



LuftBlick Report 2014007

ESA Ground-Based Air-Quality Spectrometer Validation Network and Uncertainties Study

Pandora-2S Maintenance - Quality Assurance Plan

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Document Change Record

Issue	Date	Page	Observations
0.1	24 Jul 2014	All	First draft version
1.0	30 Jul 2014	All	Minor changes; correct typos
1.1	9 Sep 2014	All	Applied changes based on ESA-review

Acronyms and Abbreviations

2D	Two dimensional
Ar	Argon
Cd	Cadmium
He	Helium
Hg	Mercury
Kr	Krypton
Na	Sodium
Ne	Neon
NO ₂	Nitrogen dioxide
O ₃	Ozone
Tl	Thallium
Xe	Xenon
Zn	Zinc
AD	Analog-to-Digital
AOD	Aerosol optical depth
DN	Digital number
FWHM	Full width at half maximum
L0	Level 0
L1	Level 1
L2	Level 2
NIST	National Institute of Standards and Technology
OBR	Optically Black Region
Pandonia	ESA Ground-Based Air-Quality Spectrometer Validation Network
Pandora	Pandora spectrometer system
PRNU	Pixel response non uniformity
ROE	Readout electronics

1 Introduction

This report is deliverable D06 of the ESA Ground-Based Air-Quality Spectrometer Validation Network (Pandonia) project [2, 1]. This document should be used in combination with the network intercalibration procedure [5], which describes how the Level 1 (L1) data (radiances, irradiances or corrected count rates) from the monitoring instruments in the network are intercompared with those from reference instruments to detect sensitivity changes in the instrument.

The present document describes the steps needed to convert the Pandora spectrometer system (Pandora) Level 0 (L0) data (raw counts) to L1 data and gives some guidelines for the instrument maintenance. Section 2 describes the calibrations done in the laboratory. Section 3 describes the correction steps applied to the L0 data. Section 4 gives guidelines for proper instrument maintenance in network operation. Section 5 gives a quality assurance plan in table form.

1.1 Applicable Documents

- [1] Ground-Based Air-Quality Spectrometer Validation Network and Uncertainties Study [Proposal], LuftBlick Proposal 201309A, Issue 2, 2013.
- [2] ESA Ground-Based Air-Quality Spectrometer Validation Network and Uncertainties Study [Statement of Work], ENVI-SPPA-EOPG-SW-13-0003, Issue 1, Revision 3, 2013.

1.2 Reference Documents

- [3] G. Bernhard, C. R. Booth, and J. C. Ehramjian. Version 2 data of the National Science Foundation's ultraviolet radiation monitoring network: South Pole. *Journal of Geophysical Research (Atmospheres)*, 109(D21), 2004.
- [4] A. Cede and M. Tiefengraber. ESA Ground-Based Air-Quality Spectrometer Validation Network and Uncertainties Study, LuftBlick Report 2014004: Pandora-2S Design and Evolution Document, 2014.
- [5] A. Cede, M. Tiefengraber, and A. Redondas. ESA Ground-Based Air-Quality Spectrometer Validation Network and Uncertainties Study, LuftBlick Report 2014001: Network Intercalibration Procedure, 2014.
- [6] D. Pissulla et al. Comparison of atmospheric radiance measurements from five independently calibrated systems. *Photochemical and Photobiological Sciences*, 8:516 – 527, 2009.
- [7] Y. Zong, S. W. Brown, B. C. Johnson, K. R. Lykke, and Y. Ohno. Simple spectral stray light correction method for array spectroradiometers. *Applied Optics*, 45(6):1111–1119, 2006.

2 Laboratory calibration

The laboratory measurements use three illumination sources for various purposes as described in the following sections. Note that the radiometric calibration (section 2.1) and the wavelength calibration (section 2.2) are always completed at three spectrometer temperatures (usually the operational temperature and also 8 °C higher and lower than that temperature) in order to characterize the instrument's temperature sensitivity.

2.1 Radiometric calibration

A FEL lamp is used for the radiometric calibration. This is a 1000 W quartz halogen lamp with a 6 cm high bulb (figure 1). The height of the tungsten coil is about 3 cm. The lamp is placed about 80 cm away from the Pandora entrance port. After warm-up, the FEL produces a constant light output with a maximum around 900 nm (figure 1). The analysis of these measurements allows us to determine instrument parameters such as the indices of hot pixels, dark-variance, gain, non-linearity, pixel response non uniformity (PRNU), and temperature dependence (see also section 3).

If the FEL lamp comes with a calibration certificate (e.g. from the National Institute of Standards and Technology (NIST) or the Physikalisch-Technische Bundesanstalt (PTB)), then these measurements can also be used for absolute radiometric calibration of the Pandora. The absolute calibration procedure has not been analyzed in detail thus far, as it is not necessary for the spectral fitting algorithms to derive ozone (O₃) and nitrogen dioxide (NO₂) column amounts. However, for Pandora it is important as it is the base to measure aerosol optical depth (AOD).

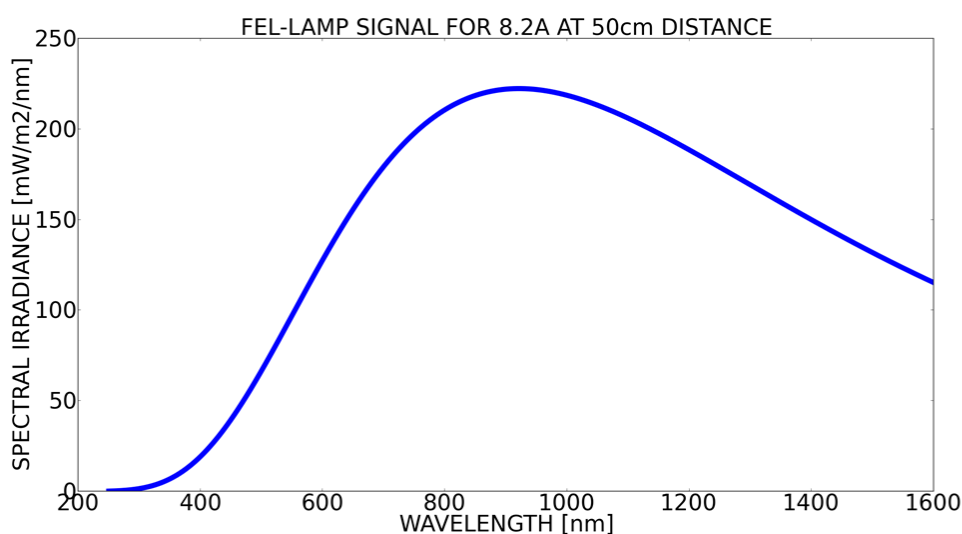


Figure 1: Right panel: picture of FEL lamp as used for the Pandora calibration. Left panel: spectral irradiance of FEL lamp running at 1000 W at 50 cm distance from the lamp.

2.2 Wavelength calibration

The determination of the dispersion (conversion from pixels to wavelength) and slit function is based on measurements with spectral lamps, which can be hollow cathode or gas discharge lamps. In our main laboratory at Innsbruck [6], we use exclusively gas discharge lamps (the preferred type) and have lamps for several atomic spectra available: Hg, Cd, He, Na, Ne, Tl, Zn, Ar, Kr, and Xe.

Figure 2 shows as an example the output of a Hg lamp measured by Pandora 34. Figure 3 shows how the slit function is determined for the strongest mercury line at 436 nm. Figure 4 shows the variation of the full width at half maximum (FWHM) of the resolution over the entire wavelength range of Pandora 41.

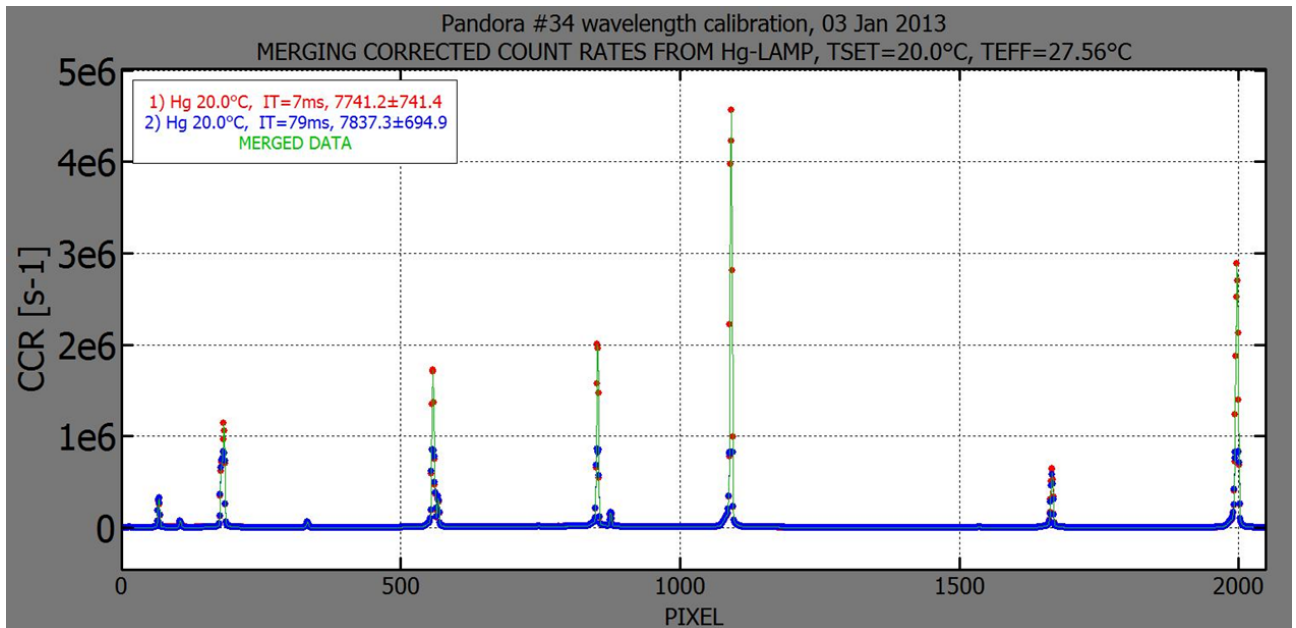


Figure 2: Corrected count rates (CCR) of Pandora 34 when illuminated by a Hg gas discharge lamp. The pixels go from 280 nm (pixel 1) to 530 nm (pixel 2048). The peaks correspond to Hg spectral lines.

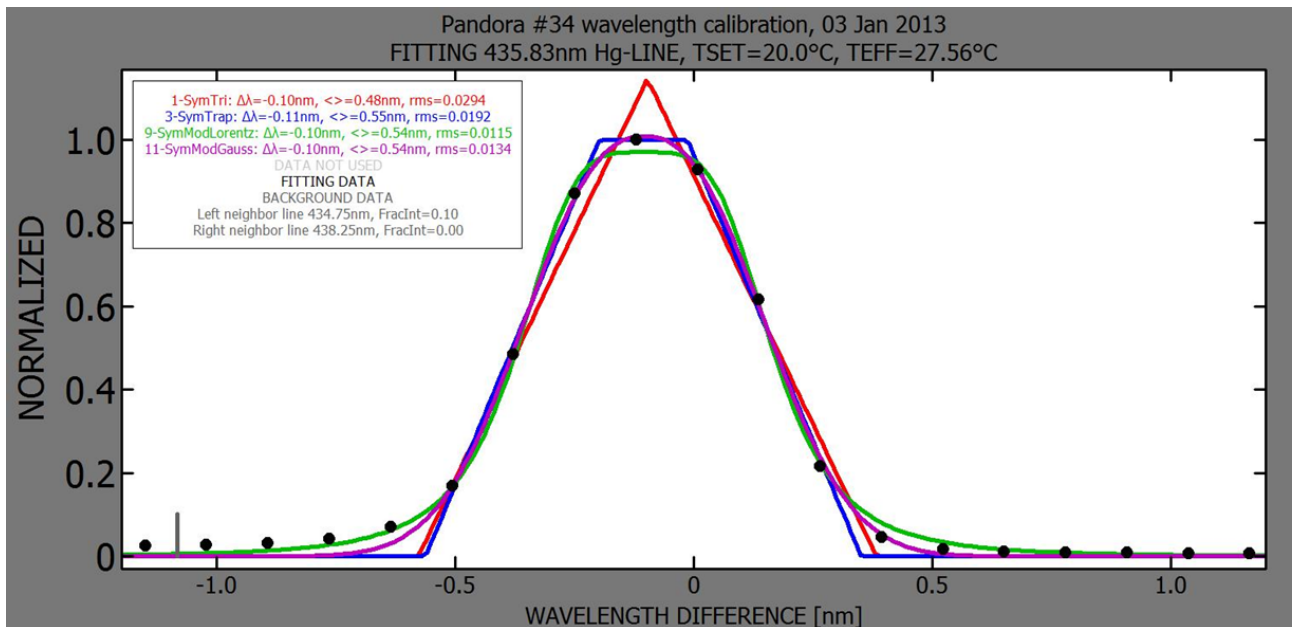


Figure 3: Slit function of a typical Pandora for the 436 nm mercury line. Black dots are measurements and colored lines are fitted mathematical functions.

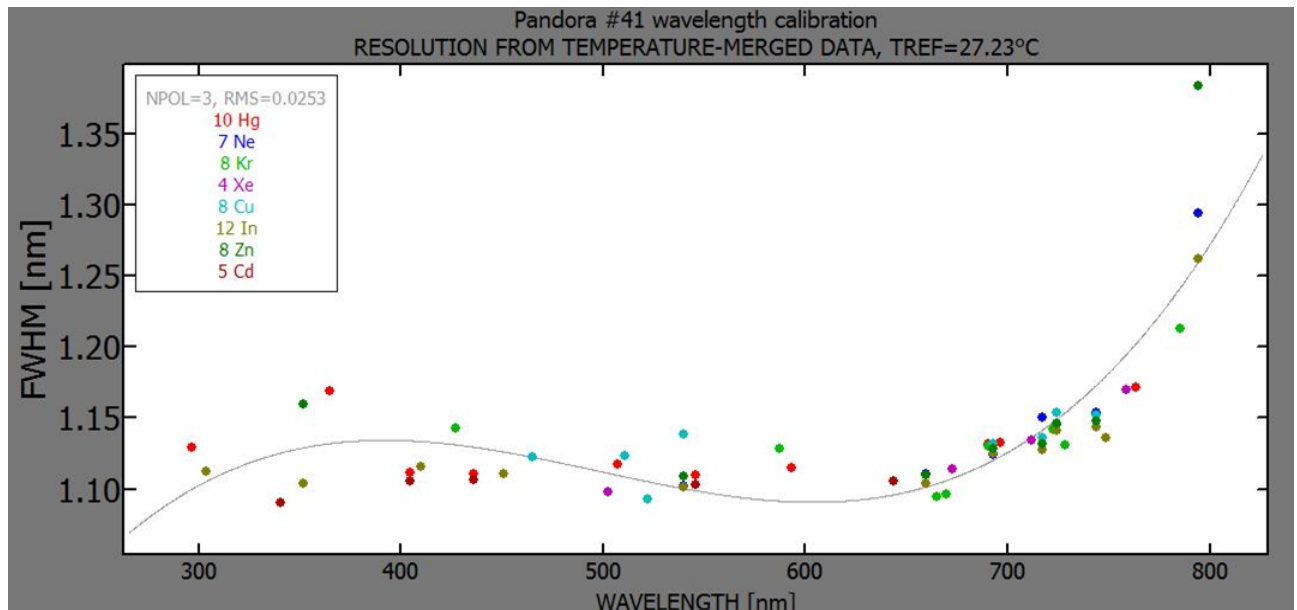


Figure 4: FWHM of the Pandora 41 resolution as measured by spectral lamps. A total of 62 spectral lines is used (see figure legend). The gray line is a third order polynomial in the data.

2.3 Stray light calibration

Since the peaks of the spectral lamps described in section 2.2 exceed the background of the spectrum by a factor of 1000 in the best case, they have limited use in the determination of the instrument's spectral stray light. Therefore, we use Lasers for this purpose. In our main laboratory at Innsbruck, we have four diode lasers at wavelengths 405, 532, 650, and 780 nm.

Figure 5 shows as an example the output of a 377 nm diode laser measured by Pandora 103. From this figure one could determine the far field stray light level of Pandora 103 is about $1e-5$. However, a problem with the current Pandora read out electronics causes an error in the dark correction as described in *Cede and Tiefengraber* [4]. Therefore, we have no confidence in the stray light level determined in these measurements and are currently not able to do a proper stray light calibration on the Pandoras. We are investigating ways to solve this issue (see *Cede and Tiefengraber* [4]).

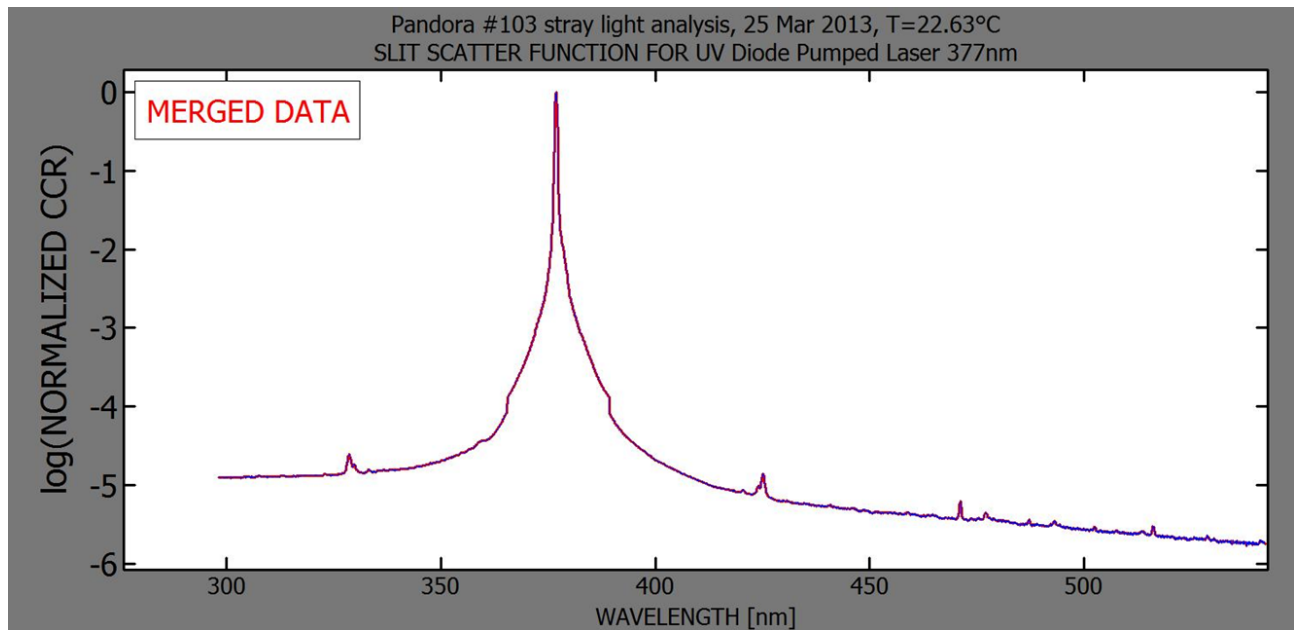


Figure 5: Logarithm of the normalized corrected count rates (CCR) of Pandora 103 when illuminated by a 377 nm diode laser as a function of wavelength. The normalization is made so that the pixel with maximum intensity is at value 1.

3 Data correction

A total of nine correction steps are applied to the Pandora L0 data. Systematic errors in the data correction will produce systematic errors in the L1 data. To conserve the network homogeneity the corrections are applied in a standardized way to all instruments. Each step is described in one of the following sections.

3.1 Dark correction

The dark count is the sum of the dark offset (given by an electronic bias of the readout electronics (ROE)) and the dark slope (charge produced by thermal electrons). Pandora has a dark offset of about 1-2 % (of the saturation value) and a dark slope of about 1-2 % per second, when using the standard detector at the current operational temperature (see figure 6). For our standard 16-bit AD converter, this corresponds to about 1000 counts dark offset and 1000 counts/s dark slope.

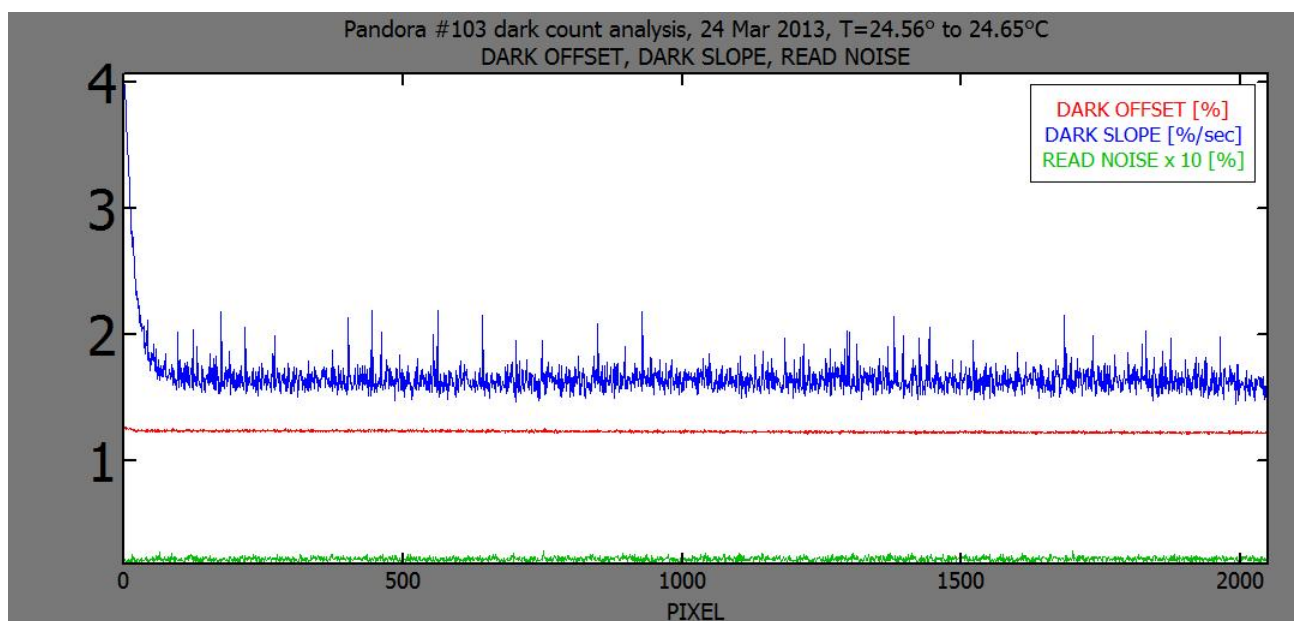


Figure 6: Dark offset (red), dark slope (blue), and read noise (green) of Pandora 103 as a function of pixel. Data are for a set temperature of 20 °C. The electronics board temperature is about 25 °C.

In the current operation, Pandora measures the dark count immediately after a regular measurement with light input ('bright measurement') by rotating the filter wheel into position 'opaque'. This dark measurement is done at the same temperature and integration time as the bright measurement and should be an excellent estimation of the dark count included in the bright measurement. However, as explained in *Cede and Tiefengraber* [4], the Pandora ROE has an issue, giving a different dark offset for dark and bright measurements (figure 7).

This is one reason we are working on a different way to perform the operational dark correction in the future. The exact method to employ is under investigation at this time.

3.2 Temperature correction

As mentioned in section 2, the radiometric calibration is performed in the laboratory at three different spectrometer temperatures in order to determine the temperature sensitivity of Pandora. Our experience has shown that a Pandora in good condition does not have radiometric temperature sensitivity, which means no temperature

correction is applied to the data. In the case a signal change as a function of temperature is noted, the instrument will give false calibration results in the other tests as well, thus leading to an investigation of a hardware problem, e.g. moisture inside the optical bench.

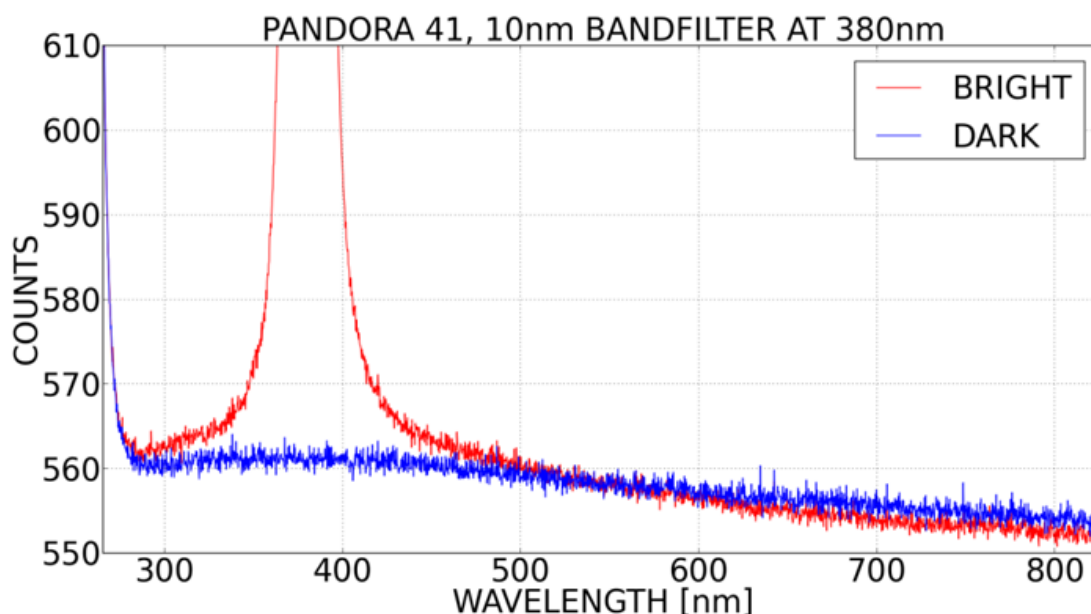


Figure 7: Measurements of a spectrally narrow signal with a Pandora spectrometer. Red line is the signal with light, blue line is the dark signal. Due to issues with the dark offset, the dark signal is larger than the bright signal above 500 nm. This makes a stray light calibration impossible.

3.3 Non-linearity correction

Image sensors are in general not linear, i.e. they do not return double signal when illuminated by double the amount of light. The non-linearity of Pandora is typically a few percent, which can be characterized very well in the laboratory (figure 8). To correct for the non-linearity, the measured counts are divided by the green line in figure 8.

3.4 Conversion to count rates

In this correction step the data are divided by the integration time, which changes their unit from 'counts' or 'DN' to 'counts/s' or 'DN/s'. For earlier generation Pandoras we noticed that the nominal integration time (given to the ROE) and the effective integration time (the 'true' number) often had a small bias relative to each other. This bias was detected during calibration and included in this correction step. Newer Pandoras show no difference between the nominal and effective integration time.

3.5 Flat field correction

Even when each pixel is illuminated by the same amount of light, they all return slightly different signals. This is called 'pixel response non uniformity', PRNU, and is caused by physical differences in the pixels. The PRNU is determined during the radiometric calibration and is expressed in percent (figure 9). Note that if the lamp signal is not smooth as a function of wavelength, lamp features might falsely be interpreted as PRNU.

The PRNU is typically on the order of $\pm 1\%$. The detectors used in newer versions of Pandora are 2D image arrays, where N vertical pixels are read in binned mode. This means that the returned value is in reality the sum over N pixels and therefore the measured PRNU is the 'true' PRNU divided by $\sqrt{N}$. E.g. Pandora 39 uses a $N=16$ detector, reducing the measured PRNU from about $\pm 1\%$ to $\pm 0.25\%$ (figure 9). During radiometric calibration we only determine the PRNU for the binned pixels.

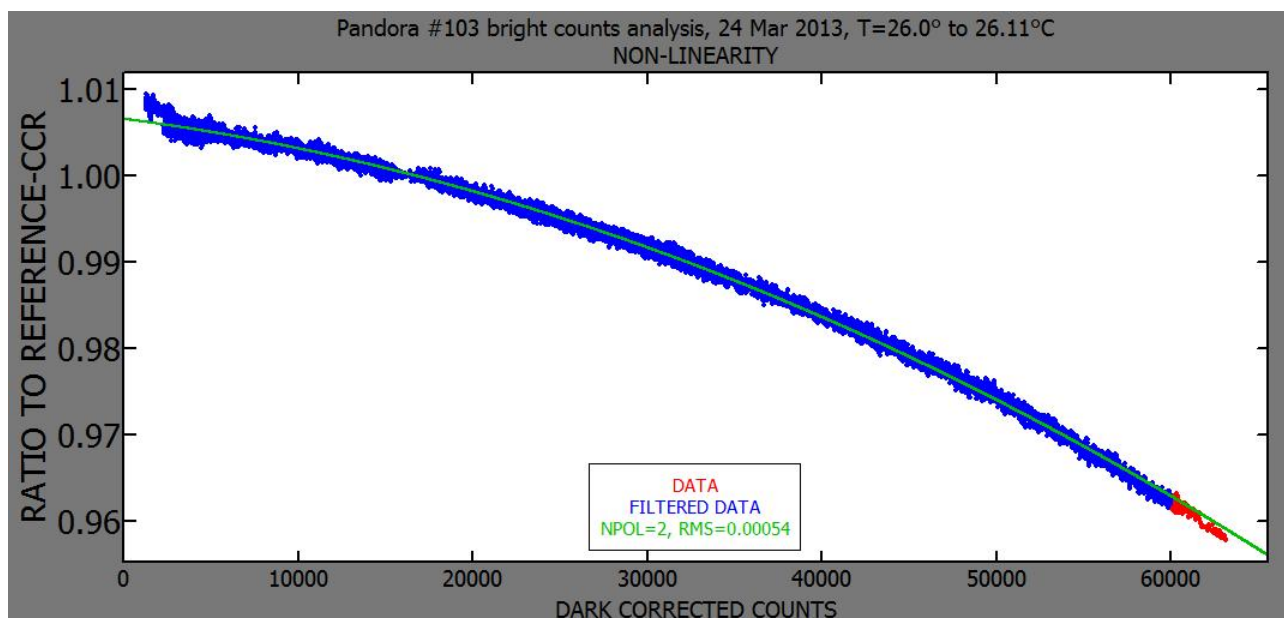


Figure 8: Non-linearity effect for Pandora 103. Data are in blue and red and a 2nd order polynomial in the blue data is in green.

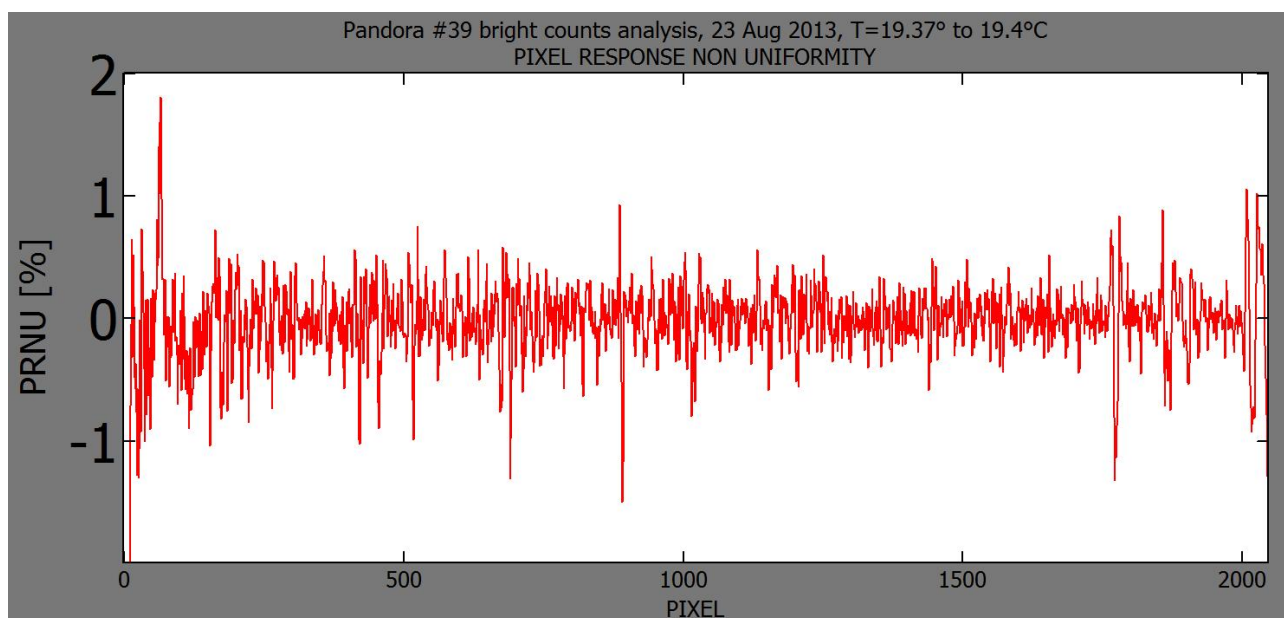


Figure 9: PRNU for Pandora 39 as a function of pixel. Note that the detector for this unit is binning 16 pixels at each scan, which reduces the true PRNU by a factor of 4.

3.6 Stray light correction

The Pandora data processing software is set up to apply a so-called matrix stray light correction method to the spectra, which is based on measured slit functions [7]. However, for reasons explained in sections 2.3 and 3.1, the determination of slit function outside the region near the target pixel is not possible. Therefore, we apply a simple stray light correction on the data, which consists of subtracting the average signal below 290 nm from the spectra. The logic being that no solar light reaches the Earth's surface in these wavelengths, thus we can attribute such residual signals to stray light.

We are currently testing the option of including an optically black region (OBR) on the detectors to improve the stray light characterization.

3.7 Filter correction

The spectra are converted to 'what would have been measured if open hole had been in both filter wheels'. In this correction step the spectra are divided by the filter transmission, which is determined in the laboratory. Figure 10 shows measured transmission for the filters in filter wheel 1 of Pandora 103. Note that the filter transmission determined in the laboratory is also affected by stray light. Therefore the transmission values in the short UV are biased high. This can only be improved with a better stray light correction (see section 3.6).

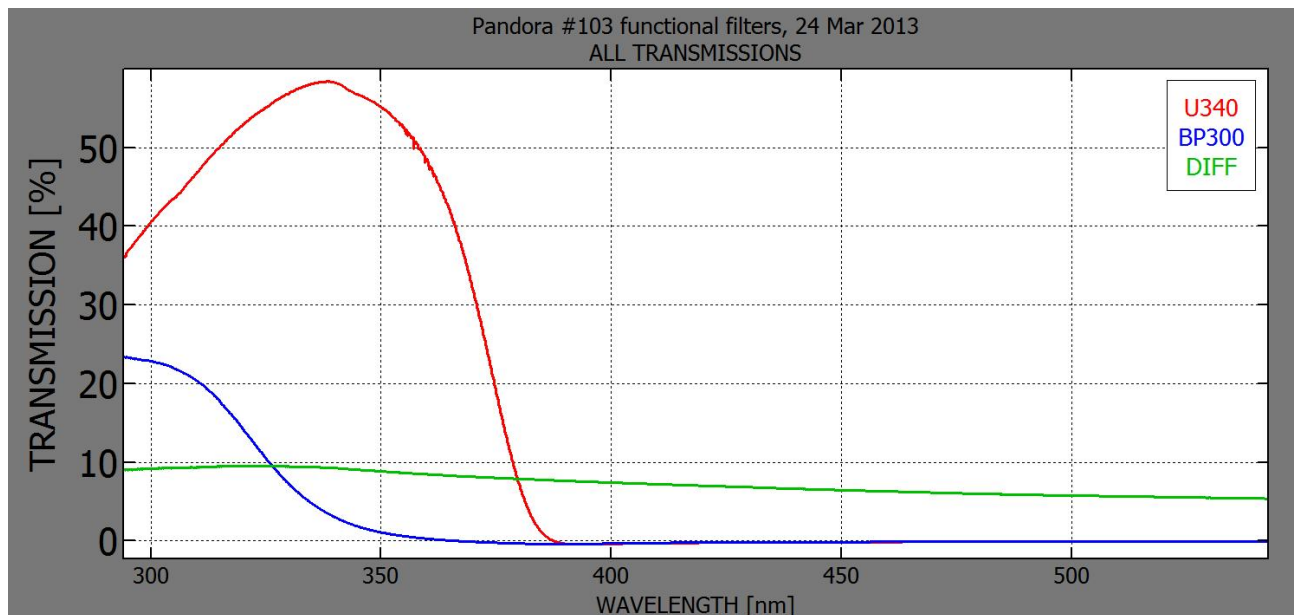


Figure 10: Measured transmissions for filters in Pandora 103 as a function for wavelength. U340 is a colored glass bandpass filter with peak transmission at 340 nm (red line). BP300 is an interference bandpass filter with peak transmission at 300 nm. DIFF is a ground quartz diffuser.

3.8 Conversion to (ir)radiances

As mentioned in section 2.1, an absolute radiometric calibration can be made if the FEL lamp used comes with a calibration certificate. This correction step is not operational at present, as we are still working on the details of this procedure. Initial tests were performed on Pandora 30 with encouraging results. The shape of the absolute sensitivity of Pandora is basically a combination of all optical elements involved (figure 11), mainly the fiber transmission, grating efficiency and quantum efficiency of the detector.

3.9 Wavelength correction

An optional last data correction step is the wavelength correction. This is only needed for users which require the L1 data to be on a fixed wavelength grid. It is not necessary for Level 2 (L2) data. In this step the measured spectra are compared to a theoretical high resolution extraterrestrial spectrum [3] and shifted to the nominal wavelength grid. Given that the typical wavelength shift of Pandora is small [4], the error introduced in the wavelength correction is also small.

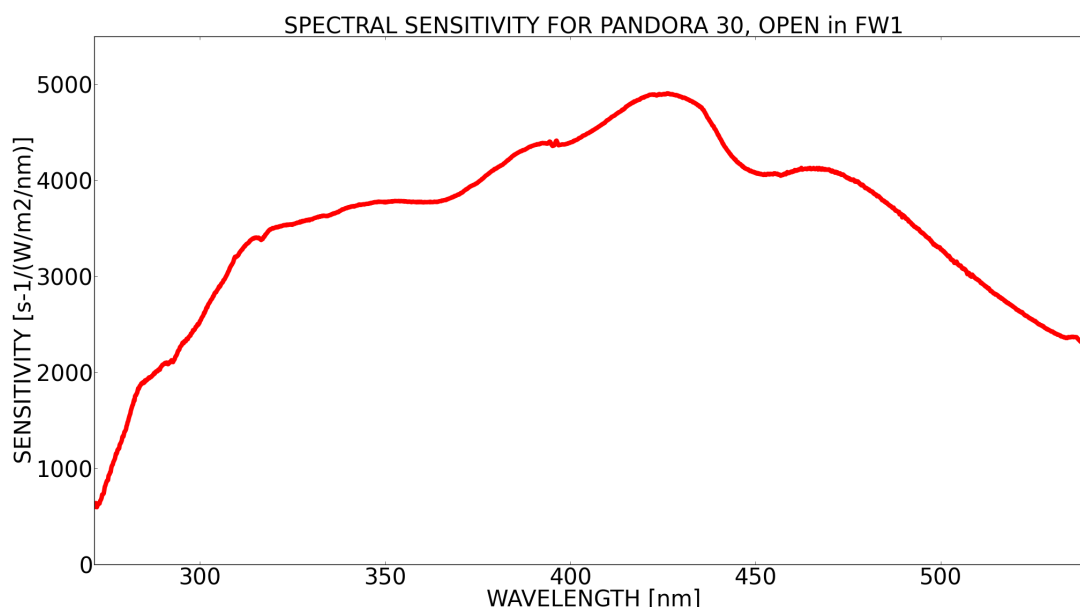


Figure 11: Absolute irradiance sensitivity for Pandora 30 measured with NIST-calibrated FEL lamp as function of wavelength. The instrument is most sensitive around 430 nm, where 1 W/m²/nm of irradiance is converted into nearly 5000 counts/s.

4 Instrument maintenance

Following thorough laboratory calibration the Pandora L1 data are 'as good as it gets'. In order to minimize the chance of faulty L1 data during operation, one should obey some practical rules, which are listed below.

- The entrance window (uncoated fused silica) should be kept clean. For this purpose the collimator should be un-screwed as shown in figure 12. Then a layer of preferably methyl alcohol (otherwise isopropyl alcohol) should be applied on the window without touching it. After the alcohol is evaporated, one should check whether the window surface is clean. If not, then a lens wipe (see e.g. http://www.zeiss.com/vision-care/en_de/products-services/other-zeiss-brand-products/lens-cleaning-solutions.html) should be gently applied to remove the residues.
- The bend of the fiber optics should be checked regularly. At no place should the fiber be bent less than the recommended minimum bend diameter, which is 26 cm for most Pandoras (600 times the clad diameter, which is 440 μm). Note that this number refers to a long-term situation. The recommended minimum bend diameter for short-term is 100 times the clad diameter, i.e. 4.4cm.
- The connectors should be inspected for corrosion.
- The alignment should be checked in the case the sun is up and not covered by clouds. The view port (figure 13) should be used for that purpose. If the instrument is repeatedly badly aligned, then a maintenance on the tracker should be performed in collaboration with LuftBlick.
- Since Pandora is on the Internet, all software updates (e.g. windows updates) should be performed periodically, preferably at night.

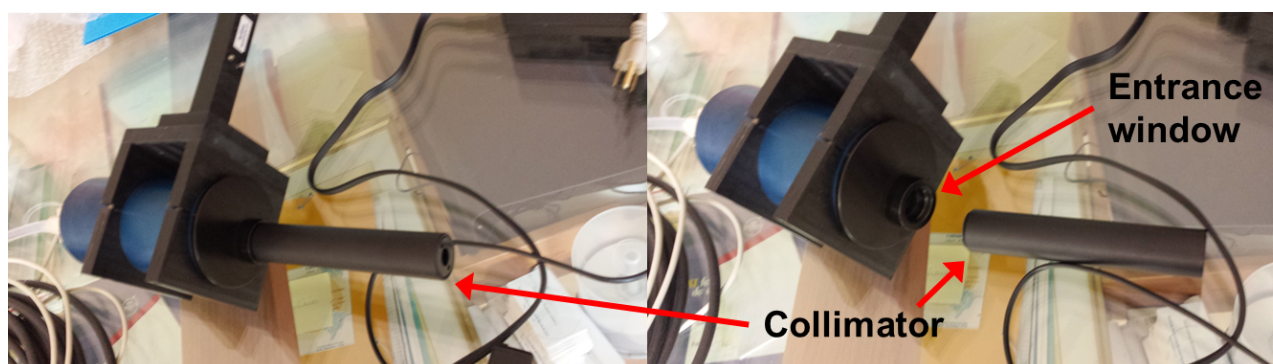


Figure 12: Head sensor with collimator connected (left panel) and unscrewed (right panel).

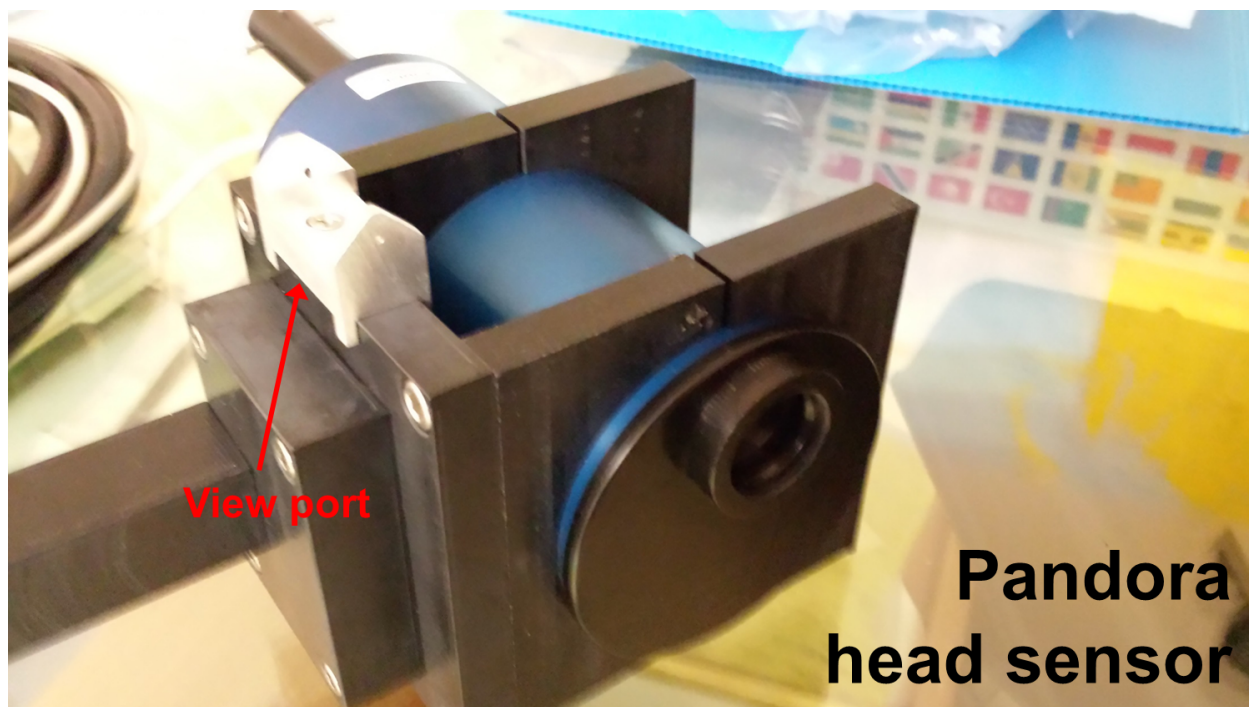


Figure 13: Pandora head sensor with view port.

5 Quality assurance plan

The Pandonia maintenance tasks are summarized in this table. The last column lists whether the task should be performed by the local operator or the network operator or either of them. The local operator is a person on site. The network operator is LuftBlick staff, who remotely checks the network instruments periodically and whenever he/she notices interruptions in the instrument operation.

Period	Name	Tasks	Operator
10 min	Status check	Check whether the instrument delivers online data	Network
Daily	Data check	Check whether the data from the previous day are complete	Network
Weekly	Instrument check	Make a physical check of the instrument (see section 4)	Local
Monthly	Computer updates	Make necessary software updates (preferably at night)	Network/Local
Yearly	Tracker check	Check whether the gears in the stepper motors are still tight	Local
Bi-yearly	Calibration check	Intercomparison with a reference instrument	Local/LuftBlick