D-240 Proceedings of WKP-1 (PROC-1)
Report of the international workshop

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Acronyms and Abbreviations

Acronym	Abbreviation
BOUSSOLE	Buoy for the acquisition of long-term optical time series
CDR	Climate Data Record
CEOS	Committee on Earth Observation Satellites
Cl	Climate
CMEMS	Copernicus Marine Environmental Monitoring Service
CNR	Consiglio Nazionale delle Richerche (Italy)
CNRS	Centre National de la Recherche Scientifique (France)
COB	Centre Oceanografic de les Balears (Spain)
EEZ	Exclusive Economic Zone (200 nautical miles)
EO	Earth Observation
ESA	European Space Agency
EU	European Union
EUMETSAT	EUropean organisation for the exploitation of METeorological SATellites
Fi	Fisheries
FRM	Fiducial Reference Measurement
HCMR	Hellenic Centre for Marine Research
LOV	Laboratoire d'Océanographie de Villefranche-sur-Mer
Ma.Bio	Marine Biology
Ma.Che	Marine Chemistry
MERIS	Medium Resolution Imaging Spectrometer
MOBY	Marine Optical BuoY
MOBY-Net	Marine Optical BuoY Network
MPC	Mission Performance Centre
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NIR	Near Infra Red
NIST	National Institute of Standards and Technology
NMI	National Metrological Institute
NPL	National Physical Laboratory
NPO	North Pacific Ocean
NRT	Near Real Time
OC	Ocean Colour
OCR	Ocean Colour Radiometry
OCR-VC	Ocean Colour Radiometry Vicarious Calibration
OCTAC	Ocean Colour Thematic Assembly Centre
OLCI	Ocean and Land Colour Instrument
PDGS	Payload Data Ground Segment
Ph.Oc.	Physical Oceanography
RT	Radiative Transfer

Acronym	Abbreviation
S2	Sentinel 2
S3	Sentinel 3
SI	International System of Units (Système international (d'unités))
SIO	South Indian Ocean
SPG	South Pacific Gyre
SVC	System Vicarious Calibration
SVA	System Vicarious Adjustment
TOA	Top Of Atmosphere
UoA	University of the Azores
VC	Vicarious Calibration

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Executive summary

Post launch system vicarious calibraton (SVC) using highly precise and accurate ground radiometric measurements is an essential step in the process of achieving sufficient satellite ocean colour product quality to meet the needs of Copernicus and the Global Climate Observing System (GCOS). At present there is only one fully operational dedicated ocean colour SVC facility run by NASA and NOAA off the coast of Hawaii, USA (MOBY); and only one other site in the world (BOUSSOLE) which, although it has reached the requirements and high standard of data quality expected for SVC purposes, is at pre-operational status due to a lack of long term investment.

From an operational perspective, it is crucial that SVC is implemented as early as possible in an ocean colour satellite mission's lifetime as it is the key to public product release (ideally SVC infrastructure should be operational before launch). Past experience has demonstrated that approximately 2 high quality matchups per month are produced by a permanent mooring for the purpose of SVC. At this rate, several years can pass before consolidated vicarious gains can be derived from a single infrastructure. In an operational context, it is therefore crucial to increase the number of operational SVC systems to reduce this delay.

Furthermore, the EC, ESA and EUMETSAT have put a significant amount of investment into the Sentinel series of satellites and the OLCI and MSI sensors to provide ocean colour products. Value for money from this investment, in terms of good quality ocean colour data and products, is potentially at serious risk if the European SVC infrastructure is not upgraded and supported in the long term.

The primary objective of this workshop was therefore to evaluate the options and approaches to the long-term vicarious calibration of the Sentinel-3 OLCI and Sentinel-2 MSI series of satellite sensors. This evaluation was performed with the support and active participation of the world's experts in ocean colour SVC and ocean colour radiometry fields. Presentations were given covering all major aspects of ocean colour SVC globally; and open debates were held to discuss lessons learned, to analyse strengths and weaknesses of the different approaches, and to review the cost and requirements to implement, operate, and maintain SVC infrastructure, in order to clearly establish Copernicus needs in the short and long term. Drawing from the current status of ocean colour SVC the workshop concluded with a consensus for the development of Copernicus ocean colour SVC capacity. All presentations are available on-line at https://frm4soc.org/index.php/activities/workshop-on-vicarious-infrastructure/.

The recommendations can be summarised as follows:

- Neither MOBY nor BOUSSOLE are directly supported by Copernicus. The risk of losing one or both and their associated expertise, and therefore losing the capacity to deliver robust EO products, must be taken into consideration. Given that the US MOBY infrastructure is secured in the long term, Copernicus should consider maintaining two operational SVC sites, resulting in a minimum of 3 sites globally. This will ensure system redundancy and robustness of ocean colour SVC as recommended by the Committee on Earth Observation Satellites (CEOS). Maintaining two sites in Europe will also: secure the existing expertise, knowledge and knowhow in Europe; develop new expertise; stimulate technical, scientific and industrial innovation; and importantly, create jobs. From a risk mitigation perspective, it is also essential that Copernicus controls its vicarious calibration capacity to ensure Sentinel 2 and Sentinel 3 product quality for the next two decades.
- For the development of these two proposed Copernicus operational SVC sites, it is clear that building upon existing systems and expertise (namely BOUSSOLE and MOBY) would be more cost effective. Consequently, the final community recommendation for SVC development within the framework of Copernicus is:
    - To maintain BOUSSOLE in the long term and upgrade it to full operational status for SVC purposes and also support the development and long term operation of a second new European infrastructure in a suitable location to ensure operational redundancy.
    - As was implemented for MOBY, and now for BOUSSOLE, for any SVC infrastructure a good metrological foundation with 'hands-on' involvement of National Metrological Institutes (NMIs) at all stages of development and operation is a key component. This fiducial reference measurement (FRM) ethos ensures SI traceability, full uncertainty characterisation and the best possible accuracy and precision for the SVC measurements and process.
    - In situ radiometry should be hyperspectral, high resolution, high quality, and of an SI-traceable FRM nature, with a full uncertainty budget and regular SI-traceable calibration.
    - For the second SVC infrastructure, the results of initial studies point out that a site located in the Eastern Mediterranean Sea would represent a good candidate, although other options (in European and non-European waters) are not excluded at this stage.
    - A MOBY-Net system, that includes the transportable modular optical system developed by NASA and the MOBY team, is recommended for the new site. It offers a technologically proven system within a realistic timeframe for Copernicus needs and its use reinforces collaboration of world class experts and centres of excellence. In parallel, steps should be taken within the frame of Copernicus to develop a European solution in the mid-term.

Contents

1 Scope

This document is the report from the workshop held from February 21st to 23rd 2017. It constitutes the first deliverable (D-240,PROC-1) of work package 1 (proceedings of WKP-1; Report of the international workshop).

2 Introduction

The sections below present a brief summary of the presentations from the workshop (section 4). The presentation summary is followed by an evaluation of the perspectives for European SVC capacity (section 5). This section provides a detailed report of the discussions held after each workshop session, the final round tables and open discussions.

The document concludes with the consensus reached by the international community and proposes a realistic plan in terms of human resources, technological achievement, operation and cost for the development of the Copernicus SVC capacity.

3 Review of workshop presentations

Session 1: Introduction

European Earth Observation background

C. Donlon, ESTEC & E. Kwiatkowska, EUMETSAT

With the Sentinel series, the European Commission, together with ESA and EUMETSAT has set up Copernicus, an ambitious program to ensure the continuity of earth observation sensors for the next 15 years (Figure 1). This program with no other equivalent represents a breakthrough for operational oceanography, Climate Data Record (CDR) construction and the development of long term reliable downstream services. Among these missions, Sentinel-3 Ocean and Land Colour Instrument (S3 OLCI) is of prime importance for the biogeochemical optical oceanography community. OLCI benefits from MERIS heritage. It has therefore similar characteristics but with improved capacities (global Full Resolution (300m) acquisition, increased spectral band set ...) and the operation of two S3 missions will improve remarkably earth coverage. Sentinel-2, although primarily developed for land applications, already demonstrates a great potential for coastal applications like sediment load and chlorophyll retrieval, swell detection (Steinmetz & Ramon 2016, Vanhellemont & Ruddick 2016, Kudryavtsev et al. 2017). At the time of the workshop, Sentinel 2A and 3A are already in orbit. Sentinel-2B is ready for launch on March 6th 2017 on a Vega rocket, Sentinel-3B is planned for launch from Plesetsk on Rockot in early 2018.

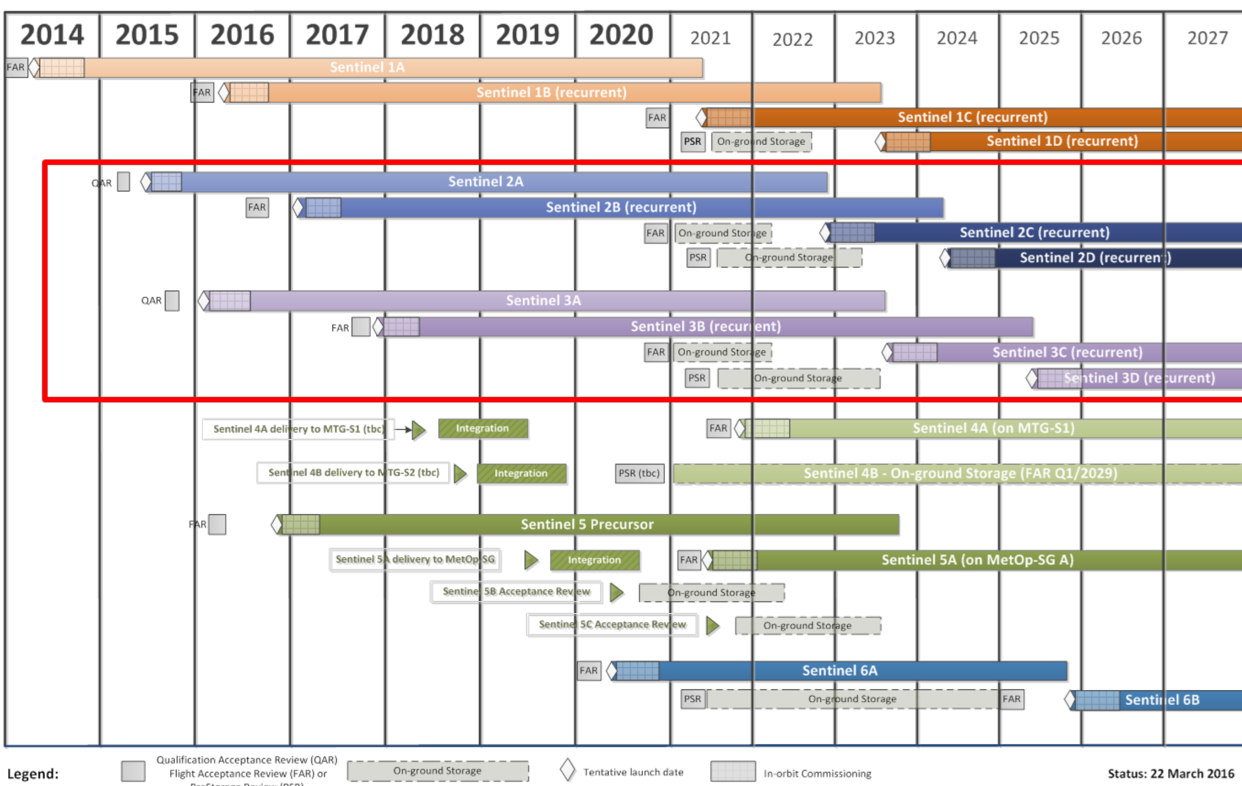

Figure 1: The Copernicus Sentinel deployment schedule.

Vicarious calibration, is the indirect sensor calibration based on ground target of known radiometry (instrumented buoys or stations) or modelled radiometry (the clearest oceanic gyres like the South Pacific Gyre ; SPG ; or the South Indian Ocean ; SIO) and is a mandatory step to reach the accuracy requirement set on Ocean Colour Radiometry (OCR) Level-2 geophysical products. In addition, although the Sentinel-2 and Sentinel-3 series are practically identical in design, it is anticipated that differences in performance of payload will exist. System Vicarious Calibration (SVC) is therefore essential to ensure data quality and intermission consistency throughout multi-mission life time for CDR and any operational services or downstream applications.

In this context, ESA has initiated the FRM4SOC project (Fiducial Reference measurements for Satellite Ocean Colour). Within this project, the current workshop has the objective to evaluate the options for future European satellite OCR vicarious calibration infrastructure (including approaches and value for money) for the sentinel-3 OLCI and Sentinel-2 MSI A/B/C and D instruments. In particular, the following points have been addressed during the workshop:

- Foster an **open-forum, wide-ranging debate** with the international ocean colour community;
- **Review** of historical and contemporary **approaches to vicarious calibration;**
- Document **Lessons Learned** from international teams;
- Review the **strengths and weakness** of alternative methods and approaches to OCR satellite vicarious calibration;
- **Consider an optimum European location for OCR vicarious calibration infrastructure** based on spatial and temporal distributions of chlorophyll, atmospheric aerosol loading and cloud cover (and other geophysical quantities if deemed appropriate);
- **Conclude with a consensus on the way forward** to deliver the best scientific outcomes to support long-term Copernicus operations using European infrastructure S3 and S2 OCR vicarious calibration infrastructure;
- **Review the costs to implement, operate and maintain** a European satellite OCR vicarious calibration infrastructure for S3 and S2 missions;
- **Review and define justified and traceable requirements** for vicarious calibration measurements (i.e. instruments) to be made in support of satellite OCR.

In parallel, OC-VCAL project, led by EUMETSAT, is currently reviewing the detailed requirements for Ocean Colour Vicarious Calibration Infrastructure for the European Commission's Copernicus programme.

Both projects will contribute to specify the needs for a long term Copernicus program to ensure product and services quality through system vicarious calibration. The definition of needs for future European SVC capability will build—up international collaboration and experience from existing systems or activities (BOUSSOLE and MOBY, MOBY refresh, ROSES-14 project, the Committee on Earth Observation Satellites (CEOS) Ocean Colour Radiometer Virtual Constellation (OCR-VC) recommendations, European Commission Joint Research Centre (EC-JRC) papers and reports. A fundamental challenge of future SVC will be to carefully assess uncertainty budget along the entire system therefore from in situ radiometry acquisition to vicarious gain computation.

This workshop is a unique opportunity for the international SVC community to consider the options for SVC infrastructure in Europe that complements that already existing to ensure the operational robustness of the Copernicus Ocean Colour Missions in the long-term.

Review of historical and contemporary approaches for vicarious calibration

D. Antoine, LOV & C. Mazeran, Solvo

Basis and principle of vicarious calibration

Equation 1 below represents the model of the radiance signal measured by a satellite borne sensor where L_t is the TOA radiance, L_{path} is the path (aerosol + Rayleigh) radiance, L_w is the water leaving radiance, t_g is the gaseous transmittance, t is the total (direct and diffuse) atmospheric transmittance, T is the total upward atmospheric transmittance and L_g ,the glint reflectance.

$$L_t(\lambda) = t_g(\lambda) \cdot \left(L_{path}(\lambda) + T(\lambda)L_g + t(\lambda)L_w(\lambda)\right)$$

Equation 1

General requirements for Ocean Colour product accuracy have been driven by the need to distinguish the fine radiometric signature due to oceanic phytoplankton content on the Top Of Atmosphere (TOA) signal (Figure 2).

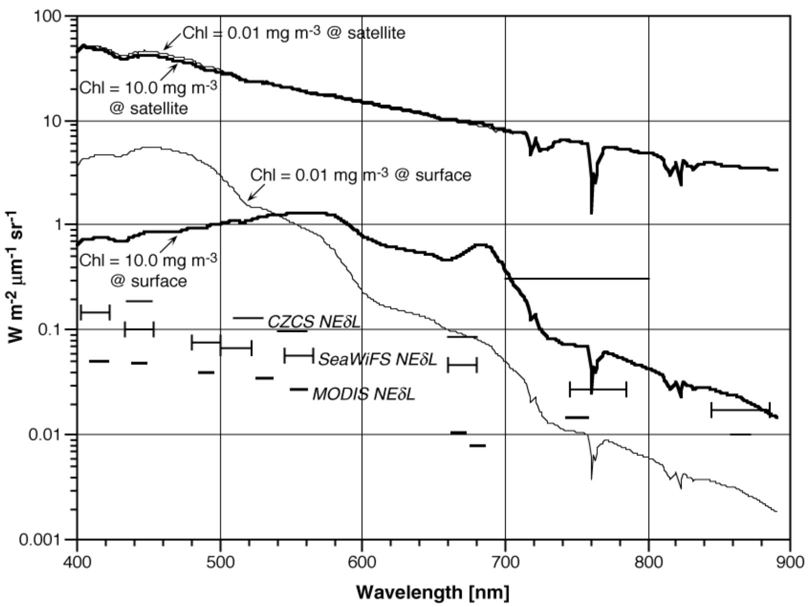

Figure 2 : Space borne sensor sensitivities compared to water-leaving radiance, and radiances measured at the satellite over cloud-free oceans according to model results (from Gordon 1982).

Early works from Gordon et al. (1982, 1994) and Gordon (1997, 1998) are at the origin of the requirement to provide water-leaving radiance (L_w) in the blue-green part of the spectrum with a 5% accuracy objective over oligotrophic, chlorophyll-depleted waters. This accuracy objective corresponds to the uncertainty of 1.10^{-3} to 5.10^{-4} defined by Antoine and Morel (1999) for the blue-green bands. These different analyses can be summarised as follows. L_w is a small fraction (<10%) of the measured signal at TOA level, so that a highly accurate calibration is needed. A requirement of 5% on L_w leads to at top of atmosphere uncertainty of 0.5%, which is not achieved through prelaunch characterisation and on-board calibration with the present technology (Equation 2). This is the reason why system vicarious calibration remains an integral part of Ocean Colour earth observation programmes.

$$\frac{\Delta L_t}{L_t}(\lambda) = \frac{\Delta L_w}{L_w}(\lambda) * \frac{t_g t L_w(\lambda)}{L_t(\lambda)} \approx 5\% * 10\% \approx 0.5\%$$

Equation 2

In Equation 2, Δ stands for the uncertainty on TOA radiance and water leaving radiance retrieval.

The general principle of vicarious calibration is to reconstruct a theoretical TOA signal L_t^t based on various possibilities or assumptions (Gordon 1998, Eplee et al. 2001, Franz et al. 2001, Franz et al. 2007, Bailey et al. 2008, Melin and Zibordi, 2010, Lerebourg et al. 2011). This includes data screening (no glint, negligible aerosol), climatology or models (e.g. L_w over stable gyres), assumption (fixed aerosol type), in situ measurement of L_w.

Then vicarious gains are computed at pixel level as:

$$g(\lambda) = \frac{L_t^t(\lambda)}{L_t(\lambda)}$$

Equation 3

Assuming that temporal trends are already corrected by instrument calibration, a unique set of spectral gains $\bar{g}(\lambda)$ is deduced by averaging individual gains over the mission's lifetime.

What System Vicarious Calibration (SVC) should (or could) be?

Ideally, all needed quantities to drive a vector Radiative Transfer (RT) model are measured with the best possible accuracy. The RT calculation then provides the total radiance at TOA level, totally independently of which sensor is to be vicariously calibrated, and which atmospheric correction algorithm is subsequently used to process observations from that sensor (Gordon and Zhang, 1996).

In practise, SVC is not performed this way essentially because the "best possible accuracy" is not met by most field instruments and procedures. This option could/should nonetheless be re-considered. For instance, could additional systems be mounted on radiometric buoys to derive atmospheric optical properties? The AERONET-OC system is clearly not designed for buoy deployment but could smaller and lighter systems, based on LIDAR technology, be used?

Terminology and key aspects of SVC

CEOS defined both calibration and calibration, and insist that they are not the same process. However, does not the CEOS definition of "calibration" fit with what we do for SVC?

CEOS definition of Calibration is "the process of quantitatively defining a system's responses to known, controlled signal inputs".

We determine the instrument response when it aims at a target.

- Lab calibration:
    - the target is a lamp (or lamp and plaque) of known uncertainty. Calibration coefficients force the instrument output to match that of the lamp. What happens in between the target and the instrument does not really matter (or marginally).
- Vicarious calibration:
    - a natural target is observed, whose properties are measured in the field with a known uncertainty. Calibration coefficients then force the instrument output to match the target. What happens in between the target and the instrument matters a lot (atmospheric path) and the end-to-end system (i.e. the L2 products) are calibrated along with the instrument and the atmospheric retrieval process.

In essence, this is the same process.

A key aspect of SVC is that this is a calibration of the satellite and the level2 processing chain rather than just the instrument. SVC gains in the visible part of the spectrum (VIS) are, with some exception (MERIS 4th reprocessing), relative to gains firstly computed in the Near Infrared (NIR) following the approach of Wang & Gordon (2002) and Wang et al. (2016).

The processing chain (atmospheric correction methodology and auxiliary data) highly influence the procedure to derive calibration gains (Figure 3 below and Mazeran et. al session 9, this workshop).

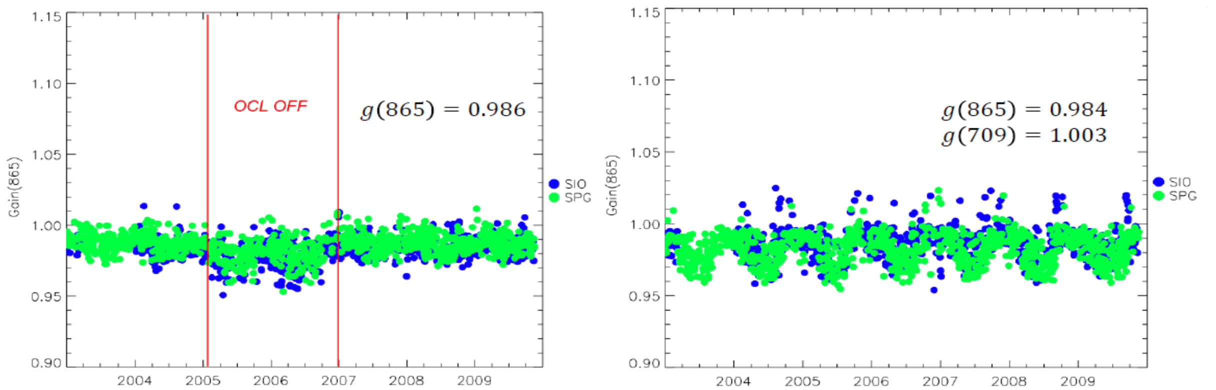

Figure 3: MERIS NIR gain time series over SIO and SPG. Left: methodology developed and implemented for the 3rd data reprocessing. Two bands used as reference other bands calibrated using a spectral slope model. Right: SeaWiFS like methodology using one NIR band as reference and fixing an aerosol model (MAR90) to calibrate the others. (From Lerebourg et al. 2011, MERIS ATBD).

By construction, at the SVC site, individual gains make the system exactly match the in situ L_w^t. Mission-average gains remove the average bias (Figure 4). Gain uncertainty and variability along the sensor lifetime propagate to uncertainty on $L_w^{\overline{cal}}$ (Water leaving radiance after vicarious calibration).

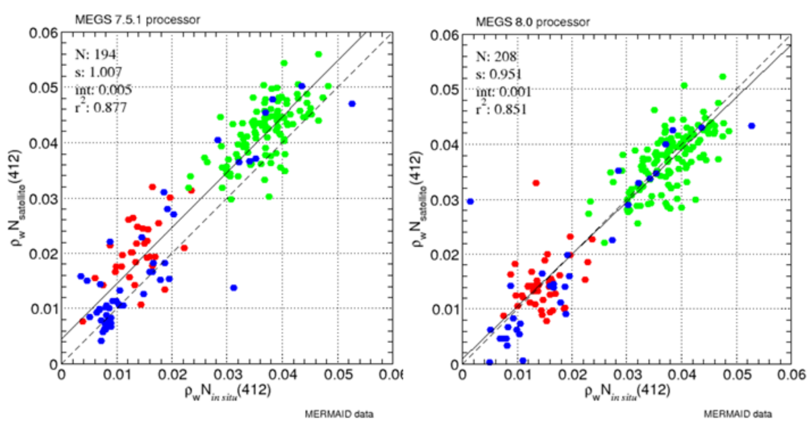

Figure 4: left, MERIS 2nd reprocessing (no SVC); right, MERIS 3rd reprocessing (with SVC). Validation at 412 nm (excluding SVC match-ups); (from Lerebourg et al. 2011, MERIS ATBD).

To date, SVC is the only method able to reach the required 0.5% uncertainty on TOA radiance. Great care must be taken for the computation of vicarious calibration gains as the impact of SVC at global scale depends on the quality of in situ data (for visible bands) and the robustness of the atmospheric correction scheme (for both visible and NIR bands).

What has been and will be done?

With the exception of POLDER, for which a methodology based on Rayleigh (absolute) and Sun-glint (inter-band) calibration was implemented (Hagolle et al. 1999, Fougnie et al. 2002), vicarious calibration of all ocean colour sensors follow the same general principal of a vicarious calibration of NIR bands over stable oceanic gyres followed by a vicarious calibration in the visible over instrumented sites or extensive field campaigns (Figure 5).

Basic principles in the VIS: computation over an instrumented site

$$L_t^t(\lambda) = \underbrace{t_g(\lambda)\cdot\big(L_R(\lambda) + L_a(\lambda) + L_{Ra}(\lambda)}_{\text{From atmospheric correction}} + \underbrace{T(\lambda)L_g}_{\text{Avoided}} + t(\lambda)\underbrace{L_w^t(\lambda)}_{\text{Sea-truth}}\big)$$

Basic principles in the NIR: computation over oligotrophic waters

$$L_t^t(\lambda) = \underbrace{t_g(\lambda)\cdot\big(L_R(\lambda) + L_a(\lambda) + L_{Ra}(\lambda)}_{\text{Assume 865 nm OK and fix an aerosol model}} + \underbrace{T(\lambda)L_g}_{\text{Avoided}} + \underbrace{t(\lambda)L_w^t(\lambda)}_{\text{Neglected}}\big)$$

Figure 5: Basic principle of SVC.

The approach for SVC can vary from one sensor to the other as described below:

- CZCS (polar orbiter):
    - initial vicarious calibration was performed by Gordon (1987), based on few points,
    - then revised by Evans & Gordon 1994 using the clear-water radiance concept.;
- SeaWiFS, MODIS-A, MODIS-T, VIIRS (polar orbiter):
    - SVC based on MOBY dataset;
- MERIS, OLCI (polar orbiter):
    - SVC based on MOBY and BOUSSOLE dataset;
- GOCI (geostationary over Korea):
    - SVC calibration based on field campaigns;
- S-GLI:
    - no consensus yet but possibly like MERIS approach based on BOUSSOLE and MOBY;
- Copernicus OLCI:
    - SVC based on MOBY and BOUSSOLE dataset;
- PACE:
    - still under evaluation (ROSES-14 call).

Whatever the origin of the in situ data used to derive SVC, it is crucial that all the measurement chain from sensor calibration to data reduction reduces uncertainty. This will be discussed in detail in next sections. With the exception of GOCI, where field campaigns are used since neither BOUSSOLE nor MOBY are in its field of view (it is in a geostationary orbit over Korea), and CZCS due to the lack of permanent SVC mooring at the time of flight, all SVC have been performed using a long term mooring.

As a rule, it is important to check that vicarious gains are stable over time and geometry (Figure 6). Any trend could originate from on-board calibration issue or atmospheric correction bias with geometry.

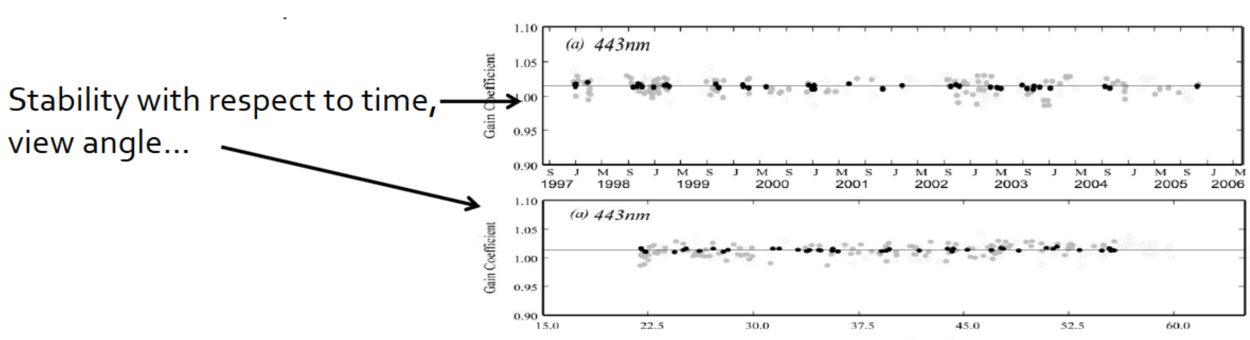

Figure 6: SeaWiFS gains derived from BOUSSOLE (from Franz et al., 2007).

Experience from the past has demonstrated that about 2.5 years can be needed to derive stable gains (Figure 7). This is an important consideration with respect to the number of available SVC sites: if more SVC sites are available the number of available data early on in the mission is dramatically increased, potentially reducing the time required to attain stable SVC gains (note that rapidly changing diffuser degradation and clouds may still confound the derivation of SVC gains).

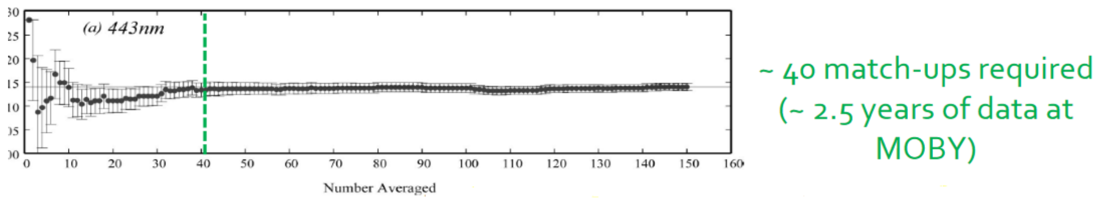

Figure 7: Number of matchups required to derived stable gains (from Franz et al., 2007).

To reduce the elapsed time to derive vicarious gains and or to increase the confidence in derived gains, several SVC sites can be used. This has been the strategy for MERIS 3rd and 4th data reprocessing. However, when several SVC sites are used to derive vicarious gains, it is even more crucial that a careful derivation of uncertainty is implemented for in situ data, and then extra care must be taken to ensure the coherence of derived vicarious gains. None coherent gains would inevitably introduce additional bias in the satellite products. In the case of the MERIS 4th reprocessing, a procedure to assess gains homogeneity was derived: Figure 8 represents the distribution of vicarious gains at 412, 442 and 681nm derived from BOUSSOLE and MOBY data. $\chi^2 = \frac{|\bar{g}_M - \bar{g}_B|}{\sqrt{\sigma_M^2/N_M + \sigma_B^2/N_B}}$ represents a homogeneity test on the gains distribution. A threshold on χ^2 at 1.96 ($\chi^2 < 1.96$) ensures that BOUSSOLE and MOBY gains set have a 95% probability to belong to the same distribution. This simple test was used to make sure that both BOUSSOLE and MOBY datasets could be used for SVC.

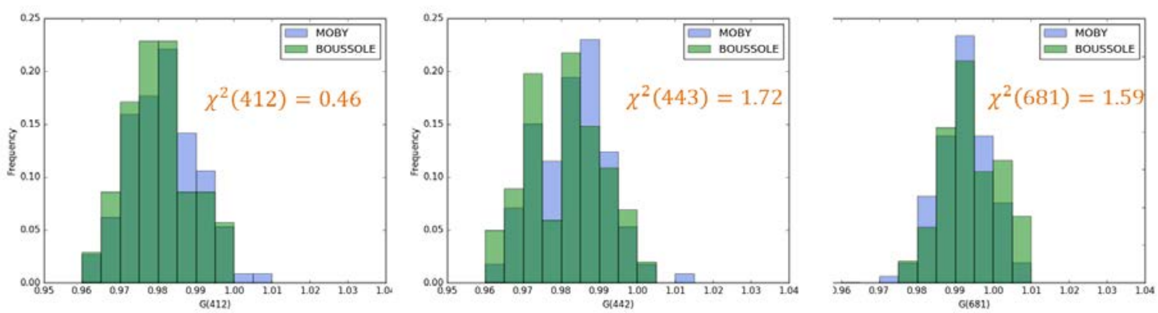

Figure 8: gain distribution derived from BOUSSOLE and MOBY for MERIS 4th reprocessing. (results of C. Mazeran (Solvo) from ESA/IDEAS, N. Lamquin (ACRI-ST) MERIS 4th reprocessing. MERIS data processed with ODESA (ESA/ACRI). MOBY data from Ken Voss (University of Miami) and BOUSSOLE data from David Antoine (CNRS-LOV).

SVC site characteristics and challenges

The following characteristic would be required for an SVC site. Feedback from BOUSSOLE and MOBY experience (Session 5 and Session 6 section) as well as section 4 on SVC requirements will add more material on this specific point.

- Clear skies, no land or bottom influences;
- Low aerosol load;
- Meso- to oligotrophic conditions;
- Marine conditions well characterized, including spatial homogeneity;
- Long-term logistical support and staff;
- SVC site and operations linked to (collaboration with) an NMI;
- Sufficient redundancy of equipment for 24/7 operations all year long;
- Bi-monthly (at least monthly) servicing;
- Radiative Transfer, field radiometry, satellite data processing expertise on site.

Among the main challenges of SVC can be mentioned:

- The need to standardize field data collection (part of FRM4SOC is meant to address this issue);
- Off the shelf instruments need to have excellent sensor characterisation (which currently need to be improved and carefully monitored);
- Maintenance of long-term sites is always challenging;
- The goals of SVC are not-so-well defined, it is therefore difficult to unambiguously decide what's appropriate and what's not for SVC;
- There is no strategy for coastal waters;
- There is no strategy for the evaluation of SVC "solutions" (sites);
- Some paradigms have to be revised? e.g. calibration vs. validation requirements.

The future of SVC

SVC is a complex process involving experts from various scientific and engineering domains like metrologists, oceanographers, physicists, biologists, remote sensing scientists etc. All aspects and issues of SVC will be addressed and discussed in this document:

- How to ensure the SI-traceability for OCR? (session 3 ; Metrology);
- What are exactly the requirements? (session 4 ; Requirements);
- Do we have the adapted field instrumentation? (session 5, 6, 7, 8; Instrumentation);
- Are the methods mature and definitive? (session 4 & 9)
    - Slope model (assumes intercept=0); what does this mean exactly?
    - What to do for spectral matching algorithms? Method in the NIR?
    - Multi-detector, multi-camera instruments vs. single-detector?
- Do we have the organisation / structure etc. for long-term SVC operations?
- How do we evaluate various SVC solutions? Which validation datasets?

Session 2: The CalVal needs for operational systems

The objective of this section was to analyse the calibration and validation needs of a Copernicus operational service, the Ocean Colour Thematic Assembly Centre of Copernicus Marine Environmental Monitoring Service (OCTAC- CMEMS) and two operational mission performance programs, Sentinel 2 and sentinel-3 Mission Performance Centres (S2-MPC and S3-MPC).

Copernicus Marine service needs for ocean colour product qualification

R. Santoleri, CNR

OCTAC CMEMS is providing NRT and reprocessed level 3 and level 4 global multisensor products as well as regional single and multisensor products of European Seas (Figure 9). OCTAC usage includes modelling quality assessment, data assimilation in bio-geochemical models (regional and global), provision of marine environment indicator for marine policy and management of marine resources, ocean state report.

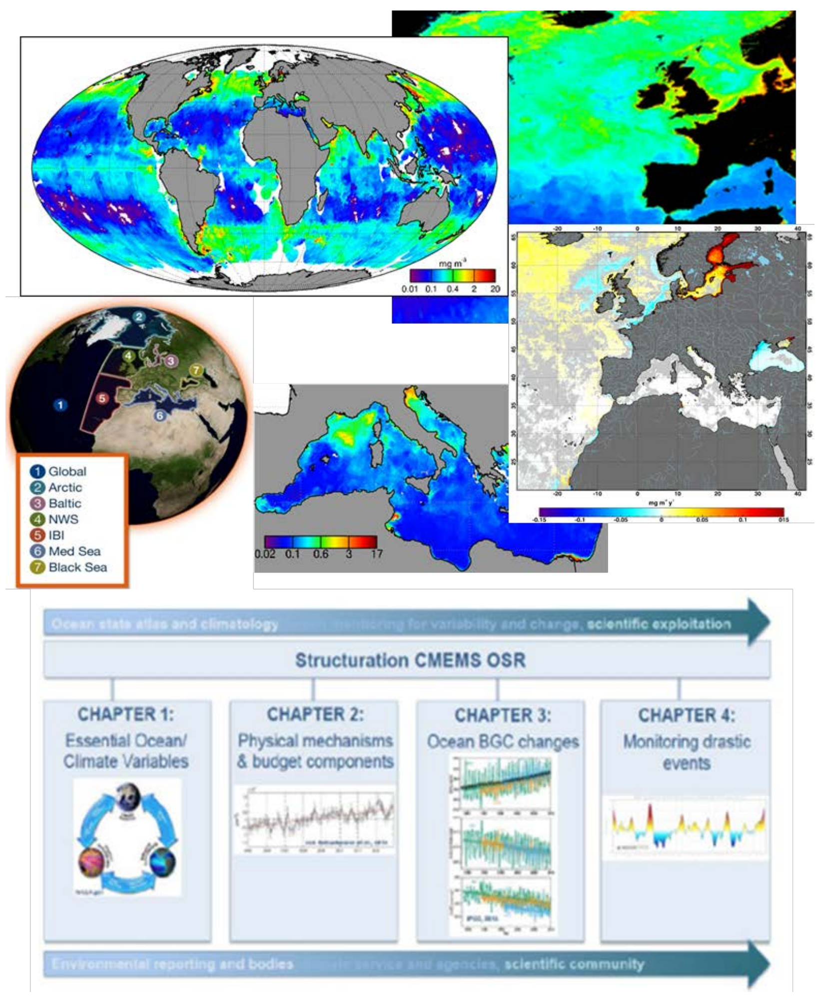

Figure 9: Use of OC products in CMEMS.

The quality of CMEMS Ocean Colour products therefore strongly depends on the quality of upstream satellite data provided by space agencies. The following requirements are stated for operational oceanography needs:

- vicarious calibration should ensure:
    - a stable long term calibration of the OC sensors required by the Copernicus climate service (required also by CMEMS for reprocessed products);
    - a prompt uncertainty assessment for operational NRT data in order to satisfy the requirements of the Copernicus marine service.
- The vicarious calibration calibration gain should be available as soon as possible following the satellite launch and frequently updated to ensure the accuracy of the NRT operational data.
- All previously-acquired data affected by calibrations should be reprocessed to improve the gain accuracy to ensure the accuracy required by climate observations.
- For regional optically complex seas, specific vicarious calibration should be considered to improve product quality as standard approach based on meso to oligotrophic sites will not be appropriate. This suggests a strong need to develop and maintain an efficient operational network like AERONET-OC in these areas.
- Currently, the SVC arrangements within Copernicus are not considered robust enough for a true operational Ocean Colour service and need to be improved. The CMEMS OCTAC supports the effort of this workshop to start to address this issue.

Assessment of the constraints on simultaneous Sentinel-2/MSI and Sentinel-3/OLCI vicarious calibration toward Level-2 products merging.

Bahjat Alhammoud[1], Vincenzo Vellucci[2], Romain Serra[3], Christophe Lerebourg[4], François-Regis Martin-Lauzer[1]. [1]ARGANS Ltd, United Kingdom; [2] LOV, France, [3]ACRI-HE, France, [4]ACRI-ST, France.

One may claim that the exponential growth in the amount of spatial EO data provides great opportunities for data merging. Reality can be different though, particularly when the data comes from multi-platform and its differences grow (e.g. spatial resolution, spectral resolution...), resulting in barriers to data merging. As the EO data collected through diverse sensors or methods are easily affected by various factors, their uncertainty increases. As there is always a local (quasi-) equilibrium at some spatial and temporal scales, it is possible to merge the EO data records. Issue is not only the coordination of different high-quality environmental and geophysical observations; but 1) their inter-calibration to correct relative biases and 2) the knowledge of their uncertainty budgets. Thus controlled fusion of remote sensing images will enhance the data reliability, which improves the large-scale remote sensing applications.

As part of the Sentinel-2 Mission Performance Centre (S2MPC) and the Sentinel-3 Mission Performance Centre (S3MPC) activities, ARGANS is tasked to assess the quality of the data product at both levels L1 & L2, to monitor both sensors evolution, and to ensure that the products meet the mission requirement accuracy.

The current Sentinel-2 systems have a swath of 290 km, sensing high spatial resolution data (10 m) with a 10-day revisit capability. This is in contrast to the 1270 km swath, moderate spatial resolution (300 m), near daily global observations sensed by Sentinel-3 OLCI. These systems are in the same polar orbit, with Sentinel-3 observations occurring approximately 30 min before Sentinel-2 nadir observations. Recognizing the complementary aspects of these systems, a data fusion technique could be used (e.g. stochastic) to combine 10 m Sentinel-2 data with daily 300 m Sentinel-3 reflectance data. The merging technique scheme is shown in Figure 10. The technique, while providing useful information, requires knowledge of the scene characteristics (e.g. viewing geometry, bidirectional reflectance distribution function (BRDF) etc.).

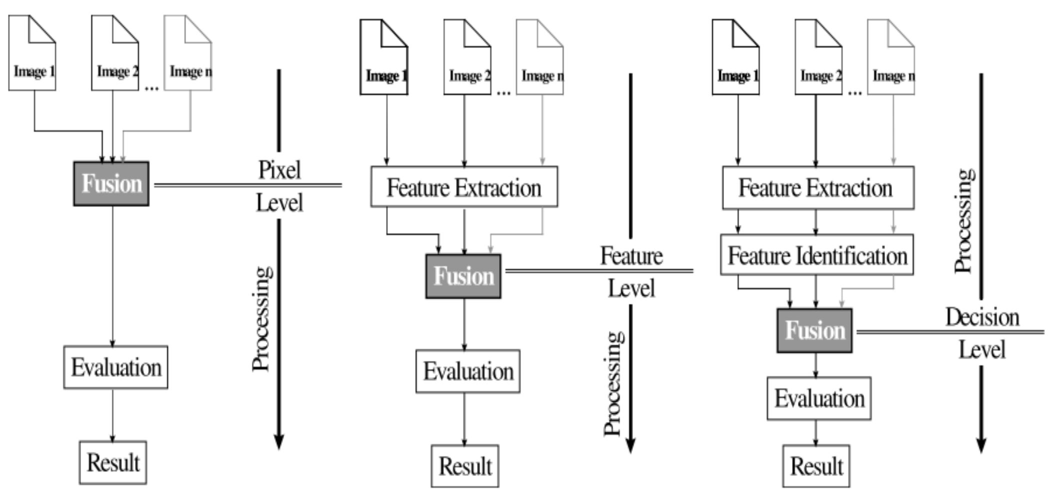

Figure 10: Data fusion scheme.

In spite of the good coherence between both sensors from Level-1 products, it seems that several requirements have to be satisfied prior to any merging, for example:

1. Consistency between data sets (to apply operations);
2. Differential Significance of data sets;
3. Accuracy & precision of data sets;
4. Information retrieval & adequate merging methodology.

The MSI sensor, with its comparatively narrow field of view, is not as severely affected by the effects of view angle variations as OLCI, although some impacts could be expected, and even when the MSI data are atmospherically corrected, seasonal solar zenith variations remain (Hansen et al., 2008; Gascon et al 2017). The impact of the spatial resolution on the BRDF has been documented (Danaher et al., 2001), although relative and absolute methods to data normalization assume implicitly that BRDF variations are negligible or treat them as a source of noise (e.g. Landsat data).

Whatever the purpose of the data merging, the homogeneity requirement imposes unbiasedness of the statistics, mainly the quality of the average estimation, which can't exist without measurements' or assessment's or estimator's accuracy. Hence, homogeneity of data sets made of measurements by different sensors implies no relative bias between data delivered by the sensors, but also the same precision, or knowledge of the precision (Figure 11).

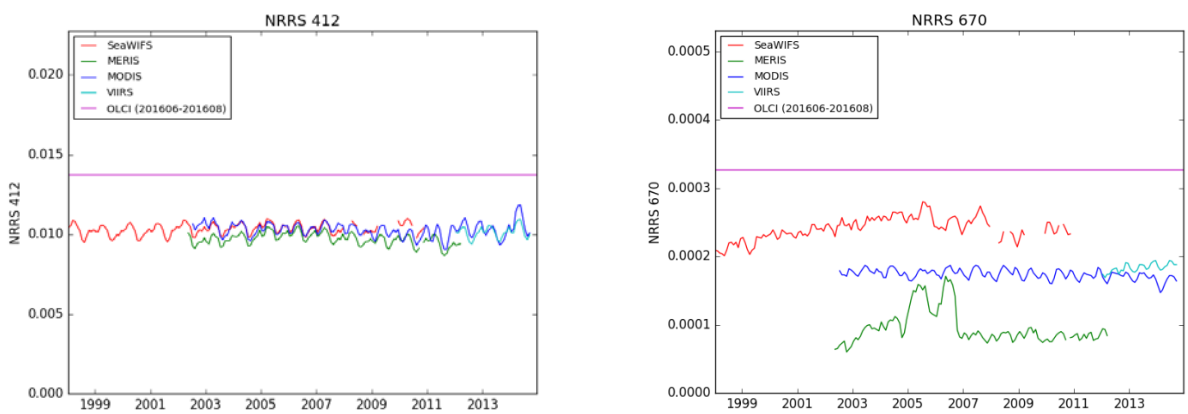

Figure 11: Time-series of (left) NRRS412 and (right) NRRS670 from SeaWiFS, MERIS, MODIS, VIIRS and OLCI.

To be able to extract information out of a set of data, i.e. EO if collected by a sensor on satellite, one needs the expression of uncertainty in the measurements. Most EO data are measurements (L1) that are transformed in so-called EO-products whose sources of uncertainties are not only the sensor, but the atmospheric carrier (e.g. the data transmission line from TOA to BOA vice & versa) and the processors algorithm as well as their parameterization (e.g.; ADFs). For example: The systematic errors at L1 are the L0 errors that are propagated in the processing chain, yet, they are neither spatially nor temporarily constant. At L2_optics, systematic errors of the atmospheric corrections and BRDF assessment add to the previous.

However, the preliminary analysis of two matchups over BOUSSOLE shows clearly the necessity of increasing the number of EO OC validation sites by a factor 5, if the QC level of MSI-L2 processors is to be similar to OLCI's. One has to take in consideration the products consistency (e.g. different transfer functions BOA <=> TOA). Finally, specific measurements required on sites to estimate the impact of sun-glint at 10m spatial resolution (e.g. sea surface roughness, swell and wind waves).

S3-MPC needs for FRM data

L. Bourg, ACRI-ST

The S3-MPC is dedicated to monitor and improve Sentinel-3 processor performance. The main usage of FRM is consequently for quantitative validation of level-2 products (Marine reflectance, chlorophyll, Kd ...). The requirement is therefore on high quality measurements accompanied with their uncertainties. S3-MPC is also responsible for the implementation of vicarious calibration. For this specific task, there is a need for independent FRM dataset to perform vicarious calibration and product validation. The main sources of FRM for S3-MPC come from BOUSSOLE, MOBY and AERONET-OC. BOUSSOLE and MOBY are in priority used for SVC while AERONET-OC is preferably used for product validation. AERONET-OC providing NRT level 1.5 in radiometric data proved to be very efficient in the critical first month on OLCI operation for data quality assessment. AERONET-OC data are now routinely matched to OLCI product for routine product quality assessment.

At the time this workshop was held, a first OLCI data reprocessing has been performed other almost four month (April 25th 2016 to august 15th 2016) providing an average of 3.75 usable matchups per month for SVC. In the literature, it can be found that for SeaWiFS, depending on the wavelength and assuming the sensor is corrected for time drifts, 30 to 50 matchups are required to derive stable gains (Franz et a. 2007). MERIS experience showed that 25 to 40 matchups would be required (Figure 12). This implies that a minimum of 9 months, using both sites is required to derived stable gains and provide acceptable products providing all other issues are dealt with (sensor calibration and time drift, troubleshooting, data access ...).

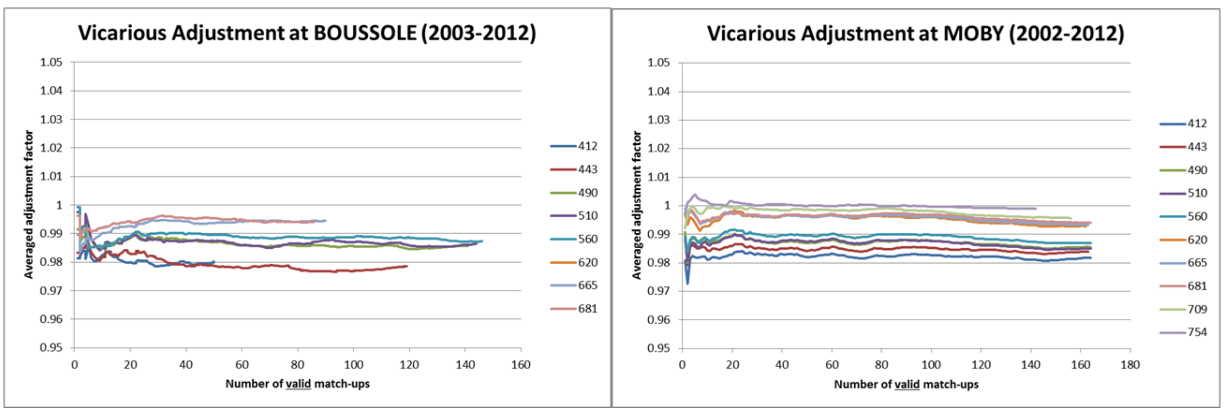

Figure 12: Average MERIS vicarious gain as a function of matchup number.
Left: BOUSSOLE (2003-2012),right: MOBY (2002-2012).

With operational product delivery constrains, S3-MPC would advocate for at least 3 "SVC class" sites in meso to oligotrophic waters to improve robustness in the long term and fast derivation of vicarious gains in the short term (i.e. the six or 9 months of sensor operation). In addition, S3-MPC would advocate to maintain and increase regional operational FRM systems like AERONET-OC over European waters. Then, there is still a gap of oceanic water data availability for satellite product validation. The Bio-Argo system has demonstrated its interest and has partially filled the gap of our capacity to validate chlorophyll product in case 1 water. The ProVal and HyperPro autonomous floats currently under development could improve significantly the availability of radiometric data availability in remote regions of the world ocean and should therefore be supported.

Session 3: Metrology foundation (SI traceability for OCR)

The metrological foundation for system vicarious calibration of satellite ocean colour data (Part 1)

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This talk summarised the metrological foundation of system vicarious calibration of satellite ocean colour data and highlighted its key importance for any future instrumented in situ sites.

The context for metrology in the system vicarious calibration (SVC) of satellite ocean colour data was given in terms of the earth observation (EO) and metrological organisations that provide the relevant global governance. The Group on Earth Observations (GEO), the Committee on Earth Observation Satellites (CEOS) and the Global Space-based Inter Calibration System (GSICS) were used as the main EO governance examples and in particular some details of the working group on calibration and validation (WGCV) of CEOS and its links with the other organisations were shown. The historical importance of metrology was also presented with an emphasis that for EO and climate data records, some translation and adaptation of standards and methods is necessary. This was linked to the reference standards provided by the "Convention of the Metre" and the "Système International d' unites" (SI) as well as the organisations that provide international governance for these in metrology such as the Bureau International Poids et Mesures (BIPM).

SI traceability and uncertainty as key concepts in metrology were introduced. The importance of having SI traceability and uncertainty evaluation for EO and climate data records was emphasized and discussed. In relation to long term data records, a particular highlight was given that showed the longer term the data record is, the more systematic uncertainty becomes important rather than random uncertainty that can dominate regional/short term measurements.

One of the central factors crucial to the maintenance of reference standards and the SI is the regular international metrological comparisons for key units undertaken at the national metrological institute (NMI) level. How these work to maintain equivalence at a global and European level was shown, including how these key comparisons feed from the NMI structure to other calibration laboratories and industry. All of the data, protocols and other essential documents relating to these key comparisons are held and maintained online by BIPM (see http://kcdb.bipm.org and links therein). An example of spectral irradiance key comparison results was presented, highlighting the importance that standards such as SI should always be accompanied by procedures.

Metrological Traceability can be defined as a property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty (BIPM, 2012). The definition of the key terms relating to this concept, particularly in relation to reference standards, were used to introduce its fundamental importance for defining in situ fiducial reference measurements (FRM) that can be used either for validation or SVC of satellite ocean colour data. For FRM additional defining principles are given by the quality assurance framework for earth observation (QA4EO – www.qa4eo.org) and these were summarised.

The radiometric traceability to SI of both EO sensors and in situ instruments for taking fiducial reference measurements were detailed. In addition to the entire SI traceability chain diagram for fiducial reference measurements for satellite ocean colour (FRM4SOC), some detail on a number of the various steps in this chain were also explained, e.g. the principle of cryogenic radiometry and the difference in uncertainty between cryogenic radiometer measurements and a following step where the spectral responsivity scale is derived. To further emphasise the importance of metrological traceability including evaluating uncertainty at each step of an SI traceability chain, results were shown from other earth observation relevant measurements where this is being undertaken by NPL, i.e. surface BRDF, surface temperature and solar irradiance measurements. Furthermore, the foremost authority and guide to the expression and calculation of uncertainty in measurement science was referenced and the GUM law of uncertainty propagation and the Monte Carlo method of propagating uncertainties were detailed (BIPM, 2008a and b); both of which are used in the metrological traceability of ocean colour measurements.

Finally, the concept and rationale of SVC of satellite ocean colour was explained and overall uncertainties were summarised in relation to BOUSSOLE (Antoine et al., 2008) and the GCOS requirements for ocean colour (WMO, 2011; Gordon and Clark, 1981; Gordon et al., 1983; Gordon, 1987; Hooker et al., 1982; Bailey et al., 2008; Zibordi, 2015). The work carried out thus far on applying metrological traceability to satellite ocean colour SVC and including the evaluation of uncertainty budgets, has raised some important questions and these were posed as possibilities for further investigation, i.e. Does the ocean colour level-2 product uncertainty after SVC meet the GCOS requirements? Is long term consistency / change monitoring the priority or is 'absolute truth' for each measurement more important? How many ‘independent references’ are needed? What implications for level-2 ocean colour product uncertainties are there the further you move away from the conditions at the SVC site (e.g. changing water type and atmospheric conditions)? Could there be potentially different SVC sites and gains for different water types? Where should we be making surface radiometric measurements for SVC: in water or above water or a combination of both? Apart from in situ radiometry improvements for SVC, where else could we focus our efforts to improve ocean colour level-2 products further: atmospheric correction?

The metrological foundation for system vicarious calibration of satellite ocean colour data (Part 2)

Carol Johnson, NIST

This talk covered the topics of uncertainty terminology (in brief), radiometric comparisons, gave an illustration of a spectral radiance scale realization, and concluded with a word on satellite system vicarious calibration (SVC).

It is important to review the uncertainty terminology and the philosophy behind the international consensus as one can easily get lost in the details. Though potentially tedious, one should always turn to the Guide to the Expression of Uncertainty in Measurement (GUM, JCGM, 2008) and the associated International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM, JCGM, 2012). These documents, and their supplements, are readily available from the web site of the Bureau International des Poids et Mesures (BIPM) and reflect international consensus on methodologies related to measurement uncertainties. The slides give an example using three common terms: accuracy, precision, and uncertainty. Recalling uncertainty is a data product that is evaluated numerically, we recognize that terms involving difference from the true value (e.g. as in the VIM definition of accuracy) cannot be assigned a numerical value because it is impossible to ever know the true value.

The archer's problem was used to illustrate the difference between accuracy and precision. The archer begins by improving their precision, e.g. getting a tight pattern that is fit for their purpose. For example, they may invest in a high quality bow or improve technique in order to achieve the desired result. In measurements, we select equipment and attempt to control influencing factors in order to improve the precision (e.g. 16 bit vs 8 bit, stable environmental temperature, etc.). If it is true we are performing "replicate measurements on the same or similar objects under specified conditions" (VIM, Sec. 2.15), then the differences in the results should be random and the uncertainty component for the mean value is reduced by $1/\sqrt{N}$ where N is the number of measurements. Accuracy is "closeness of agreement between a measured quantity value and a true quantity value of a measurand" (VIM, Sec. 2.13). At first glance, it seems we could assign a numerical value, at least for the archer, because we could measure the radial distance of the pattern mean from the bull's eye on the target. However, this is a calibration step, not a measurement. In other words, the archer is not making a dimensional measurement, but rather gauging and improving their performance in light of a different application (e.g., hunting or competition). All we can do as metrologists is design superb, fully characterized equipment, experiments that are least susceptible to influencing factors, and estimate the uncertainties so we can provide meaning to the results.

The concept of uncertainty and traceability recognize that measurements produce values for properties, termed the measurand, and a comparison to a reference gives meaningful physical results. So we design, characterize, calibrate, and measure the unknown in order to assign results. Uncertainty is a "parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be assigned to the measurand" (GUM, Sec. 2.2.3). Comparisons cannot be interpreted without prior evaluation of uncertainty.

I gave as an example the in-water comparison experiment the Spectral Ocean Radiance Transfer Investigation Experiment (SORTIE) (Voss et al. 2010). We compared the radiometric responsivities of two types of instruments prior to a field deployment and they agreed very well. However, in the field we found that while the agreement was within the expanded uncertainty (k = 2), there were unaccounted biases present in the results that remained unexplained. This work illustrates the key components of a comparison and indicated that it is difficult to design the experiment in natural conditions so as to reveal and identify all sources of bias.

I continued with an example of a "scale realization" – the procedure by which one assigns radiometric values to an artefact. In this case, we realize spectral radiance using a 1000 W lamp standard of spectral irradiance, type FEL, and a white diffuse reflectance target made from sintered polytetrafluoroethylene (PTFE). The measurement equation was described, and uncertainties for the spectral radiance in the centre of the target for normal incident and 45° view were presented. Significant terms in the uncertainty budget were the uncertainty in the spectral irradiance values of the lamp, and the 0°/45° reflectance factor for the target. Uncertainty in the lamp current and scattered light were important. In general, the distance is critical but here we measured with an uncertainty of 0.25 mm (k = 1) using an electronic ruler. A term that is often overlooked is the location of the radiometric centre, e.g. the reference location for 21d scaling. Ancillary data on the distance dependence resulted in an estimate for the offset of the radiometric centre from the NIST mechanical reference, as the lamp was operated at non-standard distances of 100 cm and 140 cm. The intensity distribution of the lamp's spectral irradiance and the bi-directional reflectance distribution function of the sintered PTFE target were used to determine the uniformity of the irradiance across the target as well as a model accounting for the range of incident and view angles. The latter is dependent on the device under test (DUT). The complete uncertainty budget depends on the imaging and radiometric characteristics of the DUT – the location of its entrance pupil, field of view, focus setting, and other instrument parameters.

The last slide addressed System Vicarious Calibration, a topic which is well documented in the literature and familiar to the workshop participants. A couple of relevant references are Franz's documentation of the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) Franz et al. (2007) and Zibordi's study of SVC requirements (Zibordi et al. 2015). It is important to recognize the observed consistency of the time series of gain factors (see Fig. 3 in Franz et al. 2007) fails to identify bias in the MOBY values that apply to every measurement condition independent of all the possible variables (solar zenith angle, wavelength, arm to sun azimuth, arm depths, etc.) as well as the satellite variables (view angle, time difference with MOBY, etc.). In other words, the lack of time and geometric dependence in the gain factors for SeaWiFS confirms the consistency of the assignment of radiometric responsivities to MOBY, but does not offer protection from unidentified sources of invariant biases. It is worth emphasizing here a point made in the study of the uncertainties in the L_u MOBY product (Brown et al. 2007): the standard deviation of the gain factor time series reported by Franz and co-workers was 0.9 % at 412 nm and 0.7 % at 670 nm. Taking the L_w to be 10 % of L_t means the standard deviation, or Type A uncertainty in the MOBY L_w values should be 9 % and 7 %, respectively. However, the Type A uncertainty for MOBY is much less, pointing to random sources of uncertainty, for example in the atmospheric correction, in the SVC analysis.

Session 4 Requirements for vicarious calibration

In situ requirements for ocean colour system vicarious calibration: a review

G. Zibordi. JRC

The results presented in this section are extracted from published documents. For detailed information, please refer to Zibordi et al. (2015) and Zibordi and Voss (2014).

The requirement legacy

There are three essential requirements available in the literature that should be considered for SVC:

- **5% uncertainty in satellite-derived L_w** in the blue spectral region to allow for the determination of *Chl-a* concentration in oligotrophic waters with a standard uncertainty of 35% quantified through the work of Gordon and Clark (1981), Gordon et al. (1983) and Gordon (1987).;
- **5% spectrally independent uncertainty** in satellite-derived L_w across the blue-red bands set as an objective (not a science requirement) of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) mission (Hooker et al. 1992). This broad objective was later interpreted or set, as a science requirement for several missions.;
- **5% radiometric uncertainty** in satellite derived L_w in the blue-green spectral bands in oceanic waters and **0.5% radiometric stability** over a decade for the creation of Climate Data Records (CDRs) of Essential Climate Variables (ECV) (WMO 2011, 2016).

Different from the 5% uncertainty requirement, which is commonly accepted by the satellite ocean colour community, the 0.5% radiometric stability requirement over a decade for the creation of CDRs through different missions appears to be a more open issue. Low uncertainties in the measurement of climate variables are essential for understanding climate processes and changes. However, it is not as necessary for determining long-term changes or trends as long as the data set has the required stability (Ohring et al. 2004, Figure 13).

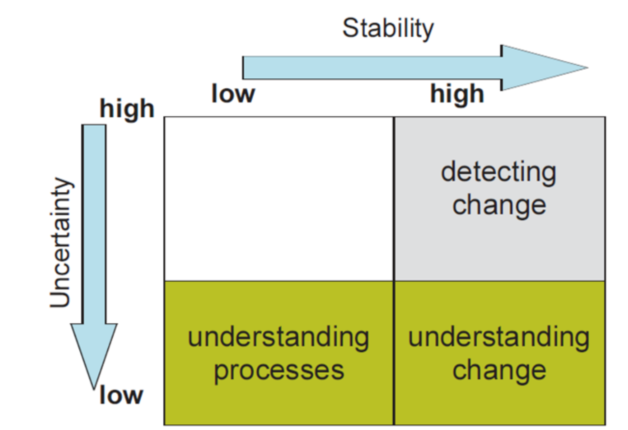

Figure 13: Uncertainty and stability requirements for a climate observing system (Ohring et al. 2004).

As an element of comparison, PACE mission requirements on in situ data were primarily defined by the PACE Mission Science Definition Team Report of October 6, 2012 and then applied to the ROSES 2014 call on “Ocean Color Remote Sensing Vicarious (In Situ) calibration Instruments”:

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

Early indications on the appropriateness of in situ data/sites for SVC included (extracted and interpreted with some freedom, from Gordon 1998):

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

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

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

Practical consideration on insitu uncertainty requirements (extract from Zibordi et al. 2015)

Equation 4 represents a simplified formulation of radiative transfer (no glint nor gaseous absorption). By assuming the values of L_r and L_a are exactly determined for any given observation condition (i.e. perfect atmospheric corrections), the relative uncertainties $u(L_T)/L_T$ are related to $u(L_w)/L_w$ as defined in Equation 5. Figure 14 shows typical spectral values of $t_d L_w/L_T$ for oligotrophic, mesotrophic and coastal waters.

$$L_T = L_R + L_A + L_w t_d$$

Equation 4

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

Equation 5

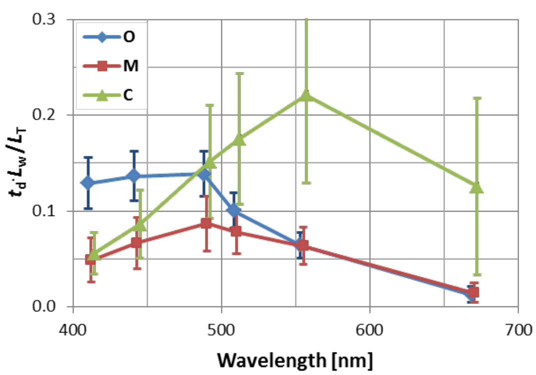

Figure 14: Spectral values of $t_d L_w/L_T$ for oligotrophic (O), mesotrophic (M) and coastal (C) waters. Mean values and standard deviations σ (indicated by the vertical error bars), result from the analysis of 814, 1487 and 1045 SeaWiFS data extractions, respectively (from Zibordi et al. 2015).

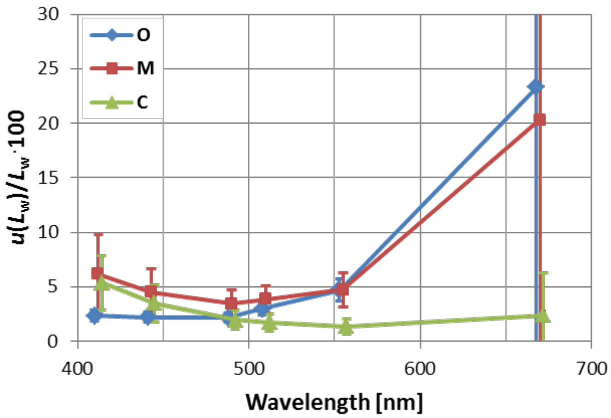

Figure 15: Relative uncertainties $u(L_w)/L_w$ determined assuming a spectrally independent 0.3% uncertainty value for L_T and the mean values of $t_d \cdot L_w/L_T$ for different water types (from Zibordi et al. 2015).

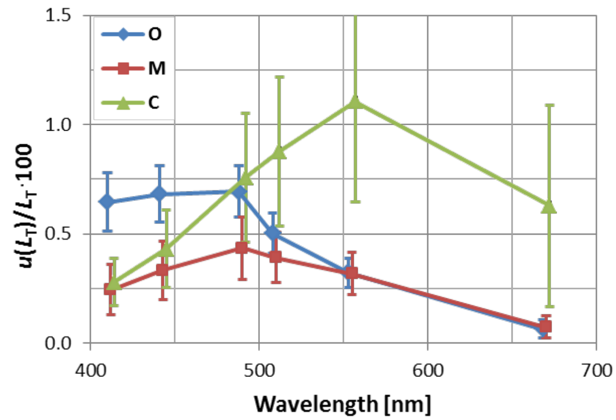

Figure 16: Relative uncertainties $u(L_T)/L_T$ determined assuming a spectrally independent 5% uncertainty value for L_w and the mean values of $t_d \cdot L_w/L_T$ for different water types: oligotrophic (O), mesotrophic (M) and coastal (C). The vertical bars refer to values determined with $t_d \cdot L_w/L_T \pm \sigma$ (from Zibordi et al. 2015).

From Figure 15 and Figure 16, it must be put forward that if vicarious calibration factors determined from independent in situ data sets differ by as low as 0.3%, their application may introduce a bias of the order of the target uncertainty (~5%) on the derived radiometric products. Thus, this bias can be a few times higher than the stability value per decade (expected to be lower than 0.5%) suggested for ocean colour missions devoted to climate change investigations (WMO 2016), and may introduce unwanted inconsistencies in long-term data records from multiple missions. This suggests that in situ data sources for vicarious calibration of satellite ocean colour sensors need to be carefully evaluated accounting for the actual application of data products recognizing that the creation of CDRs imposes the most stringent conditions. In particular, the need to merge data from multiple missions and the requirement to ensure a consistency over time much better than the uncertainty requirement, suggests caution in the application (and interchangeability) of system vicarious calibration coefficients determined from different in situ data sets. Table 1 below provides an example of gain differences on SeaWiFS SVC performed with different datasets.

Table 1: Relative differences (Δg) between g-factors at different wavelengths (adapted from Zibordi et al. 2015).

Data Source	$\Delta g(412)$ [%]	$\Delta g(443)$ [%]	$\Delta g(490)$ [%]	$\Delta g(510)$ [%]	$\Delta g(510)$ [%]	$\Delta g(670)$ [%]
BOUSSOLE	+0.33	-0.03	+0.43	+0.33	+0.14	-0.59
NOMAD	+0.26	+0.03	+0.49	-0.20	-0.04	-0.37
AAOT	+0.55	+0.11	+0.51	-0.05	+0.41	+0.93
HOT-ORM	-0.66	-0.45	-0.39	-0.03	+0.53	-0.11
BATS-ORM	-0.22	-1.11	-1.05	-0.41	+0.23	+0.02

The radiometric stability can be assessed with the Relative Standard Error of the Mean (RSEM) of g-factors. RSEM is determined from Equation 6 with σg the standard deviation of g assumed invariant with time for each considered data source, and Ny the scaled number of match-ups per decade (i.e., $N\text{y}=10 \cdot N/Y$ where N is the number of actual matchups and Y the number of measurement years scaled over a decade, to force the assumption of continuous availability of measurements for each in situ data source) and illustrated for SeaWiFS in Figure 13.

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

Equation 6

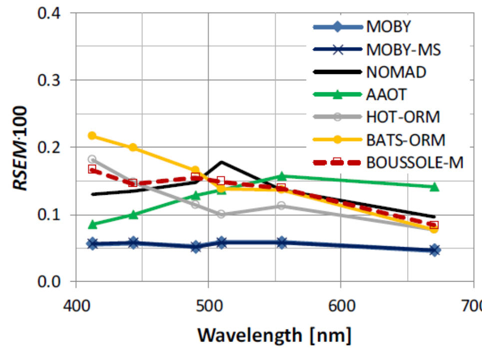

Figure 17: Plot of the standard percent error of the mean (RSEM) for the SeaWiFS g-factors and additionally for MERIS g-factors determined with BOUSSOLE data (i.e., BOUSSOLE-M). (From Zibordi et al. 2015.)

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

- measurement conditions perturbed by temporal changes in the marine and atmospheric optical properties or observation geometry;
- instability of the in situ measurement system when challenged by environmental perturbations during deployments (e.g., bio-fouling) or by variable performance of radiometer systems operated during successive deployments, or even by different measurement methods when considering a combined data set;
- or a relatively small number of matchups.

The RSEM spectra exhibit large differences across the various data sources. The relevance of these differences can be discussed through the 0.5% stability requirement over a decade. This requirement implies (standard) uncertainties lower than 0.05 and 0.025 for g-factors_determined in oligotrophic/mesotrophic waters in the blue and green spectral regions, respectively. The previous standard uncertainties are comparable to the RSEM values determined for MOBY in the blue-green spectral regions during approximately 10 years. Conversely, they are significantly lower than those determined from the other in situ data sources included in the analysis.

These results suggest:

- the use of long-term highly consistent in situ data for SVC to minimize uncertainties in g-factors determined for different satellite missions; and
- the inappropriateness of sole or multiple data sources referred to measurement conditions difficult to reproduce during the time frame of different missions.

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

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

Additionally, Zibordi et al. (2015) have stated that an ideal ocean colour SVC site should meet the following general requirements:

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

Further requirements should include the following points:

- The deployment structure should be highly stable with minimum impact on field measurements. This includes the capability to avoid bio-fouling perturbations on in-water systems;
- In situ radiometer should be preferably hyper-spectral to adapt to any sensor and fully characterized (in terms of linearity, temperature dependence, polarization sensitivity, straylight, ...), exceptionally calibrated (with standard uncertainty lower than 2% traceable to a National Metrology Institute and determined accounting for uncertainty in the source, its transfer and error corrections), highly radiometrically stable (better than 1% per deployment, with target of 0.5%), regularly checked and frequently swapped;
- In situ radiometric data products overall target should combine standard uncertainty of 3% for L_w in the blue-green spectral regions and 4% in the red (benefitting from state-of-the-art data reduction and quality control schemes). Data rate should ensure close matchups with any satellite ocean color mission;
- In situ complementary measurements should include water and atmospheric optical properties;
- The deployment time frame should be continuous and beyond the lifetime of any specific mission.

Finally, the work of Zibordi et al. (2015) recognizes "*that strategies for the construction of CDRs also suggest establishing and maintaining secondary in situ long-term systems with performance equivalent to the main one in terms of data accuracy, precision and measurement conditions. This recommendation is enforced by the fundamental need to allow for redundancy ensuring fault-tolerance to SVC and additionally to provide optimal means for continuous verification and validation of satellite primary data products including the capability to accurately investigate systematic effects induced by different observation conditions (i.e., viewing and illumination geometry, atmosphere and water types)*."

Marine regions relevant for ocean colour system vicarious calibration

G. Zibordi & F. Melin, JRC

The results available in this section are extracted from Zibordi et al., 2017 and Zibordi & Melin (2017).

Zibordi and Mélin (2017) have compared a number of established and potential SVC sites under consideration (Figure 18) based on SeaWiFS time series analysis:

- Established
  - The North Pacific Ocean (NPO) with the Marine Optical Buoy (MOBY) site managed by NOAA (Clark et al. 1997);
  - The Arabian Sea (ASea) with the Kavaratti site managed by ISRO (Shukla et al. 2011);
  - The Ligurian Sea (LSea) with the BOUée pour l'acquiSition d'une Série Optique à Long termE (BOUSSOLE) site managed by LOV (Antoine et al. 2008).

- Potential
  - The Eastern Mediterranean Sea (MSea) near the Island of Crete;
  - The Caribbean Sea (CSea) near Puerto Rico Islands;
  - The North Atlantic Ocean (NAO) near Azores Islands;
  - The Eastern Indian Ocean (EIO) near Rottnest Island off Perth;
  - The Strait of Sicily (SoS) near the Pantelleria Island;
  - The Balearic Sea (BSea) in the proximity of the Balearic Islands.

This study did not consider all potential locations for SVC and therefore does not exclude other candidate areas. The regions considered in this study nonetheless satisfy the needs for:

- nearby islands or coastal locations essential to ensure maintenance services of the offshore SVC infrastructure;
- distance from the coast to minimize adjacency effects in satellite data; and finally
- waters representative of the most common oceanic conditions.

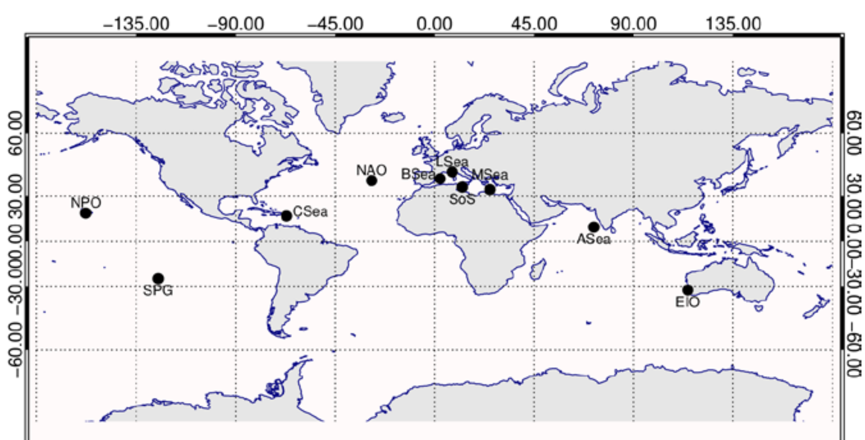

Figure 18: Maritime regions of interest (from Zibordi and Melin, 2017).

Among these sites, Mediterranean sites (Msea and Lsea) demonstrate the highest potential for matchups (Table 2)

Table 2: SeaWiFS Level-2 full-resolution data over a 5-year period (1999-2003): N indicates the number of available observations; M is the number of cases remaining after applying the SeaDAS default exclusion flags; M_{CV} indicates the number of cases that also passed the homogeneity test defined by a variation coefficient CV<0.2 determined from the 5x5 values of R_{rs} at the 443, 490 and 555 nm bands (from Zibordi and Melin, 2017).

	N	M	M vs N [%]	M_{CV}	M_{CV} vs M[%]
NPO	1768	212	12.0	187	88.2
MSea	2472	821	33.2	798	97.2
CSea	2071	242	11.7	218	90.1
ASea	1842	114	6.2	103	90.4
NAO	2796	274	9.8	256	93.4
LSea	3024	873	28.9	827	94.7
EIO	2101	382	18.2	367	96.1

Table 3 summarizes the statistical analysis of marine and atmospheric properties derived from SeaWiFS level-2 time series. NPO site (MOBY) is taken as a reference to assess potential equivalent sites as it presents unique features for SVC.

- MSea, CSea, EIO and SoS are the regions that most compare with NPO in terms of intra-annual stability and mean values of K_d490 and *Chl-a*.
- Looking at the radiometry, $R_{rs}(555)$, CSea and EIO shows lower variability than NPO site while ASea, MSea and SoS shows slightly higher variability.
- In terms of atmospheric properties,
  - NAO, LSea, EIO and BSea show the lowest intra-annual variability of the aerosol optical thickness
  - LSea and MSea show the lowest variability of spectral slope of the aerosol.

Table 3: Mean *m* and standard deviation σ of 5 years SeaWiFS Level-2 data products (*M*) non-flagged by the default SeaDAS exclusion flags: $R_{rs}(555)$ in units of $sr^{-1} \times 10^{-3}$, $k_d(490)$ in units of m^{-1}, *Chl-a* in units of $\mu g\ l^{-1}$, $\tau_a(865)$ and the α dimensionless (from Zibordi and Melin, 2017).

		$R_{rs}(555)$		$k_d(490)$		Chla		$\tau_a(865)$		α	
	M	m	σ	m	σ	m	σ	m	σ	m	σ
NPO	212	1.54	0.29	0.027	0.004	0.07	0.01	0.07	0.04	0.88	0.40
MSea	821	1.51	0.33	0.029	0.006	0.09	0.03	0.08	0.05	1.22	0.41
CSea	242	1.54	0.23	0.033	0.009	0.13	0.07	0.08	0.05	0.69	0.42
ASea	114	1.62	0.30	0.043	0.011	0.19	0.11	0.11	0.05	1.14	0.29
NAO	274	1.68	0.41	0.047	0.020	0.25	0.22	0.06	0.04	1.09	0.45
LSea	873	1.65	0.41	0.051	0.020	0.28	0.23	0.07	0.04	1.45	0.37
EIO	382	1.53	0.25	0.036	0.008	0.15	0.05	0.05	0.03	0.76	0.55
SoS	722	1.49	0.35	0.037	0.010	0.17	0.09	0.09	0.05	1.10	0.42
BSea	794	1.57	0.37	0.043	0.012	0.20	0.11	0.08	0.04	1.29	0.42

Zibordi and Melin (2017) have stated that the identification of new SVC sites should privilege equivalence of measurement conditions across marine regions in order to minimize differences in vicarious calibration gains regardless of the geographic location of the SVC site. The above tables show that none of the analysed potential locations match NPOs performances for all parameters. The identification of multiple SVC sites may imply trading-off criteria related to the marine/atmospheric properties.

The Table 4 below presents the number of potential matchups as derived from SeaWiFS level-2 observations after the application of the following filtering criteria:

- SeaDAS Level-2 default exclusion flags and passing the spatial homogeneity (M_{CV} values of Table 2).
- *Chl-a*≤0.1 μg l^{-1},
- *Chl-a*≤0.2 μg l^{-1},
- τ_a(865) ≤0.10
- τ_a(865) ≤0.15
- α≤1.0.

M_{Q1} indicates the number of potential high quality matchups identified through the application of combined tests on *Chl-a*≤0.1 μg l^{-1}, τ_a(865) ≤0.1 and α≤1.0 (M_{Q1}/year is the related number of potential high quality matchups per year).

M_{Q2} indicates results from the application of combined tests with *Chl-a*≤0.2 μg l^{-1}, τ_a(865) ≤0.15 and α≤1.0.

Table 4: Potential number of SeaWiFS matchups per sites after the application of filtering criteria (Zibordi and Melin 2017).

	M_{CV}	Chla≤0.1	Chla≤0.2	τ_a(865)≤.1	τ_a(865)≤0.15	α≤1.0	M_{Q1}(M_{Q1}/yr)	M_{Q2}(M_{Q2}/yr)
NPO	187	182	187	153	177	107	75 (15.0)	98 (19.6)
MSea	798	572	794	570	714	212	59 (11.8)	147 (29.4)
CSea	218	79	197	164	195	172	48 (9.6)	141 (28.2)
ASea	103	0	80	37	83	21	0 (0.0)	13 (2.6)
NAO	256	3	156	219	246	102	1 (0.2)	56 (11.2)
LSea	827	0	400	668	790	87	0 (0.0)	36 (7.2)
EIO	367	53	328	337	363	235	42 (8.4)	220 (44.0)
SoS	693	140	523	462	598	275	10 (2.0)	135 (27.0)
BSea	735	30	500	556	692	121	4 (0.8)	61 (12.2)

Conclusion:

From the results presented above, Zibordi and Mélin (2017) came to the conclusion that the analysis on potential high quality matchups confirms the superior location of the MOBY site in the northern Pacific Ocean for SVC. While recognizing that no site is superior for all criteria reviewed in the analysis, it nonetheless suggests that the Eastern Mediterranean Sea near the Island of Crete exhibits best equivalence with NPO and could be considered a suitable choice for a European SVC complying with requirements for the creation of CDRs.

When considering criteria less strict than those leading to best equivalence between NPO and MSea, the Eastern Indian Ocean region near Rottnest Island appears an excellent candidate for SVC. EIO also offers the unique advantage of being located in the southern hemisphere, which implies solar zenith cycles opposite to those characterizing SVC sites located in the northern hemisphere. Definitively, the existence of two sites operated in the two hemispheres would provide seasonal alternatives to SVC of satellite sensors heavily affected by glint perturbations.

It is further restated that the full analysis summarized above and the related conclusions, are strictly based on the assumption of MOBY (both region and radiometry) as the "ideal model" for SVC as a result of its demonstrated capability to deliver high precision g-factors with current atmospheric correction codes (see Zibordi et al. 2015).

The suggestion of alternative SVC sites based on selection criteria less strict than those applied in Zibordi and Mélin (2017) is definitively workable, but it would imply the need to demonstrate their suitability to meet the uncertainties required for g-factors devoted to support climate applications.

Spectral resolution requirements for ocean colour system vicarious calibration

G. Zibordi[1], M. Talone[1], K. Voss[2] & B. C. Johnson[3]

The results presented in this talk have been extracted from Zibordi et al., 2017, Johnson et al. 2007 and Flora et al., 2006.

The work aims at evaluating the impact of spectral resolution of in situ radiometric data in the determination of R_{RS} at bands representative of ocean colour sensors: OLCI and PACE. PACE-like bands have been ideally defined assuming 5 nm bandwidth, Gaussian spectral response functions, and 5 nm spectral sampling intervals. This solution leads to an oversampling of R_{RS} spectra with respect to the future PACE capabilities. The analysis is restricted to the 380–700 nm spectral region and relies on in situ reference R_{RS} from MOBY with a bandwidth $\Delta\lambda_B$ of 1 nm and a spectral sampling interval $\Delta\lambda_C$ of ~0.6 nm.

MOBY full resolution reference spectra have been applied to compute "exact" satellite R_{RS} for both OLCI and PACE-like bands, and additionally, to compute reduced resolution R_{RS} for ideal in situ multispectral and hyperspectral radiometers characterized by Gaussian spectral response, various bandwidths $\Delta\lambda_B$ and (for hyperspectral data only) different sampling intervals $\Delta\lambda_C$.

These in situ reduced resolution spectra have then been used to determine "equivalent" satellite R_{RS}. Percent differences ε between "equivalent" and "exact" R_{RS} determined for OLCI or PACE-like bands from reduced and full resolution in situ spectra, respectively, allow drawing conclusions on spectral resolution requirements for in situ radiometry supporting SVC.

$$\epsilon(k) = 100\frac{R_{RS}^{Equiv}(k)-R_{RS}^{Exact}(k)}{R_{RS}^{Exact}(k)}$$

Equation 7

Assuming a percent difference $\varepsilon < 0.5\%$ in the blue-green spectral regions between "exact" and "equivalent" R_{RS} from full and reduced resolution spectra, requirements can be determined for the spectral resolution of in situ radiometric measurements satisfying uncertainty and stability needs for SVC.

The following conclusions for SVC applications are drawn relying on R_{RS} with a spectral sampling interval close or lower than half the spectral resolution (i.e., $\Delta\lambda_C \lesssim \Delta\lambda_B/2$) for in situ hyperspectral radiometers:

- A spectral resolution better than 3 nm is required to support multispectral satellite sensors (such as OLCI);
- A spectral resolution better than 1 nm is desired to support hyperspectral satellite sensors (such as PACE).

A lower ε would imply more stringent requirements on spectral resolution of the in situ hyperspectral sensors. Additionally, the use of L_W instead of R_{RS}, also increases requirements ultimately indicating the need for sub-nanometre resolutions in the blue spectral region for hyperspectral satellite sensors such as PACE.

Requirements for Copernicus ocean colour vicarious calibration infrastructure

Constant Mazeran[1], Carsten Brockmann[2], Kevin Ruddick[3], Ken Voss[4], Francis Zagolski[1], Ewa Kwiatkowska[5]. [1] Solvo, [2] brockmann Consult, [3]MUMM, [4]University if Miami, [5]Eumetsat.

EUMETSAT is leading a project whose objective is to write a requirement document that can be used as a traceable reference for the development and operation of an OC-VCAL infrastructure, in the Copernicus Programme. The requirement document will account for the following points:

- Required quality in OCR, physics of SVC, international background;
- SI-traceability & uncertainty budget;
- Link with Space sensor calibration, methodology, required quantities;
- Radiometer, platform, measurements, environmental conditions, ... ;
- QC, post-processing, match-ups, ... ;
- Field operation & maintenance, ground segment, access, human aspects, ... ;
- The way towards a European programme.

A fundamental aspect of the project is that the requirements on OC-VCAL infrastructure are driven by the uncertainty budgets of the vicarious gains rather than the application. The analyses are based on existing infrastructure.

At the time of this workshop, the overall uncertainty budget is established. About 40 requirements have been defined. The main issue identified through the project at this stage is that some historical requirements of OCR are not always well defined or justified (red bands, coastal waters ...). OC-VCAL requirements documents will be publically available in the second half of 2017.

Both the present workshop's conclusions and OC-VCAL requirements documents will be presented to the European Commission to advocate for the development of a European SVC infrastructure. If the EC agrees to go forward, then the European Environment Agency (EEA) which is in charge of the Copernicus in situ component will go further following the conclusion and recommendations from the community.

Session 5& 6: Approaches from existing fiducial reference measurements

Throughout the ENVISAT era, instances responsible for MERIS CalVal, namely MERIS Quality Working Group and MERIS Validation Team have mainly relied on BOUSSOLE, MOBY and AERONET-OC data. Although tested with AERONET-OC data, practical implementation of SVC has only relied on BOUSSOLE and MOBY data. BOUSSOLE and MOBY are indeed the historical underwater radiometric systems in operation for more than a decade and provide high quality fiducial reference measurements for both data validation and SVC.

For the time being, operational OLCI CalVal performed by the S3-Mission Performance Centre, relies on BOUSSOLE, MOBY and AERONET-OC data. It is worth pointing out that AERONET-OC has increased in the last decade with 20 operational stations and represents up to 80% of in situ data used for validation. AERONET-OC has proven to be a key source of insitu data for providing near real time fiducial reference measurements.

It is generally accepted that radiometric acquisition for the purpose of system vicarious calibration should be below water systems. The next sections will summarize approaches an on-going evolution of the two reference systems providing SVC grade data quality, namely BOUSSOLE and MOBY.

An overview of the Marine Optical Buoy (MOBY): Past, present and future (Extended Abstract)

K. Voss[1], C. Johnson[2], M. Yarbrough[3], Art Gleason[1], S. Flora[3], M. Feinholz[3], D. Peters[3], T. Houlihan[3], S. Mundell[3], S. Yarbrough[3]. [1] University of Miami, [2] NIST, [3] Moss Landing Marine Laboratories,

This talk provided an overview of the MOBY project and the work we are doing now to move the MOBY instrumentation forward into the future. This is the first of 4 talks we gave at this workshop on various aspects of the MOBY project.

1) Description of MOBY and why it is in Hawaii

MOBY's existence grew out of Dennis Clark's experiences in vicariously calibrating the Coastal Zone Color Scanner (CZCS) in the late 1970's. In the initial work for this, 61 days of ship time on 3 cruises and 55 stations resulted in only 9 stations suitable for vicarious calibration. Dennis realized that an autonomous buoy was required to do this calibration correctly, particular if merging multiple satellite missions was required.

The requirements for a site for this buoy were clear sky, clean atmosphere, reasonably horizontally homogeneous waters, and logistic accessibility (but also remote enough to avoid vandalism). It was also desirable to have cell phone coverage for good communication and large data volume transfers. The site chosen was off of the island of Lanai, Hawaii. This site had all the requirements, including access to ships from the University of Hawaii Marine Center.

The MOBY buoy is moored in 1200 m of water with a slack line mooring. The buoy itself is approximately 15 m long, with arms to measure upwelling radiance and downwelling irradiance at 1 m, 5 m, and 9 m depth. The optical system in the heritage MOBY is called MOS, and is held in a container at the bottom of MOBY to maintain a relatively constant temperature environment. At the top of the buoy are solar panels, to allow autonomous operation, an Argos transmitter, cell phone modem, and the computer control system. The Marine Optical System (MOS) consists of two reflective holographic gratings, one to handle blue wavelengths and one to handle red wavelengths. The system also includes blue and red LED reference sources and an incandescent lamp reference source. The optical system is hyperspectral with 0.6-0.9 nm spacing of the individual channels and 0.8-1 nm full width half-maximum (FWHM) spectral resolution.

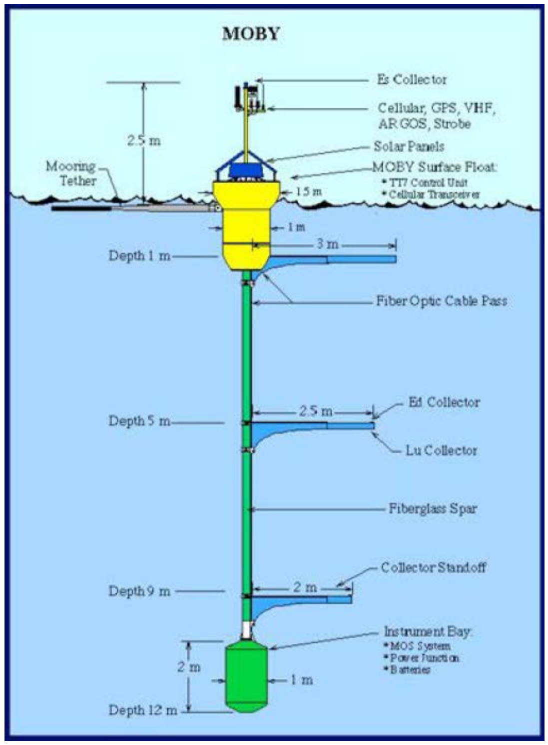

Figure 19: Cartoon illustration of the MOBY buoy.

2) The difference between MOBY/MOBY-Refresh/MOBY-Net

The new optical system on MOBY-Refresh (supported by the National Oceanic and Atmospheric Administration, NOAA) and MOBY-Net (supported by the National Aeronautics and Space Administration, NASA) will have dual in-line volume phase holographic gratings that allows simultaneous spectra at the different arms to be acquired. We have already acquired sample field data with the new blue spectrograph systems. For MOBY-Net, which is meant to be a system operated remotely from our Hawaii site, we have designed a new carbon fiber structure which will allow the optical system to be installed and removed from the buoy structure without disassembly of the optical system. By shipping the optical system intact back to the central MOBY calibration facility, this allows a remote site to maintain a common calibration with the Hawaii buoy. In addition, we are testing out a stability source and monitor which will travel with the MOBY buoy to verify the performance of the MOBY-Net optical system before and after deployment.

3) The MOBY operational program

In this talk we also gave some information on the current MOBY operational program. Currently we have two buoys that are deployed alternately in 4-month intervals. When an instrument is recovered from the field we fully calibrate it (post-deployment calibration), repair as necessary, and calibrate it for the next deployment (pre-calibration). 3 sets of data are obtained each day, and data is downloaded from the buoy daily and sent to the processing center in California. There the data is inspected, and auxiliary Geostationary Operational Environmental Satellite (GOES) images are also inspected to look for cloud free conditions. After the data is processed it is posted to the NOAA Coastwatch site, usually within 1-2 days. After the deployment ends the post-calibration is performed and a comparison is made between the pre- and post-calibrations. Depending on the individual deployment characteristics the information from both pre- and post-calibrations are used to inform reprocessing of that deployments calibration. A final scheduled reprocessing is done when the calibration lamps are recalibrated at the National Institute of Standards and Technology (NIST) after a certain number of hours (detailed in the second MOBY talk by Carol Johnson).

The normal measurement sequence for a MOBY acquisition consists of 5 samples each of the in-water optical measurements (downwelling irradiance, E_d, or upwelling radiance, L_u) with 3 samples of the downwelling surface irradiance before and after the in-water measurement. Dark images at appropriate integration times are taken before and after each sequence or set of optical measurements. Typically three measurements are obtained per day, associated with different satellite missions.

The normal MOBY products are the hyperspectral water leaving radiance, L_w, and normalized water leaving radiance, L_{wn}, using different arm measurements and arm pairs to derive the diffuse upwelling radiance attenuation coefficient, KL. The normal version of these products is L_{w1}, and L_{wn1}, which uses the top arm L_u, and KL derived from the top and middle arm. Another version, L_{w2} and L_{wn2}, uses the top arm, and KL derived from the top and bottom arm. The final version is L_{w7} and L_{wn7}, which uses the mid arm, and the KL derived from the mid and bottom arm. There is an associated product L_{w21}, L_{w22}, L_{w27}, L_{wn21}, L_{wn22}, and L_{wn27} which uses radiative transfer models to improve the product for wavelengths above 575 nm, where Raman scattering interferes with the derived KL. Associated with each of these hyperspectral products are products for each satellite program which integrate the hyperspectral data over the specific satellite bandpass.

The rest of the MOBY project, along with MOBY-Refresh and MOBY-Net, will be described in later talks.

Overview of BOUSSOLE (buoy for the acquisition of long-term optical time series)

FRM4SOC Workshop, Feb 21 – 23, 2017, Frascati, Italy

David Antoine and Vincenzo Vellucci (LOV)

The objective of this section is to provide a general overview of BOUSSOLE:

- the objective for which it has been designed;
- the description of the site;
- a presentation of the rationale for the choice of the site and instrumentation ;
- an overview of the operational aspects.

BOUSSOLE objectives

The main purpose of BOUSSOLE is to establish a long-term time series of optical properties (IOPs and AOPs) with two parallel objectives:

- A scientific research objective: documentation of IOPs and AOPs and understanding of long and short term bio-optical changes;
- An operational objective for the provision of data for vicarious calibration of ocean colour satellite observations and validation of level-2 geophysical products like the chlorophyll content and optical properties.

Site description

BOUSSOLE is located in the Ligurian Sea, 32 nm offshore from the coast where the LOV facilities are set up, in waters of 2440 m depth (Figure 20). The mooring is at the centre of an anti-cyclonic circulation with oceanic currents generally lower that 10 cm.s^{-1} and swells lower than 5 m.

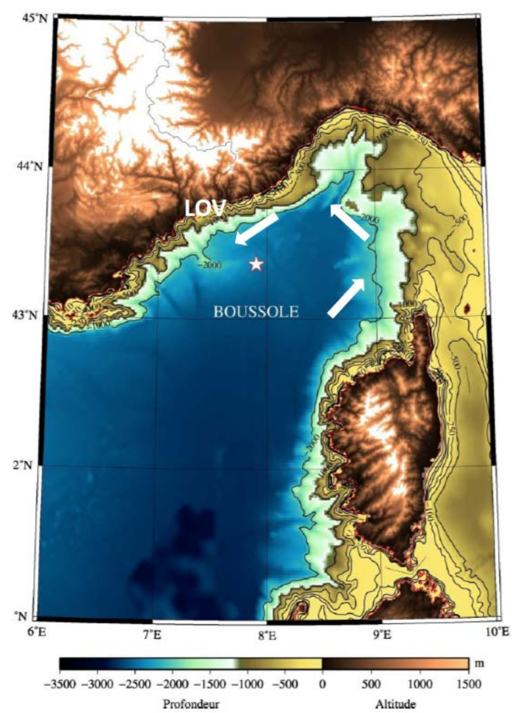

Figure 20: Location of the BOUSSOLE buoy.

Rationale

The characteristics of the atmosphere over BOUSSOLE are close to pure oceanic conditions with very low aerosol optical thickness. The cloudiness is also very low with the highest number of potential matchups as presented in Zibordi & Melin's presentation (Table 2). The site episodically experiences dust deposition events, which are easily identifiable and can be accordingly eliminated from further analyses

In terms of oceanic characteristics, BOUSSOLE is located in case 1 waters, with the Ligurian current acting as a barrier to coastal advection. Conditions are mainly oligotrophic but present a strong seasonal cycle with a range of optical properties that are representative of global case 1 waters (Figure 21). The spatial homogeneity of waters at BOUSSOLE is higher during the oligotrophic season.

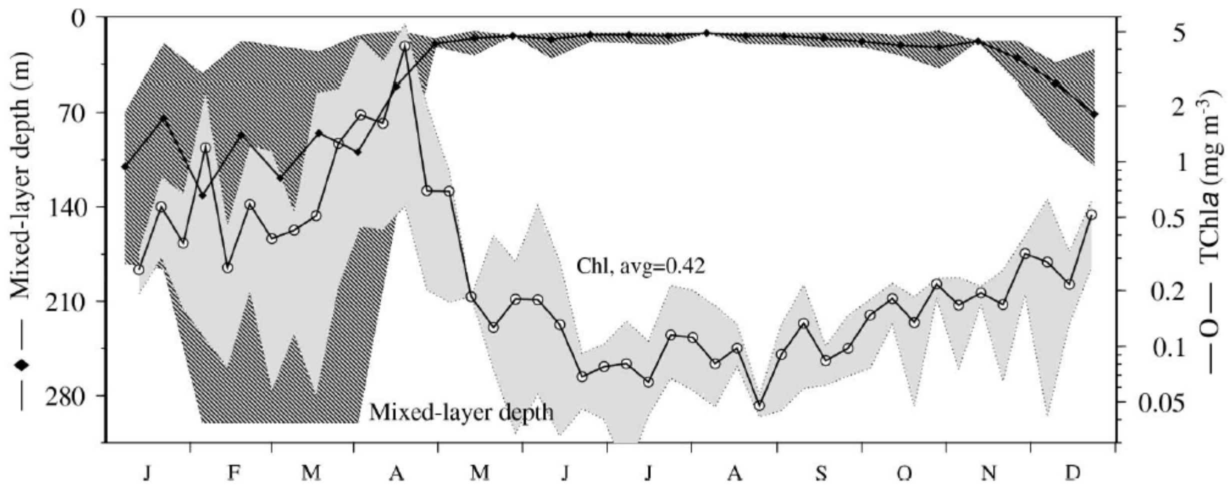

Figure 21: BOUSSOLE seasonal cycle.

The BOUSSOLE buoy superstructure has been specifically designed to minimize shading, maximize stability (minimum grip to swell and currents) so to optimize in-water radiometric observations. The solution resulted in:

- A taut mooring (reversed pendulum) with Archimedes thrust provided by a large sphere at a depth out of the effect of most swells (-17 m);
- A transparent-to-swell tubular superstructure;
- A neutrally buoyant cable;
- No large body at surface;
- Arms for hosting radiometers away from the main structure .

As a result of its design, BOUSSOLE is able to remain fairly stable and therefore performs reliable radiometric measurements (Figure 22).

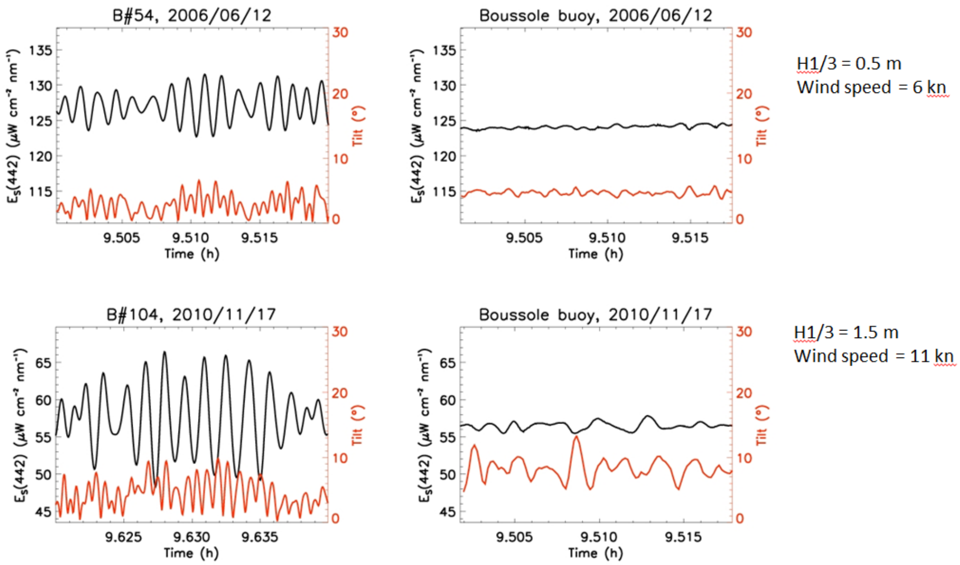

Figure 22: Examples of short (order of minute) contemporary records from ship (left) and buoy (right) surface irradiance at 0.5 m (top) and 1.5 m (bottom) significant wave height (H1/3).

BOUSSOLE uses off the shelf instrumentation. Radiometers are provided by Satlantic Inc:

- 200 series: [7 bands among 412, 443, 490, 510, 555, 560, 665, 670, 683 nm], fixed gain;
- Hyper-OCR series 350:3:800 nm (after 2007), auto integration time;
- PAR (400-700 nm) (after 2007).

And are completed with a set of IOP sensors:

- WET Labs, C-Star (cp, 650 nm, 4 et 9 m) ;
- HobiLabs, HS-IV (442,488,555,620 nm, 9 m);
- WET Labs ECOFLNTUs (fluorescence 470ex/695em, turbidity 700 nm, 4 et 9 m).

Instrument calibration is performed every 6-12 months by manufacturers with NIST traceable standards. In addition, a verification of the cosine response is implemented since 2012 and sensor inter-calibration is performed before each deployment since 2011. Collaboration with NPL has significantly improved sensor characterization from 2013 onward. The buoy is visited on a monthly basis through 3- to 5-day cruises on-board RV *Tethys II* for buoy maintenance, data download, and auxiliary data collection (AOPs and IOPs profiles + HPLC, a_P, CDOM & TSM samples). In addition, 8 to 12 on-demand short cruises per year are performed on ships of opportunity for buoy maintenance, instrument cleaning or troubleshooting.

Operational aspects

Bio-fouling mitigation is ensured with copper tape, plates, rings and shutters in addition to antifouling paints on the upper and lower superstructures. Mechanical cleaning by scuba divers is ensured during bi-monthly visits. The full BOUSSOLE mooring line is rotated every 3 years. In addition to these technical aspects, BOUSSOLE relies heavily on the expertise, efficiency and motivation of about 13 staff working various percentages of their time on the project, ending up with representing about 3.5 full time equivalents.

At this stage, BOUSSOLE cumulates about 20 years of existence with about 15 years of operational data production. In the last 6 years, BOUSSOLE experienced a 94% success rate for data acquisition due to permanent efforts towards improved system reliability, and increased data quality (calibration, characterization, QA/QC in general ...). It represents a unique and highly valuable radiometric, optical and biogeochemical time series as well as a model for how science & operational objectives can come together for mutual benefits. BOUSSOLE is currently the 2nd site for vicarious calibration of satellite ocean colour, along with MOBY. BOUSSOLE is in good standing to continue for the coming decade for the benefit of the Copernicus program and the scientific community, though buoys will soon need some renovation and instruments some refurbishment. Staff stability and number need to be improved as well.

Challenges in calibration of in-situ ocean colour radiometers

Viktor Vabson[1], Andrew Banks[2], Rüdiger Heuermann[3], Ilmar Ansko[1], Joel Kuusk[1], Riho Vendt[1], Anu Reinart[1], Agnieszka Bialek[2], Claire Greenwell[2], and Barry Scott[2]. [1] Tartu Observatory, [2] National Physical Laboratory, [3] TriOS Mess- und Datentechnik GmbH.

In radiometry, calibration of in-situ Ocean Colour Radiometers (OCRs) is a rather common routine activity with more than twenty years history. Nevertheless, data analysis of inter-comparison measurements carried out in 2016 between four participants indicates that procedures for measurement, handling of reference and measured data, and uncertainty estimation need further improvement.

In the SIRREX-7 experiments (Hooker et al.,2002), the calibration labs were ranked as primary, secondary, or tertiary based on the difficulty of improving the calibration uncertainty: tertiary labs are much easier to improve than secondary or primary labs. Most important factors determining the uncertainty and showing the rank of the lab are adequate information about reference standards, elaborated procedures for alignment and operation of instruments, and for measurement. Contribution of instruments is certainly significant, but not a key factor, as often labs using similar equipment may belong to different ranks. For improvement of measurement uncertainty, it is advisable to handle uncertainty components in the order of decreasing importance (Bernhard, G. and G. Seckmeyer, 1999):

1. Calibration of lamps and diffusing plaques, and ageing effects of lamps and plaques;
2. Operation of lamps: accuracy of lamp current;
3. Distance and alignment: lamp – plaque – radiometer;
4. Corrections: linearity, ambient temperature, stray light.

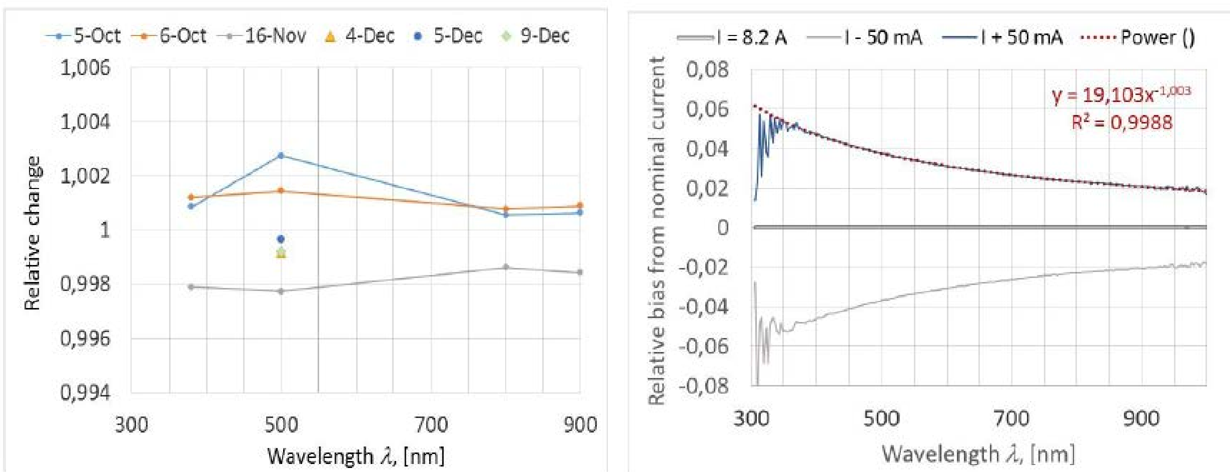

Figure 23: Relative change of the photocurrent of a filter radiometer monitoring the FEL left; effect of lamp current offset right.

Lamp ageing: the irradiance produced by standard lamps changes with burning time (Bernhard & Seckmeyer, 1999; Ohno & Jackson, 1995; Hartmann, 2001; Harrison et al., 2000). The drift of the new FEL lamps pre-aged and pre-selected before calibration, is less than 0.01 %/h, but unpredictable stepwise changes may occur. Thus, a regular check is advisable including a monitor radiometer used concurrently with the lamp, analysis of the calibration history, using at least two lamps for each sensor calibration, and regular stability check of lamps with filter radiometers. The most effective method for revealing a drift is a regular check of the lamps with a filter radiometer. Advantages of the method: recorded data are well suited to uncertainty evaluation; stability of the filter radiometer serves as a good reference for a lamp; alignment of the measurement system is quite simple. Relative change of the photocurrent of a filter radiometer monitoring the FEL at TO during three months in 2016 is shown in Figure 23 (left).

The accuracy of lamp current is the most important operational parameter of the standard lamp (Bernhard & Seckmeyer, 1999; Kostkowski, 1997). As recorded at TO, a 1 % change in lamp current leads to a 10 % change in irradiance at 300 nm. Inversely proportional dependence of uncertainty of the lamp current as a function of wavelength is evident (Figure 23, right). Lamp ageing may show similar features, because one of the major effects of ageing is an increase of resistance of the tungsten filament with working time.

Plaque calibration and ageing: few metrology institutes are calibrating bidirectional reflectance factor R (0°/45°) of plaques needed for radiance calibrations. Comparison of measured values of the bidirectional reflectance factor R (0°/45°) with directional-hemispherical spectral reflectance ρ (6°/H) for pressed PTFE, gave in the spectral interval from 400 nm to 1600 nm, for the ratio $R(0°/45°)/\rho(6°/\mathrm{H})$ values between 1.02 and 1.025 (Johnson et al. 2014, Yoon et al., 2009, Nadal & Barnes 1999). Therefore, correction for directional-hemispherical spectral reflectance R (6°/H) usually specified in certificates provided by manufacturers to obtain bidirectional reflectance factor is indispensable. Regular recalibration of hemispherical spectral reflectance is advisable for the monitoring of ageing effects, as the difference between the bidirectional reflectance factor and hemispherical spectral reflectance is not likely to be dependent on ageing, and calibration of hemispherical spectral reflectance is much more easily accessible.

Non-linearity correction: responsivity spectra of a radiometer from data obtained with different integration times may vary by several percent. As recorded at TO, responsivity spectra of some radiometers vary in a predictable way: the smaller the integration time the larger the particular spectrum and size of the effect is proportional to the integration time. If at least two such spectra measured with different integration times are available, spectrum $S_{1,2}(\lambda)$ corrected for non-linearity can be calculated by using the following formula:

$$S_{1,2}(\lambda) = \left[1 - \left(\frac{S_2(\lambda)}{S_1(\lambda)} - 1\right)\left(\frac{1}{t_2/t_1 - 1}\right)\right] S_1(\lambda).$$

Equation 8

Here $S_1(\lambda)$ and $S_2(\lambda)$are the initial spectra measured with integration times t_1 and t_2. Minimal ratio usually is $t_1/t_2 = 2$, but it may be also 4, 8, 16, etc. By using the two-spectra correction formula in the case of sensors with a systematic effect, nonlinearity can be corrected to 0.1 %, see Figure 24 left. By applying instead an average correction as a function of signal amplitude to the same sensors, the non-linearity correction to 0.3...0.6 % will be possible (Figure 24, right). Nevertheless, non-linearity effect of a random nature peculiar to some types of radiometers cannot be corrected at all, and consequently calibration uncertainty should be significantly increased.

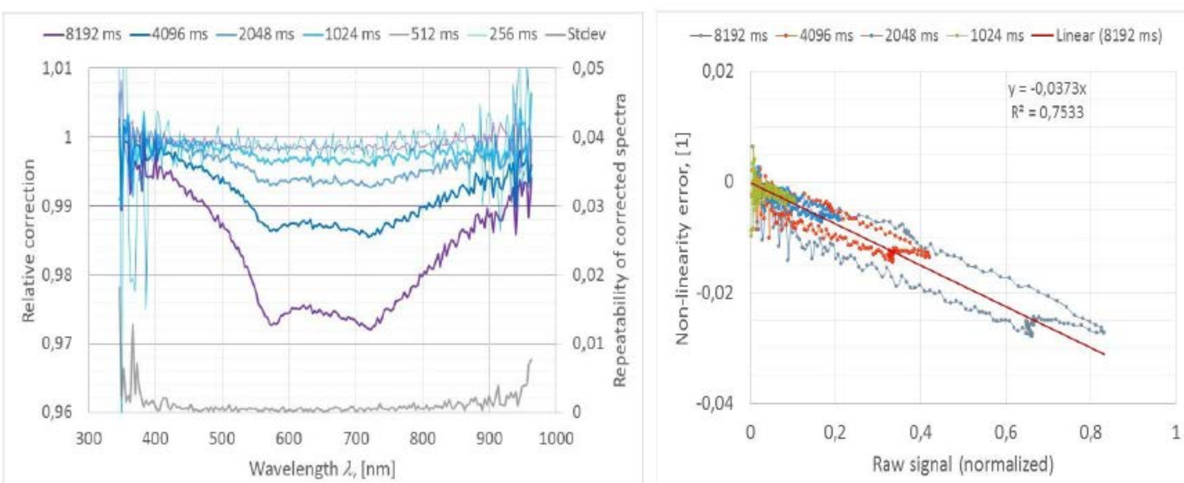

Figure 24: Non-linearity effect as a function of integration time; size of effect and effectiveness of correction left, dependence on the recorded signal amplitude right.

Alignment and temperature effects: at least three effects are present in data measured after repeated alignment of the sensor, i.e. repeatability of alignment, variations due to instability, and variations due to temperature effects (see Figure 25 left for radiance and right for an irradiance sensor). From repeated alignment data of TriOS Ramses sensors, uncertainty due to temperature effects as a function of wavelength for lab conditions (21±1.5) °C can also be modelled.

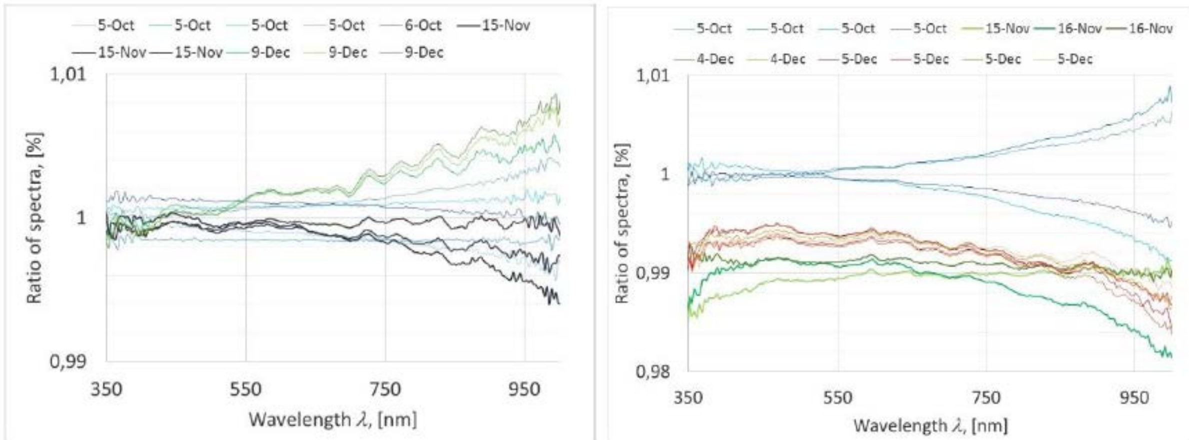

Figure 25: Alignment, non-stability and temperature effects from repeated measurements; radiance sensor left, irradiance sensor right.

Relative combined standard uncertainty for calibration of radiometric sensors and a number of respective input components have been evaluated at TO, see Figure 26 left. Combined standard uncertainty includes a number of components, which may also include sub-components:

1. Standard lamp: uncertainty specified on the calibration certificate, interpolation between certified values, lamp ageing, current shunt, lamp current deviation from nominal value;
2. Diffuse reflection plaque: uncertainty on the calibration certificate, interpolation between certified values, bidirectional correction if needed;
3. Alignments: Distance – deviation from specification, reproducibility of alignments (lamp, plaque, sensor);
4. Random effects from repeatability of spectra, and dark signal;
5. Corrections: for non-linearity, for temperature, for stray light.

Comparison of the combined standard uncertainty of TO with the uncertainties of other participants of intercomparison carried out in 2016 is shown in Figure 26 right.

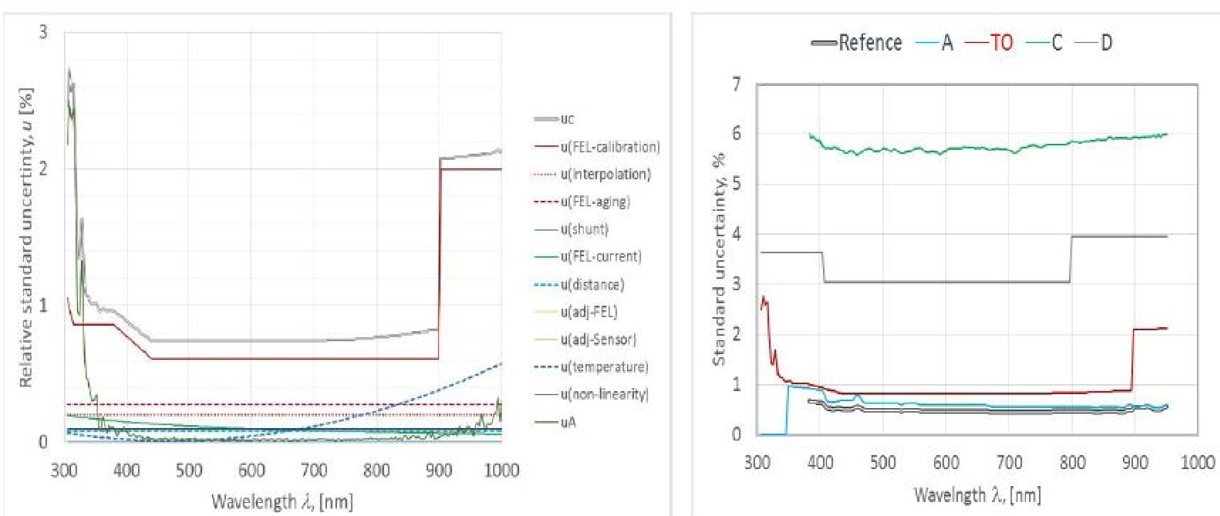

Figure 26: Relative standard uncertainty for calibration of radiance sensors; with uncertainty components evaluated at TO left, uncertainties stated by participants during inter-comparison of radiometers right.

Comparison measurements between four participants - Tartu Observatory (TO), Estonia, Joint Research Centre (JRC), EC, National Physical Laboratory (NPL), UK, and TriOS GmbH, Germany - have been carried out in September – November 2016. The purpose of the inter-comparison was confirmation of participant's measurement capabilities for the calibration of field radiometers, revealing differences in methodology and interpretation of results. As comparison instruments, two hyperspectral radiometers respectively for irradiance and radiance measurement in the spectral range of 320 to 950 nm were used. Satisfactory agreement of results reported by TO with the comparison reference values was demonstrated. Measurement uncertainties stated by the participants were suitably small for confirmation of the calibration and measurement capability stated by the optical lab of TO. Comparison results as E_n numbers are shown in Figure 27, left for the responsivity of the radiance sensor, and right for the responsivity of the irradiance sensor. Agreement is considered satisfactory if $E_n < 1$, and unsatisfactory for $E_n > 1.5$.

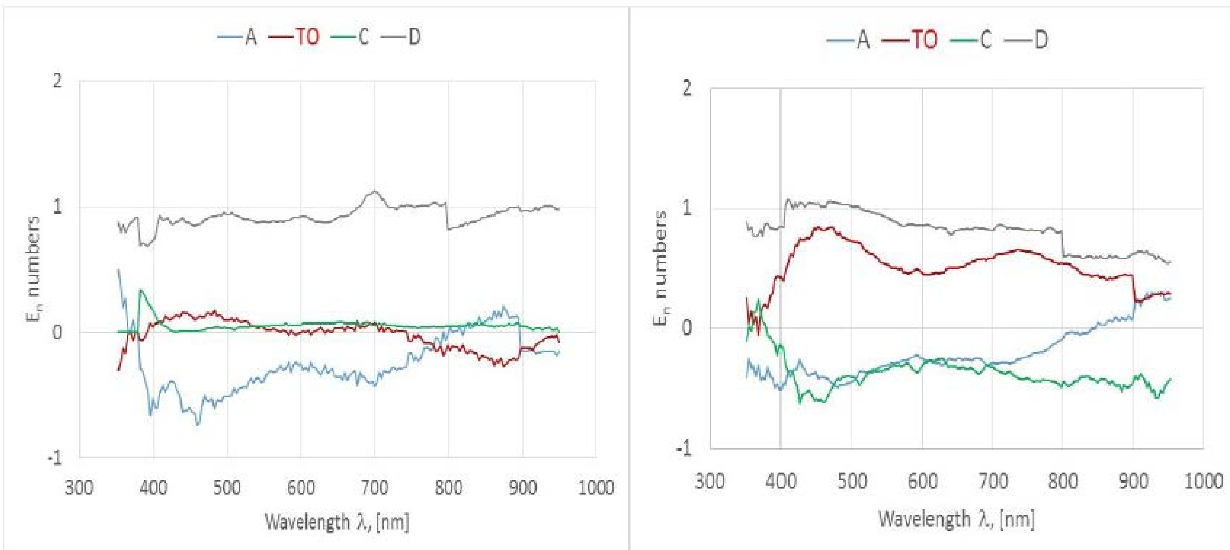

Figure 27: Agreement with the reference value by using E_n numbers; radiance sensor left, irradiance sensor right.

We have treated the sources of uncertainty in radiometric calibration in the order of decreasing importance. Uncertainty components include calibration of lamp and ageing, calibration of plaque and ageing; operation of lamps; distance measurement and alignment of lamp – plaque – radiometer system; estimation and use of corrections for non-linearity, ambient temperature, stray light. Radiometric calibration with standard uncertainty close to 1% is possible only if all significant biases are effectively corrected, and uncertainty sources carefully handled.

MOBY radiometric calibration and associated uncertainties

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The values of the MOBY radiometric retrievals of spectral radiance (L_u) and spectral irradiance (E_d, E_s) are traceable to NIST reference standards via Moss Landing Marine Labs (MLML) integrating sphere sources and MLML lamp standards of spectral irradiance (Clark et al. 2002). The complete paradigm is illustrated in Figure 28.

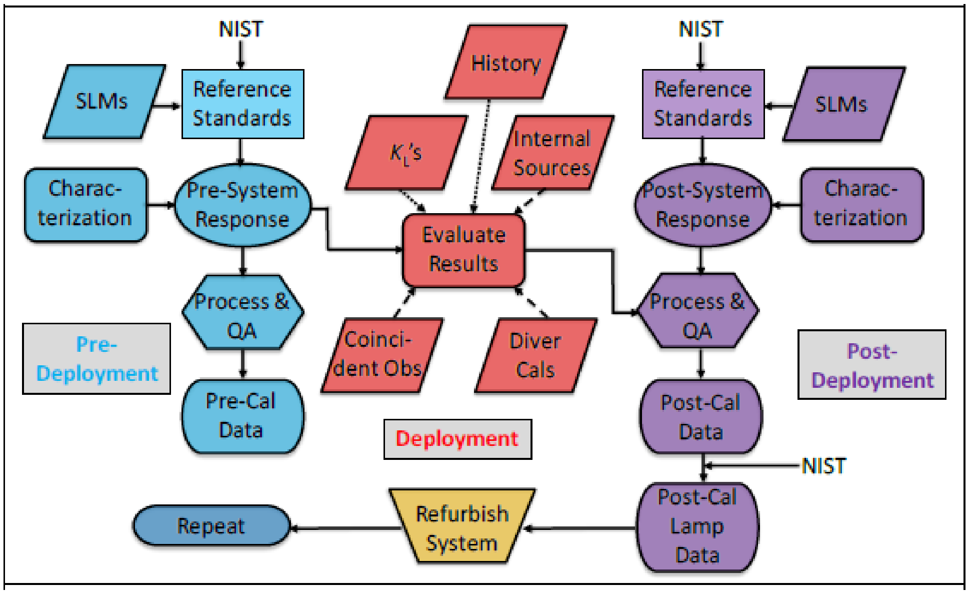

Figure 28: MOBY Radiometric procedures produce values traceable to NIST and generate levels of redundancy as part of the quality assurance program.

The blue, red, and, purple boxes represent activities performed pre-, during-, and post-deployment. The reference standards are calibrated at NIST every 50 h of burn time. The FEL lamps are recalibrated and reissued unless there are indications they are starting to drift. The lamps in the sphere sources are changed upon calibration. This results in two calibrations, a beginning of lamp life (BOL) and an end of lamp life (EOL). During operation at MOBY, the reference sources are monitored using the NIST-designed Standard Lamp Monitors (SLMs). The four MOBY E_s and E_d channels and the three arm L_u channels, all of which use fiber optics for coupling light into the spectrographs, are calibrated in the tent. The MOS Lu port is calibrated in the Cal Hut (through buoy M260) or the new laboratory at Pier 35 (from buoy M261 and forwards). Extensive characterizations are performed pre- and post-deployment by M. Feinholz. These include wavelength calibration, verification of stray light response, checks for system partial saturation, integration time normalizations, response to the internal sources, and repeatability. As needed, additional characterizations are performed, for example polarization sensitivity, cosine response, sensitivity of the radiometric responsivity to ambient temperature, full stray light characterization, L_u immersion coefficient, and linearity. The pre-deployment system responsivities are evaluated and delivered to S. Flora for incorporation into the deployment retrievals. During deployments, data are taken with the internal sources with each hour file, and monthly visits by the team include cleaning of the optics and tests with diver calibration lamps before and after the cleanings. During the deployments, the values and consistency of E_s and the three versions of KL (top/mid, top/bottom, mid/bottom) are used, along with the time series, to perform quality control and monitor for exceptions. The stability of the wavelength calibration is monitored using measured positions of Fraunhofer lines. The chromaticity coordinates, spectral purity, and dominant wavelength are calculated using the hyperspectral data and the established CIE functions. These parameters are sensitive to spectral shape and can be an indication of bio-fouling. The magnitude of the "blue/red" offset is monitored as a quality check on the stray light correction. After the buoy is retrieved, it is recalibrated, and re-characterized for wavelength calibration. The post-deployment radiometric responsivities are compared to the pre-deployment values, and, taken together with the presence of any deployment-specific anomalies, final post-deployment responsivities are assigned. When the radiometric reference source is returned to NIST for the EOL calibration, a third system response (which may be the same as the second) is assigned to the individual channels for each deployment corresponding to this BOL/EOL interval.

There are two integrating sphere sources, the OL420 and the OL425. Both have external lamps, barium sulfate interior coatings, the ability to vary the radiance levels without substantial changes to the relative spectral distribution, and exit apertures large enough for entrance pupil of the fibered L_u heads. Lamp current is monitored using a shunt resistor in series with the lamp, and the voltage drop at the lamp is monitored using a four-wire connection at the FEL kinematic lamp base. The OL425 has a photopic monitor photodiode installed to view the interior wall, and the NIST spectral radiance values are scaled by the ratio of the monitor photodiode during use to those during the NIST calibrations. To date, there have been 20 lamps used in the two spheres, for a total of 40 calibrations. The spectral radiance calibrations cover 300 nm to 1000 nm with NIST uncertainties of about 0.6 % k = 2 at 500 nm. Prior to Aug 2002, the spheres were calibrated by Optronic Laboratories. The primary reason for switching to NIST was to obtain lower uncertainties.

1 Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

The irradiance calibrations are performed using a Gamma Scientific 50001 irradiance bench, which has a housing around the 1000 W FEL lamp, a baffle tube, and an end plate that mates to the mechanical surface of the MOBY E_d, E_s heads so the diffuser is 50 cm from the front of the lamp bi-posts. As with the lamps in the spheres, the lamp current and voltage drop are monitored. Ambient temperature and relative humidity are recorded during all radiometric calibrations.

To date, fourteen FEL lamps have been used, some with multiple calibrations at approximately 50 h burn time, for a total of 38 calibrations. The sphere and FEL calibration history spans 25 years.

The two SLMs are filter radiometers, one channel per instrument (Clark et al. 2002). They date from 1996. The foreoptics are interchangeable, one for irradiance with a cosine collector and mechanical design identical to the MOBY heads, and the other with a “Pritchard” design foreoptic. This design provides an alignment axis by mounting a mirror at 45° on the optical axis. A central hole in the turning mirror allows flux to reach the detector while the rest of the mirror provides a view of the source – think of a single lens reflex camera viewfinder where the flip mirror is permanently in place, but it has a central aperture. The SLMs began life with a 412 nm and an 870 nm channel, both using ion-assisted beam deposition filters with out-of-band specified to be OD 6 and full width half-maximum (FWHM) bandpasses of about 10 nm in radiance mode. In August 2004, the E_s heads fell from a table and hit the concrete floor of the tent. As no obvious damage was observed, they were kept in use. In July 2011, the SLMs were refurbished. The 870 nm channel was replaced with a filter at 665 nm. The SLMs are measured for absolute spectral (ir)radiance responsivity on the NIST Spectral Irradiance and Radiance responsivity Calibrations using Uniform Sources (SIRCUS) and validated at NIST using broadband sources. As of January 2017, there have been 421 SLM radiance measurements of the OL420 and the OL425.

As an additional validation of the MOBY radiometric scales, NIST makes routine site visits and deploys independent artifacts. The VXR (Visible Transfer Radiometer) is a six channel filter radiometer with filters from the same lot as the SLM and designed to match the Sea-viewing Wide Field-of-view Sensor and the Moderate Resolution Imaging Spectrometer (SeaWiFS and MODIS) bands (412 nm, 441 nm, 443 nm, 551 nm, 665, and 870 nm) (Johnson et al. 2003). The NPR (NIST Portable Radiance) source is a Spectralon® sphere2 illuminated internally with four 30 W lamps (Brown & Johnson, 2003). Typically, it is calibrated at this bright (land-like) level. There are two monitor photodiodes, one in the visible and the other in the short wave infrared. The NPR was made to travel and is mounted in a shipping container. It is calibrated routinely for spectral radiance at the same NIST facility used for the MLML spheres (FASCAL, Facility for Automated Spectroradiometric Calibrations, Walker et al. 1987). Hence, a field deployment at MOBY is a validation of the reproducibility of the sphere spectral radiance values and the stability of the SLM/OL42x/VXR/NPR systems. To date, 13 trips have been made with the VXR and NPR. Prior to the development of the VXR in 1996, an earlier version, the SeaWiFS Transfer Radiometer (SXR, Johnson et al. 1998) was deployed twice. We are working on a critical compilation of these time series, to both validate the MOBY responsivity time series and to identify and then correct any biases that may be revealed in the process.

[2]Labsphere, Inc., North Sutton, NH, USA.

Starting in Jan 2015, NIST deployed an irradiance bench for the purpose of validating the Gamma 5000 and the MOBY irradiance values. This has been done twice. The first time, we used a commercial photodiode array-based spectrograph from Spectra Evolution fiber-coupled to a MOBY irradiance head, and the second time we used a charge-coupled device based spectrograph, a CAS 140CT-156, from Instrument Systems fiber-coupled to an irradiance collector from the manufacturer.

We have started the VXR/NPR time series critical compilation. The two figures are for measurements of the VXR and NII (a non-traveling sphere, made to the same specifications as NPR) and the VXR and NPR. In each case, the history for one lamp set is illustrated. The blue solid circles represent NIST spectral radiance calibrations of the sphere. These spectral radiance values have been reported at different spectral coverage and with different wavelength sampling over the years. The VXR channel wavelengths for each set of calibration values were determined according to

$$\lambda_i = \frac{\int \lambda L(\lambda) R_i(\lambda) d\lambda}{\int L(\lambda) R_i(\lambda) d\lambda}$$

Equation 9

where L(λ) is the spectral radiance of the NPR or NII, and $R_i(\lambda)$ is the absolute spectral radiance responsivity of the ith VXR channel. Note that this definition holds if only the relative spectral radiance responsivity is known.

It is clear interpolation in wavelength in the spectral radiance values and the spectral responsivity values is necessary. The results to date are based on analytical fits, but investigations are continuing. Interpolation errors can introduce bias for the narrow bands of the VXR.

By identifying the VXR file closest in time to one of the FASCAL calibrations for the sphere's lamp set, the "VXR band-averaged" FASCAL radiances (equal to $L(\lambda i, t)$) and the VXR net signals can be compared by normalizing each set by the corresponding value at the matchup time. The VXR data (red crosses) are consistent with the normalized FASCAL spectral radiances, indicating the VXR's spectral responsivity was stable over this time interval. This time series will be finalized for VXR/NPR, the VXR/NII and also the SLMs/OL42x and the SLMs/FELs.

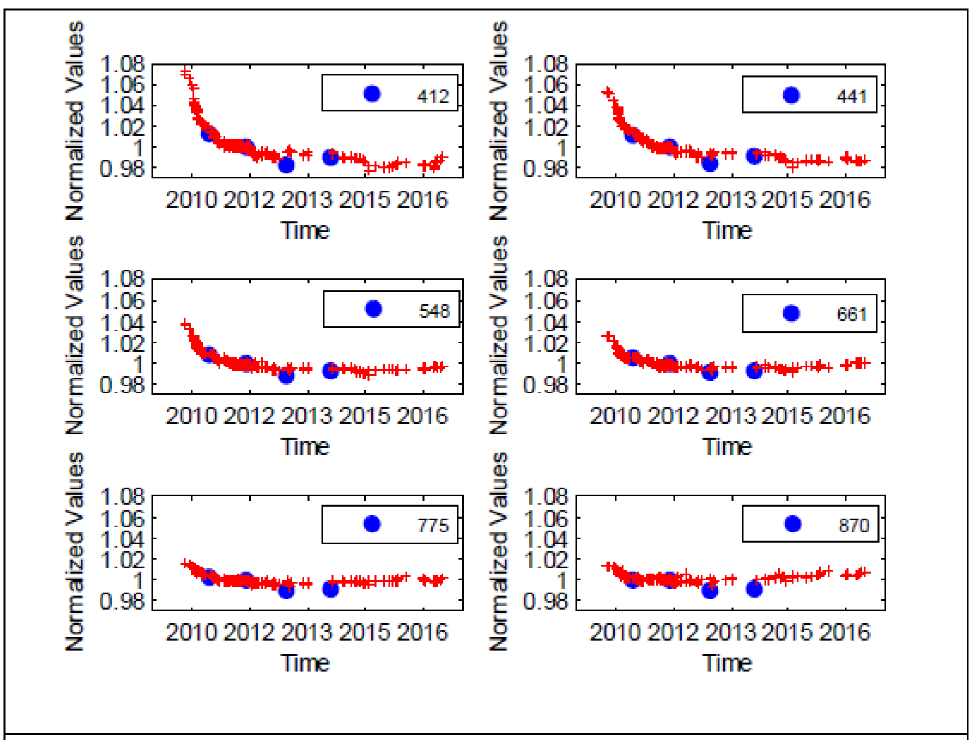

Figure 29: Time series of normalized VXR and FASCAL measurements of the NPR sphere at the VXR spectral bands.

The internal LEDs and incandescent lamp are used during radiometric calibration and every hour file for the deployments. Pre- and post-deployment results are compared to assess reproducibility. Stability during a deployment is evaluated by normalizing to the first reading. In both cases, a range of wavelengths where the LED signal is measurable allows an evaluation of spectral stability. If we look at a time history of LED signals for all deployments for wavelengths near the peak of the LED output as well as the extreme edges, we see discontinuities in the normalized signals. This is attributed to changes in the stray light characteristics of the grating in the spectrographs, and introduces additional uncertainty in the MOBY stray light correction algorithm because laser characterizations were not performed at the beginning of the MOBY project.

Monthly diver trips from Lanai include measurements at a system level with modified commercial dive lamps. The sequence is to measure, clean the optics, and re-measure. For some deployments, readings with the diver lamps were acquired at the start of the deployment. The history of the diver lamps for these deployments shows variability of a few percent with negligible bias, that is, cleaning does not seem to make a difference statistically.

Over the 25 years, various radiometric characterizations have been performed. Camera-dependent (CCD detector) characterizations include dark current, noise, bin factor, and integration time correction factor. Later, full images were studied to sort out issues with partial saturation. The temperature sensitivity of the spectrographs, electronics, and optical multiplexer was measured for one of the systems using a water bath. Numerous full stray light characterizations were performed (Feinholz et al. 1998) and the level of stray light is checked at a few wavelengths for each deployment. Pre- and post-deployment wavelength calibrations are performed, with the process improving over the years by the addition of additional atomic emission lines. The stability of the wavelength calibration is monitored during deployments using Fraunhofer and atmospheric lines. The E_d immersion factor was determined experimentally at the beginning of the MOBY project, and recently the theoretical value for the L_u immersion factor was verified experimentally. Preliminary values for the E_s cosine response were determined initially, with recent experiments providing final values. The polarization sensitivity of the L_u heads on the MOBY arms was measured and resulted in the addition of a depolarizer.

The uncertainty table for L_u and E_s reflect our current understanding. For L_u, the dominant terms reflect the reproducibility of the radiometric calibration as determined by comparing pre- and post-deployment results, the NIST uncertainty in the spectral radiance calibrations, and the temporal drift in the calibration sources. At the ends of the spectral coverage for either spectrograph, the uncertainty in the stray light correction contributes. The story is similar for E_s, except we have added a component to reflect the unusual nature of the FEL operation inside the Gamma 5000 housing. The resulting uncertainties, reported at the VIIRS ocean color bands, are between 2.6 % and 1 %, depending on wavelength and sensor type.

MOBY: quality assurance and quality control (QA/QC) and environmental uncertainties in the final MOBY product

K. Voss[1], C. Johnson[2], M. Yarbrough[3], S. Flora[3], M. Feinholz[3], D. Peters[3], T. Houlihan[3], S. Mundell[3], S. Yarbrough[3], Art Gleason[1]. [1] University of Miami, [2] NIST, [3] Moss Landing Marine Laboratories,

This talk provided an overview of the QA/QC process for MOBY along with an estimate of the environmental uncertainties in the final MOBY product.

1) QA/QC

Before any data is posted on the NOAA Coastwatch site for the MOBY project, it has been processed and undergoes a QA/QC process. This process consists of several steps. The first is to look at corresponding GOES imagery for visual identification of the cloud state (cloud free or cloudy). Looking at the variation in the downwelling irradiance (E_s) measurements during the sequence also helps to identify the state of the sky during measurement. Other checks including looking at the diffuse upwelling radiance measurements, *KL*, derived from the various arm pairs for consistency at wavelengths below 550 nm. Theoretically, with homogeneous water in the upper 9 m, they should be almost exactly the same. These steps typically define whether the data will be good, questionable, or bad.

Other steps done in the processing is to remove, by hand, anomalous data spikes in the spectral scan, and possibly out-of-family individual scans, if obviously problematic. For longer term, the data in the spectral region where the blue and red pictograph overlap is examined and the derived data are compared with the historical time series of measurements, as we now have a 20-year time series.

2) Environmental uncertainty

Sources of environmental uncertainty, the uncertainty coming from factors other than the radiometric calibration, can be found in each of the measured quantities. Light field fluctuations affect both the upwelling radiance measurements, L_u, and *KL*. Polarization sensitivity (if it exists) can affect both L_u and *KL*. Buoy tilt during measurement can cause errors in L_u or *KL* because of variations in the radiance distribution in the upwelling light field, along with changing the measurement depth because of the arms. Index of refraction of seawater variations can affect the immersion factor and the transmission through the air sea surface. Waves can affect the effective measurement depth. We looked at many of these factors and modeled the effect to get an estimate of the uncertainty they introduce into the final L_w product. We detailed one of these, light field fluctuations, but could only list the current estimates for the other factors, based on our current models.

To give an example of these uncertainties, we looked at light field fluctuations in detail. MOBY reduces these through extended integration times for L_u, typically 30-60 seconds. The literature is not extensive on the coefficient of variation (COV) for the upwelling radiance light field. Stramska and Dickey (1998) published some results where they saw a peak in a broad power spectrum at 0.4 Hz and a COV, with 6 Hz sampling time, of 4.5%-13% as for wavelengths from 412 nm to 650 nm. This variation reflects the change in incident light field from the blue, where skylight is a large proportion, to red, where the direct beam is more important.

We also had the results of an experiment in which bursts of 20 measurements of the upwelling radiance were measured. Each measurement had a 4 s integration time, and there was a 7 s gap between measurement bursts. The measured COV in these measurement bursts corresponded well to the data of Stramska and Dickey when the COV was adjusted for the longer integration time and 20 measurements. In this case the COV dropped to approximately 1% for the blue and 2% for the red wavelengths. In the case of operational MOBY measurements, with 60 s integration times and averaging 5 samples, the effect of fluctuations is expected to cause an effect between 0.1% and 0.2% from 412 nm to 650 nm. Looking at the COV between the 5 samples of individual MOBY acquisitions confirms this.

One other source of uncertainty is buoy tilt, but it is important to mention that because of the design of MOBY and its mooring, the tilt is usually small. 75% of the time MOBY has a tilt less than 1.5 degrees, while 90% of the time it is less than 2.5 degrees. So in general, tilt is not a large problem but should be taken into account.

Because of time and space limitations we cannot detail all of the factors, we are currently writing an extended paper on this, but to summarize our current thinking on these factors in Table 5.

Table 5: Because of time and space limitations we cannot detail all of the factors, we are currently writing an extended paper on this, but to summarize our current thinking on these factors.

Immersion uncertainty	0.05%	Driven by index of refraction variations
Fluctuations	0.1 – 0.2 % blue to red	Based on experimental results
Tilt	No correction for tilt< 2 deg: 0.2% BRDF uncertainty. Greater than 2 degrees, corrected result 1% uncertainty	Based on modeling and previous validation work
Polarization	None after August 2016, Before this it depends on wavelength and solar zenith angle	Based on measurements of polarization sensitivity and models.
KL depth error due to tilt	Uncertainty equal to tilt (in degrees) times 0.2%	Based on modeling
KL error due to polarization differences of arms	None after august 2016. Previous top-mid:0.2%. Mid-bottom and top-bottom <1%. Model results provide table	Based on polarization sensitivity and model results.
Air-sea transmittance factor	0.1% due to index of refraction variations, but currently a small bias because of using a constant value of 0.543	Results based on theory and measurements of the salinity at the site.
Depth uncertainty in propagation to the surface	Uncertainty is 0.4%, but wavelength dependent	Based on modeling

An example of combining all of these factors for the case of 2 deg tilt, shows an uncertainty that varies with wavelength and solar zenith angle

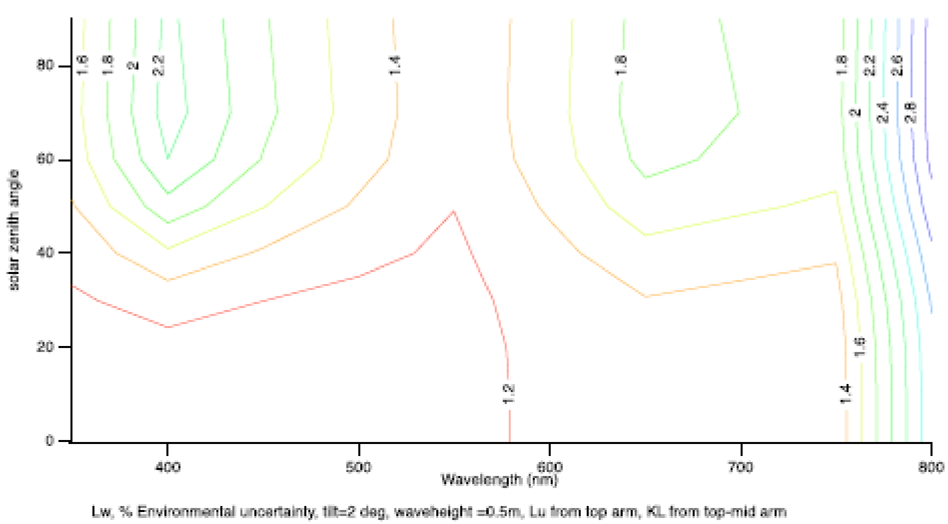

Figure 30: Shows % uncertainty as a function of wavelength and solar zenith angle. Note that the normal reported measurement range for MOBY is currently from 380 nm - 700 nm, and solar zenith angles at the measurement time rarely exceed 55 degrees.

When L_{wn} is the desired quantity, additional factors come into play due to the E_s measurement and its associated uncertainties. Because the E_s cosine collector is not perfect, a correction must be made that has uncertainties associated with it. Even small tilts can cause problems with E_s at larger solar zenith angles. The E_s uncertainties increase the uncertainty in L_{wn} relative to L_w, as shown in the figure below, which is the same case as shown above, but for L_{wn}.

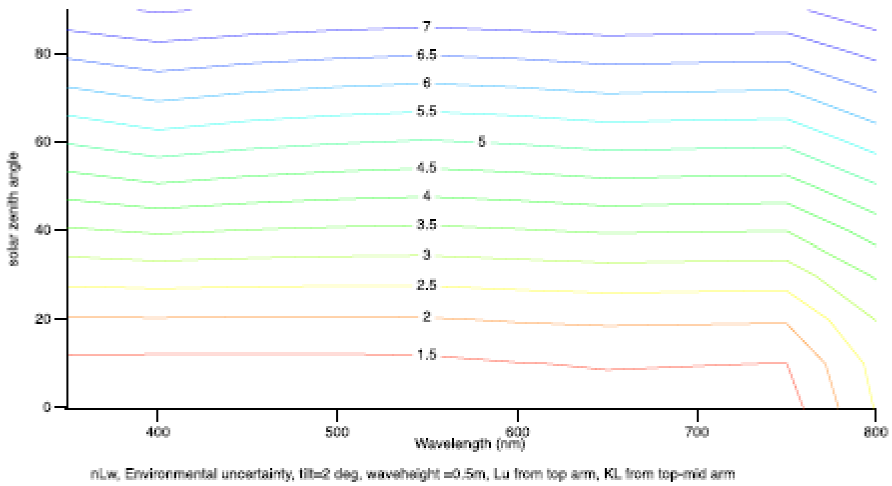

Figure 31: Shows % uncertainty as a function of wavelength and solar zenith angle. Note that the normal reported measurement range for MOBY is currently from 380 nm -700 nm, and solar zenith angles at the measurement time rarely exceed 55 degrees. Still because L_{wn} includes E_s, L_{wn} has increased uncertainty relative to L_w.

In this work, we have not quantified the error due to shadowing. We are still working on this factor, but the time series indicates that shadowing causes a large problem when the arm is within 30 degrees of being pointed directly away from the sun. It also seems to cause a problem on the order of a few percent when the solar zenith angle is less than 10 degrees, but for other geometries shadowing is not significant.

3) Conclusions

Daily QA is important, and requires someone with extended experience consistently looking at the data.

Environmental uncertainty depends on wavelength, solar zenith angle and other environmental factors.

A spectral estimate of the uncertainty should be provided with each data set.

BOUSSOLE data processing

D. Antoine, B. Gentili, E. Leymarie V. Vellucci , LOV

There are three essential steps included in the BOUSSOLE operational data processing:

1. Conversion of raw data into geophysical units
2. Application of correction factors for tilt, depth, shading effect and extrapolation to the surface
3. Quality control and data screening

Conversion to geophysical data

Radiometric raw data from BOUSSOLE are downloaded during monthly servicing cruises with a direct connection on the buoy. Calibration factors applied to raw count measurements are updated every 6 to 12 months after manufacturer (Satlantic) NIST traceable calibration (Equation 10).

$$E_s(t',\lambda)_{Dd} = \left[E_s(t',\lambda)_{Volt} - Dark_{Cal\_Es}(\lambda)\right] \cdot Lin_{Cal\_Es}(\lambda)$$
$$L_u(z',t',\lambda)_{Dd} = \left[L_u(z',t',\lambda)_{Volt} - Dark_{Cal\_Lu(z)}(\lambda)\right] \cdot Lin_{Cal\_Lu(z)}(\lambda) \cdot Imm_{Cal\_Lu(z)}(\lambda)$$
$$E_d(z',t',\lambda)_{Dd} = \left[E_d(z',t',\lambda)_{Volt} - Dark_{Cal\_Ed(z)}(\lambda)\right] \cdot Lin_{Cal\_Ed(z)}(\lambda) \cdot Imm_{Cal\_Ed(z)}(\lambda)$$
$$E_u(z',t',\lambda)_{Dd} = \left[E_u(z',t',\lambda)_{Volt} - Dark_{Cal\_Eu(z)}(\lambda)\right] \cdot Lin_{Cal\_Eu(z)}(\lambda) \cdot Imm_{Cal\_Eu(z)}(\lambda)$$

Equation 10

Up to 2007, BOUSSOLE was solely equipped with multispectral sensors. From 2007 onward hyperspectral instruments have been included as well. In the end, multi-spectral instruments will be abandoned but the objective was to operate both systems in parallel to ensure the continuity and quality of the time series.

In the case of the multi-spectral instruments (no internal shutter), the median value of a 1-minute record is retained as representative of each measurement sequence (Equation 11a). An average dark measurement is calculated from night measurements and subtracted from the day measurements (Equation 11b).

$$\overline{E_s(t,\lambda)_{Dd}} = median\left[E_s(t',\lambda)_{Dd}\right]_{t'=0s}^{60s}$$
$$\overline{L_u(z,t,\lambda)_{Dd}} = median\left[L_u(z',t',\lambda)_{Dd}\right]_{t'=0s}^{60s} \quad \text{(a)}$$

$$\overline{E_s(t,\lambda)'} = \overline{E_s(t,\lambda)_{Dd}} - mean\left[\overline{E_s(t,\lambda)_{Dd}}\right]_{t=22h}^{3h}$$
$$\overline{L_u(z,t,\lambda)'} = \overline{L_u(z,t,\lambda)_{Dd}} - mean\left[\overline{L_u(z,t,\lambda)_{Dd}}\right]_{t=22h}^{3h} \quad \text{(b)}$$

Equation 11

In the case of the hyperspectral instruments (with internal shutter), the mean of two dark measurements acquired before and after each measurement is subtracted from the actual measurement (Equation 12a). The median of each value is then computed as representative of each measurement sequence (Equation 12b).

$$E_s(t',\lambda) = E_s(t',\lambda)_{Dd} - \frac{E_s(t'-1,\lambda)_{Shutter} + E_s(t'+1,\lambda)_{Shutter}}{2}$$
$$L_u(z',t',\lambda) = L_u(z',t',\lambda)_{Dd} - \frac{L_u(z',t'-1,\lambda)_{Shutter} + L_u(z',t'+1,\lambda)_{Shutter}}{2} \quad \text{(a)}$$

$$\overline{E_s(t,\lambda)'} = median\left[E_s(t',\lambda)\right]_{t=0}^{60s}$$
$$\overline{L_u(z,t,\lambda)'} = median\left[E_s(z',t',\lambda)\right]_{t=0}^{60s} \quad \text{(b)}$$

Equation 12

Corrections for depth, tilt and shading and extrapolation to the surface

Once the daily time series are computed, a series of corrections are applied to the measured quantities, including tilt and shading corrections. Buoy tilt causes a change of the viewing geometry and of the relative distance of the sensors with respect to the reference depth as measured by a CTD. For the determination of the exact depth of the **upwelling radiance** sensors, a correction factor is computed as a function of the buoy arm length and tilt in the x and y directions (Figure 32) for each instrument. The correction factor is computed and applied to the theoretical depth of the sensor when the buoy Tilt is zero as described in Equation 13.

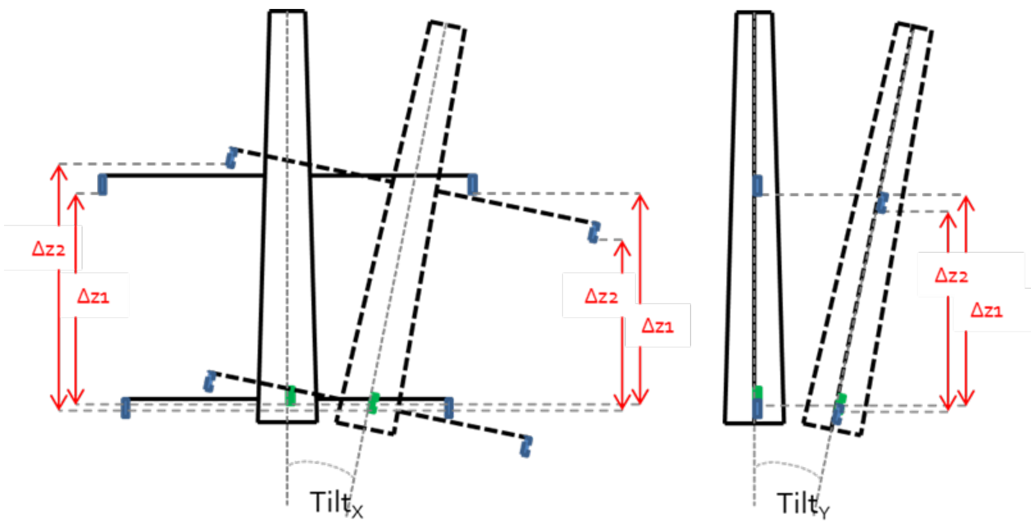

Figure 32: BOUSSOLE tilt correction.

$$z_{rad}(t) = [z_{CTD}(t) - \Delta z_{rad}] \cdot f_{depth}(t, Tilt_x, Tilt_y)$$
$$f_{depth}(t) = \left(1 - \cos Tilt_y(t)\right) \cdot \left(1 - \cos Tilt_x(t)\right) - L_{z_{rad}} \sin Tilt_x(t)$$

Equation 13

Correction of the **surface irradiance** for tilt consists in a cosine correction (Figure 33). First, the direct fraction of E_s is estimated following Gregg & Carder (1990). The correction is then applied to the direct fraction of E_s (Equation 14).

$$\overline{E_S(t,\lambda)}' = \overline{E_S(t,\lambda)}' \cdot f_{dir} + \overline{E_S(t,\lambda)}' \cdot (1 - f_{dir})$$

$$E_S(t,\lambda) = \overline{E_S(t,\lambda)}' \cdot f_{dir} \cdot f_{tilt} + \overline{E_S(t,\lambda)}' \cdot (1 - f_{dir})$$

Where $f_{tilt} = \frac{\cos(\alpha')}{\cos(\alpha)}$

Equation 14

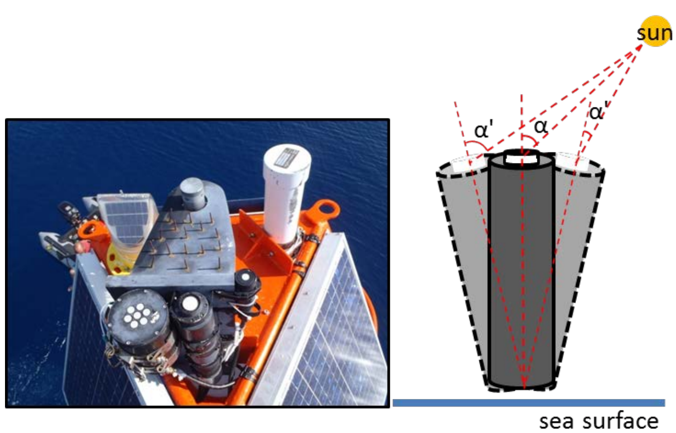

Figure 33: cosine correction of surface irradiance.

Despite its design that minimizes shading, the buoy structure still affects the different underwater sensors, together with instrument self-shading. A backward 3D Monte Carlo code (SimulO) has been implemented to quantify this effect. Several scenarios have been modelled resulting in a shading correction look up table accounting for chlorophyll concentration, sun azimuth and zenith angle for each wavelength.

The final step consists in extrapolating the underwater radiance to the surface. The procedure uses the two measurement depths (4 and 9 m) to derive the attenuation coefficient for upwelling radiance (K_L). L_u at 4 m is then extrapolated to just below the surface ($L_u(0^-)$). A correction factor derived from Look Up tables generated with *Hydrolight* radiative transfer simulations is also applied to account for the effect of the chlorophyll content (i.e. IOPs) and sun zenith angle on the extrapolation of the upwelling radiance to surface, at each wavelength with respect to a simple logarithmic extrapolation (this correction is only significant for λ>550nm, where Raman scattering can be significant). The water leaving radiance L_w, is finally derived after accounting for the water/air interface, namely the Fresnel reflection and the refractive index (Equation 15).

$$K_L = -\frac{\ln\left[\overline{L_u(z_9,t,\lambda)}/\overline{L_u(z_4,t,\lambda)}\right]}{z_9 - z_4} \qquad L_u(0^-,t,\lambda) = \overline{L_u(z_4,t,\lambda)}\; e^{-z_4 \cdot K_L} \cdot f_H$$

$$L_w(t,\lambda) = L_u(0^-,t,\lambda) \cdot \frac{1-\rho}{n^2} \;\; ; \text{where } \frac{1-\rho}{n^2} = 0.543$$

Equation 15

Chlorophyll content is needed for the two above-mentioned corrections. A single value of chlorophyll per day is used to derive the correction factor and comes from 3 sources. First, monthly cruises at BOUSSOLE allow for water sampling and total chlorophyll analysis through HPLC. To fill-up the chlorophyll time series in between cruises, the strategy consists of using a satellite derived chlorophyll time series adjusted to the in situ observations and interpolated with a polynomial function to fill satellite gaps. For the non consolidated data set (i.e. when HPLC/satellite data are still not available) the fluorescence sensors mounted on BOUSSOLE are used. A relationship has been derived between fluorescence and chlorophyll content. Night fluorescence measurements are used in order to avoid the quenching effect.

Quality control and data screening

Standard operational quality control discards the measurements acquired under the following conditions:

- Buoy depth below 11 m (E_s sensor too close to the sea surface);
- Buoy tilt greater that 10° (corrections might generate too much uncertainty, and weather conditions not suitable for cal/val);
- Ratio of measured to theoretical E_s exceed 20%.

Finer and more stringent filtering criteria can be applied on a non routine basis to select E_s with a standard deviation lower than 2% and restrict azimuth angle condition to limit the uncertainty of the shading effect. Visual inspection of the measured time series can also be included.

Possible biofouling contamination is detected by looking at eventual discontinuities on AOPs acquired before and after cleaning of the instruments. Whenever possible data are corrected by applying a specific function to each period and wavelength, otherwise data are eliminated.

Finally, climatologies of E_s and L_u measurements based on all previous buoy deployments performed at the same time of the year are used to assess the quality of the measurements for a given deployment. This procedure is still under investigation.

To account for the different processing steps, the initial equation to compute the water leaving reflectance (Equation 16a), ends up in a more complex formulation (Equation 16a) where f_{cal}, f_{cos}, f_{tilt}, f_{dir}, f_H, $f_{\rho n}$ are the correction factors for calibration, cosine response, tilt, fraction of diffuse to direct solar irradiance, surface extrapolation, air-sea interface respectively. f_{s4} and f_{s9} are the shading correction at depth 4 and 9m respectively. f_{cal} is actually equal to 1 (i.e. no correction is applied), however this formalism is here to make explicit the uncertainties related to calibration, and this will be discussed in next section.

$$R_{rs}(t,\lambda) = \frac{L_w(t,\lambda)}{E_S(t,\lambda)} \;\text{(a)} \qquad \boldsymbol{R_{rs}} = \frac{\overline{\boldsymbol{L_{u4}}}\, \boldsymbol{f_{cal}} \mathbf{f_{s4}}\, \boldsymbol{exp}\left[\boldsymbol{z_4}\left(\frac{-\ln\left(\overline{\boldsymbol{L_{u9}}}\,\boldsymbol{f_{cal}}\boldsymbol{f_{s9}}/\overline{\boldsymbol{L_{u4}}}\,\boldsymbol{f_{cal}}\boldsymbol{f_{s4}}\right)}{\boldsymbol{z_9}-\boldsymbol{z_4}}\right)\right]\boldsymbol{f_H}\boldsymbol{f_{\rho n}}}{\overline{\boldsymbol{E_s}}\,\boldsymbol{f_{cal}}\boldsymbol{f_{cos}}\boldsymbol{f_{tilt}}\boldsymbol{f_{dir}} + (\mathbf{1}-\boldsymbol{f_{dir}})\overline{\boldsymbol{E_s}}\,\boldsymbol{f_{cal}}} \;\text{(b)}$$

Equation 16

BOUSSOLE: preliminary results of an improved uncertainty budget

A. Bialek[1], V. Vellucci[2], B. Gentili[2], D. Antoine[2] and N. Fox[1].[1] NPL, [2]LOV

The previous section about the BOUSSOLE processing has presented the different steps from the data acquisition to the delivery of water leaving reflectance time series for satellite data validation or vicarious calibration. All these processing steps introduce uncertainties that have to be carefully and individually quantified if we are to achieve the highest standard of data quality, the so-called Fiducial Reference Measurements (FRMs). The objective is for BOUSSOLE to provide first an upgraded estimate of the uncertainty budget, then a per measurement uncertainty.

The procedure to estimate the uncertainty of the remote sensing reflectance derived from in situ measurements is based on a methodology recommended by the Bureau International des Poids et Mesures (BIPM) know as GUM (Guide to the expression of uncertainty in measurements). This methodology is based on the law of propagation of uncertainties. Owing to the complexity of the radiometric measurements in natural environments and particularly in the marine environment, a stochastic approach know as GUM supplement 1, based on a Monte-Carlo Methodology (MCM) is used to derive the uncertainty budget. While the regular GUM approach uses uncertainty of the different components to derive the final uncertainty budget, MCM uses Probability Distribution Functions (PDFs) as input of the model (Figure 34). The measurement model is then run a statistically significant number of times using randomly selected values on the input variables according to their respective PDFs. The output of the measurement model therefore provides a PDF for each measurement. The final uncertainty budget is deduced from the resulting PDFs.

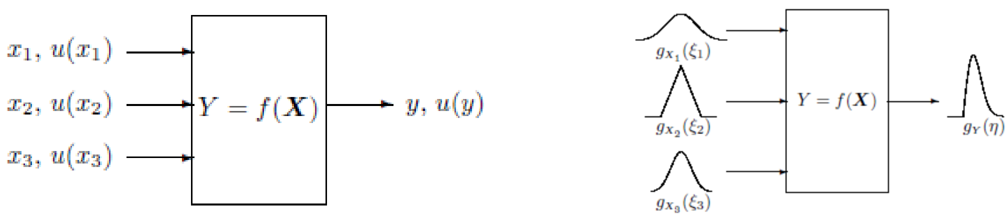

Figure 34: principle of GUM (left) and MCM (right).

From the different elements of the measurement equation, 4 categories of uncertainties have been identified (Table 6; Equation 16).

Table 6:

SIGNAL	$\overline{L_{u4}}$,$\overline{L_{u9}}$, $\overline{E_s}$ are median values of 1 minute measurements of two OCR (upwelling radiance at 4 m, L_{u4}, and 9 m, L_{u9}) and one OCI (surface irradiance, E_s) Satlantic 200 series radiometers with 7 VIS spectral bands.
INSTRUMENT RELATED	absolute radiometric calibration (f_{cal}) diffuser cosine response (f_{cos})
ENVIRONMENTAL	shading (f_s) buoy tilt (f_{tilt}) z_4 and z_9 are the actual instruments depths corrected for buoy tilt
MODELLING	extrapolation to surface correction using *Hydrolight* simulation (f_H) the constant for water-air interface fraction of the direct to total solar irradiance (f_{dir})

Signal

Variability originating from the measurement signal is mainly due to short-term environmental changes like sky illumination or wave focusing. Signal values used in the measurement equation are simultaneous 1 minute averages from the different sensors (L_{u4}, L_{u9} and E_s). A Gaussian PDF is used as the input to the model. The distribution uses the median of one minute readings as a mean and the standard deviation of the mean as expectation of the standard uncertainty.

Instrument related

Instruments uncertainties are related to their design and individual performance. Sources of uncertainties include absolute radiometric calibration, thermal sensitivity, immersion factors, cosine response, detector linearity. They are derived from laboratory tests with uncertainties defined following the standard GUM procedure. Gaussian PDFs with standard uncertainty equal to each component's standard deviation are derived. It is very important to note that the manufacturer does not provide fully detailed instrument uncertainty characterisation. This is a time-consuming and costly process, which in the case of BOUSSOLE is performed through collaboration with NPL. Table 7 summarizes the quantified uncertainties derived for one set of BOUSSOLE multi-spectral instrumentation.

Table 7:

INSTRUMENTAL	UNCERTAINTY (K = 1)	SOURCE
Absolute radiometric calibration (Irradiance)	1.6% - 1.1% (1.5%)	NPL calibration and comparison to Satlantic coefficients
Cosine diffuser (Irradiance)	3% below 60°, 10% above	Satlantic specifications
Absolute radiometric calibration (Radiance)	2.5% - 2.0% (2.2%)	NPL calibrations and comparison to Satlantic coefficients
Radiometric stability	1% (Not included)	From repeated calibrations, if no instruments issues
Immersion coefficient	Bias of 0.4 % with 0.19 % uncertainty, currently not included	Literature, Zibordi 2006
Temperature dependence	Negligible	NPL test in 2013 (for the observed at the site range)
Detector linearity	Negligible	NPL test in 2013

Environmental effects

Environmental uncertainties are intrinsic of any deployment in the field. In the particular case of BOUSSOLE, the environmental uncertainty sources originate from buoy tilt, actual instrument depth, the shading effect and the BRDF. They are evaluated from buoy ancillary data and have rectangular PDFs. Table 8 summarises the uncertainties derived from the identified sources.

Table 8:

ENVIRONMENTAL	UNCERTAINTY (κ = 1) converted to normal distribution	SOURCE
Depth	1%	To be refined by a mini MCM model
Tilt (E_S)	2%	To be refined by a mini MCM model
Shading	1.2%	Comparison of LOV MC photon tracking model with others corrections
BRDF (effect of the tilt under water)		Currently being estimated

Modelling
Several models are used within the BOUSSOLE processing chain:

- to quantify the fraction of direct to total solar irradiance (f_{dir});
- to extrapolate L_{u4} and L_{u9} to L_{u0-} (below the surface ; f_H ; under water radiative transfer ; *Hydrolight*);
- to account for the water/air ($f_{\rho n}$) (Table 9).

For each of these components, the uncertainty is derived from sensitivity analyses (extrapolation to the surface), literature (direct to total E_s fraction) and both (air/water interface). The resulting PDFs are rectangular (f_{dir}) and Gaussian (f_H and $f_{\rho n}$).

Table 9:

MODELLING	UNCERTAINTY (κ = 1) converted to Normal distribution	SOURCE
Hydrolight correction	0.5% below 600 nm 2% - 3% above 600nm (Chla dependent) (1.5%)	Sensitivity study by modelling
Water – air constant	0.5%	Literature Austin 1976, Austin and Halikas 1976, Wei et al. 2015 plus modelling
Direct to total fraction	3.5%	Literature

Results and conclusion
The model was run a large number of times using the above-defined uncertainties. The uncertainties derived from the simulations of the different components of the BOUSSOLE measurement equation are summarized in Table 10.

Table 10:

u in % / λ in nm	E_s	L_{u4}	L_W	R_{rs}	$u_{abs}(R_{rs})$
412	2.1	2.6	3.1	3.7	0.000215
443	2.0	2.6	3.1	3.7	0.000225
490	2.0	2.6	3.0	3.7	0.000175
510	2.0	2.6	3.0	3.7	0.000155
560	2.0	2.6	3.1	3.7	0.0000725
665	2.1	3.9	5.9	6.3	0.00000410
681	2.1	4.0	5.9	6.3	0.00000195

The interest of this uncertainty analysis for satellite product validation and more importantly for SVC is that uncertainty per measurement will be derived rather than a global uncertainty as used in the past. Quantifying individual uncertainty sources will allow users, depending on their objective, to relax or tighten the data filtering. This first analysis will also support future research activities dedicated to characterize and reduce the uncertainties in the different components. Within the different sources of uncertainty, radiometric absolute calibration and SI traceability is essential and continuous efforts on instrument characterization should be maintained.

The present analysis has been performed on one set of multispectral instruments deployed at BOUSSOLE over a restricted data set (about one month of measurements). The same framework should therefore be applied to the entire multispectral time series and the recently deployed hyperspectral instruments.

MOBY: time series, lessons learned and status of MOBY-Refresh and MOBY-Net

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This talk provided an overview of the 20 year MOBY time series, some of the lessons we have learned and think are important, and the current status of MOBY-Refresh and MOBY-Net.

1) MOBY time series

At this time we are only a few months short of having a 20-year operational time series with MOBY. With this long time series we can look at the stability of the data set and other issues. When seasonal and daily variations in E_s are normalized out, a very small, 5% trend over the 20 years seems to be evident. However over these 20 years, we have been modifying our data acquisition times to account for different satellite mission requirements. Most of this trend is due to our taking measurements earlier in the day during the first part of the time series, and not being able to normalize totally for E_s daily variations. The real trend is much smaller than 5% over the measurement period. We will be working on determining the true measurement trend during the summer, when the 20-year time series has been completed.

2) Lessons learned

There are several obvious lessons, such as long term funding is hard, but required and takes effort to sustain. For the MOBY project we have found that consistency of people, each with individual expertise on some aspect of the project has worked well. Being in a nearly constant environment allows careful QA/QC to be maintained. The original cost of the equipment is quickly dwarfed by the costs of maintenance, calibration, and characterization, so you might as well start with really good equipment. Finally we think it is critical that the data be inspected daily, if you are going to do an operational SVC site, to allow rapid response if there is an issue. This means following each step of the data processing, from raw data to finished data at all times.

Other timely lessons are that contingency funding must be available for emergencies; if the time series is long enough plans to upgrade equipment must be made. For MOBY it was a 10-year process to secure the funding for MOBY-Refresh. Finally, since it is an expensive operation, make sure the users are getting what they require.

One other aspect which helps with the quality control is being able to automatically update graphs, and having a web page that documents everything.

3) Progress on MOBY-Refresh and MOBY-Net

Currently we have installed the blue spectrograph from MOBY-Refresh and MOBY-Net on the MOBY buoy, and are acquiring images with the spectrograph during one of the MOBY acquisition times each day.

Figure 35: picture of new blue spectrometer installed on the MOBY buoy.

An example image from this acquisition is shown below.

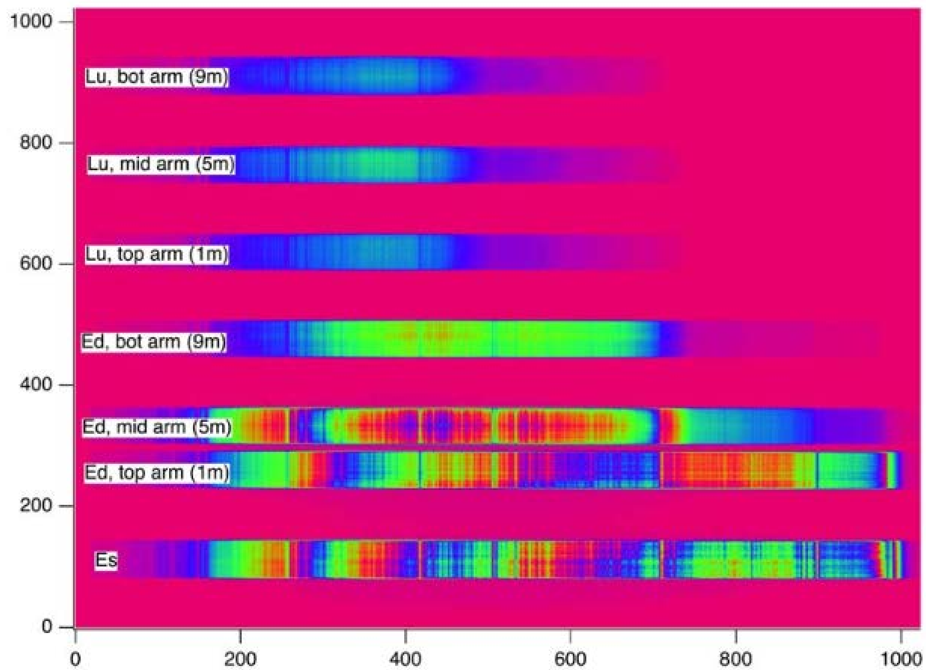

Figure 36: sample image of different environmental light field measurements, all obtained simultaneously. The x-axis is a relative wavelength scale, starting at 340 nm on the left and going to 700 nm on the right.

We have been monitoring the stability of the system over the deployment and it is working well, with less than a 0.1 nm shift over the deployment period, and less than ½ a pixel shift in track location over the deployment.

The new carbon structures for MOBY Net have been built, and we are waiting for the final stage of construction of the buoy structure.

The other part of MOBY-Net is the stability source and monitor. We are currently using a Satellite Quality Monitor (SQM) from Yankee Environmental Scientific as a stability source. We have extensively modified the software associated with the system to allow careful tracking of all the instrument parameters. An acrylic diffuser was in the original instrument, but we found that the throughput at 350 nm with this diffuser was much too small. Through tests we found that we could replace this diffuser with a quartz window that had been sand blasted on both sides, and this would both be diffuse enough, and allow for almost no spectral losses at 350 nm.

We selected a CAS spectrometer for the stability monitor device because NIST had several of them and experience with using them. We are in the middle of a long term stability study with this spectrometer. In addition we are testing its stability after transport in various ways.

4) Conclusions

Having a time series in a stable site allows many continuity tests, and since the MOBY site is specifically for System Vicarious Calibration (SVC) this is important.

Having a stable team, and relatively stable funding has been critical for the success of the MOBY team.

MOBY-Refresh and MOBY-Net are moving forward. The goal is a yearlong crossover time series between the new and old optical system completed in 2018.

BOUSSOLE status

V. Vellucci, D. Antoine , LOV

Operational activities

BOUSSOLE was first deployed in September 2003. At the end of 2016, BOUSSOLE project team had achieved 8 mooring rotations, 22 buoy rotations (i.e. instrument rotations), 178 monthly cruises and 115 on demand cruises cumulating 1.75 years at sea (Table 11). Since 2010, BOUSSOLE mooring and instrument rotations is fully operational (100% deployment days) with an average rate of 94% of successful data acquisition (Table 12). In 13 years of operation, the major data acquisition gap was the consequence of a collision with a ship in 2008, which however did not result in a loss of instrumentation.

Table 11: BOUSSOLE hardware and days at see numbers. * 71 % of the scheduled cruises, the rest was cancelled either due to bad weather, military restrictions or ship related issues.

	ACTIVITY	N	DAYS AT SEA	START
	mooring rotation	8	63	2000
	buoy rotation	22		
	monthly cruises	178	460/645*	2001
	on-demand cruises	115	115	2000

Table 12: BOUSSOLE deployment data in numbers.

YEAR	N DAYS WITH A BUOY AT SEA	N DAYS WITH DATA ACQUISITION	DEPLOYMENT RATE (%)[1]	MEAS. RATE (%)[2]
2003	91	90	100[3]	99
2004	303	241	83	79
2005	365	288	100	79
2006	365	328	100	90
2007	344	303	94	88
2008	207	133	57	64
2009	365	254	100	69
2010	365	289	100	79
2011	365	347	100	95
2012	366	351	100	96
2013	365	328	100	90
2014	365	365	100	100
2015	365	336	100	92
2016	366	335	100	92
TOTAL	4277	3699	95	86

Data exploitation

BOUSSOLE was, from the beginning, designed for both SVC and scientific research. A total of 42 peer reviewed publications and 7 PhD dissertations covering Cal/Val, optics and biogeochemistry have been written. Since MERIS 3rd data reprocessing, BOUSSOLE, together with MOBY, data are used to derive MERIS vicarious calibration gains. They are currently being used for OLCI vicarious calibration. Data are freely available through a webpage (http://www.obs-vlfr.fr/Boussole/html/home/home.php).

Budget

Access to secure funding is essential for the long term deployment of SVC infrastructure. It is essential for the maintenance of hardware and software but also for securing highly qualified and motivated human resources.

For the past 13 years, BOUSSOLE has been funded by ESA and CNES for about 90% of the budget with additional funding from NASA, CNRS/INSU, ANR, LOV and UPMC. 85% of the total budget is used for instrumentation, ship time, salaries, miscellaneous costs including lab levy, cruise instruments, instrument shipping and custom fees, external divers, buoy paint, publication, lab consumable, insurance ..., instrument calibration and repairs, mooring equipment (Figure 37). About 15 personnel are involved at a different level and represent about 4.25 full time equivalent (with respect to operational aspects, this estimate also includes work performed by manufacturers and NPL for instrument calibration and/or characterisation).

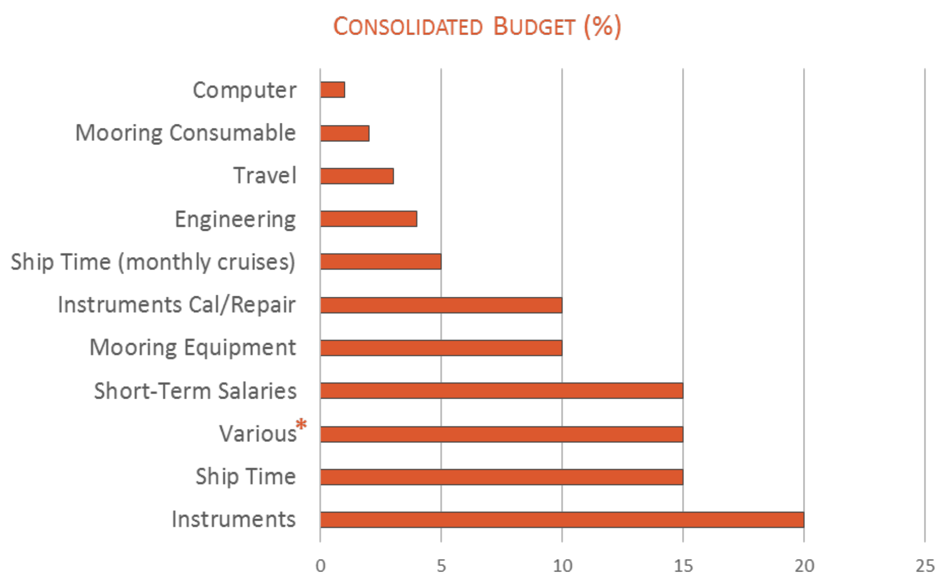

Figure 37: BOUSSOLE consolidated budget (%).Various include: lab levy, cruise instruments, instrument shipping and custom fees, external divers, buoy paint, publications, lab consumable, insurance...

Conclusion

When the first sketches of BOUSSOLE were drawn about 15 years ago, the complexity of the task was not fully foreseen. A few years of hard work of highly qualified and motived people have therefore been necessary to sort out one by one the issues inherent to the development of the platform and to the radiometric measurements in natural environments and constantly improve the level of data quality. The set of procedures involved in the BOUSSOLE deployments and data processing constantly evolves to provide the best possible outcome to the community.

Evolutions foreseen in the short term concern the data processing, the superstructure and the instrumentation. For the first one, and in order to address the specific needs of SVC, the final objective is to provide BOUSSOLE measurements with individual uncertainties. The preliminary work carried out on the characterization of uncertainty sources will be generalized and extended to hyperspectral instruments. Bi-directionality corrections will be included in the processing chain and its relative uncertainty included in the budget. Improved QC procedures will be developed for hyperspectral instruments. About the buoy superstructure, analyses are being carried out to reduce and better distribute its weight and increase energy availability. The structure will be equipped with articulated arms in the future to facilitate deployments.

Finally, for the instrumentation, the multispectral instruments will be decommissioned as the manufacturer no longer ensures their maintenance. More effort will be made to improve on instrument characterization. Possible technical evolution in the mid-term include: real time data transmission, increase of power availability and re-introduction of bio-shutters. To insure the 6-month rotations, triplicate essential radiometers (E_s, L_u) is a possible solution that is being evaluated.

In addition to BOUSSOLE continuous improvements to fulfil Copernicus needs, the next operational challenge will consist in repeated deployment/recovery of ProVal floats in the BOUSSOLE vicinity.

Session 7 – Emerging FRM

This session was intended to provide an insight into emerging technologies to collect FRM: Hypernav funded through the NASA Roses call and ProVal, an OCR validation initiative developed by LOV through CNES funding.

Hypernav: accurate measurements of high spectral resolution water leaving radiance using autonomous platforms for ocean color satellite vicarious calibrations.

Andrew Barnard[1], Emmanuel Boss[2], ; Marlon Lewis[1].,. [1]Sea-Bird Scientific, [2]University of Maine, Sea-Bird Scientific.

Project overview and background

HyperNav is one of the three projects funded by OBB/ESTO in response of NASA ROSES call. The prime objective of HyperNav project is to develop next generation of hyperspectral radiometers. They would be deployed on autonomous floats. The project also includes the end-to-end data management system. A prime motivation of the HyperNav project is to support SVC and product validation of current and next generation of hyper spectral and multispectral ocean color sensors. An advantage of this system is particularly evident in early stages of operational missions as they could provide a large number of high quality matchups in a short period of time providing a sufficient number of units are deployed.

Currently, there are two strategies for radiometric acquisition: instrumented buoys or stations and Oceanographic cruises. The trade off between the two strategies is listed in Table 13.

Table 13: Current strategies for Cal/Val of Ocean Color.

Instrumented buoy or AERONET-OC Station ex. MOBY, BOUSSOLE	Oceanographic cruises
Demonstrated high quality data	Demonstrated high quality data
Limited spatial coverage	Limited spatial coverage
Great temporal coverage	Limited temporal coverage
~ 15 matchup data points per year per site provided	Takes ~10 days at sea to get one matchup data point

Both strategies are expensive and take significant time to gather sufficient data early in sensor's life. Autonomous floats are in comparison relatively inexpensive. In this context, a fleet of instrumented profiling floats will represent a great value. They would increase spatial and temporal coverage, augment MOBY and BOUSSOLE data and augment Bio-Argo float capabilities. At this stage, data quality still has to be assessed to ensure SVC requirement compliance.

The requirement for HyperNav (designed for PACE mission CalVal) are listed in Table 14.

Table 14: HyperNav requirement.

REQUIREMENT	CAPABILITY
Spectral Range 350-900 nm	350 to >900 nm
Resolution < 3 nm	<=2.2nm (350-800nm), <=2.35nm (800-900nm)
Radiometric Uncertainty < 4% in blue-green	< 4% in the blue-green. TBD for red. Uncertainty due to extrapolation from L(z) to L(0).
Radiometric Stability O(1%) per Deployment	System will park at 1000 m depth, inhibiting biofouling.
Autonomous Field Operation	Excellent history of long-term float deployment. Float scheduling can be updated after deployment.
Fully Lab and Field Characterized	Radiometers will be fully characterized (stray light, temp, linearity, etc) Calibrated with NIST-calibrated lamps.
Fully Autonomous Data Delivery to Enable the NASA Mission Science.	A full end-to-end system with automated Prosoft processing scripts.

Hypernav system is described in Table 15. Key aspects include:

- Dual independent radiometers - relative drift;
- L_u very close to surface;
- Hyperspectral;
- Improved pressure accuracy;
- Minimization of self shading;
- Ability to extend at surface acquisition time ;
- Tilt data utilization for power saving.

Its modular design allows its deployment on freefall systems and Navis floats (Figure 38)

Figure 38: Design of Float System.

Table 15: HYPERNAV System Overview

SENSOR	LOCATION	PURPOSE
OCR-504	Top of Navis mast	(380nm, 490nm, 590nm, PAR) Validation, sky conditions
MCOMS	Base of radiometer	(Chl, 700 BB, FDOM) Data validation
Pressure	Base of radiometer	High accuracy & resolution depth for surface extrapolations
Temperature and Salinity	Top of Navis mast	For use with pressure for depth calculation
Tilt/Compass	Radiometer body	Quality control, orientation to the sun
Tilt	Radiometer heads	Head alignment and monitoring

The radiometric system is designed as follow (Figure 39):

1. Dual heads to allow sun-side radiometer & intercomparison.
2. Heads on arms reduce self-shading.
3. Right-angle design to allow near surface measurements.
4. Reduced errors in extrapolation to $L_u(0-)$.
5. Tilt sensors for alignment and to monitor position.
6. Shutters for collecting darks.
7. Depolarizer to remove uncertainty in the fore optics.

Simulations of shading effect versus zenith, azimuth, depth, wavelength and Chl-a have been performed through SimulO software (Edouard Leymarie, LOV).

Figure 39: System design.

First laboratory and field tests have so far demonstrated that Hypernav

- Resolves Fraunhofer lines;
- Difference between the two heads can be observed as the measurements are not performed simultaneously (can be used for QC and detection of varying sky conditions;
- Measurements can be performed very closed to the sea surface and therefore reduce surface extrapolation errors.

The uncertainty matrix is still to be consolidated but first results are available in Table 16.

Table 16: HYPERNAV uncertainty matrix.

SOURCE	TARGET % @550nm	METHOD OF VALIDATION	MITIGATION
Calibration			
Irradiance standard	0.78	Provided by NIST	Use NIST calibrated lamp
Reflectance target	1.8	Provided by manufacturer	Use corrections for 0-45 deg
Reproducibility	1.5	Repeated calibrations	Careful lab procedures
Instrument			
Immersion factor	0.3	Theory and experiment	Careful lab procedures
Linearity	TBD	NIST beam conjoiner	Characterization and correction
Stray light	0.04	NIST laser scanning	Characterization and correction
Thermal effects	0.02	At calibration station over 4-30 C	Characterization and correction
Polarization effects	TBD	Integrating sphere and polarizer	Depolarizer
Wavelength accuracy	0.4	Provided by mfr., verified with gas lamps	Quality control on spectrometers
Field			
Wave focusing	1.0	Field measurements	High frame rate near surface
Self-shading	0.5	Monte Carlo	Model corrections
Tilt effects	0.5	Tilt sensors in heads	Only collect data when tilts are good
Biofouling	2.0	Retrieval of floats, post calibration	Park in aphotic zone
Total	3.5		

Next step in the development of Hypernav will include improved characterization of:

- immersion coefficients through theory and experiment following the procedure of Zibordi (2005) as well as calculation using *T* and *S* measured by Navisfloat
- spectral stray light will be measured at NIST on a tunable laser to generate a correction matrix
- linearity will be measured at NIST on a beam conjoiner to generate a correction function. The goal is to reach an accuracy of <0.1% (as per Mueller)
- thermal stability will be measured using a radiometric calibration setup to generate a correction function.

ProVal : First data from a new Argo profiler dedicated to high quality radiometric measurements

E. Leymarie[1], C. Penkerc'h[1], E. Vellucci[1], C. Lerebourg[2], D. Antoine[1,3], H. Claustre[1]. [1]- Laboratoire d'Océanographie de Villefranche, 06230 Villefranche-sur-Mer, France, [2]- ACRI-ST, Biot, France, [3]- Remote Sensing and Satellite Research Group, Curtin University, Perth, Australia

Following the recommendation of the International Ocean Colour Coordinating Group in 2011 (IOCCG report #11), the Laboratoire d'Oceanographie de Villefranche (LOV) has developed a new profiling float dedicated to the validation of ocean colour remote sensing data. Taking advantage of our experience in both Argo floats and radiometric measurements, we have developed the so-called ProVal float based on a two-arm design that allows sensor redundancy and shading mitigation (Figure 40). ProVal measures downward irradiance and upwelling radiance at seven wavelengths with a special concern for the data quality for this type of platform. It also measures the downward PAR, the fluorescence of Chl-a and CDOM, and the backscattering coefficient at 700nm. ProVal is designed to monitor all year round these radiometric quantities and Inherent Optical Properties (IOPs) in the water column simultaneously with ocean colour satellite observations. These match-ups are required for the global ocean, especially in areas with known bio-optics anomalies such as the Southern Ocean or the Mediterranean Sea. Table 17 summarizes deployment information from three ProVals.

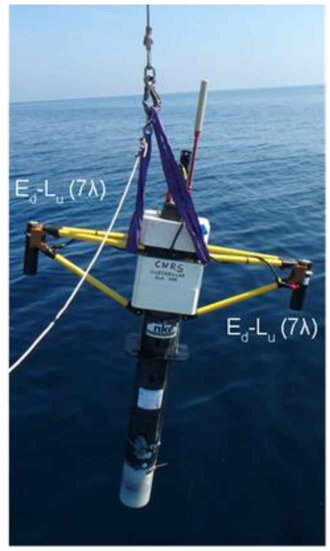

Figure 40: A ProVal float being deployed (N. Mayot).

Table 17: Summary of deployments. Latitude and longitude are an average over the deployment.

Float name	Area	Start Date	End Date	Status	No. Profiles	Lat.	Lon.
lovapm006d	BOUSSOLE NW Mediterranean	08/07/2015	30/08/2015	recovered	53	43	8
lovapm011b	W Kerguelen	19/10/2016	-	working	170	-53	67
lovapm012b	E Kerguelen	17/10/2016	01/01/2017	lost	68	-49	72

The ProVal float appears to be a very stable platform, even in the rough sea of the Kergulen area as shown on Figure 41.

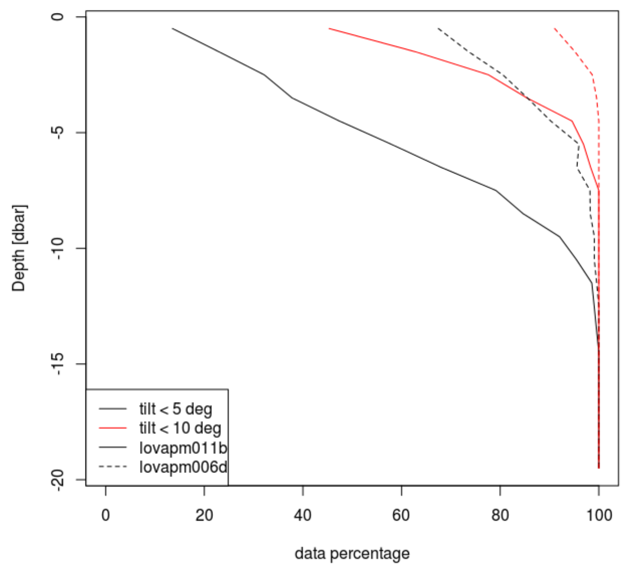

Figure 41: Percentage of data with a tilt below 5° (black line) and 10° (red line) as a function of depth for two floats deployed in the Mediterranean Seas (dotted line) and in the Kerguelen area (solid line).

A basic and preliminary data processing was applied to show first satellite matchups of R_{rs} spectra. Data collected in 2015 near BOUSSOLE were compared to MODIS data (Figure 42) while data from Kerguelen were compared to OLCI data (Figure 43).

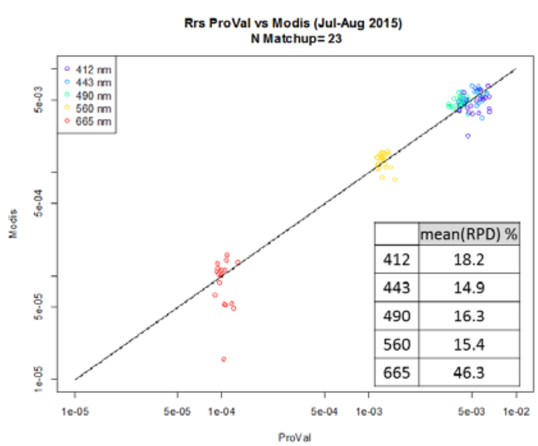

Figure 42: The 23 MODIS matchups with the ProVal obtained in two months at the BOUSSOLE site. The mean relative percentage deviation for each band is displayed too.

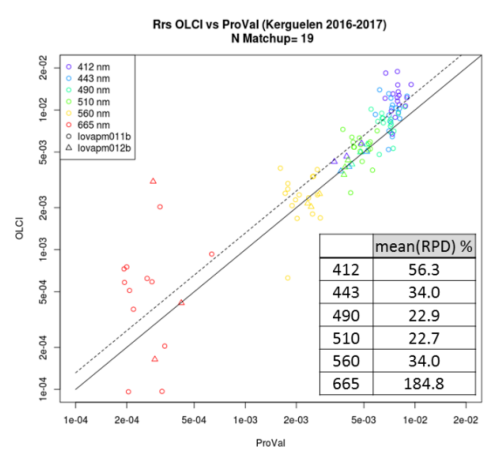

Figure 43: The 19 OLCI matchups with two ProVal obtained in six months in the Kerguelen area. The mean relative percentage deviation for each band is displayed too.

Session 8 – Potential partner programs

This session was intended to put forward new or growing OCR programs. These programs and the associated local growing expertise could potentially enable regional SVC with CoastVal (as requested by CMEMS ; session2) or operate new SVC infrastructure. The Eastern Indian Ocean has for instance been identified as a very good potential site for SVC and could be supported by IMOS.

CoastVal: ocean colour validation in coastal and inland waters

Jenny Hanafin, TechWorks, Marine

TechWorks was awarded an ESA contract to develop a dedicated coastal ocean colour observation platform for validation activities. This project started in September 2016 and it is led within the framework of sentinel-3 validation team activities. This project will potentially pave the way to establish a long-term coastal radiometric observatory infrastructure.

There are two phases in the development of this project. Phase 1 will focus on the development and tests of a buoy platform for coastal colour observations:

- Review of existing systems & protocols;
- Sensor suite;
- Engineering solutions;
- Integration of sensors and data to TWM systems;
  Test deployment;
  as well as the development of in situ data processing platform.

In phase 2 the buoy will be deployed at sea. Issues still under consideration for site selection in Irish waters include cloud cover, subpixel variability of the ocean and the atmosphere, water depth and sea states. Satellite data will be collected and processed to support CalVal activities.

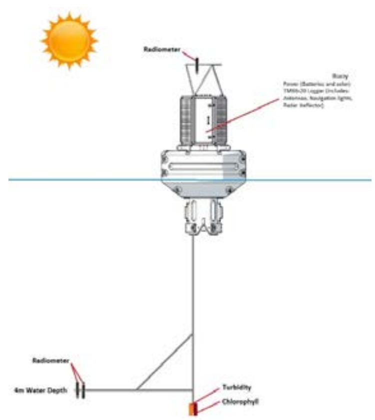

Figure 44:

Commercial radiometers equipped with bioshutters will be used on the buoy (Satlantic HOCR). TechWorks is currently involved in FRM4SOC intercalibration exercises to ensure proper data quality. Issues still to be addressed include platform stability, shadow correction and surface extrapolation.

The Australian Integrated Marine Observing System (IMOS) radiometry task team

David Antoine & Thomas Shroeder, Curtin University, Australia

Background

Given Australia's vast ocean territory, satellites form an important means by which to establish baselines and assess spatial and temporal patterns of change. The technique here considered is ocean colour radiometry (OCR), as provided now for about 18 years by dedicated NASA and ESA OCR satellite missions. IMOS currently served such products to the Australian research community, with an emphasis on tailored local products (Southern ocean, Great Barrier Reef). Local algorithms are needed, which means measurements of IOPs and radiometry are needed. In the coming 5 years, the IMOS remote sensing facility will also progressively incorporate data from the VIIRS, Copernicus Sentinels and S-GLI program missions, in order to serve the community with data for the long term (MODIS is likely close to the end of its operations). In this process, the IMOS bio-optics community should evaluate whether the data they generate for cal/val operations of ocean colour sensors remain valid or have to be adapted. This "Radiometry Task Team" (RTT) is precisely proposed to help in this process.

Current bio-optical research include dedicated cruises with the deployment of various optical systems (IMO DALEC; Brando et al., Remote Sens. 2016, 8(2), 150; doi:10.3390/rs8020150, Satlantic HyperOCR, Trios RAMSES) and an AERONET-OC station on Lucinda jetty.

IMOS objective

The objective is to perform activities that can ultimately improve usability of IMOS radiometric data sets for research purposes as well as for validation of satellite ocean colour products. These activities are upstream of the research endeavour itself. Another objective is to develop a plan for the evolution of radiometric measurements in IMOS for the next decade. This can be summarized as follows:

1. Evaluate the degree of consistency or inconsistency among existing sea-going radiometers used in IMOS and the wider bio-optical community, through dedicated laboratory and field experiments;
2. If needed, improve consistency among these instruments;
3. Develop a plan for the evolution of radiometry measurements in IMOS for the next decade.

Current activities

Lab inter-comparison experiments have been carried out in IMO (Insitu Marine Optics) facility in Perth where the above mentioned instruments have been tested. Consistency of reference lamps, temperature dependence and linearity were particularly investigated. The tests carried out in Perth will be consolidated by the FRM4SOC "LCE1" exercise.

A field intercomparison experiment was carried out at Lucinda jetty AERONET-OC station. A draft report will be released but preliminary conclusions are listed below:

- it was definitely useful to bring the community together to start building capability (field radiometry is a difficult endeavour);
- non-IMOS instruments do not depart from IMOS instruments (after all instruments went through unified calibration at IMO);
- in terms of satellite OCR validation, LJCO can generate R_{rs} within the accepted uncertainties (~5%) to the international OCR community (see initial OLCI validation results);
- E_s measurements to be checked against theoretical clear-sky computations;
- the DALEC cosine response could be improved;
- integration time matters a lot in L_{sea} measurements, so that direct comparison of L_{sea} from different instruments is not really possible;
- periodic radiometric calibration needed (annual at least); wavelength calibration to be monitored;
- sun zenith angle is one of the key parameters to be accounted for in QC.

Next step toward IMOS consolidation includes:

- finalizing reports of the lab and field (LJCO) experiments;
- presentation at the ESA's FRM4SOC workshop;
- participation to the ESA's FRM4SOC LCE1 experiment;
- collective thinking on:
    - the way to achieve the best possible results with the existing dataset? (QC, confidence level setting, reprocessing);
    - how to improve data quality in the future?
    - guidelines on best practices for different radiometer types
    - national cal. facility: role, where, how?
    - nodes and users uptake;
    - how do we keep close links with the international OCR community?
- ending up with a clear set of recommendations by June 2017.

Session 9 – Approaches for vicarious calibration procedures

This session was intended to review SVC procedures implemented on past or current satellite OCR missions. Three cases have been presented: VIIRS, MERIS, GOCI and a case study on SVC with non-standard atmospheric corrections.

The NIR- and SWIR-based on-orbit vicarious calibrations for VIIRS.

Menghua Wang, NOAA

Background

VIIRS (Visible Infrared Imaging Radiometer Suite) on-board Suomi National Polar-orbiting Partnership (SNPP) was successfully launched on October 28th 2011. Its wavebands are described in Table 18.

- At satellite altitude about 90% of sensor-measured signal over ocean comes from the atmosphere.
  - It therefore requires accurate atmospheric correction and calibration.
  - 0.5% error in the TOA radiance corresponds to about 5% error in the derived ocean water-leaving radiance.
  - We need about 0.1% sensor calibration accuracy to achieve this.
- Atmospheric correction algorithms are sensor specific.
  - Near-infrared (NIR) bands are used, e.g., Gordon & Wang (1994) for SeaWiFS/MODIS/VIIRS (open oceans).
  - shortwave infrared (SWIR) bands (Wang, 2007) can be used, e.g., VIIRS 1238 and 1601 nm bands or 1601 and 2257 nm bands (turbid waters).
  - NIR-SWIR combined algorithms have also been developed (Wang & Shi, 2007) for open oceans (NIR) and costal/inland turbid waters (SWIR).

Table 18: VIRSS band set compared to MODIS and SeaWiFS

VIIRS†		MODIS		SeaWiFS
Ocean Bands (nm)	Other Bands (nm)	Ocean Bands (nm)	Other Bands (nm)	Ocean Band (nm)
410 (M1)	638 (I1)	412	645	412
443 (M2)	862 (I2)	443	859	443
486 (M3)	1600 (I3)	488	469	490
—		531	555	510
551 (M4)	***SWIR Bands***	551	***SWIR Bands***	555
671 (M5)	1238 (M8)	667, 678	1240	670
745 (M6)	1601 (M10)	748	1640	765
862 (M7)	2257 (M11)	869	2130	865

†VIIRS-SNPP nominal center wavelength

Spatial resolution for VIIRS M-band: 750 m, I-band: 375 m

Vicarious approach for VIIRS

VIIRS vicarious calibration procedure makes the assumption that that one NIR band (862 nm) is perfectly calibrated (gain (862)=1.0. An iterative procedure is used to derive visible NIR and SWIR gains as follows:

1. Set initial vicarious calibration gains at the SWIR bands 1238 nm (M8) and 1601 nm (M10) to 1.
2. Using selected aerosol models, the SWIR-based vicarious calibration procedure is carried out to derive the vicarious calibration gain for VIIRS SWIR band M8 (1238 nm) and 1601 nm (M10) in the South Pacific Gyre (SPG) region.
3. Using the derived vicarious calibration gains at the SWIR 1238 and 1601 nm bands from the SPG region, the SWIR-based ocean color data processing is carried out to derive vicarious calibration gains for the VIIRS two NIR bands 745 and 862 nm (M6 and M7) at the MOBY site.
4. Iterate steps 2–3, adjusting the vicarious calibration gains at the VIIRS 1238 and 1601 nm bands at the SPG site until the derived gain at the NIR 862 nm band is 1.
5. With the derived two NIR vicarious calibration gains, the NIR-based ocean color data processing (inverse processing in the MSL12) is carried out to derive vicarious calibration gains for all visible bands M1–M5. It is noted that, except for the vicarious calibration gains at the two NIR bands, the SWIR1-derived and NIR-derived vicarious calibration gains at the VIIRS visible bands (M1–M5) are independently derived using the MSL12.
6. Repeat step 4 to adjust the VIIRS SWIR band at 2257 nm using the SWIR band at 1238 nm to make the gain of the VIIRS NIR 862 nm band equal to 1 at the MOBY site. Note that the two SWIR bands at 1238 and 2257 nm are used for the data processing and only vicarious calibration gain at the SWIR 2257 nm is adjusted (no gain changes for the other two SWIR bands).

Three procedures have therefore been tested to derive VIIRS vicarious calibration gains:

- NIR approach uses VIIRS 745 and 862 nm bands;
- SWIR1 approach uses VIIRS 1238 and 1601 nm bands;
-
- SWIR2 approach uses VIIRS 1238 and 2257 nm bands.

Table 19 below summarizes the results of the different approaches. With the NIR based approach, gain noise increases with decreasing wavelength as a consequence of atmospheric correction errors. For SWIR1 and SWIR2 approach, the gain decreases with decreasing wavelength which is a consequence of the sensor poor performance for these bands.

Table 19: Gain derived from the different approaches

VIIRS Band (nm)	NIR-Method		SWIR1-Method		SWIR2-Method		Difference (%)	
	Gains	STD	Gains	STD	Gains	STD	SWIR1 vs. NIR	SWIR2 vs. NIR
410 (M1)	0.979954	0.0129	0.980344	0.0190	0.980820	0.0181	0.040	0.088
443 (M2)	0.974892	0.0142	0.975344	0.0219	0.975609	0.0212	0.046	0.074
486 (M3)	0.974685	0.0131	0.975357	0.0246	0.975761	0.0240	0.069	0.110
551 (M4)	0.965832	0.0100	0.965531	0.0299	0.965888	0.0314	−0.031	0.006
671 (M5)	0.979042	0.0064	0.979518	0.0356	0.978576	0.0445	0.049	−0.048
745 (M6)	0.982065	—	0.982065	0.0379	0.981811	0.0476	0.000	−0.026
862 (M7)	1.00000	—	1.00001	0.0423	1.00000	0.0490	0.001	0.000
1238 (M8)	—	—	1.01812	—	1.01812	—	—	—
1601 (M10)	—	—	0.994676	—	—	—	—	—
2257 (M11)	—	—	—	—	1.20252	—	—	—

For operational implementation, unified NIR and SWIR vicarious calibration gains have been used

Table 20: VIIRS operational gain set.

VIIRS Spectral Band (nm)	Vicarious Gains
410 (M1)	0.979954
443 (M2)	0.974892
486 (M3)	0.974685
551 (M4)	0.965832
671 (M5)	0.979042
745 (M6)	0.982065
862 (M7)	1.00000
1238 (M8)	1.01812
1601 (M10)	0.994676
2257 (M11)	1.20252

NIR procedure

SWIR1 procedure

SWIR2 procedure

Conclusion

- The sensor on-orbit vicarious calibration is a key calibration procedure necessary for satellite ocean color remote sensing. The vicarious calibration methodology outlined by Gordon (1998) and used for various satellite ocean color sensors, e.g., SeaWiFS, MODIS, MERIS, VIIRS, is really a relative spectral vicarious calibration approach utilizing the power of Rayleigh scattering.
- A vicarious calibration approach for deriving consistent vicarious gains for the NIR- and SWIR-based ocean color data processing was developed. Specifically, using the in situ MOBY optical observations between 2012 and 2016, vicarious calibration gain coefficients for VIIRS-SNPP with the NIR and SWIR vicarious calibration approaches have been derived. The vicarious calibration gain differences between the NIR- and SWIR-based approaches are mostly within ~0.05%.
- It is required to have in situ vicarious calibration facilities for satellite ocean color sensors, such as MOBY, to provide accurate $nL_w(\lambda)$ spectra data.
- VIIRS mission-long ocean color data have been reprocessed using the MSL12 with the unified vicarious calibration gains. VIIRS ocean color validation results show consistent and improved ocean color data from the NIR- and SWIR-base approaches.
- VIIRS global ocean color data have been routinely produced using the NIR-, SWIR-, and NIR-SWIR-based ocean color data processing.

Vicarious calibration in MERIS 4th reprocessing.

N. Lamquin, ACRI-ST

Vicarious calibration has been implemented in the MERIS ground segment as part of its 3rd reprocessing. A brief review of the 3rd reprocessing methodologies is provided prior to reporting and discussing the vicarious calibration approach adopted by the MERIS Quality Working Group (QWG) for MERIS 4th reprocessing. The latest approach requires adaptations of the 3rd reprocessing methodology to account for the algorithmic evolutions of the 4th reprocessing, notably a new pressure calibration scheme and a new bright-pixel atmospheric correction. While the new bright-pixel atmospheric correction scheme avoids vicarious calibration of the NIR bands, the new pressure calibration scheme requires to take into account the calibration of the MERIS reflectance at two reference pressure levels bracketing the target local pressure. This impacts the computability and usage of the vicarious gains of the VIS bands using the 3rd reprocessing methodology. However, as in the 3rd reprocessing but using an adapted algorithm, vicarious calibration gains of the MERIS 4th reprocessing in the VIS bands are derived using the in situ water-leaving reflectance spectra from the BOUée pour l'acquiSition d'une Série Optique à Long termE (BOUSSOLE) and the Marine Optical Buoy (MOBY). Since the 3rd reprocessing such in situ measurements also benefit from additional measurements, quality control and reprocessing. Figure 1 displays the computed vicarious gains for BOUSSOLE (green) and MOBY (blue) seperately as well as the final interpolated gains in black.

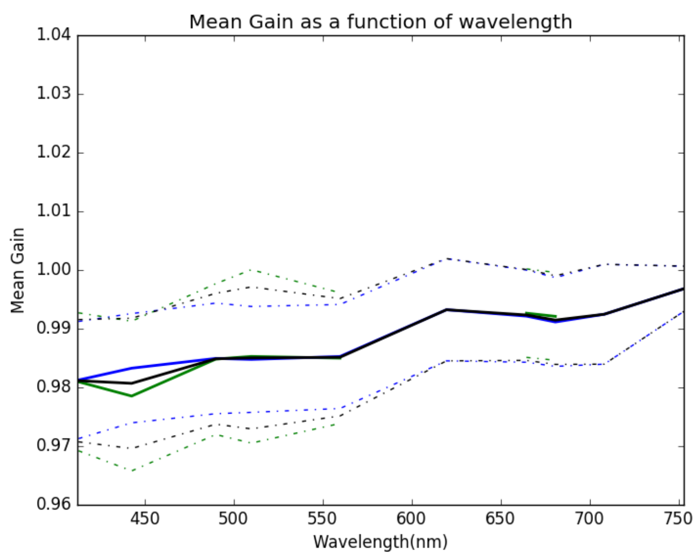

Figure 45: MERIS 4th reprocessing vicarious gains: BOUSSOLE (green), MOBY (blue), and final interpolated gains (black).

Individual vicarious gains are first computed per macropixels of 5x5 matchups carefully filtered (no glint, no cloud, low AOT…) using the median of the distribution of $\rho_{GC}(\lambda)/\rho_{GC}^{IS}(\lambda)$. $\rho_{GC}(\lambda)$ being the remote-sensing glint and gas-corrected TOA reflectance and $\rho_{GC}^{IS}(\lambda)$ being the corresponding in-situ reflectance obtained by propagation of the measured marine reflectance to TOA using the atmospheric parameters retrieved from MERIS. Mean gains are finally computed as a weighted-average over all macropixels individual values, the weighting being inversely proportional to the total uncertainty $\sigma = \sqrt{\sigma^{sat^2} + \sigma^{IS^2}}$ per macropixel with σ_{sat} the standard deviation of the remote-sensing water-leaving reflectance and $\sigma_{IS} = 5\%$, ρ_w^{IS} the one of in-situ.

Alternative methodologies for the computation of vicarious gains are also presented and discussed. Results are expressed through comparisons with in situ data from BOUSSOLE, MOBY, and other sources (among which field measurements from the AERONET-OC network) as shown in Figure 45.

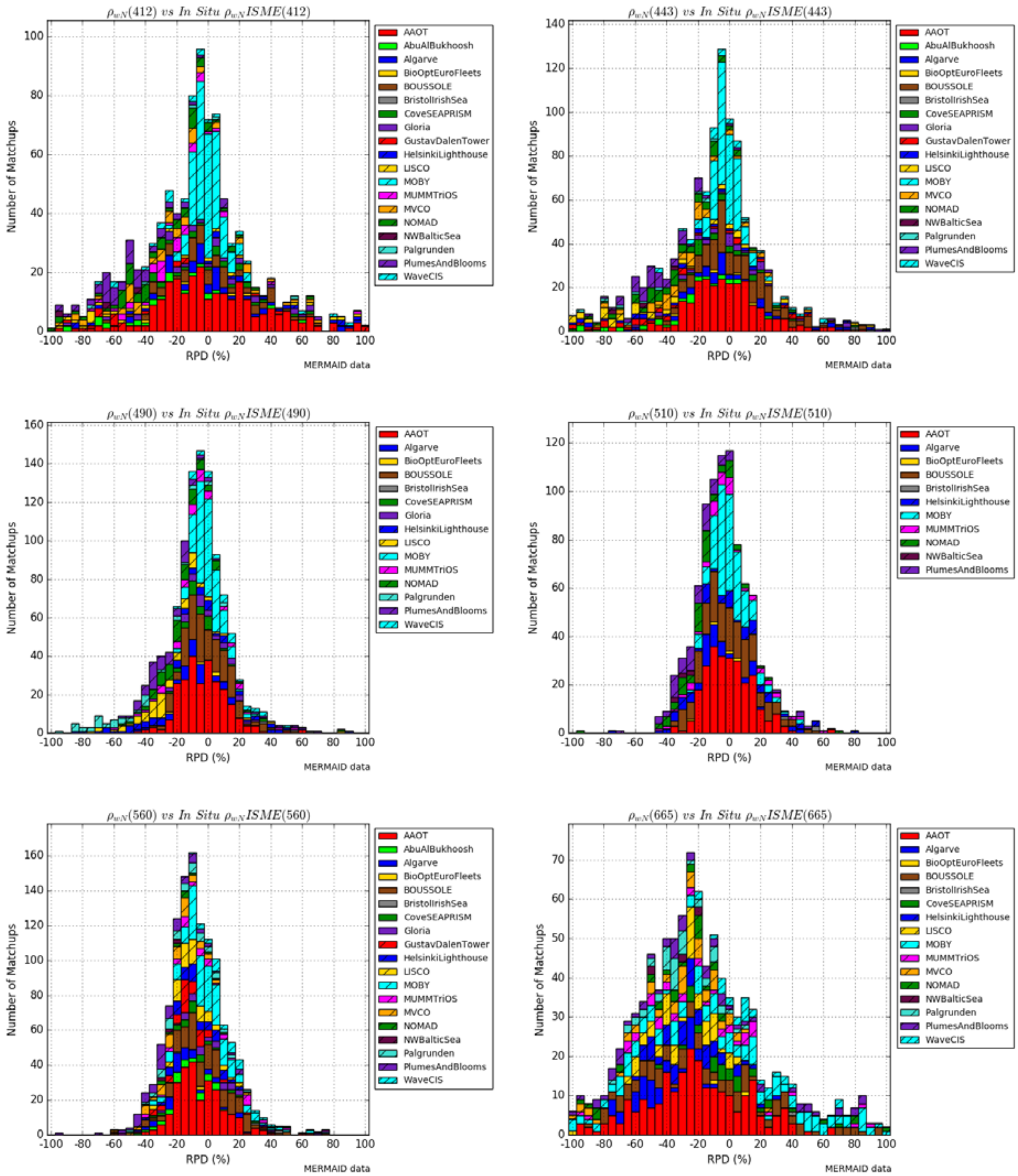

Figure 46: Relative percent differences of water-leaving reflectance between MERIS 4th reprocessing and in situ data between 412 nm and 665 nm.

Finally, the presented methodology is foreseen to be applicable to Sentinel 3 OLCI as OLCI ground segment directly benefits from MERIS reprocessing evolutions.

A revisit of system vicarious calibration for non-standard ocean colour algorithm.

Constant Mazeran[1], Carsten Brockmann[2], François Steinmetz[3], Marco Zühlke[2], Ana Ruescas[2].[1] Solvo, [2] Brockmann Consult, [3] HYGEOS.

Context

The work presented here was carried out in the context of ESA Ocean colour CCI. Past and in-flight sensors are used in ocean colour CCI (SeaWiFS, MODIS, MERIS, VIIRS and OLCI) with two types of atmospheric correction (AC):

1. Standard (historical) atmospheric corrections (Gordon 1998, Gordon and Wang 1994) where the aerosol model is computed from two NIR bands;
2. Non-standard atmospheric corrections (HYGEOS-POLYMER, HZG-NN, FUB-SIACS) where an aerosol inversion is performed over the full spectrum and marine signal derived from a marine model.

The overall objective of SVC in Ocean Colour CCI context is to remove systematic bias in ρ_w and harmonise all sensors. This work demonstrates how SVC is dependant on the actual AC process.

$$\rho_w(\lambda) = \frac{\frac{\rho_t(\lambda)}{t_g(\lambda)} - \left(\rho_R(\lambda) + \rho_a(\lambda) + \rho_{Ra}(\lambda)\right)}{t(\lambda)}$$

Equation 17

Standard AC

For standard atmospheric corrections as described in Gordon (1998), SVC standard procedures decouple visible and NIR bands. It is possible to reconstruct a targeted TOA signal through the very same physics as AC and compute explicitly the gains (Equation 18).

$$\rho_t^t(\lambda) = t_g(\lambda)\left(\rho_R(\lambda) + \rho_a^t(\lambda) + \rho_{Ra}^t(\lambda) + t^t(\lambda)\rho_w^t(\lambda)\right) \qquad g(\lambda) = \frac{\rho_t^t(\lambda)}{\rho_t(\lambda)}$$

Equation 18

Case of POLYMER SVC

In POLYMER case, the signal is formulated as follow (Steinmetz et al. 2011, Steinmetz et al. 2015).

$$\rho_t(\lambda) = t_g(\lambda)\left(\rho_R(\lambda) + \rho_{ag}(\lambda, c_0, c_1, c_2) + t(\lambda)\left(\rho_w^{mod}(\lambda, \varphi) + \varepsilon(\lambda)\right)\right)$$

Aerosol + glint residual:

$$\rho_{ag}(\lambda, c_0, c_1, c_2) = c_0 T_0(\lambda)\lambda^{p_0} + c_1\lambda^{p_1} + c_2\rho_R(\lambda)$$

Marine model wrt IOP

(φ= set of bio-optical unkwnons = Chl, bbp)

Residual

A spectral matching algorithm minimizing the residual $\varepsilon(\lambda)$ is performed to retrieve the 5 unknowns c_0, c_1, c_2, *Chl* and b_{bp}. With such an AC procedure, it is not possible to use the standard SVC approach.

By construction, POLYMER is invariant to any calibration that follows

$$g(\lambda) = 1 + t_g(\lambda)\left(c_0 T_0(\lambda) + c_1\lambda^{-1} + c_2\lambda^{-4}\right)/\rho_t(\lambda)$$

Equation 19

for any arbitrary c_0, c_1, c_2. As a consequence, the gain computation is unstable and it would be irrelevant to average individual gains.

The proposed solution consists of fixing gains at 3 bands (NIR bands). Visible gains are then derived relative to NIR gains. A numerical approach is proposed for POLYMER SVC.

The figure and table below show an example of gains computed at MOBY. The gains are characterised by a large amount of matchups, relatively low amplitude of gain, good stability and low dispersion.

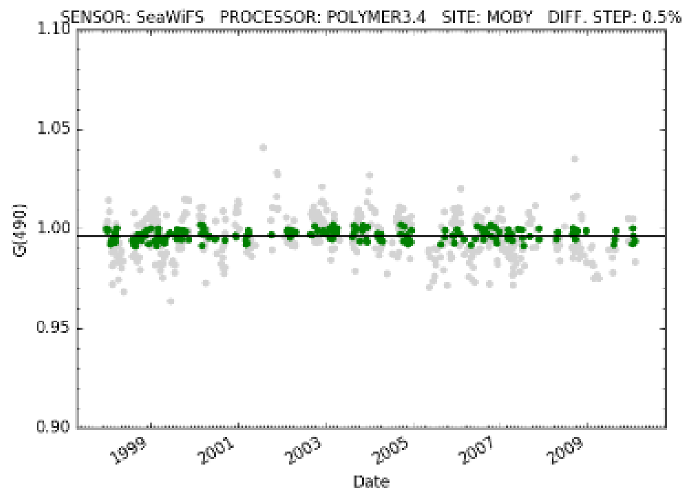

Figure 47: POLYMER gain time series at 490 computed on MOBY.

Table 21: POLYMER gain set computed on MOBY.

λ	412	443	490	510	555	670	865	N
$\bar{g}$	1.006	1.001	0.997	0.992	1(*)	1(*)	1(*)	189
σ	0.005	0.004	0.003	0.002	NA	NA	NA	

(*) fixed gains

Figure 48 and Figure 49 shows the positive effect of SVC implementation on sensor harmonisation. Although not perfect, the procedure provides a much better sensor harmonisation.

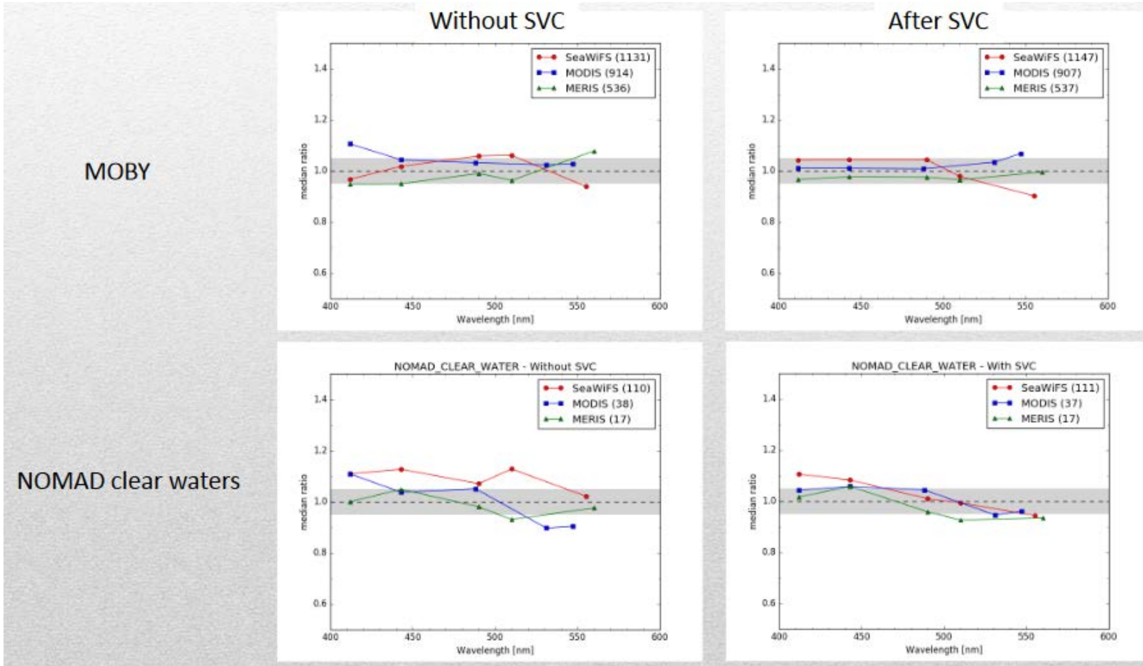

Figure 48: Impact of SVC on sensor harmonisation on clear waters.

As a conclusion of this study, it is pointed out that spectral matching ACs are more and more used in the Ocean Colour community. Within CMEMS, the OC-CCI dataset has the most downloads among all products provided by the OC TAC. Specific SVC must therefore be addressed in complement to the standard case.

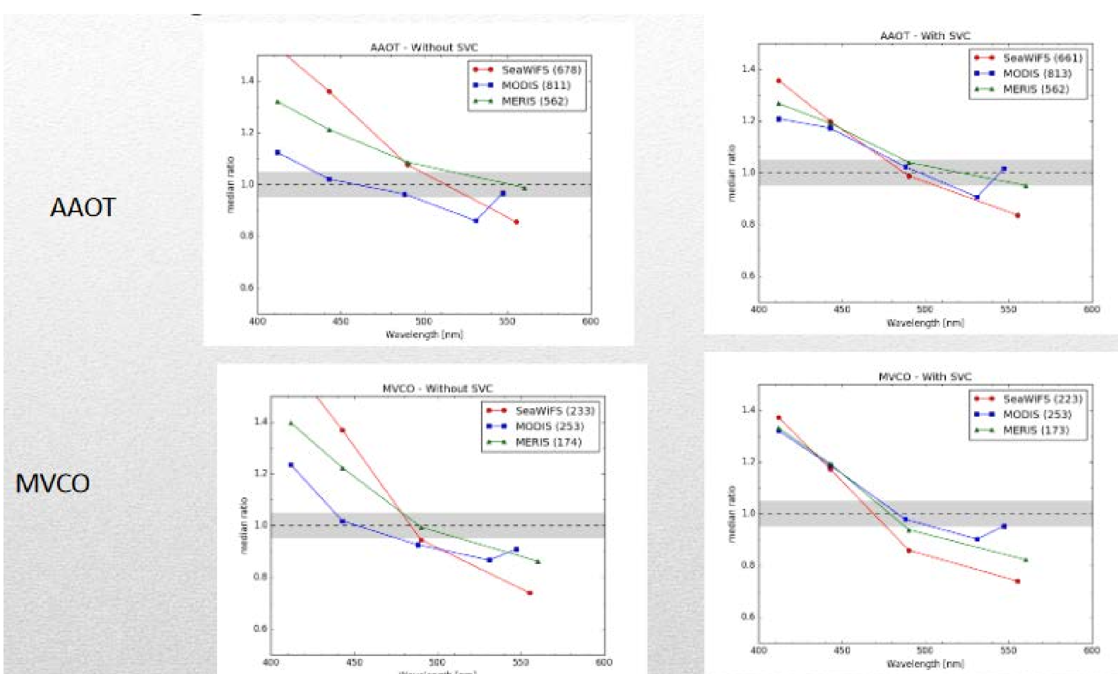

Figure 49: Impact of SVC on sensor harmonisation on AERONET-OC AAOT and MVCO station.

Vicarious Calibration of GOCI.

Jae-Hyun Ahn, Young-Je Park. Korea Institute of Ocean Science and Technology (KIOST)

GOCI represents a very interesting case for vicarious calibration owing to its unique characteristics. Due to being geostationary, it observes, several times a day, the same area of the world (Figure 50). This area covered by GOCI does not include any of the usual areas used in the past for vicarious calibration (South Indian Ocean and South Pacific Gyre for NIR calibration and BOUSSOLE or MOBY for visible bands calibration).

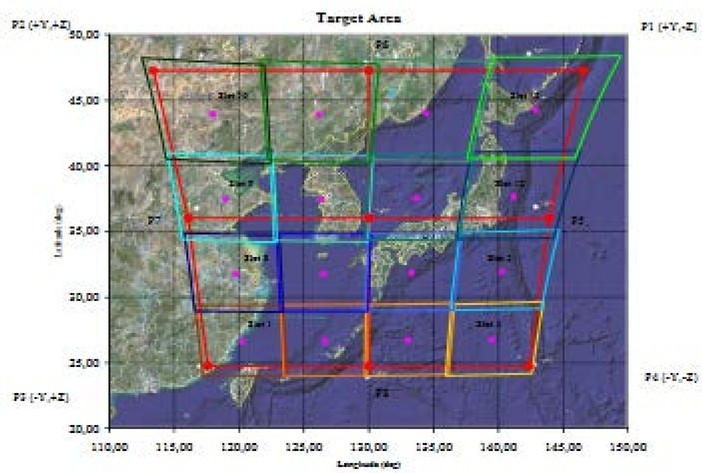

Figure 50: GOCI sampled area.

GOCI atmospheric correction (AC)

GOCI ACs are based on the approach of Gordon & Wang (1994) which is using two NIR bands to estimate aerosol optical properties. A different aerosol multiple-scattering reflectance estimation scheme (SRAMS) has been implemented (Ahn et al., Optics Express, 2015). SRAMS stands for Spectral Relationship in the Aerosol Multiple-Scattering. It estimates aerosol reflectance fraction of the two models in the multiple scattering domain directly without going through the single scattering domain. An empirical polynomial relationship is established through radiative transfer simulation to determine the reflectance of the different wavelengths.

A different turbid water NIR correction scheme has also been implemented (Ahn et al., Ocean Science Journal, 2012).

Vicarious calibration of GOCI

In general, GOCI SVC is based on Franz et al. (2007). First one NIR band is calibrated (745nm) assuming 865nm is perfectly calibrated and a specific aerosol model (maritime 80% relative humidity). Then visible bands are calibrated based on the NIR bands SVC.

For the NIR bands, a new calibration site within the GOCI field of view had to be chosen (Figure 51).

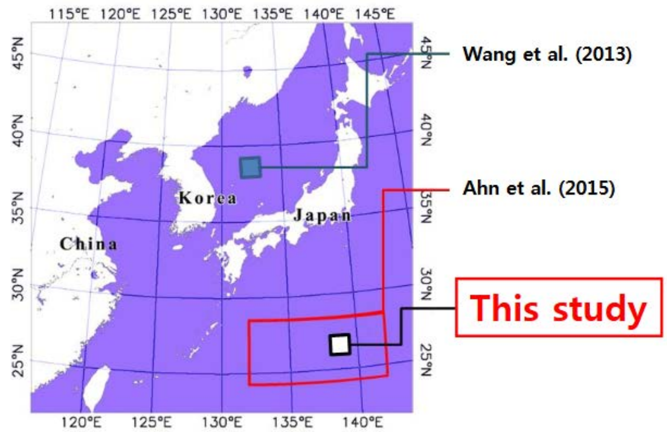

Figure 51: GOCI NIR calibration site.

Figure 52 below shows the derived gain time series at 745nm resulting in an average gain of 0.9893.

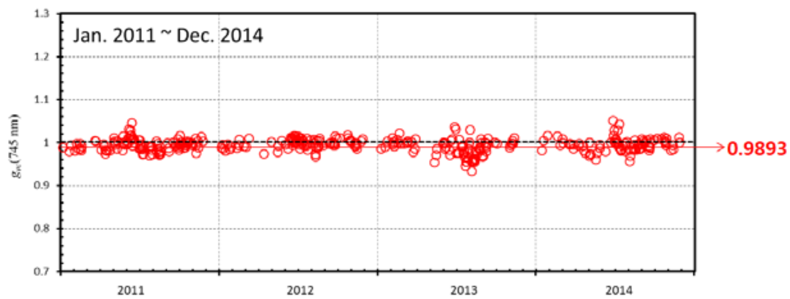

Figure 52: GOCI NIR gain time series at 745nm.

BOUSSOLE and MOBY are the long term radiometric buoys generally used for SVC. None of them being in the field of view of GOCI, visible band calibration has therefore been performed with in situ data collected during extensive field campaigns.

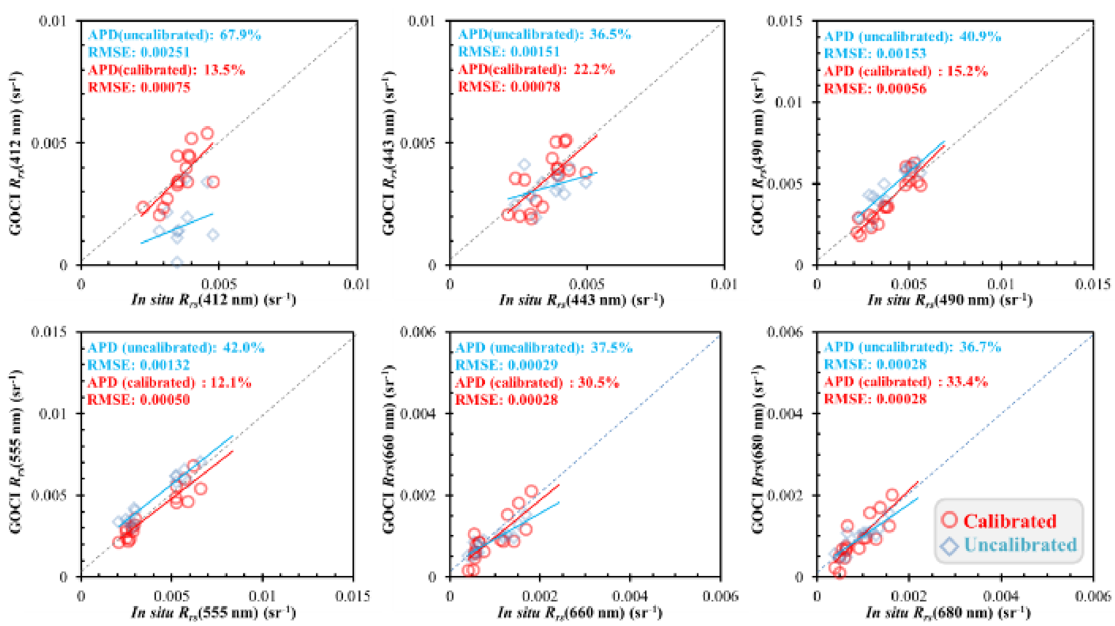

Figure 53: Verification of the vicarious calibration gain factors. Red circles and blue squares represent the GOCI and in situ R_{rs} match – up pairs derived with – and without vicarious calibration, respectively.

The final gain set derived from the current study and compared to previous ones are detailed in Table 22.

Table 22: GOCI gains sets.

	412	443	490	555	660	680	745	865
This study	1.00531	0.99113	0.96805	0.97044	0.97391	0.97698	0.9893	1
GOCI A.C. v.1.3 (Ahn et al., 2015)	1.0105	0.9891	0.9611	0.9186	0.9567	0.9659	0.9613	1.0
NOAA MSL-12 (Wang et al., 2013)	0.9862	0.9753	0.9473	0.9149	0.9245	0.9223	0.943	1.0
NASA MSL-12 (NRL-SSC)	0.9726	0.9520	0.9258	0.8974	0.9007	0.8719	0.943	1.0

Validations

Validation of the vicarious calibration has been performed against in situ data for oceanographic cruises and data collected from AERONET-OC stations Ieodo and Gageocho (Figure 54, Figure 55).

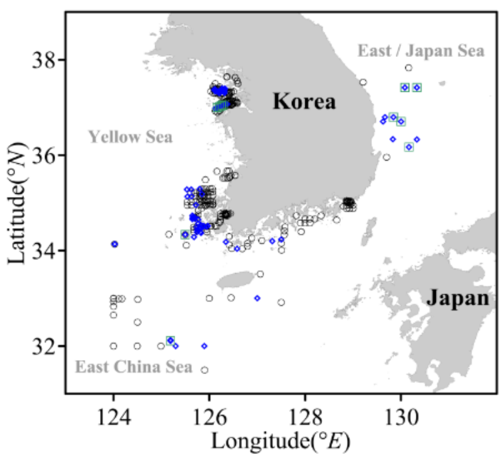

Figure 54: 65 sets of in situ R_{rs} collected from the Korea Ocean Satellite Center (KOSC) cruise campaigns since 2010.

Figure 55: 67 sets of in situ R_{rs} collected from the AERONET – OC observation installed at the Ieodo and the Gageocho Station since 2011 Oct.

Figure 56 presents the validation results derived with the latest atmospheric correction scheme. Figure 57 demonstrates the evolution of Absolute Percent Difference with the different AC versions.

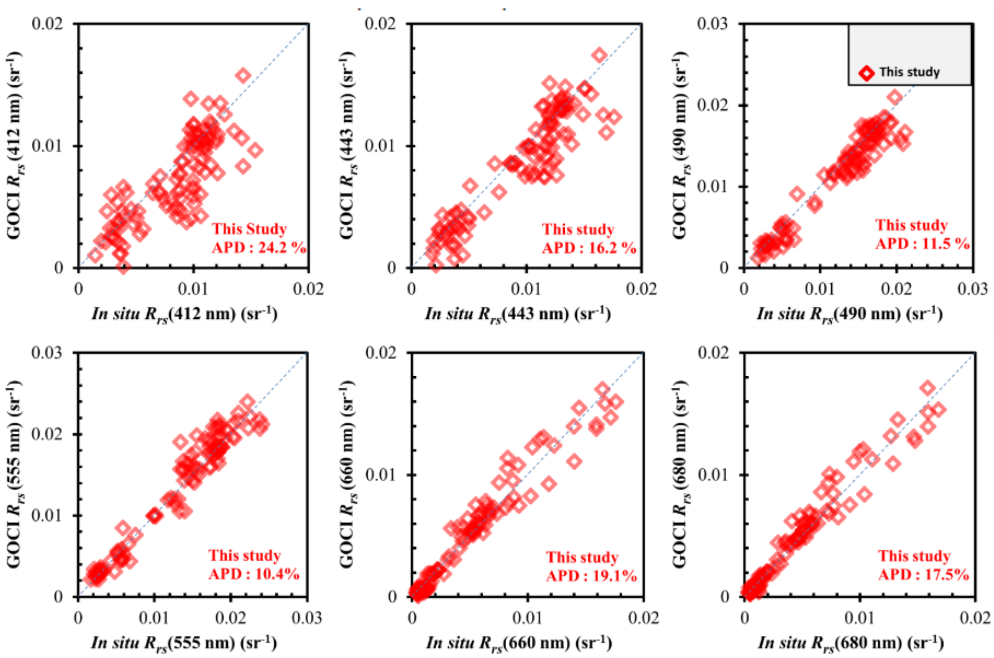

Figure 56: GOCI versus in situ data validation computed AC version 1.5: SRAMS scheme with extended number of aerosol models (Ahn et al., 2016) and water vapour absorption correction at 660, 745, 865nm.

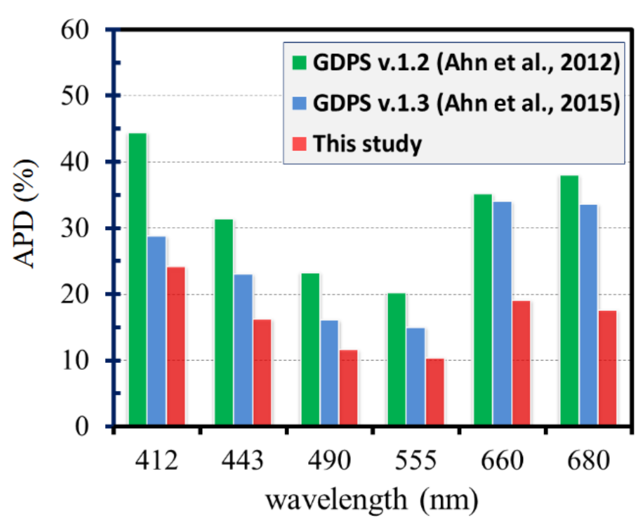

Figure 57: Evolution of the Absolute Percent Difference with the different studies.

Session 10: Copernicus in situ component

Henrik Steen Andersen, European Environment Agency

About the in situ component

The Copernicus in situ component shall provide access to in situ data, serving primarily the Copernicus services (Figure 58). In the Copernicus programme, “in situ data” is defined as observation data from ground, sea or air-borne sensors as well as reference ancillary data licensed or provided for use in Copernicus. As presented in Figure 58, in situ data is an integrated part of the Copernicus programme. As such, the objective of Copernicus in situ component is to provide reliable (e.g. the need for Fiducial Reference Measurements) and sustainable (e.g. the need for long term investment for infrastructure, expertise and personnel) access to in situ data, relying on existing capacities operated at national and European level and global observing systems. Member states’ in situ infrastructures and data are therefore essential contributions to Copernicus. The in situ component is implemented by the Copernicus Services (Figure 58) and by the EEA when overall coordination is required. It is important to note that the prime Copernicus objective is to support and finance operations rather than science.

The implementation strategy is defined at two levels:

- The Service level which responds to data requirements, negotiates access agreements and cooperation with data providers, ensures operational management and processing of in situ data;
- The Programme level evaluates the state of play across services, support data access solutions for multiple services and coordinates the exploitation across all services.

The way forward

The next programme phase –Copernicus II – is being defined in the coming months and will have an impact on the In Situ Component.

The EEA sees a need for clarifying and analysing the potential overlap between the Service and Space Component’s needs for in situ data and supporting infrastructure, and explore if better coordination would be beneficial;
The EEA has initiated two studies on

- Research Infrastructures;
- The in situ data overlap between the Service and Space Component.

Reports from these studies are expect expected Q3 or Q4.

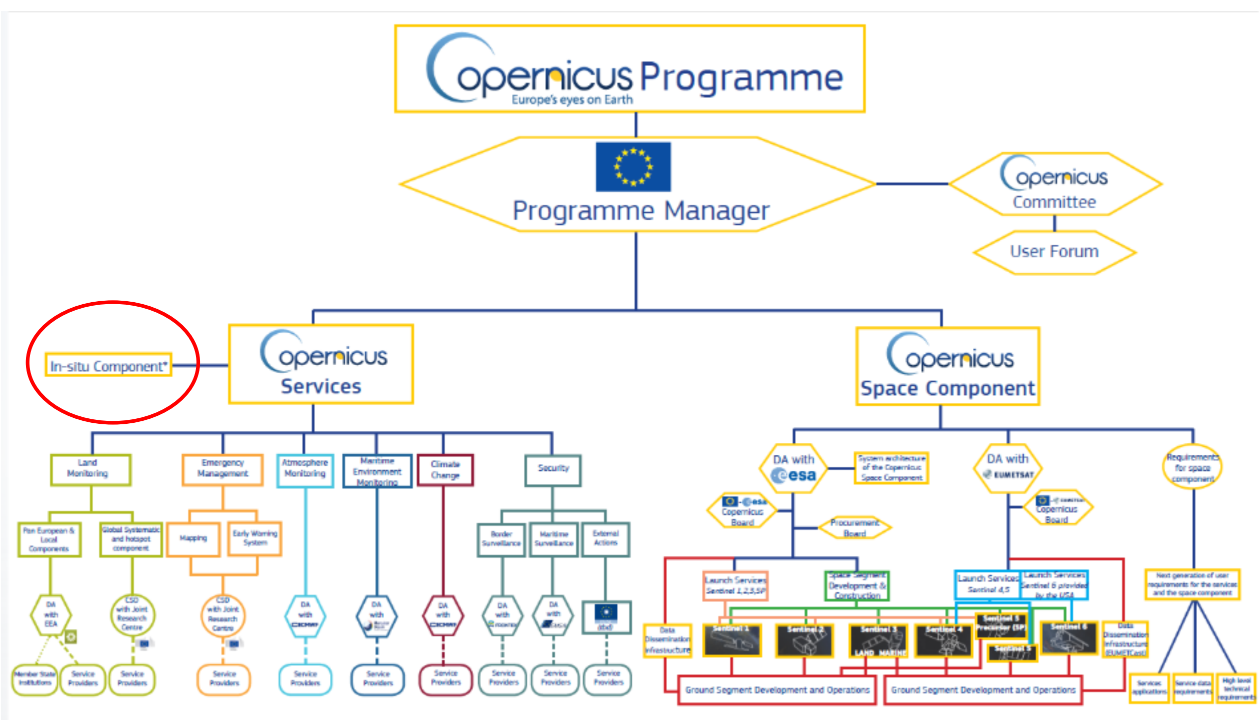

Figure 58: Overview of Copernicus programme.

4 Perspective for future FRM infrastructure

The primary objective of the FRM4SOC workshop was to evaluate the options for future European satellite OCR SVC infrastructure for the Sentinel-3 OLCI and Sentinel-2 MSI series. This evaluation was performed through an open-forum and wide-ranging debate among the international ocean colour community.

- First, the actual need for FRM was carefully analysed through feedback from the Space Components and downstream services.
- Then, historical and state of the art SVC approaches were extensively reviewed to analyse their strengths and weaknesses, to document lessons learned and gather recommendations from world class experts.
    - Reference SVC sites (BOUSSOLE and MOBY) were carefully and extensively reviewed to make sure that all aspects of SVC infrastructure was encompassed in the discussions.
    - Procedures implemented to derive vicarious gains of different sensors were reviewed to make sure that all the diversity of sensor configuration and processing scheme was encompassed.
- Finally, discussions evaluated the number and location of sites, the technology and required resources for optimum OC-SVC infrastructure.

What are the needs for Copernicus?

The operational recommendations

It has been demonstrated by several authors that the current technology available for on-board instrument calibration is not sufficient to reach the required OC product uncertainty. SVC is therefore a mandatory step to achieve sufficient OC product quality. The first question this workshop was intended to address is therefore not about the relevance but about the actual needs of SVC in a Copernicus perspective. Two practical examples presented during the workshop (session 2), and summarized below, illustrate clearly how SVC is crucial to the success of Copernicus.

1. Copernicus down stream operational services like CMEMS ingests nominal Payload Data Ground Segment (PDGS) products to generate and distribute higher-level operational products (level3 and level4) to the community. Sentinel-2 and Sentinel-3 nominal products quality is therefore of prime importance to CMEMS. Nominal (PDGS) and CMEMS products quality will remain poor without SVC.
2. S2 and S3 nominal level2 product quality are under the responsibility of their respective Mission Performance Centres (S2MPC and S3MPC), part the Copernicus space component. Their capacity to provide high-quality products mostly relies on a timely implementation of SVC in the PDGS. This essentially relies on the availability and adequate number of highly precise and accurate measurements, the so-called Fiducial Reference Measurements (FRMs) produced by SVC infrastructures.

Past experience has demonstrated that at best an operational buoy can provide between 1.5 and 2.0 high quality matchups per month for the purpose of SVC, owing to the very high level of quality needed. At this rate, it can take several years before robust vicarious gains can be derived from a single SVC infrastructure. In an operational context, it is therefore crucial to increase the number of operational SVC buoys to reduce this delay. It is recalled here that an SVC infrastructure will provide many more matchups per month for data validation and monitoring purposes, as the quality requirements are less stringent. It is also noted that timely distribution of the SVC in situ data is important for the near-real-time OC data quality monitoring.

In addition, and although out of scope of the present workshop, both Copernicus Space and Services components have stressed the need to improve the availability of radiometric ground measurements in a large diversity of water types to perform operational satellite product validation. An increased number of SVC buoys would clearly facilitate FRM access for satellite data validation. Also, operational systems like AERONET-OC have proven their efficiency. Effort should be made to maintain and increase the number of operational stations from this specific network. New technologies, like autonomous floats, presented in session 7, should be supported in order to cover areas of the World's ocean that are poorly sampled and to support SVC in the early stages of a space mission.

Implementing SVC in the early stages of missions has been very challenging and Copernicus Sentinel-3 OLCI is no exception. Both Services and Space components rely on the availability of FRMs from SVC infrastructure to provide the best quality of OCR from Space. It is recommended by the international ocean colour community that infrastructure is put in place that can operationally maintain the quality of satellite ocean colour products through:

- implementing timely and regular updates of SVC for ocean colour missions,
- performing operational (NRT) product validation.

The current Copernicus operational system does not include a robust infrastructure for SVC but instead, relies on the MOBY infrastructure owned and operated by the United States NOAA in Hawaii, Pacific Ocean and the quasi-operational research infrastructure of the BOUSSOLE buoy in the Mediterranean. This is a significant risk to the performance of S3 OLCI L2 products in the operational context.

The metrological recommendations

Metrological aspects were at the centre of discussion during the workshop as it is essential that the future SVC infrastructure, as well as future validation systems, achieve SI metrological traceability. Requirements for SVC have been studied and documented by several authors in recent years and have confirmed the need for sites with a clear atmosphere and oligotrophic to mesotrophic waters in order to minimize the uncertainties on in situ measurements.

There was a lively discussion on how many vicarious calibration sites would be optimum, but NMIs agreed that, from a purely metrological perspective, several SVC sites would be preferable. Limited resources being taken into account there is a consensus that at least 3 SVC sites are essential to ensure the robustness and necessary redundancy of data provision for sentinel SVC. Ideally more than 3 should be considered.

It is specified by NMIs that the SVC systems could be different in terms of instrumentation and infrastructure providing they are equivalent. End-to-end SI-traceable uncertainty budgets must be derived by careful analyses of the different steps, i.e. from in situ sensor calibration, through data acquisition, to data reduction (including sensor, environment and modelling related sources of uncertainties), and computed following the standardized procedures in the GUM and its supplements. Such practices should be encouraged not only for SVC infrastructures but also for OCR measurements used for validation. If, as recommended, several sites are considered for SVC, a strong international collaboration with an increased participation of NMIs is needed to make the most of the different systems and resources. As NIST has done for MOBY, NPL is developing its capability to support OC-SVC in Europe precisely for this reason.

The question of formally agreeing on equivalence (in the metrological sense) between SVC sites is still open at this stage. The overall recommendation was that the in situ data stream should aim at fully characterizing uncertainties and then attempt to minimize them. Minimizing uncertainty will be achieved, for instance, by increased effort in sensor development and refinement. The specific aspect of uncertainty requirement for SVC is addressed in the OC-VCAL final report (Mazeran et al., 2017).

Different sites will have different atmospheric characteristics. This will influence the computation of vicarious calibration gains. The uncertainty of the derived gains must also be carefully evaluated. Ideally atmospheric measurement should be considered on SVC sites to better characterize the uncertainties on derived gains. The current technologies implemented at BOUSSOLE and MOBY do not allow these kind of measurements, but emerging low weight, low power instruments based on LIDAR systems might be an option in the future.

Operational implementation of vicarious gains coming from different sites can only be considered if there is measurement equivalence between the sites. It was acknowledged that measurement equivalence between sites and using data from different sites to derive vicarious calibration gains is not trivial. Detailed studies to consolidate these factors are therefore to be supported.

From a metrological perspective,

- several SVC sites are mandatory to meet the redundancy requirements for operational activities,
- Mmeasurement equivalence between sites needs to be established,
- an SI-traceable end-to-end uncertainty budget is mandatory,
- minimizing uncertainties at all data acquisition and processing stages is essential.

The current Copernicus operational system does not include a robust infrastructure for SVC but instead, relies on the MOBY infrastructure owned and operated by the United States NOAA in Hawaii, Pacific Ocean and the quasi-operational research infrastructure of the BOUSSOLE buoy in the Mediterranean. This is a significant risk to the performance of S3 OLCI L2 products in an operational context.

The human resources aspect

Both BOUSSOLE and MOBY owe their success to the high degree of motivation and commitment of scientists. From their experience, it is clear that it takes years of effort to train people and develop the capacity to operate OC-SVC infrastructure.

Copernicus has been designed for the long term. Maintaining software and hardware in the long term, and most importantly maintaining personnel and expertise, is also fundamental. This requires that the relevant expert's jobs are secure and that new highly qualified personnel are regularly trained in order to maintain OC-SVC expertise.

Supporting several SVC sites and teams will contribute to securing and guaranteeing the long-term provision of FRM for SVC purposes.

From a HR perspective,

- securing jobs to maintain personnel and expertise within Copernicus in the long term is fundamental,
- regularly train personnel to bring them to a high level of SVC-related qualification is fundamental.

What is the status?

For the time being, ESA and EUMETSAT can rely on MOBY and BOUSSOLE for S3 OLCI SVC.

- MOBY is so far the only fully operational buoy on which we can rely for SVC. It has more than 20 years experience in sensor calibration and characterisation through strong involvement of NMIs (NIST). It can rely on secured funding from US agencies (NASA and NOAA) to ensure hardware purchase, system maintenance, risk mitigation and staff salaries.
- BOUSSOLE is technically operational yet it does not have secured funding post 2020. This system has proven its potential for SVC in the MERIS 3rd and 4th data reprocessing. Great efforts and investments have been made in recent years to consolidate the end-to-end uncertainty budgets, full instrument characterization and full environmental quantifications on the final uncertainty budget through collaboration with NMIs (NPL). Throughout the last 15 years, BOUSSOLE has consolidated a strong expertise and significantly improved the end-to-end process from data acquisition to radiometric products delivery to the community. As a demonstration of BOUSSOLE evolution, in the past four years, the system has reached a 97% deployment success. BOUSSOLE in addition to its SVC capacity has a unique potential for data validation and bio-optical research and is deployed in case 1 waters offering a chlorophyll seasonal dynamic.

Neither MOBY nor BOUSSOLE are directly supported by Copernicus. The risk of losing one or both and therefore losing the capacity to deliver robust EO products must therefore also be taken into consideration.

For the time being,

- two OC-SVC infrastructures: MOBY and BOUSSOLE are available with different operational capabilities,
- BOUSSOLE is a pre-operational system that has a joint purpose of OC-SVC and bio-optical research,
- the European site (BOUSSOLE) has not secured funding in the long-term,
- none are funded by Copernicus.

The current Copernicus operational system does not include a robust infrastructure for SVC but instead, relies on the MOBY infrastructure owned and operated by the United States NOAA in Hawaii, Pacific Ocean and the quasi-operational research infrastructure of the BOUSSOLE buoy in the Mediterranean. This is a significant risk to the performance of S3 OLCI L2 products in an operational context.

The final consensus

The current Copernicus operational system does not include a robust infrastructure for SVC but instead, relies on the MOBY infrastructure owned and operated by the United States NOAA in Hawaii, Pacific Ocean and the quasi-operational research infrastructure of the BOUSSOLE buoy in the Mediterranean. This is a significant risk to the performance of S3 OLCI L2 products in an operational context.

Discussions held during the workshop to address this issue have converged toward the consensus that, taking for granted that MOBY will be maintained, two operational sites for SVC have to be maintained in Europe. There is strong evidence that support this consensus:

- CEOS and experts attending the FRM4SOC workshop recommend redundancy of operational systems;
- from a purely metrological perspective, multiple systems are recommended to ensure robustness of SVC;
- Copernicus operations (CMEMS, MPCs, PDGS's) have stressed the need for more SVC sites for their activities,;
- maintaining two sites in Europe will secure the existing expertise, knowledge and knowhow, develop new expertise, stimulate technical, scientific and industrial innovation and create jobs;
- finally, from a risk mitigation perspective, it is essential that Copernicus owns/controls its vicarious calibration capacity to ensure S2 and S3 product quality for the next two decades.

Ideally, multiple systems with different infrastructure would be preferred. The potential development of a new SVC infrastructure (different from MOBY and BOUSSOLE) within the EU has been envisaged. It would surely stimulate research and development in Europe but this would also represent a very high level of effort, time and cost to fully characterize the different systems. From that perspective, building upon existing systems and expertise (BOUSSOLE and MOBY) would be more cost effective. From these initial considerations, the general consensus from a European perspective is that Copernicus should in priority:

- maintain BOUSSOLE, its knowledge and knowhow, and strengthen, consolidate and secure the activity for long-term operations;
- support the development of a second fully operational European infrastructure in a suitable location. A site located in the Eastern Mediterranean Sea, off the coast of Crete, has been pointed out from initial studies (Zibordi and Melin, 2017; Zibordi et al., 2017) as a very good candidate; although other options (European and none European) are not excluded at this stage.

For the second SVC infrastructure, a MOBY-Net system would be recommended as it would:

  - offer a technologically proven system within a realistic timeframe for Copernicus needs;
  - reinforce collaboration of world class experts and centres of excellence.

It is acknowledged that increased international collaboration must be supported, primarily with the BOUSSOLE and MOBY groups, to develop the required local infrastructure and to train new teams for the maintenance and operations of a second SVC infrastructure.

It is also acknowledged that scientific and research activities should be included on SVC sites as it will improve data quality in the long term.

Final Consensus:

- upgrade BOUSSOLE to fully operational status,
- develop a new infrastructure based on MOBY-Net in a suitable location, e.g. the Eastern Mediterranean,
- train a new group to operate a second SVC,
- support long-term interaction of the different SVC operations groups,
- support scientific and research activities on SVC sites.

Evaluation of the different options for a new SVC site

Optimum location

Zibordi et al. (2017) have provided a detailed analysis of potential sites for SVC. It is acknowledged that the published study is not exhaustive in terms of location but it clearly points out the environmental strengths and weaknesses of the different studied locations. For the development of an additional SVC site, several options of location should be short-listed for a detailed regional and local oceanographic and atmospheric analysis. Aerosol optical thickness, oceanic currents, swell and seasonal variability of the selected site should be at a minimum to facilitate the operations and reduce uncertainties of the buoy measurements.

In addition to environmental considerations, other aspects described below have to be considered to push further Zibordi's initial analysis.

Operational aspects

Operations at sea are not trivial. They are costly, time consuming, and highly demanding on human resources and preparation. They get increasingly costly and complicated the further you go out at sea. Figure 59, extracted from the BOUSSOLE consolidated budget, recalls that ship time, together with salaries, is the second largest cost with 15% of the total. For an operational SVC infrastructure, a compromise has to be established as a reasonable distance from the onshore facility to limit operational costs, but also far enough from shore to limit the risks of anthropic perturbation, damage or vandalism (commercial shipping route, recreational or fishing areas ...). This point should carefully be accounted for in the next phase of EU SVC capacity development.

Cruises are mandatory for buoy maintenance and auxiliary data collection. They are also a unique vehicle for collaboration, science, and inter-comparison exercises. Close interaction between SVC teams should therefore be supported. Close interaction with EU research labs should also be supported to leverage scientific and technological interactions and therefore build up EU capacity to achieve SI traceability in a large diversity of institutions. This effort will benefit both Copernicus Space and Services components.

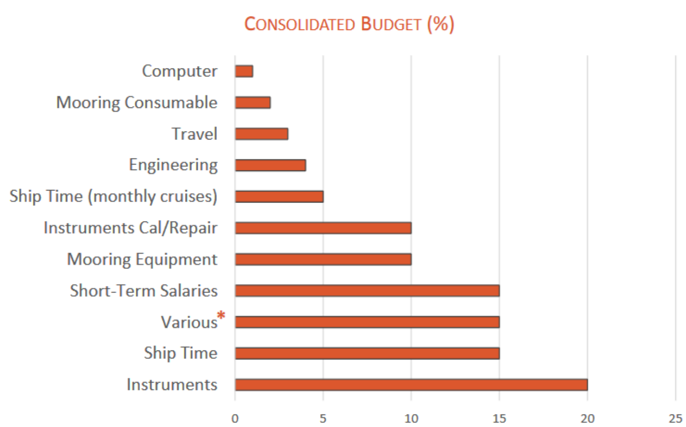

Figure 59: BOUSSOLE consolidated budget. *various includes: lab levy, cruise instruments, instrument shipping and custom fees, external divers, publications, laboratory consumables, insurance costs.

Management aspects

Involvement of motivated people in long-term activities is crucial, as is feeding this motivation over time. Ideally the team set-up should emphasize a high dynamic range of capabilities of individuals, and practically try to fit tasks and responsibilities to people's expertise and will. Continuous feedback between operational activities and science is a key factor to succeed over the many years these facilities will need to operate.

Trade off matrix of the different options

The consensus reached by the end of the workshop is that BOUSSOLE should be maintained and supported with a second SVC site in order to secure expertise, improve redundancy and increase FRM data availability for a swift implementation of SVC. The Eastern Mediterranean has been identified as a very good candidate particularly for its very good oceanic and atmospheric conditions. The different European options mentioned by Zibordi et al. (2017), in addition to the East Indian Ocean also mentioned as a very good site, are analysed in Table 23 below. This table in no way represents a final choice for a second potential site, as further and more detailed analyses would be required, in particular by using in situ data to confirm the local oceanic and atmospheric characteristics, which have only been for the moment determined by using satellite-derived products.

Two conclusions can nonetheless be taken:

- if the installation of a potential new site is restricted to European EEZ, from the research activities carried out in recent years and from the analysis of the table below, there is a consensus that the Eastern Mediterranean would be a suitable and complementary site to BOUSSOLE. In addition to its suitable oceanic and atmospheric environment the Crete area benefits from the existence of a physical oceanography lab (the Hellenic Centre for Marine Research) with easy access to harbour and ship facilities, as well as some existing expertise in marine optics;
- if other locations (outside the European EEZ) could be considered, the Australian Western coast would also represent a very good location.

More specific analysis should be performed on potential new SVC sites for a detailed local atmospheric and oceanographic analysis in order to identify an optimum SVC infrastructure location for the second site and evaluate:

- operational costs;
- local group interest in OCR and need for training.

Table 23: Trade off matrix of the different options.

	BOUSSOLE (reference)	MSea	SoS	BSea	NAO	EIO	Bay of Biscay
environment							
mean tau(865) (3)	+++	++	++	++	+++	+++	TBC
mean (α)(3)	++	++	++	++	++	+++	TBC
Mean R_{rs}(555) (3)	++(1)	+++	+++	+	+	+++	TBC
Mean *Chl* (3)	++(1)	+++	+++	++(1)	++(1)	+++	TBC
Current	+++ 3cm.s^{-1}	5-20cm/s(2)	(2)	<50cm/s	(2)	(2)	TBC
Waves	+++($H_{1/3}$)~1m	0.3-1m(2)	(2)	<1.5m	(2)	(2)	2.5m
Potential matchups (4)	+++	+++	+++	+++	+	++	TBC
risks (5)	Very limited	Limited(2)	Limited(2)	Limited(2)	(2)	Limited(2)	Limited(2)
On-shore facility							
Potential Institution	**LOV (FR)**	**HCMR (GR)**	**CRN (Sicily/IT)**	**COB (ES)**	**UoA (PT)**	**Curtin Uni. (AU)**	**Santander IEO (ES)**
Main relevant expertise	OCR	Ph.Oc.,Ma,Bio	OCR	Fi,Ma,Bio,Ma,Che	Fi, Ma, Bio	OCR	Oc, Cl, Fi, Bio
Distance from buoy	32nm/59km	3/30nm;5/58km	3.5nm/5.5km	25nm/46km	(2)	16nm/30km	22nm/41km
Long term mooring exp.	+++	+++	++	++	TBC	+++	++
Distance from harbour	+++	+++	+++	+++	(2)	+++	+++
Ship facility	+++	+++	++	+++	TBC	+	+++
Space for new facility	YES (limited)	+++	+++	+++	TBC	YES	-
Lab personnel							
Expertise in OCR	+++	++	+++	-	-	+++	Medium
Equipment	+++	++	+++	-	TBC	+++	++
Need for training	NA	Medium	Consolidate	Extensive	Extensive	Consolidate	Consolidate
Issues	None	None	Mooring in development not suitable for SVC (too close to shore)	Fairly closed from BOUSSOLE, oceanographic variability, no local expertise in OCR	Limited number of matchups, oceanographic variability, no local expertise in OCR	Not European	Suitability for SVC to be assessed
Strength	15 years experience in SVC Expertise has to be maintained	Some local expertise in OCR Good environmental condition Good local infrastructure	Coastal OCR buoy in development	Large oceanography group Good infrastructure		Local expertise in OCR National interest in EO data (Sentinel data Hub)	Research groups in Oc. and climate variability Experience in long term mooring
Overall evaluation	Very good	Very good	Good	Medium	Medium	Very good	Medium

(1) seasonal spring bloom (2) would require specific local study (3) from Zibordi et al. 2017 (4) from Zibordi et al. 2017 based on *chl-a*<=0.2 based on SeaWiFS and experience from MERIS and S3-OLCI (5)Vicinity from shipping routes, fishing or recreational areas. MSea: Eastern Mediterranean, SoS: South of Sicily, BSea: Balearic Sea, NAO: North Atlantic Ocean, EIO: East Indian Ocean.

5 Conclusion

The current Copernicus operational system does not include a robust infrastructure for SVC but instead, relies on the MOBY infrastructure owned and operated by the United States NOAA in Hawaii, Pacific Ocean and the quasi-operational research infrastructure of the BOUSSOLE buoy in the Mediterranean. This is a significant risk to the performance of S3 OLCI L2 products in an operational context.

The discussions held during the workshop have reached the consensus that two SVC sites should be operated in Europe to ensure the long-term quality of Copernicus products. BOUSSOLE should be maintained and upgraded to full operational status while a second site should be implemented. For the first site (BOUSSOLE), the main point is to secure long-term operations funding as this is one missing step to gain full operational status. Funding for refurbishment of existing infrastructure and instrument is also needed. The development of a second SVC infrastructure implies that:

- further studies should be supported to carefully identify the location of a new SVC site and the best local group to ensure the operations;
- the new local group should be trained through interaction with international experts;
- the necessary on-shore infrastructure (system maintenance and rotation, calibration labs, data processing and distribution) should be developed or upgraded.

For both SVC sites, it is stressed that:

- a good metrological foundation with 'hands-on' involvement of NMIs at all stages of development and operations is a key component in providing the best possible OC-SVC infrastructure and measurements. This includes maintaining SI-traceability and full uncertainty budgets at all points in the measurement and processing chain;
- long-term investment is critical – this should be a budget that recognises not only the cost of the initial purchase and installation of the infrastructure but also include adequate funding for on-going operations in terms of updates/upgrades, maintenance, and consistent staffing that develops and retains expertise. The BOUSSOLE and MOBY teams, after more than 15 years experience each, are now able to provide detailed budgets, hardware and human resources requirements for SVC infrastructure operations.

The next phase of a European operational SVC program should therefore focus on defining the project plan and costing for the long-term maintenance of BOUSSOLE and the development of a second SVC site.

For the second site, the choice of a MOBY-Net should be confirmed in coordination with the different agencies (ESA, EUMETSAT and NASA which is responsible for the initiative of MOBY-Net) then a further analysis including the local environment, the local facilities, and the need for staff training should be carried out to confirm the location. The realization of the new SVC infrastructure and capacity should benefit from BOUSSOLE and ideally MOBY experience.

Copernicus has committed to the operation of an outstanding Earth observation capacity. The quality of generated ocean colour data essentially relies on the capacity to perform SVC. If we are to achieve the best possible outcome of the Sentinel missions, there is a large agreement in the community that it is essential that long-term resources are made available for the operation and maintenance of at least two SVC infrastructures in order to satisfy the Copernicus long-term perspective and current/evolving user needs for ocean colour products and services. Without such an investment, a risk to the performance of S3 OLCI L2 products in the operational context remains.

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7 Appendix: Potential site inquiry

BOUSSOLE/LOV (reference)

1. Lab description
   a. Research groups, main expertise, number of personnel

   > The BOUSSOLE team sits within the Marine Optics, Remote Sensing and Biogeochemical Applications (OMTAB) research group at the *Laboratoire d'Océanographie de Villefranche* (LOV), which is part of the *Observatoire Océanologique de Villefranche* (OOV; the marine station belonging to CNRS and UPMC)
   > Main expertise : marine optics, bio-optics, radiative transfer in ocean and atmosphere, ocean colour remote sensing (validation and vicarious calibration activities, algorithm development, data processing).
   > The number of FTE per entity is given below:
   > 4-BOUSSOLE, 22-OMTAB, 75-LOV, 180-OOV

   b. Expertise in Ocean Colour Radiometry (OCR) and/or marine optics

   > *High*

   c. Which equipment related to OCR and or marine optics?

   > OMTAB *in situ* equipment:
   > Two fully equipped BOUSSOLE buoys (developed by the BOUSSOLE team in partnership with ACRI-IN and Satlantic, equipped with Satlantic hyperspectral and PAR radiometers, WET Labs C-Stars and ECOFLNTUs, Hobilabs HS-IV)
   > Profiling and surface radiometers (Biospherical C-OPS, Satlantic TSRB, Trios RAMSES)
   > Radiance cameras (CamLum, developed by OMTAB in partnership with CIMEL)
   > ProVal floats (developed by OMTAB in partnership with NKE)
   > BGC-Argo floats (developed by OMTAB in partnership with NKE)
   > Spectrophotometers (WET Labs AC-9, Hobilabs *a*-sphere)
   > Backscattering meters (WET Labs ECO-BB and Hobilabs Hydroscat-VI)
   > Transmissometers (WET Labs C-Star and AC9, Hobilabs *gamma*)
   > Chla and CDOM Fluorometers (WET Labs ECO et WetStar, Chelsea Mini-track et Fast-track)
   >
   > OMTAB *Lab* equipment:
   > Spectrophotometers (Perkin Elmer Lambda 19 and 850 with integratin sphere, Ultraphat)
   > HPLC (Agilent technologies 1100 and 1200 series, OOV hosts the French national HPLC service *Saphig* under the responsibility of OMTAB)

   d. Distance from harbour facility

   > The OOV-LOV facility is 5 km from the Nice Harbour, where the ship used for monthly servicing cruises have access. Smaller ships can have direct access to the Villefranche harbour, at the doorstep of the OMTAB facilities.

   e. Ship facility (number, size, range)

   > Sagitta III, 12 m, 20 nm from the coast with derogation for the BOUSSOLE/DYFAMED zone
   > Tethys II, 25 m, Mediterranean Sea (used for monthly servicing cruises to the mooring site)
   > R/V are managed by DT-INSU (CNRS). Other ships are accessible under request: http://www.flotteoceanographique.fr/La-flotte/Navires

   f. Is there space for new facilities construction on laboratory site?

   > Yes, but limited

   g. Would your lab have an interest in managing a radiometric buoy?

   > *Yes*

2. Mooring or monitoring site(s)
   a. Is there a permanent mooring or monitoring site managed by the lab?

   > *Yes*

   b. If so, what is measured and/or monitored?

   > The BOUSSOLE mooring measures:
   > - radiometry: hyperspectral Ed and Lu at two depths + Hyperspectral Es + PAR
   > - IOPs: backscattering coefficient (4 wavelengths), beam attenuation coefficient (660 nm, two depths)
   > - chlorophyll-a fluorescence and turbidity (two depths)
   > - ancillary: depth, temperature, salinity, tilt, heading, mooring strain
   > Other mooring managed by the lab perform hydrological and biogeochemical measurements.

   c. Is the mooring site in vicinity of shipping routes, fishing areas or recreational areas?

No major shipping route. Some recreational fishing activity in summer.

d. Is the mooring site under GSM coverage?

Yes (though the public GSM is not sufficient for data transfer, a directional dedicated GSM antenna would be necessary)

e. How long has the site(s) been monitored?

The BOUSSOLE site is monitored since 2001 with monthly cruises and since 2003 with a mooring. The DYFAMED site, 3 nm from BOUSSOLE, has been monitored since 1988.

f. Distance from the coast

32 nm

g. Mean current and waves on site(s)

Mean current is estimated at ~3 cm s^{-1}
Mean H1/3 is ~1 m
See, e.g., http://esurfmar.meteo.fr/real-time/html/dyfamed.html

Eastern Mediterranean (HCMR)

1. Lab description
   a. Research groups, main expertise, number of personnel

   Hellenic Centre for Marine Research, Institute of Oceanography.
   Marine bio-optics group.
   Expertise in IOPs, AOPs, chlorophyll-a (oxidation, HPLC), particle absorption, CDOM, SPM, POC, DOC
   3 Principal researchers, 1 electronics engineer, 3 technicians, 2 PhD students

   GIS and remote sensing group
   2 Principal researchers, 2 technicians, 1 PhD student

   b. Expertise in Ocean Colour Radiometry (OCR) and/or marine optics

   medium

   c. Which equipment related to OCR and or marine optics?

light attenuation	WET Labs transmissometer 660 nm
light attenuation	Chelsea transmissometer 470 nm
light attenuation	WET Labs ac-s (hyperspectral)
absorption	WET Labs ac-s (hyperspectral)
optical backscattering	WET Labs ECOBB3B 470, 532, 650 nm
particle-size	LISST-deep
radiance	TriOs radiometer
irradiance	TriOs radiometer
surface irradiance	TriOs radiometer

   d. Distance from harbour facility

   Depending on site location chosen: 50 km, 15 km, 0.5 km

   e. Ship facility (number, size, autonomy, range)

   3 ships: R/V Aegaeo, R/V Philia, R/V Alcyon
   63 m, 33 m, 15 m
   15 days, 7 days, 1 day
   500 nautical miles, 200 nautical miles, 100 nautical miles

   f. Is there space for new facilities construction on laboratory site?

   Yes

   g. Would your lab have an interest in managing a radiometric buoy under EU funding?

   Yes

2. Mooring or monitoring site(s)
   a. Is there a permanent mooring or monitoring site managed by the lab?

   Yes

   b. If so, what is measured and/or monitored?

   HCMR operates 6 (2 near Crete) permanent multi-parameter deep-sea moorings measuring air pressure, air temperature, wind speed and direction, wave height, water temperature, salinity, turbidity, oxygen, chlorophyll-a, PAR, current speed and direction and more, at depths up to 1000 m and sediment traps up to 4600 m depth. The latter provide settling particles analysed for total mass and constituent fluxes at 1 month temporal resolution.
   Moreover, it operates a deep-sea observatory on the seafloor at 1800 m depth (Pylos).
   Multi-parameter time series available at: http://poseidon.hcmr.gr/onlinedata.php

   c. Is the mooring site in vicinity of shipping roots, fishing areas or recreational areas?

   No

   d. Is the mooring site under GSM coverage?

   Yes

e. How long has the site(s) been monitored?

Varies between 5 and 11 years

f. Distance from the coast

Varies between 3 and 30 nautical miles

g. Mean current and waves on site(s)

Mean currents 5-20 cm/s and mean wave height 0.3-1 m

Straight of Sicily (CNR, ENEA)

1. Lab description
    a. Research groups, main expertise, number of personnel

The research team is composed of two groups : CNR - Ocean Satellite monitoring and marine ecosystem studies group (GOS) and ENEA - Laboratory for Earth Observations and Analyses. The CNR and ENEA groups are collaborating under a national inter-agency agreement.
CNR-GOS has a long experience on OC data processing, in situ radiometric measurements for OC validation and algorithm design, atmospheric dynamics and composition, oceanic and atmospheric radiative transfer modelling. Since the beginning of the SeaWiFS mission, as part of the Italian effort of OC CAL/VAL CNR-GOS carries out regular oceanographic campaigns in the Mediterranean to acquire meteorological, hydrographic, and biological data, as well as in-water and above-water optical measurements. CNR is leading the Ocean Colour Thematic Assembly Center (OCTAC) within the Copernicus Marine Environment Monitoring Service (CMEMS) and is part Sentinel-3 OLCI-SYN QWG. CNR scientists were also PIs of an AERONET-OC site and of an automated shipborne radiometry data stream for OC validation. Starting from mid 2016, GOS deployed and manage in-water radiometers on the ENEA Lampedusa Buoy (close to the Sicily channel) as part S3VT CNR's activities. GOS consists in 25 scientist and technicians.
The ENEA Laboratory has a long term expertise in the study of atmospheric radiative processes and in managing complex infrastructures, including the Station for Climate Observations on the island of Lampedusa (http://www.lampedusa.enea.it). The Station at Lampedusa contributes to international measurement networks (ICOS, EMSO, ACTRIS, AERONET, NOAA cooperative air sampling network, etc) and has been recently equipped with an oceanographic buoy deployed 5 km south-west of the island.
ENEA has a consolidated experience in measurements of solar and infrared radiation, of atmospheric composition and structure, with particular focus on aerosol optical properties, temperature structure, greenhouse gases, and water vapour. The ENEA expertise includes analysis of radiation data, data retrieval, radiative transfer modelling, as well as use of data from satellite or airborne sensors. Within this context, ENEA has a consolidated expertise in the characterization and calibration of spectral and broadband instruments for radiation measurements. The ENEA personnel involved in the measurements and analyses made at Lampedusa is constituted by 10 people (7 researchers, 2 technicians, 1 post-doc).
CNR runs permanent ocean fixed platmforms (http://www.ismar.cnr.it/infrastructures) including the "Acqua Alta" platform and atmospheric observatories (http://www.isac.cnr.it/) part of global networks as EMSO, NDACC, AERONET, EARLINET and LiNET.

    b. Expertise in Ocean Colour Radiometry (OCR) and/or marine optics

High

    c. Which equipment related to OCR and or marine optics?

- Satlantic Profiler with 3 OCR 507 radiometers for Lu, Eu and Ed measurements.
- 1 Satlantic OCR 507 Radiometer for Es
- IOPs package composed of: ACs WetLabs for attenuation and absorption measurements, VSF3 WtLabs for scattering measurements, Sea-bird Electronics MICROCAT SBE-37 SI for temperature and salinity measurements
- PHYTO-PAM-II (Heinz Walz Company) for the photosynthetic performance of the phytoplankton
- High Performance Liquid Chromatography (Agilent 1260) for pigment in-situ analysis
- Spectrophotometer UV/Vis Lambda 35 Perkin Elmer for absorption in-situ measurements
- Laboratory facilities (pumps, filtration systems, etc..) for in-situ sampling
- Satlantic HyperOCR spectrometers
- Multi-band radiometers, spectrometers, broadband radiometers and band sun photometers for atmospheric radiation measurements
- Irradiance calibration system with 1000 W NIST traceable FEL lamps

    d. Distance from harbour facility

The Station for Climate Observations is 2 km from the Lampedusa harbour

    e. Ship facility (number, size, autonomy, range)

CNR has several ship facilities that can be used by CNR Institute/researchers/laboratories for their researches.
The major ships are:

Nave Minerva UNO:

L.F.T.	46.6 m
Width	9.0 m
Draft min/max	4.50 m
Tonnage	615 TS
Autonomy	30 days
Ship & scientist Pesonnel	29 persons

Nave Dallaporta

L.F.T.	35.70 m
Width	7,67 m
Draft min/max	3.50 m
Tonnage	286 TS
Autonomy	10 days
Ship & scientist Pesonnel	20 persons

In addition the CNR has 3 ocean laboratories along the coast of Sicily: Capo Granitola, Messina, Mazara del Vallo. These laboratories have access to small ships (length of 10 m) for their research used also for buoy maintenance. More details at: https://www.cnr.it/en/node/79.

f. Is there space for new facilities construction on laboratory site?

Yes

g. Would your lab have an interest in managing a radiometric buoy under EU funding?

Yes

2. Mooring or monitoring site(s)
   a. Is there a permanent mooring or monitoring site managed by the lab?

   Yes

   b. If so, what is measured and/or monitored?

The Lampedusa Buoy is equipped with:

- 7 Satlantic OCR 507 Radiometers: 1 radiometer for Es at the top of the buoy and 6 radiometers distributed at two depths for Lu, Eu and Ed measurements;
- 1 ECO Triplet WetLabs configured for Chlophyll-a, CDOM and backscatter measurements

The other oceanographic instruments installed on the buoy are CTD, O_2, and temperature sensors at various depths and above-water instruments for meteorological parameters, surface energy budget studies, and spectral down and upwelling radiation. The buoy is open to further expansions and developments.

c. Is the mooring site in vicinity of shipping roots, fishing areas or recreational areas?

The mooring is far from shipping routes and relatively far from fishing areas.
The Pelagie Islands Marine Protected Area is about 3.5 nm from the buoy.

d. Is the mooring site under GSM coverage?

Yes

e. How long has the site(s) been monitored?

Since September 2015

f. Distance from the coast

3.3 nm

g. Mean current and waves on site(s)

Direct in situ current and wave measurements are not presently available on the buoy site. Wave height can be inferred from pressure measurements made at 1 and 2 m depth along the elastic beacon body.

The most probable significant wave height is about 1 m in winter, 0.3 m in spring, 0.2 m in summer, and 0.3 m in autumn.

The calm conditions (significant wave height less than 0.5 m) frequency of occurrence is 13% in winter, 20% in spring, 57% in summer, and 30% in autumn.

These values are based on long time series model reanalysis: CNR Sicily channel ocean circulation model & ENEA WAM wave model. These two regional models run operationally proving also forecasts of the status of ocean currents and waves in the entire *Mediterranean Sea including* Sicily channel region.

Balearic Sea (COB)

1. Lab description
   a. Research groups, main expertise, number of personnel

      Research groups in Oceanography and climate variability, fisheries and biodiversity.
      Around 100 people working.

   b. Expertise in Ocean Colour Radiometry (OCR) and/or marine optics

      poor to medium

   c. Which equipment related to OCR and or marine optics?

      None

   d. Distance from harbour facility

      1km

   e. Ship facility (number, size, autonomy, range)

      At least, every 3 months the RADMED monitoring program is covering a standard section NE of Menorca (4 stations). Using IEO multipurpose Research Vessels (R/V Ramón Margalef, R/V Ángeles Alvariño, R/V Francisco de Paula Navarro)

   f. Is there space for new facilities construction on laboratory site?

      Yes

   g. Would your lab have an interest in managing a radiometric buoy under EU funding?

      Yes

2. Mooring or monitoring site(s)
   a. Is there a permanent mooring or monitoring site managed by the lab?

      Yes, a CIESM HYDROCHANGES sub-surface mooring. http://www.ciesm.org/marine/programs/hydrochanges.htm

   b. If so, what is measured and/or monitored?

      Salinity, temperature and currents at the sea floor (2500 m depth)

   c. Is the mooring site in vicinity of shipping roots, fishing areas or recreational areas?

      No

   d. Is the mooring site under GSM coverage?

      No

   e. How long has the site(s) been monitored?

      Since 2007

   f. Distance from the coast

      25 miles

   g. Mean current and waves on site(s)

      Mean waves: less thas 1.5 m significant wave height
      mean currents: less than 0.5 m/s

Santander IEO Centre

IEO answered the site preliminary inquiery although not initially solicited. There colleagues from the Balearic Sea communicated the inquiery

1. Lab description
   a. Research groups, main expertise, number of personnel

      Research groups in Oceanography and climate variability, aquaculture , fisheries and biodiversity. Around 60 people working including the aquaculture plant

   b. Expertise in Ocean Colour Radiometry (OCR) and/or marine optics

      medium

   c. Which equipment related to OCR and or marine optics?

      Dartcom HRPT/AHRPT System receives, archives, processes and displays data from NOAA and Metop satellites

   d. Distance from harbour facility

      1km

   e. Ship facility (number, size, autonomy, range)

      At least, every month the R/V Ramon Margalef is covering a standard section (7 stations). It is a Multipurpose Research Vessel, 46.7 m long and the autonomy is around 10 days

   f. Is there space for new facilities construction on laboratory site?

      No

   g. Would your lab have an interest in managing a radiometric buoy under EU funding?

      Yes

2. Mooring or monitoring site(s)
   a. Is there a permanent mooring or monitoring site managed by the lab?

      Yes
      http://www.boya-agl.st.ieo.es/boya_agl/en/index.php

   b. If so, what is measured and/or monitored?

      waves (height, direction and period)
      meteorological parameters (3m above surface): air pressure and temperature, relative humidity. In the past radiation (net and solar)
      oceanographic parameters (3m depth): water temperature and conductivity, fluorescence, dissolved oxygen and current (to 100m depth)

   c. Is the mooring site in vicinity of shipping roots, fishing areas or recreational areas?

      During summer tuna vessels have activities near the area

   d. Is the mooring site under GSM coverage?

      No

   e. How long has the site(s) been monitored?

      Since 2007

   f. Distance from the coast

      22 miles

   g. Mean current and waves on site(s)

      Mean waves: around 2.5m significant wave height
      mean currents

Azores islands (UoA)

No feedback prior to the report delivery deadline.

EIO (Curtin University, CSIRO, IMOS)

3. Lab description

a. Research groups, main expertise, number of personnel

The combined expertise of the following 3 entities would be available, all based in Perth, Western Australia:
- Remote Sensing and Satellite Research Group (RSSRG), Curtin University (PI D. Antoine)
- Indian Ocean Ecology and Oceanography Group and IMOS shelf-moorings team, Commonwealth Scientific and Industrial Research Organisation (CSIRO) (PI N. Hardman-Mountford)
- "Insitu Marine Optics" (PI M. Slivkoff)

Expertise cover all aspects of marine optics and ocean colour science, from instrument development, characterisation and calibration, to field deployments (ships, autonomous platforms and moorings), field data processing, optics and radiative transfer modelling, satellite ocean colour data processing, matchup analyses, mooring builds, deployments and maintenance.

b. Expertise in Ocean Colour Radiometry (OCR) and/or marine optics

high

c. Which equipment related to OCR and or marine optics?

- IMO "DALEC" hyperspectral radiometers
- Satlantic hyperspectral radiometers
- WET Labs Thetis profiling system, in commissioning phase (hosting IOP+radiometry)
- WET Labs IOP instruments (AC-S, EcoFLBBs)
- Hobilabs Hydroscat-VI Backscattering meter
- Bio-Argo floats deployed in the Indian ocean, including radiometry
- Radiometric calibration facilities, both at Curtin and CSIRO
- HPLC analysis capability for phytoplankton pigments (CSIRO Hobart)
- Flow cytometry, FlowCam and microscopic phytoplankton and zooplankton analysis (CSIRO Perth and Hobart)

d. Distance from harbour facility

Curtin: 17km from Fremantle harbour, 35km from Hillary's harbour
CSIRO: 22km from Fremantle harbour, 27km from Hillary's harbour
IMO: 12km from Fremantle harbour, 40km from Hillary's harbour

e. Ship facility (number, size, range)

CSIRO Linnaeus R/V, 17m, A-frame, CTD crane/winch, suitable for oceanographic work and mooring deployments, capable of operating from coast to beyond shelf edge.
Other commercial vessels with similar capabilities within the vicinity.

f. Is there space for new facilities construction on laboratory site?

Yes

g. Would your lab have an interest in managing a radiometric buoy?

Yes

4. Mooring or monitoring site(s)

a. Is there a permanent mooring or monitoring site managed by the lab?

Yes. The current "National Reference Station" (NRS) of the Australian Integrated Marine Observing System (IMOS) is located off Rottnest island, just west off Perth. We also manage a shelf mooring array monitoring flow within the Leeuwin Current at 4 locations, from 40m to 500m bathymetry.
http://imos.org.au/facilities/nationalmooringnetwork/wamoorings/

b. If so, what is measured and/or monitored?

- Seabird SBE39 temperature logger
- Workhorse ADCP
- WET Labs Water Quality Monitor (temperature, salinity, dissolved oxygen, chlorophyll fluorescence and turbidity)
- WET Labs ECO-FL (chlorophyll-a fluorescence)
- Seabird SBE19 v2 (conductivity, temperature, pressure and oxygen)

- Niskin carousel for water sampling and subsequent analyses (please complete here; See details at: http://imos.org.au/facilities/nationalmooringnetwork/wamoorings/wainstrumentation/

If and when the Curtin's Thetis profiler is qualified at the end of its commissioning phase, it would add daily measurements of downward irradiance, upward radiance, IOPs, O_2, and variable fluorescence.

c. Is the mooring site in vicinity of shipping routes, fishing areas or recreational areas?

Yes

d. Is the mooring site under GSM coverage?

Yes

e. How long has the site(s) been monitored?

>30 years for some parameters

f. Distance from the coast

About 30km from the mainland.
Other sites could be selected in the vicinity of Rottnest, yet further offshore

g. Mean current and waves on site(s)

If no monitored stations nor oceanographic buoys exist please specify mean current and waves in the vicinity of the lab studied area if available

This site has monitoring stations with ADCP measurements at a range of locations in the area. There is also coastal HF radar available (http://oceancurrent.imos.org.au/oceancolour.php?link=DonPer_chl/latest.html)