FRM4SOC-2

Fiducial Reference Measurements for Satellite Ocean Colour - Phase 2

Riho Vendt, Viktor Vabson, Krista Alikas, Martin Ligi, Ilmar Ansko, Joel Kuusk, Christophe Lerebourg, Marine Bretagnon, Alexis Deru, Gabriele Bai, Carsten Brockmann, Uwe Lange, Helge Dzierzon, Sabine Embacher, Agnieszka Bialek, Ashley Ramsay, Gavin Tilstone, Giorgio Dall'Olmo, Kevin Ruddick, Juan Ignacio Gossn, Ewa Kwiatkowska

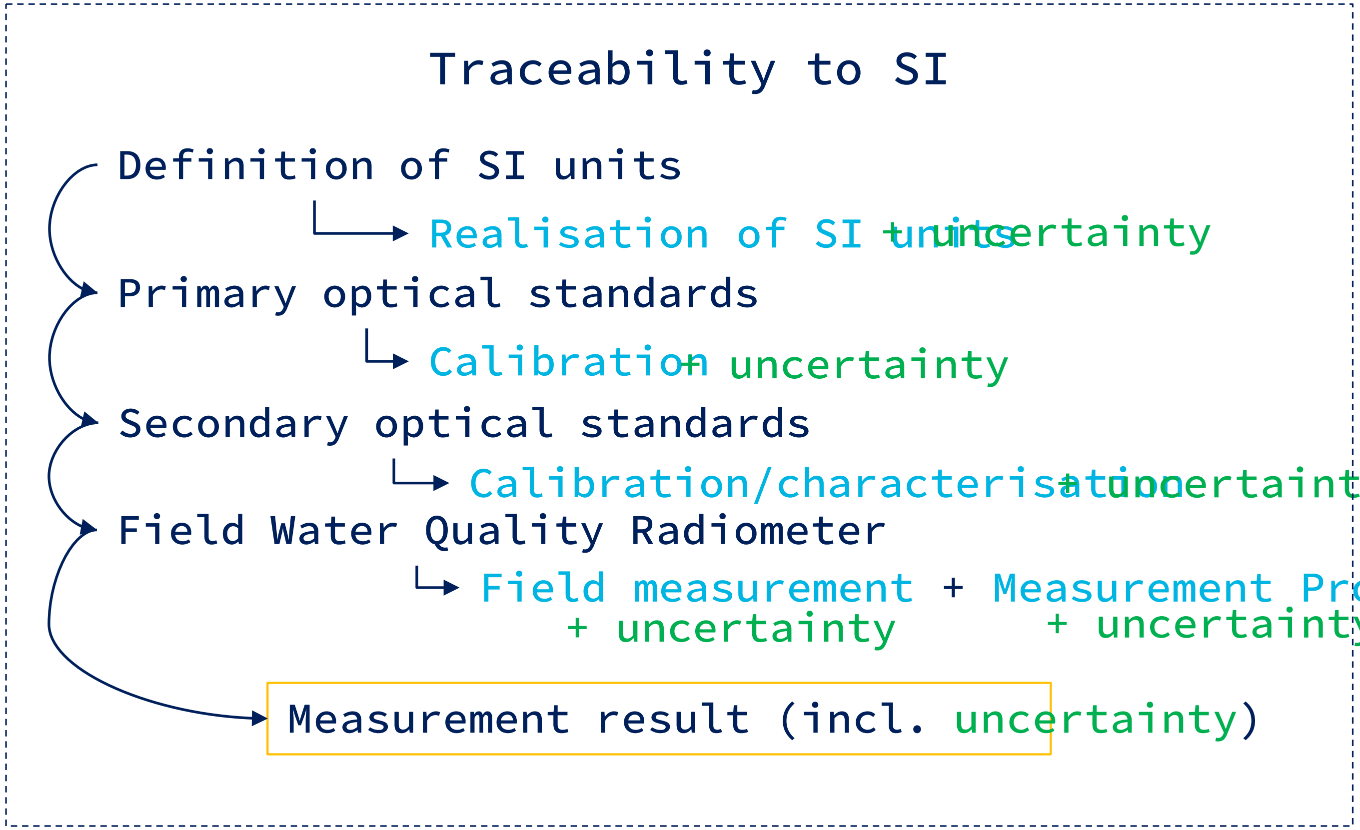
Water Qualit tion, 7 – 9 June 2022, Univ sity of Wisconsin-Madison

The Consortiu

The Fiducial Reference Measurements (FRM)

The **FRM** must:

- have documented **traceability to SI units**;
- be **independent** from the satellite retrieval process;
- include a complete **estimate of uncertainty**;
- follow **well-agreed and known procedures**
- be openly available for independent scrutiny.



Traceability to SI

Definition of SI units

↳ Realisation of SI units + uncertainty

Primary optical standards

↳ Calibration + uncertainty

Secondary optical standards

↳ Calibration/characterisation + uncertaint

Field Water Quality Radiometer

↳ Field measurement + uncertainty + Measurement Pr + uncertaint

Measurement result (incl. uncertainty)

- ✓ 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.

FRM4SOC: Brief timeline

2016 – 2019 **FRM4SOC Phase 1**

esa

- Funded and coordinated by ESA
- In a series of several other FRM projects
- https://frm4soc.org

2021 – 2023 **FRM4SOC Phase 2**

EUMETSAT

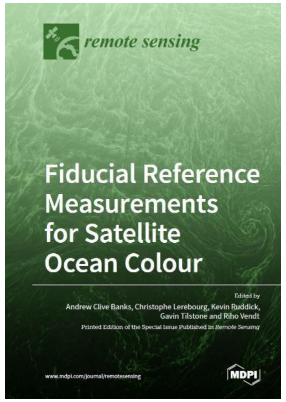
- Project kick-off 8 April 2021
- Funded by the EU and coordinated by EUMETSAT
- Two optional 1-year extensions may be granted
- https://frm4soc2.eumetsat.int/

TARTU ÜLIKOOL UNIVERSITAS TARTUENSIS 1632
ACRI ST
Brockmann Consult GmbH
NPL National Physical Laboratory
PML Plymouth Marine Laboratory
museum Royal Belgian Institute of Natural Sciences

Funded by the European Union
European Commission
Copernicus Europe's eyes on Earth

Goals of the FRM4SOC Phase 2

Overarching goal of FRM4SOC
Ensure the adoption of FRM principles across the Ocean Colour (Water Quality) community



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Fiducial Reference Measurements for Satellite Ocean Colour

Edited by
Andrew Clive Banks, Christophe Lerebourg, Kevin Ruddick, Gavin Tilstone and Riho Vendt
Printed Edition of the Special Issue Published in *Remote Sensing*

www.mdpi.com/journal/remotesensing

MDPI

FRM4SOC

Identification of gaps in
- **traceability**,
- **calibration**,
- **characterization**,
- **uncertainty estimation**

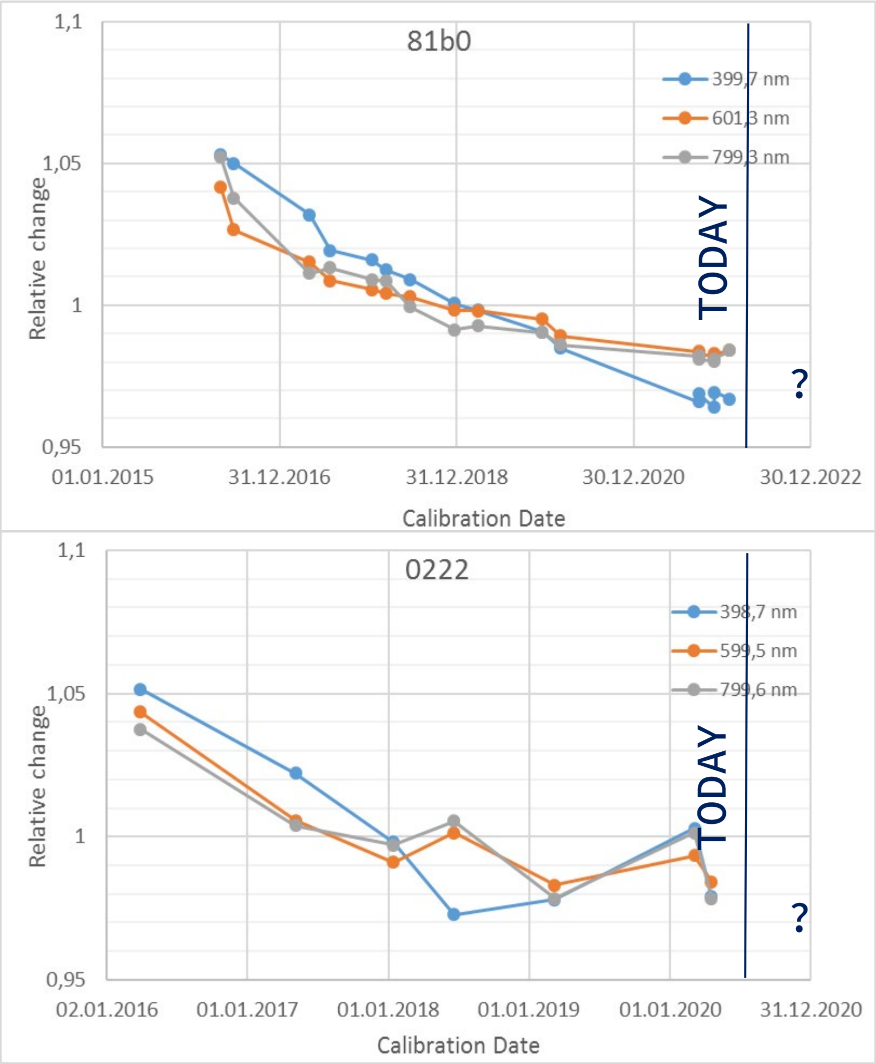
FRM4SOC-2

Consolidate **FRM4SOC-1** focusing on
- **Operational** OCR cal/char guidelines.
- **Operational** (prescriptive) FRM procedures/protocols.
- **Engagement** of the **global** community.

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

OCR Calibration, Characterisation

Examples of the calibration history

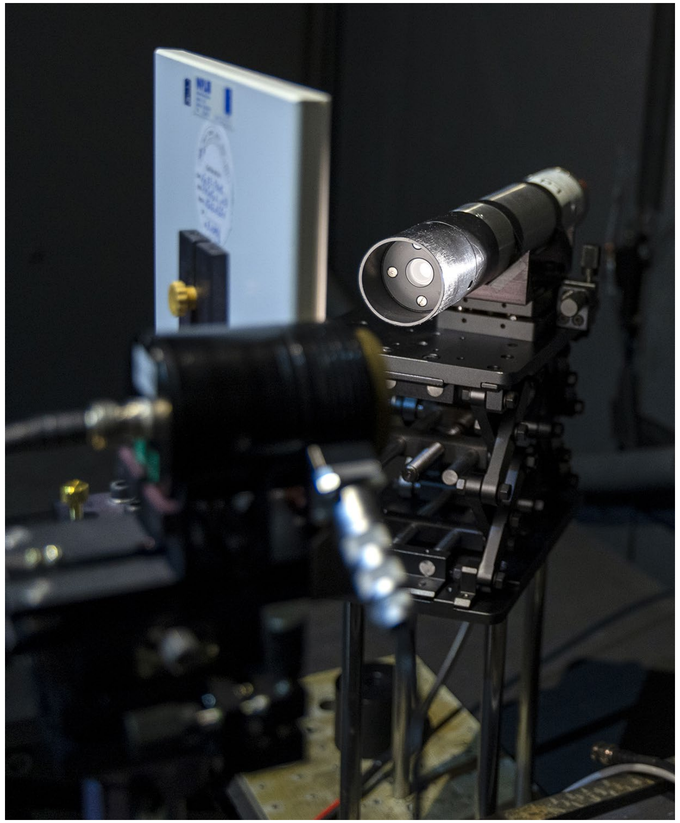


Cal/Char plan

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. Polarization sensitivity
12. Temporal response
13. Wavelength scale
14. Signal-to-noise ratio
15. Pressure effects

- **Characterisation of instruments**
- **Guidelines for laboratories**
- **Laboratory comparison**

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

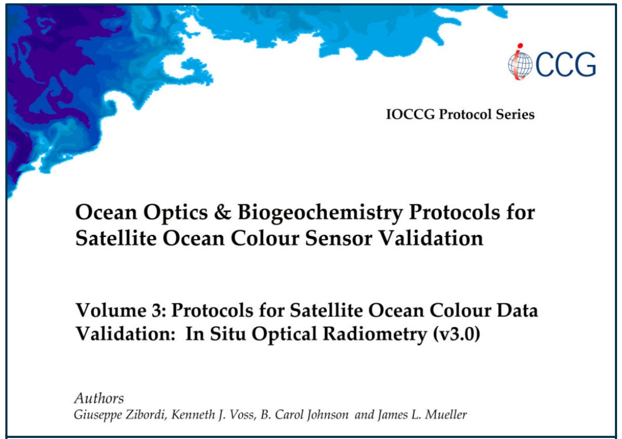


Issue recommendations for instrument manufacturers (e.g. need for internal

Tentative Cal/Char Schedule

Parameter	Scope	Type	Re-calibration	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/class specific	Recommended	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	individual/class specific	Recommended	after repair in workshop	IR4
8. Accuracy of integration times	individual/class specific	Recommended	after repair in workshop	IR4
9. Dark signal	individual	Required	1 year	IR7
10. Thermal sensitivity	individual/class specific	Required	after repair in workshop	IR5
11. Polarisation sensitivity	individual/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/class specific	Recommended	1 year	-
15. Pressure effects	TBD	TBD	TBD	-

OCR FRM Measurement ~~Methods~~ Procedures

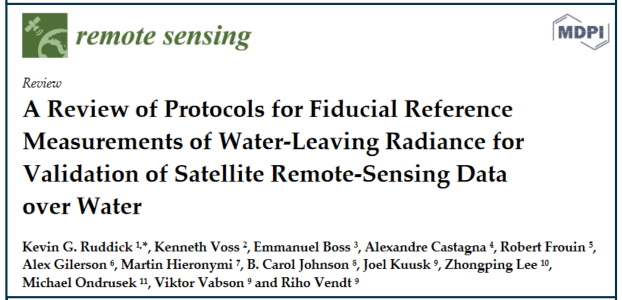

CCG

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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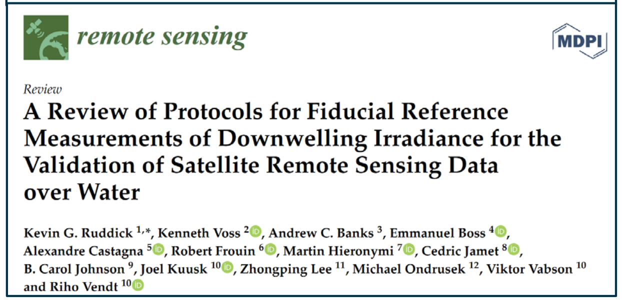
Review

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]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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]

`According to VIM (International Vocabulary of Metrology)…`

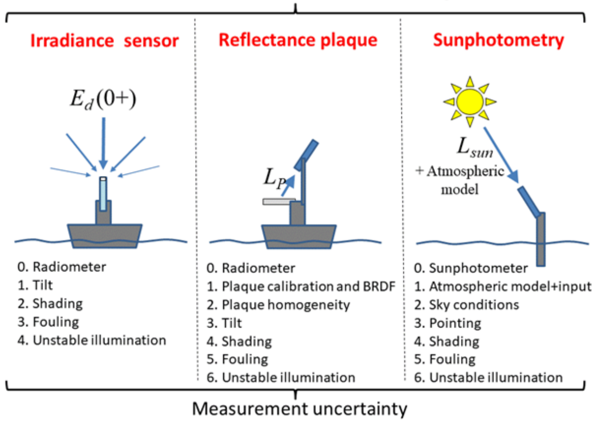
`Measurement Procedure: a detailed description of a measurement according to one or more measurement principles and to a given measurement method, based on a measurement model and including any calculation to obtain a measurement result.`

Re-elaboration of the IOCCG and FRM4SOC-1 protocols, in form of clear and prescriptive guidelines

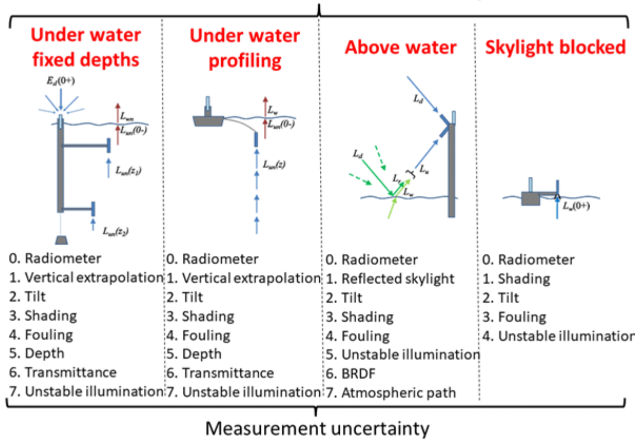
Detailed procedures vs. generalistic protocols:

Standardisation is strengthened, but at the risk of becoming **easily obsolete with the evolution** of the instruments

Fiducial Reference Measurements of downwelling irradiance



Fiducial Reference Measurements of water-leaving radiance



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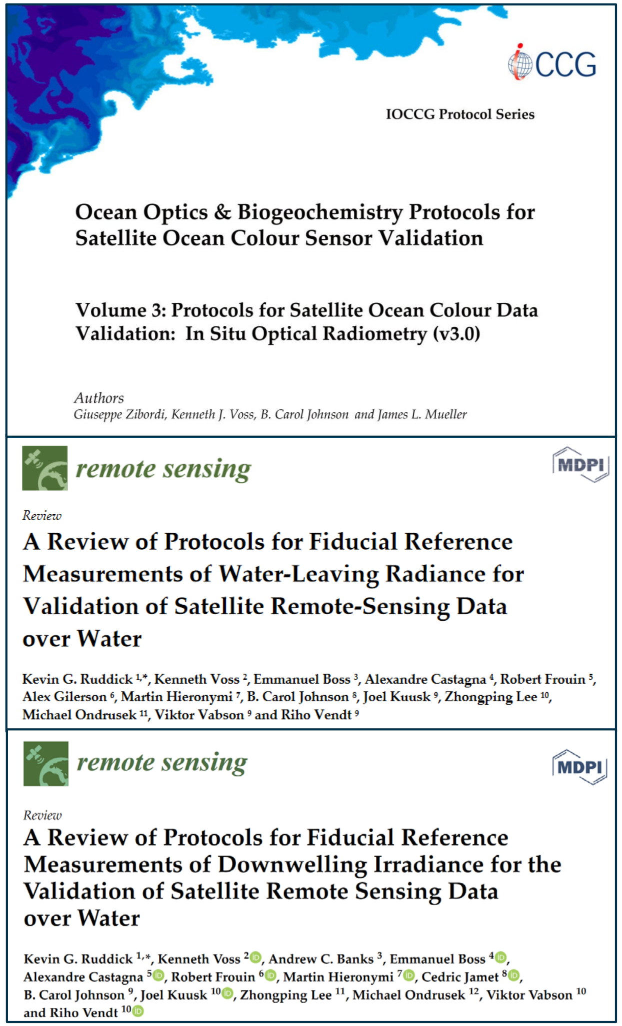
OCR FRM Measurement ~~Methods~~ Procedures



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Potential **updates** as a result of laboratory activities

- e.g. *request* integration times (~8 s) to take dark to derive internal temperature of TriOS:

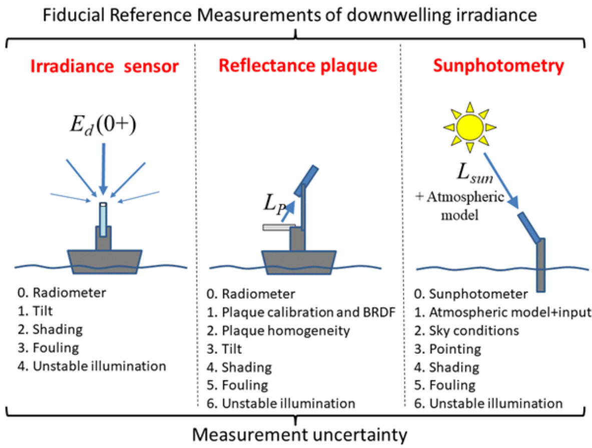
Internal temperature

$$\boxed{T = C_1 ln\left(\frac{\Delta D}{C_2}\right)}$$

$$\Delta D = D(8192\ \text{ms}) - D(4\ \text{ms})$$

$$C_1 = \frac{1}{0.147} \approx 6.8$$

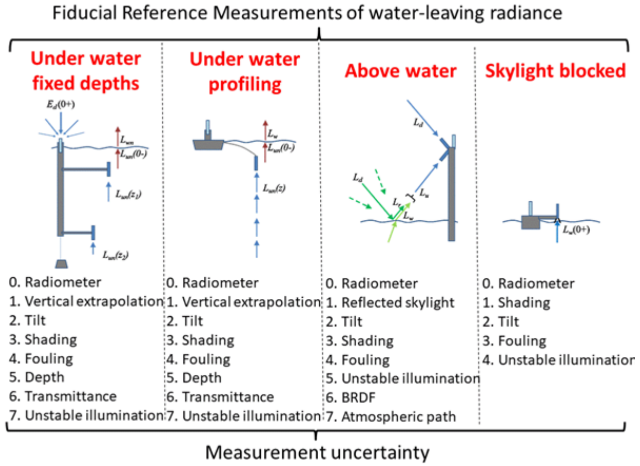
$$C_2 = 50 \pm 3.$$



Fiducial Reference Measurements of downwelling irradiance

Irradiance sensor	Reflectance plaque	Sunphotometry
0. Radiometer	0. Radiometer	0. Sunphotometer
1. Tilt	1. Plaque calibration and BRDF	1. Atmospheric model+inputs
2. Shading	2. Plaque homogeneity	2. Sky conditions
3. Fouling	3. Tilt	3. Pointing
4. Unstable illumination	4. Shading	4. Shading
	5. Fouling	5. Fouling
	6. Unstable illumination	6. Unstable illumination

Measurement uncertainty



Fiducial Reference Measurements of water-leaving radiance

Under water fixed depths	Under water profiling	Above water	Skylight blocked
0. Radiometer	0. Radiometer	0. Radiometer	0. Radiometer
1. Vertical extrapolation	1. Vertical extrapolation	1. Reflected skylight	1. Shading
2. Tilt	2. Tilt	2. Tilt	2. Tilt
3. Shading	3. Shading	3. Shading	3. Fouling
4. Fouling	4. Fouling	4. Fouling	4. Unstable illumination
5. Depth	5. Depth	5. Unstable illumination	
6. Transmittance	6. Transmittance	6. BRDF	
7. Unstable illumination	7. Unstable illumination	7. Atmospheric path	

Measurement uncertainty

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Community Processor (CP)

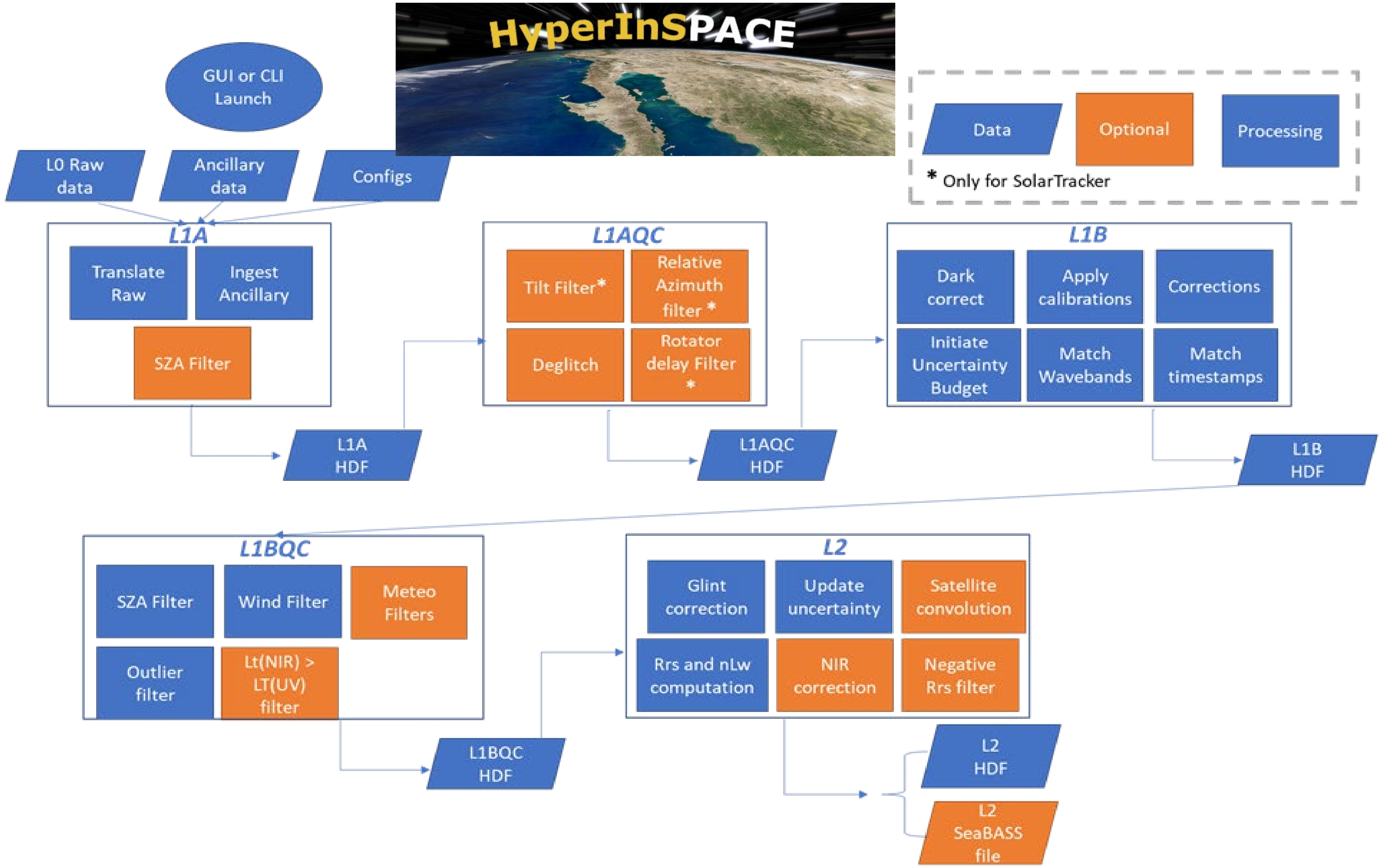
Community processor for in situ data processing and uncertainty budget calculation

Cooperation with **NASA** (HyperInSPACE)

- Currently supports
  Sea-Bird Scientific HyperSAS packages

Adding functionalitiy for:

- TriOS RAMSES data;
- Corrections and uncertainties from OCR characterisation;
- Full end-to-end uncertainty calculation;
- Command Line Interface (CLI).

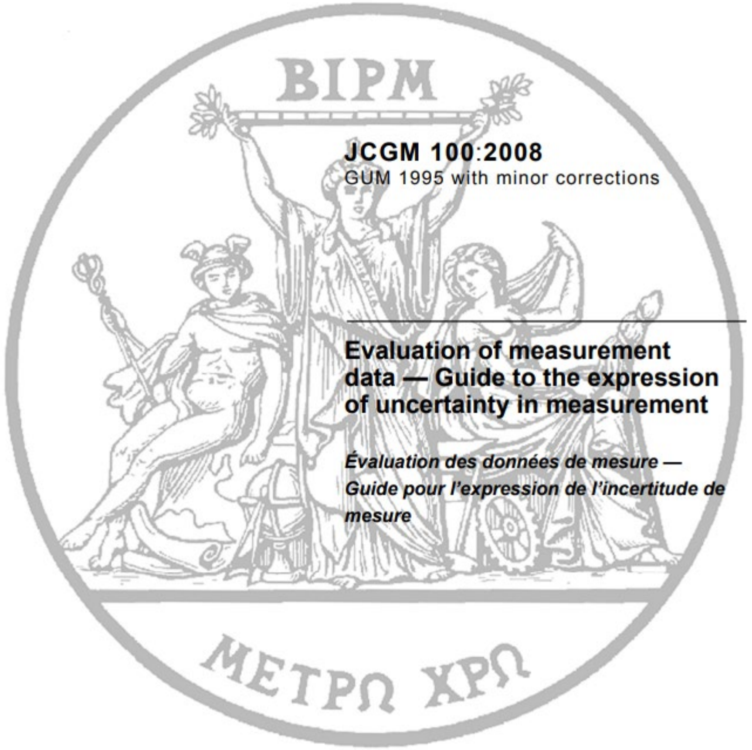


`SI-traceable remote sensing reflectance with related measure`

Uncertainty budgets

Elaboration of the FRM4SOC Phase 1 uncertainty budgets

- Conclude end-to-end uncertainty budgets for
  - remote sensing reflectance,
  - fully normalised water-leaving radiance.
- Address uncertainty components not considered in FRM4SOC Phase 1
  - e.g. environment effects:
    - ambient temperature,
    - sky radiance cosine error,
    - polarisation,
    - structure shading,
    - sun-glint, wave focusing
- Implementation of uncertainty calculations in the Community processor
- Easy and practical guidelines for uncertainty calculation.



BIPM

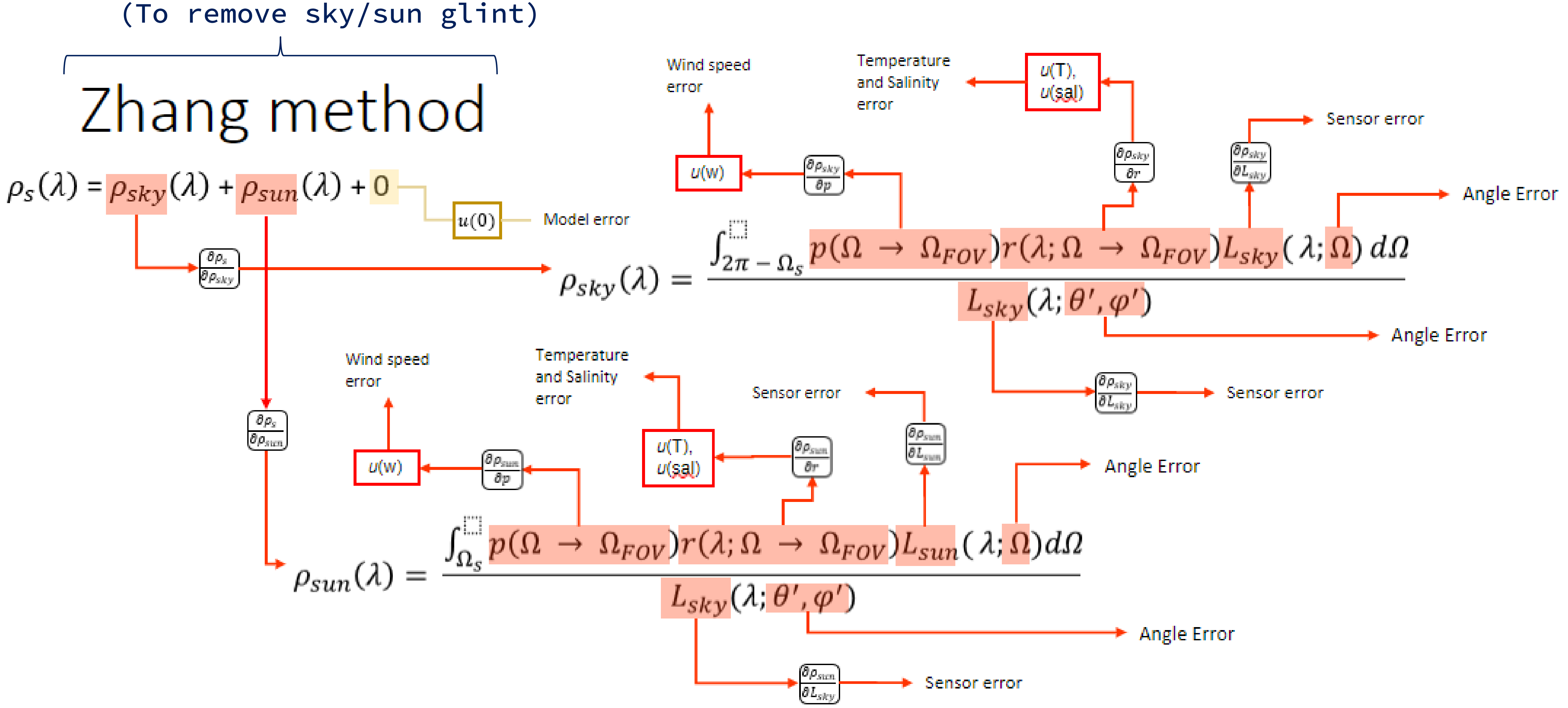
JCGM 100:2008
GUM 1995 with minor corrections

Evaluation of measurement data — Guide to the expression of uncertainty in measurement

Évaluation des données de mesure — Guide pour l'expression de l'incertitude de mesure

ΜΕΤΡΩ ΧΡΩ

Uncertainty budgets: example of added uncertainty tree



(To remove sky/sun glint)

Zhang method

$$\rho_s(\lambda) = \rho_{sky}(\lambda) + \rho_{sun}(\lambda) + 0$$

$$\rho_{sky}(\lambda) = \frac{\int_{2\pi-\Omega_s} p(\Omega \to \Omega_{FOV})\, r(\lambda;\Omega \to \Omega_{FOV})\, L_{sky}(\lambda;\Omega)\, d\Omega}{L_{sky}(\lambda;\theta',\varphi')}$$

$$\rho_{sun}(\lambda) = \frac{\int_{\Omega_s} p(\Omega \to \Omega_{FOV})\, r(\lambda;\Omega \to \Omega_{FOV})\, L_{sun}(\lambda;\Omega)\, d\Omega}{L_{sky}(\lambda;\theta',\varphi')}$$

FRM4SOC-2 [**Work in progress**]

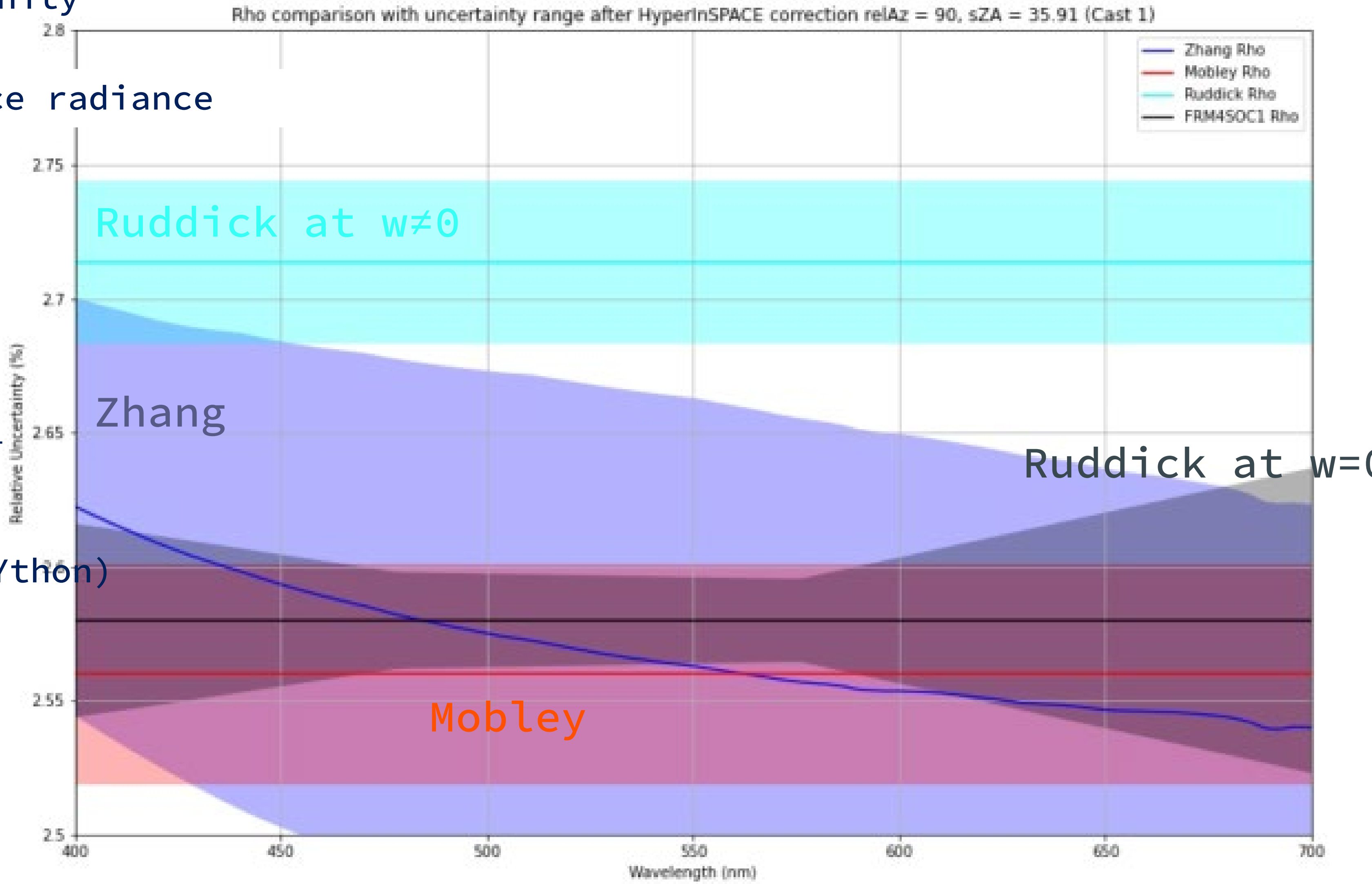
Uncertainty budgets

Main objective:

- Identify the larger sources of uncertainty in order to prioritise efforts and establish recommendations to the OC community

e.g. Uncertainty on the surface radiance reflectance (ρ_{sky}) factor

Obtained with *punpy*
(Propagating UNcertainties in PYthon)



Ocean Colour In-Situ Database (OCDB)

Brockmann Consult GmbH

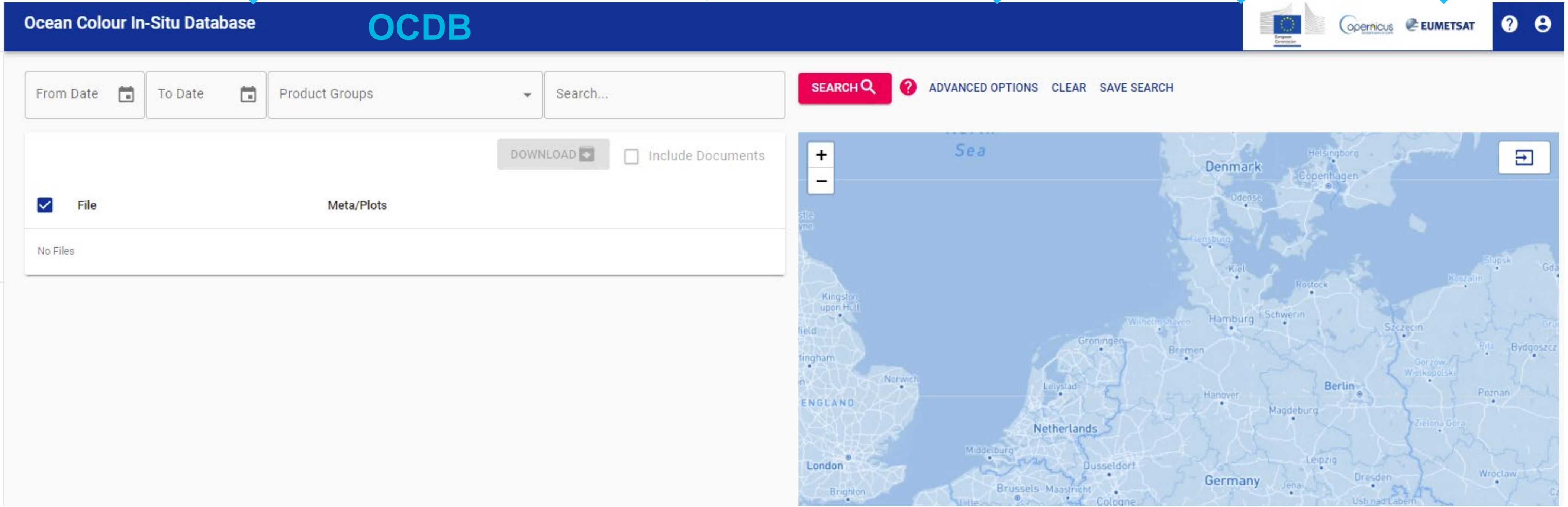
Community Processor

Data from cruises
S3VT-OC members

AERONET-OC

MOBY

BGC Argo



No Files

https://ocdb.eumetsat.int/

Data users

FRMOCnet: a network of radiometric "FRM-certified" measurements

Network of radiometric measurements with the FRM certification (FRMOCnet)

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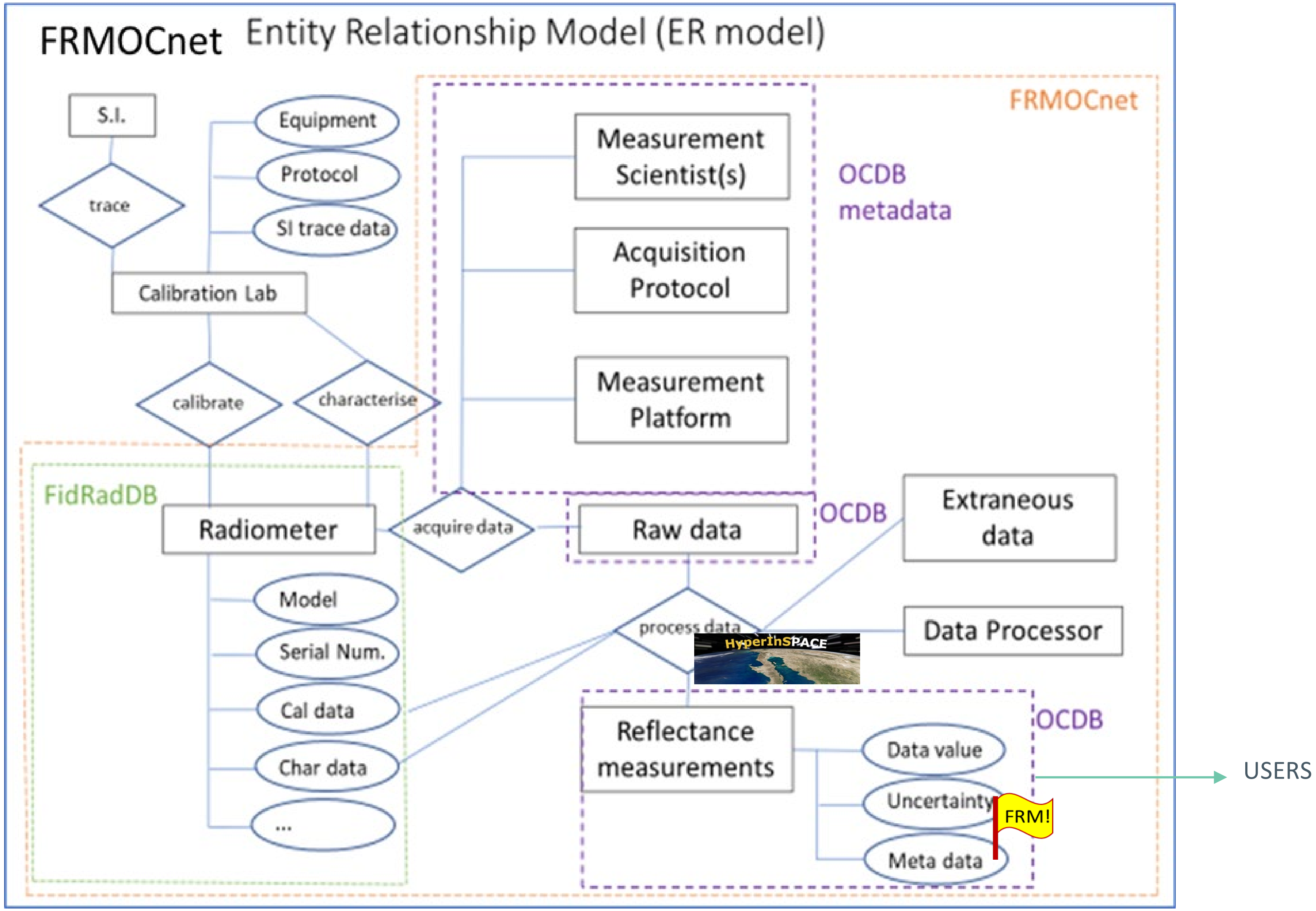


Field Inter-Comparison Exercise

11-20 July 2022, at

Acqua Alta Oceanographic Tower (AAOT), Venice, Italy.

Critical review, testing, and feedback on

- FRMOCnet;
- measurement protocols;
- Community processor;
- SI traceability;
- Application of instrument characterisation;
- Uncertainty budgets;
- Aimed uncertainty levels.

PML | Plymouth Marine Laboratory

Paricipating systems (7 institutes registered)
Above water: TRIOS RAMSES; TriOS RAMSES G2 sun tracker (SoRAD)
Hyper SAS with PySAS robot; HypSTAR

In-water: Sea-Bird HyperPro II; TriOS RAMSES floating buoy.

Water type: Optical Case 1 (clear open sea waters) 60% of the year (Zibordi et al., 2009b); 40% optical Case 2 (turbid coastal) depending on river discharge from the surrounding catchment.

FRM4SOC-2, Project Workshop

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.

Funded by the European Union

Acknowledgements

FRM4SOC – ESA Project no. 4000117454/16/I-Sbo

fiducial reference measurements for satellite ocean colour

FRM4SOC - Phase-2 – EUMETSAT project no. EUM/CO/21/460002539/JIG

Funded by the European Union

Copernicus Cal/Val Solution (CCVS) funded by the European Union's Horizon 2020 research and innovation programme under grant agreement no. 101004242

This project is funded by the European Union

Thank you!

Questions are welcome.

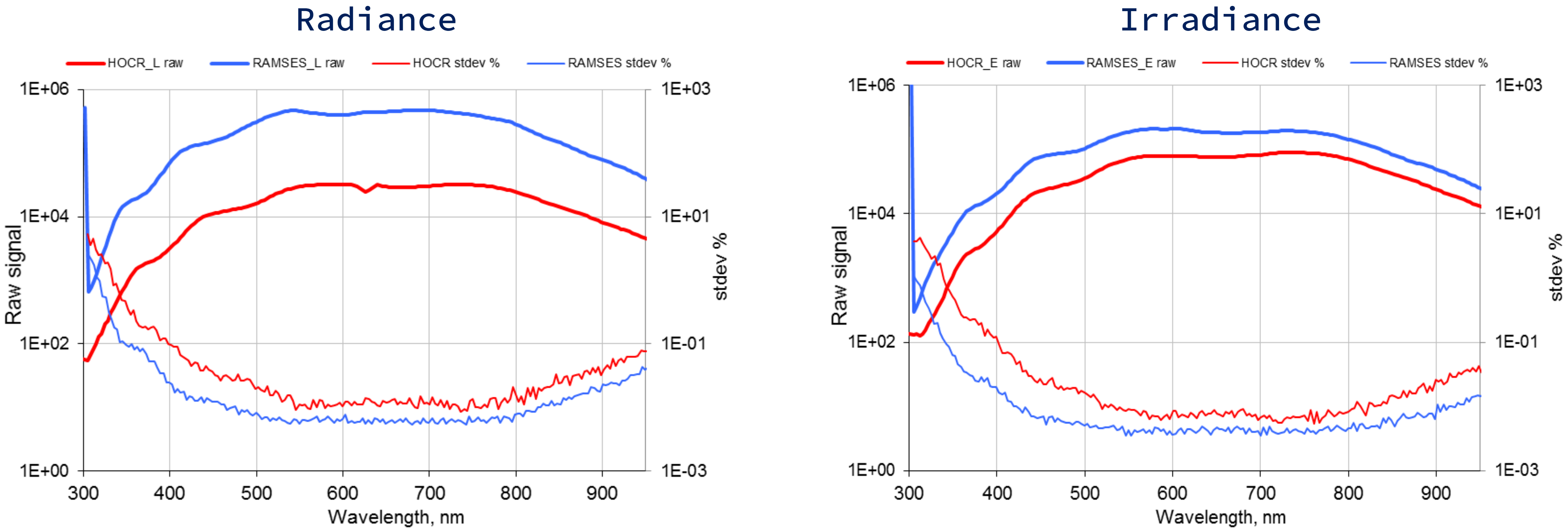
Characterization plan for OCRs

- Majority of the characterisations were carried out for (at least) four radiometers.
- Characterisations under stable laboratory conditions are in agreement with former results.
- The non-linearity of most sensors is temperature dependent
    - For the HyperOCR irradiance sensors, 10% at higher temperatures.

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

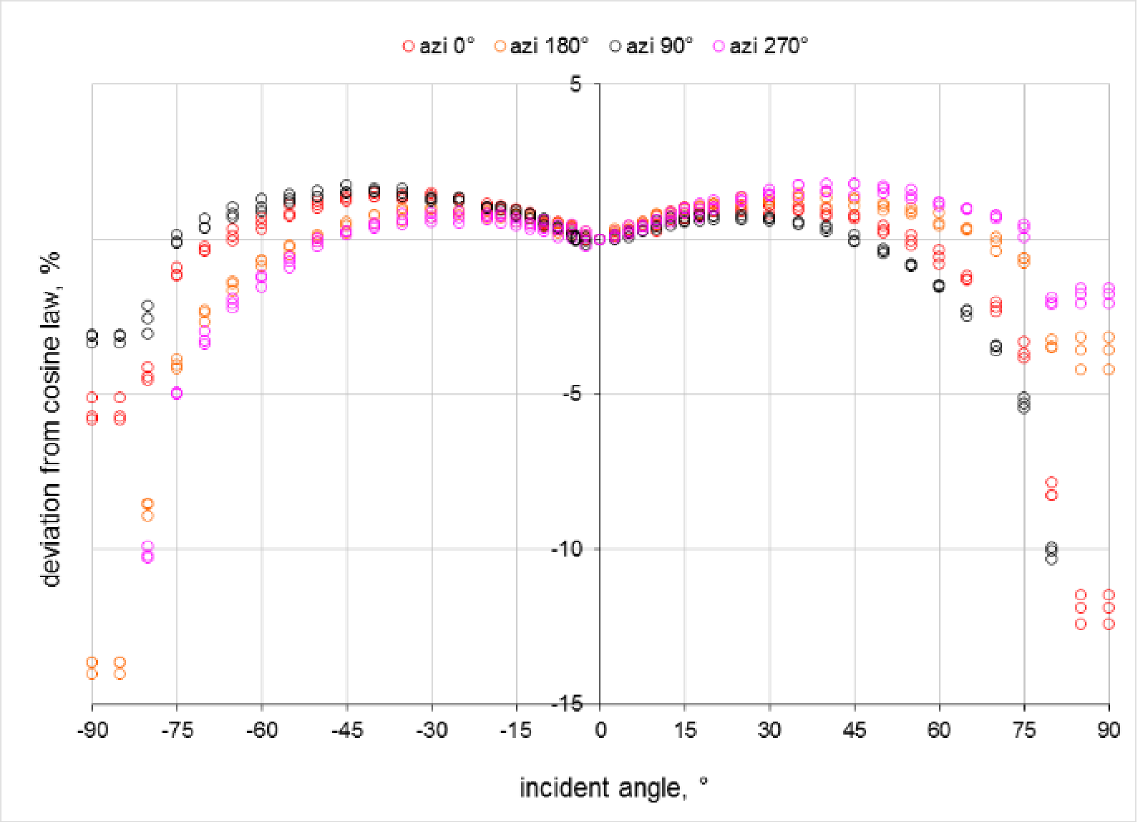
Major differences between selected models

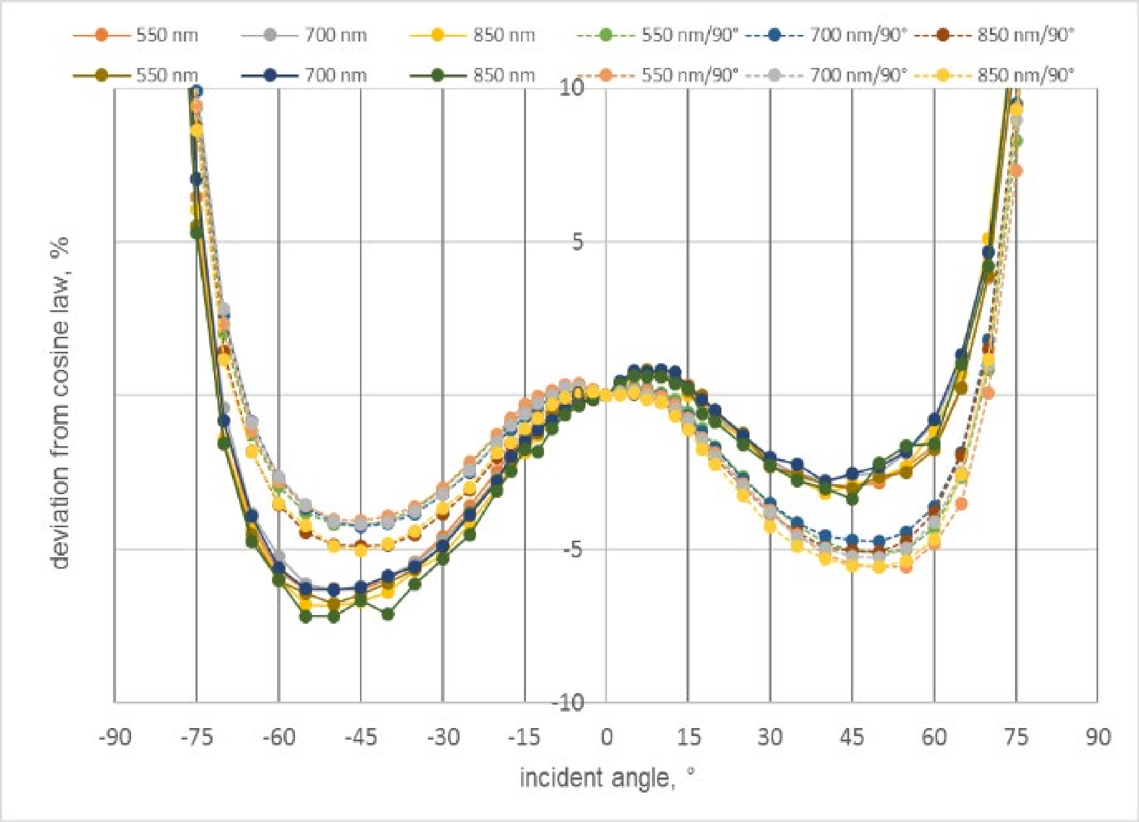
Raw signals and standard deviations of **RAMSES** and **HyperOCR** sensors during calibration measurements.



Angular response of irradiance sensors in air

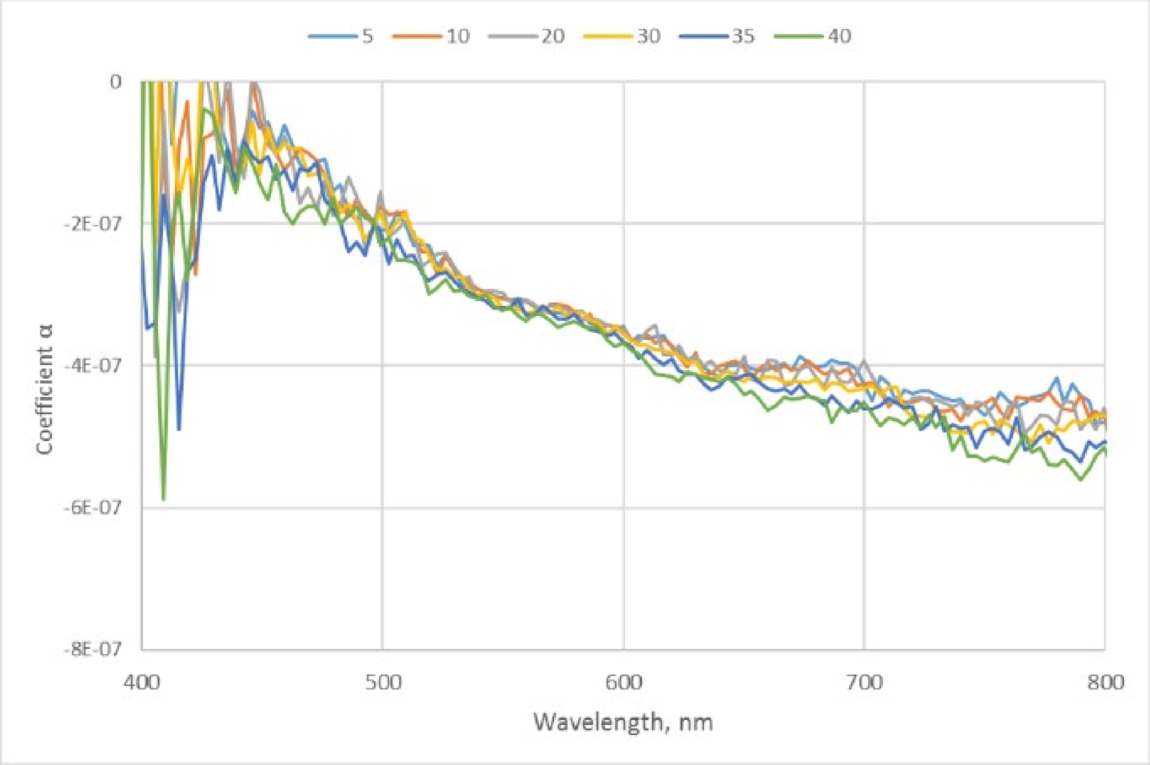
Deviation from the cosine law of **HyperOCR** (left) is usually smaller than the cosine error of **RAMSES** (right) sensors.



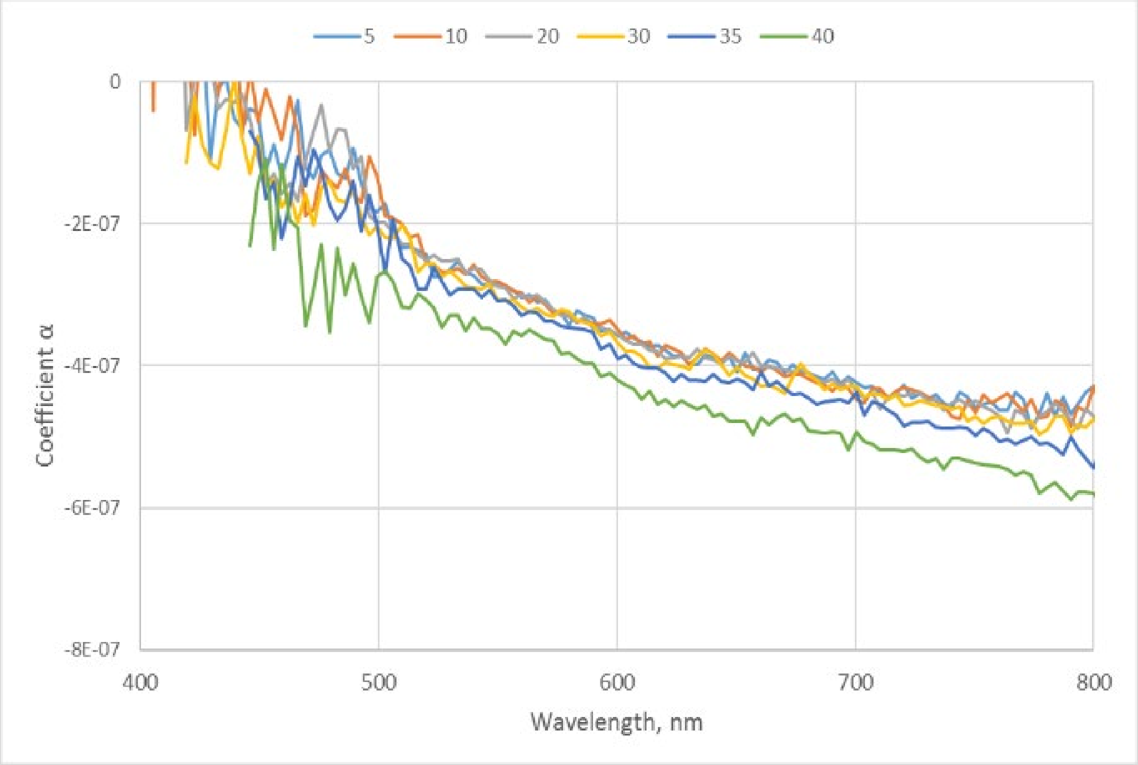


Non-linearity coefficient α for several temperatures [5ºC to 40ºC]

HyperOCR radiance sensor

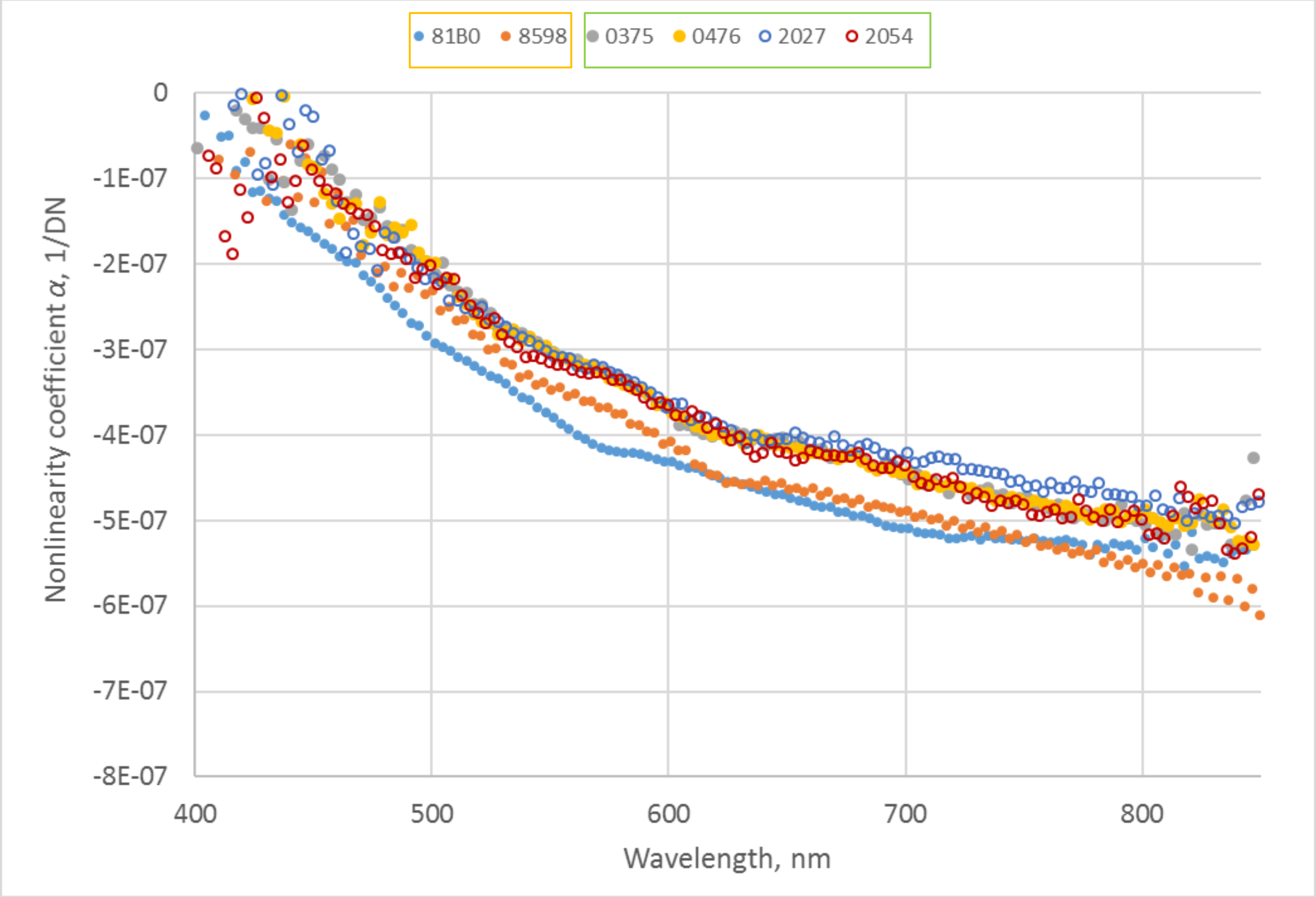


HyperOCR irradiance sensor



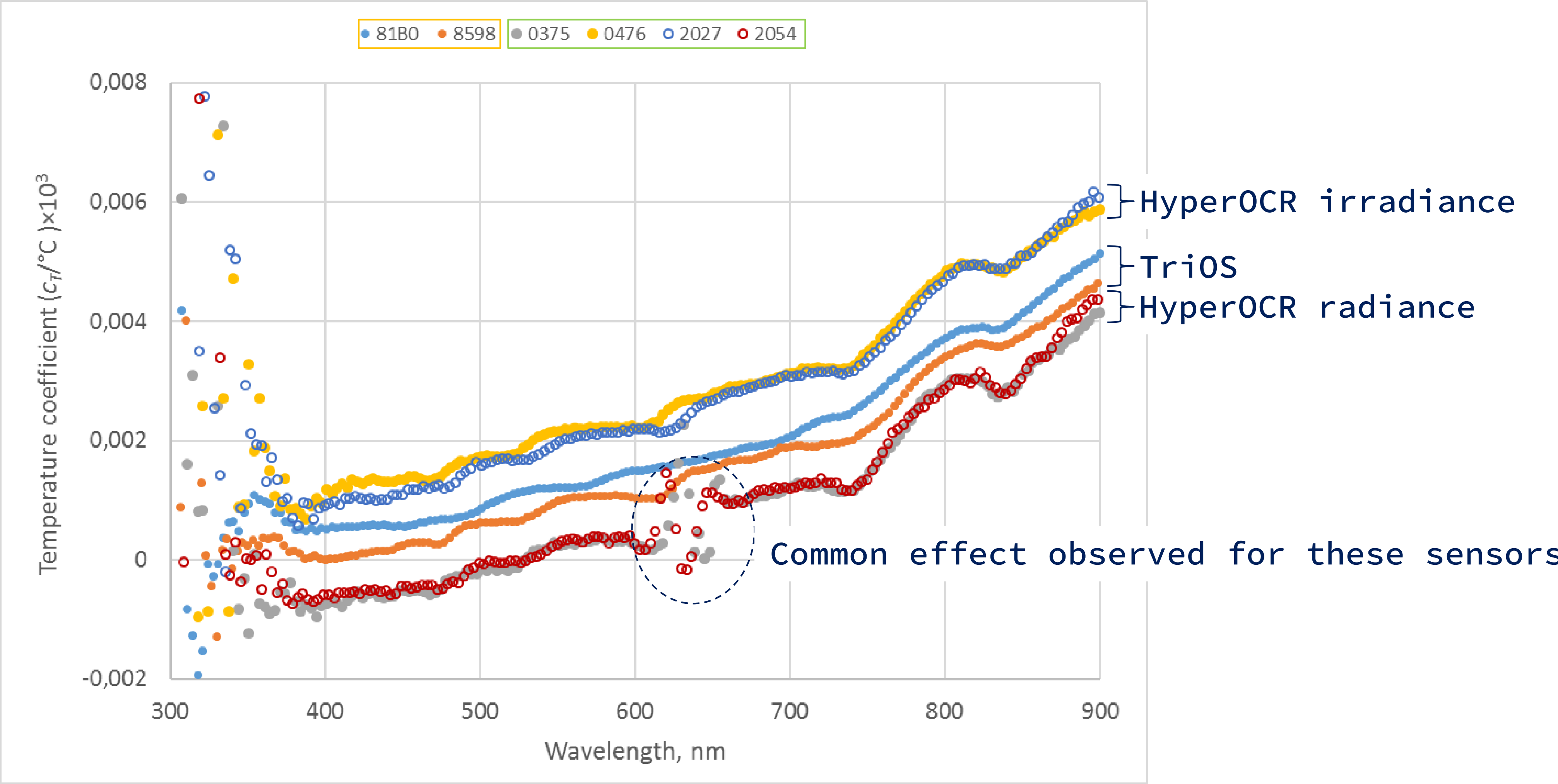
Coefficient α of RAMSES and HyperOCR sensors

Averaged non-linearity coefficient α of two **RAMSES** and four **HyperOCR** sensors (upper group)



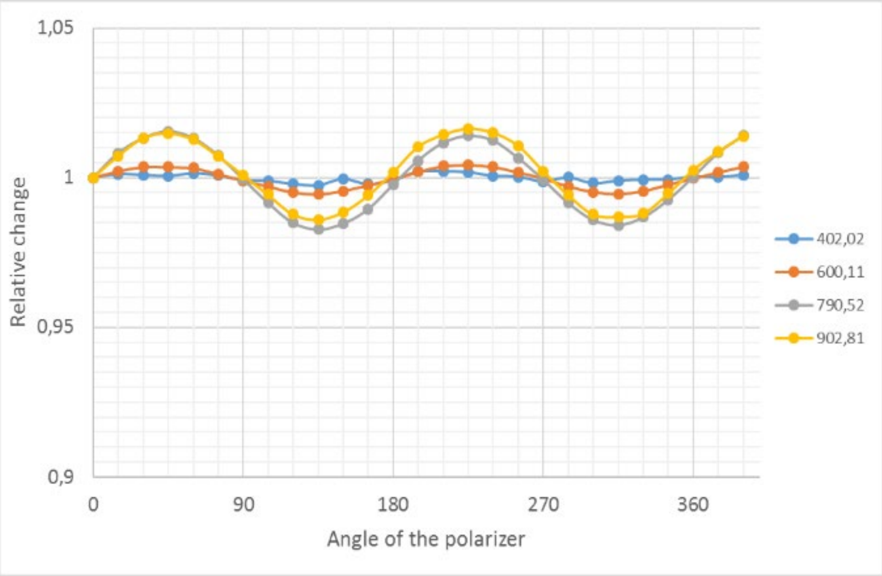
Thermal response

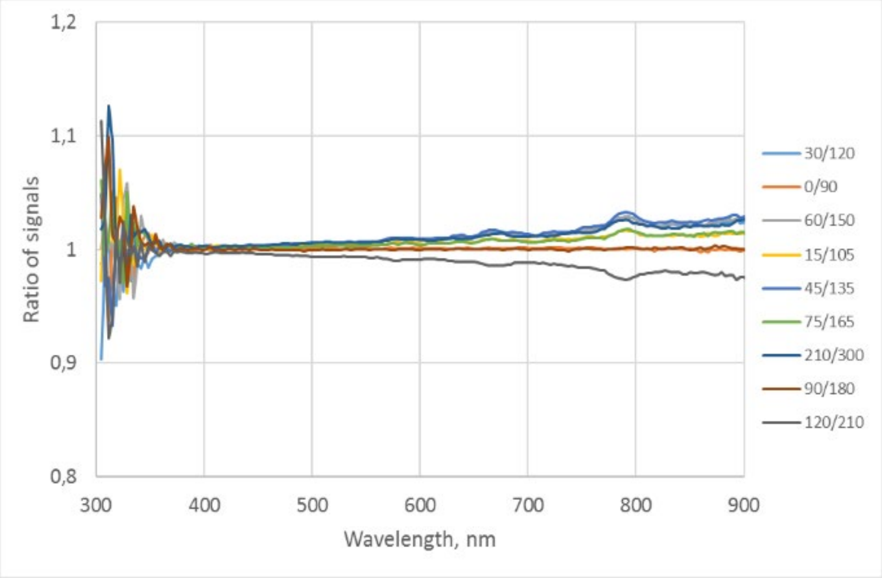
- Thermal coefficients of two RAMSES and four HyperOCR sensors after correction for non-linearity.
- Two lower curves belong to the HyperOCR radiance, and two upper curves to the HyperOCR irradiance sensors.
- Middle curves belong to the RAMSES radiance and irradiance sensor.



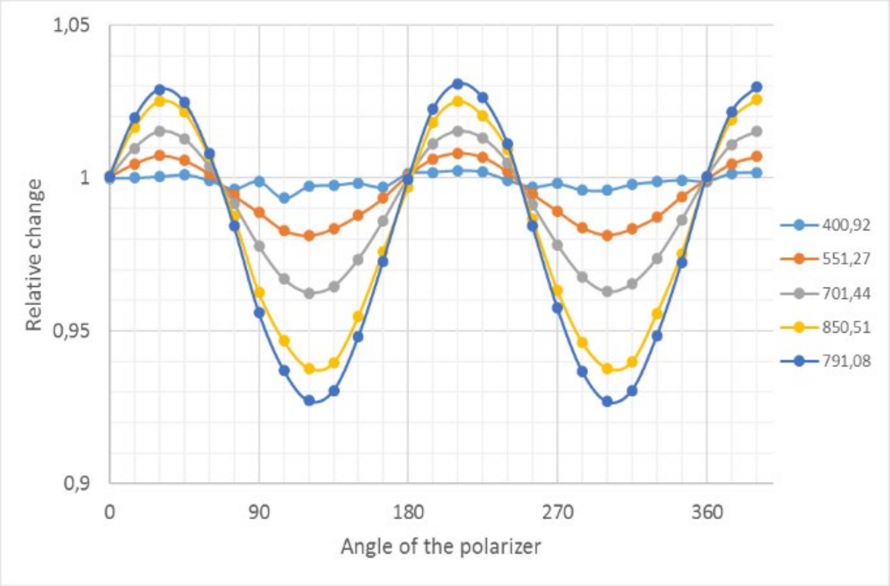
Relative polarisation effect as a function of angle and wavelength

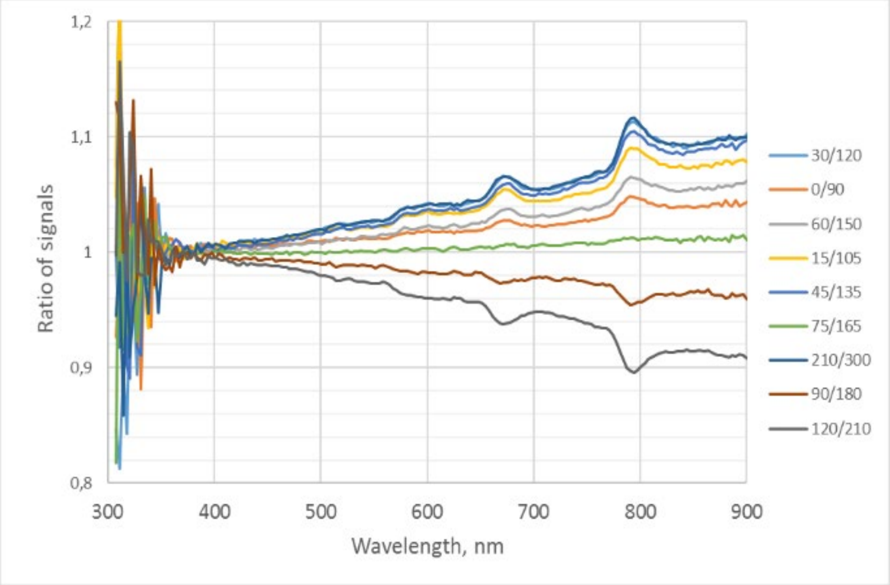
TriOS (RAMSES radiance sensor





HyperOCR (SeaBird) radiance sensor



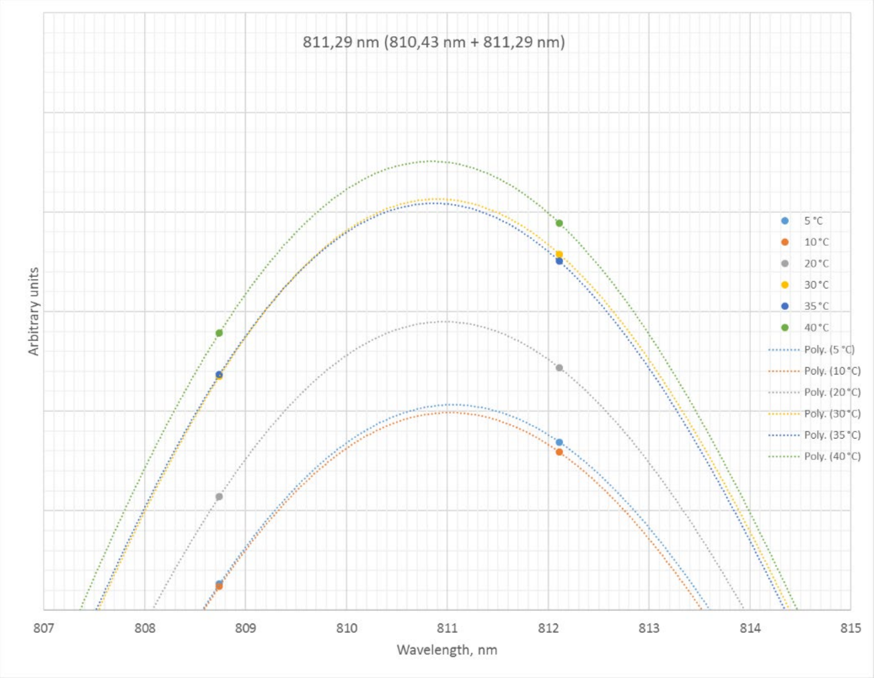


Polarimetric sensitivity: increasing with wavelength

- Results for TriOS are comparable to Talone and Zibordi 2016
- HyperOCR: also sensitivity increases with wavelength.
- HyperOCR higher sensitivity compared to TriOS.

Accuracy of wavelength scale

- Difference of measured wavelengths from Kr-lamp reference values.
- Differences found within the expectable range



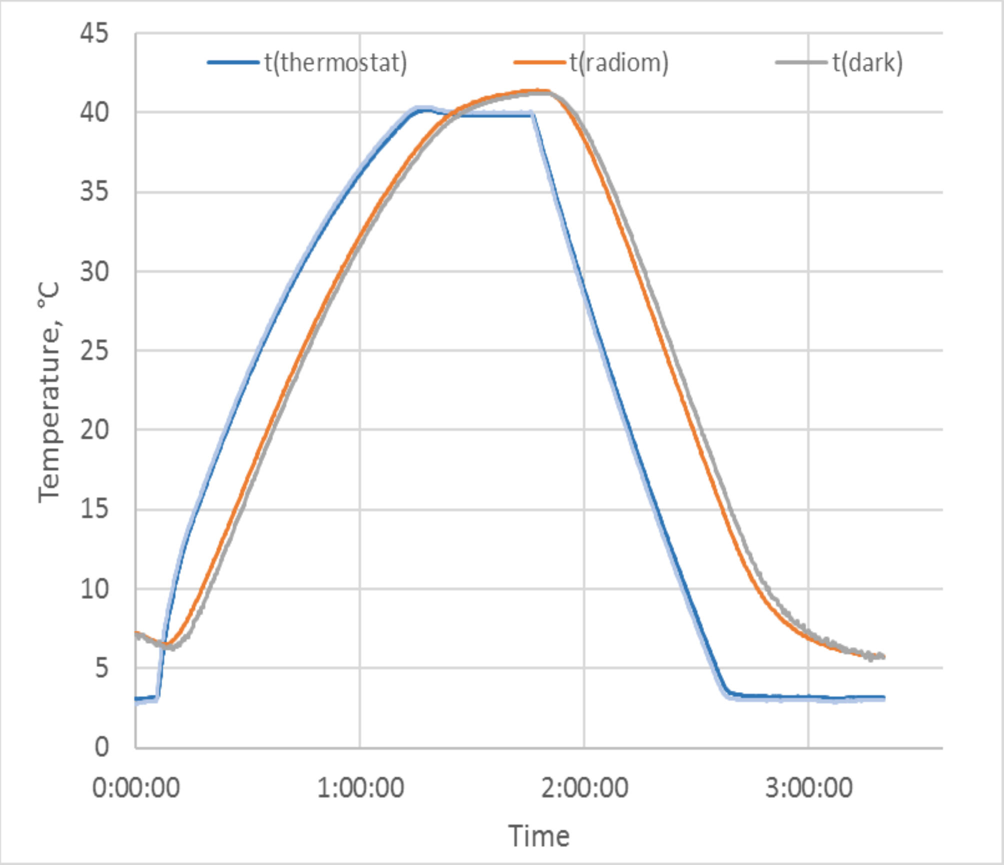
Name	**Temperature**	**λmeas**	**Δλ1**	**λmeas**	**Δλ2**	**λmeas**	**Δλ3**
RAMSES_L	5 °C	557	**0.12**	759.9	**0.05**	811.32	**0.19**
RAMSES_L	20 °C	556.9	**0.02**	759.95	**0.10**	811.3	**0.17**
RAMSES_L	40 °C	556.82	**-0.06**	759.82	**-0.03**	811.2	**0.07**
RAMSES_E	5 °C	556.75	**-0.13**	759.77	**-0.08**	811.05	**-0.08**
RAMSES_E	20 °C	556.6	**-0.28**	759.65	**-0.20**	811	**-0.13**
RAMSES_E	40 °C	556.7	**-0.18**	759.65	**-0.20**	810.87	**-0.26**
HyperOCR_L	5 °C	556.88	**0.00**	759.63	**-0.22**	810.9	**-0.23**
HyperOCR_L	20 °C	556.84	**-0.04**	759.72	**-0.13**	810.8	**-0.33**
HyperOCR_L	30 °C	556.95	**0.07**	759.82	**-0.03**	811.05	**-0.08**
HyperOCR_L	40 °C	556.72	**-0.16**	759.6	**-0.25**	810.75	**-0.38**
HyperOCR_E	5 °C	556.75	**-0.13**	759.82	**-0.03**	811.04	**-0.09**
HyperOCR_E	20 °C	556.62	**-0.26**	759.75	**-0.10**	810.95	**-0.18**
HyperOCR_E	40 °C	556.55	**-0.33**	759.64	**-0.21**	810.85	**-0.28**

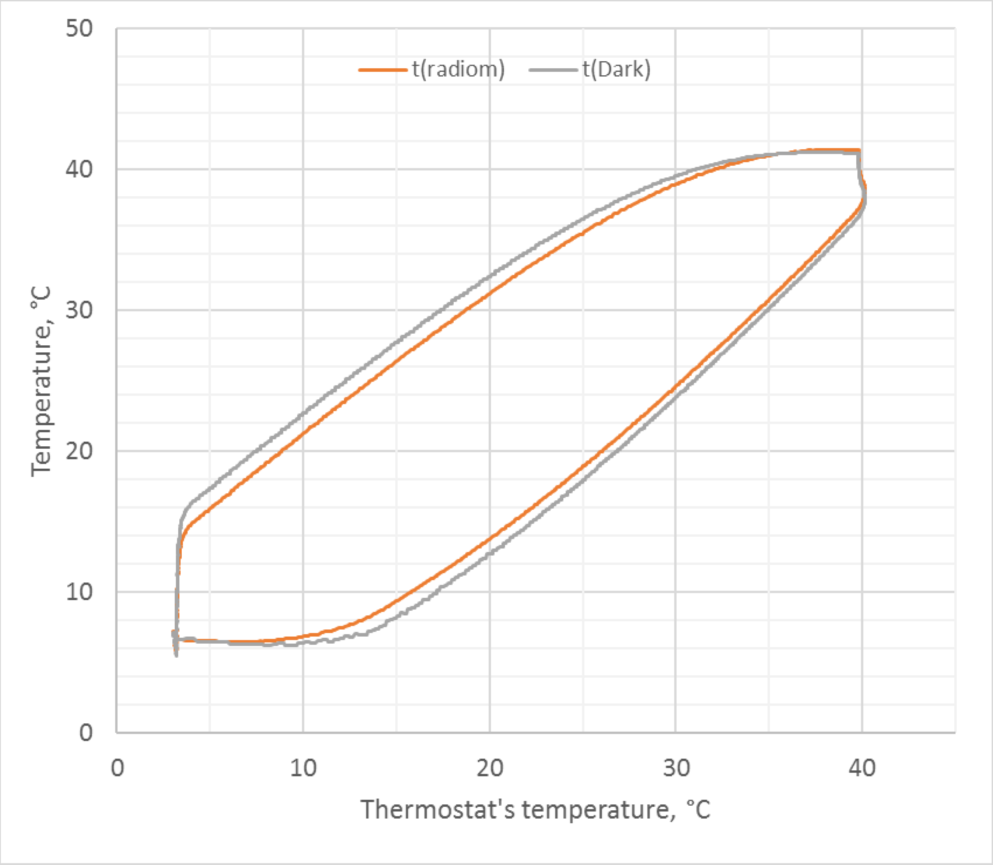
Effects from dynamic temperature change

- Dynamic tests in a thermostat have been performed to evaluate the possible effects from changing temperature on the radiometer signal by sweeping the temperature from 5 °C up to 40 °C and back down to 5 °C.
- A rather strong hysteresis of the optical signal is evident if measured data are presented as a function of the thermostat’s temperature.

Differences between temperature sensors

Time lags and differences between outside and internal temperature sensors.

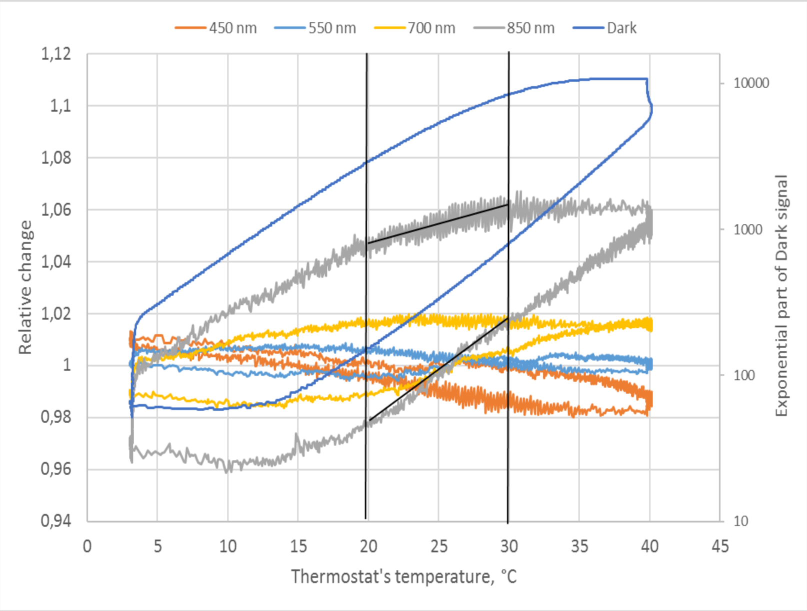




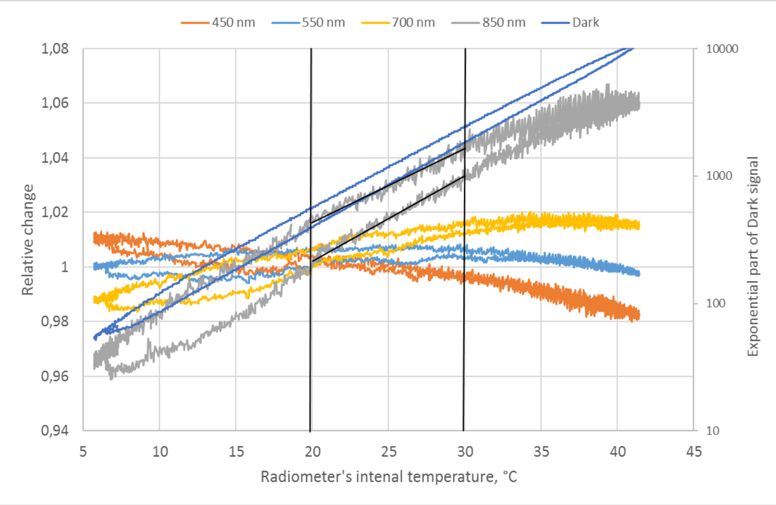
Relative change of signals due to temperature variation

HyperOCR radiance sensor

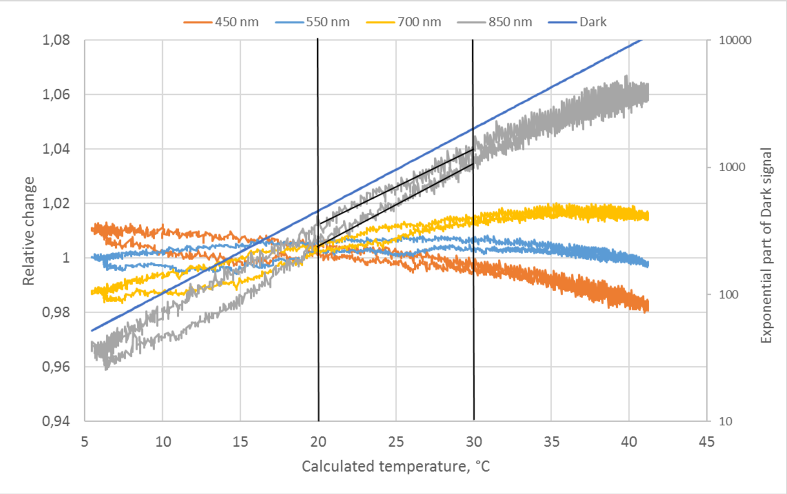
Thermostat’s temperature



Internal temperature

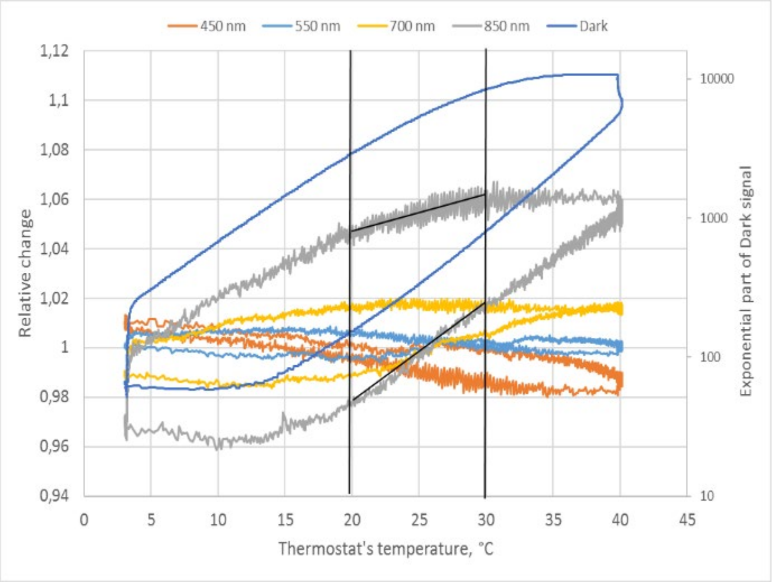


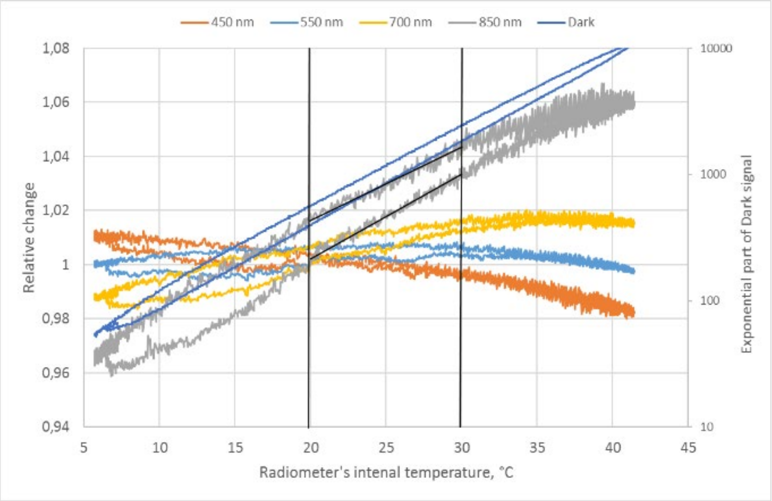
Calculated from dark signal



Dynamic temperature change

- Using thermostat’s temperature is similar to field measurements, where the temperature is obtained with an external temperature sensor, and uncertainty due to hysteresis can be larger than due to thermal responsivity.
- Hysteresis with the internal temperature sensor becomes significantly smaller, and uncertainty from temperature correction for 10 °C difference will clearly dominate.

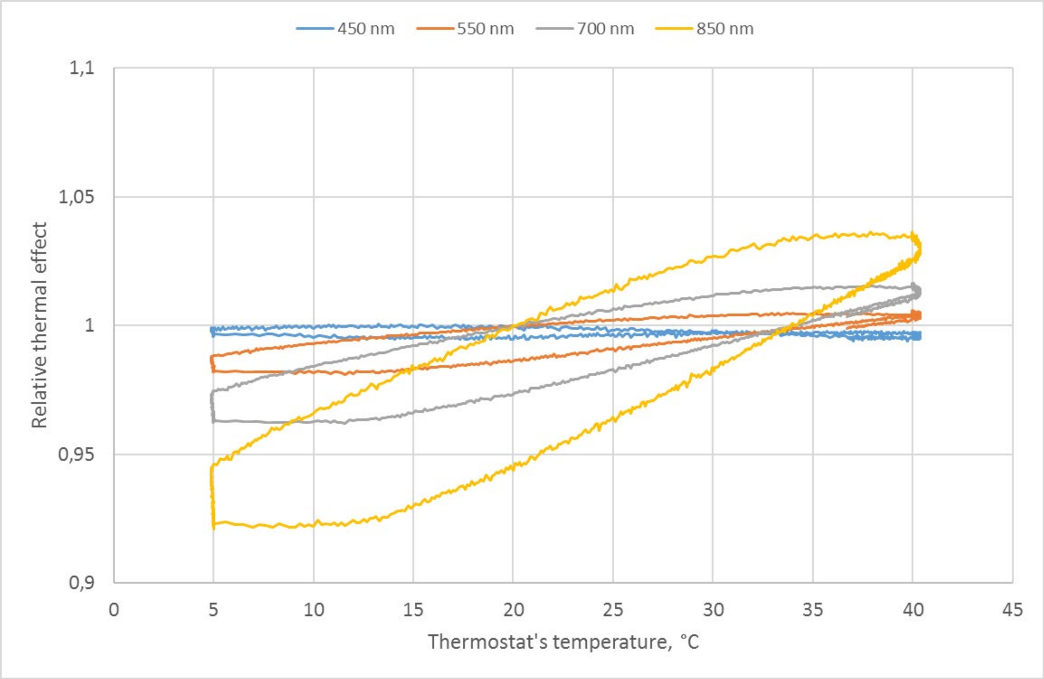




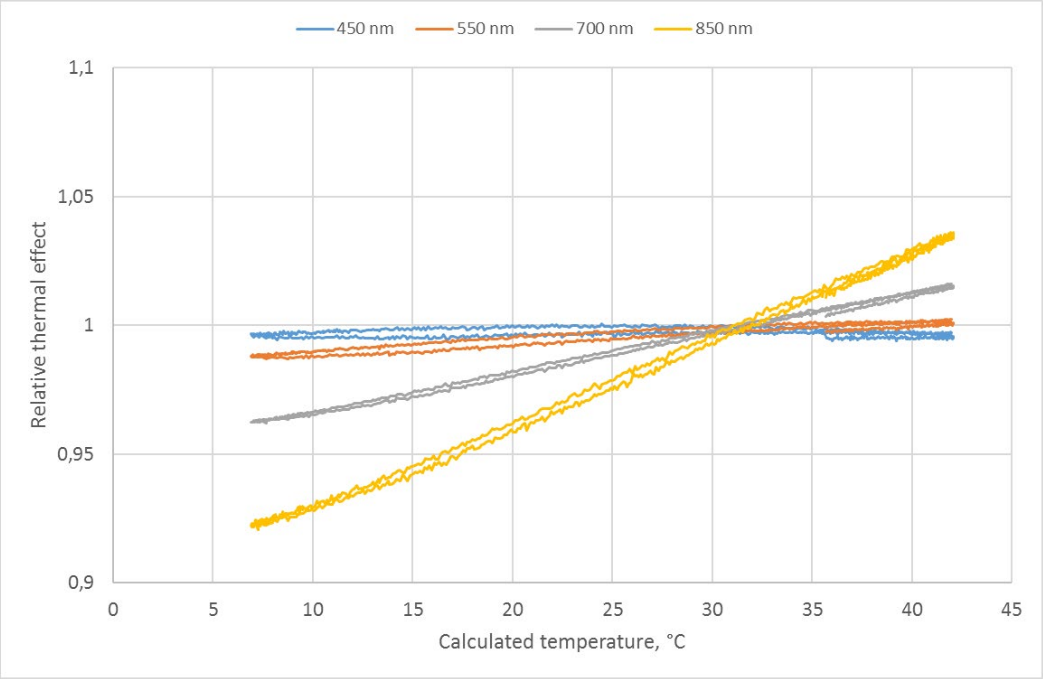
Hysteresis of a RAMSES radiance sensor

- Behavior of RAMSES and HyperOCR radiance sensors is similar.

Thermostat's temperature

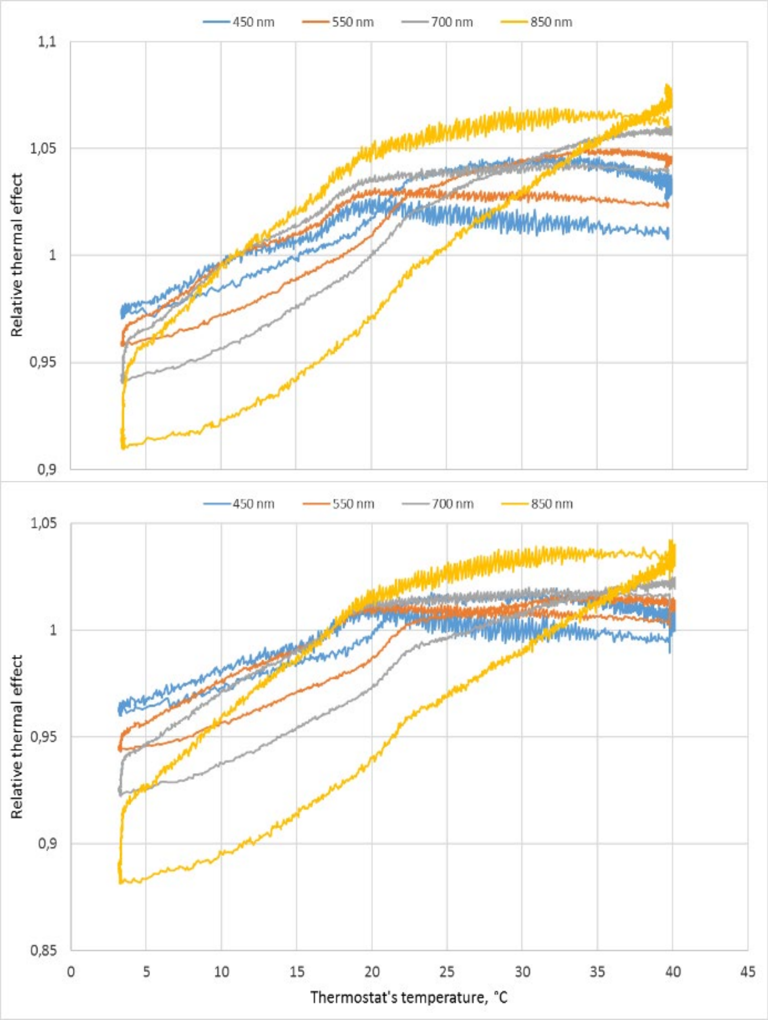


Calculated from dark signal

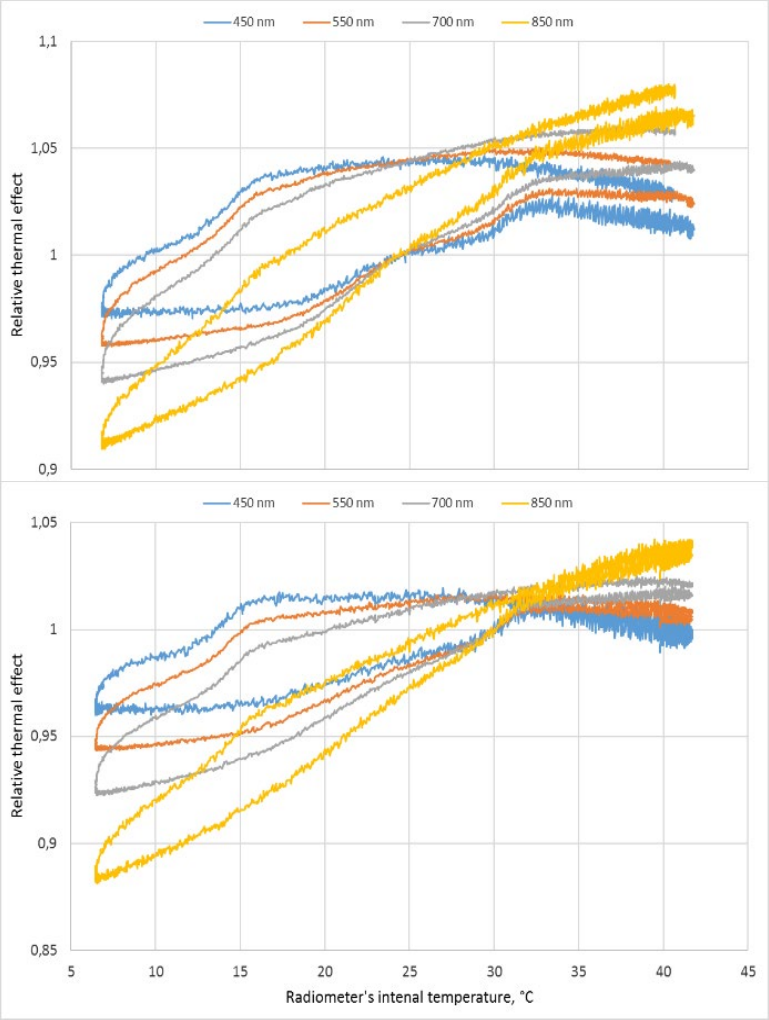


Hysteresis of two HyperOCR irradiance sensors

Thermostat’s temperature

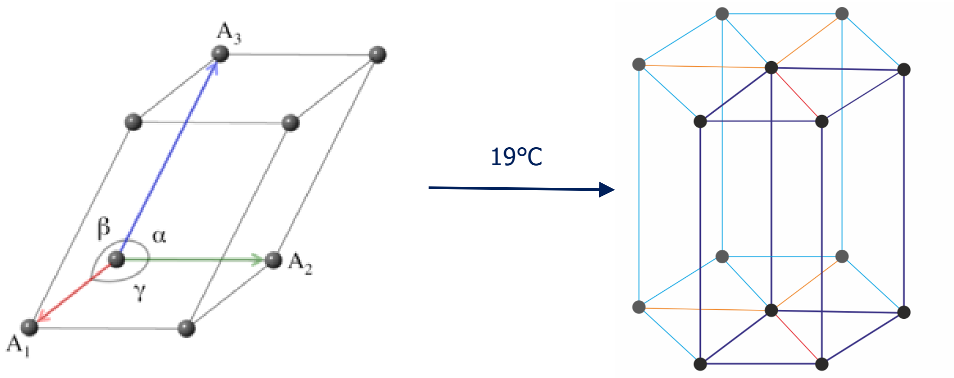


Internal temperature sensor



HyperOCR irradiance sensors

- Differently from other sensors, the hysteresis of the optical signal of a HyperOCR irradiance sensors did not decrease substantially if presented as a function of the internal temperature sensor.
- The likely reason is that the thermal response of the irradiance sensor is related to outer surface of the device – the cosine collector made of polytetrafluoroethylene (PTFE) – and not solely the optical sensor inside the radiometer.
- Transmittance of PTFE changes abruptly (1–3%) at ~19°C due to a phase shift of the crystal structure, *L. Ylianttila and J. Schreder, Optical Materials 27, 1811–1814 (2005)*



Triclinic **Hexagonal**

Dark signal

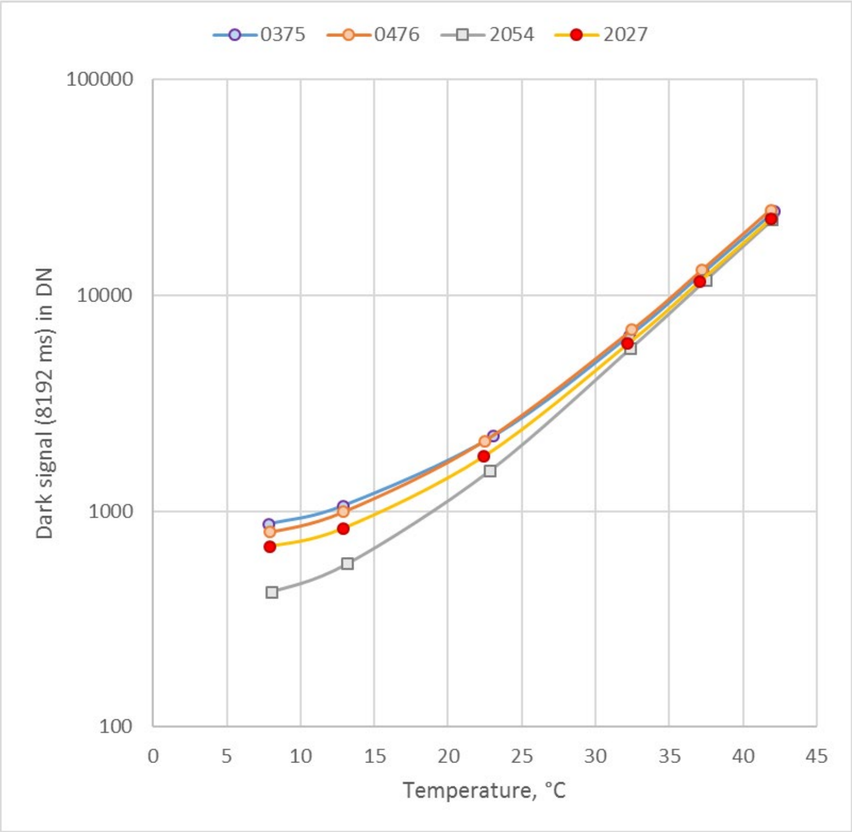
The output signal of the spectrometer is the sum of the target signal and the dark signal. The dark signal is the output signal when the optical entrance is closed.

Dark signal is the sum of two components:

1. Dark current of the detector element, which depends exponentially on the detector's temperature and is proportional to the integration time;
2. Dark current due to additional contributions such as offset of an amplifier circuit.

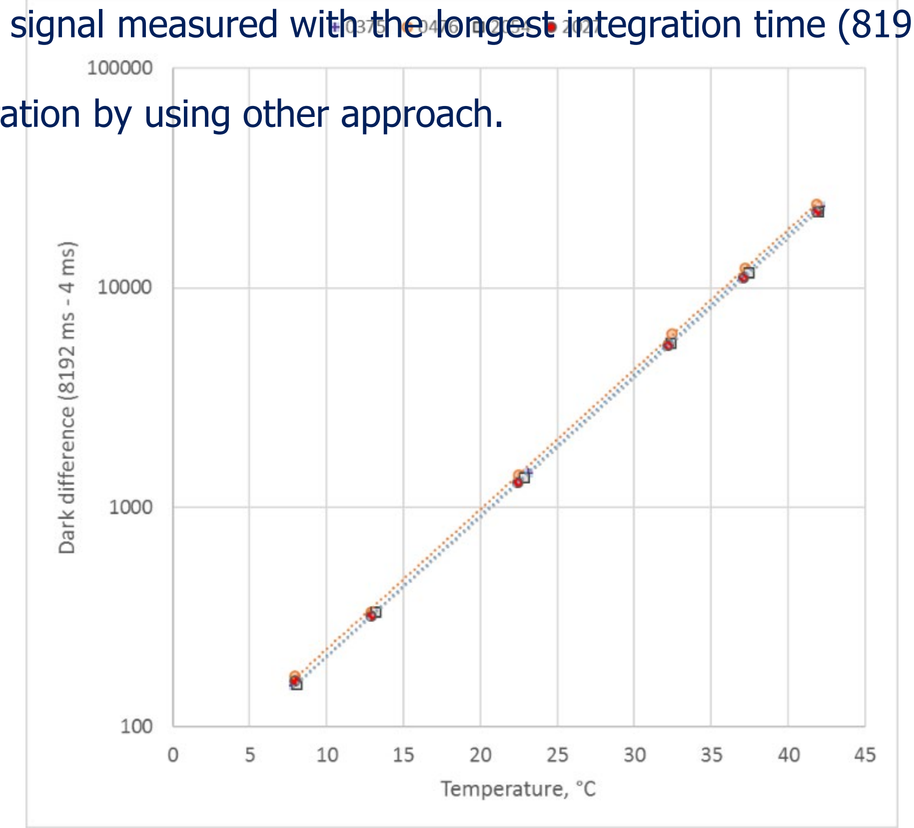
Dark signal of HyperOCR with 8192 ms integration time

- The dark signal determined at 8192 ms integration time as a function of temperature for four HyperOCR radiometers.
- Although the temperature dependence is relatively strong, it is difficult to use such a curve for direct evaluation of the sensor's temperature, as for that inverse function is needed.



Exponential part of the dark signal

- For HyperOCR sensors, we found an easy method for the effective separation of two dark components.
- Dark signal measured with the shortest integration time (4 ms) is subtracted from the dark signal measured with the longest integration time (8192 ms).
- Similar exponential dependence can also be observed for RAMSES sensors after dark separation by using other approach.



Sensor's temperature estimated from the dark signal

The temperature of the sensor can be determined from the difference in dark signals at different integration times:

Internal temperature

$$\boxed{\boldsymbol{T} = \boldsymbol{C_1} \, ln\left(\frac{\boldsymbol{\Delta D}}{\boldsymbol{C_2}}\right)}$$

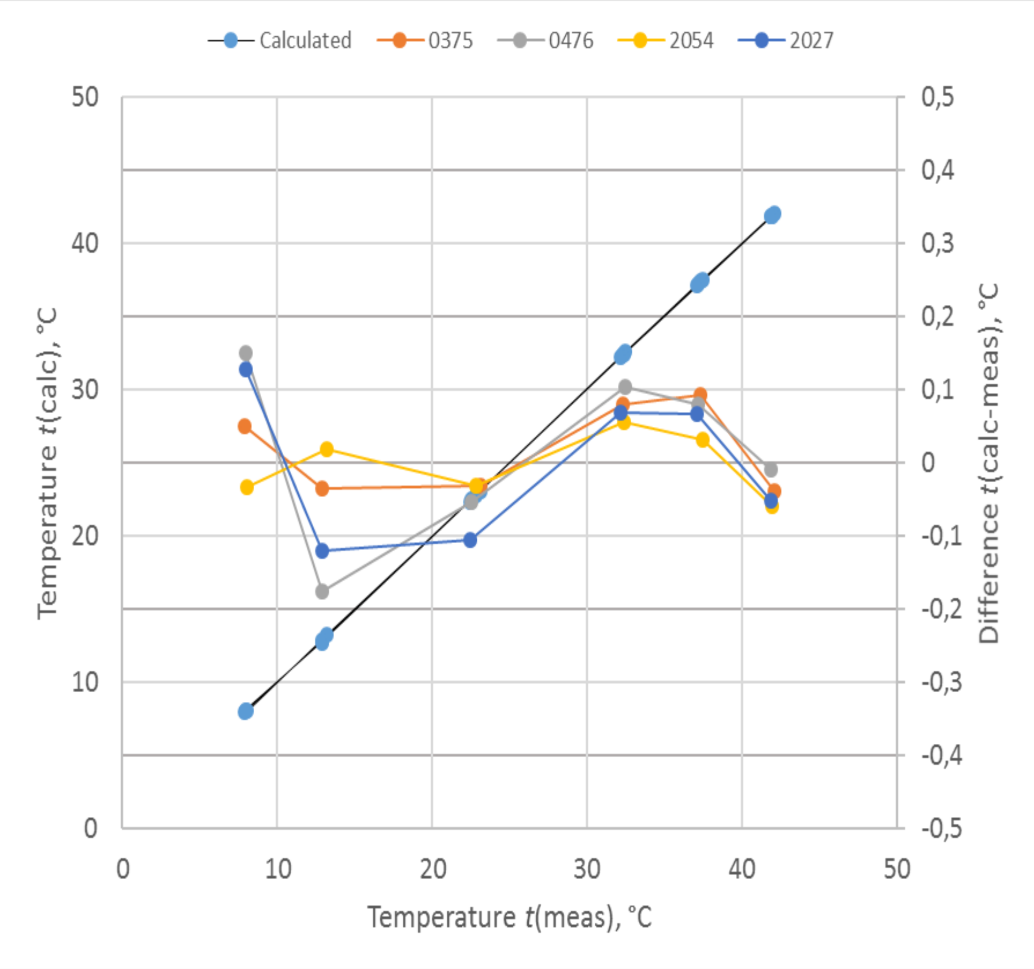
$$\boldsymbol{\Delta D} = D(8192\ \mathrm{ms}) - D(4\ \mathrm{ms})$$

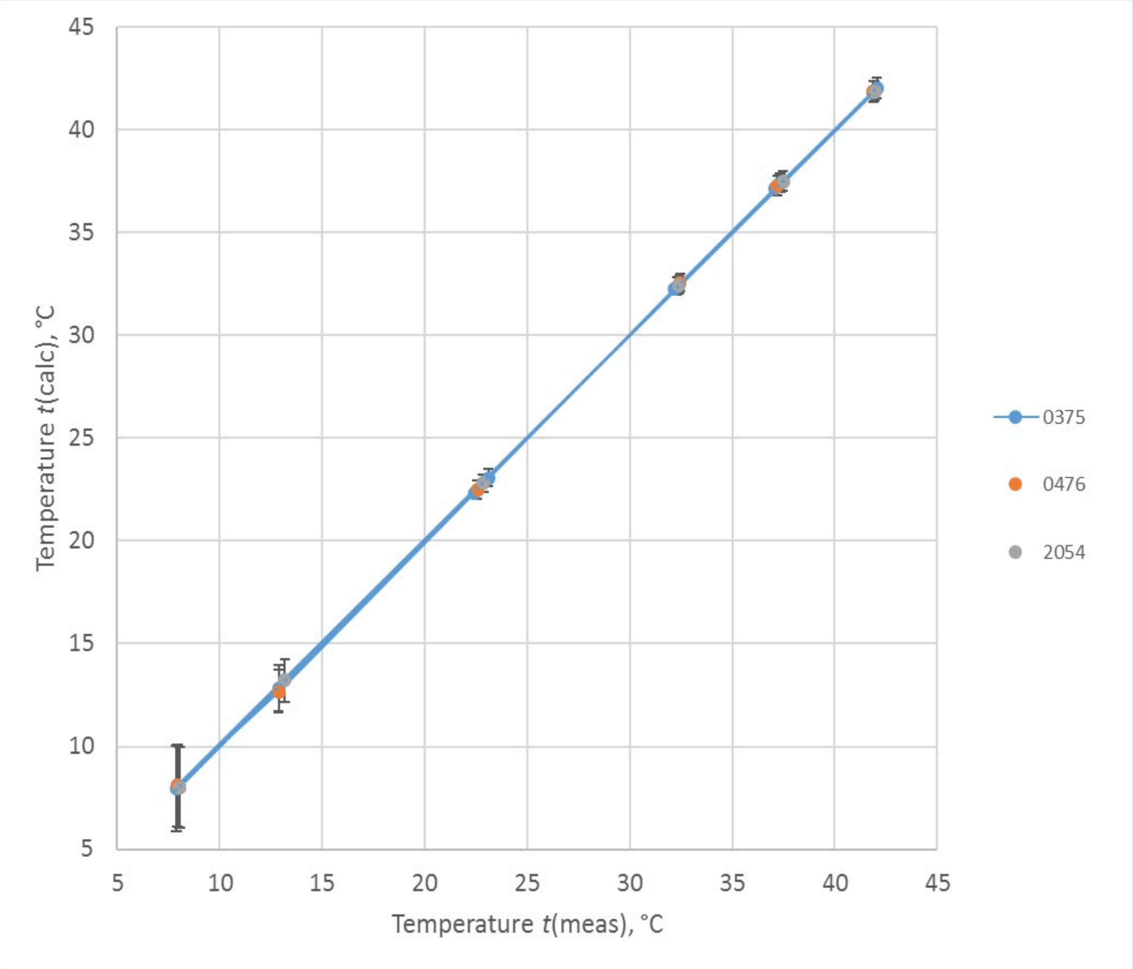
$$\boldsymbol{C_1} = \frac{1}{0.147} \approx 6.8$$

$$\boldsymbol{C_2} = 50 \pm 3.$$

Residuals and expanded uncertainty of four radiometers

- Residuals as difference between temperatures estimated from the dark signal and measured with the internal sensor.
- Differences between measured values and values calculated from the dark signal remain within ±0.2 °C.

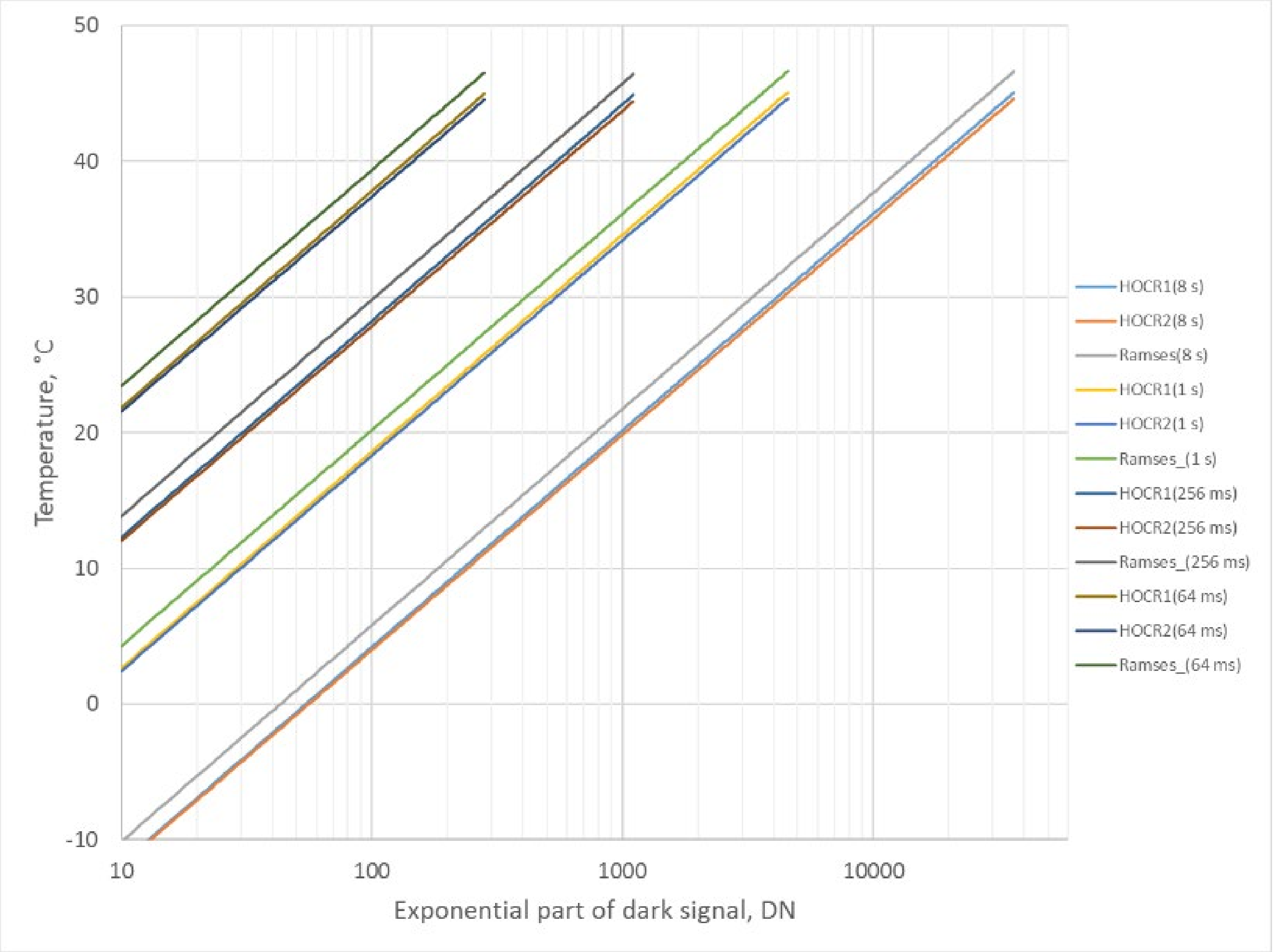




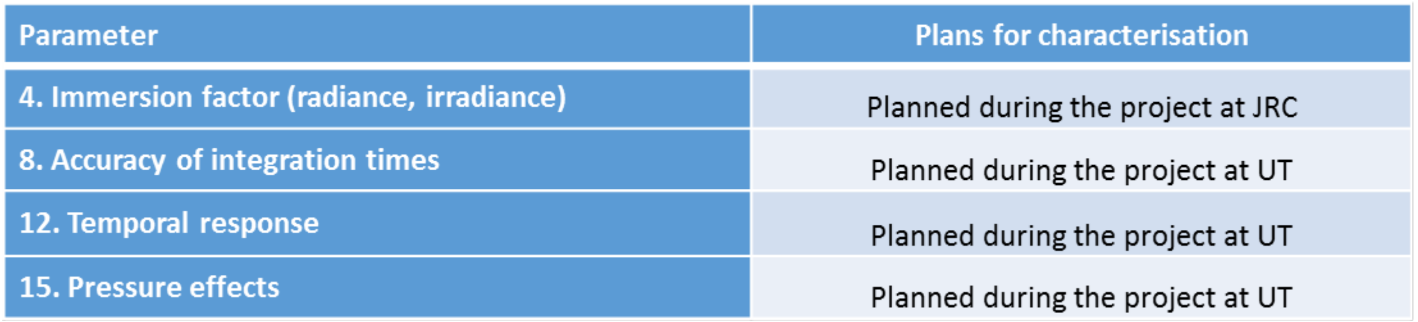
Using the dark signal for detection of the temperature

Limitations:

- Determination range depends on integration time used.
- With 8 s integration time 5 °C to 45 °C can be estimated, with 256 ms only 30 °C to 45 °C.



Gaps in characterisation results

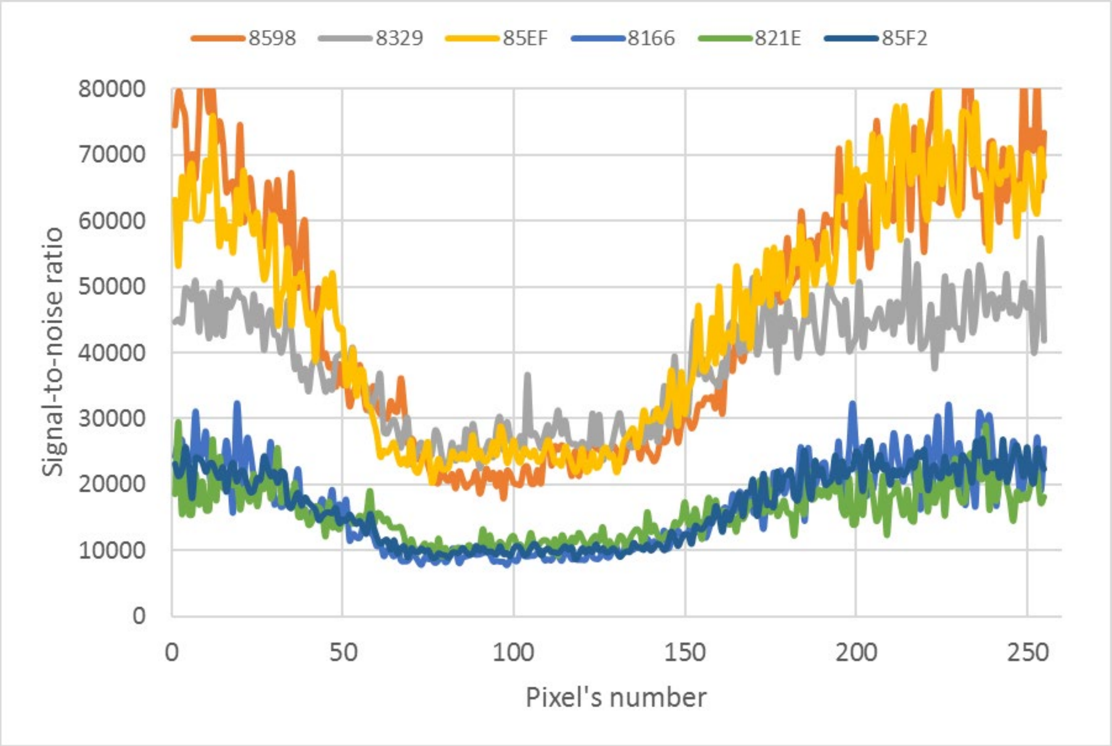


Parameter	Plans for characterisation
4. Immersion factor (radiance, irradiance)	Planned during the project at JRC
8. Accuracy of integration times	Planned during the project at UT
12. Temporal response	Planned during the project at UT
15. Pressure effects	Planned during the project at UT

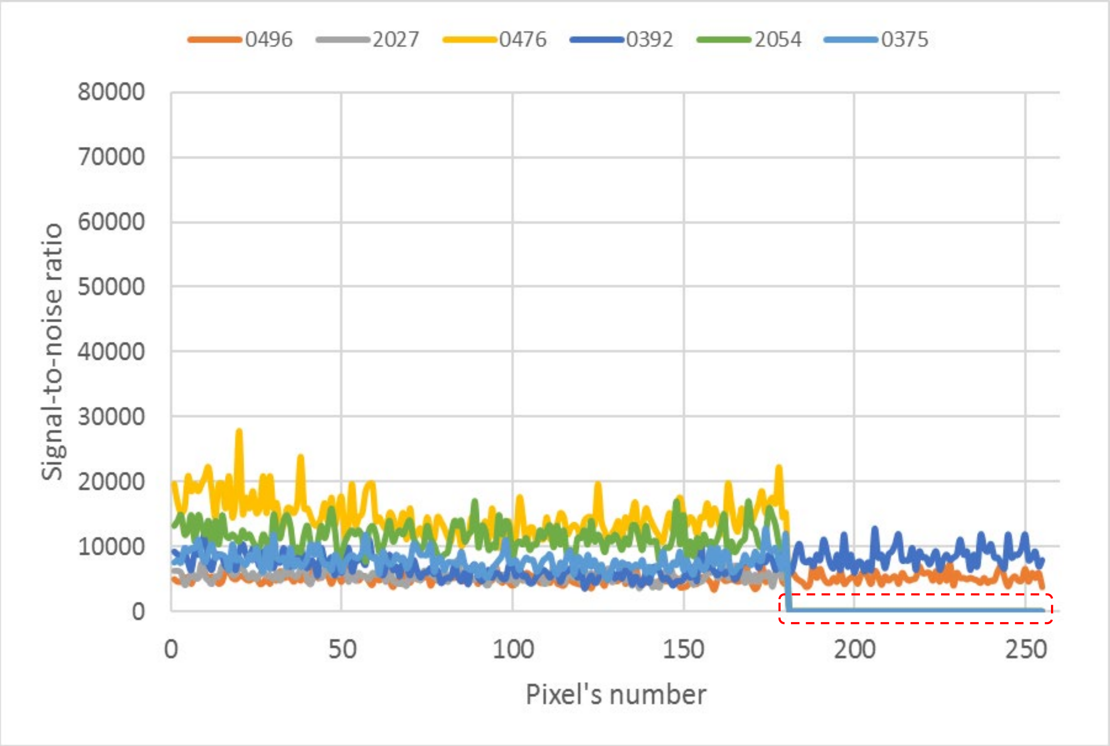
- The integration time characterization shall be performed by looking at a constant source and measuring this source at different integration times.
- Characterisation has been performed at shorter integration times used in calibration together with non-linearity for more than 40 OCRs.
- However, we plan to develop a method to measure the integration time directly without disassembling the instrument.

SNR scaled to full-range value of radiometers

Six **RAMSES** radiometers



Six **HyperOCR** radiometers



Conclusions

- Comparison standards for cal/char comparison exercise of secondary labs are re-calibrated and characterized by pilot after return from NIVA.
- Analysis is needed on how to use cal/char data for different application schemes.
- Full characterization procedures need further studies for a number of parameters, and new procedures need testing at TO.