using *Chla*, Hawaii
- Modeled L_w using *Chla*, Bermuda



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System Vicarious Calibration

Fundamental requirements for a SVC Site supporting ocean color climate change applications

- One, away from any source of land contamination (including potential adjacency effects in satellite observation)
- Horizontally homogeneous optical properties in a radius of several pixels around the deployment location
- Bio-optically stable (within the limits of likely regular seasonal changes) with accurately known (or modelable) marine and atmospheric optical properties
- Representative of the most common observation conditions and particularly of the prevalent world sea atmospheric and marine optical properties.
- Low cloudiness

Note that there is no constrain on pigments concentration and aerosol load or type. It is expected that fundamental requirements should screen unfavorable conditions.

Multiple sites are relevant and needed for continuous verification of the performance of the space system and in general for validation purposes (i.e., fully independent and suitable time-series of high quality open sea data were missing in the past).
With exclusion of the early phases of any new mission, the combined use of multiple site data for system vicarious calibration need to be carefully evaluated accounting for:
i. different performances of the field systems; ii. site differences in terms of atmospheric-marine optical properties; iii. site differences in terms of observation-illumination conditions)

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Additional requirements for SVC supporting ocean color climate change applications

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 (tentatively with time differences less than 15 minutes)

In situ complementary measurements: water and atmospheric optical properties

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