FRM4DRONES
fiducial reference measurements for water using drones

vito

NPL

The workshop will begin in a few minutes.

To help keep the session structured and smooth, we kindly ask that you:

- **Mute your microphones during presentations**
- **If you have questions, post them in the chat and tag the presenter using @**
- **Turn on your camera when speaking**

Active participation in a respect way is encouraged.

Welcome to the second FRM4Drones-AQUA Workshop

Practical Info & House Rules

- The session is being recorded for internal use only – it will not be distributed
- Questions during presentations ?

  → Use the chat – presenters will answer there
- After the presentations:
  - → Interactive session with polls and open discussion
  - → Use the “Raise Hand” function to speak
  - → Please mute your microphone when not speaking
  - → Use your camera when speaking, if possible
- We encourage active participation !

Have a great meeting !

Workshop Agenda

- Welcome & Round-the-table *– 5 min*
- FRM4Drones-AQUA- Principles of Fiducial Reference Measurement (FRM) *– 20 min*
- Expert Presentations *– 60 min*
- Polls & Questionnaires *– 10-15 min*
- Feedback Poll & Open Discussion *– 20 min as needed*

Welcome – Workshop objectives

- Share expertise on drone-based aquatic reflectance and Cal/Val
- Identify needs and user practices
- Shape the roadmap towards Fiducial Reference Measurements (FRM) from drones for aquatic Cal/Val

1st WS on data acquisition & processing protocol (held in June 2025)

FRM4DRONES-AQUATIC | VITO Remote Sensing

2nd WS on Uncertainty & Traceability

Let’s Get to Know the Audience

No round-the-table –
instead, live poll questions

Options to join :

1) Link to poll in chat
2) Scan QR code with mobile
3) Go to: menti.com; Code: **4523 0550**

Or use QR code

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FRM4drones - challenges

Aquatic reflectance

What we need :

The remote-sensing reflectance $R_{rs}(\theta, \phi, \lambda) = \frac{L_w(\theta,\phi,\lambda)}{E_d(\lambda)}$

The aquatic reflectance $R_w(\lambda) = \pi . R_{rs}(\lambda) = \pi . \frac{L_w(\lambda)}{E_d(\lambda)}$

What UAV measures :

$$L_T^{UAS}(\lambda) = L_{path}(\lambda) + t(\lambda)L_{SR}(\lambda) + t(\lambda)L_w(\lambda)$$

Atmosphere

Surface (sky glint, sun glint, white caps)

$$L_{SR}(\lambda) = L_{skyG}(\lambda) + L_{sunG}(\lambda) + L_{WF}(\lambda)$$

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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

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"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 uegetation

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

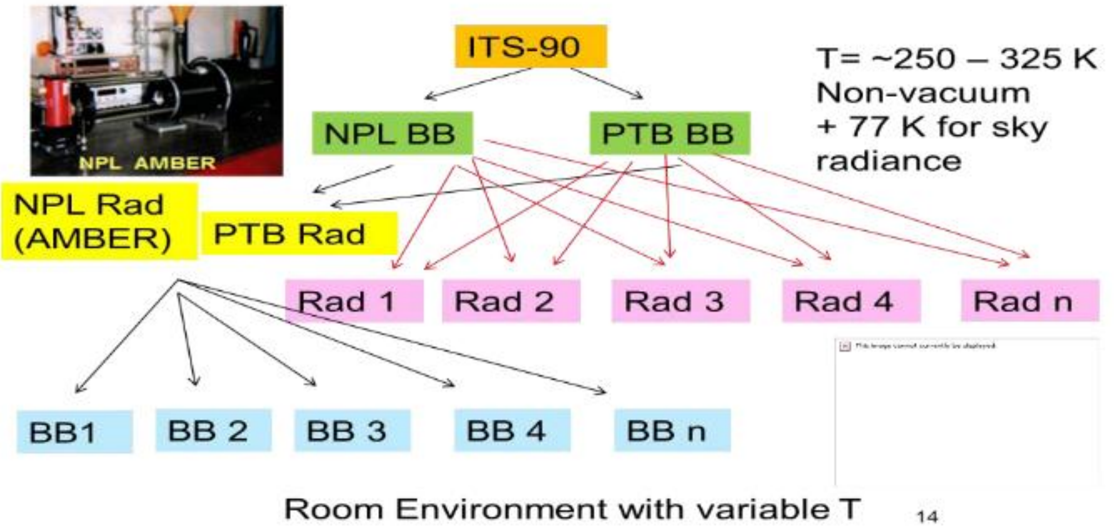
Field Inter- comparison Calibration Exercise (FICE)

Analysis

Analysis

Discussion, Workshop

Publications




JOURNAL OF ATMOSPHERIC AND OCEANIC TECHNOLOGY — VOLUME 21

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

I. J. BARTON, P. J. MINNETT, K. A. MAILLET, C. J. DONLON, S. J. HOOK, A. T. JESSUP, AND T. J. NIGHTINGALE

ABSTRACT

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

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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]

SI: Summary

- Identical worldwide
- Century-long stability
- Absolute accuracy

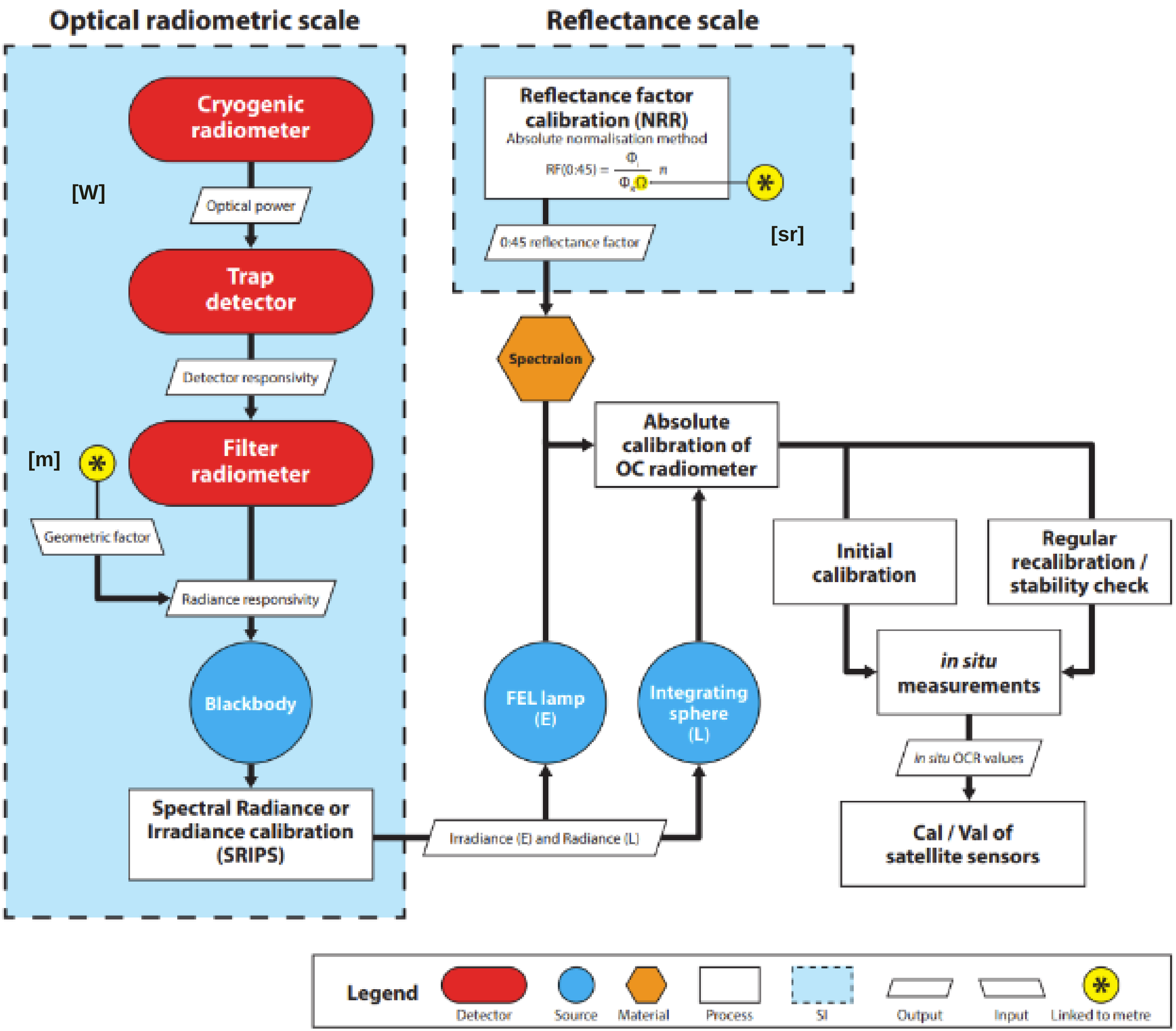
Achieved through:

- 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.

SI Traceability

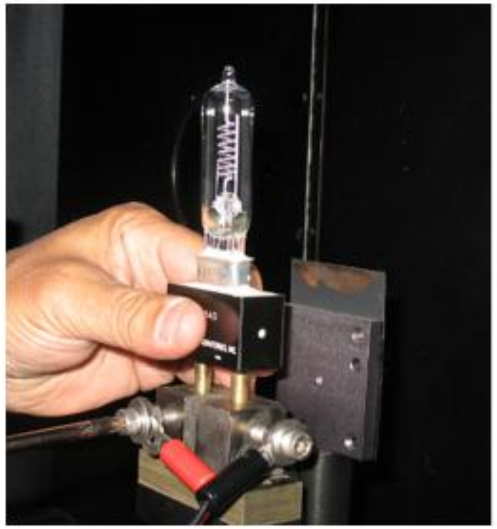
$$W = kg\ m^2\ s^{-3}.$$



Irradiance standards

NPL National Physical Laboratory

- Lamps tungsten-halogen lamp (FEL) 1 kW (~ 3000 K)



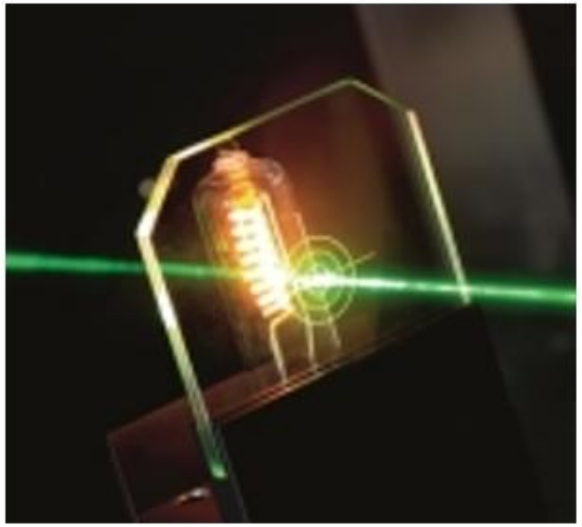
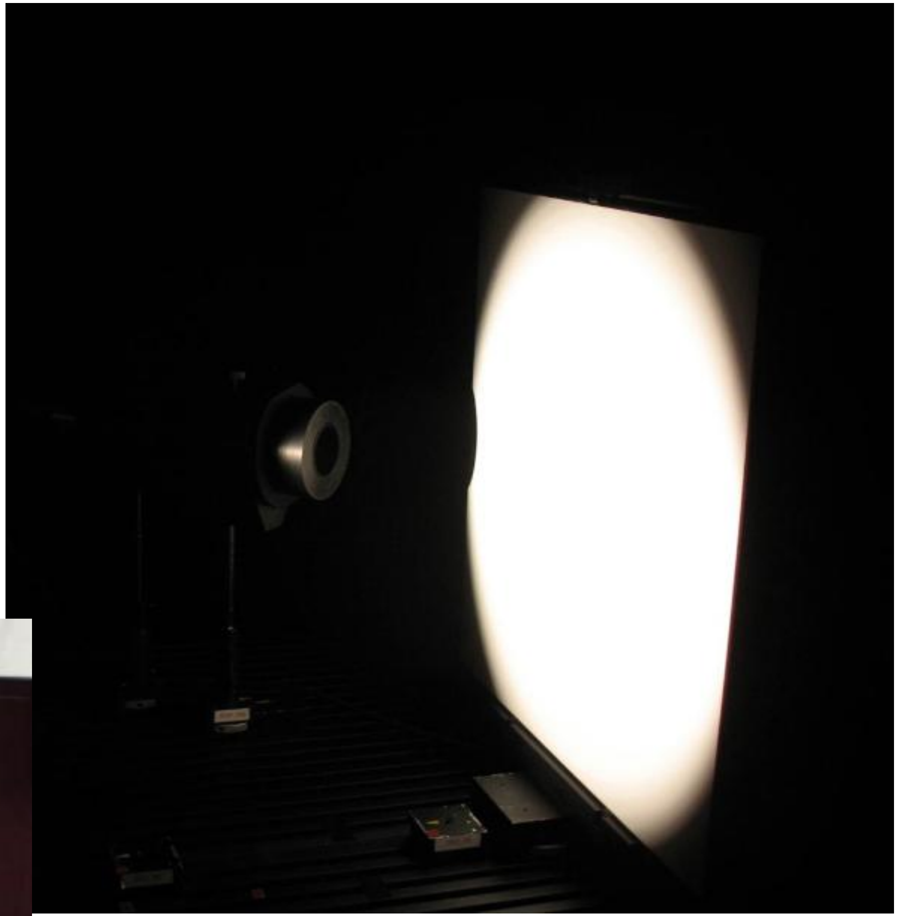


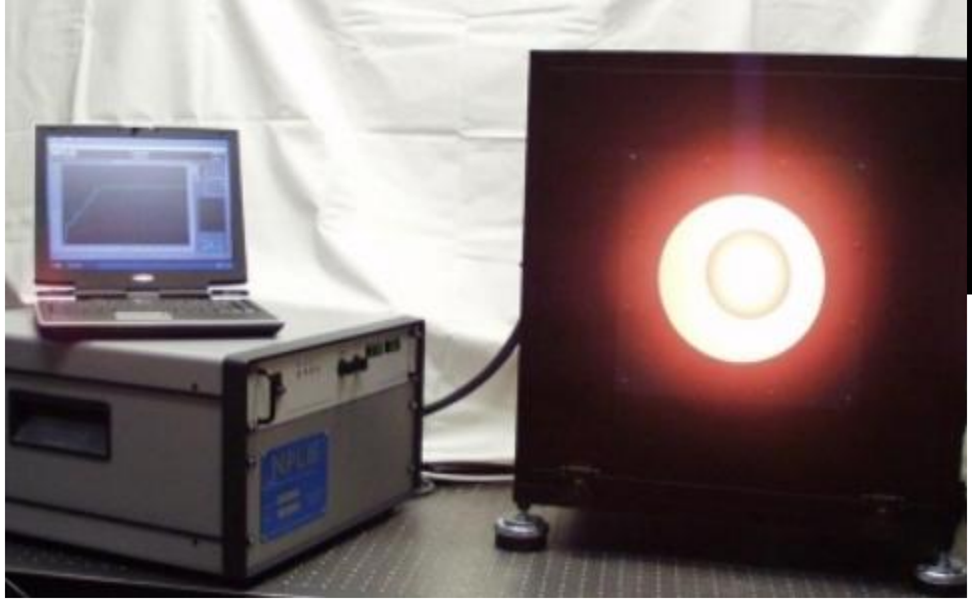
Photo courtesy of Gamma Scientific

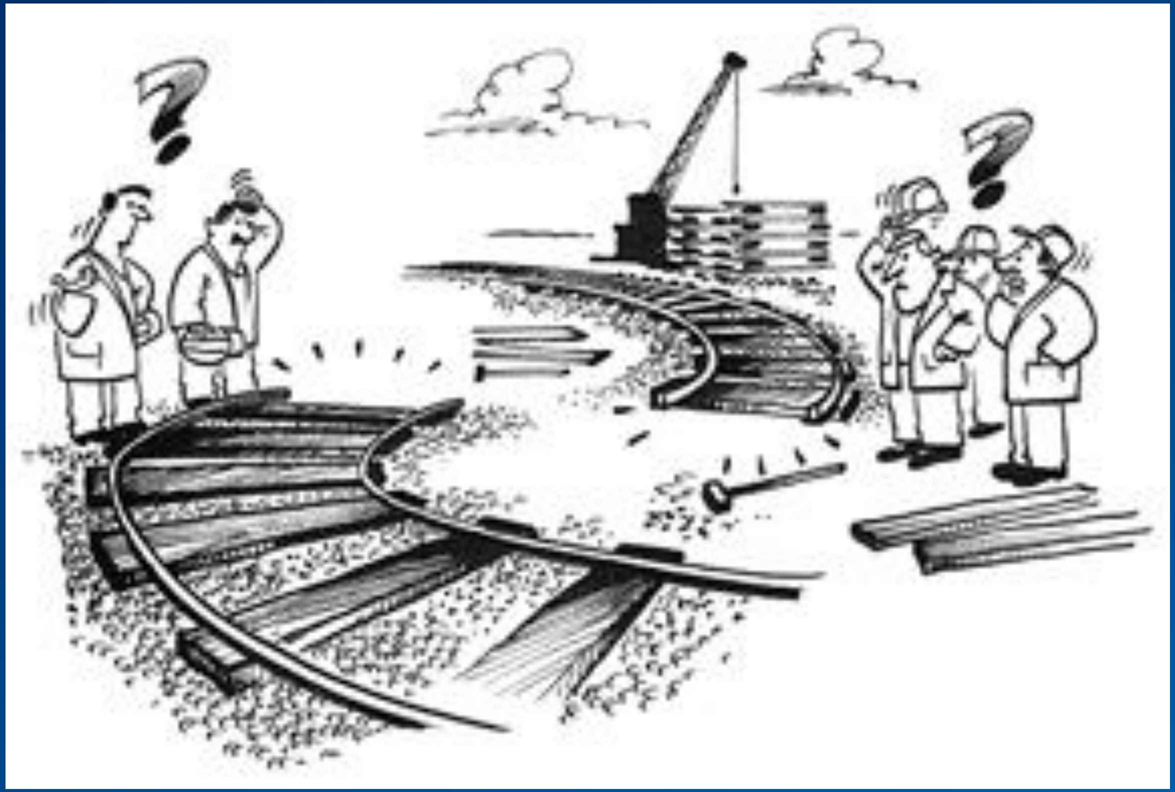
Radiance standards

- Lamp –reflectance standard



- Integrating sphere





Relevance of comparisons

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

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.

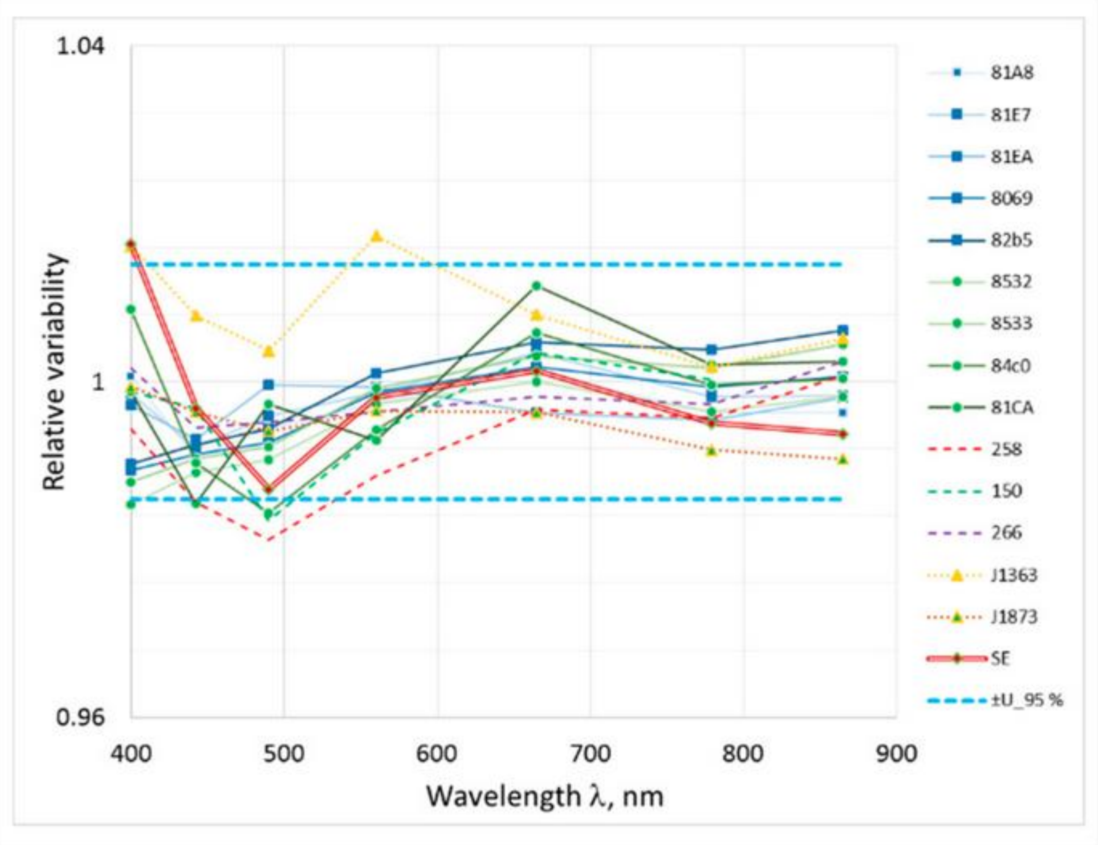
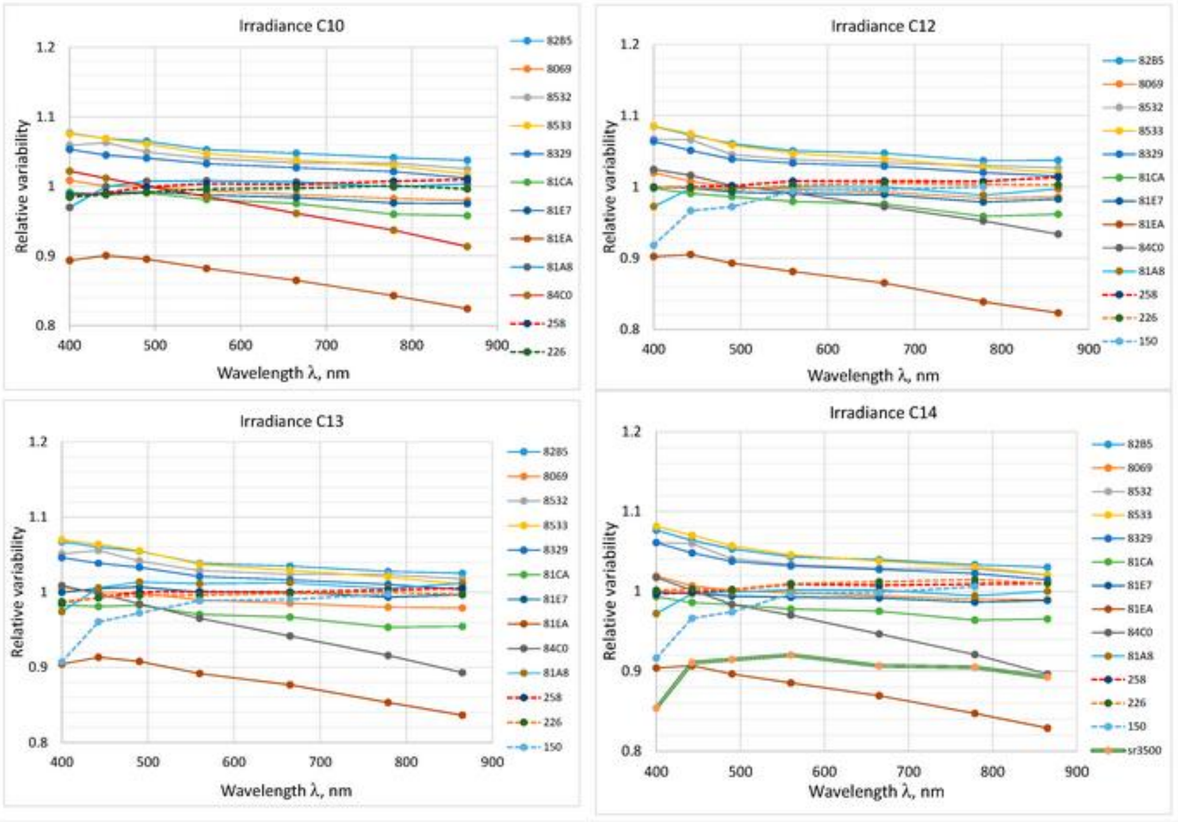


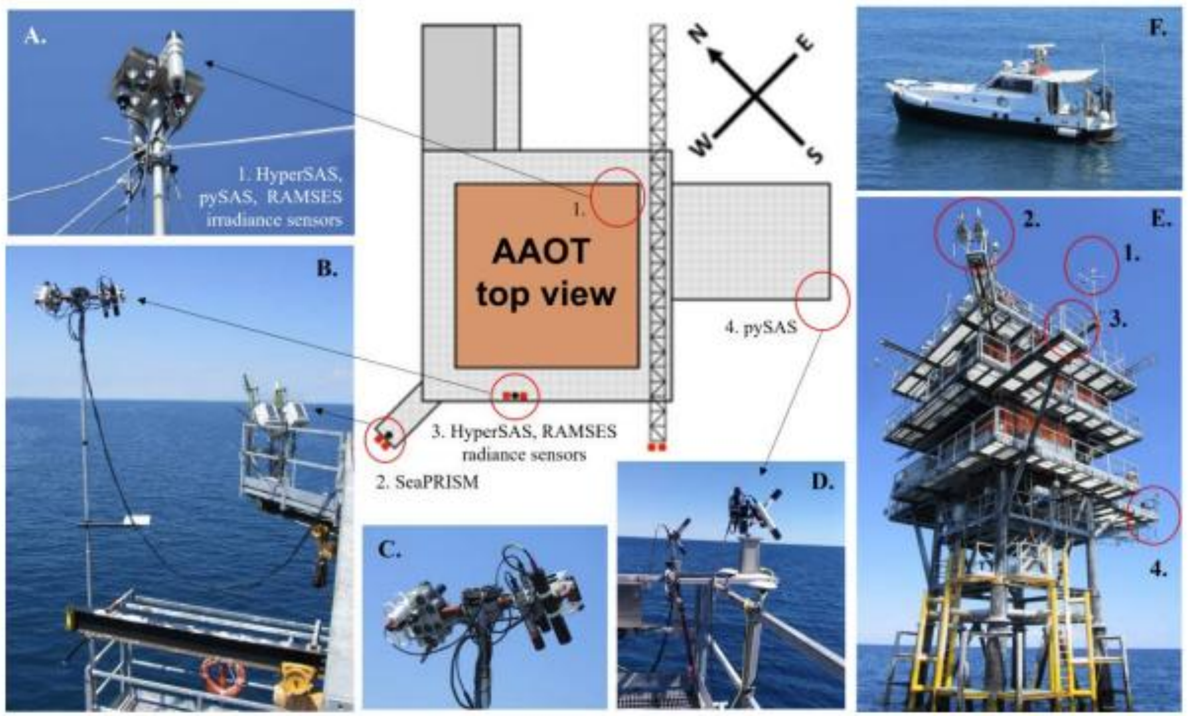
Figure 10. Irradiance sensors compared to the consensus value. Solid lines—RAMSES sensors; dashed lines—HyperOCR sensors; double line—SR-3500.



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

FRM4SOC FICE2022

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



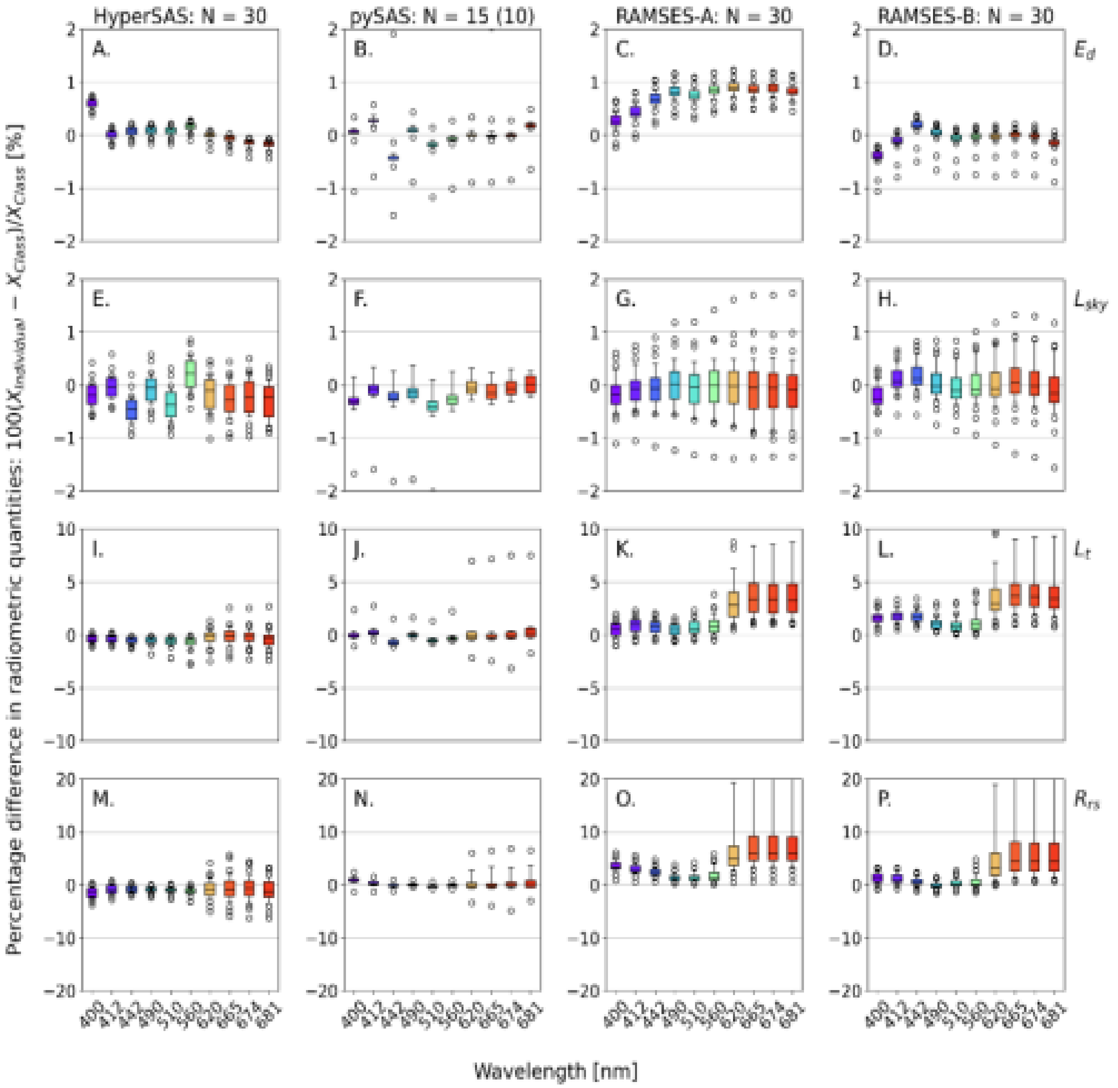


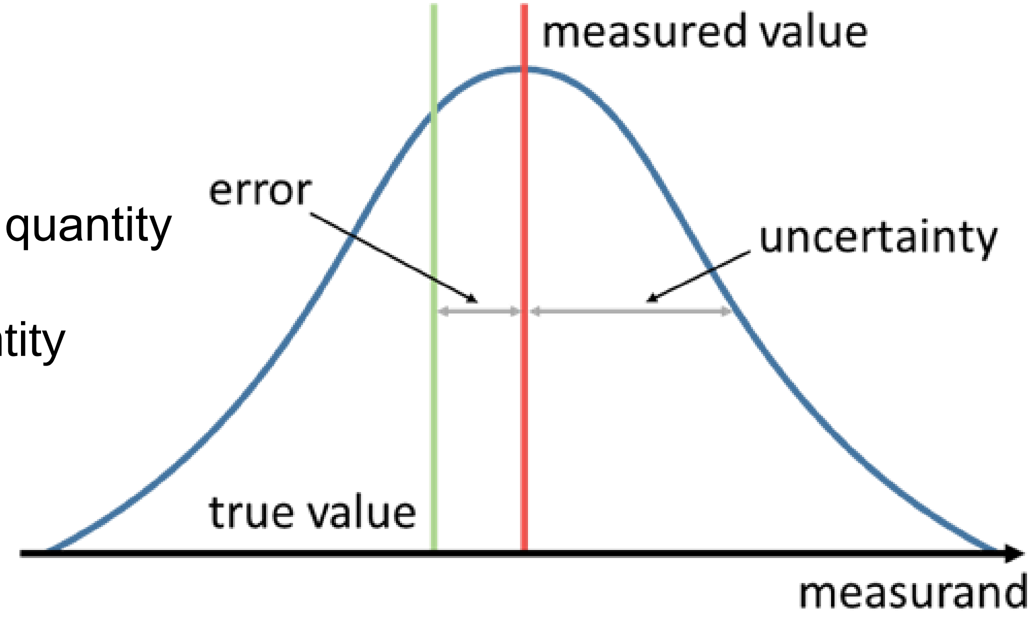
Fig. 9. Differences between individual processors and HyperCP for $E_d(\lambda)$ $L_{sky}(\lambda)$, $L_t(\lambda)$ and $R_{rs}(\lambda)$ run in class-based mode for HyperSAS (A., E., I., M.), pySAS (B., F., J., N. RAMSES-A (C., G., K., O) and RAMSES-B (D., H., L., P.).


Uncertainty
Just Ahead

Methodology and resources

- The International Vocabulary of Metrology (VIM)

“the measured quantity value minus a reference quantity value.”



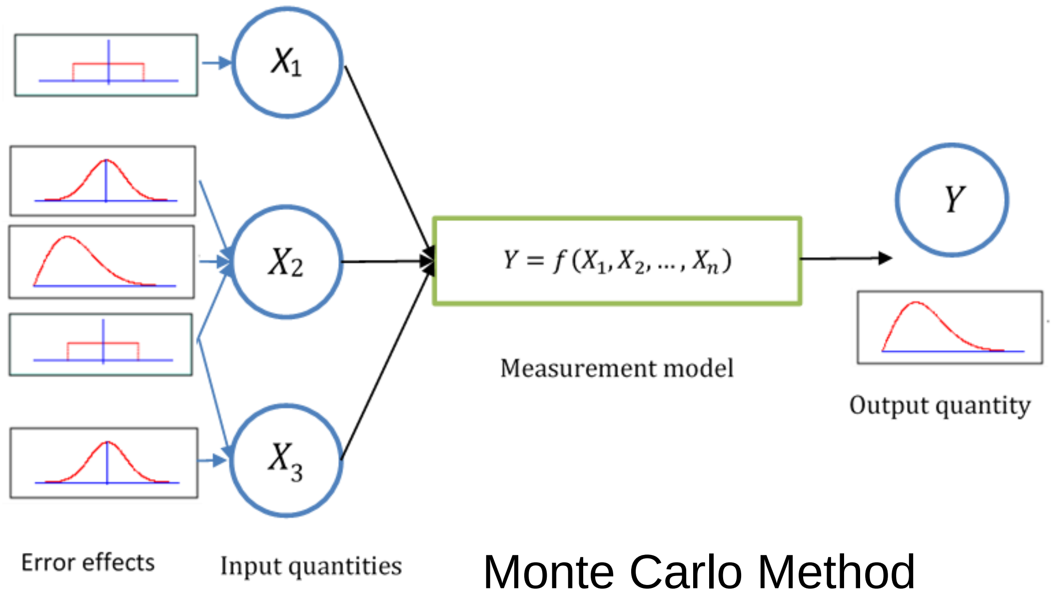
“a non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used.”

http://www.bipm.org/en/publications/guides/

Bureau International des Poids et Mesures – the intergovernmental organization through which Member States act together on matters related to measurement science and measurement standards.

Methodology and resources

- the Guide to the expression of Uncertainty in Measurement (GUM) and its supplements



Monte Carlo Method

$$u^2(y) = \sum_{i=1}^{N} c_i^2 u^2(x_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i}^{N} c_i c_j u(x_i, x_j)\,,$$

The Law of Propagation of Uncertainties

http://www.bipm.org/en/publications/guides/

Bureau International des Poids et Mesures – the intergovernmental organization through which Member States act together on matters related to measurement science and measurement standards.

QA4EO Home https://qa4eo.org/

Figure 2 An iterative framework for the CEOS Five Steps

About Tools Examples News People

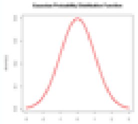
CoMet Toolkit

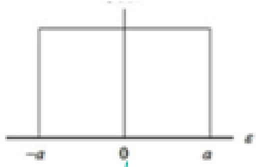
The **CoMet Toolkit** (Community Metrology Toolkit) is an open-source software project to develop Python tools for the handling of error-covariance information in the analysis of measurement data.

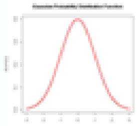
```
import xarray as xr
import obsarray
from punpy import MeasurementFunction, MCPropagation

# read digital effects table
ds = xr.open_dataset("digital_effects_table_gaslaw_example.nc")

# Define your measurement function inside a subclass of MeasurementFunction
class IdealGasLaw(MeasurementFunction):
    def meas_function(self, pres, temp, n):
        return (n *temp * 8.134)/pres

# Create Monte Carlo Propagation object, and create MeasurementFunction class
# object with required parameters such as names of input quantites in ds
prop = MCPropagation(10000)
gl = IdealGasLaw(prop, xvariables=["pressure", "temperature", "n_moles"],
                 yvariable="volume", yunit="m^3")

# propagate the uncertainties on the input quantites in ds to the measurand
# uncertainties in ds_y (propagate_ds returns random, systematic and structured)
ds_y = gl.propagate_ds(ds, store_unc_percent=True)
```

https://www.comet-toolkit.org/

GUM Methodology applied in CoMET tool







$$R_{rs} = (L_t c_{cal0222} - (\rho * L_i c_{cal0223})/E_s c_{cal0258}$$

random

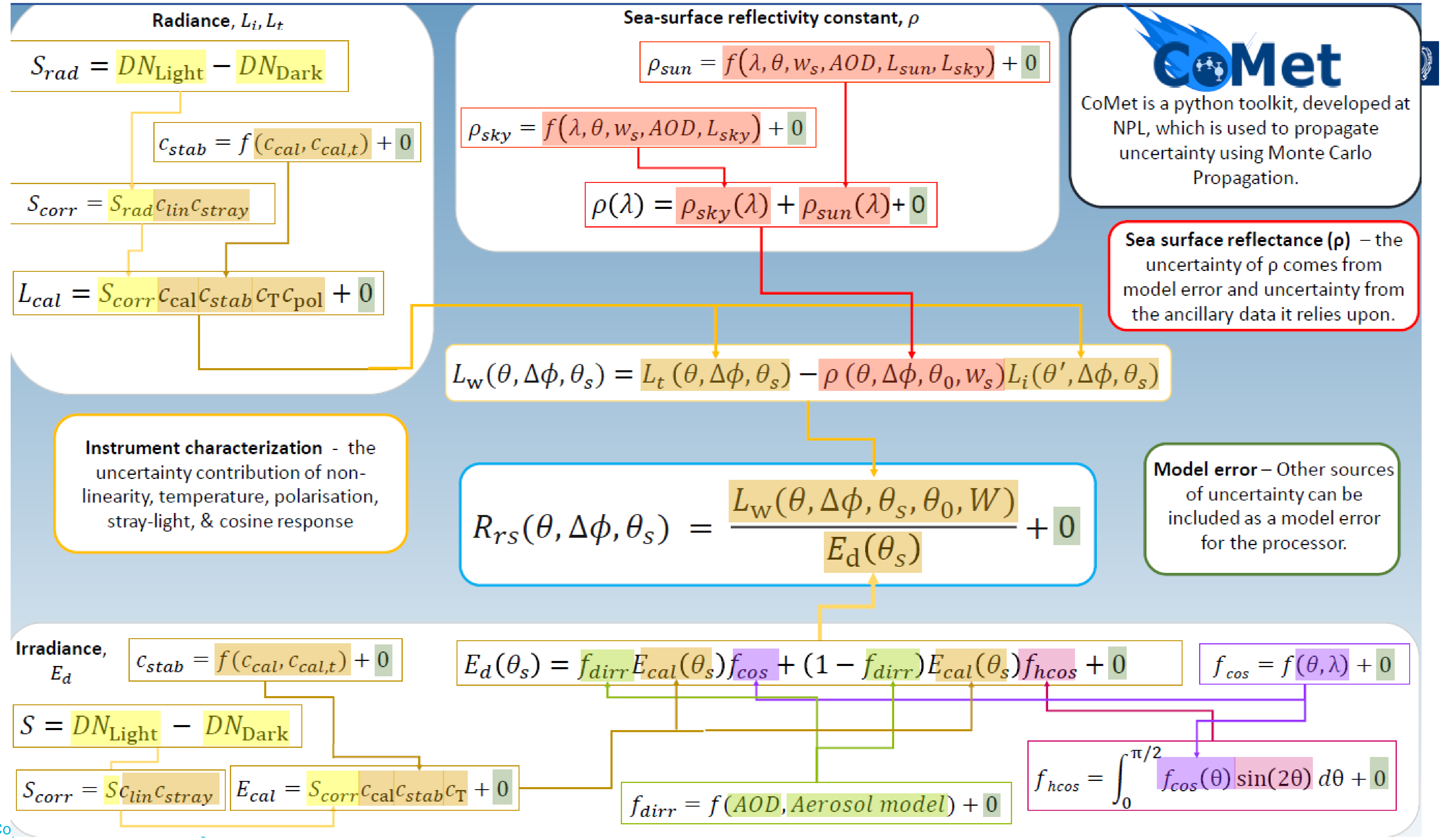
systematic

$$u_c^2(y) = \sum_{i=1}^{N} c_i^2 u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=1+1}^{N} c_i c_j u(x_i) u(x_j) r(x_i, x_j)\,,$$

L_t	c_{c2}	ρ	L_i	c_{c3}	E_s	c_{c8}
1	0	0	0	0	0	0
0	1	0	0	1	0	1
0	0	1	0	0	0	0
0	0	0	1	0	0	0
0	1	0	0	1	0	1
0	0	0	0	0	1	0
0	1	0	0	1	0	1

JCGM100:2008. Evaluation of measurement data - *Guide to the expression of uncertainty in measurement*

JCGM101:2008. Evaluation of measurement data - *Supplement 1 to the Guide to the expression of uncertainty in measurement - Propagation of distributions using a Monte Carlo method.*



Radiance, L_i, L_t
$S_{rad} = DN_{\text{Light}} - DN_{\text{Dark}}$
$c_{stab} = f(c_{cal}, c_{cal,t}) + 0$
$S_{corr} = S_{rad} c_{lin} c_{stray}$
$L_{cal} = S_{corr} c_{\text{cal}} c_{stab} c_{\text{T}} c_{\text{pol}} + 0$
Sea-surface reflectivity constant, ρ
$\rho_{sun} = f(\lambda, \theta, w_s, AOD, L_{sun}, L_{sky}) + 0$
$\rho_{sky} = f(\lambda, \theta, w_s, AOD, L_{sky}) + 0$
$\rho(\lambda) = \rho_{sky}(\lambda) + \rho_{sun}(\lambda) + 0$
CoMet
CoMet is a python toolkit, developed at NPL, which is used to propagate uncertainty using Monte Carlo Propagation.
Sea surface reflectance (ρ) – the uncertainty of ρ comes from model error and uncertainty from the ancillary data it relies upon.
$L_{\text{w}}(\theta, \Delta\phi, \theta_s) = L_t(\theta, \Delta\phi, \theta_s) - \rho(\theta, \Delta\phi, \theta_0, w_s) L_i(\theta', \Delta\phi, \theta_s)$
Instrument characterization - the uncertainty contribution of non-linearity, temperature, polarisation, stray-light, & cosine response
$R_{rs}(\theta, \Delta\phi, \theta_s) = \frac{L_{\text{w}}(\theta, \Delta\phi, \theta_s, \theta_0, W)}{E_{\text{d}}(\theta_s)} + 0$
Model error – Other sources of uncertainty can be included as a model error for the processor.
Irradiance, E_d
$c_{stab} = f(c_{cal}, c_{cal,t}) + 0$
$E_d(\theta_s) = f_{dirr} E_{cal}(\theta_s) f_{cos} + (1 - f_{dirr}) E_{cal}(\theta_s) f_{hcos} + 0$
$f_{cos} = f(\theta, \lambda) + 0$
$S = DN_{\text{Light}} - DN_{\text{Dark}}$
$f_{hcos} = \int_0^{\pi/2} f_{cos}(\theta) \sin(2\theta)\, d\theta + 0$
$S_{corr} = S c_{lin} c_{stray}$
$E_{cal} = S_{corr} c_{\text{cal}} c_{stab} c_{\text{T}} + 0$
$f_{dirr} = f(AOD, Aerosol\ model) + 0$

Co

Approach

Table 3. Summary information about each uncertainty component values for class-based approach (blue branch, Fig. 5)

Variable symbol	Variable name/description	Exemplary uncertainty magnitude for class-based characterisation		PDF shape	Correlation 'corr_x'	Correlation between 'corr_between'
		TRIOS	HyperOCR			
$(DN_{\text{light},L_X} - DN_{dark,L_X})$ $(DN_{\text{light},E_S} - DN_{dark,E_S})$	Mean value of DNs measured by a single instrument at a "station"	Standard deviation calculated per measurement from data statistics		Normal	Random	N/A
c_{cal}	Absolute radiometric calibration	Uncertainty values from calibration certificate divided by 2 to convert them back into standard uncertainty, k=1		Normal	Systematic	Between all three instruments
c_{stab}	Absolute calibration stability	1%		Rectangular	Systematic	N/A
c_{lin}	Detector non-linearity	2%		Normal	Systematic	Between all three instruments
c_{stray}	Spectral stray light	Vary spectrally and per instrument due to difference in spectral shape of the signal, should come from the class-based stray light file		Normal	Systematic	Between all three instruments
c_T	Temperature sensitivity	Vary spectrally come from the class-based temperature sensitivity file		Normal	Systematic	Between all three instruments
c_{pol}	Polarisation sensitivity (Radiance only)	Vary spectrally and per instrument to use published data from (Talone and Zibordi, 2016)	Vary spectrally and per instrument triple values for TRIOS, as shown in [AD-1]	Normal	Systematic	Between two radiance instruments
c_{cos}	Cosine response (Irradiance only)	Directional 3.5%	Directional 2%	Normal	Systematic	N/A

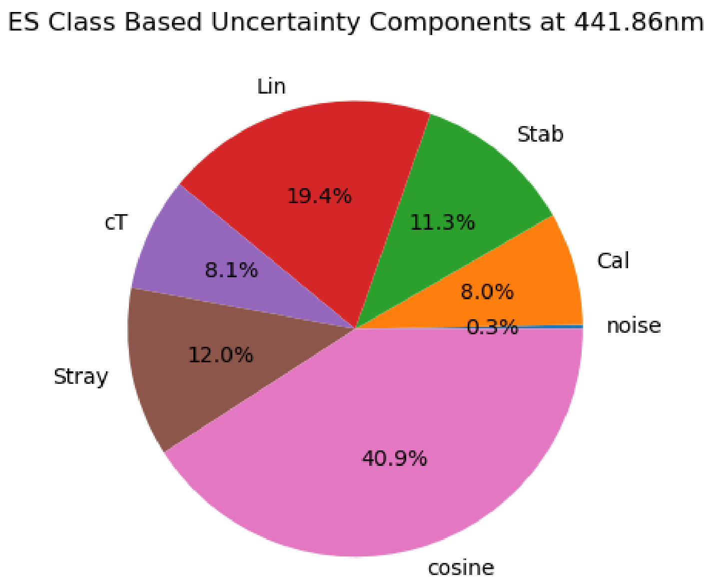
Approach

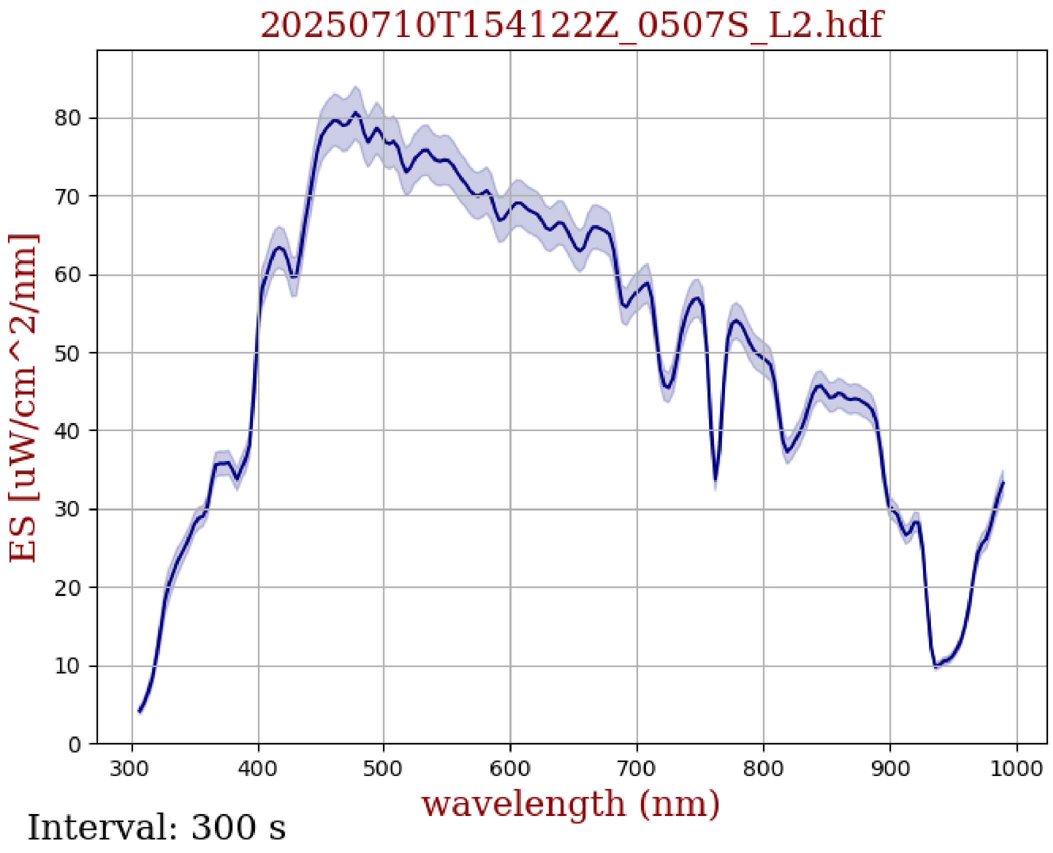
Table 3 . Summary information about each uncertainty component for sea surface reflectance factor (ρ) estimation using Mobley method to estimate the sea-surface reflectance factor (ρ).

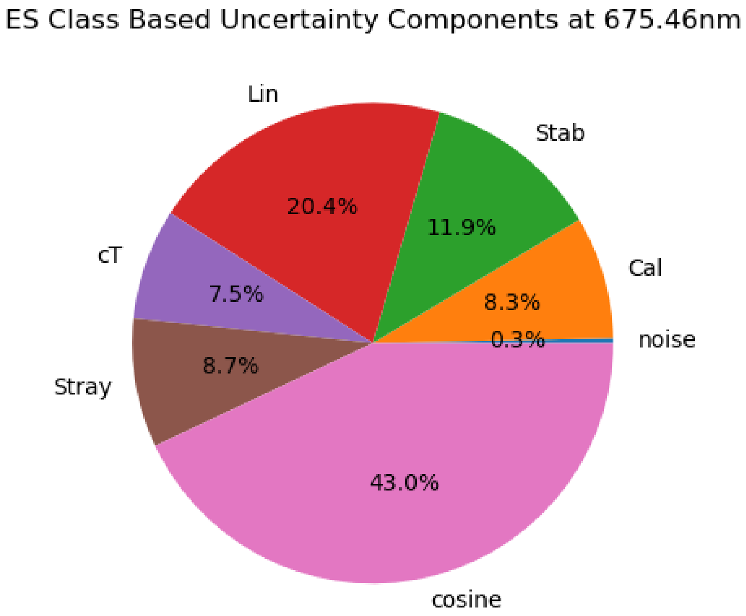
Variable symbol	**Variable name/description**	**Exemplary uncertainty magnitude**	**PDF shape**	**Correlation** 'corr_x'	**Correlation between** 'corr_between'
ρ	Sea surface reflectance	Calculated for each cast depends on all input components, especially wind speed	Normal	Random	N/A
w_s	Wind speed	2 ms^{-1}	Normal	Random	N/A
$\Delta\phi$	Relative azimuth	3°	Normal	Random[1]	N/A
θ_s	Solar zenith angle	0.5°	Normal	Random	N/A
+0	Model error	Difference between Mobley and Zhang method	Rectangular	Systematic	N/A

FICE2025

/wind_speed=4.29
SZA =59.5







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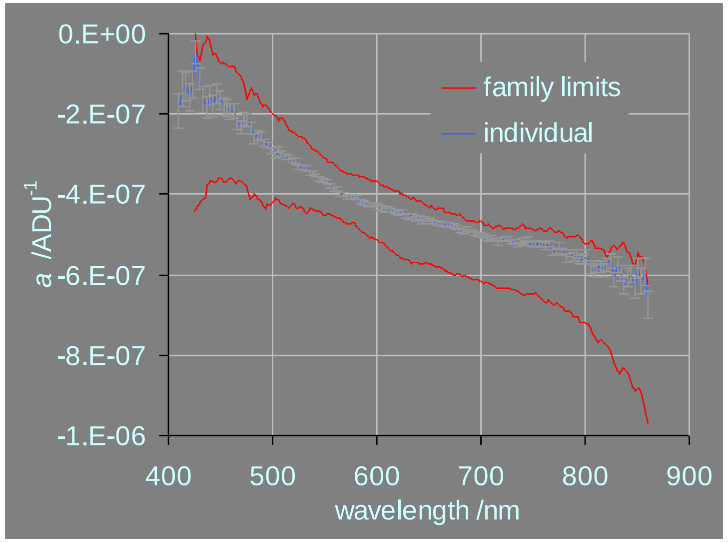
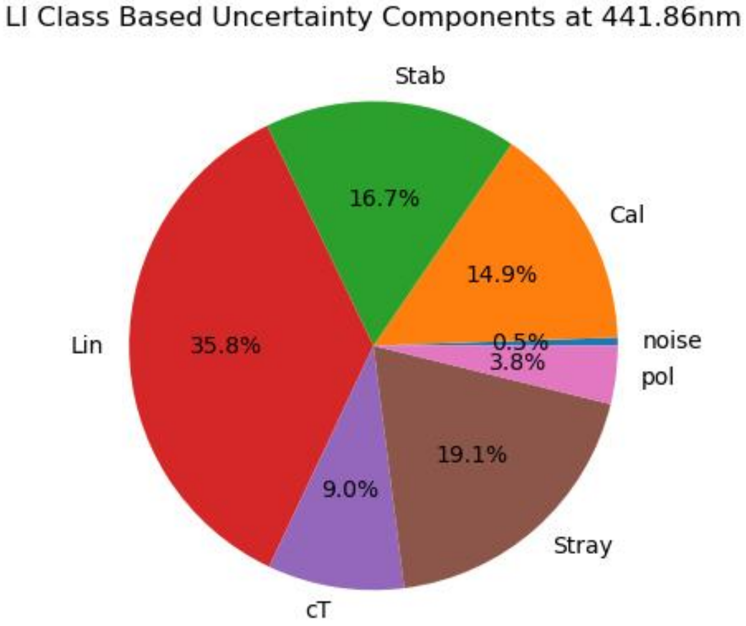
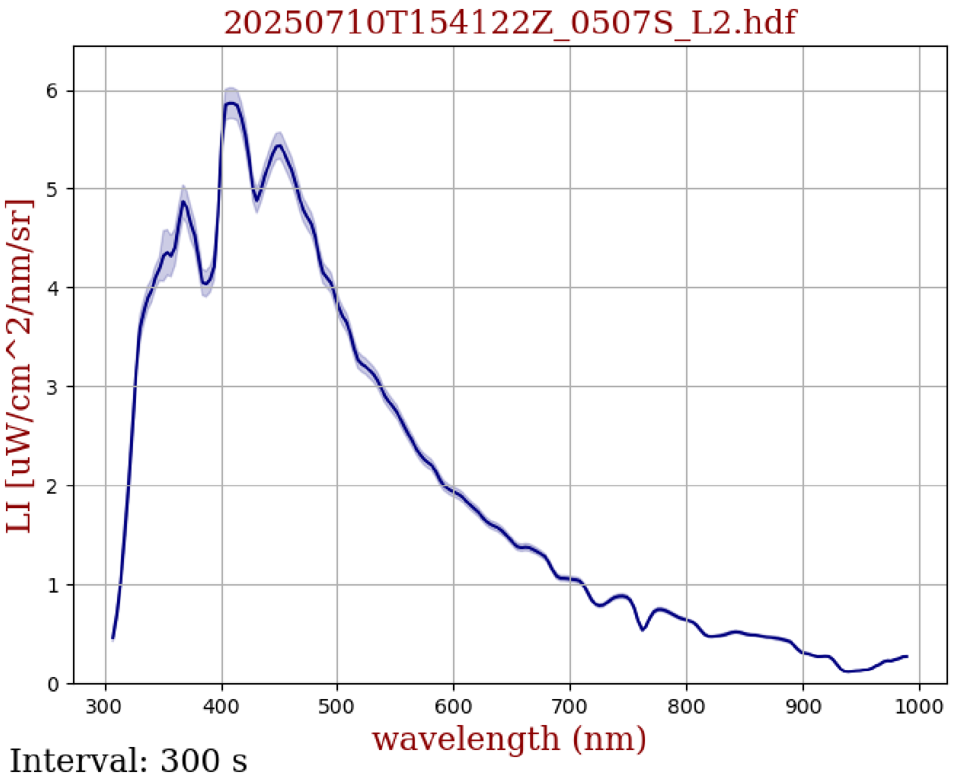
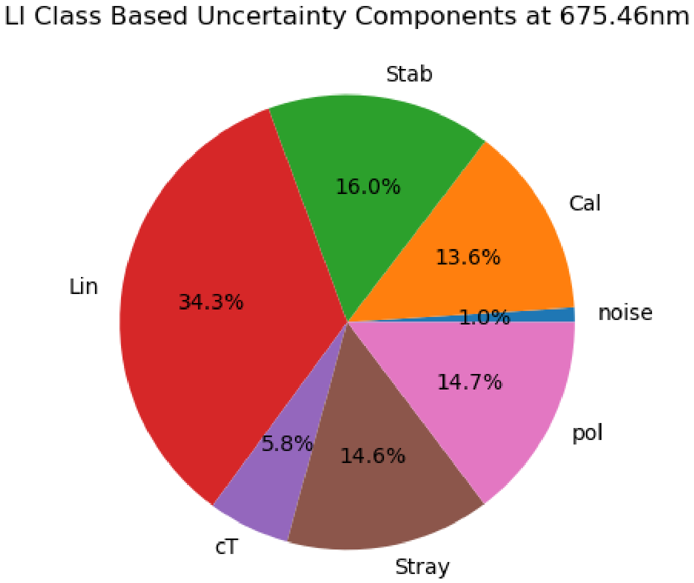
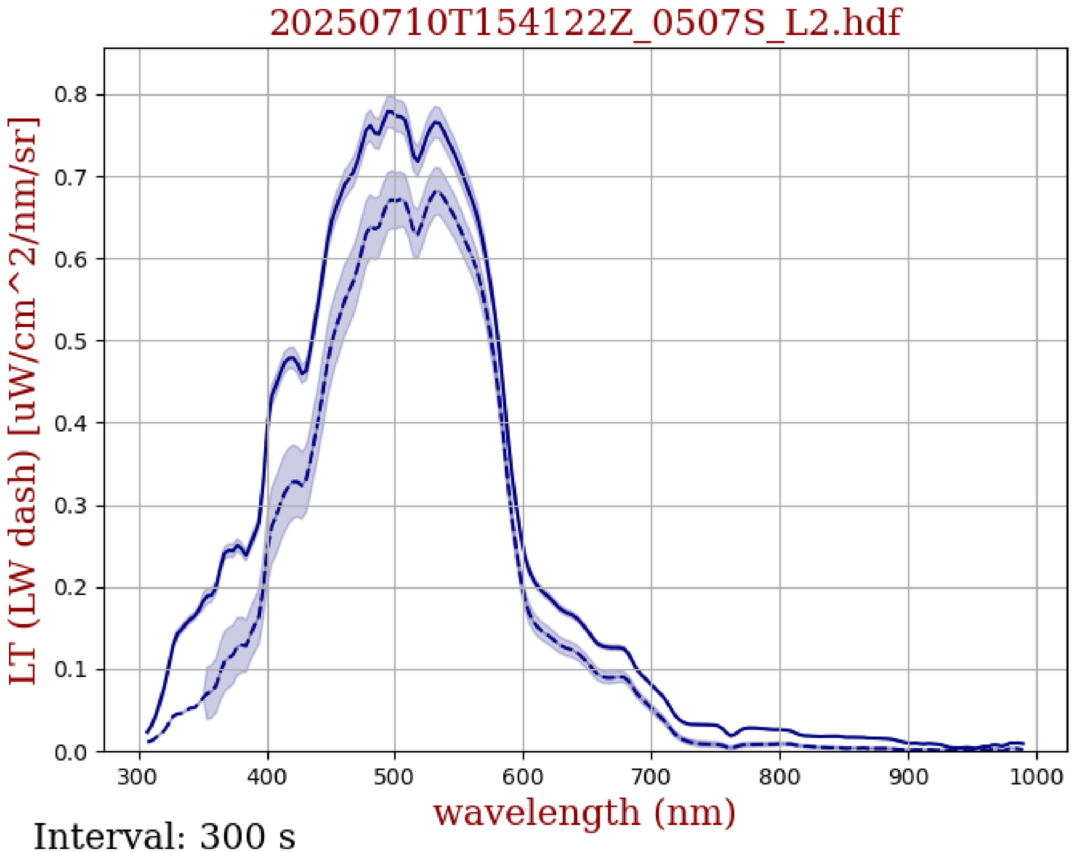

0.E+00
-2.E-07
-4.E-07
-6.E-07
-8.E-07
-1.E-06
a /ADU-1
family limits
individual
400
500
600
700
800
900
wavelength /nm


LI Class Based Uncertainty Components at 441.86nm
Stab
16.7%
Cal
14.9%
noise
0.5%
pol
3.8%
Lin
35.8%
Stray
19.1%
cT
9.0%

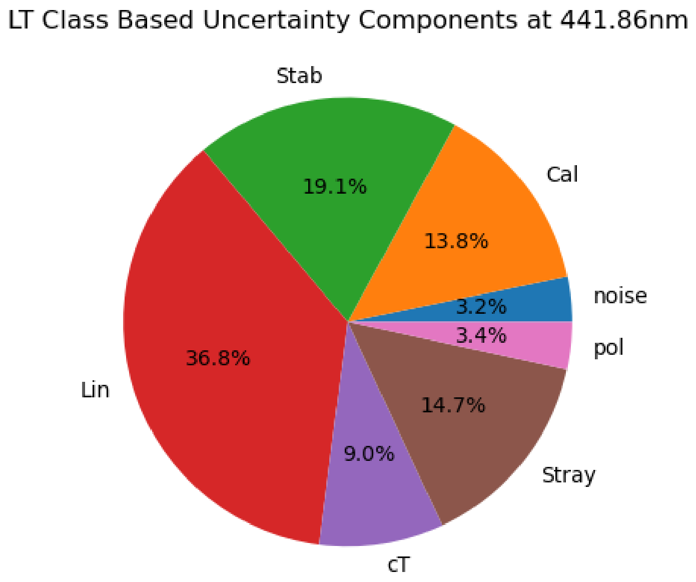

20250710T154122Z_0507S_L2.hdf
LI [uW/cm^2/nm/sr]
6
5
4
3
2
1
0
300
400
500
600
700
800
900
1000
wavelength (nm)
Interval: 300 s

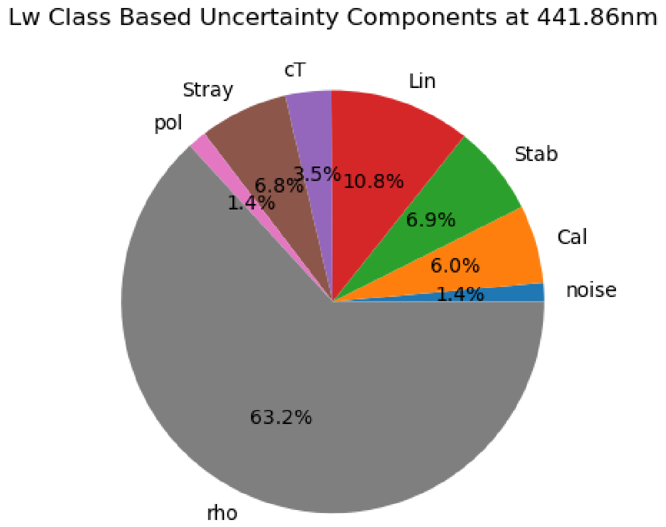

LI Class Based Uncertainty Components at 675.46nm
Stab
16.0%
Cal
13.6%
noise
1.0%
Lin
34.3%
pol
14.7%
cT
5.8%
Stray
14.6%

FICE2025



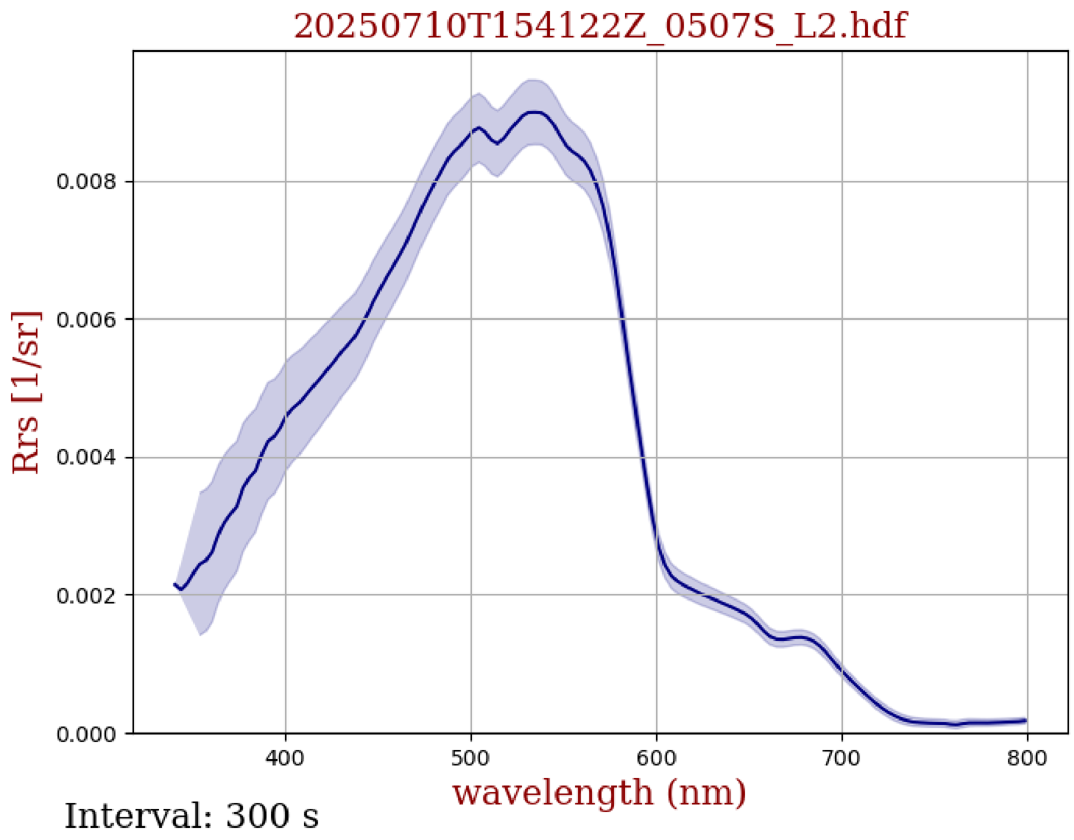
Interval: 300 s

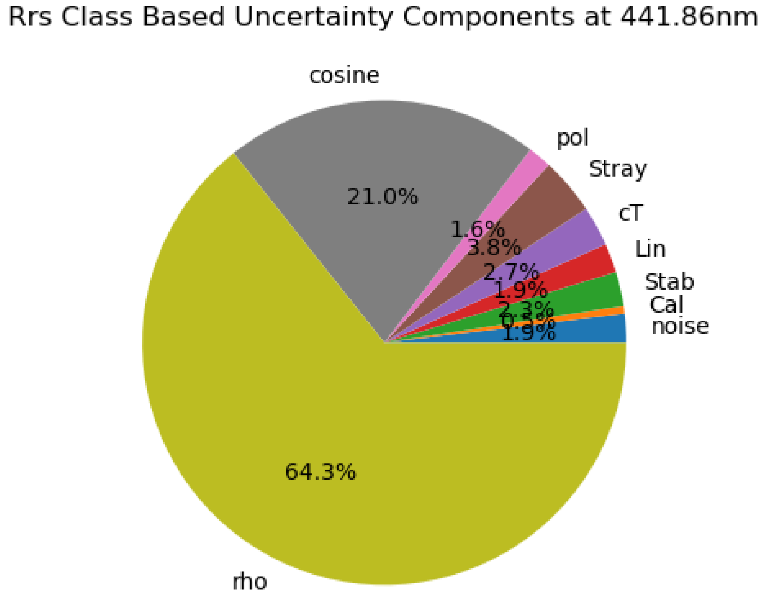


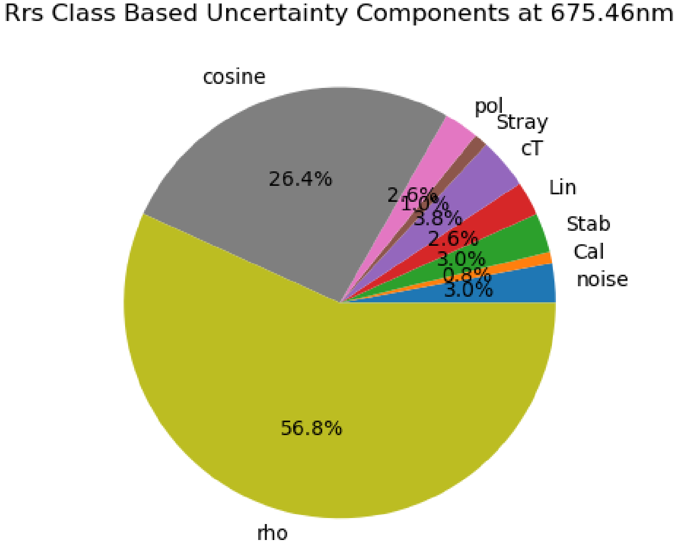


FICE2025

HyperCP







Let’s Get to Know the Audience

No round-the-table –
instead, live poll questions

Options to join :

1) Link to poll in chat
2) Scan QR code with mobile
3) Go to: menti.com; Code: **4523 0550**

Or use QR code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Thank you