System Vicarious Calibration requirements for satellite ocean colour missions targeting climate and global long-term operational applications

Executive summary

System Vicarious Calibration (SVC) is fundamental for ocean colour observations. It maximizes the accuracy of satellite ocean colour data products by minimizing the impact of biases affecting the absolute radiometric calibration of the space sensor and the atmospheric correction process. In fact, even if a perfect atmospheric correction was available, SVC would still be needed to solve limitations in satellite sensor calibration. Diverse SVC procedures have been implemented targeting different satellite ocean colour applications such as regional investigations, individual objectives, and, finally, the most demanding climate and operational applications requiring low uncertainties and high consistency across global multi-mission time series. This White Paper, which focuses on SVC for ocean colour missions with global operational and climate goals, results from a dedicated workshop held at the University of South Florida College of Marine Science in St. Petersburg as an initiative of the Ocean Colour SVC Task Force of the International Ocean Colour Coordinating Group (IOCCG). The White Paper affirms the essential need for SVC long-term and sustained infrastructures and related activities. It outlines the main requirements for a comprehensive ocean colour SVC framework with a focus on supporting the climate and global operational applications to ensure the highest accuracy and consistency of global and multi-decadal ocean colour data products. Key recommendations are provided to address future investigations on open issues relevant for SVC principles, requirements, and methods.

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1. Introduction and objective

Satellite ocean colour radiometry generically indicates the space missions designed to quantify the properties and concentrations of optically significant constituents in natural waters. The primary ocean colour data product, from which any additional higher level product is derived, is the so called water-leaving radiance L_W: the radiance leaving the water volume and carrying information on its optically significant constituents. L_W spectrally varies with the concentration and type of water constituents and it is only a small fraction, at best a few percent, of the top-of-the atmosphere signal L_T measured by a satellite sensor.

System Vicarious Calibration (SVC) is a requirement for all ocean colour missions with global operational and climate goals. It is the technique applied to meet accuracy requirements for ocean colour radiometry products (Gordon 1987, Gordon 1998). Specifically, SVC determines adjustment factors, so called *g*-factors, for the radiometric calibration coefficients of satellite sensors. These *g*-factors minimize the combined effects of biases due to the inaccuracy of: *i*. absolute radiometric calibration and characterization of the satellite sensor, previously corrected for radiometric sensitivity change over time; and *ii*. the atmosphere-water algorithms applied to quantify L_W from L_T in the process termed the atmospheric correction. Consequently, SVC applies to the combined instrument and algorithms 'system' components, from which the name originates, as opposed to alternative Vicarious Calibrations techniques (IOCCG 2013).

Over time, SVC has been implemented targeting different applications such as regional investigations (Ohde et al. 2002, Mélin and Zibordi 2010), mission explicit objectives focused on single-sensor applications (Sturm and Zibordi 2002, Gao et al. 2012, Shukla et al. 2013, Hlaing et al. 2014, Ahn 2015, Song et al. 2019, Murakami et al. 2022), and finally the most demanding climate and global long-term operational applications (Franz et al. 2007) requiring low uncertainties and high consistency across diverse missions.

The *g*-factors are determined by the ratio of simulated to measured spectral L_T values assuming the same atmosphere-water algorithms and processing chain as applied for the atmospheric correction. The goal of the SVC strategy is to maximize the accuracy of the satellite retrieved L_W by removing any systematic bias affecting its value. SVC exploits the water property that makes it increasingly absorbing towards the near-infrared (NIR) and shortwave infrared (SWIR) spectral regions with no or negligible L_W signal (Wang et al. 2016). A standard SVC process starts with NIR (and SWIR bands if available) and determines the related spectral *g*-factors over the clearest and most homogenous oligotrophic gyres assuming *i*. negligible or quantifiable L_W, *ii*. accurate satellite sensor calibration at the longest NIR band, and *iii*. a most probable aerosol model (*e.g.*, Franz et al. 2007; Wang et al. 2016). The SVC process concludes with the determination of the *g*-factors for the visible bands applying highly accurate *in situ* measurements of L_W (or the related normalized water-leaving radiance L_{WN} or remote sensing reflectance R_{RS}) performed at oligotrophic and homogenous clear-water sites. In operational data processing, the SVC naturally allows satellite derived L_W to be determined with the highest accuracy when the observation conditions are equivalent to those leading to the calculation of the *g*-factors.

The number of satellite ocean colour missions established over almost three decades by international space agencies are providing a unique opportunity to create time series supporting climate investigations (Sathyendranath, 2019; McClain, Franz, and Werdell, 2022). The impact of operational ocean colour missions dedicated to climate investigations and user services has been enormous; supporting water quality, aquatic ecosystems, fisheries, aquaculture, biodiversity applications, and now empowering environmental, health, conservancy, and management decisions (*e.g.,* missions operated by the United States (US) National Oceanic and Atmospheric Administration (NOAA) or the European Commission (EC) Copernicus Programme). The creation of Climate Data Records (CDR) and operational user services, however, requires accurate, consistent, and stable long-term data from successive missions. The accuracy, consistency and stability are crucial because climate change studies along with many service and management decisions, are based on water parameters exceeding certain absolute thresholds or exhibiting trends over time. These specific needs solicited a number of dedicated investigations aimed at advancing SVC and benefitting of new *in situ* technologies (Barnard et al. 2022) and infrastructures (European Space Agency (ESA) 2017; European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) 2017, 2022;

Antoine et al. 2020; Liberti et al. 2020), and by utilizing studies investigating the most favourable marine locations (Zibordi and Mélin 2017, Chen et al. 2021).

This White Paper is an initiative of the Ocean Colour SVC Task Force of the International Ocean Colour Coordinating Group (IOCCG) and an IOCCG contribution to the Committee on Earth Observation Satellites (CEOS) and CEOS Ocean Colour Radiometry Virtual Constellation (OCR-VC). The White Paper is based on the outcome of a dedicated workshop held at the College of Marine Science, University of South Florida St. Petersburg, and it streamlines essential requirements for a comprehensive ocean colour SVC framework supporting climate and global long-term operational applications. The White Paper reviews SVC implementations and challenges in particular focussing on the need to ensure the highest accuracy and consistency to global and multi-decadal ocean colour data products from independent missions. Additionally, aiming at further consolidating and standardizing the related processes, the White Paper provides a number of key recommendations spanning from the necessity to ensure long-term and sustained support to SVC programs, to the needs and benefits of addressing open issues on SVC principles, requirements and methods.

2. System Vicarious Calibration (SVC)

Why implement System Vicarious Calibration (SVC)?

SVC is required for satellite ocean colour because of the complexity of the retrieval process and the low magnitude of the aquatic signal. The determination of L_W is obtained through the removal of atmospheric scattering and absorption, and surface interface effects, in L_T by applying correction procedures relying on atmosphere-water algorithms (IOCCG 2010; Gordon and Wang 1994). The intrinsic uncertainties of the pre-flight and on-orbit absolute radiometric calibration of optical space sensors (Esposito et al. 2004, Butler et al. 2007) combined with the uncertainties of any atmospheric correction scheme (IOCCG 2021) generally do not allow mission target uncertainties[1] for L_W to be met. The uncertainty requirements on L_W were first derived from the uncertainties needed to differentiate across various concentrations of water constituents, such as phytoplankton chlorophyll-*a* concentrations. Long established requirements on uncertainties *e.g.*, for SeaWiFS, 5 % across the spectrum (Hooker et al. 1992) or 5 % for the blue-green spectra (Gordon 1997) are further re-confirmed for missions such as the Plankton, Aerosol, Cloud Ocean Ecosystem (PACE: Gorman et al. 2019). Assuming favourable conditions provided by oceanic waters and a perfect atmospheric correction, the typical uncertainty of 2 % in the absolute radiometric calibration of the space sensor would still lead to uncertainties in L_W varying between about 10 % and 30 % in the blue-green spectral region (Zibordi et al. 2015). Because of this, satellite ocean colour missions need to rely on the SVC indirect calibration technique. The SVC in turn relies on accurate *in situ* measurements of L_W (Clark et al. 1997; Antoine et al. 2008) and the atmosphere-water algorithms applied for the removal of atmospheric perturbations in L_T (Gordon 1998).

While a variety of SVC implementations can satisfy regional or mission specific objectives, the SVC for ocean colour missions targeting climate investigations and global long-term operational services must ensure the capability to detect signatures of climate change, water quality, ecosystem health, fisheries, aquaculture, or biodiversity. For these global missions, the SVC requirements are strict and aim to minimize satellite retrieval biases and to maximize multi-mission consistency of data products. Consequently, comprehensive long-term SVC plans are needed to maintain dedicated infrastructures across successive missions relying on state-of-the-art water radiometry, methods, and automated technology. Failing to ensure such a long-term support would challenge the climate applications and operational services. A reference for SVC operational infrastructures is the Marine Optical BuoY (MOBY), which has been supporting most of the ocean colour missions since 1997 with SI traceability (Clark et al. 2003).

[1] In this document all uncertainties are standard uncertainties, level of confidence of 68 %.

Recommendation

SVC is a mission level requirement that must be planned and operationally implemented securing the application of state-of-the-art technology and methods. Individual ocean colour missions may support specific applications, and their SVC implementations should naturally reflect those goals. However, for the missions dedicated to global climate and user services, long-term and sustained SVC infrastructures must be established aiming at metrologically equivalent performance at different SVC sites. The SVC infrastructures' goal is to secure the means to produce accurate, consistent, and long-term ocean colour data products.

Notably, regular access to SVC *in situ* data would also support the validation of the SVC process and possibly the quantification of temporal changes affecting the onboard sensor, after the determination of provisional *g*-factors during the early phases of each mission. Still, unique *g*-factors should be determined for each mission after its completion. This would provide a pathway to assigning to *g*-factors uncertainty values, which implicitly include uncertainties affecting corrections for the sensor sensitivity change over time, representative for the entire mission and benefitting of the largest number of *in situ* and satellite matchups ideally evenly distributed in time.

International collaborations are deemed essential for the standardisation and interoperability multiple SVC infrastructures, and consequently to ensure their best performance.

3. Uncertainty & stability requirements for *in situ* radiometric measurements supporting SVC

What are the uncertainty and stability requirements for in situ SVC radiometric data?

Any SVC procedure entails access to highly accurate *in situ* radiometric data (*e.g.*, L_W) to determine the visible band *g*-factors that minimize the impact of inaccuracies affecting both the absolute radiometric calibration of the space sensor and the atmospheric correction procedure applied. Implicitly, the requirements for *in situ* data must be traced to application needs for satellite data products. Considering the satellite product requirements, the World Meteorological Organization (WMO, 2011, 2022) indicated that satellite ocean colour missions supporting climate studies should ensure L_W in non-optically complex waters with:

- a radiometric uncertainty better than 5 % at blue-green spectral bands, and
- a temporal stability better than 0.5 % per decade.

The requirement on radiometric uncertainty ensures the necessary accuracy to derived data products such as chlorophyll-*a* concentration (30 % for climate studies according to WMO 2011). Assuming the 5 % uncertainty is solely due to random contributions, its value closely meets early indications for the determination of chlorophyll-*a* concentration through the application of a specific algorithm (Gordon and Clark 1981). Nevertheless, it is also recognized that the 5 % requirement is often provided as a mission uncertainty target, regardless of any algorithm used to compute derived data products.

The requirement on temporal stability is essential to allow for the discrimination of temporal changes characterizing the marine quantities of interest from any potential systematic bias likely affecting products from different missions. Regarding this stability value, Dutkiewicz et al. (2019) used a biogeochemical model to predict trends up to 1 % per decade due to climate change at the 475 nm centre-wavelength. This value is just twice that indicated by WMO (2011) for satellite data products. This confirms the need to satisfy strict stability requirements for satellite data products from individual missions as a pre-requisite for a confident quantification of changes in marine bio-optical properties through multi-decadal data products obtained from the composition of data from multiple ocean colour missions (Ohring et al. 2005). However, residual differences between mission-specific products, if not accounted for, might still introduce spurious artefacts in a multi-mission data record (Mélin 2016).

While recognizing that the generic uncertainty and stability requirements indicated by WMO (2011, 2022) are largely valid for non-optically complex waters, still their re-appraisal is a desirable goal to better address SVC activities. Such a re-appraisal should additionally: *i*. investigate uncertainty requirements beyond the blue-green spectral region accounting for uncertainty needs of high level data products including any water quality, ecosystem health and biodiversity parameter relevant for user services; and also *ii*. re-evaluate stability requirements based on most recent findings.

The uncertainty requirements on satellite global ocean L_W, L_{WN}, or R_{RS} radiometric products are however much upstream from the requirements on *in situ* radiometric measurements supporting SVC: the requirements for *in situ* SVC data need to be much tighter than those set for satellite data products. The *in situ* SVC radiometric requirements should also reflect the uncertainty needs for the various satellite ocean colour applications and their stability requirements for multi-mission time series. This implies that the impact of any systematic uncertainty component of *in situ* radiometric data applied for the determination of *g*-factors must be minimized to avoid potential step-changes in multi-mission time series and to assure the highest accuracy to the retrieval of data products in support of service and management decisions.

Recommendations

Current WMO (2022) requirements for satellite ocean colour data products supporting climate applications, which equally apply to data products for global long-term operational services, imply *in situ* measured L_W data for SVC with uncertainty lower than 5 % in the blue-green spectral regions over oligotrophic waters (where L_W is maximum), and stability below 0.5 % per decade. It is recommended that the above generic uncertainty requirement is re-evaluated accounting for specific application products, duly addressing the impact of related algorithms. Additionally, when relevant, any updated uncertainty requirement should then be extended to the red and ultraviolet spectral regions of interest for ongoing and future missions. Likewise, the stability requirement should be consolidated, accounting for expected trends in marine bio-optical data products.

Any uncertainty or stability requirement emerging for new satellite ocean colour data products should consistently lead to a re-definition of requirements for *in situ* radiometric data supporting the SVC. It is essential that each re-definition considers the random and systematic uncertainty components in *in situ* radiometric data that have an impact on *g*-factors and consequently on the consistency of time-series from ocean colour multi-missions.

4. Spectral Requirements for *In Situ* Measurements supporting SVC

What are the spectral range and resolution requirements for in situ data supporting SVC?

Aside from uncertainties and stability requirements for *in situ* radiometric data, their spectral range and spectral resolution are additional elements that characterize *in situ* SVC radiometric data. These data should inherently cover the whole range of satellite spectral bands in L_W retrieval and ensure adequate spectral resolution to maximize the accuracy of reconstructed R_{RS} and L_{WN} for each spectral band of any relevant satellite ocean colour sensor.

Most satellite ocean colour sensors have spectral bands exhibiting approximately 10 nm bandwidth extending over the visible and near infrared spectral regions. Nevertheless, the new generation satellite ocean colour sensors have a hyperspectral capability and/or bands extending in the ultraviolet spectral region. This suggests that *in situ* radiometric measurements supporting SVC should cover the spectral regions relevant for any ocean colour application with a spectral resolution satisfying accurate convolution of field data into the satellite spectral bands. In fact, alternative solutions for correcting *in situ* data for differences between *in situ* and satellite centre-wavelengths and bandwidths (*e.g.*, band-shifting), could not ensure the necessary accuracy of re-constructed L_{WN} or R_{RS} spectra (Salem et al. 2023).

When accounting for new generation satellite ocean colour sensors, SVC would benefit from *in situ* data ideally covering the 340 nm to 900 nm spectral interval. Nevertheless, it is acknowledged that current methodological and technological limitations are likely to largely affect data accuracy outside the visible spectral region.

In terms of spectral resolution, dedicated investigations focusing on *in situ* R_{RS} (Zibordi et al. 2017) have shown that a spectral resolution better than 3 nm is required for *in situ* measurements to support multispectral satellite sensors with 10 nm spectral resolution, while a spectral resolution better than 1 nm is required to support hyperspectral satellite sensors with 5 nm spectral resolution.

Recommendation

In situ SVC radiometric data should have a spectral resolution better than 3 nm to support multispectral satellite sensors with 10 nm resolution and a spectral resolution better than 1 nm for hyperspectral satellite sensors with 5 nm resolution.

In view of supporting any ocean colour mission, the spectral requirements for *in situ* optical radiometry in the ultraviolet (*i.e.*, below approximately 380 nm) and in the near-infrared (tentatively above 700 nm) should be further investigated, fully accounting for existing *in situ* SVC measurement technologies and methodologies (*e.g.*, fixed-depth or continuous in water profiling). Naturally, comprehensive spectral characterization procedures should be defined and rigorously implemented for any *in situ* radiometer.

5. Site Requirements for SVC

What are the requirements for sites meeting SVC needs?

Since early ocean colour missions, a number of indications supported the identification of marine sites better suited for SVC infrastructures (Gordon 1987). With a view to those indications and successive SVC implementations, general requirements have been identified for SVC sites considered the most appropriate for supporting ocean colour missions targeting climate and global long-term operational applications (Zibordi et al. 2015). These indicate the need for a location:

- Maximizing the number of high-quality matchups by trading off factors such as best viewing geometry, sun-glint avoidance, low cloudiness, away from any continental contamination, a distance from the land to safely exclude any adjacency effects in satellite data, and moderate currents, waves, winds, and atmospheric circulation patterns (Zibordi and Mélin 2017, Bulgarelli and Zibordi 2020, Chen et al. 2021).
- Exhibiting known and accurately modelled optical water and atmospheric properties, characterized by the lowest optical complexity to maximize the accuracy of atmosphere-water ocean colour algorithms in view of minimizing relative uncertainties in computed *g*-factors (IOCCG 2012). These locations ideally coincide with oceanic atmospheres and oligotrophic waters, which represent the majority of the world's oceans.
- Characterized by high spatial homogeneity and small environmental variability of both atmosphere and water, to maximize matchup consistency over time and increase the precision of computed *g*-factors.

The above indications are well supported by the analysis of *g*-factors determined using *in situ* data from different geographical regions and produced by applying diverse measurement methods and technology (Zibordi et al. 2015). However, when considering the potential for multiple SVC sites allowing for redundancy and cross-verification of global SVC assets, it is expected that the above requirements cannot all be fully satisfied at any potential SVC site. For instance, the impact on *g*-factors due to a moderate change of the optical complexity of water or atmosphere, or even geographic location potentially impacting the regular seasonal availability of *in situ* SVC data, is currently unknown.

Recommendation

Any SVC site location should maximize both the number of high-quality *in situ* - satellite matchups and the accuracy of the derived *g*-factors, which is done by minimizing the modelling uncertainties of atmospheric and water optical processes and relying on regions exhibiting oligotrophic waters and oceanic atmospheres characterized by low spatial and temporal variability.

It is recommended to analyse the impact of relaxing some of the key criteria associated with the SVC sites with the most potential for high-quality matchups. This study would show the impact on *g*-factors from moderate changes in the optical complexity of water and atmosphere, and would provide new material to further investigate the appropriateness of current SVC requirements. To this end, recent technological and methodological advances (*e.g.*, autonomous profiling floats (Barnard et al. 2020)) could be utilized to establish equivalent *in situ* measurement systems at different locations exhibiting diverse atmospheric and water properties. The *in situ* radiometric measurements from these systems could then be applied to new studies aiming to further investigate the appropriateness of current SVC site requirements, including those for geostationary satellite ocean colour sensors that may not observe the same key SVC infrastructure(s) accessible to all polar orbiting sensors.

Finally, establishing SVC sites with equivalent performance in opposing hemispheres would help minimizing the impact of sun-glint perturbations in satellite sensors without tilting capability.

6. Field Infrastructure Requirements for SVC

What are the requirements for marine and land infrastructures supporting SVC?

Current operational *in situ* technologies and methodologies supporting SVC for climate and global long-term operational applications rely on buoys equipped with radiometers operated at multiple fixed depths (Clark et al. 1997, Antoine et al. 2008, Voss et al. 2017). This solution would encompass:

- adopting deployment structures (*i.e.*, buoys) designed to account for local environmental conditions (*e.g.*, wave height, currents) and minimizing tilt and shading perturbations in radiometric measurements;
- having access to near-local infrastructures ensuring regular and emergency services to the deployment structure, sustained communication links, as well as ground services for regular maintenance of SVC systems (both deployment structures and instruments); and finally,
- accessing ancillary atmospheric data such as aerosol optical depth and properties, marine data such as chlorophyll-*a* concentration, and any additional quantity that could support the SVC process.

In addition to the consolidated SVC solution relying on fixed optical buoys, alternatives relying on autonomous profiling float systems are currently under investigation. These new systems require comprehensive assessment, even though most of the operational considerations are expected to be similar.

Recommendation

Any SVC long-term program should benefit from dedicated infrastructures ensuring *i.* site-specific deployment capacity for the required radiometric instrumentation, *ii.* onsite support services for regular or emergency maintenance activities, and finally *iii*. the potential for collecting ancillary data on atmospheric and water properties.

The potential use of alternative SVC technologies and methodologies should be accompanied by the definition of requirements for these new SVC field solutions including deployment and recovery needs, long-term calibration and maintenance plans, data handling and processing, the provision of ancillary data, and the calculation of complete uncertainty budgets.

7. Handling and Processing of SVC Field data

What are the handling and processing needs for in situ reference data supporting SVC?

Handling *in situ* SVC data requires dedicated facilities allowing for data processing, archival and distribution (*e.g.*, Antoine et al. 2020, Liberti et al. 2020). Data processing should rely on community shared protocols for data reduction, quality-control (including determination of bio-fouling perturbations), minimization of self- and structure-shading perturbations, and correction for in-water bidirectional effects. Processed *in situ* SVC data should be accessible at different quality levels. These should ideally include: *short-time delayed data* with basic automated quality control with less than one week latency (these data are expected to mostly support near real-time monitoring, validation, and pre-SVC automated procedures); *delayed-mode data* with tentatively three weeks latency, benefitting from automated and expert-based quality control; *deferred-mode data* with tentatively a three months delay, making use of further extended automated and expert-based assessments such as comparisons with historical data (delayed- and deferred-mode data are essential during the commissioning phase of any mission); *consolidated-mode data* within 6-month from the completion of the deployment period based on *deferred-mode data* and accounting for the re-calibration and likely any re-characterization of field instruments (consolidated-mode data should be those applied to support climate applications). Finally, the SVC *in situ* data should be openly accessible.

All quality-controlled data should include comprehensive uncertainty estimates per measurement (*e.g.*, Brown et al. 2007, Johnson et al. 2017, Białek et al. 2020). These, ideally determined following metrology principles (JCGM 2008), would provide the basis for the identification of SVC matchups.

Recommendation

It is recommended that protocols currently applied for data reduction and quality-control of *in situ* SVC measurements are duly documented and made accessible to the community together with the related processing codes. Regular updates of protocols should be planned to benefit from technological and methodological advances, and from inter-comparison exercises.

In situ SVC data should be available with different latency dependent on the extent of the quality screening, appreciating that the shortest latency does not need to be real-time. Data of the highest quality (i.e., *consolidated-mode data*) should be those operationally applied for the determination of mission specific *g*-factors.

SVC field L_W (or L_{WN} and R_{RS}) inter-comparison exercises should be supported and regularly planned to sustain the quality assurance of the SVC measurements. These inter-comparisons should include both field and laboratory exercises. In particular, *in situ* SVC measurements and related processing should undergo field inter-comparisons with alternative state-of-the-art field radiometer systems. In particular, radiometric comparisons could be performed using travelling monitoring systems, which need to exhibit demonstrated robustness and temporal stability. The inter-comparison data should be reduced using the same processor and complemented by comprehensive uncertainty analysis.

In situ SVC data should be delivered with associated uncertainties per measurement and unrestricted. The quantification of uncertainties for both inter-comparison data and *in situ* SVC measurements should rely on metrology principles and prioritize the determination of uncertainties for each individual measurement with respect to the application of statistical values assigned to measurements series.

8. Determination of Satellite SVC Correction Factors (*i.e.*, *g*-factor)

What are the best approaches for the determination of robust g-factors?

Mission specific *g*-factors are defined by the mean of g_i-factors determined from a number *i* of satellite and *in situ* matchups, ideally expected to remove any residual bias in satellite data products already corrected for drifts or changes due to the space sensor radiometric sensitivity or by sensor characterization artefacts.

The matchups should be equally distributed over the annual seasons for the period of interest (*e.g.*, the whole mission once completed). It is recalled that individual g_i-factors are the ratio of satellite simulated to measured top-of-atmosphere L_T radiances, with simulations relying on *in situ* measurements of L_W and the application of the same algorithms embedded in the atmospheric correction code. Because of this, g_i-factors require re-computation each time the processing algorithms for satellite data are updated, or after any re-determination of satellite sensor responsivity due to sensitivity decay, or even after any reprocessing of the *in situ* data.

While the general principles applied for the computation of g_i-factors are those outlined in Franz et al. (2007), the criteria for the creation of matchups, *in situ* and satellite data screening, and averaging of the g_i-factors, have not been fully standardized despite recent attempts (IOCCG 2019). Also, there is no community shared statistical index describing the robustness of *g*-factors.

Recommendation

The methods for determining g_i-factors should be further standardized implying the definition of comprehensive criteria for the construction of SVC matchups. Matchup criteria should not only define the number of pixels centred on the *in situ* SVC site and pixel exclusion rules, but the criteria should also consider compliance with uncertainty and stability requirements for climate and long-term global operational applications. These criteria should rely on the uncertainties quantified for the *in situ* SVC measurements and on all individual match-up quality checks that led to the determination of g_i-factors. Furthermore, statistical criteria such as the Relative Standard Error of the Mean (RSEM), applied in some investigations, should be considered and implemented to verify the robustness of mission specific *g*-factors.

The procedures and codes for the selection of matchups and determination of individual g_i-factors and mission-specific *g*-factors should be openly shared among the community.

9. Impact of *g*-factors on Data Products

What is the impact of g-factors on data products?

The adoption of diverse criteria and solutions for determining g_i-factors generally leads to diverse mission *g*-factors, which may diversely bias satellite data products (Bailey et al. 2008). The study from Werdell et al. (2005) indicates that differences between *g*-factors as low as 0.3 % introduce unwanted inconsistencies (*i.e.*, biases) on L_W at 555 nm of the order of 4 %, comparable to the target uncertainty and several times larger than the stability requirements set by WMO (2022). This result, which is fully supported by the analysis provided in Zibordi et al. (2017), shows how critical is the determination of *g*-factors satisfying cross-mission consistency. This finding suggests the need for caution when combining data from multiple SVC sites and diverse data sources, which could largely challenge the temporal consistency of *g*-factors.

Quality SVC *g*-factors from any mission ensure that the stability and accuracy requirements are met for this specific satellite mission in the proximity of the SVC site. But this does not imply that the requirements are satisfied for any geographic location due to the uncertainties of the atmospheric correction at places with different atmospheric and water optical properties, illumination geometries, sensor viewing geometries, or radiometric performance of satellite sensors. Such potential impacts away from the SVC site are further amplified by the adoption of different atmospheric correction codes for diverse missions.

This suggests that the creation of a consistent multi-mission time series would at least require that satellite data products are obtained by applying the same atmospheric correction code and the same SVC procedures to data for all the missions (Zibordi et al. 2017). The accuracy of this time series is still likely to degrade at locations exhibiting environmental conditions different from those characterizing the SVC site or by the different radiometric performance of satellite sensors. Nevertheless, the application of a sole robust atmospheric correction code and SVC procedure would be essential to favour best consistency over time for the radiometric products from diverse missions.

Recommendation

Considering the need to ensure the highest consistency to data products from a variety of global ocean colour missions from various space agencies, it would be of high interest to create multi-mission ocean colour data sets comprising radiometry and high level data products, generated using the same atmospheric correction code and identical SVC procedure relying on the same *in situ* data source: a solution currently allowed by the application of the SeaDAS software package (https://seadas.gsfc.nasa.gov/about/; see also Mobley et al., 2016 and references therein). This extended data set could be used to comprehensively investigate the benefits and the limits of a unified processing applied to data from multi-decadal global ocean colour missions naturally relying on multi-agency satellite sensors exhibiting diverse radiometric performance.

10. SVC in the near-infrared spectral region

Is there any need for specific actions supporting SVC in the near-infrared spectral region?

Spectral bands in the near-infrared are essential for determining the aerosol optical properties in most of the operational atmospheric correction algorithms (Wang and Gordon 2002). Because of this, the determination of *g*-factors in the near-infrared is a fundamental step in any SVC procedure. The *g*-factors for the most common atmospheric correction implementations are determined by assuming (Franz et al. 2007): *i.* negligible or quantifiable L_W in the near-infrared spectral bands in highly oligotrophic waters, and additionally *ii.* imposing the *g*-factor, typically at a longer NIR band λ_{NIR}, to be equal to 1 for a fixed aerosol model reflecting the optical properties at the SVC location. It is mentioned that the *g*-factors for other bands in the near-infrared spectral region are often determined at locations like the South Pacific Gyre (SPG) exhibiting ideal oceanic aerosols and ultra-oligotrophic waters. In some SVC implementations, this basic method has been extended to include the shortwave infrared spectral bands with benefits for ocean colour applications in both open oceans and coastal or inland waters (Wang et al. 2016, Wang and Shi 2007).

Recent investigations have shown that assuming the *g*-factor at λ_{NIR} to be equal to one can impact the accuracy of satellite data products in ultra-oligotrophic waters (Barnes et al. 2020). This calls for new methods to allow an estimation of the *g*-factor at λ_{NIR} avoiding the basic assumption $g(\lambda_{NIR}) = 1$. The benefits of defining $g(\lambda_{NIR})$ with value other than 1 were shown for the Sentinel-3 OLCI-A sensor (EUMETSAT, 2021), where $g(\lambda_{NIR})$ was derived from comparing top-of-atmosphere data between two ocean colour sensors flown in tandem and viewing the same targets several seconds apart (Lamquin et al. 2020). Similarly, resolving a calibration difference between λ_{NIR} of MODIS-Aqua and VIIRS-SNPP by assigning VIIRS $g(\lambda_{NIR}) \neq 1$ and subsequently re-deriving *g*-factors for all other VIIRS bands resulted in sporadic improvements in consistency between MODIS and VIIRS for downstream R_{RS} and chlorophyll-*a* related products (Barnes et al. 2021).

An alternative $g(\lambda_{NIR})$ solution could be offered by verifying the relative calibrations in the near-infrared spectral region of independent satellite sensors inferred with respect to a unique reference target (Tan et al. 2023). Further solutions should also consider the potential for field measurements of R_{RS} or L_{WN} in the near infrared, even though the implementation of such measurements would be challenged by a very low signal leading to large uncertainties.

Recommendation

For the SVC of the NIR bands, methods should be investigated to improve the knowledge of the absolute calibration of the band centered at λ_{NIR} to reduce the uncertainties stemming from the assumption of $g(\lambda_{NIR})$ being equal to 1. With specific attention to climate and global long-term operational applications, the potential should be considered for linking $g(\lambda_{NIR})$ values from diverse missions to a unique reference (*e.g.,* lunar calibrations). Finally, the accuracy of derived *g*-factors in the near infrared calls for the essential need to verify the accuracy of satellite retrieved aerosol types and the validation against *in situ* measurements of the aerosol optical properties.

11. Building time series including historical missions

How to address of the inclusion of historical data products in time series?

The creation of consistent and accurate data records from diverse missions, which requires the minimization of any inter-mission bias and uncertainty, currently appears feasible only through the long-term high-quality data from MOBY and the adoption of a standardized atmospheric correction procedure. In fact, MOBY has been delivering *in situ* SVC data since 1997 with radiometric features and accuracy closely satisfying the SVC requirements for climate and global long-term operational applications. This allows for considering the creation of a time series of satellite ocean colour data products including historical missions such as the Sea-viewing Wide Field-of-view Sensor

(SeaWiFS), still recognizing that the diverse radiometric performance of satellite sensors explained by their different design may lead to differences in data products away from the SVC site.

Recommendation

Consistent multi-decadal ocean colour data products from diverse missions ideally require the application of identical SVC *in situ* data sources, procedures, and atmospheric correction codes to minimize inter-mission biases. This effort naturally requires international and interdisciplinary contributions and indicates that the continuity to the MOBY infrastructure must be ensured together with the related SVC services, in order to enable concatenation of historical, ongoing, and forthcoming satellite ocean colour missions.

Aside from the above fundamental principles and related recommendations, it would be of interest to investigate processing solutions adopted or under consideration by other communities (*e.g.*, those dealing with sea surface temperature and solar irradiance measurements) to ensure full spatial and temporal consistency of products from diverse missions.

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Additional support material

Background: the OC-SVC task force was established in 2021 with the objective to have coordination across agencies for lessons learned and methodologies.

Membership: based on agency members as well as other members from the scientific community engaged with SVC.

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