Fiducial Reference Measurements for Satellite Ocean Colour Phase-2

Reflectance Measurement Requirements Document (RMRD)

FRM4SOC2-RMRD

Title	Specifications of minimum requirements for qualification of individual OCRs and their measurements as FRM and process for inclusion of any new instrument models and measurements in the FRMOCnet (RMRD)
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1	0 draft 1	0	19.09.2021	First draft for comment by partners	RBINS (Kevin Ruddick), including input from partners, e.g. via FRM4SOC-2 Proposal, Requirements Baseline Documents and deliverable D-11.
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1.2 List of Tables

1.3 Acronyms and Abbreviations

Acronym	Description
AAOT	Acqua Alta Oceanographic Tower
AATSR	Advanced Along-Track Scanning Radiometer
AD	Applicable Document
ADUM	Architecture Design and User Manual document
AERONET-OC	The Ocean Color component of the Aerosol Robotic Network
AMT	Atlantic Meridional Transect
API	Application Program Interface
ARC	Assessment of In Situ Radiometric Capabilities for Coastal Water Remote Sensing Applications
BRDF	Bidirectional reflectance distribution function
Cal	Calibration
CEOS	Committee on Earth Observation Satellites
Char	Characterization
CLI	Command-Line interface
DP	Data Package
DR	Documentation-related Requirements
EO	Earth Observation
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FOV	Field of view
FRM	Fiducial Reference Measurements
FRM4SOC	Fiducial Reference Measurements for Satellite Ocean Colour
GEO	Group on Earth Observations
HQ	Headquarters
IOCCG	International Ocean-Colour Coordinating Group
IPR	Intellectual Property Rights

Acronym	Description
IR	Instrument-related Requirements
KO	Kick Off meeting
LUT	Look Up Table
MAVT	MERIS and Advanced Along-Track Scanning Radiometer Validation Team
MERIS	Medium Resolution Imaging Spectrometer
MVT	MERIS Validation Team
NASA	National Aeronautics and Space Administration
NERC	Natural Environment Research Council
NMI	National Metrology Institute
OC	Ocean Colour
OCDB	Ocean Colour Database
OCR	Ocean Colour Radiometer
PDF	Portable Document Format
MR	Protocol-related Requirements
QA	Quality Assurance
QA4EO	Quality Assurance framework for Earth Observation
QC	Quality Control
PMP	Project Management Plan
RSP	Remote Sensing and Products Division
RD	Reference Document
S3	Sentinel-3
S3VT-OC	Sentinel-3 Validation Team – Ocean Colour group
SeaWiFS	Sea-Viewing Wide Field-of-View Sensor
SIRREX	SeaWiFS Intercalibration Round Robin Experiments
SI	International System of Units
SOW	Statement of Work
SST	Sea Surface Temperature
TO	Tartu Observatory, University of Tartu
TR	Technical Report
TSM	Total suspended material
VAL	Validation
VIM	International Vocabulary of Metrology

1.4 Applicable documents

Table 1-1. Applicable documents

ID	Description
[AD-0]	Statement of Work for FRM4SOC phase2, EUM/RSP/SOW/19/1131157
[AD-1]	ESA's contract no 4000117454/16/I-SBo (https://frm4soc.org)
[AD-2]	D-70: Technical Report TR-2 "A Review of Commonly used Fiducial Reference Measurement (FRM) Ocean Colour Radiometers (OCR) used for Satellite OCR Validation" (available at https://frm4soc.org/index.php/documents/deliverables/)
[AD-3]	'Statement of Work for Database of Ocean Colour In Situ Fiducial Reference Measurement Collections for Calibration and Validation', EUM/OPSCOPER/SOW/17/956607.
[AD-4]	IOCCG Protocol Series (2019). "Protocols for Satellite Ocean Colour Data Validation: In Situ Optical Radiometry". Zibordi, G., Voss, K. J., Johnson, B. C. and Mueller, J. L. IOCCG Ocean Optics and Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation, Volume 3.0, IOCCG, Dartmouth, NS, Canada. (Available at https://ioccg.org/what-we-do/ioccg-publications/oceanoptics-protocols-satellite-ocean-colour-sensor-validation/)
[AD-5]	K. Ruddick et. al., "A Review of Protocols for Fiducial Reference Measurements of Water-Leaving Radiance for Validation of Satellite Remote-Sensing Data over Water", Remote Sens. 2019, 11(19), 2198; https://doi.org/10.3390/rs11192198
[AD-6]	K. Ruddick et. al., "A Review of Protocols for Fiducial Reference Measurements of Downwelling Irradiance for the Validation of Satellite Remote Sensing Data over Water", Remote Sens. 2019, 11(15), 1742; https://doi.org/10.3390/rs11151742
[AD-7]	International Network for Sensor Inter-comparison and Uncertainty assessment for Ocean Color Radiometry (INSITU-OCR), http://ioccg.org/wpcontent/uploads/2016/02/INSITU-OCR-white-paper.pdf.
[AD-8]	D-80a: Technical Report TR-3a "Protocols and Procedures to Verify the Performance of Reference Irradiance Sources used by Fiducial Reference Measurement Ocean Colour Radiometers for Satellite Validation" (available at https://frm4soc.org/index.php/documents/deliverables/)
[AD-9]	D-80b Technical Report TR-3b "Protocols and Procedures to Verify the Performance of Reference Radiance Sources used by Fiducial Reference Measurement Ocean Colour Radiometers for Satellite Validation" (available at https://frm4soc.org/index.php/documents/deliverables/)
[AD-10]	Białek, A.; Douglas, S.; Kuusk, J.; Ansko, I.; Vabson, V.; Vendt, R.; Casal, A.T. Example of Monte Carlo Method Uncertainty Evaluation for Above-Water Ocean Colour Radiometry. Remote Sens. 2020, 12, 780. https://doi.org/10.3390/rs12050780
[AD-11]	TR-9 Technical Report "Results from the First FRM4SOC Field Inter-Comparison Experiment (FICE) of Ocean Colour Radiometers" (available at https://frm4soc.org/index.php/documents/deliverables/)
[AD-12]	IOCCG Ocean Optics & Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation (https://ioccg.org/what-we-do/ioccg-publications/ocean-opticsprotocols-satellite-ocean-colour-sensor-validation/)

1.5 Reference documents

Table 1-2. Reference documents

ID	Description
[RD-1]	ESA's contract no 4000117454/16/I-SBo (https://frm4soc.org)

2 Introduction

2.1 Scope of the document

The objective of this document is the specification of minimum requirements for qualification of individual ocean colour radiometers (OCRs) as FRM instruments, and for FRM qualification of measurements from these OCRs models.

This documented is intended to guide an OCR user to fulfil the requirements to acquire Fiducial Reference Measurements and thus his/her OCR, its measurements and him/herself become part of the Fiducial Reference Measurements Ocean Colour Network. This document is also intended to establish a basis for this FRMOCnet, which is envisaged as a network containing:

1. Databases with
    a. Serial number, calibration and characterization coefficients of individual OCRs (among other metadata),
    b. Measurements of Rrs with end-to-end uncertainty budget with relevant metadata.
    c. OCR users (institutions) that comply with FRM standards – to be defined in this document,
2. An "FRM community processor" software - interacting with the data described in 1 - outputting normalized water-leaving radiance or remote sensing reflectance and the corresponding end-to-end uncertainty budget from underwater/above water radiometric measurements and related needed metadata.
3. An information base of protocols, guidelines and tools to define, clarify and simplify FRM procedures.

While the FRM4SOC-2 project will focus on achieving these requirements for the two models of TriOS-Ramses and SeaBird-HyperOCR, the present document is generic enough to cover both these two models and probably most future OCR models. The process for the inclusion of any new OCR models and their measurements is also defined.

The document's target public is a user or an institution, who aspires to collect FRM-quality measurements and to join FRMOCnet. The document therefore provides a checklist of requirements that need to be met.

The requirements originate from [AD-0], the Statement of Work (SoW) for FRM4SOC phase-2 (Doc.No.:EUM/RSP/SOW/19/1131157, v5B, 29 April 2020). However, the original title of D-2 has been modified from "Specifications of minimum requirements for qualification of individual OCRs as FRM instruments and process for inclusion of any new instrument models in the FRMOCnet", to "Specifications of minimum requirements for qualification of individual OCRs and their measurements as FRM and process for inclusion of any new instrument models and their measurements in the FRMOCnet" to account for the broader nature of this deliverable.

While the scope is limited to water reflectance measurements, much of the process can be considered as quite generic with easy transposition to other measurands in the future.

This document draws heavily on heritage from the work of the FRM4SOC-1 project, as documented by papers from the FRM4SOC Special Issue of *Remote Sensing* [1–8] and FRM4SOC Technical Reports [AD-2], as well as work of the international community within the IOCCG framework [AD-4, AD-7].

2.2 Definition of radiometric quantities

In the present document the terminology of "remote-sensing reflectance", R_{rs}, is used where

$$R_{rs}(\lambda,\theta,\phi) = \frac{L_w(\lambda,\theta,\phi)}{E_d^{0+}(\lambda)} \tag{1}$$

where $E_d^{0+}(\lambda)$ is the spectral downward plane irradiance, also called "above-water downwelling irradiance", and $L_w(\lambda,\theta,\varphi)$ is the water-leaving radiance, defined, e.g. see [9], as the component of above-water directional upwelling radiance that has been transmitted across the water-air interface in the upward direction measured by the sensor and defined by above-water viewing nadir angle θ and azimuth angle φ – see Figure 1 and Figure 2 of [6] for a schematic of the geometry and the measurands respectively.

Although the independent variables (λ,θ,ϕ) may be dropped from this notation for brevity it is noted that R_{rs} has both spectral and angular variability (as well as time and horizontal space variability). R_{rs} can be very simply related [10] to other popular radiometric quantities such as normalized water-leaving radiance, $nL_w(\lambda,\theta,\phi)$, and water-leaving radiance reflectance, $\rho_w(\lambda,\theta,\phi)$. Since there are diverse and ambiguous definitions and usages for these terms, we propose to follow here the terminology of the Ocean Optics Web Book [https://oceanopticsbook.info/view/atmospheric-correction/normalized-reflectances], which is closely aligned with [9].

R_{rs} can also be "corrected" for BRDF effects [11] to yield radiometric quantities such as "exact[1]" normalised water-leaving radiance, with less sensitivity to sun and viewing geometry. Alternatively, R_{rs}, can be converted/extrapolated to a nadir-viewing geometry, e.g. equation (5) of [12] using a "view correction" or "Q-factor" but without the correction for scattering angle effects associated with the sun zenith angle, "f-factor". The nadir-viewing geometry facilitates comparison with measurements from in situ instruments and from satellite missions, provided that the latter are also corrected to a nadir-viewing angle. Except for Case 1 waters, there is no consensus at present on how to perform such viewing angle correction and it is expected that the state of the art will evolve in time as knowledge and tools improve. We therefore recommend that the in situ reflectance measurements be recorded and archived in the acquisition geometry and that software tools be made available to extrapolate to different viewing geometries both for in situ and for satellite measurements. In a validation context the viewing angle difference between in situ and satellite measurement can then be made at the moment of validationanalysis, with the latest available tools for BRDF correction.

2.3 Definition of Fiducial Reference Measurement

Within the current document we use the definition of Fiducial Reference Measurement provided by preface p xiii of [1], adapted from the original idea of [13] for Sea Surface Temperature measurements and [15] for optical radiometry in a climate change context, whereby the defining mandatory characteristics of a "Fiducial Reference Measurement (FRM)" are:

The FRM must:

- have documented traceability to SI units (via an unbroken chain of calibrations and comparisons);
- be accompanied by a complete estimate of uncertainty, including contributions from all FRM instruments and all data acquisition and processing steps[2];
- follow well-defined protocols/community-wide management practices;
- be openly available for independent scrutiny and;
- be independent from the satellite retrieval process;

Of these five characteristics, the second (uncertainty estimation) is the most demanding and receives most attention in the current document.

The fifth characteristic (independence from the satellite retrieval process) is primarily a warning that the use of measurements for satellite validation should avoid measurements that have already been used in the satellite retrieval process, i.e. for vicarious calibration. As such, this characteristic is not intrinsic to the measurement itself but depends on how/if it is used and so is not relevant to the current document.

2.4 FRMOCnet objectives

The FRMOCnet as proposed by EUMETSAT and illustrated in Figure 2-1 is envisaged as a network containing:

1. Databases with
   a. Serial number, calibration and characterization coefficients of individual OCRs (among other metadata),
   b. Measurements of Rrs with end-to-end uncertainty budget with relevant metadata.
   c. OCR users (institutions) that comply with FRM standards – to be defined in this document,

[1] Here the word "exact" is used following the definition of [11], but it is noted that this word is used confusingly since there is nothing particularly "exact" about this radiometric quantity, it is just less sensitive to sun and viewing geometry (if the BRDF correction is good).

[2] Here the original phrase has been truncated with removal of the second part "[An uncertainty budget for all FRM ... measurements,] *traceable where appropriate to the International System of Units/Système International d'unités (SI), ideally through a National Metrology Institute*". It is the measurement result that must be traceable to SI (as noted in the first mandatory characteristic), not the uncertainty estimate. The VIM [14] defines metrological traceability as "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". SI traceability is related to measurements, calibrations, scale realisation but not to the uncertainty estimate. SI traceable measurement results by default come with a robust uncertainty budget.

2. An "FRM community processor" software - interacting with the data described in 1 - outputting normalized water-leaving radiance and the corresponding end-to-end uncertainty budget from underwater/above water radiometric measurements and related needed metadata.
3. An information base of protocols, guidelines and tools to define, clarify and streamline FRM procedures.

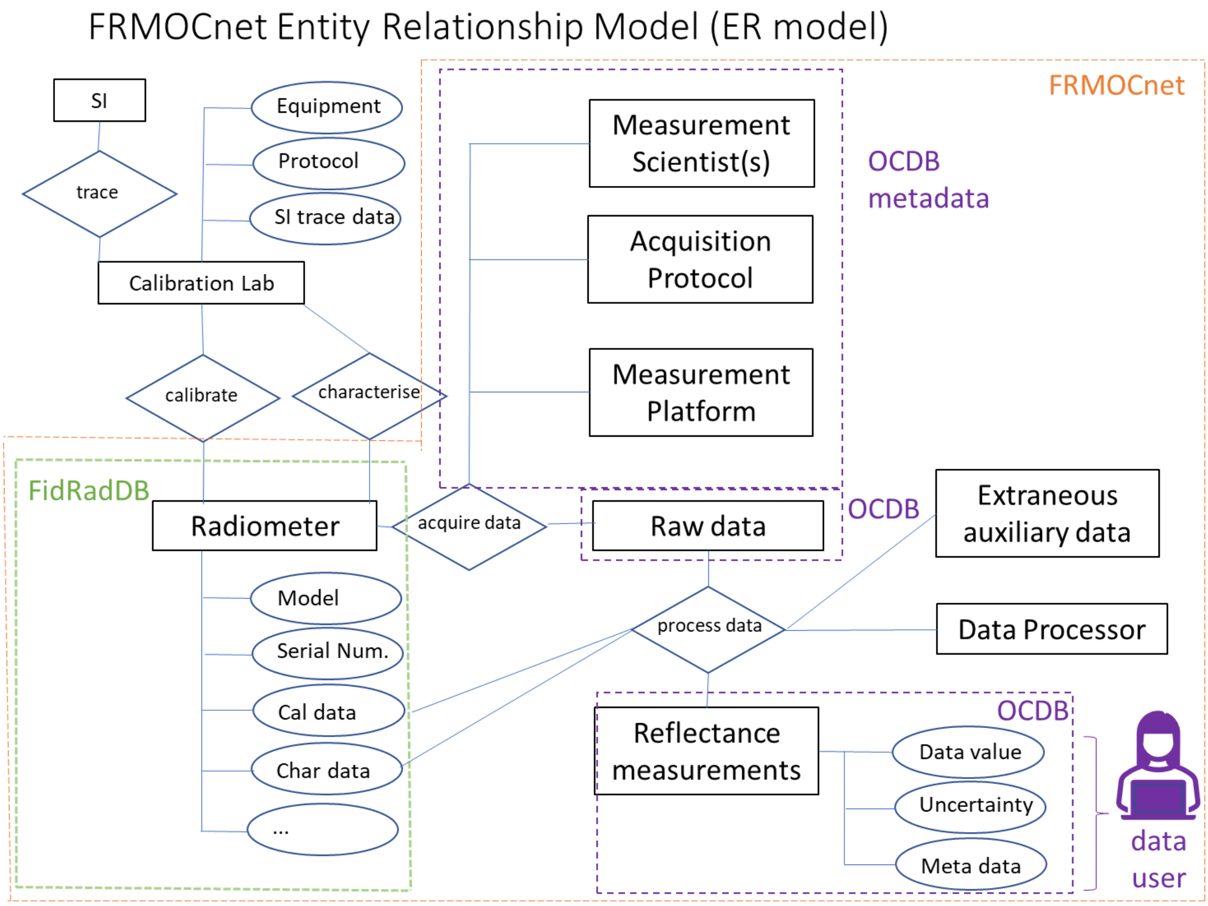

Figure 2-1 Heavily simplified proposal for a FRMOCnet Entity Relationship model ("ER model") following the notation of [Chen, 1976]. "Extraneous data" refers to data from other sources needed for processing, e.g. wind speed.

The FRMOCnet is motivated by the goal to provide the maximum Return On Investment for EC Copernicus satellite Ocean Colour missions by delivering, to users, the required confidence in satellite data products, in the form of qualified validation results and satellite product uncertainty estimations over the entire duration of the missions. Such qualified validations and uncertainties can only be achieved using in situ measurements[3] that themselves represent the highest quality. These Fiducial Reference Measurements must have documented traceability to SI (calibration, comparison); evaluated uncertainty budgets for measurements; and defined and adhered-to protocols and community-wide management practices, from the measurement through the processing and documentation to the archiving.

The main goal of FRMOCnet is to ensure the adoption of FRM principles across the Ocean Colour community. To achieve this goal, FRMOCnet aims to develop an information base, protocols, guidelines and tools to define, clarify

[3] The term "ground truth" is often used for such measurements, but is not recommended here. The "true value" of radiometric quantities measured in the field is not known.

and streamline FRM procedures. These resources are designed to make it easier for broader community to implement FRM standards and to minimize in situ measurement uncertainties as required for FRMs.

The specific objective of FRMOCnet is to establish foundations for an operational implementation of the FRM principles for an initial set of in situ radiometric instruments from the two models of TriOS-Ramses and SeaBird-HyperOCR, and for their measurements. The required background to be developed is:

- complete laboratory radiometer characterization[4] and calibration,
- further detailing of the measurement protocols,
- definition of an end-to-end uncertainty budget,
- community processor for protocoled processing of the measurements and the associated uncertainties.

In support of the laboratories, the following specifications are to be developed:

- guidelines for laboratory calibrations and characterizations of the radiometers.

In support of instrument manufacturers, the following recommendations are to be issued:

- specifications of minimum requirements for radiometer manufacturers.

The developed FRMOCnet uncertainty propagation, protocols and tools are to be verified through:

- expert and community reviews, and
- practical laboratory and field exercises.

The data, protocols, guidelines and documentation developed in the process of FRMOCnet are to be stored in:

- FidRadDB and accessible online on FRM4SOC-2 website,
- OCDB (https://ocdb.eumetsat.int/) for in situ measurement results only.

The target for this FRMOCnet development is to demonstrate operational FRM capabilities and community processes for the TriOS-Ramses and SeaBird-HyperOCR radiometers and their measurements.

The goal of the current document is to serve as terms of reference for the FRMOCnet. The document defines the minimum requirements that need to be met by individual radiometers from the initial set of two models and by these radiometer measurements to be qualified as FRM quality, and for their acceptance in FRMOCnet. This document also specifies the procedure for inclusion of other or new radiometer models in FRMOCnet.

2.5 FRMOCnet data users

It is useful to set this document within the future vision for an FRMOCnet, thus clarifying how the requirements established here will support future users of the FRMOCnet.

The main future users of water reflectance data from the FRMOCnet are identified as:

- **Satellite mission validation entities.** These users are space agencies and/or their collaborators, validation teams and mission performance centres who typically want to develop comprehensive and global comparisons of satellite products with in situ water measurements in order to independently assess the quality of the satellite-derived measurements. These users generally download many in situ measurements, e.g. all measurements within a specified time and space proximity [16,17] to the satellite-derived measurement during the duration of a satellite mission, and process them to generate scatterplots and regression statistics, e.g.Figure 2-2a, or combine satellite and in situ measurements side-by-side in time series. These users may test two or more processor versions, e.g. to ensure that any processor modifications do not degrade performance for the water reflectance products.
- **Atmospheric correction algorithm developers.** These users, often individual researchers, perform very similar activities to the satellite mission validation entities, except that they develop or use new algorithms to generate the satellite-derived products and often compare many algorithms or versions of algorithms to assess algorithm performance over a range of water and atmosphere conditions and to identify any problematic situations where improvements are needed – e.g. see Figure 2-2b.
- **Satellite data users.** These users want to investigate satellite data quality for their regional or global applications and services, or want to use satellite and in situ measurements in combination.

[4] "Characterisation" of a measurement instrument is a measurement (VIM 2.1) aimed to determine a special set (spectrum) of sensitivity coefficients or errors due to some particular systematic effect.

In-water (Level 2 Water) algorithm developers. These users, developing algorithms for Level 2 Water (L2W) bio-optical products such as chlorophyll *a* concentration, typically download all in situ water reflectance measurements where there are simultaneous L2W in situ bio-optical measurements, e.g. reflectance and chlorophyll *a*.

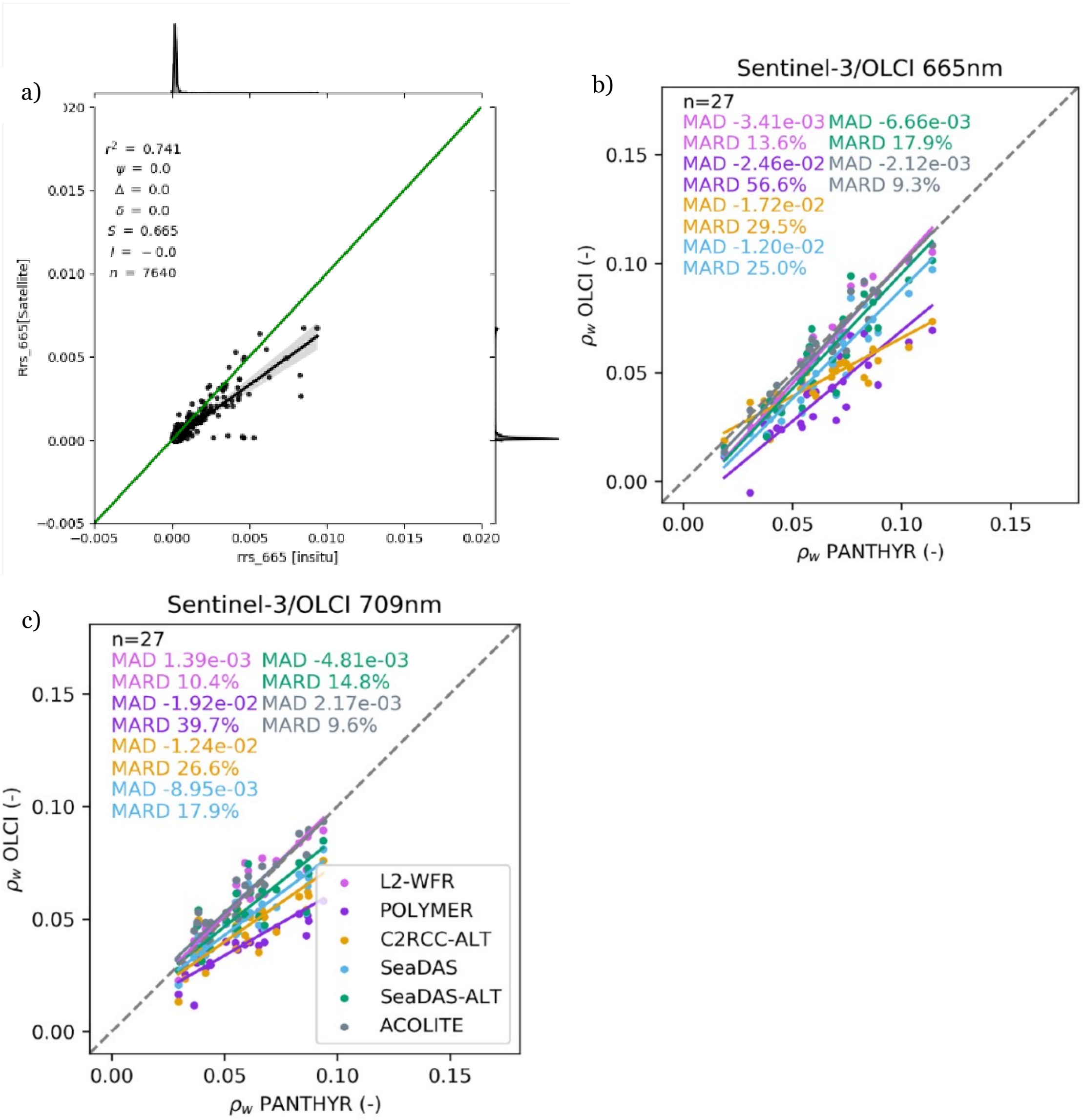

Figure 2-2.Typical usage of water reflectance in situ measurements for validation of satellite measurements: (a) comparison of remote sensing reflectance at 665nm from SeaWiFS, MODIS and MERIS processed by OC-CCI for the Atlantic region with in situ measurements, reproduced from CMEMS Atlantic and Arctic Quality Information Document [18]. Comparison of water reflectance at 665 nm (b) and 709 nm (c) from OLCI processed by 6 different atmospheric correction algorithms, compared with PANTHYR measurements, reproduced from [19].

These four user types will typically see FRMOCnet as shown in Figure 2-3. They want measurement quantity values[5] (termed "data values" here), a limited set of metadata (especially space-time coordinates) and estimated

[5] Following the terminology of the International Vocabulary of Metrology (VIM) 200:2012(E) [14], section 2.9, "measurement result" refers to a (set of) quantity value(s) being attributed to a measurand

uncertainty of each measurement result. Given this information, and supposing that the uncertainty estimates can be trusted, it is expected that the FRMOCnet data users do not need to know more about how a measurement was made. They will not want to spend time investigating in situ measurement quality or provenance but will simply download and use the data.

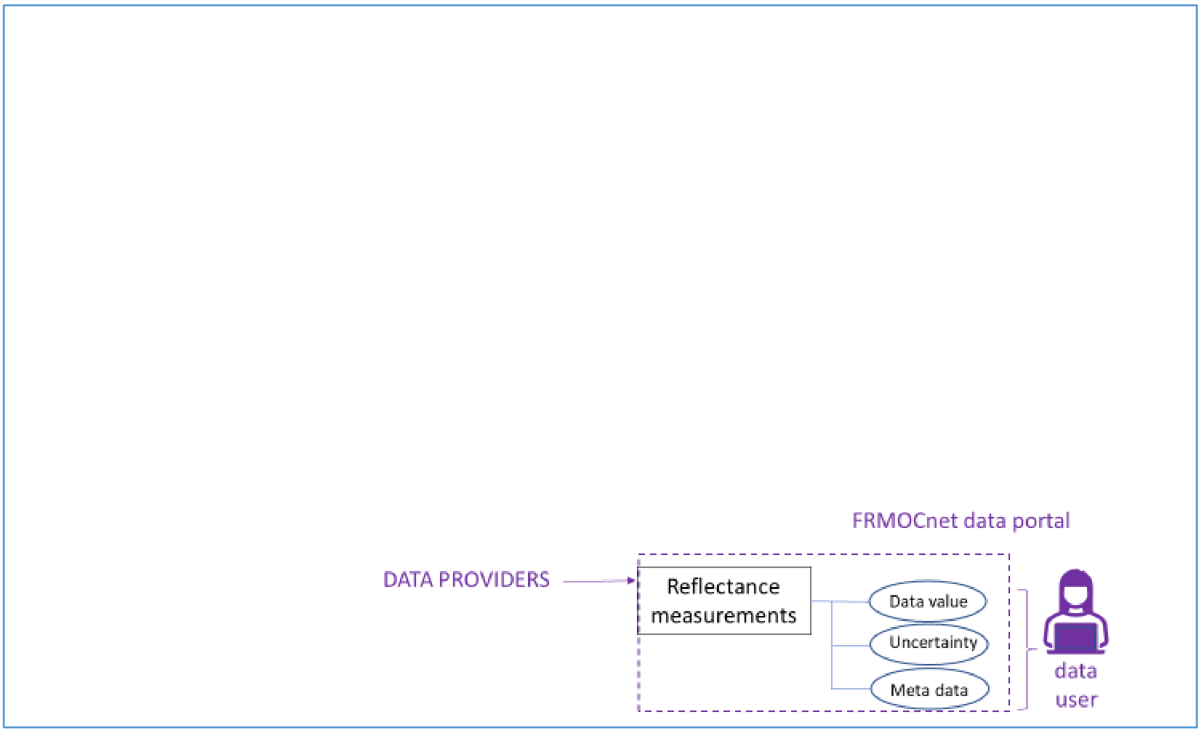

Figure 2-3. Expected vision for the FRMOCnet data portal (i.e. OCDB) from the users' perspective. This figure is deliberately left mainly empty for comparison with Figure 2-1.

However, the current state of databases for in situ measurements is that such uncertainty estimates are generally not available for each measurement result and the data users must make their own decisions on what data to use (based on perceived quality of data provider or other subjective criteria) and either obtain uncertainty estimates from elsewhere (e.g. published documentation) or simply wrongly assume that the in situ measurements represent "truth" with zero uncertainty. To a scientist from outside the ocean colour community, this situation would clearly be unsound, but it has become common ocean colour practice for want of better and because of the paucity of any in situ measurements. Now that satellite-derived ocean colour products are being produced operationally, e.g. by EC Copernicus Programme from Sentinel-3 and Sentinel-2, and by USA NOAA from VIIRS, it is even more critical to address this weakness in the in situ measurements needed for validation of the satellite-derived products.

The FRM4SOC-1 activity therefore had the overarching goal of ensuring that uncertainty estimates are available for each measurement that could be used and ensuring that the data users can trust such uncertainty estimates. This goal was not fully achieved, although considerable progress was made.

2.6 Maturity of the FRM concept and practice

The international community and FRM4SOC-1 project have clarified the overall methodology for achieving uncertainty estimates for in situ measurements, as illustrated in Figure 2-4. Considerable progress has been made

together with any other available relevant information. A measurement result is generally expressed as a single measured quantity value and a measurement uncertainty. Although not defined explicitly by the VIM, we use the term "metadata" to cover all other available reliable information, including space-time coordinates, measurement scientist, measurement procedure, etc. See also Appendix A for definition of terminology.

on detailing many components of this process, as detailed in the IOCCG protocols document [20], the peer-reviewed papers [1–8] and Technical Reports [AD-2] of the FRM4SOC-1 project and prior studies, including the NASA Ocean Optics Protocols, and SIMRIC and SIRREX comparisons [21–23]. While there are clearly still some gaps in knowledge and much work to be done in the FRM4SOC-2 project to fill these gaps and provide a clear and detailed methodology, the desired situation is described in the current document in terms of what requirements must be met for measurement results to be considered as Fiducial Reference Measurements and included/flagged as such within the FRMOCnet.

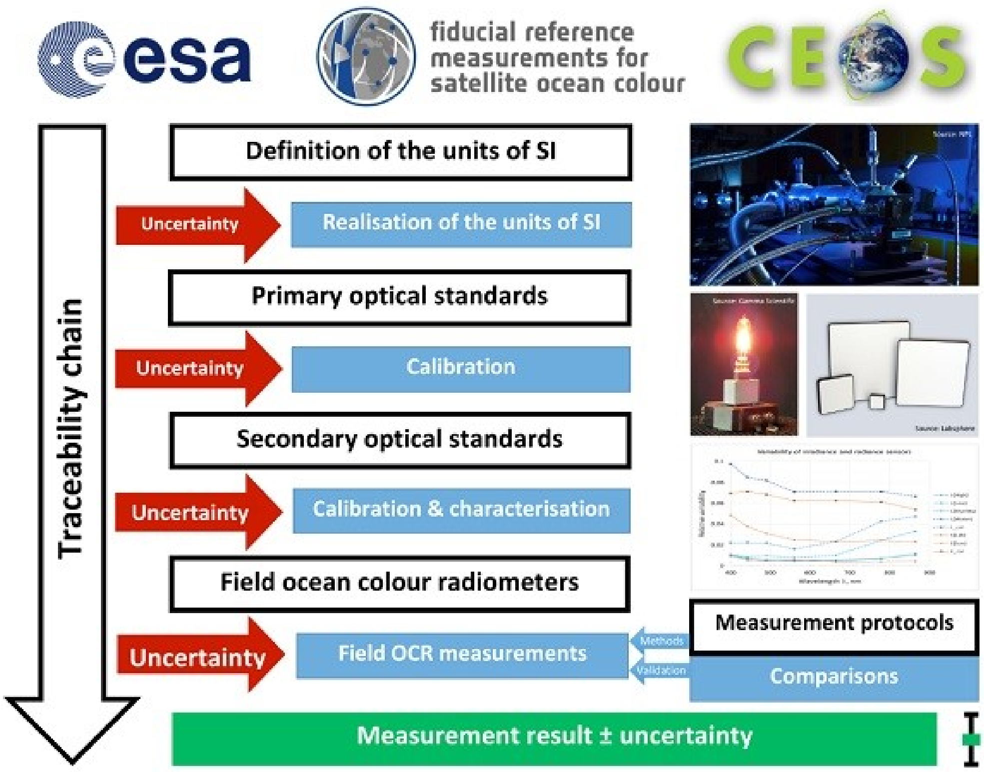

Figure 2-4 Elements of the full traceability chain that needs to be included in the uncertainty estimation, as adapted from (Banks et al., 2020).

2.7 General Requirement for inclusion of OCR measurements as FRM in FRMOCnet

The General Requirement for inclusion/flagging of an OCR measurement as FRM in FRMOCnet is trivially that it fulfils the first four characteristics of the definition in section 2.3. The following sections of this document deal with each of these characteristics in detail.

A consequent structure for the FRMOCnet entity relationship model is proposed in Figure 2-1.

While the FRMOCnet concept encompasses all elements shown in Figure 2-1., we suggest that only the items included within the “FidRadDB” and “OCDB” boxes need to be stored in a central repository. As regards the other elements, not centrally stored:

- While the FRM4SOC-2 project aims to develop a Community Data Processor at least for the TRIOS/RAMSES and Seabird/HyperOCR sensors, the scope of this Community Data Processor, in its first version, will cover only a subset of all measurements to be stored within the OCDB. Moreover, storage and usage of raw instrument data is a particularly challenging activity with issues of responsibility (the measurement scientist should take responsibility for the measurement result at least to the level of water reflectance at the wavelength, spatial location, time and viewing geometry of acquisition) and perhaps raw data format.
- While the full SI traceability chain requires that the calibration and characterisation data associated with a radiometer Serial Number be available all the way back to the SI primary standard cryogenic radiometer (see Figure 2-4) it is inconvenient and unnecessary to store the entire traceability data itself in the same repository as the measurement result for water reflectance. We suggest that it is sufficient to store the

calibration and characterisation certificates for the radiometer Serial Number in FidRadDB; these certificates should document how the SI traceability is established and should be machine-readable for use by the Community Processor.

2.8 Concept of certification in the context of FRM4SOC

The definition and concept of certification is not specified in the SOW [AD-0], however it mentions certification in relation to the following aspects:

- FRM compliant cal/char laboratories (Scope of the SOW);
- FRM certification of OCR instrument models (Req. 4);
- FRM certification of single individual OCR instrument (Req. 5);
- FRM certified cal/char status (Scope of the SoW);
- FRM competence certified operators (Scope of the SoW);
- FRM certified measurement protocols (Req. 23);
- Network of radiometric measurements with the FRM certification (Description of Task 1).

In this document, we understand the term *certification* [see www.iso.org] in the most general meaning that is *the provision by an independent body of written assurance (a certificate) that the product, service or system in question meets specific requirements.*

In other words as concluded directly from the definition:

- a result of a certification process is compliance/non-compliance (PASS/FAIL);
- the decision on PASS/FAIL must be based on defined criteria (list of requirements[6], standard, directive, etc.)
- the decision on PASS/FAIL (awarding the certificate) must be made by an independent authorised body.

Overall PASS requires PASS on all component criteria.

The term *FRM Certification* is not meant in sense of "ISO certification", (i.e. compliance to ISO standards) here as not fully applicable in the Ocean Colour domain[7]. However, definition of clear requirements and an independent authorised certification body is assumed.

Nevertheless, the *FRM Certification* may include elements from ISO certification/accreditation e.g. requirement for FRM compliant cal/char laboratories to have an operational quality management system of ISO 17025 or equivalent [see FRM4SOC-2 D-11].

[6] These requirements are mostly defined in the present document.

[7] It is noted here that some in situ measurement results corresponding to measurands that can be derived from Ocean Colour data may be ISO certified. A good example is chlorophyll *a* concentration, for which ISO-certified measurement results are available from a number of laboratories in Europe. However, for the case of water reflectance there is currently no ISO standard.

3 Requirement of SI-traceability and existence of an Uncertainty estimate

FRM requirements of SI-traceability and the existence of an uncertainty estimate are detailed in the following subsections, dealing with all elements of Figure 2-4.

The following sections approach the requirements for Fiducial Reference Measurements in the following order:

- Is the OCR instrument ready to be used? i.e. are all Instrument Requirements (IR) fulfilled?
- Has the calibration/characterisation laboratory fulfilled all calibration/characterisation (CR)?
- How should the measurements be acquired in the field, processed and reported (MR: Measurement Requirements)?
- What other requirement (OR) should be fulfilled, e.g. regarding the measurement scientist and/or documentation?

3.1 Calibration and characterisation of OCR – from Secondary Optical Standards to OCR ready for use in the field

3.1.1 Elements of OCR calibration and characterisation

The Ocean Colour Radiometers (OCR) to be deployed in the field measure radiances and irradiances with an associated uncertainty. This uncertainty is broadly separated into “calibration” and “characterisation”. Calibration (radiometric) refers to the conversion of Digital Numbers from each photodetector to a radiance or irradiance in SI units at a certain wavelength, generally by use of linear slope (“responsivity”) and offset (“dark”) coefficients, which may vary in time and may require special attention to immersion effects for in-water measurements [24,25]. A calibration result shall always include a statement on uncertainty. Characterisation refers to all other processes which modify the assumed linear calibration model, including [3,20,26]:

- Non-linearity
- Thermal response
- Angular response (especially imperfect cosine response for planar irradiance sensors)
- Spectral response (including straylight for hyperspectral spectrometers, out of band response for filter radiometers)
- Polarisation sensitivity
- Temporal response
- Pressure effects

These instrument properties have been well-known for decades and corresponding characterisations are considered necessary already by the 2003 NASA Ocean Optics Protocols [26], with reinforcement of the need for such characterisations and updated review of the state of the art in the 2019 IOCCG Protocols [20]. In the FRM context, estimation of uncertainty related to all such instrument properties is needed to complete the total measurement uncertainty estimate … but is often lacking. The need for regular[8], e.g. annual, calibration of radiometers is well-understood and recognised by measurement scientists, who make appropriate preparations for the financial, down-time and transport/customs/logistical implications of such calibrations[9]. The need for full characterisation of instruments is less well-established, presumably because of the high cost of such characterisations and the low availability of laboratories equipped to perform such characterisations. The FRM4SOC-1 review of radiometer instruments [AD-4] revealed a high diversity in the availability of information on and understanding of such characterisation from the instrument manufacturers. The possibility of performing such characterisations is beyond the capabilities of some instrument manufacturers and, if not required by their customers, is difficult to justify financially because of the high cost of both infrastructure and expertise.

[8] Even the requirement for “regular” calibration is open to discussion and improvement, especially in the context of long-term, e.g. one year, automated deployments. For example, the EU/HYPERNETS project is investigating processes affecting temporal change in sensitivity associated with possible fore-optics contamination (aerosol deposition, rain, etc.) during a deployment of above-water radiometers, as well as calibration monitoring devices. For supervised deployments, the use of portable stability monitoring devices was recommended already in Chapter 5 of Volume II of the NASA Ocean Optics Protocols [26] and reiterated in section 3.10 of the IOCCG Protocols [20]. Some instrument manufacturers provide such devices, e.g. the TRIOS/RAMSES Fieldcal device and the Ocean Optics LS-1-Cal device used with the WaterInsight/WISP radiometer.

[9] There is, however, no clear (consensus on the) requirement on the absolute uncertainty of such calibrations, nor on the quality system of the service provider, although such requirements may be developed in the future. A reasonable approach could be to require “best available” uncertainty and quality.

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It is noted that these radiometric characterisations are generally considered as independent, in view of the already difficulties in establishing adequate corrections and quantifying residual uncertainties. However, there may be complex situations where two or more characteristics are related, e.g. thermal effects may affect responsivity, dark current *and* wavelength scale.

Because of the high cost of both infrastructure and expertise required for these instrument characterisations, there is also little knowledge on the possible time variation of such characterisations. The FRM4SOC and EU/HYPERNETS projects are considering the design of less expensive tests to identify any time variation of characteristics such as straylight distribution function and hence trigger, when necessary, an update laboratory re-characterisation. As an example, the MOBY system includes internal reference sources [27] to monitor continuously and validate the straylight distribution correction using the straylight distribution function from less frequent laboratory characterisations.

3.1.2 OCR calibration and characterization review

As regards *requirements* on radiometer performance, the NASA Ocean Optics Protocols Volume II, in Chapter 3 [22], already back in 2003 provided *insight* and *recommendations* on how instrument calibration and characterisation should be performed as well as, in Chapter 2, some minimum *specifications* or *requirements* for individual characteristics, e.g. (their Table 2.2) “straylight rejection of 10^{-6}”, “signal:noise ratio of 1000:1 (at minimum)”, etc. The 2019 IOCCG Ocean Optics Protocols adopted a similar approach, including *recommended specifications* (e.g. Table 3-1 reproduced from their Table 2.2), which can be considered as target values,as well as a combination of limits beyond which characterisation and correction are required, e.g. “Sensors with temperature coefficients greater than 0.01% per °C should be characterized and a correction applied to the data to constrain residual temperature dependence below 0.01% per °C”.

It is noted that some of the specifications provided in Table 3-1 may be difficult to achieve with current hyperspectral radiometers. E.g. correction of non-linearities to 0.1% may be very challenging. Straylight rejection of 10^{-5} (at the maximum signal level) may be difficult to achieve [28] and translation of the driving requirement of “residual after correction for this effect, below 1% in each band across the full spectral range” into requirements on the radiometer depends on the spectral composition of the (undefined) target. It is the ambition of the FRM4SOC-2 project to better understand how the final measurement uncertainty for water reflectance is affected by uncertainties from each such radiometer instrument characteristic, to assist in refining requirements on instrument characterisation.

Table 3-1. Recommended specifications for hyperspectral radiometers applied for validation activities. Reproduced from Table 2.2 of [20].

Optical Sensors	
Spectral Range	380 to 900 nm (an extension in the ultraviolet is desirable)
Spectral Resolution	3-10 nm (FWHM)
Spectral Sampling[10]	1-3 nm (or at least 2 times the spectral resolution)
Wavelength Accuracy	10% FWHM resolution
Wavelength Stability	5% FWHM of resolution
Signal-to-Noise Ratio	1000:1 (at minimum)
Straylight Rejection	10^{-5} (of the maximum radiometric signal at each spectral band)
FOV Maximum (full-angle)	5°, 20° (for above-water, and in-water, respectively)
Temperature Stability	Specified for the range from 0 °C to 45 °C
Linearity[11]	Correctable to 0.1%

The IOCCG protocols [20] also provide helpful guidance on the type and occurrence of calibrations and characterisations that are needed for validation activities – see their Table 3.1, which is a precursor to current Table 3-2Table 3-1.

The FRMSOC2 consortium considers that [20] is a most comprehensive summary of former efforts during the last 20–30 years about cal/char activities, including recommendations on the regularity/type of the characterisation/calibration requirements. Calibration of OCR shall be performed regularly, once a year. All other characteristics of the FRM OCR instruments listed by [20] shall be determined at least once before its application for FRM purposes. Repeated characterisation of some parameters of OCR is needed after known significant constructional or other changes of the OCR instrument or in case of doubts. Such cases are detailed in FRM4SOC-2 D-8.

[10] Spectral Sampling or Pixel dispersion (or spectral distance between pixels) should be such that at least three pixels will be covered by the FWHM.
[11] Non-linearity error cannot be corrected to 0.1 % with present class-based characterization.

Table 3-2. Basic requirements on the type and occurrence of calibrations and main characterizations of field radiometers supporting ocean colour validation activities. Reproduced from Table 3.1 of [20].

Characteristic	Regular	Occasional	Initial	Class-based	FRM4SOC Phase 2 project recommendation
Radiometric responsivity	x				
Spectral Response		x			
Out-of band & straylight		x			
Immersion factor (irradiance)			x		
Immersion factor (radiance)				x	
Angular Response			x		
Linearity				x	
Integration time				x	
Temperature response					Individual[12]
Polarization sensitivity				x	
Dark-signal	x				
Temporal response				x	
Pressure effects				x	

3.1.3 Requirements for calibration and characterisation of Ocean Colour Radiometers

In summary, as regards the calibration and characterisation of Ocean Colour radiometers, the inclusion of any OCR measurement result to FRMOCnet/OCDB and the inclusion of any OCR in FRMOCnet/FidRadDB should be subject to the instrument-related requirements ("IR") that:

IR1. The uncertainty associated with radiometric responsivity of an OCR shall be estimated and delivered to FRMOCnet, including: the quantification of uncertainties from the radiometric calibration laboratory and their propagation; an estimation of any temporal changes in responsivity between such calibrations; and, for in-water measurements, (residual) uncertainties associated with immersion factors and possible pressure effects. The FRM4SOC-2 project deliverable D-10, using elements from chapters 3.2, 3.4, 3.10 and 3.13 of [20], provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR, while the FRM4SOC-2 project deliverable D-12 will provide guidance on how to perform the laboratory measurements themselves.

IR2. The uncertainty associated with straylight/out-of-band response of an OCR shall be estimated and delivered to FRMOCnet, including: the laboratory straylight characterisation and propagation of this characterisation as well as an estimation of any temporal changes since/ between such characterisations. If a straylight/out-of-band correction is applied to a measurement result then the residual uncertainty associated with such a correction must be estimated. The FRM4SOC-2 project deliverable D-8, using elements from chapter 3.3 of [20], will provide guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR, while the FRM4SOC-2 project deliverable D-12 will provide guidance on how to perform the laboratory measurements themselves.

IR3. The uncertainty associated with angular response of an OCR shall be estimated and delivered to FRMOCnet, including: the laboratory angular characterisation and propagation of this characterisation; as well as an estimation

[12] Due to substantial spread of individual temperature response characteristics, individual characterization is preferable in present stage of the project.

of any temporal changes since/between such characterisations, especially for irradiance sensors. If a cosine response correction is applied to irradiance measurements, then the residual uncertainty associated with such as correction must be estimated. The FRM4SOC-2 project deliverable D-8, using elements from chapter 3.5 of [20], provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR, while the FRM4SOC-2 project deliverable D-12 provides guidance on how to perform the laboratory measurements themselves.

IR4. The uncertainty associated with non-linearity of an OCR shall be estimated and delivered to FRMOCnet, including the laboratory non-linear characterisation and propagation of this characterisation, including any integration time response. If a non-linearity correction is applied, then the residual uncertainty associated with such a correction must be estimated. The FRM4SOC-2 project deliverable D-8, using elements from chapters 3.6 and 3.7 of [20], provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR, while the FRM4SOC-2 project deliverable D-12 provides guidance on how to perform the laboratory measurements themselves.

IR5. The uncertainty associated with thermal response of an OCR shall be estimated and delivered to FRMOCnet including the laboratory thermal characterisation and propagation of this characterisation. If a temperature correction is applied, then the residual uncertainty associated with such a correction must be estimated. The FRM4SOC-2 project deliverable D-8, using elements from chapters 3.8 of [20], provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR, while the FRM4SOC-2 project deliverable D-12 provides guidance on how to perform the laboratory measurements themselves.

IR6. The uncertainty associated with polarisation response of an OCR shall be estimated and delivered to FRMOCnet, including the laboratory polarisation characterisation and propagation of this characterisation. The FRM4SOC-2 project deliverable D-8, using elements from chapters 3.9 of [20], provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR, while the FRM4SOC-2 project deliverable D-12 provides guidance on how to perform the laboratory measurements themselves.

IR7. The uncertainty associated with dark signal removal for an OCR measurement shall be estimated and delivered to FRMOCnet, including the dark signal characterisation and propagation of this characterisation, including any possible temperature effects. The FRM4SOC-2 project deliverable D-8, using elements from chapters 3.11 of [20], provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR, while the FRM4SOC-2 project deliverable D-12 provides guidance on how to perform the laboratory measurements themselves.

IR8. The uncertainty associated with temporal response (system transient response) for an OCR measurement shall be estimated and delivered to FRMOCnet, including the laboratory characterisation of transient response and propagation of this characeterisation. The FRM4SOC-2 project deliverable D-8, using elements from chapters 3.12 of [20], provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR, while the FRM4SOC-2 project deliverable D-12 provides guidance on how to perform the laboratory measurements themselves.

For new OCR models to be included the FRMOCnet, they must provide the abovementioned IR1-IR8 laboratory characterisations.

In addition to the above requirements related to the measurement result, it is necessary to assign a value to the wavelength to which the measurement result refers. Like space and time coordinates, wavelength is an independent variable. When data users download data from a database such as the proposed FRMOCnet/OCDB it is typical to have as metadata only the central wavelength and perhaps the bandwidth (as Full Width Half Maximum, FWHM). In the best cases the full spectral response function may be supplied, as needed in upstream processing for convolution of quantities such as the downwelling irradiance – see [20] section 3.3 – and as needed for convolution to specific satellite sensor bands.

With the increased usage of satellite optical missions with broad and highly asymmetric spectral bands designed for land applications (Landsat-8, Sentinel-2) or atmospheric applications (MSG/SEVIRI, MTG/FCI) as well as missions with spectral bands finer than 10nm FWHM (NASA/PACE, ...) the question of bandwidth and spectral response function will become even more important than was previously the case for medium resolution OC sensors (SeaWiFS, MODIS, MERIS, VIIRS, OLCI, etc.) and may require more attention. For example, should radiometric data be stored with corresponding spectral response function for each measurement result, or with simplified central wavelength and bandwidth as metadata or even at idealised ocean colour bands e.g. square response function with width 10nm centred on 443nm? Should an uncertainty be associated with the wavelength scale[13] itself

[13] The wavelength scale is a definition of the wavelengths at which measurement results are reported.

or with the radiometric measurement result as reported for a nominal or central wavelength? And how to process and store spectrally-binned data for measurands such as reflectance, which are obtained from radiance and irradiance measurements made with slightly different spectral response functions? What about uncertainties on the wavelength scale itself?

While such questions need to be addressed carefully, it is proposed here that measurement results should be recorded for a central wavelength and bandwidth specific to each pixel or, for multispectral instruments, each spectral band on each OCR. The underlying spectral response function should be available in FRMOCnet/FidRadDB.

During the satellite validation process, i.e. after storage of measurement results in FRMOCnet/OCDB, in situ measurements made with the OCR spectral response function need to be further processed to convert to the satellite spectral response function. This processing step, typically called "band-shifting" for multispectral instruments, involves interpolation/extrapolation and/or convolution.

Thus, it is tentatively proposed here that:

IR9. The uncertainty associated with wavelength scale for an OCR instrument shall be estimated and propagated, including any temporal variation of wavelength scale, but excluding factors such as straylight and out-of-band response already included in IR2. This estimation shall be made relative to the central wavelength and bandwidth (assumed square or Gaussian) or full spectral response function stated as metadata when the measurement result is stored. The FRM4SOC-2 project deliverable D-8, using elements from chapter 3.4 of [20], provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR.

Again, for new OCR models to be included the FRMOCnet/FidRadDB, they must provide the abovementioned IR9 information.

Finally, for measurements to be included/flagged in FRMOCnet as "FRM" there should clearly be some documentation to describe traceably how these instrument-related requirements have been fulfilled. It is therefore suggested that inclusion of any measurement result as FRM in FRMOCnet should be subject to the documentation-related requirement ("DR") that:

DR1. Each measurement result shall be linked to an OCR instrument, identified by serial number, and for which a document is available describing the SI traceable calibration and characterisation history.

and

DR2. Each measurement result shall be linked to a document describing the detailed methodology used to estimate uncertainties IR1-IR9, including all relevant equations, physical models and their associated parameters.

3.2 Requirements for calibration of Secondary Optical Standards - from Primary Optical Standards to Secondary Optical Standards

3.2.1 Laboratory standards and processes

Working up the traceability chain depicted in Figure 2-4, the laboratories assigned to calibrate and characterise the Ocean Colour Radiometers (OCR) that are deployed in the field must themselves employ Secondary Optical Standards and processes ensuring traceability to SI units with an associated uncertainty. This upstream traceability, generally provided by National Metrology Institutes (NMIs), falls outside the scope of the 2003 NASA and 2019 IOCCG Ocean Optics Protocols, but was previously addressed by the NASA/SIRREX ("SeaWiFS Intercalibration Round Robin Experiments") activity, SIMBIOS program ("Second Intercomparison and Merger for Interdisciplinary Ocean Studies) [22], and the FRM4SOC-1 project Laboratory Calibration Experiment [Bialek et al, 2020].

In summary, as regards the calibration and characterisation laboratory standards and processes, inclusion of an OCR as FRM in FRMOCnet/FidRadDB should be subject to the calibration/characterisation laboratory-related requirements ("CR") that:

The wavelength scale is ideally described via a sensor response function (SRF) for each pixel of a hyperspectral OCR or each spectral band of a multispectral OCR. The SRF should include spectral straylight/out-of-band response.
Wavelength scale is often simplified to a central wavelength and bandwidth (e.g. FWHM), with an implicit assumption of a Gaussian or square SRF.

CR1. The Secondary Laboratory performing calibration and characterisation of OCR instruments shall follow harmonized calibration and characterisation laboratory guidelines. The FRM4SOC-2 project D-12 will provide detailed requirements for these processes for the TRIOS/RAMSES and Seabird/HyperOCR OCR.

CR2. The calibration and characterisation data needed for IR1-IR9 shall be supplied to FRMOCnet/FidRadDB in SI units and include the estimated uncertainty of such data. The FRM4SOC-2 project D-7 and D-10 will provide detailed guidance on how to achieve this for the TRIOS/RAMSES and Seabird/HyperOCR OCR.

DR3. The Secondary Laboratory performing calibration and characterisation of OCR instruments shall provide to FRMOCnet/FidRadDB documentation describing the SI traceability of their in-house optical standards and calibration/characterisation processes.

Again, for new OCR models to be included the FRMOCnet/FidRadDB, they must comply with the abovementioned CR1 and CR2 requirements and must provide the corresponding DR4 documentation.

DR-3 may be achieved by suitably documented calibration/characterisation certificates provided together with any calibration/characterisation data.

As explained in detail in FRM4SOC-2 Deliverable D-11, FRM compliant cal/char laboratories shall have an operational quality management system of ISO 17025 or equivalent plus compliance to specific requirements for FRM. There are several ways to provide proof of this.

- Participation in an international comparison such as FRM4SOC Task 6, according to requirements detailed in D-12, and obtain results that agree with the comparison reference value with set uncertainties. Guidance on international comparison exercises are provided by [29,30].
- International Laboratory Accreditation Cooperation (ILAC) recognised accreditation,
- NMIs under International Committee for Weights and Measures Mutual Recognition Arrangement (CIPM MRA),
- Establishing or designating a dedicated independent and authorised certification body outside the “ISO” system to make the audits and decisions on conformity

The main issues required by ISO 17025 or equivalent involve (not a complete list; for full requirements refer to ISO 17025):

- qualified personnel, with permanent monitoring of competence;
- facilities with the controlled environment;
- permanent presence and redundancy of measurement standards and instrumentation;
- firm traceability to SI by regular calibrations and checks between calibrations;
- defined calibration and characterisation procedures;
- uncertainty budgets compiled and evaluated according to calibration and characterisation procedures;
- periodic participation in all relevant comparison measurements.

This can be easily translated into the further documentation-related requirement (“DR”) that:

DR4. The Secondary Laboratory performing calibration and characterisation of OCR instruments shall be able to provide to FRMOCnet, (ILAC) recognised accreditation certificate to ISO 17025 standard or self-declaration documentation about conformance[14] to this standard regarding their OCR calibration and characterisation activities.

3.3 Measurements of water reflectance using calibrated and characterised OCR – from ready to use in the field OCR to measurement result

When calibrated and characterised OCR are used to measure water reflectance following a measurement method, there are many sources of uncertainty that need to be quantified relating to the imperfect assumptions, approximations and corrections inherent to the measurement method and the associated data processor. These

[14] ISO “self-declaration” is not just a statement. All requirements of a standard (or other requirements document) apply. The conformance must be presented on a relevant forum or must have passed an external audit. The difference from accreditation is that the process is not done by a dedicated authorized (ILAC) body.

sources of uncertainty have been listed and described in detail in [5,6] for the component measurements of water-leaving radiance, L_w , and downwelling irradiance, E_d^{0+} , and are summarised in Figure 3-1 and Figure 3-2.

In addition to the uncertainties relating to the component L_w and E_d^{0+} measurement results, combination of these two measurements to give a directional reflectance measurand such as R_{rs} requires the estimation of further uncertainties associated with:

- Spatial differences between L_w and E_d^{0+} and the resulting R_{rs}
- Temporal differences between L_w and E_d^{0+} and the resulting R_{rs}
- Spectral differences between L_w and E_d^{0+} and the resulting R_{rs}

In practice, spatial differences between L_w and E_d^{0+} are generally quite small, since the measurement locations (target patch of water for L_w, diffuser fore-optics for E_d^{0+} measurement by an irradiance sensor) are quite close, within a few metres or even centimetres, and natural horizontal and vertical variability of E_d^{0+} is low in the absence of artificial structures. Since these distances may become important for L_w and consequently the validation of metre-scale satellite missions [31,32] it is recommended but not required that the R_{rs} measurement result be reported at the horizontal coordinates of the L_w target water patch.

Similarly, in good measurement conditions (cloud-free sky) the temporal variability of E_d^{0+} is essentially limited to the natural variability of E_d^{0+} with sun zenith angle and this temporal variability is generally tracked by replicate measurements inherent to the measurement method. It is therefore recommended but not required that the R_{rs} measurement result be reported at the mean average time of any replicates used for L_w measurement.

Spectral differences between the instruments used to measure L_w and E_d^{0+} are generally accounted for by spectral binning (for hyperspectral) or band-shifting to nominal wavelengths (for multispectral) of these measurements prior to their use for calculation of R_{rs}.

In summary, as regards the measurement step of using calibrated and characterised OCR to measure water reflectance following a measurement method, inclusion of any new measurement result as FRM in FRMOCnet should be subject to the documentation-related requirements ("DR") and method-related requirements ("MR") that:

MR1. The uncertainty of L_w measurement result associated with each of the sources listed in [6] [AD-5] (Figure 3-1) shall be estimated and propagated. The FRM4SOC-2 project deliverable D-10 provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR.

MR2. The uncertainty of E_d^{0+} measurement result associated with each of the sources listed in [5] [AD-5] (Figure 3-2) shall be estimated and propagated. The FRM4SOC-2 project deliverable D-10 provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR.

MR3. Any further uncertainties associated with spatial, temporal or spectral differences between L_w and E_d^{0+} and the resulting R_{rs} shall be estimated and propagated. The FRM4SOC-2 project deliverables D-10 and D-6 provide guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR.

MR4. If measurement results are provided for BRDF-corrected radiometric quantities, any uncertainties associated with BRDF correction shall be estimated and propagated. The FRM4SOC-2 project deliverables D-10 and D-6 provide guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR.

DR5. Each measurement result shall be linked to a document describing the measurement method used and the detailed methodology used to fulfil MR1-MR4, including all relevant equations, physical models and their associated parameters. The FRM4SOC-2 project deliverable D-6 provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR.

In the case where a new measurement method is proposed for FRM, the estimation and propagation of uncertainties is required, as in MR1-MR4 above, and full supporting documentation is required, as in DR5 above.

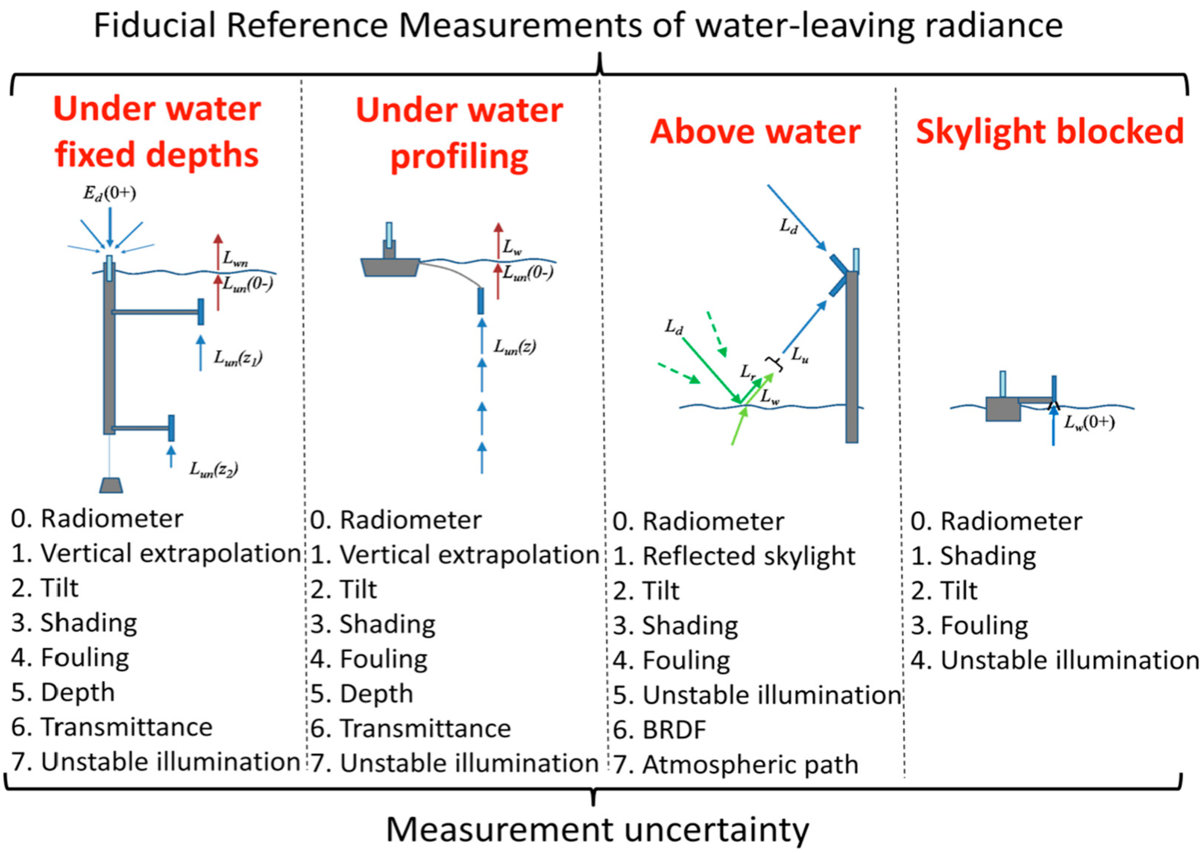

Figure 3-1. Overview of the sources that need to be included in the uncertainty estimation of measurements for the four main families of measurement method for water-leaving radiance. Reproduced from [6] [AD-5]

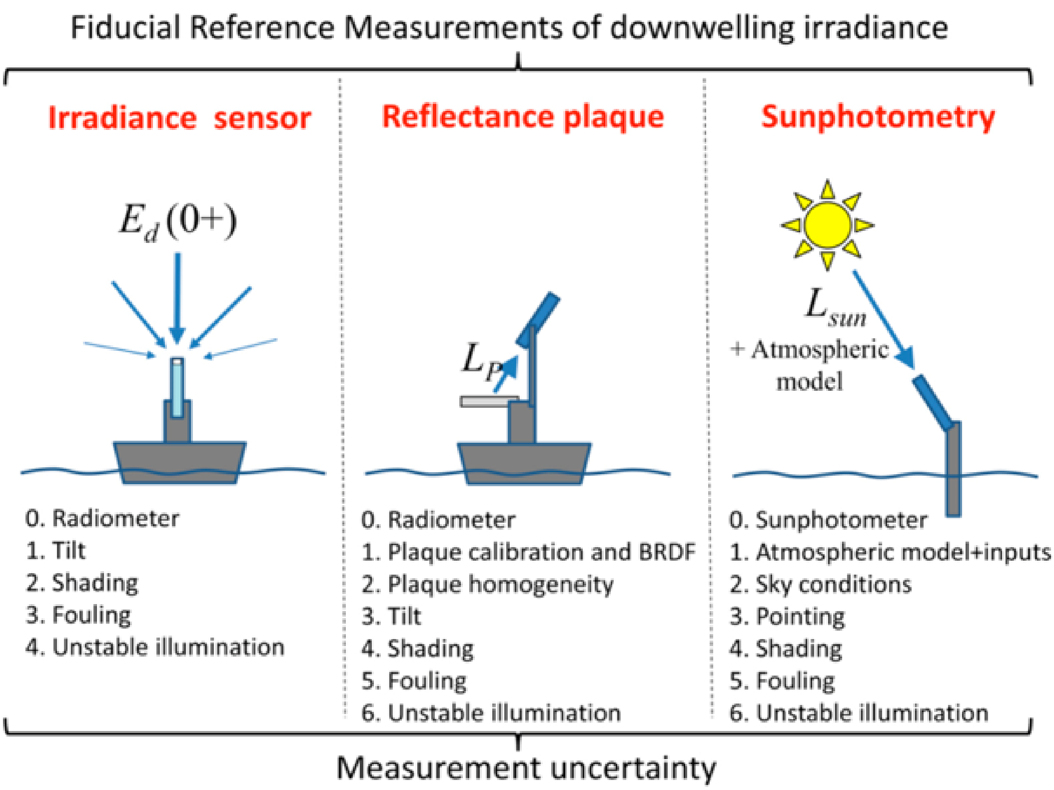

Figure 3-2. Overview of the sources that need to be included in the uncertainty estimation of measurements for the three main families of measurement method for downwelling irradiance, reproduced from [5][AD-6]

4 Further requirements

Returning to the defining characteristics of a Fiducial Reference Measurement given in section 2.3, the previous section 3 has dealt with the requirement that

- **An uncertainty budget for all FRM instruments and derived measurements is available and maintained.**

The current section describes requirements arising from the other defining FRM characteristics, namely that:

- FRM measurement protocols and community-wide management practices (measurement, processing, archive, documents, etc.) are defined and adhered to
- FRM measurements have documented evidence of SI traceability and are validated by comparison instruments under operational-like conditions

In the context of OCR and their measurements to be included/flagged in FRMOCnet as "FRM" the first of these characteristics can be satisfied by the other requirements ("OR") that:

OR1. The measurements shall be processed from raw data using corrections and end-to-end uncertainty propagation according to agreed measurement methods and community-wide management practices. The FRM4SOC-2 project deliverables D-17 and D-10 provide guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR.

DR6. The document referred to in DR1 shall be delivered to FRMOCnet, including a section on how the adopted measurement protocol and detailed methodology relates to community-wide management practices (measurement, processing, archive, documents, etc.)

As regards the second of these characteristics, documented evidence of SI-traceability is already included in DR5 described in section 3.2.1., while the requirement for validation by comparison can be satisfied by:

OR2. The FRM qualification shall be confirmed by participation of the OCR and the measurement scientist/team in relevant comparison exercises.

DR7. The document referred to in DR1 shall include a section on comparison exercises followed by the measurement scientist/team.

These intercomparison exercises can include, but are clearly not limited to, the FRM4SOC-1/2 Project Field Intercomparison Exercises (FICE).

For new OCR models to be included in the FRMOCnet/FidRadDB, the abovementioned requirements OR1-OR2 and DR6-DR7 shall be satisfied, implying that suitable processing methods for raw data and end-to-end uncertainty propagation shall be developed.

5 Process for FRM "certification"

While sections 3 and 4 of this document have proposed a set of method-, instrument-, calibration/characterisation laboratory-related and other- requirements ("MRx", "IRx", "CRx", and "ORx") and associated documentation-related requirements ("DR"), the question of how such requirements are checked or certified and by whom has not yet been decided. The topic of FRM "certification" requires further discussion – some preliminary ideas are provided in Appendix B.

6 Conclusions

This document aims to specify the minimum requirements for qualification of individual OCRs as FRM instruments and the process for the inclusion of any measurement results in the FRMOCnet/OCDB.

The requirements consist of instrument-,,calibration/characterisation laboratory-related requirements and method-, ("IRx", "CRx" and "MRx",) and associated documentation-related and other requirements ("DRx", "ORx"),. These have been explained in the preceding sections and are summarised in Table 6-1.

A tentative proposal for a FRM "certification" process, based on the analogous process for inclusion of new sites within the RadCalNet, is also and associated topics for further discussion are provided in Appendix B, to be incorporated in future versions of this deliverable after suitable discussions and decisions have been made.

It is noted that the requirements stated here are already ambitious and some requirements may be difficult to reach for many measurement scientists and instrument manufacturers in the short/medium term (3-5 year). The lack of radiometer characterisation information from manufacturers is of particular concern.

This is the first version (v1) of a document that will be further consolidated during the FRM4SOC-2 project in the light of the progress made by this project and the consultations with the wider ocean colour community, including with the project Expert Review Board and at the FRM4SOC-2 Project Workshop.

Table 6-1. Summary of proposed method-, instrument-, calibration/characterisation laboratory-related requirements ("MRx", "IRx" and "CRx") and associated documentation-related and other requirements ("DRx", "ORx") for the inclusion of any reflectance measurement results in the FRMOCnet.

Type	Description
IR1.	The uncertainty associated with radiometric responsivity of an OCR shall be estimated and delivered to FRMOCnet, including: the quantification of uncertainties from the radiometric calibration laboratory and their propagation; an estimation of any temporal changes in responsivity between such calibrations; and, for in-water measurements, (residual) uncertainties associated with immersion factors and possible pressure effects. The FRM4SOC-2 project deliverable D-10, using ideas from chapters 3.2, 3.4, 3.10 and 3.13 of [20], provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR, while the FRM4SOC-2 project deliverable D-12 provides guidance on how to perform the laboratory measurements themselves.
IR2.	The uncertainty associated with straylight/out-of-band response of an OCR shall be estimated and delivered to FRMOCnet, including: the laboratory straylight characterisation and propagation of this characterisation as well as an estimation of any temporal changes since/ between such characterisations. If a straylight/out-of-band correction is applied to a measurement result then the residual uncertainty associated with such a correction must be estimated. The FRM4SOC-2 project deliverable D-8, using ideas from chapter 3.3 of [20], provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR, while the FRM4SOC-2 project deliverable D-12 provides guidance on how to perform the laboratory measurements themselves.
IR3.	The uncertainty associated with angular response of an OCR shall be estimated and delivered to FRMOCnet, including: the laboratory angular characterisation and propagation of this characterisation; as well as an estimation of any temporal changes since/between such characterisations, especially for irradiance sensors. If a cosine response correction is applied to irradiance measurements, then the residual uncertainty associated with such as correction must be estimated. The FRM4SOC-2 project deliverable D-8, using ideas from chapter 3.5 of [20], provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR, while the FRM4SOC-2 project deliverable D-12 provides guidance on how to perform the laboratory measurements themselves.
IR4.	The uncertainty associated with non-linearity of an OCR shall be estimated and delivered to FRMOCnet, including the laboratory non-linear characterisation and propagation of this characterisation, including any integration time response. If a non-linearity correction is applied then the residual uncertainty associated with such a correction must be estimated. The FRM4SOC-2 project deliverable D-8, using ideas from chapters 3.6 and 3.7 of [20], provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR, while the FRM4SOC-2 project deliverable D-12 provides guidance on how to perform the laboratory measurements themselves.
IR5.	The uncertainty associated with thermal sensitivity of an OCR shall be estimated and delivered to FRMOCnet including the laboratory thermal characterisation and propagation of this characterisation. If a temperature correction is applied then the residual uncertainty associated with such a correction must be estimated. The FRM4SOC-2 project deliverable D-8, using ideas from chapters 3.8 of [20], provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR, while the FRM4SOC-2 project deliverable D-12 provides guidance on how to perform the laboratory measurements themselves.
IR6.	The uncertainty associated with polarisation sensitivity of an OCR shall be estimated and delivered to FRMOCnet, including the laboratory polarisation characterisation and propagation of this characterisation. The FRM4SOC-2 project deliverable D-8, using ideas from chapters 3.9 of [20], provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR, while the FRM4SOC-2 project deliverable D-12 provides guidance on how to perform the laboratory measurements themselves.
IR7.	The uncertainty associated with dark signal removal for an OCR measurement shall be estimated and delivered to FRMOCnet, including the dark signal characterisation and propagation of this characterisation, including any possible temperature effects. The FRM4SOC-2 project deliverable D-8, using ideas from chapters 3.11 of [20], provide guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR, while the FRM4SOC-2 project deliverable D-12 provides guidance on how to perform the laboratory measurements themselves.
IR8.	The uncertainty associated with temporal response (system transient response) for an OCR measurement shall be estimated and delivered to FRMOCnet, including the laboratory characterisation of transient response and propagation of this characeterisation. The FRM4SOC-2 project deliverable D-8, using ideas from chapters 3.12 of [20], provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR, while the FRM4SOC-2 project deliverable D-12 provides guidance on how to perform the laboratory measurements themselves.
IR9.	The uncertainty associated with wavelength scale for an OCR instrument shall be estimated and propagated, including any temporal variation of wavelength scale, but excluding factors such as straylight and out-of-band response already included in IR2. This estimation shall be made relative to

	the central wavelength and bandwidth (assumed square or Gaussian) or full spectral response function stated as metadata when the measurement result is stored. The FRM4SOC-2 project deliverable D-8, using ideas from chapter 3.4 of [20], provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR.
DR1.	Each measurement result shall be linked to an OCR instrument, identified by serial number, and for which a document is available describing the S.I. traceable calibration and characterisation history.
DR2.	Each measurement result shall be linked to a document describing the detailed methodology used to estimate uncertainties IR1-IR9, including all relevant equations, physical models and their associated parameters.
CR1.	The Secondary Laboratory performing calibration and characterisation of OCR instruments shall follow harmonized calibration and characterisation laboratory guidelines. The FRM4SOC-2 project D-12 provides detailed requirements for these processes for the TRIOS/RAMSES and Seabird/HyperOCR OCR.
CR2.	The calibration and characterisation data needed for IR1-IR9 shall be supplied to FRMOCnet/FidRadDB in SI units and include the estimated uncertainty of such data. The FRM4SOC-2 project D-7 and D-10 provide detailed guidance on how to achieve this for the TRIOS/RAMSES and Seabird/HyperOCR OCR.
DR3.	The Secondary Laboratory performing calibration and characterisation of OCR instruments shall provide to FRMOCnet/FidRadDB documentation describing the SI traceability of their in-house optical standards and calibration/characterisation processes.
DR4.	The Secondary Laboratory performing calibration and characterisation of OCR instruments shall be able to provide to FRMOCnet, (ILAC) recognised accreditation certificate to ISO 17025 standard or self-declaration documentation about conformance[1] to this standard regarding their OCR calibration and characterisation activities.
MR1.	The uncertainty of L_w measurement result associated with each of the sources listed in [6] [AD-5] (Figure 3-1) <u>shall</u> be estimated and propagated. The FRM4SOC-2 project deliverable D-10 provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR.
MR2.	The uncertainty of E_d^{0+} measurement result associated with each of the sources listed in [5] [AD-5] (Figure 3-2) <u>shall</u> be estimated and propagated. The FRM4SOC-2 project deliverable D-10 provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR.
MR3.	Any further uncertainties associated with spatial, temporal or spectral differences between L_w and E_d^{0+} and the resulting R_{rs} <u>shall</u> be estimated and propagated. The FRM4SOC-2 project deliverables D-10 and D-6 provide guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR.
MR4.	If measurement results are provided for BRDF-corrected radiometric quantities, any uncertainties associated with BRDF correction <u>shall</u> be estimated and propagated. The FRM4SOC-2 project deliverables D-10 and D-6 provide guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR.
DR5.	Each measurement result <u>shall</u> be linked to a document describing the measurement method used and the detailed methodology used to fulfil MR1-MR4, including all relevant equations, physical models and their associated parameters. The FRM4SOC-2 project deliverable D-6 provides guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR.
OR1.	The measurements shall be processed from raw data using corrections and end-to-end uncertainty propagation according to agreed measurement methods and community-wide management practices. The FRM4SOC-2 project D-17 and D-10 provide guidance on how to do this for the TRIOS/RAMSES and Seabird/HyperOCR OCR.
DR6.	The document referred to in DR1 shall be delivered to FRMOCnet, including a section on how the adopted measurement protocol and detailed methodology relates to community-wide management practices (measurement, processing, archive, documents, etc.)
OR2.	The FRM qualification shall be confirmed by participation of the OCR and the measurement scientist/team in relevant comparison exercises.
DR7.	The document referred to in DR1 shall include a section on comparison exercises followed by the measurement scientist/team.

[1] ISO "self-declaration" is not just a statement. All requirements of a standard (or other requirements document) apply. The conformance must be presented on a relevant forum or must have passed an external audit. The difference from accreditation is that the process is not done by a dedicated authorized (ILAC) body.

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Appendix A Terminology

During preparation and implementation of the FRM4SOC-2 project, it has become clear that some terms are used with different meanings and, particularly that the Ocean Color community may have different understanding from the metrology community. Since the FRM projects aim to bridge this case between the thematic communities (Ocean Colour, Sea Surface Temperature, Vegetation, etc.) and metrology, we propose to adopt wherever possibility terminology from the metrological community, as defined in the **VIM** [33] (JCGM200:2008).

The following terms, most used by the FRM4SOC-2 project, are clarified in Table A-1.

Table A-1. Glossary of terms defined in the VIM and used extensively in FRM4SOC2.

VIM section and term	Definition, example and notes
1.19 **quantity value** (value of a quantity, value)	VIM: "number and reference together expressing magnitude of a **quantity**" e.g. Length of a given rod: 5.34 m or 534 cm e.g. Water-leaving radiance reflectance at a given wavelength (e.g. spectral response function for OLCI 412nm band), location and time: 0.01 W m^{-2} nm^{-1} sr^{-1} FRM4SOC2 note: 1. the term "data value" is often used for "quantity value" in OC and database communities.
2.3 **measurand**	VIM: "quantity intended to be measured" e.g. Length e.g. Water-leaving radiance reflectance FRM4SOC2 note: 1. the term "parameter" is often used for measurand in the OC literature.
2.5 **measurement method** (method of measurement)	VIM: "Generic description of a logical organization of operations used in a **measurement**" FRM4SOC2 note: 1. the term "protocol" is often used in the OC literature (including in the IOCCG protocols and FRM4SOC protocol reviews) to refer to a measurement method.
2.6 **measurement procedure**	VIM: "detailed description of a **measurement** according to one or more **measurement principles** and to a given **measurement method**, based on a **measurement model** and including any calculation to obtain a **measurement result**." VIM NOTE 1: "A measurement procedure is usually documented in sufficient detail to enable an operator to perform a measurement."
2.9 **measurement result** (result of measurement)	VIM: "Set of **quantity values** being attributed to a **measurand** together with any other available relevant information" VIMNOTE 1: "A measurement result generally contains relevant information about the set of quantity values, such that some may be more representative of the measurand than others. This may be expressed in the form of a probability density function (PDF)." VIMNOTE 2: "A measurement result is generally expressed as a single **measured quantity value** and a **measurement uncertainty**. If the measurement uncertainty is considered to be negligible for some purpose, the measurement result may be expressed as a single measured quantity value. In many fields, this is the common way of expressing a measurement result." FRM4SOC2 note: VIMNOTE2 is an essential part of the FRM process and represents a major challenge for the OC community.
2.13 **measurement accuracy** (accuracy of measurement, accuracy)	VIM: "closeness of agreement between a **measured quantity value** and a **true quantity value** of a **measurand**."

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	FRM4SOC2 note: For field radiometric measurements the true quantity value is generally not known and so the measurement accuracy cannot be evaluated.
2.15 **measurement precision** (precision)	VIM: "closeness of agreement between **indications** or **measured quantity values** obtained by replicate **measurements** on the same or similar objects under specified conditions." VIMNOTE 1: "Measurement precision is usually expressed numerically by measures of imprecision, such as standard deviation, variance, or coefficient of variation under the specified conditions of measurement." FRM4SOC2 note: For field radiometric measurements the measurement precision, in contrast to the measurement accuracy, can generally be evaluated.
2.16 **measurement error** (error of measurement, error)	VIM: "**measured quantity value** minus a **reference quantity value**." VIMNOTE 1: "The concept of 'measurement error' can be used both: a) when there is a single reference quantity value to refer to, which occurs if a **calibration** is made by means of a **measurement standard** with a **measured quantity value** having a negligible **measurement uncertainty** or if a **conventional quantity value** is given, in which case the measurement error is known, and b) if a **measurand** is supposed to be represented by a unique **true quantity value** or a set of true quantity values of negligible range, in which case the measurement error is not known." FRM4SOC2 note: For field radiometric measurements the true quantity value is generally not known and so the measurement error cannot be evaluated.
2.26 **measurement uncertainty** (uncertainty of measurement, uncertainty)	VIM: "non-negative parameter characterizing the dispersion of the **quantity values** being attributed to a **measurand**, based on the information used." VIMNOTE 1: "Measurement uncertainty includes components arising from systematic effects, such as components associated with **corrections** and the assigned quantity values of **measurement standards**, as well as the **definitional uncertainty**. Sometimes estimated systematic effects are not corrected for but, instead, associated measurement uncertainty components are incorporated." VIMNOTE 2: "The parameter may be, for example, a standard deviation called **standard measurement uncertainty** (or a specified multiple of it), or the half-width of an interval, having a stated **coverage probability**." VIMNOTE 3: "Measurement uncertainty comprises, in general, many components. Some of these may be evaluated by **Type A evaluation of measurement uncertainty** from the statistical distribution of the quantity values from series of **measurements** and can be characterized by standard deviations. The other components, which may be evaluated by **Type B evaluation of measurement uncertainty**, can also be characterized by standard deviations, evaluated from probability density functions based on experience or other information." VIMNOTE 4: "In general, for a given set of information, it is understood that the measurement uncertainty is associated with a stated quantity value attributed to the measurand. A modification of this value results in a modification of the associated uncertainty."
2.33 **uncertainty budget**	VIM: "statement of a **measurement uncertainty**, of the components of that measurement uncertainty, and of their calculation and combination."

	VIMNOTE: "An uncertainty budget should include the **measurement model**, estimates, and measurement uncertainties associated with the **quantities** in the measurement model, covariances, type of applied probability density functions, degrees of freedom, type of evaluation of measurement uncertainty, and any **coverage factor**."
2.39 **calibration**	VIM: "operation that, under specified conditions, in a first step, establishes a relation between the **quantity values** with **measurement uncertainties** provided by **measurement standards** and corresponding **indications** with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a **measurement result** from an indication." VIMNOTE 1: "A calibration may be expressed by a statement, calibration function, **calibration diagram**, **calibration curve**, or calibration table. In some cases, it may consist of an additive or multiplicative **correction** of the indication with associated measurement uncertainty."

A number of terms, not defined by the VIM, are commonly used by the OC community and are described in Table A-2.

Table A-2. Glossary of terms commonly used by the OC community but not defined in the VIM.

Other OC terms	FRM4SOC2 Notes
Data value (data)	Generally refers to a **quantity value**
Metadata	information about a resource (identifiable asset or means that fulfils a requirement) according to: ISO 19115-1:2014 Geographic information — Metadata — Part 1: Fundamentals https://www.iso.org/obp/ui/#iso:std:iso:19115:-1:ed-1:v1:en Generally understood to refer to information about data values. When the latter is a measurement result, the metadata would typically provide information on space-time coordinates and any documentation related to the measurement result, potentially including measurement instrument model and serial number, calibration and characterisation history, measurement scientist/organisation, measurement equipment, etc.
Parameter	Often refers to a **measurand**
Measurement protocol	Generally refers to a **measurement method** (e.g. IOCCG protocols, FRM4SOC protocol reviews), but may refer to a **measurement procedure** (if sufficiently detailed). FRM4SOC2 recommends to avoid using this term and to specify instead **measurement method** or **measurement procedure**. Unfortunately the term "protocol" is already embedded in the FRM definition and FRM4SOC2 SOW.
(instrument) characterisation	Characterisation of a measurement instrument is a **measurement** aimed to determine a special set (spectrum) of sensitivity coefficients or errors due to some particular systematic effect. i.e. Characterisation is a measurement -- a part of a "larger measurement". e.g. • characterisation of responsivity as a function of thermal effects → temperature coefficients; • characterisation of responsivity as a function of radiant exposure[1] effects → nonlinearity coefficients;

[1] Radiant exposure is radiant energy received by a surface per unit area, or equivalently irradiance of a surface integrated over time of irradiation.

	• characterisation of angle responsivity of cosine collector → error distribution or maximum error of the radiometer.
Instrument imperfections/artefacts	Generally refers to instrument properties that affect instrument performance for a given application. FRM4SOC2 recommends to avoid the term "imperfections". The fundamental idea is that no perfect instrument exists. Instead, a radiometer's specification shall list all the relevant metrological properties. Evaluation on compliance is done with respect to the instrument specification.
Wavelength scale	The wavelength scale is a definition of the wavelengths at which measurement results are reported. This is ideally described via a sensor response function (SRF) for each pixel of a hyperspectral OCR or each spectral band of a multispectral OCR. The SRF should include spectral straylight/out-of-band response. Wavelength scale is often simplified to a central wavelength and bandwidth (e.g. FWHM), with an implicit assumption of a Gaussian or square SRF.
comparison (intercomparison, inter-comparison)	Intercomparison, inter-comparison and comparison all mean the same thing FRM4SOC2 recommends to use just "comparison" in accordance with metrology Terms and definitions from CIPM. Mutual Recognition of National Measurement Standards and of Calibration and Measurement Certificates Issued by National Metrology Institutes. Guidance document, BIPM, 1999. https://www.bipm.org/en/cipm-mra/cipm-mra-documents/ ISO/IEC 17043:2010 Conformity assessment — General requirements for proficiency testing. https://www.iso.org/obp/ui/#iso:std:iso-iec:17043:ed-1:v1:en ISO 13528:2015 Statistical methods for use in proficiency testing by interlaboratory comparison. https://www.iso.org/obp/ui/#iso:std:iso:13528:ed-2:v2:en

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Appendix B Process for FRM certification – preliminary ideas for discussion

Application of ISO 9001 or ISO 17025 standards may provide a convenient framework for FRM certification. However, ISO 17025 accreditation is a familiar process for many calibration/characterisation laboratories but is relatively unknown to water reflectance measurement scientists.

A simpler, but less rigorous approach to FRM "certification" of OCR and their measurements included in the FRMOCnet may be for the data providers (measurement scientists) to self-certify compliance with the abovementioned requirements MR1-4, IR1-9, CR1-2 and DR1-7. Such self-certification may, however, be treated with varying degrees of seriousness by different data providers and may lead to a weakening of the whole process of establishing trust in the measurement results for the data users.

An alternative to self-certification of FRM-compliance could be to assign the task of checking conformity with the stated requirements MR1-4, IR1-9, CR1-2 and DR1-7 to an outside body, such as the FRMOCnet manager, the FRMOCnet owner or a suitably contracted National Meteorological Institute. The latter model has been adopted, for example, by RadCalNet, where the requirements for inclusion of a new site within the RadCalNet [34] are stated in the RadCalNet Membership Criteria Document, which is itself supported by detailed Guidance Documents. The process for inclusion of a new RadCalNet site then involves:

- Submission of data and documents from the potential new site/location to the RadCalNet Working Group (WG), which reviews this information and discusses this iteratively with the site owner. Site owners must provide evidence of the traceability to SI and uncertainty of their data and consequently consistency with other sites using existing or new comparisons and/or satellite data.
- Following the RadCalNet WG's peer review of the site, the site's documentation and the peer review comments are submitted to the WGCV Testsite Admissions Panel for them to make a recommendation to CEOS WGCV on site admission.

Such a process, which would typically involve one or more NMIs, seems a promising model for FRM "certification" and consequent inclusion of new measurements in the FRMOCnet, although this is only a very preliminary idea, which requires further consideration during the FRM4SOC-2 project and consultation with the community of data providers (measurement scientists/teams).

The idea of FRM certification is being raised here and certainly requires more thought and consultation before becoming finalised. This evolution process is foreseen in the FRM4SOC-2 SOW [AD-0] which plans for an update, v2 of the present Requirements Document at KO+21Months, to benefit from the experience of the other project Tasks, including the FRM4SOC-2 workshop (Task 8) and other consultations with the Ocean Colour community, e.g. via the Expert Review Board. To initiate this process, we suggest here some elements that should/could be part of the FRM Certification process (as originally introduced in FRM4SOC-2 deliverable D-11):

- **FRM compliant cal/char laboratories (Scope of the SOW);**

  Described in D-12.

- **FRM certification of OCR instrument models (SOW Req. 4);**
  An instrument model passing requirements of the present document D-2, D-12, and D-27.
  Tests can be done by a FRM compliant cal/char laboratory (above).
  Type approval by manufacturer + Sample test batch should be defined by external (project can define size of batch).
  The manufacturer should be ISO 9001 certified in order to ensure steady quality of the production.
  Decision on compliance could be self-declaration on the basis of reports from the FRM compliant cal/char laboratory (above). External audit/peer review/presentation on relevant forum is required.

- **FRM certification of single individual OCR instrument (SOW Req. 5);**

  Individual instrument passing an initial/periodical calibration and characterisation routine according to requirements of the present document D-2 and D-12 in a FRM compliant cal/char laboratory (above).

  Result for compliance is the decision on FRM certified cal/char status as follows.

- **FRM certified cal/char status (Scope of the SOW);**

  This could be implemented via an automatic check in FRM4OCnet on the basis of entered data. e.g. is cal field filled in? cal period valid according to our reqts?

- **FRM competence certified operators (Scope of the SOW);**

General ISO procedures for certification of personnel may be difficult to apply to FRM measurement scientists because of lack of standardised procedures for radiometry, the small number of laboratories concerned and the difficulty to find assessors. However, there could be at least some form of a) documented in-house training and b) external intercomparison. A requirement for participation in dedicated training/comparison/coordination campaigns organised by an authorised body could be a solution but will then require organisation of such comparison exercises open to the participation of any interested measurement scientist.

- **FRM certified measurement protocols (SOW Req. 23);**

The protocols must be scientifically proven and accepted by the international expert community.