# Fiducial Reference Measurements for Satellite Ocean Colour Phase 2

## Proceedings of the Second Workshop on Calibration and Characterisation of Ocean Colour Radiometers

20 - 22 May 2025

Tartu Observatory, University of Tartu / MS Teams
Tõravere, Estonia

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## Acronyms and Abbreviations

| Acronym | Description |
|---|---|
| Cal/Char | Calibration and Characterisation |
| CEOS | Committee on Earth Observation Satellites |
| CNR | Consiglio Nazionale delle Ricerche (Italy) |
| CNRS | Centre national de la recherche scientifique (France) |
| CONICET | Consejo Nacional de Investigaciones Científicas y Técnicas (Argentina) |
| DALEC | Dynamic Above-water Radiance (*L*) and Irradiance (*E*) Collector |
| DLR | Deutsche Zentrum für Luft- und Raumfahrt |
| EC | European Commission |
| EUMETSAT | European Organisation for the Exploitation of Meteorological Satellites |
| ESA | European Space Agency |
| FidRadDB | Fiducia Reference Measurement Radiometer Database |
| FRM | Fiducial Reference Measurements |
| FRMOCnet | Fiducial Reference Measurements Ocean Colour Network |
| FRM4SOC | Fiducial Reference Measurements for Satellite Ocean Colour |
| GEO | Group on Earth Observations |
| HCMR | Hellenic Centre for Marine Research |
| HyperCP | Hyperspectral In situ Support for PACE (HyperInSPACE) Community Processor |
| IAFE | Instituto de Astronimía y Física del Espacio |
| IMEV | L'Institut de la Mer de Villefranche |
| IMO | In-Situ Marine Optics |
| INTI | Instituto Nacional de Tecnología Industrial |
| IOCCG | International Ocean Colour Coordination Group |
| ISO | International Organization for Standardization |
| JiAR | Joint Inter-Agency Request |
| JRC | Joint Research Centre |
| LOV | Laboratoire d'Océanographie de Villefranche |
| NASA | National Aeronautics and Space Administration |
| NPL | National Physical Laboratory |
| OC | Ocean Colour |
| OCDB | Ocean Colour in Situ Database |
| OCR | Ocean Colour Radiometer |
| PTB | Physikalisch-Technische Bundesanstalt |
| RMRD | Reflectance Measurement Requirements Document |
| QA | Quality Assurance |
| QA4EO | Quality Assurance Network for Earth Observation |
| QC | Quality Control |
| SI | Système International d'Unités |
| So-Rad | Solar Tracking Radiometry Platform |
| UBA | Universidad de Buenos Aires |
| UT | University of Tartu |
| TO | Tartu Observatory, University of Tartu |

# Contents

## 1. Scope

This document corresponds to the deliverable D-23b, "Proceedings of the Second Workshop on Calibration and Characterisation of Ocean Colour Radiometers" as described in the Statement of Work of the second optional extension of the FRM4SOC Phase 2 project and provides a summary on the workshop held from 20 to 22 May 2025 at Tartu Observatory, University of Tartu, Estonia.

## 2. Introduction

The quality of satellite Ocean Colour (OC) data products and user services relies on the quality of in situ radiometric measurements used in algorithm development and product validations. Space-borne instruments must be accurately calibrated and characterised before launch, monitored while in space, and additionally vicariously calibrated. Calibration and characterisation activities are also performed on in situ Ocean Colour Radiometers (OCR) so that the community can rely on the validation and the algorithms that define the performance of satellite missions [1], [2].

Fiducial Reference Measurements (FRM) are

*"A suite of **independent, fully characterized**, and **traceable** (to a **community agreed reference**, ideally **SI**) measurements of a **satellite relevant measurand**, tailored specifically to address the **calibration/validation needs** of a class of satellite-borne sensors, and following the guidelines outlined by the **GEO/CEOS Quality Assurance framework for Earth Observation (QA4EO)"*** [3]

The concept involves a series of requirements on measurement procedures and instruments to ensure documented traceability to SI units via an unbroken chain of calibrations, the assessment of instrument-related uncertainties and a series of recommended characterisations.

In this context, the European Space Agency (ESA) funded the first phase of the FRM4SOC (Fiducial Reference Measurements for Satellite Ocean Colour, 2016 – 2019) project to improve ocean colour validation through a series of proof-of-concept tasks [4]. The FRM4SOC Phase 2, funded by the European Commission via its Space Programme Copernicus and implemented by EUMETSAT, was launched in April 2021 [5].

The overarching goal of the FRM4SOC Phase 2 initiative is to promote the adoption of FRM principles across the OC community towards enhancing satellite product validation and algorithm development. To achieve this goal, the project team focuses on the following tasks:

1. Provide practical *guidelines and procedures* for calibration, characterisation, use of radiometric instruments, best practices in the field, and how to derive the uncertainty budget of the acquired measurements.
2. Provide *tools* to process radiometric *field measurements with associated uncertainties* (e.g. HyperCP [6]) and *databases* to store results of *calibrations* (e.g. FidRadDB [7]) and *field measurements* (e.g. OCDB [8]).

3. *Test and validate* what is being implemented, achieved by means of *laboratory and field inter-comparison experiments*.
4. *Broadcast* the guidelines and tools to the OC community. This is mainly achieved through workshops and training events.

Guided by these tasks, **the Second Workshop on Calibration and Characterisation of Ocean Colour Radiometers was hosted by the University of Tartu from 20 to 22 May 2025, at Tartu Observatory, Tõravere, Estonia.**

## 3. Objectives of the workshop

The main objective of the workshop was to reach out to the interested parties working on the calibration and characterisation (Cal/Char) of OCR (Figure 1) and discuss the following topics:

- present and future challenges in calibration and characterisation of OCR, e.g.
  - calibration and characterisation principles, facilities, and methods,
  - data acquisition, processing, and formats,
  - evaluation of uncertainties for different calibration equipment, measurement conditions and methods,
  - development of metrologically sound as well as operationally achievable uncertainty budgets,
- the requirements to achieve FRM quality of in situ measurements for satellite data validation (need for calibration and characterisation of OCR),
- existing guidelines, procedures, tools, and best laboratory practices for OCR calibration and characterisation,
- organisation of future comparison measurements,
- knowledge exchange on the methods, procedures and facilities,
- visit the calibration and characterisation laboratories at Tartu Observatory (TO) of the University of Tartu (UT),
- improvement and harmonisation of the developed guidelines, procedures and tools.

## 4. Programme

The workshop gathered different interest groups of the OC community (Figure 1) – the leading experts in the field, representatives of agencies (EUMETSAT, and NASA), manufacturers of OCR (Sea-Bird Scientific, TriOS, In-Situ Marine Optics, Water Insight), calibration laboratories and national metrology institutes (DLR, HEREON, JRC, UT, NPL, INTI), institutes actively deploying OCRs (HCMR, HEREON, Sorbonne Université IMEV, CNRS LOV, JRC, IAFE CONICET/UBA), as well as software and database developers/maintainers (Brockmann Consult GmbH).

The workshop was organised as a seminar, with plenty of room for discussion after every presentation to get feedback from the community. The presentations are available at [https://frm4soc2.eumetsat.int/frm4soc-workshop-2025](https://frm4soc2.eumetsat.int/frm4soc-workshop-2025).


Figure 1. Cross-section of the FRM4SOC Phase 2 workshop forum.

## Tuesday, 20 May 2025

*Session 1 – Calibration and characterisation of OCR*

1. Opening and welcome from the director of TO
   *A. Tamm (UT)*
2. Introduction of the agenda, practical information
   *R. Vendt (UT), M. Jauk (UT)*
3. FRM4SOC project overview and overarching goal of the workshop
   *J. I. Gossn (EUMETSAT)*
4. Rationale and requirements for calibration and characterisation of field OC radiometers
   *G. Zibordi (EOScience)*
5. Guidelines for calibration and characterisation of OCR
   Part 1 - Calibration
   *I. Ansko (UT)*
6. Guidelines for calibration and characterisation of OCR
   Part 2 – Characterisation
   *I. Ansko (UT)*
7. FRM4SOC Phase 2 Laboratory Comparison and lessons learned
   *V. Vabson (UT)*
8. Calibration and characterisation file formats
   Manufacturer and FidRadDB/HyperCP format
   *I. Ansko (UT)*

*Session 2 – Groupwork*

1. Groupwork rotation 1
   (A: Cal/Char setups; B: Uncertainty Workshop; C: Facilities tour)
2. Groupwork rotation 2
   (B: Cal/Char setups; C: Uncertainty Workshop; A: Facilities tour)

**Wednesday, 21 May 2025**

*Session 2 – Groupwork continues*

1. Groupwork rotation 3
2. (C: Cal/Char setups; A: Uncertainty Workshop; B: Facilities tour)

*Session 3 – Uncertainties*

1. Uncertainty budgets in OCR calibration and characterisation
   *V. Vabson (UT)*
2. Measurement uncertainties in processing field data with HyperCP
   *A. Bialek (NPL)*

*Session 4 – Manufacturers of OCR*

1. IOCCG Joint Inter-Agency Request to OCR Manufacturers
   *J. I. Gossn (EUMETSAT)*
2. Presentation from SeaBird Scientific
   *E. Rehm (SeaBird Scientific)*
3. Presentation from TriOS
   *A. Köppen (TriOS)*
4. Presentation from In-Situ Marine Optics
   *W. Klonowski (In-Situ Marine Optics)*
5. Presentation from Water Insight (online)
   *S. Peters (Water Insight)*

*Session 5 – Implementing OCR calibration and characterisation procedures*

1. Achievements and challenges at HCMR, Greece
   *A. C. Banks (HCMR)*
2. Achievements and challenges at INTI, Argentina
   *J. P. Babaro (INTI)*
3. Calibration and characterisation capabilities at HEREON, Germany
   *H. Burmester (HEREON)*
4. Calibration and characterisation capabilities at JRC, European Commission
   *P. Sciuto (JRC-EC), G. Zibordi (EOScience)*
5. Calibration and characterisation capabilities at DLR, Germany
   *P. Gege (DLR)*

**Thursday, 22 May 2025**

*Session 6 – Discussion and conclusions*

1. Discussion "A way forward"
2. Conclusions and final remarks

# 5. Rationale and requirements for Cal/Char of OCR

## 5.1 Requirements

The following list of documentation summarises the rationale and requirements for cal/char of OCRs, many of which were issues in the frame of FRM4SOC Phase 2. As an outcome of this workshop, [10] (D-27 RMANU) was updated to reflect the discussions and agreements.

[1] 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. http://dx.doi.org/10.25607/OBP-691

[2] Addendum (June 2024) to IOCCG Protocol Series (2019) Volume 3: Request to manufacturers of in situ and above-water spectral imaging radiometers in the UV, VIS and NIR range

i. Provide absolute calibration coefficients with associated **uncertainties**.
ii. Participate in **comparison experiments** with national metrology institutes and/or secondary calibration laboratories.
iii. Help to **propagate FRM guidelines, procedures and tools**.

[3] P. Goryl, N. Fox, C. Donlon, and P. Castracane, Fiducial Reference Measurements (FRMs): What Are They?, Remote Sensing, vol. 15, no. 20, Art. no. 20, Jan. 2023, doi: 10.3390/rs15205017.

[9] FRM4SOC-2, Reflectance Measurement Requirements Document (RMRD), Deliverable D-2, April 2023, *https://frm4soc2.eumetsat.int*

[10] FRM4SOC-2, FRM Requirements Document for Instrument Manufacturers (RMANU), Deliverable D-27, May 2023, *https://frm4soc2.eumetsat.int*

## 5.2 Reaching FRM

Reaching FRM quality can be challenging, albeit achievable if proper coordination is achieved between the key stakeholders and focus is given to the priority tasks. To fulfil FRM requirements, *in situ* radiometric measurements should be:

*Performed following*

i. published and verified, ideally community-shared, measurement protocols and
ii. detailed quality assurance (QA) procedures.

*Performed with instruments*

i. that allow keeping uncertainty levels constrained within the threshold imposed by the target application.
ii. with documented radiometric performance (i.e., supported by absolute calibrations traceable to SI and characterisations determining instrumental biases as a function of varying measurement conditions).

*Reduced and processed in agreement with community-shared protocols, supported by documented details on*

i. the flow leading to the determination of data products, including the application of radiometric calibrations and corrections for the instrumental biases,
ii. the quality control procedures (QC), and
iii. the metrology principles applied for the determination of the uncertainty budget.

*Accessible through consolidated databases supported by*

i. details on units and data formats, and
ii. ideally, community-shared indices identifying the measurement method and the fitness for application.

### 5.3 IOCCG Joint Inter-Agency Request to OCR Manufacturers

- To achieve the "FRM goal", the OC community must maintain continuous communication with manufacturers.
- The IOCCG JiAR [2] request addresses providing uncertainties for OCR calibration coefficients, but it doesn't require manufacturers of OCR to perform a full characterisation of each instrument.

## 6. Calibration and characterisation of OCR

Guidelines for OCR calibration, individual characterisation programme, and recommended periods are given in IOCCG Protocols [1] and FRM4SOC-2 guides D-8 [11] and D-12 [12]. The following is considered input for amendments and updates to the guidelines D-12.

### 6.1 Individual and class-based characterisation

- Calibration and characterisation (either sensor- or class-specific, depending on the particular case) of OCR are required to achieve traceability to SI with adequate uncertainty evaluation.
- Radiometers must be calibrated at least once a year, or preferably before and after a measurement campaign.
- Characterisation of OCR is needed due to biases of instruments depending on varying measurement conditions.
- Full characterisation of OCR is very time-consuming and expensive. In reality, it is not possible to make a full characterisation for all instruments. Therefore, some compromises (as described in the following points) must be made.
- Recommended periods for individual characterisation are given in the IOCCG Protocols [1] and FRM4SOC-2 guides D-8 [11].
- The class-based characterisation, which evaluates the averaged bias and spread of biases across an instrument type, aims at a compromise [1], [11].
- Class-based characterisation results in higher uncertainty compared to individual characterisation. The choice between the two depends on the required uncertainty level.

- However, some effects, such as those arising from the build of each instrument (e.g. angular response), still require individual characterisation.

## 6.2 Guidelines

There has been an ongoing debate about whether calibration laboratories should strictly adhere to prescriptive guidelines or adopt general metrology guidelines that suit their specific instruments and facilities.

- Detailed, even step-by-step, guidelines for measurement procedures and uncertainty evaluation are strongly requested by calibration laboratories and manufacturers of OCR.
- However, the implemented procedures depend on the available equipment, technical solutions (e.g. integrating spheres versus reflectance panels for radiance measurements), etc. Each laboratory must adapt the procedures to suit its specific case.
- Guidelines for harmonising data handling and processing are required.
- There has been some confusion because the responsivity coefficients for TriOS Ramses and Sea-Bird Scientific HyperOCR radiometers are presented differently. Therefore, differences in data processing must be carefully observed.
- Training and close cooperation among the key stakeholders (see Fig. 1) are necessary for harmonising procedures, calibration, characterisation, data handling, and uncertainty evaluation.

## 6.3 Measurement capability of laboratories

With limited resources, we need to base our focus and priorities on pragmatic considerations.

- Start with the most common instrument types: HyperOCR, Ramses, and DALEC.
- The minimum requirement for manufacturer laboratories is the ability to provide SI traceable calibration of radiometers, along with a related uncertainty statement.
- Manufacturer laboratories are also encouraged to develop characterisation capability for some of the most significant uncertainty sources, such as angular response and linearity of OCR.
- Characterisation activities could be divided into laboratories on networking principles, allowing each laboratory to focus on specific characterisations.
- The uncertainty limits should be targeted to respond to the validation requirements.
- Only a few laboratories (such as JRC, TriOS Mess- und Datentechnik GmbH, and Sea-Bird Electronics Inc.) currently have the facilities and ability to perform in-water characterisation of OCR. More laboratories with such capabilities are needed.

## 6.4 FEL lamps

- Reference lamps come in various designs, including holders, reference surfaces, and orientations. It is important to ensure that a lamp is used as intended, i.e. powered, monitored, positioned, and oriented according to its calibration specifications.
- FEL lamps are disappearing from the market, so new alternatives must be searched for.
- Having several lamps in a lab for reference is essential.
  - Several lamps form a pool of reference, which enables checking and discovering any discrepancies in traceability.
  - Several lamps are needed to ensure the sustainability of a lab.
- FEL lamp calibration results are usually given in 5 nm, 10 nm or even 50 nm to 100 nm steps without the interpolation formula.
- Comparing various interpolation techniques directly to the Planck formula-based method shows that using data with 10 nm or smaller wavelength steps makes the calculations simpler and accurate. Using linear interpolation is also often justified with 10 nm or smaller steps. Therefore, requesting a lamp calibration certificate (or an additional data file to it) with 10 nm or smaller wavelength steps is recommended.
- If calibration results are only available with larger than 10 nm steps, more complicated interpolation methods (e.g. Planck formula approximation [13]) are needed to obtain lamp irradiance values at any wavelength, and an additional increase of uncertainties for the interpolated values is to be expected.
- The recommendations will be provided in the updated version of D-12 [12].
- Recommended period for calibrating an FEL lamp is 50 working hours.
  - Some manufacturers recommend a one-year calibration period, but this is justified when the laboratory has no means of monitoring the lamp's stability.

## 6.5 Reflectance Panels

- Reflectance panel calibration in 0°/45° geometry should be preferred. However, this calibration is very expensive and only a few calibration laboratories can provide it (e.g. NPL and PTB).
- Manufacturers of panels provide spectral reflectance for 8°/hemispherical geometry, which must be corrected for 0°/45° geometry.
  - Several experimental datasets indicate that in the wavelength range of (300…800) nm, a correction factor of 1.024 can be used. This factor has an uncertainty of about 0.5% [14], [15].
- Linear interpolation between calibration points can be used. Further recommendations on interpolation will be provided in the updated version of D-12 [12].
- Some manufacturers of reflectance panels issue class-based calibration certificates for their products. This approach is also acceptable, but the uncertainty of the correction factor in this case is larger (more than 0.5%).

### 6.6 Comparison measurements

- Comparison measurements are essential for validating calibration and characterisation procedures, as well as uncertainty budgets.
- As emphasised by the IOCCG JiAR [2] request, the manufacturers of OCR are kindly requested to take part in comparison measurement exercises if FRMs are to be obtained with their OCR.
- Comparison measurement exercises must be planned carefully. The choice of comparison objects and methods to establish the reference value depends on targeting the comparison focus (e.g. validating specific procedures, measurement capabilities of particular laboratories, or both).
- Cal/char labs as well as manufacturers of OCR have participated in several comparisons and are motivated to participate in the future.
- There are not many laboratories available with specific measurement capabilities. More laboratories are needed to
  - share the increasing workload, and
  - establish a reliable reference pool.
- Funding for organising dedicated comparison measurements is needed.
- Financial support is needed for laboratories to participate in the comparison measurements.

## 7. FidradDB

The FidRadDB ("Fiducial Radiometer" Data Base) is a database containing information on radiometric calibration and characterisations done on field Ocean Colour radiometers. The objective of the FidRadDB is to centralise all existing information on cal/char of TriOS and SeaBird radiometers in the frame of the FRM4SOC-2 project.

- The FidRadDB is accessible via OCDB command line client (ocdb-cli), Python API, and HyperCP community processor. For details please refer to: *https://ocdb.eumetsat.int/docs/fidrad-database.html* and *https://ocdb.eumetsat.int/docs/fidrad-api.html*
- The FidRadDB is not easy to find on the web. Promoted gateways shall be designed for https://ocdb.eumetsat.int and *https://ocdb.eumetsat.int/docs/*.
- OCR calibration and characterisation laboratories having appropriate capabilities (including manufacturers of OCR) can submit cal/char data to FidRadDB.
- No DOI is provided for the cal/char files.
- Guidelines on file structure and submission procedures, as well as example files, are available at *https://ocdb.eumetsat.int/docs/fidrad-database.html*. However, the information provided needs to be amended and updated.
- Files submitted to FidRadDB will pass the format check and will be rejected if any mismatch is found with the format.

# 8. HyperCP

HyperInSPACE (Hyperspectral In-situ Support for PACE) Community Processor (HyperCP) is an open-source processor for above-water radiometry from autonomous or manually operated in situ platforms that facilitates protocol-driven data correction and reduction, yielding high-quality surface reflectance measurements with end-to-end uncertainty analysis.

The latest version of HyperCP now supports Sea-Bird Scientific HyperSAS packages with and without SolarTracker or pySAS robotic platforms, as well as TriOS used in manual configuration and IMO DALEC. Support of Monocle/PML So-Rad is undergoing. HyperCP is compatible with FidRadDB cal/char inputs and outputs follow the SeaBASS format, compatible with OCDB.

## 8.1 Processing regimes

At present, three processing regimes have been implemented in HyperCP.

1. Full FRM processing regime, which is able to retrieve OCR calibration and characterisation files from FidRadDB.
2. Class-based FRM processing regime.
3. Factory processing regime (non-FRM, no calibration uncertainties).

However, a “Hybrid FRM” processing regime (i.e. a combination of “Full FRM” and “Class-based FRM”) would be the most practical one.

- The Hybrid FRM regime will likely be the most widely deployed processing chain, serving as a reasonable compromise between the limited available resources for OCR calibration and characterisation, and the larger uncertainties evaluated over a given instrument class.
- The implementation of the Hybrid FRM regime is planned for the next development phases of the HyperCP.
- In practice, the Class-based FRM regime will evolve into the Hybrid FRM regime by incorporating individual characterisation options.

## 8.2 Evaluation of the drift of OCR properties between calibrations

- If an OCR has undergone multiple calibrations over time, there are several options for applying the calibration coefficients:
    - use the coefficients closest to the given field measurement by default,
    - evaluate the drift between two recent calibrations.
- It’s important to check the properties of OCR before and after the campaign. Depending on the type of deployment, these changes should be evaluated on a case-by-case basis.
- For example, if the drift is small, then the average of two calibrations or interpolations for the time period can be used.
- However, if an instrument experiences failures or changes in its optical properties (e.g. a broken diffuser), averaging or interpolation of calibration results cannot be applied. In such cases, the moment of a significant change on

a timescale should be evaluated based on available measurement data. Data collected after the event should be considered unreliable for further use.
- After-campaign checks can also be made for certain wavelengths to save limited resources.

### 8.3 General notes

- HyperCP does not perform tilt correction, but tilt can be filtered and reported using the ship attitude variables.
- HyperCP still needs to be tested for extremely turbid waters.
- High solar zenith angles may become critical for the rho correction. Polarisation may play an important role, but this has not yet been assessed.
- Photos of the sky and water are only considered qualitatively. Therefore, a generic operational assessment of superstructure perturbations cannot be derived from these photos.
- The HyperCP does not process in-water measurements.

## 9. Manufacturers view

Presentations were given by

- SeaBird Scientific (E. Rehm),
- TriOS (A. Köppen),
- In-Situ Marine Optics (W. Klonowski),
- Water Insight (online, S. Peters).

Manufacturers of OCR

- are very much motivated to work closely with the OCR community and strive to meet the FRM requirements [1], [2], [3],
- are open to recommendations for procedures and technical solutions to implement these in the development process,
- have participated in several comparison campaigns and are also motivated to participate in future,
- need detailed prescriptive guidelines for calibration, characterisation, uncertainty evaluation, and requirements for quality management (e.g. ISO certification or accreditation),
- need guidelines on how much of the OCR characterisations manufacturers need to perform,
- can provide some characterisations of OCR, but (due to high costs) will never be able to provide a full characterisation for each instrument.

## 10. Cal/Char lab view

Presentations were given by

- HCMR, Greece (A. C. Banks),
- INTI, Argentina (J. P. Babaro),
- HEREON, Germany (H. Burmester),
- JRC, EC, (G. Zibordi),

- DLR, Germany (P. Gege).

Motivation

Continue contributing to the European/International effort to ensure and improve the quality of ocean colour satellite data by

- calibrating own OCR sensors,
- providing OCR calibration service in the region,
- and developing experience and capabilities.

Challenges
(especially when starting a new laboratory)

- lack of funding, space, and motivated and qualified personnel,
- sustainability of resources (facilities and personnel),
- maintaining traceability to SI,
- procurements (regulations, possible providers, affordability),
- meeting the requirements for facilities, equipment, methods, procedures, and quality management (especially when starting a new laboratory).

Needs

- an understanding of the requirements,
- detailed guidelines on cal/char procedures, uncertainty evaluation, and quality management (e.g. requirements for ISO certification or accreditation),
- availability of suitable comparison measurements,
- financial support for participation in comparison exercises.

## 11. Achieving FRM-compliant laboratory status

- General guidelines (CEOS approach) to achieve FRM-compliant laboratory status are given in

[3] P. Goryl, N. Fox, C. Donlon, and P. Castracane, 'Fiducial Reference Measurements (FRMs): What Are They?', Remote Sensing, vol. 15, no. 20, Art. no. 20, Jan. 2023, doi: 10.3390/rs15205017.

- The CEOS FRM approach uses a software tool for self-evaluation of FRM status. However, it lacks guidelines for implementation in the OC domain.
- The OC community follows the technical framework provided by the IOCCG Protocols [1].
- The guidelines to achieve FRM quality in the OC domain are given in the FRM4SOC-2 report D-2 "Reflectance Measurement Requirements Document (RMRD) [9].
- The CEOS FRM and FRM4SOC D-2 guidelines agree on the requirements for quality management in an FRM laboratory:

- Maintaining a quality management system (e.g., ISO 17025 or equivalent) and ensuring traceability of measurements to the units of SI with adequate evaluation of measurement uncertainty.
- Accreditation of the quality management system is not always necessary. Instead, organisations can self-evaluate their compliance with requirements and be prepared to provide relevant documentation at all times and have independent experts perform peer-review audits of the quality management system.

# 12. Guidelines and recommendations for the manufacturers of OCR

The following is considered input for amendments and updates to the guidelines FRM4SOC-2 D-27 [10].

- Manufacturers of OCR need clarification on the requirements listed in D-27 [10].
- The minimum set of essential requirements is listed in the IOCCG JiAR [2] request
  - Provide absolute calibration coefficients with associated **uncertainties**.
  - Participate in **comparison experiments** with national metrology institutes and/or secondary calibration laboratories.
  - Help to **propagate FRM guidelines, procedures and tools**.
- Manufacturers are also encouraged to develop characterisation capability for some of the most significant uncertainty sources, such as angular response and linearity of OCR.

Recommendations for the manufacturers of OCR.

- Ensuring the quality of the OCR components that define the radiometric and metrological performance of the instruments (such as the input optics, spectrometer module, image sensor, signal amplifier & conditioner, analogue-to-digital converter and voltage references) should be the top priority in product development. Enhanced communication means (such as web servers) do not improve the achievement of FRM quality, but add complexity and power consumption.
- Manufacturers of OCR systems should be able to demonstrate their ability to provide high-quality angular diffusers. The choice of a suitable material, such as fused silica, is of great importance.
- Such ability involves maintaining a laboratory for the characterisation of angular diffusers, and also publishing the results.
- Full characterisation of OCR, with extensive analysis of the results, is not typically expected from manufacturers; however, it is still encouraged.
- Manufacturers of OCR could address a maximum uncertainty level that a user would consider acceptable when purchasing the instrument. For example, having the capability to evaluate uncertainty contributions, giving the largest contribution (~3...10%) to the overall uncertainty budget.
- The maximum permitted working temperature for an OCR should be higher than +40 °C. The radiometers may have higher temperatures in field conditions. The recommended operating range is from 0 °C up to 50 °C.
- The communication protocol with instruments should be kept simple and straightforward (e.g., a single command to start the acquisition with a defined integration time, gain, etc., and after completion of the measurement, to return the raw data from all available pixels, temperature sensors, etc.).
- Internal automatic application of calibration coefficients and corrections should be avoided.

- Maintaining the 12 V operating voltage (supported by a wider range) is preferred.
- Simple shape form factor (e.g. cylindrical) is favoured for adjustment accuracy and repeatability.

## 13. Conclusions

- All laboratories across the world face a lack of experienced staff and funding issues.
- Initiatives such as FRM4SOC are essential to keep the community motivated to progress and face the local challenges in a cooperative, coordinated way.
- Achieving and promoting the FRM standard for OCR is a hard task, but not impossible. The FRM4SOC consortium is willing to spread the expertise and support the OC community.
- Several guidelines are available for calibrating and characterising OCR, as well as evaluating uncertainty. However, these guidelines require regular updating and clarification.
- Regular training, workshops, and visits to other laboratories are necessary to ensure a harmonised understanding and implementation of the guidelines.
- Regular dedicated comparison exercises are required.
- Financial support for organising as well as participation in the comparison exercises is needed.
- Manufacturers should consistently prioritise adhering to the IOCCG JiAR [2] request and strive to meet the requirements listed in FRM4SOC-2 D-2 [9] and D-27 [10]. Open dialogue between space agencies and manufacturers could foster a sustainable business case for compliance.
- FRMOCnet is planning to expand to new instrument classes, systems, and methods (e.g. IMO DALEC, So-RAD, in-water measurements).
- Development of the HyperCP must be continued – the implementation of the Hybrid FRM regime is needed to support users having only some of the instrument-specific characterisations.

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