JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. D12, PAGES 12,509-12,525, JUNE 27, 2001

SUSPEN intercomparison of ultraviolet spectroradiometers

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Abstract. Results from an intercomparison campaign of ultraviolet spectroradiometers that was organized at Nea Michaniona, Greece July, 1-13 1997, are presented. Nineteen instrument systems from 15 different countries took part and provided spectra of global solar UV irradiance for two consecutive days from sunrise to sunset every half hour. No data exchange was allowed between participants in order to achieve absolutely independent results among the instruments. The data analysis procedure included the determination of wavelength shifts and the application of suitable corrections to the measured spectra, their standardization to common spectral resolution of 1 nm full width at half maximum and the application of cosine corrections. Reference spectra were calculated for each observational time, derived for a set of instruments which were objectively selected and used as comparison norms for the assessment of the relative agreement among the various instruments. With regard to the absolute irradiance measurements, the range of the deviations from the reference for all spectra was within ±20%. About half of the instruments agreed to within ±5%, while only three fell outside the ±10% agreement limit. As for the accuracy of the wavelength registration of the recorded spectra, for most of the spectroradiometers (14) the calculated wavelength shifts were smaller than 0.2 nm. The overall outcome of the campaign was very encouraging, as it was proven that the agreement among the majority of the instruments was good and comparable to the commonly accepted uncertainties of spectral UV measurements. In addition, many of the instruments provided consistent results relative to at least the previous two intercomparison campaigns, held in 1995 in Ispra, Italy and in 1993 in Garmisch-Partenkirchen, Germany. As a result of this series of intercomparison campaigns, several of the currently operating spectroradiometers operating may be regarded as a core group of instruments, which with the employment of proper operational procedures are capable of providing quality spectral solar UV measurements.

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Paper number 2000JD900561
0148-0227/01/2000JD900561$09 00

1. Introduction

Monitoring of solar ultraviolet (UV) radiation is one of the most important activities to have been stimulated in recent years by the observed decreases in stratospheric ozone [*World Meteorological Organization*, 1999; *United Nations Environment Programme*, 1998]. During the last decade a large number of stations have been established worldwide for monitoring the spectrum of solar ultraviolet radiation reaching the Earth's surface [*Weatherhead and Webb*, 1997]. Solar UV radiation is known to have adverse effects on the biosphere, including terrestrial and aquatic ecosystems and public health. Concerning the human beings, exposure to UV radiation from the sun is associated with skin cancer, acceleration of skin ageing, and cataracts or other eye damages. It may also affect the people's immune system and reduce the effectiveness of vaccination. Several plants react to increased UV radiation with reduced growth or diminished photosynthetic activity. Phytoplankton, which is the first link in the maritime food chain, may be damaged as well. With regard to atmospheric chemistry, UV is capable in triggering chemical reactions in the atmosphere or photodissociation of atmospheric species. The association of solar UV radiation with all these processes imposed the necessity of performing measurements that would help in addressing these issues.

It follows naturally from the inverse relationship between photon energy and wavelength that the chemical and biological effects of ultraviolet radiation are generally very dependent on wavelength. It is therefore essential to obtain spectrally resolved measurements when monitoring ultraviolet irradiance. As with any environmental or geophysical parameter, these measurements must also reach an appropriate level of accuracy and reliability [*Seckmeyer et al.*, 2001; *Weatherhead et al.*, 1998] if they are to be of any use in elucidating the nature of the processes that give rise to the observed variations.

Spectral ultraviolet irradiance is a difficult parameter to monitor for several reasons: first it involves not one but many measurements over a wide dynamic range, in order to cover the required wavelength range with sufficient spectral resolution; second, the spectral requirement is confounded by the Fraunhofer structure of the solar extraterrestrial spectrum, which displays large fluctuations on a finer spectral scale than can be resolved by the slit functions of the spectrometers currently in use; and third, the radiation arrives from all parts of the sky, to be collected by a receiver of finite area, which must faithfully deliver the incoming photons to the spectrometer proportionally to the cosine of the incidence angle. But the aspect that sets irradiance measurements apart and presents the most intractable obstacle to progress is the inherent difficulty of transferring the absolute scale of spectral irradiance from a national standards laboratory to a field instrument or even from one laboratory to another. To cope with those difficulties, high-level technology as well as sophisticated instrumentation and procedures are required for performing spectral measurements of solar ultraviolet irradiance.

A typical spectroradiometer for irradiance measurements comprises the foreoptics (usually a diffuser plate or an averaging sphere), the monochromator (with one or two dispersing elements), and the detector, which is either a photomultiplier or a diode array [*Kostkowski*, 1997]. The foreoptics is coupled to the monochromator either with a fiber or with a series of prisms and lenses. Usually, the monochromator is set to the measuring wavelength mechanically by rotating the grating or the two grating in case of a double monochromator. The appropriate wavelength alignment is achieved either by scanning a spectral line from an artificial source or by shifting the measured spectrum to match the Fraunhofer lines of the solar spectrum. An important aspect in spectroradiometry is the absolute calibration, which is currently achieved almost exclusively by comparison to standard sources of spectral irradiance. A significant part of the overall uncertainly in spectral UV measurements is associated to the absolute calibration technology and procedures, including the stability of the lamps with time, their traceability to the standards of certified institutes (e.g., National Institute for Standards and Technology, National Physical Laboratory, Physicalisch-Technische Bundesanstalt), and the conditions during the lamp operation (stability and accuracy of current, lamp petitioning, temperature), etc. Other uncertainties may arise from the individual characteristics of the spectroradiometer, for example, its angular response, wavelength alignment precision and accuracy, linearity, rejection level of stray light, spectral resolution (bandwidth), detection threshold and temperature effects [*Seckmeyer et al*, 2001].

The need for quality control and quality assurance of UV measurements has been recognized since the beginning of the 1990s. The establishment of international databases of solar UV measurements (e.g. Scientific UV Data Management, SUVDAMA and World Ozone and UV Data Center, WOUDC) and particularly their open availability to the user community call for strict application of such procedures in order to ensure the accuracy of the information provided. Quality control is performed at the monitoring stations through the development and application of appropriate procedures, most of which have already been tested and verified in the framework of international collaboration between UV instrument operators [*Webb et al.*, 1998; *Bernhard and Seckmeyer*, 1999]. Up to the present, quality assurance has been successfully achieved through a series of intercomparison campaigns, which have been organized either in the framework of research projects or as national and international initiatives [*Josefsson*, 1991; *Gardiner and Kirsch*, 1992, 1993, 1995; *Koskela*, 1994; *Webb*, 1997; *Thompson et al.*, 1997; *Kjeldstad et al.*, 1997; *Early et al.*, 1998; *Seckmeyer et al.*, 1998]. Despite the risks of damage to spectroradiometers and changes in their sensitivity during transportation and despite the significant interruption of the regular monitoring programs intercomparisons have so far been the main mechanism for quality assurance of UV spectroradiometers. As the number of deployed instruments is constantly increasing, such campaigns are becoming impracticable, and soon new methodologies or approaches will be required. These campaigns show a constant improvement in the agreement among the participating spectroradiometers, as a result of technological advancements in the instruments, improved operational and calibration procedures, and the accumulated experience of their operators.

The most recent, and so far the largest, in this series of intercomparison campaigns took place in July 1997 in Greece in the framework of the EC project Standardization of Ultraviolet Spectroradiometry in Preparation of a European Network (SUSPEN). The objective of SUSPEN was to bring together a reasonable number of UV spectroradiometers ensuring the largest possible diversity of instrument types and sufficiently large geographical coverage. Details of the organization of the campaign and the major findings are presented in this paper.

2. The Campaign

2.1. Location and Time

The campaign took place at Nea Michaniona in Greece, on the flat roof of a building in a coastal complex with an extensive sea horizon. The factors which are critical to success in selecting an intercomparison site are the climate, the absence of local obstructions to the field of view, particularly those which are close enough to present a different field of view to different parts of the roof, and the operational effectiveness and convenience of the control room facilities. The site at Nea Michaniona satisfied these requirements almost perfectly. The terrain on the landward side was low enough to present no significant obstruction to the view of the instruments, and the other buildings on the site did not interfere with the field of view. The outlook from the roof was uniformly clear, and the climate delivered a suitable period of stable skies for the observations. The roof was ~44 m long in the east-west direction and 9 m from north to south. The control equipment of the spectroradiometers and the calibration facility were arranged in a series of rooms directly below the observation roof. The geographical position of the observation site was 40°28' N, 22°51' E, and the altitude of the instruments on the roof was ~30 m above sea level.

The campaign started on July 1, 1997, and lasted for 12 days, although only 2 days, July 4 and 5 were the official blind intercomparison dates. The time before these dates was devoted to instrument installation and calibrations while the subsequent period was used for lamp measurements and for other instrument checks and testing.

2.2. Participants

This was the most ambitious campaign to date, with 19 instruments taking part in the blind intercomparison. A wide range of instrument types was represented, and the participating groups

Table 1. List of Participants in SUSPEN Campaign

Institute	ID	Instrument Type
Institut für Medizinische Physik, Austria	ATI	Bentham DM150
Universität für Bodenkultur, Austria	ATW	Bentham DM150
Radiation and Nuclear Safety Authority, Finland	FIH	Bentham DM150
Fraunhofer Institut fur Atmosphärische Umweltforschung, Germany	DEG	Bentham DTM300
University of Manchester Inst of Science and Technology, United Kingdom	GBM	Bentham DTM300
National Inst of Water and Atmospheric Research, New Zealand	NZL	Bentham DTM300
Biospherical Instruments Inc., United States	USS	Biospherical SUV-150
Instituto Nacional de Meteorología, Spain	ESI	Brewer MkII
Atmospheric Environment Service, Canada	CAT	Brewer MkIII
Finnish Meteorological Institute, Finland	FIJ	Brewer MkIII
University of Thessaloniki, Greece	GRT	Brewer MkIII
Royal Netherlands Meteorological Institute, Netherlands	NLK	Brewer MkIII
University of Tromsø, Norway	NOT	Brewer MkIII
Swedish Meteorological and Hydrological Institute, Sweden	SEN	Brewer MkIII (thermostated)
National Inst of Public Health & the Environment, Netherlands	NLR	Dilor XY
Université des Sciences et Technologies de Lille, France	FRL	Jobin Yvon HD10
Danish Meteorological Institute, Denmark	DKK	Metcon CVI CM112
Norwegian University of Science and Technology, Norway	NOD	Optronic 752
Institut d'Aéronomie Spatiale de Belgique, Belgium	BEB	Optronic 754

came from 15 nations. This reflected the original selection criteria, which sought to combine a broad geographical range with as much technical diversity as practicable in the instruments themselves. There were ten different models of spectroradiometer, but the distribution of the instruments among these ten types was rather uneven. In practice, it is impossible to gather high-quality instruments representative of the leading groups in Europe, or the world for that matter, without accumulating sets of almost identical instruments from a few manufacturers. Consequently, the selection of instruments was a compromise, consisting of a few individual instruments together with two large sets. It did, however, succeed in encompassing a wide geographical coverage. A list of the instruments that took part in SUSPEN is shown in Table 1, together with the names of the institutes that operate them and the three-letter codes that will be used in the following to identify each instrument.

2.3. Campaign Protocol

The official topic of the campaign was the measurement of solar ultraviolet spectral irradiance incident on a horizontal surface, and one of the most important aspects was to maintain the blindness of the produced results in order to assess objectively the performance of the spectroradiometers. The objective analysis and assessment of the results was further ensured by introducing an independent referee, who supervised the proper conduct of the intercomparison, particularly the blind aspects of the campaign protocol, and collected the spectroradiometric measurement data from the instrument operators. This role was undertaken by the group from the British Antarctic Survey (BAS), who had already carried out the same task in several previous campaigns.

To enable proper analysis of the measurements and methodical operation of the campaign, a set of rules was adopted with regard to the data collection and delivery. These rules provided for synchronized scans of the global spectral irradiance every half an hour UT, in the wavelength range 285 - 365 nm. The scans advanced by 0.5 nm every 3 s, so that all instruments could measure the same wavelength at once. A standard format was used, in which the operators provided their best available determination of the spectral irradiance at each wavelength, together with the cosine correction factor which they had applied. This factor was unity for those operators who did not apply any cosine correction. To enable the application of the wavelength-shift algorithms to the campaign data, each operator was also obliged to provide the slit function of the spectroradiometer, or at least its full width at half maximum (FWHM). All measured solar spectra were delivered by noon on the day following the measurements, and the operators were not allowed to exchange or compare any measured spectra or lamp scans before or during the period of the blind protocol.

2.4. Mobile Lamp Unit

In addition to the solar irradiance measurements by the instruments participating in SUSPEN a series of lamp measurements was included in the measurement protocol. In previous campaigns (Panorama 1991 and 1992, NOGIC 1996) it was found that various instruments produced different relative results, according to whether the comparison took place under the sky, or under the same lamp in the laboratory. This was frequently attributed to possible changes in their characteristics when they were moved from their measurement position to the darkroom for the lamp measurements. Another possible reason for such behavior could be the effect of their different angular responses. When the instruments are compared under the sky their cosine response plays a significant role, in contrast to the measurements under a lamp, when the beam illuminates the input optics vertically, and practically no diffuse light is present. To eliminate the risk of changes in the instruments during transportation, in this campaign another approach was tested, i.e., to use a mobile lamp system instead that would be placed over each spectroradiometer. This way the spectroradiometers would measure the lamp at exactly the same position and under the same conditions as for the solar irradiance spectrum.

The unit was designed and constructed at the Laboratory of Atmospheric Physics of the University of Thessaloniki, and special attention was paid to minimizing all possible factors that would interfere with the measurements. Such a system must be rigid to avoid any movements during the measurements and to protect the illuminating lamp from undesirable shocks. Thus it was constructed from thick metallic rods and was mounted on four rubber wheels, which prevented significant disturbances when the unit was moving. The whole structure was secured at its operational position with the aid of four vertical screws, capable of lifting the whole system, enabling its accurate leveling, and ensuring its robustness and stability. Extensive testing showed that the system was sufficiently stable, even during the lamp adjustment procedure, with respect to the orientation of the lamp and its distance from the instrument's diffuser.

The elimination of stray light is one of the important requirements. Stray light may originate either from the sunlight and skylight reaching the input optics during the lamp measurements or from reflections of the lamp light on the system components. To eliminate the problem, a pair of flat baffles was placed between the lamp and the entrance optics of the spectroradiometer, with openings sufficiently large to enable the unobscured illumination of the entire diffuser. A nonreflecting cone was positioned above the lamp blocking the field of view of the instrument behind the lamp and at the same time eliminating any back-reflections of the lamp light toward the entrance of the spectroradiometer. Finally, a thick black cloth that was fixed around the edge of the lower baffle protected the space between the baffles and the instrument from external light. By testing the device, it appeared that the light from the surroundings was reduced appreciably, to nonmeasurable levels. Reflections of the lamp's light on the system's components were reduced significantly almost to a nonmeasurable level by painting all the metallic parts with matt black paint.

A 1000 watt DXW lamp was used in this unit, mounted on a system of three micrometer translators, which allowed the adjustment of the lamp horizontally in two directions and vertically. The lamp power supply output was automatically controlled through a current-feedback system connected to a personal computer. To protect the lamp's calibration and its lifetime, both the start-up and switch-off of the lamp were achieved by gradually ramping the voltage supply. The most essential parameters of the calibration procedure, namely the lamp current and the voltage across the lamp, were monitored and recorded continuously. Finally, to protect the lamp from the wind, the unit and the underlying spectroradiometer were enclosed in a metallic frame of height 2.5 m and base 2.0 m by 1.6 m, covered by a thick cloth.

All spectroradiometers measured the lamp, except NLR because it was located at some distance from the campaign platform and it was impossible to place the unit on top of the 3-m-high metallic container enclosing the spectroradiometer. According to the campaign protocol, all instruments were supposed to measure the lamp after the second blind day before they were moved for any reason. The ATI and GRT measured the lamp once at the beginning and once at the end of the exercise, proving that the lamp was stable to within 1%.

3. Data-Analysis Procedure

An efficient and illustrative way of comparing spectra recorded simultaneously by two different collocated spectroradiometers is to present their ratio over the entire measured spectral range. By taking the ratio, the effect of the large dynamic range of the solar UV spectrum at the ground is removed, and the differences are easily exposed [*Bernhard et al.*, 1998]. In the case where more than two spectra are to be compared, their ratios against one common spectrum, which serves as a comparison reference, is more appropriate. This reference spectrum must be selected objectively to avoid giving preference to any particular instrument. Unfortunately, the true solar spectrum at a certain time is unknown, and there is no way to prove that a measured spectrum is equal to the actual spectrum at that time, no matter how good the quality of the spectroradiometer and the operational procedures.

For comparison purposes, however, it is sufficient to have as reference a spectrum the shape and absolute magnitude of which are as close as possible to the truth. One may consider that the average of the spectra measured at the same time by several instruments is close to the truth, especially when differences among the various instruments are small. When many instruments are compared, such an average spectrum can be further refined by excluding some of the instruments whose spectra lie outside certain limits. The selection of the comparison reference has been an important issue during previous major intercomparisons and imposed the development of an objective algorithm for the construction of the reference. A description of the methodology for the

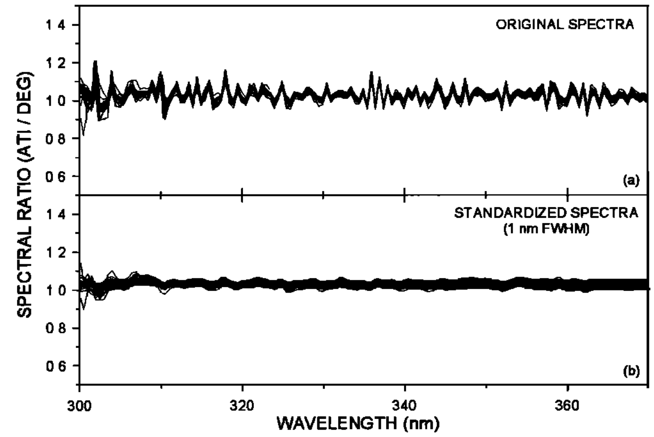

Figure 1. (a) Ratios of global irradiance spectra recorded by the ATI and DEG spectroradiometers from sunrise to sunset. (b) The same ratios after the spectra have been standardized to 1 nm FWHM triangular slit function.

construction of the reference is presented in section 3.4, while more details about the algorithm are given by *Gardiner and Kirsch* [1997].

3.1. Standardization of Spectra to Common Spectral Resolution

When taking the ratio of spectra recorded by two different spectroradiometers, a marked wavelength structure may appear, which is also repeatable for any pair of spectra measured by those two instruments, as long as nothing changes in the optical characteristics of the instruments. An example showing ratios between spectra recorded by two different instruments at various times during the same day is given in Figure 1a. The wavelength structure is mostly due to the two instruments not having the same spectral response (or slit function), which causes each instrument to sense the solar spectrum differently. The slit function is an intrinsic characteristic of each spectroradiometer. In this particular example the FWHM of the slit function was 0.76 nm for the ATI instrument and 0.57 nm for DEG. In reality, a measurement that is provided at a given wavelength by a spectroradiometer is the integral of the solar spectrum weighted by its slit function, over the spectral range in which the slit function has a nonzero value. Different instruments have slit functions of different width and shape, and therefore the integral is produced by a different part of the solar spectrum, also with different weighting. At the steep part of the UV spectrum (below ~310 nm) the effect is more important and if the effective slit widths of two instruments are significantly different, important artificial wavelength dependence may appear in the ratio.

The effect of the slit function is systematic for each instrument and at present, all data sets provided by UV spectroradiometers operating regularly at their home sites have this systematic difference. However this known and more or less predictable factor may easily mask differences arising from other instrumental factors, when comparing spectra from different instruments. Such differences can be exposed only if the effect of the slit function is removed from each spectrum, by standardization to a common slit function. The standardization can be achieved by applying a deconvolution technique, which transforms the measured spectrum to a high-resolution spectrum, followed by a reconvolution to some standard common slit function. Such a methodology and the relevant algorithm (SHICrivm) have been developed by H. Slaper [*Slaper et al.*, 1995; *Slaper and Koskela*, 1997] and have been extensively tested in various campaigns. The effect of the slit function standardization on the spectral ratios of Figure 1a is illustrated in Figure 1b, which presents the ratios computed from the same spectra after they were standardized to a common triangular slit function of 1 nm FWHM. Evidently, the marked structure has been reduced significantly; the remnants may be due to factors other than the slit function difference as well as to the uncertainties in the method and in the representation of the slit functions. Although with this standardization the actual measurements of each instrument are somewhat manipulated, for the intercomparison it is a great advantage as it removes the significant and systematic wavelength structure to reveal differences in the spectra of different origin.

3.2. Wavelength Shift Corrections

Apart from the absolute irradiance calibration, perhaps the most important factor in the quality of spectral measurements is the accuracy of the wavelength registration. Several studies have shown the significance of this factor and have demonstrated that even small wavelength shifts can produce large errors in the measured irradiances [*Bais*, 1997; *Bernhard and Seckmeyer*, 1999]. Two methods are mainly used for the wavelength alignment of the spectroradiometric measurements; the first is based on aligning the spectrometer before the measurement with the aid of emission lines of known wavelength, such as mercury lines [*Gröbner et al*, 1998], and the second is based on shifting the entire measured spectrum according to the position of the Fraunhofer lines in the measured spectrum, after the measurement is completed [e.g., *Huber et al*, 1993]. Sometimes, a combination of the two methods is used to align spectra and remove nonlinearities [*Liley and McKenzie*, 1997]. Wavelength shift corrections may also be applied during postprocessing of the measured spectra by comparison to high-resolution spectra of known accuracy in the wavelength registration. The SHICrivm algorithm uses the high-resolution spectrum measured at Kitt Peak [*Kurucz et al.*, 1984] which is provided at fine wavelength steps. This solar spectrum, after being convolved with the slit function of the spectroradiometer, is shifted backward and forward at fine steps, and each time is compared with the measured spectrum. The wavelength shift of the measured spectrum is determined by the shift of the solar spectrum that gives the smallest standard deviation of the residuals.

The performance of the algorithm depends on many factors including the stability of the atmospheric transmission during the scan, the measurement noise, the smoothness of the wavelength error in the instrument as a function of the wavelength setting, and the accuracy of the reference spectrum. The original paper [*Slaper et al.*, 1995] demonstrates that the precision of the algorithm can be better than 0.01 nm, which is confirmed by the results from several of the instruments during this comparison.

In the analysis of data from the SUSPEN campaign, the wavelength shift for each instrument was determined and reported. All spectra were then corrected for the wavelength shift before comparison with the reference for the determination of the deviation of their absolute irradiance calibration.

3.3. Cosine Response Corrections

Deviations in the angular response of the entrance optics of spectroradiometers constitute one of the major sources of errors in solar ultraviolet measurements. These are commonly referred as "cosine errors." The construction of most types of the entrance optics in current use generally leads to underestimation of the measured irradiances by a few percent; the magnitude depending on solar zenith angle and the atmospheric conditions. Only recently have special types of entrance optics been developed, which diminish the cosine errors to levels below 2%. However, the majority of the operating spectroradiometers suffer from errors, which can be as high as 20% [e.g., *Blumthaler and Bais*, 1997]. Several studies have shown that the cosine error can be quantified and largely removed from the measurements by using either supplementary data or theoretical calculations [*Seckmeyer and Bernhard*, 1993; *Feister et al.*, 1997; *Blumthaler and Bais*, 1997; *Bais et al.*, 1998; *Leszczynski et al*, 1998; *den Outer et al*, 1998]. Following the methodologies proposed in the above studies, cosine corrections to measured spectral irradiances are regularly applied at a number of UV monitoring stations.

Of the nineteen spectroradiometers participating in SUSPEN only four were equipped with diffusers with close to ideal angular response (ATI, DEG, NZL, USS), while three other instruments (GRT, FIH, and FRL) submitted cosine corrected measurements. Despite their superior cosine response, the ATI, DEG, and NZL instruments also provided cosine corrected data. The rest of the instruments provided spectral measurements without any angular response correction. Their data were expected to be underestimated by a few percent, as none of them was equipped with low cosine-error diffusers. However, for consistency with the measurements that these instruments provide during their regular operation at their home sites, their data were used in the comparisons as submitted.

Owing to the importance of the cosine error, in this study we included a separate investigation of the effect of the cosine corrections on the intercomparison results. For this purpose, two different data sets were produced: one including cosine corrections and one excluding cosine corrections. Postcampaign cosine corrections were applied to the measurements of eight instruments (ATW, CAT, FIJ, GBM, NLK, NOD, SEN, USS) for which the angular response was available. The methodology for calculating the cosine correction for those instruments was similar to the one described by *Blumthaler and Bais* [1997] and by *Bais et al.* [1998]. The spectral direct-to-global ratios were derived using the direct spectra acquired by the ATI instrument during the campaign. As the direct spectra were recorded ~10 min after each global spectrum, the direct spectrum corresponding to the time at which the global spectrum was measured was calculated by interpolation between two direct spectra measured before and after the global spectrum following a methodology described by *Huber et al.* [1995]. No wavelength-shift corrections were applied to global and direct spectra that were used for the determination of the direct-to-global ratio because they were recorded by the same instrument and within only a few minutes and consequently the same shifts are expected for both types of measurements. Finally, postcampaign cosine correction factors were also provided by the operators of the NLR instrument.

Thus a data set with cosine-corrected spectra was produced for all but four instruments (BEB, DKK, ESI, NOT), for which no information on their cosine response was available. In the case of spectra which were submitted as cosine-corrected, it was straightforward to remove the cosine corrections, as the correction factors had been supplied with the measured spectra.

3.4. Comparison Reference

Building on the experience gained in earlier intercomparison projects, BAS scientists formulated a comprehensive protocol for the objective analysis of the data to be received by the referee during the campaign. In particular, a detailed technical algorithm was developed [*Gardiner and Kirsch*, 1997] to establish an objective reference to which the results of the various participating instruments could be related. This reference algorithm is required because there is no absolute standard of ultraviolet spectral irradiance with which the measurements can be compared. In the absence of a true reference, it is necessary to relate the results to one of the participating instruments or to the average of a group of instruments, but in each case the choice is liable to be arbitrary. Following practices applied also in previous campaigns, the reference in SUSPEN is determined by an objective algorithm in which all the participants are treated impartially. This has two advantages: first it is seen to be fair, and second it allows the reference to reflect the actual outcome of the measurements. In general, this means that the reference should be more stable and well behaved, as the consistency of the measurements has been taken into account.

The objective procedure for obtaining the reference is in two parts: the arena algorithm and the reference algorithm. In a typical intercomparison campaign, the instruments are scheduled to observe at a preordained sequence of times, but in practice it is unlikely that all the instruments will succeed in making a satisfactory observation at every set time. Minor technical difficulties, power failures, optical obstructions, rain and strong winds can vitiate the efforts of even the best operators. The arena algorithm was constructed to cope with this problem and is designed to encompass the most general case that it is likely to face. It selects a group of instruments and observation times, such that all the instruments made a successful observation at each of the times, by applying numerical scoring techniques to arrive at an objective compromise between maximizing the number of instruments and the number of observations. Moreover, it takes into account the relative importance of the observations made at different times of day, according to the variations in solar zenith angle, and selects an optimal set of observations from those available. Using the output of the arena algorithm, the reference algorithm then seeks a group of instruments which show close consistency around the medians of the measured results throughout the day. This group constitutes the objective reference, which provides a standard against which the other instruments can be compared. Throughout this procedure, the most important governing principle is that the rules are established beforehand so that the algorithms can be seen to operate without subjective intervention.

The arena and reference algorithms, which determine the objective reference, were implemented on both blind intercomparison days, and successfully established an operational Reference for each day. There were 19 instruments and 29 scheduled observation times, making a total of 551 possible observations, 97% of which was actually achieved. The arena algorithm selected 13 instruments and 27 observation times. The reference algorithm selected six instruments (ATI, ATW, DEG, FRL, GBM, NLK), which were all present at all 29 observation times. The algorithm automatically selects one of three levels according to the performance of the instruments. At the Nea Michaniona intercomparison, the algorithm selected the highest level, reflecting the presence of a set of highly consistent instruments. This is a most encouraging result and suggests that (1) the standard of the best instruments has been maintained from previous campaigns and (2) the Nea Michaniona intercomparison provides a reliable guide to the performance and calibration of the participating spectroradiometers.

According to the campaign protocol, the spectra considered for the arena and reference algorithms were those delivered by the operators as their "best estimates" of global solar UV irradiance at the ground. Therefore the Reference established through this procedure might be slightly biased by the inclusion of instruments with systematic errors, like the cosine error which tends to underestimate the measured irradiances. This is discussed further in section 4.3, where it is shown that any bias is likely to be less than 2%.

4. Results and Discussion

The main aim of the intercomparison is to investigate the degree of absolute agreement amongst the various types of spectroradiometers. This is determined by various parameters, which contribute to the overall uncertainty of spectral UV measurements [*Webb et al.*, 1998]. The origin of the calibration standards, the calibration procedures, and the stability of the instruments' sensitivity are among the most important sources of uncertainty. Incomplete rejection of stray light can lead to significant overestimations of the irradiances at short wavelengths in the UV-B region. The nonideal cosine response of the entrance optics can produce a serious systematic error, which varies with solar zenith angle and depends on atmospheric and sky conditions (aerosols and clouds). Finally, wavelength shifts may also affect the absolute agreement between spectra from different instruments, although for relatively small shifts their effect would be rather insignificant. In the following the absolute agreement between global spectra recorded by the 19 instruments during the campaign is discussed, as well as the effects of the aforementioned parameters on the final results.

4.1. Wavelength Shifts in the Measured Spectra

From the application of the SHICrivm algorithm on all global irradiance spectra recorded during the SUSPEN campaign, their wavelength-dependent wavelength shift was determined. The range of the calculated shifts varies between instruments, with the smallest shifts (within ±0.1 nm) found in the CAT, DEG, SEN, NZL, ESI, and NLR instruments, and the largest ones in the BEB and ATW instruments (being occasionally close to ±0.5 nm). Figure 2 presents the wavelength shift range for each instrument during the 2 days of the blind intercomparison, before applying any corrections to the data. This range was determined by taking

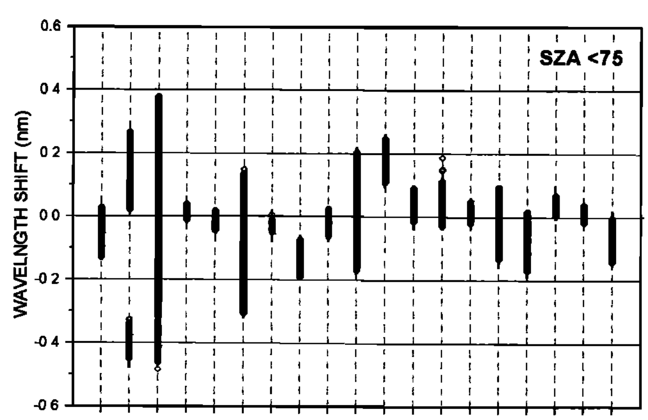

Figure 2. Wavelength shifts derived from all spectra during the blind intercomparison for each instrument.

Table 2. Errors in Global Irradiance Resulting From Wavelength Shift, Based on a Spectrum Calculated for 300 Dobson Units of Total Ozone and at 30° Solar Zenith Angle

	Resultant Error in Global Irradiance, %	
Wavelength Shift, nm	300 nm	CIE Weighted
0.30	14.0	5.6
0.20	9.4	3.7
0.10	4.7	1.9
0.05	2.4	0.9

into account the shifts that were calculated for each single wavelength of all spectra, as long as the associated error was within acceptable limits [*Slaper et al.*, 1995]. It should be noted that at large solar zenith angles or at low signals, the uncertainty in the determination of the shifts from SHICrivm increases, thus only the results from spectra recorded at solar zenith angles smaller than 75° and at wavelengths longer than 300 nm are presented. In many instruments the shift is wavelength-dependent and systematic, which implies a nonlinearity in the wavelength drive of the spectrometers and/or false determination of the dispersion coefficients that are used to translate the mechanical movement of the grating to wavelength scale. Although in most of the instruments the shifts were stable over their entire operational range, in some instruments (BEB, DKK, FRL, NLK, and NOT), important wavelength dependences were found in the calculated shifts. For ATW, FIH, GBM, NOD, and USS the range of the wavelength variation of the shifts was ~0.1 nm. In some instruments (particularly BEB and to a lesser extend ATI, GBM, and NOD) the absolute magnitude of the wavelength shift changes during the day, either as a result of temperature dependence or due to nonlinearity. Finally in a few instruments (CAT, DEG, NLR, and NZL) the wavelength shift was not only small but also remarkably stable with respect to wavelength dependence. To provide an indication of the magnitude of the resultant error from those wavelength shifts, Table 2 summarizes the error in global irradiance at 300 nm and in erythemal irradiance (CIE weighted) as a function of wavelength shift. The calculated wavelength shifts for each spectrum were used to correct all spectra recorded during the blind intercomparison dates and these new spectra were then standardized to 1 nm slit function and used for the comparisons with the Reference.

4.2. Absolute Comparison of Spectra

Comparisons of UV spectra recorded by the 19 spectroradiometers are shown in Plate 1 as spectral ratios with respect to the corresponding Reference spectrum. The upper and lower parts of Plate 1 refer to two selected solar zenith angles, respectively, 21° and 69° on the first day of the blind intercomparison. The data used for the computation of these ratios are as originally delivered by the instrument operators, before the application of the slit-function standardization or any other corrections. This comparison reflects the actual level of agreement that one should expect when the 19 instruments operating side by side report the spectrum of global solar irradiance. The factors that determine the agreement among the instruments are spectral resolution, stray light rejection, cosine response, origin and stability of irradiance calibration sources, temperature effects, operational procedures, and stability of the instruments themselves.

With the exception of 3 instruments, the overall agreement appears to be satisfactory, as the ratios to the Reference generally vary within about ±10% from unity, both at small and at large solar zenith angles. The significant scatter in the lower part of the spectrum (below about 300 nm for 21° and 305 nm for 69° SZA) results from different slit functions of the instruments, wavelength shifts, and increased uncertainty in the measurements owing to low radiation signal. Unfortunately, the marked structure through the entire spectral region (caused by the different slit functions) enhances the differences between the instruments giving a worse impression for the overall agreement. As discussed in section 3.1, convolution of spectra to a common slit function removes much of this structure (see Figure 1).

For each instrument, the mean, the root mean square (rms) and the standard deviation (σ) of the differences of the measured spectral irradiances from the corresponding Reference values over the entire spectral region are given in Table 3, separately for the two chosen solar zenith angles. Here:

$$\mathrm{rms} = \sqrt{\frac{\sum x^2}{n}} \quad \text{and} \quad \sigma = \sqrt{\frac{\sum x^2 - n\langle x\rangle^2}{n-1}} \,, \qquad (1)$$

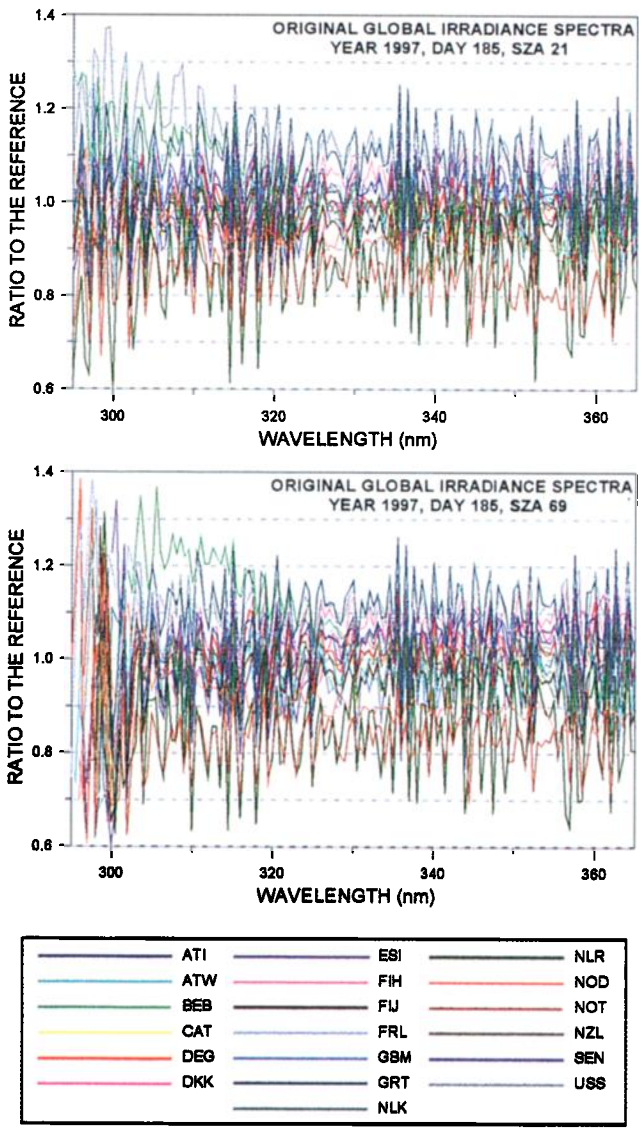

Plate 1. Ratios of global irradiance spectra recorded at (upper) 21° SZA and (lower) 69° SZA to the corresponding Reference spectrum.

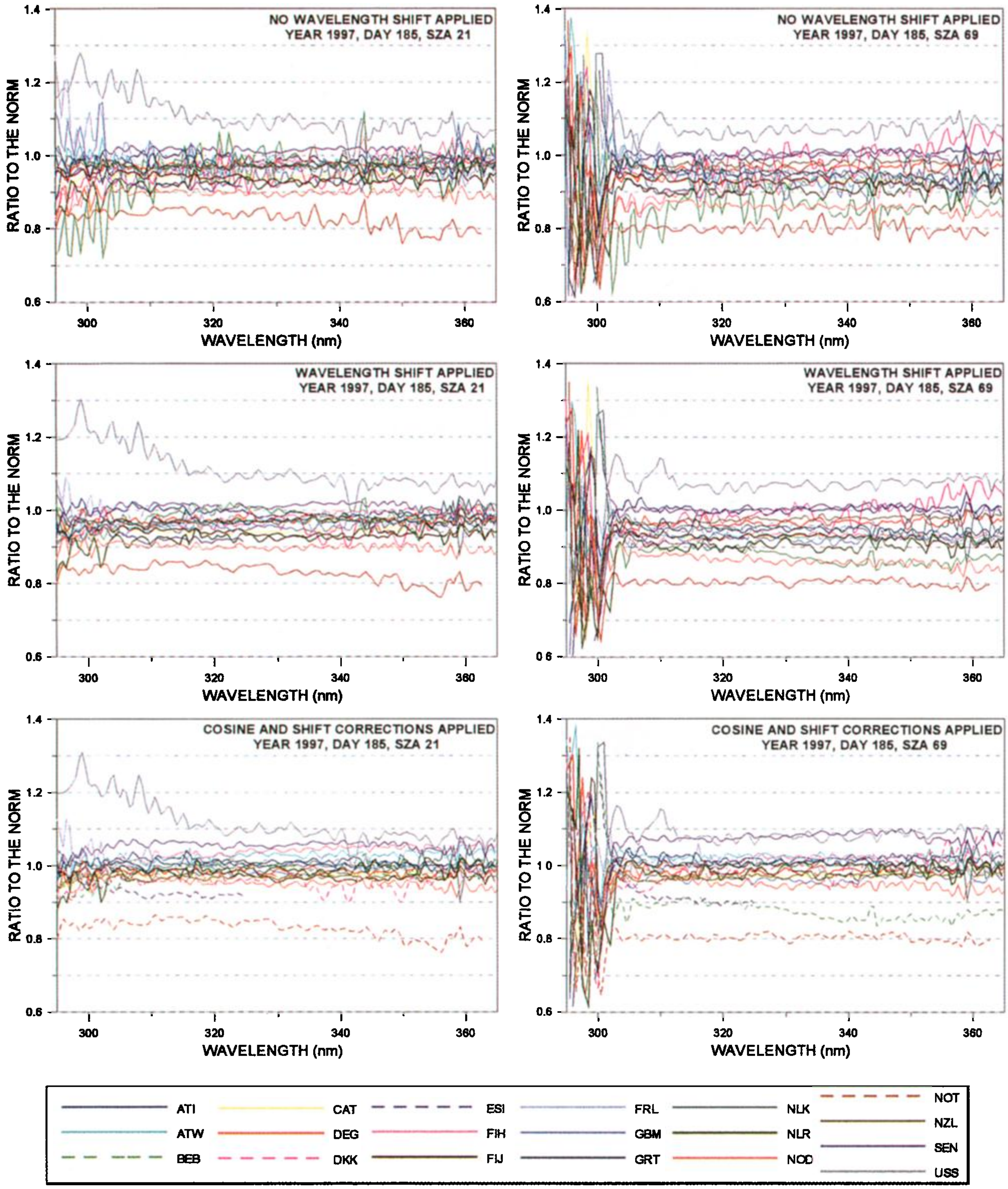

Plate 2. Ratios of global irradiance spectra recorded at (left) 21° SZA and (right) 69° SZA to the corresponding Norm. The upper panels correspond to spectra, which were only standardized to a common slit function, the middle panels include the correction for wavelength shifts and the lower panels include, in addition, cosine corrections. The dashed lines denote spectra uncorrected for cosine response.

Table 3. Statistical Estimates of the Differences of Measured Spectral Irradiances From the Reference at Two Selected Solar Zenith Angles

Instrument	SZA 21° (λ>300 nm)						SZA 69°(λ>305 nm)					
ID	Mean[a]	rms[a]	σ^a	Mean[b]	rms[b]	σ^b	Mean[a]	rms[a]	σ^a	Mean[b]	rms[b]	σ^b
ATI	2.1	4.2	3.7	2.7	2.9	1.1	5.1	6.0	3.3	5.6	5.7	0.9
ATW	-0.2	4.3	4.3	-1.0	1.5	1.1	-3.1	5.2	4.2	-4.0	4.1	0.6
BEB	1.2	8.9	8.9	1.9	9.5	9.3	5.2	11.6	10.5	5.7	12.2	10.9
CAT	-3.7	6.7	5.6	-3.5	3.6	0.6	-4.0	6.5	5.2	-3.8	3.8	0.5
DEG	0.1	6.2	6.3	0.4	1.0	0.9	1.8	6.3	6.1	2.2	2.4	1.1
DKK	-2.6	3.9	2.8	-2.0	2.9	2.2	2.5	5.3	4.7	3.3	5.1	3.8
ESI	-6.3	9.1	6.6	-5.4	5.6	1.1	-7.2	9.4	6.1	-6.1	6.2	1.1
FIH	5.6	7.8	5.5	6.2	6.5	1.9	7.3	8.8	4.9	7.9	8.0	1.2
FIJ	-4.6	7.4	5.9	-4.3	4.4	1.1	-4.5	7.4	5.9	-4.2	4.3	1.0
FRL	2.6	4.1	3.3	2.1	3.0	2.1	4.1	5.0	2.9	3.7	4.2	2.0
GBM	-1.7	7.8	7.7	-2.1	2.4	1.2	-4.1	8.2	7.0	-4.4	4.6	1.1
GRT	9.8	12.2	7.3	9.6	9.7	1.4	11.1	13.2	7.1	10.9	11.0	1.2
NLK	-1.2	7.3	7.2	-0.9	2.1	1.9	-1.8	7.1	6.9	-1.5	2.4	1.8
NLR	-13.9	18.1	18.1	-14.1	14.2	2.1	-16.1	19.2	10.5	-16.1	16.2	1.3
NOD	-7.0	7.6	3.1	-8.2	8.2	1.0	-9.7	10.2	3.4	-10.9	11.0	1.4
NOT	-15.7	16.7	5.8	-15.4	15.6	2.5	-17.2	18.0	5.3	-16.7	16.7	0.9
NZL	-1.0	3.4	3.2	-1.0	1.2	0.6	0.7	3.2	3.1	0.6	1.0	0.8
SEN	3.1	7.5	6.8	3.4	3.5	1.0	3.7	7.5	6.5	4.0	4.1	1.0
USS	12.2	14.0	6.9	12.6	13.5	5.0	10.9	11.9	4.8	11.2	11.4	1.7

[a]Original Data.
[b]Processed Data.

where x denotes the difference of the measured irradiance from the corresponding value of the Reference in percent, <x> denotes the average x, and n denotes the number of data points. Since the standard deviation expresses the dispersion of the differences about their average, its magnitude is dominated by the effect of the slit functions of the spectroradiometers. When data that were first standardized to a common slit function and corrected for the wavelength shifts are used, the variability is reduced significantly, as can be seen in the columns of Table 3 denoted as "processed" data. The results presented in these columns are in fact those produced by the independent referees, following the data analysis protocol of the campaign. A comparison between the means of the "original" and "processed" data reveals that the standardization and shift correction processes has only a minor effect on the absolute agreement of the spectra with the Reference.

Table 3 confirms the previous statement that the spectra from all but three instruments (NLR, NOT, and USS) agree with the Reference on the average to within ±10%. The rms differences derived from the "processed" data provide a more realistic representation of the absolute deviations of the spectra from the Reference, and expose some cases where small values of the mean error resulted from fortuitously balanced positive and negative deviations (e.g., BEB). Another observation is that BEB, GRT, and NLR have significantly higher standard deviations compared with the other instruments, which remain high also in the "processed" data. Such high values could not be attributed to the effect of the slit functions alone. As was discovered later, these three instruments experienced significant problems during the campaign for various reasons that are presented by their operators in appendix A.

Agreement with the Reference in absolute sense to better than 5% can be found in several instruments (ATI, ATW, CAT, DEG, DKK, FIJ, GBM, NLK, FRL, NZL, and SEN), although some of them show quite high spectral variability. Here it should be made clear that the absolute magnitude of the differences from the Reference shown so far do not necessarily reflect the deviation of a particular instrument from truth. The Reference serves only as a norm for comparisons, and it cannot be regarded as representative of the actual irradiance at the ground. In fact, as will be shown in the section 4.3, the Reference is probably underestimated by ~2-3%, owing to the inclusion of instruments uncorrected for their cosine response error. Consequently, the figures of Table 3 should be viewed mainly in relative sense, and conclusions about the accuracy of the irradiance measured by the instruments should be avoided.

The overall results of SUSPEN are significantly better than those obtained in previous intercomparison campaigns [*Gardiner and Kirsch*, 1992, 1993, 1995; *Webb*, 1997] in which a large subset of these instruments was also present. Even the few outliers are not as different as was frequently the case in the past, where instruments differed by 50% or more [*Gardiner et al.*, 1992]. Apparently, the experience gained by the operators during recent years, the improvements made in the operational and calibration procedures, and instrumental modifications made on a few of the instruments resulted in this remarkable advancement in agreement between the measurements. Although the improved instrumental performance with respect to the previous campaigns is a significant achievement of SUSPEN, an equally important outcome is the consistency of several instruments, which have maintained their level of quality through several campaigns.

To keep the paper a reasonable size, the results so far have been presented only for two observational times during the first day of the campaign, which were considered representative of high and low solar elevation conditions. This selective presentation, however, prevents a more detailed assessment of the instruments' behavior during the course of the day. An ideal spectroradiometer must have the same response to the incoming solar irradiance irrespective of the solar zenith angle and the level of the signal. Assuming that the Reference accurately represents the actual solar irradiance spectrum, for such an instrument the ratio of the measured irradiance to the Reference should remain stable throughout the day. Deviations may occur owing to nonideal cosine response, to temperature dependence or to nonlinear response of an instrument. Figure 3 shows the diurnal variation of the ratio of measured spectral irradiance to the corresponding Reference value separately for each instrument averaged over three wavelength bands covering their operational spectral range.

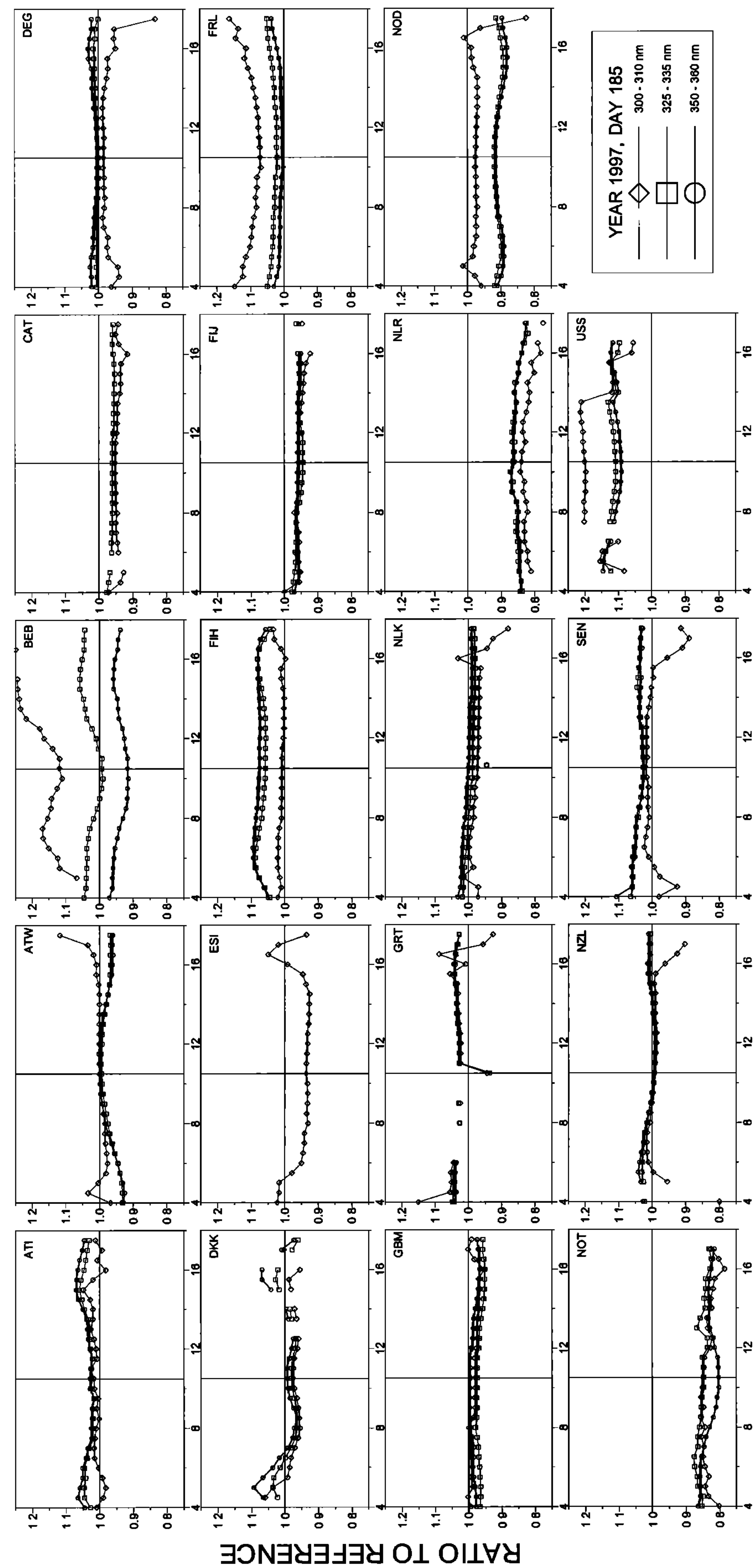

Figure 3. Diurnal variation of ratios of global spectral irradiance measured by each spectroradiometer to the corresponding Reference for July 4, 1997, averaged over three wavelength bands: 300-310 nm (diamonds), 325-335 nm (squares), and 350-360 nm (circles). The spectral irradiance measurements used are those delivered by the instrument operators without the application of any kind of correction. The vertical lines around 1030 UT mark the local noon.

The data used in Figure 3 are those from the first observation day (July 4, 1997), delivered by the operators to the referees, i.e., without slit-function standardization or wavelength shift corrections. For some instruments, cosine corrections are included, since their operators had applied them already. The results of the second day are not shown because they behave similarly to those of the first day. It should be noted that the Reference used is the one derived from the standardized to 1 nm triangular slit and shift-corrected spectra, and therefore it would be reasonable to expect that for instruments with resolution different from 1 nm FWHM the ratios at low wavelengths will deviate from unity and this effect will be more pronounced at large solar zenith angles.

The ratios for several instruments (ATI, CAT, FIJ, GBM, NLK) are very stable, to within less than 5% and close to unity. The same can be said also for DEG and NZL, as the deviation of the low-wavelength ratio at high solar zenith angles is probably due to the narrower slit function of these instruments. The smaller values in the NZL results at 310 nm for larger SZA were identified [*Bernhard et al*, 1998] as being due to errors in the determination of offsets. As mentioned in section 3.3, the Reference included both cosine corrected and noncorrected measurements, and therefore Figure 3 shows a slight cosine-dependent behavior for the instruments equipped with a diffuser close to an ideal angular response (ATI, DEG, NZL, and USS) which would not be expected if the Reference were ideal. NOT and NLR are also stable to within ~5%, but in absolute scale, they are both very far from unity. Other instruments show distinct diurnal variation, perhaps each for different reasons. Diurnally symmetric variations (e.g., ATW, DKK, GBM, NOD, and perhaps NLR) can be mostly attributed to the cosine response of the instruments, since the cosine correction factor depends on solar zenith angle and therefore the correct application of cosine correction should lead to improvement of the diurnal behavior of the instruments ratio to the Reference. It should be noted that the Reference could be contaminated from the cosine error of three of the instruments, although the results of the low cosine error instruments suggest that this effect is rather small. The downward slope of the ratio for NLK may suggest a leveling problem. Although GRT suffered from various operational failures, the ratio in most of the available observation times is very stable and wavelength independent. Peculiar behaviors such as those of BEB and USS were caused by hardware malfunctions or operational failures, as described in appendix A.

4.3. Effect of Wavelength-Shift and Cosine-Response Corrections

As discussed in the previous paragraph, the comparison among the instruments is strongly affected by various instrumental features, one of the most important being their differences in spectral resolution. To investigate the performance of the instruments in more detail, a series of corrections is applied, one at a time, and their relative importance is discussed in this section. As the aim of this section is to uncover the generally small differences between the spectra and to determine their origin, for the instruments that had errors in their spectra (BEB, GRT, and NLR), revised data sets are used. In addition, to minimize the systematic bias of the Reference owing to the inclusion of spectra from three instruments without cosine correction, a new comparison norm is used hereafter, which was formed by the same instruments using only cosine corrected spectra. Within the spectral range of the measurements, this Norm is on the average 2.1±0.3 % higher than the Reference for 21° SZA and 3.6±0 7 % for 69° SZA.

Ratios of spectra over this Norm are presented in Plate 2 for the two solar zenith angles of 21° and 69°. The three panels correspond to spectra derived from three different levels of data processing. The first level refers to spectra standardized to a common slit function (see section 3.1), which removes the marked structure from the ratios, thus eliminating the effect of the different spectral resolution of the instruments. The data used at this point were not corrected for wavelength shifts or cosine errors. For uniformity in the data set, the cosine corrections were removed from the spectra on which they were already applied. At the second level, wavelength shift corrections, as described in section 4.1, were applied on the spectra of level one, followed by slit-function standardization. Finally, at the third level, cosine corrections were applied to the spectra for which the cosine response was available.

A comparison between the upper panels of Plates 2 and 1 reveals the importance of the slit-function standardization process, as now the spectral ratios are clearly distinguishable and more easily comparable. It is immediately evident that the ratios for most of the instruments are clustered together around unity, and with the exception of BEB, NOT, NOD, and USS, they agree to within ~10% at 21° SZA. At 69° the agreement becomes slightly worse, with more instruments deviating from the 10% zone mainly at low wavelengths (e.g., FIH and NLR) but also at the high end (e.g., DKK). It is noticeable that BEB presents strong wavelength dependence almost through the entire spectral range at both solar zenith angles, while weaker dependences may be seen at USS and NOT mainly at their noon spectra. In most cases the causes for these discrepancies were identified by the instrument operators and described in appendix A. Encouraging is the result for NOD which, although it deviates significantly from the Norm (mostly due to cosine error, but also a drift in calibration, see Table 5), has no wavelength dependence. Finally, excursions from the cluster at wavelength below 305 nm can be found in other instruments, for example, FRL and GBM, instruments that were included in the Reference.

The effect of wavelength shift corrections that were applied to the spectra can be seen in the middle panels of Plate 2, especially in comparison to the upper panels. Although there is no obvious change in the absolute level of the ratios, one can easily distinguish the improvement of the wavelength dependence in many of the instruments. Small wavelength-shift corrections (the order of a few tenths of a nanometer) cannot produce significant changes in the absolute irradiance levels, except from the lowest wavelengths where the solar spectrum at the surface is very steep [*Bais*, 1997; *Bernhard and Seckmeyer*, 1999]. At the low end of the spectrum, changes were observed for almost all instruments. Perhaps the most striking effect of the wavelength-shift corrections can be seen in the ratios of BEB, FIH, GBM, and FRL at low wavelengths, where their deviations have now disappeared. The latter three are clustered now with the other instruments, again to within ~10%. Improvements have occurred also in several other instruments, mainly as suppression of the wavelength structure of their ratios to the Norm, which now are smoother.

Quantitative estimates of the effect of wavelength shift corrections can be drawn from Table 4, which shows the standard deviations (σ) of the differences from the Norm throughout the operational spectral range of each instrument, before and after the wavelength shift corrections. Changes in the magnitude of the standard deviation are significant only for the instruments with large wavelength shifts, as they were determined in section 4.1. For this reason, the standard deviations of Table 4 remain practi-

Table 4. Standard Deviations of the Spectral Differences From the Norm Before and After the Application of Wavelength Shift Corrections at Two Selected Solar Zenith Angles

	Standard Deviation of Differences, %			
Instrument ID	NS[a]	SH[a]	NS[b]	SH[b]
ATI	1.4	1.0	1.1	1.0
ATW	2.4	1.2	2.6	0.8
BEB	5.9	2.2	3.5	2.0
CAT	0.6	0.6	0.5	0.5
DEG	1.0	0.9	1.1	1.0
DKK	2.6	2.2	4 3	3.6
ESI	1.1	1.1	1.2	1.2
FIH	3.4	1.9	2.8	1.0
FIJ	1.2	1.0	1.1	1.0
FRL	3.3	1.9	2.7	1.8
GBM	3.8	1.2	3.0	1.0
GRT	1.2	0.9	1.4	1.1
NLK	1.6	1.7	1.6	1.7
NLR	2.1	1.8	1.8	1.4
NOD	1.0	0.9	1.2	1.4
NOT	2.6	2.4	1.5	0.9
NZL	0.7	0.6	0.8	0.8
SEN	1.1	1.0	1.1	1.0
USS	4.7	4.9	1.9	1.6

NS, no wavelength shift applied; SH, wavelength shift applied.
[a]21° SZA.
[b]69° SZA.

cally the same for the very stable instruments, like CAT, DEG, NZL, and SEN. In two cases (USS and NLR) the results show the opposite effect (i.e., increase of σ), but the change is very small, in the order of 0.1%, and probably is within the uncertainty of the calculations. The overall picture from Table 4 is that, with the exception of DKK and USS, the dispersion of the spectral differences from the Norm with regard to wavelength stability is generally within ±4% (±2σ).

To conclude, after the application of the wavelength-shift corrections there are still instruments (USS, NOT, NOD, BEB, and DKK) that deviate from the cluster of the other instruments. Apart from instrumental problems, the reasons for such deviations may be related either to absolute calibration issues or to cosine errors.

It appears from the above comparisons that the two procedures, the wavelength shift correction and the slit-function standardization, can be applied successfully to spectral measurements, significantly enhancing the comparability among measurements derived from different instruments. An exceptional case that would need some attention would be an instrument with a significant wavelength shift which also occurred during its absolute calibration procedure. Such an instrument may have a significant error in its irradiance calibration due to the error in the wavelength scale. For example, a shift of 0.5 nm may produce an error in the absolute calibration of ~2% at 300 nm and ~1% at 350 nm.

The lower panels of Plate 2 show the spectral ratios as computed after the spectral measurements were corrected for the cosine response of the spectroradiometers. The most noticeable effect of the cosine corrections is the upward shift of the cluster of the ratios towards unity by ~5%. This result was expected because for the instruments that participated in SUSPEN the cosine error generally leads to underestimation of the measured irradiances.

The effect of the applied corrections depends on angular response of the instrument. Table 5 summarizes the average deviations from the Norm for each instrument and for the two solar zenith angles, before and after the application of the cosine corrections. Results for the four instruments for which the cosine response was unavailable are not included. Generally, the cosine corrections increased the irradiances by a few percent and up to ~9% in one case.

From the outliers identified in the previous discussion on Plate 2, the cosine correction brought the NOD instrument very close to the others, since the spectral irradiance has changed on the average by 5.3% at 21° and by 8.7% at 69° SZA. By contrast, SEN moved away from the cluster after the cosine correction, especially at 69° SZA, probably owing to reasons related to its absolute calibration. Similar behavior, but only for 21° SZA and at the long wavelength side, can be seen also in FIH. For the majority of the instruments, however, the cosine corrected spectra came closer to the Norm and only in a few cases did the agreement with the Norm became worse or remained unchanged. As mentioned previously, the Reference or the Norm do not necessarily represent the true solar spectrum at the ground, and therefore it would be dangerous to derive conclusions about the accuracy of the measurements of an instrument based simply on whether it agrees or not with the Norm. Similarly, from a change in the absolute level of a spectrum relative to a norm, it is not safe to judge whether the application of a cosine correction improves the measurement or not because its absolute level also depends on the instrument's calibration. Assuming that the cosine error of an instrument has been correctly determined and that an appropriate methodology is used, the application of a cosine correction should in principle improve the measurements.

The final conclusion, after the application of the cosine corrections to the measurements, is that the agreement between the majority of the instruments is within ~10%, at both solar zenith angles. Assuming that all the previous corrections (wavelength shift, slit-function standardization and cosine correction) were appropriately applied to the data, the main factors that could explain the remaining deviations would be absolute calibration problems, arising either from instrumental drifts (including temperature dependence and nonlinear response) or from their calibration standards. It should be noted that all instruments used different calibration sources and that most of these standards rely on calibration checks that took place at their home sites before moving to the campaign site. It is therefore reasonable to assume either that changes occurred in the sensitivity of some of the instruments during transportation or that their calibration sources disagree. The latter may be due to their aging or to their traceabil-

Table 5. Average Deviations From the Norm Before and After the Application of Cosine Corrections to the Measured Global Irradiance Spectra

	Average Differences, %			
Instrument ID	NCC[a]	CC[a]	NCC[b]	CC[b]
ATI	-0.8	0.7	0.4	2.1
ATW	-3.2	2.6	-7.4	2.5
CAT	-5.6	-2 7	-7.1	-2.6
DEG	-2.4	-1.7	-3.3	-1.4
FIH	-1.8	3.7	-7.3	1.6
FIJ	-6.3	-2.6	-7.5	0
FRL	-3.3	0	-5.9	0.2
GBM	-4.2	-1.5	-7.7	-3.5
GRT	-3	0.6	-5.3	0 6
NLK	-3.1	0	-4.9	0.3
NLR	-7.2	-1.3	-9.5	-1.6
NOD	-10.1	-4.8	-13.9	-5.2
NZL	-3.1	-3.1	-2.3	-2.9
SEN	1.1	5.5	0.3	8
USS	10.4	10.8	7.5	8.6

NCC, no cosine correction applied; CC, cosine correction applied.
[a]21° SZA.
[b]69° SZA.

ity to different standards laboratories. However, differences of the size observed are within the uncertainty limits of the instruments and of the calibration standards, and so it is meaningless to try to resolve their causes.

4.4. Lamp Measurements

Contrary to the measurements under the sky, the UV spectra under the lamp are smoother in terms of wavelength structure and have a much smaller dynamic range, varying to within 1 order of magnitude in the spectral range under study. In addition these measurements can be considered unaffected by the nonideal cosine response of the spectroradiometers, while small wavelength shifts are not expected to affect the measurements seriously. Thus it is in principle easier to compare measurements from different instruments, as the previously described "treatment" of the measurements (slit-function standardization, wavelength-shift, and cosine-response corrections) is not necessary.

Since the lamp spectra are smooth, it is enough to focus on the comparison of a few representative wavelengths. Three wavelengths were chosen (300 , 320 , and 350 nm), and their deviations in percent from the mean of all instruments were calculated and are presented in Figure 4 (top). Only three instruments (DKK, NOT, and USS) deviate significantly (more than 5% from the average) whereas 10 of the rest (ATI, ATW, CAT, DEG, ESI, FIH, FIJ, GRT, NOD, and SEN) agree to within ±2%. As mentioned already, such small deviations are difficult to overcome as they are well within the uncertainties of both the lamp output and the measurements. It appears from Figure 4 that only 3 - 4 instruments showed spectrally dependent differences from the mean greater than ~1-2%, as in most cases all three symbols are virtually on top of each other.

The results from the lamp measurements should be comparable with the results from the sky measurements after they passed through the three correction procedures. This comparison is therefore an independent check on the propriety of these corrections, assuming that the instrument characteristics and behavior were stable during both types of measurements (lamp and sky). To assist the comparison, Figure 4, middle, presents ratios from the sky measurements in a similar way. Variations in the ratios are similar for the two cases and in particular for those instruments that deviate significantly from unity.

Assuming that the lamp was stable during the whole measurement period, the lamp spectra measured by each instrument can be used to adjust the campaign data to a common calibration scale. A similar attempt was made during the NOGIC 1996 intercomparison campaign [*Kjeldstad et al.*, 2000] with encouraging results, which showed that the standard deviation of solar UV measurements made by different instruments was improved from ±10% to ±3% when a common lamp was used for their calibration. Figure 4, bottom, shows the sky ratios of the middle panel adjusted for the variations shown in the lamp ratios (Figure 4, top). As expected, these adjustments produce only marginal improvement in the ratios because they are similar in magnitude with the uncertainties associated with the spectroradiometric measurements and with the operation and stability of the lamp.

Finally, we can conclude that the agreement attainable among the majority of the 19 instruments is of the order of ±5%. However, even this level of agreement is not easily achieved as was proven by the blind intercomparison data that were submitted by the operators. It should be remembered that the results presented here refer to clear skies, and it is reasonable to expect much different behavior during overcast and especially during partly cloudy conditions, when the distribution of diffuse radiation which in these cases dominates the cosine error, is more complicated. Also, such good agreement would be much more difficult to achieve under conditions where the direct beam component of radiation is larger (e.g., aerosol-free conditions or at high altitudes), since cosine response errors then become much more important.

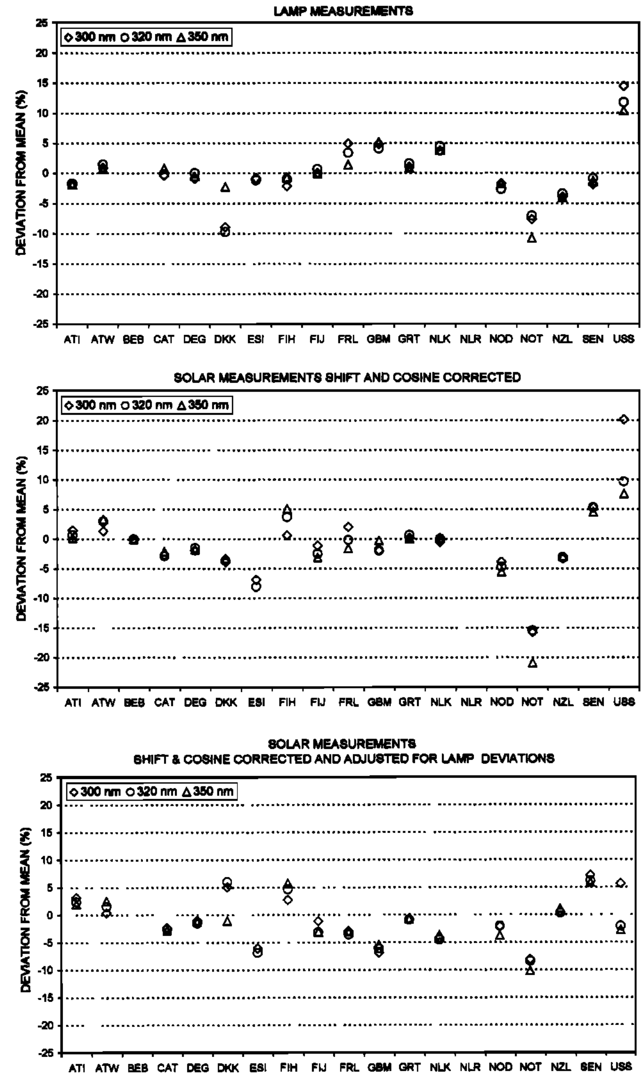

Figure 4. (top) Ratios of lamp irradiance measurements to their average at three selected wavelengths. (middle) The corresponding ratios of global solar irradiance to the Reference at 21° SZA calculated from standardized, shift- and cosine-corrected spectra are shown for comparison. (bottom) These ratios after the solar measurements were adjusted according to the lamp measurements of the mobile unit.

5. Conclusions

The ultraviolet spectroradiometer intercomparison at Nea Michaniona in July 1997 was a considerable improvement on previous campaigns, both in the quality of the measurements and the operational efficiency of the participants. After about 10 years since the first attempt to compare UV spectroradiometers, the observed large discrepancies have been reduced remarkably. With the exception of three instruments the others agree to within about ±10%, in their slit-function standardized spectral measurements. In addition, a core of instruments has been established which with proper maintenance and calibration protocols can provide reliable and quality controlled spectral measurements of solar UV irradiance. Judging from their agreement with the Reference and their overall stability, it can be said that the ATI, CAT, DEG, FIJ, GBM, NLK, and NZL spectroradiometers performed the best.

Without exception, the 19 instruments showed themselves capable of producing consistent and repeatable responses to the incident radiation. Those responses that departed from the norm were directly attributable either to known technical faults for which a solution was already at hand or to the more general problem of achieving an accurate spectral irradiance calibration throughout the required spectral range. There were no outright failures, and it seems reasonable to suppose that all the instruments could be made to achieve high quality results through technical or procedural adjustment and appropriate recalibration in front of a spectral irradiance lamp. There were only a few occasions where instruments did not perform as planned. These were mainly due to technical problems, which in most cases were identified and solved by their operators.

Perhaps the most encouraging aspect of this campaign was the general absence of large unexplained diurnal and spectral anomalies. The unexplained systematic variations were generally within acceptable limits by current standards and comparable with the other sources of uncertainty. Conversely, the most problematic aspect was the magnitude of the largest discrepancies in absolute spectral irradiance, some of which exceeded 20%, relative to the norm. Nevertheless, the better instruments performed very well in this respect, and about half of the participating instruments fell generally within 5% of the Reference. Postcampaign investigations by the instrument operators showed that the observed large discrepancies were caused mainly by instrumental malfunctions (e.g., in BEB, GRT, and USS instruments) but also by problems in their absolute calibration (e.g., NOT and NLR).

A few instruments (BEB, ATW, DKK, and FRL) suffered from significant wavelength instabilities, which were later corrected through the application of the SHICrivm algorithm. The correction for wavelength-shifts improved significantly the agreement amongst the measurements of the different instruments. Finally, the slit-function standardization proved to be a useful tool for the comparability of the spectra recorded instruments of different spectral resolution.

The postcampaign application of cosine corrections to the instruments, which initially submitted spectra uncorrected for cosine error, improved the general agreement. This was more evident in NOD, CAT, FIJ, and GBM spectroradiometers. After the application of cosine corrections to 15 instruments, 12 of them agreed on the average to within ±3%, both at small and large solar zenith angles.

Finally, the use of the mobile lamp system proved to be useful for tracing the causes of relatively large differences of instruments from the norm. However, small remaining deviations of the order of 2-3% could not be explained or eliminated because they are smaller than, or at least comparable to, the overall experimental uncertainties.

Appendix A: Justification of Revisions and Notes on Instrument Performance

A1. Revision of GRT Data Set

A revised set of the spectra recorded by the GRT spectroradiometer during both days of the blind intercomparison was submitted after the end of the campaign. The revision was imposed by several problems that arose in the instrument operation and in the data processing procedure during the campaign. Although these problems were discovered in time, the operators did not succeed in fully correcting the measurements within the agreed deadline for the data submission.

The first, and less important, problem was caused by a sudden instability of the internal mercury lamp which is used for the wavelength alignment of the spectrometer and is done automatically by the operating software before each spectral measurement. The lamp instability caused the instrument to perform repeatable wavelength alignment checks and initializations of the spectrometer, and the result was to miss several of the scheduled scans in the first day.

A more important problem was the use of wrong dispersion constants that determine the measuring wavelength of the spectrometer. Consequently, all spectra recorded until the middle of the second day were out of wavelength calibration. The operators were able to correct all these spectra by applying interpolation techniques with the aid of a high-resolution extraterrestrial spectrum and to deliver the data within the predefined deadline. However, after the presentation of the preliminary results from the referees, it appeared that all but six spectra around the middle of the second day were higher than the Reference by ~5-6%. A more careful checking of the of the wavelength correction algorithms revealed that the cosine correction that is regularly applied to the global irradiance spectra had been applied twice. Thus the first corrective action for the revised data set was to remove the second cosine correction.

The last problem that was encountered in the GRT instruments was initiated by a general power failure that occurred before 0930 UT of the second day. A false reset of the spectroradiometer after the power was restored leaded to an error in positioning of the prism that directs the light from the diffuser into the spectrometer. The effect was equivalent to the reduction of the instrument's sensitivity and because the position of the prism was random, there was no basis for applying any correction to these spectra. The only solution was to discard them from the data set.

A2. Revision of BEB Data Set

In order to understand the discrepancies between the BEB data set submitted during the campaign and the Reference, a full characterization of the instrument was performed in the optics laboratory of IASB, in Brussels immediately after the campaign. The tests included a study of the temperature effects on the wavelength scale and the absolute response of the detector, a mapping of the transmission of the dome and an absolute calibration of the instrument with three standards lamps. The main results of the tests are briefly presented to justify the submission of a revised data set.

Temperature variations have an important effect on the wavelength shift, which was determined by measuring the emission line of a low-pressure Hg lamp as a function of temperature. Measurements made with different lines and different temperature sequence showed that the shifts are practically independent of wavelength and reproducible for temperature increase and decrease. The shift was estimated to 1 nm for 15°C, and the value of 0.067 nm $°C^{-1}$ was used in the algorithm to correct the data. By analyzing the raw signal, produced by a very stable continuous source, at fixed wavelengths over a large spectral range (253-575 nm) and for temperatures ranging from 15° to 35°C, it was proven that temperature variations do not affect the absolute response of the detector.

The transmission of the dome was measured at five meridians and at 8 wavelengths ranging from 280 to 400 nm, with the instrument temperature stabilized at 20.0° ± 0.1°C. The results show a strong wavelength dependence of the dome transmission, which varies also with respect to the angle from the normal incidence between 0.3 and 0.7. This can be explained by the presence of a halo (a result of the degradation of the dome by UVC from the 253.7 nm Hg line that was used during the wavelength calibration), which seems to absorb the shorter wavelengths more strongly. The cosine response of the instrument under different configurations (integrating sphere alone, integrating sphere with a quartz blade, and integrating sphere with the dome) was also measured to confirm the degradation of the polyacrylate dome used during the campaign.

Finally, a series of absolute calibration checks were performed between September 1997 and April 1998 showing very good stability and reproducibility of the instrument, within 1-2 %, for very stable instrument temperature (within 0.1°C). From the information obtained during the laboratory postcampaign tests and measurements, a method was derived for correcting the data obtained during the two blind days of the campaign. This exercise was performed to verify the coherency of the approach and to confirm that the conclusions obtained in the laboratory are sufficient to understand the unexpected behavior of the BEB spectroradiometer. The correction method included the following steps.

First, the wavelength shift was calculated from the temperature of the instrument, which was continuously monitored and recorded during the campaign and applied to the raw data. The wavelength-adjusted measurements were converted to irradiance by using the response curve measured just after the blind days of the campaign.

The angular response was corrected for the discrepancies induced by the damaged polyacrylate dome, for the different wavelengths and zenith angles taking into account the direct-to-diffuse irradiance ratio measured during the campaign at seven wavelengths by an UVMFR-7 and the cosine responses measured in Brussels before and after the campaign. Only the direct component of the total solar irradiance was corrected for the deviation from the angular response of the instrument equipped with a non-damaged dome, assuming an isotropic diffuse component and a total resultant of 1 for the entire dome transmission.

The revised spectra are ~10% higher from the originally submitted in the UVA region, while they decrease constantly with decreasing wavelength, becoming 30% lower at 300 nm In conclusion, the problems that were identified in the BEB data were caused by the temperature stabilization, which was insufficient for the hot conditions of the Greek summer and by the dome transmission that was damaged by the 253.7 Hg line during the wavelength checks. These problems were identified, understood and solved after the campaign using intensive verifications, measurements and tests in the laboratory, and a method to correct the data was deduced from in situ ancillary measurements and laboratory tests.

A3. Revision of NLR Data Set

The NLR spectral measurement system is built into a light tight container, which is temperature stabilized and can be mounted on a truck. The irradiance calibration of the system during the SUSPEN-campaign was performed inside the container, using a 1000 W calibration lamp ("indoor" calibration). This procedure had been operational since February 1996, following a change in the input-optics of the instrument. The new input-optics consists of a flat diffuser with fiber optics attached, whereas prior to 1996 it consisted of an integrating sphere and mirrors. Following the SUSPEN-campaign, a careful reinvestigation of the irradiance calibration procedure took place, during which "outdoor" calibrations, using the calibration source on top of the container, were compared with "indoor" calibrations. This revealed a discrepancy of 10-12% in the absolute irradiance calibration and explains a large part of the discrepancies observed in the SUSPEN campaign. The discrepancy was reproducible, and the outdoor calibration was shown to be stable within 1-2% over a period of 9 months. The calibration procedure is now changed, and the regular indoor calibrations are used as a stability check only. The absolute irradiance calibration is now referred to the "outdoor" calibration, which matches with the situation during the solar measurements. In this way all spectral data from the beginning of 1996 onward could be recalibrated, including the data set obtained during the SUSPEN-campaign and data submitted to the SUVDAMA-database.

The year-to-year averaged stabilization checks revealed that the average instrument irradiance calibration was stable within 1-2% for the years 1996, 1997, 1998, and 1999. The data as delivered during the SUSPEN-campaign were not corrected for the cosine error of the input-optics. The cosine error of the instrumental readings (using the method of *den Outer et al.* [1998]) has since been calculated and is now applied to obtain a cosine corrected data set for the SUSPEN campaign. The cosine correction increases the irradiance with around 7.5% (6.5- 8.5% in the UVB; 6-9% at 360 nm, depending on the solar elevation).

During the cause of the investigation on the instrument calibration, further improvements were made regarding the dead-time correction of the measurements and the slit-function characterization of the instrument. These improvements were incorporated in the revised and reprocessed data sets for SUSPEN and the SUVDAMA UV-database. The revised calibration procedure was used in a recent intercomparison during the combined MAUVE/CUVRA-campaign in March 1999 in Garmisch-Partenkirchen. The cosine corrected data set obtained with the NLR-instrument was in between the results from ATI and DEG: the two participating groups in that campaign that were ranked among the best in the blind SUSPEN-intercomparison. Deviations in spectral ratios were on average no more than 3-5%. These findings are in good agreement with the results obtained when comparing the revised NLR data set with the norm and reference spectra obtained during the SUSPEN campaign: the mean deviations from the norm are now less than 2%, as illustrated in the results presented in Table 5 and Plate 2.

A4. Performance of the USS Instrument

The USS SUV-150 spectroradiometer was built for the U.S. Antarctic Program and was first assembled two weeks before the start of the intercomparison. Owing to time constraints, it took part without being thoroughly tested and was consequently affected by several problems, some of which were caused by overheating of the instrument. The internal temperature of the instrument reached 50°C during the first day, partly owing to the high ambient temperatures prevailing during the campaign, and partly from an internal step-down transformer, which was used to convert the line-voltage of 220 to 110V, the voltage normally required by the instrument. The transformer was not tested prior to the campaign and heated the instrument beyond the cooling capacity of its air-conditioning module. The overheating severely damaged the instrument's photomultiplier tube (PMT). As a result, the PMT's noise level was 2 orders of magnitude higher than originally measured. In addition, its dark current showed large fluctuations. The dynamic range of the instrument was therefore significantly reduced and not sufficient to cover the different signal levels of calibration and solar scans. As a consequence, the spectral responsivity of the instrument could not be accurately determined, particularly at shorter wavelengths.

During the course of a day, different PMT high voltages were applied to adjust the system responsivity to different ambient radiation levels. This method has been successfully applied in the past to prevent saturation of PMT currents at high midday radiation levels allowing at the same time an optimal responsivity when radiation levels are low in the early morning or late afternoon. Calibration scans were performed at different PMT high voltages, matching the voltage settings applied during solar scans. During the SUSPEN campaign, the calibration scans with the lowest high voltage applied were the measurements mostly affected by the unstable PMT. This can clearly be seen in the USS panel of Figure 3: When the high voltage changed from 600 to 550 V at 0730 UT, the ratio of the USS measurements to the Campaign-Reference changed by ~8% in the 300-310 nm wavelength band. The ratio jumped back to the morning value at 1400 UT, when again 600 V were applied. Although the problem mostly affected short wavelengths, this jump can also be seen in the 325-335 and 350-360 nm wavelength bands. Similarly, the change in the ratio between 1530 and 1600 occurs when the high voltage was adjusted from 600 to 650 V.

The difference of ~10% between the USS measurements in the 350-360 nm bands and the Reference, however, can only partly be explained by PMT-drift. Further reasons for the deviation are (1) the calibration source was 0.7 cm too far away from the instrument's fore-optics, leading to 3% higher solar measurements and (2) the instrument's foreoptics have a superior cosine response. The Reference, however, also includes spectra uncorrected for cosine-errors, suggesting that it is too low by 2-3% (see section 4.3). The reasons for the remaining 5% deviation are unknown.

Acknowledgments. This work was conducted in the framework of the project SUSPEN that was supported by the European Commission's Environment and Climate Programme, Contract ENV4-CT95-0056. The development of the SHICrivm software package was partly supported by the SUVDAMA project of the European Commission's Environment and Climate Programme, Contract ENV4-CT95-0177. Participation of the USS instrument was supported by the NSF Office of Polar Programs. The participants of the SUSPEN intercomparison campaign would like to express their appreciation to the director and the staff of the State Technical College of Mercantile Navy of Macedonia, for hosting the campaign and for providing all the available facilities at Nea Michaniona. In addition to the authors of this paper, the following scientists supported the operation of the instruments during the campaign: Walter Allabar, Willy DeCuyper, Mike Gay, David Goebel, Martin Huber, Paul Johnston, Jan-Erik Karlsson, Mike Kotkamp, Juan Manzano, Tim Martin, Dominique Masseraud, Chariklea Meleti. Tanya Mestechkina, Eric Pachart, Tore Persen, Govindaraj Rengarajan, James Robertson, Esa Saarinen, Rainer Schmitt, Josef Schreder, Rick Tax, Trond-Morten Thorseth, Reijo Visuri, Bruno Walravens, and Wiel Wauben.

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(Received February 28, 2000; revised August 17, 2000; accepted August 24, 2000)