FRM4SOC project overview and overarching goal of this workshop

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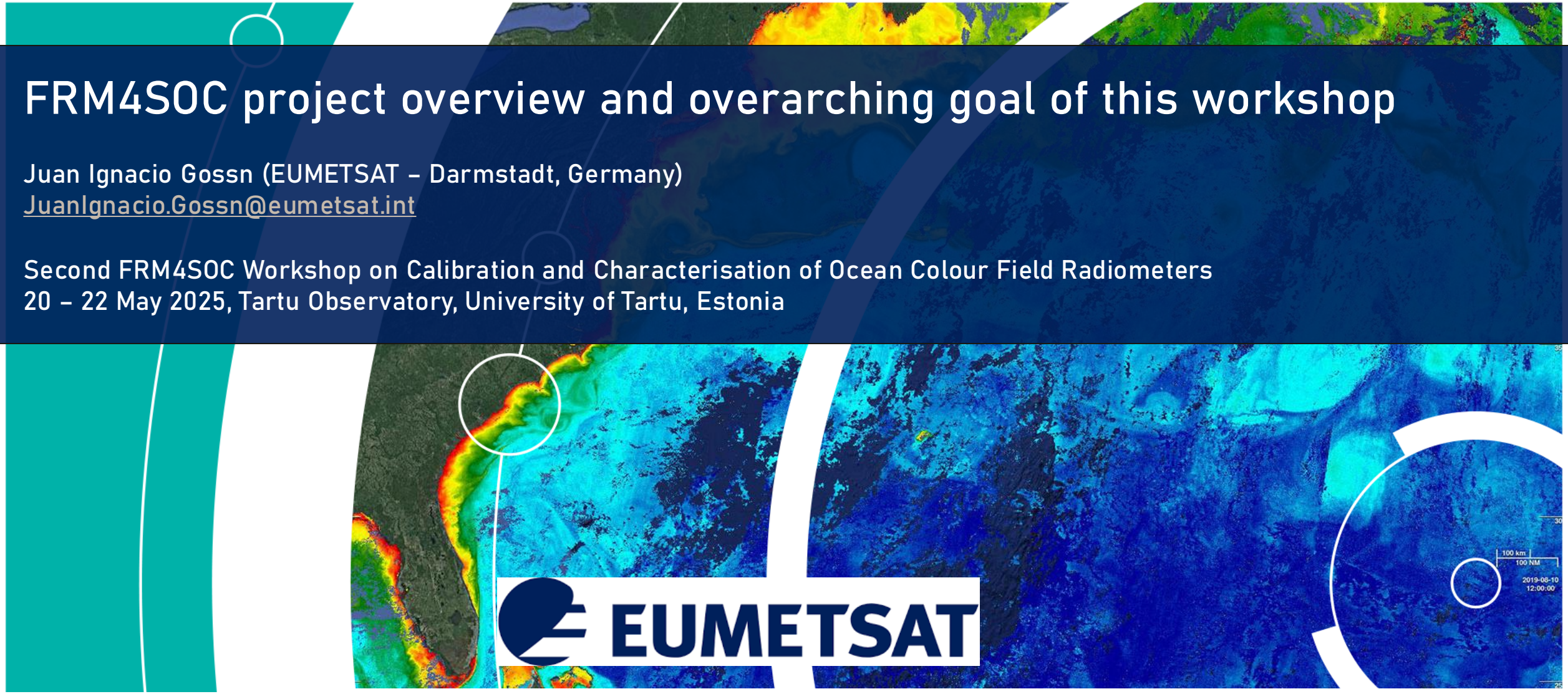
Second FRM4SOC Workshop on Calibration and Characterisation of Ocean Colour Field Radiometers
20 – 22 May 2025, Tartu Observatory, University of Tartu, Estonia



Why are we here today?

A chain of reasons:

1. We are here to continuously improve **Ocean Colour observations** from space
2. To improve **Ocean Colour observations** we must validate them with **field measurements**
3. Our **field measurements** must be acquired with **trustworthy field radiometers**
4. To **trust our field radiometers** we must properly **calibrate** and **characterize** them, among other things
5. To properly **calibrate** and **characterize** them, we must arrive at **internationally agreed laboratory practices** and **promote them internationally**
6. To arrive to **internationally agreed laboratory practices for OCR** and **promote them internationally** we are **all** sitting here today

Why are we here today?

To arrive to internationally agreed laboratory practices for OCR and promote them internationally we are all sitting here today

Who are we **all**?

We are the main Ocean Colour Field Radiometry stakeholders

Research Institutions

OC scientists acquiring the data, and defining measurement and validation protocols

Metrologists and laboratory experts defining cal/char procedures

Space Agencies

Filed Measurement database maintainers and developers

National Metrology Institutes, "Secondary" Cal/Char Labs

Instrument processing software developers

Radiometer manufacturers

All of us around the table today are crucial to achieve a common understanding of what is needed to effectively **promote FRM principles across the Ocean Colour community**

Why are we here today?

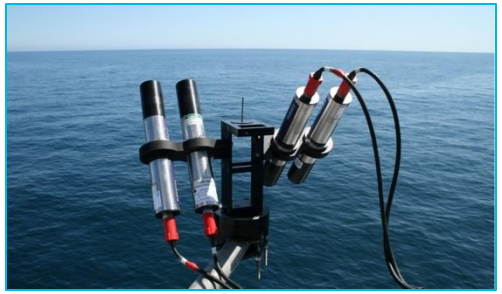
What are **Fiducial Reference Measurements** (FRMs)?

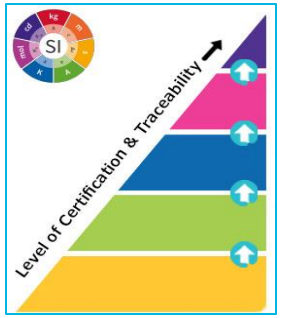
QA4EO

GEO GROUP ON EARTH OBSERVATIONS

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

[Goryl *et al.* 2023]





$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u(x_i, x_j) \, .$$

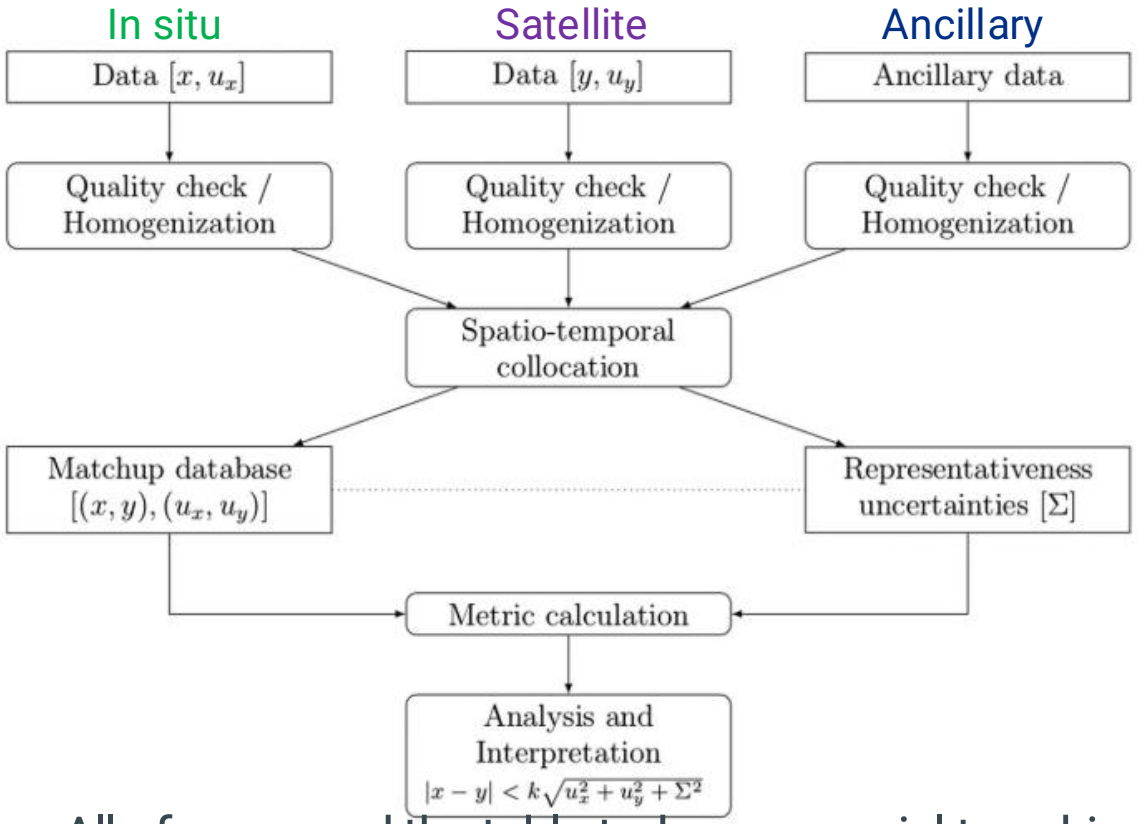
CEOS Committee on Earth Observation Satellites

The FRM concept naturally goes beyond OC...

All of us around the table today are crucial to achieve a common understanding of what is needed to effectively **promote FRM principles across the Ocean Colour community**

FRM: A dialogue between Earth Observation and Metrology

- The EO data are in practice rarely fully traceable, for instance, because fundamental calibrations done in the laboratory prelaunch **cannot be repeated in space**.
- Consequently the **comparison against reference measurements** in a validation exercise is often the only way to link the EO data back to an agreed standard.



[Loew et al. 2017]

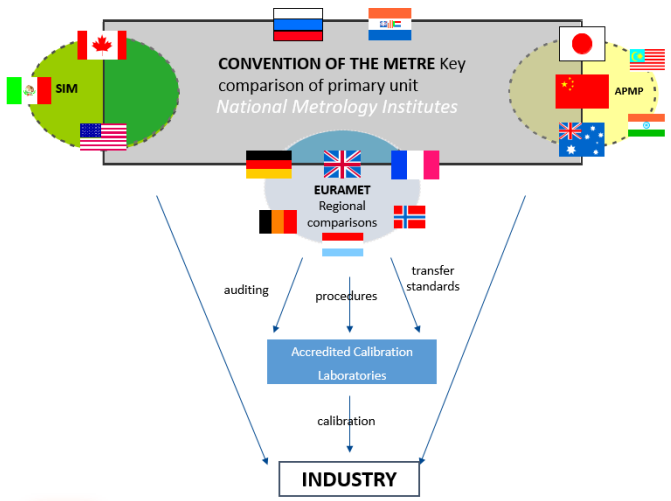
x = "reference" measurement (in situ)
u_x = insitu uncertainty

y = EO measurement (satellite)
u_y = satellite uncertainty

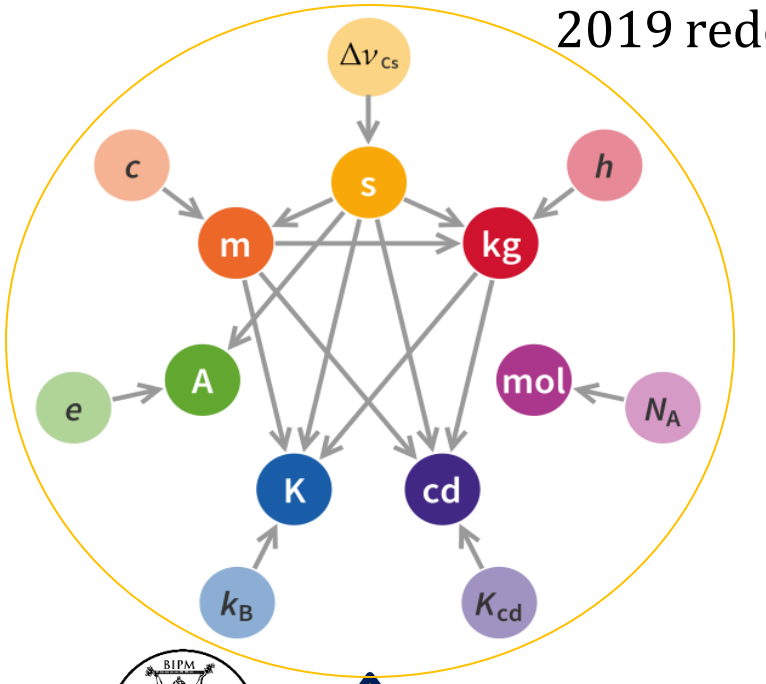
All of us around the table today are crucial to achieve a common understanding of what is needed to effectively **promote FRM principles across the Ocean Colour community**

FRM: A dialogue between Earth Observation and Metrology

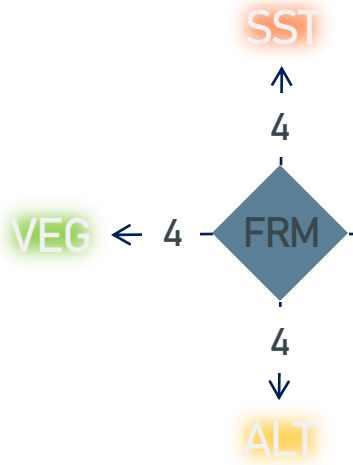
National Metrology Institutes Mutual Recognition Arrangement



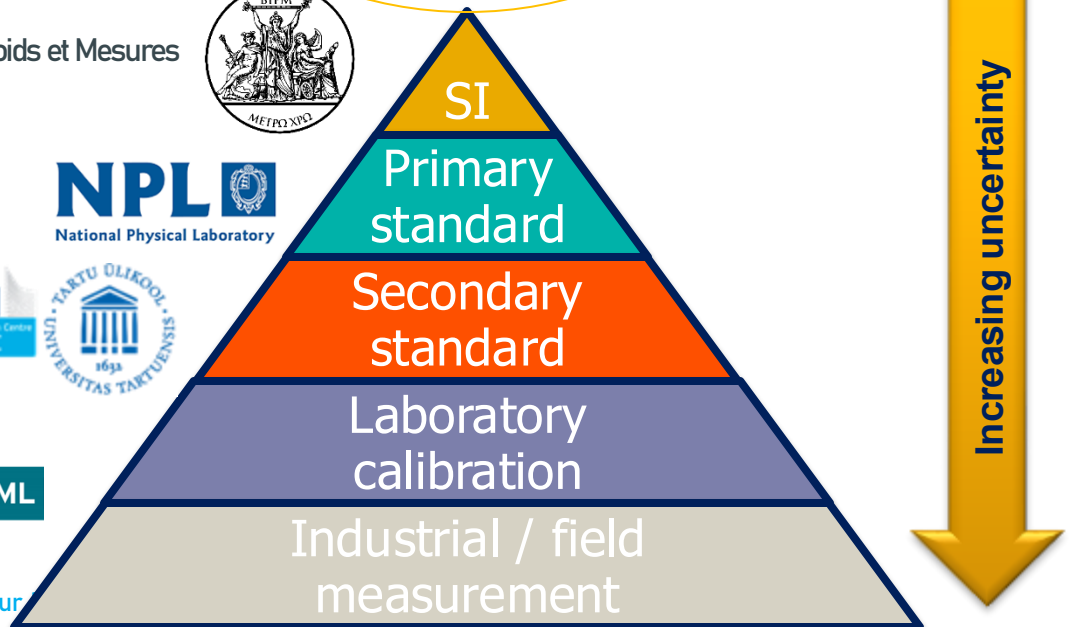
2019 redefinition of the SI base units



Bureau International de Poids et Mesures

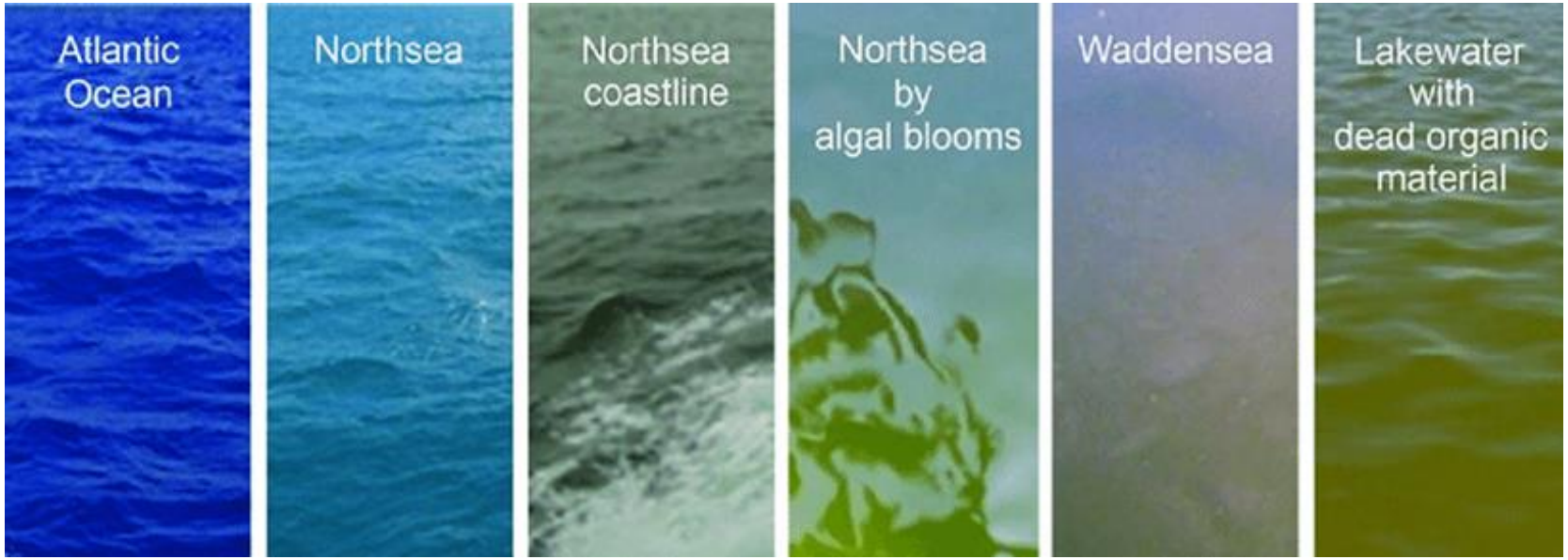


FRM4SOC metrologic pyramid



Ocean Colour: concentrations of optically-active substances from space

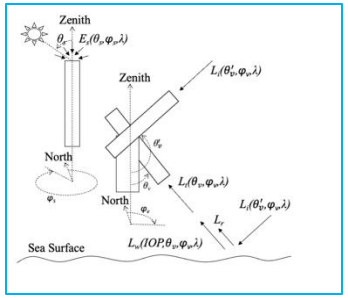
Ocean colour depends on concentrations of phytoplankton, coloured dissolved material and sediments

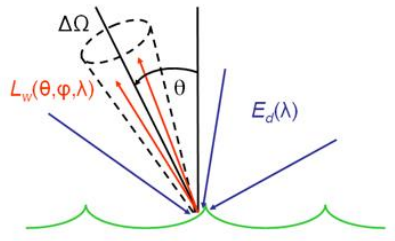


"Ocean Colour" seems like a qualitative definition, however it's all about quantifying these substances

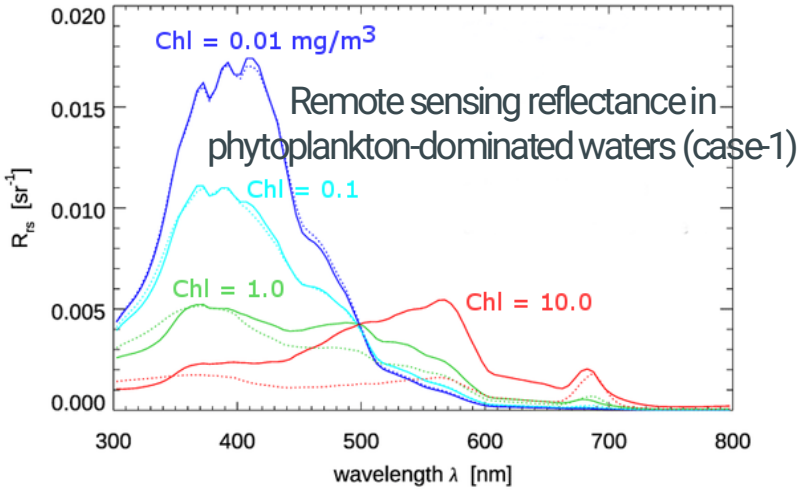
Our key quantity is the Remote-sensing reflectance (Rrs) at surface

$$R_{\mathrm{rs}}(\theta,\phi,\lambda) \equiv \frac{L_w(\text{in air},\theta,\phi,\lambda)}{E_d(\text{in air},\lambda)} \quad (\mathrm{sr}^{-1}) .$$





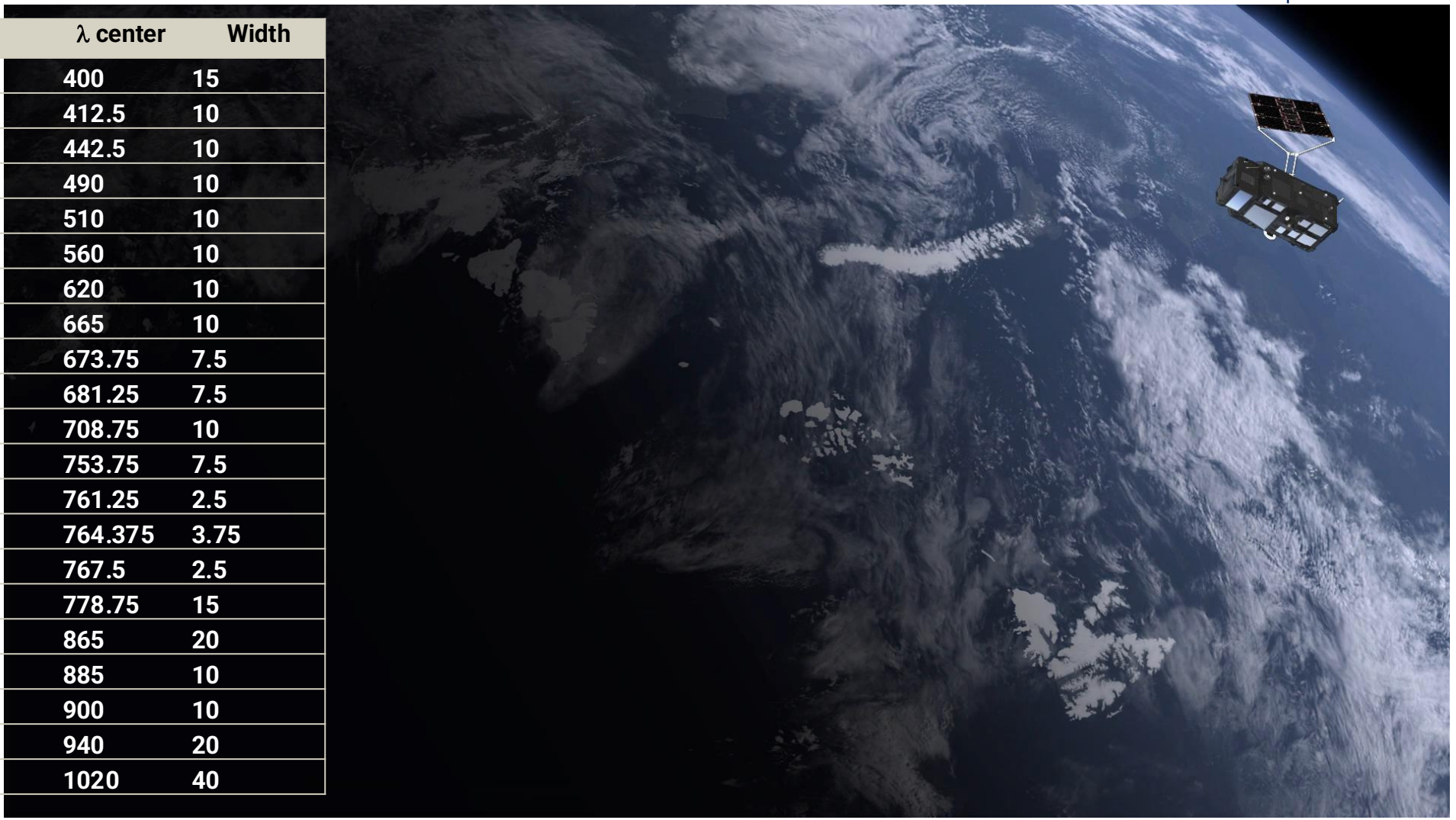
OO Web Book, Mobley, Boss & Roesler



EU Copernicus Sentinel-3 Ocean and Land Colour Instrument (OLCI)

copernicus.eumetsat.int

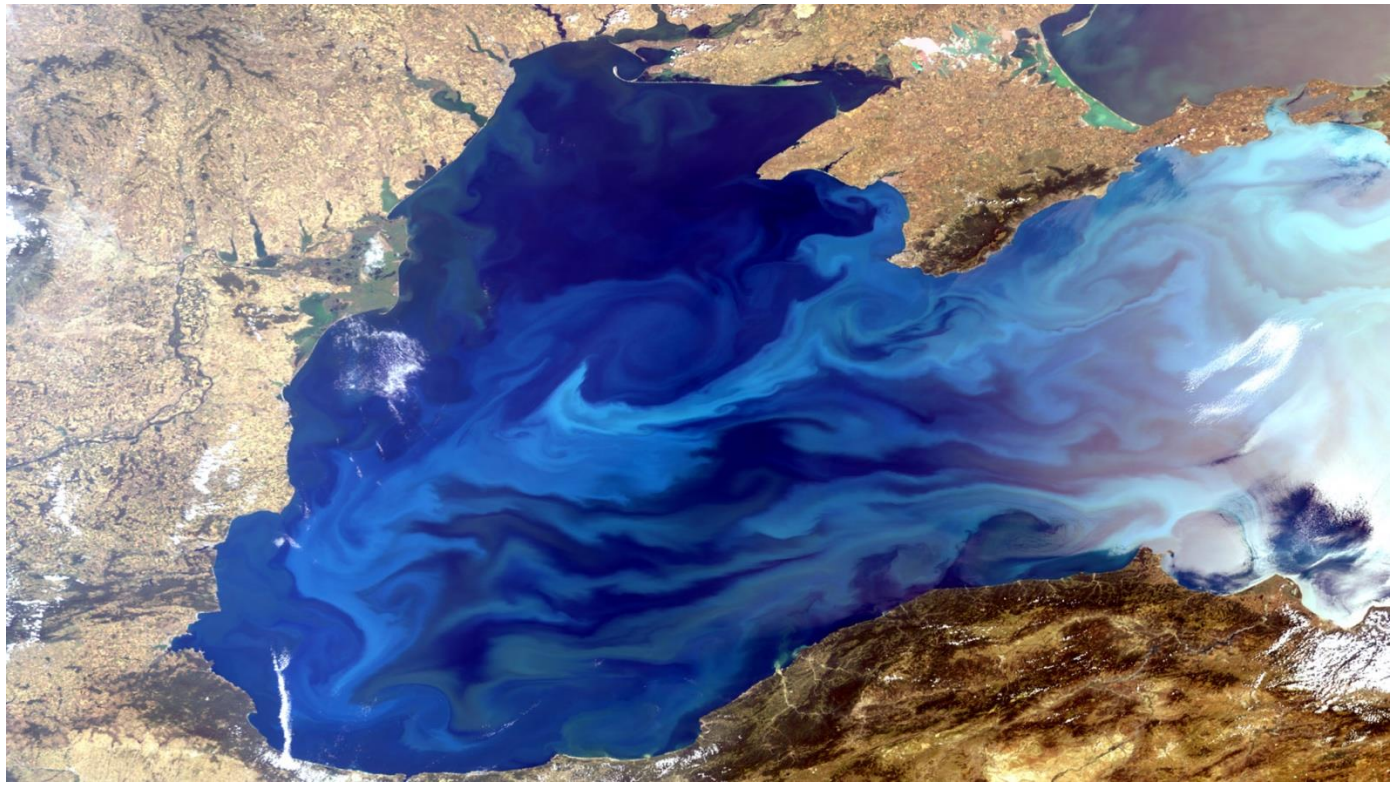
	OLCI spectral bands	λ center	Width
1	aerosol, in-water properties	400	15
2	yellow substance, detritus	412.5	10
3	chlorophyll absorption max	442.5	10
4	chlorophyll and other pigments	490	10
5	suspended sediments, red tide	510	10
6	chlorophyll absorption min	560	10
7	suspended sediments	620	10
8	Chlor. absorption, fluorescence	665	10
9	fluorescence	673.75	7.5
10	chlorophyll fluorescence peak	681.25	7.5
11	Chlor. fluoresc. ref., atm. corr.	708.75	10
12	vegetation, clouds	753.75	7.5
13	O_2 R-branch absorption	761.25	2.5
14	atmospheric parameters	764.375	3.75
15	cloud top pressure	767.5	2.5
16	O_2 P-branch absorption	778.75	15
17	atmospheric correction	865	20
18	vegetation, water vapour ref.	885	10
19	water vapour, land	900	10
20	atmospheric correction	940	20
21	atmospheric correction	1020	40



All of us around the table today are crucial to achieve a common understanding of what is needed to effectively **promote FRM principles across the Ocean Colour community**

What is Ocean Colour for?

Ocean colour data provide a window into the **living ecosystems** in our **oceans** and **coastal and inland waters**, and measure **water quality** and **sediment dynamics**.



All of us around the table today are crucial to achieve a common understanding of what is needed to effectively **promote FRM principles across the Ocean Colour community**

FRM for Ocean Colour product validations and calibration

System Vicarious Calibration

Calibration using the FRM Gold Standard in Ocean Colour

Validation

Validation Fiducial Reference Measurements

- Do the products meet the Mission Requirements, justifying mission Return on Investment?
- Do we instil user confidence in the products by delivering qualified validation results and product uncertainties?

All of us around the table today are crucial to achieve a common understanding of what is needed to effectively **promote FRM principles across the Ocean Colour community**

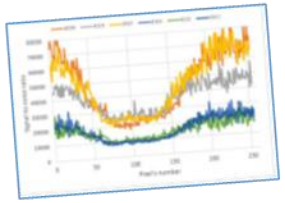
FRM4SOC2 resources, guidelines, tools

copernicus.eumetsat.int

https://frm4soc2.eumetsat.int/

+ …

1. Field radiometer classes to conform to the FRMOCnet standards

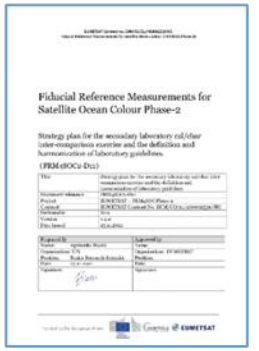


2. Full characterisation of batches of field radiometers and a service of free calibrations and rentals of fully calibrated/characterised instruments

3. Community guidelines on radiometer cal/char standards and FRM certification

Parameter	Scope
1. Absolute calibration for radiometric responsivity	individual
2. Long term stability	individual
3. Stray light and out of band response	individual
4. Immersion factor (irradiance)	individual
4b.Immersion factor (radiance)	individual
5. Angular response of irradiance sensors in air	class-specific
6. Response angle (FOV) of radiance sensors in air	individual
7. Non-linearity	individual
8. Accuracy of integration times	individual
9. Dark signal	individual
10. Thermal responsivity	individual
11. Polarisation sensitivity	individual
12. Temporal response	class-specific
13. Wavelength scale	TBD
14. Signal-to-noise ratio	class-specific
15. Pressure effects	individual
	TBD

4. Radiometer cal/char guidelines for laboratories, international lab exercises and continuous communication with manufacturers and users



5. In situ **measurement procedures**, specific to the radiometer classes, and recommendations that complement those in the IOCCG protocols

6. HyperCP community processor for hyperspectral above-water radiometric measurements, extension of use cases

https://github.com/nasa/HyperCP/tree/master

7. Complete **end-to-end uncertainty budget** included in HyperCP, thoroughly documented and clear to users

8. Maintenance of Ocean Colour **In-Situ Database** OCDB, Fiducial Radiometer Data Base FidRadDB and promotion of their use

https://ocdb.eumetsat.int/

9. Review, test and promote: field comparisons, training, international workshops, feedback from experts

fiducial reference measurements for satellite ocean colour

https://frm4soc2.eumetsat.int

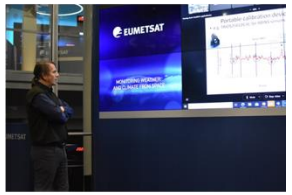
Promoting the adoption of FRM principles across the community

Context: Fiducial Reference Measurements for Satellite Ocean Colour – FRM4SOC

$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} \frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j} u(x_i, x_j)$$

CEOS Committee on Earth Observation Satellites

fiducial reference measurements for satellite ocean colour



2016 – 2019 FRM4SOC Phase 1

- Funded and coordinated by ESA
- Foundations and missing elements to achieve FRM quality
- *https://frm4soc.org*

2021 – present FRM4SOC Phase 2

- Funded by the EU and coordinated by EUMETSAT
- Promote the adoption of FRM principles across the OC community
- Develop foundations for operational implementation of the FRM principles by the Ocean Colour community, start with in situ hyperspectral radiometry
- Verify and demonstrate the operations of the FRM community framework
- Visit: *https://frm4soc2.eumetsat.int/*

University of Tartu Tartu Observatory 1632

ACRI ST

Brockmann Consult GmbH

EOScience

NPL National Physical Laboratory

natural sciences .be

PML Plymouth Marine Laboratory

Consiglio Nazionale delle Ricerche

Programme of the European Union

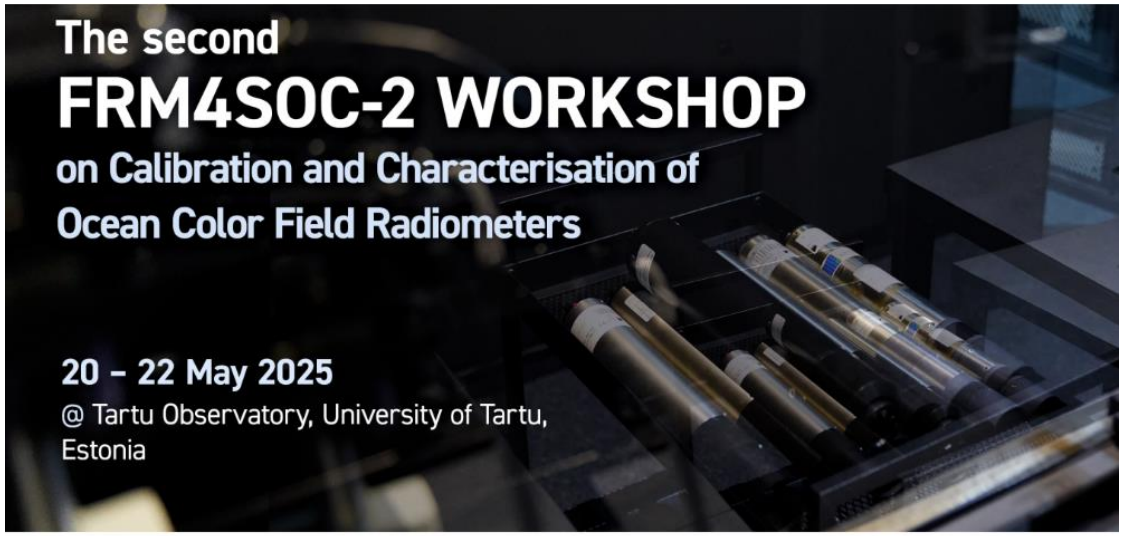
Copernicus Europe's eyes on Earth

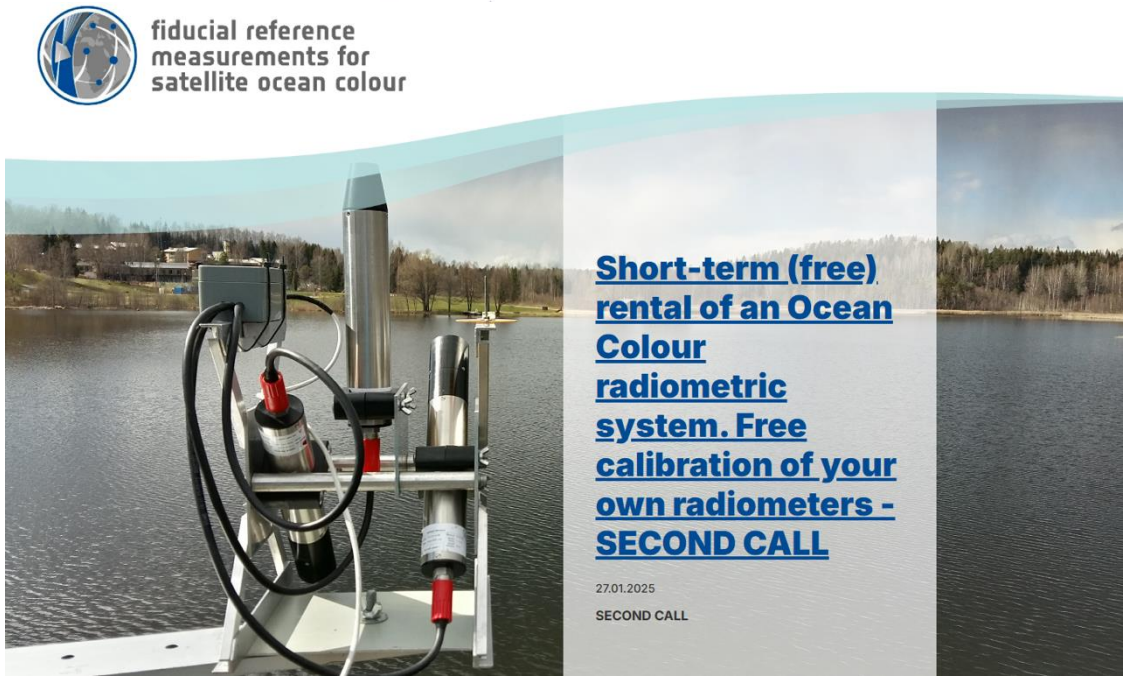
Implemented by EUMETSAT

FRM4SOC2 community services

copernicus.eumetsat.int

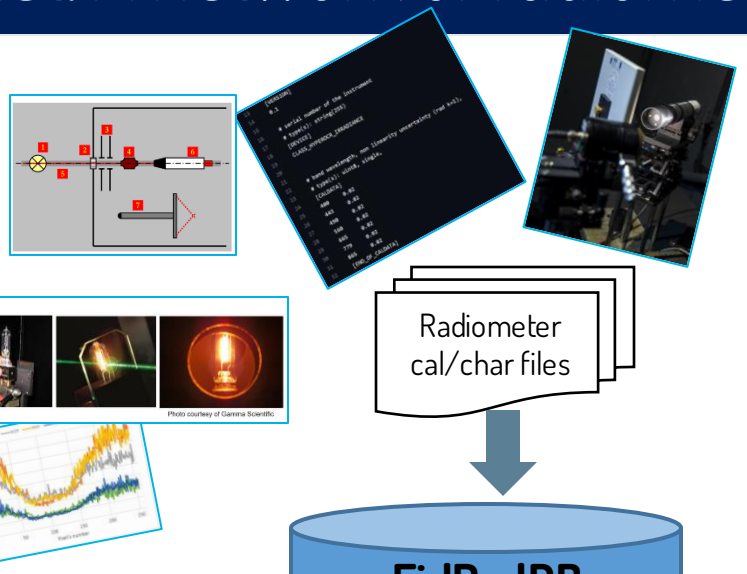
https://frm4soc2.eumetsat.int/





FRMOCnet: A network of radiometric measurements with the FRM quality

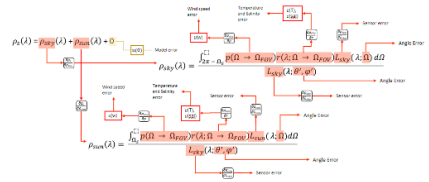
copernicus.eumetsat.int



Radiometer cal/char files

Field raw measurements

HyperCP



FidRadDB

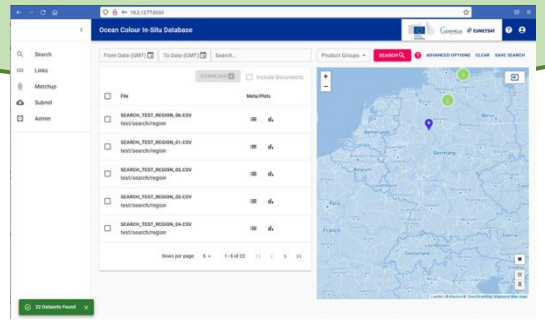
Radiometer calibration and characterisation files

HyperCP

- Process hyper AWR (SeaBird, TriOS)
- Obtain Rrs, nLw, OC parameters + uncertainties
- Determine FRM quality

OC Data Base

- other OC related insitu data
- AWR measurements (FRM and non-FRM)



SeaBASS files

SeaBASS files

HDF files

Inter-operable

SeaBASS

seabass.gsfc.nasa.gov

OCDB

https://ocdb.eumetsat.int

ThoMaS

- Perform match-ups with satellite data
- Assessment of the uncertainty budget of the match-up process

FRM for Ocean Colour: Other efforts

The development and implementation of the FRM principles is an incremental process.
FRM4SOC phase 2 is built on the decades of work done previously by several teams worldwide.

FRM4SOC (Phase 1)

Fiducial Reference Measurements for Satellite Ocean Colour

Fiducial Reference Measurements for Satellite Ocean Colour (FRM4SOC)

by Andrew Clive Banks [1,*], Riho Vendt [2], Krista Alikas [2], Agnieszka Bialek [3], Joel Kuusk [2], Christophe Lerebourg [4], Kevin Ruddick [5], Gavin Tilstone [6], Viktor Vabson [2], Craig Donlon [7] and Tania Casal [7]

remote sensing — MDPI

Review

A Review of Protocols for Fiducial Reference Measurements of Downwelling Irradiance for the Validation of Satellite Remote Sensing Data over Water

Kevin G. Ruddick [1,*], Kenneth Voss [2], Andrew C. Banks [3], Emmanuel Boss [4], Alexandre Castagna [5], Robert Frouin [6], Martin Hieronymi [7], Cedric Jamet [8], B. Carol Johnson [9], Joel Kuusk [10], Zhongping Lee [11], Michael Ondrusek [12], Viktor Vabson [10] and Riho Vendt [10]

remote sensing — MDPI

Article

Example of Monte Carlo Method Uncertainty Evaluation for Above-Water Ocean Colour Radiometry

Agnieszka Bialek [1,*], Sarah Douglas [1], Joel Kuusk [2], Ilmar Ansko [2], Viktor Vabson [2], Riho Vendt [2] and Tânia Casal [3]

remote sensing — MDPI

Article

Field Intercomparison of Radiometer Measurements for Ocean Colour Validation

Gavin Tilstone [1,*], Giorgio Dall'Olmo [1,2], Martin Hieronymi [3], Kevin Ruddick [4], Matthew Beck [4], Martin Ligi [5], Maycira Costa [6], Davide D'Alimonte [7], Vincenzo Vellucci [8], Dieter Vansteenwegen [9], Astrid Bracher [10], Sonja Wiegmann [10], Joel Kuusk [5], Viktor Vabson [5], Ilmar Ansko [5], Riho Vendt [5], Craig Donlon [11] and Tânia Casal [11]

remote sensing

Article

Comparison of Above-Water Seabird and TriOS Radiometers along an Atlantic Meridional Transect

Krista Alikas [1,*], Viktor Vabson [1], Ilmar Ansko [1], Gavin H. Tilstone [2], Giorgio Dall'Olmo [2], Francesco Nencioli [2], Riho Vendt [1], Craig Donlon [3] and Tania Casal [3]

remote sensing — MDPI

Article

Field Intercomparison of Radiometers Used for Satellite Validation in the 400–900 nm Range

Viktor Vabson [1,*], Joel Kuusk [1], Ilmar Ansko [1], Riho Vendt [1], Krista Alikas [1], Kevin Ruddick [2], Ave Ansper [1], Mariano Bresciani [3], Henning Burmester [4], Maycira Costa [5], Davide D'Alimonte [6], Giorgio Dall'Olmo [7,8], Bahaiddin Damiri [9], Tilman Dinter [10], Claudia Giardino [3], Kersti Kangro [1], Martin Ligi [1], Birgot Paavel [11], Gavin Tilstone [7], Ronnie Van Dommelen [12], Sonja Wiegmann [10], Astrid Bracher [10], Craig Donlon [13] and Tânia Casal [13]

SIRREX

SeaWiFS Intercalibration Round-Robin **Experiment**

NASA Technical Reports Server (NTRS)

IOCCG

International Ocean Colour Coordinating Group

IOCCG Ocean Optics & Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation

- Volume 1.0 - Inherent Optical Property Measurements and Protocols: Absorption Coefficient (November 2018)
- Volume 2.0 - Beam Transmission and Attenuation Coefficients: Instruments, Characterization, Field Measurements and Data Analysis Protocols (April 2019)
- Volume 3.0 - Protocols for Satellite Ocean Color Data Validation: In situ Optical Radiometry (December 2019)
- Volume 4.0 - Inherent Optical Property Measurements and Protocols: Best Practices for the Collection and Processing of Ship-Based Underway Flow-Through Optical Data (November 2019)
- Volume 5.0: Measurement Protocol of Absorption by Chromophoric Dissolved Organic Matter (CDOM) and Other Dissolved Materials (DRAFT)
- Volume 6.0: Particulate Organic Matter Sampling and Measurement Protocols: Consensus Towards Future Ocean Color Missions (August 2021)
- Volume 7.0: Aquatic Primary Productivity Field Protocols for Satellite Validation and Model Synthesis (September 2022)
- Noteworthy and Supplemental Topics on Ocean Colour Radiometry Protocols (DRAFT)

+ other studies belonging to other initiatives

Non-linear response of a class of hyper-spectral radiometers

Marco Talone and Giuseppe Zibordi

Immersion Factor of In-Water Radiance Sensors: Assessment for a Class of Radiometers

Giuseppe Zibordi

Principles of Optical Radiometry and Measurement Uncertainty

B. Carol Johnson,[1,*] Howard Yoon,[1] Joseph P. Rice,[1] Albert C. Parr[1,2]

[1] Sensor Science Division, National Institute of Standards and Technology, Gaithersburg, MD, USA; [2] Space Dynamics Laboratory, Utah State University, Logan, UT, USA

Polarimetric characteristics of a class of hyperspectral radiometers

Marco Talone* and Giuseppe Zibordi

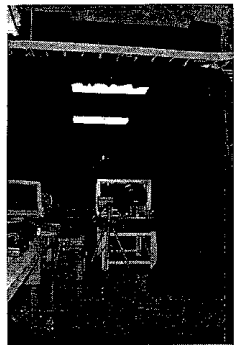
Assessment of AERONET-OC L_{WN} uncertainties

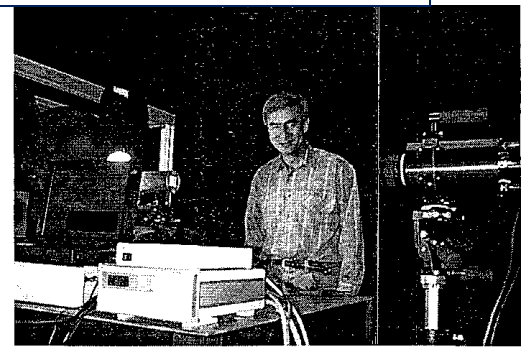
Mathias Gergely and Giuseppe Zibordi

European Commission, Joint Research Centre, Institute for Environment and Sustainability, Ispra, Italy

SIMRIC

The SIMBIOS Radiometric Intercomparison





In summary …

Fiducial Reference Measurements are required for Ocean Colour product Validation to certify meeting the Mission Requirements and to deliver qualified products and uncertainties to users

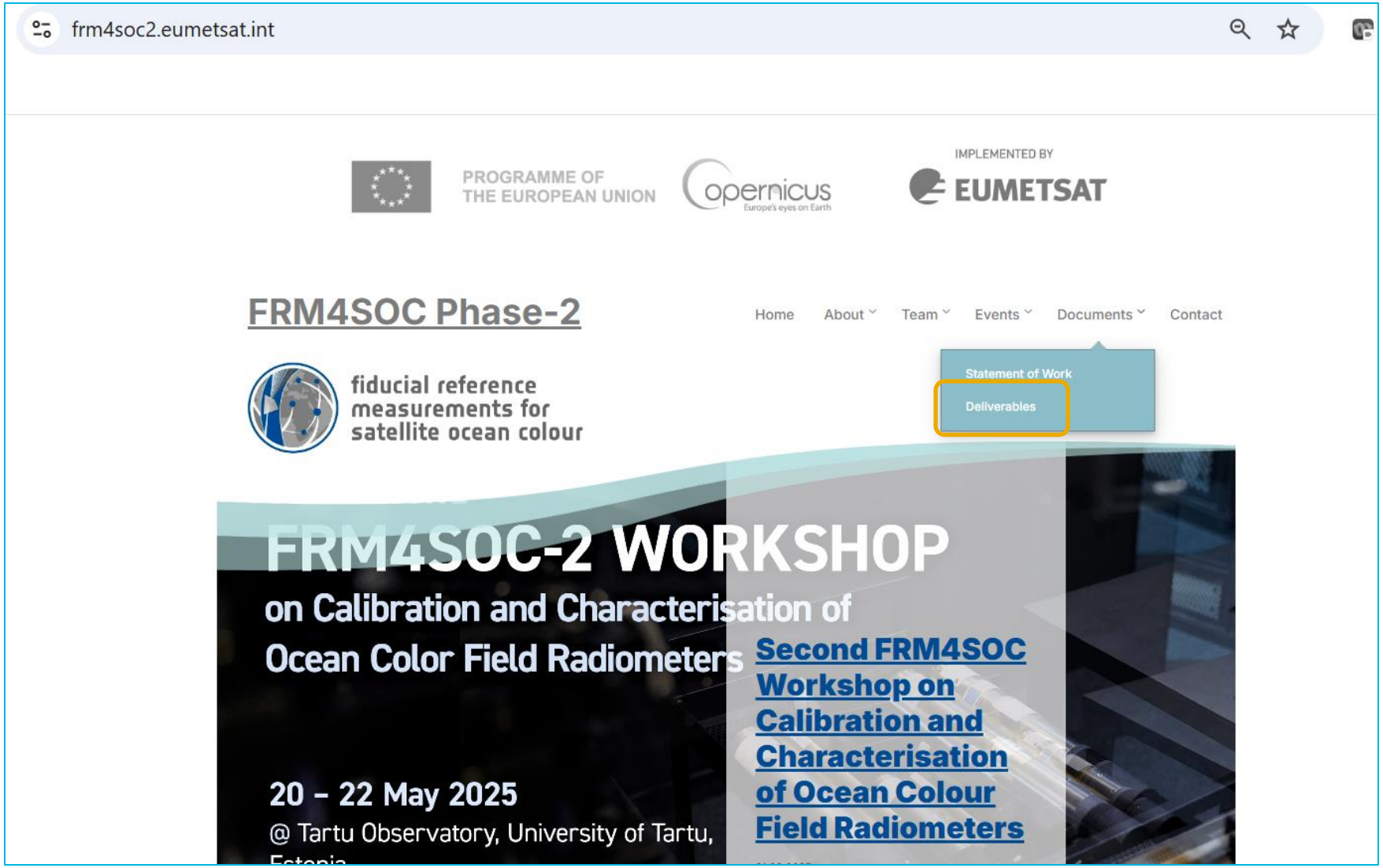
To arrive to internationally agreed laboratory practices and promote them internationally we are all sitting here today

We are the main Ocean Colour Field Radiometry stakeholders

All of us around the table today are crucial to achieve a common understanding of what is needed to effectively **promote FRM principles across the Ocean Colour community**

Resources: FRM4SOC-2 website

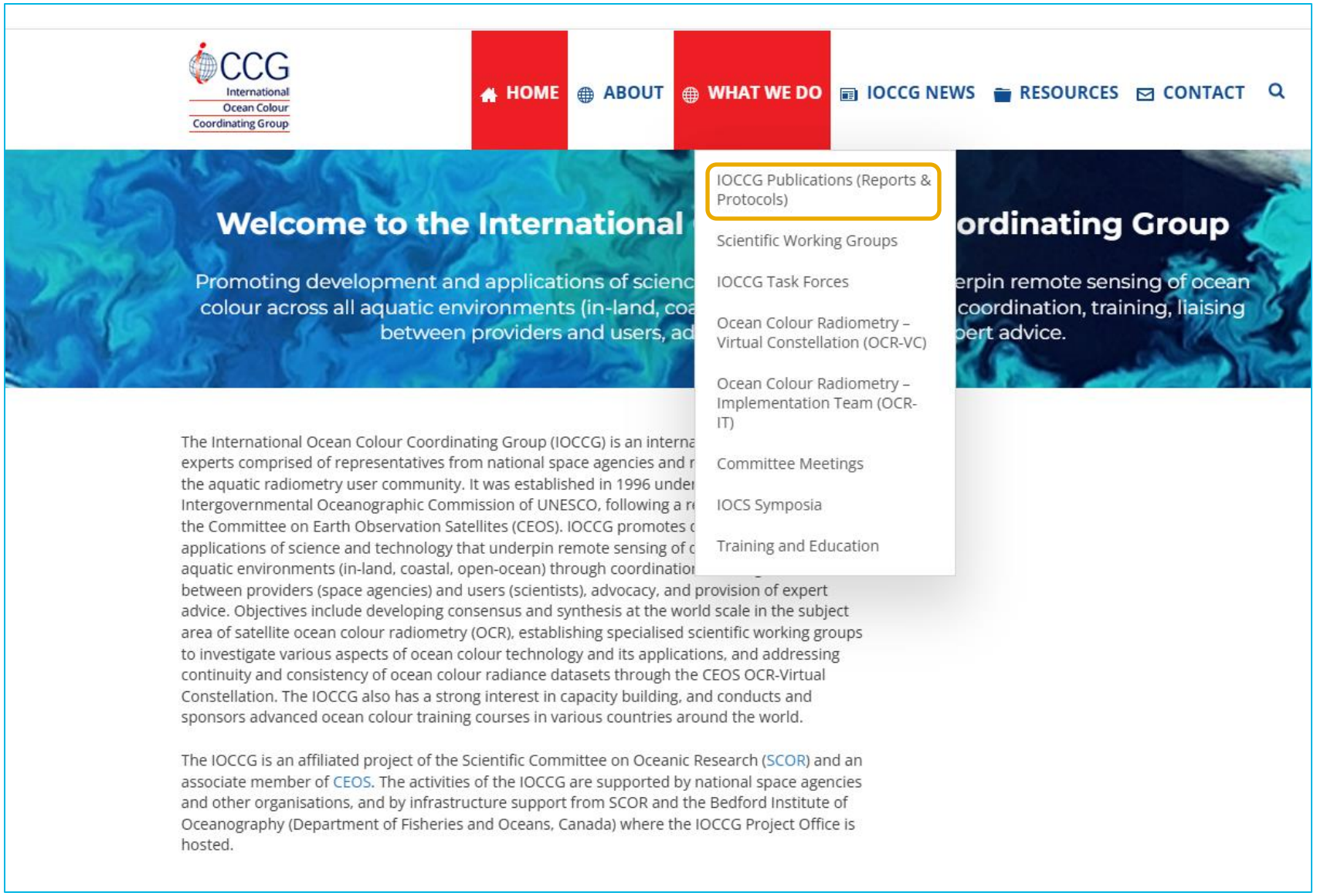
copernicus.eumetsat.int



https://frm4soc2.eumetsat.int

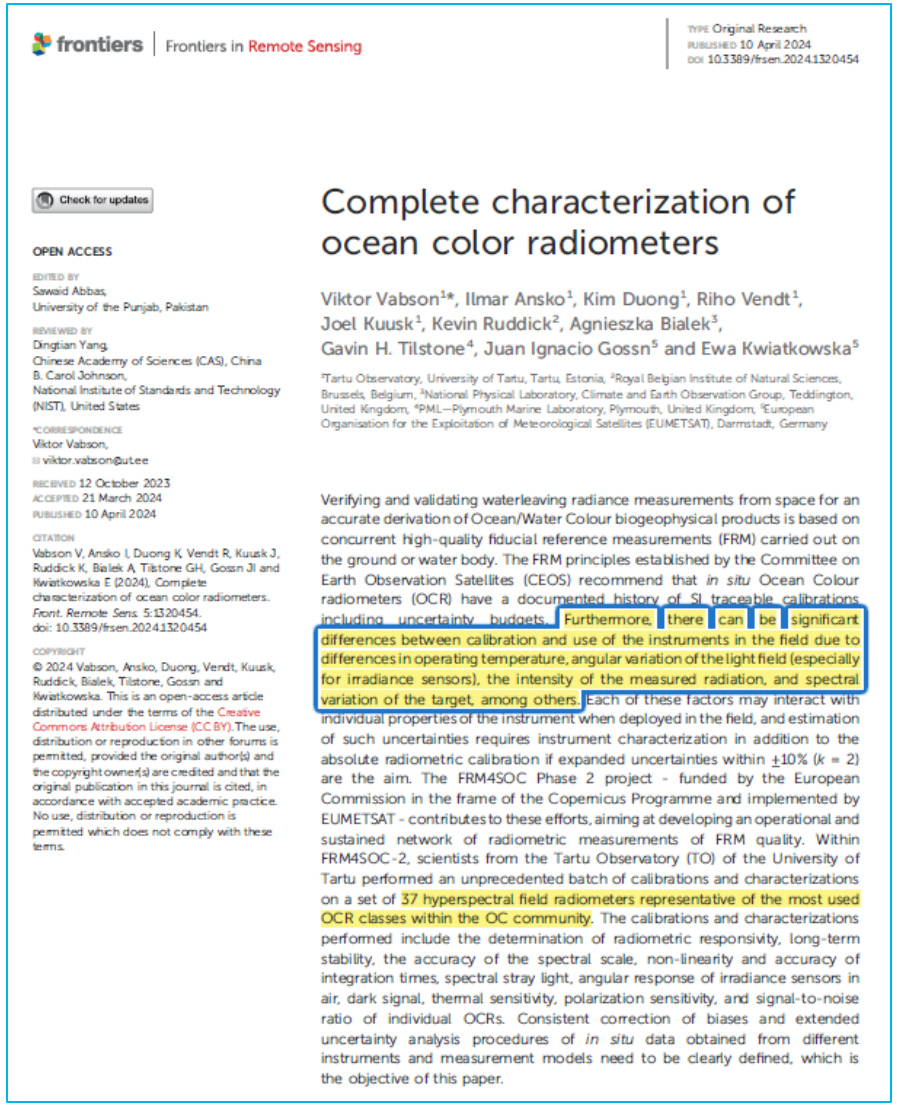
Resources: IOCCG website

copernicus.eumetsat.int



https://ioccg.org

Resources: Vabson *et al.* 2024 paper



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Complete characterization of ocean color radiometers

Viktor Vabson[1]*, Ilmar Ansko[1], Kim Duong[1], Riho Vendt[1], Joel Kuusk[1], Kevin Ruddick[2], Agnieszka Bialek[3], Gavin H. Tilstone[4], Juan Ignacio Gossn[5] and Ewa Kwiatkowska[5]

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Verifying and validating waterleaving radiance measurements from space for an accurate derivation of Ocean/Water Colour biogeophysical products is based on concurrent high-quality fiducial reference measurements (FRM) carried out on the ground or water body. The FRM principles established by the Committee on Earth Observation Satellites (CEOS) recommend that *in situ* Ocean Colour radiometers (OCR) have a documented history of SI traceable calibrations including uncertainty budgets. Furthermore, there can be significant differences between calibration and use of the instruments in the field due to differences in operating temperature, angular variation of the light field (especially for irradiance sensors), the intensity of the measured radiation, and spectral variation of the target, among others. Each of these factors may interact with individual properties of the instrument when deployed in the field, and estimation of such uncertainties requires instrument characterization in addition to the absolute radiometric calibration if expanded uncertainties within ±10% ($k = 2$) are the aim. The FRM4SOC Phase 2 project - funded by the European Commission in the frame of the Copernicus Programme and implemented by EUMETSAT - contributes to these efforts, aiming at developing an operational and sustained network of radiometric measurements of FRM quality. Within FRM4SOC-2, scientists from the Tartu Observatory (TO) of the University of Tartu performed an unprecedented batch of calibrations and characterizations on a set of 37 hyperspectral field radiometers representative of the most used OCR classes within the OC community. The calibrations and characterizations performed include the determination of radiometric responsivity, long-term stability, the accuracy of the spectral scale, non-linearity and accuracy of integration times, spectral stray light, angular response of irradiance sensors in air, dark signal, thermal sensitivity, polarization sensitivity, and signal-to-noise ratio of individual OCRs. Consistent correction of biases and extended uncertainty analysis procedures of *in situ* data obtained from different instruments and measurement models need to be clearly defined, which is the objective of this paper.

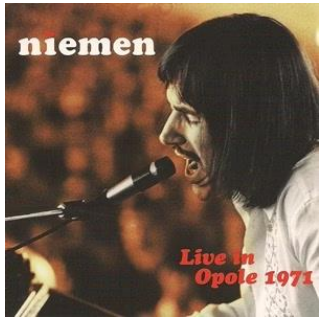
Vabson et al. 2024, *Complete characterization of OC radiometers*
Front. Remote Sens., 10 April 2024
Sec. Multi- and Hyper-Spectral Imaging
Volume 5 - 2024 | https://doi.org/10.3389/frsen.2024.1320454

A reminder: This workshop is hybrid!

Let our voices be heard

Let's keep everyone out there awake and listening ☺

Czesław Niemen, Poland



Charles Aznavour, France

Natalie Imbruglia, Australia

Jaak Joala, Estonia

Victoria Santa Cruz, Peru

Marlene Dietrich, Germany

Giorgos Mazonakis, Greece

Luciano Pavarotti, Italy

Mari Pokinen, Estonia

Djavan, Brazil

Concha Buika, Spain

Eason Chan, China

Mercedes Sosa, Argentina

Freddie Mercury, UK

Taylor Swift, US

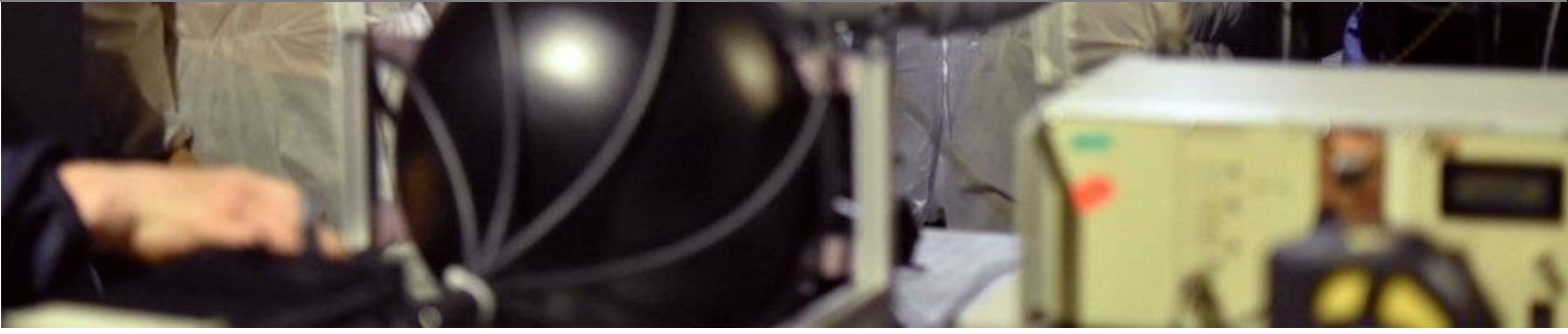
John Fogerty, US

Anouk Teeuwe, The Netherlands

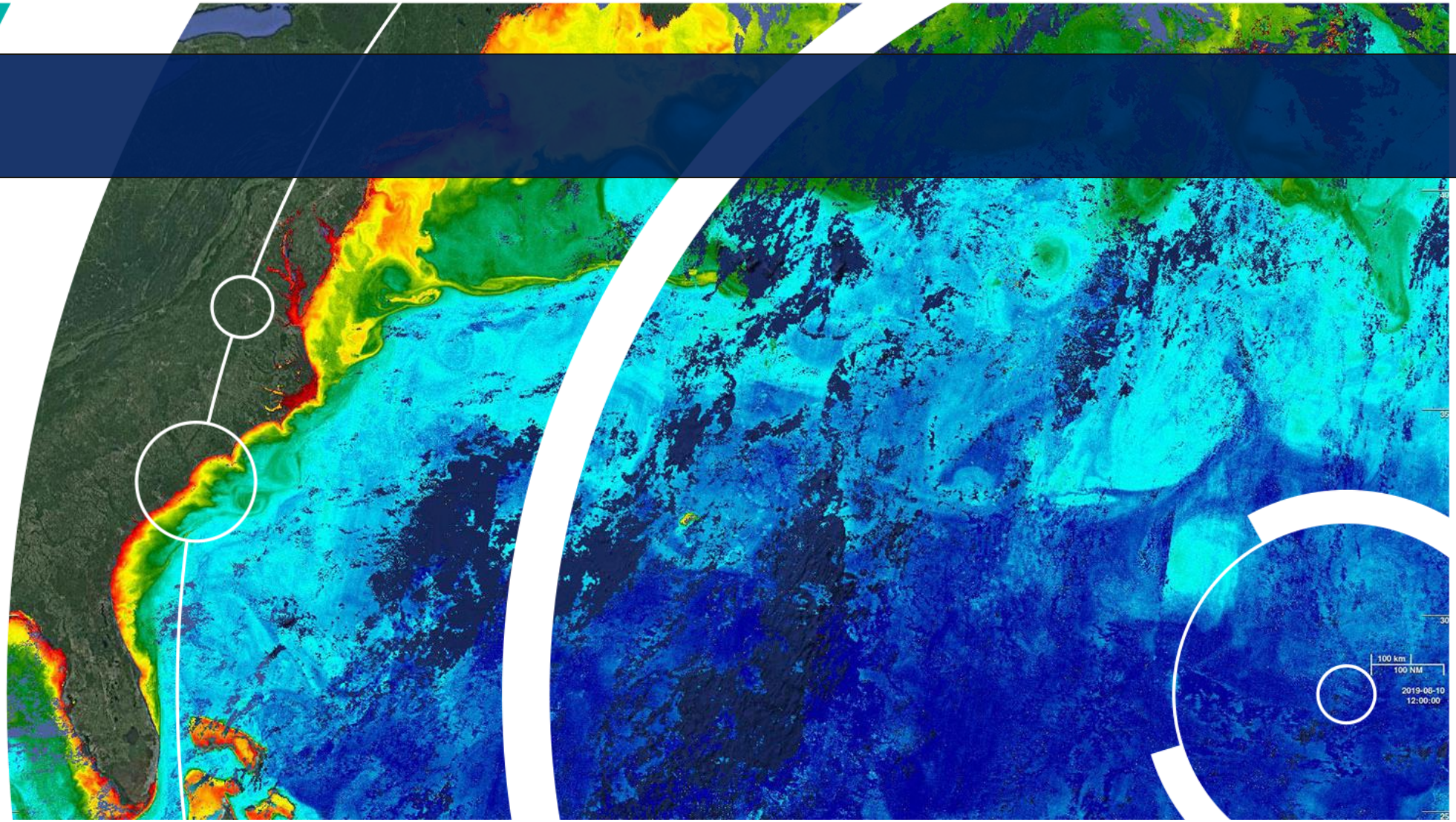
Tours around the Tartu Observatory
Live streaming for those attending online

Cal/char setups: 14:00 – 15:30 Estonian time (GMT + 3), same MS Teams link

Facilities tour: 16:00 – 17:30 Estonian time (GMT + 3), same MS Teams link



Extra slides



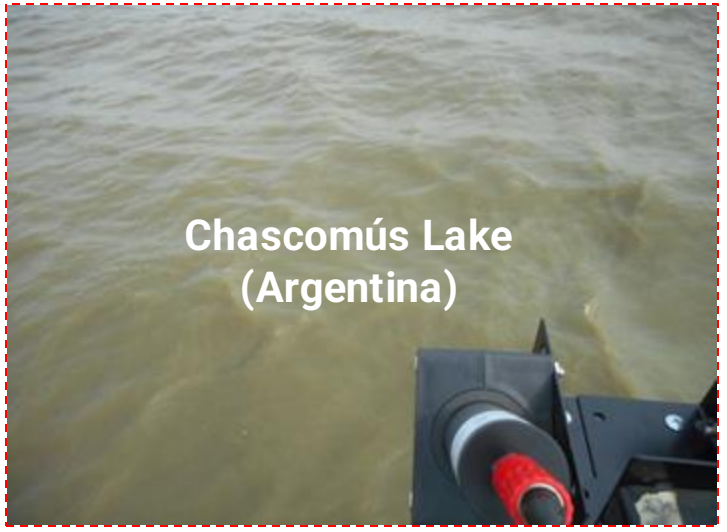
For those here not as familiar with Ocean Colour…

near-UV - VIS – NIR

Ocean Colour scientists study the "colour" of natural water bodies from space to determine what substances are dissolved/suspended in the water and in what concentrations …

optically-active

Someone out there may say "well, the ocean is blue, what's all the fuss about?" …



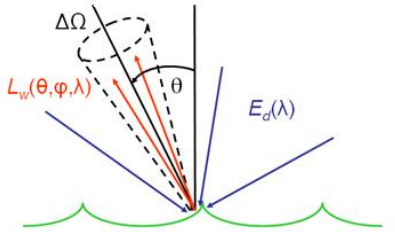
Sediments? How much?
Photosynthetic organisms? How much? Which species?
Dissolved organic matter? How much?
Floating vegetation? Cyanobacteria? Etc…

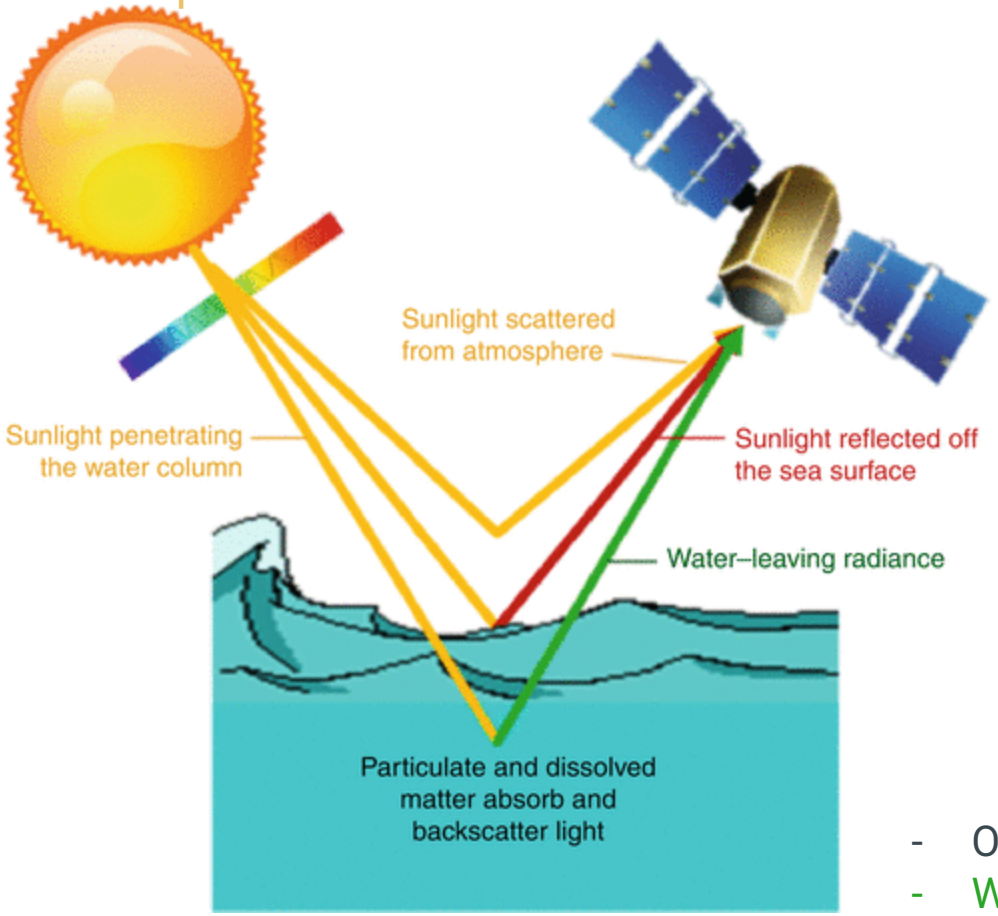
All of us around the table today are crucial to achieve a common understanding of what is needed to effectively **promote FRM principles across the Ocean Colour community**

Ocean Colour: Removal of atmospheric signal and uncertainties

Satellite measurement, L_{TOA} [mW/m^2/sr/nm]
Water-leaving radiance, L_w ~ 10%
Atmosphere and sea surface ~ 90%

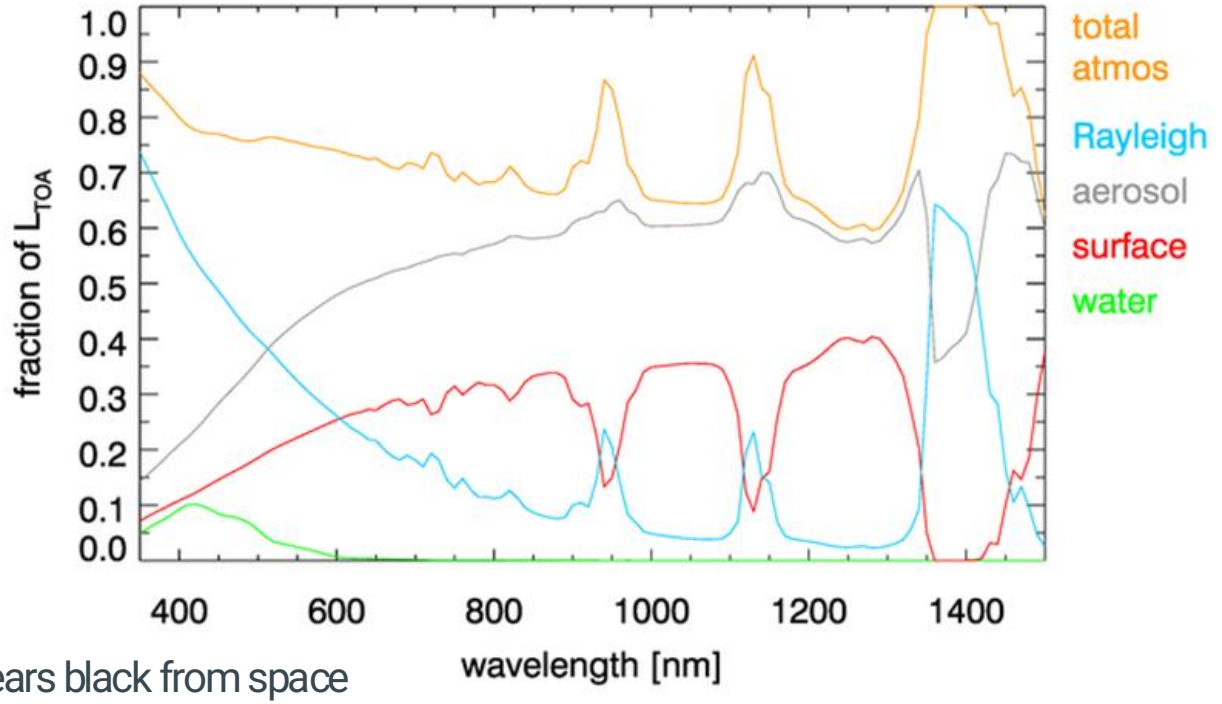
$$R_{rs}(\theta,\phi,\lambda) \equiv \frac{L_w(\text{in air},\theta,\phi,\lambda)}{E_d(\text{in air},\lambda)} \quad (\text{sr}^{-1}) .$$





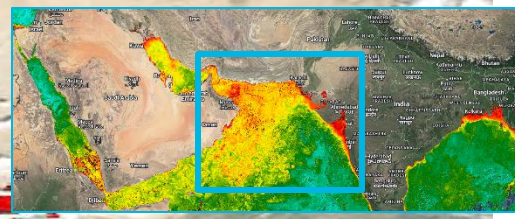
Dierssen and Randolph, 2012, Earth System Monitoring

Clear water chl-a = 0.05 mg/m^3, clear sky, tropical marine atmosphere
Water-leaving radiance ~ 10% in the blue and green spectral range



- Ocean appears black from space
- Water-leaving radiance is a small fraction of the total radiance measured by the satellite
- Satellite instrument calibration and algorithms require the lowest possible uncertainties
- The uncertainties are magnified for water-leaving radiances

Ocean Colour – observing the living aquatic ecosystems



Climate

Biological Carbon Pump – oceans constitute about 50% of Earth's carbon sequestration

Aquatic phytoplankton – about 50% of Earth's primary production, fraction of the fixed Carbon is buried into the deep ocean

Ocean absorbs 20 – 30% of anthropogenic CO_2 emissions, also contributing to ocean acidification

Water Quality

Harmful Algal Blooms

Drinking water quality

Tourism and coastal communities

Eutrophication

Ecosystem status and services

Legislation, e.g. EU Water Framework Directive

Marine resources

Fisheries

Aquaculture

Coastal management / ports

Legislation, e.g. EU Marine Strategy Framework Directive

chl-a [mg/m^3] 0.02 0.06 0.13 0.25 0.5 1.0 2.0 4.0 8.0 16.0 35.0

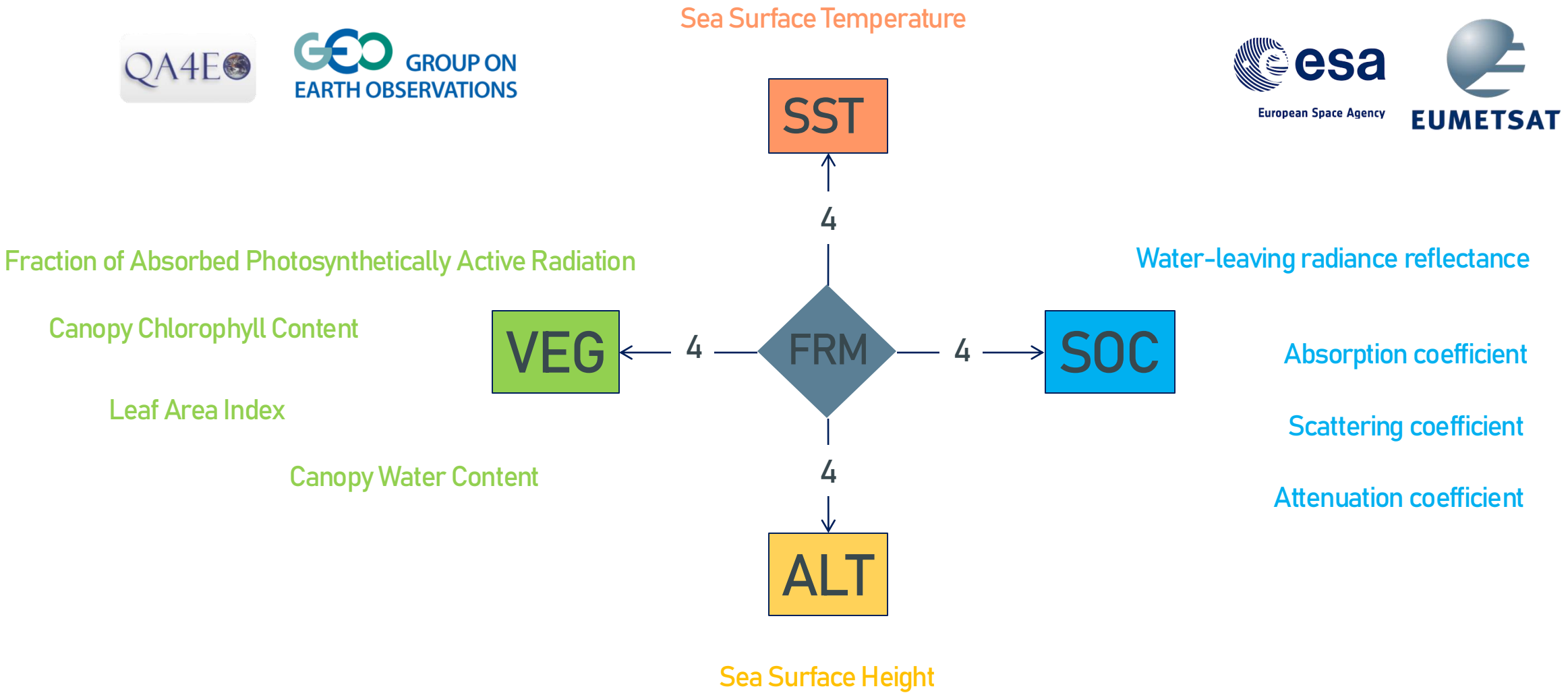
FRM: A dialogue between Earth Observation and Metrology

QA4EO

GEO GROUP ON EARTH OBSERVATIONS

esa European Space Agency

EUMETSAT



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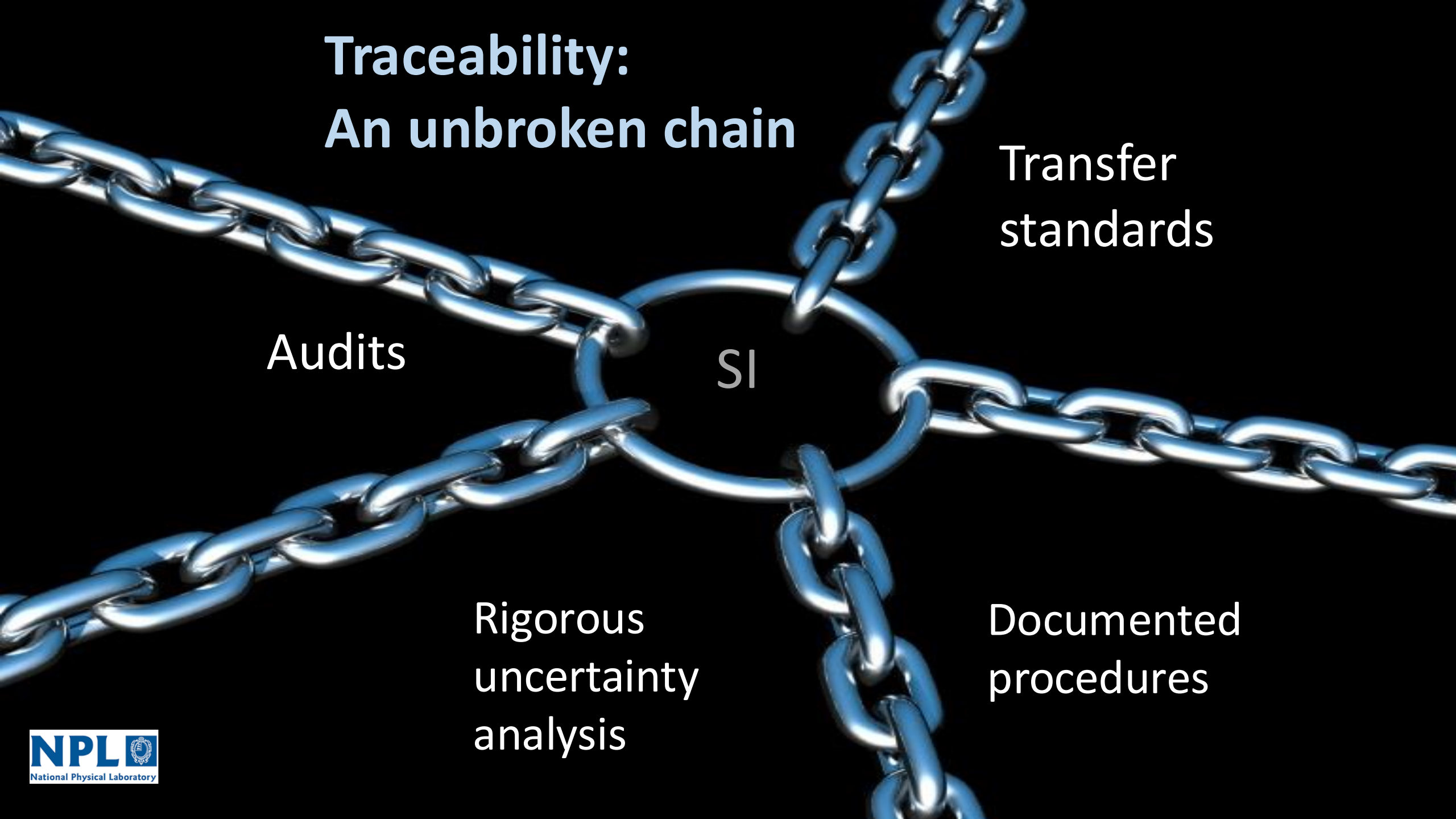
Traceability:
An unbroken chain



NPL National Physical Laboratory