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System Vicarious Calibration for Climate and Global Long-Term Operational Ocean Color Applications

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ABSTRACT: System vicarious calibration (SVC) enhances the accuracy of satellite ocean color radiometric data products by removing the bias due to the intrinsic inaccuracies affecting both the responsivity of the space sensor and the correction for the atmospheric and sea surface contributions to the measured signal. Various SVC procedures have been implemented and applied for regional studies, specific mission goals, and the most challenging quantification of global long-term climate-driven changes that require accurate and consistent data products across multiple missions. This paper summarizes the outcome of a workshop organized by the ocean color SVC task force of the International Ocean Color Coordinating Group (IOCCG) to review requirements for SVC supporting ocean color missions for climate and global long-term operational applications. The work emphasizes the essential need for long-term sustained SVC infrastructures and associated services, summarizes the primary requirements for establishing a comprehensive ocean color SVC framework, and provides directions for new investigations to tackle arising needs on SVC advancements and methods.

SIGNIFICANCE STATEMENT: System vicarious calibration is the process applied to satellite ocean color missions to achieve the required accuracy over time for data products targeting climate and global long-term operational applications. This process requires access to dedicated long-term marine infrastructures and services to sustain the creation of consistent multimission time series. Aiming at unifying system vicarious calibration across missions managed by independent space agencies, this work streamlines the requirements for establishing the necessary infrastructures and services, standardizing the methods, and providing guidance to new advancements as well as maintaining current capabilities to enable steady linkage to historical satellite ocean color missions.

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1. Introduction

Satellite ocean color radiometry refers to Earth-observing missions specifically designed to measure the properties and concentrations of optically significant constituents in natural waters. The basic ocean color quantity is the water-leaving radiance L_W: the amount of light that leaves the water volume and carries spectral information on its optically significant constituents. Fundamental ocean color quantities, from which any subsequent high-level data product is derived, are the remote sensing reflectance R_{RS} (or the corresponding normalized water-leaving radiance L_{WN}) obtained from L_W applying corrections minimizing the effects of illumination changes with sun–Earth distance, sun and viewing angles, and atmospheric and water optical properties (IOCCG 2019).

The L_W is determined from the total radiance L_T detected by a sensor at the top of the atmosphere through the application of atmosphere–water algorithms to remove contributions from atmospheric scattering and absorption as well as sea surface reflectance (IOCCG 2010; Gordon and Wang 1994). Significantly, L_W exhibits values varying with wavelength and water type, and it typically is a few percent of L_T (Zibordi et al. 2015). The uncertainties associated with the responsivity of the space sensors (Esposito et al. 2004; Butler et al. 2007), along with the inaccuracy of any atmospheric correction procedure (IOCCG 2010), largely limit the capability to meet L_W target uncertainties for ocean color missions (Zibordi et al. 2014).

Uncertainty requirements for satellite ocean color data products are commonly driven by application needs tied to the quantification of optically significant water constituents such as phytoplankton chlorophyll-a concentration. Implicitly assuming a coverage probability $k = 1$ (expressing a confidence level determined by one standard deviation), the target uncertainties for L_W from the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) were set to a constant value throughout the entire visible spectrum (Hooker et al. 1992). Successively, these target uncertainties were less strictly set to 5% for R_{RS} in the blue and green spectral regions in clear waters (Gordon 1997) and largely endorsed by most of the ocean color missions up to the recent Plankton, Aerosol, Cloud, Ocean Ecosystem (PACE; Werdell et al. 2019). However, without system vicarious calibration (SVC), a typical 2% uncertainty in the absolute radiometric calibration of a space sensor leads to uncertainties in L_W ranging approximately 10%–30% in the blue–green spectral region, even when neglecting any additional atmospheric correction uncertainty (Zibordi et al. 2015). These uncertainties largely exceed the 5% requirement and are the reasons for SVC.

SVC, as illustrated in Fig. 1, is a critical process strengthening the capability to meet uncertainty requirements for R_{RS} (Gordon 1987, 1998) across independent missions.

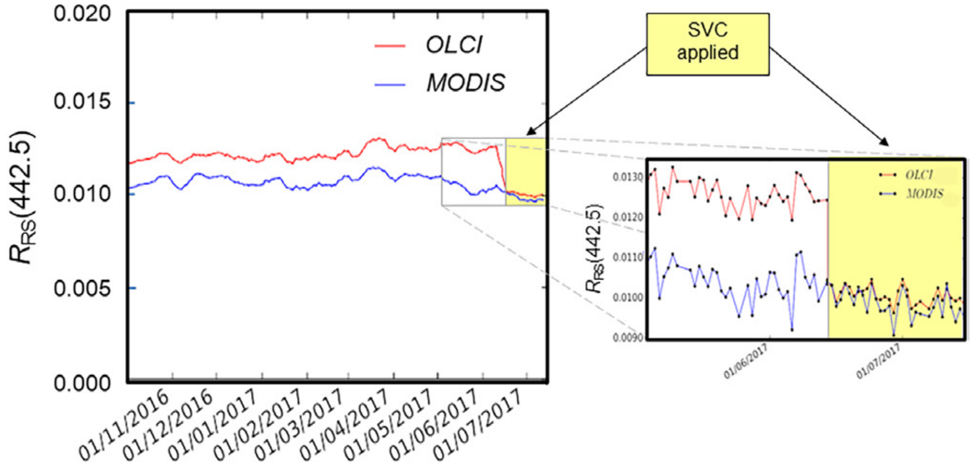

Fig. 1. R_{RS} **time series at the 442.5-nm center wavelength determined over oceanic waters from the OLCI onboard** ***Sentinel-3A*** **and MODIS-*Aqua*. The figure shows that the application of SVC to OLCI data from 15 Jun 2017 (an illustrative date) reconciles OLCI and MODIS** R_{RS}**.**

It relies on the application of adjustment gains, g factors, to the responsivity of satellite sensors implying that their temporal sensitivity changes have been accounted for (see Eplee et al. 2015). The g factors are determined by the ratio of simulated to measured spectral L_T values, where simulations entail the application of the same atmosphere–water algorithms as the ones used to determine L_W from L_T in operational processing. SVC is consequently intended to minimize the overall impact of systematic biases caused by the inaccuracies affecting (i) the responsivity of the space sensor and (ii) the atmospheric correction process. Contrary to other vicarious calibration techniques (IOCCG 2013), SVC thus applies to the combined instrument and algorithms *system*.

Various SVC procedures relying on the use of in situ measurements of R_{RS} or L_{WN} from different sources have been implemented for diverse satellite data applications. These include implementations supporting regional investigations (Ohde et al. 2002; Mélin and Zibordi 2010) and mission-specific objectives restricted to single ocean color sensor missions (Sturm and Zibordi 2002; Gao et al. 2012; Shukla et al. 2013; Hlaing et al. 2014; Ahn et al. 2015; Song et al. 2019; Murakami et al. 2022). Data applications also include climate and global long-term operational services, which further require the lowest uncertainties and a high consistency of satellite-derived R_{RS} across different and successive missions (Franz et al. 2007). It is intended that high intermission consistency requires metrological stability implying equivalent accuracy of data products over time (Ohring et al. 2005).

The atmospheric correction of satellite ocean color observations takes advantage of the high water absorption in the near-infrared (NIR) spectral region leading to little or negligible L_W signal (Wang et al. 2016). A typical SVC procedure designed to support climate and global long-term operational applications (see Fig. 2) begins by calculating g_j factors in the NIR for all relevant images j. It utilizes L_T data (i.e., macropixels composed of a number of close image elements) from the NIR spectral bands λ_{nir} from a time series of satellite observations ideally uniformly distributed over seasons, in highly oligotrophic regions characterized by oceanic aerosols and homogeneous clear waters (e.g., the South Pacific Gyre). This is done by assuming (i) negligible or quantifiable L_W at any λ_{nir}, (ii) accurate calibration of the space sensor at a NIR reference band λ_0 [i.e., implying $g_j(\lambda_0) = 1$], and (iii) known or at least accurately predictable optical properties of the regional atmospheric aerosols (e.g., Franz et al. 2007; Wang et al. 2016). The $g(\lambda_{\mathrm{nir}})$ factors are then determined from the average of quality-controlled $g_j(\lambda_{\mathrm{nir}})$ values.

Some implementations of SVC have extended this approach to incorporate the shortwave infrared (SWIR) bands where water absorption is even stronger, or assumed $g_i(\lambda_0) \neq 1$ when

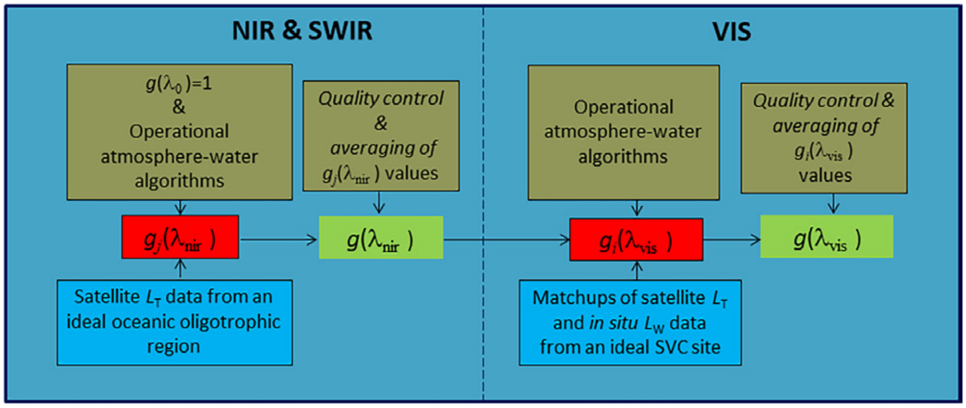

Fig. 2. Schematic illustrating the determination of *g* factors for the λ_{nir} spectral bands in the NIR and the SWIR from a number of satellite observations (indexed by *j*) and for the λ_{vis} spectral bands in the VIS relying on matchups of satellite and in situ data (indexed by *i*). The azure frames indicate inputs for the SVC process, while the fern frames identify actual processes. The intermediate $g_j(\lambda_{nir})$ and $g_i(\lambda_{vis})$ products from individual matchups are identified by the red frames, while the final data products $g(\lambda_{nir})$ and $g(\lambda_{vis})$ are identified by the green frames.

external information is available on the calibration of the reference band. These extensions have proven advantageous for the accuracy of ocean color data products and their application (Wang et al. 2016; Wang and Shi 2007; Barnes et al. 2020; EUMETSAT 2021).

After determining the *g* factors in the NIR from the $g_j(\lambda_{nir})$ values, the SVC process calculates g_i factors for the visible (VIS) spectral bands, λ_{vis}, using a time series of matching L_T from macropixels associated with images *i* and highly accurate in situ measurements of R_{RS} (note the use of the *j* and *i* indices advised by the independence of the two processing steps). These collocated and close-in-time pairs of in situ and satellite data (i.e., matchups) should be evenly distributed seasonally and from oceanic oligotrophic regions exhibiting spatially homogenous clear waters to ensure the best reproducibility of *g* factors over time. In fact, a regular seasonal distribution of matchups maximizes temporal representativity over years, while an oceanic atmosphere and oligotrophic waters maximize the accuracy of the atmospheric correction process. Finally, spatial homogeneity minimizes the impact of subpixel variability across matchups. Equivalent to the NIR spectral bands, $g(\lambda_{vis})$ for the VIS bands are obtained from the average of quality-controlled individual $g_i(\lambda_{vis})$ values.

The *g* factors need to be recalculated if the processing algorithms for satellite data are modified, or when there is a change in the satellite sensor responsivity. This element already anticipates that the accuracy of any SVC procedure largely depends on the accuracy of in situ R_{RS}.

Several satellite ocean color missions launched by international space agencies over the course of nearly three decades now offer a unique opportunity to generate time series data that can benefit climate change investigations as well as operational applications on water quality, aquatic ecosystems, fisheries, aquaculture, and biodiversity (Sathyendranath et al. 2019; McClain et al. 2022). The SVC requirements for these applications are stringent and must minimize the R_{RS} uncertainties and maximize the consistency of data products over multiple missions. Consequently, the applied SVC procedure aims at supporting the capacity to detect temporal changes in time series of multimission satellite data products enforcing intermission consistency through a common accurate and a metrologically stable reference.

Global sustained climate and operational services require the existence of long-term SVC infrastructures ensuring access to highly accurate and International System of Units (SI)-traceable in situ R_{RS} data across multiple missions (Clark et al. 1997; Antoine et al. 2008). These requirements prompted several studies to advance SVC through new infrastructures (ESA 2017; EUMETSAT 2017, 2022; Antoine et al. 2020; Liberti et al. 2020) and new in situ technologies (Barnard et al. 2024a,b). The need for strengthening the SVC performance also prompted the search for the most favorable marine locations (Zibordi and Mélin 2017; Chen et al. 2021; EUMETSAT 2022; Chamberlain et al. 2024). The potential for multiple SVC infrastructures also enacted the demand for their standardization and interoperability through worldwide collaborations to ensure equivalence of SVC performances and procedures across independent sites in regions exhibiting equivalent atmospheric and marine optical features.

Building on current knowledge and on the essential need for sustained and continuing SVC programs, the ocean color SVC task force of the International Ocean Color Coordinating Group (IOCCG) organized a workshop at the University of South Florida College of Marine Science in St. Petersburg, Florida, to review SVC requirements for ocean color missions targeting climate and global long-term operational applications (IOCCG 2024). This work presents the outcome of the workshop by summarizing the fundamental requirements and providing directions for investigations to strengthen procedures and address arising needs.

2. Uncertainty and metrological stability requirements for in situ radiometric data

As already detailed, the computation of g factors in the visible spectral bands requires access to highly accurate in situ R_{RS}. The accuracy requirements for these data must be linked back to the satellite data products and their applications.

As a recommendation, the World Meteorological Organization (WMO 2011, 2022) indicated that satellite ocean color missions aimed at sustaining climate studies must guarantee the determination of L_W (at a 4-km scale) in nonoptically complex waters with

- a radiometric uncertainty of less than 5% for the blue–green spectral bands and
- a temporal stability better than 0.5% decade^{-1} (where stability must be intended as metrological stability, that is the capability to produce time series characterized by equivalent accuracy over time).

Although WMO (2011) does not contain information about the coverage probability for the uncertainty requirements, the updated edition (WMO 2022) clearly states the uncertainty requirement for L_W with coverage factor $k = 2$ expressing a confidence level determined by two standard deviations.

These requirements, which are also common to global operational applications, are intended to guarantee the essential level of accuracy for derived bio-optical data products. They are thus expected to support investigations of changes in marine bio-optical properties through data products from combined ocean color missions, still recognizing that residual differences between products from individual missions might introduce artifacts in multimission data records (Mélin 2016).

The temporal stability of R_{RS} measurements, which quantifies the change in bias over time for identical observation conditions, is crucial to detect variations in the marine quantities of interest. Dutkiewicz et al. (2019) utilized a biogeochemical model to forecast trends due to climate change in ocean color radiometry data. Their findings indicate a projected increase up to 1% decade^{-1} of R_{RS} at the 475-nm center wavelength. This amount is only twice the value for the stability of L_W specified by WMO (2022), which further strengthens the importance of adopting rigorous metrological stability requirements for data products from each mission.

To date, the WMO (2022) requirements for satellite data provide a common foundation for the creation of climate data records largely centered on chlorophyll-a concentration. Nevertheless, for a more comprehensive support to climate and operational services, it is advisable to reassess those uncertainty and stability figures by taking into consideration of new and evolving algorithms and products. The revisited requirements should include spectral radiometric dependence, extended where applicable, to the red and ultraviolet spectral regions relevant to the recent and upcoming missions and applications. Finally, any new stability requirement should support response strategies to observed aquatic bio-optical changes.

Any uncertainty or stability figure for satellite data products arising from new investigations should carry through to establishing updated requirements for in situ R_{RS} measurements supporting the SVC. These requirements, which currently generically duplicate those provided by WMO (2022) for L_W satellite products, should include both the random and systematic uncertainty components of in situ radiometric data. Ultimately, the minimization of each systematic component, achieved through the design of the SVC infrastructure, comprehensive characterizations of radiometric performance (e.g., Brown et al. 2003), and assessments of the data reduction methods (e.g., Voss et al. 2017), would enhance the accuracy of *g* factors and consequently increase the accuracy of retrieved satellite data products and their consistency across multiple missions.

3. Spectral requirements for in situ radiometric data

Satellite ocean color sensors typically include spectral bands covering the VIS and NIR regions with a bandwidth of approximately 10 nm. Nevertheless, some of the new-generation satellite ocean color sensors are hyperspectral and extend to the ultraviolet (UV) spectral region. This implies that in situ radiometric measurements for SVC should cover each spectral region relevant for any ocean color application and exhibit resolution satisfying the accurate convolution of in situ data into the satellite spectral bands.

Spectral resolution for in situ radiometric data tailored to SVC applications was investigated using in situ R_{RS} data exhibiting subnanometer spectral resolution and imposing a maximum difference of ±0.5% between satellite spectral R_{RS} convolved using the original high-resolution and degraded spectra (Zibordi et al. 2017). Results indicate that the in situ R_{RS} data should have a spectral resolution of less than 3 nm to support SVC for multispectral satellite sensors that have a resolution of 10 nm. For hyperspectral satellite sensors with a resolution of 5 nm, the in situ R_{RS} data should have a spectral resolution of less than 1 nm. Requirements for L_W indicate the need for a subnanometer resolution to properly resolve the spectral response functions of the satellite sensor and the narrow absorption bands of the solar spectrum. These latter are often used to monitor the wavelength calibration of the in situ SVC instruments.

When considering the specific needs for new-generation satellite sensors, SVC would benefit from in situ data that ideally encompass the spectral range from 340 to 900 nm. However, it is recognized that the accuracy of data outside the VIS is likely to be significantly impacted by current limits of in situ above- or in-water measurement methods due to radiometric technological limits in the UV (e.g., accuracy of calibration sources, stability of detectors) and the very low L_w values in the NIR. This calls for advances in marine field radiometry to increase measurement accuracy of R_{RS} in the UV and NIR.

4. Requirements for SVC sites

Since early ocean color missions, oceanic oligotrophic or mesotrophic regions were considered as the most suitable for SVC infrastructures (Gordon 1987). Based on those initial indications and successive investigations, several requirements have been developed for SVC sites and deemed the most suitable for supporting climate and long-term global ocean color services (Zibordi et al. 2015). These requirements imply locations:

- Maximizing the number of high-quality matchups by considering factors, such as optimal viewing geometry, sun-glint avoidance, low cloudiness, away from any continental contamination and atmospheric circulation patterns, at a suitable distance from land to exclude

any appreciable adjacency perturbations in satellite data, and finally ensuring low impact by currents, waves, and winds (Zibordi and Mélin 2017; Bulgarelli and Zibordi 2020; Chen et al. 2021; EUMETSAT 2022).
- Showing well-defined and accurately modeled optical properties of water and atmosphere, by benefitting from minimal optical complexity expected to enhance the accuracy of the atmosphere–water algorithms, in view of minimizing the uncertainty in computed *g* factors.
- Ensuring a high spatial homogeneity and small temporal variability for both the atmosphere and water to maximize matchup consistency over time and consequently increase the precision of computed *g* factors across multiple missions.

The above requirements for SVC locations expected to sustain climate and long-term global ocean color services are well supported by a study on the *g* factors determined with in situ data from various geographical regions and diverse measurement methods and technologies (Zibordi et al. 2015).

The potential for multiple metrologically equivalent SVC sites can provide the benefit for cross verification of SVC assets and for redundancy granting operational robustness in the case of environmental disturbances or equipment failures. Considering the difficulty to establish SVC sites in regions exhibiting identical environmental conditions, it would then be important to assess the impact on *g* factors of slightly different optical complexity of water or atmosphere, or of diverse geographic locations affecting the availability of SVC matchups across seasons. It is thus advisable to investigate the consequences of varying certain essential criteria related to the SVC locations that currently exhibit the most potential for high-quality matchups, such as aerosol optical depth or chlorophyll-a concentration. This could be best done relying on identical measurement technology and data processing to remove the impact of diverse methodological solutions. These studies should provide new insights essential to consolidate or alternatively advance the existing SVC site requirements.

With a view to future investigations on the requirements for the most suitable SVC locations, it is worth mentioning recent developments in technology and methods, such as those associated with autonomous profiling floats (Barnard et al. 2024a; Chamberlain et al. 2024). These profiling floats, upon successfully proven fitness-of-purpose, could offer the capability to deploy equivalent measuring systems at diverse regions. Several such systems placed at diverse suitable locations could offer the possibility to investigate the impact of differences in marine and atmospheric properties. They could additionally provide the capability to investigate SVC solutions for those geostationary satellite ocean color sensors that do not have access to the current fixed SVC infrastructures serving polar orbiting sensors.

5. Requirements for field infrastructures

So far, in situ technologies supporting SVC have involved the use of moored buoys (see Fig. 3) equipped with radiometers that are operated at various depths such as the Marine Optical Buoy (MOBY; Clark et al. 1997) and the Bouée pour l'acquisition d'une Série Optique à Long Terme (BOUSSOLE; Antoine et al. 2008).

This solution implies the following:

- Platforms specifically designed for the local environmental conditions (e.g., wave height and currents) and to minimize any disturbance in radiometric measurements caused by tilt and shading of the structure, hosting the required radiometric instrumentation (e.g., hyperspectral upwelling radiance and downward irradiance optical sensors).
- Access to nearby local infrastructures to guarantee regular site servicing and emergency access for the deployment assembly and availability of ground services for routine calibrations and maintenance of the system components.

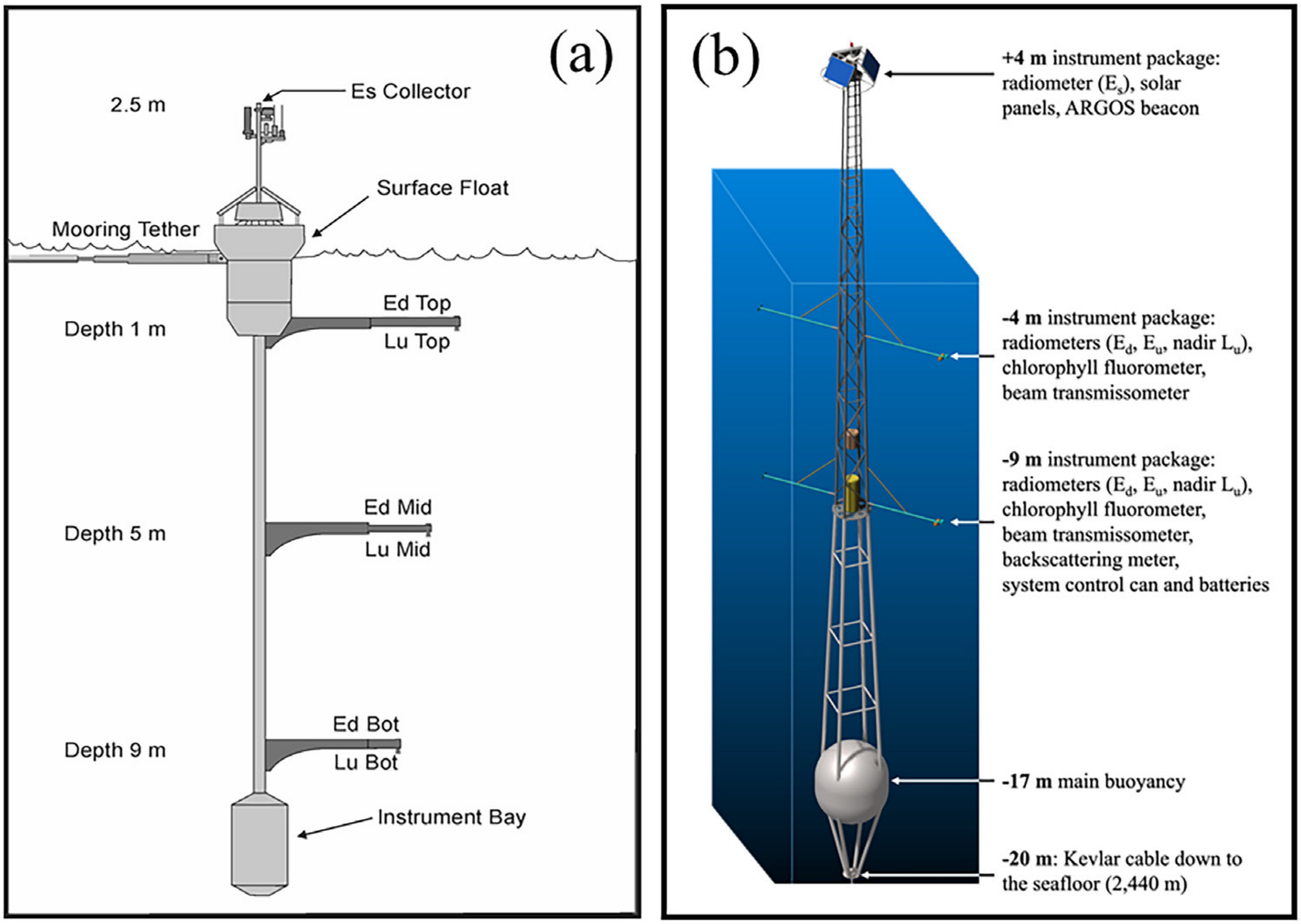

Fig. 3. **(a) Schematic of the MOBY (by courtesy of Stephanie Flora, Moss Landing Marine Laboratories, San Jose State University) and (b) "artist view" of the BOUSSOLE [redrawn from Antoine et al. (2008)].**

- Collection of supplementary atmospheric data such as aerosol optical depth and properties, as well as marine data such as chlorophyll-a concentration, and any other relevant data that can assist in situ data reduction, quality control, and the SVC process in general.

For any new technology, such as the already mentioned autonomous profiling floats, all the related measurement procedures and functioning aspects, such as deployment and recovery, long-term calibration and maintenance, data handling and processing, and acquisition of ancillary data, should be thoroughly investigated and assessed, even though most of the operational factors will be comparable to those of existing SVC infrastructures.

Finally, it is emphasized that uncertainty budgets accounting for comprehensive uncertainty analyses of instruments performance, measurement methods, and data reduction are essential to support the SVC status.

6. Handling and processing of in situ data

The management of in situ SVC data necessitates specialized personnel, dedicated planning and infrastructure that enable 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 identifying the impact of biofouling), minimization of perturbations caused by optical collectors and structure shading, and correction for in-water bidirectional effects. These protocols should be comprehensively documented, regularly updated, and openly accessible along with the corresponding processing scripts.

The processed in situ SVC data should be available at various levels of quality control. These should ideally include the following:

- *Delayed-mode data* with a tentative latency of 3 weeks relying on automated and expert-based quality control and *deferred-mode data* with a tentative delay of 3 months benefitting of extended automated and expert-based assessments such as comparisons with historical data. Delayed- and deferred-mode data are crucial during the commissioning phase of any satellite mission. In addition, during each period following the determination of a set of provisional g factors, they would also support the validation of the SVC process and perhaps the evaluation of temporal changes affecting the satellite sensor responsivity.
- *Consolidated-mode data* within 6 months from the completion of the deployment period based on deferred-mode data and accounting for the recalibration and eventually any recharacterization of field instruments. Consolidated-mode data should be those applied to derive the g factors supporting climate and long-term operational applications.

Even though not used for SVC, *short-delay-mode data* with a latency of less than 1 week and only with basic automated quality control are relevant to support near-real-time monitoring of the space sensor performance, validation of the radiometric data products, and pre-SVC automated procedures.

The in situ SVC data should be openly accessible with the corresponding measurement uncertainties quantified using metrology principles [e.g., Joint Committee for Guides in Metrology (JCGM) 2008; Brown et al. 2007; ESA 2017 (see section 3); Białek et al. 2020]. It is important to prioritize the determination of uncertainties for each individual measurement instead of applying single values assigned to measurement series. These per measurement uncertainties, established accounting for their random and systematic components, should provide the basis for the selection of SVC matchups.

Regularly planned and supported intercomparison exercises for in situ R_{RS} are of utmost relevance to verify the performance of the SVC infrastructure and its data processing solutions and implementations and naturally support the quality control of in situ radiometric products. The intercomparisons should encompass exercises conducted both in the field and in the laboratory benefitting from state-of-the-art radiometer systems. Traveling radiometers exhibiting proven durability and consistent performance over time should be those considered for these intercomparisons. Last, the intercomparison data should be reduced using the same processor (i.e., processing code) to minimize the potential impact of diverse processing solutions and should be necessarily supported by a thorough uncertainty analysis.

7. Determination of the *g* factors

Provisional g factors are generally determined during the early phases of each ocean color mission and their values are successively updated over time to benefit from an increased number of in situ and satellite matchups. The accuracy of each g factor, when expressed by a statistical index, primarily accounts for the inaccuracies affecting (i) the satellite sensor responsivity, (ii) the atmospheric correction process, and (iii) the in situ radiometric data. Consequently, to reduce the contribution of random uncertainties, the g factors for each mission should be calculated as the average of g_i factors obtained from a large number of satellite and in situ matchups evenly distributed over the mission lifespan.

Despite international efforts, there is no standardization for the assembly of matchups, the screening of in situ and satellite data, and the averaging of g_j and g_i factors. Furthermore, there is no community shared statistical index that may describe the robustness of g factors. Because of this, it would be essential to establish standardized techniques for determining the g_j and g_i factors, including the definition of detailed criteria for constructing SVC matchups. These criteria should not only encompass the specification of the number of pixels centered at the in situ SVC site leading to macropixels and the general rules for screening pixel values but should also furthermore enforce the compliance with uncertainty and metrological stability requirements fully exploiting the results from quality checks performed on each individual result that led to the determination of g_j and g_i factor. Also, it would be important to agree on defining which statistical indices should be used to assess the reliability of g factors for each mission, e.g., the *relative standard error of the mean* (RSEM).

The protocols and codes used to construct matchups, and to calculate the g_j and g_i factors and the resultant g factors for each mission, should be openly shared among the community.

8. Impact of *g* factors on data product accuracy

The use of diverse methods to determine g_j and g_i factors typically results in different mission g factors, which can introduce significant biases in satellite data products (Bailey et al. 2008). The work by Werdell et al. (2007) indicated that even variations in g factors as little as 0.3% can lead to unwanted inconsistencies in L_W at 555 nm of the order of 4%. Although this 4% bias is within the L_W uncertainty requirement established by WMO (2022), if each mission would exhibit such a discrepancy, the multimission time series stability could be several times larger than the 0.5% stability requirement. This result, supported by the analysis presented in Zibordi et al. (2015), highlights the importance of accurately determining g factors in regions that ensure the best cross-mission consistency. This implies exercising caution when combining in situ radiometric data of R_{RS} using diverse measurement technologies and from regions characterized by different atmospheric and marine optical properties.

Properly determined g factors guarantee that the stability and uncertainty requirements are met in the proximity of the SVC site. However, the fulfilment of requirements is not guaranteed at all geographic locations because the uncertainties affecting atmospheric correction may increase in regions exhibiting different atmospheric and/or water optical properties, or simply illumination or sensor viewing geometries, from those typical of the SVC site. These potential effects outside the SVC region may be further degraded by the application of atmospheric correction codes that may differ across missions.

The above findings and considerations suggest that the development of accurate and robust atmospheric correction algorithms is critical, as documented by many ongoing community activities. In the meantime, the creation of a consistent multimission time series could be enabled by the adoption of the same atmospheric correction code and SVC procedure relying on the same in situ data source for all ocean color missions (Zibordi et al. 2015). The multimission dataset resulting from such an effort would allow further investigations into the limitations in the generation of time series for climate and global long-term operational applications. This would specifically support studies addressing the accuracy of data products over regions with environmental conditions differing from those at the SVC site or across satellite sensors exhibiting diverse radiometric features and performance.

9. SVC in the near-infrared spectral region

The NIR spectral bands play a crucial role in identifying the aerosol optical properties in many operational atmospheric correction algorithms (Wang and Gordon 2002). Consequently, the calculation of g factors in the NIR is an essential component of any SVC procedure.

As already explicated, the g factors in the most common atmospheric correction implementations are determined by forcing $g(\lambda_0)$ equal to 1 at a reference NIR wavelength λ_0. However, recent investigations have shown that such an assumption can lead to a significant impact on the accuracy of satellite data products in highly oligotrophic waters (Barnes et al. 2020). This finding suggests the need for novel techniques to better address the satellite sensor calibration in the NIR without assuming $g(\lambda_0) = 1$.

The importance of assigning a value other than 1 to $g(\lambda_0)$ was demonstrated in the case of the Ocean and Land Color Imager (OLCI) sensors onboard the *Sentinel-3A* and *Sentinel-3B* satellites (EUMETSAT 2021). In this specific case, the values of $g(\lambda_0)$ were adjusted by comparing top-of-atmosphere data from the two ocean color sensors that were flown in tandem and observed the same targets with a time difference of several seconds (Lamquin et al. 2020). Similarly, a calibration discrepancy at the NIR wavelength λ_0 between the Moderate Resolution Imaging Spectroradiometer onboard the *Aqua* platform (MODIS-*Aqua*) and the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the *Suomi National Polar-orbiting Partnership* (VIIRS-SNPP) satellite was resolved by assigning a value different from 1 to the VIIRS-SNPP $g(\lambda_0)$. This led to the recalculation of g factors for all other VIIRS-SNPP bands and enhanced the consistency between MODIS-*Aqua* and VIIRS-SNPP for downstream products (Barnes et al. 2021). An alternative solution allowing for the determination of $g(\lambda_0)$ may be feasible through the comparison of relative calibrations of different satellite sensors in the NIR with respect to natural targets (Tan et al. 2023). Further solution may be offered by field measurements of R_{RS} in the NIR; however, such implementations are difficult due to the extremely weak NIR R_{RS} signal leading to large measurement uncertainties.

The above results clearly indicate that satellite ocean color missions targeting climate and global long-term operational applications should explore a potential for relating the $g(\lambda_0)$ values to a common reference. Crucially, the derived g factors in the NIR should be verified by comparing the accuracy of satellite retrieved aerosol optical properties against in situ measurements.

10. Building long-term satellite data records including historical missions

Currently, the only feasible way to create the longest satellite ocean color data record, while minimizing intermission biases through SVC, is by using the long-term in situ R_{RS} data from MOBY and by applying a standardized atmospheric correction procedure. Since 1997, MOBY has provided radiometric data with SI traceability (Clark et al. 2003), exhibiting accuracy and stability figures closely satisfying the SVC requirements for climate and global long-term operational applications (Zibordi et al. 2015). Consequently, MOBY is the SVC infrastructure that can support the construction of time series of satellite ocean color data products for any ocean color mission since the launch of the SeaWiFS.

The above consideration emphasizes the need to ensure continuity of MOBY, or alternatively, of a strictly metrologically equivalent infrastructure after a multiannual cross over interval. Only this can ensure the provision of in situ quality-checked R_{RS} essential for the integration of past, present, and future satellite ocean color missions. Notably, the example of MOBY further strengthens the importance of establishing and sustaining long-term SVC infrastructures beyond the lifetime of individual missions.

11. Conclusions

SVC is an essential need for all ocean color missions. This need is further strengthened for climate and global long-term applications, which require SVC infrastructures and services sustained beyond individual missions. It is acknowledged that the current single available SVC infrastructure supporting international missions since 1997, i.e., MOBY, is essential to link all past mission data with current and forthcoming ones in a consistent time series.

It is also recognized that multiple and interoperable SVC infrastructures would ensure robustness and the highest performance of the SVC capabilities into the future. Multiple SVC infrastructures, developed within international and interdisciplinary collaborations across space agencies, would indeed ensure redundancy and cross verification of global SVC assets.

SVC strategies developed during the previous decades are established. Nevertheless, advances are required to further improve the SVC methodologies and to further reduce the uncertainties and increase metrological stability in satellite data products supporting climate and global long-term operational applications. This requires further investigations:

- Reassess uncertainty and stability requirements for satellite data products depending on applications, with clearly stated expectation of the uncertainty coverage factors. These requirements should be ideally expressed as a function of wavelength or at least for relevant spectral regions.
- Evaluate the impact on *g* factors of in situ data from SVC sites located at different latitudes or exhibiting differences in the optical properties of atmosphere and waters.
- Standardize methods for the determination of *g* factors and for the assessment of their fitness-for-purpose accounting for emerging technologies and methods.
- Define techniques to determine the *g* factors in the NIR with respect to a single common reference, without any prior assumption on the accuracy of sensor absolute calibration.

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