Process Description

PFR AOD uncertainty budget

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# Introduction

This document contains a comprehensive uncertainty estimate of spectral AOD retrieved from solar irradiance measurements using narrowband filter radiometers. The uncertainty estimation will be aimed at reference radiometers. The uncertainty of AOD obtained from instruments operated operationally in a network will be included at a later stage. The uncertainty estimations will be specifically aimed at the three main aerosol monitoring networks GAWPFR, AERONET, SKYNET.

# Measurement equation

The spectral AOD is calculated using the Beer-Lambert law as,

Where

Expanded to explicitly mention all main gases, yields the measurement equation for AOD,

Where

Where the wavelength term has been omitted for simplicity.

* is the measured direct solar irradiance I (signal or calibrated) corrected for the contributions of cleaning efficiency , straylight in the FOV of the instrument and attenuation due to clouds .
* I0 is the solar irradiance at the top of the atmosphere
* τray is the optical depth of Rayleigh scattering
* mray is the airmass for Rayleigh scattering
* τNO2 is the optical depth of nitrogen dioxide
* mNO2 is the airmass for nitrogen dioxide
* τO3 is the ozone optical depth
* mO3 is the ozone airmass
* m is the aerosol airmass
* P is the pressure at the site
* P0 is the pressure at 1 atm, 1013.25 mbar
* total column of trace gas
* trace gas absorption cross-section weighted by the normalized measured or assumed responsivity of the filter with centroid wavelength λ

# Sensitivity components

The sensitivity components are:

|  |  |  |  |
| --- | --- | --- | --- |
| **Irradiance** | **Optical path - Airmass** | **Trace Gases Concentration/ Total column** | **Wavelength** |
|  |  | Where  Or |  |
|  |  |  |  |
|  |  |  |  |
|  | …. | …. | … |
|  |  |  |  |

# Uncertainty components

The uncertainty budget is then calculated from the individual uncertainty components according to

The partial derivatives for *u*xi are as defined above.

## Direct solar irradiance measurement I

The measurement uncertainty ui is composed of the uncertainty of the data acquisition unit udaq, the uncertainty in the dark signal, udark, the standard deviation of the measurements, ustd, the electronic stability of the instrument and the DAQ system uref 2.5V and the uncertainty uFOV-Hom associated with the pointing tolerance of 10 arcmin from the centre of the plateau in conjunction with the field of view homogeneity of 2%. For the PFRs operated within the GAWPFR network, typical values are udaq=10-6 V, udark=3\*10-6 V, ustd=0.01 %. For uFOV-Hom it is assumed that the uncertainties are maximum limits (rectangular distribution), so uFOV-Hom = 1/ %.

The average signal level is of the order of S=2.0 V, and 10 measurements (N) are acquired to form an average value, the relative standard measurement uncertainty is:

|  |  |  |  |
| --- | --- | --- | --- |
|  | udark | ustd | uFOV-Hom |
| 10-6 V | 3E-6 V | 0.01 % | 1/√3 % |

## 

## Top of atmosphere solar irradiance

The top-of-atmosphere irradiance value is retrieved by the Langley extrapolation procedure of several days of measurements. PFR Langley are performed in a 6-month period. This aims in increasing the number of Langley days in the statistics, based on the fact that instruments have negligible change in responsivity within this period. The average number of points used is in the order of 70. Based on Eq. 1 the AOD uncertainty,that is related only to the Langley calibration factor equals where is the uncertainty of Napierian logarithm of defined be the Langley extrapolation or the relative uncertainty of , . The uncertainty of can be described by the coefficient of variation (standard deviation / mean, (CV)) column 2 of next table) or in the case of a normal distribution by the standard error (standard deviation divided by the square root of the number of measurements, (SE)) (column 3).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **(aod)** | | **(%)** | |
| **PFR wavelength**  **(nm)** | **Coefficient of variation** | Standard Error (norm. distribution) | **Coefficient of variation** | Standard Error (norm. distribution) |
| **368** | **0.0013** | 0.00015 | **0.13** | 0.015 |
| **412** | **0.0015** | 0.00015 | **0.15** | 0.015 |
| **500** | **0.0014** | 0.00014 | **0.14** | 0.014 |
| **863** | **0.0017** | 0.00009 | **0.17** | 0.009 |

## Rayleigh optical depth

The Rayleigh optical depth is calculated according to the formula of Bodhaine, 1999, or Nicolet, 1984. For the wavelength range between 300 nm and 1200 nm and at STP, the Rayleigh optical depth calculated with the two formulas, diverge by not more 0.001 in optical depth. Therefore, the standard uncertainty .

## Atmospheric pressure

The ambient pressure is monitored with a calibrated air pressure sensor connected to the data acquisition system of the PFR unit. The corresponding standard uncertainty uP is assumed to be less than 2 mbar. The main impact is on the Rayleigh correction, so at 500 nm, and using the formula of Bodhaine, the sensitivity coefficient

## Ozone optical depth

The only sensitivity to atmospheric ozone is for the 500 nm channel of the PFR. For all other channels it is assumed to be negligible. The uncertainty of the total column ozone is assumed to be maximal 10 DU (uncertainty of the climatology used), which at 500 nm and using the absorption ozone cross-sections of Serdyuchenko et al., 2013 at -45 °C results in a standard expanded uncertainty of

## Nitrogen Dioxide optical depth

The sensitivity to nitrogen dioxide is calculated similarly to the one for atmospheric ozone. This estimation applies to pristine conditions for example at Davos. Currently WORCC does not correct for NO2, so the values are bias. It is calculated assuming a standard uncertainty of the nitrogen dioxide of 0.05 DU, which yields for the PFR channels (NO2 absorption cross sections from Vandaele A.C., et. Al. (1996), at 294 K):

|  |  |
| --- | --- |
| Channel /nm | assuming 0.05 DU |
| 368 | 7e-4 |
| 412 | 8e-4 |
| 500 | 2.5e-4 |
| 862 | 0 |

## 

## Airmass

#### Aerosol airmass

Uncertainty in the optical path for aerosols (m) is calculated assuming the aerosol layer at 4 km and an uncertainty of ±1 km of the layer height.

= 0.001)= 5.7735e-04.

#### Ozone airmass

The height of the effective ozone layer is assumed to be at 22 km. The seasonal variability of this height depends on latitude and can be up to 4 km at low to middle latitudes. The corresponding uncertainty of the airmass calculation

= 0.003)= 0. 0017

#### NO2 airmass

The height of the peak concentration of NO2 is assumed to be at the same height of the aerosol layer.

## Field of view stray light

The stray light from the finite field of view depends strongly on the amount and type of aerosols, which affects the forward scattering into the field of view of the instrument. For reference instruments and pristine conditions, the uncertainty is less than 0.5% of the measured AOD for all wavelengths.

Instruments performing measurements at areas with large particles ( e.g. Deserts) would have additional uncertainties due to the larger effect of forward scattering. For that case we have calculated using two conditions/scenarios : AOD at 500 nm [0.15 0.4] (global average and relatively high) and two aerosol mean effective radii [0.2 1.5] (μm) (small and large particles). The forward scattered radiation is also a function of the airmass, with larger scattering at higher airmass (Cuevas et al., 2019)

The corresponding uncertainty is shown here for an airmass of 2, corresponding to a solar zenith angle of 60:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Channel /nm | Stray-light contribution in optical depth units | | | |
| AOD @ 500 nm = 0.15 | | AOD @ 500 nm = 0.4 | |
| Aer. radii 0.2 μm | Aer. radii 1.5 μm | Aer. radii 0.2 μm | Aer. radii 1.5 μm |
| 368 | <0.0004 | 0.0075 | <0.001 | 0.02 |
| 412 | <0.0004 | 0.006 | <0.001 | 0.016 |
| 500 | <0.0004 | 0.0045 | <0.001 | 0.012 |
| 862 | <0.0004 | 0.003 | <0.001 | 0.008 |

## Window cleaning

For good cleaning (daily), the differences are less than 0.1% in signal levels.

## Cloud contamination

The uncertainty described here is for best case scenarios for clear sky conditions. For this report, it is assumed to be zero. It is a difficult parameter to assess. For a network product it is non-zero, but for a reference measurement it can be assumed zero (best case conditions).

## Uncertainty Budget

The uncertainty components depend on the airmass and specific wavelength. For this table, the compiled values are calculated for a solar zenith angle of 60° (airmass 2), a wavelength of 500 nm and a pressure of 1013.15 mbar, O3=350 DU, N02 =0.2 DU and AOD at 500 nm = 0.15 and Aer. radii 0.2 μm.

Table 1: Optical depth uncertainty budget for a reference precision filter radiometer (PFR) of GAWPFR-WORCC at 500 nm and at ground level for O3=350 DU ,N02 =0.2 DU and AOD at 500 nm = 0.15. The resulting optical depth uncertainty is unitless.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Parameter** | **Value xi** | **Uncertainty**  **unit** | **Uncert type** | **Distribution** | **Nb. Deg. Freedom** | **Uncertainty u(xi)** | **Sensitivity coeff. C** | **C.u(xi)** | **Unit C.u(xi)** |
| ***I*** | 2 | Relative | A | Normal | 10 | 5.77E-03 | 0.50 | 2.89E-03 | aod (dimensionless) |
|  | 0 | Relative |  |  |  | 4.00E-04 | 0.50 | 2.00E-04 |
|  | 0 | Relative |  | Rectangular |  | 5.00E-04 | 0.50 | 2.50E-04 |
|  | 0 | Relative |  | Rectangular |  | 0.00E+00 | 0.50 | 0.00E+00 |
| ***I0*** | 3.7 | Relative | A | Normal | 30 | 1.40E-03 | 0.50 | 7.00E-04 |
| **P** | 1013.15 | mbar | B | Normal |  | 2.00E+00 | 7.1E-5 | 1.41E-4 |
| **τray** | 0.1434 | OD |  |  |  | 5.8E-04 | 1.00 | 5.8E-04 |
| **τΝ02** | 0.001 | OD | B | Rectangular |  | u(**TCNO2**) | 1.00 | 2.49E-04 |
| **τΟ3** | 0.0118 | OD | B | Rectangular |  | u(**TCO3**) | 1.00 | 1.80E-04 |
| **M** | 2 |  | B | Rectangular |  | 5.77E-04 | 0.075 | 4.33E-05 |
| **mray** | 2 |  | B | Rectangular |  | 5.77E-04 | 0.072 | 4.14E-05 |
| **mO3** | 2 |  | B | Rectangular |  | 1.70E-03 | 0.011 | 1.92E-05 |
| **mNO2** | 2 |  | B | Rectangular |  | 5.77E-04 | 0.001 | 5.76E-07 |
| **XSray** | 0.1434 | 1/cm | B | Rectangular |  | 5.90E-04 | 1.000 | 5.90E-04 |
| **XSo3** |  | 1/DU | B | Rectangular |  | 1.16E-03 | 0.350 | 4.07E-04 |
| **XSN02** |  | 1/DU | B | Rectangular |  | 4.96E-05 | 0.200 | 9.92E-06 |
| **Combined uncertainty** | | | | | | | | **0.0031** |
| **Expanded uncertainty (k=2)** | | | | | | | | **0.0063** |

# Document Revisions

|  |  |  |  |  |  |
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| **Version** | **Release Date** | **Approved By** | **Modified on** | Created/  Edited by | **Changes** |
| 1.0 |  |  | 19.01.2023 | nk | created |
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*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*

# Reference Documents