Physikalisch-Meteorologisches Observatorium Davos
World Radiation Center

T5.4: Report on Direct Irradiance Calibration of Pandora 120

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Direct Irradiance Calibration Setup

The direct irradiance calibration unit of PMOD/WRC consists a light source type FEL 1000 W traceable to (PTB) and a fully motorized system with 5 degrees of freedom (XYZ and azimuthal, zenithal adjustments) for the alignment between the lamp and the entrance optics. The current of the light source is regulated by a current control unit. The unit consists of an Agilent 34420A voltmeter, a 100 mΩ shunt from Burster, 1282-0.1, sn 187275, and a 1000 W switched power supply from Xantrex. A current of 8.1 A is used to power the 1000 W lamp, with a feedback precision of 0.25 mA. The temperature of the shunt is monitored, as well as the current and the lamp voltage. The shunt is calibrated yearly relative to the reference shunt of EUVC and traceable to SI units using the procedure described in QM-SOP-UV-0069_EUVC_Voltmeter_SOP_Shunt.

The calibration room is temperature stabilized to 22 °C.

The center of the telescope of each spectroradiometer of Pandora (UV/Vis & Vis/NIR) has been visually aligned to the lamp using a laser so that the spot of the laser on the telescope remains at the center for distances between 1000 mm to 2800 mm as well as the back reflectance is at the center of the lamp (Photo 1). The distances have been measured from the lamp's reference plane to the front entrance of the telescope (Photo 2).

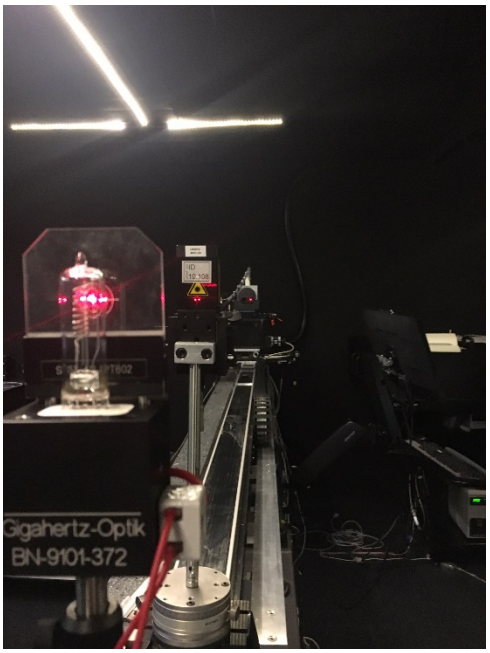

Photo 1: Direct irradiance calibration unit of PMOD/WRC – Pandora 120

Photo 2 : Reference distance measuring point of Pandora's foreoptics

Motorized stages Traveling Distances & Resolution:
X: 3.0m – 1.0mm
Y: 1.0m – 0.1mm
Z: 0.5m – 0.1mm
AZ : ±3° – 0.005°
ZE : ±3°– 0.005°

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Direct Irradiance Calibration Measuring and Analysis Procedure

The two spectroradiometers of Pandora-120 UV/Vis and Vis/NIR have been calibrated under the attenuators configuration of ground quartz diffuser and clear aperture. The measurement sequence of the calibration is:

1. Optical alignment of the entrance optics to the lamp by scanning the lamp in azimuthal and zenithal direction and selecting the center of the plateau. The optical alignment has been verified/ adjusted at each distance.
2. Measurements of the F372 transfer standard at 5 distances, 1000 mm, 1500 mm, 2000 mm, 2500 mm and 2800 mm for the determination of the refence plane of the entrance optics of the Pandora spectrometers.
3. 50 Dark signal measurements with the integration times used for the lamp measurements.

Absolute Direct Irradiance Calibration Analysis

1. The signals are corrected for the dark signal, the non-linearity, converted to counts per milliseconds and corrected for the stray light contribution.
2. The inverse square law is applied to all distances to determine the reference plane of the entrance optics of the spectroradiometer.
3. The minimum distances where the lamp can be considered as light point light source (the inverse square law is valid) is combined with the maximum distance in order to minimize the noise in the part of the spectrum where the responsivity of the spectroradiometer is low and at the same time reduce the uncertainty of response functions due to the uncertainty of the position of the reference plane.
4. The irradiance of the lamp (I_{di}), certified at the distance of 700 mm (I_{dref}), is calculated at each distance *di* following the inverse square law:

$$I_{\mathrm{di}} = I_{\mathrm{dref}} \left(\frac{dref + df}{di + df} \right)^2$$

where *df* is the distance between the reference plane and the center of the filament of the lamp.

Spectrally the irradiance is splined to the wavelengths of each spectroradiometer. The wavelength calibration of the spectroradiometers has been described in TD5.3_Report_on_wavelength_dispersion_function.pdf (Table 1).

Table 1: Dispersion functions of Pandora 120

								$\boldsymbol{wavelength} = \sum_{n=0}^{8} a_n . pixel^n$
a_8	**a_7**	**a_6**	**a_5**	**a_4**	**a_3**	**a_2**	**a_1**	**a_0**
Pandora120 UV (1511216U1)								
0.0000E+00	0.0000E+00	-2.8507E-19	1.8624E-15	-4.7084E-12	5.1776E-09	-8.8050E-06	1.4501E-01	272.6438291
Pandora120 Vis(1508054U1)								
2.0768E-24	-1.6444E-20	5.3996E-17	-9.5475E-14	9.8722E-11	-6.1934E-08	1.2603E-05	2.8971E-01	386.8355695

5. The relative uncertainty of the response function (k=1) is the square root sum of

i. Standard error of the measured irradiance spectra using N measurements $\left(std/\sqrt{N}\right)$
ii. Uncertainty arising from the determination of the reference plane
iii. Uncertainty in the stray light correction. Estimated to 10% of the calculated correction.
iv. Uncertainty in the non-linearity correction estimated to 10% of the calculated correction.
v. Uncertainty introduced from smoothing the response function (residuals $/\sqrt{3}$)
vi. Uncertainty in the irradiance of the lamp

The expanded relative uncertainty of measurement is obtained from the standard relative measurement uncertainty multiplied by the coverage factor k=2, which for a normal distribution corresponds to a coverage factor of 95%.

Calibration of Pandora 120 – Vis/NIR -1508054U1

The calibration of Pandora 120-Vis/NIR-1508054U has been performed of on 30.Mar.2017. The reference irradiance source is the FEL lamp F372 (secondary transfer standard) re-calibrated on 17-May-2017 following the protocol QM-PD-UV-0050_EUVC_QASUME_IRRSCALE.
The overview of the measurements performed is shown in the Table 2:

Table 2: The overview of the measurements performed on 30.Mar.2017 for the direct irradiance calibration of Pandora 120-Vis/NIR-1508054U.

Distance (mm)	Number of FEL scans	Number of Dark signal scans beginning and end of FEL scan1	Integration Time (ms)	Spectroradiometer Housing temperature (V)	Room Temperature (°C)	FEL mean Voltage and std (V)
2800	50	10	70	2.628 ±0.002	22.53	110.6123 ± 0.0015
2500	50	10	60	2.625±0.002	22.57	110.6148 ±0.0010
2000	50	10	40	2.625±0.002	22.57	110.6140 ±0.0017
1500	50	10	20	2.625±0.002	22.60	110.6204 ±0.0014
1000	50	10	10	2.624 ±0.001	22.63	110.6249 ±0.0008
2800	40	10	70	2.624 ±0.001	22.64	110.6283 ±0.0011

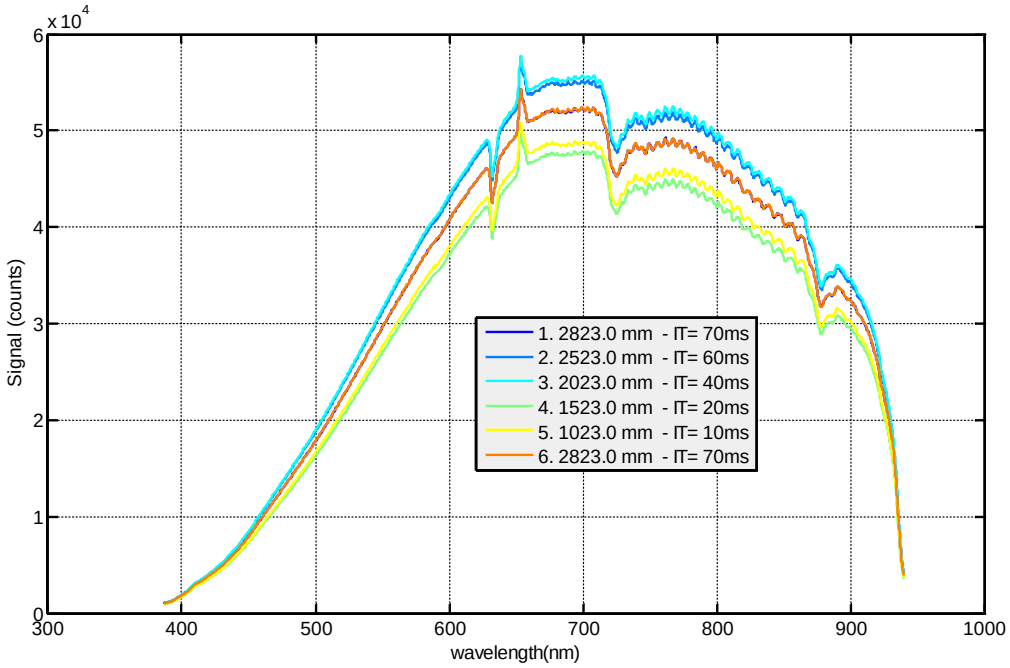

Figure 1: Signal (counts) as measured with the Pandora120- Vis/NIR-1508054U1 system at different distances between lamp and entrance optics.

The signals are corrected for the dark contribution based on the 50 measurements taken at the end of the calibration. No adjustment has been done to the dark level measured during the calibration since the differences were within 1 std of the dark signal.

The non-linearity correction (Certificate No. 2017_ATLAS_2) is applied to the dark corrected signals and divided by the corresponding integration time for the conversion to counts per millisecond (cpms). The stray light contribution has been accounted for based on the correction matrix measured with the ATLAS system at PMOD/WRC (T5.2). In Figure 2 the percentage contribution of these corrections is shown as a function of wavelength.

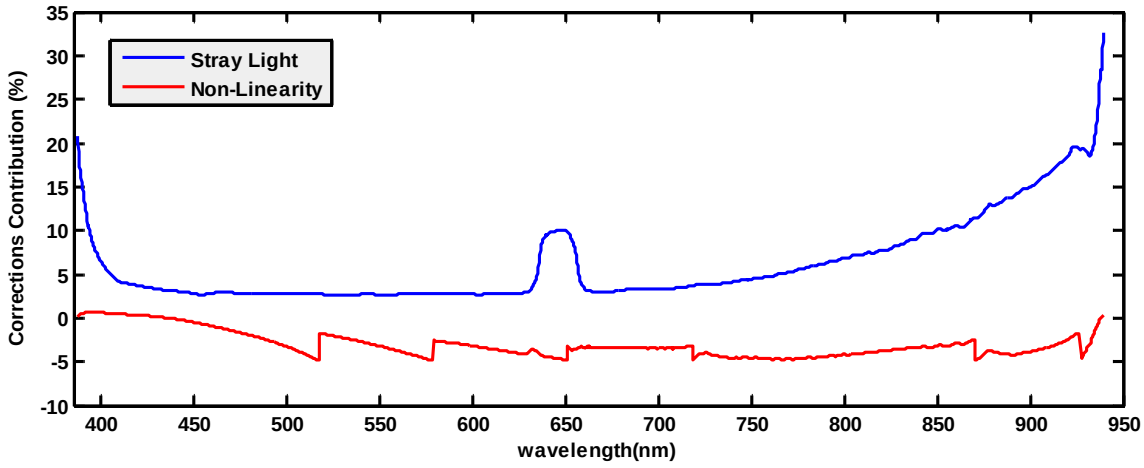

Figure 2: Contribution (%) of stray light and non-linearity to the lamp measurement as a function of wavelength for Pandora120- Vis/NIR -1508054U1

Inverse Square Law: The irradiance of a point source is inversely proportional to the square of the distance from the source to the detector reference plane. Therefore, the corrected signal *Sc* follow the equation:

$$Sc \sim (X + dx)^{-2} \Rightarrow Y = Sc^{-1/2} = a_1(X) + a_0 = a_1\left(X + \frac{a_0}{a_1}\right) \Rightarrow dx = \frac{a_0}{a_1}$$

The position of the reference plane is calculated by a least square fit of $Scl^{-1/2}$ to the distance adjusted for the offset of the lamps reference plane to the center of the lamps filament (*df*=+23mm). the results of the regression analysis for each pixel is shown in Figure 5. For the final calculation of the distance *dx* only signal values higher than 3 times the dark signal have been accounted in the mean spectral value of *dx*. A sensitivity in the results of *dx* concerning the minimum distance of 1023 mm has been performed by omitting this distance from the regression analysis. The results of *dx* differ by 1.6 mm. The distance *dx*=135.7 mm has been selected based on the spectral ratios. The observed spectral dependency has not been accounted, which introduces an uncertainty of ±5 mm (k=2) in the determination of the refence plan.

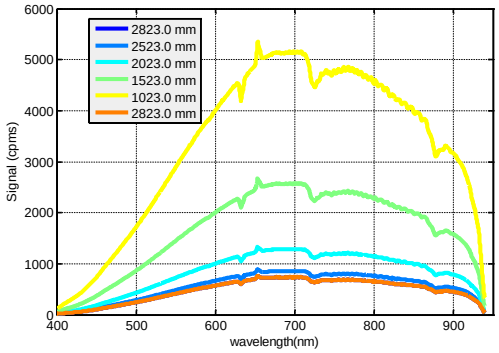

Figure 3: Dark corrected signal (counts per millisecond) as measured with the Pandora120-Vis/NIR-1508054U1 system at different distances between lamp and entrance optics.

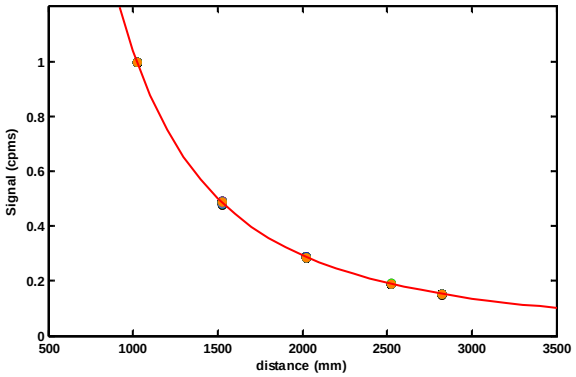

Figure 4: Dark, non-linearity and stray light corrected signal (counts per millisecond) as a function of distance between lamp and entrance optics.

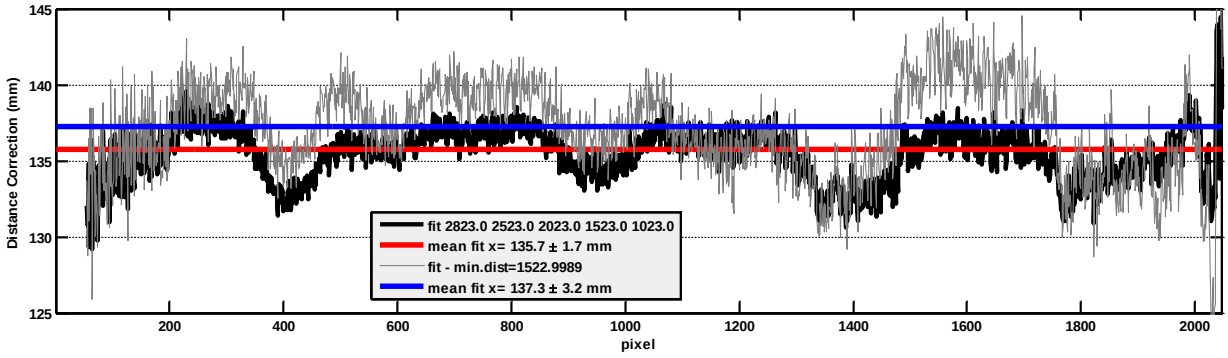

Figure 5: Distance from the measuring point to the reference plane of Pandora120-Vis/NIR-1508054U1 as calculated by applying the inverse square law.

The repeatability of the optical alignment of the Pandora telescope to the lamp has been tested by repeating the measurement at 2823 mm at the end of the calibration procedure. The initial and final measurements agree to within ±0.5% (Figure 6).

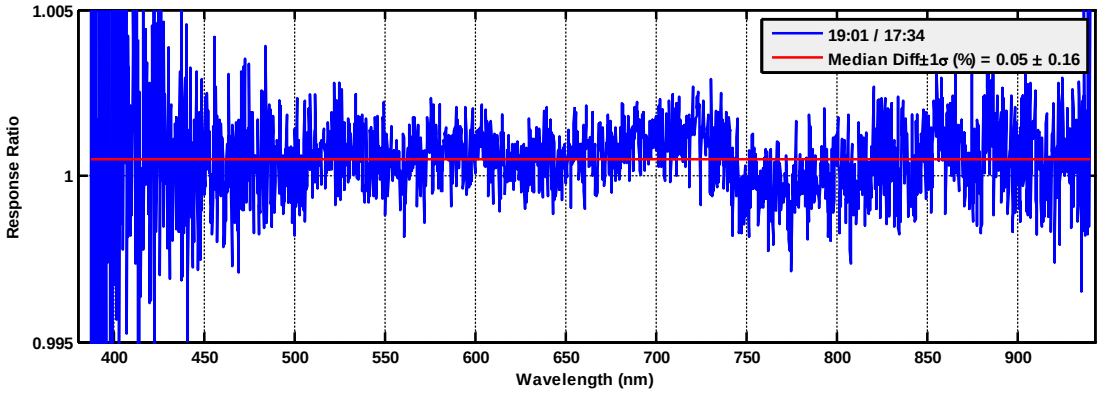

Figure 6: Repeatability test at the distance of 2823 mm. Ratio of lamp spectra at the beginning and end of calibration.

After the determination of the reference plane of the system, the response function is produced by combining the response functions at the distance of 2958.73 mm and 1658.73 mm. The absolute irradiance scale is obtained from the distance of 2958.73 mm while the 1658.73 mm is used for the relative spectral responsivity. The final product is smoothed (splined) to reduce the noise (Figure 7). The response function of Pandora120-Vis/NIR-1508054U1 has been determined with an expanded uncertainty ranging between 3% and 7% (Figure 8).

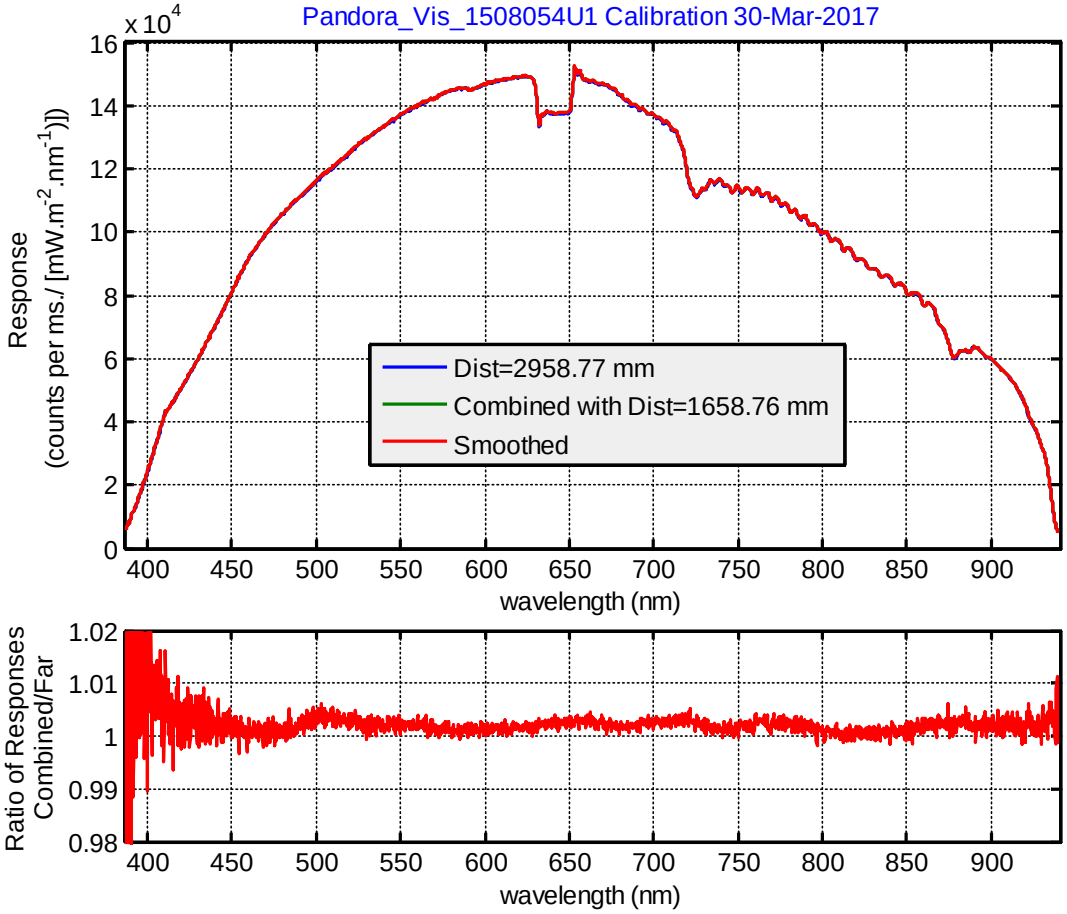

Figure 7: Spectral response function of Pandora120-Vis/NIR-1508054U1 as calculated at the distance of 2956.37 mm and the one with the combination of 2 distances (upper panel). Spectral ratio of combined to single distance (2956.37 mm).

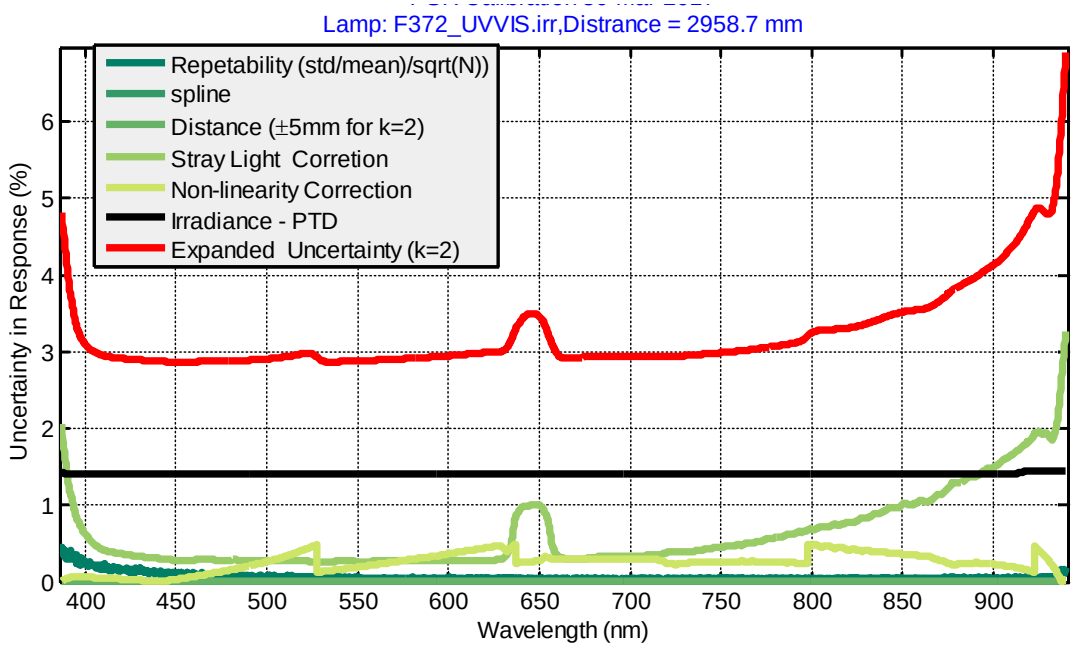

Figure 8: Uncertainty budget of the spectral response function of Pandora120-Vis/NIR-1508054U1

Calibration of Pandora120-UV/Vis-1511216U1 spectroradiometer

The calibration of Pandora120-UV/Vis-1511216U1 has been performed of on 6.Mar.2017. The reference irradiance source is the FEL lamp F372 (secondary transfer standard) re-calibrated on 17-May-2017 following the protocol QM-PD-UV-0050_EUVC_QASUME_IRRSCALE.
The overview of the measurements performed is shown in the Table 3:

Table 3: The overview of the measurements performed on 06.Mar.2017 for the direct irradiance calibration of Pandora120-UV/Vis-1511216U1.

Distance (mm)	Number of FEL scans	Number of Dark signal scans beginning and end of FEL scan1	Integration Time (ms)	Spectroradiometer Housing temperature (V)	Room Temperature (°C)	FEL mean Voltage and std (V)
2800	50	10	1500	2.649 ±0.001	22.70	110.530 ±0.001
1000	50	10	200	2.647 ± 0.002	22.80	110.454 ±0.001
1500	50	10	500	2.649 ± 0.001	22.79	110.457 ±0.001
2000	50	10	900	2.648 ± 0.002	22.80	110.461 ±0.001
2500	50	10	1300	2.646 ± 0.002	22.82	110.463 ±0.001
2800	50	10	1500	2.645 ± 0.002	22.80	110.475 ±0.005

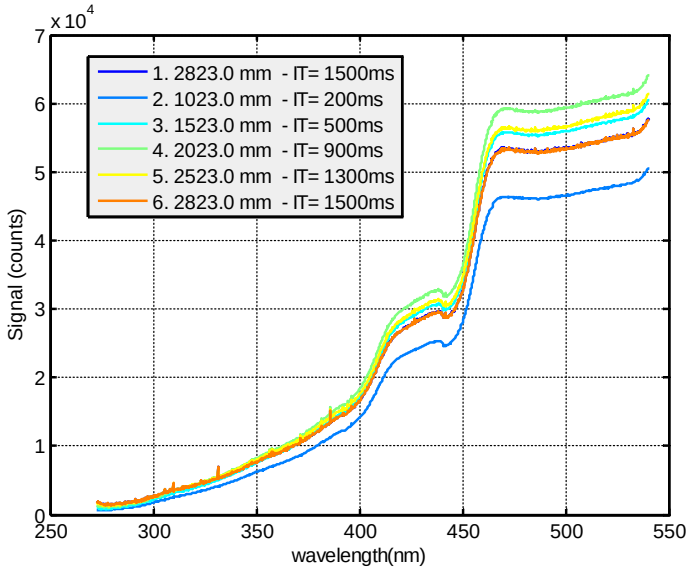

Figure 9: Signal (counts) as measured with the Pandora120-UV/Vis-1511216U1 system at different distances between lamp and entrance optics.

The signals are corrected for the dark contribution based on the 50 measurements taken at the end of the calibration. No adjustment has been done to the dark level measured during the calibration since the differences were within 1 std of the dark signal.

The non-linearity correction (Certificate No. 2017_ATLAS_1) is applied to the dark corrected signals and divided by the corresponding integration time for the conversion to counts per millisecond (cpms). The stray light contribution has been accounted for based on the correction matrix measured with the ATLAS system at PMOD/WRC (T5.2). In Figure 10 the percentage contribution of these corrections is shown as a function of wavelength.

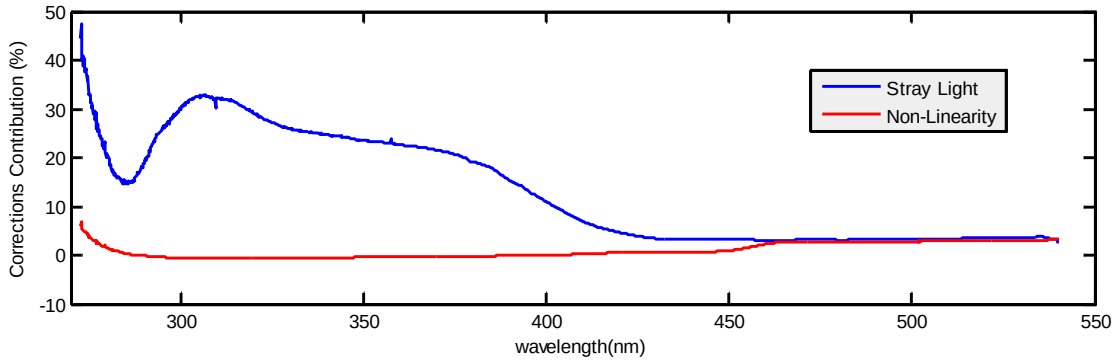

Figure 10: Contribution (%) of stray light and non-linearity as a function of wavelength for Pandora120-UV/Vis-1511216U1.

The position of the reference plane is calculated by a least square fit of $Scl^{-1/2}$ to the distance adjusted for the offset of the lamps reference plane to the center of the lamps filament (df=+23mm). the results of the regression analysis for each pixel is shown in Figure 10. For the final calculation of the distance dx only signal values higher than 2 times the dark signal has been accounted in the mean spectral value of dx. A sensitivity in the results of dx concerning the minimum distance of 1023 mm has been performed by omitting this distance from the regression analysis. The results of dx differ by 4.5 mm. Based on the spectral ratios of the response function derived for all distances and the two dx values the $dx=134.3 \pm 14.3$ mm has been selected. The observed spectral dependency has not been accounted, which introduces an uncertainty of ± 29 mm (k=2) in the determination of the refence plan.

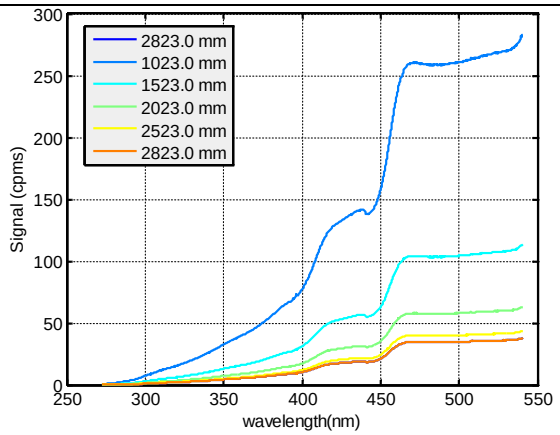

Figure 11: Dark corrected signal (counts per millisecond) as measured with the Pandora120-UV/Vis-1511216U1 system at different distances between lamp and entrance optics.

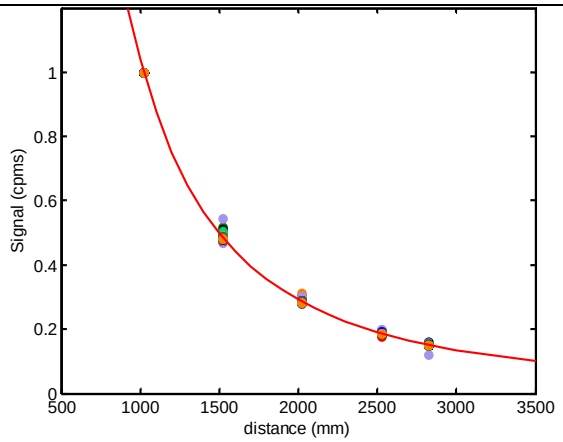

Figure 12: Dark, non-linearity and stray light corrected signal (counts per millisecond) as a function of distance between lamp and entrance optics.

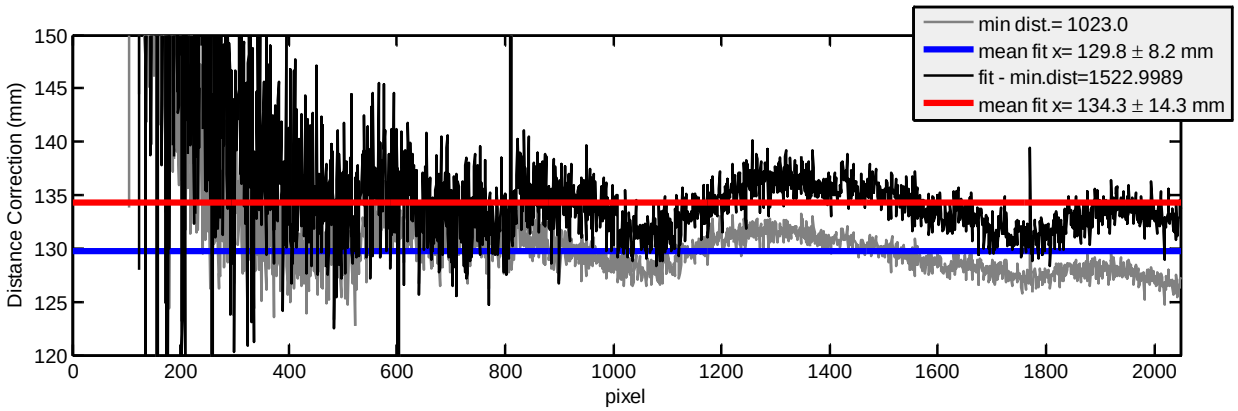

Figure 13: Distance from the measuring point to the reference plane of Pandora120-UV/Vis-1511216U1 as calculated by applying the inverse square law.

After the determination of the reference plane of the system, the response function is produced by combining the response functions at the distance of 2958.73 mm and 1658.73 mm. The absolute irradiance scale is obtained from the distance of 2958.73 mm while the 1658.73 mm is used for the relative spectral responsivity. The final product is smoothed (splined) in order to reduce the noise (Figure 14). The response function of Pandora120-UV/Vis-1511216U1 has been determined with an expanded uncertainty of ranging between 3% and 10% (Figure 15).

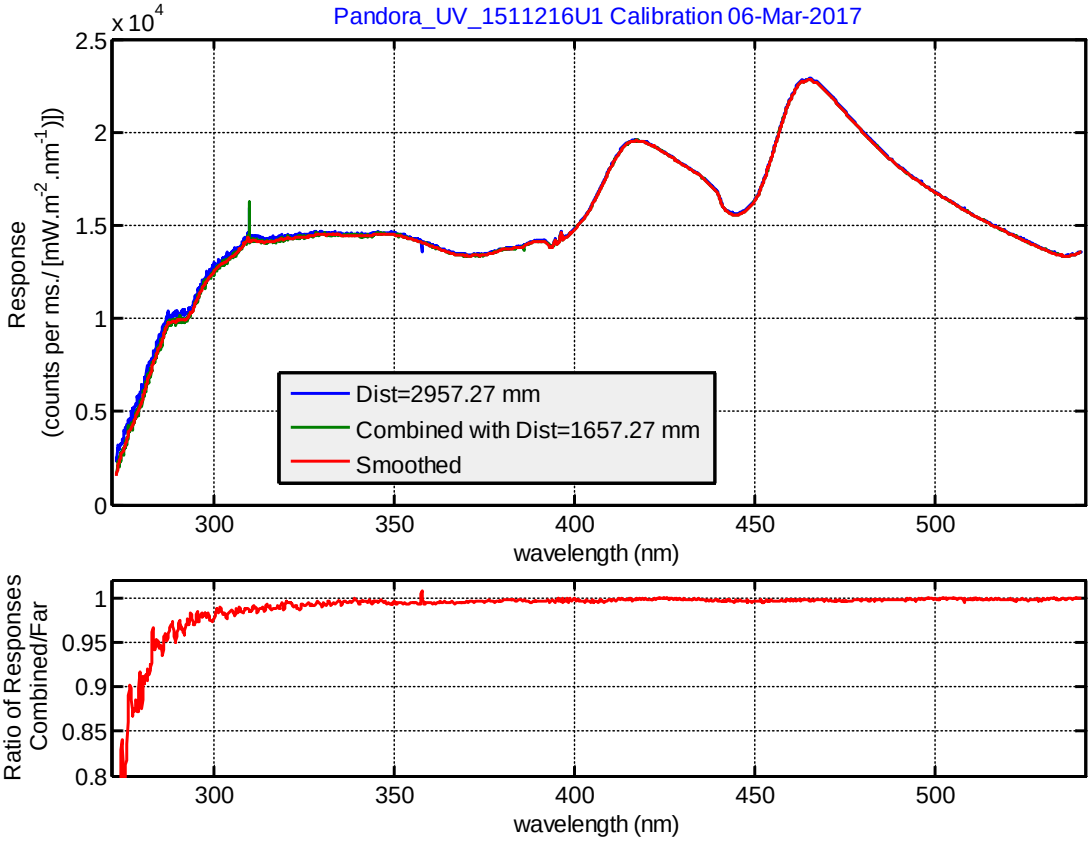

Figure 14: Spectral response function of Pandora120-UV/Vis-1511216U1 as calculated at the distance of 2957.27 mm and the one with the combination of 2 distances (upper panel). Spectral ratio of combined to single distance (2957.27 mm).

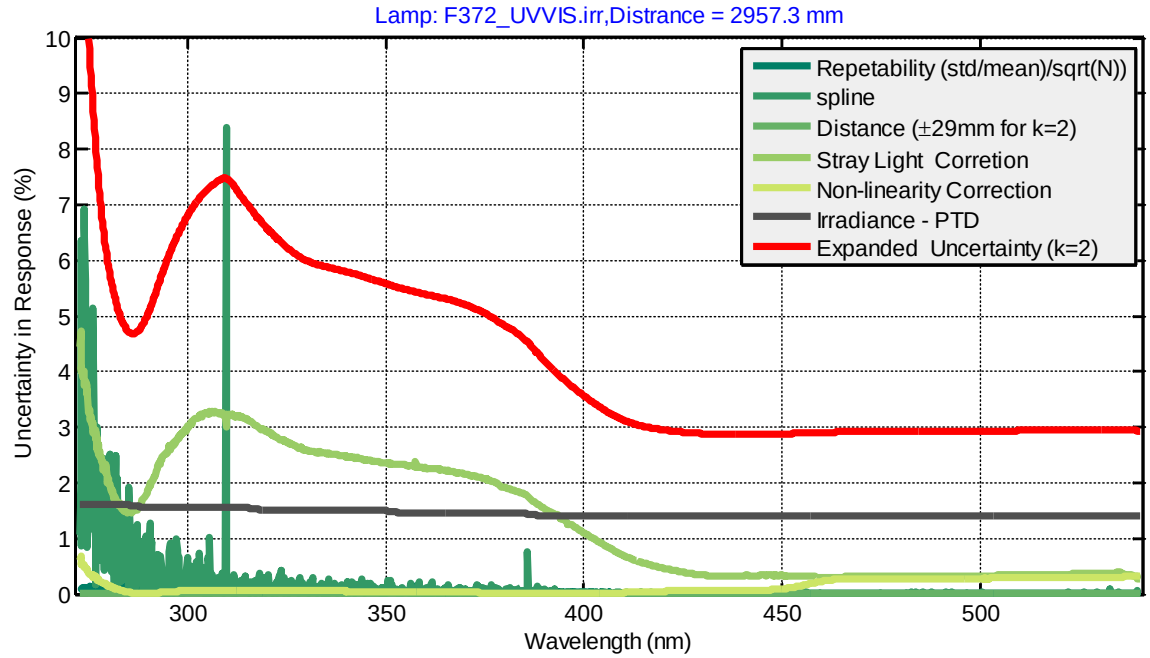

Figure 15: Uncertainty budget of the spectral response function of Pandora120-UV/Vis-1511216U1

Certificates and Data Availability

Based on the present analysis the following certificates have been issued for the direct irradiance calibration of Pandora 120:

TD5.4_ATLAS_2017_01_03-calibration_certificate_Pandora120 - 1511216U1.pdf

TD5.4_ATLAS_2017_01_04-calibration_certificate_Pandora120 - 1508054U1.pdf

Data Available at

\\ad.pmodwrc.ch\Institute\Projects\ATLAS\ATLAS\DirectIrradianceCalib\Pandora_UV_1511216U1\20170306/

\\ad.pmodwrc.ch\Institute\Projects\ATLAS\ATLAS\DirectIrradianceCalib\Pandora_Vis_1508054U1\20170330