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Quality assurance of the Brewer UV measurements in Finland

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Abstract

The quality assurance of the two Brewer spectrophotometers of the Finnish Meteorological Institute is discussed in this paper. The complete data processing chain from raw signal to high quality spectra is presented. The quality assurance includes daily maintenance, laboratory characterizations, calculation of long term spectral responsivity, data processing and quality assessment. The cosine correction of the measurements is based on a new method, and included in the data processing software. The results showed that the actual cosine correction factor of the Finnish Brewers can vary between 1.08–1.13 and 1.08–1.12, respectively, depending on the sky radiance distribution and wavelength. The temperature characterization showed a linear temperature dependence between the internal temperature and the photon counts per cycle, and a temperature correction was used for correcting the measurements. The long term spectral responsivity was calculated using time series of several lamps using two slightly different methods. The long term spectral responsivity was scaled to the irradiance scale of the Helsinki University of Technology (HUT) for the whole measurement time periods 1990–2006 and 1995–2006 for Sodankylä and Jokioinen, respectively. Both Brewers have participated in many international spectroradiometer comparisons, and have shown good stability. The differences between the Brewers and the portable reference spectroradiometer QASUME have been within 5% during 2002–2007.

1 Introduction

Many spectral UV measurement programs started in the end of the 1980s, after recognizing that the stratospheric ozone content was declining not only over Antarctica but also over the Arctic and at mid-latitudes (Booth et al., 1992; WMO, 1990). Decrease in total ozone is observed as wavelength dependent increase in UV radiation. Therefore spectral measurements are needed to assess the influence of the ozone depletion on the ecosystem, as the biologically most effective wavelengths are the short UV wave-

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lengths (Young et al., 1993). Measuring the complete UV spectrum offers many possibilities for different kind of research, compared with measuring the UV radiation using a broadband instrument. The challenge is to maintain the sensitivity of the instrument at all wavelengths, as the dynamical range of the UV is huge. Well characterized and maintained spectroradiometers are needed to detect possible, even small, changes in these high precision demanding wavelengths (Seckmeyer et al., 2002).

The Brewer spectrophotometer MK II of the Finnish Meteorological Institute (FMI) in Sodankylä, 67° N Finland, was installed in 1988, to monitor total column ozone in this site influenced by the Arctic ozone depletion (Kyrö et al., 1992; Von der Gathen et al., 1995). Since 1990 it has also monitored spectral UV radiation, and the UV time series of Sodankylä is one of the longest in Europe. The time series has been homogenized and is continuous since then. A second Brewer spectrophotometer, was installed in the observatory of Jokioinen, 61° N Finland, in 1995. The Brewer is a MK III -type spectrophotometer, which fulfills the WMO level S-2 requirements (Seckmeyer et al., 2002) for detection of trends in UV irradiance. Both spectral UV time series have been used in many studies and that way served the scientific community to study the UV features since more than 15 years (Gardiner and Kirsch, 1997; Bais et al., 2001; De Backer et al., 2001; Meinander et al., 2003; Arola et al., 2003b; Lakkala et al., 2003; Lindfors et al., 2003; Glandorf et al., 2005; Gröbner et al., 2005; Huttunen et al., 2005; Kazantzidis et al., 2006; Meinander et al., 2006; Lindfors et al., 2007; Tanskanen et al., 2007).

In this paper, we present the complete data processing of the FMI's Brewer spectrophotometers from raw signal to quality controlled UV spectra. This includes a new way of processing the spectral responsivity time series and correcting for temperature dependence and cosine error. The terminology "quality control" and "quality assurance" is based on Webb et al. (2003). Sections 2, 3, 4 and 5 are part of the quality control, describing the standard operating procedures, laboratory characterizations, long term spectral responsivity and the data processing. The quality assurance itself is discussed in section 5, using the inductive method described by Webb et al. (2003).

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There, the quality of the measurements is evaluated using comparisons with other independent spectral measurements as well as comparisons with reconstructed UV values. The flagging of the European data base (EUVDB) is also used as independent quality statement.

5 [Bernhard and Seckmeyer \(1999\)](#) have reviewed the various sources of uncertainty in spectral measurements, and [Webb et al. \(1998\)](#) have described calibration and quality control procedures. Papers about the quality assurance procedure of broad band or multichannel instruments ([Blumthaler, 2004](#); [Bernhard et al., 2005](#); [Lakkala et al., 2005](#); [Josefsson, 2006](#)) have been published, but only the National Science Foundation
10 (NSF) has published the complete data processing of their spectral UV measurements ([Booth et al., 2001](#); [Bernhard et al., 2004](#)). Their instrument is a SUV-type spectroradiometer, so that quality assurance of Brewer spectrophotometers is discussed here for the first time.

2 Standard operating procedures

15 We start by presenting the standard operating procedures of the two Brewer spectrophotometers of the Finnish Meteorological Institute (FMI), including routine stability check and daily quality control. The characteristics of the two Brewers are presented in Table 1.

2.1 Lamp measurements

20 The spectral stability of the Brewers is monitored by 50 W and 1000 W lamp measurements. The 50 W lamps are measured every second week outdoors and every second week in the dark room laboratory. The 1000 W lamps are measured in the laboratory in average every month, since 1997 and 1998 at Jokioinen and Sodankylä, respectively. The 1000 W lamp dark room measurements are performed following a standard procedure
25 in order to achieve most accurate measurements. Both the temperature of the

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dark room and the current of the lamp are controlled. The intensity of the calibration lamp is also recorded by both a UV-B and a UV-A sensor; the current and voltage of the lamp are recorded as well. All reflecting surfaces are covered with black cloths, and baffles are used in order to minimize diffuse light.

5 Several lamps are measured each time so that lamps are burned different amount of time, as recommended in [Webb et al. \(1998\)](#). Thus some lamps are used more frequently, as others are burned only a few times per year. This enable distinguishing drifts related to the ageing of an individual lamp.

2.2 Maintenance

10 The daily operation routine consist of a series of measurements, which depend on the solar zenith angle. The measurement series is mostly started at constant air masses, where two types of measurements are performed: global UV radiation measurements and total ozone measurements using direct sky or zenith sky measurements. Between the measurements, some routine checks are automatically performed. E.g. standard
15 lamp measurements allow to follow the daily stability of the instrument, and mercury lamp measurements are made regularly to ensure the right wavelength alignment at 296.7 nm. At both stations the spectrum is recorded typically every half an hour in steps of 0.5 nm. The total scanning time is around 4 and 8 min for Sodankylä and Jokioinen, respectively. At the end of the day, the raw data is automatically transfered to a data
20 base, and daily measurement events are listed.

The maintenance, including regular check of levelling and cleaning is performed by the operators of the sounding station. Each operator has been trained to ensure the operation of the instrument and the control software. The Brewer stands on a tripod, and the levelling is checked at least every time the instrument is placed back after e.g. a
25 darkroom calibration.

The Arctic conditions bring special challenges to the instruments. As the frost is a problem during the winter, air is blowed on the diffuser in order to keep it as dry as possible and free from frost. The dome is also cleaned after rain and snow, whenever

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an operator is at work. In order to keep the Brewer dry inside, Nitrogen is circulated through it. At both sites, the outside temperature can be -30°C during winter time, and in Sodankylä almost every winter the temperature reaches -40°C . In order to keep the temperature above zero degrees, both Brewers have heating elements inside the instrument.

2.3 Ancillary measurements

As Sodankylä and Jokioinen are both synoptical weather stations, many different type of ancillary measurements are available. From the point of view of the UV radiation measurements, the most important ones are sky condition regarding clouds and precipitation. The snow depth is recorded, and has been related to surface albedo (Arola et al., 2003a). Continuous radiation measurements are maintained routinely, e.g., global, direct, diffuse and reflected global radiation measurements are available. Total ozone column measurements are available, besides the Brewer measurements, from SAOZ measurements. Ozone soundings are performed once a week at Sodankylä. Both stations have been equipped with PFR type aerosol optical depth measurements since 2004. Many other air quality and atmospheric composition measurements are as well available at both stations.

In addition to these standard radiation measurements, Brewer scan synchronized broadband UV and global pyranometer measurements started in 2001 and 2000 at Sodankylä and Jokioinen, respectively. A SI501A radiometer, measuring erythemally weighted UV radiation, and a CM11 pyranometer, measuring global radiation have been set up by the side of the Brewers. The measurements are synchronized so that a reading is recorded each time a wavelength is measured with the Brewer. Broadband measurement can be used to identify the stability of the sky conditions during a Brewer scan.

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3 Characterizations

In order to make reliable measurements and to process the data correctly, laboratory characterizations of the instrument are needed. In the following subsections we present the characterizations which have been made for the Brewers of FMI.

5 3.1 Angular response

The signal of a spectroradiometer should be proportional to the cosine of the angle θ between the direction of the incident radiation and the normal of the radiometer's diffuser. The deviation from this ideal response is called the cosine error. In order to be able to correct the data, the angular response of the instrument has to be characterized.

10 The incident angle of radiation should be measured with respect to the most sensitive part of the diffuser. For the Brewers of FMI, the diffusers were characterized following W. Josefsson (personal communication). The quartz dome of the diffuser was removed, in order to quantify only the properties of the diffuser. A black paper screen with a 4 mm hole was moved on a grid of 4 mm while measuring a calibration
15 lamp. The results of the Brewer #037 at 310 nm is presented in Fig. 1, where it is seen that the most sensitive parts are situated, as expected, more or less around the centre of the diffuser. The result of the Brewer #107 was similar, except that the most sensitive part was even more centered.

20 The angular response measurements were performed in the dark room at constant temperature. A 1000 W DXW, a vertical beam lamp, was seated in a holder, which could be moved to different angles. Four azimuth angles (north=0°, east=90°, south=180°, west=270°) were measured for zenith angles from 0° up to 85° and back to 0°, in steps of 5° or 10°. The angular responses obtained, normalized to the ideal cosine response, are shown in Fig. 2 for the four azimuth angles for the Brewer #037.
25 The results of the Brewer #107 were comparable to the results of the Brewer #037, with slightly less steep curves. The cosine error of the direct beam exceeded 10% at SZA higher than 50°. The results of both Brewers showed no dependency to the azimuth

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angles, and the final angular response was calculated by taking the average of the azimuths. The final normalized and interpolated angular responses of both Brewers are also shown in Fig. 2.

3.2 Slit function and wavelength calibration

5 The entrance and exit apertures of a monochromator have finite widths. As a consequence, not only photons with the desired wavelength λ_0 pass through the monochromator, but also those with wavelengths within a certain interval around λ_0 . When the monochromator is set to a fixed wavelength λ_0 , its transmittance, as a function of wavelength, is called the slit function $f(\lambda)$. The width of the slit function is often quantified by
10 the full width of the function at half of its maximum (FWHM).

The slit functions for the spectrophotometer at Sodankylä and Jokioinen have been characterized for the first time during the intercomparison at Izaña in 1996 (Kyrö, 1997). They were determined using the HeCd-laser line at 325.029 nm as a source of monochromatic light. The slit function of the Brewer #107 have been measured in
15 addition twice in 1997 and once in 2002. The Fig. 3 shows the measured slit functions of both Brewers. For the Brewer #107, the slit function “slit1” was used before the day 114 in 1997, and the “slit2” was used from that day onwards. The FWHM for the Brewer #037 and #107 are 0.56 and 0.59, respectively.

The wavelength calibration is made as a part of the annual maintenance. In case of
20 Brewer #107 the year-to-year need to change the calibration has always been equivalent to a very small, i.e. from zero to 0.1 nm, adjustment in the wavelength scale. During the last five years there has been no need for any change for the Brewer #107, which indicates a good wavelength stability.

3.3 Temperature dependence

25 Brewer spectrophotometers are provided with a heating element maintaining the internal temperature above around +8°C in all circumstances. However, the instrument

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is not temperature stabilized. According to, e.g., Cappellani and Kochler (1999) and Weatherhead et al. (2001) the Brewer measurements have temperature dependency, which may be attributable to temperature dependences in the photomultiplier tube itself and in the filters in front of the photomultiplier. Ylianttila and Schreder (2005) have discussed the temperature sensitivity of teflon diffusers.

In 1998, in order to determine the temperature dependence of the Brewers #037 and #107, the routine lamp irradiance measurements were analyzed with respect to the temperature. The study indicated temperature dependences that could not be overlooked. The dependences were subsequently characterized for both instruments by on-site laboratory measurements of 1000 W working standard lamps from Optronics Inc.

The procedure for the characterization measurements was as follows: The Brewers were heated and cooled by using an air blow system built for the purpose. Each scan was taken after the internal temperature of the Brewer had stabilized to a suitable level. The range of the internal temperatures covered values from 15.3 to 47.6°C and 14.8 to 45.2°C for #107 and #037, respectively. The temperature of the dark room was stabilized to 23°C.

The results suggested linear dependency between the internal temperature and the photon counts per cycle, which can be used for correcting the data. A linear model relating the irradiance and the temperature was formulated as follows:

$$I(\lambda) = I_0(\lambda) * (1 + c(\lambda) * dT) \quad (1)$$

Here, $dT = T - T_0$ is the temperature difference between the Brewer's internal temperature T and the reference temperature $T_0 = 23^\circ\text{C}$; $I_0 = I(T_0)$ is the reference irradiance (in counts/cycle); I is the measured irradiance (in counts/cycle); and $c(\lambda)$ is the temperature dependence factor (in units $1/^\circ\text{C}$). The temperature dependence factors obtained by linear regression for each wavelength are shown in Fig. 4. Also shown are the fits (polynomial for #107 and two-piece linear for #037) that are performed in order to smooth the ripple in the curves.

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4 Long term spectral responsivity

The long term spectral responsivity of both Brewers have been calculated for the whole period of measurements. The objective is to obtain instrument spectral responsivity time series based on one specific irradiance scale for the whole measurement period.

5 A set of lamp measurements during the period are used. The lamp measurements are made on the roof and in the dark room laboratory of both sites, and the data is corrected to the reference temperature. In Sodankylä and Jokioinen, before the years 1998 and 1997, respectively, only 50 W lamp measurements made on the roof were available. Thereafter mainly laboratory measurements of 1000 W lamps have been
10 used. The process involves the use of several lamps throughout the whole period and the way individual lamps are used is slightly different for the two Brewers, and both methods are presented here.

Firstly, the lamp measurements are quality checked manually. Secondly, the chosen irradiance scale is transferred from the primary standard to the working standard and
15 working lamps. Thereafter, the possible drifts of the lamps are detected by comparing time series of all lamp measurements against each other. If a drift is detected, the measurements of that lamp are either excluded or, if possible, re-calibrated with the help of other lamps. The irradiance scale used in this analysis is provided by the Helsinki University of Technology (HUT). The primary standards of both Brewers are
20 calibrated in average once a year at the HUT, which is an accredited national Standard Laboratory (Kübarsepp et al., 2000).

Once the set of trusted lamp measurements has been compiled, the calculation of the instrument spectral responsivity is possible for each measurement time of individual lamp and for each wavelength. In case of Brewer #107, a linear time interpolation is thereafter performed to each lamp separately to give continuous spectral responsivity
25 time series based on that lamp. Thereafter all the these spectral responsivity time series are averaged, and finally a running average is calculated using a ± 15 day window, which smooths out small scale time variations from the final product. However, in the

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case of the Brewer #037 all available lamp measurements during a given day are firstly averaged, and thereafter time interpolated and smoothed. The choice between the order in time interpolating and averaging individual lamps is subjective, and depends on the number of trusted lamps, on the frequency of laboratory calibrations, and on the desired level of small scale features in the final spectral responsivity time series.

The Fig. 5 shows the 305 nm responsivity time series for the Brewers #037 and #107. The sudden severe drop in the responsivity in 1993 for the Brewer #037 is due to accidental burning of a heating element inside the instrument box. The instrument has slightly recovered from that accident and the average ageing is seen as a downward drift of a couple of percent per year. Approximately same drift is observed for the Brewer #107. The points of discontinuity in the responsivity time series denote instants of instrument maintenance and repair when the instrument characteristics have changed.

During our work, we have compared spectral responsivities produced only using 50 W working lamps and only using 1000 W lamps. This was important, as in the beginning of the time series we had only 50 W lamp measurements, and the question was, how well we can trust to these measurements. Nowadays, each time the Brewer measures 1000 W lamps in the dark room laboratory, also 50 W lamps are measured. Also between laboratory measurements, 50 W lamps are measured on the roof. We can therefore produce two different spectral responsivity time series; one processed with only the 1000 W lamps and one with only the 50 W lamps. In both time series, the irradiance scale has been transferred from the primary standard 1000 W lamp, and the spectral responsivity has been corrected to the reference temperature. These two spectral responsivity time series follow each other within the measurement uncertainties, and give us the confidence that the whole time series is homogenized, even if in the beginning only 50 W lamps were used.

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5 Data processing

In the previous section, we have described the laboratory characterizations performed for our spectrophotometers. In this section the known errors will be corrected using these laboratory characterizations, or using a theoretical approach or a combination of these two.

The raw data is processed into irradiances using a perl language program called `spede.pl`. It is based on the `Qbasic` program, which was released by the manufacturer of the Brewer spectrophotometers (SCI-TEC). Some own corrections, e.g. the cosine correction, spike correction and the temperature correction have been implemented by the FMI. During the processing of the data, some check values, e.g. impossible high UV index, are calculated on fly, in order to warn for suspicious measurements.

5.1 Noise spikes

The first step for raw data is to remove noise spikes. By spikes we refer to an anomalous number of counts recorded at one wavelength channel causing a peak upwards or downwards that does not originate from the true radiation signal (Meinander et al., 2003). The origin for spikes is not fully understood, but the spectrum can be corrected. The data processing of the Brewer data includes a spike correction algorithm based on Meinander et al. (2003), where a statistical method is used to identify the noise spikes in the Brewer UV spectra. In order to work out both for small and big count values of the raw data, the method is based on differences of relative changes in the spectra.

For the correction, two main part have to be done beforehand. First a clear sky reference spectrum is needed. For Sodankylä and Jokioinen, two years of cloud free data were used for calculating an average clear sky spectrum. Secondly, a statistical standard deviation file was computed, based on a large data set, where two years of data were used.

Next, the spectral ratios of raw counts (C) divided by the reference (R) are computed. These are named as Ratios. The differences of these Ratios between the neighbor

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channels λ and $\lambda - i$, where i denotes the Brewer spectrum step, are calculated. These differences are named as *Dratios*, as given by

$$Dratio(\lambda) = \frac{C(\lambda)}{R(\lambda)} - \frac{C(\lambda - i)}{R(\lambda - i)}. \quad (2)$$

Dratios are then compared against the chosen confidence level.

It means that a peak is detected if the signal at the first channel goes up and the next channel down, or vice versa. Other kinds of peaky features are expected to be due to changes in the cloud conditions. In addition, only relatively big spikes are considered, i.e. the ratio of counts divided by the corrected counts exceeds 1.5 or is less than 0.5.

The new corrected value for the removed peak is calculated as the average of the ratios of the neighbor channels multiplied with the reference spectrum value at that channel, as given by

$$C(\lambda) \text{ corrected} = 0.5 * \left(\frac{C(\lambda - i)}{R(\lambda - i)} + \frac{C(\lambda + i)}{R(\lambda + i)} \right) * R(\lambda). \quad (3)$$

This way the shape and the fine structure of the spectral features are preserved.

5.2 Dark current, dead time and stray light

Dark current is the response exhibited by the photomultiplier during periods when it is not actively being exposed to light. Dark current is recorded before each scan. Raw count values for further data processing are gained by subtracting the measured dark current from the measured counts in a function including the number of cycles and the integration time.

The dead time is the time after each light exposure, during which the photomultiplier is not able to record another exposure if it happen. The dead time of the Brewer is regularly recorded and daily values are saved in a dead time history file. The typical dead time values are 30–40 ns for both Brewers. Dead time correction to the raw counts

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is performed using iteration of an exponential function including number of counts and dead time values.

Stray light consists of radiation at wavelengths outside the wavelength range of the slit function that is detected inside the range expected. This is a special problem inherent in single monochromator spectroradiometers. The Brewer #107 is a double monochromator and the amount of stray light passing to the detector is minimal. The average of counts at wavelengths smaller than 292 nm is calculated. This average value is subtracted from the count values at each wavelength of the spectrum. Since the Brewer # 037 is a single monochromator, the stray light disturbs measurements up to around 305 nm (Bais et al., 1996). For the Brewer #037, signal at wavelengths lower than 293 nm are considered as stray light, and subtracted from longer wavelengths.

5.3 Temperature

The temperature dependencies of the Brewers are corrected using the temperature dependence coefficients derived from the characterization measurements described in Sect. 3.3. Each scan is normalized to the reference temperature by computing $I_0(\lambda)$ on the basis of Eq. (1). The procedure yields a time series of irradiance scans (in units counts/cycle) normalized to the same reference (laboratory) temperature in which the response of the instrument has been derived.

5.4 Cosine error

Several papers have been written about methods for the cosine correction of radiometers (Landelius and Josefsson, 2000; Bais et al., 1998; Feister et al., 1997; Seckmeyer and Bernhard, 1993). They differ mostly by the way of handling the radiation distribution of the sky. The method of FMI is shortly described here.

If F denotes the actual and F' the measured irradiance, we can define the correction factor for the angular response of a spectroradiometer (f_{glob}) for a particular global

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irradiance measurement as

$$f_{\text{glob}} = \frac{F_{\text{glob}}}{F'_{\text{glob}}} = \frac{F_{\text{diff}} + F_{\text{dir}}}{F'_{\text{diff}} + F'_{\text{dir}}}, \quad (4)$$

where the subscripts glob, diff, and dir correspond to global irradiance and its diffuse and direct components, respectively.

5 Equation (4) can be rewritten as

$$f_{\text{glob}} = \frac{(F_{\text{dir}}/F_{\text{diff}} + 1)}{(F'_{\text{dir}}/F_{\text{dir}} * F_{\text{dir}}/F_{\text{diff}} + F'_{\text{diff}}/F_{\text{diff}})}. \quad (5)$$

Equation (5) suggests that in order to obtain the cosine correction factor, three components are needed:

- 1) $F'_{\text{dir}}/F_{\text{dir}}$, the ratio between measured and actual direct irradiance, i.e. direct cosine error,
- 10 2) $F'_{\text{diff}}/F_{\text{diff}}$, the ratio between measured and actual diffuse irradiance, i.e. diffuse cosine error,
- and 3) $F_{\text{dir}}/F_{\text{diff}}$, the ratio between actual direct and diffuse irradiance.

15 The ratio between the measured and actual direct irradiance can be expressed as the ratio of the angular response of the diffuser ($C(\theta, \lambda)$) and the cosine of the solar zenith angle (θ),

$$\frac{F'_{\text{dir}}}{F_{\text{dir}}} = \frac{C(\theta, \lambda)}{\cos(\theta)}. \quad (6)$$

The ratio between the measured and actual direct diffuse radiation is

$$20 \frac{F'_{\text{diff}}}{F_{\text{diff}}} = \frac{\int L(\theta, \phi, \lambda) * C(\theta, \lambda) d\Omega}{\int L(\theta, \phi, \lambda) * \cos(\theta) d\Omega}, \quad (7)$$

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where the spectral radiance $L(\theta)$ is integrated over the upper hemisphere, θ is the zenith angle and ϕ the azimuth angle. In general, the exact sky radiance distribution ($L(\theta, \phi, \lambda)$) is not known. By assuming isotropic diffuse radiation, however, Eq. (7) can be simplified to

$$\frac{F'_{\text{diff}}}{F_{\text{diff}}} = \frac{\int C(\theta, \lambda) d\Omega}{\pi}. \quad (8)$$

In our method, the ratio between the actual direct and diffuse irradiance, $F_{\text{dir}}/F_{\text{diff}}$, is obtained using a radiative transfer model. The LibRadtran package and UVspec-sort version (<http://www.libradtran.org>) (Mayer and Kylling, 2005) was used the following way: Assuming the UV irradiance can be expressed as a function of wavelength, solar zenith angle, cloud optical depth, ozone absorption, aerosols and albedo, a six-dimensional lookup table can be constructed. Using the lookup table and knowing the irradiance at each wavelength from the measured Brewer spectrum, the cloud optical depth, $\tau_{\text{cloud}}(\lambda)$, can be found as a function of wavelength. Further details of this approach to estimate the cloud optical depth can be found in Arola et al. (2003b). Once $\tau_{\text{cloud}}(\lambda)$ is found, the radiative transfer model is used to derive the direct-to-diffuse ratio as a function of wavelength.

Once $F_{\text{dir}}/F_{\text{diff}}$ is obtained and the angular response of the diffuser, $C(\text{sza}, \lambda)$ is known, Eq. (5) can be used to estimate the cosine correction factor for each wavelength. Inserting the angular response of the Brewer at Sodankylä and Jokioinen in Eq. (8), and assuming the diffuse radiation isotropic, the ratio between measured and actual diffuse irradiance is 0.90 and 0.91, respectively. This means that, when there is no direct light coming into the instrument's diffuser, the error in the measurements due to the non-ideal angular response can be as much as 10% and 9% for Sodankylä and Jokioinen, respectively. This value is modified in the presence of direct irradiance, and its change depends on the ratio between the actual direct and diffuse radiation. The actual cosine correction factor of the Brewer at Sodankylä and Jokioinen can vary between 1.08–1.13 and 1.08–1.12, respectively, depending on the wavelength.

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5.5 Wavelength alignment

Because of the strong decrease with wavelength of the solar spectrum in the UV-B range, even small errors in the wavelength alignment of a spectroradiometer lead to significant errors in measured spectral irradiance. The Brewer spectrophotometers are typically assumed to have minor problems with wavelength alignment. Therefore the need of performing wavelength shift correction is not seen critical. This is the case for most of the Brewers, as well as for the Brewer #107. In those case, the wavelength error is randomly spread around the average wavelength error.

In the case of the Brewer #037, [Arola et al. \(2003b\)](#) found out that a stepwise change in the wavelength alignment has occurred between 1993 and 1994. The typical value for the wavelength shift before 1994 was -0.06 nm, and 0.01 nm thereafter. In case that the wavelength error would have not been corrected, an error of several percentage could have been introduced in long term change analysis of UV spectra.

The current data processing includes the wavelength shift correction using the SHICRIVM wavelength shift correction package described in [Slaper et al. \(1995\)](#). E.g. spectra transferred to the EUVDB database have been corrected for the possible wavelength shift.

6 Quality assessment

Following [Webb et al. \(2003\)](#) the quality assessment of an instrument can be done by comparing the instrument to other independent instruments measuring the same quantities. In this section, we review the results of intercomparison campaigns and comparison with the portable reference spectroradiometer QASUME (Quality Assurance of Spectral Ultraviolet Measurements in Europe) ([Bais et al., 2003](#)). For quality assurance purposes the measurements are also compared with reconstructed UV dose rates. The flagging reports of the spectra transferred to the European UV Data Base (EUVDB) are also discussed.

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6.1 Intercomparison campaigns

Both Brewer spectrophotometers of FMI have participated to several international UV spectroradiometer comparisons (Koskela, 1994; Kjeldstad et al., 1997; Gardiner and Kirsch, 1997; Bais et al., 2001; Meinander et al., 2003; Thorseth et al., 2002). Table 2 shows in detail the year of the campaign, the location and which Brewer has participated. The Brewer #037 mainly participated to the Nordic comparisons and has been the host for two portable reference spectroradiometer QASUME visits, whereas the Brewer #107 has travelled successfully around Europe. This instrument took part in the comparison of Ispra in 2002, where six spectroradiometers performing consistently in previous intercomparisons, were invited. Besides the intercomparison campaigns with several instruments, smaller intercomparison campaigns have been organized. A regular comparison is done during the yearly visit of the reference Brewer #017 of the International Ozone Services (IOS). During these visits, both UV and ozone measurements are compared and the instruments are checked and maintained, if necessary. National comparisons have also been performed during many of these visits.

When interpreting the results of the intercomparison campaigns, we need to keep in mind that especially results of the earliest campaigns represent the situation during that time, and that the data can nowadays be reanalyzed using different method and knowledge. In those first intercomparisons, almost no instrument had correction for the cosine error. Also, the intercomparisons were concentrated on clear sky weather.

Every campaign has been a good step to improve the measurements. Regarding the Brewers of FMI, the NOGIC-00 campaign was the first, where the data processing procedures presented in this paper was in use. In that campaign, the cosine correction and temperature correction procedures were used for the first time. An example of one day measurements (06:00 UTC–20:00 UTC) compared to the reference spectra is shown in Fig. 6. The plots are ratios between the daily sums of irradiances measured with the Brewers and the calculated reference daily sums. The measurements were processed using the SHICrvm QA/QC software package (Slaper et al., 1995), and

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the reference spectra were calculated following [Slaper and Koskela \(1997\)](#). From the Figure, it can be seen that compared to the reference spectra, the Brewer #037 was within $\pm 5\%$ at wavelengths longer than 305 nm and the Brewer #107 was within $\pm 5\%$ at most of the wavelengths. Individual spikes can be due to changing cloud conditions at a single moment. The observed downward drift observed at wavelengths longer than 317 nm for the Brewer #037 was due to problems with the irradiance scale of one calibration lamp. The lamp was recalibrated after the campaign.

From previous intercomparisons, the most important result is that the ratio to the reference was stable during the comparison days. E.g. in the NOGIC-96 intercomparison, for both instruments the standard deviation of the ratio of the measured dose rate to that of the reference was 1–2%. The other important result is, that all measurements starting from the beginning of the time series are appropriate after applying all known corrections to the data.

6.2 QASUME reference

The portable reference spectroradiometer QASUME from Physikalisch-Meteorologisches Observatorium Davos, World radiation Center (PMOD/WRC) is a Bentham spectroradiometer, whose irradiance scale is traceable to the primary standard of the Physikalisch-Technische Bundesanstalt (PTB), Germany, through transfer standard lamps ([Gröbner and Sperfeld, 2005](#)). It can be seen as “European standard spectroradiometer”, and the irradiance scale is assumed to be stable during the years. As spectroradiometers are challenging instruments for travelling, this gives a good possibility to check the performance of a site spectroradiometer without travelling.

The portable reference spectroradiometer QASUME has visited Jokioinen and Sodankylä in 2003 and 2007. In addition to this, the instrument visited Jokioinen during the first experimental year in 2002. Also, the Brewer #107 of Jokioinen was part of the core group, and participated to the starting comparison of the QASUME project in 2002, in Ispra, Italy ([Gröbner et al., 2005](#)). The protocol of each site visit included

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measurements of the spectral solar irradiance, which were performed every half an hour from the morning to the evening. Synchronized solar spectra were obtained in the range of site spectroradiometer, every 0.5 nm, with a wavelength increment every 3 s. The solar spectra were converted to a common wavelength scale and to a nominal resolution of 1 nm using the SHICRivm software package. A detailed description of the measurement procedure is published in Gröbner et al. (2005).

The summary of the results is shown in Fig. 7 for both the Brewers. The mean ratio to the QASUME reference for SZA smaller than 75° are shown for all comparison years. For the Brewer #037, the results of both comparisons, in 2003 and 2007, are near each others. A difference of around 5% can be seen in wavelengths longer than 305 nm. At shorter wavelengths, the typical single monochromator stray light problem disturbs the readings, and those wavelengths need to be rejected. The small downward shift at longer wavelengths in 2003 may be due to problems with one single calibration lamp.

For the Brewer #107, a difference of around 4–5% was observed in 2002 and 2007, at Ispra and Jokioinen, respectively. In Jokioinen in 2002 and 2003 the mean difference was around 2%. These results show very good agreement within the measurement uncertainties of spectral measurements and good stability of the instrument. As the irradiance scale of the Brewers of FMI is traceable to the HUT, and that of QASUME to PTB, some differences in the scale can be possible (Gröbner et al., 2002). The stable difference between the instruments over all wavelengths also support the theory of differences in irradiance scale. In 2007, at Jokioinen, via laboratory lamp measurements the difference of irradiance scale was found to be 3%. Which makes only 2% of the differences to be inexplicable, which can be considered as very good results in the challenging work of measuring UV wavelengths.

6.3 Comparison with reconstructed UV

For quality assurance purposes the processed UV spectra are derived to UV erythemally weighted UV dose rates and compared with reconstructed UV dose rates. The

reconstruction of the UV dose rates is based on the method described in Lindfors et al. (2007). The method uses the pyranometer measurements in order to quantify the influence of clouds. A radiative transfer model is used to reproduce the UV dose rates using an appropriate cloud modification factor.

5 For the quality assurance purposes figures, including the reconstructed erythemally weighted UV dose rates, measured UV dose rates, modeled clear sky UV dose rates, and figures including modelled clear sky global radiation and measured global radiation with a CM-11 -type pyranometer are plotted. Figure 8 shows an example of a suspicious measurement day, the 29 April 2001 in Sodankylä. Also one minute dose rates measured with a nearby SI501A radiometer are plotted. Both the modelled values and the SL501a data behavior differ from that of the Brewer measurement at around 10:00 UTC. The Brewer seems to have measured too low values.

10 One need to be careful, when interpreting figures like Fig. 8. As the modeled data is presented as one hour average, the data represent the average situation of this hour. Whereas the Brewer data represents the sky conditions of some minutes, which means that obvious differences from the model are possible, e.g. big changes in cloudiness can be observed in the time scale of minutes, which leads to high variations in the UV radiation. The feature like observed in the Fig. 8 could be due to sudden rain shower, heavy clouds, malfunction of the instrument, local shadow on the diffuser by e.g. a walking person, cleaning of the dome or some other unknown reasons. Ancillary measurements are often needed in order to find out if the feature is real or not. In this specific case, the sl501A erythemal UV dose rates confirm the doubt that something is wrong with the Brewer measurement. The most probable reason was shadowing people around the instrument during maintenance event.

25 6.4 European UV database

Jokioinen and Sodankylä spectral UV data are regularly submitted to the European Database of UV radiation (EUVD) (<http://uv.fmi.fi/uvdb/index.html>). At the EUVD all incoming spectra undergo an automatical quality flagging process by

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the SHICrvm package developed by the RIVM, Netherlands (Slaper et al., 1995) (<http://www.rivm.nl/shicrvm>) and CheckUVSpec package by the NILU, Norway (<http://zardoz.nilu.no/~olaeng/CheckUVSpec/CheckUVSpec.html>). The SHICrvm tool assigns each spectrum quantitative quality indicators for wavelength scale errors, spikes and shape problems, lowest wavelength with accurate measurement, and atmospheric transmission. The CheckUVSpec tool assigns spectra with atmospheric signature flag which is related to the prevailing atmospheric conditions. It should be noted that while some of the quality flags, e.g. wavelength scale errors, can be determined with high accuracy problems with irradiance scale errors can only be detected if the error is very large.

Table 3 shows the summary of selected EUDVB quality flags related to errors and problems that can be determined with accuracy. The majority of the flags of both instruments are in GREEN category, with some YELLOW flags in the spike and shape category, which is expected because changing cloudiness causes spectral shape distortions. E.g. in Sodankylä 98% of the spectra are flagged as green for the wavelength shifts, 99% for the start irradiance, i.e. instrument sensitivity and 95% for the spike detection and shape problems. For Jokioinen the values are 99%, 99% and 90%, respectively. In general, the number of RED, GREY and BLACK flags is very small and in this respect the data can be considered of high quality. Further details about flagging can be found here:

http://uv.fmi.fi/uvdb/html/flag_information.html

<http://www.muk.uni-hannover.de/~seckmeyer/EDUCE>

7 Conclusions

Since early 90's spectral UV radiation is measured with Brewer spectrophotometers #037 and #107 at two sites in Finland. From the very beginning special attention has been paid to the quality of these measurements, and a comprehensive quality assurance scheme has been developed. A lot of work has also been done for character-

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ization of the instruments, which has resulted in better monitoring of the instrument stability and improved postcorrection methods. This paper presents the quality assurance work and data processing scheme for spectral UV measurements of FMI. The future objective is to make a quantitative uncertainty analysis of these measurements.

At FMI, a lot of effort has been put on the quality assurance of the spectral UV measurements, starting from careful training of the operators. The standard operating procedures include daily routine check of the operation of the instrument, and regular lamp measurements in order to monitor the stability of the instruments. Since late 90's both FMI's measurement sites have a well equipped dark room laboratory that enables absolute calibration in a temperature controlled environment with a 1000 W lamp. The lamp measurements are carried out varying the lamp set. This allows use of lamps with different burn history and better identification of the lamp drifts.

The lamp measurements have been used to determine the whole spectral responsivity time series of the spectral UV measurements starting from 1990 and 1995 for Sodankylä and Jokioinen, respectively. The construction of the spectral responsivity time series is based on transfer of the HUT irradiance scale to the whole time period, also including the first measurement years when only 50 W lamp measurements were available. The procedure normalizes the lamp measurements to the reference temperature as well as the whole time series. This is essential, because otherwise the temperature dependent outdoor lamp calibrations would cause a seasonal calibration error.

The most important laboratory characterizations of the Brewer instruments have been carried out, and the whole spectral UV time series have been corrected and reprocessed using the results. The temperature characterization showed linear temperature dependence that can be accounted for in postprocessing. Using the angular response measurements and radiative transfer model a wavelength dependent cosine correction factor can be determined for each spectrum. The spectral resolution of the instrument has also been characterized, as well as the entrance optics. The processing software also includes corrections for noise spikes, dark current, dead time and

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stray light. The processing scheme can be applied for other spectroradiometers as well, assuming that the required instrument characteristics are available.

Intercomparisons with other spectroradiometers have shown good agreement within the measurement uncertainties. The latest comparison with the portable reference spectroradiometer QASUME showed a mean difference of around 5% for both Brewers. Around half of this difference can be explained by differences in the irradiance scale, and the rest stands well inside the measurement uncertainties.

Reconstructed UV dose rate data can contribute to quality assurance. They can be used to identify suspicious measurements that require more careful manual quality check. The future objective is to implement this tool as part of the automated quality assurance process, so that the whole time series could be checked, and new measurement could be checked online. Reconstruction methods can also be used to produce UV spectra which have further potential for quality check.

The spectral UV data of both Brewers are submitted to the European UV database (EUVDB) and can be downloaded at <http://uv.fmi.fi/uvdb/index.html>. All spectral UV data undergo an automatic flagging procedure at the EUVDB, and the results for Finnish Brewers indicate good wavelength accuracy and that the anomalies in the spectra are very rare. It should be noted that the quality flagging does not give precise information about the accuracy of the absolute calibration of the measurements.

Spectral UV data contain a lot of information about the atmosphere. Traditionally they have been used for monitoring of the ozone layer, but they contain also information on aerosols, trace gases, surface albedo, and clouds. Combined with other measurements and models, the longterm time series of spectral UV data can be used for versatile study of the changing climate.

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and ancillary software for the determination of reference spectra from the campaign data. The QASUME spectroradiometer is made available by the Joint Research Centre of the European Commission in Ispra under the cooperation agreement 2004-SOCP-22187. G. Hülsen acknowledges support from the Swiss European Cooperation in the field of Scientific and Technical Research (COST) office, SBF No. C05.0068.

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Table 1. The Brewer spectrophotometers of the Finnish Meteorological Institute and their characteristics.

	Brewer #037	Brewer #107
location	Sodankylä (67° N, 27° E)	Jokioinen (61° N, 24° E)
start of UV meas.	1990	1995
surroundings	forest and swamp	fields and forest
monochromator	single	double
diffuser	35 mm Teflon, quartz dome	35 mm Teflon, quartz dome
wavelength range	290–325 nm	→ 24.4.1997 : 290–363 nm 25.4.1997–9.11.1997 : 286.5–363 nm 11.11.1997 → : 286.5–365 nm

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Table 2. Intercomparison campaigns of the Brewers of FMI.

Year	Campaign	Place	#037	#107
1993	NOGIC-93 Nordic comp.	Izaña, Spain	x	
1995	CAMSSUM European comp.	Ispra, Italy		x
1996	NOGIC-96 Nordic comp.	Izaña, Spain	x	x
1997	SUSPEN European comp.	Nea Mihaniona, Greece		x
2000	NOGIC-00 Nordic comp.	Tylösand, Sweden	x	x
2002	QASUME Core group of Europe	Ispra, Italy		x
2002	QASUME portable reference visit	Jokioinen		x
2003	QASUME portable reference visit	Jokioinen and Sodankylä	x	x
2005	QASUME portable reference and Iberonesian network comp.	Huelva, Spain		x
2007	QASUME portable reference visit	Jokioinen and Sodankylä	x	x

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Table 3. Summary of the all Sodankylä and Jokioinen quality flags at the EUVDB database.

Sodankylä	GREEN	YELLOW	RED	GREY	BLACK
shift1	97.98%	0.00%	0.00%	2.02%	0.00%
start irr	99.61%	0.13%	0.08%	0.07%	0.11%
spike+shape	94.87%	4.20%	0.69%	0.08%	0.16%
Jokioinen	GREEN	YELLOW	RED	GREY	BLACK
shift1	99.12%	0.60%	0.00%	0.27%	0.00%
shift2	99.83%	0.00%	0.00%	0.17%	0.00%
start irr	99.86%	0.05%	0.04%	0.01%	0.03%
spike+shape	89.93%	8.17%	1.65%	0.01%	0.24%

shift1=shifts in the wavelength range 300–325 nm
 shift2=shifts in the wavelength range 325–400 nm,
 start irr=irradiance level at which the readings start to become significant (i.e. noise in the spectrum below 25% of the signal),
 spike+shape=local deviation from the expected spectral structure

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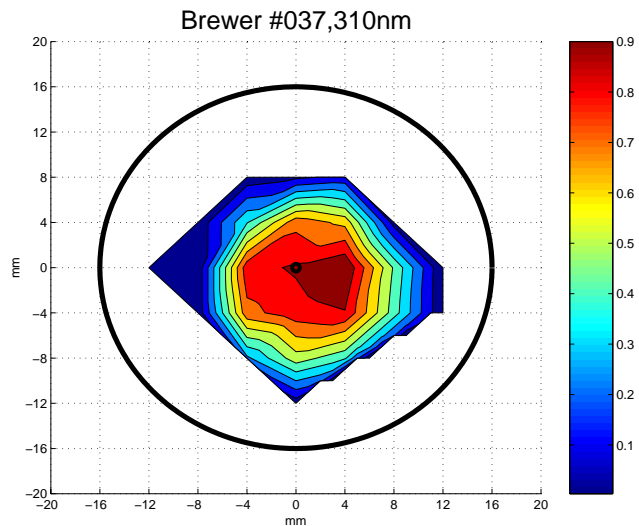


Fig. 1. The response from different part of the diffusor of Brewer #037 at 310 nm. The areas around the centre are the most sensitive.

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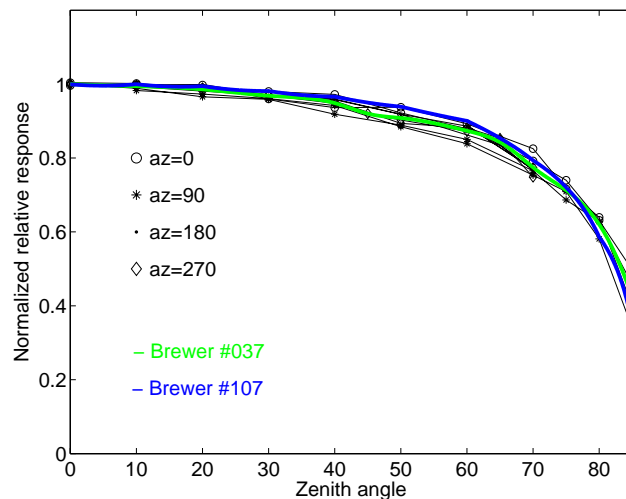


Fig. 2. The characterization of the cosine response of Brewer #037 at four azimuth angles (north=0°, east=90°, south=180°, west=270°) and steps of 5° or 10°. The normalized relative response is shown. The averaged and interpolated normalized relative response is also shown for the Brewer #107 (blue line) and the Brewer #037 (green line).

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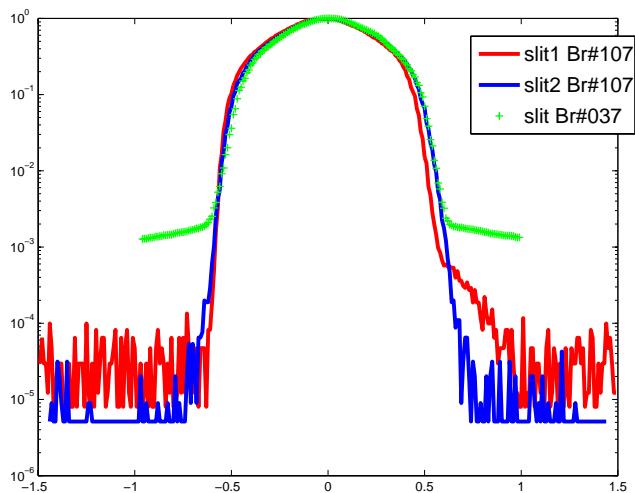


Fig. 3. The slit functions of the Brewers #037 and #107.

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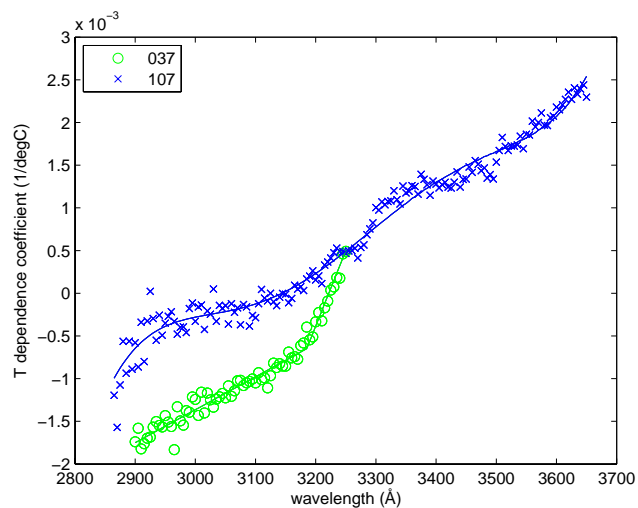


Fig. 4. Temperature dependence factors obtained for Brewer #107 (green crosses) and Brewer #037 (blue circles).

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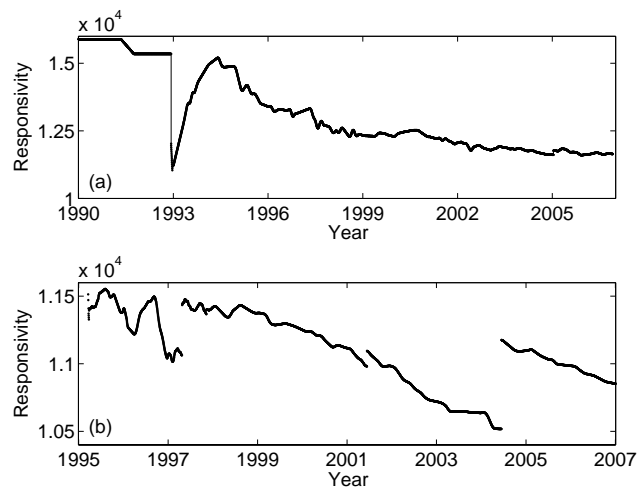


Fig. 5. The responsivity time series 1990–2006 and 1995–2006 for the Brewers **(a)** #037 and **(b)** #107, respectively, at 305 nm.

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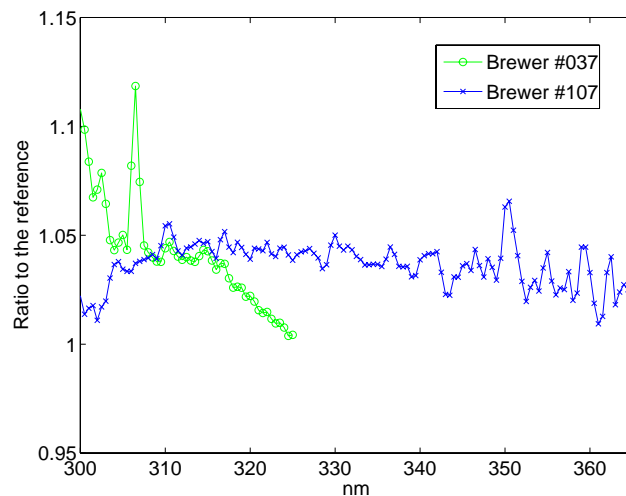


Fig. 6. The ratios (Brewer/Reference) of daily sums of irradiances for the Brewers #037 (green) and #107 (blue) during the NOGIC-2000 intercomparison campaign for day number 164.

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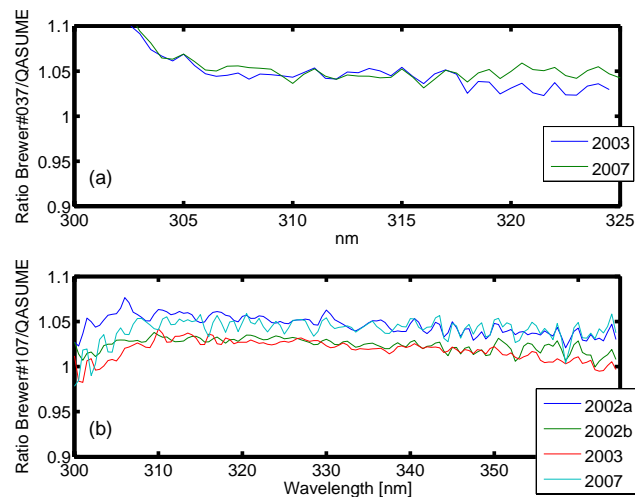


Fig. 7. The results of the comparisons between the **(a)** Brewer #037, **(b)** Brewer #107 and the portable reference spectroradiometer QASUME.

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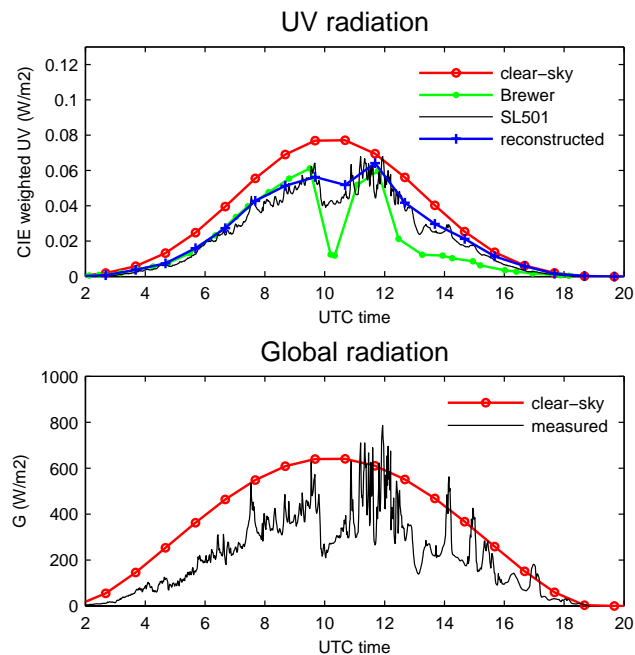


Fig. 8. Brewer #037 UV dose rates plotted together with modelled clear sky UV dose rates, reconstructed dose rates, SI501A dose rates, modelled clear sky global radiation and CM-11 pyranometer global radiation measurements at Sodankylä for 29 April 2001.

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