Copernicus FICE 2024

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

GUM general metrological framework

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PROGRAMME OF THE EUROPEAN UNION · Copernicus · IMPLEMENTED BY EUMETSAT

FRM4SOC Phase-2 · fiducial reference measurements for satellite ocean colour

CNR ISMAR ISTITUTO DI SCIENZE MARINE

6-17 May 2024
Venice, Italy

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Outline

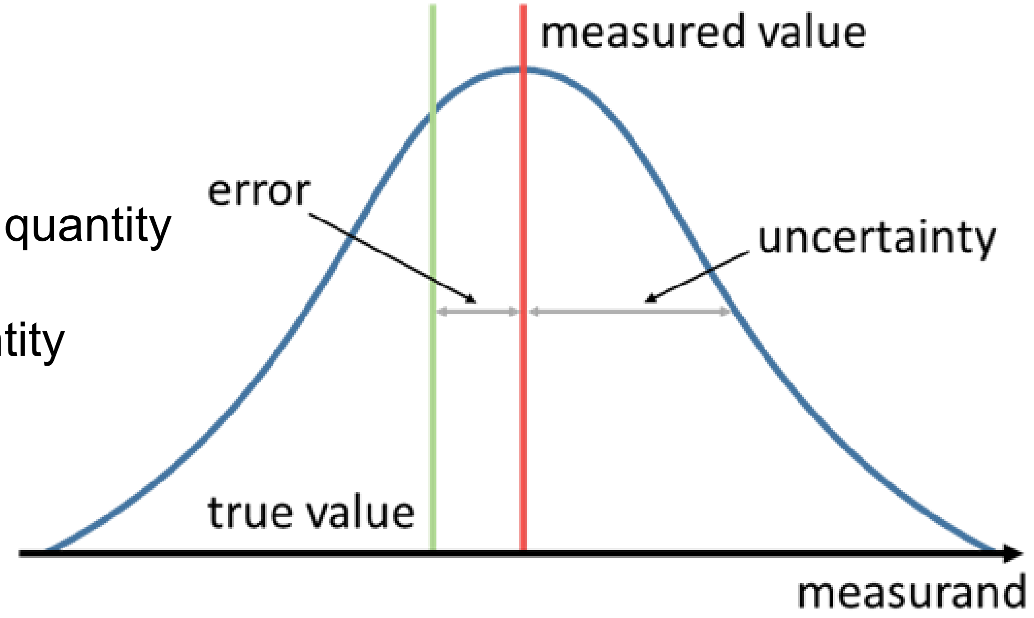
- Methodology and resources
- Basic uncertainty concepts
- Absolute calibration measurement equation
- Above water radiometry measurement equation
- Uncertainty propagation in HyperCP

Methodology and resources

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.

Contents

[VIM3] 2.26 measurement uncertainty
uncertainty of measurement, uncertainty

Options

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

Notes

NOTE 1 Measurement uncertainty includes components arising from systematic effects, such as components associated with corrections and the assigned quantity values of measurement standards, as well as the definitional uncertainty. Sometimes estimated systematic effects are not corrected for but, instead, associated measurement uncertainty components are incorporated.

NOTE 2 The parameter may be, for example, a standard deviation called standard measurement uncertainty (or a specified multiple of it), or the half-width of an interval, having a stated coverage probability.

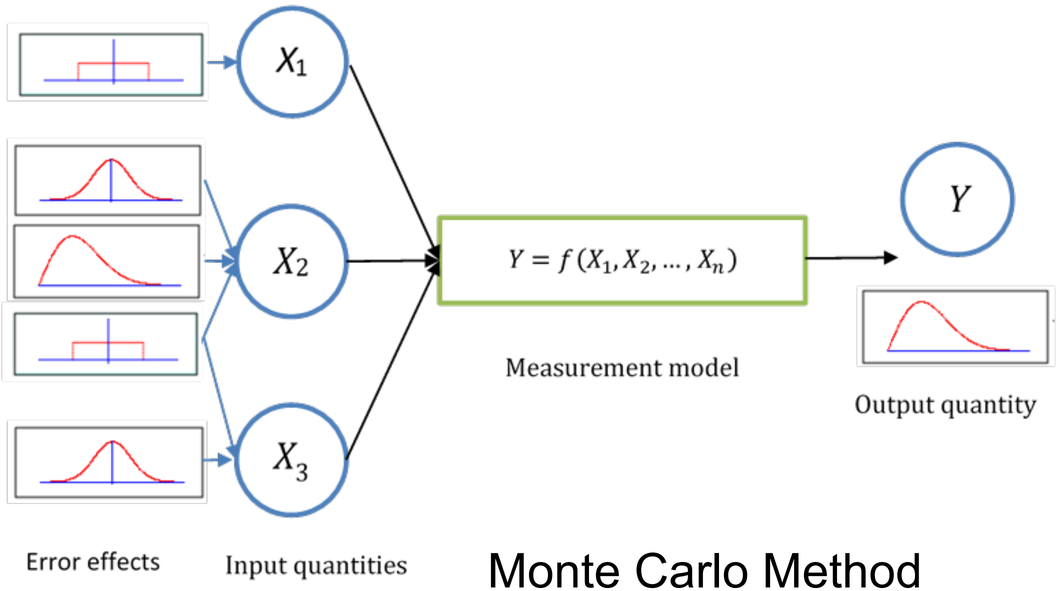
NOTE 3 Measurement uncertainty comprises, in general, many components. Some of these may be evaluated by Type A evaluation of measurement uncertainty from the statistical distribution of the quantity values from series of measurements and can be characterized by standard deviations. The other components, which may be evaluated by Type B evaluation of measurement uncertainty, can also be characterized by standard deviations, evaluated from probability density functions based on experience or other information.

NOTE 4 In general, for a given set of information, it is understood that the measurement uncertainty is associated with a stated quantity value attributed to the measurand. A modification of this value results in a modification of the associated uncertainty.

https://jcgm.bipm.org/vim/en/2.26.html

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/

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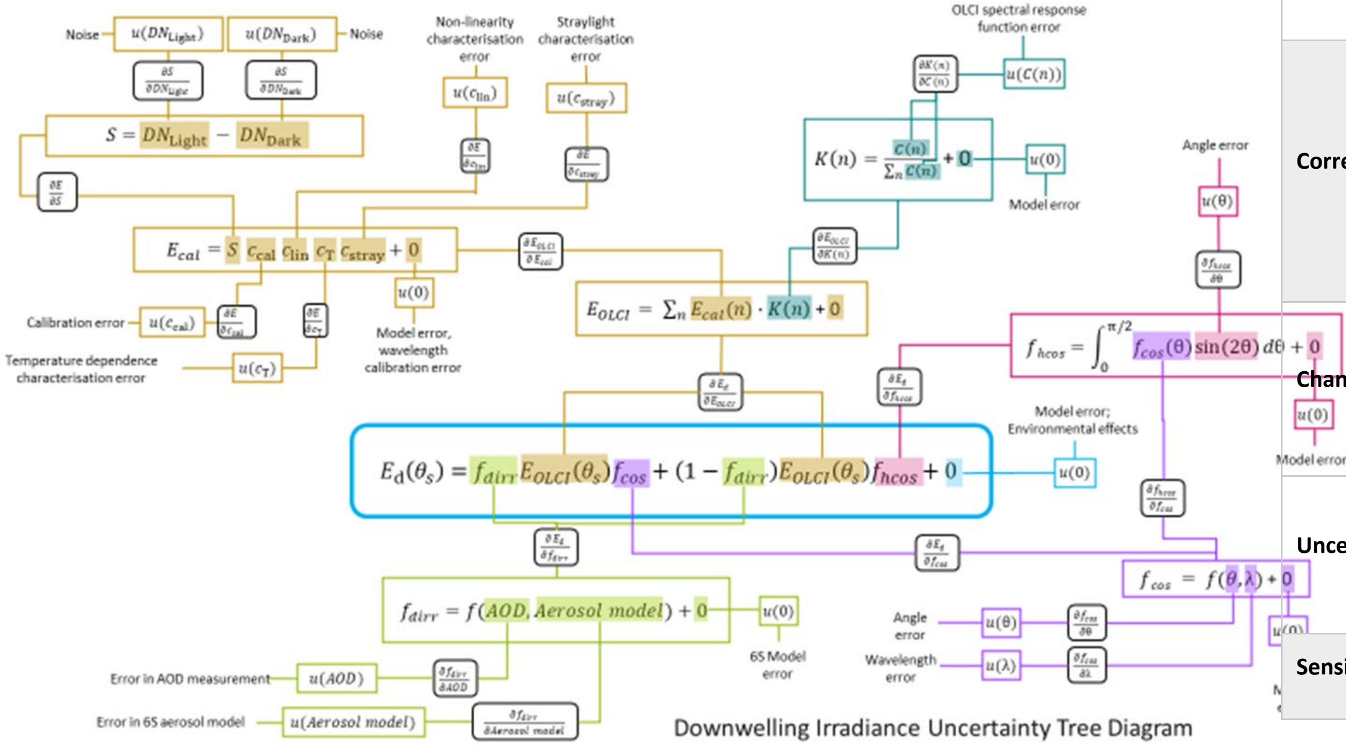
Methodology and resources

- FIDUCEO (FIDelity and Uncertainty in Climate data records from Earth Observations)



Downwelling Irradiance Uncertainty Tree Diagram

Table descriptor				
Name of effect		Detector calibration systematic error	Detector calibration random error 1, 2	Detector calibration stability model error 1, 2
Affected term in measurement function		c_{cal,z_1}, c_{cal,z_2}, $c_{\text{cal},z_1,t}$, $c_{\text{cal},z_2,t}$	c_{cal,z_1}, c_{cal,z_2}, $c_{\text{cal},z_1,t}$, $c_{\text{cal},z_2,t}$	c_{stab,z_1}, c_{stab,z_2}
Instruments in the series affected		All	All	All
Correlation type and form	Temporal within deployment	Rectangular Absolute	Rectangular Absolute	Rectangular Absolute
	Temporal between deployments	Rectangular Absolute	Random	Random
	Spectral (hyperspectral in-situ)	To be defined	To be defined	To be defined
Correlation scale	Temporal within deployment	-∞,+∞	-∞,+∞	-∞,+∞
	Temporal between deployments	a,b[1]	0	0
	Spectral (hyperspectral in-situ)	To be defined	To be defined	To be defined
Channels/bands	List of channels / bands affected	All	All	All
	Error correlation coefficient matrix	Identity – No correlation	Identity – No correlation	Identity – No correlation
Uncertainty	PDF shape	Gaussian	Gaussian	Gaussian
	units	Radiance/Counts	Radiance/Counts	Radiance/Counts
	magnitude	0.70%	0.25%	Less than 1%
Sensitivity coefficient		$\frac{\partial f}{\partial c_{cal\_s}}$	$\frac{\partial f}{\partial c_{cal\_r1}}, \frac{\partial f}{\partial c_{cal\_r2}}$	$\frac{\partial L_w}{\partial c_{stab1}}, \frac{\partial L_w}{\partial c_{stab2}},$

CoMet

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/

Basic uncertainty concepts

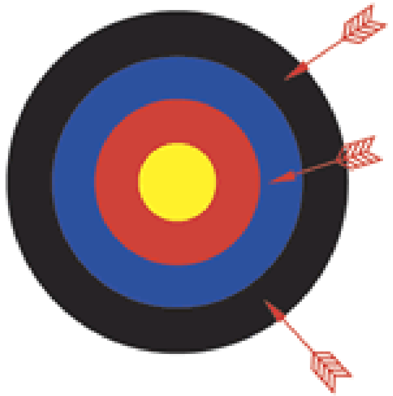
What is not a measurement uncertainty?

- Mistakes made by operators are not measurement uncertainties. They should not be counted as contributing to uncertainty. They should be avoided by working carefully and by checking work.
- Accuracy (or rather inaccuracy) is not the same as uncertainty. Unfortunately, usage of these words is often confused. Correctly speaking, ‘accuracy’ is a qualitative term (e.g. you could say that a measurement was ‘accurate’ or ‘not accurate’). Uncertainty is quantitative. When a ‘plus or minus’ figure is quoted, it may be called an uncertainty, but not an accuracy.
- Errors are not the same as uncertainties (even though it has been common in the past to use the words interchangeably in phrases like ‘error analysis’).
- Statistical analysis is not the same as uncertainty analysis. Statistics can be used to draw all kinds of conclusions which do not by themselves tell us anything about uncertainty. Uncertainty analysis is only one of the uses of statistics.

Measurement Uncertainty: Accuracy and Precision

Accuracy ⇒ qualitative term relating the mean of the measurements to the true value

Precision ⇒ represents the spread of the measurements



Poor precision, poor accuracy

Poor precision, good accuracy

Good precision, poor accuracy

Good precision, good accuracy

Basic concepts

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Uncertainty

Type A

Type B

Expanded

Standard

Coverage factor

Absolute

Relative

Effects of the errors

Systematic

Random

Correction

Uncertainty types

There are two methods for estimating uncertainties:

Type-A:

uncertainty estimates using statistics i.e. by taking multiple readings and using that information

Type-B:

uncertainty estimates from any other information, e.g. past experience, calibration certificates, etc.

Confidence intervals

- Uncertainty is given with respect to a given confidence interval:

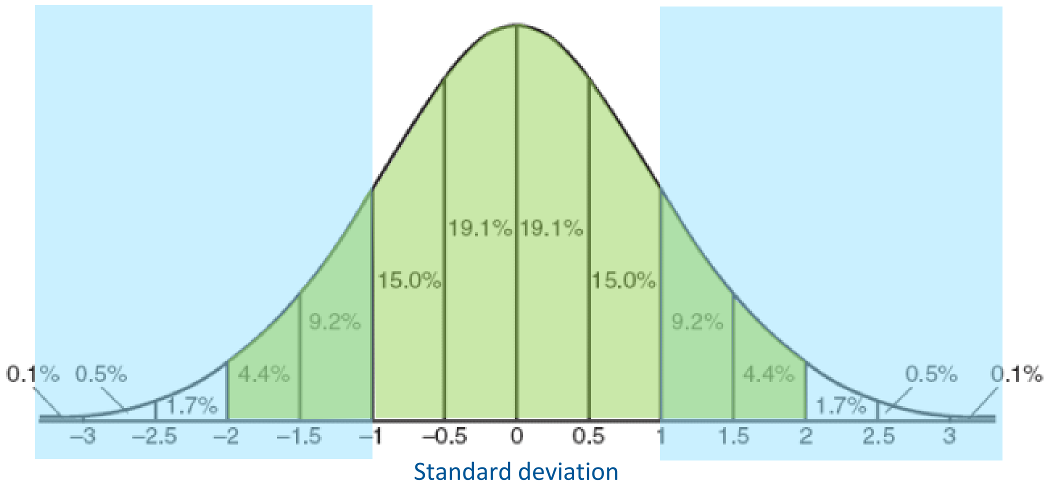
u(y) = ± 3 cm

at the 68.2% coverage probability (1σ or $k = 1$)

at the 95.4% confidence level

u(y) = ± 6 cm

at the 95.4% coverage probability (2σ or $k = 2$)



Uncertainty expression

Relative uncertainty:

5 mW m^{-2} nm^{-1} $\pm$ 0.2 %

i.e. uncertainty expressed as a percentage

Absolute uncertainty:

5 mW m^{-2} nm^{-1} $\pm$ 0.01 mW m^{-2} nm^{-1} i.e. uncertainty expressed in the native measurement units

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First order Taylor series approximation
uncorrelated input quantities version

$$u_c^2(y) = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i)$$

THE LAW OF PROPAGATION OF UNCERTAINTIES

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$$u_c^2(y) = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i)$$

Sensitivity Coefficients

Sensitivity coefficients cheatsheets

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Summation in quadrature for addition and subtraction

$e = a + b - c,$

$$Combined\ uncertainty = \sqrt{a^2 + b^2 + c^2 + \ldots etc}.$$

Summation in quadrature for multiplication or division

$A = L \cdot W,$

$$\frac{u(A)}{A} = \sqrt{\left(\frac{u(L)}{L}\right)^2 + \left(\frac{u(W)}{W}\right)^2}.$$

Sensitivity coefficients cheatsheets

National Physical Laboratory

Squared value

$$Z^2,$$

$$\frac{2u(Z)}{Z}.$$

Summation in quadrature for more complicated function

$$P = \frac{V^2}{R},$$

$$\frac{u(P)}{P} = \sqrt{\left(\frac{2u(V)}{V}\right)^2 + \left(\frac{u(R)}{R}\right)^2}.$$

Steps to an uncertainty budget

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1. Traceability Chain
2. Calculation Equation
3. Sources of Uncertainty
4. Measurement Equation
5. Sensitivity Coefficients
6. Assigning Uncertainties
7. Combining your uncertainties
8. Expanding your uncertainties

Symbol	Uncertainty component	Size of effect	Correction applied?	Residual uncertainty	Divisor	Sensitivity coefficient	Uncertainty associated with final value due to effect
Combined standard uncertainty							
Expanded uncertainty							

Absolute calibration measurement equation

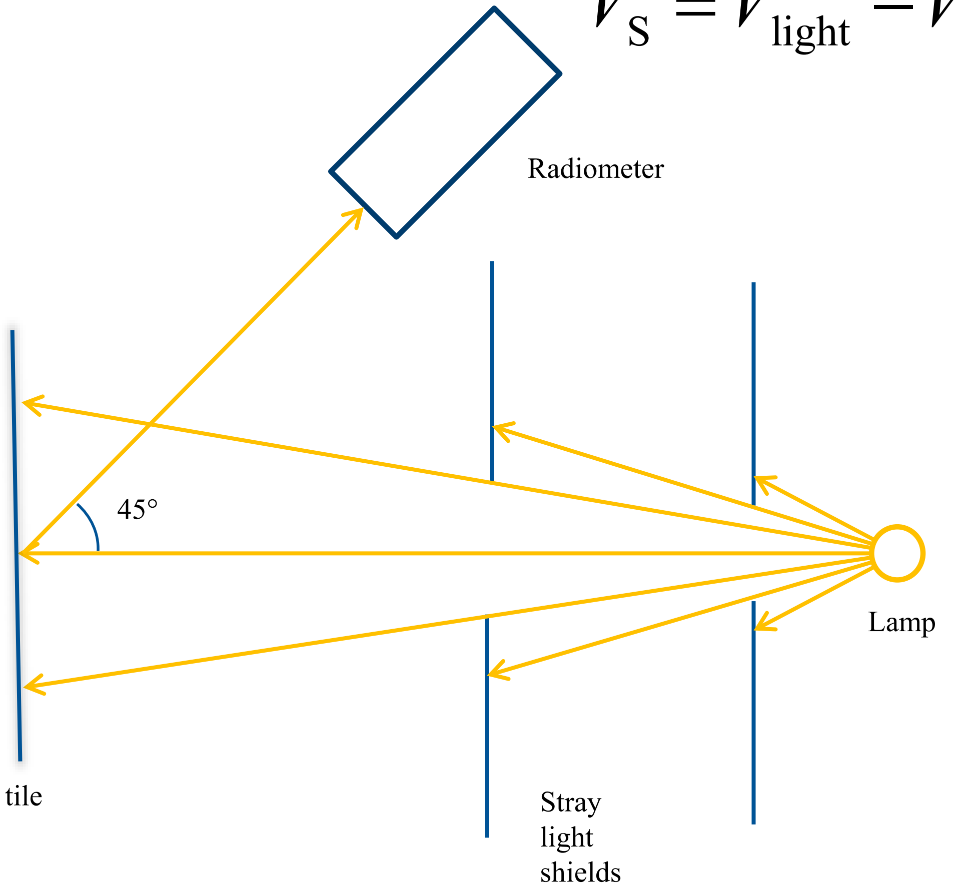
Calculation equation

Absolute calibration coefficient

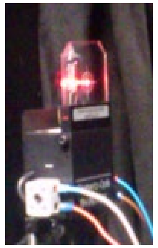
$$A_L = \frac{L_s}{V_s}$$

$$V_S = V_{\text{light}} - V_{\text{dark}}$$

$$L_s = \frac{E_{FEL}\beta_{0:45}}{\pi}\frac{d_{cal}^2}{d_{use}^2}$$



Sources of uncertainty



Calibration certificate

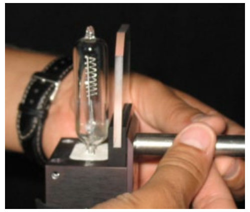
Lamp additional effects

- Ageing
- Alignment
- Current stability

Calibration certificate

Diffuser additional effects

- Ageing
- Uniformity



Distance accuracy

Random noise

Instrument additional effects

- Stability (drift)
- Room stray light

Measurement equations

$$L_s = \frac{E_{FEL}\beta_{0:45}}{\pi}\frac{d_{cal}^2}{d_{use}^2}$$

$$L_s = \frac{E_{FEL}\beta_{0:45}}{\pi}\frac{d_{cal}^2}{d_{use}^2} K_{lamp\_stab} K_{align} K_{current} K_{diff\_stab} K_{unif}$$

$$V_S = V_{light} - V_{dark}$$

$$V_S = V_{light} K_{light\_stab} + K_{stray} - V_{dark} K_{dark\_stab}$$

Calibration certificate

Remember calibration certificates almost always quote uncertainties at $k = 2$!

Rectangular uncertainty distributions

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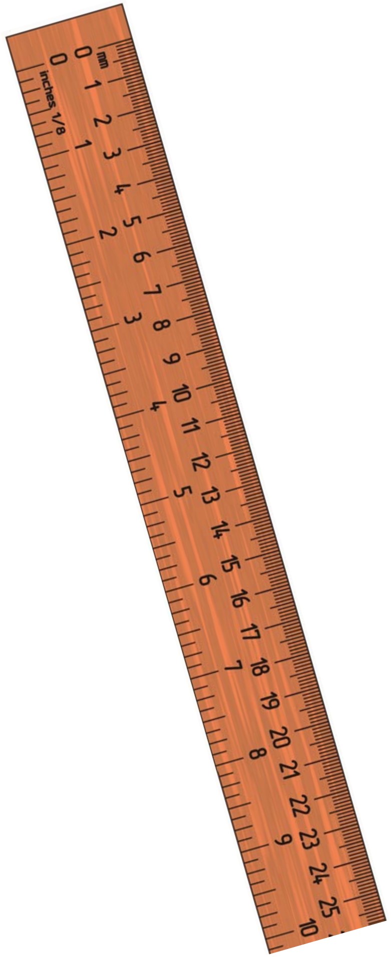
$$-2 \cdot u\left(d_{\text{use}}\right)/d_{\text{use}}$$

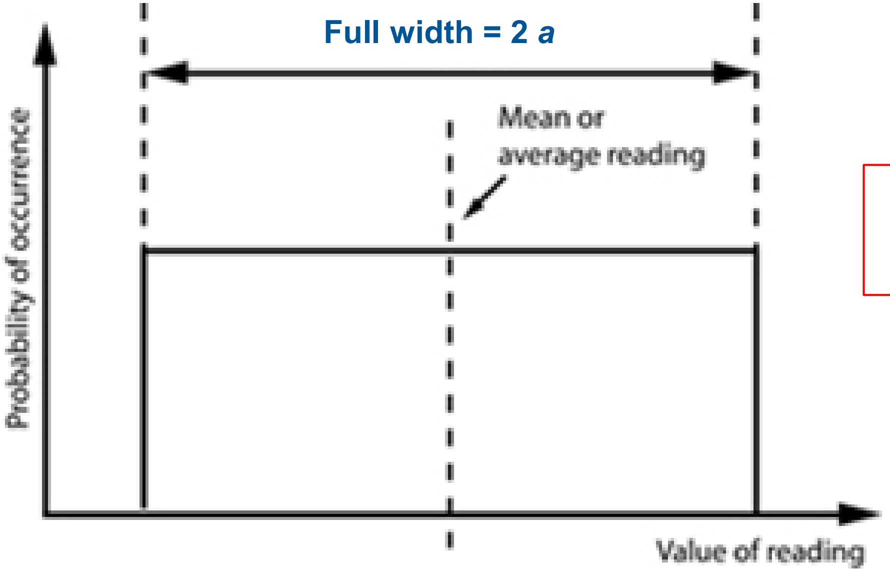


Resolution of distance measuring instrument = 0.1 mm

Measurement distance = 500.0 mm

Uncertainty associated with distance measurement =
(0.05 / 500) / √3 = 0.006 %

Uncertainty in irradiance from distance measurement =
2 × 0.006 % = 0.012 %



$$\frac{a}{\sqrt{3}}$$

Uncertainty budget

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Symbol	Uncertainty component	Size of effect	Correction applied?	Residual uncertainty	Divisor	Sensitivity coefficient	Uncertainty associated with final value due to effect
$u(E_{\mathrm{FEL}})$	Ref. lamp irradiance	1.5 %	N	1.5 %	2	1	0.75 %
$u(\beta_{0:45})$	Tile radiance factor	2.0 %	N	2.0 %	2	1	1.00 %
$u(d_{\mathrm{use}})$	Lamp distance (500 mm)	0.05 mm	N	0.01 %	√3	2	0.012 %
$u(K_{\mathrm{align}})$	Lamp alignment	0.15 %	N	0.15 %	1	1	0.15 %
$u(K_{\mathrm{l\_stab}})$	Light reading stability	negligible	N	negligible			negligible
$u(K_{\mathrm{d\_stab}})$	Dark reading stability	negligible	N	negligible			negligible
$u(K_{\mathrm{lamp\_stab}})$	Lamp stability	0.083 %	N	0.083 %	√3	1	0.048 %
$u(K_{\mathrm{diff\_stab}})$	Diffuser stability	0.125 %	N	0.125 %	√3	1	0.072 %
$u(K_{\mathrm{stray}})$	Stray light in lab	negligible	N	negligible			negligible
$u(K_{\mathrm{current}})$	Lamp current (8.000 A)	0.004 A	N	0.25 % in *I*, or 0.99 % in E_{FEL} at 600 nm	√3	1	0.572 % (at 600 nm)
$u(K_{\mathrm{unif}})$	Radiance uniformity	1.50 %	N	1.50 %	√3	1	0.866 %
Combined standard uncertainty							1.63 %
Expanded uncertainty (*k*=2)							3.3 %

Uncertainty budget

1. Traceability Chain

Uncertainty evaluation type ?

Type B – information form calibration certificates !

Symbol	Uncertainty component	Size of effect	Correction applied?	Residual uncertainty	Divisor	Sensitivity coefficient	Uncertainty associated with final value due to effect
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Coverage factor ?
Probability distribution?

k = 2, Gaussian

Uncertainty budget

2. Calculation equation

Uncertainty evaluation type ?

Type B – information form calibration certificates
Type A – repeated measurements

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$u(d_{\mathrm{use}})$	Lamp distance (500 mm)	0.05 mm	N	0.01 %	$\sqrt{3}$	2	0.012 %

Absolute uncertainty

Relative uncertainty

Uncertainty budget

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3. Sources of uncertainty
4. Measurement equation (all components with assigned size of effect)
5. Sensitivity coefficient

Symbol	Uncertainty component	Size of effect	Correction applied?	Residual uncertainty	Divisor	Sensitivity coefficient	Uncertainty associated with final value due to effect
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Uncertainty budget

6. Assigning Uncertainties
7. Combining your uncertainties

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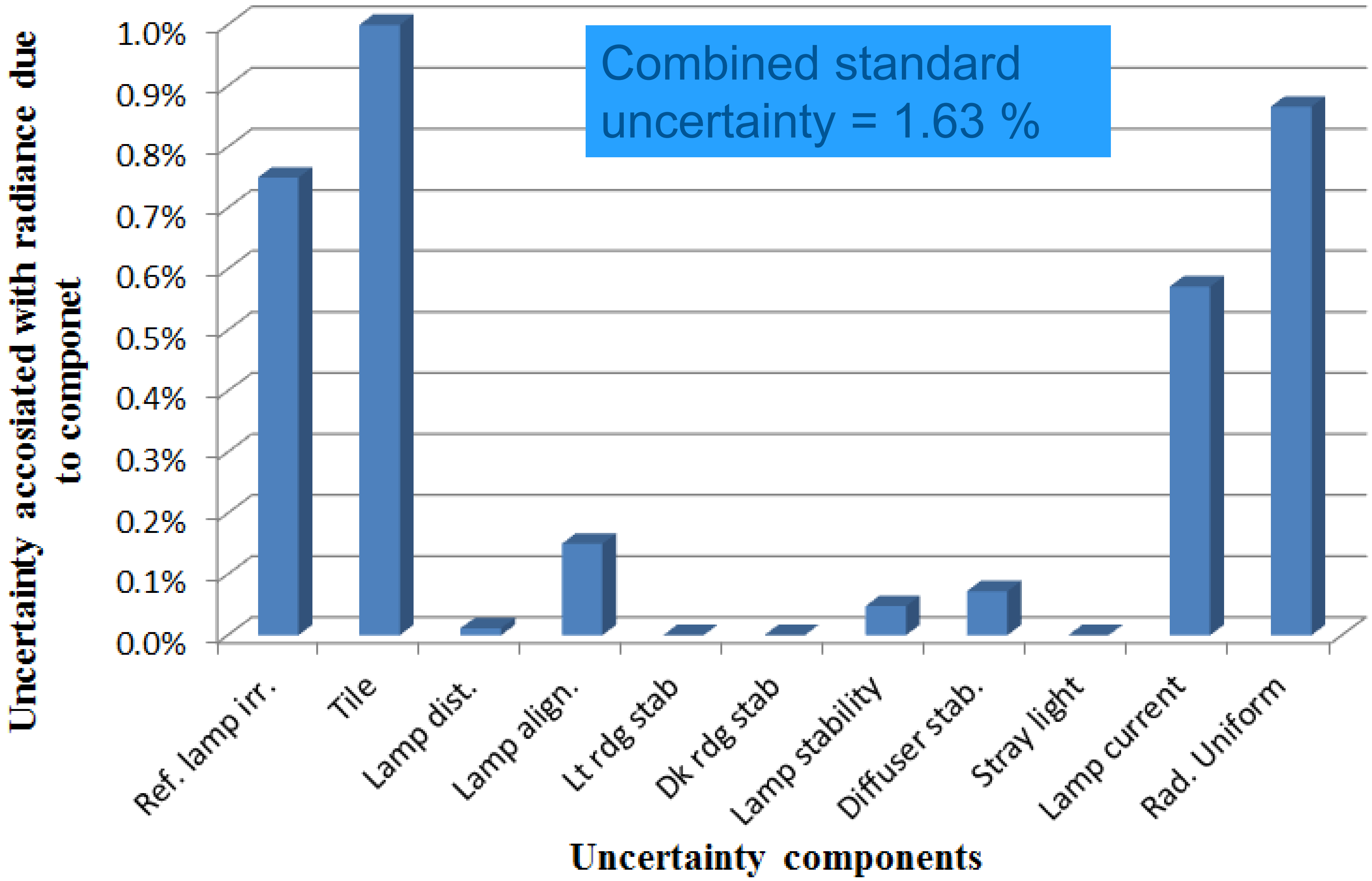
Expanded uncertainty (k=2)							3.3 %

8. Expanding your uncertainties

When to stop



Combined standard uncertainty = 1.63 %
Uncertainty accosiated with radiance due to componet
1.0%
0.9%
0.8%
0.7%
0.6%
0.5%
0.4%
0.3%
0.2%
0.1%
0.0%
Ref. lamp irr.
Tile
Lamp dist.
Lamp align.
Lt rdg stab
Dk rdg stab
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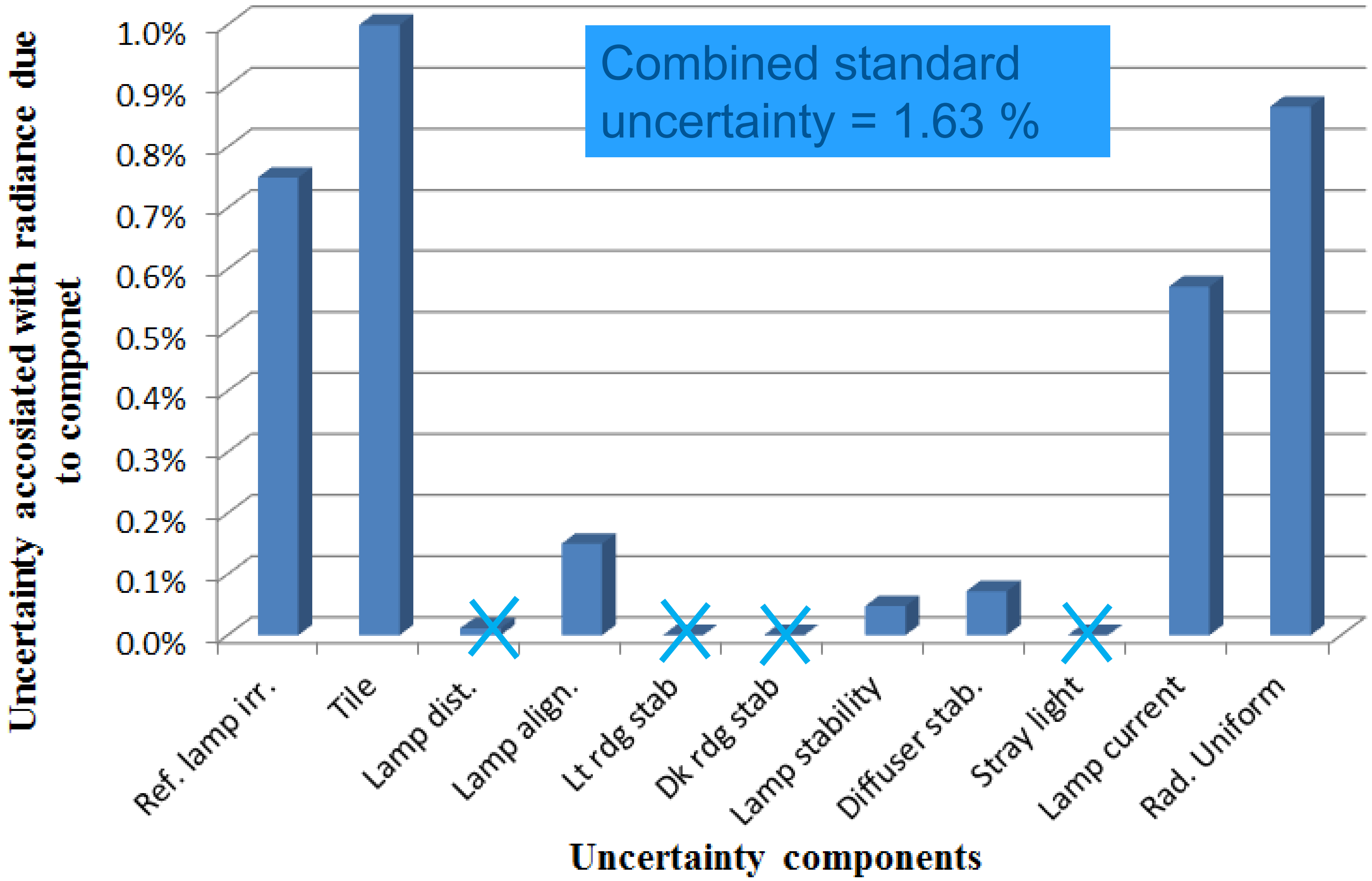
Diffuser stab.
Stray light
Lamp current
Rad. Uniform
Uncertainty components

When to stop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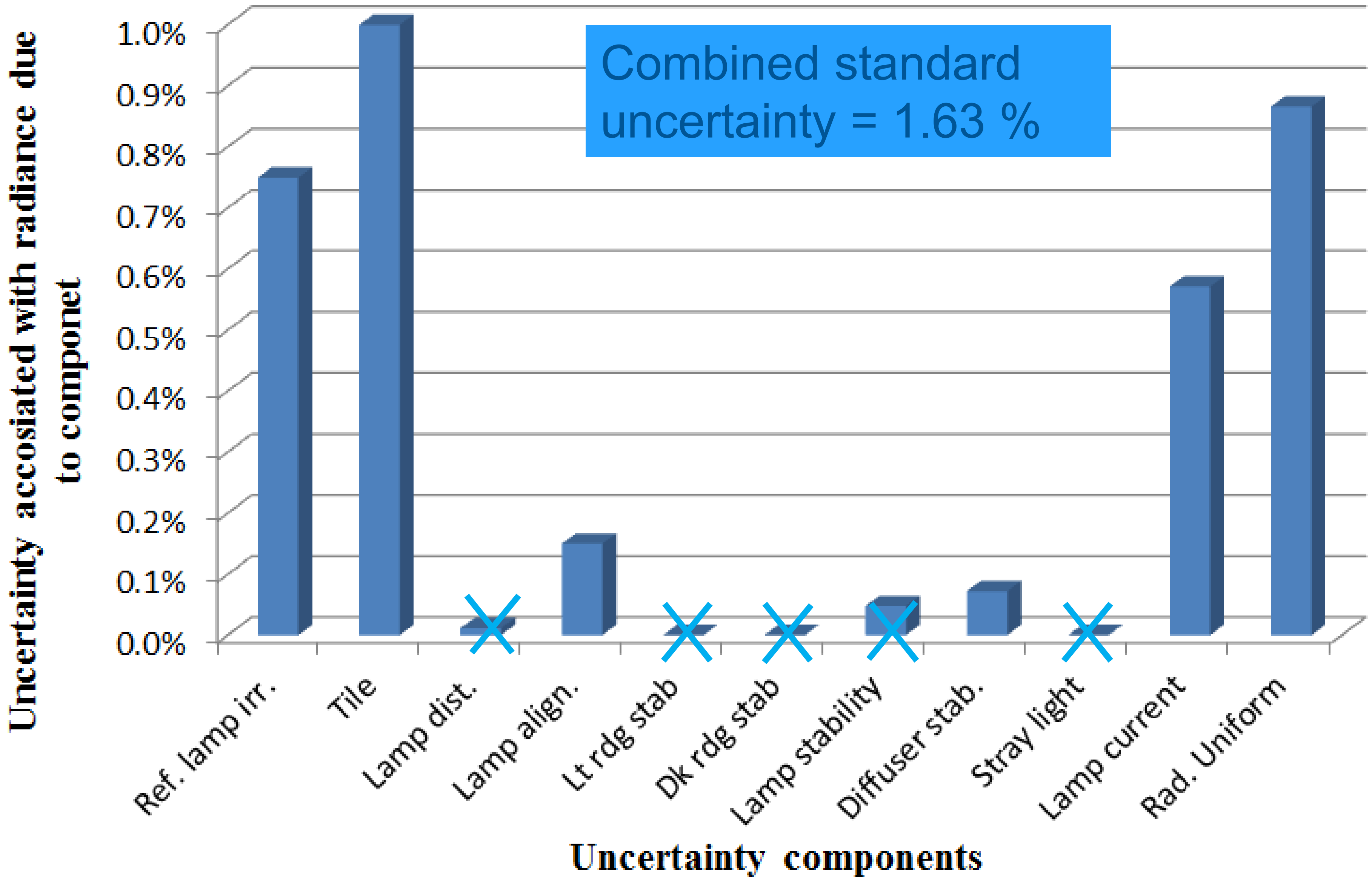

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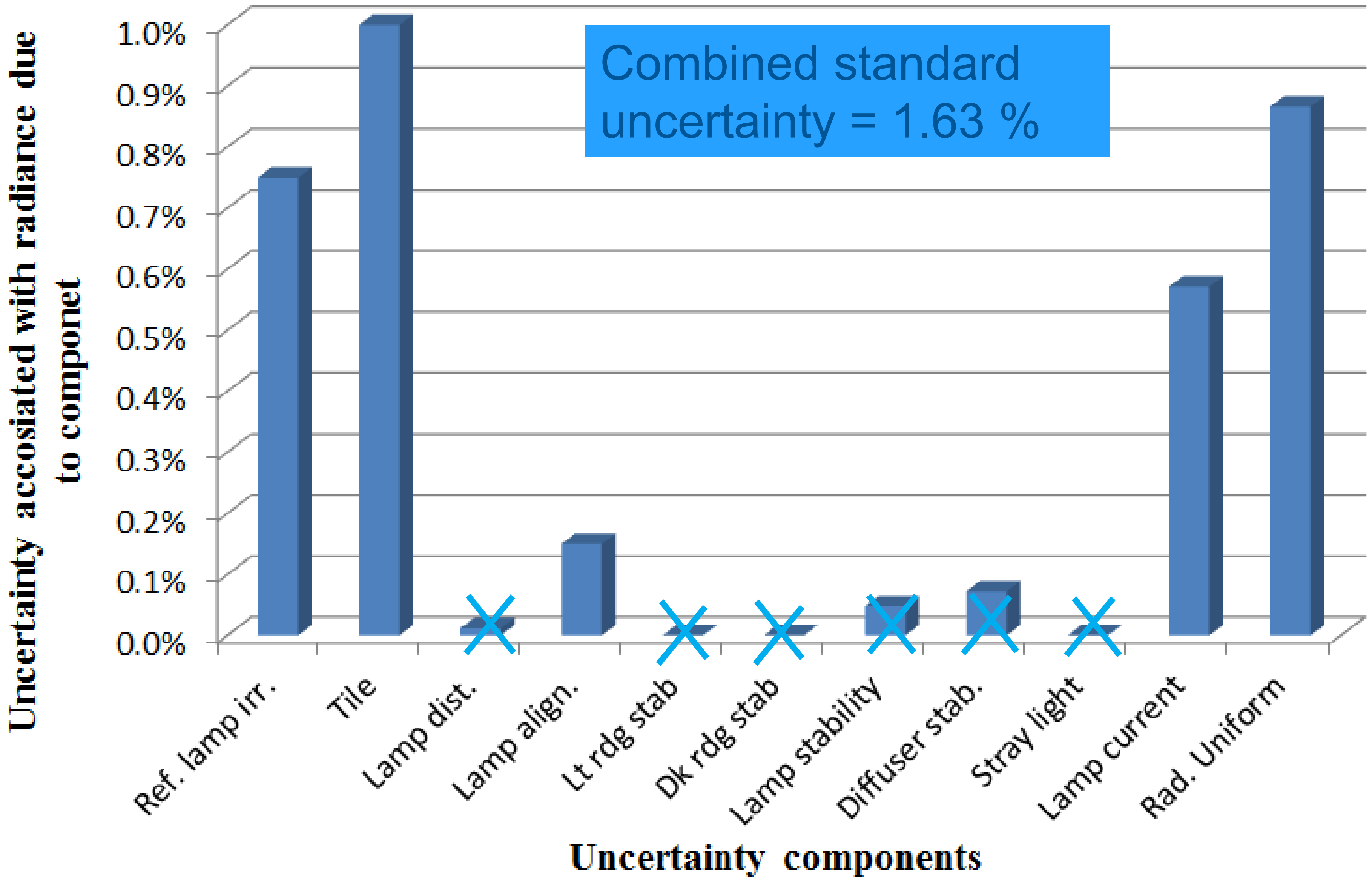
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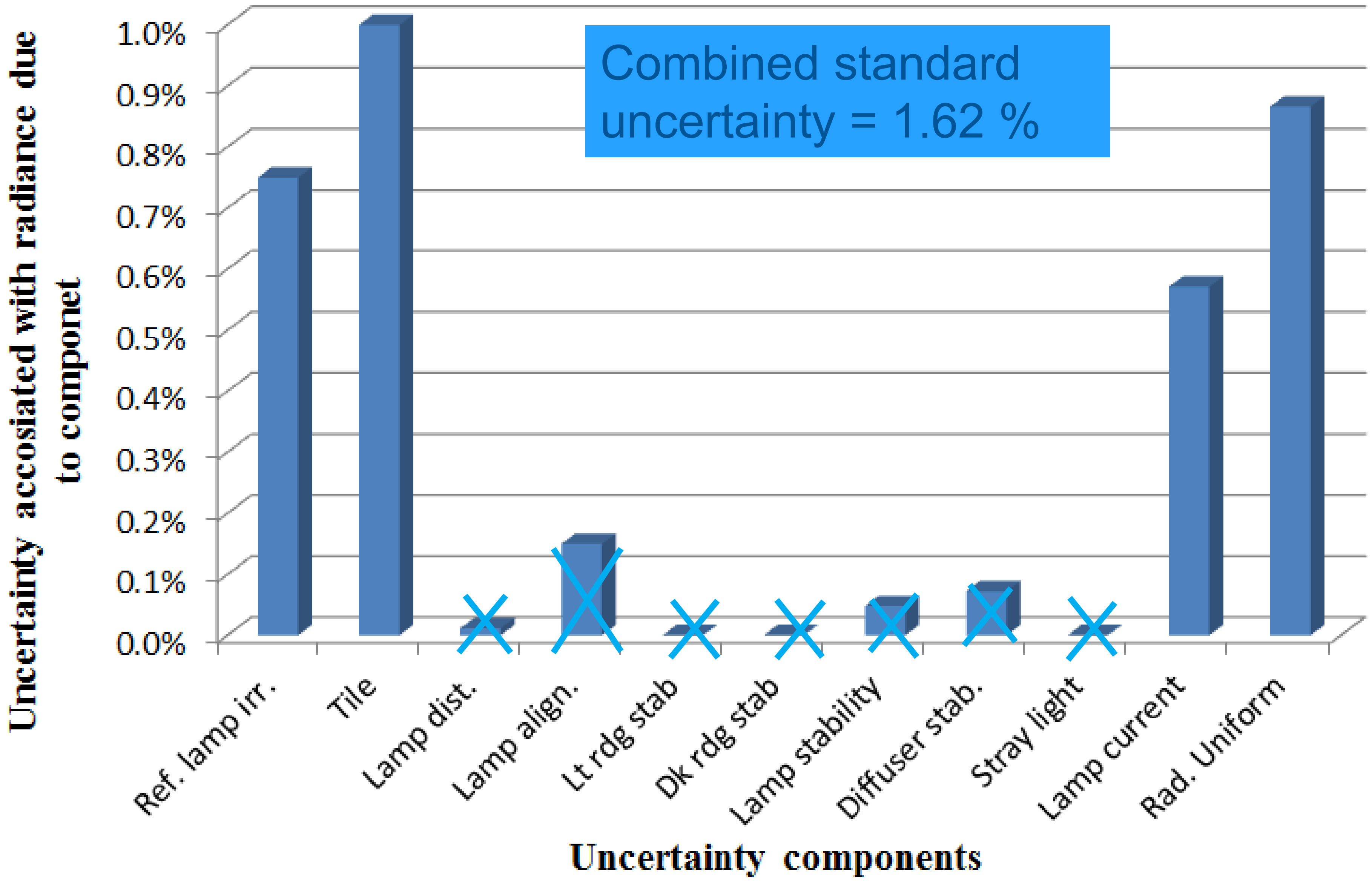
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Above water radiometry measurement equation

Remote sensing reflectance cheatsheet

$$R_{rs} = \frac{L_t - \rho L_i}{E_s}$$

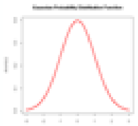
$$u_{rel}(L_r) = \sqrt{u_{rel}(\rho)^2 + u_{rel}(L_i)^2}$$

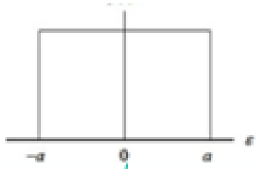
$$u_{asbl}(L_w) = \sqrt{u_{abs}(L_t)^2 + u_{abs}(L_r)^2}$$

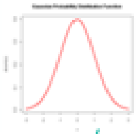
$$u_{rel}(L_w) = \sqrt{\frac{u_{abs}(L_t)^2 + u_{abs}(L_r)^2}{L_w^2}}$$

$$u_{rel}(R_{rs}) = \sqrt{u_{rel}(L_w)^2 + u_{rel}(E_s)^2}$$

GUM Methodology applied in CoMET tool







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

random

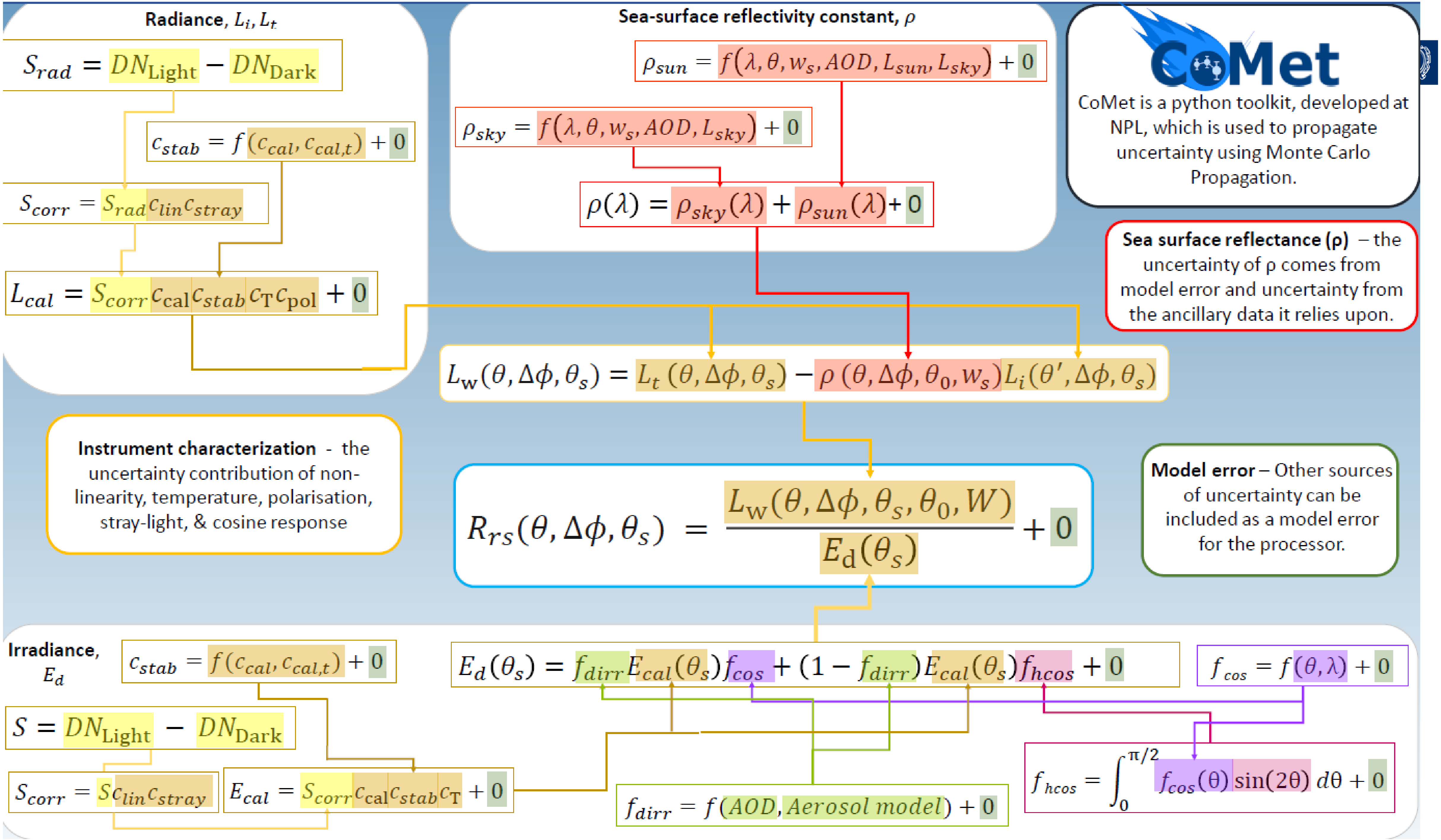
systematic

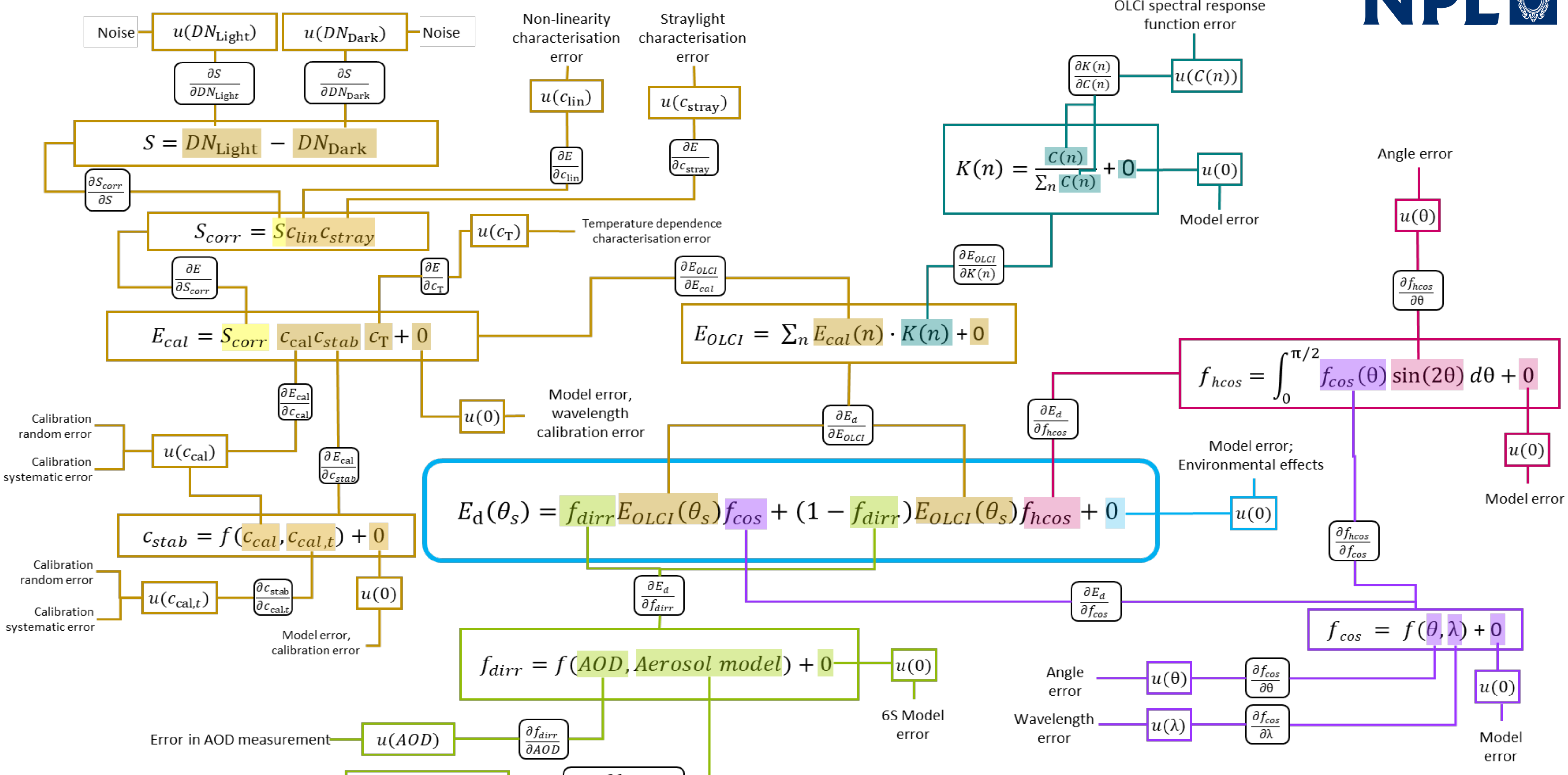
L_t	c_{c2}	ρ	L_i	c_{c3}	E_s	c_{c8}
1	0	0	0	0	0	0
0	1	0	0	1	0	1
0	0	1	0	0	0	0
0	0	0	1	0	0	0
0	1	0	0	1	0	1
0	0	0	0	0	1	0
0	1	0	0	1	0	1

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

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

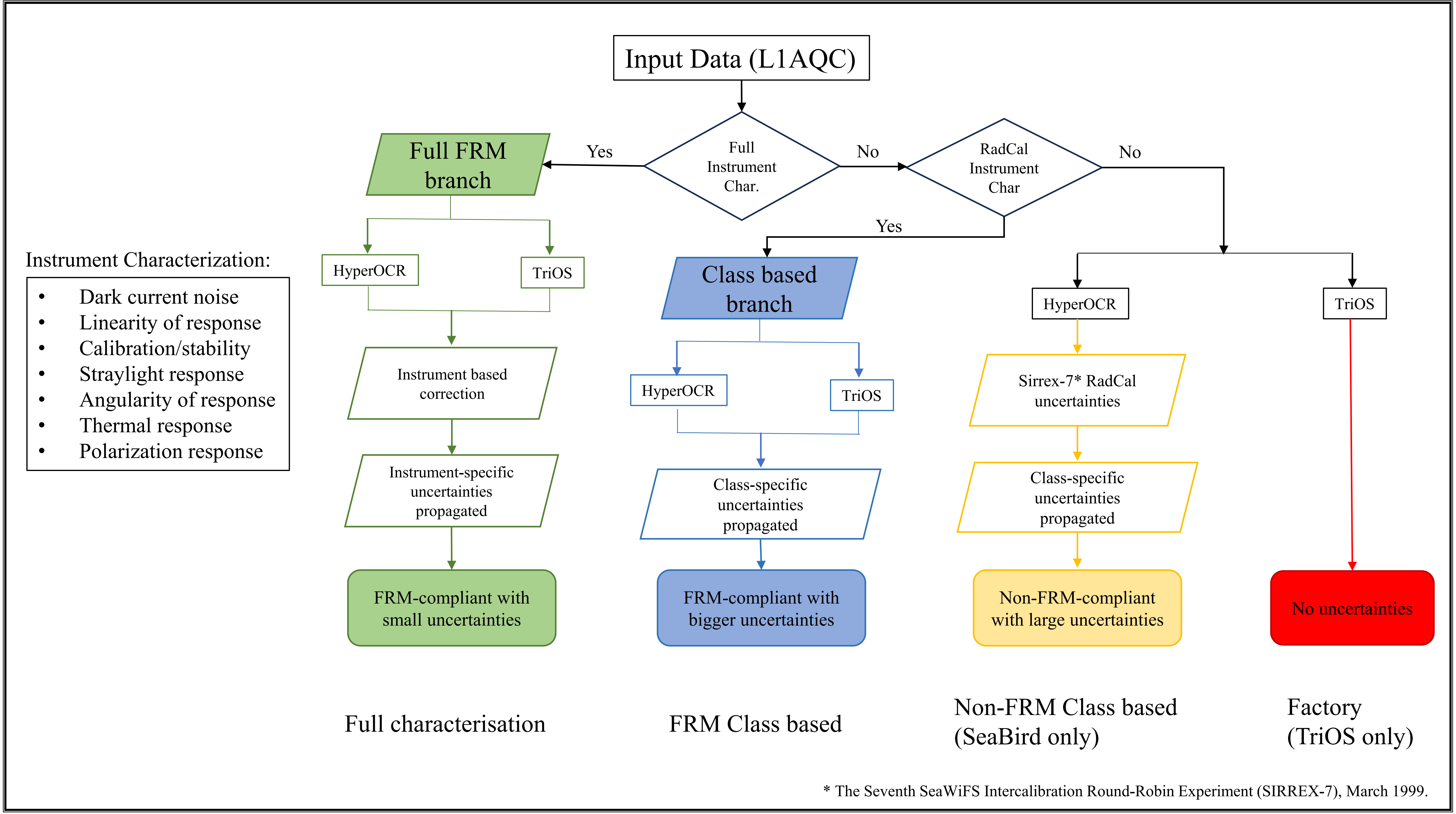
JCGM101:2008. Evaluation of measurement data - *Supplement 1 to the Guide to the expression of uncertainty in measurement - Propagation of distributions using a Monte Carlo method.*


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
$c_{stab} = f(c_{cal}, c_{cal,t}) + 0$
$S = DN_{\text{Light}} - DN_{\text{Dark}}$
$S_{corr} = S c_{lin} c_{stray}$
$E_{cal} = S_{corr} c_{\text{cal}} c_{stab} c_{\text{T}} + 0$
$E_d(\theta_s) = f_{dirr} E_{cal}(\theta_s) f_{cos} + (1 - f_{dirr}) E_{cal}(\theta_s) f_{hcos} + 0$
$f_{cos} = f(\theta, \lambda) + 0$
$f_{dirr} = f(AOD, Aerosol\ model) + 0$
$f_{hcos} = \int_0^{\pi/2} f_{cos}(\theta) \sin(2\theta)\, d\theta + 0$



Downwelling Irradiance Uncertainty Tree Diagram – FRM branch

Uncertainty propagation in HyperCP



Input Data (L1AQC)
Full Instrument Char.
Yes
No
Full FRM branch
RadCal Instrument Char
No
Yes
Instrument Characterization:
Dark current noise
Linearity of response
Calibration/stability
Straylight response
Angularity of response
Thermal response
Polarization response
HyperOCR
TriOS
Instrument based correction
Instrument-specific uncertainties propagated
FRM-compliant with small uncertainties
Class based branch
HyperOCR
TriOS
Class-specific uncertainties propagated
FRM-compliant with bigger uncertainties
HyperOCR
Sirrex-7* RadCal uncertainties
Class-specific uncertainties propagated
Non-FRM-compliant with large uncertainties
TriOS
No uncertainties
Full characterisation
FRM Class based
Non-FRM Class based (SeaBird only)
Factory (TriOS only)
* The Seventh SeaWiFS Intercalibration Round-Robin Experiment (SIRREX-7), March 1999.

Default branch measurements equations

- Irradiance

$$E_d(\lambda) = \overline{E_d(\lambda)} \cdot c_{cal}(\lambda) c_{stab}(\lambda) c_{lin}(\lambda) c_{stray}(\lambda) c_T(\lambda) f_{cos}$$

- Radiance

$$L_t(\lambda) = \overline{L_t(\lambda)} \cdot c_{cal}(\lambda) c_{stab}(\lambda) c_{lin}(\lambda) c_{stray}(\lambda) c_T(\lambda) c_{pol}(\lambda)$$

Approach

NPL

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 4 – Summary information about each uncertainty component for sea surface reflectance factor (ρ) estimation using Mobley method

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	$1 ms^{-1}$	Normal	Random	N/A
$\Delta\phi$	Relative azimuth	3°	Normal	Random²	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

Default Branch CP Implementation Example

NPL

Source of Uncertainty	Input Uncertainty
DN_{light}	Std (k=1)
DN_{dark}	Std (k=1)
c_{cal}	Tartu file
c_{stab}	1%
c_{lin}	2%
c_{stray}	FRM4SOC-1
c_{temp}	Tartu file
c_{cos}	2%

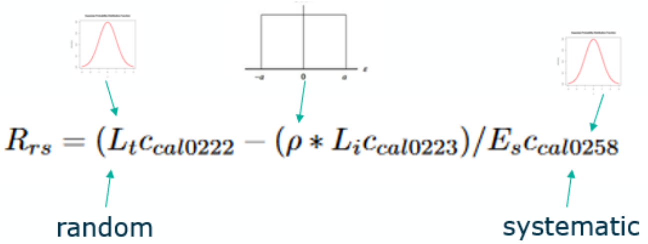
```
    @staticmethod
    def Es(DNLight, DNDark, Ccal, Cstab, Clin, Cstray, Ct, Ccos):
        """(DNLIGHT-DNDARK).Ccal.Cstab.Clin.Cstray.Ct.Ccos"""
        return (DNLight - DNDark) * Ccal * Cstab * Clin * Cstray * Ct * Ccos
```

- Occurs at L1B during dark correction, c_{cal} is taken from Tartu file.
- Time average DN_{light} & DN_{dark}.
- Remaining coefficients are set to 1.
- Measurement function is defined in python.
- Punpy generates samples from inputs and uncertainties.
- Runs M=10000 Monte Carlo uncertainty propagation according to the GUM.
- Output is divided by signal to generate relative uncertainty.
- Saved in the uncertainty budget group.

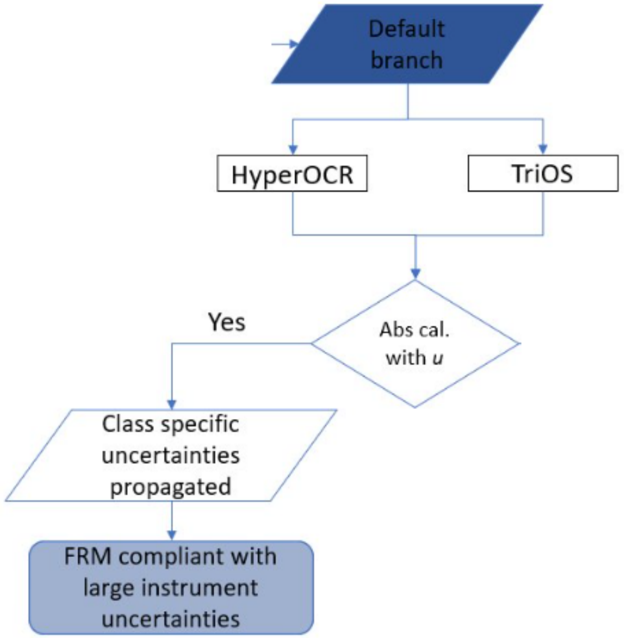
Using Monte Carlo

- First, we need to identify our measurement function, f
- We need our inputs to the measurement function with their associated uncertainties
- Then we build samples of M draws, based on known input correlation
- We run those samples through f
- $u_c(y)$ can be found from the statistics o the output

GUM Methodology applied in CoMET tool

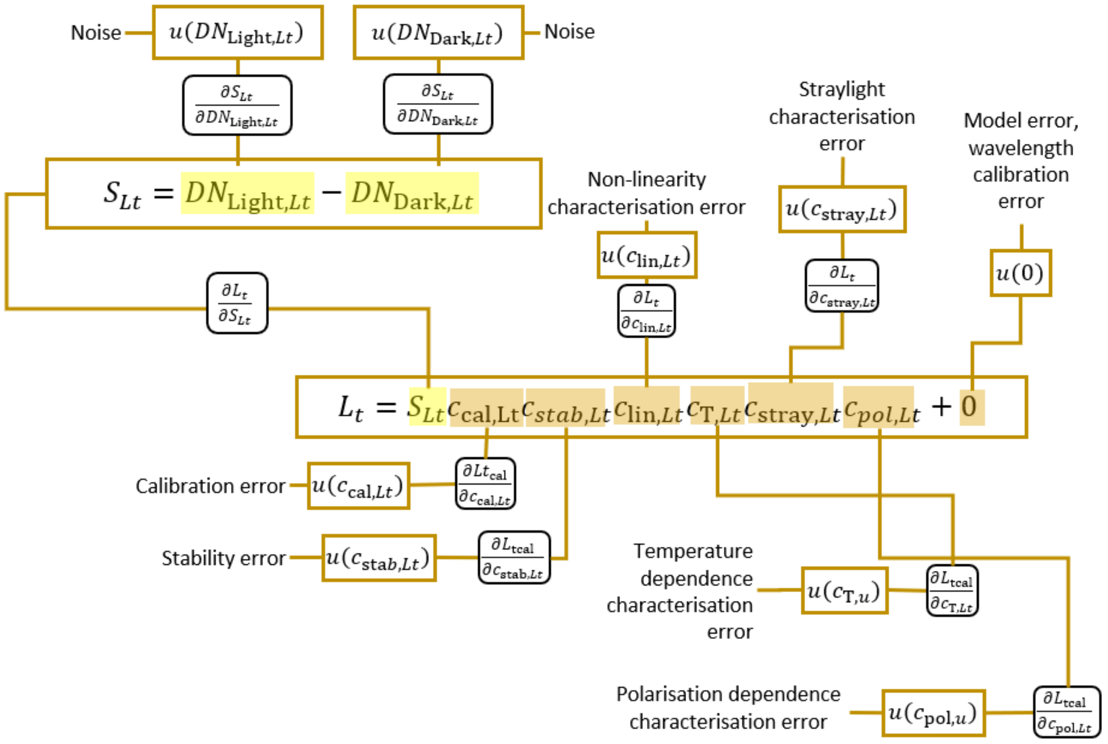


	L_t	c_{c2}	ρ	L_i	c_{c3}	E_s	c_{c8}
L_t	1	0	0	0	0	0	0
c_{c2}	0	1	0	0	1	0	1
ρ	0	0	1	0	0	0	0
L_i	0	0	0	1	0	0	0
c_{c3}	0	1	0	0	1	0	1
E_s	0	0	0	0	0	1	0
c_{c8}	0	1	0	0	1	0	1



How FRM Uncertainties are Propagated

- We combine and process samples directly
- We calculate uncertainty (in theory) alongside the processor
- Correlations are engendered within the samples
- L2 uncertainties (R_{rs}, Lw, NLw), are calculated using distributions of Es, Li, Lt, & Rho which contain information of uncertainty and correlation



FRM Uncertainties – an example

$$L_{\mathrm{w}}(\theta, \Delta\phi, \theta_s) = L_t\,(\theta, \Delta\phi, \theta_s) - \rho\,(\theta, \Delta\phi, \theta_0, W) L_i(\theta', \Delta\phi, \theta_s) + 0$$

$\frac{\partial L_w}{\partial \rho}$

$u(0)$ — Model error, Environmental effects

```
sample_Lw = Propagate_L2_FRM.run_samples(Propagate.Lw_FRM, MC_x: [ltSample, rhoSample, liSample])
sample_Rrs = Propagate_L2_FRM.run_samples(Propagate.Rrs_FRM, MC_x: [ltSample, rhoSample, liSample, esSample])
```

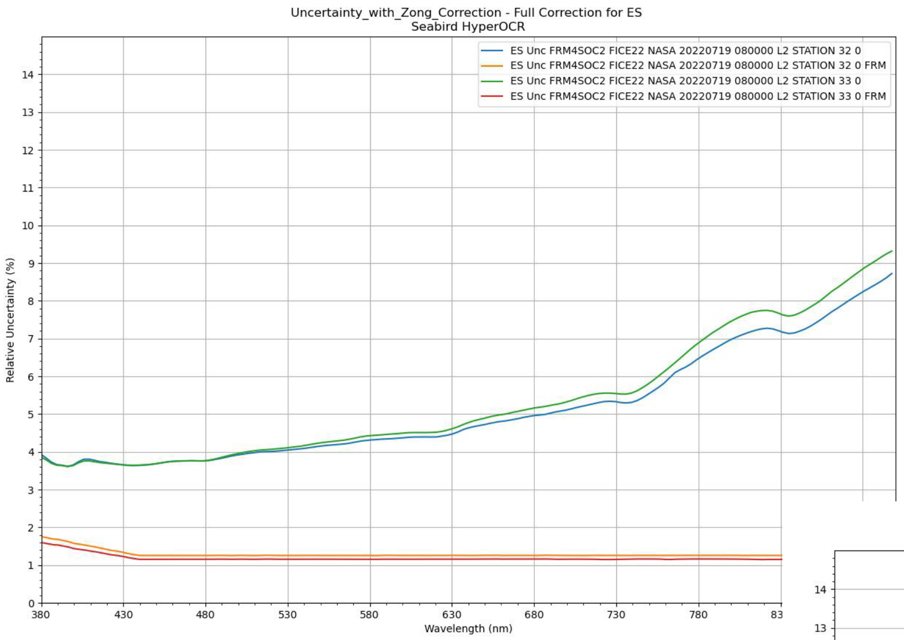
```
3 usages  ARamsay17
@staticmethod
def Lw_FRM(lt, rho, li):
    """ Lw FRM branch measurment function """
    return lt - (rho * li)
```

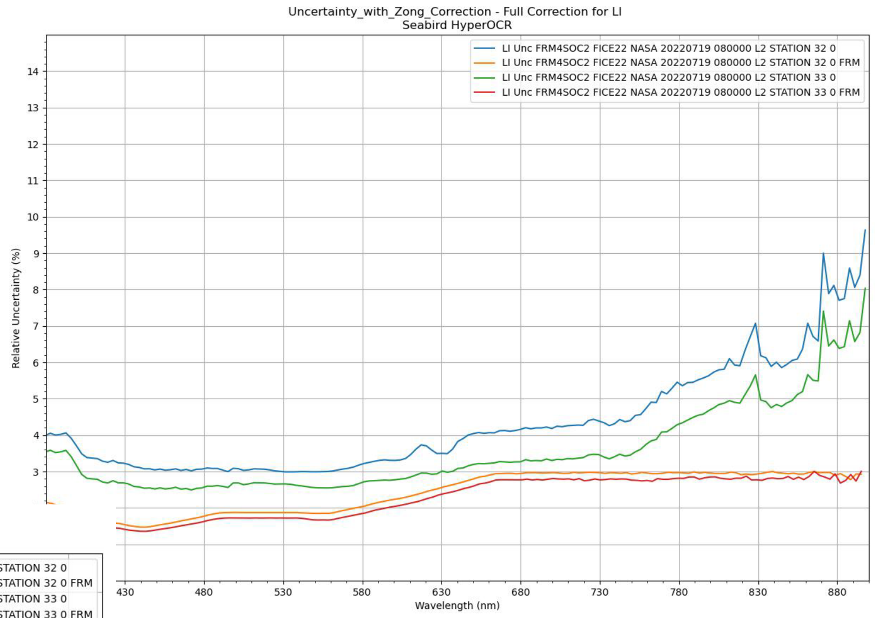
```
@staticmethod
def Rrs_FRM(lt, rho, li, es):
    """ Rrs FRM branch measurment function """
    return (lt - (rho * li)) / es
```

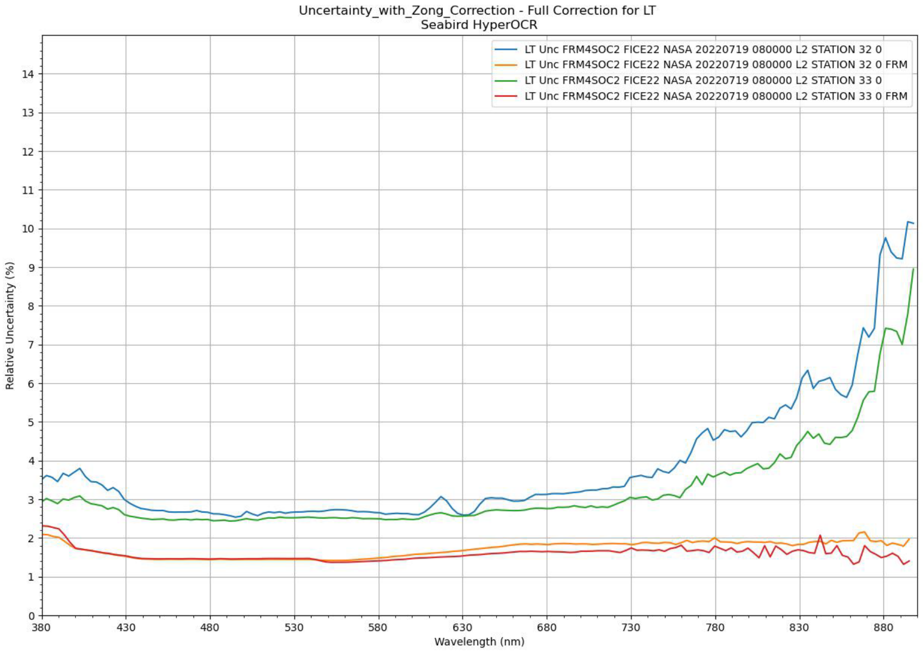
HyperCP

Variable Symbol	Variable Name	Uncertainty Source	Class Based	FRM
			Correction Applied	
$\left(DN_{\text{light},L_X} - DN_{dark,L_X}\right)$ $\left(DN_{\text{light},E_S} - DN_{dark,E_S}\right)$	Mean value of DNs measured by a single instrument at a "station"	Standard deviation calculated from statistics of filtered measurements	NA	NA
c_{cal}	Absolute Radiometric Calibration	Instrument specific characterisation	NA	NA
c_{stab}	Absolute Calibration Stability	Instrument specific characterisation	NA	NA
c_{lin}	Detector Non-Linearity	Instrument specific characterisation	No	Yes
c_{stray}	Spectral Stray Light	Zong stray light correction method	No	Yes
c_T	Temperature Sensitivity	Instrument specific characterisation	No	Yes
c_{pol}	Polarisation Sensitivity (Radiance)	Class specific characterisation	No	No
c_{cos}	Cosine Response (Irradiance)	Instrument specific characterisation	No	Yes

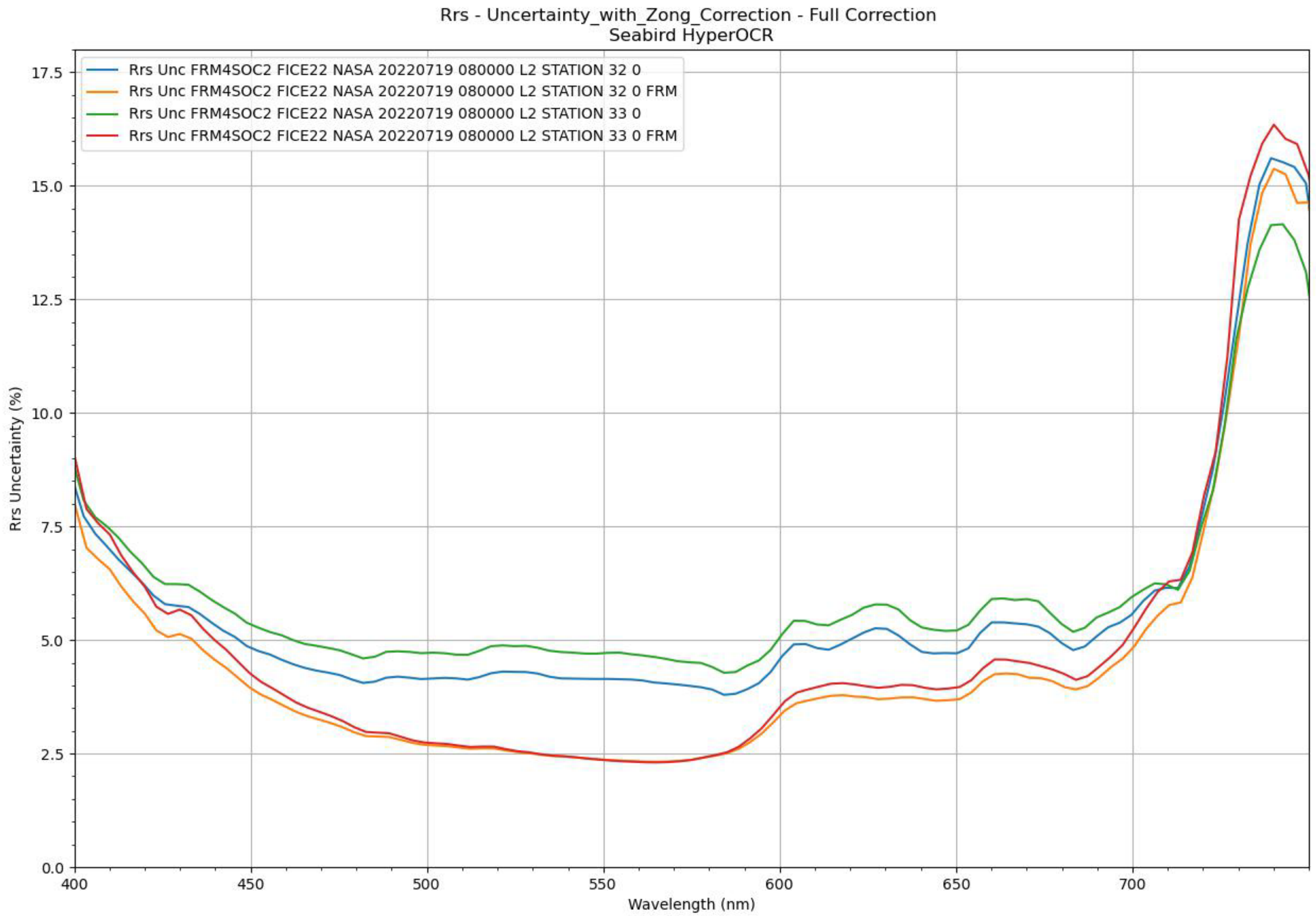
Uncertainty Results – PySAS sample data







Uncertainty Results – PySAS sample data



Congratulation!

I finished and you survived ;-)