LuftBlick Report 2014009

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

Laboratory Report

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1.0	19 Dec 2014	All	Minor changes; Section 6 added
1.1	29 Jan 2015	5, 8, 16, 22, 24, 25, 26	Minor changes in section 1, 2.3, 2.5.1 and 6; Part of section removed in 2.5.1; Table added in section 3.2; Sections 4 and 5 added

Acronyms and Abbreviations

AbsRadCal	Absolute radiometric calibration
AOD	Aerosol optical depth
Ar	Argon
BlickC	Blick Calibration Software
BlickO	Blick Operation Software
BlickSW	Blick Software Suite
Cd	Cadmium
DL	Diode laser
DOAS	Differential optical absorption spectroscopy
FCT	field calibration tool
FWHM	Full width half maximum
GUI	Graphical user interface
He	Helium
Hg	Mercury
ISR	instrument spectral resolution
Kr	Krypton
LabCIAI	Laboratory Centro de Investigación Atmosférica de Izaña (Izaña Atmospheric Research Center)
LabIMU	Laboratory Innsbruck Medical University
LSF	line-spread function
Na	Sodium
ND	Neutral density
Ne	Neon
Pandonia	ESA Ground-Based Air-Quality Spectrometer Validation Network
PanS1	Single spectrometer Pandora system
PanS2	Dual spectrometer Pandora system
PTB	Physikalisch-Technische Bundesanstalt (Germany's national metrology institute)
RelRadCal	Relative radiometric calibration
SMA	sub miniature version A
SpcStrCal	spectral stray light calibration
Tl	Thallium
UV	Ultra violet
WvlCal	Wavelength calibration
Xe	Xenon
Zn	Zinc

1 Introduction

This report is deliverable D10 of the Pandonia project [2, 1]. Within the framework of this project agreements have been made that two existing laboratories can be used to periodically calibrate the Pandonia instruments participating in the network. The agreements are good for the duration of the project. The two laboratories receive the necessary upgrades to perform this task, funded by the project. These laboratories are LabIMU, at the Innsbruck Medical University in Austria, and LabCIAI, at the Izaña Atmospheric Research Center in Spain (Tenerife). A full laboratory calibration at LabIMU will be done for each Pandonia instrument before it is deployed in the field. LabIMU shall be the reference laboratory for the Pandonia network. In section 2 of this report we will give an overview about the capabilities of LabIMU as a calibration laboratory for Pandonia instruments, in particular addressing optomechanical capabilities (section 2.2) and the applicability for doing radiometric calibration (section 2.3), wavelength calibration (section 2.4) and spectral stray light calibration (section 2.5). A complete listing of the main equipment is given in section 2.6. LabIMU has already been upgraded with the missing equipment.

LabCIAI is equally capable to fully calibrate Pandonia instruments, but CIAI is due to its favorable atmospheric conditions throughout the year in particular valuable for field calibration. CIAI is the primary field calibration site in the Pandonia network. In section 3.1 we will introduce a field calibration tool which is currently tested in CIAI. LabCIAI has not been upgraded up to now, but will receive upgrades during 2015 (see section 5.2).

The laboratory and field calibration capabilities of LabIMU and LabCIAI are meant to handle both the standard Pandora systems (PanS1) and dual spectrometer Pandora systems (PanS2, to be developed in the framework of this project).

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.

[3] A. Cede. *Manual for Blick Software Suite Version 1.0.1*, 2014. URL `http://pandonia.net/docs/BlickSoftwareSuite_Manual_v1.0.1.pdf`.

1.2 Reference Documents

[4] A. Cede and M. Schwärz. ESA Ground-Based Air-Quality Spectrometer Validation Network and Uncertainties Study, LuftBlick Report 2014010: Processor ATBD and SUM, Instrument Software Maintenance Plan, 2014.

[5] G. R. Gray and R. Roy. Bistability and mode hopping in a semiconductor laser. *Journal of the Optical Society of America B Optical Physics*, 8:632–638, March 1991. doi: 10.1364/JOSAB.8.000632.

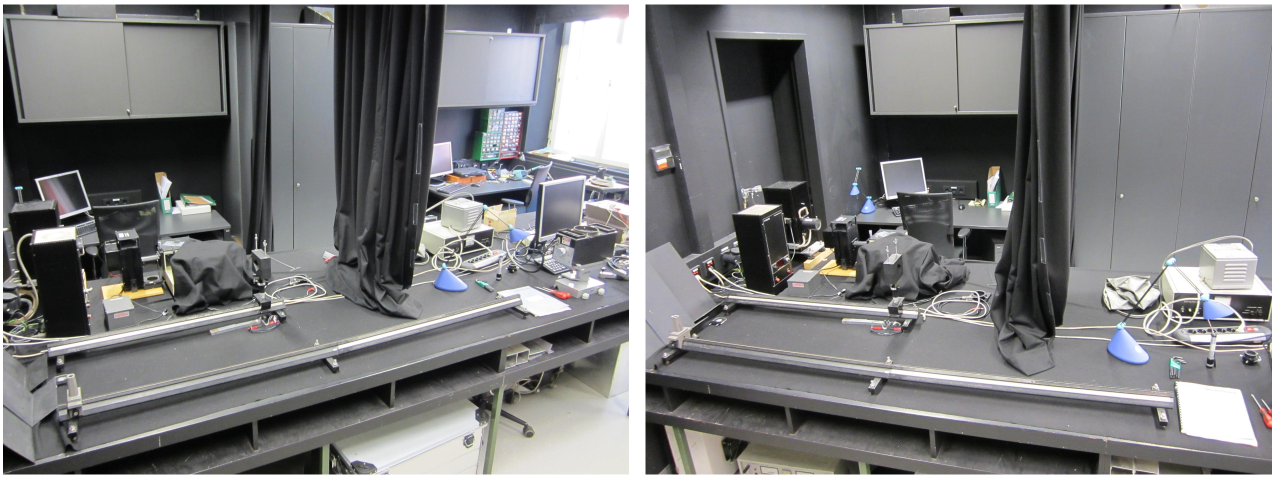
[6] S. Nevas, J. Gröbner, L. Egli, and M. Blumthaler. Stray light correction of array spectroradiometers for solar UV measurements. *Appl. Opt.*, 53(19):4313–9, July 2014. ISSN 1539-4522. URL `http://www.ncbi.nlm.nih.gov/pubmed/25089995`.

[7] M. Schwärz and A. Cede. ESA Ground-Based Air-Quality Spectrometer Validation Network and Uncertainties Study, LuftBlick Report 2014002: Pandonia Network Web Site Technical Baseline and Architectural Design Document (ADD), 2014.

[8] G. Seckmayer, A. Bais, G. Bernhard, M. Blumthaler, S. Drüke, P. Kiedron, K. Lantz, R. L. McKenzie, and S. Riechelmann. World Meteorological Organization, Global Atmosphere Watch, No. 191: Instruments to Measure Solar Ultraviolet Radiation Part 4: Array Spectroradiometers, 2010.

[9] Y. Zong, S. W. Brown, B. C. Johnson, K. R. Lykke, and Y. Ohno. Simple spectral stray light correction method for array spectroradiometers. *Appl. Opt.*, 45(6):1111–9, February 2006. ISSN 0003-6935. URL `http://www.ncbi.nlm.nih.gov/pubmed/16523771`.

2 Laboratory Innsbruck Medical University



(a) (b)

Figure 1: Laboratory in Innsbruck (Austria) at the Medical University (LabIMU). LabIMU ia a full-featured optical laboratory. **(a)** LabIMU overview showing the optical working area in the front and the mechanical, electrical working are in the back. **(b)** focus on the optical working area.

2.1 General information

LabIMU is a full-featured, air conditioned darkroom laboratory hosted by the biomedical physics group of the Medical University Innsbruck. The laboratory is located in the close vicinity of the Pandonia instrument deployment site of Innsbruck. LabIMU was initially built for characterizing and refining broadband and spectrometer detector systems. In this way LabIMU was already well equipped for our purpose of calibrating Pandonia network instruments. Figure 1 demonstrates the spatiality of the laboratory. The optical working area can be seen in the front of the figure and the mechanical and electrical working area can be seen on the right hand side in the back (left figure panel).

2.2 Optomechanical capabilities

LabIMU is not equipped with a commonly used threaded optical table to arrange the components. Instead, triangular optical rails are used to align the components used in the laboratory set up. The one meter long single rails can be combined to cover the wanted distance. Each component, e.g. the PanS1(S2) head sensor, can be shifted along the rail using carriers. This allows a very flexible positioning. Figure 2 illustrates an example laboratory set up showing the mounting rail with a PanS1 head sensor fixed in the head sensor holder (left hand side), a FEL light source (right hand side) and a neutral density (ND) filter holder between them.

The head sensor dimensions of PanS1 and PanS2 are equal, thus only one holder unit is necessary. This holder unit makes use of two V-shaped brackets to fix the head sensor and includes a positioning element, which allows to vertically adjust the fixed head sensor.

For uniform beam attenuation a set of reflective ND filters can be placed in between the light source and the input optics. One can choose between ND0.5, ND1 and ND2. NDx means an attenuation of $\frac{I}{I_0} = 10^{-x}$. The corresponding filter holder would in principle allow to cascade the ND filters.

For a first guess alignment of the head senor and a light source a laser alignment tool is utilized.

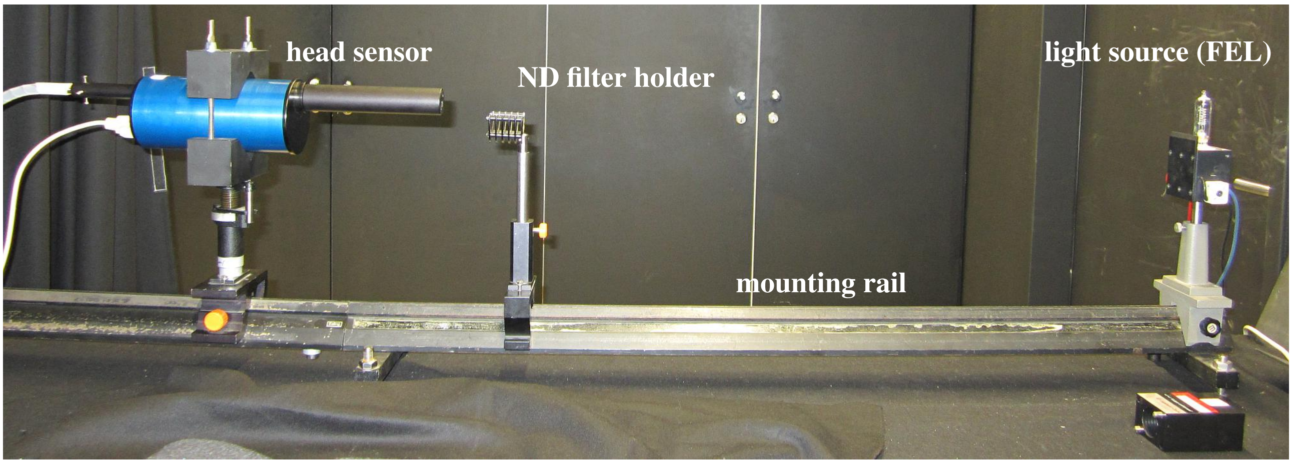


Figure 2: Example set up in LabIMU showing the PanS1 head sensor mounted in the holder unit (left hand side), a FEL light source (right hand side) and a ND filter holder placed in between. All components are installed on carries which can easily be moved along the mounting rail.

2.3 Radiometric calibrations

This section decribes so-called "characterization steps" for the relative radiometric calibration (RelRadCal), which determines the relative spectral response of the instrument to a broadband light source. These characterization steps are

- Non linearity
- Pixel response non uniformity
- Radiometric temperature dependence
- Filter transmissions

If the absolute spectral responsivity of the instrument is characterized, this process is called absolute radiometric calibration (AbsRadCal). A proper AbsRadCal is mandatory in order to allow an accurate aerosol optical depths (AOD) retrieval.

2.3.1 Requirements

The light source needs to be spectrally smooth and the emission spectrum should embrace the spectral range of the spectrometer. To perform AbsRadCal the radiant power of the light source needs to be known, whereas this is not necessary for RelRadCal. The most critical point for the radiometric calibration is to provide a highly accurate and stable power supply for the light source: even a 1 % variation in the light source current would yield a 10 % change in the ultra violet (UV) radiant power of the light source [8].

2.3.2 Light source

As broadband light source we use 1000 W tungsten halogen FEL lamps. We categorize these light sources in two groups: reference standards and working standards [8]. Reference standards are thought of to be of the highest metrological quality available in the laboratory. These kind of light sources are provided by certified laboratories (Physikalisch-Technische Bundesanstalt (PTB) in our case) and include a certificate which defines the radiant power of the light source at a defined distance. We use reference standards only for AbsRadCal. When a reference standard exceeds a threshold of burning hours it is downgraded to a working standard. Working standards should still deliver stable radiant power output, however its magnitude may deviate from that given in the certificate. We use working standards for RelRadCal.

2.3.3 Light source power supply

In the LabIMU two power supply units are available: one is stationary and the other is a compact version also suited for transportation. The stationary unit is composed of a Heinzinger power supply controlled by a Keithley multimeter while the mobile unit is composed of a Xantrex power supply with a Agilent multimeter. Both read the potential drop at the measuring resistor (0.1 Ω, the power supply and the light source. Power supply and multimeter are connected via a local area network to immediately communicate differences of the measured to the nominal current. Both units include a current ramping facility for switching on and off the light source. Figure 3 shows the temporal variation of the potential drop at the measuring resistor (lower panel, green curve), the potential drop at the light source (lower panel, gray curve) and the current (upper panel) for one typical laboratory session. The data is given as the percentage deviation of each measurement relative to the last measurement. After about 5 minutes the light source is warmed up, which is indicated by the voltage level starting to variate rather smooth in time. Throughout this example laboratory session (about 130 minutes) the current is fluctuating less than about ± 5e-3 %.

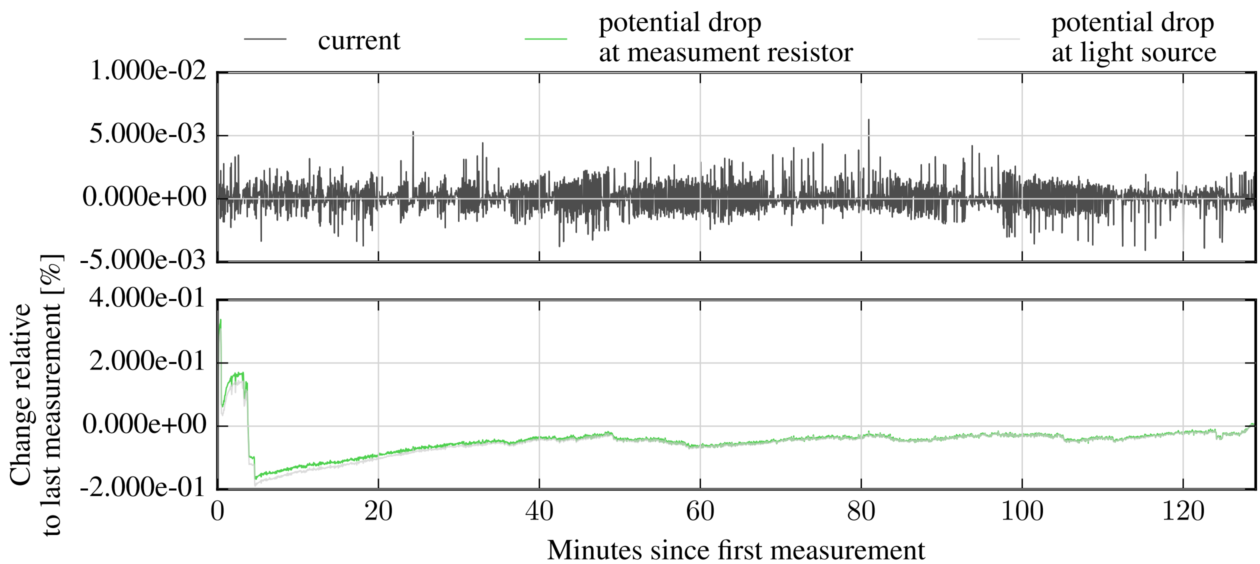


Figure 3: Stability of the light source power supply for an example laboratory session given in relative changes to the latest measurement. **Top panel**: the temporal variation of the current. The variation stays well within ± 5e-3 % **Bottom panel**: the temporal variation of the potential drop at the power supply (gray) and the light source (green). The strong variation in the first 5 minutes is related to the warm up time of the light source.

This small variation in the current creates a very stable radiant power emitted by the light source. Figure 4 shows the signal stability when measured with a fully temperature stabilized Pandora instrument (number 106, a PanS1 system). The data is given as the relative change in the signal with respect to the last measurement. Each measurement is the mean value over pixel 1000 to 2000 (410 to 534 nm). The given period starts after the light source has been warmed up adequately. The variation in the detected signal is less than ± 4e-2 %.

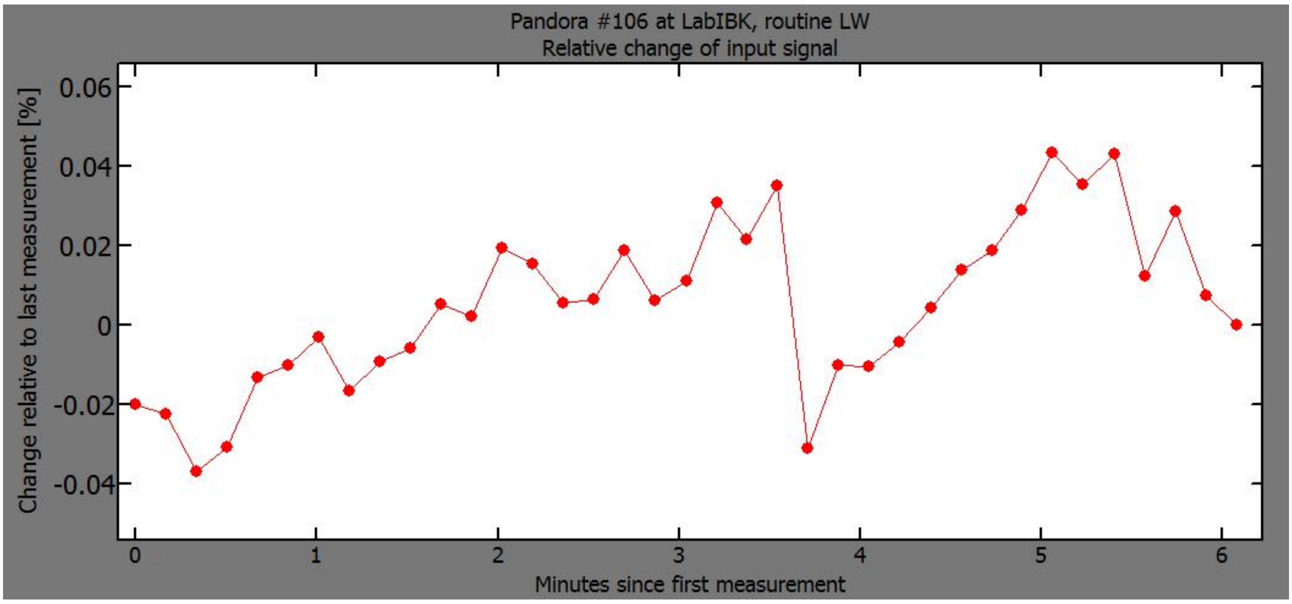


Figure 4: Stability of the input signal measured by Pandora 106 for one example laboratory session. The data is given in relative changes with respect to the last measurements. The signal fluctuation is less than ± 4e-2 %.

Generally the radiant power of a incandescent light source is determined by the temperature of the tungsten filament. The temperature of the filament is for the most part controlled by the current applied to the light source, but also on the environmental temperature effecting the bulb. In addition the reading of the potential drop at the measuring resistor is affected by the temperature dependency of the resistor itself. As a preventative measure it is recommended to switch off the air condition for very sensitive RelRadCal steps (e.g. non-linearity determination), since using air-conditioning could exacerbate reaching a thermodynamic equilibrium in the environment of the light source and the power supply.

2.3.4 Overview of equipment for radiometric calibration

Item	**usable for PanS1**	**usable for PanS2**	**Existing**	**Added**
Mounting				
FEL lamp holder, carrier	✓	✓	✓	
head sensor holder, carrier	✓	✓	✓	
Light source				
FEL lamp working standard	✓	✓	✓	
FEL lamp reference standard	✓	✓	✓	
Light source power supply				
Heinzinger / Keithley system	✓	✓	✓	
Xantrex / Agilent system	✓	✓	✓	

2.4 Wavelength calibration

The purpose of the wavelength calibration (WvlCal) is firstly the assignment of a wavelength scale to the pixels of a spectrometer and secondly the determination of the instrument's relative spectral response to a monochromatic illumination for a number of wavelengths. The former is denoted as dispersion and the latter as slit function. We define the full width half maximum (FWHM) of the slit function to be a measure of the instrument's spectral resolution (ISR), which in general is not constant across the instruments spectral range. The dispersion and the slit function can be determined by means of spectral light sources.

This instrument characterization step is the most critical one if the final data analysis procedure is based on so called DOAS techniques.

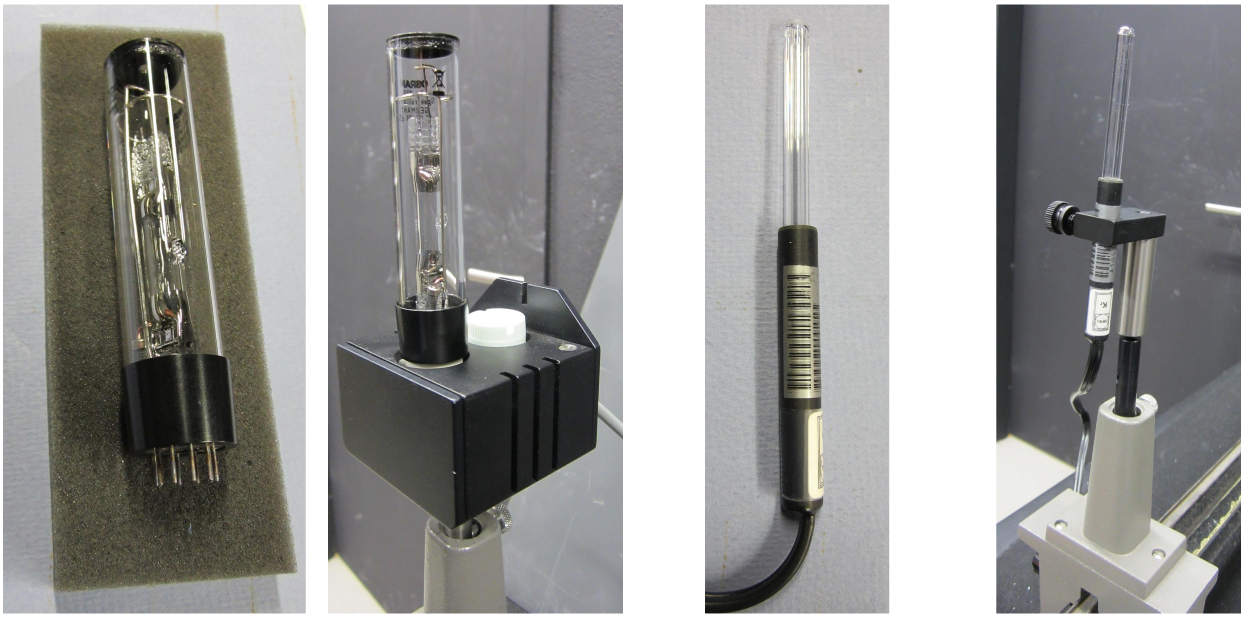
2.4.1 Requirements

In principle one could measure only one spectral light source which is assumed to cover the instruments spectral range adequately. However, in terms of DOAS based data analysis we claim to determine the spectral characteristics of the instrument as dense as possible. Since the DOAS approach applies spectra not measured with the instrument (e.g. gas cross sections), an inappropriate dispersion and ISR is an error source and enhances the measurement errors.

The obvious advantage of this approach is to have more sampling points for the calculation of the dispersion and the slit functions across the instrument's spectral range. The second advantage is to gain accuracy in the determination of ISR by taken into account that ISR is dependent on the alignment of the spectral light source and the optical path of the instrument (explanation is given in the next section).

2.4.2 Spectral lights sources

As spectral light source we use gas discharge lamps of two different designs (Figure 5). The first are socket based spectral lamps manufactured by Osram (Figure 5a and Figure 5b mounted on socket) and the second are pencil style lamps provided by Oriel (Figure 5c and mounted in Figure 5d). We selected the following spectral light sources:



(a) (b) (c) (d)

Figure 5: Spectral light sources of two different designs. **(a)** socket based Osram spectral light source. **(b)** the Osram spectral light source placed on the socket. **(c)** pencil style spectral light source. **(d)** pencil style spectral light source with holder.

- Osram
  - Cd, Cadmium
  - He, Helium
  - Hg, Mercury
  - Na, Sodium
  - Ne, Neon
  - Tl, Thallium
  - Zn, Zinc
- Pencil style
  - Ar, Argon
  - Kr, Krypton
  - Xe, Xenon

Figure 6 visualizes the normalized emission spectra of each spectral source for the Osram light source (in black) and the pencil style light source (in blue). The spectra have been recorded with an Ocean Optics USB4000 (3648 pixel CCD array spectrometer, spectral range 280 to 890 nm, ISR 1.3 nm). The spectral range which coincides with spectrometer 1 and spectrometer 2 of PanS2 is emphasized with green and yellow shading, respectively. Spectrometer 1 in identical to the spectral range of PanS1.

In principle, both PanS1 and PanS2 can make use of all of the spectral light sources, however not necessarily the same emission lines. Ar, e.g., provides for PanS1 valuable emission lines around 400 nm. But since PanS2 is sensitive up to 900 nm, the emission lines from 700 to 900 nm will dominate and those around 400 nm will suffer large amount of instrumental noise.

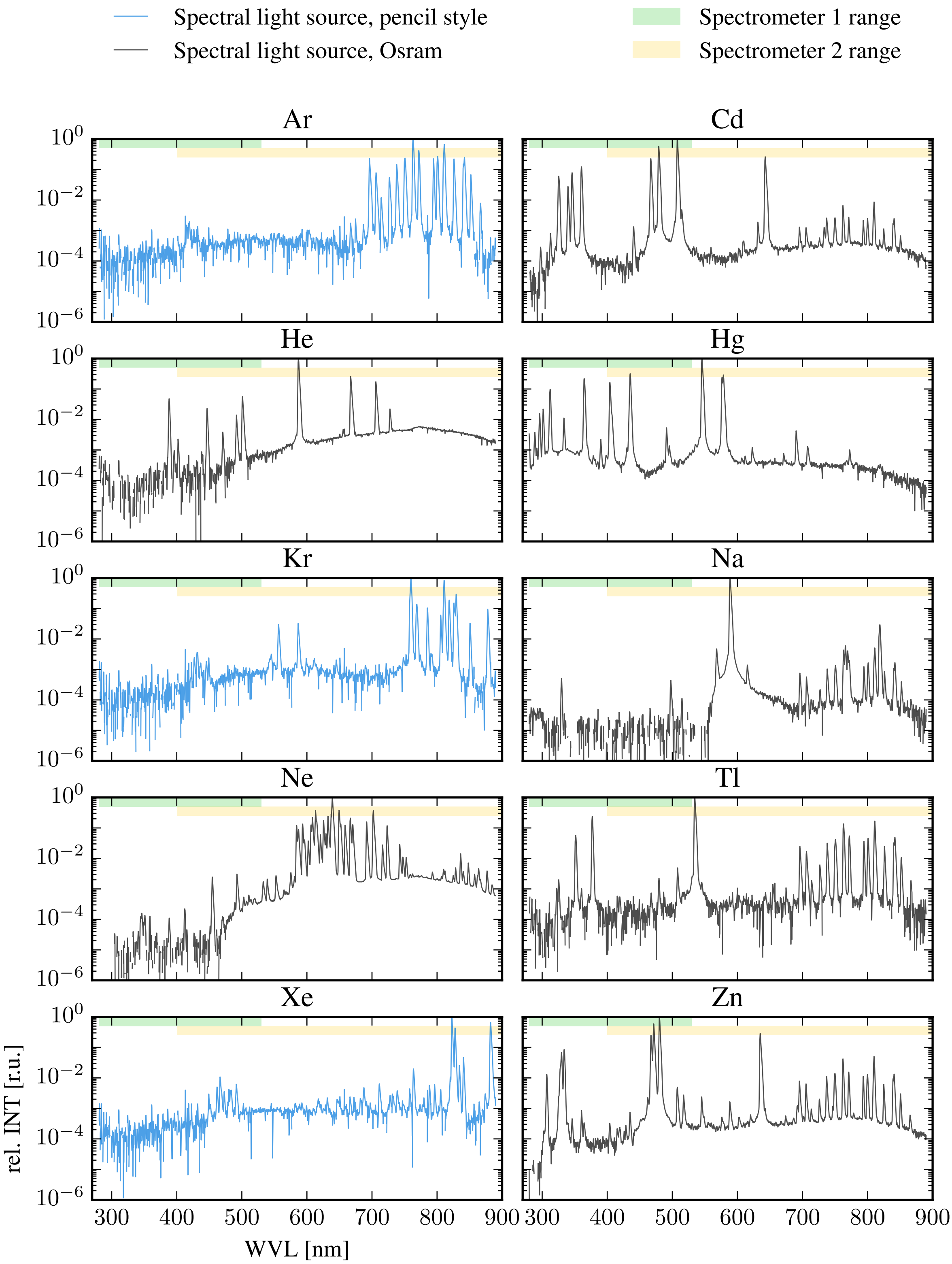
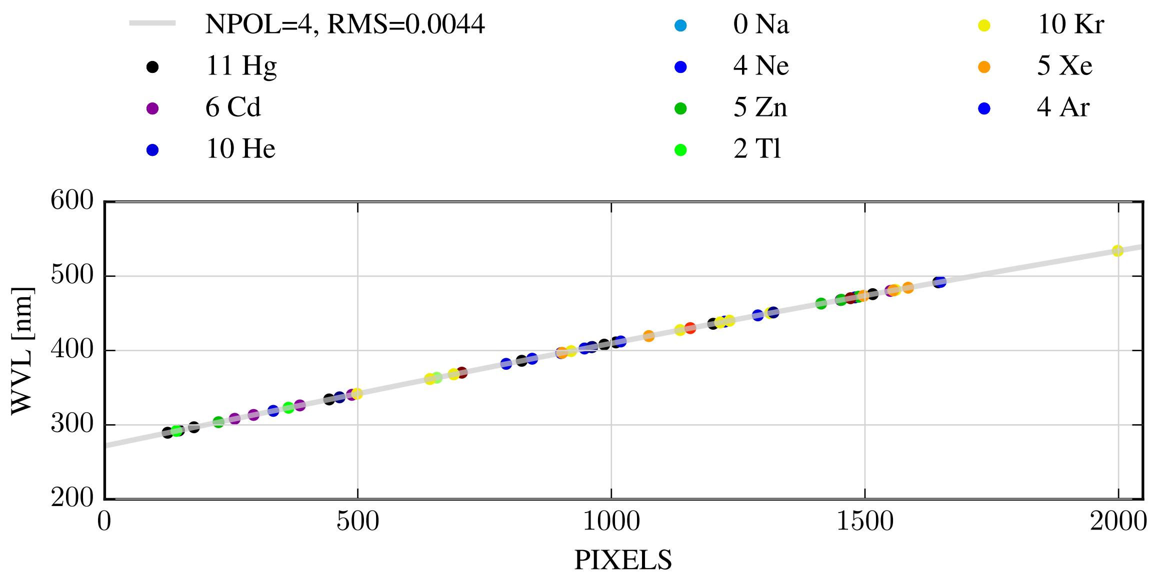
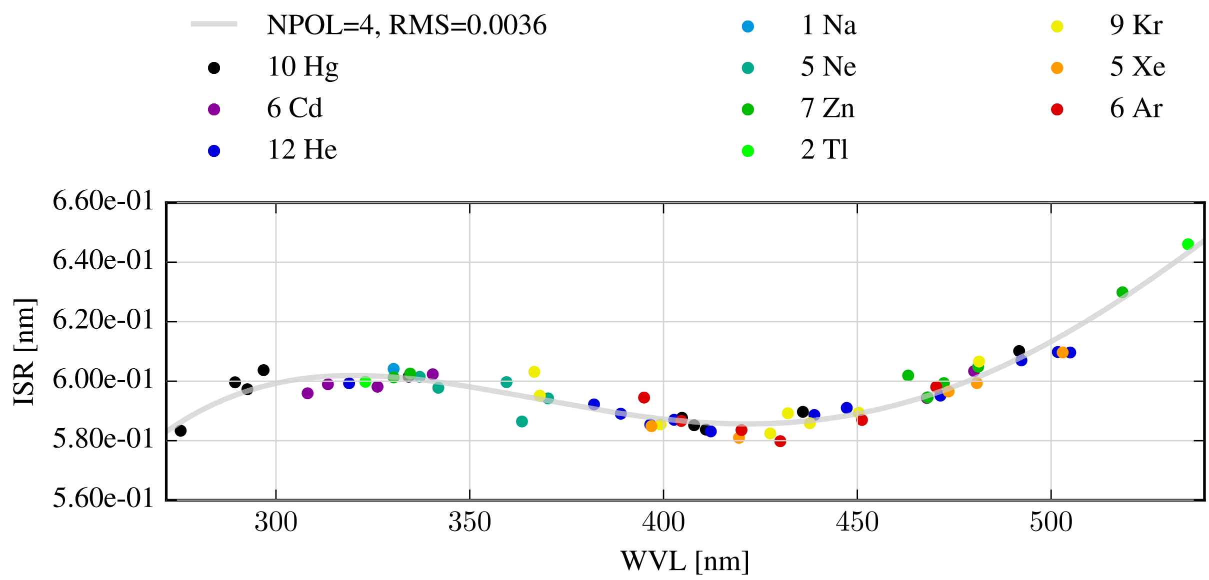


Figure 6: Recorded spectra of spectral light sources used in LabIMU. Spectra have been taken with an Ocean Optics USB4000. Blue colored spectra are pencil style spectral light sources, black colored are Osram spectral light sources. The shaded areas indicate the spectral coverage for spectrometer 1 (green) and spectrometer 2 (yellow) of PanS2. Spectrometer 1 is identical to the spectral range of PanS1.

The benefit of this large number of spectral light sources is that one can apply very strict selection criteria to the emission lines to ensure that only the most reliable are included in the determination of the dispersion and the ISR. Figure 7 illustrates the dispersion (7a) and the ISR (7b) for Pandora 106. The sampling points (emission lines) offer a good coverage of the instrument's spectral range.



(a)



(b)

Figure 7: Dispersion and spectral resolution of Pandora 106. **(a)** dispersion relation **(b)** full width half maximum (FWHM) of the instruments slit function (spectral resolution, ISR) as a function of wavelength. The polynomial which fits the measured emission lines (different colors) best is shown in gray.

If one examines Figure 7b more closely it reveals that ISR tends to scatter slightly around the fitted polynomial. E.g. ISR around ∼ 365 nm is calculated to be ∼ 0.586 nm based on the Ne spectral light source and ∼

0.603 nm based on the Kr spectral light source. Both deviate about 8e-3 nm from the fitted 4th order polynomial at that wavelength.

We performed a test with Pandora 106 where we measured the Hg spectral light source at different offset angles with respect to the “true” optical axis of the instrument. These are -0.9°:0.3°:0.9° in azimuthal and zenithal direction. To be able to adjust the head sensor accurately we moved the sun tracking unit to the laboratory. The “true” optical axis is the position which yields the maximum signal. The ISR based on the strong Hg 435 nm emission line for each offset measurement is depicted in Figure 8 (dark gray) as difference to the ISR from the polynomial fit at that wavelength. An offset of about 1 ° in azimuthal direction would be able to explain the observed differences in ISR up to about 1e-2 nm. If the same measurements are carried out by employing the diffuser (ground quartz) from the filter wheels, the offset dependence vanishes (gray lines in Figure 8). The ISR for the measurements with diffuser is slightly increased compared to the results without diffuser at normal incidence, since the diffuser averages all incidence angles. The emission line peak location is not affected by this broadening effect and hence also not the dispersion determination.

This issue could be minimized by always performing WvlCal with a tracking unit or spend great effort to find the best alignment manually. Both is not practical. Using a larger number of spectral light sources is capable to mitigate the broadening effect on the ISR. The findings further suggest to determine ISR also for diffuse input to be able to adapt ISR for sky measurements.

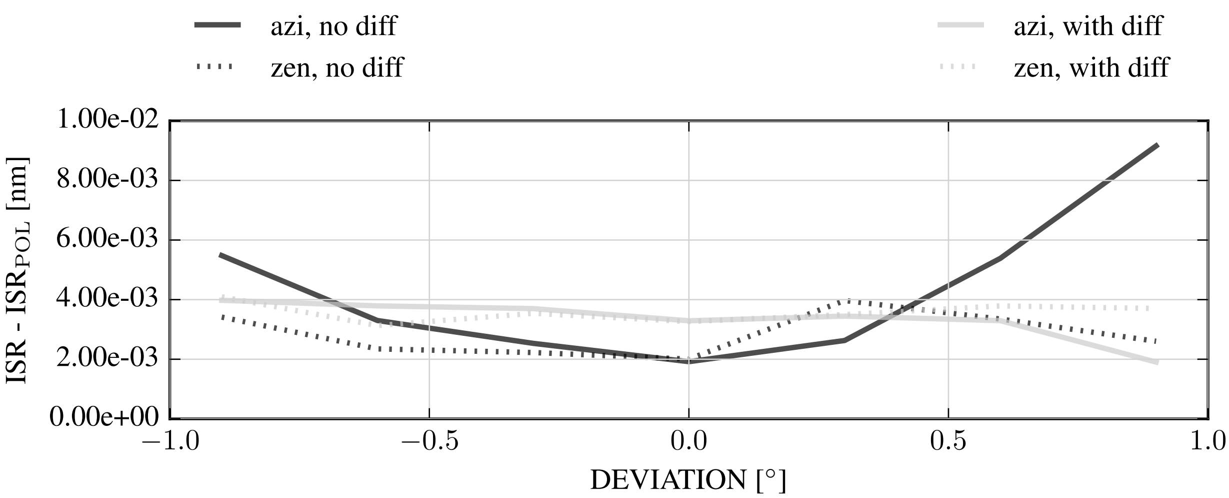


Figure 8: Difference of ISR based on the 435 Hg emission line to ISR of the polynomial at that wavelength (compare Figure 7b) as a function of azimuthal (solid lines) and zenithal (dashed lines) alignment deviation. Measurements without diffuser in black and with diffuser in gray.

2.4.3 Overview of equipment for wavelength calibration

Item	usable for PanS1	usable for PanS2	Existing	Added
Mounting				
Osram lamp holder	✓	✓	✓	
Pencil style lamp holder	✓	✓		✓
Light source				
Ar (pencil style)	✓	✓		✓
Cd (Osram)	✓	✓	✓	
He (Osram)	✓	✓		✓
Hg (Osram)	✓	✓		✓
Hg (pencil style)	✓	✓	✓	
Kr (pencil style)	✓	✓		✓
Na (Osram)	✓	✓		✓
Ne (Osram)	✓	✓	✓	
Tl (Osram)	✓	✓		✓
Xe (pencil style)	✓	✓		✓
Zn (Osram)	✓	✓	✓	
Light source power supply				
Osram lamp power supply	✓	✓	✓	
Pencil style lamp power supply	✓	✓		✓

2.5 Spectral stray light calibration

The spectral stray light calibration (SpcStrCal) has the goal to correct for radiation that reaches a detector position which does not correspond to the wavelength of the radiation. Since PanS1(2S) are single monochromator systems they are prone to spectral stray light.

2.5.1 Requirements

The most sophisticated technique for stray light characterization is to calculate a correction matrix based on measured line-spread functions [9]. A line-spread function (LSF) is the normalized spectral response of the instrument to a monochromatic illumination and should be measured over more than 5 orders of magnitude [8]. The most complete approach would be attained by a tunable laser source (however, very expensive). Using such a laser a desired number of LSFs populating the instruments spectral range can be measured to build up the stray light correction matrix. However, if the instruments line-spread functions vary only gradually over the instruments spectral range, we claim that it is also sufficient to choose a few selected lasers. Since the enhanced variation of the spectral ISR around a fitted polynomial can be explained by the method of illumination (see section 2.4.2 and Figure 7b), we assume a smooth spectral variation of ISR for PanS1(S2) instruments.

Like regular spectrometers used for solar UV measurements PanS1(S2) systems are also equipped with silicon detectors. Since these detectors are typically sensitive to optical radiation up to 1100 nm, we have to consider out-of-range stray light in addition to the in-range stray light [e.g. 6].

2.5.2 Monochromatic light sources

We make use of four collimated diode lasers (DL) which cover the spectral range of PanS1 and PanS2 approximately equally spaced. The DLs are at the wavelengths

- 405 nm,
- 532 nm,
- 650 nm and
- 780 nm.

First tests on the 405 and 532DL revealed, however, some limitations. We carried out 1000 consecutive measurements with a low integration time of 3 ms in order to see if or how the laser line is changing over the time (measurement duration approximately 2 minutes). In Figure 9 the normalized 405DL (532DL) measurements are shown in the left (right) panel. Note that the given spectra are corrected for temperature, non-linearity and flat field but not corrected for dark signal. For 405DL the central wavelength is located almost exactly between two pixels, which makes the maximum toggle between them (a feature when normalizing discrete values). 532DL in contrary is very asymmetric in its line shape with the strongest variation on the low wavelength tail.

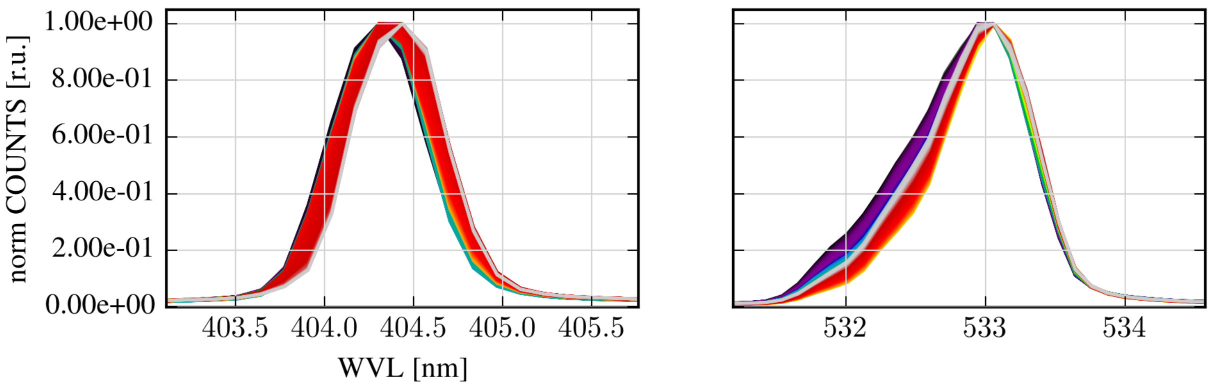


Figure 9: Normalized intensities of 1000 measurements (each measurment a color) carried out with 405DL (left panel) and 532DL (right panel). The 532DL shows in comparison to 405DL very asymmetric line shape. This is probably related to enhanced mode-hopping for 532DL.

This behavior is probably related to so called mode-hopping. Mode-hopping comes along with a change from one longitudinal mode to another and is to a certain extend a response to a temperature sensitivity [5]. Under given circumstances the mode-hopping takes place in a erratic manner, which makes the laser line switching back and fourth rapidly between wavelengths. The mode-hopping appears to happen quickly enough to be able to virtually broaden the measured line shape during the 3 ms of integration. This is also reflected by the apparent resolution obtainable for 405DL and 532DL during the measurement duration (visualized in Figure 10). While the resolution for 405DL (left panel) seems to vary around a common value, the resolution for 532DL is far off the expected value.

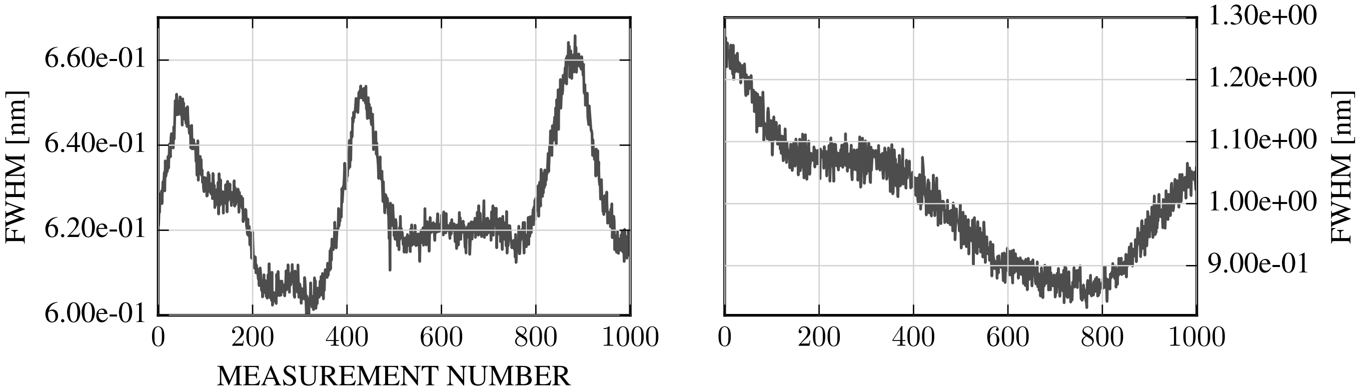
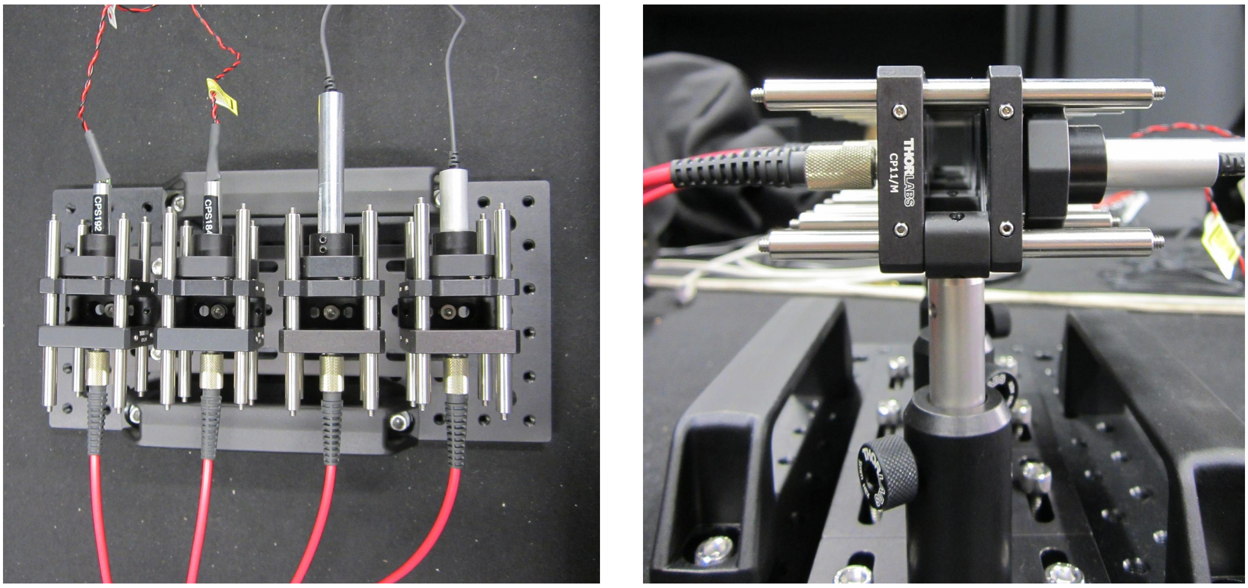


Figure 10: Calculated FWHM for 1000 measurements of 405DL (left panel) and 532DL (right panel). Whereas 405DL yields reasonable values for FHWM, 532DL is considerably broadened probably due to mode-hopping of the 532DL.

In terms of obtaining the stray light correction matrix it is uncertain whether 532DL is usable.

2.5.3 Laser set up

For the laser alignment we make use of cage systems, which allow us to perfectly align the diode laser and a sub miniature version A (SMA) fiber adapter. We apply this layout to all four diode lasers. All four laser systems are further lined up on an optical breadboard as is depicted in Figure 11. By this means we can couple in all four DLs into one multi-furcated fiber optic cable which allows us to use each laser without the need to change the set up.



(a) **(b)**

Figure 11: Laser set up for all four DL. Each DL is aligned to a SMA connector using a cage system and further mounted on a optical breadboard. By this means each laser can be used without changing the set up. **(a)** top view. **(b)** lateral view

2.5.4 Overview of equipment for spectral straylight calibration

Item	usable for PanS1	usable for PanS2	Existing	Added
Mounting				
Diode laser mounting system	✓	✓		✓
Light source				
405 nm diode laser	✓	✓		✓
532 nm diode laser	✓	✓		✓
650 nm diode laser		✓		✓
780 nm diode laser		✓		✓
Light source power supply				
405 nm diode laser power supply	✓	✓		✓
532 nm diode laser power supply	✓	✓		✓
650 nm diode laser power supply		✓		✓
780 nm diode laser power supply		✓		✓

2.6 Complete overview of relevant equipment

Item	usable for PanS1	usable for PanS2	Existing	Added
General equipment				
Mounting rails	✓	✓	✓	
Laser alignment tool	✓	✓	✓	
ND0.5 filter	✓	✓		✓
ND1 filter	✓	✓		✓
ND2 filter	✓	✓		✓
ND filter holder, carrier	✓	✓		✓
RelRadCal				
Mounting				
FEL lamp holder, carrier	✓	✓	✓	
head sensor holder, carrier	✓	✓	✓	
Light source				
FEL lamp working standard	✓	✓	✓	
FEL lamp reference standard	✓	✓	✓	
Light source power supply				
Heinzinger / Keithley system	✓	✓	✓	
Xantrex / Agilent system	✓	✓	✓	
WvlCal				
Mounting				
Osram lamp holder	✓	✓	✓	
Pencil style lamp holder	✓	✓		✓
Light source				

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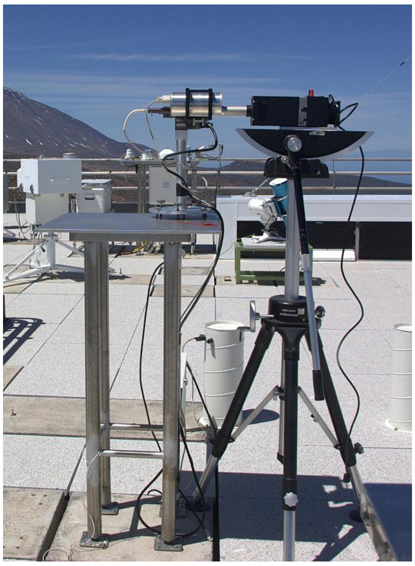
Item	usable for PanS1	usable for PanS2	Existing	Added
Ar (pencil style)	✓	✓		✓
Cd (Osram)	✓	✓	✓	
He (Osram)	✓	✓		✓
Hg (Osram)	✓	✓		✓
Hg (pencil style)	✓	✓	✓	
Kr (pencil style)	✓	✓		✓
Na (Osram)	✓	✓		✓
Ne (Osram)	✓	✓	✓	
Tl (Osram)	✓	✓		✓
Xe (pencil style)	✓	✓		✓
Zn (Osram)	✓	✓	✓	
Light source power supply				
Osram lamp power supply	✓	✓	✓	
Pencil style lamp power supply	✓	✓		✓
SpcStrCal				
Mounting				
Diode laser mounting system	✓	✓		✓
Light source				
405 nm diode laser	✓	✓		✓
532 nm diode laser	✓	✓		✓
650 nm diode laser		✓		✓
780 nm diode laser		✓		✓
Light source power supply				
405 nm diode laser power supply	✓	✓		✓
532 nm diode laser power supply	✓	✓		✓
650 nm diode laser power supply		✓		✓
780 nm diode laser power supply		✓		✓

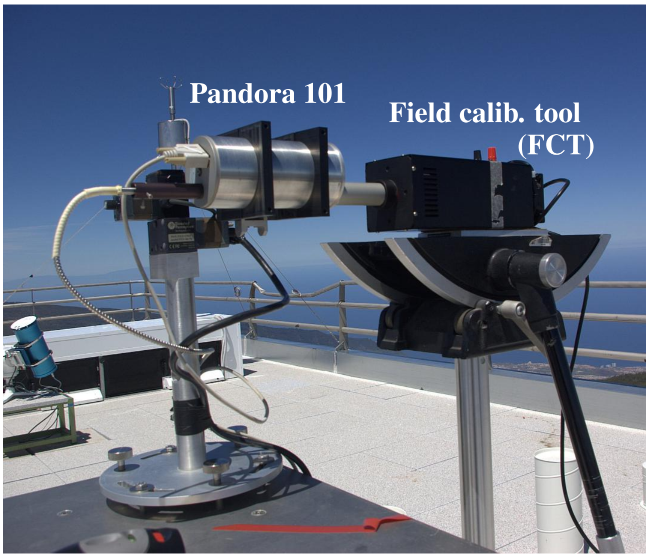
3 Laboratory Izaña Observatory

3.1 Field calibration tool

The primary products which are currently delivered by Pandora are based on DOAS like retrieval approaches. Due to the fact that the spectral background is removed by fitting a suitable polynomial, an AbsRadCal was not imperative up to now. In the framework of this project the development of an AOD retrieval is planned. Hence it is important to investigate the radiometric stability of Pandonia instruments by performing stability tests on a frequent basis. To avoid additional uncertainties by moving the instrument to the laboratory and back again the tests should be performed in the field. To do so a field calibration tool (FCT) manufactured by Bentham (CL6 Enclosed Spectral Irradiance) is adapted to be applicable also for Pandonia instruments. With this method the spectral response of the Pandonia instrument can be measured on a e.g. weekly basis without great effort. Figure 12 shows Pandora 101 at CIAI during a field calibration with FCT.



(a)



(b)

Figure 12: Pandora 101 during the field calibration using the adapted field calibration tool (FCT). **(a)** full view. **(a)** close up view.

The FCT is equipped with a 150 W quartz halogen light source. When the head sensor is coupled, the fixed effective distance between the FCT light source and the expected reference point of the Pandora instrument (the fiber surface in the head sensor) is about 55.3 cm.

We are currently at the very beginning of adapting the FCT to work properly for Pandonia instruments. As an initial step we tested the stability of the FCT radiant power measured with Pandora 101 at CIAI. Figure 13 illustrates the data in terms of signal change relative to the last measurement. Each data point is calculated by averaging over the pixels corresponding to wavelengths 410 to 534 nm. The shown period starts after about 20 minutes warm up time of the FCT. Beside an up down variation of approximately 1 % an additional drift in the signal is apparent, which adds another 1 or 2 % uncertainty. This tests has been performed under laboratory conditions. Therefore we can expect the Pandora instrument not to be responsible for this variations and must address them to the FCT stability. The estimated 3 % uncertainty in the FCT stability is about 100 times larger than it can be expected using a proper laboratory light source set up (compare Figure 4). 3 % uncertainty in the spectral signal would be reflected by an uncertainty of about 0.03 expressed in optical depths, which would be already above the AOD uncertainty we would like to reach with Pandonia. The signal variation is most likely related to the quality of the light source used in the FCT. The current performance of the FCT is not sufficient to carry out stability tests. Further improvements are necessary.

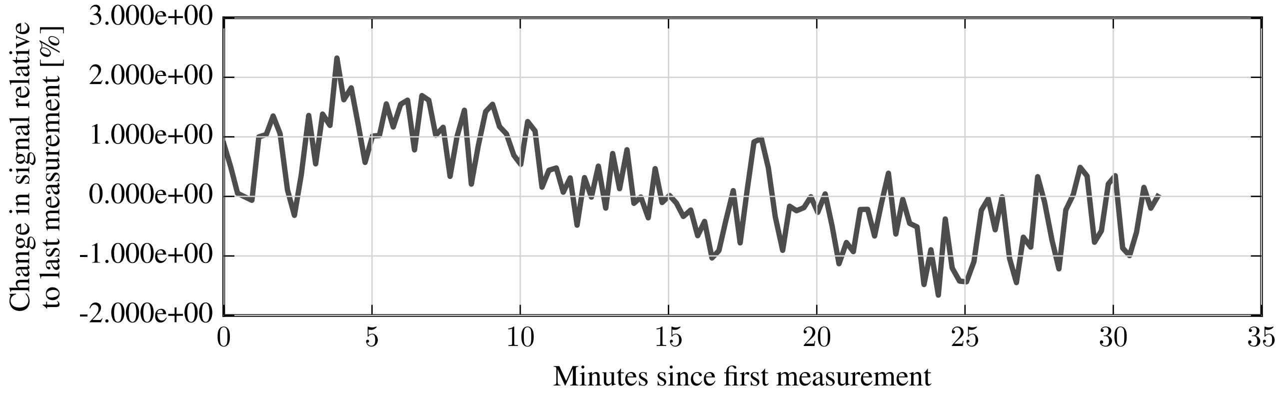


Figure 13: Stability of the input signal measured by Pandora 101 during one example field calibration session using the FCT. Data is given in relative change with respect to the last measurement.

3.2 Complete overview of relevant equipment

Item	**usable for PanS1**	**usable for PanS2**	**Existing**	**Added**
	General equipment			
Mounting rails	✓	✓	✓	
	RelRadCal			
	Mounting			
FEL lamp holder, carrier	✓	✓	✓	
DXW lamp holder, carrier	✓	✓	✓	
	Light source			
FEL lamp	✓	✓	✓	
DXW lamp	✓	✓	✓	
	Light source power supply			
Agilent / Tinsley calibrated shunt	✓	✓	✓	
	WvlCal			
	Mounting			
Osram lamp holder	✓	✓	✓	
Pencil style lamp holder	✓	✓	✓	
	Light source			
Ar (pencil style)	✓	✓	✓	
Cd (Osram)	✓	✓	✓	
Hg (Osram)	✓	✓	✓	
Xe (pencil style)	✓	✓	✓	
Zn (Osram)	✓	✓	✓	
	Light source power supply			
Osram lamp power supply	✓	✓	✓	
Pencil style lamp power supply	✓	✓	✓	
	SpcStrCal			

continued . . .

. . . continued

Item	**usable for PanS1**	**usable for PanS2**	**Existing**	**Added**
Light source				
325 nm HeCd plasma laser	✓	✓	✓	
632 nm HeNe plasma laser		✓	✓	
Light source power supply				
325 nm HeCd plasma laser power supply	✓	✓	✓	
632 nm HeNe plasma laser power supply		✓	✓	

4 Laboratory procedures

Repeatability is a mandatory requirement for the measurement and analysis of laboratory data. It ensures homogeneous instrument characterization and provides the basis for homogeneous data in a network. In order to meet this requirement we use predefined procedures for both the measurement of the laboratory data and its analysis.

Laboratory measurement routines
The measurement sequences used for each instrument characterization step (RelRadCal, AbsRadCal, WvlCal, SpcStrCal) are condensed into standardized laboratory routines [3]. These routines can be executed in the laboratory by the Blick Operation Software (BlickO), which is part of the Blick Sofware Suite (BlickSW) [7, 4].

Analysis of laboratory measurements
For analyzing the measured laboratory routines we use the Blick Calibration Software (BlickC), which is also part of BlickSW [7, 4]. BlickC is a GUI based software which visualizes the characterization process to allow the experienced user to choose the calibration parameters properly. The calibration outcome is stored in an instrument specific calibration file [3], which is finally needed for processing from L0 data (raw data) to L1 data (corrected spectra) [3, 4].

Laboratory measurement documentation
Both the laboratory measurement procedure and the laboratory data analysis are documented in dedicated overview spread sheets (Google docs). These overview files are stored on-line to allow easy sharing with designated personnel. A future version of BlickC will automatically generate a summarizing calibration report.

5 Future laboratory needs

5.1 Laboratory Innsbruck Medical University

No major upgrades are planned for LabIMU in the year 2015, except some optomechanic pieces.

5.2 Laboratory Izaña Observatory

Planned upgrades for LabCIAI (in order of importance):

1. FCT alternative: in order to test an alternative FCT (manufactured by Schreder CMS, already available at LabCIAI) an adapter piece is needed to connect the FCT and the PanS1(S2) head sensor.

2. Complete set of spectral light sources: available are Hg, Cd, Zn (Osram) and Ar, Xe (pencil style). Possible additions: He, Na, Ne, Tl (Osram); Kr (pencil style).

3. Laser facilities: available is a 325 nm laser (HeCd) and a 632 nm laser (HeNe). Possible additions: 405 nm, 780 nm laser.

4. Spectral radiance calibration: add a Spectralon® target.

6 Summary

LabIMU is the reference calibration laboratory for Pandonia instruments. Due to its initial purpose LabIMU was already well equipped and we primarily needed upgrades for WvlCal and SpcStrCal to ensure full calibration capability (compare table in section 2.6). For WvlCal we added seven spectral light sources, primarily to spectrally cover PanS2. For SpcStrCal a diode laser system was established including 4 lasers (covering PanS1 and PanS2) which are compactly placed on a movable board.

We are able to maintain a stable radiant power output for FEL light sources (see Figures 3 and 4) which is mandatory to make RelRadCal and AbsRadCal of high quality. The WvlCal benefits from ten different spectral light sources which are used for the calibration. The resulting large number of emission lines allows to apply stringed selection criteria and simultaneously ensures a very dense spectral coverage to calibrate PanS1 and PanS2 systems (see Figures 7a and 7b). In terms of DOAS based retrievals the WvlCal has the greatest impact on the trace gas and AbsRadCal on the AOD retrieval quality.

LabCIAI was not upgraded up to now, since we are concentrating on the refinement of a FCT. The FCT should allow to check the spectral stability of PanS1 and PanS2 instruments on a regular basis without the need to move the instrument to the laboratory. This is primarily important for the AOD product which will be developed as part of this project. Initial tests on the FCT revealed, however, issues with the light source stability (see Figure 13). This is presumably related to poor quality of the light source itself. Future works on this will try to enhance the FCT quality to be comparable to laboratory standards.

LabIMU will not receive further major upgrades in the year 2015. For LabCIAI upgrades will concern the FCT and spectral light sources.

All laboratory measuremnts in the course of the instrument characterization and their analysis is done in a standardized way. By this means a maxiumum of repetability is given to provide the basis for homogenized network data.