SOUTH AFRICAN NATIONAL SPACE AGENCY (SANSA)

Some thoughts on the history and value of the FRM4SOC initiatives to the global ocean colour community….

Stewart Bernard

Chief Scientist, Earth Observation

Funded by the European Union

European Commission

Copernicus Europe's eyes on Earth

EUMETSAT

FRM4SOC-2

Riho Vendt, Agnieszka Bialek, Carsten Brockmann, Christophe Lerebourg, Kevin Ruddick, Gavin Tilstone, Juan Ignacio Gossn, Ewa Kwiatkowska

Funded by the European Union

Copernicus – Fiducial Reference Measurements for Satellite Ocean Colour – FRM4SOC Phase-2

Ocean Colour Radiometry has some very demanding specifications e.g. <2% uncertainty at TOA, <5% uncertainty for water leaving radiance, plus some other rather demanding goal specifications for key biogeochemical variables such as Chl a….

Sentinel 3

Table 7: Geophysical parameters and accuracies for Ocean Colour (under clear daytime conditions)

Parameter	Range	Accuracy Case 1 water	Accuracy Case 2 water
Marine Reflectance [at 442 nm]	0.001 – 0.04	5×10^{-4}	5×10^{-4}
Water leaving radiance L_w (λ) (atmospherically corrected) [$mW/cm^2/\mu m/Sr$]	0.0 – 1.0	5%	5%
Photosynthetically available radiation, PAR [μmol quanta/m^2/s]	0 – 1400	5%	5%
Diffuse attenuation coefficient (or turbidity), K [m^{-1}]	0.001 – 0.1	5%	5%
Chlorophyll, Chl [mg/m^3]	0.001 – 150	threshold 30 % goal 10 %	threshold 70 % goal 10 %
Total Suspended Matter [g/m^3]	0.0 – 100	threshold 30 % goal 10 %	threshold 70 % goal 10 %
Coloured Dissolved Organic Material (CDOM) (a_{412} [m^{-1}])	0.01 – 2	threshold 50 % goal 10 %	threshold 70 % goal 10 %
Harmful Algae Bloom [mg/m^3] (same req. as Chlorophyll)	0.1 – 100	threshold 30 % goal 20 %	threshold 70 % goal 30 %

Sources: RD19, RD20 and references therein.

Technical Characteristics of the Sentinel-3 Ocean and Land Colour Imager Instrument

Radiometric accuracy	< 2% with reference to the sun for the 400-900 nm waveband and < 5% with reference to the sun for wavebands > 900 nm. 0.1% stability for radiometric accuracy over each orbit and 0.5% relative accuracy for the calibration diffuser BRDF.

NASA PACE

1.2. Level-1 Requirements

Threshold and baseline requirements for ocean color data products are as follows:

Data Product	Threshold Uncertainty	Baseline Uncertainty
Water-leaving reflectances centered on (±2.5 nm) 350, 360, and 385 nm (15 nm bandwidth)	0.0083 or 30%	0.0057 or 20%
Water-leaving reflectances centered on (±2.5 nm) 412, 425, 443, 460, 475, 490, 510, 532, 555, and 583 (15 nm bandwidth)	0.0024 or 6%	0.0020 or 5%
Water-leaving reflectances centered on (±2.5 nm) 617, 640, 655, 665, 678, and 710 (15 nm bandwidth, except for 10 nm bandwidth for 665 and 678 nm)	0.00084 or 12%	0.0007 or 10%

Table 1. Uncertainty in $L_u(Top)$

Uncertainty Component [%]	8	9	10	11	12	13
	411.8 nm	442.1 nm	486.9 nm	529.7 nm	546.8 nm	665.6 nm
Responsivity						
Radiometric Calibration Source						
Spectral radiance	0.65	0.60	0.53	0.47	0.45	0.35
Stability	0.41	0.46	0.51	0.53	0.53	0.48
Transfer to MOBY						
Interpolation to MOBY wavelengths	0.2	0.15	0.03	0.03	0.03	0.03
Reproducibility	0.37	0.39	0.42	0.44	0.42	0.3
Wavelength accuracy	0.29	0.08	0.04	0.03	0.01	0.04
Stray light	0.75	0.3	0.1	0.15	0.3	0.3
Temperature	0.25	0.25	0.25	0.25	0.25	0.25
Measurements of L_u						
MOBY stability during deployment						
System response	1.59	1.3	1.19	1.11	1.08	0.92
In-water internal calibration	0.43	0.42	0.44	0.46	0.51	0.55
Wavelength stability	0.132	0.138	1.122	0.816	1.368	0.65
Environmental						
Type A (good scans &all days)	4.1	4.4	4.5	4.4	4	3.2
(good days only)*	***0.80***	***0.83***	***0.87***	***1.02***	***0.64***	***1.31***
Temporal overlap	0.3	0.3	0.3	0.3	0.3	0.3
Self-shading (uncorrected)	1	1	1.2	1.75	2.5	12
(corrected)*	***0.200***	***0.200***	***0.240***	***0.350***	***0.500***	***2.400***
In-water bio-fouling	1	1	1	1	1	1
Combined Standard Uncertainty	4.7	4.8	5.1	5.1	5.2	12.5
Combined Standard Uncertainty*	***2.4***	***2.1***	***2.4***	***2.3***	***2.4***	***3.3***

These very tight uncertainty specifications can only be achieved through a combination of vicarious calibration - typically through large agency infrastructure - and extremely carefully constrained radiometric and geophysical validation - typically through both agency and distributed community activities…

This means the distributed validation efforts by the R&D community play a very valuable role in achieving the mission objectives…. whilst empowering and developing the expertise of the R&D community

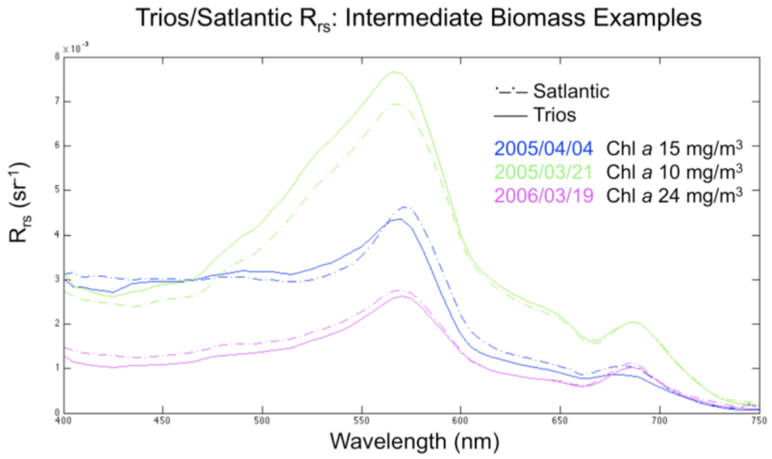
The Marine Optical BuoY (MOBY) Radiometric Calibration and Uncertainty Budget for Ocean Color Satellite Sensor Vicarious Calibration

Steven W. Brown[a], Stephanie J. Flora[b],Michael E. Feinholz[b], Mark A. Yarbrough[b], Terrence Houlihan[b], Darryl Peters[b], Yong Sung Kim[c], James L. Mueller[d], B. Carol Johnson [a], and Dennis K. Clark[e]

Needs from a Community and Misson/Agency perspectives….

Capability	R&D community needs	Mission/agency impact
Procurement	For what purpose? What instrument options?What platform? What resources? How long? Opportunity to enter existing supported network?	Growing the distributed validation capability, enhancing European (& other) science base….
Training	Calibration, deployment, protocols, processing,…	Growing the distributed validation capability, enhancing European (& other) science base….
Upskilling	Better understanding of : signal variability & bio-optic causality; holistic approach to error sources; algorithmic and AC approaches & needs	Growing the distributed validation capability, enhancing European (& other) science base….
Deployment	Logistics, protocols	Growth of high quality validation data base
Processing	Processing to common standard with standard quantified errors	Growth of high quality validation data base, enhanced mission science base
Curation	Contribution to, and availability of, validation and R&D data suites & associated community	Growth of high quality validation data base, stimulating R&D community
Analysis	Better understanding of mission performance across water types and applications, development of new products, development of new mission specification options	Enhanced mission effectiveness, development of optimized distributed mission science base

Some seeding thoughts, mostly around the community processor….



Across wide ranges of optical water types and phytoplankton biomass, there is considerable intra-spectral variability in optical depth and spectral attenuation…

For waters with any substantial spectral attenuation these can become large sources of uncertainty…

Table 2.2 Sources of error in the Trios-derived R_{rs}, and estimates of their magnitude

Source of Error in R_{rs}	Estimated magnitude (%)
L_u and E_d measurement uncertainty (including instrument calibration accuracy)	5
Use of K_u to extrapolate $L_u(z)$ to surface	10
Bidirectionality	2
Biofouling of in-water sensors	1
Instrument Self-shading	1
No tilt/roll filtering or depth adjustment	10
Scale differences with satellite matchups	2

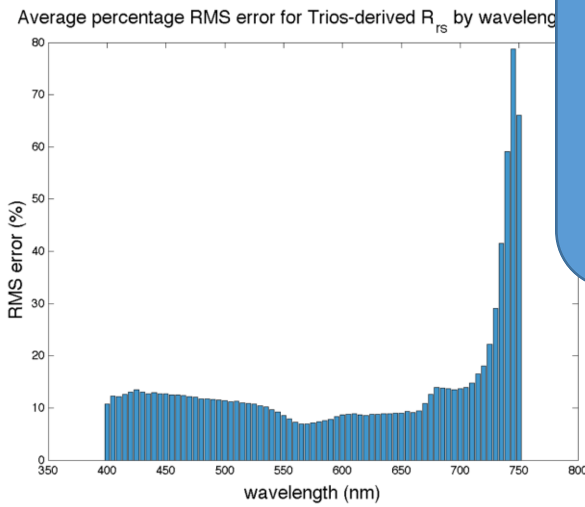


Figure 2.6 Average percentage RMS errors across the spectrum for the Trios-derived R

AN OWT type approach may be very useful for uncertainty quantification (in addition to algorithmic application!)…

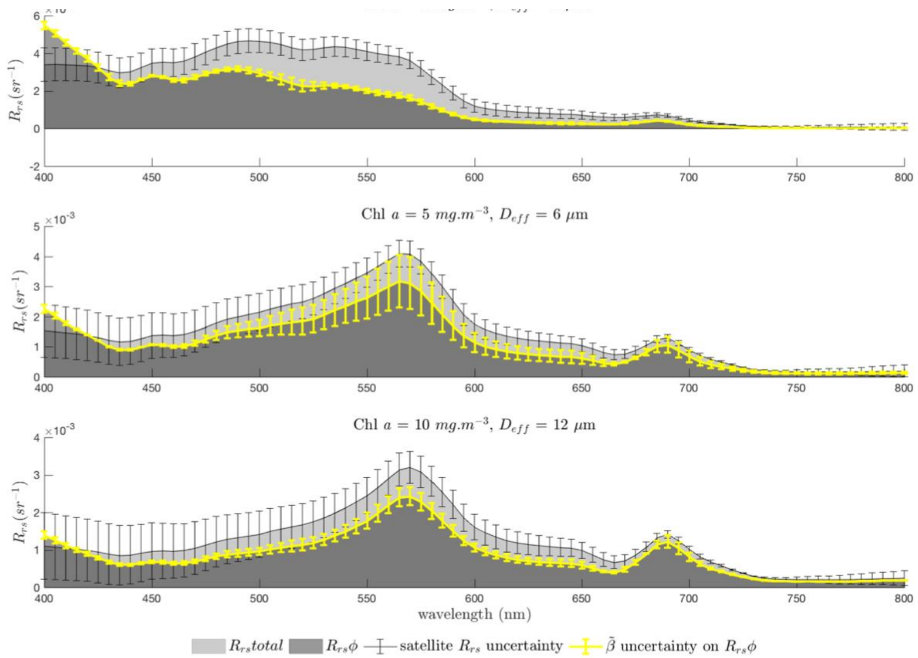
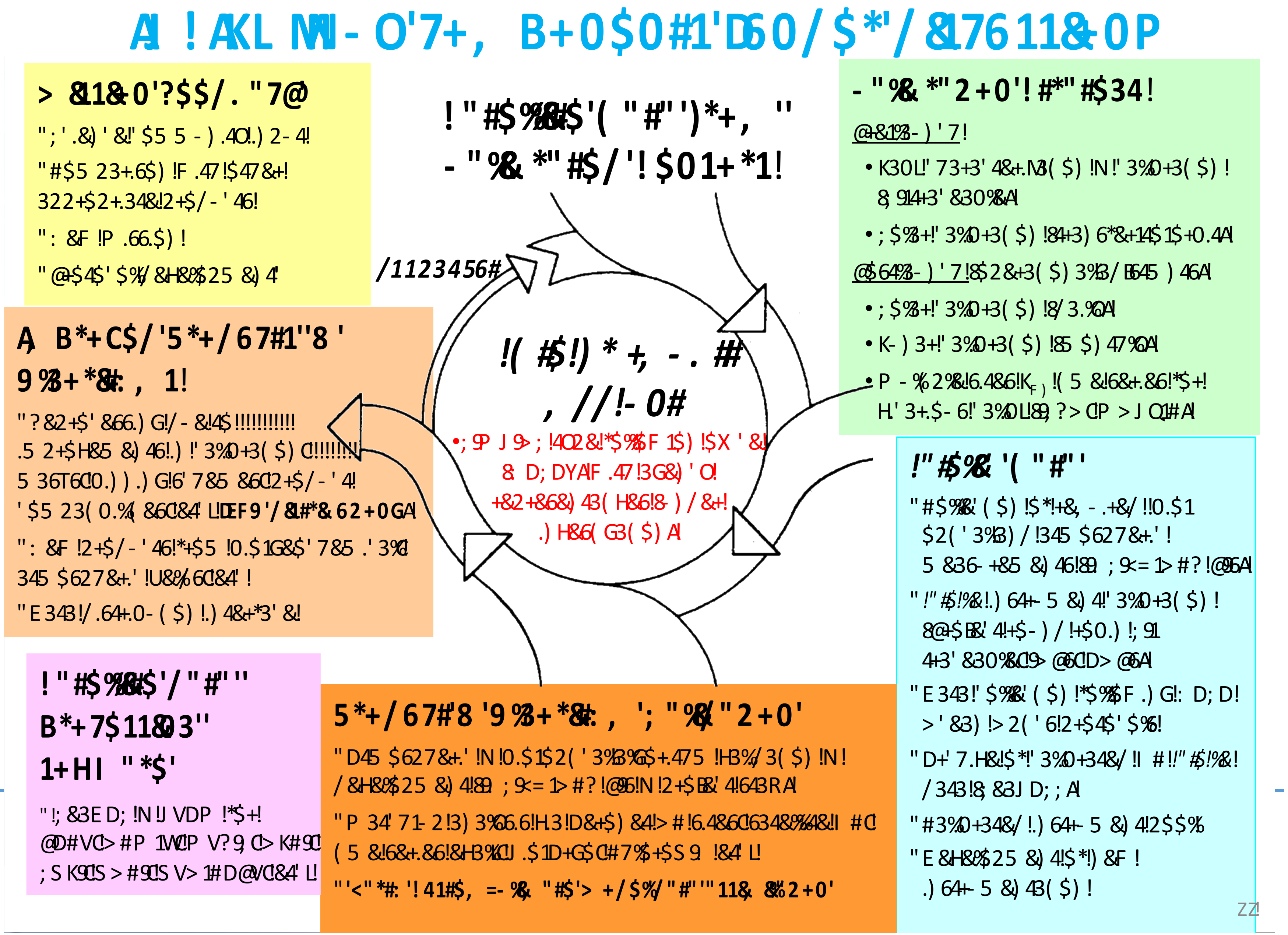


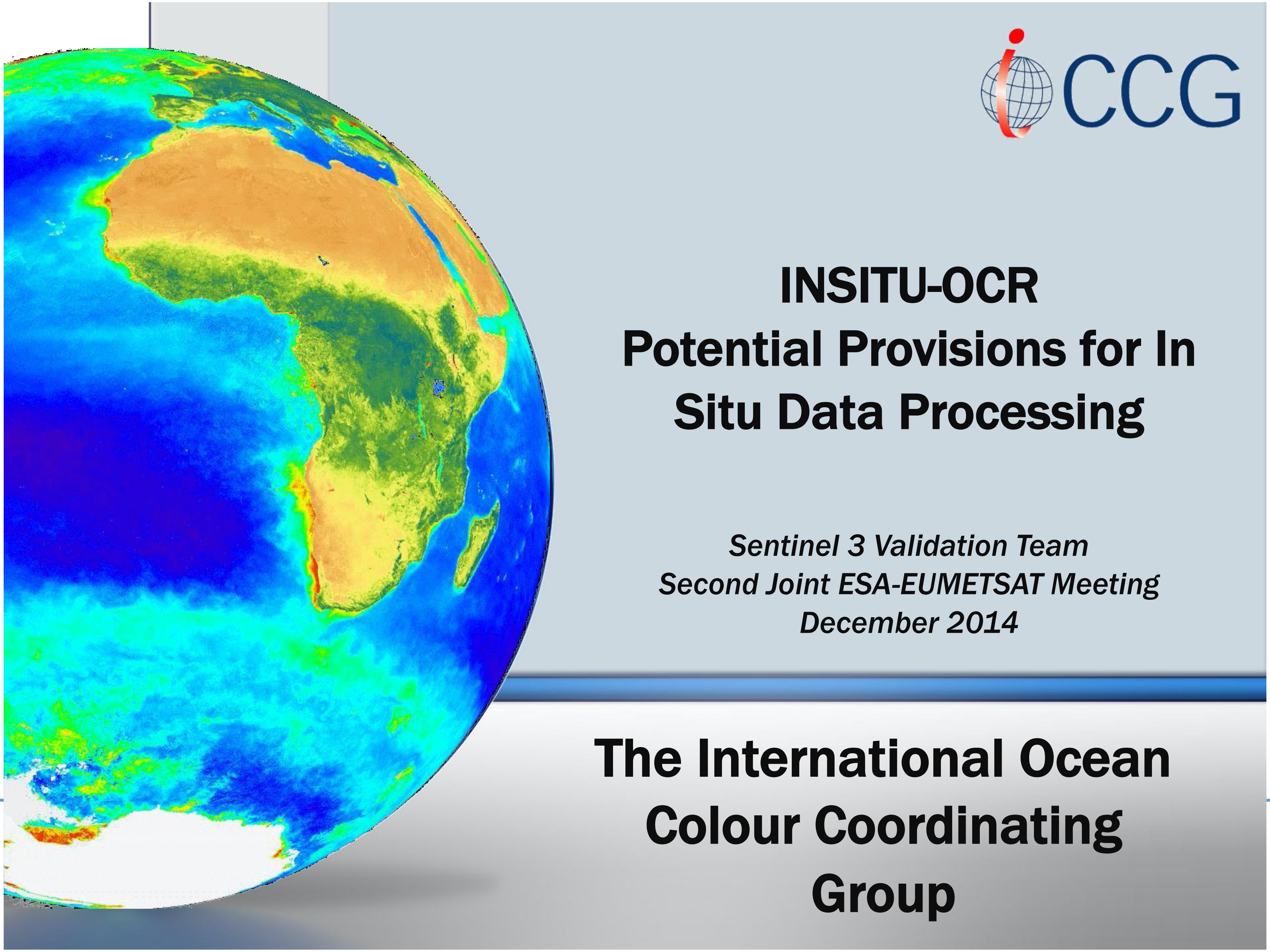
Figure A6. Total R_{rs} with satellite measurement uncertainties in the blue and red bands from [16] and linearly interpolated between them. An indication of model uncertainty on the $R_{rs}\phi$ is calculated by the spectral differences resulting from the use of a combined $b_{bp}(\lambda)$-specific Fournier Forand phase function independent of wavelength, vs. wavelength- and $b_{b\phi}(\lambda)$-dependent EAP phase functions.

Coupled radiative transfer models (with enough veracity) can play a substantial role in quantifying and reducing errors – and reaching closure between AOPS. IOPS and biogeochemistry



All of these considerations started being discussed ±10 years ago at IOCCG – how to go about working together to try and achieve these demanding mission specifications….

…in particular finding ways to empower and enable the substantial ocean colour R&D community to realise the full value of their validation efforts….


IOCCG
INSITU-OCR
Potential Provisions for In Situ Data Processing
Sentinel 3 Validation Team
Second Joint ESA-EUMETSAT Meeting
December 2014
The International Ocean Colour Coordinating Group

INSITU-OCR: activities of relevance to S3VT activities

…the INSITU-OCR initiative aims at integrating and rationalizing inter-agency efforts on satellite sensor inter-comparisons and uncertainty assessment for remote sensing products with particular emphasis on requirements addressing the generation of Ocean Color Essential Climate Variables (ECV)…

1. Space sensor radiometric calibration, characterization and temporal stability;
   - 1.4 Vicarious calibration

2. Development and assessment of satellite products;
   - 2.2 Permanent working groups on algorithm topics
   - 2.3 Product uncertainties
   - 2.4 Regional bio-optical algorithms
   - 2.6 Long-term field measurement programs

3. In situ data generation and handling;

4. information management and support.
   - 4.2 Processing capabilities for calibration and validation activities

INSITU-OCR: In situ data generation and handling

3.1: Improving traceability of in situ measurements

3.2: Continuous consolidation and update of measurement protocols

3.3: Uncertainty budgets

3.4: Quality Assurance of in situ data

3.5: Archival of in situ data

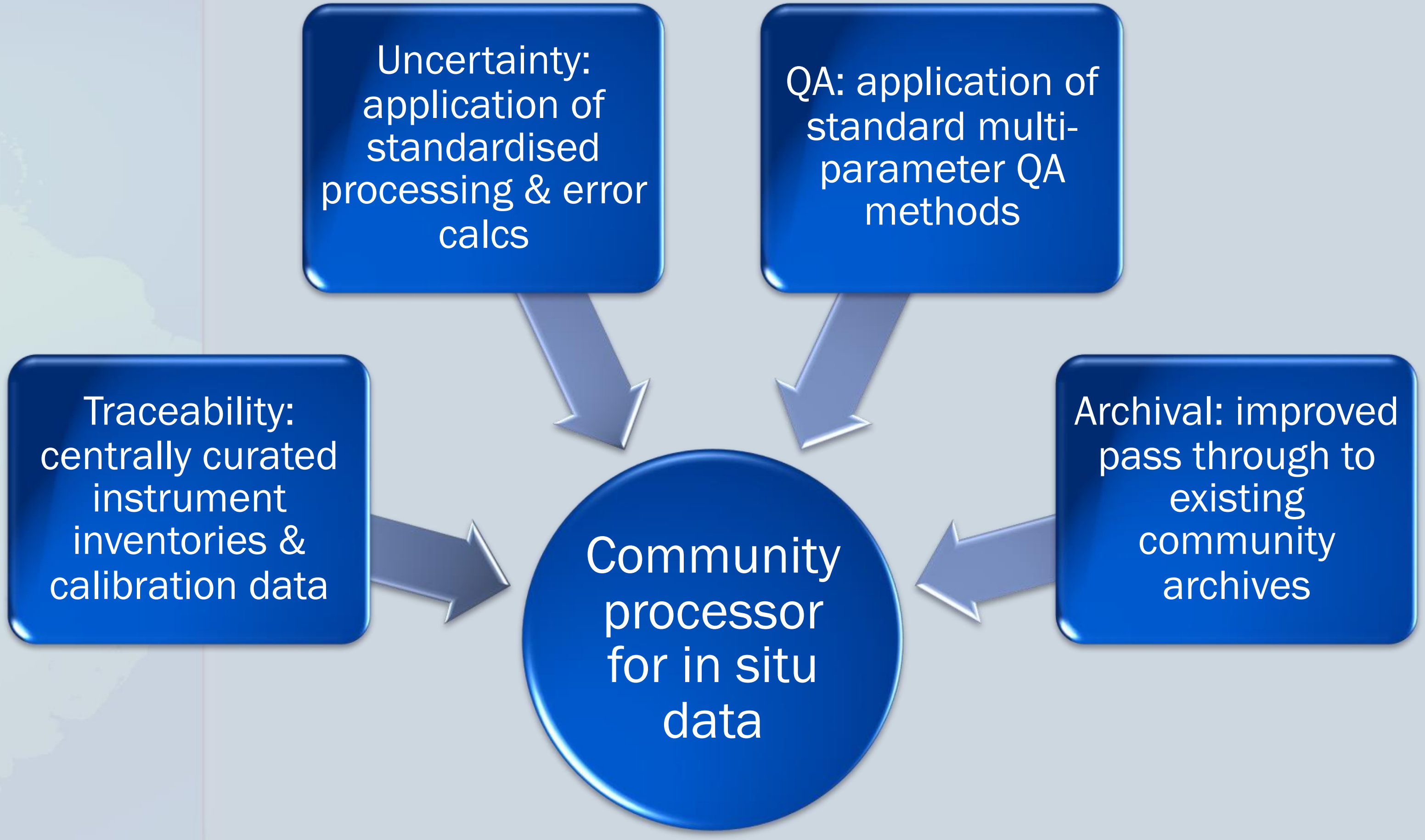
3.6: Community processor for in situ data

3.7: Priority for variables to be collected

3.8: General coordination of field campaigns

AOP/IOP Community Processor

AOP/IOP Community Processor



AOP/IOP Community Processor: Ambitious

End- end processing & archiving system requiring substantial resources for scoping, development and dedicated ongoing operations....

Benefits: traceability, uncertainty estimates, QA, archiving

....substantial improvement in data quality and utility with little overhead for the community....

- submitted common format raw data from most major instrument types
- Calibration: curated PI instrument inventories & calibration data application
- Processing: common schemes, providing detailed best error estimates
- Quality Assurance: application of consensus standard methods
- Archive: common formats for archive, pass through to existing archives

AOP/IOP Community Processor: Lightweight

Community code base requiring moderate resources for scoping and development with minimal ongoing maintenance....

Benefits: ~~traceability,~~ uncertainty estimates, QA(?), ~~archiving~~....

- submitted common format raw data from most major instrument types
- Calibration: curated PI instrument inventories & calibration data application
- Processing: common schemes, providing detailed best error estimates
- Quality Assurance: application of consensus standard methods
- Archive: common formats for archive, easy dissemination, IP protection

AOP Community Processor: Preliminary Example

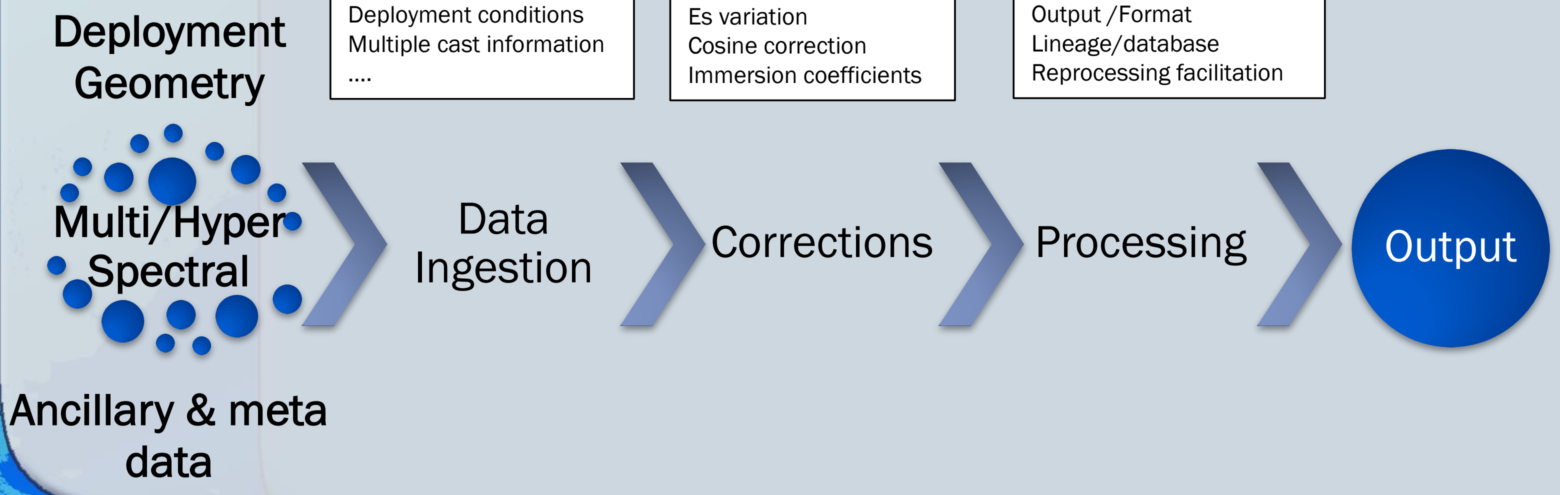
The 2009 and 2010 AOP Community Processor Workshop reports (Wright & Hooker 2009, Hooker et al 2011) laid out an example framework of requirements for a community AOP processor PROSIT e.g.

Radiometric data (raw, calibration & dark)
Ed, Lu, Es, Eu
Pressure (depth)
Time and geolocation

Pitch/Roll
Profiling data and Es
Station Data
Cruise information
Deployment conditions
Multiple cast information
....

Time Synching
Pressure tare
Surface file
Depth correction
Position information
Self-shading
Diffuse to direct
l co-registration
Choice of algorithm for interpolation
Es variation
Cosine correction
Immersion coefficients

Base calculations
error calculations and data flags
Optional binning
Products calculations
Error calculations (interactive)
Multi-cast aggregation
Statistics and uncertainties
Output /Format
Lineage/database
Reprocessing facilitation



Community Processor Priorities: a PFT-type Example

An example of potentially high impact products with large user pull, typically currently working from a sub-optimal quantitative framework – especially with regard to fiducial reference measurements - and with highly demanding dependency on second-order variability.....

Biogeochemistry & Phytoplankton Community:

New methods for quantitative assemblage measurements e.g. holographic / cytometric sensors & methods

Inherent Optical Properties:

Establishing common uncertainty methods

Establishing phytoplankton specific IOP methods e.g. backscattering

Apparent Optical Properties:

Establishing common uncertainty methods

Establishing common processing methods for complex/turbid waters

New capability to determine PFT related signal content and evaluate candidate algorithms

Community Processing of In Situ Data: Issues

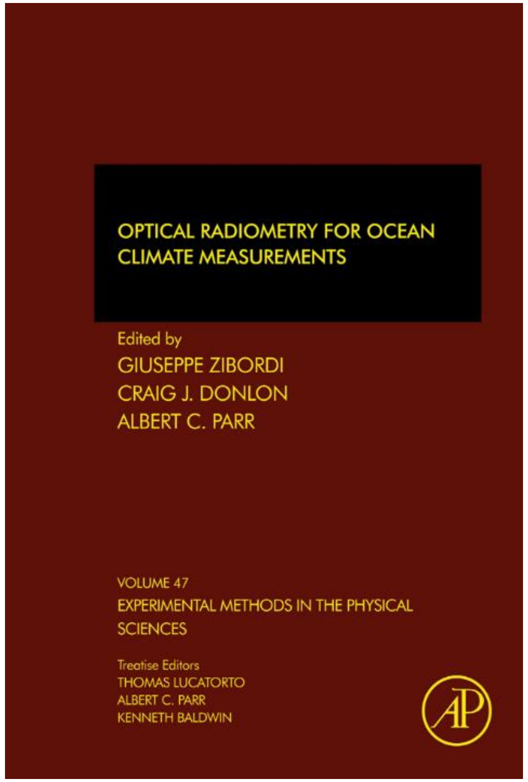
- Community buy in: confirmation of anticipated benefits, system characteristics needed, IP & exploitation concerns, feedback please?!
- Agency buy in: modular & distributed implementation an advantage, TBD by scoping & cost : benefit, system hosting....
- Manufacturer buy in: primarily formatting/open code issues, could be assisted by agency push....
- Technical Issues: substantial but manageable, primarily dealing with multiple instruments, data products, and deployment configurations and variable availability of “base” processing data
- How to complement/make best advantage of/integrate with existing capabilities e.g. existing processors, MERMAID, SEABASS etc
- Scoping important: first analysis of range of possible modular services to determine resources needed for implementation options

The Fiducial Reference Measurements (FRM)

fi·du·cial *(adj)* *Regarded or employed as a standard of reference, as in surveying.*

[Latin *fīdūciālis*, *fīdūcia* – trust,confidence.]

In Earth Observation – a best estimate for the „ground truth“



The FRM must:

- have documented **traceability to SI units** (via an unbroken chain of calibrations and comparisons);
- be independent from the satellite retrieval process;
- be accompanied by a complete **estimate of uncertainty**, including contributions from all FRM instruments and all data acquisition and processing steps;
- follow **well-defined procedures**/community-wide management practices and;
- be openly available for independent scrutiny.

✓ 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.
✓ Donlon, C.J.; Wimmer, W.; Robinson, I.; Fisher, G.; Ferlet, M.; Nightingale, T.; Bras, B. A., Second-Generation Blackbody System for the Calibration and Verification of Seagoing Infrared Radiometers. J. Atmospheric Ocean. Technol. 2014, 31, 1104–1127.
✓ G. Zibordi and C. J. Donlon, Chapters 3 and 5, vol. 47, G. Zibordi, C. J. Donlon, and A. C. Parr, Eds. Academic Press, 2014.

fiducial reference measurements for satellite ocean colour

esa

FRM4SOC (Phase 1) 2016 – 2019

- Initiated, funded and coordinated by ESA
- In a series of several other FRM projects
- *https://frm4soc.org*

FRM4SOC Phase 2

- Project kick-off 8 April 2021
- Funded by the EU and coordinated by EUMETSAT
- Project end March 2023 (24 months)
- Two optional 12 month extensions may be granted
- *https://frm4soc2.eumetsat.int/*

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ACRI ST

BROCKMANN CONSULT GMBH

NPL National Physical Laboratory

PML Plymouth Marine Laboratory

museum Royal Belgian Institute of Natural Sciences

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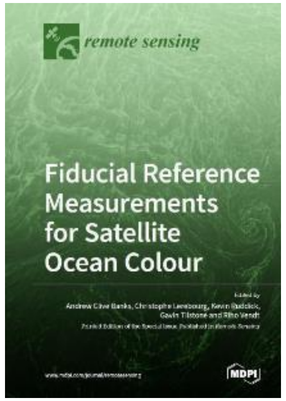
Copernicus Europe's eyes on Earth

EUMETSAT

Goals of the FRM4SOC Phase 2

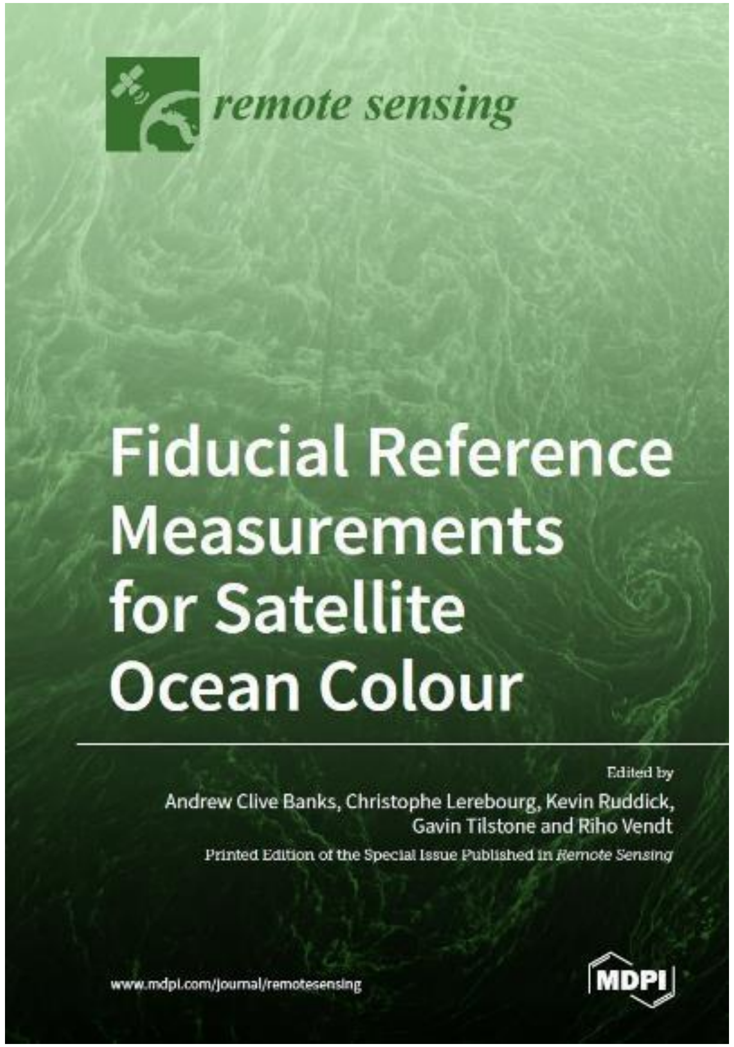
Ensure the adoption of FRM principles across the Ocean Colour community.

- FRM4SOC-2 builds on the outcomes from earlier studies in the field and the first FRM4SOC study managed by ESA
- We are developing a network of radiometric measurements with the FRM certification.



FRM4SOC		**FRM4SOC-2**
Identification of gaps in • **traceability,** • **calibration,** • **characterization,** • **uncertainty estimation**	→	Consolidate **FRM4SOC-1** focusing on • **Operational** OCR cal/char guidelines. • **Operational** (prescriptive) FRM procedures/protocols. • in discussion wit the **global** community.

The guidelines to obtain FRMs must be clear and as straightforward as possible.



Fiducial Reference Measurements for Satellite Ocean Colour

Andrew Clive Banks, Christophe Lerebourg, Kevin Ruddick, Gavin Tilstone and Riho Vendt (Eds.)

The results of the FRM4SOC project are published as a special issue of the MDPI journal Remote Sensing.

Open Access

Book (Hard Cover): ISBN 978-3-03943-064-2 (Hbk)

PDF: ISBN 978-3-03943-065-9 (PDF)

https://doi.org/10.3390/books978-3-03943-065-9

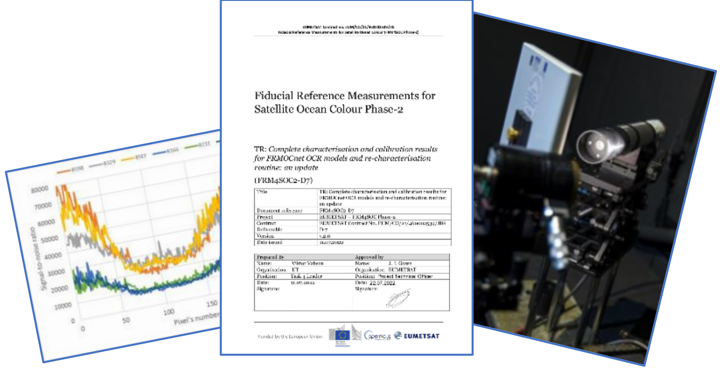
Individual papers (web page of the special issue)

fiducial reference measurements for satellite ocean colour

FRM4SOC Phase-1

9. Review and test the developed procedures, guidelines and tools: a field experiment, an international workshop, Expert Review Board

1. Initially focus on the two most common Ocean Colour hyperspectral radiometer classes



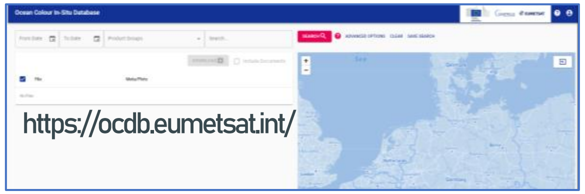
2. Fully characterise the two Ocean Colour radiometer classes

(issue recommendations to instrument manufacturers)

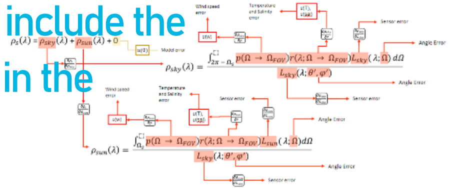
Parameter	Scope	Before initial use	Re-cal/char	D-2 requirement
1. Absolute calibration for radiometric responsivity	individual	required	1 year	IR1
2. Long term stability	individual	required	after every calibration	IR1
3. Stray light and out of band response	individual	required	3 – 5 years	IR2
4. Immersion 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. Provide community guidelines on radiometer cal/char schedules

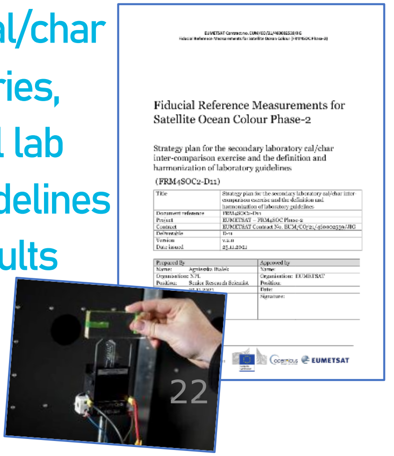
8. Adapt and maintain Ocean Colour In-Situ Database OCDB



7. Develop a complete end-to-end uncertainty budget for the instruments and the measurements, include the uncertainty calculations in the community processor



4. Develop radiometer cal/char guidelines for laboratories, include an international lab exercise to test the guidelines and inter-compare results

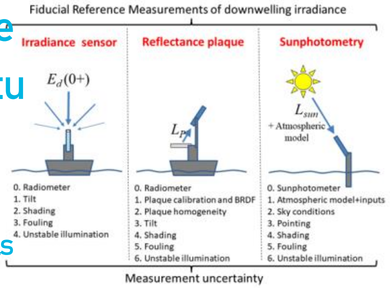


6. Develop a community processor for in situ radiometric measurements

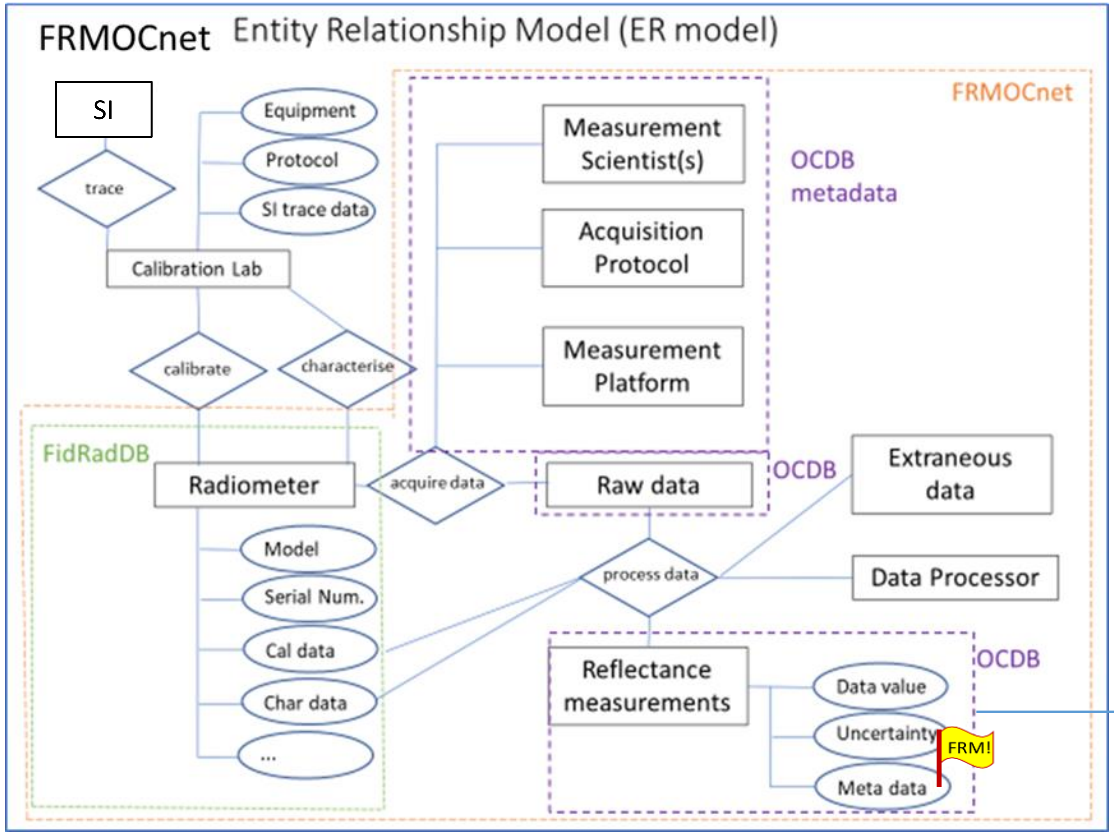
(cooperating with NASA on HyperInSPACE)

5. Provide prescriptive and detailed FRM in situ measurement procedures

(following from the IOCCG protocols and FRM4SOC-1 experience)



FRMOCnet (network of radiometric measurements with FRM certification)



FRM4SOC Phase 2 focus on two most common Ocean Colour Radiometer (OCR) types

museum
Royal Belgian Institute of Natural Sciences

OCR Calibration and characterisatio

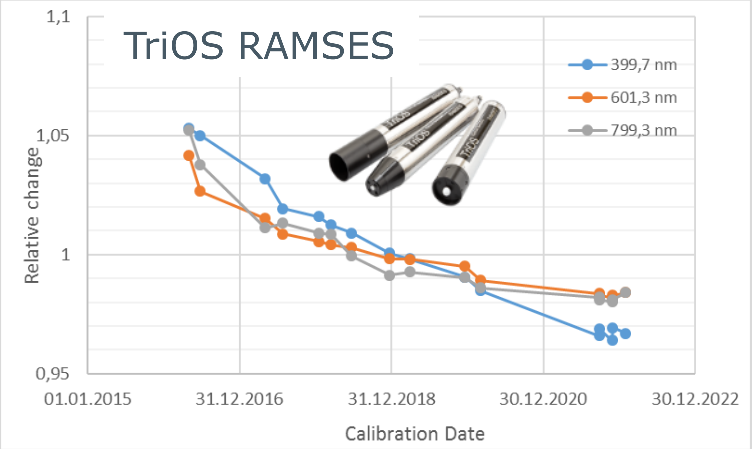
1. Absolute calibration for radiometric responsivity
2. Long term stability
3. Stray light and out of band response
4. Immersion factor (irradiance)

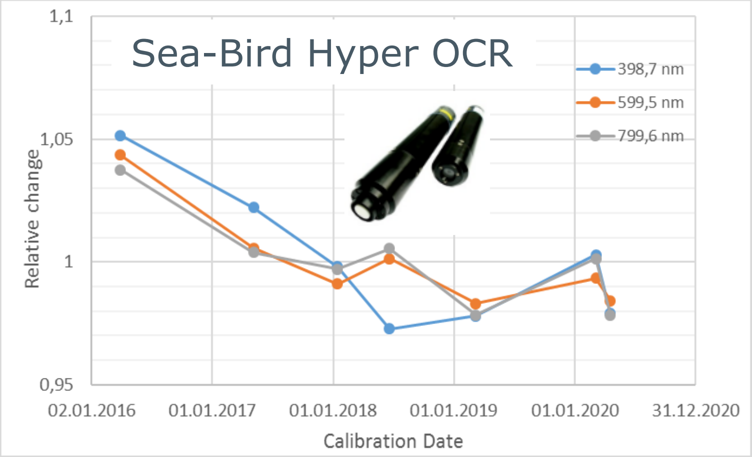
4b.Immersion factor (radiance)

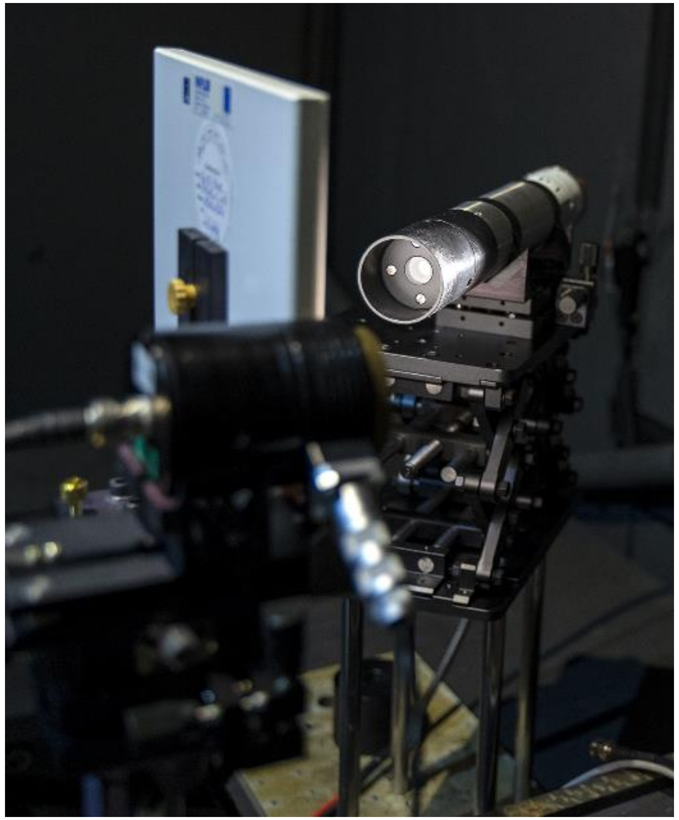
5. Angular response of irradiance sensors in air
6. Response angle (FOV) of radiance sensors in air
7. Non-linearity
8. Accuracy of integration times
9. Dark signal
10. Thermal sensitivity
11. Polarisation sensitivity
12. Temporal response
13. Wavelength scale
14. Signal-to-noise ratio
15. Pressure effects

- Characterisation of instruments
- Guidelines for laboratories
- Laboratory comparison

Example of the calibration history







✓ IOCCG Protocol Series 2019
✓ Vabson, et al. 2019

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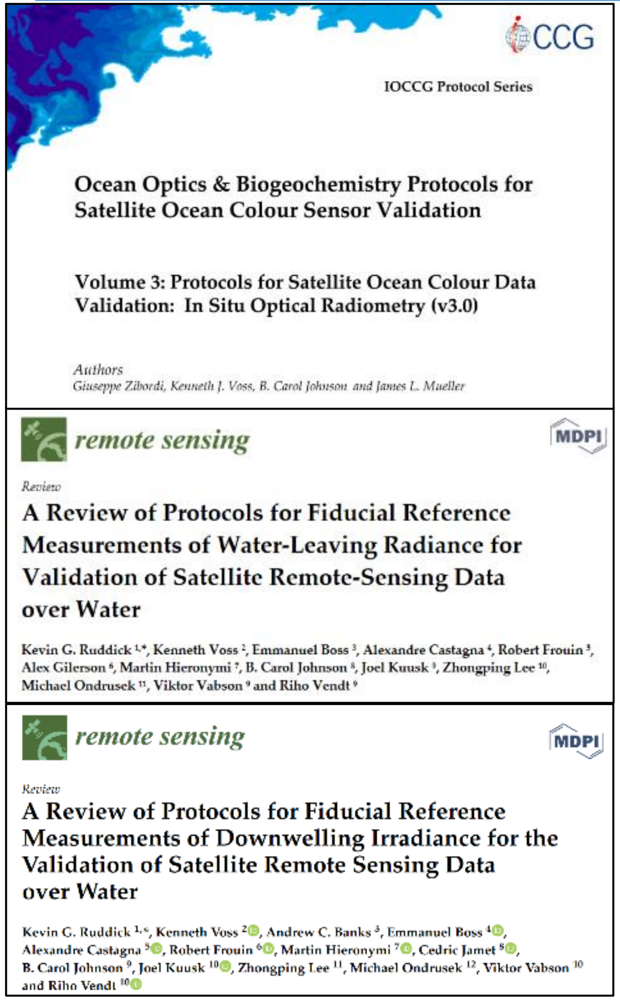

IOCCG Protocol Series

Ocean Optics & Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation

Volume 3: Protocols for Satellite Ocean Colour Data Validation: In Situ Optical Radiometry (v3.0)

Authors
Giuseppe Zibordi, Kenneth J. Voss, B. Carol Johnson and James L. Mueller

remote sensing

Review
A Review of Protocols for Fiducial Reference Measurements of Water-Leaving Radiance for Validation of Satellite Remote-Sensing Data over Water

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

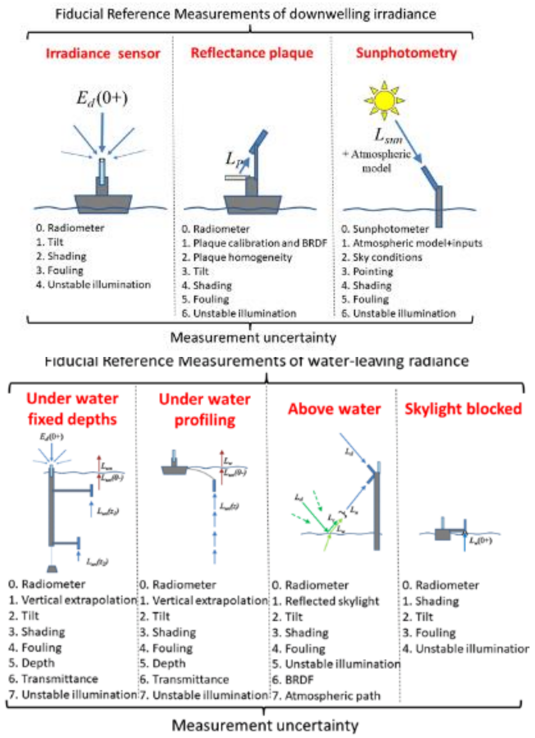
remote sensing

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]

A Measurement Procedure for shipborne operation of the TriOS RAMSES and SeaBird/Satlantic HyperOCR radiometers to obtain Fiducial Reference Measurements (MPROC)

- Elaboration of the IOCCG and FRM4SOC-1 protocols
- In form of clear and prescriptive guidelines
- Examples of complete uncertainty analysis following FRM principles



Terminology

OC Community
- NASA Ocean Optics Protocols
- IOCCG Protocols
- FRM4SOC Protocol Reviews

Metrological community / VIM
- Measurement principle
- Measurement method
- Measurement procedure

museum
Royal Belgian Institute of Natural Sciences

Community processor for in situ data processing and uncertainty budget calculation

Latest updates:

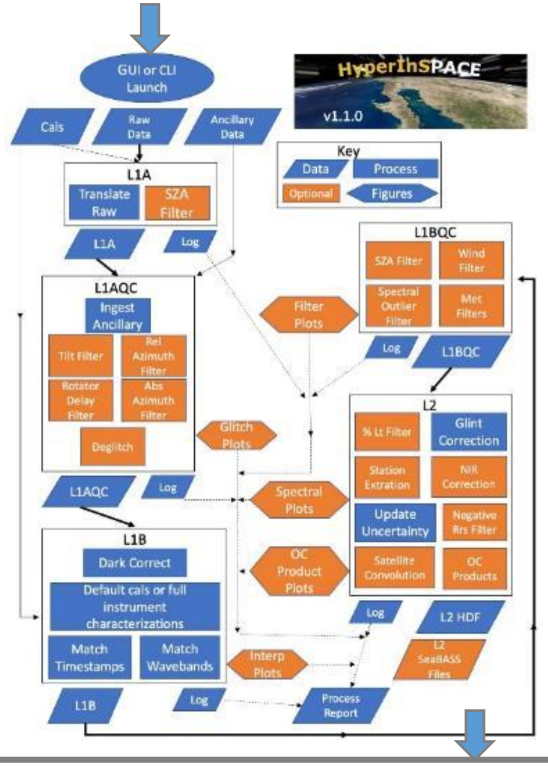
(Presentation following)

- Now 2 instruments supported:
  - ➢ Seabird HyperOCR (initally)
  - ➢ TriOS RAMSES (added)
- End-to-end uncertainty budget computation following GUM recommendation.
- GUI + CLI + batch processing under Linux.

https://github.com/nasa/HyperInSPACE

N. Vandenberg, M. Costa, Y. Coady and T. Agbaje, "PySciDON: A python scientific framework for development of ocean network applications," *2017 IEEE Pacific Rim Conference on Communications, Computers and Signal Processing (PACRIM)*, 2017, pp. 1-6,

SI traceable measurement data from calibrated and characterised radiometers



SI traceable remote sensing reflectance R_{rs} with related measurement uncertainty

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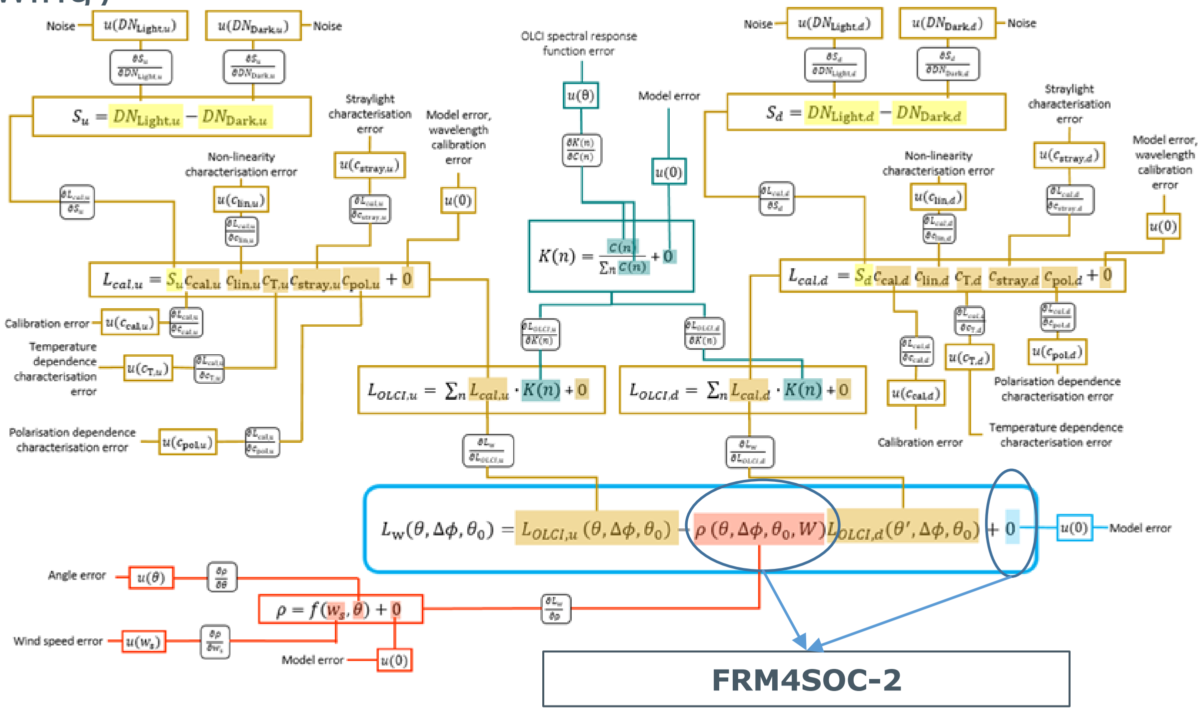
Uncertainty budgets (Presentation following)

Elaboration of the FRM4SOC Phase 1 uncertainty budgets

- Developing end-to-end uncertainty budgets for
  - remote sensing reflectance,
  - fully normalised water-leaving radiance.
- Implementing uncertainty calculations in the CP processing chain.
- Providing easy and practical guidelines for uncertainty calculation.



Water leaving radiance uncertainty tree diagramm.
Adapted from (Bialek et al. 2020).

NPL National Physical Laboratory

Ocean Colour In-Situ Database (OCDB)

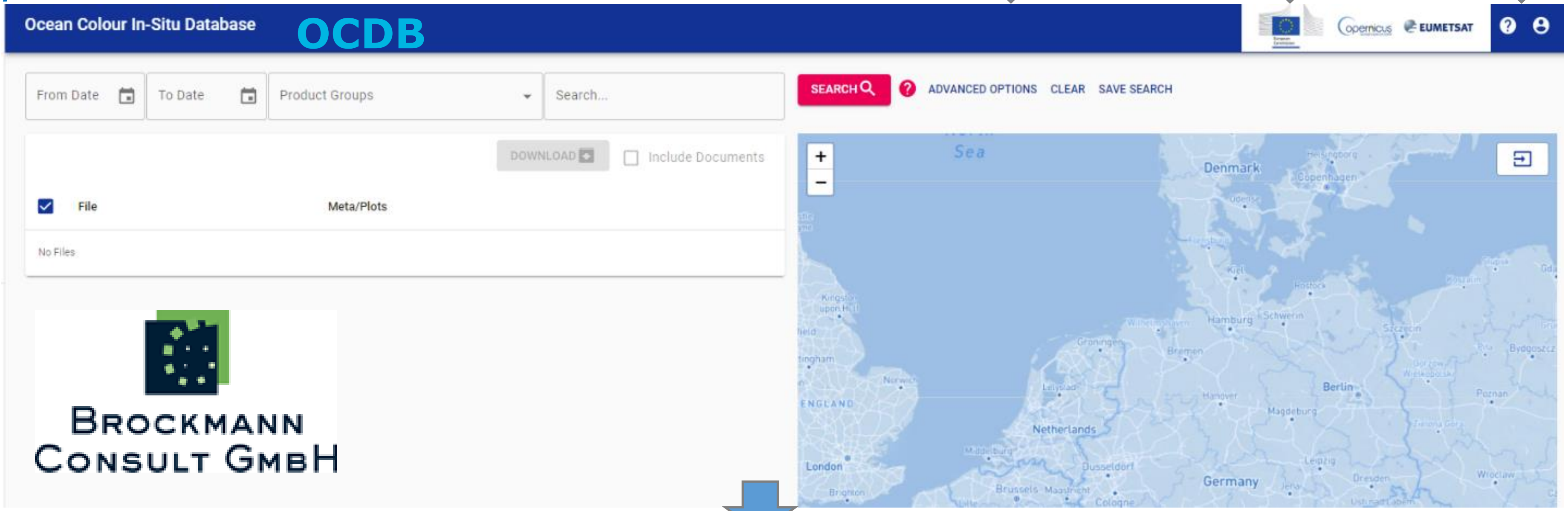
Community Processor

AERONET-OC

MOBY

BGC Argo

https://ocdb.eumetsat.in



Data users

Funded by the European Union


Fiducial Reference Measurements
for Satellite Ocean Colour Phase 2
FRM4SOC-2
Project Workshop
Save the date! 5 – 7 December 2022 – Darmstadt/Online
Consortium partners and project-related experts will attend physically.
You are invited to join either physically or online.
No registration fees will be charged.
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