→ frm4soc.org

Martin Ligi (University of Tartu) and Mathew Beck (RBINS) mount the irradiance sensors at the Acqua Alta Oceanographic Tower during the FRM4SOC field inter-comparison exercise, 2018. Photo by courtesy of PML. Author: Gavin Tilstone.

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UNIVERSITY OF TARTU Tartu Observatory
NPL National Physical Laboratory
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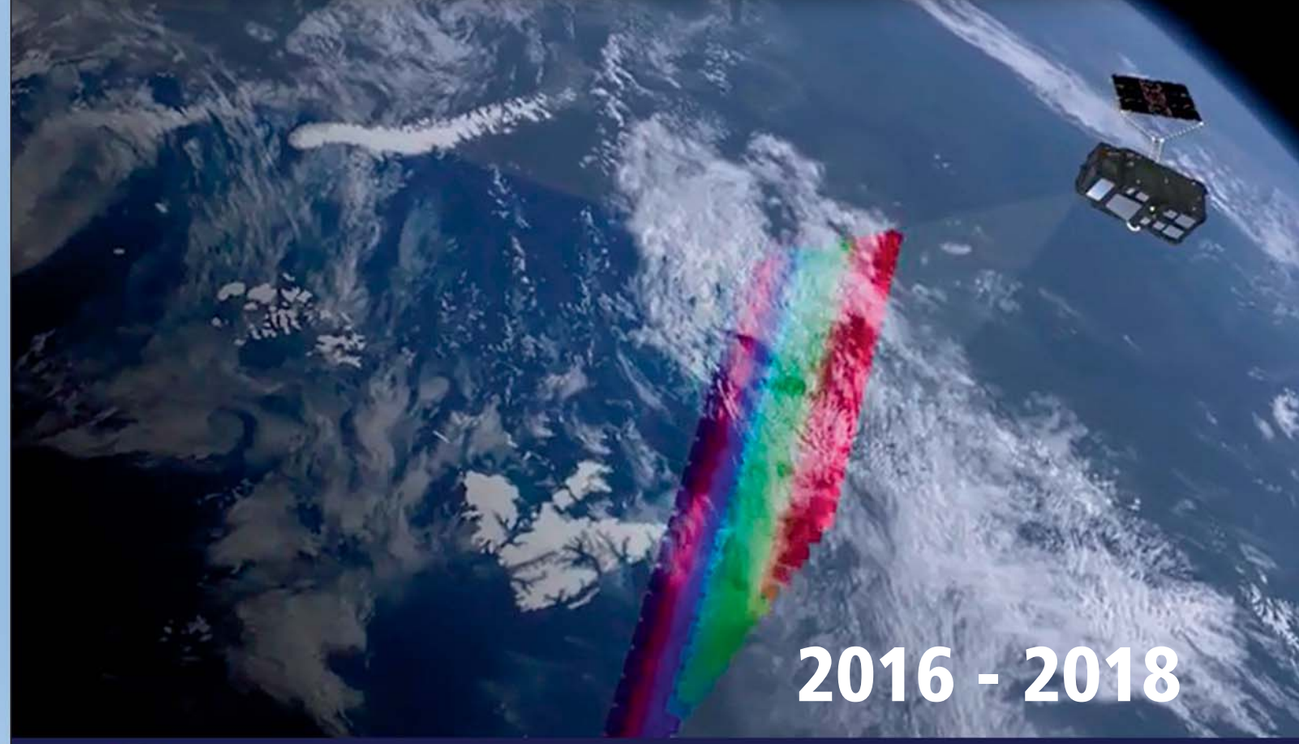
museum



2016 - 2018

fiducial reference measurements for satellite ocean colour

→ FRM4SOC

esa

Revealing the colour of ocean life.
Released 13/01/2016. © ESA/ATG medialab

Front cover photo: Sentinel-3 scans Earth's colour.
Released 06/03/2018. © ESA/ATG medialab

Lower: Measurement site of LCE-2 in comparison experiment at Lake Kääriku in Estonia. 12/05/2017. Photo by courtesy of UT. Author: Viljo Allik, UT.

→ FRM4SOC

The FRM4SOC project, funded by ESA, has been supporting of the evaluation and improvement of 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 (WGCV) and in support of the CEOS ocean colour virtual constellation. FRM4SOC activities have also contributed to fulfillment of the International Ocean Colour Coordinating Group (IOCCG) in situ ocean colour radiometry white paper objectives and the relevant IOCCG working groups and task forces (e.g. the working group on uncertainties in ocean colour remote sensing and the ocean colour satellite sensor calibration task force).

The project achievements have made a fundamental contribution to the European system for monitoring the Earth (Copernicus) through its core role of working to ensure that ground-based measurements of ocean colour parameters are traceable to SI standards. This helps to ensure high-quality and accurate Copernicus satellite mission data, in particular Sentinel-2 MSI and Sentinel-3 OLCI ocean colour products. The FRM4SOC project has also contributed to the work of ESA and EUMETSAT to ensure that these instruments are validated in orbit.

The aim of the FRM4SOC project has been to establish and maintain SI traceability of Fiducial Reference Measurements (FRM) for satellite Ocean Colour Radiometry (OCR) with accompanying uncertainty budgets.

''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 Mètre.''

Resolution 1 of the 20th Conférence Générale des Poids et Mesures (CGPM, 1995).

→ SCIENTIFIC BACKGROUND

Calibration and Validation of Satellite Ocean Colour Sensors

Accurate radiometric calibration and characterization of the individual satellite sensors is the most critical component of working towards achieving the goal of consistent, long-term multi-mission Ocean Colour products.

Once on-orbit, the uncertainty characteristics of the satellite instruments established during pre-launch laboratory calibration and characterization activities and the end-to-end geophysical measurement retrieval process can only be assessed via independent calibration and validation activities.

BOUSSOLE mooring. 2015. Photo: Courtesy of the Laboratoire d'Oceanographie de Villefranche (LOV). | Acqua Alta Oceanographic Tower in the Adriatic Sea where the FRM4SOC FICE was conducted in July 2018. | Plymouth Marine Laboratory and Tartu Observatory radiometers measuring in the blue waters of the Southern Gyre. | RRS Discovery arrives at South Georgia on 02/11/2017 as part of the AMT4SentinelFRM voyage. Photos by courtesy of PML. Author: Gavin Tilstone, PML.

Ground Measurements

Ground measurements are essential to Ocean Colour remote sensing for:

- Vicarious adjustment of L2 products;
- Continuous assessment of OCR quality (i.e., validation of normalized water leaving radiance or the equivalent remote sensing reflectance);
- Validation of derived satellite ocean colour products (e.g., chlorophyll-a concentration);
- Development and verification of the bio-optical algorithms required for generating derived products (independent of any specific satellite mission).

Fiducial Reference Measurement

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.

https://earth.esa.int/web/sppa/activities

The defining mandatory characteristics for FRM are:

- FRM measurements have documented SI traceability (e.g. via round-robin intercalibration of instruments) using metrology standards.
- FRM measurements are independent from the satellite geophysical retrieval process, noting the exception of L2 product vicarious adjustment that fundamentally depends on FRM ground based measurements.
- An uncertainty budget for all FRM instruments and derived measurements is available and maintained.
- 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.

The Committee for Earth Observation Satellites (CEOS) define

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

Validation, on the other hand, is "the process of assessing, by independent means, the quality [uncertainty] of the data products derived from those system outputs".

Validation is a core component of a satellite mission and should be planned for accordingly starting at the moment satellite instrument data begin to flow until the end of the mission.

VIM: International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM) states

Adjustment is "set of operations carried out on a measuring system so that it provides prescribed indications corresponding to given values of a quantity to be measured".

Adjustment of a measuring system should not be confused with calibration, which is a prerequisite for adjustment.

→ TRACEABILITY TO SI

The International System of Units, the SI, provides the foundation for measurement around seven base units and a system of coherent derived units. SI units are uniform worldwide, independent of the method used realise each unit and stable over centuries.

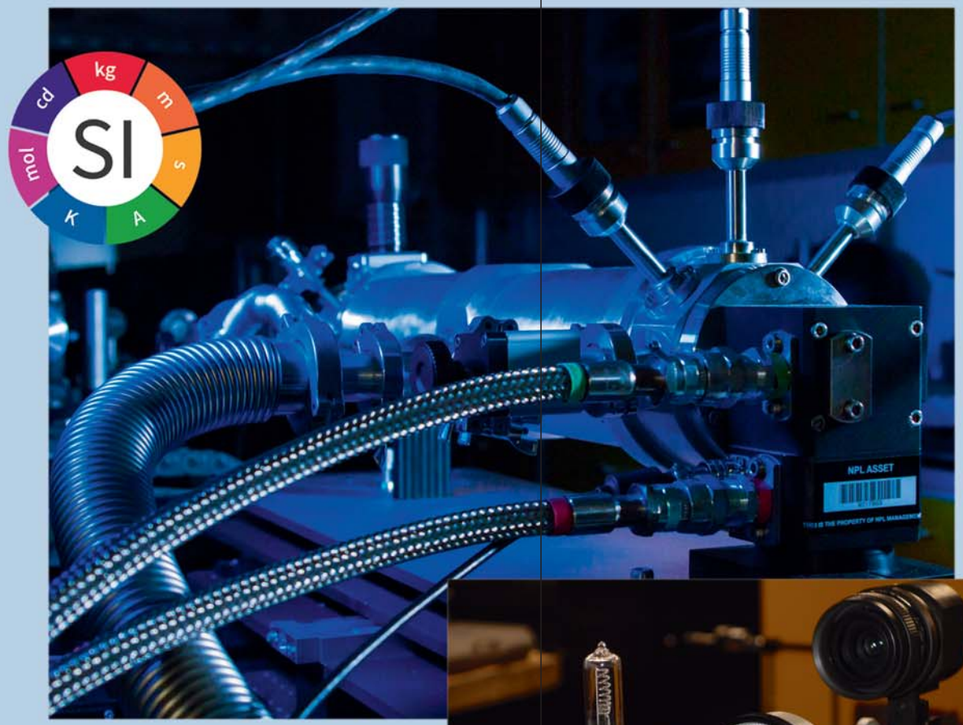
The metrological community achieves these desirable properties through three technical concepts: traceability, uncertainty analysis and comparison.

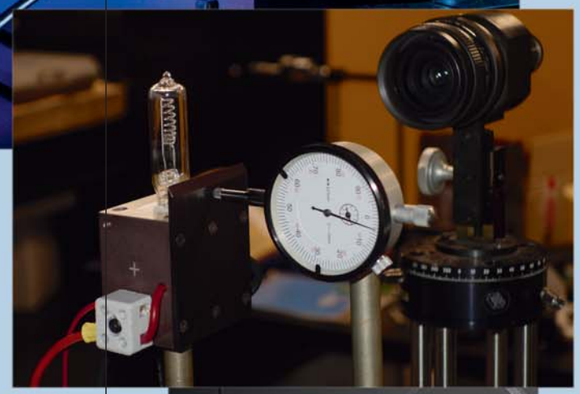
Metrological traceability is a property of a measurement that relates the measured value to a stated metrological reference through an unbroken chain of calibrations or comparisons.

Uncertainty analysis is the review of all sources of uncertainty and the propagation of that uncertainty through the traceability chain.

Comparison is the process of validating uncertainty analyses through several organisations with independent processes calibrating the same artefacts and considering the differences with respect to the uncertainty. National Metrology Institutes perform regular formal comparisons to audit their uncertainty statements, as part of the Mutual Recognition Arrangement organised by the CIPM.

For ocean colour radiometers, traceability is to radiometric standards. An example traceability chain, that for radiometric measurements at NPL as applied in the FRM4SOC project is given below.

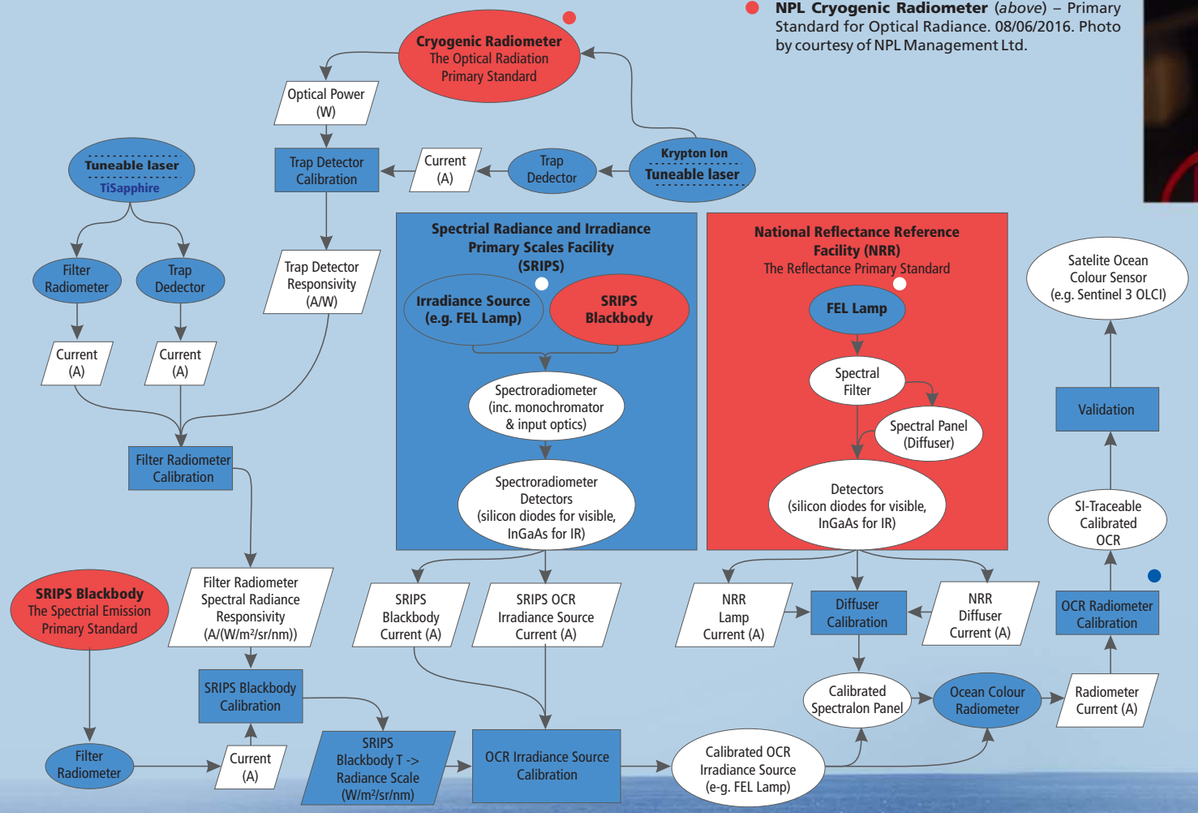




NPL Cryogenic Radiometer (*above*) – Primary Standard for Optical Radiance. 08/06/2016. Photo by courtesy of NPL Management Ltd.

FEL lamp – Reference Source for Irradiance and Radiance. 03/04/2017. Photo by courtesy of NPL Management Ltd.

CR Radiometer Calibration at Tartu Observatory of the University of Tartu. 22/04/2014. Photo by courtesy of University of Tartu. Author: Riho Vendt, UT.



The main aim of the Fiducial Reference Measurements for Satellite Ocean Colour (FRM4SOC) project is to bring these metrological principles – uncertainty analysis, SI-traceability and comparison – to in situ observations of ocean colour parameters to support the validationof satellite products, particularly for ocean colour from Sentinel-2 MSI and Sentinel-3 OLCI.

→ THE IMPORTANCE OF UNCERTAINTY BUDGETS

All measurements are imperfect and have errors that can be random (e.g.noise on detectors) or systematic (common to all measurements, e.g. due to a calibration process), or structured (common to certain measurements, e.g. those taken close to each other in space and or time, but random over larger spatial/temporal scales) .

Uncertainty describes the spread of possible errors, and arises due to many aspects that can be generally grouped into the following primary categories:

- Instrument uncertainty (calibration and measurement),
- Retrieval/algorithm uncertainty (model assumptions, input parameters),
- Environmental condition uncertainty,
- Scaling and applicability of point/ instantaneous measurement to derived product.

Establishing an uncertainty budget for FRM is a fundamental step that drives a better understanding of the various error sources. Reliable and well defined uncertainty budgets ensure traceability of measurement results obtained with FRM field radiometers to the units of SI when matched to satellite measurements.

FICE-AAOT radiance sensors alongside the AERONET-OC SeaPrism sensors and RV Litus below used to make the C-OPS in water optical deployments. Photo by courtesy of PML. Author: Gavin Tilstone.

→ ACHIEVEMENTS

The FRM4SOC consortium organized a set of events to establish and maintain SI traceability of Fiducial Reference Measurements for satellite ocean colour radiometry. The results and findings of these activities were formulated in technical reports (TR), proceedings (PROC) and a roadmap (SOR) available at the webpage **https://frm4soc.org**

MEASUREMENT REQUIREMENTS AND PROTOCOLS

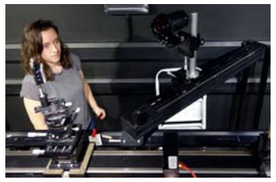
The FRM4SOC consortium reviewed common fiducial reference measurement (FRM) ocean colour radiometers (OCR) used for Satellite OCR validation and worked out requirements and protocols for operating these measurements. The reports were discussed with instrument manufactures and scientist users to arrive at final consensus. See details in TR-1 and TR-2.

TR-1 "Measurement Requirements and Protocols when Operating Fiducial Reference Measurement (FRM) Ocean Colour Radiometers (OCR) for Satellite Validation"

TR-2 "A Review of Commonly used Fiducial Reference Measurement (FRM) Ocean Colour Radiometers (OCR) used for Satellite OCR Validation"

Contact: Kevin Ruddick, *kruddick@naturalsciences.be*

LCE-1



3.-7.04.2017 NPL, Teddington, UK

SI-traceable laboratory comparison experiment for FRM OCR. Verification of reference irradiance and radiance sources.

NPL led international comparisons of (a) irradiance sources and (b) the radiance measurement capability of laboratories that calibrate ocean colour radiometers. The irradiance comparison was held at NPL using the Spectral Radiance and Irradiance Primary Scales (SRIPS) facility and the radiance comparison via am international round robin using transfer radiometers. Both comparisons had participants from Europe, North America and Australia. See details in TR-3a, TR-3b and TR-4.

TR-3a, b "Protocols and Procedures to Verify the Performance of Reference Irradiance (a) and Radiance (b) Sources used by Fiducial Reference Measurement Ocean Colour Radiometers for Satellite Validation"

TR-4 "Results from the First FRM4SOC Reference Radiance and Irradiance Source Verification Laboratory Calibration Experiment Campaign"

Contact: Agnieszka Bialek, *agnieszka.bialek@npl.co.uk*
Andrew Clive Banks, *andrew.banks@npl.co.uk*

LCE-2

8.-13.05.2017 TO, Tõravere, Estonia

SI-traceable Laboratory Intercomparison Experiment to verify the performance of FRM field OCR.

The LCE-2 exercise consisted SI-traceable radiometric calibration of participating radiance and irradiance spectroradiometers followed by indoor and outdoor intercomparison. The agreement between all the sensors was good in the indoor intercomparison, but the variability between the sensors increased two (radiance) to five (irradiance) times when natural targets such as sky and water were measured in outdoor conditions. See details in TR-5 and TR-6.

TR-5 "Protocols and Procedures to Verify the Performance of Fiducial Reference Measurement (FRM) Field Ocean Colour Radiometers (OCR) used for Satellite Validation"

TR-6 "Results from the First FRM4SOC Field Ocean Colour Radiometer Verification Round Robin Campaign"

Contact: Joel Kuusk, joel.kuusk@ut.ee

FICE AMT

20.09 - 4.11.2017 Atlantic Meridional Transect 27

Fiducial Inter-Comparison Experiment at the Atlantic Meridional Transect (AMT)

FICE AMT was conducted on the Atlantic Meridional Transect 27 during which PML, RBINS, and UT compared above water radiometer measurements. See details in TR-8 and TR-9.

TR-8 "Protocols and Procedures for Field Inter-Comparisons of Fiducial Reference Measurement (FRM) Field Ocean Colour Radiometers (OCR) used for Satellite Validation"

TR-9 "Results from the First FRM4SOC Field Inter-Comparison Experiment (FICE) of Ocean Colour Radiometers"

Contact: Gavin Tilstone, *ghti@pml.ac.uk*

FICE AAOT

9.-19.07.2018 Gulf of Venice, Italy

Fiducial Inter-Comparison Experiment for Sentinel-3 at the Acqua Alta Oceanographic Tower (AAOT)

An inter-comparison was conducted at the AAOT to assess differences between eight measurement systems.

The preliminary results show that for Ed(0+, lambda), Lsky(Lambda) and Lt(Lambda) there was generally good agreement with differences of <5% between institutes. Differences were greater for Rrs. See details in TR-8 and TR-9.

Contact: Gavin Tilstone, *ghti@pml.ac.uk*

FICE-AAOT inter-comparison participants on boat from left to right: Kevin Ruddick (RBINS), Gavin Tilstone (PML), Martin Ligi (Uni Tartu), Astrid Bracher (AWI), Maycira Costa (Uni Victoria), Martin Hieronymi (HZG), Giorgio Dall'Olmo (PML), Vincenzo Vellucci (LoV), Davide D'Alimonte (CIMA)

WKP-1

21.-23.02.2017
ESA/ESRIN, Frascati, Italy

Workshop "Options for future European satellite OCR vicarious adjustment infrastructure for the Sentinel-3 OLCI and Sentinel-2 MSI series"

Consensus on the way forward to ensure the highest Copernicus Ocean Colour products quality through System Vicarious Calibration was reached. See details in PROC-1 and TR-10.

PROC-1 "Proceedings of the international workshop on system vicarious calibration"

TR 10 "Requirements and recommendations for infrastructure required for the long-term vicarious adjustment of the Sentinel-3 OLCI and Sentinel-2 MSI A/B/C and D instruments"

Contact: Christophe Lerebourg, *christophe.lerebourg@acri-st.fr*

WKP-2

5.-6.10.2018 NPL, Teddington, UK

Workshop "The Fiducial Reference Measurement Network for Satellite Ocean Colour"

The major recommendations and findings and of the FRM4SOC project were presented.

The Scientific and Operational Roadmap for future FRM activities was formulated. See details in SOR and PROC-2.

SOR "FRM4SOC Scientific and Operational Roadmap"

PROC-2 "Special issue of MDPI journal *Remote Sensing* (ISSN 2072-4292) "Fiducial Reference Measurements for Satellite Ocean Colour"

Contact: Garry Hensey, *garry.hensey@npl.co.uk*
Andrew Clive Banks, *andrew.banks@npl.co.uk*

LCE-1 in NPL labs. 05/04/2017. Photo by courtesy of NPL Management Ltd. **LCE-2 in TO labs.** 10/05/2017. Photo by courtesy of UT. Author: Joel Kuusk. **A purpose-built stainless steel frame used to position all the optical sensors at the same viewing geometry in FICE AMT.** Photo by courtesy of PML. Author: Gavin Tilstone (taken by Krista Alikas). **AAOT tower and FICE AAOT participants on boat.** Photo by courtesy of PML. Author: Gavin Tilstone.
Panel discussion on WKP-1. 23/02/2017. Photo by courtesy of UT. Author: Joel Kuusk. **Reception of NPL main building**. Photo by courtesy of NPL Management Ltd.

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The European Space Agency (ESA) is Europe's gateway to space. Its mission is to shape the development of Europe's space capability and ensure that investment in space continues to deliver benefits to the citizens of Europe and the world.

ESA is an international organization with 22 Member States. By coordinating the financial and intellectual resources of its members, it can undertake programs and activities far beyond the scope of any single European country.

FRM4SOC kick-off meeting in ESTEC/ESA. 05/27/2016. Photo by courtesy of UT

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https://frm4soc.org

Having 200+ years of experience in space research, Tartu Observatory of the University of Tartu is the leading centre of astronomical research in Estonia, also possessing an internationally acknowledged competence in remote sensing of natural environment.

Tartu Observatory research strategy brings together scientific and public goals. Here meet the high competence of internationally recognized senior researchers with splendid enthusiasm of young scientists to find solutions for new challenging research questions. This enables to respond to the challenges that modern technology, political situation and economic needs create.

Main building of Tartu Observatory of the University of Tartu.
08/09/2012. Photo by courtesy of UT. Author: Kalju Annuk, UT.

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The National Physical Laboratory (NPL) is the UK's National Measurement Institute and is a world-leading centre of excellence in developing and applying the most accurate measurement standards, science and technology available. NPL ensures that cutting-edge measurement science and technology have a positive impact in the real world.

NPL has been promoting the benefits of SI-traceability to the EO community for more than two decades and has established strong links with the Earth Observation community through CEOS, GEO and WMO. NPL is well-known by the space agencies, particularly in Europe, but also in the USA and Asia. NPL led the development of the Quality Assurance Framework for Earth Observation (QA4EO), which is now recognised and accepted by the international EO communities.

Main building of NPL in Teddington, UK. © NPL Management Ltd. Photoby courtesy of NPL

PLYMOUTH MARINE LABORATORY, UK

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Plymouth Marine Laboratory (PML) is an independent, impartial provider of scientific research and contract services relating to the marine environment.

PML has world-class research capacity in global Earth Observation, ecosystem modelling, and marine ecosystem functioning. Its core research programme contributes to the issues of climate change, marine pollution and sustainability. PML's research is highly innovative, relevant and applicable, feeding into national and international marine and coastal programmes in anticipation of societal needs.

PML has a long history of Earth Observation applications, software development and data processing for national, European Commission and ESA projects. Activities range from scientific research and development (algorithms, models, etc.) to reprocessing/reanalysis, and from near real-time and climate-quality/delayed-mode data provision to cutting-edge large scale data distribution and visualisation.

Main building of Plymouth Marine Laboratory. © PML

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The Royal Belgian Institute for Natural Sciences (RBINS) is a Belgian Federal Government Scientific Establishment. The RBINS Remote Sensing and Ecosystem Modelling (REMSEM) is carrying out scientific research and analysis in the field of marine ecosystems to improve the long term scientific basis for management of the marine ecosystems.

The team has 20 years' experience in the development of algorithms for the processing of ocean colour data (including atmospheric correction) and in the validation and exploitation of satellite-derived products with particular expertise in turbid coastal waters.

RBINS has been making measurements of Ocean Colour radiometry since 2001 using a three-sensor abovewater TRIOS system and was a de facto leader of this methodology, termed "MUMM_TRIOS", within the MERIS Validation Team.

Muséum des Sciences naturelles de Belgique, Bruxelles.
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ACRI-ST, France

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ACRI-ST is a member of the ACRI Group established in 1989, comprising companies providing services from satellite remote sensing, ocean & land surveys to hydraulic civil engineering through environmental research Computational Fluid Dynamics and dynamic similitude.

ACRI-ST has more than twenty-five years of experience in Cal/Val for Earth Observations missions. They built up their expertise particularly on MERIS/ENVISAT. They have further confirmed this expertise and ACRI is now a key expert in the frame of Sentinel-2 and Sentinel-3 mission performance centres.

ACRI-ST is a supplier to space agencies (simulation of space-based sensors; operational chains development; processing, archiving and mission performance centres) and develops/operates environmental Copernicus services to end users.

ACRI head office in Sophia Antipolis, France. © ACRI-ST