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DOCUMENT

Outcomes and recommendations from the workshop:

Fiducial Reference Measurements (FRMs)

NPL, London, UK, 18 – 20 May 2026



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1 SUMMARY

The ESA FRM workshop is a two-day workshop that was held at the National Physical Laboratory (NPL) in London, United Kingdom, on 18–20 May 2026. The workshop aimed to provide participants with examples of Fiducial Reference Measurement (FRM) activities, used to validate satellite observations, from different disciplines and stages of development, and to discuss challenges, lessons learnt and the transition to the FRM classification and label. Presentations, including example projects, were provide background to the discussion sessions to engage the community to identify evolutions that might be needed as compliance to FRM criteria becomes of increasing importance.

The workshop was organised by ESA Earth Observation Programmes - Ground Segment Mission Quality (EOP-GMQ) section, with the support of NPL. The outcomes of the workshop will contribute to define evolutions in the CEOS-FRM framework that might be needed to ensure rapid uptake and minimal additional cost/effort to the Cal/Val community.

This document provides an overview of the main outcomes, along with **recommendations, actions and decisions gathered from participants** during the discussion sessions.

Additional material, including presentations, is available at the following address: https://qa4eo.org/met4eo/esa-frm-workshop/ .

2 ACRONYMS

API	Application Programming Interface
ARIA	Advanced Research + Invention Agency
ATBD	Algorithm Theoretical Basis Document
BOA	Bot Of Atmosphere
BT	Brightness Temperature
Cal/Val	Calibration and Validation
CCC	
CCM	Copernicus Contributing Mission
CEOS	Committee on Earth Observation Satellites
CIMR	Copernicus Imaging Microwave Radiometer
COCCON	COllaborative Carbon Column Observing Network
CRISTAL	Copernicus Polar Ice and Snow Topography Altimeter
DHP	Digital Hemispherical Photography
ECMWF	European Centre for Medium-Range Weather Forecasts
ECVs	Essential Climate Variables

EDAP	Earthnet Data Assessment Pilot
EOP	Earth Observation Programmes
ESA	European Space Agency
ESRIN	European Space Research Institute
ESTEC	European Space Research and Technology Centre
FAPAR	Fraction of Absorbed PAR
FRM	Fiducial Reference Measurement
FRP	Fire Radiative Power
GBOV	Ground-Based Observations for Validation of Copernicus Global Land Products
GEO	Geostationary Earth Orbit
GHG	GreenHouse Gases
GMQ	Ground Segment Mission Quality
GPG	Good Practice Guidelines
HYPSTAR	HYperspectral Pointable System for Terrestrial and Aquatic Radiometry
ISAR	Infrared Sea surface temperature Autonomous Radiometer
ISMN	International Soil Moisture Network
IST	Ice Surface Temperature
JPL	(NASA) Jet Propulsion Laboratory
LAI	Leaf Area Index
LEO	Low Earth Orbit
LPV	(CEOS) Land Product Validation
LST	Land Surface Temperature
MDT	Mean Dynamic Topography
MM	Maturity Matrix
NG	Next Generation
NPL	National Physical Laboratory
FRM	Fiducial Reference Measurement
MAG	Mission Advisor Group
PAR	Photosynthetically Active Radiation
PM	Particular Matter
QA	Quality Assurance
RadCalNet	Radiometric Calibration Network
RT	Radiative Transfer

ROSE-L	Radar Observing System for Europe in L-band
SAR	Synthetic Aperture Radar
SM	Soil Moisture
SI	International System (of unit)
SR	Surface Reflectance
SRAL	(Sentinel-3) Radar ALtimeter (SRAL)
SST	Sea Surface Temperature
SWH	Significant Wave Height
St3TART	Sentinel-3 Topography mission Assessment through Reference Techniques Follow-On
S3-NGT	Sentinel-3 Next Generation Topography
S3VT	Sentinel-3 Validation Team
TOA	Top Of Atmosphere
TPM	Third Pary Mission
TSIS	Total and Spectral Solar Irradiance Sensor
TU	Technischen Universität (Wien)
UAV	Unmanned Aerial Vehicle
USGS	United States Geological Survey
UV	Ultraviolet
WGCV	(CEOS) Working Group on Calibration and Validation

3 INTRODUCTION

The workshop aims at consolidating the understanding of CEOS-FRM and prepare its future evolution by aligning the community on key concepts, activities, and priorities. It combines knowledge exchange, identification of challenges, and forward planning to ensure a coherent approach. Key points are:

- Sharing information on CEOS-FRM, progress and success of CEOS-FRM projects, identify gaps and priorities;
- Discussing challenges and interpretation of data;
- Looking at the evolution shaping a CEOS-FRM future road maps;
- Improving clarity on evidencing compliance with criteria and fit for purpose;
- Looking beyond Cal/Val from space to include non-space segments.

4 SUMMARY OF SESSIONS

4.1 Introductory presentations about FRMs and QA Framework

The FRM concept has its roots in both scientific and programmatic needs, emerging from efforts to improve the quality, traceability, and understanding of measurements while providing a clearer and more robust reference framework for satellite validation activities. Since its introduction around 2013 (November 2013 at the S3VT at ESRIN and at ESTEC after S3 MAG), the concept has evolved significantly, building on earlier experimental practices and progressively integrating metrological principles such as traceability, uncertainty estimation, and comparability.

"FRM is a suite of independent tailored and fully characterised measurements that provide the maximum Return On Investment 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." (Goryl et al. 2023, https://www.mdpi.com/2072-4292/15/20/5017)

FRM can be provided from a single location or from a network. FRM networks are often the results of a coordinated effort from multiple organisations, generally at global level. As not all sites or networks can be considered FRM, there is the need to establish the correct mechanism to declare a site/network as CEOS-FRM-compliant.

One of the main challenges in the domain of FRMs lies in the transition from concept to operationalization. In this regard, significant efforts are ongoing as part of ESA R&D activities

(e.g., ESA St3TART and CRISTAL-IN-PROVA) to qualify validation measurements as FRMs and stimulate knowledge exchange between projects.

The FRM concept has so far proven highly successful worldwide, strengthening Cal/Val activities, improving data quality, and enhancing trust and interoperability across missions. At the same time, the concept is clearly expanding, as illustrated by new ideas such as FRMsat (formerly SITsat) .

However, this evolution raises important (yet) open questions:

'What should be considered FRM in practice?'

'Can satellite missions or long-term datasets such as Landsat be classified as FRM?'

Similarly, the definition itself remains open: does FRM refer to a measurement, an instrument or an entire network (e.g., RadCalNet)? Maintaining a certain degree of flexibility around these definitions may be beneficial, to avoid over-constraining the concept while it evolves. Moreover, the CEOS qualification of FRM has moved away from a binary definition and is now better represented as a "grey" spectrum; yet this also raises the question of how objective and consistent such qualification processes truly are. Therefore, while the extension of FRM is both natural and valuable, it is essential to preserve clarity, coherence, and relevance to ensure the concept remains robust and meaningful.

Some seed questions have been identified to facilitate the discussion, which has been organised in a group-based approach. A table with the list of seeds questions is provided in Appendix B and the summary of the discussion in Paragraph 5.

Statement on the use of the terms FRM and CEOS-FRM: To ensure clarity and consistency in future discussions, the workshop agreed that the term Fiducial Reference Measurement (FRM) should be used to describe a trustworthy reference measurement suitable for validation purposes although not necessarily independently reviewed. When such a measurement is explicitly tailored for the calibration and/or validation of satellite observations i.e. it has specific guidance and indicative analysis on its use for satellites, it must comply with the applicable CEOS guidelines and can be specifically designated as a CEOS-FRM. The designation CEOS-FRM should therefore be reserved for satellite Cal/Val applications, while the term FRM may be used in a broader context and the criterium that they are for satellites can be removed. Consistent application of this terminology is essential to avoid ambiguity, confusion and misunderstanding within and across communities.

4.2 CEOS FRM Assessment framework

The CEOS Working Group Cal/Val (WGCV) has put in place a framework to assess the maturity and CEOS-FRM compliance of a "Cal/Val reference measurement" through a set of community-agreed criteria. The assessment process is based on a tool, the Maturity Matrix (MM), that

provides a visual assessment of the state of any FRM against each of a set of given criteria, making visible where it is mature and where evolution and effort are still needed. General information and the last version of the guidelines are available on the CEOS Cal/Val Portal (https://calvalportal.ceos.org/web/guest/frms-assessment-framework).

A first round of exercise between a series of projects led to a second version of the guidelines. A second round has started in March-April 2026 and it is still ongoing, it is involving, at the moment, 16 teams (self-assessor and verifier) for measurements in different domains. It aims to apply and improve both the current guidelines and the FRM MM tool while evaluating existing network sites. Results showed that not all sites have the same maturity, impacting the overall score of the network. This approach can be also applied to FRM for satellite or drone measurements, as specified in the CEOS guidelines. An example, still to be verified, is reported about USGS Surface Temperature measured from Landsat, with highest grades in all MM entries coming from an USGS self-assessment.

4.3 Report on FRM projects

4.3.1 FRM4VEG

The main objective of the FRM4VEG (Fiducial Reference Measurements for Vegetation, https://frm4veg.org/) project is to support the validation of key European Satellites (Sentinel -2, PROBA-V, Sentinel-3) vegetation biophysical products (surface reflectance (SR), fraction of absorbed PAR (faPAR), Canopy Chlorophyll content (CCC) by developing dedicated protocols and guidelines.

The project provided important insights into the current state and future direction of FRM for vegetation products. The results demonstrated both the progress achieved in implementing uncertainty-aware validation approaches and the remaining challenges in ensuring consistency across missions. The key outcomes summarised below highlight the main findings:

- Uncertainty-aware validation framework established for vegetation products (CCC, fAPAR, SR).
- Sentinel-2 largely meets SR requirements (~75%), while Sentinel-3 compliance remains inconclusive.
- Standardized FRM protocols are confirmed as essential for consistent satellite validation.
- Shift toward continuous and harmonized FRM monitoring beyond campaign-based approaches.

During the project, an additional activity was performed with the aim to prepare a Good Practice Guidelines (GPG) document for UAV measurements for Surface Reflectance Validation (SRIX4VEG).

REC-01 **to update the FRM4VEG best practice considering the LAI/FAPAR network instead of DHP.**

4.3.2 FRM4Fire

The main challenge to validate fire products is the generation of reference data. Reference data samples are scarce and not coincident with product acquisitions. Fires cannot be easily forecasted, and the real time measurements could be challenging and expensive. However, in the framework of FRM4fire project (https://frm4fire.org/), two airborne campaigns equipped with thermal sensors were conducted in 2018 and 2023, respectively, to collect data for FRP (Fire Radiative Power) validation. The first phase of the project was focused on Traceability, Uncertainty Budget and Representativeness for both airborne and satellite measurements putting particular attention on directional effects, temporal mismatching, and spectral response function, that have a strong impact on the uncertainty. The final aim of the project is to develop an uncertainty model and a Validation Protocol for Spaceborne FRP retrievals using airborne measurements.

Phase-2 of the project will focus on: 1) further improvements on the uncertainties propagation model; 2) potential improvements in validation protocols, possibly taking advantage of satellite tandem phase products; and 3) the improvement of interoperability with other missions, also including the ESA Third Party Missions (TPM) programme.

4.3.3 GBOV

The Ground-Based Observations for Validation (GBOV) service is funded by the European Commission and is part of the Copernicus Land Monitoring service. It provides Analysis Ready Validation data since almost a decade covering several Essential Climate Variables (ECVs) including short and longwave radiation, vegetation products and Surface Soil Moisture.

GBOV bridges the scale gap between point-source field measurements and large-scale satellite grids by processing key ecosystem indicators like soil moisture, land surface temperature, and vegetation health.

A new PAR network has been funded and development by GBOV consisting in the installation of sensors and data acquisition campaigns.

An important task within the project is the development and maintenance of a data portal (https://gbov.land.copernicus.eu/data-access). The audience suggested to apply the CEOS FRM MM assessment on GBOV.

REC-02 **to apply the CEOS FRM Maturity Matrix Assessment on GBOV.**

4.3.4 FRM4SM

The FRM for Soil Moisture (FRM4SM) project is well advanced from the CEOS-FRM MM perspective. The International Soil Moisture Network (ISMN - https://ismn.earth/en/) provides harmonized access to quality-controlled data from >3300 stations, operated by 89 networks. It was established by TU Wien in 2008, before the FRM concept emerged, and has been hosted by the German Federal Institute of Hydrology since 2022.

The Soil Moisture Product Validation Good practices protocol was developed by the community under the guidance of the CEOS Land Product Validation (LPV) subgroup.

Lessons learned from the FRM4SM are:

- For soil moisture at satellite footprint scale (25-50 km), spatial representativeness is the largest part of uncertainty.
- High quality "supersites" are hard to maintain, struggling with coverage, continuation, and credit. The main challenges are associated with the acquisition of more relevant data (not more data) and the deployment of new instruments, especially in underrepresented regions.
- Concerning the CEOS FRM MM assessment, what is the impact for users using class A/B/C etc? The quality of the dataset varies among different areas/land types. It is hard to assign a general quality to the overall dataset. As is, the CEOS FRM MM assessment seems more relevant to FRM providers than to users. Therefore, the knowledge of the users' scope in using a specific dataset might be helpful. Different tailored datasets could also be an option, because private data providers might be interested in validating their products at higher level, and so class A or B might be used. However, the CEOS-FRM-MM assessment is also useful to identify areas of improvement/evolution of a FRM project.
- FRMs could also be associated with a network of networks, but this would need to be carefully assessed because each network would have its own variable and/or measurement retrieval approach, which cannot be easily mixed.

REC-03 **to understand how many satellite commercial companies are using FRMs in their validation activity, for example using a user's survey.**

4.3.5 QA4SAR

The aim of Quality Assurance for SAR (QA4SAR) project is to create a harmonized QA framework for SAR data for past, present and future SAR missions for both L1 and L2 products for ocean and land including SM, wet snow, SWH, ocean surface vector winds.

Beside quality assurance, there is also a project focused on developing the ROSE-L L2 ocean processor and a project named ROSS (ROSE-L Ocean Science Study), aimed at developing Geophysical Model Functions, etc.

A maturity matrix has been created for the artificial point targets related to the projects, showing some of the gaps, e.g., geographical coverage. Results show that for:

- Buoys (US National Data Buoy Center - https://www.ndbc.noaa.gov/) – the relative maturity matrix shows lack of evidence of traceable collocation.
- Scatterometer-derived winds - the relative maturity matrix is greener with respect to buoys.
- Altimeter-based FRM for SWH- the relative maturity matrix is greener with respect to buoys.

However, this analysis needs to be repeated using the official CEOS-FRM MM tool. In general, the community is not fully aware of CEOS-FRM initiatives. The FRM web page on ESA Earth online is currently still in draft and needs to be improved.

REC-04 to improve the communication of CEOS-FRM initiatives to user communities.

With respect to the geopolitical situation and uncertain US involvement in open data projects, even if the buoy data center is based in the US, most of the data are already stored by ECMWF, so access to historical data is secured.

A domain-based FRM approach, instead of mission-based, could also be used as input/a-priori information within other domains (e.g., ocean variables to be used for atmospheric applications). FRM from satellites are only useful if they are providing new or improved information that cannot be retrieved by other mean (i.e., no need to use FRM from satellites to replace in-situ FRM measurements, unless there is a clear quality improvement).

4.3.6 FRM4SST

The FRM for Sea Surface Temperature (FRM4SST) project is one of the earliest to date. The project has several objectives; the main being maintaining the instrument quality ensuring that measurements are traceable to SI standards. It started in 1990s and is now financed by ESA from 2020. In-situ measurements are mainly acquired using ISAR radiometers, which are calibrated in laboratory. The uncertainty model has also been significantly developed.

An evolution could be the inclusion of microwave radiometers in the SST network along with synergies with other projects/missions (e.g., the upcoming CIMR mission).

REC-05 **to support the inclusion of the microwave radiometers in the future ships4sst project (for example to support CIMR mission).**

Another possible development of FRM4SST is to reinforce the link with LST (Land Surface Temperature) and IST (Ice Surface Temperature) at level of the radiometer itself from lessons learned. An inter-comparison exercise could be done in 2028/29.

REC-06 **to support an inter-comparison exercise on the radiometers, including MWR radiometers (e.g., CIMR), used in SST, LST, IST to reinforce the link with LST/SST/IST.**

4.3.7 TIRCALNET

The TIRCalNet project, is a 'RadCalNet-like' initiative but in the thermal domain. The main objective is to collect surface temperature, emissivity, and atmospheric data for deriving TOA brightness temperature signals with an uncertainty of 0.5 K over both land and water sites. First criteria for site selection were discussed; the main aspects concern the homogeneity in the footprint and clear sky days, as also the characterization of the instrumentation. Upscaling method (JPL) is known and discussed to understand where the main uncertainty in all this process will be.

A nice inter-comparison has been done between different Radiative Transfer (RT) models, used for simulating TOA Brightness Temperature, developed by: 1) University of Leicester and NASA/JPL RT, and applied on MODIS data over Lake Tahoe and Salton Sea; and 2) CNES applied to ECOSTRESS over La Crau. In both cases, results show a very good agreement. Analyses like these need to be supported more.

The project is ongoing, next steps will focus on the consolidation of the uncertainty budget, and to converge to a common RT model over the different communities. The surface-dependent drop in emissivity at off-nadir will be investigated.

The project is a good example of inter-Agencies collaboration between JPL, CNES, ESA.

REC-07 **to provide FRM data acquired from different observation angles to expand the user's audience. Commercial providers require 'off nadir' data for their sensors but current networks often provide only nadir data.**

4.3.8 FRM4ALT

The FRM for Altimetry (FRM4ALT) project (https://www.frm4alt.eu/), aimed at establishing and demonstrating the SI-traceability of FRMs and their use for satellite altimetry data calibration and validation.

To *"facilitate comparison and interoperability between products and missions in a cost-efficient manner"* (Goryl et al. 2023), three pillars are needed, i.e., Redundancy, Diversity (several ground references), and Traceability. For a successful FRM site, finding the right location and achieving the required measurement accuracy are key aspects. In the framework of the project, calibration sites were established in Gavdos and West Crete, Greece, producing reference data to monitor several altimetry missions.

The CEOS FRM MM assessment can be fully applied to FRM4ALT project.

Data are acquired by different transponders, and the use of different software for post-processing contribute to generate different outputs. For this reason, it is very important to perform intercomparison exercises. Geoid is also an important aspect in the altimetry measurement, more efforts are needed to better characterize it in terms of gravity, coordinate system and time.

REC-08 **to support an intercomparison exercise in the ALT community between different satellite missions using FRM–compliant calibration sites; to ensure consistency and data reliability and share Cal/Val results to create an international altimetry Cal/Val community. Other points requiring investigations: geoid model, mean dynamic topography (MDT), gravity, coordinate system, time reference.**

Another important topic is the long-term stability of ground reference infrastructures and their sustainability. These are important assets for satellite altimetry missions that need reliable and consistent reference calibration products.

4.3.9 St3TART

The St3TART (Sentinel-3 Topography mission Assessment through Reference Techniques Follow-On, https://sentinel3-st3tart.noveltis.fr/) project aims at providing an operational framework for FRM provisioning to support the validation activities of the Sentinel-3 SRAL altimeter over inland water (including estuaries), sea ice and land ice domains (ice caps, mountain glaciers, etc.). The project will pave the way for future altimetry missions such as CRISTAL and Sentinel-3 NGT.

An FRM Data Hub has been developed in the frame of the project, to provide centralized access to FRM data. Collaborative campaigns were also established through announcement of opportunities.

CEOS FRM guidelines are followed, providing a specific maturity matrix for each sensor involved in St3TART.

4.3.10 FRM for Atmosphere domain

Atmospheric missions can be distributed into different categories, including LEO limb and occultation profiles, LEO UV–visible nadir sounders, LEO infrared nadir sounders, and GEO UV–visible and infrared nadir sounders.

There are specific needs for atmospheric FRM-based validation, since a wide portfolio of sounding techniques, spectral ranges, orbits, and products are involved. This includes the vertical dimension of the measurand, as well as different temporal signals, from intraday variability using GEO diurnal cycles to seasonal, interannual, and decadal scales through multi-mission Climate Data Records. Validation is also needed for thematic constellations, such as air quality, greenhouse gases (GHG), ozone/UV, and PM2.5.

FRM4DOAS (https://frm4doas.aeronomie.be/) and FRM4PGN have been assessed using the CEOS FRM MMT tool, results are published in Remote Sensing journal. A second round of exercises for CEOS-FRM maturity assessment has recently started with a wider portfolio of involved projects. This second self-assessment will shows how different networks measuring same quantities could lead to different MM results in terms of quality. This is due to an intrinsic subjectivity of the self-assessor, subjectivity that we should reduce or even limit

REC-09 **In the CEOS FRM MM the current use of "class of instrument" (e.g. nadir UV–VIS imaging spectrometer) is too vague and does not clearly refer to the measurand (e.g. tropospheric column). "Class of product" would be a more appropriate in the classification approach.**

The discussion highlighted the wide portfolio of atmospheric species, states, signals, and measurement techniques, which often require tailoring. In this context, it was questioned whether a full classification of all key FRMs is realistic or even necessary.

It was also recognised that several types of FRM may be required to properly validate a given measurand, including its uncertainty estimates and information content diagnostics, following an end-to-end validation approach. The importance of clearly defining the fitness-for-purpose or scope of an FRM was emphasised, particularly in relation to bias estimation, stability assessment, and validation of satellite uncertainty and information content.

Although representativeness is a major source of comparison uncertainty, it remains insufficiently understood. Key aspects highlighted include ground pixel size, vertical averaging kernels, and spatiotemporal co-location.

REC-10 **Version 2 Maturity Matrix (V2 MM) represents an improvement. However, further work is needed to reduce the subjectivity of the self-assessment process, potentially through clearer guidelines supported by practical illustrations.**

The interaction between the self-assessor and the verifier was considered essential and could be framed more explicitly as a peer-review process.
Overall, the CEOS-FRM framework is appreciated as a tool for understanding and improvement. However, questions were raised regarding the overall classification (A/B/C/D), its meaning, its intended audience, and the purpose it is meant to serve. With respect to the Maturity Matrix Tool:

- It is currently assumed that FRM owners provide justification text and supporting evidence within each matrix cell. However, evidence should not be implicit and should be explicitly requested for each entry, ideally in a dedicated field rather than optional comments.
- With an increasing number of assessments expected the need for a structured catalogue of assessments was highlighted, potentially aligned with community-agreed metadata standards.
- It was noted that self-assessors often evaluate multiple species within a single assessment round, indicating a need for clearer guidance on scope and consistency.
- The potential for a copy-and-paste functionality was raised to support more efficient handling of multi-species FRM instrument assessments.
- Is the information stemming from the MM improving the validation? It shows data gap analysis was missing, so it is a very good tool to identify what is missing and what are the improvement areas, but with respect to validation itself, the MM is not giving a direct improvement.

Tier approach like the one used and presented in FRMs for the Atmospheric Domain by Jean-Christopere Lambert could be a possible approach, it was also highlighted at GCOS.

REC-11 **Better align the satellite FRM program to the reference tier of tiered networks and enhance/expand FRM to fill gaps in satellite Cal/Val.**

REC-12 **To divide the approach for aerosols and reactive gases because the physics behind is completely different (separate FRM projects with tailored requirements).**

4.3.11 FRM4GHG to COCCON experience and evolution

FRM4GHG (https://frm4ghg.aeronomie.be/) to COCCON (COllaborative Carbon Column Observing Network) is a good example of an ESA-funded R&D project aimed at developing FRM for greenhouse gases operational monitoring. CH4 scientific and operational products present several differences given the different processing and more auxiliaries data for the post processing added. The question is: which is the best? Who is better representing the reality?

For CO2 products, validation is essential to improve the quality to reduce the uncertainty, but there are gaps of in situ stations in the tropics and at the poles. A recommendation has been already provided at past VH-RODAs for supporting light and portable instruments. EO4AFRICA could be the right programme for the tropic area.

4.3.12 RadCalNet

RadCalNEt (https://www.radcalnet.org/) is an initiative of the Working Group on Calibration and Validation of CEOS. It provides SI-traceable TOA/BOA reflectance. It is currently composed by 5 sites, globally distributed with more to come. Data are available since 2013. Railroad Valley was reprocessed in 2025 using TSIS solar spectrum. To become a RadCalNet site, a specific procedure must be followed, with a dedicated panel of experts in charge of reviewing the dataset and provided documentation. Data are provided using a standard approach for each site: nadir observation, 10 nm spectral resolution; but users can ask for more details or data to site owners. Users asked for more clarity in data access information, for example APIs are available but users seem not be aware.

REC-13 Sites owners of RadCalNet need to verify that data access options are well described and easily accessible, especially concerning API.

4.3.13 LANDHYPERNET

LANDHYPERNET is part of HYPERNET network. The network is equipped with HYPSTAR instrument able to acquire multi-spectral and multi-angular radiance. It is composed by sites located over different land cover types. All measurements are sent to a central server and automatically processed and quality-checked to derive surface reflectance with associated uncertainty. Data are available from LANHYPERNET data portal (https://landhypernet.org.uk/). The CEOS FRM MM assessment for LANDHYPERNET resulted in a Class C (Good), but also in this case, as evidenced for other networks during this workshop, not all sites have the same degree of maturity.

4.4 QA frameworks and EDAP

The ESA/NASA Quality Assurance (QA) Framework for EO products was initially specifically designed within the Earthnet Data Assessment Pilot (EDAP) project to assess missions from private sector satellite operators. It is now also being applied within the Copernicus Contributing Missions (CCM) programme.

EDAP was the starting point for the definition of guidelines and MM, and now this approach has been expanded to other "domains", as the FRMs. The aim is to define comprehensive standards for mission quality, tailored for specific domains. The approach has been tested in numerous ESA/NASA QA activities. It is now important to further develop the MM and its associated guidelines. While the concept of fitness for purpose remains challenging to define and quantify, it is a fundamental aspect of data quality assessment, both for commercial satellite data and for the evaluation of FRMs maturity.

The Product Validation Platform is a new CEOS initiative that leverages data from RadCalNet and other in situ networks to establish a harmonised validation framework. It aims to address feedback from the commercial sector, which has highlighted the need for Agencies to agree on a limited set of reference sites where all capabilities can be assessed consistently on a single platform, following a common approach.

4.5 FRM applied to non-satellite datasets

ARIA (Advanced Research + Invention Agency) at NPL includes a programme called 'ARIA Forecasting Tipping Points' dedicated to developing early warning systems for climate tipping point.

The program mainly focuses on three types of challenges:

- Mature instruments in extreme/remote environments
- Measurements on novel platforms
- Entirely new sensing approach (small submarines, …)

The idea is to establish a consistent approach on Calibration, Validation and Standardization for these activities, similar for what is done for satellite observations. As an example, for the measurement of snow depth with cosmic rays, there is no established good practice since is a novel sensing method. The project applied the QA4EO five steps, which is a lengthy process but extremely valuable, allowing identifying circularity in traceability when adapting soil moisture approach, and changing the laboratory plan for how to calibrate the instrument.

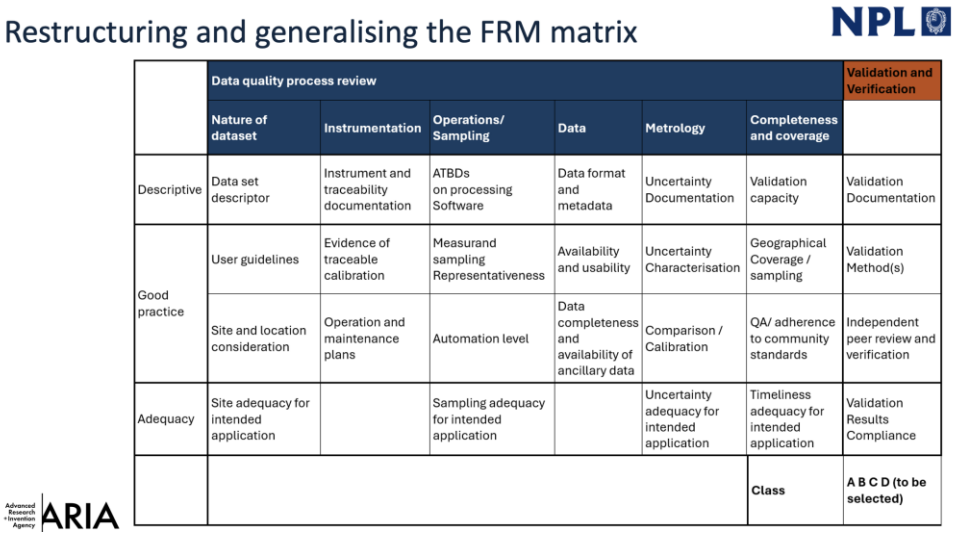
It is stressed out that adequacy depends on intended applications. Within the CEOS-FRM context datasets are judged in terms of how well they meet the requirements of their intended application. But datasets may be used beyond their intended application, so responsibility lies with the user to assess fitness-for-purpose. A distinction can be made:

- **CEOS-FRM**: application is to validate, through comparison, a (defined) class of satellite products.
- **General FRM:** likely to be primary application – why data is collected. This may be broader than the requirements for satellite validation.

Only few points in the CEOS-FRM MM are satellite-specific. All the rest are generic requirements that can be met by generic in-situ site, a similar discussion could be interesting also for Copernicus in situ service where in situ measurements does not have to be specifically for the purpose of satellite validation.

Regarding drones, acquiring data from mobile platforms is challenging but necessary, as this is where much of the innovation is taking place (e.g., ships are the best examples for atmospheric community). However, fast-moving platforms like drones and small boats pose significant difficulties, requiring the definition of best practices.

In this context a re-organization of the FRM Maturity Matrix has been proposed, it includes two complementary dimensions: Categories, represented by the columns, which cover the different aspects (cells) of data quality, and Themes, (the new dimension) represented by the rows, which group these aspects into three thematic areas: Descriptive, Good Practice, and Adequacy (Figure 1). The maturity level of each individual aspect is still indicated by its cell colour. This structure provides a consistent and flexible framework for assessing whether a dataset is fit for its intended purpose, considering its documentation, adherence to good practice, and suitability for the intended application.



	Data quality process review						Validation and Verification
	Nature of dataset	Instrumentation	Operations/ Sampling	Data	Metrology	Completeness and coverage	
Descriptive	Data set descriptor	Instrument and traceability documentation	ATBDs on processing Software	Data format and metadata	Uncertainty Documentation	Validation capacity	Validation Documentation
Good practice	User guidelines	Evidence of traceable calibration	Measurand sampling Representativeness	Availability and usability	Uncertainty Characterisation	Geographical Coverage / sampling	Validation Method(s)
	Site and location consideration	Operation and maintenance plans	Automation level	Data completeness and availability of ancillary data	Comparison / Calibration	QA/ adherence to community standards	Independent peer review and verification
Adequacy	Site adequacy for intended application		Sampling adequacy for intended application		Uncertainty adequacy for intended application	Timeliness adequacy for intended application	Validation Results Compliance
						Class	A B C D (to be selected)

Figure 1 Proposed re-organization for the CEOS FRM Maturity Matrix including themes.

4.6 Copernicus In-Situ Overview

In-situ data are all the reference geospatial data which are used for the Copernicus Services. Not all observations are used for Cal/Val, since some are used for the sake of their own scientific interest, so not all observations are FRM. Nevertheless, FRM play a specific role within the Copernicus programme and within the Copernicus In-Situ Component. Fit for purpose, resilient and forward-looking, coordination and efficiency, cooperation, fair and open are clear aspects.

The Copernicus In-Situ Team identified some FRM-related strategic recommendations:

- Recognize and acknowledge data providers (e.g., Copernicus in-situ community label).
- Optimize data processing and distribution, for example by supporting the development of community processors and data distribution platforms.
- Promote competitiveness and innovation of European in situ capabilities, for example through Copernicus partnerships with private or public data providers. An approach analogous to the CCM project could be developed for the in-situ environment. CEOS FRM certification adopting an FRM label within Copernicus could foster improvement of in-situ data quality and usability. A similar discussion on Copernicus labelling is ongoing.

FRMs were initially developed as mandatory for satellite Cal/Val activities also to get funding from Copernicus. But now the concept extended a lot, and not all FRMs can be funded within Copernicus.

What are the essential FRM?

ESA has been working on a document to identify guidelines for FRM within Copernicus Space Programme. The document is available at https://sentiwiki.copernicus.eu/__attachments/a_eea9e00df5d41cb0a4f57fa70af8a335423b02a795407dc431bc438e285d15af/high-level-guidance-ceos-frm-cal-val-copernicus-sentinel-missions.pdf.

5 CONCLUSION AND WAY FORWARD

The conclusive discussion followed a series of seed questions as reported in Annex C. This paragraph summarises the main outcomes of the discussion and outlines the proposed way forward.

CEOS-FRM Matrity Matrix improvement

The minimum set of requirements that are needed to claim a site or a network CEOS-FRM were discussed. Future efforts shall aim at standardizing CEOS-FRM metadata, harmonizing the terminology and making ATBDs available. CEOS-FRM metadata standard across different domains needs to be better define and mandatory fields in the Maturity Matrix clarified. An activity like CEOS-ARD could support the improvement of CEOS-FRM MM. The A/B/C/D classification is also not fully understood as well as how different classes should be combined to get a single indicator, especially in case of FRM networks. MMs should be updated during the FRM lifetime.

ACT-01 **on ESA, to 1) improve CEOS-FRM MM by defining a minimum set of requirements for metadata common to all domains (ARD4FRM); and 2) harmonize the used terminology.**

ACT-02 **on ESA, to clarify the mandatory fields in the CEOS FRM Maturity Matrix.**

ACT-03 **on ESA, to provide clear indications on 1) how to interpret the Maturity Matrix classes (A, B, C, D) in the FRM framework, 2) how to apply MM to single site and networks.**

It has been underlined that the MM scoring is too subjective as well as the role that communities should have establishing good practices against the MM scores. In general, there is the need to build a more objective MM.

CEOS-FRM definition

The definition is quite clear; but some concerns have been raised about:

'*Community agreed reference*'

How is the *community* defined and monitored? If there are newcomers, how can they join?

CEOS-FRM process for compliancy

The concept of CEOS-FRM is well known and accepted at CEOS level. However, funding is needed as the formal process needs to become more visible and structured.

About the process to declare a site CEOS-FRM compliant, the community agreed that the process should not only rely on self-assessment, as it is now, but an independent review process shall be defined at CEOS-WGCV level. Being not all disciplines represented in CEOS (e.g., altimetry has other bodies for collaboration), a possible solution to investigate is bringing in

the GSICS community, or expanding WGCV for including non-represented communities in the group.

DE-1 **Independent peer-reviewed process needs to be put in place to assess CEOS-FRM compliancy; self-assessment is not sufficient. For the review process there is the agreement that the review shall be at CEOS level, in working groups devoted Cal/Val. Being important for interoperability and inter-agencies collaboration, the CEOS-ARD could be a good example for putting in place this process.**

CEOS-FRM vs FRM

CEOS-FRM shall be applied to satellites Cal/Val only. Other types of FRM might be created with different scopes and organized differently (e.g., defined or grouped for sensor type, domain, etc). CEOS-FRM is a label that does not preclude others. The risk is losing the control on the FRM wording, but with CEOS-FRM the control can be maintained to restrict the concept avoiding that all in-situ measurements become CEOS-FRMs. CEOS-FRM brand is useful to define where standards are coming from and to encourage a place for debate on criteria.

DE-2 **CEOS-FRM is for satellite Cal/Val only (FRM without the 'CEOS' appendix can then be used with a broader meaning).**

ACT-04 **on ESA, to put in place a CEOS-FRM catalogue for listing all the CEOS-FRM projects. The list should act as an entry point for FRMs with links to data and quality information also providing a "start here" guide on key references (papers, training materials, etc).**

Reference

More efforts are necessary in some communities to define what the reference standards should be (e.g. time reference, geodetic reference). Communities need to develop such standards which then the maturity matrix can judge adherence to. While ESA has led the initiative, it is important to build international agreement frameworks.

Community members need to give evidence of requirements they are following:

- **Lack of common reference system needed for better comparison.**

  Reference of the product to be considered.

  How to describe uncertainty/accuracy? -> Community members should follow the same guidelines/good practices.

- **What would we like to make standard guidelines for the CEOS-FRM?**

REC-14 To put more effort to reach an agreement at international level on common reference for different domains (e.g. using the same geoid for altimetry validation).

In the atmospheric domain, a distinction between the quality of the measurement and the quality of the network is made. As an example, a variable could be well measured yet still lack sufficient spatial representativeness. Could we introduce hybrid classes (e.g., A1C) ?

REC-15 Upscaling methods need to be better documented and discussed and eventually defined as community-accepted good practices associated with a CEOS-FRM.

The role of classification for individual facilities vs networks is not yet clear. Also, fitness for purpose is very different for LEO satellites vs GEO satellites.

CEOS-FRM gaps and links

Several groups identified the need to improve the overall geographical coverage of FRM projects. Efforts should be made to identify how to fund sites in critical regions that are not yet sampled but are representative for Cal/Val activities.

Some gaps are also identified concerning variables: vegetation chemical content, phenology that could be included in a future FRm4VEG; gaps are highlighted in snow characterization, hydrology, inland waters, sea surface salinity and microwave domains.

REC-16 Before setting up new FRM, a holistic view is necessary to identify gaps, priorities and costs vs benefits for existing FRM vs new FRM.

REC-17 FRM for the far-Infrared to be considered in view of FORUM mission.

REC-18 To investigate more the FRM-Satellite concept as a valid experiment of FRM from space.

Increasing synergies among FRM projects is recommended because some projects outputs could be useful inputs for others. Co-located stations in the same area could be useful in this

sense. Geolocation is identified as one of the main problems in the FRM domain. Need to focus on network design & evolution and improving the maturity of campaign data.

CEOS-FRM and communication aspect

A clear recommendation to improve communication has been raised during the whole workshop.

REC-19 **Improve communication and awareness on technical definition and basic principle of CEOS-FRM, and the difference between CEOS-FRM vs FRM, some ideas could be:**

- **Organising FRM workshops every 12/18 months, including more educational sessions with case studies, also inviting other agencies & communities;**
- **Sharing success stories on CEOS-FRM projects' outputs;**
- **Linking to previous action about listing FRM projects;**
- **Setting clearer guidelines/procedures for future teams that aim to become CEOS-FRM providers.**

Concluding thoughts

When a mission is designed, a lot is invested into defining accuracy requirements, but less on the capacity to validate these requirements. In the mission design phase, there should be dedicated efforts to specifying what the requirements for FRMs are to demonstrate that mission requirements are met.

FRMs are not the only reference that can be used for validation, and the CEOS-FRM framework should not be designed solely to validate Mission Requirements (as per MRDs), as this may be too restrictive. Validation is fundamentally based on comparison of satellite observations against reference measurements. CEOS-FRMs represent a subset of these references, providing higher confidence due to their traceability and rigorous characterisation, but they should be seen as part of a broader validation ecosystem rather than the only option.

The CEOS-FRM framework enables a consistent and objective approach to interoperability across agencies. If organisations such as NASA, ESA, and EUMETSAT would adopt a common framework, this would significantly facilitate intercomparisons and interoperability of data from instruments. The conclusive recommendation is:

REC-20 **Cal/Val is a fundamental requirement that calls for of a dedicated budget throughout a satellite mission.**

5.1 Summary of Recommendations

ID	Recommendation	Priority
REC-01	to update the FRM4VEG best practice considering the LAI/FAPAR network instead of DHP.	Medium
REC-02	to apply the CEOS FRM Maturity Matrix Assessment on GBOV	Medium
REC-03	to understand how many satellite commercial companies are using FRMs in their validation activity, for example using a user's survey	Medium
REC-04	to improve the communication of CEOS-FRM initiatives to user communities	High
REC-05	to support the inclusion of the microwave radiometers in the future ships4sst project (for example to support CIMR mission)	Medium
REC-06	to support an inter-comparison exercise on the radiometers, including MWR radiometers (e.g., CIMR), used in SST, LST, IST to reinforce the link with LST/SST/IST	Medium
REC-07	to provide FRM data acquired from different observation angles to expand the user's audience. Commercial providers require 'off nadir' data for their sensors but current networks often provide only nadir data.	Medium
REC-08	to support an intercomparison exercise in the ALT community between different satellite missions using FRM–compliant calibration sites; to ensure consistency and data reliability and share Cal/Val results to create an international altimetry Cal/Val community. Other points requiring investigations: geoid model, mean dynamic topography (MDT), gravity, coordinate system, time reference	Low (as partially ongoing)
REC-09	In the CEOS FRM MM the current use of "class of instrument" (e.g. nadir UV–VIS imaging spectrometer) is too vague and does not clearly refer to the measurand (e.g. tropospheric column). "Class of product" would be a more appropriate in the classification approach.	Medium
REC-10	Version 2 Maturity Matrix (V2 MM) represents an improvement. However, further work is needed to reduce the subjectivity of the self-assessment process, potentially through clearer guidelines supported by practical illustrations	High
REC-11	Better align the satellite FRM program to the reference tier of tiered networks and enhance/expand FRM to fill gaps in satellite cal/val.	High
REC-12	To divide the approach for aerosols and reactive gases because the physics behind is completely different (separate FRM projects with tailored requirements).	Medium
REC-13	Sites owners of RadCalNet need to verify that data access options are well described and easily accessible, especially concerning API	High

REC-14	To put more effort to reach an agreement at international level on common reference for different domains (e.g. using the same geoid for altimetry validation).	Low
REC-15	Upscaling methods need to be better documented and discussed and eventually defined as community-accepted good practices associated with a CEOS-FRM	Low
REC-16	before setting up new FRM, a holistic view is necessary to identify gaps, priorities and costs vs benefits for existing FRM vs new FRM.	Medium
REC-17	FRM for the far-Infrared to be considered in view of FORUM mission	Medium
REC-18	to investigate more the FRM-Satellite concept as a valid experiment of FRM from space.	Medium
REC-19	Improve communication and awareness on technical definition and basic principle of CEOS-FRM, and the difference between CEOS-FRM vs FRM, some ideas could be: - Organising FRM workshops every 12/18 months, including more educational sessions with case studies, also inviting other agencies & communities; - Sharing success stories on CEOS-FRM projects' outputs; - Linking to previous action about listing FRM projects; - Setting clearer guidelines/procedures for future teams that aim to become CEOS-FRM providers.	High
REC-20	Cal/Val is a fundamental requirement that calls for of a dedicated budget throughout a satellite mission.	High

5.2 Summary of Actions

ID	Action	Actioner	Due date
ACT-01	to 1) improve CEOS-FRM MM by defining a minimum set of requirements for metadata common to all domains (ARD4FRM); and 2) harmonize the used terminology.	ESA	2027
ACT-02	to clarify the mandatory fields in the CEOS FRM Maturity Matrix.	ESA	2027

ACT-03	to provide clear indications on 1) how to interpret the Maturity Matrix classes (A, B, C, D) in the FRM framework, 2) how to apply MM to single site and networks.	ESA	2027
ACT-04	to put in place a CEOS-FRM catalogue for listing all the CEOS-FRM projects. The list should act as an entry point for FRMs with links to data and quality information also providing a "start here" guide on key references (papers, training materials, etc).	ESA	2027

5.3 Summary of Decisions

ID	Decision
DE-01	Independent peer-reviewed process needs to be put in place to assess CEOS-FRM compliancy; self-assessment is not sufficient. For the review process there is the agreement that the review shall be at CEOS level, in working groups devoted Cal/Val. Being important for interoperability and inter-agencies collaboration, the CEOS-ARD could be a good example for putting in place this process.
DE-02	CEOS-FRM is for satellite Cal/Val only (FRM without the 'CEOS' appendix can then be used with a broader meaning).

6 APPENDIX A: AGENDA

Monday 18 May 2026 12:30 – 19:00

13:15 – 13:30	Welcome to NPL, practicalities and aims of meeting
13:30 – 15:00	**Introductory presentations about FRMs and QA Framework**. • ESA intro (Philippe Goryl) - 15 min • The journey of an FRM (Philippe Goryl) 45 min ▪ FRM categories ▪ Type of projects conducted at ESA ▪ FRM status, preparation vs operational ▪ Intro to Workshop content and seed questions • The CEOS-FRM tool / portal (Paolo Castracane)- 30 min
15:30 – 16:45	▪ FRM4VEG (Harry Morris - 15 + 5min) ▪ FRM4Fire (Bernardo Mota - 15 + 5 min) ▪ GBOV (Rémi Grousset - 15 + 5 min) ▪ FRM4SM (Alexander Gruber – 15 + 5 min) ▪ QA4SAR (Alberto Sanchez Rabaneda - 15+ 5 min) Discussion (15 min)
16:45 – 17:30	**Definition of subgroups (5 min)** **Breakout group discussion (40)**

Tuesday 19 May 08:30 – 17:30

09:00 – 10:30	▪ FRM4SST (Werenfrid Wimmer - 15+5 min) ▪ TirCalNet (Darren Ghent - 15+ 5min) ▪ FRM4ALT (Stelios Mertikas 15+5 min) Discussion (15 min)

11:00 – 12:15	▪ St3TART (Eva Le Merle - 15 +5 min) ▪ FRMs for the Atmosphere domain (Jean-Christopher Lambert -15 + 5 min) ▪ FRM4GHG to COCCON experience and evolution (Mahesh Kumar Sha - 15 + 5 min) Discussion (15 min)
13:45 – 15:40	▪ RadCalNet (Morven Sinclair, NPL – 15 + 5 min) ▪ LANDHYPERNET (Pieter De Vis – 15 + 5 min) • QA frameworks and EDAP (Nigel Fox – 15 + 5 min) • FRM applied to non-satellite datasets (Emma Woolliams - 15+5 min) • Copernicus In-Situ Overview (Sebastian Clerc -15+5 min)
16:15 – 17:30	Breakout group discussion Part 2

Wednesday 20 May 2026 08:30 – 13:45

09:00 – 10:30	**Plenary discussion** 10/15 min presentation by each subgroup to present their conclusions
13:30 – 15:00	**Plenary discussion/wrap up (led by ESA):** • Next steps for FRMs

7 APPENDIX B: WORKSHOP SEED QUESTIONS

Compliancy	What is the shared and accepted definition of FRM and the relevance of the prefix 'CEOS', what evidence and minimum requirements are needed to claim CEOS-FRM status, and how can this concept be translated in a consistent and systematic manner across different missions? Is the understanding of 'class ABCD' of CEOS-FRM compliance understood and useful? Are these definitions/concepts applicable to all primary levels of products (e.g. Level-1 and Level-2)?
Inter-consistency	How can we ensure coherence, comparability, and transparency of CEOS-FRMs across different missions, domains and projects? How should inter-consistency be addressed in FRM-related activities, in terms of systematically planning cross-checks e.g. comparisons and improving visibility and coordination of parallel FRM efforts?
Awareness	How and what CEOS-FRM activities, datasets and best practices be centralised and communicated to improve awareness and uptake across the wider community, including centralised information resources and better exploitation of lessons learned, to inform future CEOS-FRM development and operations? Should missions explicitly require CEOS-FRM compliance for Cal/Val activities?
Gaps & Needs	What are the key gaps and challenges in establishing, sustaining, and prioritising CEOS-FRMs across technical, organisational, financial, and representativeness dimensions, and how should future investments balance consolidation of existing CEOS-FRM initiatives with the development of new sites, regions, domains?
Standards & Harmonisation	How should FRM compliance categories within the CEOS FRM framework be strengthened (covering maturity assessment, uncertainty requirements, QA and comparison practices, publication, measurand definition, and cross-domain consistency) while remaining fit for purpose across different application domains and to support consistent FRM implementation? Should there be minimum requirements for categories such as achievable uncertainty?
Synergies & Partnerships	How can synergies and partnerships be strengthened across agencies, industry, and the wider CEOS-FRM international community to improve coordination, consistency, participation, and long-term sustainability, including appropriate incentives and funding pathways for both public and commercial missions, and to ensure a coordinated and sustainable CEOS-FRM development and use that meets the Cal/Val needs of the missions?
Impact	How can the impact of CEOS-FRM be demonstrated? What metrics and verification procedures are needed to systematically assess the impact of CEOS-FRMs on Cal/Val activities, mission performance, and downstream services?
Other Points	Can and should the CEOS-FRM framework evolve to extend its value beyond space applications, engaging non-space user communities, and encompassing different historic quality-assurance approaches? Is there a value in a FRM classification and/or label beyond space applications e.g. WMO networks and Copernicus in situ, and how can this relate to CEOS-FRM? Is it largely just removing the 'explicit space requirements' in the criteria?