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The second FRM4SOC-2 WORKSHOP on Calibration and Characterisation of Ocean Color Field Radiometers

Uncertainty group-work, data handling, uncertainty budgets

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Motivation for the group-works

- FRM4SOC-2 Laboratory Comparison Exercise - International comparison of the spectral responsivity of irradiance and radiance OCRs between six participants was performed in 2022-2023.
- The relative expanded uncertainty stated by the participants for the comparison standards was around 2 %.
- Initial discrepancies between participant’s results were ±10 %.
- Satisfactory metrological consistency was achieved only after correcting for the data handling errors and biases due to varying measurement conditions.

Instructions to Participants

Participant should fulfill the following tasks:

1. Transfer the Measured calibration spectra in raw counts - (plain text files) to an Excel file (open text file in Excel)
2. Process the Instrument data in Excel (Averaging, Dark correction, Normalising)
3. Interpolate Calibration data of the FEL standard lamp with respective uncertainty estimates - to the radiometer pixel wavelengths
4. Interpolate Calibration data of the reflectance standard with respective uncertainty estimates - to the radiometer pixel wavelengths
5. Calculate the Responsivity calibration coefficients
6. Calculate the Uncertainties

Data provided in the SharePoint

OCR calibration inputs provided in the SharePoint:

- TriOS Ramses text files (ARC – SAM_8525, ACC – SAM_8526, in Folder Raw Data)
- Folder Certificates: (FEL – T-R_827, Plaque – SG3151-1_2023 and E8-21_2023)
- Folder Certificates: Excel files of the FEL cal data (Copy of T-R_827), and (Reflectance factor_PTB vs Manufacturer_2024) contains the Plaque cal data provided in the certificates SG3151-1_2023 and E8-21_2023
- Calibration data of the OCR provided by manufacturer in Folder Raw Data – Excel files SAM_8525ARC and SAM_8526ACC

Averaging, normalising

Wavelength scale of the radiometer as a function of pixel number *n* = (0 … 255) is provided by manufacturer in the calibration certificate of the radiometer (in text files).

For each series, arithmetic average and respective standard deviation should be calculated.

The raw signal of the radiometer $I(n)$ for the pixel *n* is recorded in counts. It is normalized to the maximum value achievable with a 16-bit unsigned integer to get floating point data in the interval [0, 1] as follows:

$$S_c(n) = \frac{I(n)}{65535}$$

Dark correction

In the case of measured background spectrum (both spectra with the same integration time):

$$S_{c1}(n) = S_c(n) - S_{back}(n)$$

The average signal D_0 of the 16 masked pixels of the array is determined and subtracted:

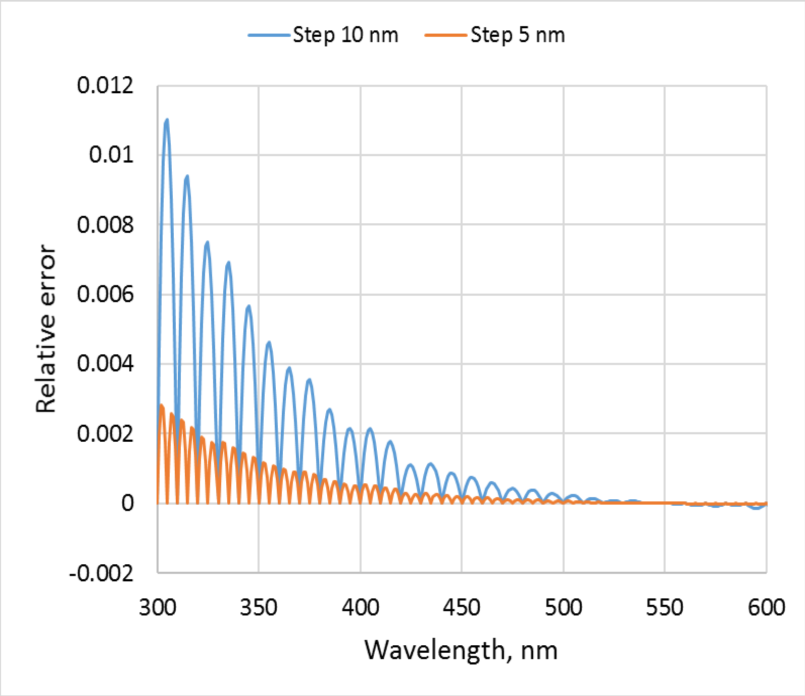
$$S_{c2}(n) = S_{c1}(n) - D_0$$

Interpolation of calibration values

Irradiance values are given with the suitably small wavelength step (1 nm).

Use linear interpolation for both the values and uncertainties.

Linear interpolation error as a function of wavelength step of the tabulated irradiance calibration data is shown in Figure right.



Measurement equations for TriOS RAMSES

Calibration coefficient $F_E(\lambda)$ of irradiance sensor

$$F_E(\lambda) = \frac{S_{c2}(\lambda)\left(C_{stray}C_{lin}C_{temp}\right)}{E_{\mathrm{r}}(\lambda)(C_1 C_2 \ldots C_i \ldots)} \frac{t_{\mathrm{max}}}{t_{\mathrm{used}}} \ [\mathrm{m^2 nm\ mW^{-1}}]$$

$S(\lambda)$ is dark corrected raw signal normalized to [0, 1]; $E(\lambda)$ is the lamp irradiance at the reference distance; t_{max}=8192 ms is the largest integration time; t_{used} was used for the measurements.

Calibration coefficient $F_L(\lambda)$ of radiance sensor

$$F_L(\lambda) = \frac{S(\lambda)\left(C_{stray}C_{lin}C_{temp}\right)}{L(\lambda)} \frac{t_{max}}{t_{used}} \ [\mathrm{m^2 nm\ sr\ mW^{-1}}]$$

$L(\lambda)$ is the target radiance for the lamp-panel setup, see next slide

Measurement equation for the lamp-panel setup

The target radiance $L(\lambda)$ for the lamp panel setup is calculated as

$$L(\lambda) = E_r(\lambda)(C_1 C_2 \dots C_i \dots)\frac{R(0/45;\lambda)(C_{p1} C_{p2} \dots C_{pi} \dots)}{\pi}\frac{(50cm + \Delta d)^2}{(d + \Delta d)^2}$$

- d is the distance from the front of the plaque to reference plain of the FEL
- Δd is the combined offset of the lamp and radiometer effective working planes from specified reference planes.
- $R(0/45, \lambda)$ is the reflectance factor of the plaque, normal incidence, 45° view
- C_i is the *i*-th correction factor of the irradiance source
- C_{pi} is the *i*-th correction factor of the plaque

Correction factors for the FEL lamps

Often correction factors are taken equal to one, but with uncertainties differing from zero.

- $\boldsymbol{C_1}$ – relative change of irradiance due to the ***aging of the working standards***
- $\boldsymbol{C_2}$ – relative change of irradiance due to **interpolation** of irradiance/radiance values
- $\boldsymbol{C_3}$ – relative change of irradiance due to **wavelength error** of the radiometer
- $\boldsymbol{C_4}$ – relative change of irradiance due to **distance** from the lamp to the radiometer
- $\boldsymbol{C_5}$ – relative change of irradiance/radiance due to **operating current** of the working standard (lamp, sphere)

Correction factors for the plaques

- $\boldsymbol{C_{p1}}$ – Relative change of reflectance factor due to the aging of the plaque
- $\boldsymbol{C_{p2}}$ – Plaque's reflectance factor, corrected from *R*(8/H) to *R*(0/45) geometry
- $\boldsymbol{C_{p3}}$ – Non-uniformity of the Plaque

Often correction factor $\boldsymbol{C_{p2}}$ is taken equal

$$\boldsymbol{C_{p2}} = 1.024 \ldots 1.026$$

Measurement uncertainty analysis

Measurement uncertainty is an integral part of a calibration. The uncertainty analysis is based on the GUM methodology.

GUM: Guide to the Expression of Uncertainty in Measurement

JCGM 100:2008(E) – Evaluation of measurement data - Guide to the expression of uncertainty in measurement (2008)

https://doi.org/10.59161/JCGM100-2008E

Central concept in GUM is a Measurement equation relating input quantities with the output quantity subject to measurement.

Law of propagation of uncertainty

The standard uncertainty of **the result of the measurement** is obtained by appropriately combining the standard uncertainties of the input estimates. This **combined standard uncertainty** is denoted by $u_c(y)$.

The combined standard uncertainty $u_c(y)$ is the positive square root of the combined variance $u_c^2(y)$, which is given by

$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) = \sum_{i=1}^{N} [c_i u(x_i)]^2 \equiv \sum_{i=1}^{N} u_i^2(y)$$

Here c_i is **the sensitivity coefficient**, calculated as partial derivative of the measurement equation

$$c_i = \frac{\partial f}{\partial x_i} = \left.\frac{\partial f}{\partial X_i}\right|_{x_1, x_2, \ldots x_N}$$

Excel spreadsheet for the uncertainty evaluation (*Es*)

For the uncertainty evaluation similar spreadsheet can be used.

Values of Input uncertainties in percent's in column E can be set as needed. Their sensitivity coefficients are equal to one.

Sensitivity coefficients of distance components are calculated as partial derivatives from the distance equation.

	SAT2072										
				Distance inputs							
	Reference distance of the FEL calibration			500	mm						
	Distance FEL - Radiometer			500	mm		Uncertainty in percents, %				
	Pixel number						0	1	2	3	4
	Wavelength				nm	654.6	0.00	306.51	309.82	313.14	316.45
	Combined standard uncertainty (k = 1)	uc(Lu)						1.31	1.25	1.21	1.18
	Expanded uncertainty (k = 2)	Uc(Lu)						2.62	2.5	2.42	2.36
	Component	Symbol	Type	any inpu	units	Equation					
1	FEL calibration uncertainty (k = 1)	u(cal)	B					1.124565	1.06333	1.03174	1.00195
2	FEL potential drift since calibration	u(C1)	B	0.12	%			0.12	0.12	0.12	0.12
3	Lamp interpolation	u(C2)	A	0.05	%			0.05	0.05	0.05	0.05
4	Wavelength error (radiometer)	u(C3)	B	0.3	nm			0.58955	0.573489	0.558351	0.543319
5	Distance FEL - Radiometer	u(C4)	B	0.3	mm	0.12		0.12	0.12	0.12	0.12
6	FEL - offset's uncertainty	u(C4)	B	0.6	mm	0		0	0	0	0
7	Operating current	u(C5)	B	0.8	mA	0.048		0.102512	0.101416	0.100341	0.099292
8	Alignment of lamp position		B	0.1	%			0.1	0.1	0.1	0.1
9	Alignment of radiometer		B	0.1	%			0.1	0.1	0.1	0.1
10	Reproducibility		B	0.1	%			0.1	0.1	0.1	0.1
11	Repeatability including dark signal		A	0.05	%			0.05	0.05	0.05	0.05
12	Scattered room light		A	0.15	%			0.15	0.15	0.15	0.15

Excel spreadsheet for the uncertainty evaluation (*L*u)

For the uncertainty evaluation similar spreadsheet can be used.

Values of Input uncertainties in percent's in column E can be set as needed. Their sensitivity coefficients are equal to one.

Sensitivity coefficients of distance components are calculated as partial derivatives from the distance equation.

	SAM_81B0										
				Distance inputs							
	Reference distance of the FEL calibration			500	mm						
	Distance FEL - Radiometer			1400	mm		Uncertainty in percents, %				
	Pixel number						0	1	2	3	4
	Wavelength				nm	654.6	302.89	306.21	309.54	312.87	316.20
	Combined standard uncertainty (k = 1)	uc(FLu)						1.4	1.34	1.29	1.25
	Expanded uncertainty (k = 2)	Uc(FLu)						2.8	2.68	2.58	2.5
	Component	Symbol	Type	any inp	units	Equation					
1	FEL calibration uncertainty (k = 1)	u(cal)	B					1.191535	1.130115	1.06851	1.03417
2	FEL potential drift since calibration	u(C1)	B	0.17	%			0.17	0.17	0.17	0.17
3	Lamp interpolation	u(C2)	A	0.05	%			0.05	0.05	0.05	0.05
4	Wavelength error (radiometer)	u(C3)	B	0.3	nm			0.602504	0.58609	0.570619	0.555257
5	Distance FEL - Plaque	u(C4)	B	0.5	mm	0.0714		0.071429	0.071429	0.071429	0.071429
6	Distance FEL - Radiometer	u(C4)	B	0.6	mm	0.1543		0.154286	0.154286	0.154286	0.154286
7	FEL - offset's uncertainty	u(C5)	B	0.8	mA	0.048		0.102612	0.101508	0.100428	0.09937
8	Plaque calibration uncertainty (k = 1)	up(cal)	B	0.21	%			0.21	0.21	0.21	0.21
9	Plaque potential drift since calibration	up(C1)	B	0.1	%			0.1	0.1	0.1	0.1
10	Plaque refl. Factor, corrected to $R(0^\circ/45^\circ)$	up(C2)	B					0.0065	0.0065	0.0065	0.0065
11	Plaque non-uniformity	up(C3)	B	0.1	%			0.1	0.1	0.1	0.1
12	Alignment of lamp position		B	0.1	%			0.1	0.1	0.1	0.1
13	Alignment of radiometer		B	0.1	%			0.1	0.1	0.1	0.1
14	Alignment of plaque position		B	0.1	%			0.1	0.1	0.1	0.1
15	Reproducibility		B	0.1	%			0.1	0.1	0.1	0.1
16	Repeatability including dark signal		A	0.05	%			0.05	0.05	0.05	0.05
17	Scattered room light		A	0.1	%			0.1	0.1	0.1	0.1

Calibration uncertainty of radiometric sensors

The uncertainty budget of each of the traveling hyperspectral radiometer should include the following **Type B uncertainty components** associated with:

- **the radiometric scale** (calibration uncertainty of standard lamp, plaque, sphere).
- $u(C_1)$ – uncertainty due to the ***aging of the working standards***
- $u(C_2)$ – uncertainty due to **interpolation** of irradiance/radiance values
- $u(C_3)$ – uncertainty due to **wavelength error** of the radiometer
- $u(C_4)$ – uncertainty due to **distance** from the lamp to the radiometer
- $u(C_5)$ – uncertainty due to **operating current** of the working standard (lamp, sphere)
- uncertainty due to the alignment **of the position** of the lamp and radiometer
- $u(C_{temp})$ – uncertainty due to ***variability of the calibration temperature***
- $u(C_{8/\mathrm{H};0/45})$ – uncertainty due to the ***correction from R(8/H) to R(0/45) spectral reflectance factor***

Calibration uncertainty of radiometric sensors

The uncertainty budget should include the following **Type A components**:

1. ***Repeatability*** – Standard deviation of the mean calculated from a set of spectra when calibrating the hyperspectral radiometer.
2. ***Reproducibility*** – Standard deviation of the mean calculated from the results of independent measurements, where each independent measurement is carried out after realignment of the working standard and the radiometer subject to calibration. (long-time component, which partly includes Repeatability)

Potential Drift in Source since the Last Calibration

The drift of the new FEL lamps is less than 0.01 %/h (Metzdorf et al., 1998). Drift estimate after 50 working hours is 0.5 %, but stepwise changes up to ±1 % may occur.

Usual recommendation for the uncertainty due to lamp aging after the 40 working hours is:

$$u(C_1) = \frac{u_{aging}\big(E(\lambda)\big)}{E(\lambda)} \cong \frac{0.5\ \%}{\sqrt{3}} \frac{40\ \text{h}}{50\ \text{h}} = 0.23\ \%$$

Optronic Laboratories: Lamp calibration is valid for a period of 50 hours of use or 1 year, whichever occurs first. FEL's long term stability is <0.06 %/h.

It is advisable to evaluate a source drift regularly:

- Monitoring the voltage across the lamp terminals when the lamp is in operation
- Using a monitoring radiometer concurrently with a lamp
- Having at least two standard lamps and performing regular comparisons between lamps
- Analyzing calibration history

Stability of the FEL-type quartz halogen lamp

According to *J. Metzdorf e.a.*, 1998, Metrologia, 35, 423: A new FEL-type quartz-halogen lamp as an improved standard of spectral irradiance was described.

Maximum drift rates at wavelengths above 300 nm between ± 0.2 % and ± 1 % per 100 h were found in optimal operating conditions.

Thus, 1998, *J. Metzdorf e.a.*, Metrologia, 35, 423, Long term stability of FELs <0.01 %/hour

Data Sheet of Optronic Laboratories

Long term stability <0.06 %/hour

Lamp calibration is valid for a period of 50 hours of use or 1 year, which ever occurs first.

Wavelength error of the radiometer

The accuracy of relation between pixel number and wavelength must be established to obtain the signal as a function of wavelength λ, and uncertainty $u_{\Delta\lambda}(E)$ is associated with this accuracy

$$u(C_3) = \frac{u_{\Delta\lambda}(E)}{E(\lambda)} = \frac{u(\Delta\lambda)[\mathrm{nm}]}{\sqrt{3}} \frac{100}{E(\lambda)} \left| \frac{\partial E}{\partial \lambda} \right| [\%].$$

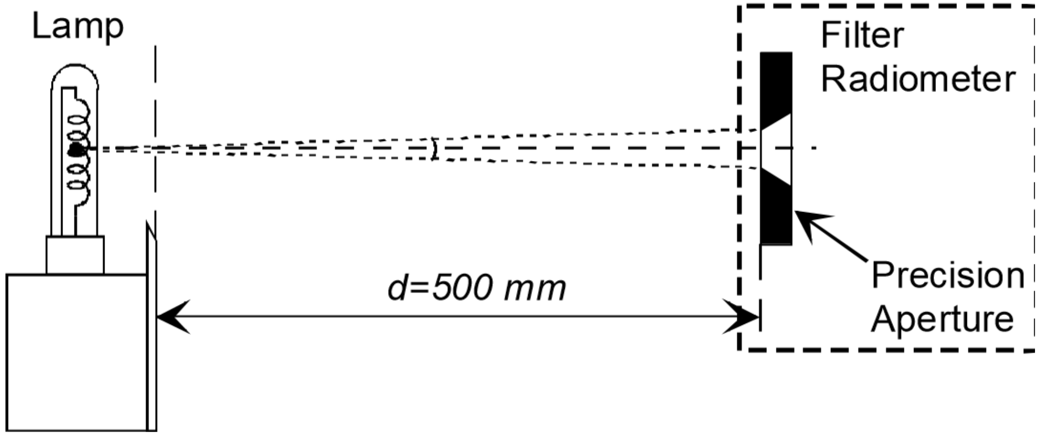
Wavelength error limit value of the radiometer according to the manufacturer specification is $\Delta\lambda$=0.3 nm and $|\ \partial E/\partial\lambda|$ depends on the spectral irradiance E(λ) of the radiation source.

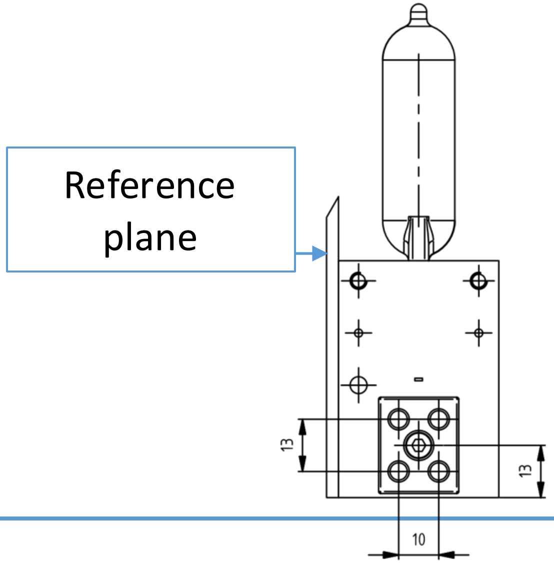
Distance adjustment between the FEL and the Radiometer

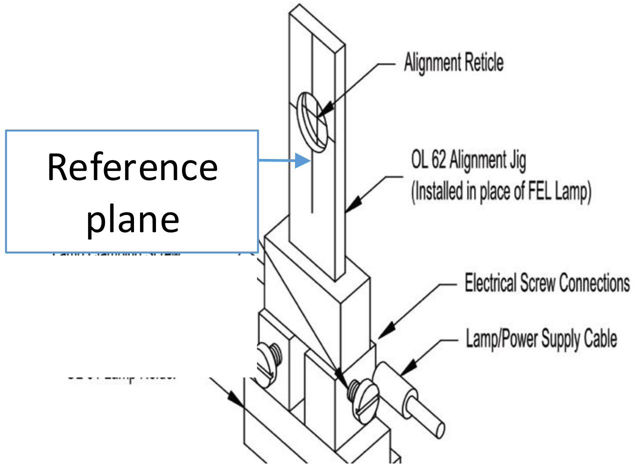
The specified in the calibration certificate distance of 500 mm is measured from the reference plane of the FEL to the entrance reference plane of the spectral irradiance measurement instrument.

At the correct calibration conditions, the certified irradiance values are valid for any types of the lamp holders.

If the distance is changed, inverse-square law describing the irradiance level created by the lamp as a function of the distance between the lamp and the radiometer shall be followed.







Distance to the FEL

If the realized distance d is different from the standard distance (usually 500 mm) the spectral irradiance at distance d can be determined using the formula

$$E_{\mathrm{r}}(d) = E_{\mathrm{r}}(50\ cm)\frac{(50+\Delta d)^2}{(d+\Delta d)^2}$$

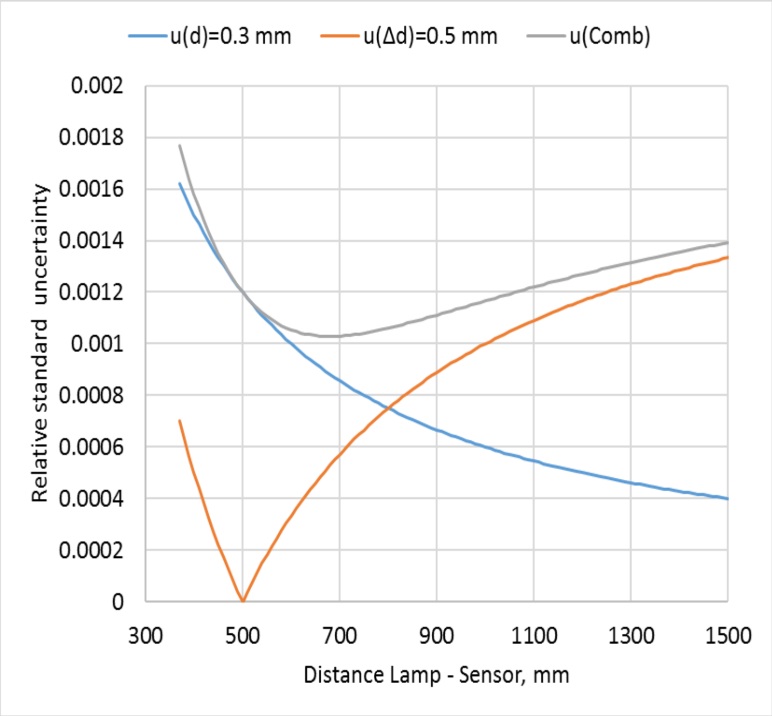
Uncertainty component of irradiance related with the distance measurement from the lamp to the radiometer $u'(C_4)$ can be determined as

$$u'(C_4) = \frac{u_d(E)}{E} \cong \frac{2u(d)}{d}$$

$$u''(C_4) = \frac{u_{\Delta d}(E)}{E} \cong \frac{2u(\Delta d)}{d}\left|1 - \frac{d}{50\ \mathrm{cm}}\right|$$

$u''(C_4)$ is caused by $u_{\Delta d}(E)$ - offset uncertainty of the lamp's working plane.

Combined uncertainty of $u(d)$ and $u(\Delta d)$ is shown in Figure right. Here $u(d)$ = 0.3 mm and $u(\Delta d)$ = 0.5 mm. For d=500 mm, $u_{\Delta d}(E)$ is zero, but it is increasing with the distance.



Uncertainty in the Lamp Current

Relative uncertainty of the lamp's spectral irradiance as a function of the lamp's current uncertainty in the UV/VIS/IR range can estimated as

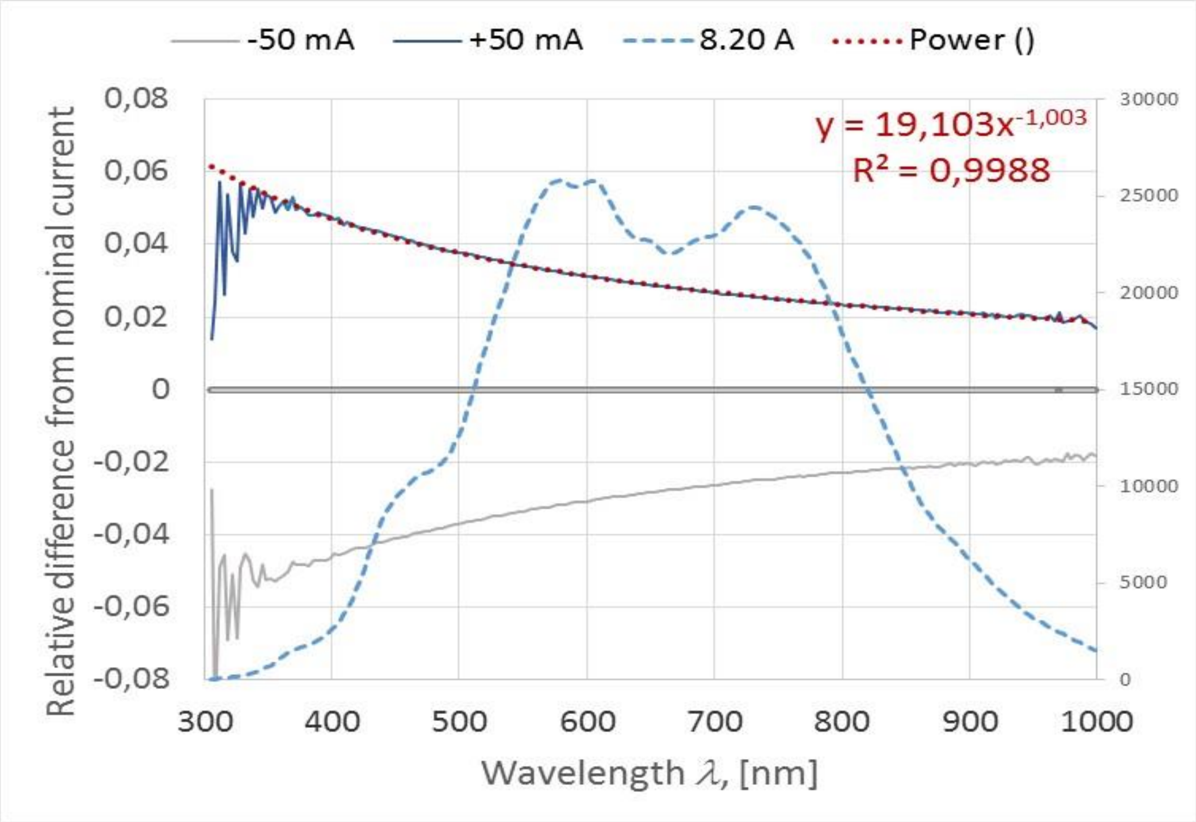
$$u(C_5) = \frac{u_{\text{cur}}\big(E(\lambda)\big)}{E(\lambda)} \cong 0.0006 \left(\frac{654.6[\text{nm}]}{\lambda[\text{nm}]} \right) u(I)[\text{mA}].$$

The component $u(I)$ combines the uncertainties due to the current source, shunt, and voltage measurement.

The effect of lamp current offset

Three spectra are measured, one with nominal current of 8.2 A and two with current deviating ±50 mA from nominal. Power function trendline is added.

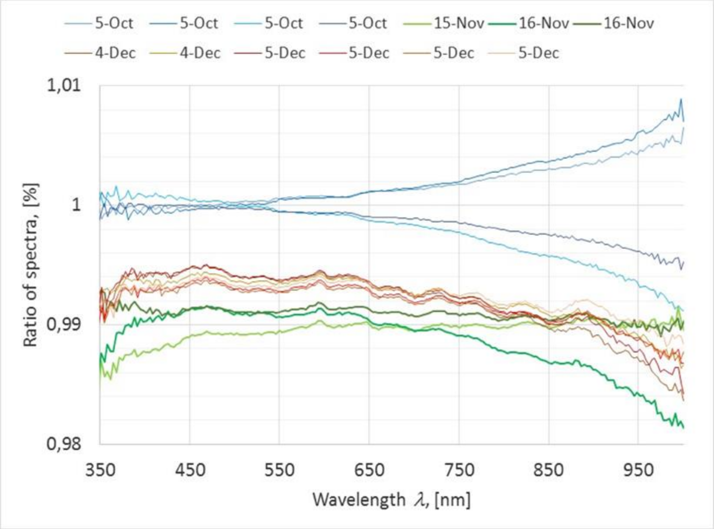
Relative spectral change of a lamp as a function of wavelength is due to change of the effective radiation temperature of the lamp.



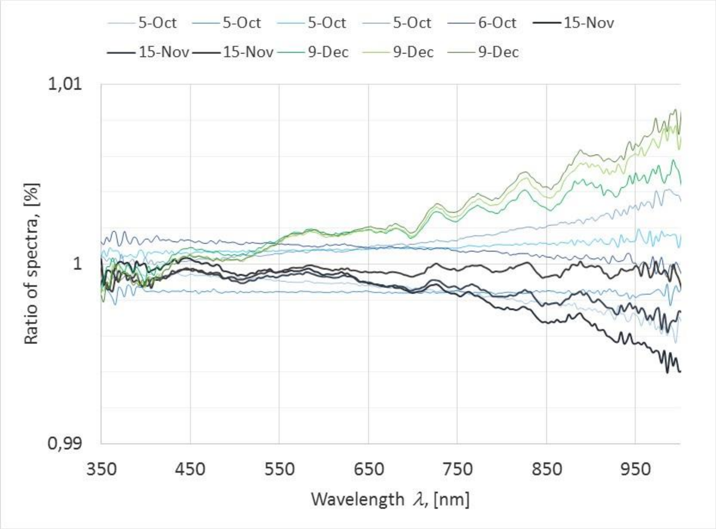
Alignment and temperature effects; Reproducibility

Repeated alignment and measurement of TriOS Ramses ACC and ARC sensors during two months. Variability due to temperature effects, alignments of the lamp and sensor, and due to possible instability of the sensor is evident. Laboratory ambient within (21±1.5) °C.

TriOS Ramses ACC sensor



TriOS Ramses ARC sensor



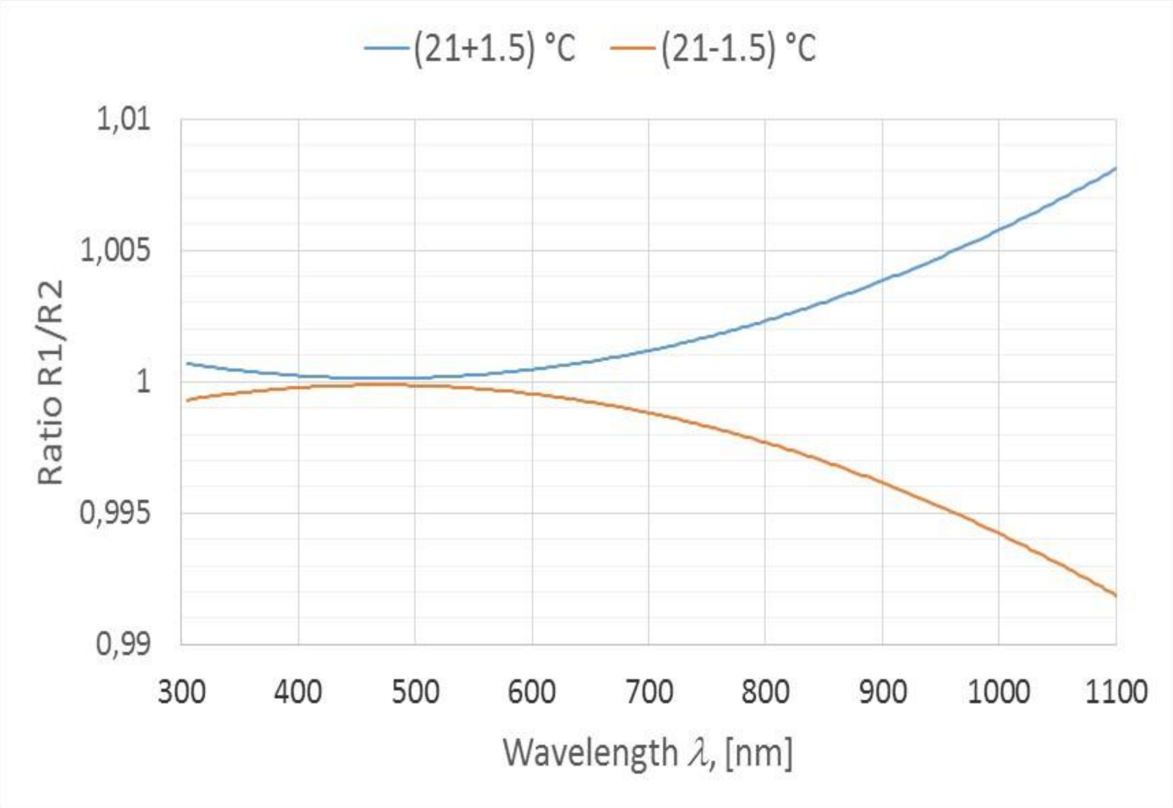
Temperature effects from repeated measurements

Modelled temperature effects for the laboratory ambient within (21±1.5) °C.

Average ambient temperature is 21 °C.

Spectrum R1 assumed at 22.5 °C and R2 at 19.5 °C.

Larger variability in IR range is due to radiometer's temperature sensitivity.



Results of the group-works

Participants present in an Excel file:

1. Responsivity calibration coefficients
2. Uncertainties of the Responsivity calibration coefficients
3. Spreadsheet with the process of data handling