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# An evaluation of marine regions relevant for ocean color system vicarious calibration

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## ABSTRACT

System Vicarious Calibration (SVC) is the fundamental process commonly implemented to meet uncertainty requirements in satellite ocean color data. It is performed by applying gain factors, *g*-factors, to the pre-launch calibration coefficients of the space sensor already corrected for sensitivity decay with time. Mission specific *g*-factors are determined from top-of-the-atmosphere data computed by propagating highly accurate in situ values of the water-leaving radiance, $L_w$, to the satellite sensor. Values of $L_w$ from marine regions characterized by oligotrophic/mesotrophic waters and maritime aerosols, high environmental stability and spatial homogeneity, low cloudiness and absence of any source of land contamination, are essential to determine *g*-factors applicable to the creation of Climate Data Records (CDRs) from multiple ocean color missions. Accounting for the location of existing and potential new SVC fixed sites, marine regions satisfying SVC requirements for the generation of CDRs have been identified through the analysis of satellite data from recent ocean color missions.

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## 1. Introduction

System Vicarious Calibration (SVC) is the indirect calibration of satellite ocean color sensors that minimizes the combined effects of atmospheric correction and sensor calibration uncertainties on derived radiometric data. SVC is performed to meet uncertainty requirements in data products such as the spectral water leaving radiance $L_w$ determined from the top-of-atmosphere radiance $L_T$ (Gordon, 1987, 1998): it is accomplished by applying gain factors, *g*-factors, to pre-launch spectral calibration coefficients already corrected for sensitivity change with time (e.g., Eplee et al., 2001; Franz et al., 2007; Werdell et al., 2007; Bailey et al., 2008; Mélin and Zibordi, 2010).

Values of *g*-factors are determined by the ratio of simulated to measured top-of-the-atmosphere spectral $L_T$ values, where the simulated ones are derived by propagating accurate in situ $L_w$ to the satellite level. Unique to SVC is the use of the same models and algorithms embedded in the atmospheric correction process for the determination of satellite-derived radiometric data. Thus SVC is a relative radiometric calibration specific for each mission, i.e., for each ocean color sensor and atmospheric correction framework.

It is emphasized that SVC implies availability of highly accurate in situ $L_w$ data in the visible spectral region. This is as opposed to the near-infrared bands where modeled $L_T$ values with uncertainties up to a few percent (which may imply extremely high relative uncertainties in the corresponding $L_w$) do not significantly affect the SVC process (Wang and Gordon, 2002).

In addition to the accuracy of in situ $L_w$ data, a number of features specific to the measurement site such as small environmental variability (i.e., a high intra-annual stability), high spatial homogeneity, mesotrophic/oligotrophic waters, maritime aerosols and lack of any land perturbation (Zibordi et al., 2015), are also fundamental requirements for ocean color SVC supporting climate change applications. This implies that not all individual in situ measurements or series of measurements, regardless of their level of accuracy, meet SVC needs for the construction of Climate Data Records (CDRs) from multiple ocean color missions.

The objective of this study is to identify marine regions satisfying SVC requirements for the construction of CDRs. By using time-series of satellite ocean color global data products, the study investigates the fulfilment of the requirements mentioned above for a number of regions already hosting SVC fixed sites or for which new sites are under consideration.

This work adds to ongoing investigations like those on data merging (e.g., Maritorena et al., 2010) or on the effects of biases affecting independent missions (e.g., Mélin, 2016), all contributing to the international effort to create ocean color CDRs by benefitting from global long-term missions such as the Joint Polar Satellite System (JPSS) from the National Oceanic and Atmospheric Administration (NOAA) started in 2011, Sentinel-3 from the European Space Agency (ESA) started in 2016, the Global Change Observation Mission-Climate (GCOM-C) from the Japan Aerospace Exploration Agency (JAXA) scheduled from 2017, and the

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Plankton Aerosols Clouds and ocean Ecosystems (PACE) from the National Aeronautics and Space Administration (NASA) scheduled from 2022.

## 2. Background

The water-leaving radiance $L_w$ is the primary satellite-derived radiometric quantity from which high-level data products such as the remote sensing reflectance $R_{rs}$ or chlorophyll-a concentration *Chla* are determined. This has led to the inclusion of $L_w$ among the oceanic Essential Climate Variables (ECV) in association with uncertainty requirements of 5% in the blue-green spectral regions and radiometric stability better than 0.5% per decade (WMO, 2011). SVC is the technique commonly used to address such requirements. However, while the 5% uncertainty can be met with moderate efforts using alternative sources of in situ data, the 0.5% stability requirement is only achievable at the expense of extraordinary efforts through the application of state of the art radiometry and at sites exhibiting high intra-annual stability and spatial homogeneity of marine and atmospheric optical properties (Zibordi et al., 2015). This comprehensive framework is required by the need to ensure the same high precision to *g*-factors determined for successive missions. In fact, changes with time of uncertainties characterizing in situ measurements or observation conditions, may affect the precision of *g*-factors determined during the different time intervals of independent missions. This need for high precision ultimately favors SVC sites exhibiting: *i*. a high spatial homogeneity that minimizes the impact of the different geometric resolutions characterizing in situ and satellite observations; and *ii*. a high intra-annual stability of the marine and atmospheric optical properties that minimizes uncertainties due to the varying performance of the atmospheric correction process across different observation conditions. It must be additionally noted that a high intra-annual stability is commonly associated with low concentrations of seawater optically significant constituents typical of oligotrophic waters (Iverson et al., 2000). This implies a low bio-optical complexity that improves modeling accuracy (e.g., while removing the effects of the non-isotropic distribution of the in-water light field in satellite data to match satellite and in situ viewing geometries) and that consequently increases the precision of *g*-factors.

Overall, general requirements for in situ data supporting SVC for ocean color climate applications (see Zibordi et al., 2015) are summarized by the need for long-term, hyperspectral, traceable and highly accurate measurements performed at sites:

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

It is mentioned that the work by Zibordi et al. (2015) indicates that the creation of CDRs from independent ocean color missions should ideally rely on the application of the same atmospheric correction process and on time-series of in situ $L_w$ data from a single reference SVC site. However, the work also recognizes that strategies to support long-term climate investigations recommend redundancy of in situ SVC measurement sites (IOCCG, 2012). This implies establishing multiple SVC sites: i. relying on in situ radiometry systems equivalent in terms of data accuracy and long-term performance; ii. and located in regions also exhibiting ideal and likely similar measurement conditions.

The high cost of establishing and maintaining over decades SVC sites meeting the requirements for the creation of CDRs from multiple ocean color missions, nevertheless, suggests a careful evaluation of suitable marine regions without neglecting the fundamental necessity to benefit from logistical support from infrastructures located at nearby islands or coastal locations.

## 3. Regions, data and methods

### 3.1. Marine regions

As already anticipated, the regions considered in this analysis (see Table 1), are those related to fixed sites already in use for ocean color SVC or alternatively potential SVC sites under consideration because of their atmospheric and marine optical properties expected to be representative of the world oceans.

The regions hosting established SVC sites include: the North Pacific Ocean (NPO) with the Marine Optical Buoy (MOBY) site managed by the US National Oceanic and Atmospheric Administration (NOAA; Clark et al., 1997, 2002, 2003); the Arabian Sea (ASea) with the Kavaratti Site managed by the Indian Space Research Organization (ISRO; Shukla et al., 2013); the Ligurian Sea (LSea) with the BOUée pour l'acquiSition d'une Série Optique à Long termE (BOUSSOLE) site managed by the French Laboratoire d'Océanographie de Villefranche (LOV; Antoine et al., 2008b). The regions for which the setting up of new SVC sites has been a matter of discussion within the scientific community comprise: the Mediterranean Sea (MSea) near the Island of Crete; the Caribbean Sea (CSea) near Puerto Rico Islands; the North Atlantic Ocean (NAO) near Azores Islands; and the Eastern Indian Ocean (EIO) near Rottnest Island off Perth. In addition to the previous regions, the South Pacific Gyre (SPG) is also included as a virtual reference region due to its highly oligotrophic waters and its expected high temporal stability (Twardowski et al., 2007).

It is noted that the considered regions are characterized by Case-1 waters (i.e., exhibit optical properties that can be described as a function of *Chla*, only), which are representative of the most common oceanic waters. It is also pointed out that all regions, with the exception of the virtual SPG one, are located nearby islands or coastal locations favouring maintenance services of the offshore SVC measurement infrastructure, but also at distances from the coast minimizing land contamination such as adjacency effects in satellite data (Bulgarelli et al., 2014).

It is finally recognized that the regions included in this study are not likely to reflect all those potentially suitable for ocean color SVC. Still, not excluding alternatives, the regions considered provide an overview of the marine/atmospheric optical properties of those potential SVC sites currently considered of major relevance to support the creation of ocean color CDRs.

### 3.2. Remote sensing data and methods

The accuracy of ocean color data products is related to a number of factors encompassing the overall calibration of the space sensor and atmospheric correction scheme applied in conjunction with the embedded marine/atmospheric models and algorithms. These factors may certainly lead to the generation of data products with uncertainties varying from region to region as a function of different marine/atmospheric optical properties or observation/illumination geometries (Mélin et al., 2016).

The Sea-Viewing Wide Field-of-View Sensor (SeaWiFS, Hooker et al., 1992) ocean color data products, besides constituting one of the longest time-series from a single mission, are among those most investigated and exploited. In particular they benefitted from a number of incremental improvements in data processing and related models/algorithms (e.g., Gordon and Wang, 1994; Wang et al., 2005; Franz et al., 2007; Ahmad et al., 2010; Hu et al., 2012b), and additionally were the foundation of extensive and geographically distributed validation exercises for

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