New Spectroradiometers Complying with the NDSC Standards

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ABSTRACT

The investigation of the effect of solar ultraviolet (UV) and visible radiation on biological organisms and photochemical reactions requires spectral measurements of the desired radiation parameters of high accuracy. The Network for the Detection of Stratospheric Change (NDSC) and the World Meteorological Organization have set up stringent requirements for high-quality spectral measurements of ultraviolet radiation. It is shown that two new instruments comply with these standards. One is the newly developed spectroradiometer of the Institute of Meteorology and Climatology, University of Hannover, Hannover, Germany. It is capable of covering the spectral range from the UV to the near-infrared (290–1050 nm) in a comparably fine resolution. One major aim is to deploy this instrument as a traveling NDSC spectroradiometer. The other new instrument is built for the U.S. National Science Foundation's UV Monitoring Network. It is designed to monitor UV and visible irradiance at high latitudes and covers a wavelength range from 280 to 600 nm. Data of both instruments show deviations of less than 5% for a wide range of atmospheric conditions compared to a NDSC spectroradiometer owned by the Climate Monitoring and Diagnostics Laboratory during the fifth North American Interagency Intercomparison for UV Spectroradiometers. Such deviations represent state-of-the-art instrumentation for conducting long-term measurements of solar UV radiation capable of detecting trends and supporting long-term measurements by traveling standards. Furthermore, there is now an instrument capable of measuring solar irradiance in a wavelength range from 250 to 1050 nm.

1. Introduction

Aquatic and terrestrial biological systems as well as pollution photochemistry are sensitive to ultraviolet (UV) radiation (280–400 nm). In most cases, the sensitivity increases with decreasing wavelength (Kerr et al. 2003). However, processes such as photosynthesis respond to radiation in the visible part (400–780 nm) of the electromagnetic spectrum (McMinn et al. 1999), too. Studies on impacts of UV and visible radiation require knowledge of present radiation levels as well as changes that have occurred in the past.

Increases in surface UV radiation in association with ozone decline have been detected by spectral measurements at a number of sites (Zerefos 2002; McKenzie et al. 1999). However, incident UV radiation is affected by a number of parameters (Kerr et al. 2003; Arola et al. 2003; McKenzie et al. 1999). The most important ones

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are solar zenith angle, total ozone column (McKenzie et al. 1999), cloud cover (Schwander et al. 2002), surface albedo (Weihs et al. 2001), and aerosol content (Kylling et al. 1998). To detect possible trends in surface UV radiation all of these parameters have to be considered. Glandorf et al. (2004) investigated the two longest European time series of measured spectral surface UV irradiance and concluded that yearly trends of surface UV irradiance cannot yet be unambiguously defined. They concluded that longer time series of measured spectral UV irradiance need to be available, which presents the need for continuing spectral surface UV measurements. It is also crucial to continue spectrally resolved measurements of UV and visible radiation in order to provide high-quality data for biological and photochemical investigations. Databases providing spectrally resolved radiation data as well as additional data products already exist (Glandorf et al. 2004, Kerr et al. 2003; Hare et al. 2000; Seckmeyer 2000; McKenzie et al. 1997; Booth et al. 1994). Quality control (QC) and quality assurance (QA) procedures have to be followed rigorously in order to achieve such a high data quality (Gröbner et al. 2004; Webb et al. 2000). The Network for the Detection of Stratospheric Change (NDSC) has assembled a list of data specifications that have to be met in order to submit data to the NDSC database. Two aims of the NDSC are to monitor long-term changes in UV and to make properly calibrated UV data available to the community (McKenzie et al. 1997).

The objective here is to show that the newly developed spectroradiometer of the Institute of Meteorology and Climatology (IMUK) as well as the SUV-150B spectroradiometer of Biospherical Instruments, Inc. (BSI) comply with these high standards. Because of the fact that the IMUK spectroradiometer is capable of measuring spectral radiation from the UV to the near-infrared (250–1050 nm), its data can be used for a wide range of biological and photochemical applications. The SUV-150B was built for the National Science Foundation's (NSF's) Office of Polar Programs UV Monitoring Network (Booth et al. 1994). It is an advanced version of the SUV-150 spectroradiometer that took part in the fourth North American Interagency Intercomparison of UV Spectroradiometers (Lantz et al. 2002). It is planned to use the IMUK instrument as a mobile NDSC instrument, supporting long-term measurements as a traveling standard. Because the IMUK instrument is not incorporated into a monitoring program, data series will not be interrupted during campaigns. Instruments applying for the NDSC status can be compared with this new traveling NDSC instrument in order to achieve the desired status. As a result of excellent agreement during the fifth North American Interagency Intercomparison for UV Spectroradiometers, the IMUK instrument has been accredited as an official NDSC instrument that can be used as a traveling standard. The IMUK instrument has also successfully participated in European intercomparisons within the project Quality Assurance of Spectral Ultraviolet Measurements in Europe through the Development of a Transportable Unit (QASUME; see information available online at http://lap.phys.auth.gr/qasume/Files/layouts/qasumereport.pdf; Gröbner et al. 2004). It thus also provides a link between these European instruments and the NDSC instruments.

2. Materials and methods

The IMUK and BSI spectroradiometers as well as the NDSC spectroradiometer operated by personnel from the National Institute for Water and Atmospheric Research (NIWA) of New Zealand and the Cooperative Institute for Research in Environmental Sciences (CIRES) took part in the fifth North American Interagency Intercomparison for UV Spectroradiometers, which was held at Table Mountain, located 8 km north of Boulder, Colorado, from 13 to 21 June 2003. The campaign was organized by the Central UV Calibration Facility (CUCF) of the National Oceanic and Atmospheric Administration's (NOAA's) Air Resources Laboratory. During the first part, all participating instruments measured spectral irradiance simultaneously between 290 and 360 nm in a blind intercomparison. A publication presenting results of this intercomparison is currently being prepared. During the second part, the NDSC spectroradiometer operated by CIRES–NIWA was compared with the two instruments operated by BSI and IMUK over an extended wavelength range. BSI and IMUK measured from 280 up to 600 nm, and NIWA measured from 285 to 450 nm. Results from this part are the focus of this paper.

The instruments are described in more detail in the following sections. An overview of the optical component is given in Table 1.

a. NDSC spectroradiometer

The NDSC spectroradiometer used in this intercomparison campaign was constructed by NIWA of New Zealand, and is designated as the UV5 instrument. It is owned by the Climate Monitoring and Diagnostics Laboratory (CMDL) of NOAA and has been operated in Boulder since June 2001. It is calibrated with respect to the CUCF realization of the National Institute of Standards and Technology (NIST) standard, and final data quality control is performed by NIWA. The instru-

TABLE 1. Summary of the optical components of the NDSC–NIWA, IMUK, and BSI spectroradiometers.

	IMUK	BSI	NDSC–NIWA
Make	Bentham DTM300	Biospherical Instruments, Inc., SUV-150B	Bentham DTM300
Focal length	300 mm	150 mm	300 mm
Entrance and exit slits	280–500 nm: 0.74 mm 501–1050 nm: 1.48 mm	Entrance: 0.51 mm; exit: 0.31 mm	1.0 mm
Middle slit	1.85 mm	0.84 mm	1.5 mm
Gratings	Holographic reflection gratings with 2400 grooves per millimeter (280–500 nm), 1200 grooves per millimeter (501–1050 mm)	Ruled reflection gratings with 2400 grooves per millimeter	Holographic reflection gratings with 2400 grooves per millimeter
Detector type	280–500 nm: photomultiplier DH-10Te; 501–1050 nm: silicon diode	Bialkali photomultiplier model R2371P from Hamamatsu	Photomultiplier 1527 by Hamamatsu
Entrance optics	Cosine PTFE diffuser by Schreder CMS coupled to the entrance slit by an optical fiber	In-house-designed PTFE diffuser covering the entrance port of a baffled integrating sphere	In-house-designed PTFE diffuser coupled to the entrance slit by an optical fiber

ment was temporarily moved from its usual site at the NOAA building in Boulder to the campaign site for the purposes of the intercomparison. The heart of the instrument is a Bentham DTM300 double monochromator. The entrance optics is an in-house-designed polytetrafluoroethylene (PTFE) diffuser, which is coupled to the spectroradiometer via a quartz fiber optic bundle. The spectroradiometer is equipped with gratings of 2400 grooves per millimeter and the slits have widths 1.0, 1.5, and 1.0 mm. All slit heights are 20 mm. A small portion of the entrance slit is blocked by a diode detector that measures any changes in UVA radiation during the scan. In usual operation, a measurement typically consists of a scan from 450 to 285 nm, followed by a scan from 285 to 450 nm. The standard total measurement time is 270 s (4.5 min). Dark current offsets are measured before and after each scan and these signals are subtracted. Slower scan rates are employed at the short wavelength end of the scan. The photomultiplier detector is a Hamamatsu 1527 operated in analog mode. The signal is sampled by a 24-bit analog-to-digital converter. The bandwidth of the spectroradiometer is 0.75 nm [full width, half maximum (FWHM)], and the spectra are sampled at intervals of 0.2 nm. The oversampling allows for the improved characterization of wavelength errors. These errors are corrected using correlation against solar Fraunhofer absorption features, which are present in all solar spectra. The instrument is housed in a weatherproof enclosure that is temperature controlled to 30° ± 1°C. The enclosure also incorporates lamps and power supplies that enable regular on-site calibrations of irradiance and wavelength, using 45-W tungsten-quartz halogen lamps traceable to NIST, and mercury lamps. More information on these spectroradiometers and their performance can be found online at http://www.niwascience.co.nz/rc/instruments/lauder/uvspec.

b. IMUK spectroradiometer

The IMUK scanning spectroradiometer basically contains four components. They consist of the entrance optics, a double monochromator, radiation detectors, and devices to control the measurements and store the data.

The entrance optics consists of a shaped Teflon diffuser, which is protected by a quartz dome. This diffuser is optimized for a low cosine error. The radiation is guided into the entrance slit of the monochromator through an optical fiber. The diffuser is heated for the temperature never to sink below 30°C to avoid humidity affecting the measurement.

The central element of the spectroradiometer is a model DTM300 double monochromator manufactured by Bentham Instruments, Ltd. The double monochromator consists of two identical single Czerny–Turner monochromators. The focal length is 300 mm. The light enters the monochromator through a motorized entrance slit, which is set to 0.74 mm for wavelengths between 280 and 500 nm and to 1.48 mm for wavelengths between 500 and 1050 nm. These are also the widths of the exit slits. The middle slit is set to 1.85 mm. For the wavelength ranges of 280–500 and 500–1050 nm holographic reflection gratings with 2400 and 1200 grooves per millimeter are employed in each monochromator, respectively. Stray light is suppressed by a number of baffles and the middle slit. The nominal bandwidth of the spectroradiometer is 0.5 nm.

A photomultiplier tube (PMT), model DH-10-Te, is employed as a detector for the wavelength range from 280 to 500 nm, whereas a silicon diode is used from 500 to 1050 nm. The output current of the PMT is further processed by a decadal current amplifier. This signal is converted to a digital signal, which can be further processed by computer.

To operate the spectroradiometer in a stable manner, it is placed inside a temperature-controlled box. The temperature inside this weatherproof box is held at 20°C (±0.5°C) during measurements. Radiometric stability and wavelength accuracy are frequently tested. The responsivity of the spectroradiometer in the field is determined by scanning a 100-W halogen lamp, which is operated inside a portable field calibrator (Seckmeyer 1989). A mercury line source can also be operated inside this field calibrator to test the wavelength alignment. In addition, the wavelength alignment is also tested by comparison with the Fraunhofer absorption lines of high-resolution extraterrestrial solar spectra (Slaper et al. 1995).

The instrument design and performance is similar to instruments used within the NDSC (Seckmeyer et al. 1995; Bernhard and Seckmeyer 1999), but compared with these earlier built instruments, its major advantage is the more extensive wavelength range.

c. *BSI spectroradiometer*

The instrument operated by BSI is an SUV-150B spectroradiometer, which is an advanced version of the SUV-150 described by Lantz et al. (2002). The entrance optics of the SUV-150B consists of a PTFE diffuser covering the entrance port of a baffled integrating sphere. The sphere's exit port is coupled with fiber optics to a scanning 150-mm *f*/4.4 Czerny–Turner double monochromator, which uses ruled gratings with 2400 grooves per millimeter. Each grating is independently positioned by a microstep motor. High-resolution optical encoders provide active-feedback motor position control. The monochromator's exit port is coupled to a bialkali PMT from Hamamatsu. All parts of the instrument are temperature stabilized to within ±1°C by a thermoelectric heater/cooler. The instrument is fully automated and weatherproofed for use in extreme conditions. In normal network operation, the SUV-150B executes four solar scans per hour between 280 and 600 nm. A low pressure mercury lamp and a 45-W quartz-tungsten-halogen lamp are integral to the system and are used for daily wavelength and responsivity checks. The absolute calibration is based on biweekly scans with 200-W irradiance standards traceable to the NIST, which are mounted 50 cm above the collector in a specially designed fixture. Data processing includes checks for wavelength shifts by means of a Fraunhofer line correlation algorithm, and adjustment for the small but existent cosine error of the instrument's collector.

3. Results

To develop and maintain an internationally recognized spectroradiometric system it is vital to meet the data requirements set up by international organizations. The NDSC as well as the World Meteorological Organization (WMO) have assembled a list of data specifications that have to be met in order to submit data to their databases (McKenzie et al. 1997; Seckmeyer et al. 2001). Two aims are to monitor long-term changes in UV and to make properly calibrated UV data available to the scientific community. The analysis focuses on the NDSC specifications.

a. *Compliance with NDSC standards*

To become an NDSC instrument it is necessary to comply with the NDSC standards (McKenzie et al. 1997), which are summarized in Table 2. Another requirement is the successful participation in an intercomparison between a current NDSC instrument and the instrument applying for NDSC status. Within the context of the fifth North American Interagency Intercomparison for UV Spectroradiometers, held near Boulder in June 2003, the IMUK and BSI instruments have been compared to the NDSC instrument operated by NIWA–CIRES. It is shown that the IMUK and BSI spectroradiometers performed similar to the NDSC instrument.

The different specifications set up by the NDSC have been tested for both the IMUK and BSI spectroradiometers. They are also included in Table 2. Remarks to some of the specifications are given below.

1) COSINE ERROR

Figure 1 shows the deviation from the real cosine response for the input optics of the three different spectroradiometers. The cosine error of the IMUK spectroradiometer is determined at 320, 400, and 500 nm. The average is shown in Fig. 1. For isotropic irradiance averaged over wavelength the cosine error is 3.1% (2.3% at 320 nm, 2.9% at 400 nm, and 4.0% at 500 nm).

The cosine error of the BSI spectroradiometer was determined by measurements at azimuth angles of 0°, 90°, 180°, and 270°, and at 320, 350, 400, 500, and 600 nm. The deviation from the ideal cosine response agrees to within ±1% for these azimuth directions and wavelengths. For isotropic irradiance and averaged over wavelength the cosine error is 1.5%. The spectra were cosine error corrected. The correction is smaller

TABLE 2. NDSC specifications for UV spectroradiometry. The specifications are given in terms of final data quality desired (McKenzie et al. 1997).

Quantity	NDSC specification	IMUK	BSI	NDSC–NIWA
Cosine response error	$<\pm5\%$ to isotropic irradiance, and for all angles $< 60°$ from the zenith	$<\pm3\%$ to isotropic irradiance, and for all angles $< 60°$ from the zenith	$<\pm1.5\%$ to isotropic irradiance; $< \pm2\%$ for all angles $< 75°$ from the zenith	$<\pm1\%$ to isotropic irradiance; $< \pm3\%$ for all angles $< 70°$ from the zenith
Minimum spectral range	>290–400 nm	290–1050 nm (capable of 250–1050 nm)	290–600 nm (capable of 200–700 nm)	285–450 nm
Bandwidth (FWHM)*	<1 nm	0.54 nm at 253.65 nm*	0.63 nm at 325 nm	0.75 nm at 296 nm
Wavelength alignment	$<\pm0.03$ nm (precision), $<\pm0.05$ nm (absolute accuracy)	$<\pm0.03$ nm (precision), $<\pm0.05$ nm (absolute accuracy)	±0.02 nm (precision), ±0.04 nm (absolute accuracy)	$<\pm0.02$ nm (precision), $<\pm0.04$ nm (absolute accuracy)
Slit function	$<10^{-3}$ of max 2.5 × FWHM from line center, $<10^{-5}$ of max 6.0 × FWHM from line center	At least 1.76×10^{-3} of max 2.5 × FWHM from line center, and likely better	$<10^{-4}$ of max 2.5 × FWHM from line center $<10^{-5}$ of max 6.0 × FWHM from line center	$<10^{-4}$ of max 2.5 × FWHM from line center
Sampling step interval	<0.5 × FWHM	0.25 nm (290–500 nm); 1 nm (500–1000 nm)	0.2 nm (280–405 nm); 0.5 nm (405–600 nm)	0.2 nm
Saturation threshold	>1.5 W m^{-2} nm^{-1} (noon max at 400 nm)	>1.8 W m^{-2} nm^{-1} (noon max at 400 nm)	>1.8 W m^{-2} nm^{-1} (noon max at 400 nm)	>2.0 W m^{-2} nm^{-1} (noon max at 450 nm)
Detection threshold	$<10^{-6}$ W m^{-2} nm^{-1} (for S/N = 1 at 1-nm FWHM)	9×10^{-7} W m^{-2} nm^{-1} (for S/N = 1 at 1 nm FWHM)	6×10^{-6} W m^{-2} nm^{-1} (for S/N = 1 at 0.63-nm FWHM)	$<10^{-6}$ W m^{-2} nm^{-1} (for S/N = 1)
Scan time	<10 min	Typical 9 min 30 s (290–400 nm); 33 min (290–1000 nm)	Typical 9 min (280–400 nm); 14 min (280–600 nm)	4.5 min (285–450 nm); a full measurement usually consists of a reverse scan + forward scan (~4.5 min total)
Overall calibration accuracy	<5% (unless limited by threshold)	±4.6%	$\pm5.4\%$ ($\pm2\sigma$) at 310 nm; $\pm4.2\%$ ($\pm2\sigma$) at 400 and 600 nm	±5%
Stray light	As defined by the detection threshold	Only noise below the detection threshold	Only noise below the detection threshold	Only noise below the detection threshold
Temperature	Monitored and with stability sufficient to maintain overall stability (typical T stability $< \pm2$ K)	Stabilized and monitored (T stability $< \pm1$ K)	Stabilized and monitored (T stability $< \pm0.5$ K at 1 σ)	29.0 ± 0.5°C, stabilized and monitored
Scan date and time	Recorded with each spectrum (so that timing is known to within ±10 s at each wavelength)	Date: recorded with each scan; time: recorded at each wavelength; time base: GPS	Recorded at each wavelength; time base either GPS or Internet time server	
Diffuse/direct measurements	Capability of distinguishing each component	Diffuse measurements possible with shading disk positioned manually	Diffuse measurements possible with shading disk positioned manually	Diffuse measurements possible with shading disk positioned manually

* Values are adjustable if necessary.

than 1.5% at all times and wavelengths. The average of all measurements is presented in Fig. 1.

The cosine error of the NDSC spectroradiometer was determined at azimuth angles of 0°, 90°, 180°, and 270° at 400 nm. Tests with similar diffusers at wavelengths of 300, 350, 400, and 450 nm confirm that over the wavelength range of the scans, any variations in cosine response are below the detection threshold (i.e., less than

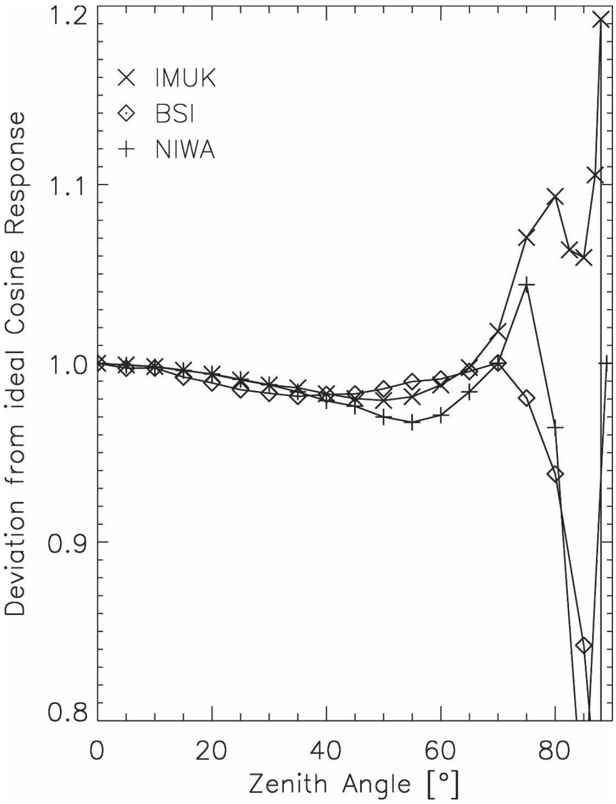

FIG. 1. Deviation from the ideal cosine response at several wavelengths for all three spectroradiometers: IMUK, BSI, and NDSC–NIWA. For solar zenith angles smaller than 70° the cosine responses of all input optics deviate less than 3% from unity.

±1% for wavelengths lower than or equal to 350 nm). For isotropic irradiance averaged over wavelength, the cosine error is 2.5%.

For the wavelength region between 290 and 450 nm, which is relevant with respect to the NDSC standards, the wavelength dependence of the cosine error is negligible for all three input optics.

2) BANDWIDTH (FWHM) AND SLIT FUNCTION

The slit function of the IMUK instrument is based on a number of measurements of the 253.65-nm mercury line, which are normalized and averaged. Measurements of mercury lines at longer wavelengths confirm this slit function. This justifies the usage of the slit function measured at 253.65 nm, even though it is out of the measuring range for the spectral surface UV irradiance measurements. For wavelengths longer than 500 nm another grating and wider entrance and exit slits are used. Based on measurements of the 546.07-nm mercury line, the FWHM is 1.96 nm. The slit function of the NDSC instrument is also based on scans of a mercury line, but at 296.73 nm. Measurements of other mercury lines indicate a slight decrease in FWHM from 0.75 to 0.73 nm over the wavelength range from 296 to 435 nm. Both are mirrored at the center wavelength. The slit function of the BSI spectroradiometer is derived from scans of the 325-nm line of a helium–cadmium (HeCd) laser. It is mirrored at the center wavelength, which was determined by fitting a Gauss function to the data. The bandwidth of the BSI instrument is 0.65 nm at 300 nm and decreases slightly to 0.61 nm at 600 nm. All three slit functions are shown in Fig. 2 on a linear scale and in Fig. 3 on a logarithmic scale.

3) SATURATION THRESHOLD

The maximum spectral irradiance observed during the Boulder campaign is 1.8 W m^{-2} nm^{-1}. Comparisons with model results and between the instruments of the NDSC, BSI, and IMUK indicate that none of the systems is saturated at this radiation level.

4) DETECTION THRESHOLD

The detection threshold is reached at a measured spectral irradiance where the signal-to-noise ratio (S/N) equals 1 (Seckmeyer et al. 2001). The detection threshold for the IMUK spectroradiometer has been determined by measuring a 100-W lamp through a cutoff filter. A WG320 filter by Schott with a thickness of 2 mm has been placed between the lamp and the entrance optics. The transmission of the filter is available online at http://www.newportglass.com/schott.htm. Numerous spectra from 280 to 400 nm in steps of 1 nm have been recorded. The signal-to-noise ratio has been

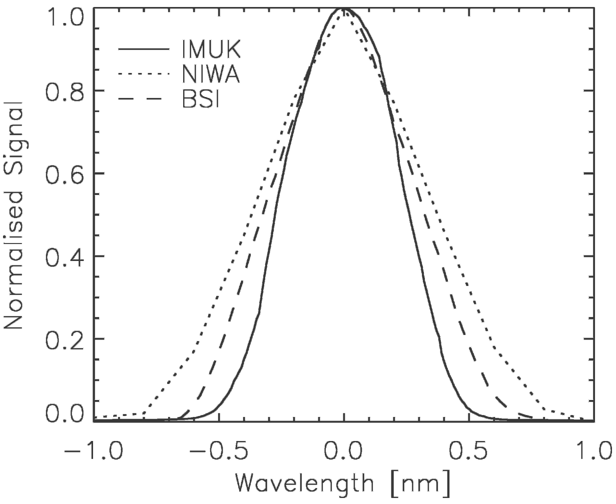

FIG. 2. Slit functions of the three different instruments: IMUK, NDSC–NIWA, and BSI. The FWHM of the NDSC instrument is 0.75 nm, the FWHM of the BSI is 0.63 nm, and the FWHM of the IMUK spectroradiometer is 0.54 nm.

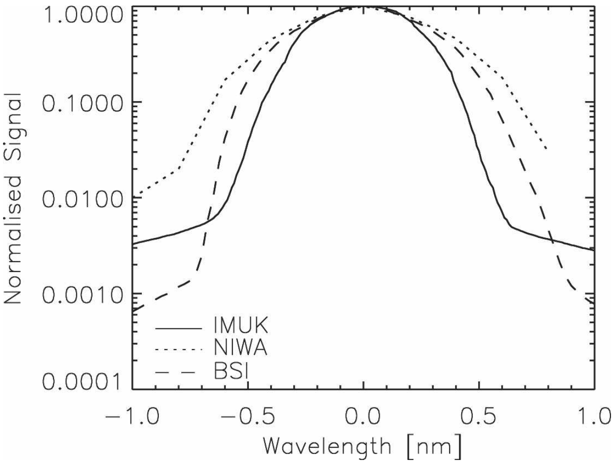

FIG. 3. Slit functions of the three spectroradiometers (IMUK, NDSC–NIWA, and BSI) on a logarithmic scale. The IMUK and NDSC slit functions are based on measurements of a mercury lamp. Therefore, it is not possible to measure the slit function down to the detection limit of the instruments. Both the IMUK and the NDSC slit function stretch over fewer orders of magnitude than that of the SUV-150B, which was derived from HeCd laser measurements.

calculated for each wavelength. According to Seckmeyer et al. (2001), the signal-to-noise ratio is the ratio between the average reading of a radiometer calculated from sufficient single measurements to the standard deviation of the readings of single measurements. The corresponding measured spectral irradiance at the wavelength where the signal-to-noise ratio equals 1 determines the absolute value of the minimal spectral irradiance that can be detected. To be able to compare the detection threshold of different instruments the measurements have been convoluted with a triangular slit function with a FWHM of 1 nm. BSI has determined the detection threshold by calculating the standard deviation of sky measurements at 285 nm. The detection limit given in Table 1 translates to a detection limit of approximately 4×10^{-6} W m^{-2} nm^{-1} at 1-nm FWHM. For both instruments the detection threshold is given at a FWHM of 1 nm, as suggested in McKenzie et al. (1997), to facilitate an easy comparison of this instrumental feature.

5) STRAY LIGHT

Only noise is detected by all three spectroradiometers when sky irradiance is measured at wavelengths below 285 nm, indicating that stray-light levels are below the detection limit. The stray-light contribution to measurements of the BSI instrument was additionally estimated with a HeCd laser. The measurement indicated an out-of-band rejection of at least 7.5 orders of magnitude. The true out-of-band rejection may be larger, but a more accurate assessment is limited by the instrument's dynamic range of about eight orders of magnitude.

6) OVERALL CALIBRATION UNCERTAINTY

The overall calibration uncertainty includes all uncertainties associated with the irradiance calibration. The calibration of the IMUK spectroradiometer is based on a 100-W tungsten-halogen lamp. This standard was calibrated by Gigahertz Optik against lamps calibrated at the German Physikalisch-Technische Bundesanstalt (PTB). Gigahertz Optik maintains a PTB-accredited calibration laboratory. The calibration accuracy of the 100-W standard was additionally verified by comparing the lamp against two independent 1000-W standards from PTB. The deviation between the 100-W lamp and the two 1000-W standards was less than 3% above 300 nm and hardly depends on wavelength (see information online at http://lap.phys.auth.gr/qasume/Progress.asp?typeId=2). This difference is within the typical calibration uncertainty of 3.5% that applies to lamps disseminated by standards laboratories (Bernhard and Seckmeyer 1999; Kiedron et al. 1999).

The calibration certificate of the 100-W lamp is given in wavelength steps of 5 nm. The values were interpolated to intermediate wavelengths with natural cubic splines; the associated uncertainty is 0.2%. The 100-W secondary standard was calibrated at a distance of 50 cm but is deployed at a distance of 40 cm, utilizing a portable field calibrator, which was already used in earlier campaigns (e.g., Seckmeyer et al. 1995). The inverse square law is applied to scale the irradiance values from a distance of 50 cm to a distance of 40 cm. This method is widely employed in the UV community (Bernhard and Seckmeyer 1999, 1997). The scaling factor is accurate to within ±0.3%. The uncertainty caused by alignment errors of the lamps and the entrance optics is about 0.1%.

The irradiance collector of the IMUK spectroradiometer contains a shaped diffuser made of Teflon, which is covered by a quartz dome. The reference point of the diffuser was determined according to Bernhard and Seckmeyer (1997) and the associated uncertainty is 0.3%. The influence of the quartz dome leads to an additional uncertainty of 0.2% (Bernhard and Seckmeyer 1999).

Although a high-quality current source is used, the precision of the current setting is limited to ±0.01%, resulting in an irradiance uncertainty of approximately 0.1% at 300 nm. The combined uncertainty of all factors contributing to the calibration uncertainty is 4.6%.

Calibration standards and methods used for the BSI instrument are identical to those employed in the NSF

UV monitoring network. Calibration uncertainties of the NSF network instruments have been analyzed in detail by Bernhard et al. (2004) and are 2.7% at 310 nm and 2.1% at 400 and 600 nm (uncertainties refer to one sigma level).

b. *Intercomparison with the NDSC spectroradiometer*

The intercomparison on 22 June 2003 between the IMUK, BSI, and NDSC spectroradiometer served as the last requirement in order for the IMUK and BSI instruments to be considered NDSC spectroradiometers. This day was nearly ideal; only a few clouds were present during the afternoon. Note that the instruments have been compared during the six previous days as well but in a shorter wavelength range. Therefore, the results are only shown for this one extra day of intercomparison and are representative for the complete duration of the campaign.

For meaningful comparisons of single spectra, the spectral data have been convoluted with a triangular slit function of 1-nm FWHM by applying the tool CONV, which is available in the Library for Radiative Transfer (libRadtran) calculations. LibRadtran has been developed by Mayer and Kylling (2005) and is freely available online at http://www.libradtran.org. Because the input optics from all three spectroradiometers do not show a significant deviation from the ideal cosine response, a cosine correction is only applied to the spectra measured by the BSI and NDSC spectroradiometers. The correction applied to the NDSC data is typically +1%, and the correction applied to the BSI data is smaller than 1.5% at all times and wavelengths. Spectra from the NDSC instrument were correlation aligned against the solar reference spectrum measured by the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) flown on the third Atmospheric Laboratory for Applications and Science (ATLAS-3) Space Shuttle mission (VanHoosier 1996). The key region for the alignment is the calcium (Ca) doublet near 390 nm. Spectra measured by BSI and IMUK have not been postcorrected for wavelength shifts because the measurements were stable with respect to wavelength.

All spectra measured by BSI and IMUK were ratioed against spectra measured by the NDSC spectroradiometer. The ratio spectra at three different times of the day, including midday spectra, are illustrated in Fig. 4. The ratio between BSI and IMUK is also shown, because both instruments have detected the irradiance up to 600 nm.

For wavelengths between 295 and 315 nm (UVB) all instruments agree to within ±8%. For wavelengths above 315 nm the deviation between the three instruments is less than ±5%. Compared to the NDSC instrument, the spectral irradiance measured by BSI is higher by 3%, on average. A slight spectral dependence between the IMUK and NDSC spectroradiometers can be observed. At 300 nm, IMUK measures roughly 8% higher than the NDSC instrument. The ratio decreases steadily with increasing wavelength. At 450 nm, the irradiance measured by IMUK is about 2% lower than the one detected by the NDSC spectroradiometer. In the UVB, the deviation between BSI and IMUK is less than 5%. For wavelengths larger than 320 nm, the spectral irradiance measured by IMUK is about 4% lower compared to the BSI instrument. A step change of about 5% occurs at 500 nm, but the deviation between IMUK and BSI stays below 4% for wavelengths longer than 500 nm. At 500 nm, the IMUK instrument changes detectors [from PMT to silicon (Si) diode] and gratings (from 2400 to 1200 grooves per millimeter).

To evaluate the complete day, ratios of different wavelengths over the course of the day are plotted in Fig. 5a for BSI–NDSC and Fig. 5b IMUK–NDSC. The

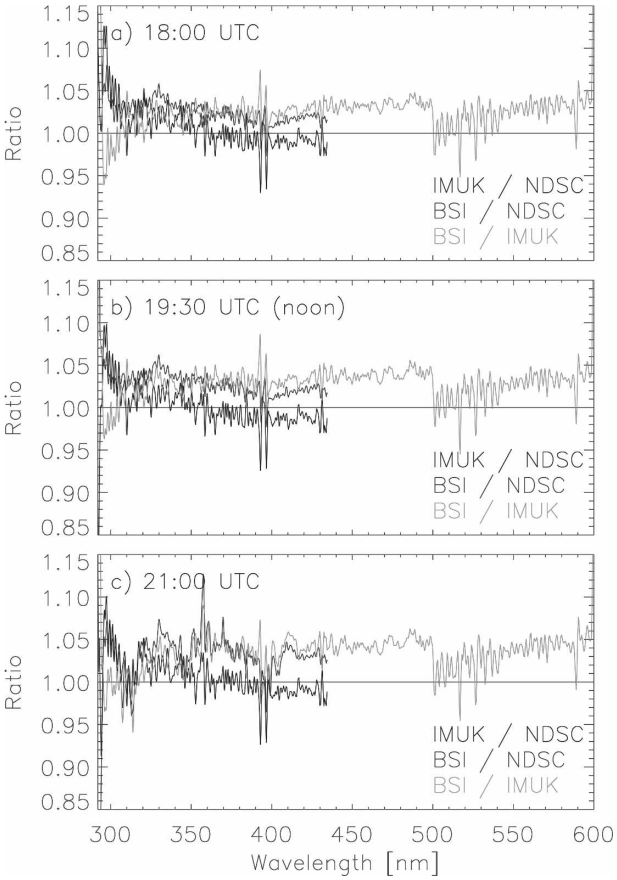

FIG. 4. Spectral ratios IMUK/NDSC, BSI/NDSC, and BSI/IMUK for (b) the 1930 UTC (noon) spectrum and (a) 1.5 h before and (c) 1.5 h after on 22 Jun 2003.

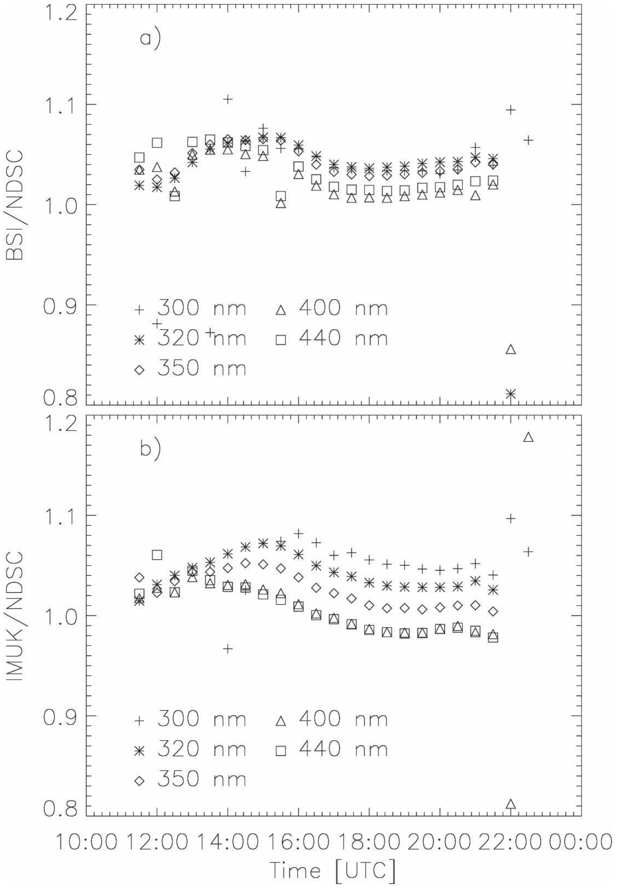

FIG. 5. Diurnal cycle of instrument ratios at different wavelengths on 22 Jun 2003: (a) BSI/NDSC: between 1700 and 2200 UTC the BSI measures about 5% higher than the NDSC spectroradiometer at 320 nm, whereas the deviation is less than 1% at 400 nm; (b) IMUK/NDSC: the deviation between the IMUK and NDSC spectroradiometer is about +6% and −1% for 300 and 440 nm, respectively, between 1700 and 2200 UTC.

spectral dependence between the BSI and NDSC spectroradiometer is not as pronounced as between the IMUK and NDSC instrument. Between 1700 and 2200 UTC the BSI measures about 5% higher than the NDSC spectroradiometer at 320 nm, whereas the deviation is less than 1% at 400 nm. During the same time of day, the deviation between the IMUK and NDSC spectroradiometers is about +6% and −1% for 300 and 440 nm, respectively. Outliers are observed in both panels at 2200 UTC. They are the result of synchronization problems during cloudy periods in the afternoon.

The ratio BSI/IMUK is shown in Fig. 6. The deviation between both instruments is ±3% between 1100 and 2100 UTC, thus during most of the day. Only the ratio at 590 nm shows larger deviations in the morning hours from 0.9 at 1100 UTC increasing to 1.6 at 1400 UTC. This large deviation may be because of the fact that IMUK did not adjust the wavelength setting of the monochromator for wavelengths above 500 nm properly.

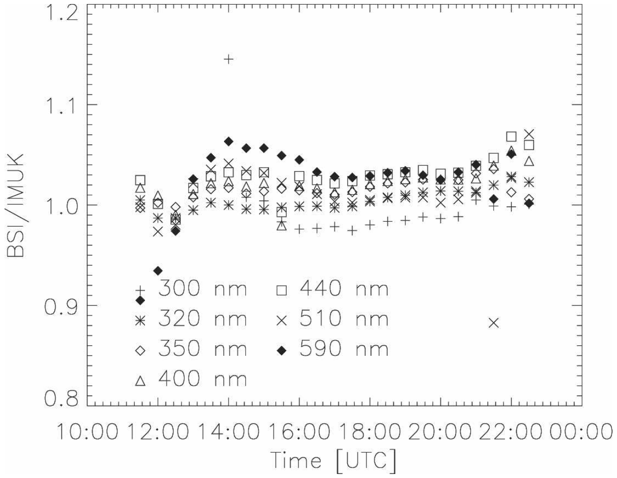

FIG. 6. Diurnal cycle of the ratio BSI/IMUK at different wavelengths on 22 Jun 2003. Except for 590 nm, the ratio between the two instruments stays within ±3% for most of the day for the wavelengths considered.

The spectral irradiance measured by the IMUK spectroradiometer generally agrees better with the BSI instrument than with the NDSC instrument. During this campaign, the NIWA instrument used a PTFE diffuser that did not include any temperature control. For temperatures below 19°C, the application of a correction for the recently reported temperature coefficient of PTFE (McKenzie et al. 2005) would have lead to an increase in irradiance of about 1% for the morning data and thus to a better agreement to the other two spectroradiometers.

4. Discussion

The main goal of this paper is to show that two new instruments comply with NDSC specifications. It is worth noting that all three instruments discussed in this paper also meet the requirements for type S-2 UV spectroradiometers set up by the WMO (Seckmeyer et al. 2001). The instruments can therefore be used for the most demanding application in UV research, such as trend detection, process studies, validation of radiative transfer models, and validation of satellite data.

a. Compliance with the NDSC standards

The IMUK spectroradiometer complies with all specifications set up by the NDSC with the exception of the slit function criterion, which could not be validated with sufficient accuracy. This criterion requires that the slit function is smaller than 10^{-3} of its maximum at

2.5 × FWHM (i.e., 1.35 nm) away from the center. Measurements based on the 253.65-nm mercury line indicate that the slit function is at least 1.76×10^{-3} at the specified distance. The actual value is likely smaller, but this could not be proven because the emission continuum of the mercury lamp limits the measurement to about 2.5 orders of magnitude. A more accurate measurement would have required a laser, which was not available.

The BSI instrument fulfills all specifications indicated in Table 1 with the exception of a slight deviation for the detection threshold criterion.

b. Intercomparison with the NDSC instrument

Spectral measurements performed by the IMUK and BSI spectroradiometers on 22 June 2003 agree well with results from the NDSC spectroradiometer operated by NIWA–CIRES. Deviations in the UVA and visible are smaller than ±5%. Differences in the UVB are smaller than ±8%. Considering the low absolute irradiance levels and the strong increase of the solar spectrum in the UVB, deviations of 8% are still acceptable. Such deviations represent state-of-the-art spectroradiometers for measuring spectral surface UV irradiance. The deviations of 5%–8% between the three instruments compared in this study are lower than or equal to deviations seen at recent intercomparisons for UV spectroradiometers (Kjeldstad et al. 1997; Seckmeyer et al. 1998; Bais et al. 2001; Lantz et al. 2002).

Small differences in absolute irradiance levels and small wavelength shifts between the instruments are likely responsible for the somewhat larger deviation at shorter wavelengths. The ratio of IMUK/NDSC exhibits a small (i.e., 7% between 300 and 440 nm) wavelength dependence for unknown reasons. However, these deviations are within the stated uncertainties (Slaper et al. 1995; Bernhard and Seckmeyer 1999; Bernhard et al. 2004) of UV spectroradiometry. The outliers observed in Fig. 5a (e.g., at 2200 UTC) may be because of synchronization problems during cloudy periods in the afternoon. We note that although all three instruments are capable of distinguishing between the direct and diffuse measurements, as required by the NDSC (McKenzie et al. 1997), at present this achieved only with manually located shading disks.

5. Conclusions

It has been shown that the IMUK and BSI spectroradiometers comply with the NDSC standards for UV spectroradiometry. All necessary requirements have been met. For one, the IMUK and BSI spectroradiometers have been compared successfully to a NDSC spectroradiometer operated by NIWA–CIRES at the fifth North American Interagency Intercomparison for UV Spectroradiometers. Further, the specifications set up by the NDSC, which are summarized in Table 2, are met. According to this characterization, the spectral UV data of the BSI and IMUK instruments are of the high quality demanded by the scientific user communities. It will be possible to use the IMUK spectroradiometer as a traveling standard on behalf of the NDSC. Furthermore, there is now an instrument that is capable of measuring solar irradiance in a wavelength range from 250 to 1050 nm. Further, extension into the infrared is possible, but not realized yet.

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