Process Description

Filter-Radiometer Calibration against the reference PFR-Triad

Contents

[1 Document Overview 3](#_Toc111814009)

[2 Calibration Overview 3](#_Toc111814010)

[3 Solar Direct Irradiance Measurements – Signals 3](#_Toc111814011)

[4 Data Selection 4](#_Toc111814012)

[4.1 Synchronization 4](#_Toc111814013)

[4.2 Cloud Screening 4](#_Toc111814014)

[4.3 Solar Tracing Efficiency 5](#_Toc111814015)

[4.4 PFR-Triad Covariance 5](#_Toc111814016)

[5 Signal Ratios comparison 5](#_Toc111814017)

[5.1 Daily Mean Top-of- Atmosphere calibration spectral values 6](#_Toc111814018)

[5.2 Point -to-point Top-of- Atmosphere calibration spectral values 6](#_Toc111814019)

[5.3 Final calibration results 7](#_Toc111814020)

[6 Wavelength Shifts 7](#_Toc111814021)

[7 Uncertainty Budget 7](#_Toc111814022)

[7.1 Calibration of Reference instruments 9](#_Toc111814023)

[7.2 Signals 9](#_Toc111814024)

[7.3 Signal Ratios Calibration Analysis 10](#_Toc111814025)

[7.3.1 Daily Mean Top-of- Atmosphere calibration spectral values 10](#_Toc111814026)

[7.3.2 Point -to-point Top-of- Atmosphere calibration spectral values 11](#_Toc111814027)

[8 Certificate Description 12](#_Toc111814028)

[9 Document Revisions 13](#_Toc111814029)

[10 Referenced Documents 13](#_Toc111814030)

# Document Overview

This document describes the calibration process of a filter radiometer against the reference PFR-Triad. The calibration of the reference instruments is described in QM-PD-WORCC-1002.

# Calibration Overview

Calibration of a filter radiometer against the reference PFR-Triad is the process of transferring the calibration factor V0 of the PFR triad to the device under test (DUT), by comparing the signal ratios of co-located and synchronized measurements under cloudless conditions.

The reference PFR-Triad consist of three PFRs at nominal center filter wavelengths 368 nm, 412 nm, 500 nm and 862 nm and bandpass of 4 ,4 ,4, 5 nm respectively. A certified calibration is possible for filter radiometers with center filter wavelengths ±2 nm up to 412nm and ±5 nm for the rest of the channels due to the recommended uncertainty by WMO for the calibration values of Langley calibrated instruments (QM-OA-WORCC-6001).

# Solar Direct Irradiance Measurements – Signals

The device under test (DUT) is installed at PMOD/WRC to perform co-located measurements with PFR-Triad. Depending on the type of the DUT, a solar tracking system of WORCC (QM-DD-WORCC-4001\_Measuring\_Equipment\_List .xlsx) with be used (e.g., PFR, SP02), unless the DUT has its own tracking system (e.g., Cimel, Prede). Similarly, the data acquisition will be performed using either the WORCC data loggers in case of PFR instruments, (QM-DD-WORCC-4003\_DataAcquisition.docx) or DUT accompanied data logging systems. The PFR-Triad is measuring the direct solar irradiance every 1-minute starting at the full minute and performing 10 sequential measurements with an integration time of 0.2ms. The average of these measurements and the standard deviation is stored by the WORCC datalogger systems. The direct Sun measurement is followed by the housekeeping and the dark signal measurements (QM-SD-WORCC-30001\_PFR\_CampellSci\_Loggers.docx). A DUT will follow the same measurements schedule by using the same DAQ program (QM-SOP-WORCC-2001\_PFR\_FR\_Calibration\_Instalation.docx), while other than PFR-DUT systems follow as frequent measurement schedule as possible providing information about the time stamps and the averaging method if any.

 Table 1. Types of instrumentation

|  |  |  |
| --- | --- | --- |
| **Device Under Test** **Type Abbreviation**  | **Data Acquisition**  | **Solar Tracker**  |
| DUT | WORCC | WORCC |
| saDUT (semi-autonomous) | X  | WORCC |
| aDUT (autonomous) | X  | X |

# Data Selection

The collected raw signal data (level1) from reference PFR-Triad and DUT are analyzed based on the most recent calibration values. In addition, for the AOD calculation it is used:

* Dark correction
* Correction for sun-earth distance (level2)
* Could flagging (level2)
* Retrieval of aerosol optical depth (AOD), and Angstrom exponent (AE) (level3)

## Synchronization

The synchronization method is based on selecting the nearest measurement of DUT to the PFR-Triad with maximum difference 30 sec which is limited for higher airmasses by a solar zenith angle (SZA) difference of ±0.03o. This SZA difference is equivalent with a time difference 15 seconds for 75 degrees SZAs.

## Cloud Screening

The cloud screening of one of the PFR-Triad instruments is used to identify clear sun time intervals with atmospheric variability, compared to a clear sky radiative transfer model of better than 0.5% per min over a time window ± 10 min from each comparison point. Cloud screening procedures for PFR instruments are described in detail in Kazadzis et al., 2018.

## Solar Tracing Efficiency

The solar tracking efficiency is monitored and evaluated by the four-quadrant sensor of the PFR-Triad reference instruments and the DUT (in case of a PFR). The references signals are accepted when the calculated pointing values within 10 arcmin both in azimuth and zenith directions relative to the sun center.

## PFR-Triad Covariance

The covariance of the PFR-Triad is checked and data with an agreement of better than 0.25% with the mean signal of the reference instruments are selected. This filtering procedure is aiming in removing outliers due cleaning or any other technical reason e.g., inhomogeneous shadowing of the reference instruments.

## Airmass Constrains - Span of measurements over airmass

The comparison is limited to airmass 4. Moreover, the span of the measurements over the day should give representative results for the methodology used to analyze the dataset. The criteria are discussed in section 5.

# Signal Ratios comparison

Using the following indexes : the reference instruments,: day of the comparison and : single measurement, a calibration based on reference instruments, lasting for days would lead to a synchronized and quality assured dataset of for each instrument.

 Each signal measurement of DUT, is converted to Top-of-Atmosphere calibration value for the DUT, denoted as , through the signal ratios ,

  where [1]

where and are the signals of the DUT and the reference PFR with a calibration factor at center wavelength of the filterradiometer channel and at the comparison point . To retrieve the final calibration of DUT, these single calibration values are analyzed following two methodologies:

* Daily Mean Top-of-Atmosphere calibration spectral values (DMC)
* Point-to-point Top-of-Atmosphere calibration spectral values (PPC)

The reason for this is that the DMC is unbalanced system as the number of measurements between-days and possibly the between-instrument varies after applying the data selection criteria. The final selection of the calibration methodology is discussed in 5.3 paragraph within the general frame that the primary calibration is the DMC and the PPC is used as verification of the DMC. In specific circumstances, such as time limitations opposed by the customer and unfavorable weather conditions, the PPC could be used.

## Daily Mean Top-of- Atmosphere calibration spectral values

The median value of signal ratios within one day ( measurements), for each comparison day , are calculated to provide the daily calibration value, based on each reference instrument (). The daily mean values are averaged for each reference instrument over the calibration period () providing the mean . The final calibration of the DUT at wavelength λ () is given by averaging the calibration factors derived by the reference instruments (). Equations 2,3,4 describe this analysis while the uncertainties are discussed in section 7.

 [2]

Where

 [3]

With daily-reference mean: [4]

and reference mean: [5]

## Point -to-point Top-of- Atmosphere calibration spectral values

In the point-to-point method all from the reference instruments and the selected data over the whole calibration period are used having the same weight on the calibration result. Their distribution is simulated with a gaussian fit (1st or 2nd order). The maximum or the centroid of the distribution, depending on the shape is the calibration of the DUT at wavelength λ () , and the spread of the distribution at the 95% percent confidence level (2σ) is the statistical uncertainty of the calibration. The probability distribution of the random variability of all signal ratios is described by the Equation 6, and similarly the associated uncertainties are discussed in section 7.

 []

 Where all available measurements and G the selected degree of the gaussian fit.

# Wavelength Shifts

The test instrument center wavelength could differ from the central wavelengths of the reference PFR-Triad resulting in a strong diurnal pattern to the signal ratios which a directly translated in a diurnal pattern in the AOD comparison result. Currently no correction is applied for this parameter. However, the impact on the calibration is assessed using the following steps

1. Verification of the of the wavelength difference impact

Following the publication Souaidia Nordine, et al. (2003), the Top-of-Atmosphere spectrum QASUME/FTS-TSIS attenuated by simulating the atmospheric condition at the time of the measurement using the measured pressure, the PFR-Triad AOD and a fixed AE (1.5 representative for Davos) and the total ozone column for the co-located measurements. The attenuated spectrum is convolved with simulated by a trapezoid filter function at central wavelength and bandpass of the reference and test instruments. The ratios of the simulated DUT values of the reference instruments provides a scaling factor accounting for the provided optical characteristics of the interference filters. If the diurnal pattern is reduced significantly then the impact of the wavelength difference is verified, and any other possibly e.g. strong non-linearity issue is excluded.

1. Assessment on the impact on the calibration

This diurnal pattern creates a bias in the calibration, depending on the time of the year that is performed, the number of clear Sun points with respect the airmass acquired during the calibration. To overcome these discrepancies a linear regression of over the airmass for each day, limiting the comparison practically days with at least half-day clear Sun conditions. The regression result replaces the daily mean values to calculate unbiased DMC . Alternatively, if the instrument is stable during the calibration, the regression analysis is performed on the whole dataset to provide a PPC . The difference is the estimated impact of the airmass due to wavelength differences with an uncertainty given by the statistics of the regression analysis.

# Uncertainty Budget

In the uncertainty analysis of the calibration transfer from the PFR-Triad to the DUT the components listed in the following table are considered. The values provided correspond to the minimum uncertainty of each component.

| **Component** | **Description** | **Type** | **Symbol** | **Sensitivity Coefficient** | **DF** | **units** | **Value** |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Calibration of Reference |  |  |  |  |  |  |
| Single Langley extrapolation  | Regression analysis  | B |  | 1 |  | % | 0.001 |
| Mean Langley calibration | Standard deviation of Langley extrapolation values over the calibration period  | B |  | 1 |  | % | 0.14 |
| Calibration Transfer | Calibration transfer to the PFR-Triad | B |  | 1 |  | % | 0.2 |
| Signals |  |  |  |  |  |  |
| Signal NoiseAtmospheric | Standard deviation of the 10 sequential measurements | A |  | 1 | 9 | V | 0.01 |
| Signal NoiseElectronic | Standard deviation of 4 months of measurement of the reference 2500 mV channel  | B |  | 1 |  | % | 0.01 |
| Dark Noise | Standard deviation of the day / period  | A |  | 1 | Ndark-1 | V | 3.10-6 |
| Dark Level  | Gain\*Dark/Signal  | B |  | 1 |  | % |  |
| FOV | 0.05%/arcmin within the range of ±10arcmin | B |  | 1 |  | % | 1/ |
| DAQ | 0.1% signal range 1-5000 mV | B |  | 1 |  | V | 10-6 |
| Non-Linearity-Gain | Gain uncertainty : estimated to 0.001%  | B |  | 1 |  | % | 0.001 |
| Non-Linearity-Logger | Manufacturer  | B |  | 1 |  | % | 0.0001  |
| Signal Ratios Calibration Analysis |  |  |  |  |  |  |
| Ratio uncertainty  | Combined uncertainty of the signals  | A |  |  |  | % |  |
| Daily mean ratio | Experimental standard deviation of the signals ratios acquired during one day | A |  |  | *Nj* |  % | 0.1 |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |

## Uncertainty of the calibration of the reference instruments

The combined standard uncertainty of the calibration of reference instruments is given by the Equation 6 and is equal for the PFR-Trial instruments.

 *[7]*

Details on the determination of the uncertainty components are given in QM-PD-WORCC-1002, QM-OA-WORCC-6006.

## Signals

The combined standard variance of the measured signal of each instrument is given by:

 [8]

The description of the symbols is on Table 1. All components with exception the have been evaluated though experience. The measurement relative uncertainty for PFRs is given by the recorded standard deviation of the 10 single measurements ,

 []

## Signal Ratios Calibration Analysis

The combined standard uncertainty of the signal ratio of the DUT measured signal over the signal of the reference instrument *i* is calculated based on the equation:

 [10]

With the uncertainty of the calibration to represented by mean ,

 [11]

The statistical uncertainty analysis for the DMC and PPC is discussed separately

###  Daily Mean Top-of- Atmosphere calibration spectral values

The experimental variance of the ratio of day, for reference of the the PFR-Triad, reference-daily mean signal ratio is given by:

  *[12]*

The experimental variance of the ratio between the days of the comparison with respect to the mean of reference PFR ratio is given by:

 []

While the variance of the individual measurements within one day is given by

 [14]

And the overall measurement variance for the campaign to be represented by the mean

 [15]

The combined variance for the duration of the campaign and the PFR-Triad is then given by,

 [16]

### Point -to-point Top-of- Atmosphere calibration spectral values

In this analysis the standard uncertainty of each is given by

 [17]

Where and are given by Equations 13 and 7 respectively. The overall uncertainty (k=2) of the calibration is given by the sum of the variance of the distribution (2σ) and the mean uncertainty of the ,

 [18]

## Total combined uncertainty

The total combined standard uncertainty in mile-Volt of the calibration based on the measurement Equation 1 is

# Final calibration results

The primary calibration is the DMC and the PPC is used as verification of the DMC and of the assumption of the random noise (gaussian distributions). In specific circumstances, such as time limitations opposed by the customer and unfavorable weather conditions, the PPC could be used after scientific judgment.

The minimum period for a complete calibration is 5 days with at least 3 hours of clear Sun data, 100 common measurements points and a span over airmass difference of 1.6. The span of 5 days has proven to be sufficient for identifying expected drifts in the instruments. In case of differences more than 1% in the calibration constants derived for different days the calibration is extended to 5 more days. If the DUT continuous to show strong degradation the customer is contacted to decide on the final duration of the calibration and a comment a comment of the observed drift is added in the certificate.

# Certificate Description

The criteria of issuing a certificate are defined:

* Calibration of the instrument should include at least 5 days of measurements with more than 900 measurement points of cloudless sky conditions in front of the sun.
* Aerosol optical depth load less than 0.4 for 500 nm for instruments that all have the same field of view and lower than 0.2 for instrument with different field of view.

Following the norm (article 7.8.2) the information included in the certificate are:

* The identification mask is constructed by the first measurement date (dd.mm.yyyy) and the certificate issue date.
* The calibration values along with the combined expanded uncertainty at the instrument’s wavelength are clearly stated.
* The serial numbers of the PFRs forming the reference PFR-Triad at that time is stated along with the range of the ambient operating temperatures during the calibration period.
* The criteria reported in section 4 and 8 of this document are fulfilled.
* Comments on the mechanical, electronic and pressure status of DUT up on arrival to WORCC, PMOD/WRC and its performance during the calibration are added.

In the certificate the calibration methodology is briefly presented. An example of a WORCC certificate is shown in QM-FS-WORCC-5002.

# Document Revisions

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Version** | **Release Date** | **Approved By** | **Modified on** | Created/Edited by | **Changes** |
| 0.0 |  |  | 02.Sep.2021 | NK | Document created |
| 0.1 |  |  | 18.Oct. 2021 | SK | Revised  |
| 0.2 |  |  | 20.Oct. 2021 | JG | Revised  |
| 0.3 |  |  | 27.Apr.2021 | NK | Revised A certified calibration is possible for filter radiometers with center filter wavelengths ±2 nm up to 412nm and ±5 nm for the Derivatives , reference for wavelength shift  |
| 0.4 |  |  | 04 May 2022 | SK |  |
| 0.5 |  |  | 29.Aug.2022 | NK | Uncertainty added, wavelength shift - revised  |

*Note:*

*Versioning a draft document: 0.x*

*Versioning of a shared document: 1.x*

*Version increment (x) for a significant change: x.1*

*Version increment (x) for a minor change: 1.x*

# Referenced Documents

1. 2003: Comparison of laser-based and conventional calibrations of sun photometers (<https://doi.org/10.1117/12.508197>)

2. QM-PD-WORCC-1002: PFR\_TRIAD\_Calibration\_Validation\_Operation.docx

3. QM-FS-WORCC-5002: WORCC\_Calibration\_Certificate\_example.pdf

4. QM-OA-WORCC-6001: WMO\_GAW\_ReportNo227.pdf (<https://library.wmo.int/doc_num.php?explnum_id=3073>)

5. QM-OA-WORCC-6006: Langley validation report.docx