Copernicus FICE 2025

Training on
In situ Ocean Colour Above-Water Radiometry towards Satellite Validation

What are Fiducial Reference Measurements?

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fiducial reference measurements for satellite ocean colour | UNIVERSITY OF TARTU | BROCKMANN CONSULT | CNR ISMAR | NPL National Physical Laboratory | EOScience | Venice International University | PROGRAMME OF THE EUROPEAN UNION | Copernicus | IMPLEMENTED BY EUMETSAT | NASA

6-20 July 2025
Venice, Italy

NPL National Physical Laboratory

Outline

- Fiducial Reference Measurements – what they are?
  - Brief history
  - Recent changes
- FRM4SOC approach
- The relevance of laboratory and field comparisons

Introduction to some governing bodies

https://ioccg.org/

https://www.bipm.org/en/

https://ceos.org/

https://earthobservations.org/

https://qa4eo.org/

Fiducial Reference Measurements (FRM)

fiducial

UK:* /fɪˈdjuːʃɪəl/ | US: (fi do͞o′shəl, -dyo͞o′-)

in Spanish | in French | in Italian | English synonyms | English Usage | Conjugator | in context | images

WordReference Random House Unabridged Dictionary of American English © 2024

fi•du•cial (fi do͞o′shəl, -dyo͞o′-),
adj.

1. accepted as a fixed basis of reference or comparison:
   a fiducial point; a fiducial temperature.
2. based on or having trust:
   fiducial dependence upon God.

Etymology
➜ Late Latin *fīdūciālis,* equivalent. to *fīdūci*(*a*) trust (akin to *fīdere* to trust) + -*ālis* -AL[1]
➜ 1565–75

https://www.wordreference.com/definition/fiducial

FRM the beginning

NPL

"The suite of independent ground measurements that 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."

Donlon, C.; Goryl, P. Fiducial Reference Measurements (FRM) for Sentinel-3. In Proceedings of the Sentinel-3 Validation Team (S3VT) Meeting, ESA/ESRIN, Frascati, Italy, 26–29 November 2013

fiducial reference measurements for satellite ocean colour

FRM4DRONES-AQUA
Towards FRM drone data for satellite aquatic reflectance Cal/Val

fiducial reference measurements for fluorescence

fiducial reference temperature measurements

fiducial reference measurements for vegetation

fiducial reference measurements for fire

FRM4 projects

A number of projects have been initiated for FRMs qualification.

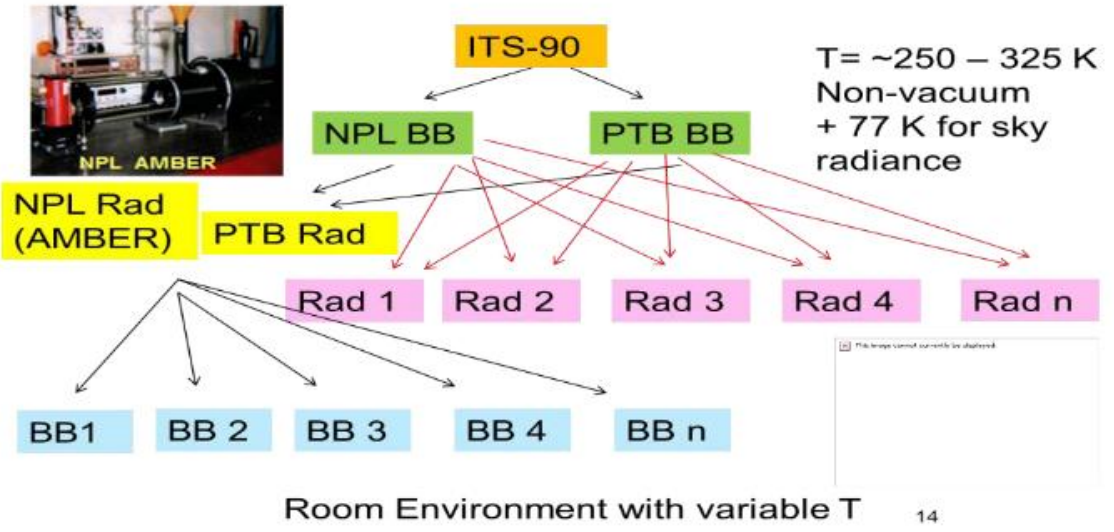
Based on generic model:

Laboratory
Laboratory Calibration Exercise (LCE) →
SI traceability
Necessary for all participants to assess biases to SI under Laboratory conditions

Protocols definition

Field campaigns
Field Inter- comparison Calibration Exercise (FICE)

Analysis
Analysis
Discussion, Workshop
Publications



JOURNAL OF ATMOSPHERIC AND OCEANIC TECHNOLOGY VOLUME 21

The Miami2001 Infrared Radiometer Calibration and Intercomparison. Part II: Shipboard Results

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(Manuscript received 27 August 2002, in final form 6 May 2003)

ABSTRACT

The second calibration and intercomparison of infrared radiometers (Miami2001) was held at the University of Miami's Rosenstiel School of Marine and Atmospheric Science (RSMAS) during a workshop held from May to June 2001. The radiometers targeted in these two campaigns (laboratory-based and at-sea measurements) are those used to validate the skin sea surface temperatures and land surface temperatures derived from the measurements of imaging radiometers on earth observation satellites. These satellite instruments include those on currently operational satellites and others that will be launched within two years following the workshop. The experimental campaigns were completed in one week and included laboratory measurements using blackbody calibration targets characterized by the National Institute of Standards and Technology (NIST), and an intercomparison of the radiometers on a short cruise on board the R/V F. G. Walton Smith in Gulf Stream waters off the eastern coast of Florida. This paper reports on the results obtained from the shipborne measurements.
Seven radiometers were mounted alongside each other on the R/V Walton Smith for an intercomparison under seagoing conditions. The ship results confirm that all radiometers are suitable for the validation of land surface temperature, and the majority are able to provide high quality data for the more difficult validation of satellite-derived sea surface temperature, contributing less than 0.1 K to the error budget of the validation. The measurements provided by two prototype instruments developed for ship-of-opportunity use confirmed their potential to provide regular reliable data for satellite-derived SST validation. Four high quality radiometers showed agreements within 0.05 K confirming that these instruments are suitable for detailed studies of the dynamics of air–sea interaction at the ocean surface as well as providing high quality validation data. The data analysis confirms the importance of including an accurate correction for reflected sky radiance when using infrared radiometers to measure SST. The results presented here also show the value of regular intercomparisons of ground-based instruments that are to be used for the validation of satellite-derived data products—products that will be an essential component of future assessments of climate change and variability.

Slide in courtesy of Philippe Goryl

CEOS FRM

Fiducial Reference Measurements (FRMs): What Are They?

Goryl *et al.* 2023
DOI: 10.3390/rs15205017

Fiducial Reference Measurements (FRM) are a suite of independent, fully characterised, and traceable (to a community agreed reference ideally SI) measurements, tailored specifically to address the calibration and validation needs of a class of satellite borne sensor and that follow the guidelines outlined by the GEO/CEOS Quality Assurance framework for Earth Observation (QA4EO).

QA4EO A QUALITY ASSURANCE FRAMEWORK FOR EARTH OBSERVATION

CEOS FRM

The defining mandatory characteristics for FRM are:

1. FRM measurements should have documented **evidence of their traceability (bias and associated uncertainty) to a community agreed reference ideally tied to the International System of units, SI**, (e.g. via a comparison 'round robin' or other) with peers and/or a metrology institute together with regular pre-and post- deployment calibration of instruments). This should be carried out using SI-traceable 'metrology' standards and/or community recognised best practices, for both instrumentation and observations;
2. FRM measurements are **independent from the satellite geophysical retrieval process**;
3. A comprehensive **uncertainty budget** for all FRM instruments, and derived measurements, is **available and maintained**;
4. FRM measurement **protocols, procedures and community-wide quality management practices** (measurement, processing, archive, documents, etc.) are **defined, published and adhered to by FRM instrument deployments**;
5. **FRM datasets**, including metadata and reports documenting processing, are **accessible to other researchers allowing independent verification** of processing systems;
6. FRM datasets are required to determine the **on-orbit uncertainty characteristics of satellite** geophysical measurements via **independent validation activities** and thus representativeness and the satellite to FRM comparison process needs **to be documented and the uncertainty assessed**. Note for any individual satellite sensor the exact sampling and elements of the comparison process may differ, even within a generic sensor class, but the documentation and evidence to support the uncertainty analysis must be presented in a manner that can be readily interpreted by a user.
7. The **uncertainty of the FRM measurements**, including the comparison process, **must be commensurate with the requirements of the class of satellite sensor they are specified to support**.
8. **FRM datasets are designed to apply to a class of satellite missions. They are not mission specific**.

CEOS-FRM Maturity Matrix

Self-assessment					Independent assessor
Nature of FRM	FRM Instrumentation	Operations/ sampling	Data	Metrology	Verification
Descriptor	Instrument Documentation	Automation level	Data completeness	Uncertainty Characterisation	Guidelines adherence
Location/ availability of FRM	Evidence of traceable calibration	Measurand sampling	Availability and Usability	Traceability Documentation	Utilisation/Feedback
Range of sensors	Maintenance plan	ATBDs on processing/software	Data Format	Comparison/calibration of FRM	Metrology verification
Complementary observations	Operator expertise	Guidelines on transformation to satellite Pixel	Ancillary Data	Adequacy for intended class of sensors	Independent Verificaton
				FRM CLASSIFICATION	**A B C D** (to be selected)

Grade
Not Assessed
Not Assessable
Basic
Good
Excellent
Ideal

Framework document:
[CEOS-FRM_Assessment_Framework_V1]

Critical verification categories

GUIDELINES

Grade	Criteria
Not Assessed	Assessment outside of the scope of study.
No Assesable	Relevant information not made available.
Basic	All categories should be at least basic and if not there should be a clear strategy to progress within a short (<3 month) timescale. Those categories in basic should have a strategy to progress towards greater compliance.
Good	More than 80% must meet the good category and those in basic should indicate a strategy to progress. >30 % should be in the green classification. There should be no basic classifications in the metrology or Instrument columns and any in these columns indicating good should indicate a strategy to progress
Excellent	All categories are good or above with > than 80% in the green classification and those in the Metrology or instrument columns must meet excellent or above.
Ideal	All categories in the matrix fully meet the green classification i.e. Excellent or Ideal with at least half reaching the ideal category and of these half must include those in the metrology and FRM instrument column

Independent Verification

Grade	Criteria
Not Assessed	Assessment outside of the scope of study.
Not Assessable	Relevant information not made available.
Basic	Some comparison evidence but limited ability to confirm or otherwise the declared FRM uncertainty
Good	Full compliance of declared FRM uncertainties through comparison to a reference of good but higher uncertainty than the FRM or near but not full compliance against a reference of comparable or lower uncertainty.
Excellent	Full compliance of declared FRM uncertainties through comparison to a reference with comparable uncertainties.
Ideal	Full compliance of declared FRM uncertainties through independent comparison to a reference of lower overall uncertainty

Class A & B must achieve some form of Green for all categories,

CEOS-FRM Overall Classification

To provide overall summary guidance to a user we have created the following four classes.

Class A – Where the **FRM fully meets all the criteria necessary to be considered an FRM for a particular class of sensor.** It should achieve a class of Ideal in the 'guidance criteria' in the 'independent verification' section of the MM and green (at least excellent) for all other verification categories where these have been carried out.

Class B – Where the **FRM meets many of the key criteria and has a path towards meeting the Class A status** in the near term. It should achieve at least Excellent in the guidance criteria in the independent verification section of the MM and green (at least excellent) for all other verification categories where these have been carried out. Ideally it should indicate a path towards achieving the high class.

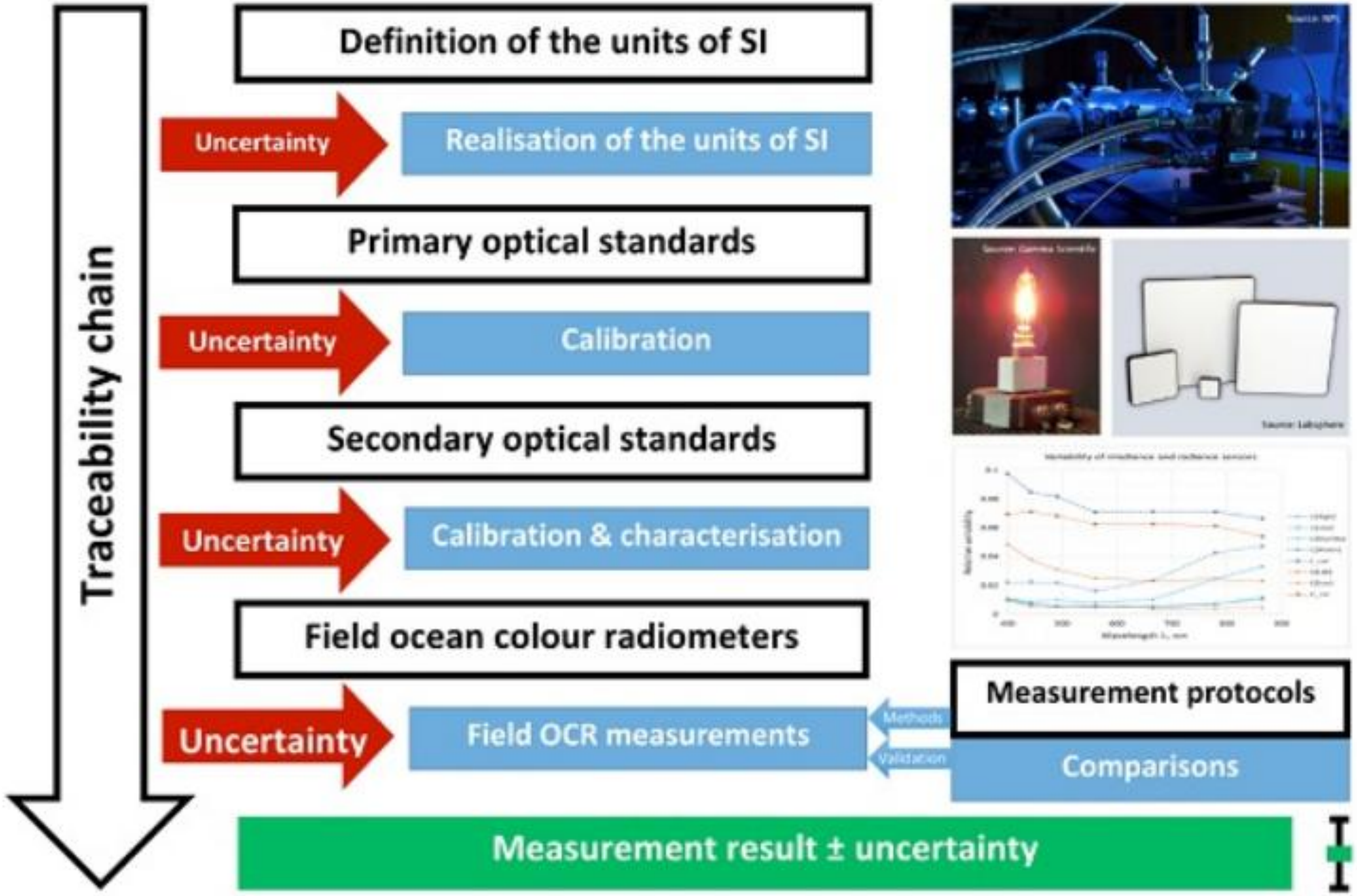
Class C – **Meets or has some clear path towards achieving the criteria needed** to reach a higher class and provides some clear value to the validation of a class of satellite sensors.

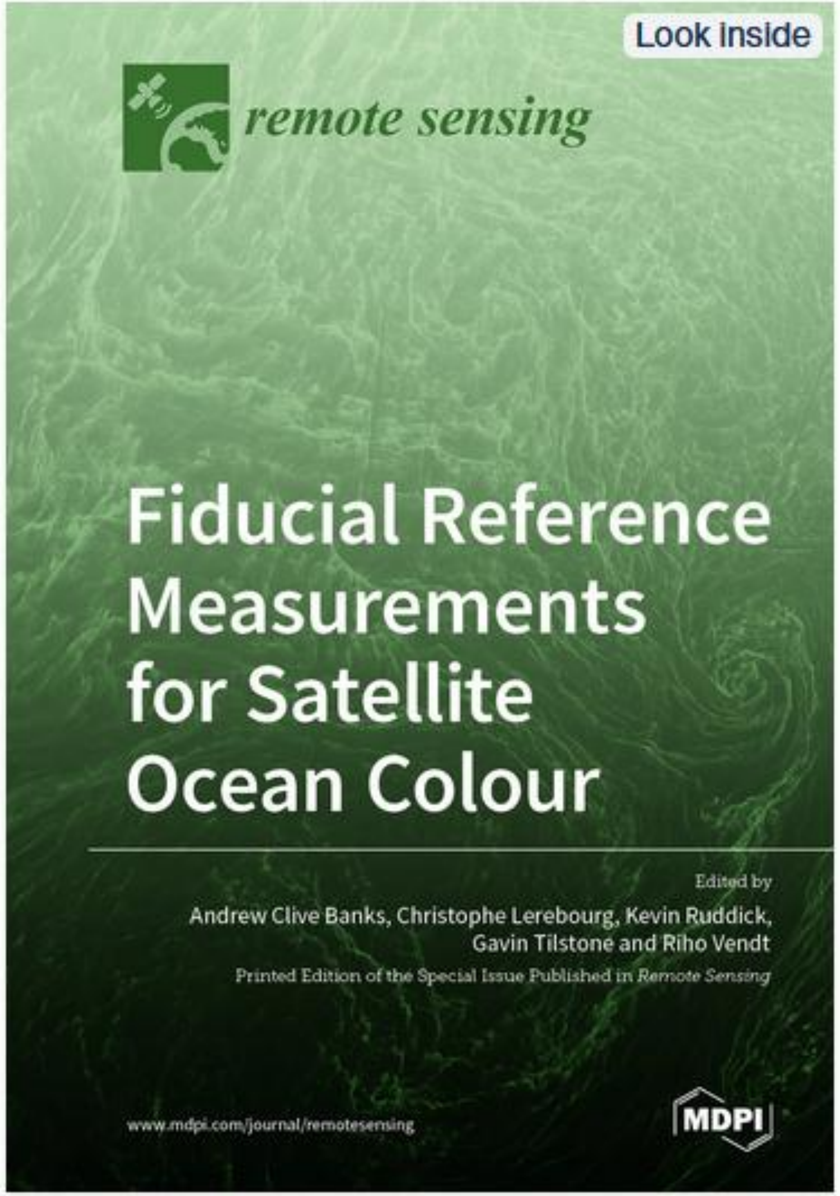
It should achieve at least Good in the guidance criteria in the independent verification section of the MM and at least good for all other verification categories where these have been carried out. Ideally it should indicate a path towards achieving the high class.

Class D - Is a relatively **basic adherence to the FRM criteria** but where this is a strategy and aspiration to progress towards a higher class. This can be considered an entry level class for those starting out on developing an FRM. It should achieve at least Basic in the guidance criteria in the independent verification section of the MM and at least Good for all other verification categories where these have been carried out. FRM owners/developers must indicate a path towards achieving the high class.

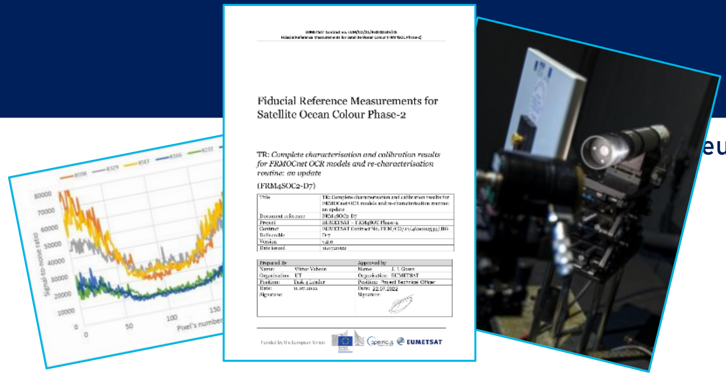
FRM4SOC

esa fiducial reference measurements for satellite ocean colour CEOS





https://www.mdpi.com/books/reprint/2960-fiducial-reference-measurements-for-satellite-ocean-colour

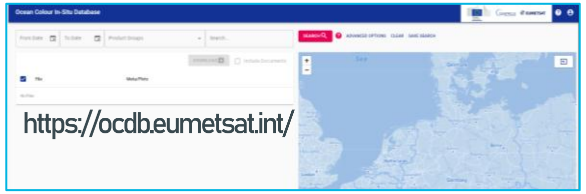


9. Review and test: a field experiment, an international workshop, Expert Review Board

1. Define the two most common hyperspectral OCR classes

2. Fully characterise a batch of OCRs

8. Adapt and maintain Ocean Colour In-Situ Database OCDB



fiducial reference measurements for satellite ocean colour

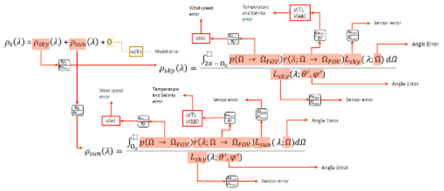
https://frm4soc2.eumetsat.int

Several tasks, one overarching goal:
to promote the adoption of FRM principles across the OC community

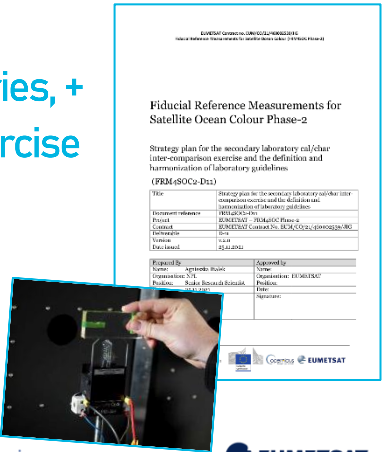
Parameter	Scope	Before initial use	Re-cal/char	D-2 requirement
1. Absolute calibration for radiometric responsivity	individual	required	1 year	IR1
2. Long term stability	individual	required	after every calibration	IR1
3. Stray light and out of band response	individual	required	3 – 5 years	IR2
4. Immersion factor (irradiance)	individual	required for under-water	after fore-optics modification	-
4b.Immersion factor (radiance)	individual/class-specific	required for under-water	after fore-optics modification	-
5. Angular response of irradiance sensors in air	individual	required	after fore-optics modification	IR3
6. Response angle (FOV) of radiance sensors in air	class-specific	recommended	after fore-optics modification	-
7. Non-linearity	class-specific	recommended	after repair in workshop	IR4
8. Accuracy of integration times	class-specific	recommended	after repair in workshop	IR4
9. Dark signal	individual	required	1 year	IR7
10. Thermal responsivity	class-specific	recommended	after repair in workshop	IR5
11. Polarisation sensitivity	class-specific	recommended	after repair in workshop	IR6
12. Temporal response	TBD	TBD	TBD	IR8
13. Wavelength scale	class-specific	recommended	after fore-optics modification	IR9
14. Signal-to-noise ratio	individual	recommended	1 year	-
15. Pressure effects	TBD	TBD	TBD	-

3. Community guidelines on radiometer cal/char schedules

7. Develop a complete end-to-end uncertainty budget, to be included in HyperCP



4. Develop OCR cal/char guidelines for laboratories, + an international lab exercise

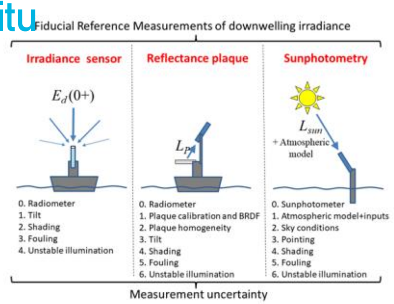


6. Develop a community processor for hyperspectral AWR

HyperCP

NASA University of Victoria ACRI-ST THE UNIVERSITY OF MAINE NPL MORGAN STATE UNIVERSITY Gybe EUMETSAT Copernicus Europe's eyes on Earth

5. Provide FRM in situ measurement procedures



FRM4SOC phase 2

NPL

Copernicus FRM-certified OC instrument network (FRMOCnet) this is a network that will be established and include of FRM-certified instruments and measurements.

FRM "certification "term will be defined during the study following discussion with the experts in the field and the community. FRM certification will be applied to several stages of the FRMOCnet including:

- FRM compliant cal/char laboratories
- FRM Certification of OCR instrument models
- FRM certification of single individual OCR instrument
- FRM certified cal/char status
- FRM competence certified operators
- FRM certified measurement protocols
- Network of radiometric measurements with the FRM certification

We were missing certification scheme

CEOS FRM

NPL

The defining mandatory characteristics for FRM are:

1. FRM measurements should ... greed reference **ideally tied to the Interna** ... institute together with regular pre-and post- ... nd/or community recognised best practices, ...
2. FRM measurements are **in**...
3. A comprehensive **uncertai**...
4. FRM measurement **protoc** ... hive, documents, etc.) are **defined, publishe**...

fiducial reference
measurements for
satellite ocean colour

5. **FRM datasets**, including metadata and reports documenting processing, are **accessible to other researchers allowing independent verification** of processing systems;
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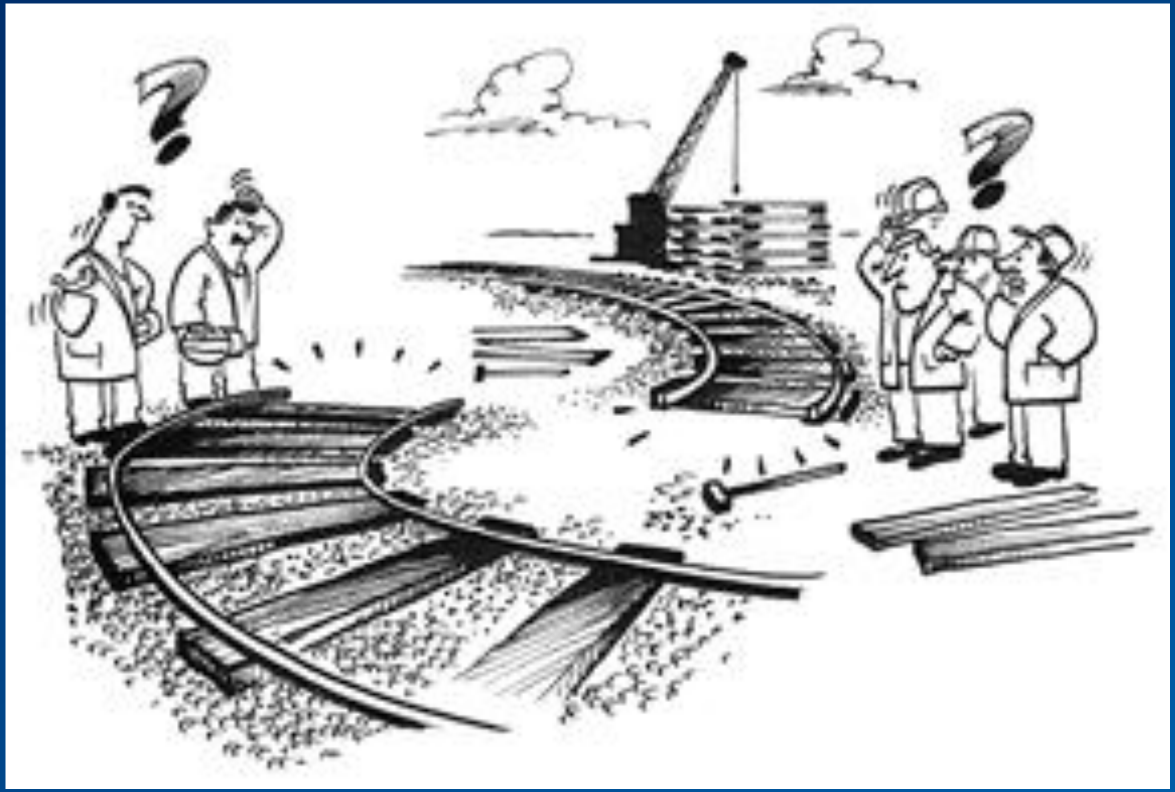
ThoMaS
A TOOLKIT FOR GENERATING OC MATCHUPS

7. The **uncertainty of the FRM** ... **ements of the class of satellite sensor they are spe**...
8. **FRM datasets are designed to apply to a class of satellite missions. They are not mission specific**.



Relevance of comparisons

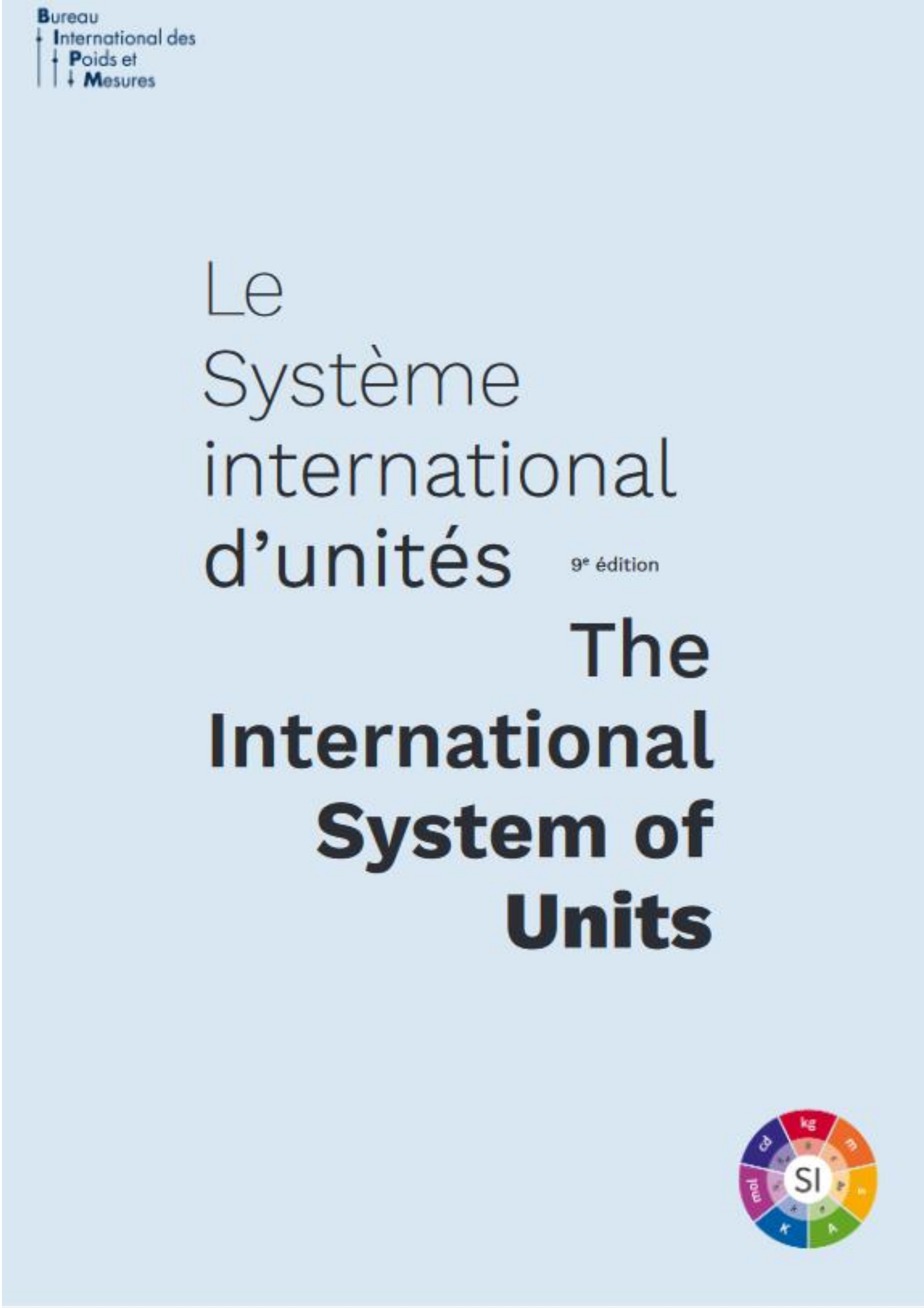
International System of Units

The Convention of the Metre:
Created BIPM
the intergovernmental organization through which Member States act together
on matters related to measurement science and measurement standards.

First signed in 1837 in Paris by 17 nations

Now 64 countries members states and 37 associate

http://www.bipm.org/en/about-us/



SI: Summary

- Identical worldwide
- Century-long stability
- Absolute accuracy

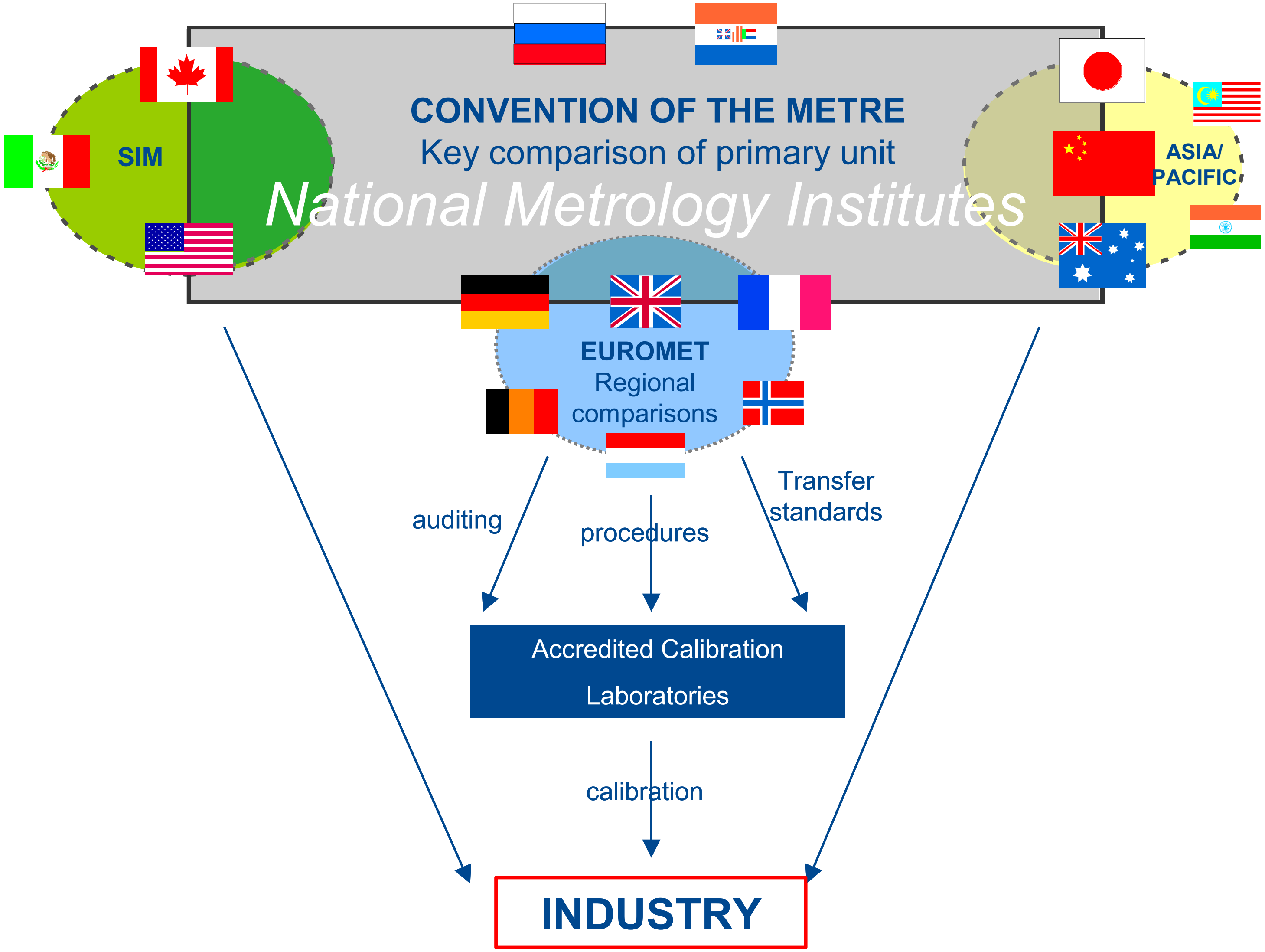
Achieved through:

- Traceability
- Uncertainty Analysis
- Comparison

From 20 May 2019 all SI units are defined in terms of constants that describe the natural world. This assures the future stability of the SI and opens the opportunity for the use of new technologies, including quantum technologies, to implement the definitions.

Traceability

- Calibration must be linked to accepted national standards, via an unbroken chain of calibrations, preferably carried out by an approved calibration laboratory



- ❖ Ensures compatibility with other instruments
- ❖ Ensures consistency of measurements over time
- ❖ Ensures measurement uncertainty is properly evaluated

Traceability: why do we need it?

- By linking back to a primary standard, we provide a reference for our measurements
- This reference is (ideally) non-changing e.g. based on a fundamental constant of nature (e.g. Boltzmann constant)
- Therefore, our measurements will be reliable and reproducible in time (over decades)

Coherent

Stable

- Coherent: only conversion factor used is 1 so it doesn’t matter how you get to a result, you’ll get the same answer (i.e. a watt is 1 J per 1 second, but also 1 kg per 1 m^2 per 1 s^3 – so if you measure it optically, electrically, thermally, … it’s still a watt)

Intercomparion /comparison

- Obligatory for NMI to:

- To establish the degree of equivalence between the realisation of the scales and measurements using them

- To validate uncertainty evaluation

Selection of Pre-existing comparisons

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, Kenneth Voss, Andrew C. Banks, Emmanuel Boss, Alexandre Castagna, Robert Frouin, Martin Hieronymi, Cedric Jamet, B. Carol Johnson, Joel Kuusk, Zhongping Lee, Michael Ondrusek, Viktor Vabson and Riho Vendt

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

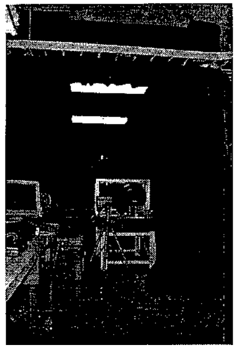
IOCCG International Ocean Colour Coordinating Group

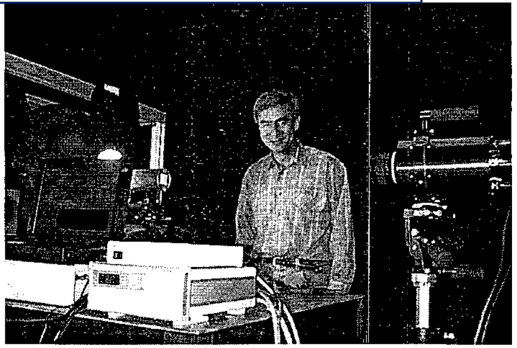
IOCCG Ocean Optics & Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation

- 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)

SIMRIC

The SIMBIOS Radiometric Intercomparison





+ 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

SIRREX SeaWiFS

A series of dedicated laboratory comparison exercises were conducted in the frame of SeaWiFS Intercalibration Round-Robin Experiment (SIRREX 1-8) (Mueller, 1993; Mueller *et al.*, 1994, 1996; Johnson *et al.*, 1996, 1999; Riley and Bailey, 1998; Hooker *et al.*, 2002; Zibordi, G. *et al.*, 2003) .

Second Intercomparison and Merger for Interdisciplinary Ocean Studies (SIMBIOS) Radiometric Intercomparison (SIMRIC) -1 and -2 (Meister *et al.*, 2002, 2003) programmes.

MERIS

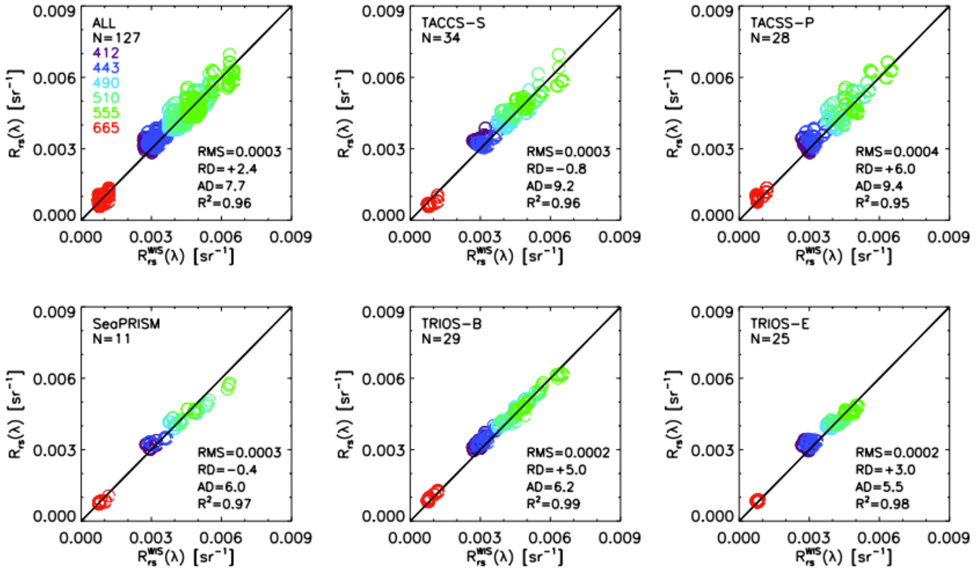
MERIS Validation Team (MVT) activities like PlymCal (Tilstone *et al.*, 2002) that were related to inter-calibration of several radiometers using one irradiance and radiance source in one laboratory were implemented. Similar activity was them performed before Assessment of In Situ Radiometric Capabilities for Coastal Water Remote Sensing Applications (ARC) in situ comparison activities, where all participating radiometers were calibrated in the one laboratory (Zibordi at all 2012).

Ocean Sci., 8, 567–586, 2012
www.ocean-sci.net/8/567/2012/
doi:10.5194/os-8-567-2012

Ocean Science

In situ determination of the remote sensing reflectance: an inter-comparison

G. Zibordi[1], K. Ruddick[2], I. Ansko[3], G. Moore[4], S. Kratzer[5], J. Icely[6], and A. Reinart[3]
[1]Institute for Environment and Sustainability, Joint Research Centre, Ispra, Italy



Main conclusion

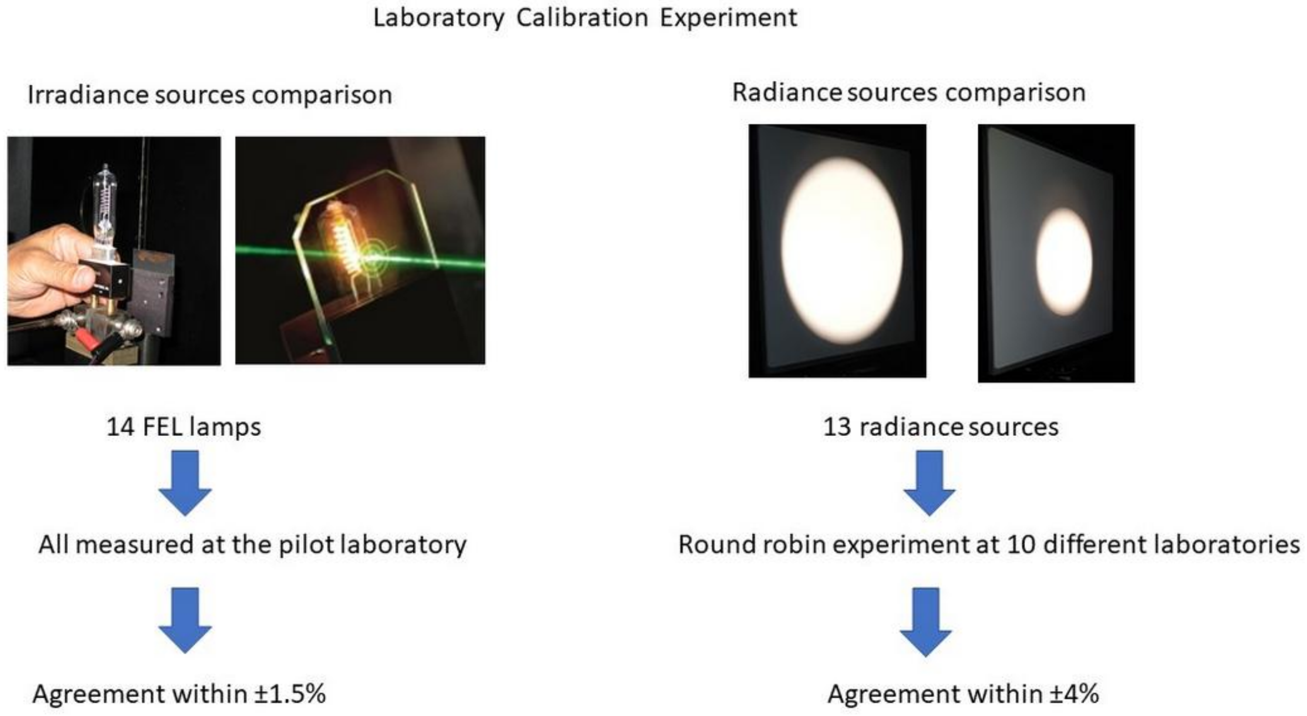
NPL

tainties in $E_d(0^+, \lambda)$. Results for $R_{rs}(\lambda)$ indicate spectrally averaged relative differences generally within -1 and $+6$ %. Spectrally averaged values of the absolute differences are approximately 6 % for the above-water systems/methods, and increase to 9 % for the buoy-based systems/methods. The general agreement of this latter spectral $R_{rs}(\lambda)$ uncertainty index with the combined uncertainties of inter-compared systems/methods is notable. This result undoubtedly con-

S3 FRM4SOC

The most recently in support of Sentinel 3 in the frame of Fiducial Reference Measurements for Satellite Ocean Colour (FRM4SOC) (Banks *et al.*, 2020) the laboratory comparisons were performed (Białek *et al.*, 2020).

FRM4SOC	1	2017-2018	FEL comparison 14 lamps	Radiance comparison as participant laboratory using lamp + plaque	Lamp comparison and training based at NPL; radiance comparison based at each participant own lab. Irradiance results within uncertainty radiance saw two distinctive groups of results.



S3 FRM4SOC

Lab

Field

NPL

Figure 8. Irradiance sensors; agreement with reference values of the filter radiometer. Blue dashed lines—expanded uncertainty covering 95% of all data points. Uncertainty of radiometric calibration is included.

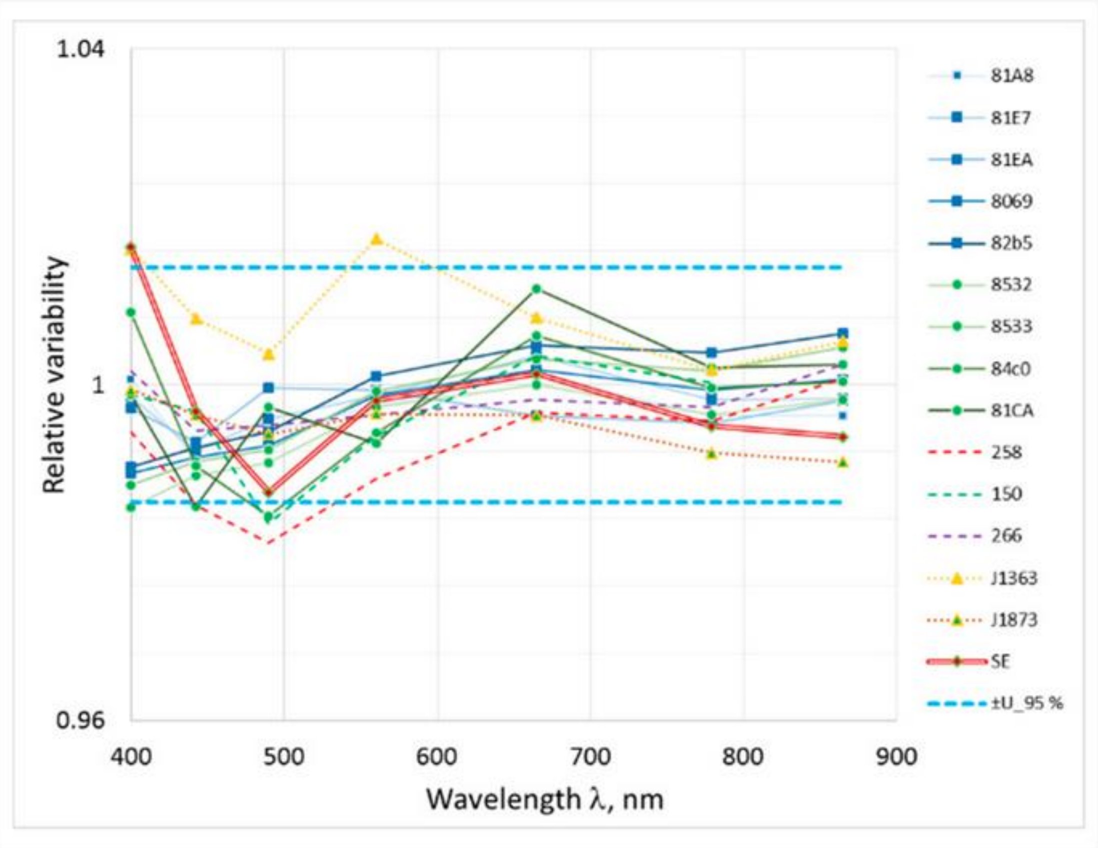
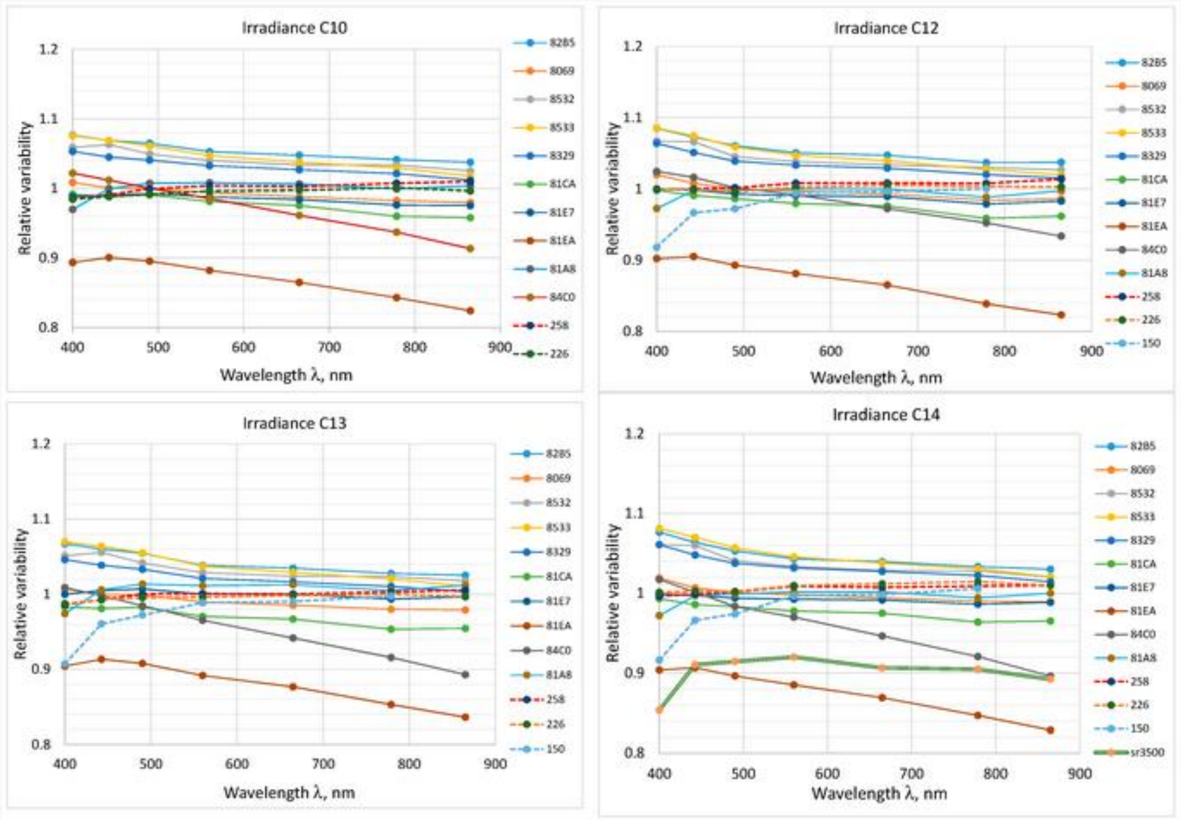
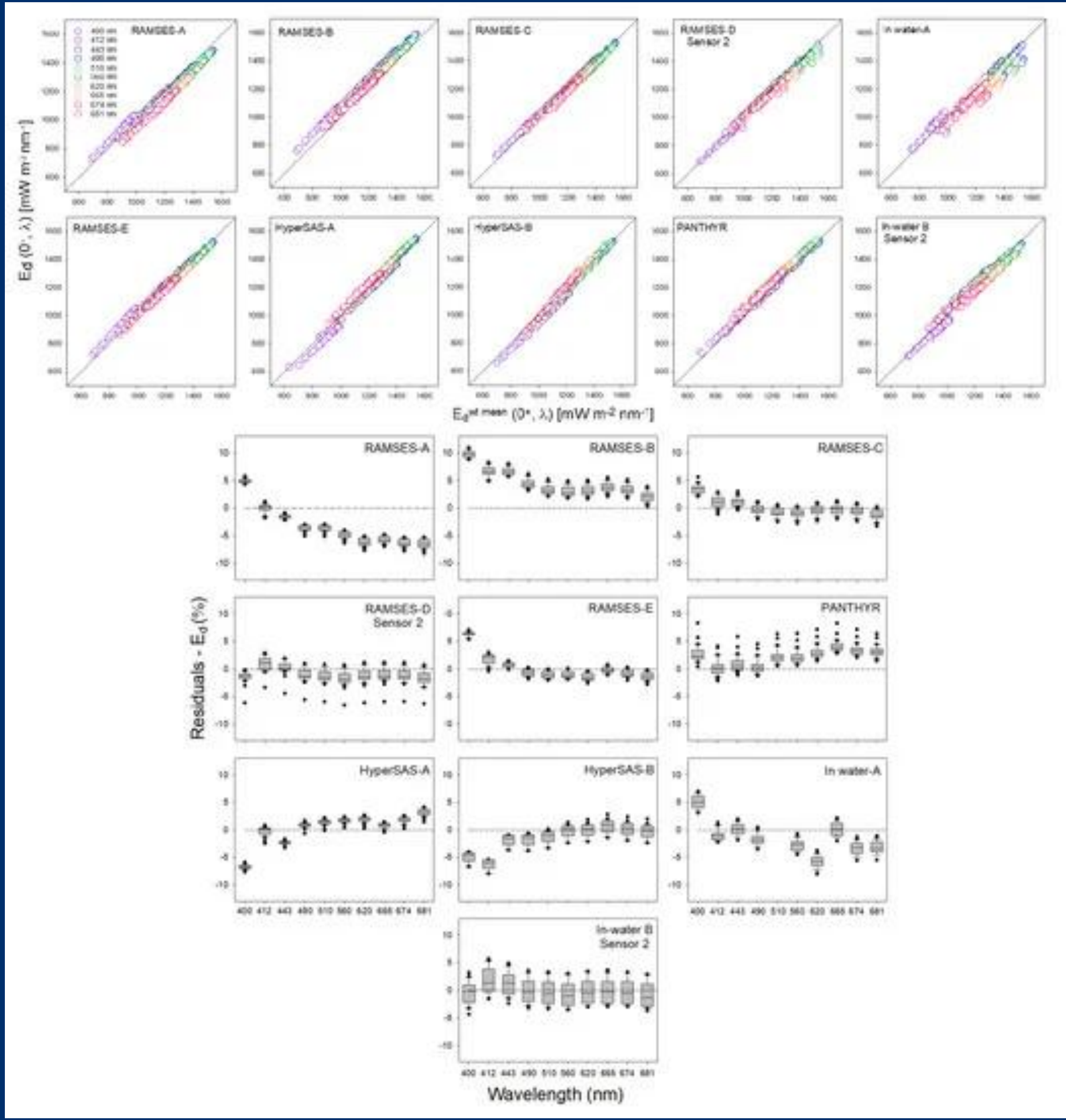


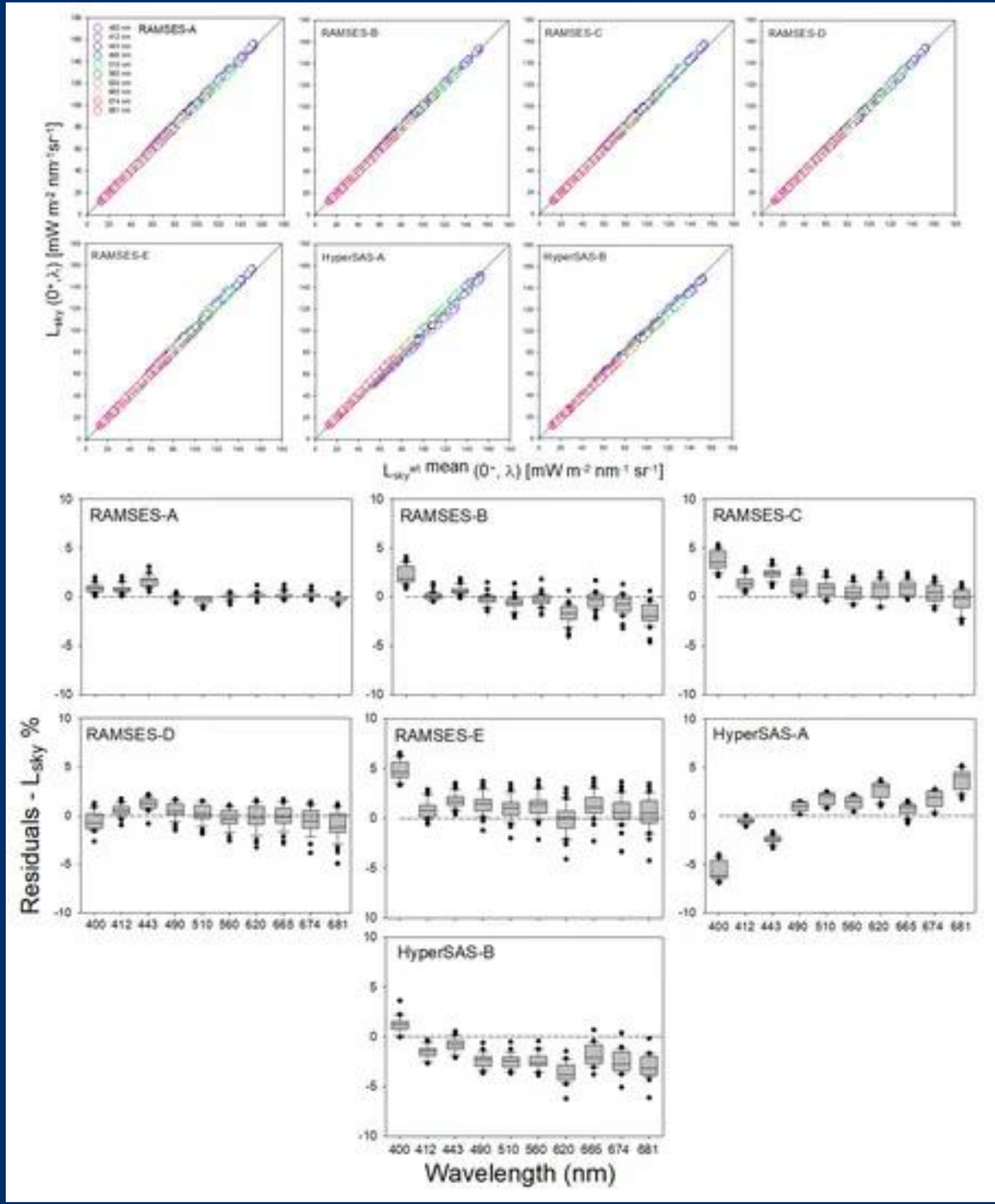
Figure 10. Irradiance sensors compared to the consensus value. Solid lines—RAMSES sensors; dashed lines—HyperOCR sensors; double line—SR-3500.



Vabson at al. 2019a, https://doi.org/10.3390/rs11091101 Vabson at al. 2019b, https://doi.org/10.3390/rs11091129

Field FICE 2020 Tilstone et al. 2020 https://doi.org/10.3390/rs12101587





Main conclusion

in the red. For R_{rs}, the differences among TriOS-RAMSES systems varied from 0.01% to −7.5% at visible bands, whereas for HyperSAS the differences were −0.01% to 5.0%. For in-water A the difference in R_{rs} was <10%. For the in-water B system the differences were greater and varied from −12.3% to 36.6%, although this may be largely constrained by using a weighted mean based on above-water measurements. L_{wn} was therefore computed to compare all sensors to SeaPRISM AERONET-OC as an independent reference measurement. The above-water TriOS-RAMSES had an average difference of <4.7% at 441, 551 and 667 nm compared to SeaPRISM. For Seabird-HyperSAS the mean difference over these bands was 4.9%, for in-water A 10.3% and for in-water B 13.3%. Differences between the in-water and above-water systems arise from differences in spatial and temporal sampling and extrapolating the in-water data from depth to the subsurface. The differences between above-water systems mainly arose from differences in E_d cosine response and FOV between L_{sky} and to a lesser extent L_t sensors, and the Fresnel reflectance value used and whether or not an NIR correction was applied at the data processing stage.

FRM4SOC phase 2

Hyperspectral radiometers comparison TRIOS and SeaBird

Comparison's transfer radiometers

Four hyperspectral radiometers were applied as comparison artefacts: TriOS GmbH (Germany) RAMSES radiance and irradiance sensors, and Sea Bird Scientific (US) HyperOCR radiance and irradiance sensors.

No	Serial Number	Manufacture Date	Function	Manufacturer	OCR's family
1	SAM_81B0	2006	Radiance (L)	TriOS GmbH	RAMSES
2	SAM_8598	2018	Irradiance (E)	TriOS GmbH	RAMSES
3	SAT2073	2021	Radiance (L)	Sea-Bird Scientific	HyperOCR
4	SAT2072	2021	Irradiance (E)	Sea-Bird Scientific	HyperOCR



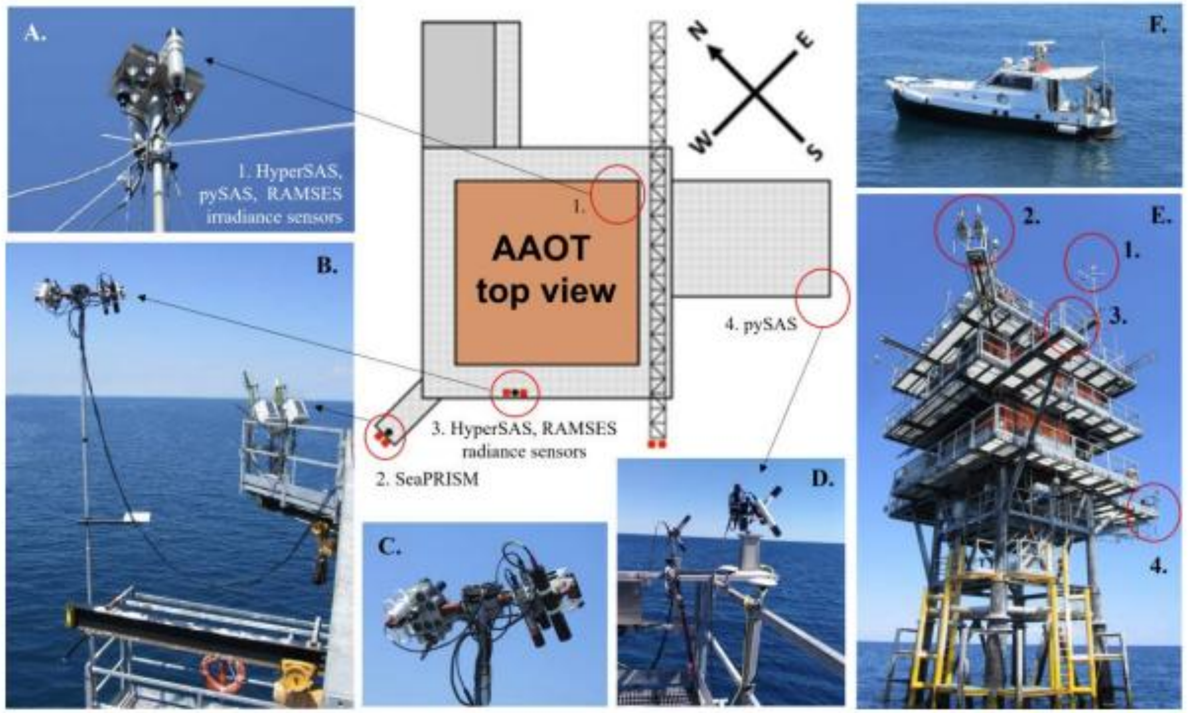
Main conclusion

Vabson at al. in prep.

- Confusion in data handling was significant. Errors detected in data handling imply that for the calculation procedures improved protocols are needed
- After reprocessing, the metrological equivalence of the OCR calibrations was satisfactory
- Small number of participants limits the reliability of consensus value (ISO/IEC 17043 and ISO 13528)
- Technical barriers hinder the comparison significantly: shorter time schedule is strongly preferable
- Harmonization of procedures for the measurement and data handling, intermediate checks and training are needed to improve metrological consistency of the spectral responsivity calibrations
- Further inter-comparison measurements are regularly needed to confirm the capabilities of participants

FRM4SOC FICE2022

Tilstone at al. 2025 DOI: https://doi.org/10.1364/OE.551042



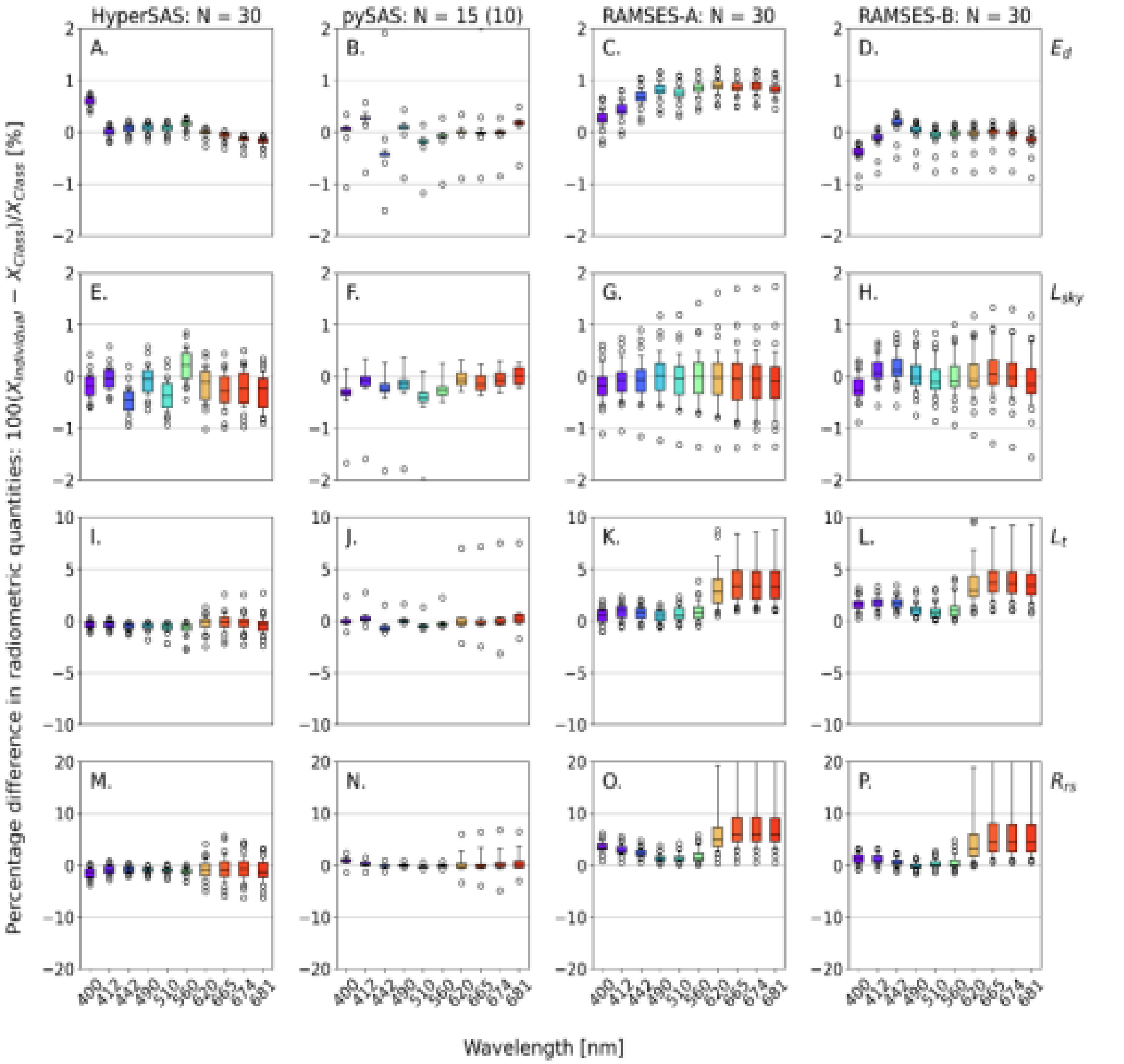


Fig. 9. Differences between individual processors and HyperCP for $E_d(\lambda)$ $L_{sky}(\lambda)$, $L_t(\lambda)$ and $R_{rs}(\lambda)$ run in class-based mode for HyperSAS (A., E., I., M.), pySAS (B., F., J., N. RAMSES-A (C., G., K., O) and RAMSES-B (D., H., L., P.).

Main conclusion

related uncertainties, is a major advance. The differences between above-water systems processed with HyperCP, using sensor-specific radiometric characteristics and M99NN, were 2% for $E_d(\lambda)$, $L_{sky}(\lambda)$, $L_t(\lambda)$ and 2.5% for $R_{rs}(\lambda)$. The associated uncertainties were 1.5%, 2%, 1.5% and 5%, respectively. For class-based radiometric characteristics, differences in the radiometric quantities were <5%, but the uncertainties, especially in $R_{rs}(\lambda)$ were higher and were not sufficient to keep the uncertainties to <5%. The uncertainties in the radiometric quantities could

be appreciably reduced if sensor-specific rather than class-based correction factors were used. When comparing HyperSAS and RAMSES $L_{wn}(\lambda)$ processed using M99NN against SeaPRiSM, the differences were <5% over all bands, and the uncertainties were <5% over blue and green bands. Compared to HyperPro II, the magnitude and range of the differences in the above-water systems processed using M99NN were higher and <10% for blue and green bands. For the

FICE 2025 is being conducted now we shall see what improvements it will bring

Thank you

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