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The second

FRM4SOC-2 WORKSHOP

on Calibration and Characterisation of Ocean Color Field Radiometers

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@ Tartu Observatory, University of Tartu, Estonia

Uncertainty budgets in OCR calibration and characterization

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PROGRAMME OF THE EUROPEAN UNION
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Brockmann Consult GmbH
EOScience
Consiglio Nazionale delle Ricerche
NPL National Physical Laboratory

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.

Measurement equations for TriOS RAMSES

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

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

$S(\lambda)$ 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

Measurement equations for Seabird HyperOCR

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

$$F_E(\lambda) = \frac{E_{\mathrm{r}}(\lambda)(C_1 C_2 \dots C_i \dots)}{S(\lambda)\left(C_{stray} C_{lin} C_{temp}\right)} \; [\mu\mathrm{Wcm}^{-2}\mathrm{nm}^{-1}]$$

S(λ) is dark corrected raw signal in digital counts without any modification, $E_{\mathrm{r}}(\lambda)$ is the lamp irradiance at the reference distance. Integration time IT_{cal} shall be present in the calibration data set

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

$$F_L(\lambda) = \frac{L(\lambda)}{S(\lambda)\left(C_{stray} C_{lin} C_{temp}\right)} \; [\mu\mathrm{W\,cm}^{-2}\mathrm{nm}^{-1}\mathrm{sr}^{-1}]$$

The target radiance $L(\lambda)$ for the lamp panel setup is calculated using the equation on the previous slide

Correction factors for the radiometers

Calculation formulas for the correction factors of the RAMSES sensors are:

- $C_{lin}(\lambda) = 1 - \alpha_L(\lambda) \cdot S_{DN}(\lambda)$
- $C_{temp}(\lambda) = 1 - \alpha_T(\lambda) \cdot \left(T_{lab} - T_{ref}\right)$
- $C_{drift}(\lambda) = 1 - \alpha_t(\lambda) \cdot \left(t_{lab} - t_{ref}\right)$

For application of correction factors, characterisation data (non-linearity, thermal sensitivity, temporal drift coefficients, straylight matrix etc. are needed. Additionally, raw spectrum in digital numbers $S_{DN}(\lambda)$, temperature differences, time differences etc., are needed.

Correction factors are wavelength dependent.

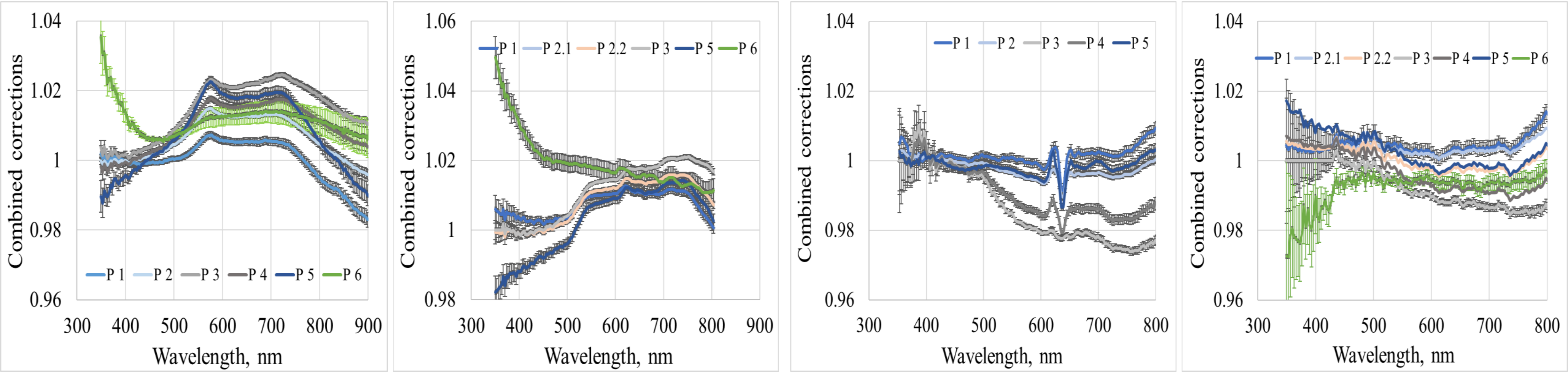
Combined corrections with uncertainties

Corrections for the non-linearity, temperature differences, and temporal drift applied during LCE.

Correction factors are close to one, uncertainties 0.1 ... 0.4 %.

RAMSES sensors left

HyperOCR sensors right



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 plaque

- $\boldsymbol{C_{p1}}$ – 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

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

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)

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 $u_\mathrm{c}(y)$.

The combined standard uncertainty $u_\mathrm{c}(y)$ 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

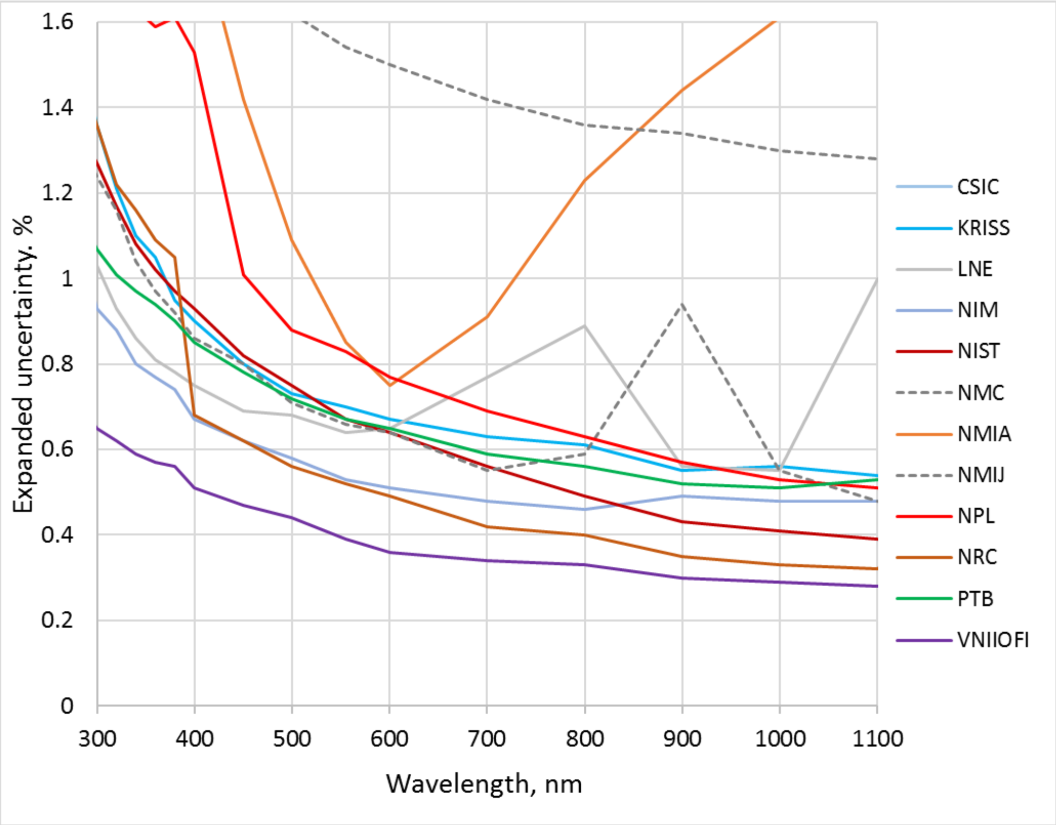
$$c_i = \frac{\partial f}{\partial x_i} = \left.\frac{\partial f}{\partial X_i}\right|_{x_1, x_2, \ldots x_N}$$

Calibration uncertainty of FEL lamp standards

Spectral irradiance: The Quartz Tungsten Halogen (QTH) FEL type 120V/1000W lamp is currently most widely used as transfer standard of a spectral irradiance.

Expanded uncertainties of leading NMIs demonstrated by calibrating FEL type lamps during CIPM Key comparison CCPR-K1.a.2017.

Key Comparison of the Consultative Committee for Photometry and Radiometry CCPR-K1.a.2017 for Spectral Irradiance in the wavelength range of 250 nm to 2500 nm.



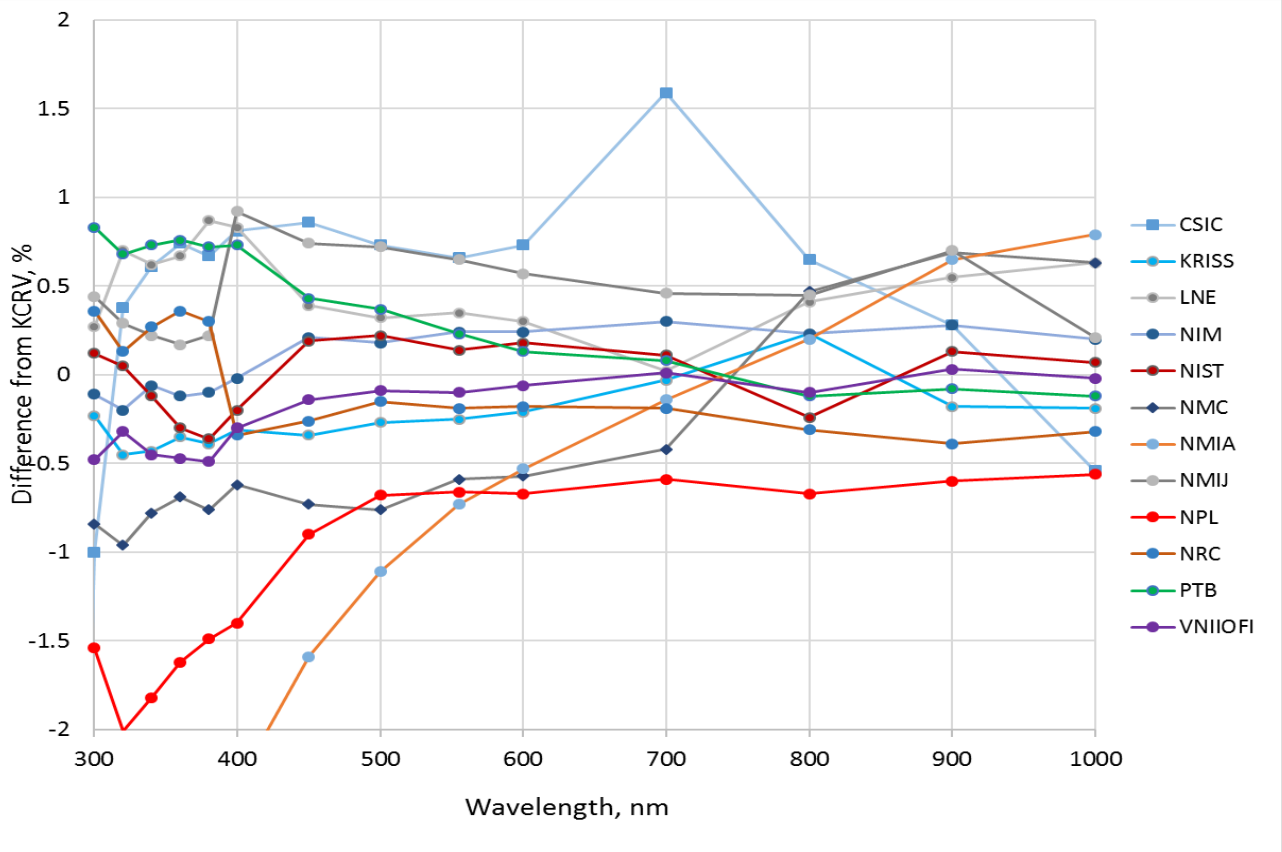
Differences form the Key Comparison Reference Value

CIPM Key comparison CCPR-K1.a.2017

Calibration of the FEL type (1000 W) lamps used as artefacts.

The star scheme of measurements was applied with the sequence participant – pilot – participant. Each participant used its own set of lamps.

Majority of results show an agreement within ±0.8 %.

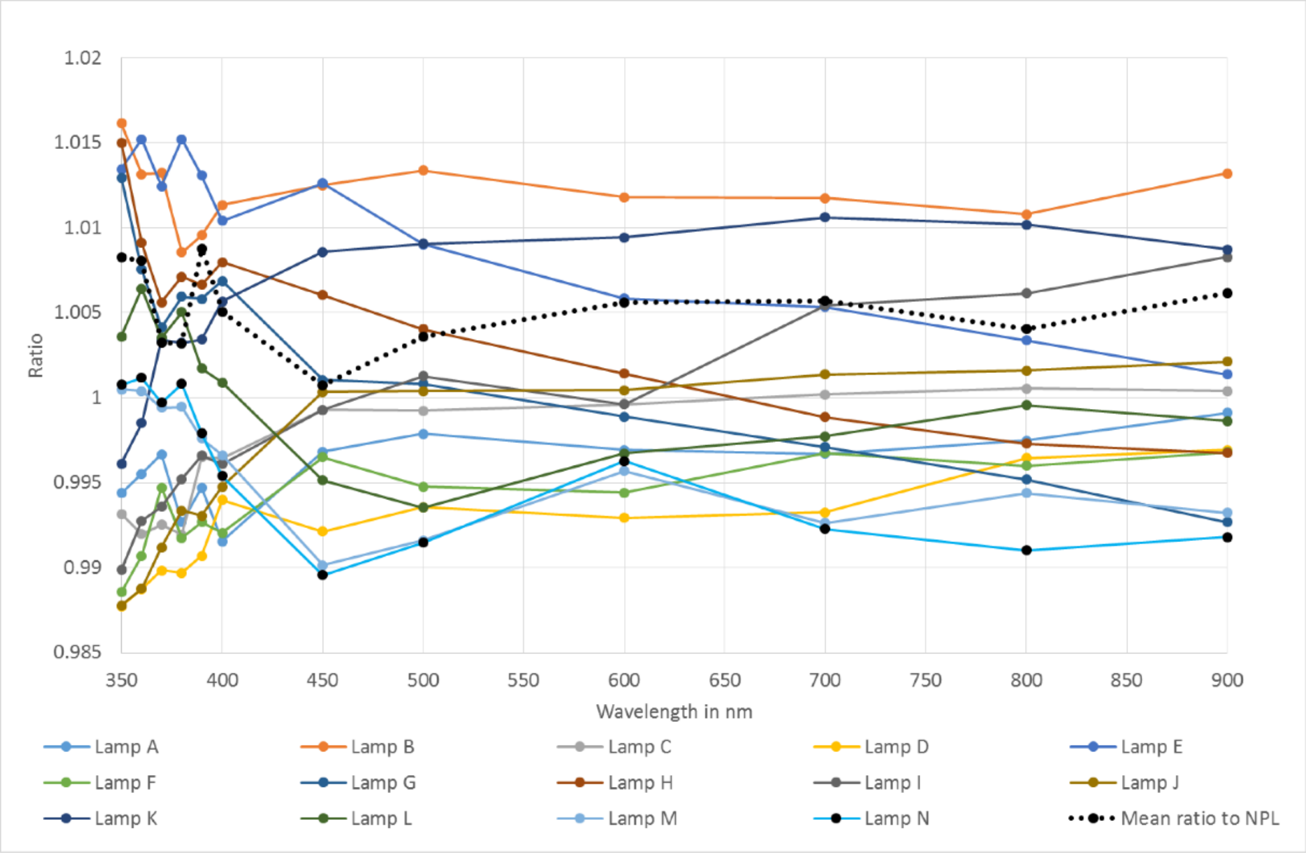


FRM4SOC-1 laboratory comparison of the irradiance sources

National Physical Laboratory conducted a laboratory comparison of the irradiance sources involving measurements of 14 FEL lamps at NPL in April 2017.

Tungsten quartz halogen lamps of the FEL type (1000 W) were used as artefacts. Each participant used its own set of lamps.

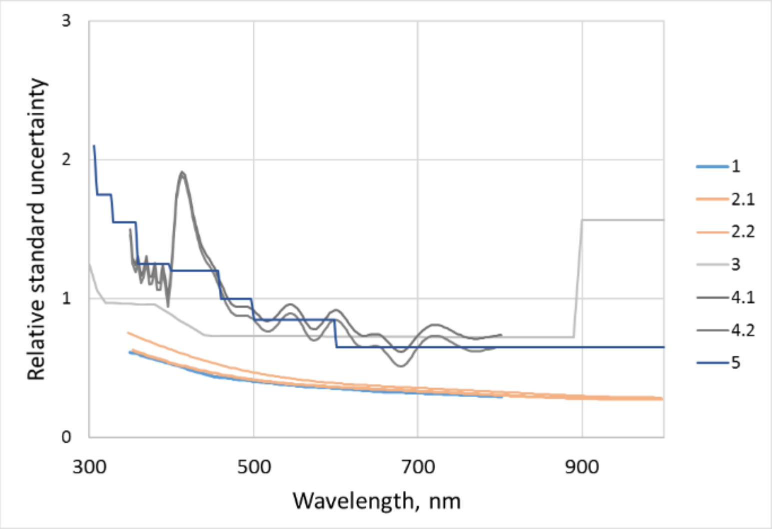
The spectral irradiance comparison results showed an agreement between all lamps within ±1.2 %.



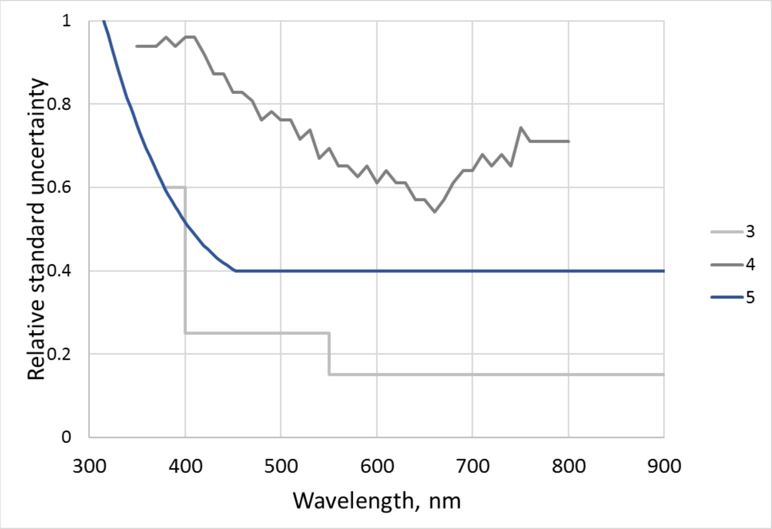
Traceability of radiometric standards (LCE)

Calibration standard uncertainty in percent's of the radiometric standard lamps, the diffusing plaques and radiance standards. The participants had different SI-traceability routes for their standards.

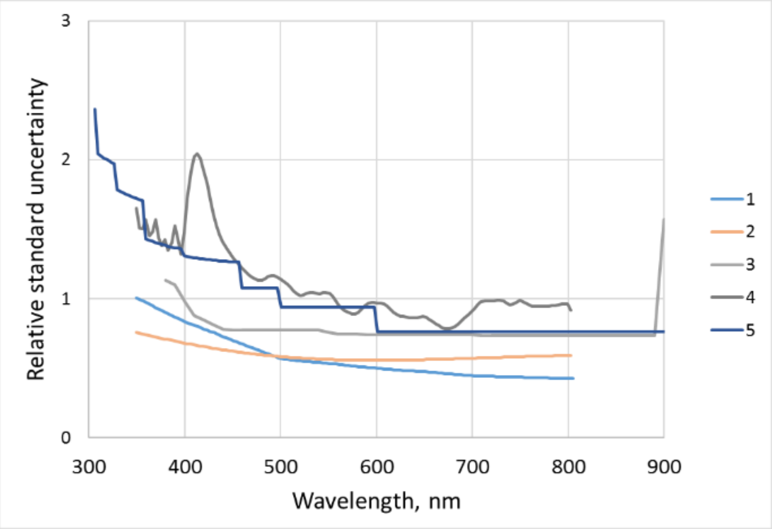
FEL lamps



Diffuse plaques



Radiance standards



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:

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

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

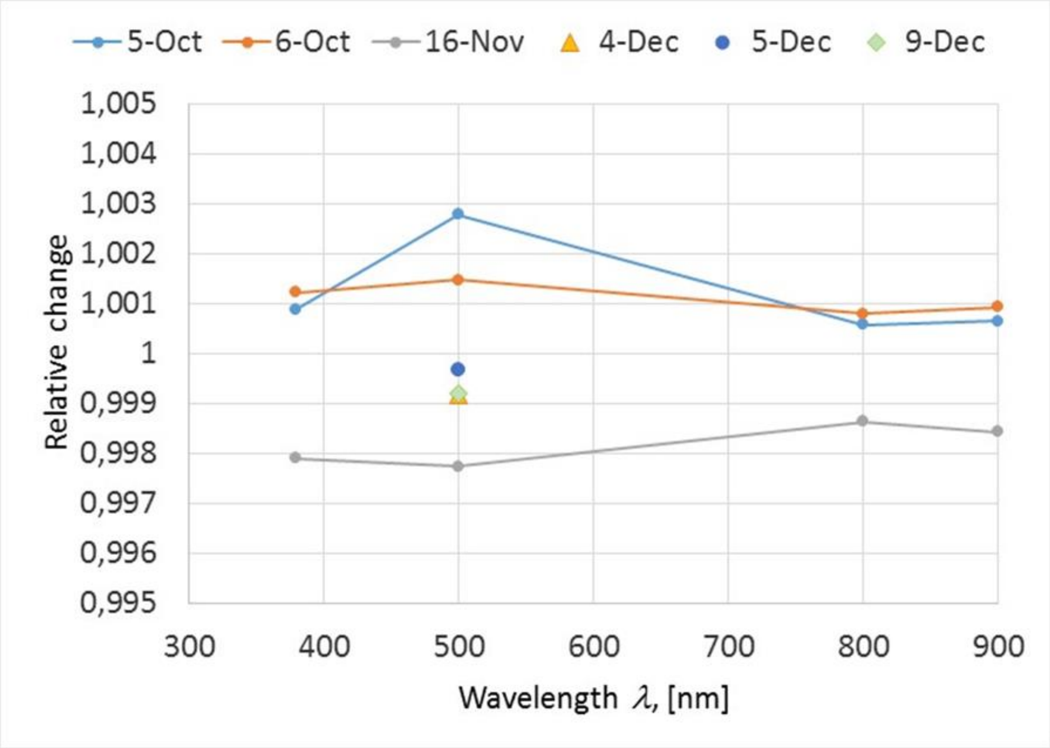
Long term stability <0.06 %/hour

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

Monitoring the FEL source with a filter radiometer

Monitoring the stability of the FEL during two months with the relative change of the photocurrent of a filter radiometer.

Filter radiometer is an effective mean for comparison calibration of lamps.



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

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

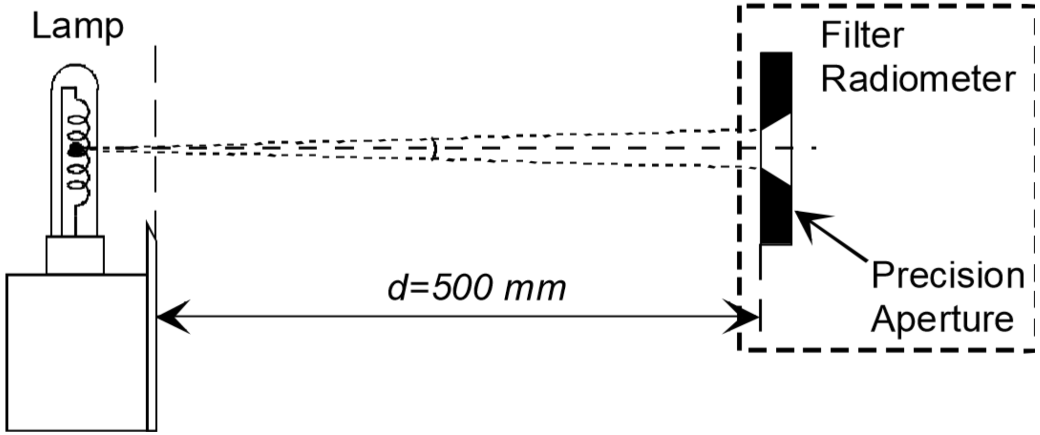
Wavelength error limit value of the radiometer according to the manufacturer specification is $\Delta\lambda$=0.3 nm and | $\partial E/\partial\lambda$| depends on the spectral irradiance E(λ) of the radiation source.

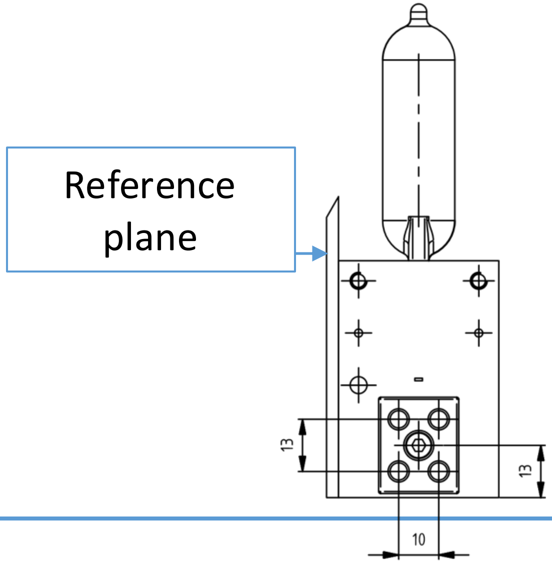
Distance adjustment between the FEL and the Radiometer

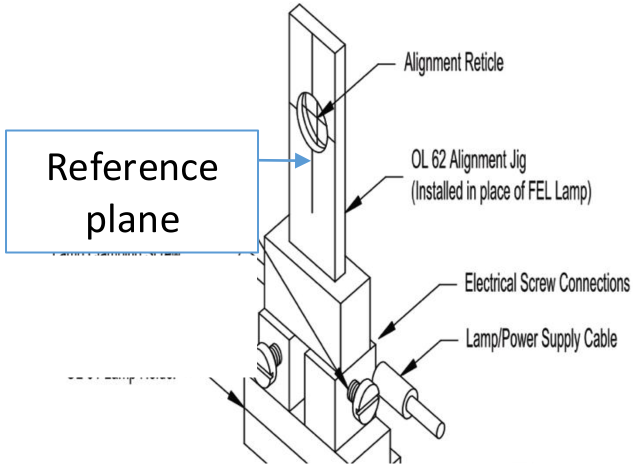
The specified in the calibration certificate distance of 500 mm is measured from the reference plane of the FEL to the entrance reference plane of the spectral irradiance measurement instrument.

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

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

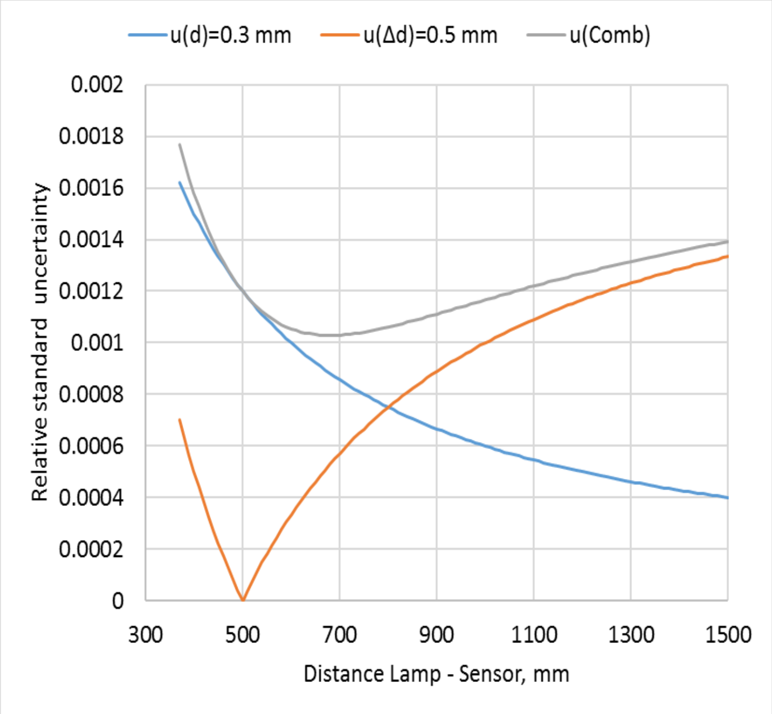
Uncertainty component of irradiance related with the distance measurement from the lamp to the radiometer $u'(C_4)$ can be determined as

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

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

$u''(C_4)$ 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

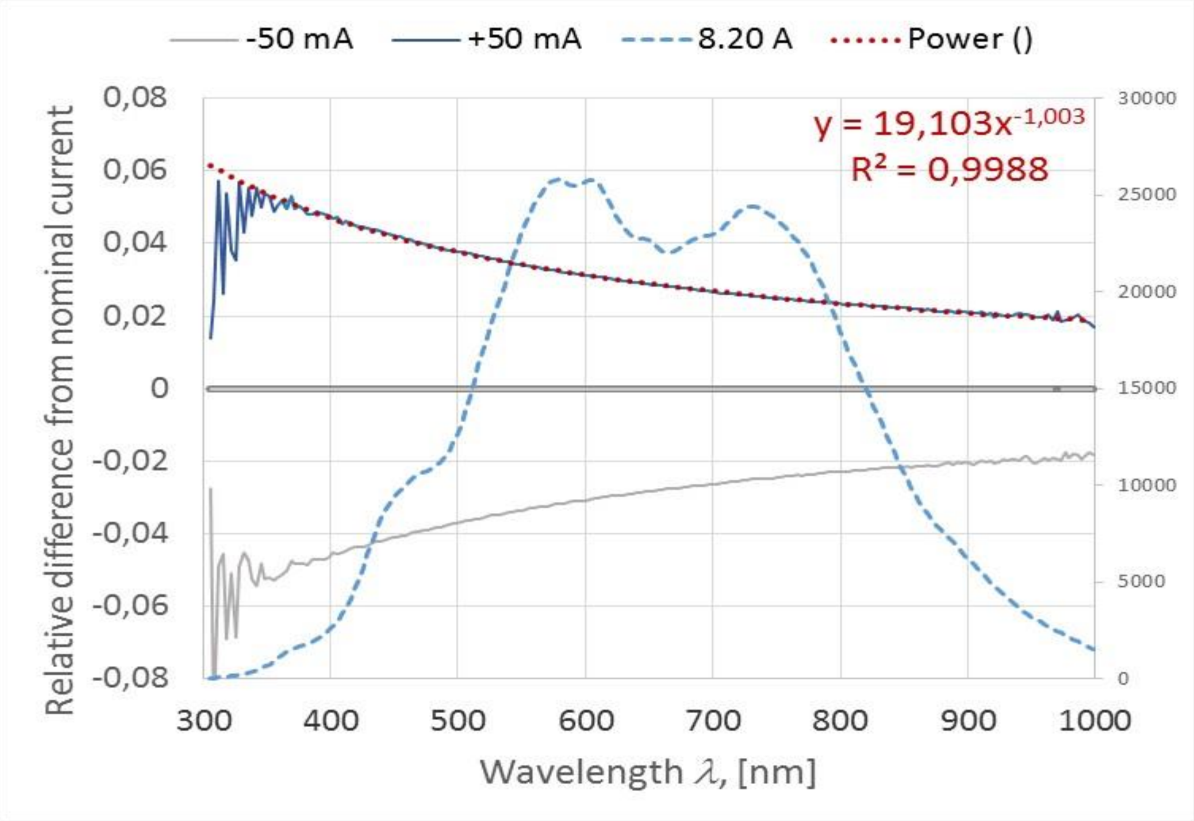
$$u(C_5) = \frac{u_{\mathrm{cur}}\big(E(\lambda)\big)}{E(\lambda)} \cong 0.0006\left(\frac{654.6[\mathrm{nm}]}{\lambda[\mathrm{nm}]}\right)u(I)[\mathrm{mA}].$$

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.

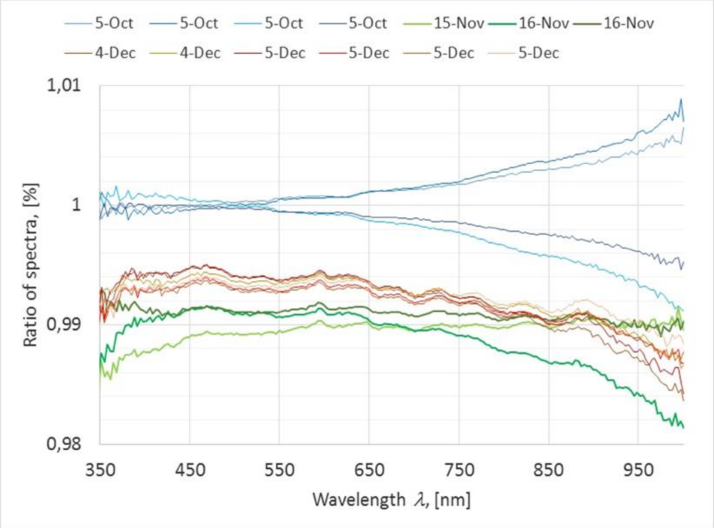
Relative spectral change of a lamp as a function of wavelength is due to change of the effective radiation temperature of the lamp.



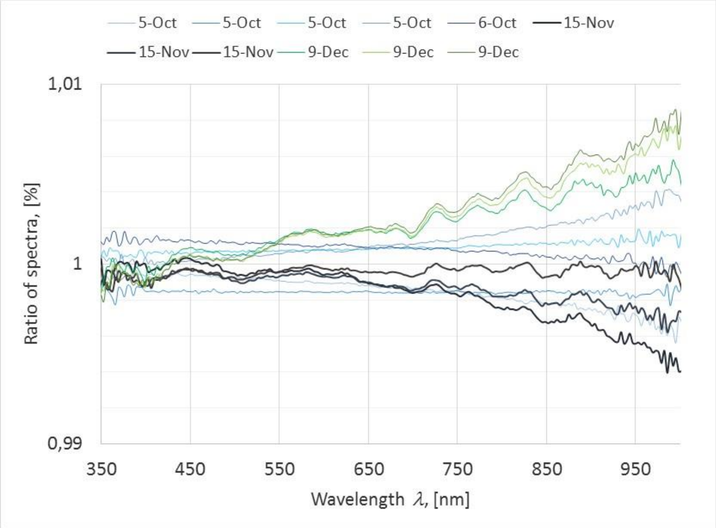
Alignment and temperature effects; Reproducibility

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



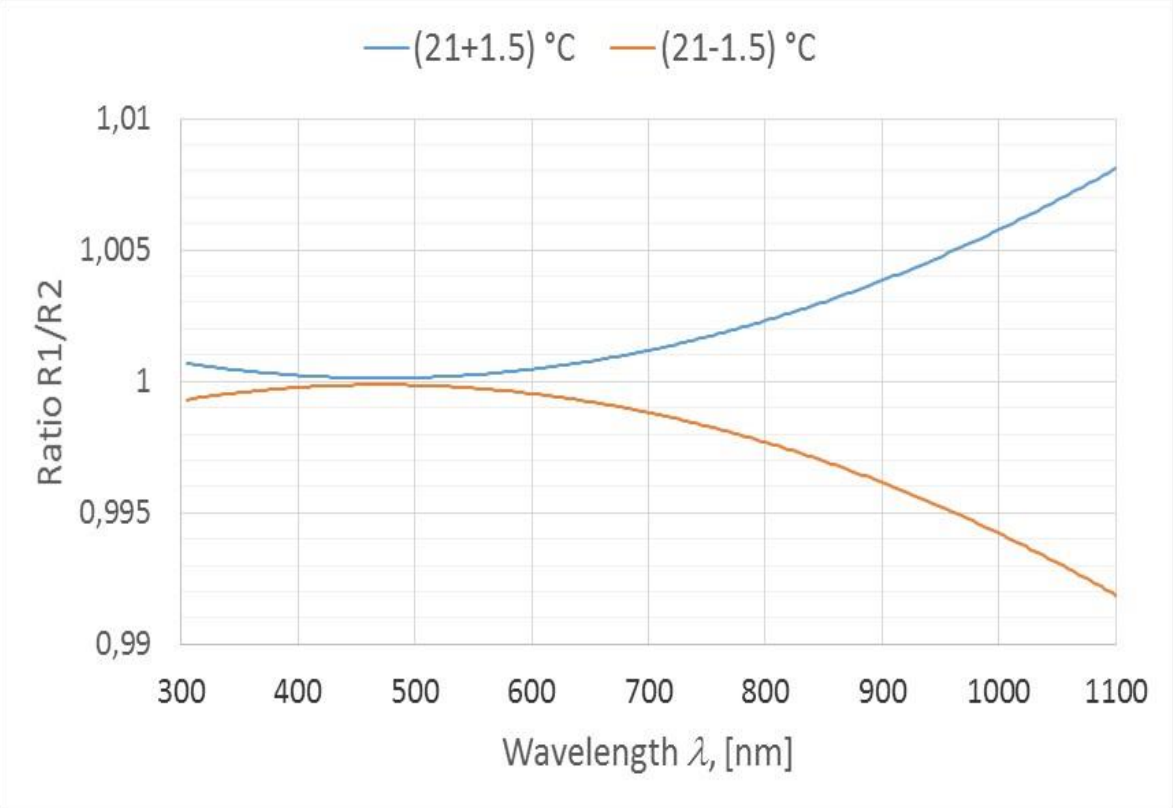
Temperature effects from repeated measurements

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.



Temperatures during LCE calibrations

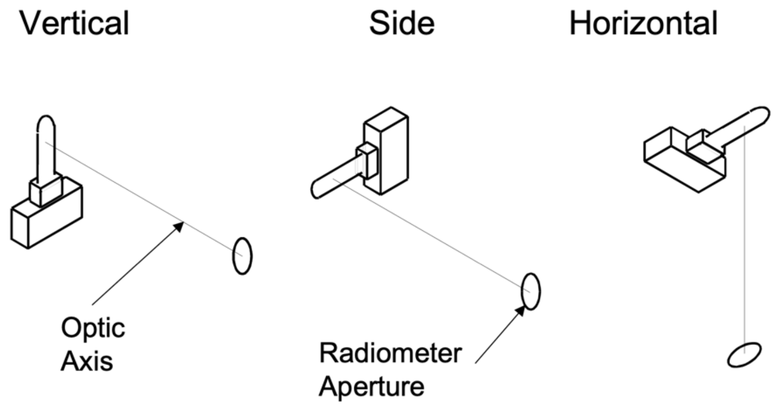
Laboratory	Measurement location	Temperature, °C			
		SAM_81B0	SAM_8598	SAT2072	SAT2073
P1	Ambient	N/A	N/A	26.0	26.2
	Device internal	26.8	27.7	30.3	30.1
P2	Ambient	N/A	23.8 – 25.1	N/A	N/A
	Device internal	23.3 – 25	24 – 24.3	26.3 – 30.0	26.2 – 26.8
P3	Ambient	21.5	21.5	21.5	21.5
	Device internal	23.5	22.8	24.3 – 24.5	23.5 – 24.5
P4	Ambient	21.9 – 22.4	N/A	22.6 – 23.1	22.9 – 23.1
	Device internal	N/A	N/A	26.3 – 27.2	26.8 – 27.3
P5	Ambient	26	26	26	26
	Device internal	N/A	N/A	N/A	N/A
P6	Ambient	21.5 – 21.8	21.3 – 22.1	21.5 – 22.1	N/A
	Device internal	22 – 22.3	21.3 – 21.7	24.1 – 25.1	N/A

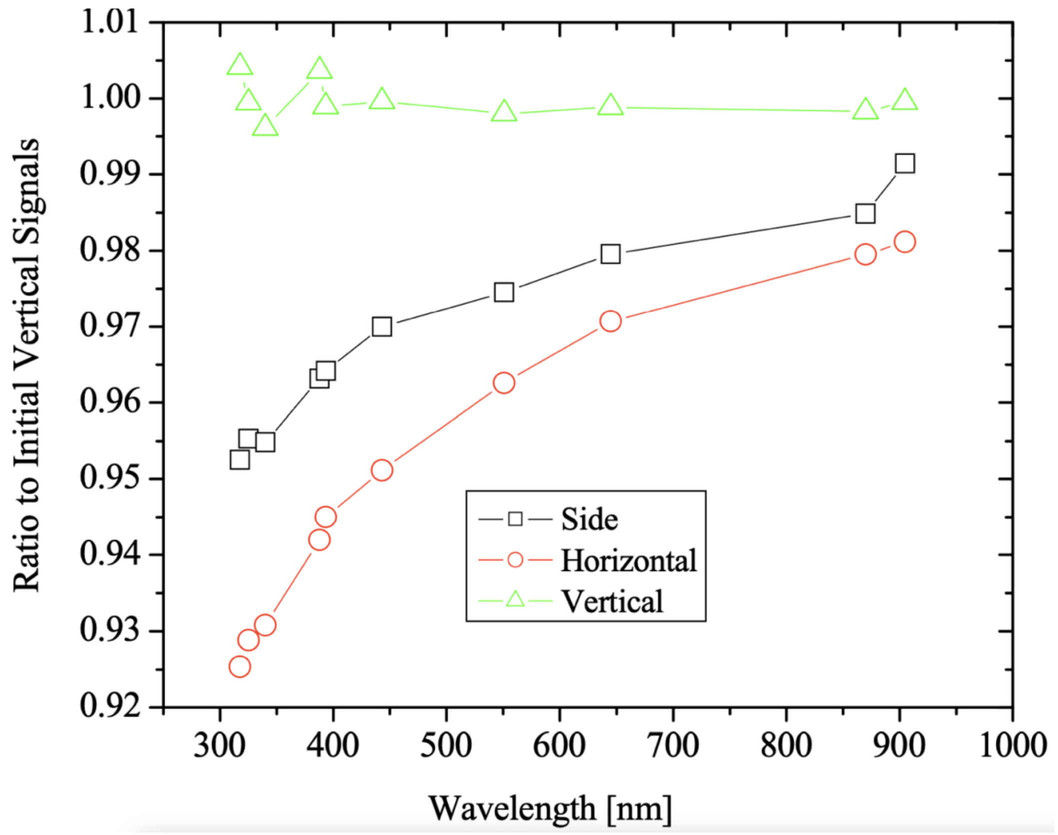
The FEL signal sensitivity to orientation of the lamp

From the NIST Special Publication 250-89

The FEL lamp orientations, and the respective signal ratios to the initial vertical orientation.

The spectral irradiance depends on the angular orientation of the FEL lamp significantly.





Template for calibration uncertainty: irradiance sensors

Uncertainty components	Relative uncertainty in percent’s					
	Selected Sentinel 3 OLCI spectral bands					
	400 nm	442,5 nm	490 nm	560 nm	665 nm	778,8 nm
FEL standard lamp irradiance	0.78	0.6	0.6	0.6	0.6	0.6
Interpolation of irradiance scale	0.2	0.2	0.2	0.2	0.2	0.2
Lamp aging	0.28	0.28	0.28	0.28	0.28	0.28
Lamp current + shunt	0.15	0.14	0.12	0.11	0.09	0.08
Wavelength of the radiometer	0.29	0.22	0.16	0.1	0.06	0.02
Distance lamp - sensor	0.08	0.08	0.08	0.08	0.08	0.08
Alignment of lamp position	0.2	0.2	0.2	0.2	0.2	0.2
Alignment of radiometer	0.1	0.1	0.1	0.1	0.1	0.1
Temperature variability	0.03	0.02	0.02	0.03	0.09	0.2
Reproducibility of calibration	0.1	0.1	0.1	0.1	0.1	0.1
Repeatability including dark signal	0.08	0.03	0.03	0.02	0.02	0.03
Combined standard uncertainty	**0.95**	**0.78**	**0.77**	**0.75**	**0.75**	**0.77**
Expanded uncertainty	**1.9**	**1.6**	**1.5**	**1.5**	**1.5**	**1.5**

Template for calibration uncertainty: radiance sensors

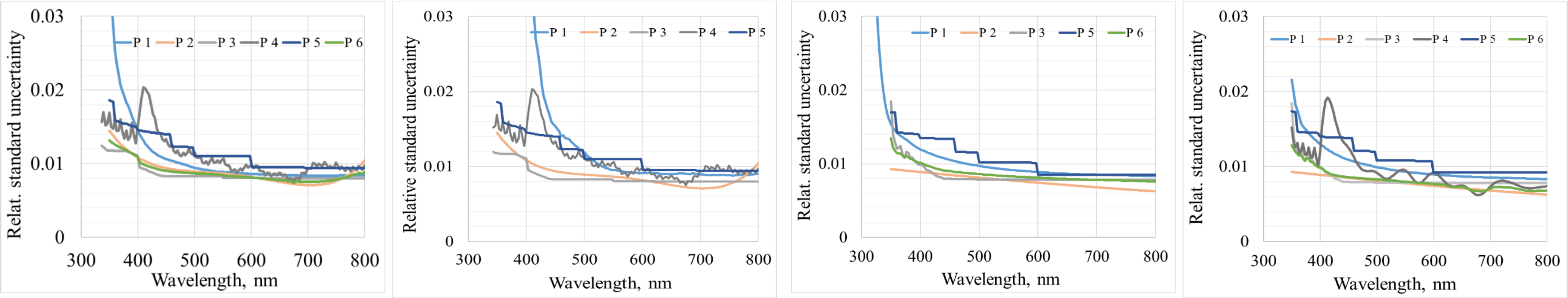
	Relative uncertainty in percent's					
	Selected Sentinel 3 OLCI spectral bands					
Uncertainty components	400 nm	442,5 nm	490 nm	560 nm	665 nm	778,8 nm
FEL standard lamp irradiance	0.78	0.6	0.6	0.6	0.6	0.6
Interpolation of irradiance	0.2	0.2	0.2	0.2	0.2	0.2
Lamp aging	0.28	0.28	0.28	0.28	0.28	0.28
Lamp current	0.15	0.14	0.12	0.11	0.09	0.08
Distance lamp - plaque	0.08	0.08	0.08	0.08	0.08	0.08
Plaque refl. factor R(0°/45°)	0.25	0.25	0.25	0.15	0.15	0.15
If correction to R(0°/45°) geometry is required	0.35	0.35	0.35	0.25	0.3	0.3
Alignment of lamp position	0.2	0.2	0.2	0.2	0.2	0.2
Alignment of radiometer	0.1	0.1	0.1	0.1	0.1	0.1
Alignment of plaque position	0.1	0.1	0.1	0.1	0.1	0.1
Temperature variations	0.03	0.02	0.02	0.03	0.09	0.2
Reproducibility of calibration	0.1	0.1	0.1	0.1	0.1	0.1
Repeatability including dark signal	0.08	0.03	0.03	0.02	0.02	0.03
Combined standard uncertainty	**0.95**	**0.81**	**0.8**	**0.78**	**0.78**	**0.8**
Expanded uncertainty	**1.9**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**

Calibration uncertainty of OCRs reported by participants

The combined uncertainties shown here are much closer as the calibration uncertainties of radiometric standards that did differ more than twice.

All the other contributions compensate the difference substantially.

Left: radiance sensors *Right: irradiance sensors*



Comparison with SIRREX-7 experiments

The uncertainties estimated in current FRM4SOC-2 LCE where compared with the uncertainties in irradiance and radiance calibrations as determined from the SIRREX-7 experiments (Hooker et al., 2002).

In the spectral range from 500 nm to 800 nm, all the LCE participant's uncertainties could be classified as primary.

In SIRREX-7, the uncertainties were ranked as primary, secondary or tertiary sources based on the difficulty of reducing the size of the uncertainty.

Table 14. The estimated uncertainties in irradiance (E) and radiance (L) calibrations as determined from the SIRREX-7 experiments. The uncertainties are ranked as primary, secondary, or tertiary sources based on the difficulty of reducing the size of the uncertainty—tertiary sources are easier to reduce than secondary sources, etc.

Source of Uncertainty		*E*	*L*
NIST Lamp Standard	1	1.0	1.0
Secondary Lamp Standard	2	+1.0	+1.0
Excessive Lamp Age	3	+1.0	+1.0
Excessive Lamp Wear	3	+2.0	+2.0
Positioning Discrepancies	2	+1.5	+1.5
Unseasoned Lamp	3	+0.5	+0.5
Low Operating Current†	3	+1.0	+1.0
Mechanical Setup	1	0.5	0.5
Rotational Discrepancies	2	+0.5	+0.5
Alignment Discrepancies	2	+0.5	+0.5
Inadequate Baffling	2	+0.5	+0.5
NIST Plaque Standard	1		1.0
Secondary Plaque Standard	2		+1.0
Excessive Plaque Age	3		+2.0
Excessive Plaque Wear	3		+4.0
Non-White (Doped) Plaque	3		+2.0
1 *Minimum Quadrature Sum*		*1.1*	*1.5*
1 2 *Typical Quadrature Sum*		*2.3*	*2.7*
1 2 3 *Maximum Quadrature Sum*		*3.4*	*6.3*

Comparison with IOCCG Protocol Series (2019)

Table 3.2 lists the best-effort uncertainties achievable in the visible spectral region with current technology and expertise.

Target uncertainties at k = 1 for most relevant radiometric quantities.

	L_u	L_i	L_T	E_d	E_u	E_s
Responsivity [%]	2	2	2	1.5	1.5	1.5

These values of the target uncertainties for the (E_s and L_u) comparison radiometers are fulfilled in the spectral range from 300 nm to 800 nm.

Conclusions

Uncertainty analysis based on the GUM methodology is presented, basing on the measurement equations for all comparison radiometers

Significant correction factors and respective uncertainties are described

Templates for the uncertainty budgets of irradiance and radiance calibration are presented

Combined expanded uncertainties reported by participants were around 2 %

In comparison with SIRREX-7 experiments these estimates could be ranked as primary, and they meet the requirement for the target uncertainty of (*Es* and *Lu*) after IOCCG Protocol Series (2019)

However, biases due to data handling often exceeded the reported uncertainties