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Measurement uncertainty in the context of LCE-2 project

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Outline

1. Wavelength’s bands chosen for the comparison points
2. Measurement equations relevant to LCE-2 comparisons
3. Calibration uncertainty of radiometric sensors
4. Uncertainty of the signal of radiometer
5. Contributions from additional corrections
    1. Correcting spectra for non-linearity C_{lin}
    2. Temperature effects C_{temp}
    3. Contribution from alignment of instruments
    4. Correcting spectra for stray light C_{stray}
5. Conclusions

Wavelength’s bands for comparison

All radiometers involved in LCE-2 project may have different wavelength’s bands or scales.

Therefore, from 21-band of Ocean and Land Colour Instrument (OLCI) seven more suitable bands have been chosen to be used as the reference points of comparison.

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

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

Wavelength's bands for comparison

Two approaches can be used for averaging data in connection with the bands listed before:

1. Experimental shape following the OLCI mean spectral response or
2. Gaussian line shape with OLCI specification for central wavelengths and band widths

Second approach is less sensitive to small variations between wavelength scales present for different radiometers.

For easy of data handling a special matrix has to be prepared for each radiometer transforming measured spectra to the values of comparison points.

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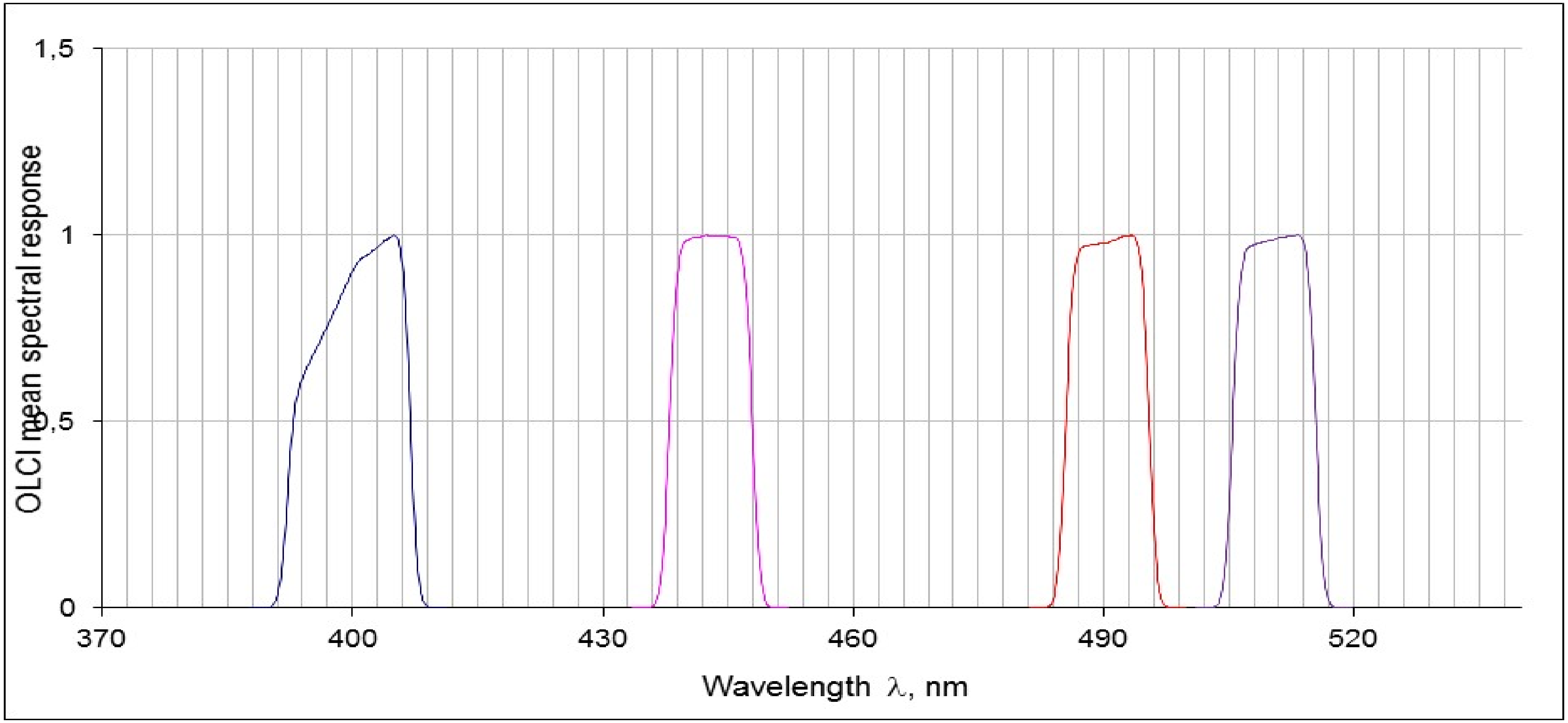
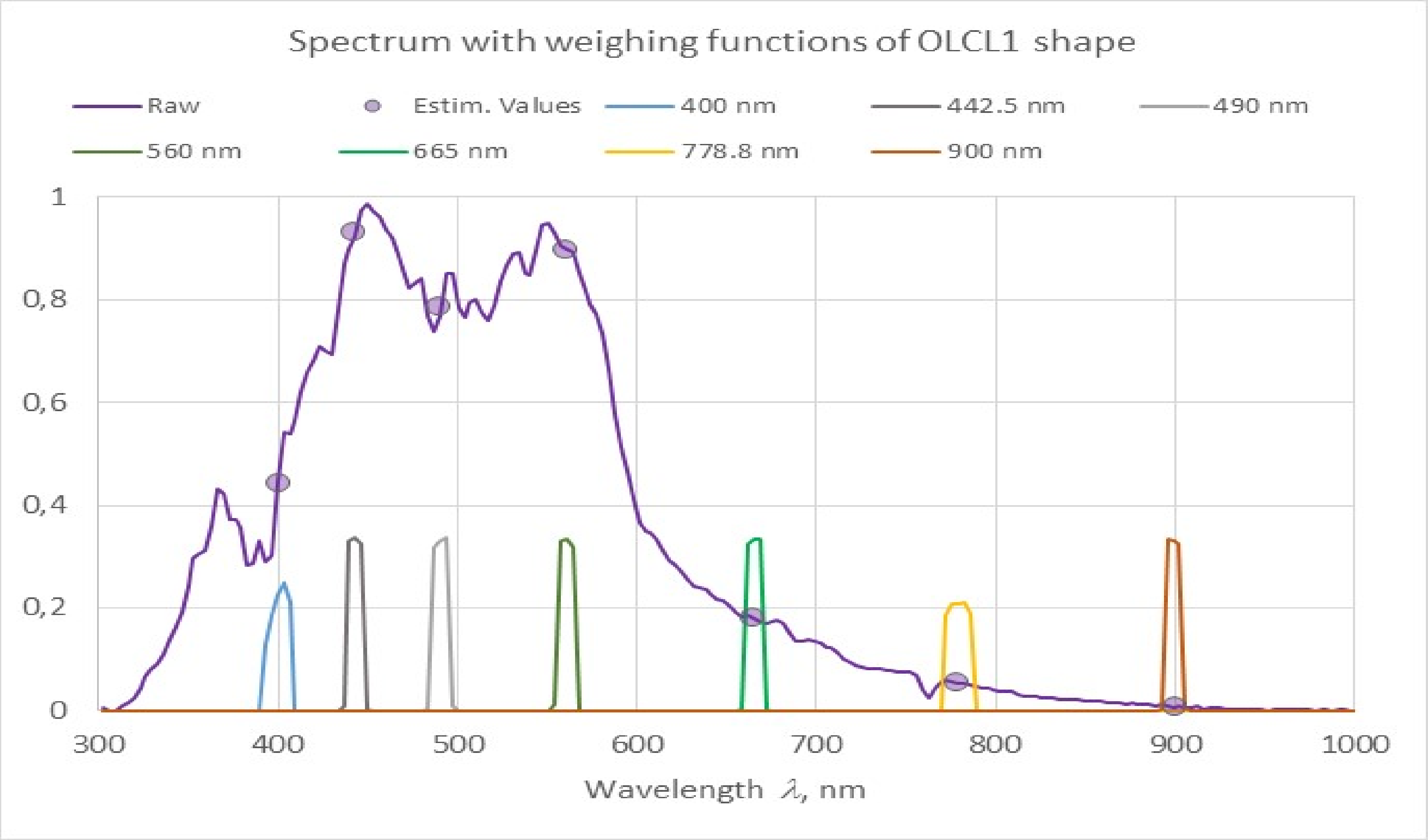
Shape and width of OLCL1 bands

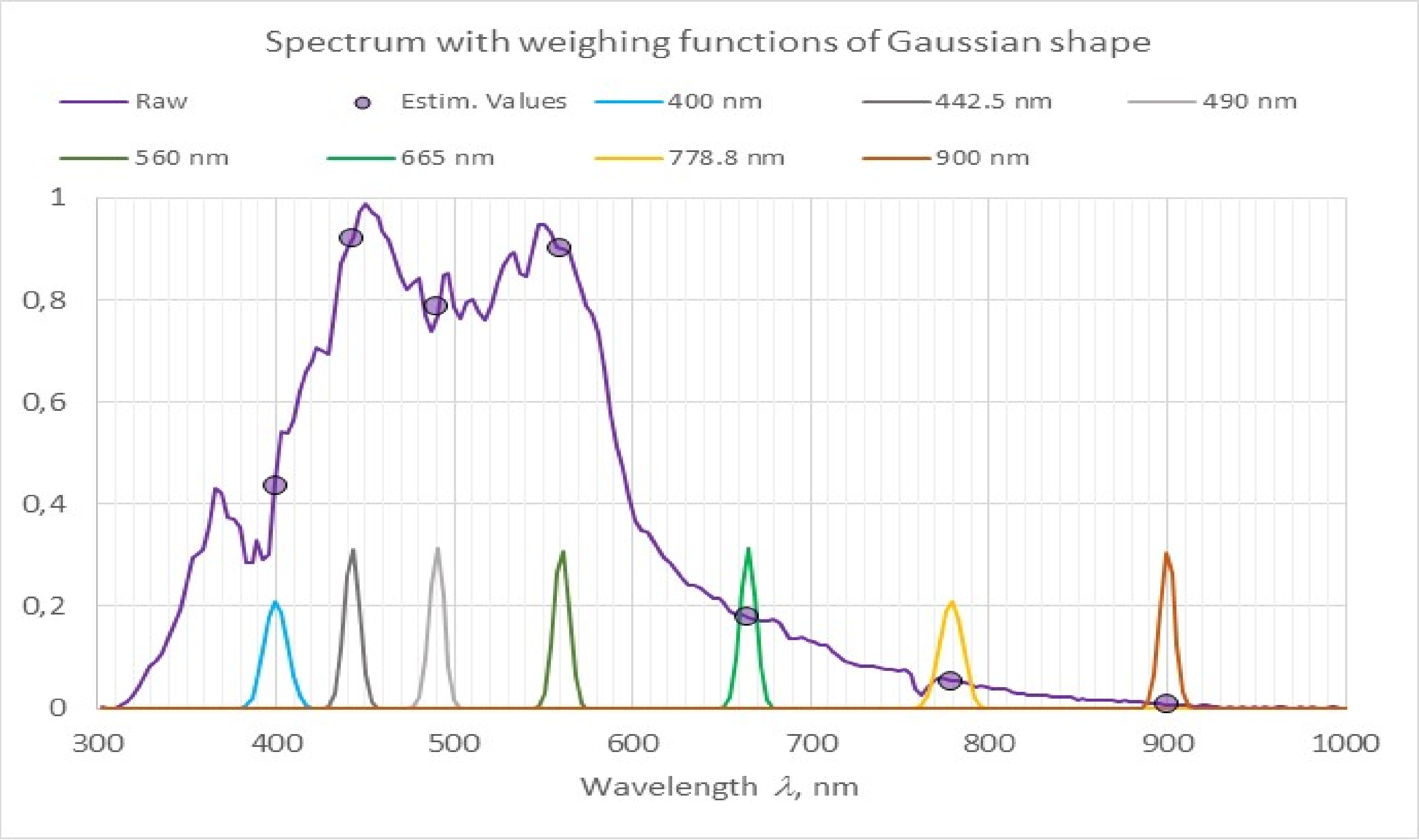
Minor gridlines show an approximate distribution of the sensor's pixels of the TriOS RAMSES radiometer. Value of the data point will be estimated from the pixels, central wavelengths of which are covered by the band. Pixels values are averaged, and the shape of the band is used as a weighing function.



Estimating comparison points



Estimating comparison points



Measurement equation for irradiance $E(\lambda)$

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

Here, $\left(\mathrm{S}(\lambda) - S_0(\lambda)\right)$ 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_{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.

Measurement equation for radiance $L(\lambda)$

$$L(\lambda) = \frac{\left(S_{\mathrm{r}}(\lambda) - S_{\mathrm{r0}}(\lambda)\right) C_{\mathrm{stray}} C_{\mathrm{temp}} C_{\mathrm{lin}}}{R_L(\lambda)\, G_{\mathrm{c}}}$$

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

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

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

C_{stray} is correction for the stray light;

C_{temp} is correction for temperature;

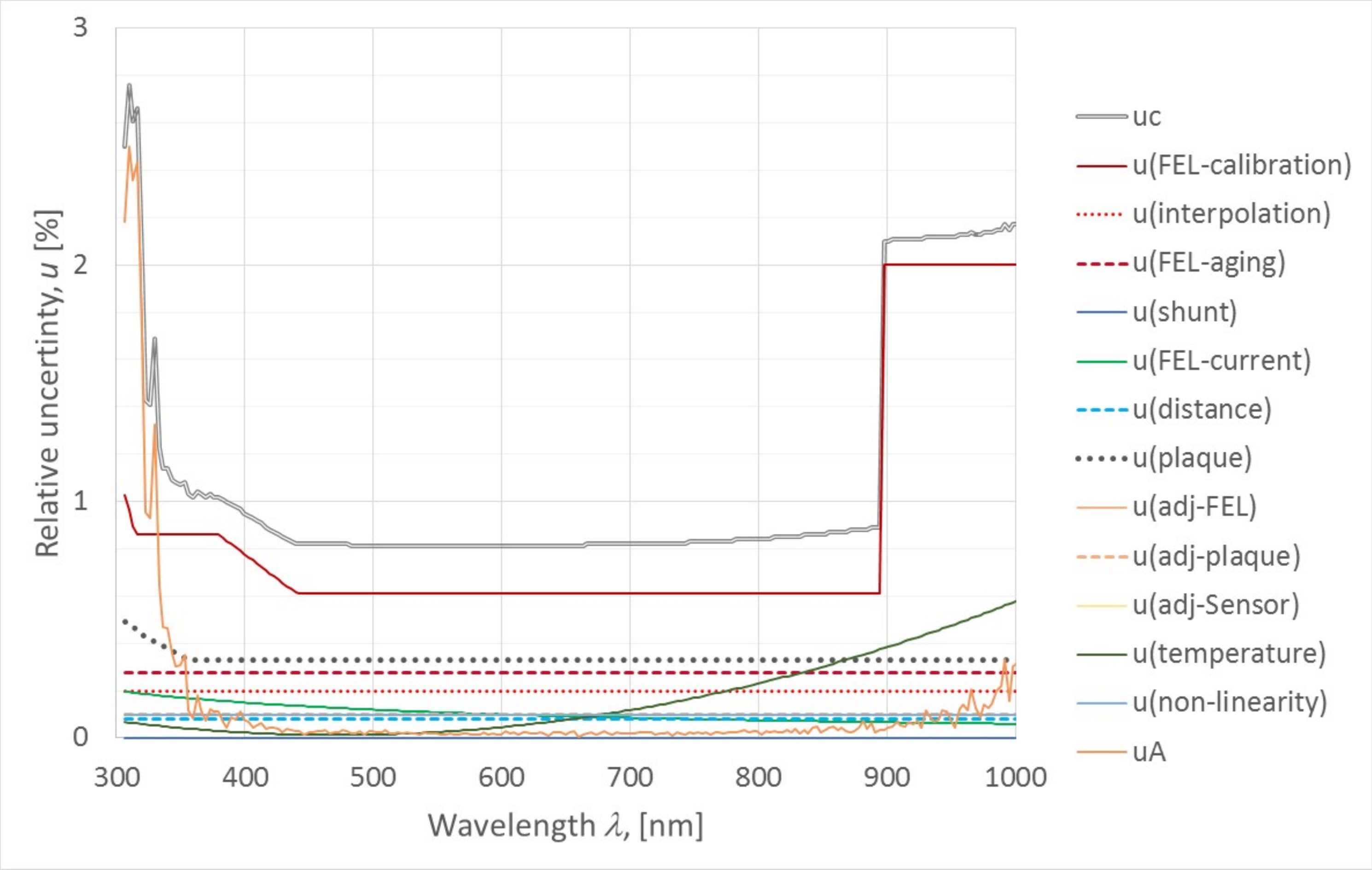
C_{lin} is correction for instrument non-linearity.

Calibration uncertainty of radiometric sensors

Uncertainty contributions accounted for:

1. Standard lamp
    - 1.1 Calibration certificate (often dominating contribution)
    - 1.2 Lamp ageing
    - 1.3 Interpolation
    - 1.4 Shunt
    - 1.5 Lamp current
2. Diffuse reflection plaque (certificate, correction if needed)
3. Alignments
    - 3.1 Distance
    - 3.2 Reproducibility (lamp, plaque, sensor)
4. Random effects (repeatability of spectra, and dark signal)
5. Correcting for non-linearity
6. Correcting for temperature

Relative standard uncertainty for calibration of radiance sensors of TRioS Ramses radiometers



Uncertainty of the radiometer’s signal

From recorded multiple measurement series, averaged spectrum is calculated together with experimental standard deviation of the mean (relative standard uncertainty of the mean).

Similarly, averaged spectrum of background series with relative experimental standard deviation of the mean is calculated.

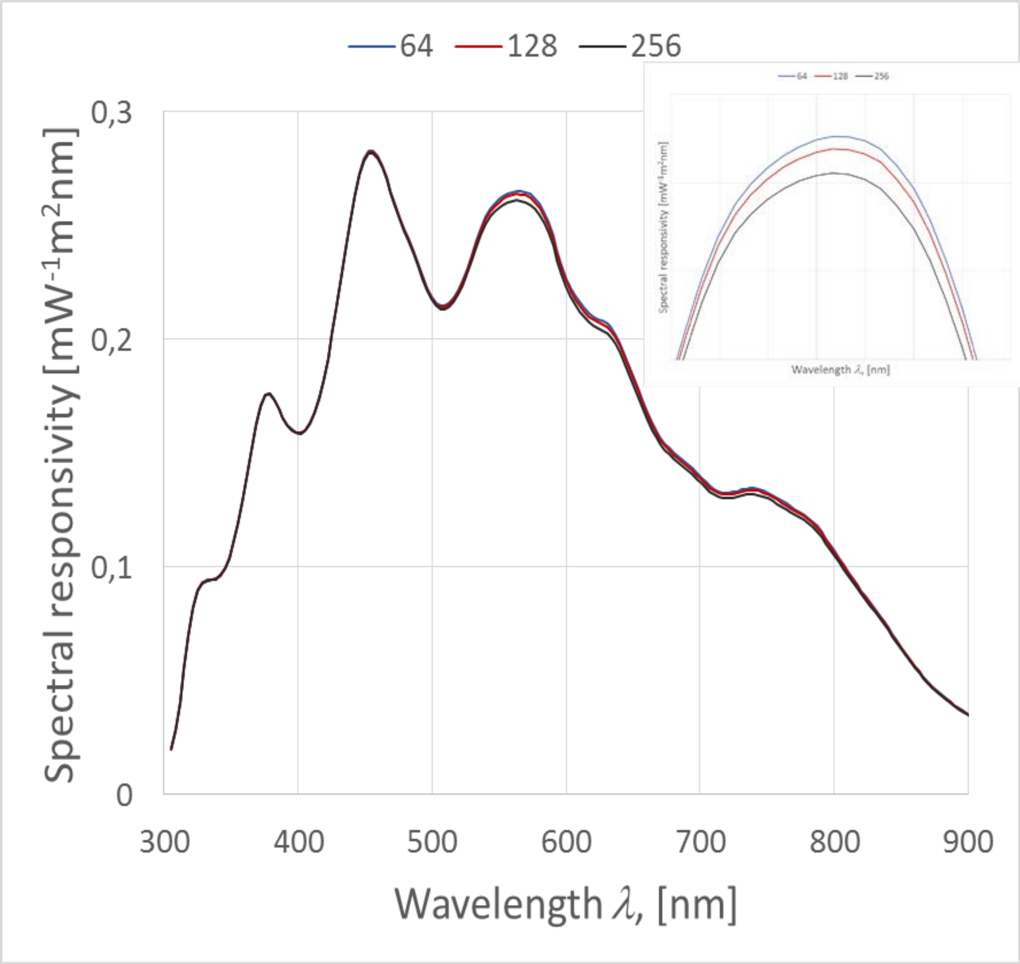
Standard uncertainty of the normalized raw signal of the radiometer with dark signal subtracted is calculated as the geometrical sum of standard uncertainties of these means (signal and dark).

Non-linearity due to different integration times.

Spectra of a radiometer from data obtained with different integration times may vary several percent's.

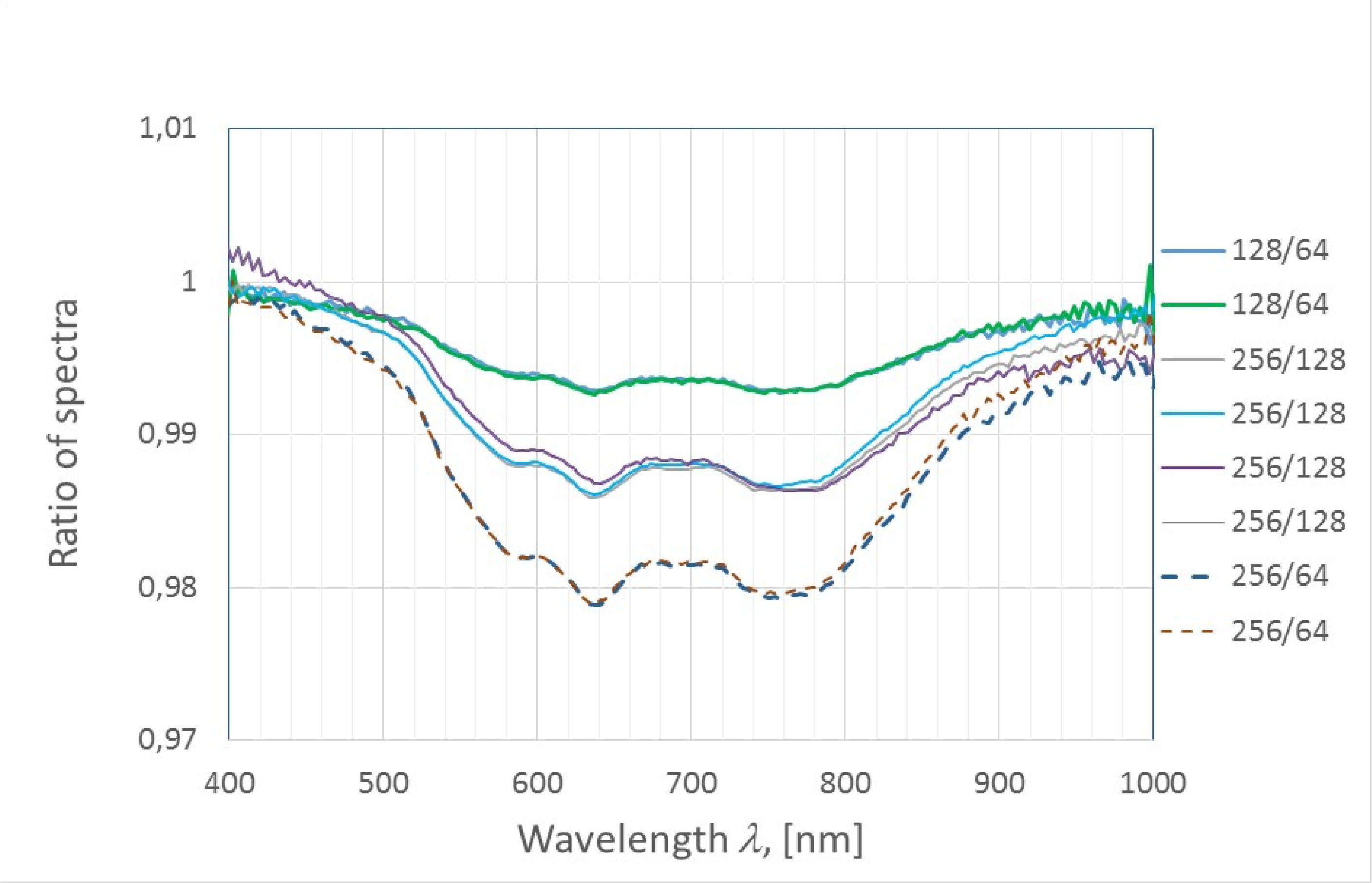
Nature of variation may be predictable or non-predictable.

Responsivity spectra of TriOS RAMSES vary in predictable way: the smaller the integration time the larger the particular spectrum, and the non-linearity effect is proportional to the integration time used.



Non-linearity effect of systematic nature

Ratio of spectra with integration times of 256 ms, 128 ms and 64 ms.



Non-linearity correction

At least two different spectra are needed for every corrected spectrum. Spectrum $S_{1,2}(\lambda)$ corrected for nonlinearity is calculated by using the following formula:

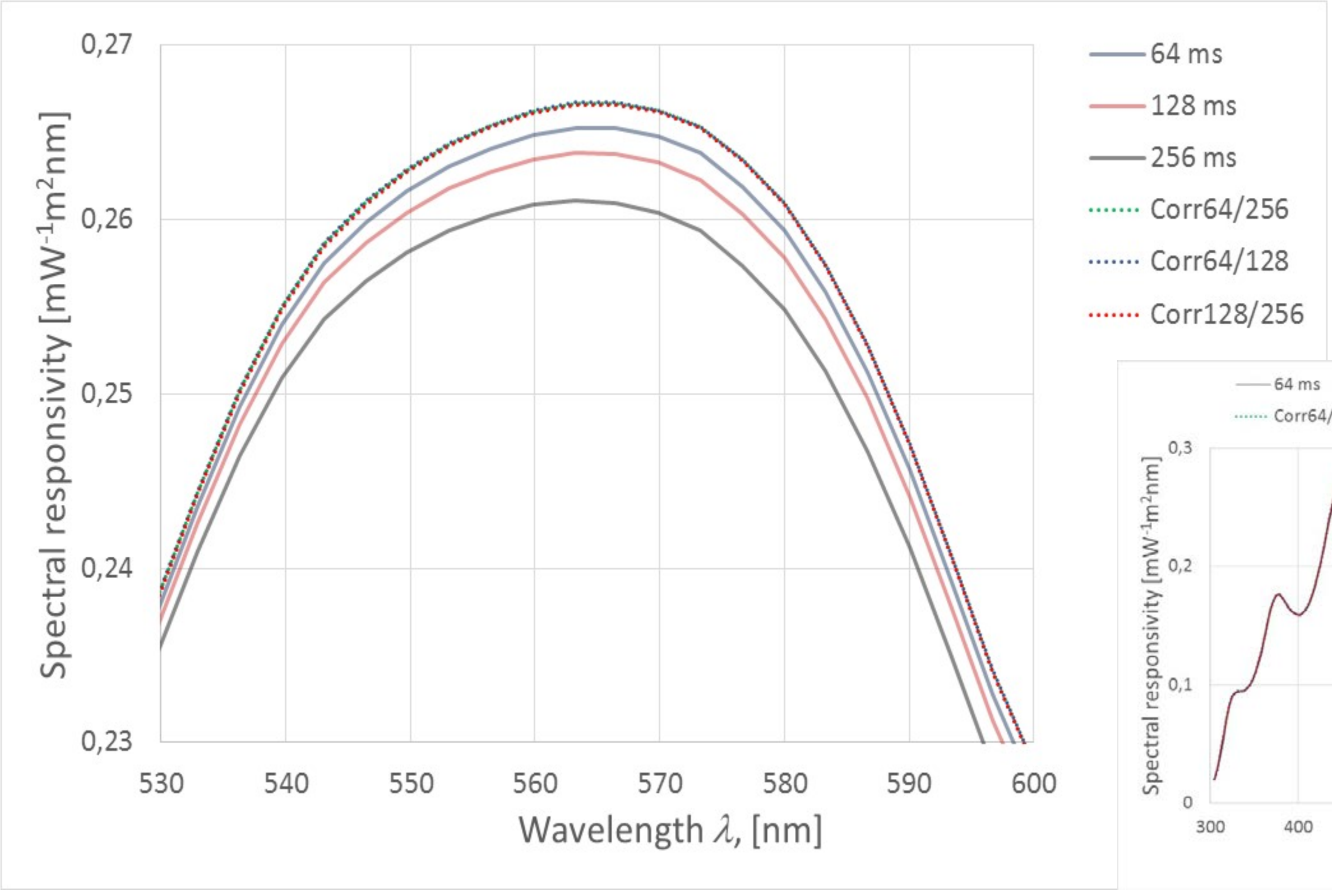
$$S_{1,2}(\lambda) = \left[1 - \left(\frac{S_2(\lambda)}{S_1(\lambda)} - 1\right)\left(\frac{1}{t_2/t_1 - 1}\right)\right] S_1(\lambda) .$$

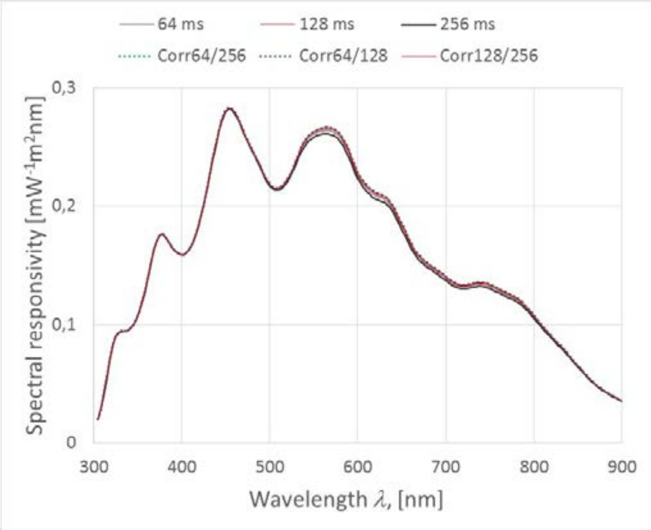
Here $S_1(\lambda)$ and $S_2(\lambda)$ are the initial spectra measured with integration times t_1 and t_2. Minimal ratio usually is t_2/t_1=2, but it may be also 4, 8, 16, etc.

For large ratios t_2/t_1 > 8 the spectrum $S_1(\lambda)$ is close to $S_{1,2}(\lambda)$, so that correction is usually not needed.

Spectra corrected for non-linearity

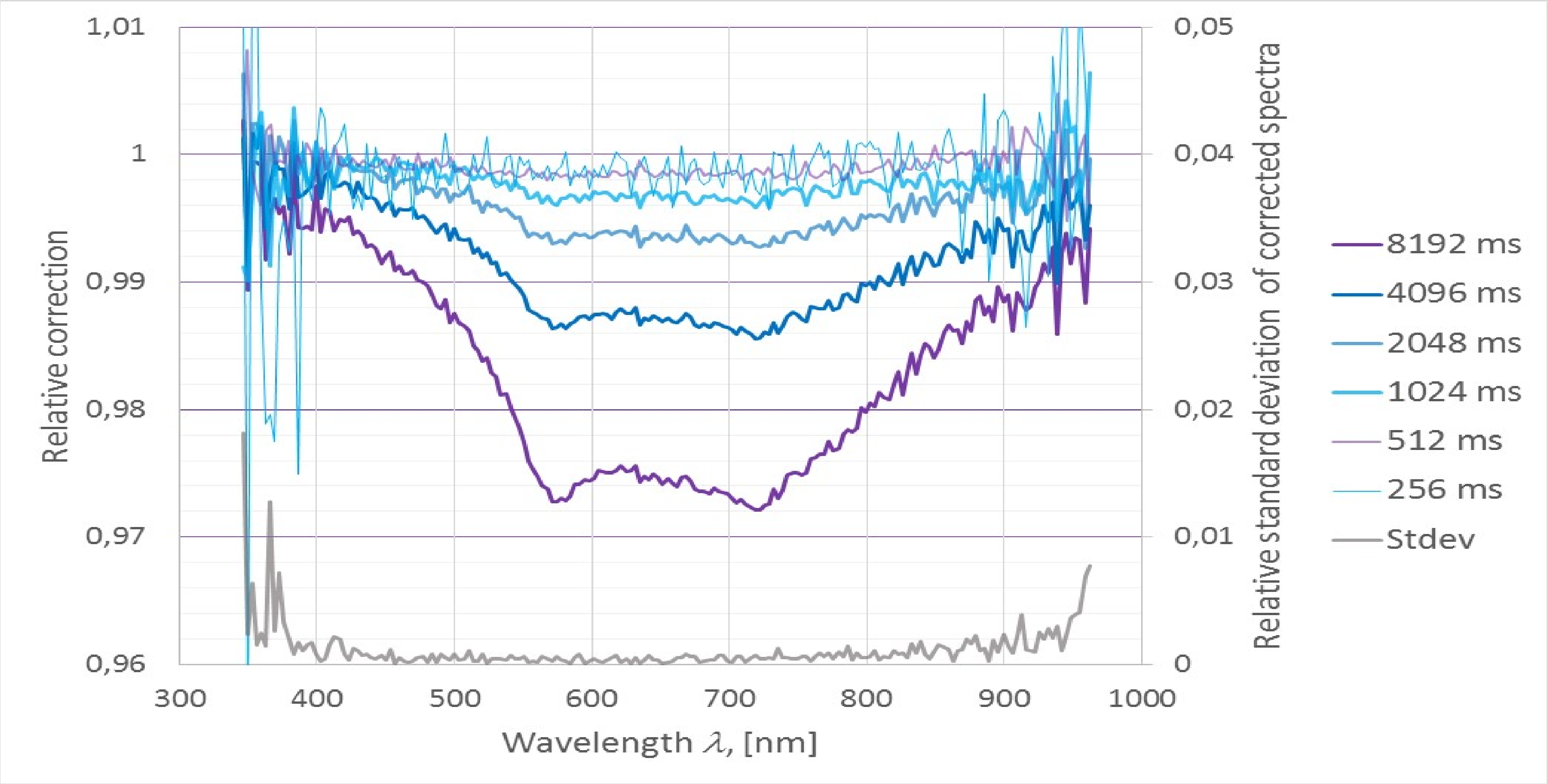
Measured and corrected spectra as a function of integration time.





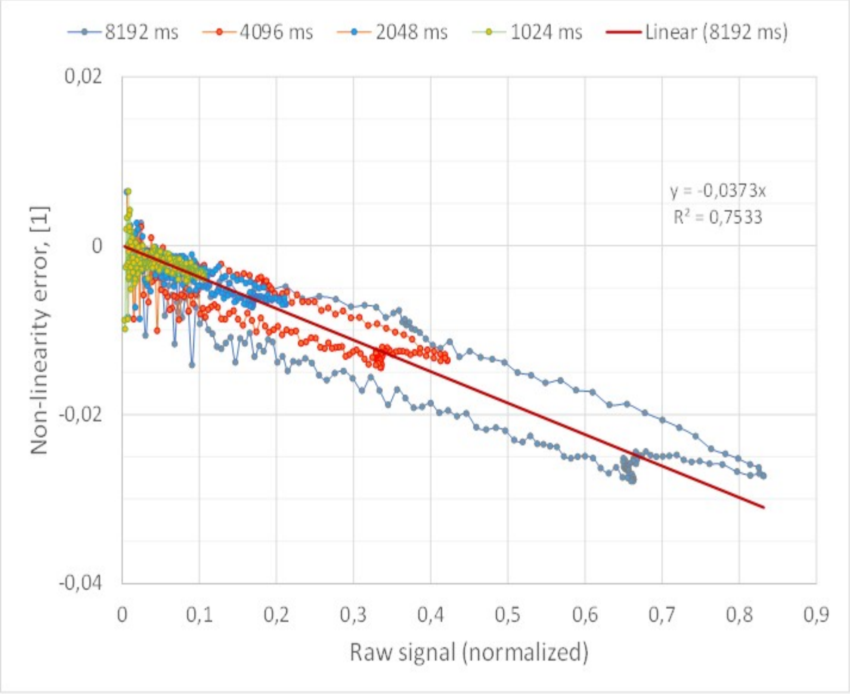
Effectiveness of non-linearity correction

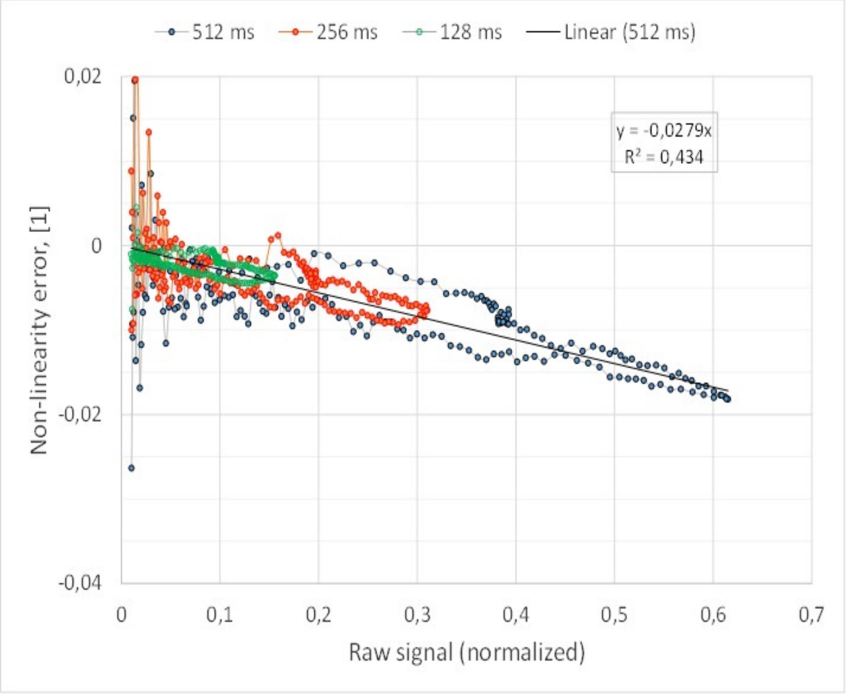
The correction formula is quite useful for certain types of radiometers (TriOS RAMSES, Satlantic HyperOCR).



Non-linearity correction

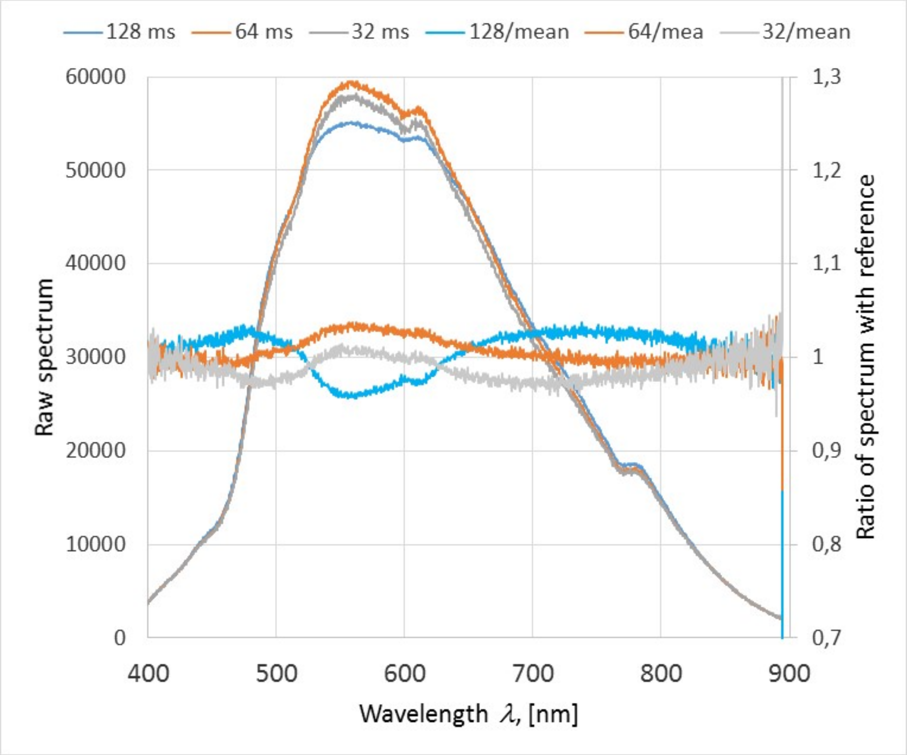
By using the two-spectra formula, the non-linearity effect due to different integration times can be corrected to 0,1 %. It is impossible by using average correction as a function of signal amplitude. Non-linearity error of TriOS RAMSES (left) and Satlantic HyperOCR (right) radiometers.

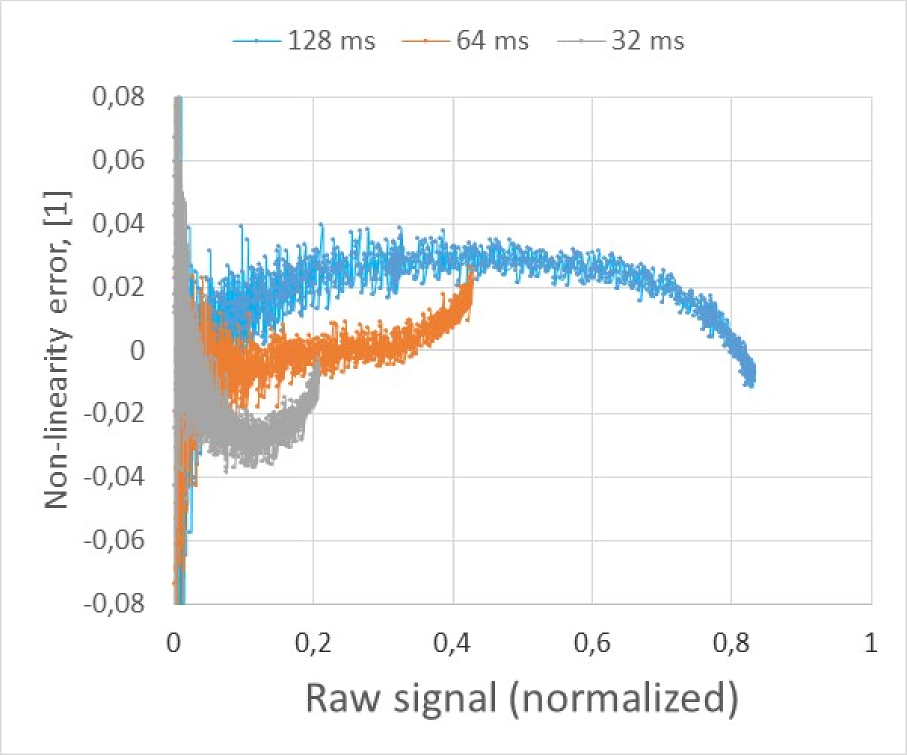




Non-linearity effect of non-predictable nature

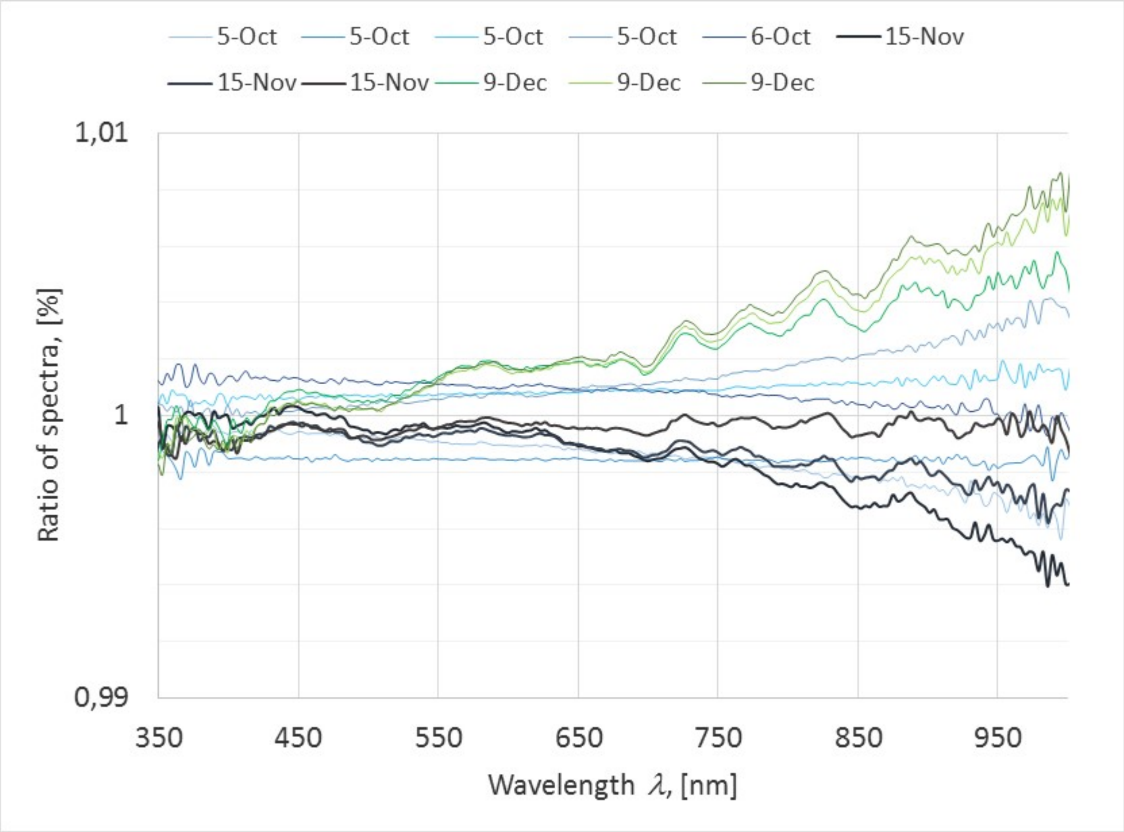
Non-linearity error of the WISP-3 radiometer (downwelling radiance channel): constant source measured with different integration times. Non-linearity error against the averaged value of spectra.





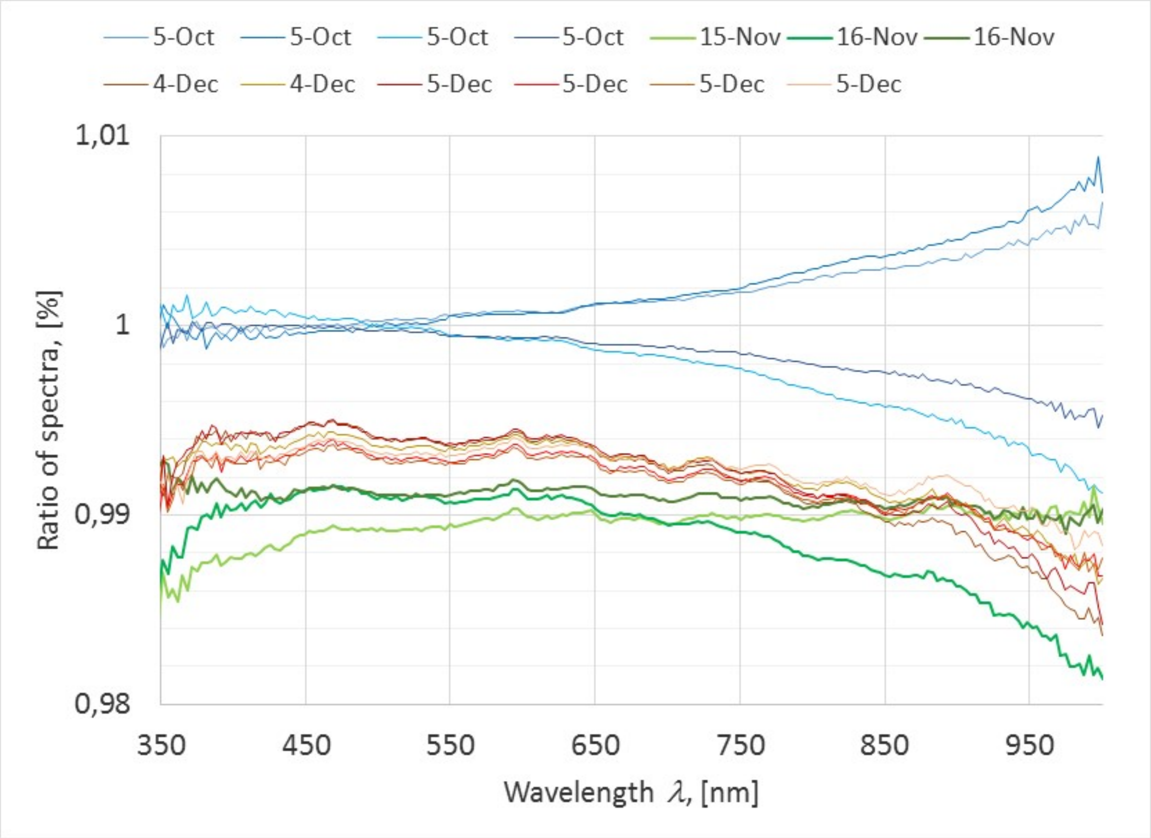
Alignment and temperature effects

Repeated alignment of TriOS Ramses ARC sensor. Variability due to instability of the sensor and due to temperature effects also may be involved.



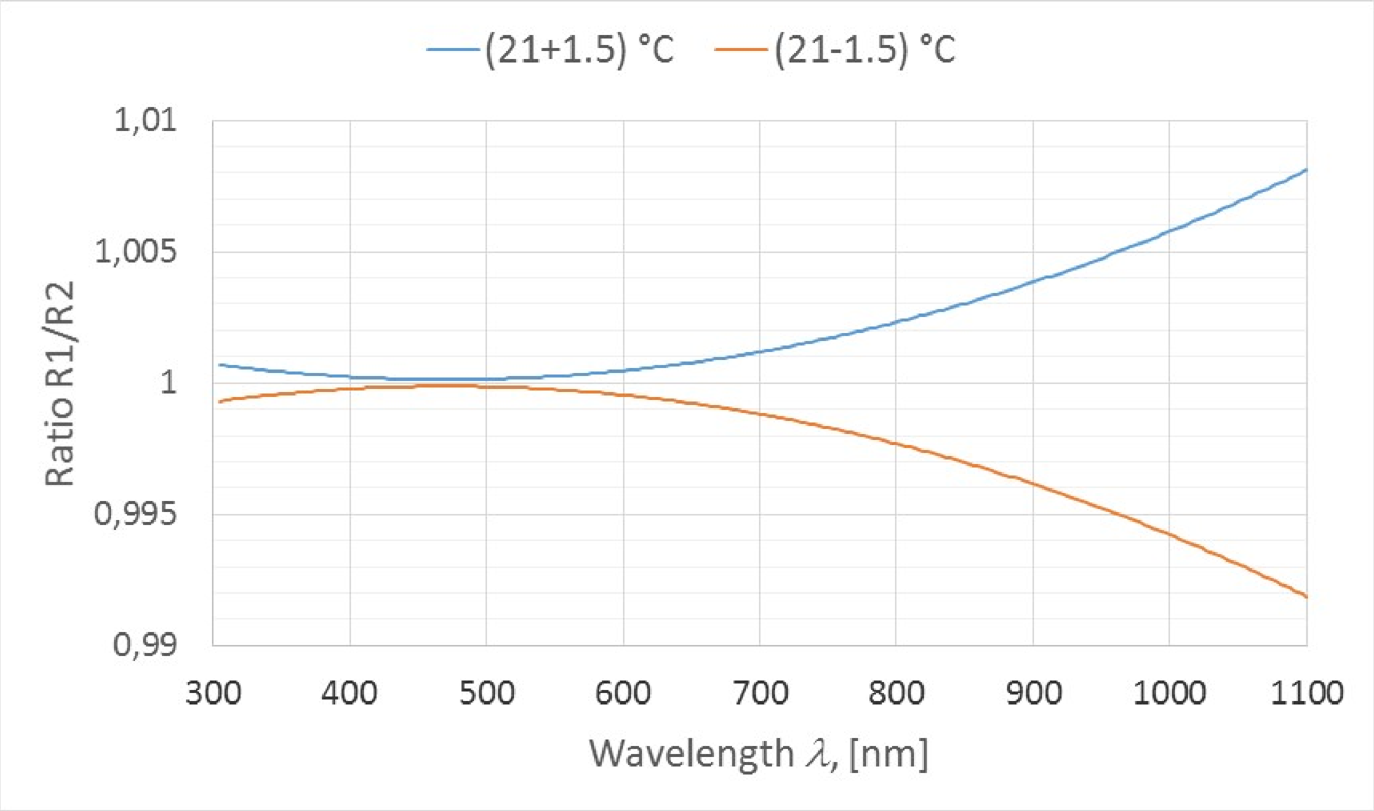
Alignment and temperature effects

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.



Temperature effects during field measurements

During field campaign, due to different relaxation times the temperature differences between radiometers may be somewhat larger than in the laboratory with temperature control.

We expect that maximum difference in the range about ±3 °C will be reasonable.

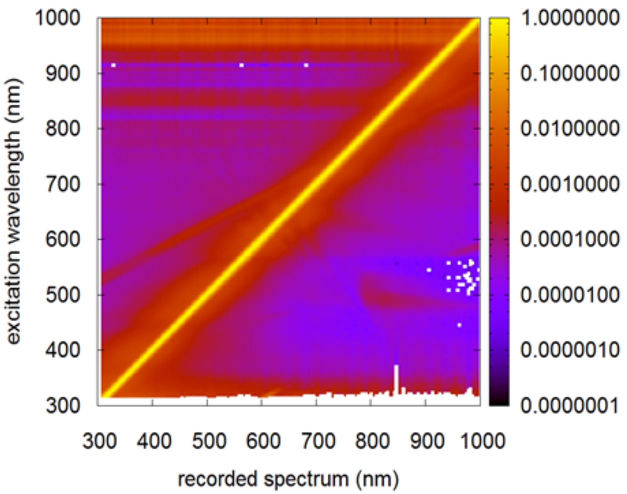
This assumption is not valid for radiometers, which may have internal temperature control of sensor arrays.

Stray light correction C_{stray}

All correction algorithms reducing the stray light effect are based on the spectral stray light matrix (SLM).

SLM of a radiometer can be determined by measuring a monochromatic line source adjusted at the central wavelength of every element of the sensor array.

SLM is a square matrix which columns present line-spread functions (LSFs), and rows slit-scattering functions (SSF).



Effectiveness of the stray light correction

Multiplying SLM to a corrected for stray light spectrum, an initial measured spectrum is expected as a result.

Relative difference of the product from measured spectrum – relative error of correction – will provide a method to compare the effectiveness of different correction approaches.

This correction error contributes also substantially to the uncertainty of the stray light correction.

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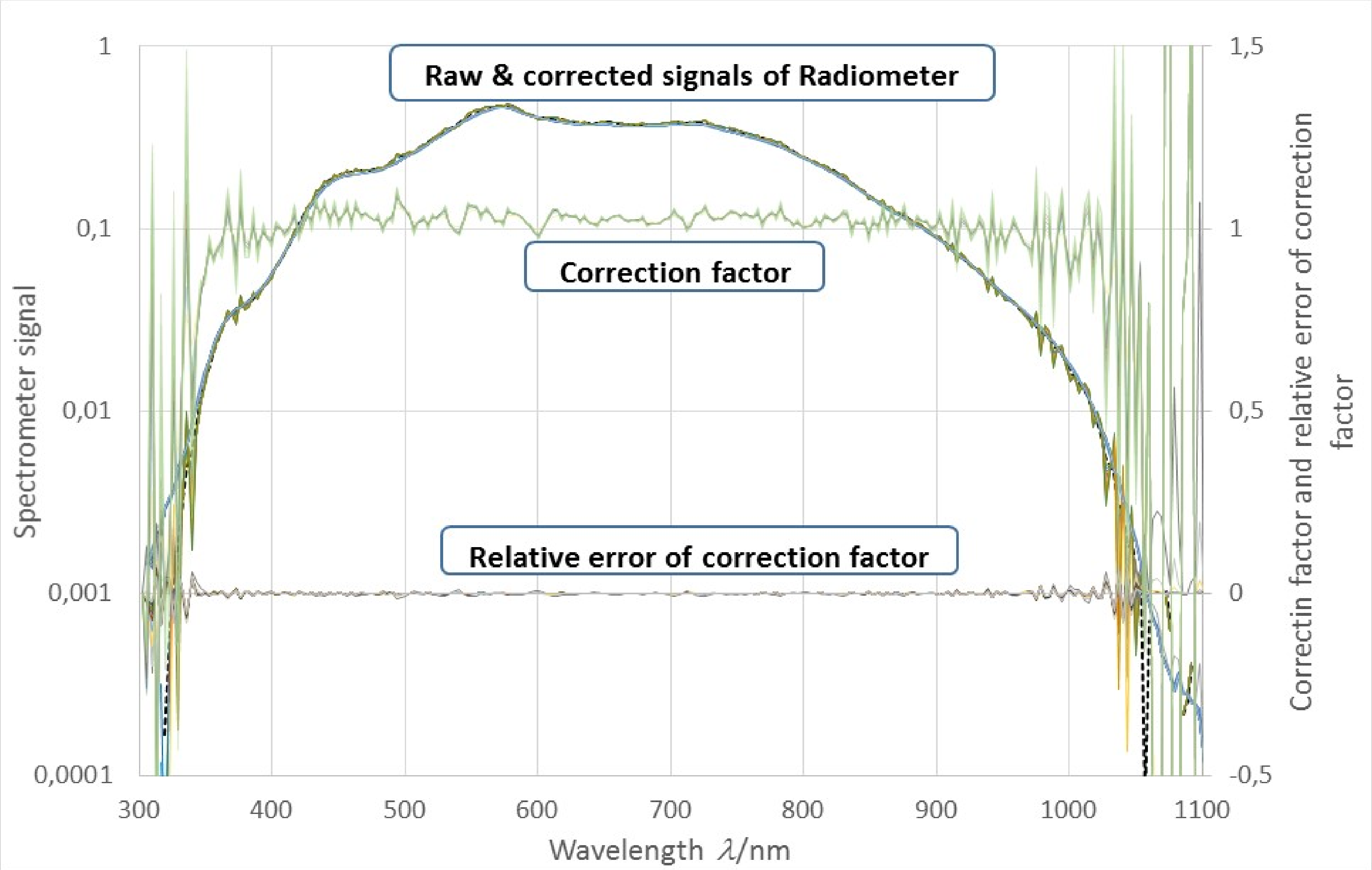
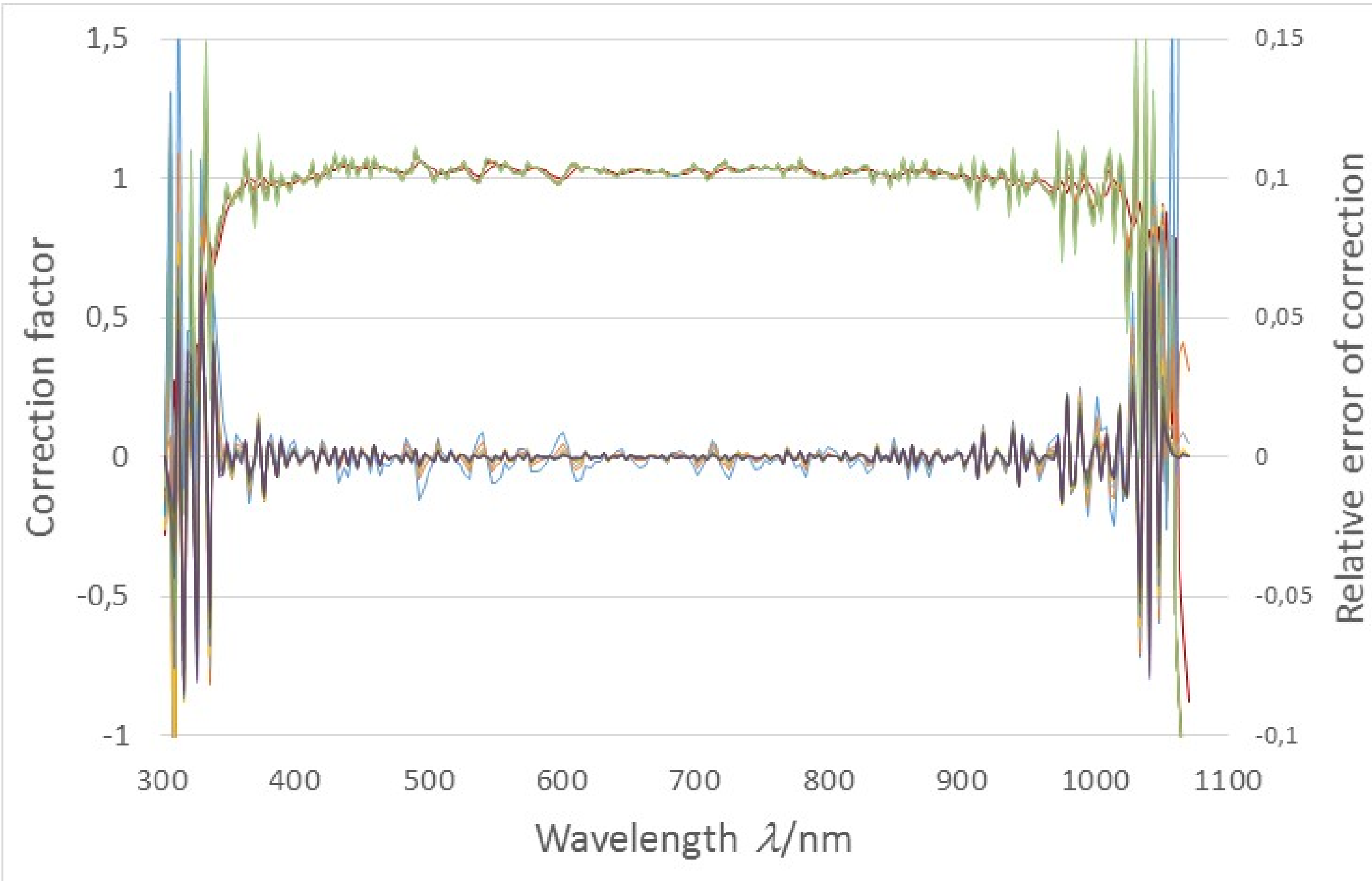
Stray light effect on the FEL radiance spectrum



Stray light correction for the FEL radiance spectrum



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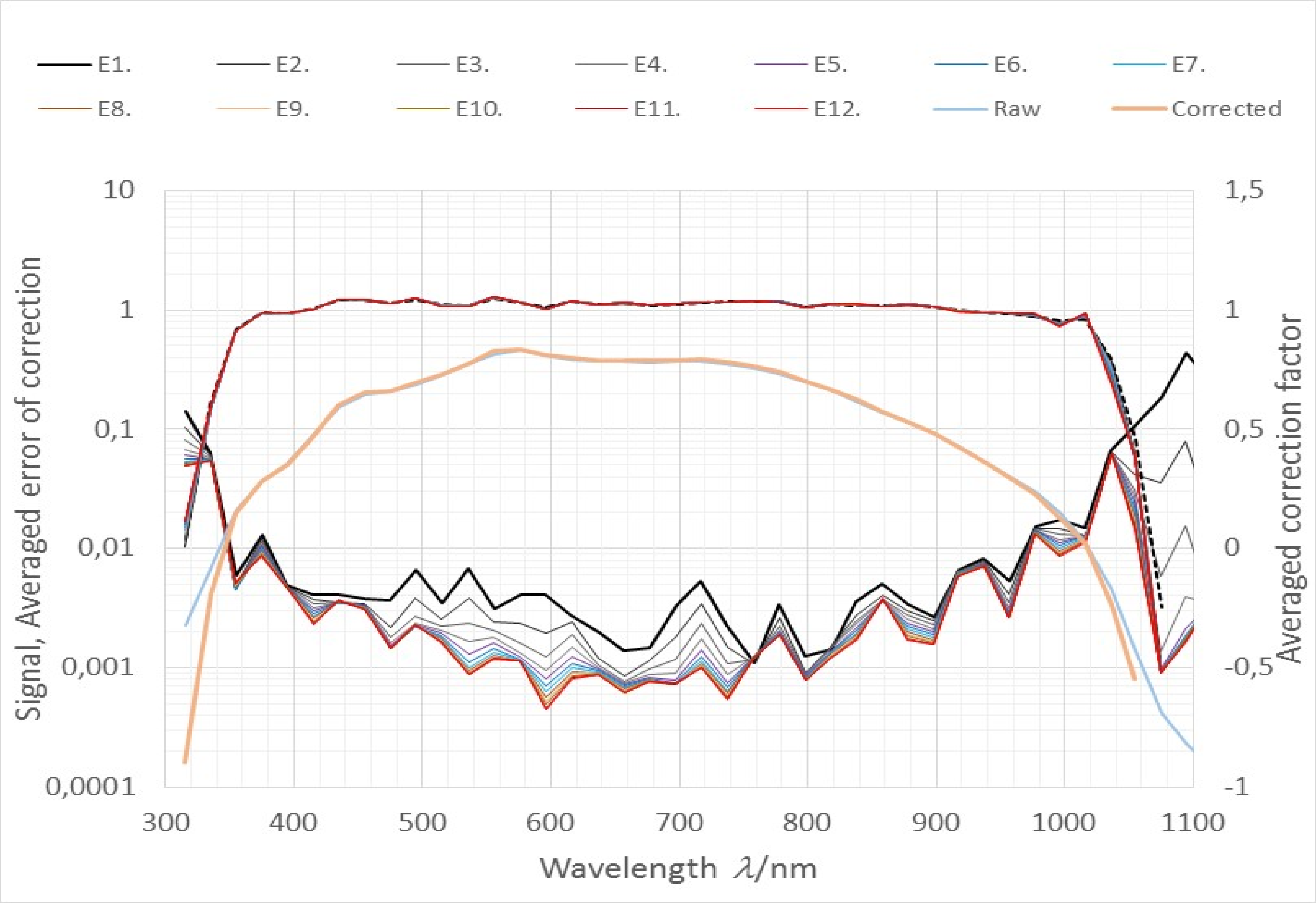
Averaged stray light effect on the FEL spectrum



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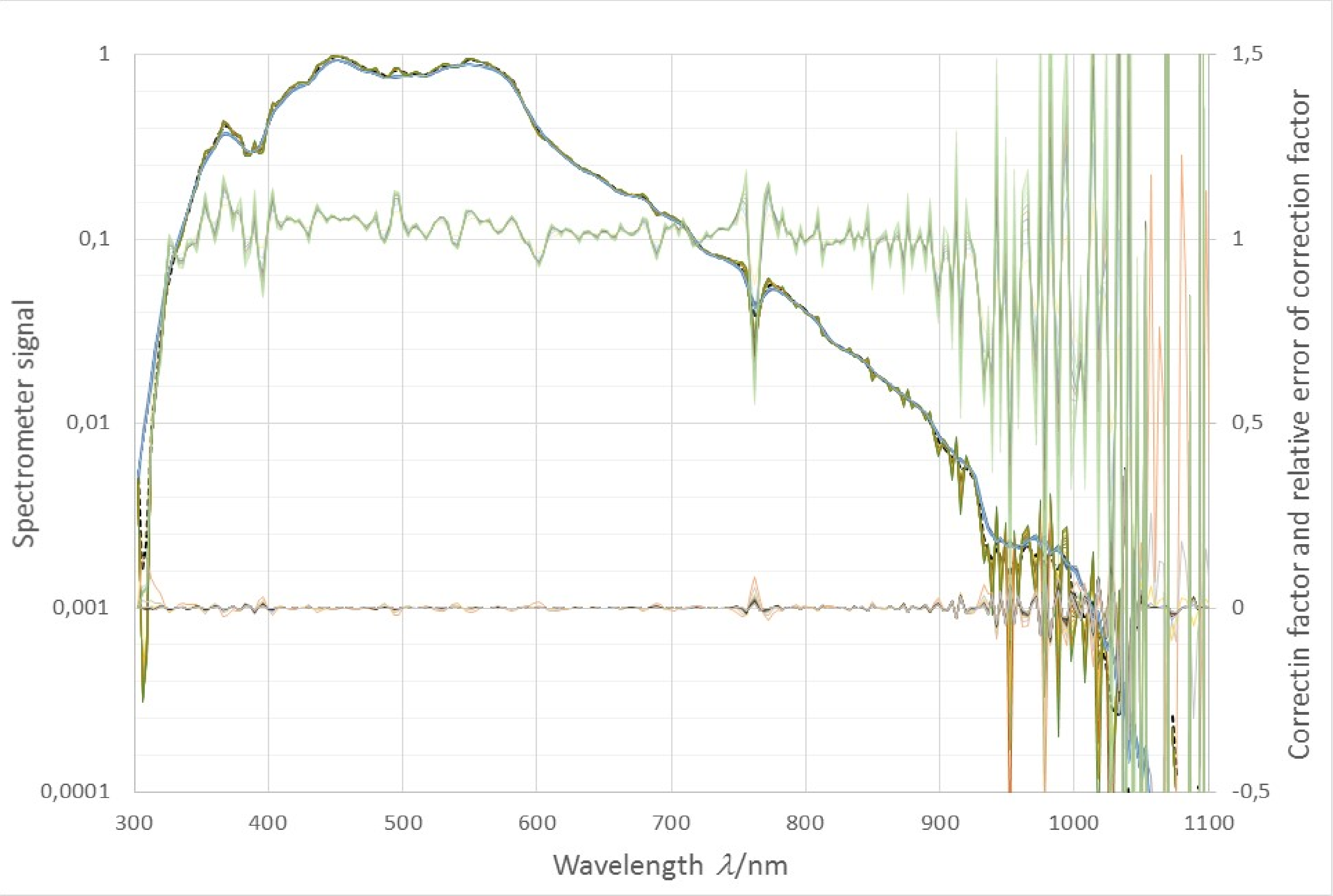
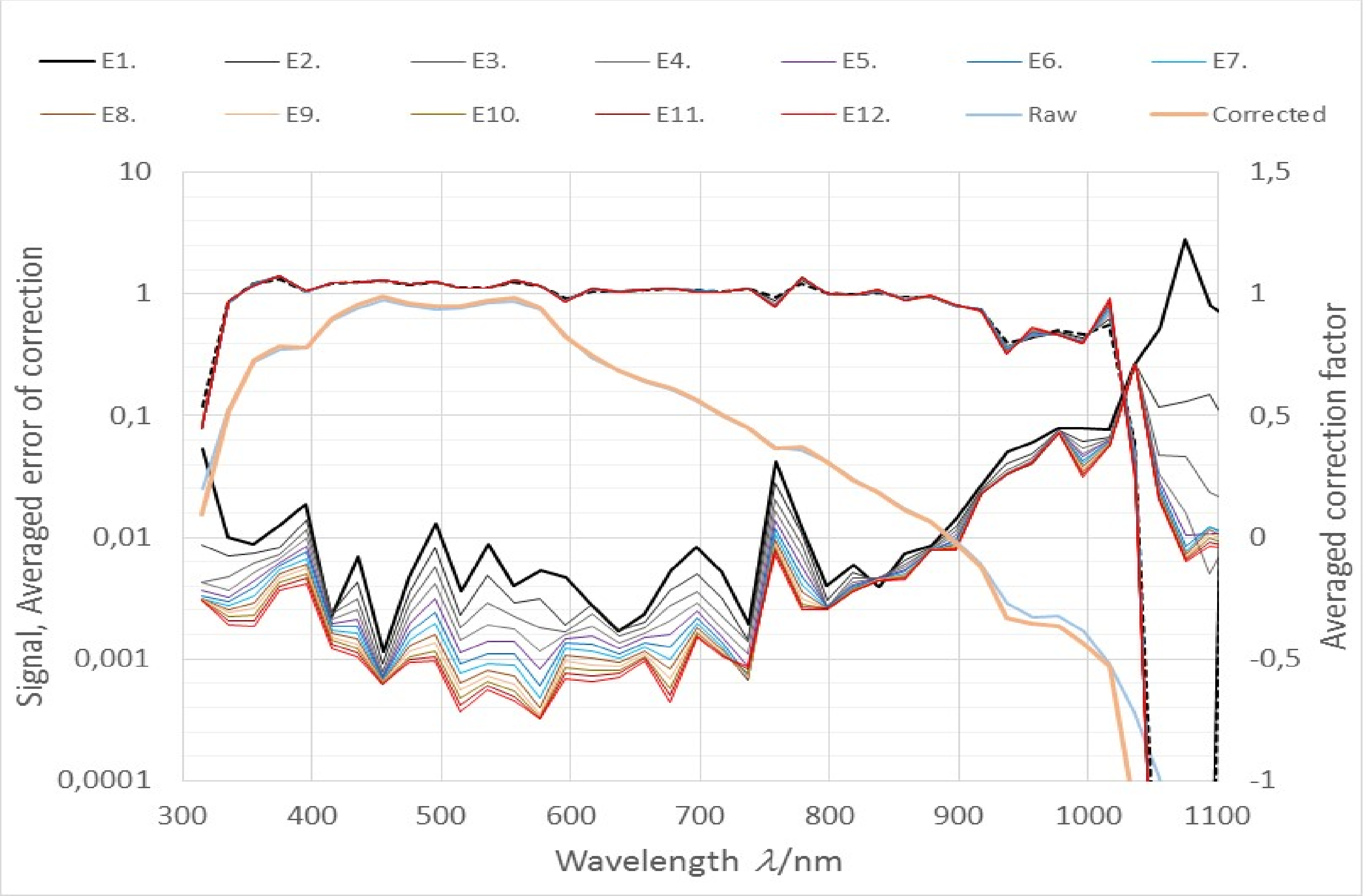
Stray light effect on sunlight radiance spectrum



Averaged stray light effect on sunlight radiance



Stray light correction factor for spectral radiance

Stray light correction factors: test source, FEL, and their ratio.

Centre	OLCL1 shape of bands			Gaussian shape of bands			Ratio
of Bands	Test	FEL	Final effec	Test	FEL	Final effec	of Shapes
400 nm	1,033	0,992	1,041	1,03	0,987	1,044	0,997
442.5 nm	1,058	1,05	1,008	1,06	1,044	1,015	0,993
490 nm	1,049	1,053	0,996	1,047	1,044	1,003	0,993
560 nm	1,047	1,044	1,003	1,048	1,045	1,003	1
665 nm	1,025	1,027	0,998	1,021	1,028	0,993	1,005
778.8 nm	1,063	1,041	1,021	1,055	1,038	1,016	1,005
900 nm	0,901	1,012	0,89	0,92	1,011	0,91	0,978

Effect of not accounting for stray light is up to 10 % for 900 nm.

Gaussian shapes are much broader than OLCL1 experimental shapes. Nevertheless, dependence on the shape of bands is less than ±1 %, except nearly 2 % for 900 nm.

Summary

Comparison measurement can be evaluated only on the basis of relevant uncertainty estimates.

At the same time, comparison measurement is a main tool to reveal unknown uncertainty sources or to improve the current uncertainty estimates.

Measurement model including all known sources of uncertainty is critically important.

Calibration status of instruments used for comparison is also very important.

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