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Uncertainty budget for the measurement with the lamp source. An example

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Outline

1. Reference points
2. Measurement equation for the lamp source
3. Uncertainty due to radiometric sensor
4. Uncertainty due to lamp source
5. Contributions from additional corrections
   5.1 Non-linearity
   5.2 Stray light
6. Conclusions

Reference points of comparison

Measured data, corrections and uncertainties will be averaged, compared and analysed in connection of these wavelength's bands.

Centre	400 nm	442.5 nm	490 nm	560 nm	665 nm	778.8 nm	900 nm
With	15 nm	10 nm	10 nm	10 nm	10 nm	15 nm	10 nm

Measurement equation for irradiance $E(\lambda, I, d)$ of the lamp source

$$E(\lambda, I, d) = \frac{\left(\mathrm{S}(\lambda) - S_0(\lambda)\right) C_{\mathrm{stray}} C_{\mathrm{temp}} C_{\mathrm{lin}}}{R_E(\lambda) G_{\mathrm{c}}}$$

Here, I is the current and d is the distance of the lamp source,

$\left(\mathrm{S}(\lambda) - S_0(\lambda)\right)$ is normalized raw signal of the radiometer with dark signal subtracted;

$R_E(\lambda)$ is the spectral responsivity of the radiometer from the calibration certificate;

$G_{\mathrm{c}} = t/t_0$ is the gain amplification factor;

C_{stray} is correction for the stray light;

C_{temp} is correction for temperature;

C_{lin} is correction for instrument non-linearity.

Considerations about the lamp source

The lamp source is an unpolarised point source.

Light collection area A[cm^2] ≤ d/50; for d = 50 cm, A ≤ 1 cm^2.

Here d[cm] is a distance between the lamp and sensor.

Lamp is pre-selected, and pre-aged.

Lamp stability is monitored (voltage measured).

Lamp current and distance are controlled with relatively small uncertainty.

The system is adequately baffled for scattered radiant flux.

Uniformity and polarization effects

FEL lamps are not point sources; alignment effects of lamps are caused by the individual intensity distributions.

FEL lamps are slightly polarized: Irradiance from several 1000 W FEL lamps measured between 450 and 900 nm was polarized between 2.3 % and 3.2 %. Polarization of these lamps should be considered when the lamps are used to characterize grating spectrometers.

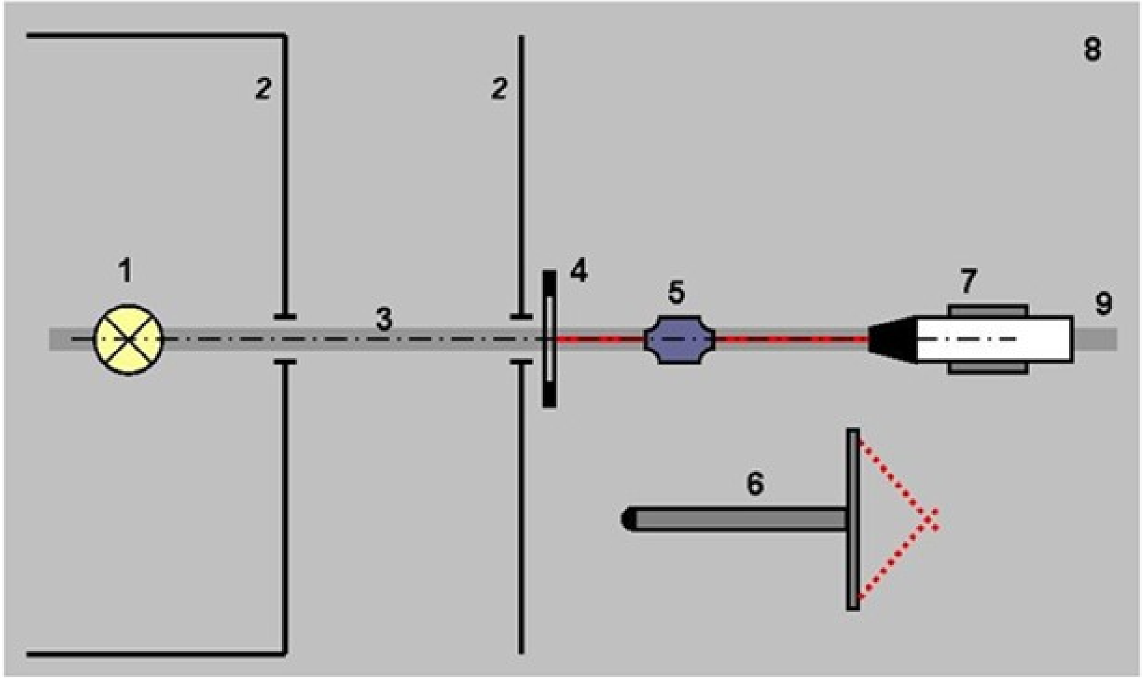
In the case of irradiance sensors, due to depolarizing effects of the diffusing collector, the maximum differences between horizontal and vertical polarization sensitivities vary from approximately 0.3 % at 400 nm to 0.6 % at 750 nm.

K. J. Voss and L. B. da Costa, "Polarization properties of FEL lamps as applied to radiometric calibration," *Appl. Opt.*, vol. 55, no. 31, pp. 8829–8832, Nov. 2016.

M. Talone and G. Zibordi, "Polarimetric characteristics of a class of hyperspectral radiometers," *Appl. Opt.*, vol. 55, no. 35, pp. 10092–10104, Dec. 2016

Scheme of the FEL source comparison

1 - FEL lamp; 2 - baffles; 3 - main optical axis; 4 – additional alignment jig;
5 - alignment laser; 6 - distance tool; 7 - radiometer on the support;
8 - optical table; 9 - optical rail.



Measurement uncertainty of the FEL source

Uncertainty contributions:

1. Radiometer
   - 1.1 Calibration certificate
   - 1.2 Instability
   - 1.3 Alignment
   - 1.4 Repeatability of the signal (Type A estimate)
   - 1.5 Temperature effects
   - 1.6 Correction of non-linearity
   - 1.7 Correction of stray light
2. FEL lamp source
   - 2.1 Shunt
   - 2.2 Lamp current
   - 2.3 Alignment
   - 2.4 Distance

Measurement uncertainty of the radiometer

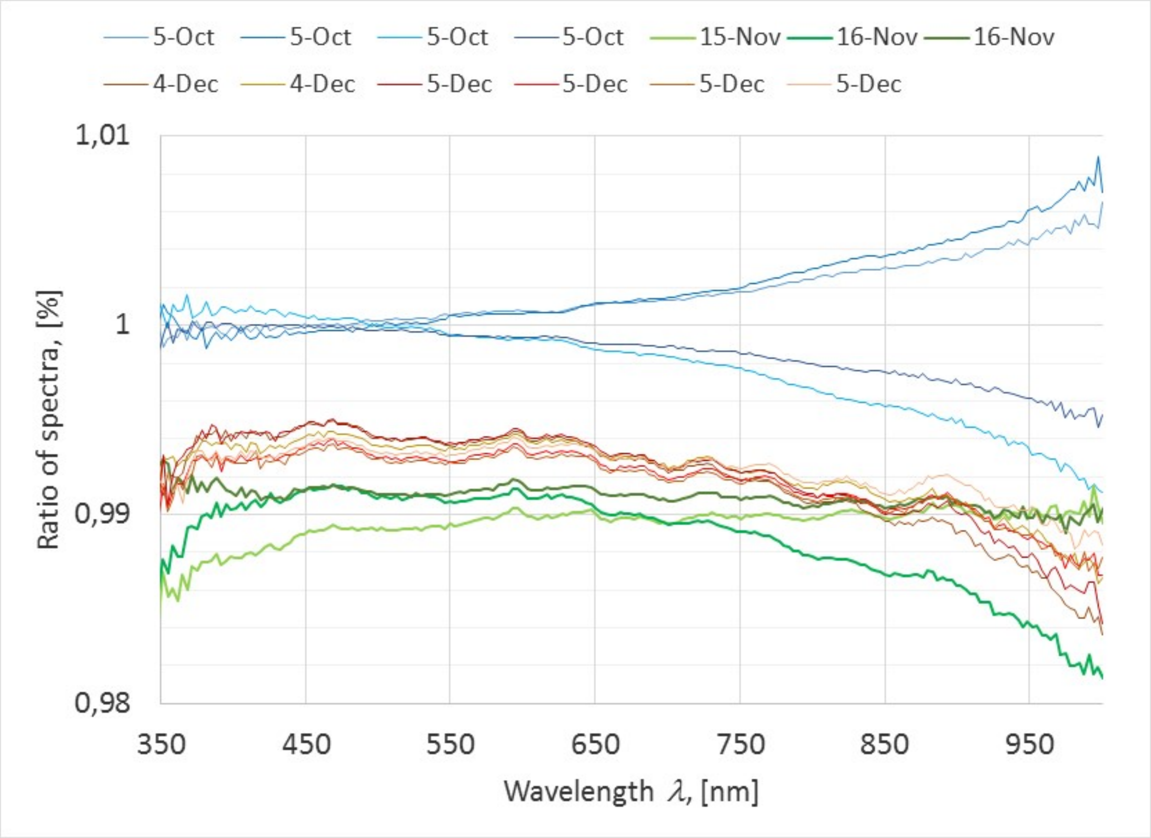
Contributions of TriOS RAMSES ACC radiometer as relative standard uncertainties *u*, [%]

1.1 Calibration certificate
1.2 Instability of the radiometer
1.3 Adjustment of the radiometer
1.4 Variability of signal due to temperature
1.5 Repeatability of the averaged signal

	400 nm	442.5 nm	490 nm	560 nm	665 nm	778.8 nm	900 nm
Certificate	0.89	0.74	0.74	0.74	0.74	0.76	0.83
Instability	0.5	0.3	0.3	0.3	0.5	0.7	0.9
Adjustment	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Temperature	0.02	0.01	0.01	0.03	0.09	0.2	0.38
Signal, u_A	0.074	0.025	0.023	0.016	0.017	0.024	0.04

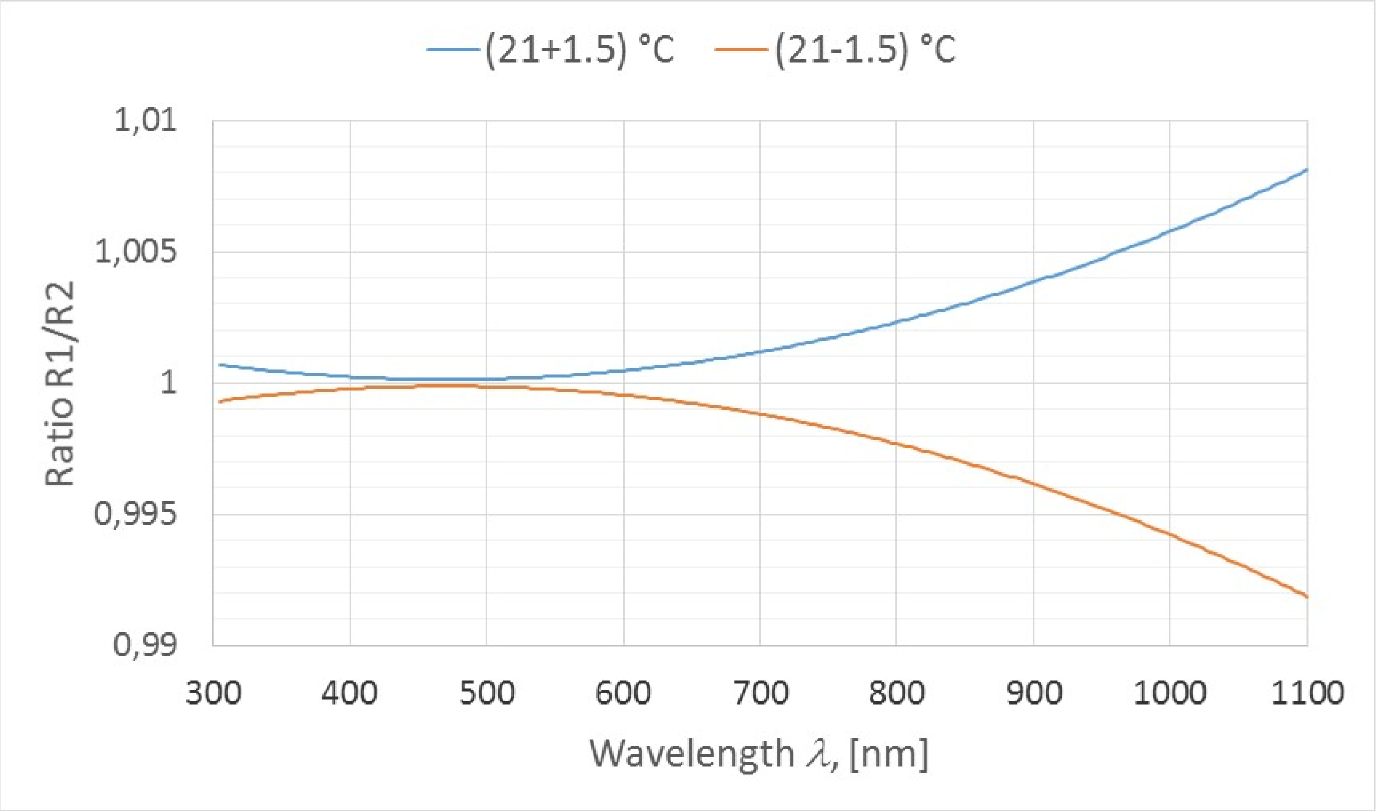
Alignment and temperature effects

Repeated alignment of TriOS Ramses ACC sensor. Variability due to instability of the sensor and due to temperature effects also is evident.



Modelled temperature effects

Modelled temperature effects for lab conditions (21±1.5) °C. Spectrum R1 assumed at 22.5 °C and 20.5 °C. Spectrum R2 assumed at 21 °C.



Measurement uncertainty of the lamp source

Contributions of lamp as relative standard uncertainties *u*, [%] :

1.1 Calibration and stability of shunt resistance

1.2 Uncertainty of the lamp current

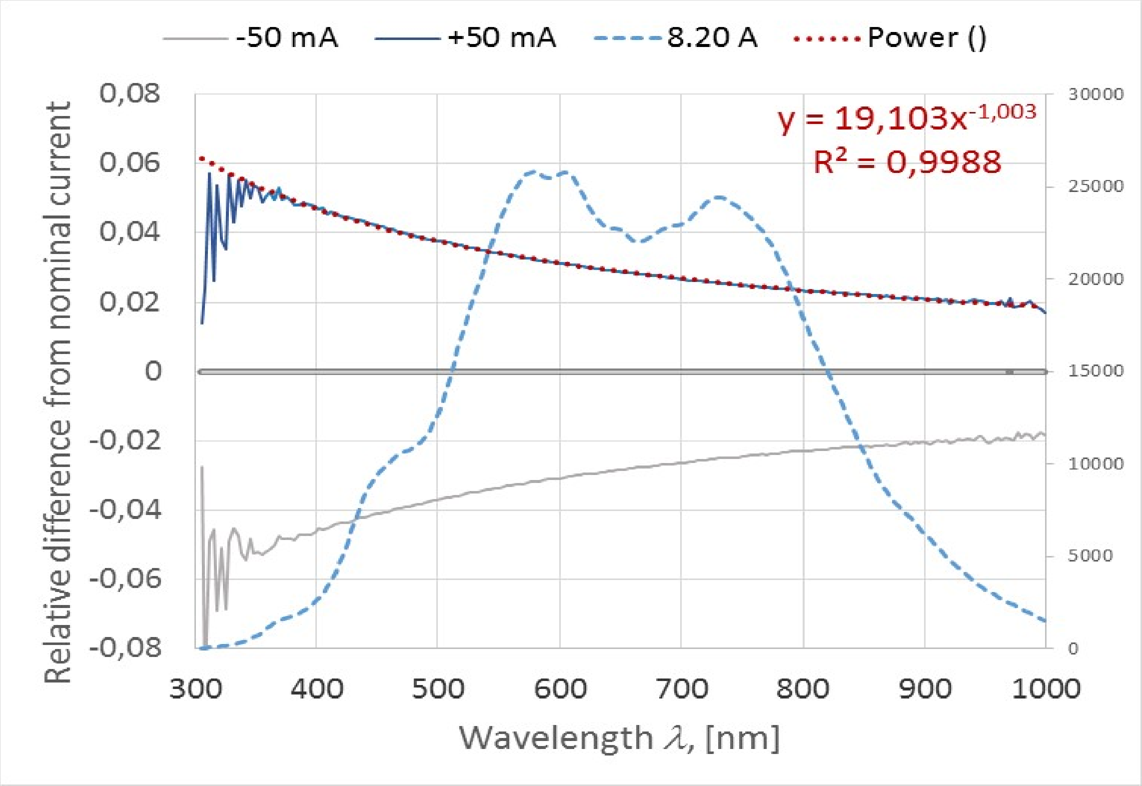
1.3 Distance between the lamp and the radiometer

1.4 Adjustment reproducibility of the lamp

	400 nm	442.5 nm	490 nm	560 nm	665 nm	778.8 nm	900 nm
Shunt	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Current	0.15	0.14	0.12	0.11	0.09	0.08	0.07
Distance	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Position	0.1	0.1	0.1	0.1	0.1	0.1	0.1

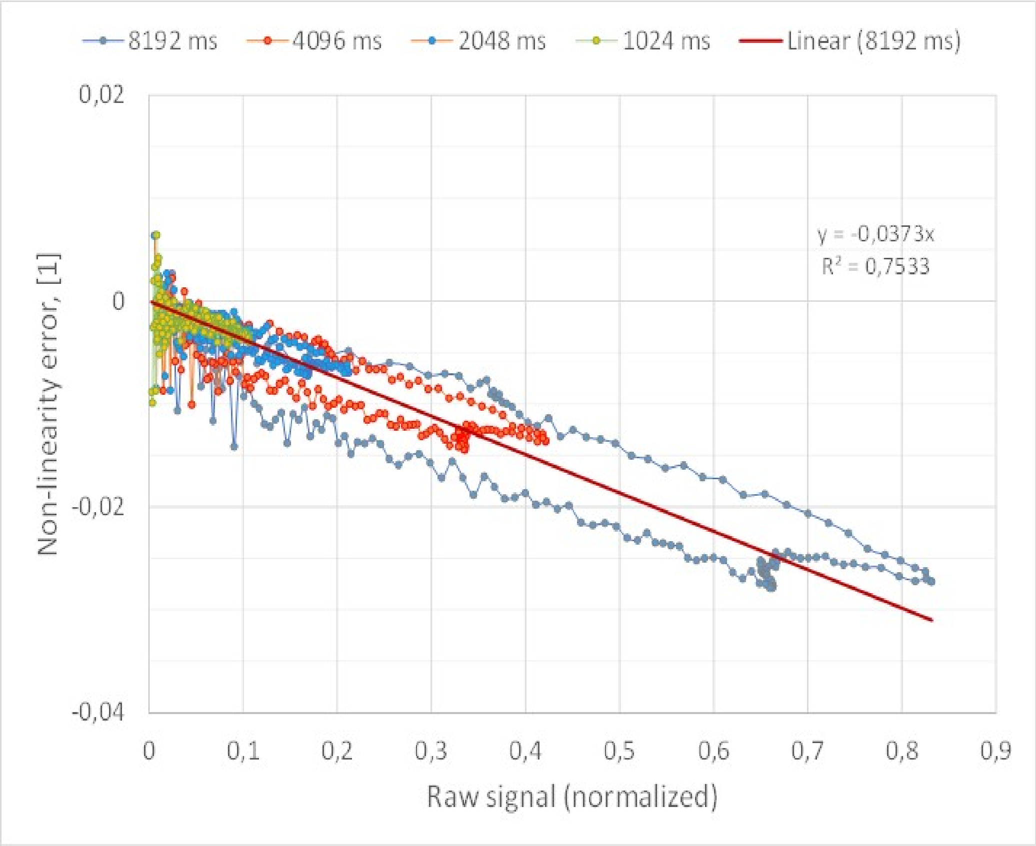
The effect of lamp current offset

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.



Non-linearity error of TriOS RAMSES radiometer

By using the two-spectra formula, the non-linearity effect can be corrected to 0,1 %.



Measurement uncertainty due to non-linearity

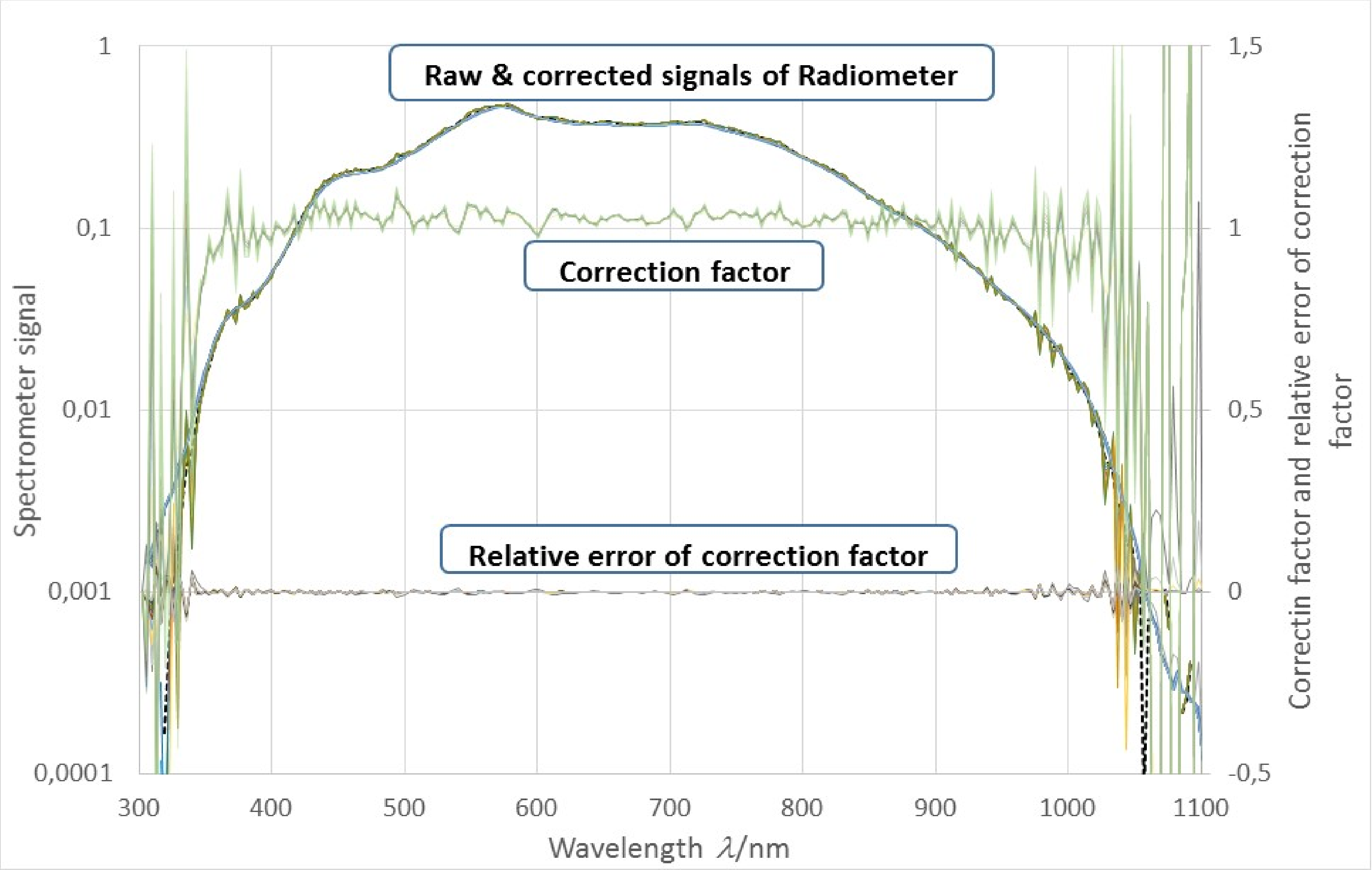
Contribution of non-linearity as relative standard uncertainty *u*, [%]

Uncertainty due to non-linearity, if corrected, is smaller than 0.2 %.

If not corrected, the contribution due to nonlinearity may be up to 2 %. In the case of similar light source the variability between different instruments likely will be below the possible maximum values.

	400 nm	442.5 nm	490 nm	560 nm	665 nm	778.8 nm	900 nm
Corrected	0.1	0.06	0.05	0.04	0.07	0.08	0.18
Not corrected	0.28	0.46	0.7	1.5	1.48	1.27	0.69

Stray light effect on the FEL radiance spectrum



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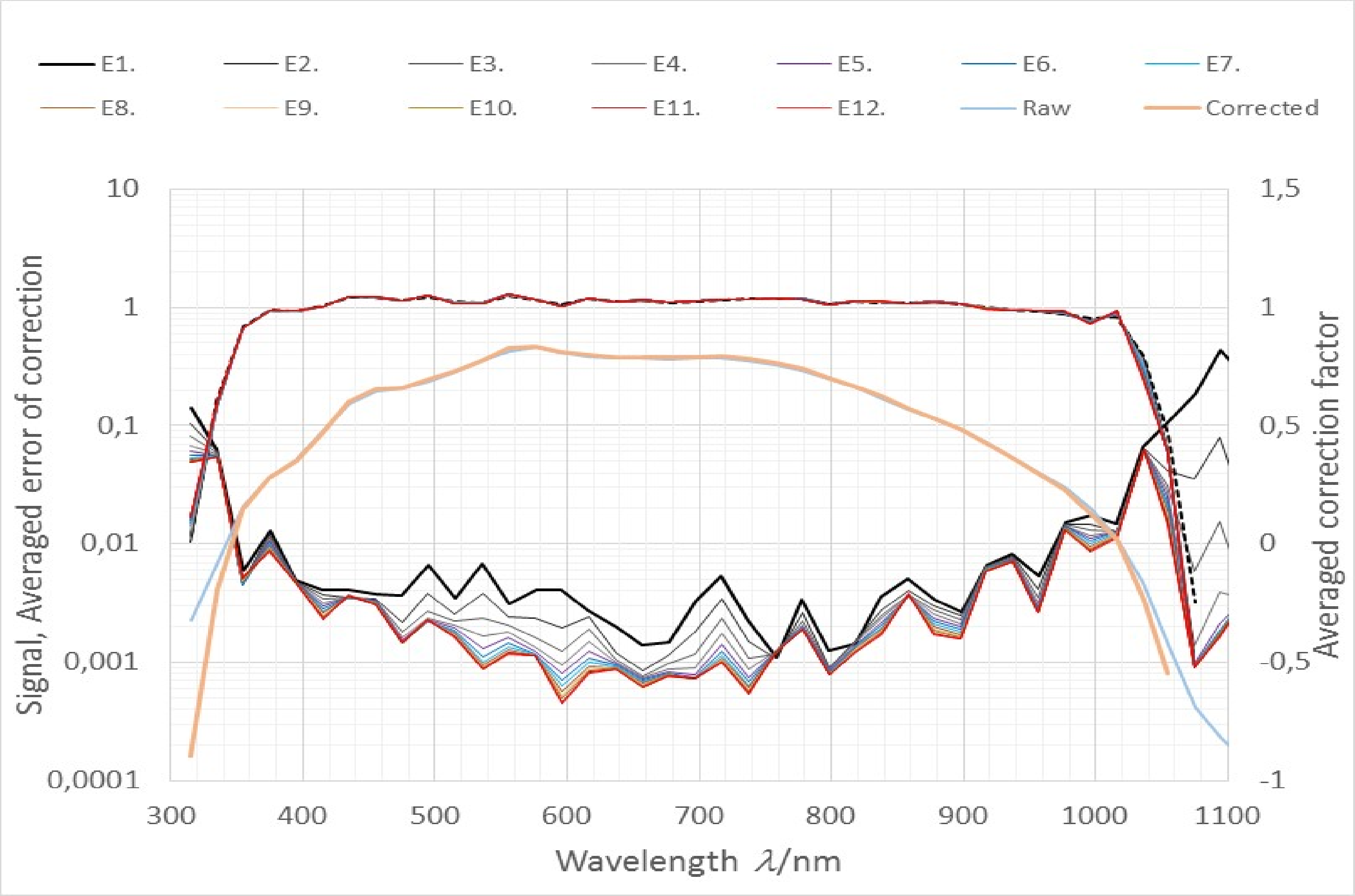
Averaged stray light effect on the FEL spectrum



Stray light correction

Spectral irradiance response of the radiometer has to be calibrated against standard lamp. The stray light correction should be applied to every measured spectrum, i.e. in the case of the calibration spectrum as well.

If the comparison source is the similar FEL type lamp as used for calibration, the stray light effects are for both spectra also very alike and by calculating the final result as a ratio of spectra it will cancel out.

Measurement uncertainty due to stray light

Contribution of stray light as relative standard uncertainty *u*, [%]

Uncertainty due to stray light, if corrected, is smaller than 0.4 %.

If not corrected, the contribution due to stray light may be up to 5 %. In the case of similar light sources the contribution to the final result will stay below 0.5 % not depending from correcting status.

	400 nm	442.5 nm	490 nm	560 nm	665 nm	778.8 nm	900 nm
Corrected	0.3	0.4	0.4	0.2	0.2	0.2	0.4
Not corrected	1.3	4.2	4.9	4.4	2.6	3.7	1.1

Uncertainty budget

Uncertainty budget for the lamp source measurement with the radiometer (relative standard uncertainties *u*, [%])

		400 nm	442.5 nm	490 nm	560 nm	665 nm	778.8 nm	900 nm
Radiometer	Certificate	0.89	0.74	0.74	0.74	0.74	0.76	0.83
	Instability	0.5	0.3	0.3	0.3	0.5	0.7	0.9
	Alignment	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Temperature	0.02	0.01	0.01	0.03	0.09	0.2	0.38
	Signal, uA	0.074	0.025	0.023	0.016	0.017	0.024	0.04
	Non-Linearity	0.1	0.06	0.05	0.04	0.07	0.08	0.18
	Stray light	0.3	0.4	0.4	0.2	0.2	0.2	0.4
FEL source	Shunt	0.002	0.002	0.002	0.002	0.002	0.002	0.002
	Current	0.15	0.14	0.12	0.11	0.09	0.08	0.07
	Distance	0.08	0.08	0.08	0.08	0.08	0.08	0.08
	Alignment	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Combined (k=1)	1.09	0.92	0.92	0.85	0.94	1.09	1.37
	Expanded (k=2)	2.2	1.8	1.8	1.7	1.9	2.2	2.7

Additional uncertainty contributions relevant for field exercise

1. Radiometer

- 1.1 Calibration certificate
- 1.2 Responsivity change
- 1.3 Alignment
- 1.4 Repeatability
- 1.5 Temperature effects
- 1.6 Correction of non-linearity
- 1.7 Correction of stray light
- **1.8 Polarization effects**
- **1.9 Non-cosine response**

2. Measurand

- **2.1 Viewing angle effects**
- **2.2 Environmental effects**

Summary

Comparison measurement is a main tool to reveal unknown uncertainty sources or to improve the current estimates.

Measurement comparison can be evaluated only on the basis of relevant uncertainty estimates.

Relevant measurement model including all sources of uncertainty is critically important.

All significant input contributions of the model should be evaluated.

Correcting for different systematic effects is preferable as compared to fully adding them in uncertainty budget.