D-280: FRM4SOC Scientific and Operational Roadmap

Title	FRM4SOC Scientific and Operational Roadmap
Document reference	FRM4SOC-SOR
Project	ESA – FRM4SOC
Contract	ESRIN/Contract No. 4000117454/16/1-SBo
Deliverable	D-280
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Version	**1**
Date issued	04.11.2019

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Responsibility

Statements made in this report are the responsibility of the lead author and the FRM4SOC Project Team and do not necessarily represent the official views of the European Space Agency or the organisations of any of the scientists who contributed to this report. The FRM4SOC project is funded by the European Space Agency.

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Acknowledgements

Input and comments from numerous scientists and experts are gratefully acknowledged. The FRM4SOC team, G. Zibordi, D. Antoine, all participants of the project events, and manufacturers of the ocean colour radiometers are kindly thanked for the valuable support and contribution to the project outcomes and the current document.

1. Document Control Table

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2. Document Change Record

Index	Issue	Revision	Date	Brief description	Issued by
1.	1	0	04.11.2019	Original issue	Riho Vendt

3. Distribution List

Company/Organisation	Name	Format	No. of Copies
UT	Riho Vendt	Electronic file – word	1 docx
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4. Contents

5. Executive Summary

The FRM4SOC project, with funding from ESA, has been structured to provide support for evaluating and improving the state of the art in OC validation through a series of comparisons under the auspices of CEOS WGCV and in support of the CEOS OCR virtual constellation. This document, the "D-280: FRM4SOC Scientific Operational Roadmap (SOR)" is written following the Contract No. 4000117454/16/I-SBo between the European Space Agency (ESA) and University of Tartu as stated in the Statement of Work, for the ESA Invitation to Tender (ITT) ESA/AO/1-8500/15/I-SBo Fiducial Reference Measurements for Satellite Ocean Colour (FRM4SOC).

The document i) provides a critical analysis of all the feedback from participants and institutions working in the project (Section 13), ii) identifies potential strategies for integrating the project outcomes into existing initiatives and operational institutions (Section 14), iii) defines a plan for fostering a transition of FRM4SOC outcomes from research to operational activities (Section 15), and iv) identifies priority areas to be addressed in potential future projects in support of OCR calibration and validation activities (Section 16).

The document lists 24 main conclusions summarised from the reports and series of discussions on several events in the framework of the FRM4SOC project. A strategy, implementation plan and 17 actions are proposed to integrate the FRM4SOC outcomes with existing initiatives, operational institutions and activities.

The following **priority areas** to be addressed in implementation and further development of FRM for satellite ocean colour are identified.

1. Updating measurement protocols and uncertainty budgets
2. Development of a community processor for data handling and uncertainty evaluation
3. Providing examples and short practical guides for uncertainty evaluation
4. Training on implementation of measurement protocols and end-to-end uncertainty evaluation
5. Establishment of required specifications of FRM OCR
6. General plan for calibration and characterisation of OC radiometers
7. Development of metrology infrastructure for calibration and characterisation of new generation OC radiometers
8. Periodic calibration and characterisation of OC radiometers
9. Describing a global comparison strategy for FRM4SOC measurements
10. Organising periodic comparison measurements on all levels of the traceability chain.
11. Development of ocean colour system vicarious calibration infrastructure.

6. Acronyms and Abbreviations

Acronym	Abbreviation
AAOT	Acqua Alta Oceanographic Tower
AERONET	Aerosol Robotic Network
AERONET-OC	Aerosol Robotic Network Ocean Colour
AMT	Atlantic Meridional Transect
BIPM	Bureau International des Poids et Mesures
BOUSSOLE	BOUée pour l'acquiSition d'une Série Optique à Long termE
BRDF	Bidirectional Reflectance Distribution Function
CEOS	Committee on Earth Observation Satellites
WGCV	Working Group on Calibration & Validation
CMEMS	Copernicus Marine Environment Monitoring Service
CNR	Consiglio Nazionale delle Ricerche
CZCS	Coastal Zone Colour Scanner
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
EO	Earth Observation
EOEP	Earth Observation Envelope Programme
ESA	European Space Agency
ESRIN	European Space Research Institute
ESTEC	European Space Research and Technology Centre
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FCDR	Fundamental Climate Data Record
FICE	Field Comparison Experiment
FRM	Fiducial Reference Measurements
FRM4SOC	Fiducial Reference Measurements for Satellite Ocean Colour
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
IOCCG	International Ocean Colour Coordinating Group
IOP	Inherent Optical Properties
ITT	Invitation To Tender
JRC	Joint Research Centre
LCE	Laboratory Comparison Exercise
MERIS	Medium Resolution Imaging Spectrometer (of the ESA ENVISAT mission)
MOBY	Marine Optical BuoY
MSI	Multispectral Imager
NASA	National Aeronautics and Space Administration
NMI	National Metrology Institute
NOAA	National Oceanic and Atmospheric Administration
NPL	National Physical Laboratory
OC	Ocean Colour
OCR	Ocean Colour Radiometer

Acronym	Abbreviation
OCR-VC	Ocean Colour Radiometry-Virtual Constellation
OLCI	Ocean and Land Colour Instrument
PACE	Plankton, Aerosol, Cloud ocean Ecosystem
QA4EO	Quality Assurance for Earth Observation
ROI	Return on Investment
S3VT	Sentinel-3 Validation Team
SDG	Sustainable Development Goal
SeaBASS	Bio-optical Archive and Storage System (of SeaWiFS)
SeaWiFS	Sea-Viewing Wide Field-of-View Sensor
SI	Systeme International d'Unites
SIMBIOS	Sensor Intercomparison for Marine Biological and Interdisciplinary Ocean Studies
SOR	Scientific Operational Roadmap
SoW	Statement of Work
SVC	System Vicarious Calibration
TO	Tartu Observatory of University of Tartu
TR	Technical Report
UN	United Nations
UT	University of Tartu
VIM	International Vocabulary of Metrology

7. Introduction

This document, the D-280 “FRM4SOC Scientific and Operational Roadmap (SOR)” is written following the Contract No. 4000117454/16/I-SBo between the European Space Agency (ESA) and University of Tartu as stated in the Statement of Work, for the ESA Invitation to Tender (ITT) ESA/AO/1-8500/15/I-SBo Fiducial Reference Measurements for Satellite Ocean Colour (FRM4SOC) [1]. The FRM4SOC project, with funding from ESA, has been structured to provide support for evaluating and improving the state of the art in ocean colour validation through a series of comparisons under the auspices of the Committee on Earth Observation Satellites (CEOS) Working Group on Calibration & Validation and in support of the CEOS ocean colour virtual constellation. The document addresses the requirement to write a Scientific and Operational Roadmap (SOR) building on the outputs, knowledge and tools developed by the project, to foster future development that could potentially transfer the outcomes of the project into future sustained activities. The SOR shall:

i. Provide a critical analysis of all the feedbacks from participants and institutions working in the project,

ii. Identify potential strategies for integrating the project outcomes into existing initiatives and operational institutions,

iii. Define a plan for fostering a transition of FRM4SOC methods and results from research to operational activities,

iv. Identify priority areas to be addressed in potential future projects in support of OCR calibration and validation activities.

The document is based on discussions and conclusions collected from series of events organised in the framework of the FRM4SOC project:

1. International workshop “Options for future European satellite OCR vicarious adjustment infrastructure required for the long-term vicarious adjustment of the Sentinel-3 OLCI and Sentinel-2 MSI A/B/C and D instruments”, 21 – 23 February 2017 at ESRIN, Frascati, Italy [2], [3];

2. Laboratory Comparison Exercise (LCE-1) “SI-traceable comparison experiment to verify the performance of reference irradiance sources” 3 – 7 April 2017 at the National Physical Laboratory (NPL), London, UK and “SI-traceable comparison experiment to verify the performance of reference radiance sources” using a circulating NPL calibrated transfer radiometer between April and December 2017. [4], [5];

3. Laboratory Comparison Exercise (LCE-2) “SI-traceable Laboratory comparison experiment for verification of Fiducial Reference Measurement (FRM) Field Ocean Colour Radiometers (OCR)”, 8 – 13 May 2017 at Tartu Observatory, Tõravere, Estonia [6]–[9];

4. FRM4SOC Seminar with the manufacturers of the FRM OCR, “Radiometers used to make Fiducial Reference Measurements for Ocean Colour Satellite Validation”, 6 September 2017 at ESTEC, Noordwijk, Netherlands [10];

5. Field Comparison Experiment (FICE) on the Atlantic Meridional Transect (AMT) held from 20 September to 5 November 2017 on Atlantic Ocean [11], [12];

6. Field Comparison Experiment (FICE) at the Acqua Alta Oceanographic Tower (AAOT), 8 – 18 July 2018 off the Gulf of Venice, Italy in the northern Adriatic Sea [12], [13];
7. Final workshop of the FRM4SOC "The Fiducial Reference Measurement Network for Satellite Ocean Colour", on 4 – 5 October 2018 at National Physical Laboratory (NPL), Teddington, London, UK [14], [15].

As well as the meetings of the Sentinel-3 Validation Team (S3VT):

1. The third Sentinel-3 Validation Team Meeting (S3VT), 15 – 17 February 2017 at ESRIN, Frascati Italy [16], [17];
2. The fourth Sentinel-3 Validation Team Meeting (S3VT), 13 – 15 March 2018 at EUMETSAT Darmstadt, Germany [18], [19];
3. The fifth Sentinel-3 Validation Team Meeting (S3VT), 7—9 May 2019 at ESRIN, Frascati Italy [20]

Inputs from all participants and institutions are gratefully acknowledged.

8. Grand challenges

Increasing needs of modern society require more and more of the limited natural resources available on Earth. We depend on these resources for our survival and development however, our global population continues to grow, thus generating an ever-increasing demand for [21]–[24]:

- safe living space,
- fresh water,
- fertile land, and
- clean air.

Society as a whole is facing numerous global threats, including [21]–[24]:

- climate change,
- a threatening energy crisis,
- potential food shortages,
- a higher frequency and intensity of natural and manmade disasters.

The United Nations (UN) General Assembly adopted the resolution "Transforming Our World: the 2030 Agenda for Sustainable Development" in September 2015. This is a global development agenda for all countries and stakeholders serving as a guide to ensure economic, social, and environmental sustainability. Seventeen Sustainable Development Goals (SDGs) and associated Targets and Indicators are listed in the 2030 Agenda, which specifically calls for new data acquisition and exploitation of a wide range of data sources to support implementation [21]. The Goals and targets will stimulate action over the next 15 years in areas of critical importance for humanity and the planet [21], [25].

The 2030 Agenda states, *inter alia*, "We are determined to …:

- end poverty and hunger, in all their forms and dimensions, and to ensure that all human beings can fulfil their potential in dignity and equality and in a healthy environment;
- protect the planet from degradation, including through sustainable consumption and production, sustainably managing its natural resources and taking urgent action on climate change, so that it can support the needs of the present and future generations … " [21].

The 2030 Agenda also calls for new Earth Observation (EO) methods, data acquisition and exploitation of a wide range of data sources to support implementation. In particular, Article 76 states,

"*We will promote transparent and accountable scaling-up of appropriate public-private cooperation to exploit the contribution to be made by a wide range of data, including Earth Observation and geo-spatial information, while ensuring national ownership in supporting and tracking progress*" [21].

9. Addressing the challenges

The Group on Earth Observations (GEO) joins more than 100 national governments and in excess of 100 Participating Organizations in envisioning a future where decisions and actions for the benefit of humankind are informed by coordinated, comprehensive and sustained Earth observations. Together, the GEO community is creating a Global Earth Observation System of Systems (GEOSS) to better integrate observing systems and share data by connecting existing infrastructures using common standards. [25]–[27].

The Committee on Earth Observation Satellites (CEOS) joins 34 member agencies and 28 associate organisations focusing on validated requirements levied by external organizations and serving as the primary forum for international coordination of space-based Earth observations [27], [28].

EO activities are carried out and data are provided by a variety of actors, such as the European Space Agency (ESA), the US National Aeronautics and Space Administration (NASA), US National Oceanic and Atmospheric, Administration (NOAA), and many others.

In Europe, the *ESA Earth Observation Strategy 2040* sets the vision in response to global challenges as "… *to enable the maximum benefit of Earth observation for science, society and economic growth in Europe, served by European industry. ESA will implement this vision through its Earth observation programmes, working in close cooperation with Member States, the EU, EUMETSAT and European industry within the widest international framework.*" The ESA Earth Observation Strategy 2040 is implemented through a number of programmes that are dedicated to both scientific (EOEP, Earthwatch, Climate Change Initiative) and operational demands (Copernicus, MetOp, Meteosat). [23]

The Earth Observation Envelope Programme (EOEP) is the backbone for implementing the ESA Earth Observation Strategy 2040 whose prime objectives are to help society to:

- Observe: develop and provide the observations to better understand the complexity of our planet and monitor its health;
- Understand: enable improved predictions of the physical interaction of society with the Earth system;
- Decide: inform decision makers and citizens on scenarios and consequences of political and economic decisions regarding our home planet.[29], [30]

With its four core activities:

- Future Missions,
- Mission Development,
- Mission Management, and
- EO Science for Society

the EOEP is dedicated to bring Earth Observation to society by addressing the Scientific and Societal Challenges as well as promoting Excellence and Innovation and building Industrial Competiveness. [29], [30]

Copernicus is the European Union's Earth Observation Programme, looking at our planet and its environment for the ultimate benefit of all European citizens. It offers information services based on satellite Earth Observation and *in situ* (non-space) data. The Programme is coordinated and managed by the European Commission (EC). It is implemented in partnership with the Member States, the European Space Agency (ESA), the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), the European Centre for Medium-Range Weather Forecasts (ECMWF), EU Agencies and Mercator Océan. [23], [24]

10. Need for Reliable Earth Observation Data

Vast amounts of global data are being collected from satellites as well as airborne, ground-based, and seaborne (*in situ*) measurement systems all over the world as a key resource to support the decision-making in addressing environmental challenges, provide information for service providers, public authorities and other international organisations in improving the quality of life. [22], [24]

Decision-making relies, and will continue to rely, on the ability of expert communities to utilize complex data from Earth observations and combine these with social and economic analyses. Sound, evidence-based decision-making will encourage sustainable behaviour by humankind in relation to Earth's resources, leading to economic benefits for all of society. [22]

This will be achieved through the synergistic collection and use of data. Data may be derived from a variety of sources (satellite, airborne and *in situ*) at all scales – global, regional and local – through the coordinated resources and efforts of the GEO members. [22], [31], [32]

It is recognised, that collected EO data must be reliable and of high quality. For example if ground-based measurements are to be credibly used for satellite validation activities (particularly for assessment of climate data record stability (e.g. [33], [34]) then they must be obtained contemporaneously, co-located with satellite measurements and be accurate and precise [1]. For that purpose, GEO has identified the need to develop and implement a data quality assurance strategy and works closely with the Committee on Earth Observation Satellites (CEOS). The mission of the CEOS Working Group on Calibration & Validation (WGCV) is to ensure long-term confidence in the accuracy and quality of Earth Observation data and products and to provide a forum for the exchange of information about calibration and validation, including the coordination of cooperative activities. The CEOS Quality Assurance Framework for Earth Observation (QA4EO) has set general principles for EO data quality assurance. [22], [31], [35]–[38]

As noted in 1995 at the 20th Conference Generale des Poids et Mesures [39], a recommendation was made that:

"*those responsible for studies of Earth resources, the environment, human wellbeing and related issues ensure that measurements made within their programs are in terms of well-characterized SI units so that they are reliable in the long term, are comparable world-wide and are linked to other areas of science and technology through the world's measurement system established and maintained under the Convention du Metre*".

This lays the foundation to relate satellite measurements to Systeme International d'Unites (SI) standards and gives the guiding principle for EO data quality assurance strategy to relate all data and derived products associated with them to SI reference standards. [1], [31], [40], [41].

In addition, in order to have an objective indication of the quality level of data and compare available datasets meaningfully, all relevant measurement uncertainties must be evaluated [42]. The principles of metrological traceability and measurement uncertainty being a part of general, internationally recognised good practices for conducting measurements are developed and endorsed by the Bureau International des Poids et Mesures (BIPM) and National Metrology Institutes (NMI) [40], [42]–[45].

As defined by BIPM and the International Vocabulary of Metrology (VIM) [43], [44]:

Metrology *is the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology.*

Traceability *is a property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.*

Calibration *is an 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.*

Unequivocally linking an "observation" to an invariant constant of nature (e.g. international system of units) with a robust estimate of uncertainty ensures the "measurement" can be: trusted, coherent and comparable with others, have longevity as "improving with age" [27].

We need to trust our collected measurement data, for example:

- Fundamental Climate Data Records (FCDR),
- Satellite and in situ data time series and products,
- Maintaining SI traceability for space borne sensors.

This can be achieved by implementation of the principles and methods of metrology as

establishment of the metrological traceability of the measurement data to the units of SI with related end-to-end uncertainty analysis.

11. Fiducial Reference Measruements (FRM)

In order to build trust for EO data and address the principles described in Section 10. the concept of Fiducial Reference Measurements (FRM) has been established as defined in [46], [47].

Fiducial Reference Measurements (FRM) are a suite of independent, fully characterized, and traceable ground measurements that follow the guidelines outlined by the GEO/CEOS Quality Assurance framework for Earth Observation (QA4EO). These FRM provide the maximum Return On Investment (ROI) for a satellite mission by delivering, to users, the required confidence in data products, in the form of independent validation results and satellite measurement uncertainty estimation, over the entire end-to-end duration of a satellite mission. [46], [47]

The defining mandatory characteristics for FRM as listed in [46], [47] are:

- FRM measurements have documented SI traceability (e.g. via calibration and evidenced by round-robin intercalibration of instruments). For measurements requiring the highest accuracy direct traceability to an NMI is encouraged.
- FRM measurements are independent from the satellite geophysical retrieval process.
- An uncertainty budget for all FRM instruments and derived measurements is available and maintained, demonstrating consistency with a community reference ideally tied to SI directly through an NMI.
- FRM measurement protocols and community-wide management practices (measurement, processing, archive, documents etc.) are defined, published openly and adhered to by FRM instrument deployments.
- FRM measurements are openly and freely available for independent scrutiny.

12. The FRM4SOC project

Within the context described above ESA has initiated a series of projects targeting the validation of ESA altimetry, atmosphere, land, and ocean products [47]. The FRM4SOC project, with funding from ESA, has been structured to provide support for evaluating and improving the state of the art in OC validation through a series of comparisons under the auspices of CEOS WGCV and in support of the CEOS OCR virtual constellation.

The societal Benefits of Ocean Colour Radiometry (OCR) are well articulated (e.g. [48]–[50]) and include management of the marine ecosystem, role of the ocean ecosystem in climate change, aquaculture, fisheries, coastal zone water quality, mapping and monitoring harmful algal blooms.

In response to the main driver in addressing the grand challenges – the need for reliable EO data – a series of recommendations on activities critical to ensure high accuracy and consistency for ocean color mission products have been agreed under the guidance of the International Ocean Color Coordinating Group (IOCCG), representatives of Space Agencies and Institutions supporting INSITU-OCR. [32]

The aim of the FRM4SOC (Fiducial Reference Measurements for Satellite Ocean Colour) project is: *"To establish and maintain SI traceability of Fiducial Reference Measurements (FRM) for satellite ocean colour radiometry (OCR)"* [1].

The Objectives for FRM4SOC are [1]:

Obj1. Design and document **measurement procedures and protocols for OCR FRM** used for satellite OCR validation activities.

Obj2. Document the design and **performance of OCR radiometers** commonly used for satellite OCR validation including a review of their known characterisation (e.g. immersion factor, cosine response, linearity, straylight, spectral, temperature sensitivity, dark currents etc.) and identify significant issues to address.

Obj3. Design, document protocols and procedures and implement a laboratory based (round-robin) **comparison experiment to verify the performance of reference irradiance and radiance sources** (i.e. lamps, plaques etc.) used to maintain the calibration of FRM OCR radiometers traceable to SI.

Obj4. Design, document protocols and procedures and implement a **laboratory based comparison experiment to verify the performance** (i.e., absolute radiometric calibration and characterization) **of FRM Field Ocean Colour Radiometers (OCR)** used for Satellite Validation.

Obj5. Design, document protocols and procedures and implement **field comparisons of FRM OCR radiometers and build a database of OCR field radiometer performance** knowledge over a several years.

Obj6. **Conduct a full data analysis, derivation and specification of uncertainty budgets**, following agreed NMI protocols, for FRM OCR field measurements used for satellite OCR validation collected as part of FRM4SOC.

Obj7. Evaluate options for **long-term future European satellite OCR vicarious adjustment**.

13. Feedback from participants and institutions working in the project

13.1. Implementing the principles of FRM

The requirement for FRM is clearly defined by the ocean color community. High quality data is needed for both vicarious calibration and product validation. This data must follow sampling, analysis, quality control and protocol methods approved by the community. [27], [30], [32], [51]–[55]

- FRMs give evidence about the quality of ocean color products and data services;
- FRMs provide empirical knowledge to develop bio-optical models for algorithm and product development;
- FRMs are critical to establish
  - SI-traceable L2 product validation,
  - L2 algorithm evolution (now particularly for complex waters),
  - New L2 products requested by CMEMS and other users.

Measurements preformed for EO data validation must have metrological traceability to the units of SI with related uncertainty evaluation. This is achieved via calibration and characterisation of measurement instruments and evidenced by comparison.

The term “FRM” is of relatively recent origin however, the fundamental understanding and general principles of FRM have been implemented over decades by ESA, NASA, NOAA, EUMETSAT, JRC, etc. [56] [53]. Just a few examples from the list are CZCS [57], SeaWiFS [58], SeaBASS [59], MOBY [60], [61], BOUSSOLE [62], SIMBIOS [63]; MERIS [64], AERONET-OC [65] CEOS OCR-VC / INSITU-OCR activities [32], Copernicus OC-SVC [66], PACE [67], etc. Sometimes calibration and validation programs for individual missions have had a wide range of approaches and methodologies [52], [56]. Therefore, agencies such as ESA, NASA, NOAA, EUMETSAT etc. and National Metrology Institutes (NMI) should consider forming a symbiotic relationship in order to harmonise approaches, methodologies and implement the principles of FRM worldwide [56]. Financial support from agencies for that purpose must be considered [3], [5, p. 4], [56].

The FRM4SOC project has proved itself as very successful, needed and having great impact to the community. For example the FRM4SOC was one of the few projects specifically mentioned in the conclusions of the Sentinel-3 Validation Team meeting (S3VT) [16].

The S3VT concluded in Frascati, February 2017:

"*Great thanks to ESA for FRM4SOC project" and recommends "S3VT and the broader community to participate in the FRM4SOC project developments*". [16]

On the following S3VT meeting in Darmstadt, March 2018 [18], [19] it was concluded:

"*FRM4SOC – important activities to support field instrument characterization and measurement protocols:*

- *forced the manufacturers to better characterize their instruments;*
- *inter-calibrations across labs enabled maintaining the standards and consistency;*
- *continuation recommended.*"

And on the 5th S3VT Meeting 2019 at ESA-ESRIN, Frascati:

Recommendation on "*Continuation of FRM4SOC activities to ensure the quality of in situ ground truth (instrument inter-calibrations -traceability to SI, measurement round robins, data processing harmonization –community processor)*" [20]

The FRM4SOC project has made a major contribution in support of the Copernicus OC-SVC infrastructure activities, has defined strategies, protocols and good practices for FRMs for satellite product validation and algorithm development that should be [51]:

- implemented by the community, e.g. S3VT-OC,
- continued and expanded to bio-optical measurements like IOPs, Chl, etc.,
- sustained throughout the lifetime of the Copernicus Ocean Colour missions.

It is important that the principles of FRM are accepted and implemented by the community and the FRM(4SOC) activities should be continued for that purpose.

CONCLUSIONS FROM THE PROJECT

C1 Measurement results collected for EO data validation shall have metrological traceability to the units of SI with related uncertainty evaluation.

C2 Space agencies should: *i.* in the medium term, encourage and stimulate the adoption of FRM requirements, and *ii.* in the long term, when sufficient progress and consensus is achieved, use only FRM for the routine validation of satellite ocean colour data. In the near term use of non-FRM quality data for satellite calibration or validation should only be done with great care.

C3 Space agencies and National Metrology Institutes should consider forming a symbiotic relationship in order to harmonise approaches, methodologies and implement the principles of FRM worldwide.

C4 Financial support from ESA and other space agencies or entities shall be ensured for implementing the principles of FRM.

13.2. Measurement procedures, protocols and uncertainty budgets for OCR FRM

The fundamental principle of FRM is to evaluate all contributing uncertainty sources in measurements performed for satellite OCR validation. The evaluated uncertainty budget shall combine all *in situ* contributions: "from instrument absolute calibration, characterisation (including at least spectral calibration, nonlinearity, stray light perturbation and polarisation sensitivity, temperature dependence and, if applicable, geometrical and in-water response), environmental perturbation, and data processing" etc. [32], [68]–[71].

A lot of work on OCR protocols has been done over the years. Historically, the key protocol document for aquatic radiometric measurements for satellite validation has been provided by the NASA Ocean Optics Protocols series [71]–[74], but there are also other protocols developed e.g. "Regional validation of MERIS chlorophyll products in North Sea coastal waters" [75], MERIS Optical Measurement Protocols and MERMAID database [76] etc.

International worldwide cooperation is imperative to ensure high quality global climate data. It is important that data and expertise collected internationally over years is acknowledged and preserved.

Generally, the available protocols do not differ much from each other, however sometimes there is a gap in how the protocols are understood and applied in practice. A good communication, between agencies, research institutes as well as people in-field, laboratories and offices is needed [3], [56], [66].

Measurement protocols used globally for OCR data validation shall be harmonised as well as understood and followed uniformly on all levels.

The S3VT Ocean Colour Subgroup pointed out some conclusions and recommendations from the 4th S3VT meeting at Darmstadt in 2018 as [19]:

"Towards Fiducial Reference Measurements"

- environmental uncertainties are the key;
- large share of the total uncertainty budget;
- observations for validation need to be collected in ideal conditions (clouds, wind, etc);
- need to define recommendations for environmental 'ideal conditions';
- 'ideal conditions' may be dependent on the water types and types field systems used, e.g. autonomous systems;
- specific types of platforms may consider standard definition of environmental condition in protocols;

and "Feasibility of standardized processing of raw FRM measurements"

- community processor in open source;
- processor to quantify uncertainties based on characterization/protocols/measurements provided by investigators;
- start with processing data from a single instrument that is most commonly used by the community.

Community has to make an effort to come out with consolidated examples of uncertainty budgets for OCR protocols.

Funding agencies should enforce common calibration schemes and measurement protocols, and unifying processing schemes and quality assurance criteria to ensure consistency and traceability of *in situ* measurements to SI standards. [32]

In order to achieve FRM status as regards the measurement protocols, it is recommended to [5]:

- Consider the IOCCG INSITU-OCR White Paper [32], analyse carefully a current measurement protocol and construct an uncertainty budget including minimum set of elements e.g. as listed in [5];
- Participate in comparison exercises to validate their uncertainty estimates against those of other methods/scientists;

and it is recommended to ESA and other space agencies to [5]:

- facilitate discussion and adoption of good practice and uncertainty estimation by sponsoring comparison exercises with appropriate funding for post-measurement analysis of results;
- in the medium term encourage and stimulate the adoption of FRM requirements and in the long term, when sufficient progress and consensus is achieved, use only FRM for the routine validation of satellite ocean colour data.

Discrepancies in following protocols may be due to several reasons e.g. lack of knowledge and experience, incorrect habits or because of impractical requirements of a protocol. Sometimes there is no real indication of what needs to be done to validate your data. [14] Practical implementation of comparisons may entail a series of round-robins on specific topics together with training opportunities. [31]

Therefore, it is important to:

- ensure that requirements of a protocol correspond to actual needs and purpose of the measurements and are not developed so that they may favour or bias any particular instrument or method ;
- document good practice for performing measurements;
- provide training and real practice for young scientists in order to gain experience and correct habits, whilst ensuring that any analysis is not inappropriately biased;
- provide support and practical examples on compiling uncertainty budgets;
- validate established uncertainty budgets and methods in comparison campaigns.

Measurement requirements and protocols are subject to constant evolution alongside the progress of technology, measurement methods and needs of society. It is important to track these developments and identify the requirements of the community being addressed. Therefore it is also important to evaluate acceptable error limits and uncertainties that shall meet these requirements and address critical elements in that chain to be tackled – i.e. to map required uncertainty levels that are currently being achieved, not currently achieved, or a long way from being achieved. Any improvements in metrology needed to keep up with development of future technologies must be started today. [3], [56]

The vital components and specifications of new generation instruments (e.g. hyperspectral) shall be identified and calibration / characterisation capabilities of required metrology infrastructure shall be developed accordingly.

CONCLUSIONS FROM THE PROJECT

C5 International worldwide cooperation on all levels (e.g. agencies, research institutes, experts, etc.) is imperative in order to ensure high quality global climate data. Different protocols existing for OCR data validation all over the world shall be harmonised, understood and applied in a consistent manner to ensure global uniformity of measurements.

C6 Data (including appropriate metadata) and expertise collected over years by the international community shall be acknowledged, preserved and passed on to the next generations.

C7 Principles of good practice in performing measurements shall be documented and their application encouraged.

C8 Practical consolidated examples on compiling uncertainty budgets shall be provided.

C9 Established methods, principles of good practice, and uncertainty budgets shall be validated in comparison measurements.

C10 Definition, adoption and validation of the principles of good practice and uncertainty budgets shall be supported with appropriate funding from ESA and other space agencies or entities.

13.3. Review of OC radiometers commonly used for FRM field measurements

Properties of OC radiometers such as measurement range, expected error and uncertainty limits must reflect the needed accuracy for satellite OCR data validation and correspond to requirements as identified and established by the international community in the field [66], [68], [69], [74], [77].

Therefore, in order to ensure the reliability of measurement results i.e. traceability to the units of SI with the associated uncertainty evaluation it is recommended [70]

to instrument manufacturers:

- characterise new types of instruments in well-equipped optics laboratories under stable reference conditions as well as under varied conditions similar to in-field measurements;
- provide further public information on instrument performance and characterisation where necessary to fill gaps in present knowledge;

to instrument users:

- order regularly the radiometric calibration of instruments in well-equipped calibration labs, collect and carefully analyse the results, verify SI traceability chain and request uncertainty values for the calibration;
- request, as customers, detailed performance information from the instrument manufacturers;
- verify specifications of instrument performance by performing independent tests.

For scientists with access to a well-equipped optics laboratory these tests could be quite detailed, e.g. measurement of angular response of irradiance sensors, measurement of thermal sensitivity, measurement of stray light/out of band response, although it is fully recognised that such tests may be very time-consuming and will generally require external funding. For scientists without access to a well-equipped optics laboratory it is still possible to verify certain aspects of instrument performance, e.g. by comparison of measurements made by different instruments pointing at a uniform target such as a cloudless sky or by participation in multi-partner comparison activities (such as the LCE activities of the FRM4SOC Project). [70]

Considering the statements above, the following questions were asked from the manufacturers of the OCR during the seminar, "Radiometers used to make Fiducial Reference Measurements for Ocean Colour Satellite Validation" held at ESA ESTEC on the 6th of September 2017 [10].

1. **Would the manufacturers of OCR benefit from services of a common European e.g. NPL and UT (TO) joint laboratory for calibration and characterisation of radiometers?**

    - Most of the manufacturers have their own calibration facilities. However, in general the manufacturers of OCR are open to performing more detailed characterisation in a common lab.
    - A common calibration lab would also benefit from standardisation of calibration/ measurement procedures, quality cross checking, and reducing risks of damage during OCR transportation.

2. **Would the manufacturers be interested in the continuation of round table seminars for discussing requirements for the OCR?**

    - It was the first time that the manufacturers of OCR, ESA, National Metrology Institutes, and EO institutes have met together in the same room to discuss OCR requirements. This is impressive. Manufacturers have several new systems under development and there is a need to work together in order to reach the next generation of OCR.
    - The FRM4SOC team needs input from manufacturers of OCR. We also need editors in order to review requirements and share the best knowledge.
    - We are looking for consensus in the community on practically feasible requirements, however, the principles of metrology must be followed and the concept of uncertainty must reach the community. There is a need for fundamental scientific understanding in the field.
    - It would be beneficial to continue the initiative and establish an OCR forum in a form of a series of seminars.

It is important, that agencies in co-operation with the OC community establish the link between scientific research, the industrial world, innovative technologies, and operational solutions and define goals to be achieved.

It is recommended to ESA and other space agencies or entities, including Copernicus Services, requiring Fiducial Reference Measurements for satellite validation to [10], [56], [70]:

- fund and encourage preparation of a guidance document setting minimum requirements for the most important properties of OCR instruments (like temporal stability, linearity, thermal stability etc);
- fund and encourage activities to test radiometers from all manufacturers according to standardised methodologies;

- fund and encourage further development of OCR instruments, including a requirement that such developments provide FRM-compatible information on radiometer characterisation.

It is important to identify the vital components and specifications of new generation instruments (e.g. hyperspectral) and develop the calibration and characterisation capability of the required metrology infrastructure accordingly.

At the FRM4SOC Final Workshop the manufacturers [56], [78], [79]:

- declared dedication to producing high quality, robust *in situ* radiometric sensors to support existing and future needs for Ocean Colour;
- are also looking to the future in advancing the state of the art in radiometric measurements and in developing the next set of tools for accurate, cost effective satellite ocean colour calibration/validation;
- support activities such as FRM4SOC to both define existing and future requirements, but also to work in collaboration with industry to verify uncertainties and make recommendations for improvements.

A document setting minimum requirements for most important properties of OCR instruments used for satellite OCR validation is needed.

CONCLUSIONS FROM THE PROJECT

C11 Properties of OC radiometers must reflect the needed accuracy for satellite OCR data validation and correspond to requirements as identified and established by the international community in the field. Community consensus on practically feasible requirements is needed. However, the principles of metrology - SI traceability and acceptable uncertainty limits - must be followed.

C12 A document setting minimum requirements for the most important properties of radiometric instruments used for satellite OCR validation is needed. Preparation of such a document should be encouraged and funded by ESA and other space agencies or entities.

C13 Vital components and specifications for new generation (e.g. hyperspectral) instruments shall be identified and characterisation capabilities of required metrology infrastructure shall be developed accordingly.

C14 ESA and other space agencies or entities should encourage further development of OCR instruments, including a requirement that such developments provide FRM-compatible information on radiometer characterisation.

C15 Characterisation and regular calibration of OCR is needed in order to ensure traceability to the units of SI and evaluate the instrument related uncertainty contributions.

C16 ESA and other space agencies or entities should fund and encourage activities to test radiometers from all manufacturers according to a standardised methodology.

13.4. Comparison experiments for validation of methods and uncertainty budgets

Periodic comparison measurements are required to provide evidence to support claims on traceability, uncertainty and as a means of evaluating any bias from sensors or processes. [32], [80]

Application of a robust radiometric calibration chain using common setup and calibration standards for all participating instruments is required for detecting measurement errors and discovering discrepancies in uncertainty budgets. (Section 13.2), [5], [7]–[9], [12], [56]

The comparison exercise campaigns also serve the purpose of training, sharing experience, and support in achievement of common understanding and interpretation of the measurement protocols. This is an opportunity to document and support application of "*good practice*" in performing measurements; provide support and practical consolidated examples on compiling uncertainty budgets and real practice for young scientists in order to gain experience and right habits. (Section 13.2) [32], [56]

Conclusions from the FRM4SOC project show that **carefully planned comparison measurements have revealed errors that would have not been discovered in regular measurement campaigns** [7]–[9], [81]. For example, in the comparison exercises of LCE-1, LCE-2 and FICE-AAOT several cases were found where human errors or specific properties of a particular measurement instrument would not have been detected in straightforward field measurement. It was also noted, that application of *unified data handling* or a *community processor* would reduce overall uncertainty and improve the agreement between individual datasets. [7]–[9], [12]

Worldwide international participation of agencies and research organisations in comparison exercises shall be aimed for. [7], [56]

Such comparison exercises demand a vast amount of effort as well as human and infrastructural resources. Therefore, financial support from agencies for implementing comparison experiments is needed. [3], [56]

CONCLUSIONS FROM THE PROJECT

C17 Periodic comparison experiments are needed for validation of established methods and uncertainty budgets on all levels of the traceability chain.

C18 Comparison experiments also serve the purpose of training, sharing experience, and support achievement of common understanding and interpretation of the measurement protocols.

C19 Application of unified data handling or a community processor will reduce overall uncertainty and improve agreement between individual datasets, although care not to limit innovation must be ensured.

C20 Worldwide international participation of agencies and research organisations in comparison exercises shall be aimed for.

C21 ESA and other space agencies or entities shall encourage and support implementing of comparison experiments with appropriate funding.

13.5. Options for long-term future European satellite OCR vicarious adjustment.

With the Sentinel programme, Copernicus is at the forefront of Earth Observation for the next decades to come. To make the best of European Union investments, it is mandatory that Copernicus mobilize resources to secure in the long-term SVC infrastructures as well as operational data validation capacity. The FRM4SOC project has documented general requirements for European SVC infrastructure [3]. In depth requirements for future SVC infrastructures can be found in EUMETSAT requirements documents [66].

The current Copernicus operational system does not include a robust infrastructure for SVC but instead, relies on the MOBY infrastructure owned and operated by the United States NOAA in Hawaii, Pacific Ocean and the quasi-operational research infrastructure of the BOUSSOLE buoy in the Mediterranean. This is a significant risk to the performance of S3 OLCI L2 products in an operational context. It was discussed at the international FRM4SOC workshop on SVC [2], [3] that:

- Neither MOBY nor BOUSSOLE are directly supported by Copernicus. The risk of losing one or both and their associated expertise, and therefore losing the capacity to deliver robust EO products, must be taken into consideration.
- Given that the US MOBY infrastructure is secured in the long term, Copernicus should consider maintaining two operational SVC sites, resulting in a minimum of 3 sites globally. This will ensure system redundancy and robustness of ocean colour SVC as recommended by the Committee on Earth Observation Satellites (CEOS).
- Maintaining two sites in Europe will also: secure the existing expertise, knowledge and knowhow in Europe; develop new expertise; stimulate technical, scientific and industrial innovation.
- From a risk mitigation perspective, it is also essential that Copernicus has control on vicarious calibration capacity to ensure Sentinel 2 and Sentinel 3 product quality for the next two decades.

- For the development of these two proposed Copernicus operational SVC sites, it is clear that building upon existing systems and expertise (namely BOUSSOLE and MOBY) would be more cost effective.

Consequently, the community recommendations for the development of the SVC infrastructure within the framework of Copernicus are:

- The BOUSSOLE as existing unique validation site in Europe must be maintained in the long term and upgraded to full operational status.
- Development and long term operation of a second new European infrastructure in a suitable location to gain ideal SVC conditions and ensure operational redundancy is needed.
- Good metrological foundation with 'hands-on' involvement of National Metrological Institutes (NMIs) at all stages of development of an SVC infrastructure is of key importance.
- The fiducial reference measurement (FRM) ethos ensures SI traceability, full uncertainty characterisation and the best possible accuracy and precision for the SVC measurements and process. Note that the FRM element is limited to the *in situ* component of the SVC process.
- *In situ* radiometry should be hyperspectral, high spectral resolution, high quality, and of an SI-traceable FRM nature, with a full uncertainty budget and regular SI-traceable radiometric calibration.
- A MOBY-Net system, that includes the transportable modular optical system developed by NASA and the MOBY team, is recommended for the new site. It offers a technologically proven system within a realistic timeframe for Copernicus needs and its use reinforces collaboration of world-class experts and centres of excellence. In parallel, steps should be taken within the framework of Copernicus to develop a European solution in the mid-term.

CONCLUSIONS FROM THE PROJECT

C22 Operational FRM infrastructures to underpin SVC with SI traceability, full uncertainty characterisation and the best possible accuracy and precision are mandatory. Such FRM infrastructure of the quality needed for SVC shall be redundant in order to ensure steady and sufficient data provision.

C23 The BOUSSOLE as existing unique validation site in Europe must be maintained in the long term and upgraded to full operational status.

C24 Development and long term operation of a second new European infrastructure in a suitable location to gain ideal SVC conditions and ensure operational redundancy is needed.

14. Potential strategies for integrating the project outcomes into existing initiatives and operational institutions

The strategy for integrating the project outcomes into existing initiatives and operational institutions follow the principles as established by CEOS, IOCCG and the BIPM [31], [38], [39], [42], [43], [71], [73], [74] and as reflected by the activities of the FRM4SOC project [1].

Reliable measurements for EO data validation must have metrological traceability to the units of SI with related uncertainty evaluation.

This is generally achieved by implementing the following flow cycle periodically:

1) Analysis and establishment of **requirements,**
2) Definition of measurement **methods and protocols** to meet the requirements
3) Selection of **instruments** to meet the established requirements and protocols,
4) Establishment of the **traceability** chain by calibration (Figure 1.),
5) Evaluation of uncertainty sources (including characterisation of instruments) and compilation of end-to-end **uncertainty budgets** (incl. characterisation),
6) Validation of the methods and uncertainty budgets in **comparison experiments**,
7) Collection and filing of measurement and comparison **data.**

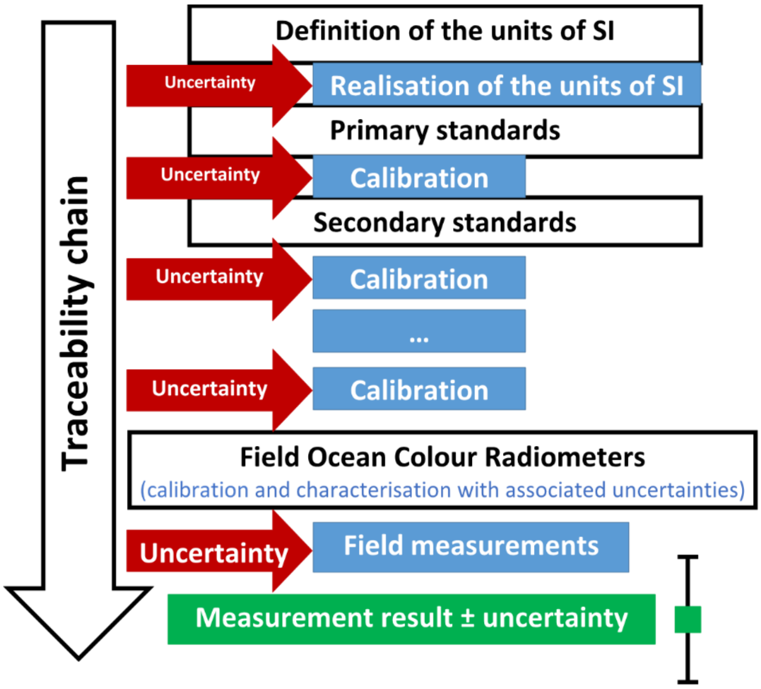

Figure 1. Establishment of the traceability chain with related uncertainty evaluation for collection of reliable EO data.

A way to implement the strategy by integrating the FRM4SOC outcomes into existing initiatives and operational institutions is presented in Table 1.

Table 1. Potential strategies for integrating the project outcomes into existing initiatives and operational institutions.

FRM4SOC Outcomes	Existing initiatives and operational institutions	Actions
1. Implementing FRM.		
C1 Measurement results collected for EO data validation shall have metrological traceability to the units of SI with related uncertainty evaluation. C2 Space agencies should: ***i.*** in the medium term, encourage and stimulate the adoption of FRM requirements, and ***ii.*** in the long term, when sufficient progress and consensus is achieved, use only FRM for the routine validation of satellite ocean colour data. In the near term use of non-FRM quality data for satellite calibration or validation should only be done with great care. C3 Space agencies and National Metrology Institutes should consider forming a symbiotic relationship in order to harmonise approaches, methodologies and implement the principles of FRM worldwide. C4 Financial support from ESA and other space agencies or entities shall be ensured for implementing the principles of FRM.	Existing forums to harmonise methodologies and implement the principles of FRM worldwide • CEOS • IOCCG • Space agencies Sources for metrological traceability: • NMIs • Calibration laboratories Funding sources • Space Agencies • EC • National research funds	A1. International communication and agreement on establishment and implementing FRM requirements.

FRM4SOC Outcomes	Existing initiatives and operational institutions	Actions
2. Methods, protocols and procedures (Obj1); Uncertainty budgets (Obj6).		
C5 International worldwide cooperation on all levels (e.g. agencies, research institutes, experts, etc.) is imperative in order to ensure high quality global climate data. Different protocols existing for OCR data validation all over the world shall be harmonised, understood and applied in a consistent manner to ensure global uniformity of measurements. C6 Data (including appropriate metadata) and expertise collected over years by the international community shall be acknowledged, preserved and passed on to the next generations. C7 Principles of good practice in performing measurements shall be documented and their application encouraged. C8 Practical consolidated examples on compiling uncertainty budgets shall be provided. C9 Established methods, principles of good practice, and uncertainty budgets shall be validated in comparison measurements. C10 Definition, adoption and validation of the principles of good practice and uncertainty budgets shall be supported with appropriate funding from ESA and other space agencies or entities.	• IOCCG, OCR-VC, OCR-IT, • Space agencies; • FRM(4SOC) teams; • Mission data validation teams (e.g. Sentinel VTs); • NMIs; • Calibration and characterisation labs; • Research institutes / *in situ* teams.	A2. International co-operation on all levels to: a. harmonise measurement protocols; b. agree and establish principles of good practice in performing measurements; c. identify, harmonise and establish requirements for measurement and correction of gain and assess its uncertainty gained measurement uncertainty levels; d. provide consolidated examples on compiling uncertainty budgets e. provide training on good practice and building uncertainty budgets. A3. Ensure appropriate funding to define, adopt and validate the principles of good practice and uncertainty budgets.

FRM4SOC Outcomes	Existing initiatives and operational institutions	Actions
3. Properties of OCR (Obj2)		
C11 Properties of OC radiometers must reflect the needed accuracy for satellite OCR data validation and correspond to requirements as identified and established by the international community in the field. Community consensus on practically feasible requirements is needed. However, the principles of metrology - SI traceability and acceptable uncertainty limits - must be followed. C12 A document setting minimum requirements for the most important properties of radiometric instruments used for satellite OCR validation is needed. Preparation of such a document should be encouraged and funded by ESA and other space agencies or entities. C13 Vital components and specifications for new generation (e.g. hyperspectral) instruments shall be identified and characterisation capabilities of required metrology infrastructure shall be developed accordingly. C14 ESA and other space agencies or entities should encourage further development of OCR instruments, including a requirement that such developments provide FRM-compatible information on radiometer characterisation. C15 Characterisation and regular calibration of OCR is needed in order to ensure traceability to the units of SI and evaluate the instrument related uncertainty contributions. C16 ESA and other space agencies or entities should fund and encourage activities to test radiometers from all manufacturers according to a standardised methodology.	• IOCCG; • Space agencies; • Mission data validation teams (e.g. Sentinel VTs); • FRM(4SOC) teams; • NMIs; • Manufacturers of OCR; • Calibration and characterisation laboratories of OCR.	A4. Identify and document requirements and expected specifications (e.g. measurement range, maximum permissible errors, uncertainties, etc.) for OCR instruments to meet the requirements for validation of mission data (A2. c.) A5. Identify, document, map existing and develop missing metrology infrastructure and its capabilities required for calibration and characterisation of OCR (incl. new generation e.g. hyperspectral) instruments. A6. Identify, document and implement a recommended (standardised) plan for initial and periodic calibration and characterisation of OCR instruments. A7. Establishment of regional reference laboratories for calibration and characterisation OCR. A8. Ensure appropriate funding to identify and document requirements for specifications of OCR instruments and their calibration and characterisation.

FRM4SOC Outcomes	**Existing initiatives and operational institutions**	**Actions**
4. Comparison experiments (Obj3 - Obj5) Database of OCR field radiometer performance (Obj5)		
C17 Periodic comparison experiments are needed for validation of established methods and uncertainty budgets on all levels of the traceability chain. C18 Comparison experiments also serve the purpose of training, sharing experience, and support achievement of common understanding and interpretation of the measurement protocols. C19 Application of unified data handling or a community processor will reduce overall uncertainty and improve agreement between individual datasets, although care not to limit innovation must be ensured. C20 Worldwide international participation of agencies and research organisations in comparison exercises should be aimed for. C21 ESA and other space agencies or entities shall encourage and support implementing of comparison experiments with appropriate funding.	Organising: • NMIs; • Calibration and characterisation laboratories; • FRM(4SOC) teams. Participating: • NMIs; • Calibration and characterisation laboratories; • FRM(4SOC) teams; • Manufacturers of OCR • Research institutes / *in situ* validation teams; Funding: • Space agencies.	A9. Organise periodic comparison experiments on all levels of the traceability chain: a. reference standards (NMI and OCR calibration laboratory level); b. calibration and characterisation methods of OCR (calibration laboratory level); c. *In situ* field measurements; • understanding, interpretation, and following established protocols; • competence and experience of personnel (all levels). A10. Development and application of unified data handling/ community processor. A11. Ensure appropriate funding to organise comparison experiments for validation of established methods and uncertainty budgets on all levels of the traceability chain.

FRM4SOC Outcomes	Existing initiatives and operational institutions	Actions
5. Options for long-term future European satellite OCR vicarious adjustment (Obj7)		
C22 Operational FRM infrastructures to underpin SVC with SI traceability, full uncertainty characterisation and the best possible accuracy and precision are mandatory. Such FRM infrastructure of the quality needed for SVC shall be redundant in order to ensure steady and sufficient data provision. C23 The BOUSSOLE as existing unique validation site in Europe must be maintained in the long term and upgraded to full operational status. C24 Development and long term operation of a second new European infrastructure in a suitable location to gain ideal SVC conditions and ensure operational redundancy is needed.	• Copernicus program; • Space agencies; • BOUSSOLE; • NMI-s.	A12. Upgrade BOUSSOLE to fully operational status. A13. Develop a new infrastructure based on MOBY-Net in a suitable location, e.g. the Eastern Mediterranean. A14. Involvement of National Metrological Institutes (NMIs) at all stages of development of an SVC infrastructure. A15. Train a new group to operate a second SVC. A16. Support long-term interaction of the different SVC operations groups. A17. Support scientific and research activities on SVC sites. A18. Ensure long-term investments for both SVC sites.

15. Plan for fostering a transition of FRM4SOC outcomes from research to operational activities

The plan for fostering a transition of FRM4SOC outcomes from research to operational activities follows the strategy described in Section 14 of the present document. The plan is presented in form of a graphical diagram in Figure 2.

Building on the work done over years by the OCR community, the FRM4SOC project has further analysed the requirements for satellite data validation [3], [14], [82]; described the protocols, procedures and instruments for making measurements [5], [70], [83]–[88]; and evaluated the uncertainty budgets [89].

This makes the basis for further operational activities such as:

- Establishment of the traceability chain by periodic calibration of reference sources for irradiance and radiance by NMI-s and,
- Initial and periodic calibration and characterisation of OCR at calibration laboratories,
- Validation of calibration and characterisation by periodic comparison experiments for calibration of OCR between calibration laboratories,
- Performing *in situ* measurement campaigns for FRM and validation teams,
- Validation of methods and uncertainty budgets by periodic comparison measurement experiments led by FRM(4SOC) teams,
- Training, implementation of good practice,
- Keeping OC measurement database.

These activities are to be performed by existing initiatives and operational institutions as described in Table 1.

The priority areas to be addressed in implementation and further development of this plan follow directly from the strategy described in Section 14 and are described in Section 16.

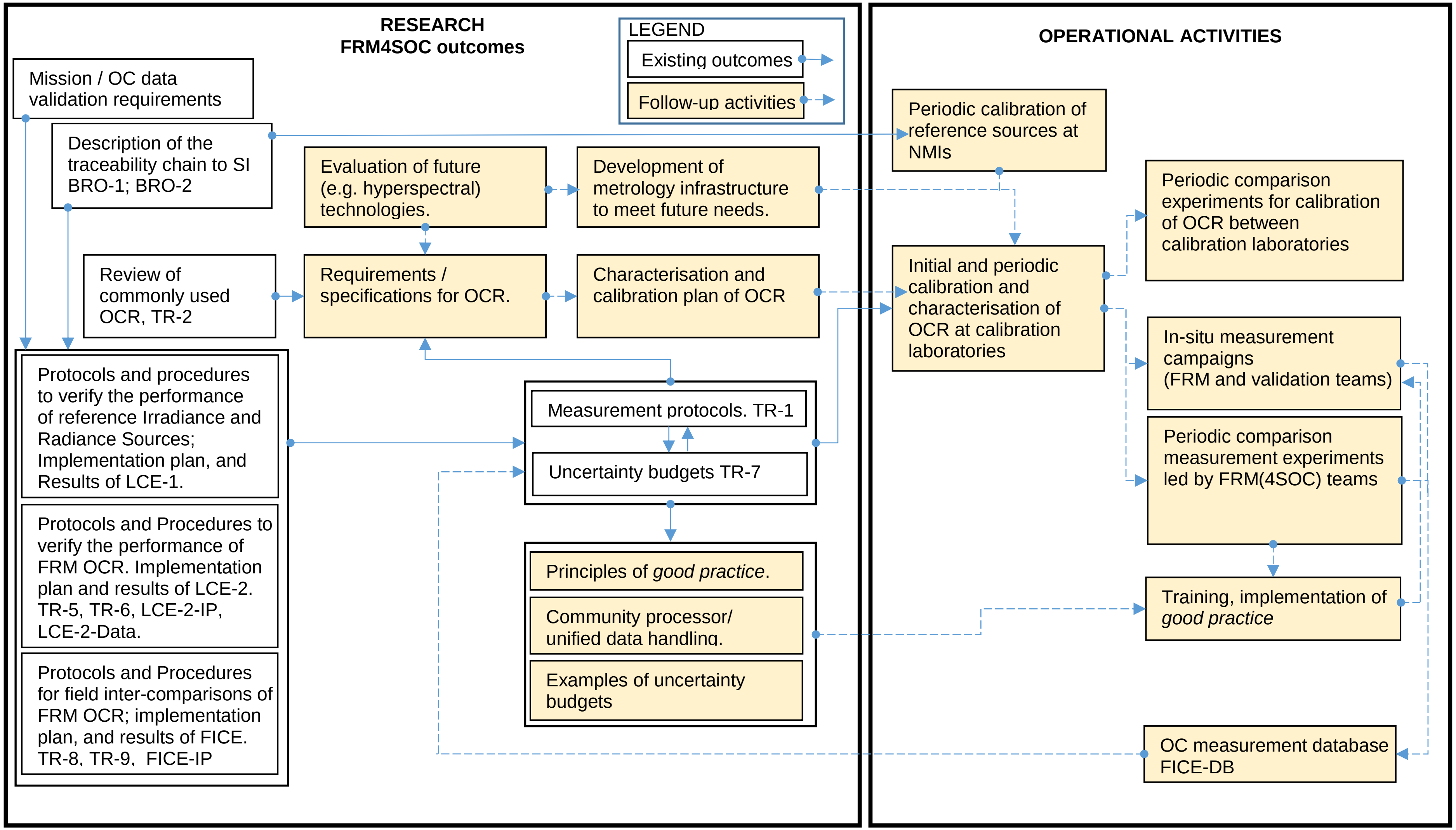

Figure 2. Plan for transitioning of FRM4SOC outcomes to operational activities.

16. Priority areas to be addressed in future projects in support of OCR calibration and validation activities

The outcomes from the FRM4SOC project reconfirm the need for a number of developments and requirements in OCR calibration and validation activities. The priority areas to be addressed in the further development of fiducial reference measurements for satellite ocean colour are listed as follows.

16.1. Measurement protocols and uncertainty budgets

16.1.1. Update the OCR measurement protocols

Issues to be addressed and updated further in OCR measurement protocols. [5], [20], [56], [87], [88], [90]

- For above-water radiometry, it is clear that the skyglint/sunglint correction for light reflected at the air-water interface is a critical source of uncertainty with significant diversity of methods and no real consensus.
- The current protocols review focuses on how to make a reflectance measurement, but only touches briefly the topic of how to use that measurement for satellite validation. In particular, little work has been done by the ocean colour community on validation uncertainties associated with space-time mismatches between *in situ* and satellite measurements.
- Discussions in the community during FRM4SOC regarding the use of a reflectance plaque to measure down-welling irradiance have stimulated further experiments and simulations by external partners.
- The OCR measurement protocols review highlighted the importance of assessing uncertainties associated with shading of the water target by the deployment platform (ship, offshore structure, buoy, etc.) and in some cases the radiometers themselves.
- The application of Bidirectional Reflectance Distribution Function (BRDF) corrections is mature for Case 1 waters, but not well established for Case 2 waters.
- Description of good practice.
- Description of community data processor / unified data handling.
- Guidelines on compiling uncertainty budgets with consolidated examples.

16.1.2. Evaluation and compilation of end-to-end uncertainty budgets for *in situ* measurements

Reliable climate data records are required to have comprehensive uncertainty budgets. The fundamental principle of FRM is to evaluate all contributing uncertainty sources in measurements performed for satellite OCR validation. [66], [68]–[71]

In the process of continuous technical evolution the measurement protocols need to be improved for advanced evaluation of different uncertainty components, with a minimum set addressing:

- instrument absolute calibration,
- characterisation of instruments
    - stray light perturbation,
    - polarisation sensitivity,
    - actual plane of radiance/irradiance,
    - thermal sensitivity,
    - linearity,

  - angular response,
  - field of view,
  - size-of-source effects,
- in-water response,
- environmental perturbations,
- evaluation of uncertainty contributions specific to OCR hyperspectral instruments,
- data processing.

16.2. Community processor for data handling and uncertainty evaluation

One of the largest sources of variance in determining remote sensing reflectance is how individual radiance and irradiance measurements are used in the computation of reflectance values. A high degree of variation between above water measurements arises from the use of different air-sea interface reflection coefficients, Fresnel reflection corrections and BRDF corrections.

The need for a community processor enabling the reduction of the variance in the computation of remote sensing reflectance has often been discussed by the OC community [17], [19], [20], [56]. The need for such a community processor has also been observed in the conclusions of the FRM4SOC comparison experiments [7]–[9], [12].

16.2.1. Examples and short practical guides for uncertainty evaluation

It has been pointed out in several discussions [2], [19], [20], [56] that the OC community has to make an effort to produce consolidated examples and templates of uncertainty budgets for OCR protocols. Also simple practical guides, e.g. on *in situ* uncertainty evaluation for above water operations for one type of commonly used radiometers, are needed.

16.2.2. Training on implementation of measurement protocols and end-to-end uncertainty evaluation

The importance of harmonised understanding and application of measurement protocols has been pointed out as one of the key factors in gaining reliable and meaningfully comparable climate observation data. This can be achieved by organising regular, dedicated and carefully planned training, exchange of experience and the establishment of good practice. [2], [19], [20], [32], [56], [90]

Training events e.g. 2-3 workshops allowing the wider community of water colour scientists to discuss harmonised understanding and application of measurement protocols as well as following the principles of good practice should be organised.

This would establish a forum for sharing knowledge and experience between different institutions as well as gaining common interpretation of FRM measurement procedures. Examples of possible discussion topics would be:

- Ensuring traceability to SI;
- Lessons learned from the FRM4SOC comparison exercises;
- Planning measurement setups;
- Unified data handling and uncertainty evaluation;
- Practical (possibly hands on) exercises.

Any remaining gaps in knowledge should be identified and recommendations for further improvements should be drafted from these workshops.

16.3. Ocean colour radiometers – specifications, characterisation and calibration

The following priorities on development and use of ocean colour radiometers for satellite validation have been identified [56], [70]:

- Description of requirements/specifications for OCR;
- Evaluation of future (e.g. hyperspectral) technologies;
- Development of metrology infrastructure to meet future needs;
- Development of a characterisation and calibration plan of OCR.

16.3.1. Specifications of FRM OCR for manufacturers

A report TR-2 from the FRM4SOC project "A Review of Commonly used Fiducial Reference Measurement (FRM) Ocean Colour Radiometers (OCR) used for Satellite OCR Validation" [70] is a first comprehensive collection of information on OC radiometers to our current best knowledge. Remarkable willingness and contribution to the document from manufacturers is acknowledged as the first round table seminar with manufacturers of Ocean Colour Radiometers was held on the 6th of September 2017 at ESTEC [10].

The current review on ocean colour radiometers does not specify any good/bad or acceptable/unacceptable levels of characterisation. The objective was rather to document what is already known about the performance of the various instruments, according to traceable references, and to identify what still needs to be characterised, in order to construct a full uncertainty estimate for instrument-related factors.

However as concluded at the FRM4SOC Final Workshop [14].

- Properties of OC radiometers must reflect the needed accuracy for Satellite OCR data validation and correspond to requirements as identified and established by the international community in the field. Community consensus on practically feasible requirements is aimed for, and the principles of metrology – traceability and acceptable uncertainty limits – must be followed.

- A document setting minimum requirements for the most important properties of radiometric instruments used for satellite OCR validation is needed. Preparation of such a document should be encouraged and funded by ESA and other space agencies or entities.

- Vital components and specifications for new generation (e.g. hyperspectral) instruments shall be identified and characterisation capabilities of required metrology infrastructure shall be developed accordingly.

- ESA and other space agencies or entities should encourage further development of OCR instruments, including a requirement that such developments provide FRM-compatible information on radiometer characterisation.

It is proposed that, in close collaboration with manufacturers, a standard set of specifications that is expected from FRM OC radiometers should be provided.

16.3.2. Calibration and characterisation of OC radiometers

Following the principles of FRM, the field radiometers must be periodically calibrated and characterised with traceability to SI and evaluated measurement uncertainty [46], [71], [90]. Conclusions from the FRM4SOC project identify what needs to be characterised in addition to calibration in order to construct a full uncertainty estimate for instrument-related factors [8], [70]. However, information on important issues such as long-term stability of radiometers is barely available. It is noted, that OCR calibrated under laboratory conditions perform significantly different under the environmental conditions in field [8], [9].

The results from the FRM4SOC comparisons [8], [9] give clear indications that the ocean colour radiometers used for Satellite OCR validation must be periodically calibrated as well as characterised for key parameters such as straylight, thermal effects, linearity, field of view, angular response, etc., in order to ensure traceability to the units of SI and evaluate the instrument related uncertainty contributions.

Periodic calibration of field radiometers will develop a certain routine and should ensure that different types of radiometers are calibrated at required level of uncertainty under similar conditions and period of time. Periodic calibration in one calibration facility would also enable gathering history on individual radiometers for evaluating long-term trends.

A document "Calibration and characterisation plan for ocean colour radiometers used for Satellite OCR validation" is needed in order to ensure that the FRM requirements for field measurements – traceability to SI with objective uncertainty evaluation – are fulfilled.

The calibration and characterisation plan should address at least the following issues:

- Optimal calibration period of sensors (e.g. once a year, before campaigns, etc.);
- Mandatory minimum set of parameters to be characterised before first exploitation of sensors;
- Minimum set of parameters and recommended period for periodic characterisation of sensors in use.

It has been discussed, that establishment of a central SI-traceable European calibration and characterisation laboratory for field OCR as well as a unified approach to data handling would be beneficial in gaining reliable and meaningfully comparable measurement results. [10]

It is also essential to develop the required metrology infrastructure for calibration and characterisation of new generation (e.g. hyperspectral) radiometric instruments.

16.4. Comparison measurements

Comparisons are required to validate claims on traceability, uncertainty and as means of evaluating any bias between sensors or processes. This should be done by promoting the state-of-the-art in instrument calibration, measurement methods, data processing, and quality assurance. Conclusions from the FRM4SOC project give clear examples that carefully planned comparison measurements have revealed errors that would have not been discovered in regular measurement campaigns [7]–[9], [81]. Ideally, (peer to peer) comparisons should be carried out to test all aspects of the data processing chain, complementing specific local calibration or characterisation activities. [32], [80]

This includes comparisons on all levels of the traceability chain [20], [32], [56], [80], [90]:

a) reference standards – source of radiance and irradiance
(NMI and OCR calibration laboratory level);

b) calibration and characterisation methods of OCR
(calibration laboratory level);
c) *In situ* field measurements;
understanding, interpretation, and following established protocols;
d) competence and experience of personnel (all levels).

16.4.1. Global comparison strategy for FRM4SOC measurements

In order to build and ensure that a coordinated system of comparisons is manageable, and adequate to underpin the principles established by CEOS, IOCCG, and QA4EO, a global comparison strategy for FRM4SOC measurements should be developed.

"*Notably, oceanographic activities require extensive planning and are quite demanding in terms of infrastructure, personnel and equipment. Often, a lack of information prevents exploitation of opportunities, which may ensure a better use of available resources (e.g., access to instrumentation or expertise through collaborations, or simply the chance for training of young scientists).*" [32]

For that purpose the IOCCG INSITU-OCR white paper recommends to "*Establish a coordination mechanism to allow for a continuous exchange of information on forthcoming field activities to create opportunities for collaboration including instrument exchange, field training, inter-comparisons. The coordination should be instrumental in ensuring the collection of prioritized in situ variables meeting the basic needs for satellite ocean colour applications.* [32]

The aim should be to organise pilot 'harmonising global' comparisons (or "key comparisons" [80]) between America, Europe and Asia which would be followed by regional comparisons led by these 'linking' participants. Participation of calibration laboratories from Northern-America, Europe and Asia should be aimed for. For example participation of NIST, NASA/GSFC, and NPL would enable demonstration of equivalence for OC FRM data collected for NASA and ESA. Potentially participation of NIM in China would add a similar link for the Asia-Pacific region. National Metrology institutes participating in these global (key) comparisons are potentially able to carry out regional linked follow-on comparisons.

Feedback from global space agencies and coordination bodies such as CEOS and IOCCG shall be collected in order to enable the community to be fully aware of the process and to be involved in its formulation.

16.4.2. Regular comparisons of radiance and irradiance sources

Regular comparison measurements of radiance and irradiance sources used for calibration of FRM OC radiometers are needed in order to demonstrate global equivalence of reference standards and calibration methods to maintain the traceability of measurements to SI.

16.4.3. Comparisons for calibration of OC radiometers

Regular comparison measurements of FRM OC radiometers used for satellite validation are needed. Carefully planned comparison measurements will reveal errors that would not be discovered in regular measurement campaigns [7]–[9], [20], [56], [80].

It is especially important to establish the robust methodology for comparison exercises for hyperspectral instruments. As a long-term strategy, comparisons are envisaged to be more frequent at the initial stage (2-3-yearly) until the process matures and the comparison results present the required consistency, then the time span can be extended.

The comparison methods must also address the issue that, generally, OC radiometers are calibrated in laboratory conditions that are significantly different from the conditions in field. As concluded from the FRM4SOC comparison exercise LCE-2, this is a source of additional uncertainty contributions (e.g. thermal sensitivity, etc.) [7], [9]. Therefore, the aim of the comparison exercise is not just to compare particular measurement setups in the laboratory, but also to gain matching measurement results by evaluating and correcting for different uncertainty sources.

16.4.4. Field comparison experiments

Regular field comparison experiments to validate measurement methods, traceability claims, uncertainty budgets, and field training are needed [12], [20], [32], [56], [80], [90].

Future field comparisons should build on the experience from previous experiments e.g. Zibordi, et. al. 2012 [91], IMOS Radiometry Task Team 2017 [90], FRM4SOC AAOT [12], etc. with additional aims to [12], [56]:

- include more radiometric systems that are commonly used internationally, both above water (e.g. DALEC, Sun Photometers, fast-rotating shadow band radiometers, MicroSAS, MVDS) and in water (e.g. HyperPRO II, TACCS) and new technological developments (e.g. Seabird HyperNav, ProVal) plus autonomous sun tracker systems;
- capture wider global participation including key expert laboratories from US (NASA, NOAA, University of Miami), Australia (IMOS, CSIRO, Curtin University), etc., radiometer manufacturers (Seabird, TRIOS, etc.);
- balance between representative sensor types of different above-, in-water and new technological systems whilst capturing a broader international range of participants.

16.5. Ocean Colour Vicarious Calibration Infrastructure

The FRM4SOC has initiated a discussion and provided a detailed analysis of SVC requirements [3], [51], [56], [82], [92]. New Copernicus projects led by EUMETSAT have initiated studies for the preliminary design of Ocean Colour System Vicarious Calibration [66], [93].

A roadmap for the development of the Copernicus OC-SVC infrastructure has been described by EUMETSAT [51]

1. Describing requirements [3], [66], [82],
2. Preliminary Design, Project Plan and Costing [93],
3. Technical Definition, Specifications, Detailed Design,
4. Development, Testing and Demonstration in the Field,
5. Operations.

17. Conclusions

The Scientific Operational Roadmap addresses the requirements as established by the statement of work of the FRM4SOC project (2016-2018).

This document i) provides a critical analysis of all the feedback from participants and institutions working in the project (Section 13), ii) identifies potential strategies for integrating the project outcomes into existing initiatives and operational institutions (Section 14), iii) defines a plan for fostering a transition of FRM4SOC outcomes from research to operational activities (Section 15), and iv) identifies priority areas to be addressed in potential future projects in support of OCR calibration and validation activities (Section 16).

The document lists 24 main conclusions summarised from the reports and series of discussions on several events in the framework of the FRM4SOC project. A strategy, implementation plan and 17 actions are proposed to integrate the FRM4SOC outcomes with existing initiatives, operational institutions and activities.

The following **priority areas** to be addressed in implementation and further development of FRM for satellite ocean colour are identified.

1. Updating measurement protocols and uncertainty budgets
2. Development of a community processor for data handling and uncertainty evaluation
3. Providing examples and short practical guides for uncertainty evaluation
4. Training on implementation of measurement protocols and end-to-end uncertainty evaluation
5. Establishment of required specifications for FRM OCR
6. General plan for calibration and characterisation of OC radiometers
7. Development of metrology infrastructure for calibration and characterisation of new generation OC radiometers
8. Periodic calibration and characterisation of OC radiometers
9. Describing a global comparison strategy for FRM4SOC measurements
10. Organising periodic comparison measurements at all levels of the traceability chain
11. Development of ocean colour system vicarious calibration infrastructure.

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