Brewer UV measurement and calibration

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Overview

• Comparison Brewer O3 and UV measurements
• Brewer characterisation
  • UV Calibration
  • Wavelength scale
  • Temperature correction
  • Angular response
• QA/QC procedures
• Comparison with QASUME reference
The Brewer spectrophotometer

Modified Ebert Grating Spectrometer with photon counting detection and six exit slits

Basic design features:
• Spectral purity
• Wavelength step 0.0075 nm/step
• Passive temperature compensation
• High wavelength stability

Figure 2.5: Top View of Spectrophotometer
Brewer O3 versus UV

Ozone measurement ds (zs)
1. Direct sun, FOV ~ 2°
2. Ground quartz
3. ND filter selection automatic
4. Measurements through all exit slits
5. Grating fixed
6. Quasi-simultaneous measurements at 6 wavelengths

7. Temperature correction using R6-ratios
8. Relative measurement (double ratio)
9. Calibration using travel standard or in-situ (langley-plot)

UV measurement ul, ux, ua
1. Global irradiance, FOV 2π
2. Teflon diffuser (UVB port)
3. ND filter manual (constant in icf file)
4. Slit 1 and slit 5 (above 350 nm)
5. Grating rotated
6. Each wavelength measured sequentially

7. No automatic temperature correction
8. Absolute measurement (W/m²/nm)
9. Laboratory calibration using irradiance transfer standards (1000 W lamps)
Characterisation of a Brewer spectrophotometer for global spectral UV measurements

- Spectral responsivity
- Wavelength dispersion relation
- Spectral resolution (slit function)
- Angular response of entrance optic (diffuser)
- Temperature dependence
- Linearity
Measurement principle for spectral solar UV irradiance

\[ I \left[ \frac{W}{m^2 \cdot nm} \right] = \frac{signal_{SUN} \left[ \text{photons} \cdot s^{-1} \right]}{\text{Responsivity} \left[ \text{photons} \cdot s^{-1} \cdot W^{-1} \cdot m^2 \cdot nm \right]} \]

The Instrument responsivity is obtained by measuring the response of the instrument to a source with known radiation.

Typically a tungsten-halogen lamp with a calibration certificate

\[ \text{Responsivity} \left[ \text{photons} \cdot s^{-1} \cdot W^{-1} \cdot m^2 \cdot nm \right] = \frac{signal_{LAMP} \left[ \text{photons} \cdot s^{-1} \right]}{\text{Lamp Irradiance} \left[ W \cdot m^{-2} \cdot nm^{-1} \right]} \]

\[ I \left[ \frac{W}{m^2 \cdot nm} \right] = \frac{signal_{SUN}}{signal_{LAMP}} \cdot \text{Lamp Irradiance} \left[ W \cdot m^{-2} \cdot nm^{-1} \right] \]

We assume that the relationship is independent on the level of radiation e.g. the instrument is linear...
Linearity

The radiation from lamps used for the calibration is 10 to 100 times weaker than the solar radiation. It is necessary to check the linearity of the spectroradiometer to be able to convert from photons to irradiance:

\[ I[Wm^{-2}nm^{-1}] = \frac{signal_{SUN}}{signal_{LAMP}} \cdot Lamp\ Irradiance\ [Wm^{-2}nm^{-1}] \]
Linearity and Neutral Density choice for global UV measurements

The radiation from lamps used for the calibration is 10-100 times weaker than the solar radiation. It is necessary to check the linearity of the spectroradiometer to be able to convert from counts to irradiance:

\[
I \left[ \text{Wm}^{-2} \text{nm}^{-1} \right] = \frac{\text{signal}_{\text{SUN}}}{\text{signal}_{\text{LAMP}}} \cdot \text{Lamp Irradiance} \left[ \text{Wm}^{-2} \text{nm}^{-1} \right]
\]

Deadtime correction algorithm: Brewer uses up to 80000 counts/cycle (for ds). This corresponds to \( \sim 1.5 \times 10^6 \) photons/sec

\[
N = N_0 e^{-\tau N_0} \quad \text{Deadtime correction of about 6%}
\]

The UV scans (ul, ux) use a fixed ND-Filter which needs to be selected based on the maximum expected irradiance at each measuring site.
Brewer specifics

Brewer counts photons for a defined time

- It returns **counts** summed over the number of measurement cycles
- For example: \[ R, 2, 2, N:0 \]
  means, measure on slit 1 for \( N \) cycles and return the number of counts.

- In the Brewer, **1 count = 4 photons** (prescaler mounted directly on the PMT)
- Integration time: \( N \) cycles = **0.1147 seconds \( \times 2N \)** ("N scans up & down")

- Thus, the number of photons:

\[
\text{photons / second} = \frac{\text{counts} \times 4}{0.1147 \times 2 \times N}
\]
Brewer specifics

Statistical measurement uncertainty (standard deviation)

Measurement statistics follow Poisson statistics (discrete probability function).

For the Brewer, this can be used to estimate the standard deviation of the measurements.

\[
\text{Signal} = N \text{ photons}
\]
\[
\text{std}(\text{signal}) = \sqrt{N}
\]

Example: 10 cycles, Signal = 3000 counts = 12000 photons total, and 50000 ph/sec

\[\rightarrow \text{std}(\text{signal}) = 109 \text{ photons}, \sim 0.9\% \ (109/12000)\]

**Rule of thumb**

- 2500 counts = \(10^4\) photons \(\rightarrow\) 1\% uncertainty
- 250 000 counts = \(10^6\) photons \(\rightarrow\) 0.1\% uncertainty
Wavelength scale calibration

Goal: find a relationship between the grating rotation and wavelength.

- The wavelength scale is determined from measurements of discrete spectral lines from spectral discharge lamps (Mercury, Cadmium, Zinc, Indium).
- A smooth function (polynomial) describes the relation between the grating angle (micrometer steps) and the wavelength of each spectral line.

<table>
<thead>
<tr>
<th>Emission lines:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mercury</strong></td>
<td>289.360 nm</td>
</tr>
<tr>
<td></td>
<td>296.728 nm</td>
</tr>
<tr>
<td></td>
<td>334.148</td>
</tr>
<tr>
<td><strong>Cadmium</strong></td>
<td>313.317</td>
</tr>
<tr>
<td></td>
<td>326.105</td>
</tr>
<tr>
<td></td>
<td>340.365</td>
</tr>
<tr>
<td></td>
<td>349.995</td>
</tr>
<tr>
<td><strong>Indium</strong></td>
<td>293.263</td>
</tr>
<tr>
<td></td>
<td>303.936</td>
</tr>
<tr>
<td><strong>Zinc</strong></td>
<td>310.836</td>
</tr>
<tr>
<td></td>
<td>303.578</td>
</tr>
<tr>
<td></td>
<td>328.233</td>
</tr>
</tbody>
</table>
Example of dispersion measurement on slit 1

\[ f(\text{nm}) = -7.3 \times 10^{-7} x^2 + 0.0768 x + 280.21 \]
Slit function

The slit function represents the response of the spectroradiometer to monochromatic light.
It is obtained by scanning though the output of a monochromatic source i.e. laser line or spectral discharge lamp.

The slit function is necessary for determining the spectral resolution of the spectroradiometer (stray light, Full width at half maximum)
Resolution of Solar Spectra

![Resolution of Solar Spectra Graph](image)

- Resolution: 0.5 nm and 1 nm
- Wavelength: 360 to 400 nm
Resolution of solar spectra

![Graph showing the resolution of solar spectra with wavelength on the x-axis and ratio on the y-axis.]
Slit function
Single versus double Brewer

The double Brewer includes a second monochromator (called recombining monochromator), to reduce the stray light of a single Brewer. Laboratory measurements using HeCd laser line and outdoor comparisons demonstrate the improved stray light reduction in double Brewers:

Slit function measurement

![Slit function graph](image)

<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
<th>Signal normalized to maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2</td>
<td>10^-2</td>
</tr>
<tr>
<td>-1.5</td>
<td>10^-1</td>
</tr>
<tr>
<td>-1</td>
<td>10^0</td>
</tr>
<tr>
<td>-0.5</td>
<td>10^1</td>
</tr>
<tr>
<td>0</td>
<td>10^2</td>
</tr>
<tr>
<td>0.5</td>
<td>10^3</td>
</tr>
<tr>
<td>1</td>
<td>10^4</td>
</tr>
<tr>
<td>1.5</td>
<td>10^5</td>
</tr>
<tr>
<td>2</td>
<td>10^6</td>
</tr>
</tbody>
</table>

HeCd Laser scan at 325 nm

Mean ratio FIS/QASUME at Sodankyla: 08–Jun–2007(159) to 12–Jun–2007(163)

- Mean ratio SZA=75
- Mean ratio SZA=50
- 95th percentile
- Range of values

NB_spectra = 120
Angular response

To measure spectral global irradiance, the detector needs to weight incoming radiation with the cosine of the incident angle relative to normal incidence. A deviation from this cosine response leads to errors in the measured global solar irradiance which depends on the atmospheric conditions.

\[
E_{\text{glo}} = E_{\text{dir}} + E_{\text{dif}}
\]

Cosine error

Clear atmospheric conditions

Daily variation. Wavelength bands

TIME [UT](SZA)
Temperature correction

The temperature dependence is determined by measuring a stable radiation source (for example a 50 W lamp), at different instrument temperatures. The measurements will result in a spectral temperature coefficient for a specific instrument.

~ -0.3% K^{-1}
Temperature dependence of the entrance optic

At 19°C, there is a change in the crystal structure of Teflon which produces an abrupt change in transmission of the order of 3%, probably depending on the thickness of Teflon.

Global UV irradiance evaluation

Procedure to go from raw (counts) to calibrated (Wm\textsuperscript{-2}nm\textsuperscript{-1}) spectrum:

1) Raw spectrum \( S(\lambda) \) counts
Global UV irradiance evaluation

Procedure to go from raw (counts) to calibrated (Wm$^{-2}$nm$^{-1}$) spectrum:

1) Raw spectrum $S(\lambda)$ counts
2) Remove dark signal $S(\lambda)$-dark counts
Global UV irradiance evaluation

Procedure to go from raw (counts) to calibrated (Wm\(^{-2}\)nm\(^{-1}\)) spectrum:

1) Raw spectrum \( S(\lambda) \) counts
2) Remove dark signal \( S(\lambda) \)-dark counts
3) Remove Straylight (Single Br) \( S(\lambda) \)-dark-S(<292nm) counts

Br #66 Single
Global UV irradiance evaluation

Procedure to go from raw (counts) to calibrated (Wm$^{-2}$nm$^{-1}$) spectrum:

1) Raw spectrum $S(\lambda)$ counts
2) Remove dark signal $S(\lambda)$-dark counts
3) Remove Straylight (Single Br) $S(\lambda)$-dark-$S(<292\text{nm})$ counts
4) Convert to photons/sec $(S(\lambda)$-dark-sr)*4/IT photons/sec
Global UV irradiance evaluation

Procedure to go from raw (counts) to calibrated (Wm$^{-2}$nm$^{-1}$) spectrum:

1) Raw spectrum  
   $S(\lambda)$  
   counts

2) Remove dark signal  
   $S(\lambda)$-dark  
   counts

3) Remove Straylight (Single Br)  
   $S(\lambda)$-dark-$S(<292\text{nm})$  
   counts

4) Convert to photons/sec  
   $(S(\lambda)$-dark-$sr)*4/IT$  
   photons/sec

5) Correct for Linearity  
   $S'(\lambda)$  
   photons/sec

14/10/2014
Brewer UV Measurements and calibration
Global UV irradiance evaluation

Procedure to go from raw (counts) to calibrated \((Wm^{-2}nm^{-1})\) spectrum:

1) Raw spectrum \(S(\lambda)\) counts
2) Remove dark signal \(S(\lambda) - \text{dark}\) counts
3) Remove Straylight (Single Br) \(S(\lambda) - \text{dark} - S(<292nm)\) counts
4) Convert to photons/sec \((S(\lambda) - \text{dark} - \text{sr}) * 4/IT\) photons/sec
5) Correct for Linearity \(S'(\lambda)\) photons/sec
6) Apply Sensitivity \(E(\lambda) = S'(\lambda) / \text{Sens}(\lambda)\) \(Wm^{-2}nm^{-1}\)
Global UV irradiance evaluation

Procedure to go from raw (counts) to calibrated (Wm$^{-2}$nm$^{-1}$) spectrum:

1) Raw spectrum \( S(\lambda) \) counts
2) Remove dark signal \( S(\lambda) - \text{dark} \) counts
3) Remove Straylight (Single Br) \( S(\lambda) - \text{dark} - S(<292\text{nm}) \) counts
4) Convert to photons/sec \( (S(\lambda) - \text{dark} - \text{sr}) \times 4/IT \) photons/sec
5) Correct for Linearity \( S'(\lambda) \) photons/sec
6) **Apply Sensitivity** \( E(\lambda) = S'(\lambda)/S_{\text{ens}}(\lambda) \) Wm$^{-2}$nm$^{-1}$

Advanced

7) Apply Temp. Corr \( dT/K \)
8) Apply Wavelength shift \( d\lambda \)
9) Spike correction
10) Cosine correction
Lamp irradiance traceability chain

cryogenic radiometer ±0.01%

Filter radiometer (trap detector)

Transfer standard (horizontal beam) ~±1%

Transfer standard (vertical beam) ~±1.5%

black-body ±0.5 K ~±0.5%

Portable transfer Standard ±3%

Spectroradiometer ~±5%
Spectral responsivity calibration
Example Brewer #163

![Graph showing responsivity change from slit 1 to 5](image)

Responsivity

- photons/mW/m2/nm/s
- Wavelength /nm

Change from slit 1 to 5
Example Brewer #163

Ratio of 2 scans vs Wavelength (nm)

Wavelength (nm):
- 280
- 300
- 320
- 340
- 360

Ratio:
- 0.97
- 0.98
- 0.99
- 1.00
- 1.01
- 1.02
- 1.03

Graph showing the ratio of 2 scans across different wavelengths.
Spectral responsivity calibration in the field

How to transfer the laboratory calibration to the outdoor measurement site?

Calibrated transfer standards (1000 W lamps) are used in a dark room laboratory in controlled ambient conditions (temperature, humidity, stray light). Instrument transportation?

Use a **portable calibrator** to transfer the laboratory calibration to the outdoor site (50W lamp system for example). The portable field calibrator is only used as a **relative** transfer standard, usually for a specific Brewer.
Lamp Current

Spectral Irradiance standards operate at a stable nominal current, typically, 1000W and 8.0 A. The voltage is monitored to check for drifts and changes of the lamp.
Summary of a lamp calibration

1000 W Calibration:

- Lamp current should be stabilised to within 0.1% of the nominal value (for example 8.0 A) for an irradiance stability of 1%.
  - In the UV, 1% change in current corresponds to 10% change in lamp radiation output.
- Distance between spectroradiometer reference plane and lamp reference plane should be well known (square law).
  - Error = $2\Delta d/d$,
    i.e. ±1 mm uncertainty in 500 mm produces uncertainty in calibration of ±0.4%.
- Calibration frequency ~ 1/month.

Portable calibration (50 W lamps):

- Portable calibrator should be calibrated relative to 1000 W calibration.
- Calibration frequency ~ 1/week.

Each calibration should consist of the average of several lamps (i.e. at least three) to detect drifts and fluctuations of individual lamps.
QA/QC procedures

- Ancillary instruments (UV broadband radiometer)
- Comparison with model calculations
  - Only upper limit from clear-sky simulation
- Comparison with satellite estimation
  - Satellite products still have uncertainties of the order of ±20%.

- Wavelength alignment using matSHIC or SHICRivm
- Comparison with a reference instrument
  (transportable QASUME reference spectroradiometer)
Broadband weighting

\[ E_{\text{erythema}} = \int \text{Nominal Broadband weighting function} \cdot \text{solar spectrum} \, d\lambda \]

\[ \cdots + \delta E \text{ (360-400 nm)} \]
Brewer Spectra are integrated with the weighting function representative for the broadband radiometer (for example erythemal weighted irradiance).
Model & Satellite comparison

Clear Sky

Satellite

Model

Courtesy N. Kouremeti

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Brewer UV Measurements and calibration
Wavelength alignment

Comparison of measured solar spectra with a high resolution spectrum convolved with the instrument slit function.

Residuals of the ratio between the two spectra are minimised by shifting the wavelength of the high resolution spectrum.

Wavelength differences between the two spectra can be determined with a precision of 0.01 nm (or better).

at 317 nm: \( \text{dwl} = -0.015 \text{ nm} \)
Example of use

Two available packages:

- **SHICRivm**, stand-alone software
  http://www.rivm.nl/shicrivm

- **matSHIC**, open-source, based on matlab
  email to julian.groebner@pmodwrc.ch
European UV Quality Assurance Program

Quality site audit with the QASUME reference spectroradiometer

Status 2002 - 2013

- 64 site visits
- 34 sites
- >150 spectroradiometer intercomparisons

Ny Ålesund, Spitzbergen, 2009

RBCC-E, 2005-2013

Gröbner et al., Appl. Opt. 2005
Gröbner et al., Metrologia, 2006

Comparison of spectroradiometers

- Same wavelength scale
- Uniform slit width (1 nm default)

\[
R(\lambda) = \frac{\text{TEST}(\lambda)}{\text{QASUME}(\lambda)}
\]
Daily ratios to QASUME: The ideal case
And what we often see...
Conclusions

• Calibrations using traceable transfer standards (1000 W lamps) are necessary to obtain reliable solar UV measurements.
• Individual characterisation of each spectroradiometer is necessary to achieve reliable performance.
• Regular quality control procedures provide confidence in the measurements and allow the early detection of instrumental problems.
• Brewer specifics:
  – Temperature correction (including entrance optic)
  – Cosine error correction
  – Stray light in single Brewers
  – Neutral density filter selection to limit the nonlinearity correction (correction should be below 5%)
  – 50 W lamps (or other portable lamp system) for routine spectral sensitivity checks.
• QASUME site visit provides objective assessment of instrument performance in a European context.
Supplementary Material
Brewer O3 versus UV

Quality control tools

O₃

• Standard tests
  – sl  R6 ratios
  – rs  run-stop

• O₃ from satellite (TOMS, …)
• close-by sites (good correlation)

UV

• ul  50 W lamps
• SHICRivm – wavelength alignment check

dt  Linearity test (deadtime)
dsp  Dispersion relation

• UV from satellite ???
• Ancillary instruments (broadband radiometers)
• Radiative transfer calculations using Brewer O₃ (and aod)

Quality Assurance / calibration

Travel standard (Br#17)  ↔  Travel standard (QASUME)
Problematic:

1) Solar irradiance measurements are obtained with the detector looking upwards (vertical beam), while lamps are calibrated for a horizontal beam (vertical detector).
Example of Calibration history on Brewer #66
Angular response

To measure spectral global irradiance, the detector needs to weight incoming radiation with the cosine of the incident angle relative to normal incidence. A deviation from this cosine response leads to errors in the measured global solar irradiance which depends on the atmospheric conditions.

\[ f_{\text{glo}} = f_{\text{dir}} \frac{I_{\text{dir}}}{I_{\text{glo}}} + f_{\text{dif}} \frac{I_{\text{dif}}}{I_{\text{glo}}} \]

Hazy atmospheric conditions
Brewer Temperature Sensitivity

Data from Brewer#066

Before

After:
SHICRivm single scan statistics

2221000G 2007 sza 36.218 UVA_transmission: GREEN  LOW_OR_NO_CLOUDS  scan_variability: VERY_STABLE_SCAN
shift1_flagging  GREEN  0.011 (nm)
shift2_flagging  GREEN  0.032 (nm)
start_irradiance_flag  GREEN  0.000032 maximum_below_first: 0.000011
Spike+local_shape  GREEN
Transmission_2  GREEN  LOW_OR_NO_CLOUDS  1.12423035  1.52  all 1.08779426  7.49
scan_variability_2  GREEN  VERY_STABLE_SCAN  1.52 =sd trans2
spike_flag_median_based  GREEN
start_wavelength_flag  GREEN  293.23 (nm)  efuv_below: 0.00 %
last_wavelength_flag  GREEN  400.00 (nm)  efuv_above: 0.00 %
Median_irradiance_flag  NOT_EXTREME  Median_Irradiance: 0.07496681 at 310.00 nm
**SHICRivm single scan statistics**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2201000G 2007 sza 35.747 UVA_transmission: GREEN</td>
<td>CLOUDS scanVariability: VERY_LARGE_VARIATION_SCAN</td>
</tr>
<tr>
<td>shift1_flagging</td>
<td>GREEN -0.017 (nm)</td>
</tr>
<tr>
<td>shift2_flagging</td>
<td>GREEN -0.035 (nm)</td>
</tr>
<tr>
<td>start_irradiance_flag</td>
<td>GREEN 0.0000031 maximum_below_first: 0.0000011</td>
</tr>
<tr>
<td>spike+local_shape</td>
<td>YELLOW</td>
</tr>
<tr>
<td>Transmission_2</td>
<td>GREEN CLOUDS 0.63481954 22.63 all 0.66000457 20.37</td>
</tr>
<tr>
<td>scanVariability_2</td>
<td>VERY_LARGE_VARIATION_SCAN 22.63 =sd trans2</td>
</tr>
<tr>
<td>spike_flag_median_based</td>
<td>YELLOW 292.98 (nm) efuv_below: -0.00 %</td>
</tr>
<tr>
<td>start_wavelength_flag</td>
<td>GREEN 400.00 (nm) efuv_above: 0.00 %</td>
</tr>
<tr>
<td>last_wavelength_flag</td>
<td>GREEN</td>
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<tr>
<td>Median_irradiance_flag</td>
<td>NOT_EXTREME</td>
</tr>
<tr>
<td>Median_Irradiance:</td>
<td>0.05867378 at 310.00 nm</td>
</tr>
</tbody>
</table>
SHICRivm single scan statistics

2201500G 2007 sza 51.575 UVA_transmission: RED VERY_VERY_THICK_CLOUDS scan_variability: SOME_VARIATION_SCAN
shift1_flagging GREEN -0.027 (nm)
shift2_flagging GREEN -0.033 (nm)
start_irradiance_flag GREEN 0.0000047 maximum_below_first: 0.0000030
Spike+local_shape GREEN
Transmission_2 RED VERY_VERY_THICK_CLOUDS 0.04312109 7.48 all 0.03752876 30.78
scan_variability_2 SOME_VARIATION_SCAN 7.48 =sd trans2
spike_flag_median_based GREEN
start_wavelength_flag RED 302.00 (nm) efuv_below: -0.38 %
last_wavelength_flag GREEN 400.00 (nm) efuv_above: 0.00 %
Median_irradiance_flag LOW_IRRADIANCE Median_Irradiance: 0.00049609 at 310.00 nm
Resolution of Solar Spectra
Results from repeated site audits 2002 to 2007

Brewer #163
PMOD/WRC

Var ±2%

Var ±1%

Var ±4%
QASUME site visit

- Synchronised measurements between the site instrument and the transportable QASUME reference spectroradiometer, i.e. every wavelength is sampled at the same time to minimise the influence of changing atmospheric conditions (clouds).
Linearity and Neutral Density choice for global UV measurements

Problematic:
The radiation from lamps used for the calibration is 10-100 times weaker than the solar radiation. It is necessary to check the linearity of the spectroradiometer to be able to convert from counts to irradiance:

\[ I \left[ W m^{-2} nm^{-1} \right] = \frac{signal_{SUN}}{signal_{LAMP}} \cdot Lamp \text{ Irradiance} \left[ W m^{-2} nm^{-1} \right] \]

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\[ N = N_0 e^{-\tau N_0} \]

The UV scans (ul, ux) use a fixed ND-Filter which needs to be selected based on the maximum expected irradiance at each measuring site.