JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 110, D15101, doi:10.1029/2004JD005584, 2005

Quality assurance of the solar UV network in the Antarctic

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Received 8 November 2004; revised 24 February 2005; accepted 29 March 2005; published 3 August 2005.

[1] Measuring ultraviolet radiation in the Antarctic region, where weather conditions are extremely challenging, is a demanding task. Proper quality control of the measurements and quality assurance of the data, which are the basis of all scientific use of data, has to be especially well planned and executed. In this paper we show the importance of proper quality assurance and describe the methods used to successfully operate the NILU-UV multichannel radiometers of the Antarctic network stations at Ushuaia, 54°S, and Marambio, 64°S. According to our experience, even though multichannel instruments are supposed to be rather stable as a function of time, severe drifts can occur in the sensitivity of the channels under these harsh conditions. During 2000–2003 the biggest drifts were 35%, both at Ushuaia and Marambio, with the sensitivity of the channels dropping at different rates. Without proper corrections in the data, this would have seriously affected the calculated UV dose rates. As part of the quality assurance of the network a traveling reference NILU-UV, which was found to be stable, was used to transfer the desired irradiance scale to the site NILU-UV data. Relative lamp tests were used to monitor the stability of the instruments. Each site NILU-UV was scaled channel by channel to the traveling reference by performing solar comparisons. The method of scaling each channel separately was found to be successful, even though the differences between the raw data of the site NILU-UV and the reference instruments were, before the data correction, as much as 40%. After the correction, the mean ratios of erythemally weighted UV dose rates measured during the solar comparisons in 2000–2003 between the reference NILU-UV and the site NILU-UV were 1.007 ± 0.011 and 1.012 ± 0.012 for Ushuaia and Marambio, respectively, when the solar zenith angle varied up to 80°. These results make possible the scientific use of NILU-UV data measured simultaneously at quite different locations, e.g., the Antarctic and Arctic, and the method presented is also practicable for other multichannel radiometer networks.

Citation: Lakkala, K., et al. (2005), Quality assurance of the solar UV network in the Antarctic, *J. Geophys. Res.*, *110*, D15101, doi:10.1029/2004JD005584.

1. Introduction

[2] The Antarctic ozone hole is well known and has been extensively studied since the mid-1980s; the stratospheric ozone depletion is monitored by both ground-based and satellite measurements. Signs of the recovery of the Antarctic ozone depletion are expected in the near future; this presents a new challenge to the monitoring of atmospheric parameters linked to ozone. As the solar ultraviolet (UV) radiation reaching the ground depends strongly on total ozone, the predicted recovery may also be detected in the UV radiation level. However, the effect of a possible ozone recovery on UV radiation is not straightforward, as changes in other parameters affecting UV, such as clouds, aerosols and ground albedo, may also play an important role [*World Meteorological Organization*, 2003]. Well-maintained ground-based measurements both in ozone and UV radiation are therefore needed.

[3] Until now, only a few stations in the Antarctic have recorded UV radiation using ground-based instrumentation. The U.S. National Science Foundation (NSF) makes spectral UV measurement at the sites of McMurdo, 77°S, Palmer, 64°S, the South Pole, 90°S and Ushuaia, 54°S. The Ultraviolet Monitoring Network of the Argentine Servicio Meterológico Nacional includes broadband instruments also measuring UV radiation at Ushuaia and Marambio. Recent results of Antarctic UV measurements have been given by *Sobolev* [2000], *Diaz et al.* [2001], *Cede et al.* [2002], *Bernhard et al.* [2003], and *Pazmiño et al.* [2005]. The highest UV levels ever recorded at the NSF

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0148-0227/05/2004JD005584$09.00

Antarctic stations occurred in the austral spring of 1998, whereas the levels in 1999, 2000 and 2001 were generally lower. The record-sized ozone hole in 2000 led to extreme UV values at Ushuaia during October of that year.

[4] Even though satellite-based ozone measurements are routinely in use in the Antarctic, satellite UV estimations have not replaced ground-based measurements. Cloud and aerosols are still critical in the UV retrieval process, where systematic errors in the presence of snow and ice are also to be found [*Kalliskota et al.*, 2000; *Arola et al.*, 2003].

[5] One reason for the lack of ground-based UV measurements in the Antarctic are the demanding conditions of the area, where measurements need daily control and maintenance. Instruments cannot be left to carry out measurements alone in areas where wind, snow and very cold temperatures occur. These extremely wearing conditions also demand durability and stability from the instruments. The key question is how to ensure the quality of the data, as quality assurance is the basis for all scientific use of the data. UV climatology and UV impact studies, for example, can only be done if, as a result of proper quality assurance, the irradiance scale is stable. Quality assurance is also crucial for the accuracy of climate change assessments and impact studies.

[6] Guidelines have been published for the quality control and quality assurance of UV measurements [*Webb et al.*, 1998, 2003], but the question as to how the instructions are applicable to multichannel radiometers under hard conditions still remains. When studying data from different locations, the most important requirement is that the data are homogeneous and comparable with each other. A big challenge is, then, how to transfer the irradiance scale from one site to another. Most of the time, the time interval between calibrations is long, and between these no information about the stability of the instrument is available. In this paper we present a method for the quality assurance of a multichannel radiometer network working under difficult conditions, using the NILU-UV data from Marambio and Ushuaia in the Antarctic NILU-UV network. The quality control and quality assurance procedures presented include a combination of relative lamp tests and a well-maintained traveling reference instrument. Relative lamp tests have been commonly used to follow the stability of spectroradiometers, but, together with the traveling reference solar comparisons, are here for the first time used for the quality assurance of multichannel radiometers.

[7] The results presented in this paper for the Antarctic NILU-UV network are also practicable for use with other multichannel radiometer networks. A NILU-UV multichannel radiometer network is being established, for example, in Greece and Cyprus [*Bais et al.*, 2004]. This consists of seven stations located in different environments, with a central station at Thessaloniki. The aim of the network is to establish long-term monitoring of UV radiation in the eastern Mediterranean.

[8] Another high-latitude multichannel UV network exists in Norway, where the Norwegian UV monitoring network is maintained by the Norwegian Radiation Protection Authority (NRPA) and the Norwegian Institute for Air Research (NILU) on behalf of the Norwegian Pollution Control Authority [*Johnsen et al.*, 2002]. The network consists of 8 stations, at which UV radiation is monitored with GUV multichannel UV radiometers. Drift factors for the individual channels of the radiometer are derived from annual visits of a traveling reference. The reference spectroradiometer is a double monochromator Bentham at the NRPA.

2. Materials and Methods

[9] In 1999, as part of the MAR (Measurement of Antarctic Radiance for monitoring the ozone layer, Project REN2000-0245-C02-01 financed by Ministerio de Ciencia y Tecnología) project, a multichannel NILU-UV instrument network was established in order to measure real-time ground-based UV and ozone values. The project was established by INM, the Instituto Nacional de Meteorología, Spain, in collaboration with FMI, the Finnish Meteorological Institute, DNA-IAA, the Dirección Nacional del Antártico-Instituto Antártico Argentino, and CADIC, the Centro Austral de Investigaciones Cientificas, Argentina. The general goals of the project are (1) to promote observations and research of stratospheric ozone, UV radiation, and related physical parameters in the Antarctic region; (2) to determine the variations in ozone concentration, spectral UV radiation, and photosynthetic active (PAR) radiation; and (3) to improve the knowledge of the meteorological and chemical mechanisms that determine the Antarctic atmosphere throughout the winter and its features in summer.

[10] Within the MAR project, three NILU-UV multichannel filter radiometers have been set up at Antarctic stations in order to monitor ground-based ozone, UV and photosynthetic active (PAR) radiation. The location of the stations with respect to the stratospheric polar vortex is interesting, as the vortex plays an important role in the mechanism of ozone depletion. Belgrano II, at 77°52′S 34°37′W, is mostly located inside the vortex; Marambio, at 64°14′S 56°37′W, is at various time inside, on the edge of, or outside the vortex, while Ushuaia, at 54°48′S 68°19′W, is mostly outside the vortex. Ushuaia is one of the few inhabited towns situated in an area of severe Antarctic ozone loss [*Pazmiño et al.*, 2005]. These stations, equipped with three similar ozone and UV recording instruments, make possible real-time studies of the impact of daily changes in the polar vortex on total ozone and UV radiation reaching the ground.

2.1. NILU-UV Instrument

[11] NILU-UV multichannel radiometers, model NILU-UV6T, have been set up at the Antarctic stations of Belgrano II, Marambio and Ushuaia in order to monitor the UVB, UVA and erythemally weighted [*McKinlay and Diffey*, 1987] UV radiation, photosynthetic active radiation and total ozone column, and to also provide information on cloudiness. The radiometer is a filter instrument with five UV channels, with central wavelengths around 305, 312, 320, 340 and 380 nm, and bandwidths of around 10 nm at full width at half maximum. The sixth channel measures the photosynthetic active radiation (PAR) in the 400–700 nm wavelength region. The radiometer has a Teflon diffuser, silicon detectors, high-quality bandpass filters and is temperature-stabilized to 40°C. One-minute averages of measured irradiances and detector temperature are recorded. The characteristics of the instrument are described in more detail by *Høiskar et al.* [2003].

[12] The method used to derive the biologically effective UV dose rates, total ozone abundances and cloud information is described by *Dahlback* [1996]. The UV dose rates (D in equation (1)) are determined by a linear combination of the irradiances, represented by NILU-UV raw data (V_i), obtained from the five UV channels (i). In order to obtain the coefficients of the linear combination (a_i), spectroradiometer-based calibration and radiative transfer calculations are needed.

$$D = \sum_{i=1}^{5} a_i V_i. \quad (1)$$

[13] As the NILU-UV is a filter radiometer, it is considered to be more stable than a spectroradiometer and easier to transport. It is also cheaper, smaller and easier to use than a spectroradiometer. The advantage compared to a single-channel radiometer is that one can get more information by combining the readings of different channels, in the NILU-UV case the UVB, UVA and erythemally weighted UV. Even though the instrument is considered to be stable [*Høiskar et al.*, 2003], proper quality control and quality assurance has to be done [*Webb et al.*, 1998].

2.2. Quality Control

[14] One part of the quality control has been to train the operators of the stations; training is repeated every second year. The operators perform daily checks which include timing control and cleaning of the diffuser. The leveling of the instrument is also regularly checked. The operators perform lamp tests and dark current measurements, as well as solar comparisons between the station instrument and the traveling reference NILU-UV radiometer. The network data is transferred daily to databases.

[15] The quality control procedure includes lamp and dark current measurements every second week at the stations. Lamp and dark current measurements are also performed before and after each solar comparison. The lamp measurements are performed using 100 W OSRAM Radium lamps mounted in lamp units produced by the manufacturer of the NILU-UV instrument. The lamp is set in a dark box placed above the diffuser, giving a vertical beam. The current is regulated at each site by a local power supply. The fixed warmup time of the lamp and the time to measure the irradiance are both 15 min. The data is recorded with a time step of one second.

[16] During the project we discovered that the regulation of the power supply is essential for proper lamp measurements. Using the original measurement arrangements, successive lamp measurements could differ by 5%. In 2003 new power supplies and shunts were installed at the stations of Ushuaia and Marambio. The warming up of the NILU-UV during successive lamp tests was also found to be problematic. The effects of the warming were reduced by waiting between successive measurements until the NILU-UV had cooled down to the primary temperature. As the burning time of the lamps is the same during every lamp test, the warming is expected to affect the measurements in a similar way.

[17] A time series of lamp measurements allows the possible drift of a single channel to be detected. In order to exclude possible lamp drift, two lamps are measured on each occasion, and a third lamp is measured every three months. The different burning time of the lamps permits the detection of possible drift or a problem with one lamp irradiance caused, e.g., by aging of the lamp or careless transport.

2.3. Quality Assurance

[18] The quality assurance is based on a traveling reference NILU-UV which maintains the absolute irradiance scale of the different stations. The traveling reference visits Ushuaia three times and Marambio twice during the spring-summer-autumn season. Visits of the traveling reference to Belgrano are impossible due to the inaccessibility of the site for most of the year. Access is possible, using an icebreaker, only during the summer, when the NILU-UV at Belgrano is replaced each year by a well-calibrated NILU-UV, of which the calibration is traceable to the irradiance scale used at Marambio and Ushuaia. Lamp measurements are also regularly performed at Belgrano in order to monitor the stability of the instrument and to maintain the irradiance scale stable.

[19] As part of the quality assurance protocol, the traveling reference participates in international comparisons during the winter period of the Antarctic. The comparison sites have been chosen to be those whose atmospheric conditions most closely resemble those in the Antarctic. Table 1 shows the solar comparisons performed with the traveling reference, NILU 008, during 1999–2003, excluding manufacturer calibrations. Both routine solar comparisons inside the network and the occasional international comparison campaigns are listed. Other UV instruments which have participated in the comparisons are also listed in Table 1. The SUV, Brewer and Bentham are spectroradiometers. Every time the traveling reference makes measurements at Ushuaia, a solar comparison with the station's SUV spectroradiometer is also performed. During the international intercomparison at Tylösand in 2000, about 10 spectroradiometers [*Thorseth et al.*, 2002], 10 radiometers and 3 multichannel radiometers (A. Dahlback et al., Intercomparison of 5 multi-channel filter radiometers: Measurements of UV-doses, total ozone abundances and cloud effects, submitted to *The Nordic Intercomparison of Ultraviolet and Total Ozone Instruments at Tylösand, Sweden, in 2000*, final report, Finnish Meteorological Institute, Helsinki, 2004, hereinafter referred to as Dahlback et al., submitted manuscript, 2004) participated in the comparison. The Bentham spectroradiometer of the European Union project called "Quality Assurance of Spectral Ultraviolet Measurements in Europe" (QASUME) also made measurements during the solar comparison at Jokioinen, Finland in 2002 [*Bais et al.*, 2003]. In addition to these comparisons, the traveling reference was returned to the manufacturer in Norway for calibration in 2001 and 2002.

[20] Since the traveling reference NILU-UV is transported frequently, it is very important to check its sensitivity before and after a solar comparison. For this purpose, traveling lamp test equipment has been built to travel with the reference. It contains three lamps and lamp holders, a multimeter and a shunt, and a black cover where the lamps are put during the test. The power supplies of the sites visited are used. Lamp measurements are performed before

Table 1. Solar Comparisons Carried Out by the Traveling Reference NILU-UV 008[a]

Date	Site	Instruments
19 Aug 1999	Izaña	NILU-UV 009, 011, 012, 010, Brewer 157, Bentham
22 Oct 1999	Sodankylä	Brewer 037
2 Dec 1999	Ushuaia	NILU-UV 011, 012, SUV
12 Dec 1999 to 6 Jan 2000	Marambio	NILU-UV 011
10–15 Feb 2000	Ushuaia	NILU-UV 012, SUV
20–21 Mar 2000	Marambio	NILU-UV 011
4–10 May 2000	Ushuaia	NILU-UV 012, SUV
10–14 Jun 2000	Tylösand	NOGIC intercomparison, Brewer 037, 107
27–29 Oct 2000	Ushuaia	NILU-UV 012, SUV
10 Dec 2000 to 8 Jan 2001	Marambio	NILU-UV 011
8–12 Feb 2001	Ushuaia	NILU-UV 012, SUV
24 Mar to 1 Apr 2001	Marambio	NILU-UV 011
16–21 May 2001	Ushuaia	NILU-UV 012, SUV
12–16 Jun 2001	Jokioinen	Brewer 037 and 107
15 Aug 2001	Sodankylä	Brewer 037
11–17 Oct 2001	Ushuaia	NILU-UV 012, SUV
12–22 Nov 2001	Marambio	NILU-UV 011
10–13 Jan 2002	Ushuaia	NILU-UV 012, SUV
17–27 Feb 2002	Marambio	NILU-UV 011
10–15 Apr 2002:	Ushuaia	NILU-UV 012, SUV
9–11 Jul 2002	Jokioinen	NILU-UV 031, Brewer 037, 107, QASUME Bentham
8–18 Nov 2002	Ushuaia	NILU-UV 012, SUV
20 Dec 2002 to 11 Jan 2003	Marambio	NILU-UV 011
21 Feb to 2 Mar 2003	Ushuaia	NILU-UV 012, SUV
18 Mar to 1 Apr 2003	Marambio	NILU-UV 012
25 June to 1 Jul 2003	Jokioinen	Brewer 107
10–21 Oct 2003	Ushuaia	NILU-UV 012, SUV
5 Nov to 5 Dec 2003	Marambio	NILU-UV 011

[a]The serial numbers of the NILU-UV at Marambio and Ushuaia are 011 and 012, respectively.

and after each solar comparison in Ushuaia and Marambio and similarly during other solar comparisons.

3. Results and Discussion

[21] The starting point for the quality assurance was to study the lamp test time series of the site NILU-UVs in order to see if drift in the sensitivity of the channels had occurred. The second step was to ensure that the traveling reference had stayed stable as a function of time after its annual calibration. The last step was to transfer the irradiance scale from the traveling reference to the site NILU-UV data.

3.1. Lamp Measurements in Marambio and Ushuaia

[22] On studying the lamp measurement time series for the Marambio and Ushuaia NILU-UVs, it was discovered that both radiometers showed changes in the sensitivity of the channels during 2000–2003. The lamp measurements made at Marambio are shown in Figure 1, and those made at Ushuaia are shown in Figure 2, where the time series of each channel are shown separately. One measurement means the average of the 13 min of lamp measurement data, where data outside the 3 σ limit were excluded. The ratios of each measurement to the average of the first three measurements are plotted, as well as the mean temperature during the lamp test.

[23] Concerning the drift of their channels, the two instruments show a totally different behavior. During the year 2000, the channels of the Marambio NILU-UV drifted downward dramatically, by around 20%, but then recovered during the year 2001. The sensitivity of channel 1 even increased, by as much as 15%, during 2001. After 2002, a severe regular downward drift occurred, reaching 35% by the end of the year 2003. A regular but gentler drift, even down to −35%, is found in channels 2–4 of the Ushuaia radiometer. Channels 1 and 6 remained stable, whereas channel 5 drifted downward during 2000 and upward during 2003. The lamp measurement time series show the importance of using three lamps. If one differs from the other two, that one can most likely be discarded.

[24] At present, the reasons for the drift in the channels' sensitivity is unknown. The channels use interference-type filters that are by nature different in composition depending what wavelength they are designed to work at; they may therefore drift at different rates in an optical sense. Penetration of moisture into the detector followed by a slow drying could be one reason, at least at Marambio, where the drift was already noted during the first year of measurements in 2000, with a recovery occurring in 2001. The more gentle and regular drift could be due to natural aging of the filters and the Teflon diffuser. The Teflon diffuser of the NILU-UV is unprotected, and both sites experience severe meteorological conditions. At both sites strong winds deposit dust on the diffuser, and frost and snow are present during the winter time. During the first year of measurements, the NILU-UV at Marambio was equipped with a defrost system blowing warm air, but the system was found to be inadequate. The defrost system was removed after the year 2000. A similar drift of channel sensitivity was detected by *Norsang* [2004], who found a linear drift of 13.4% in the UVB channels of their NILU-UV instrument during 3.5 years of measurements.

[25] As at both Marambio and Ushuaia the sensitivity of single channels has changed, a change in the measured irradiance levels is assumed to have occurred. In addition, the fact that the channels have changed at different rates affects the SZA dependence of the weighted irradiance

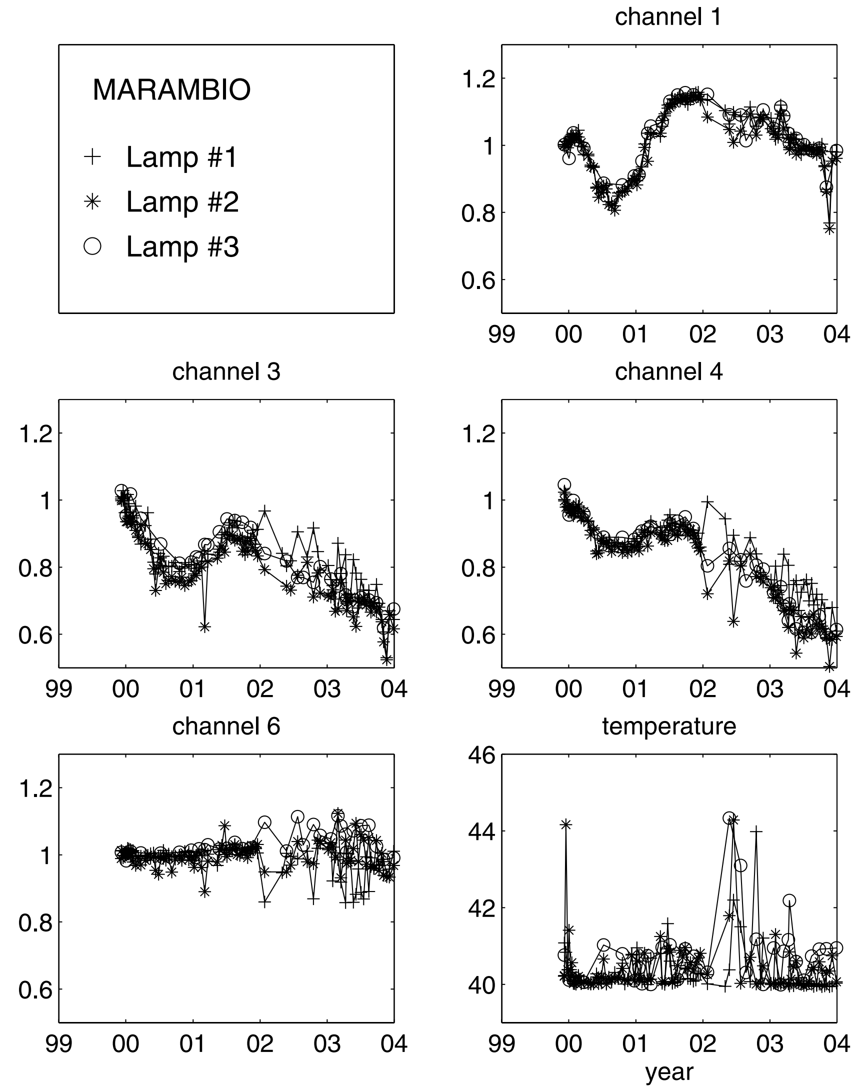

Figure 1. The lamp test time series of the Marambio NILU-UV during 2000–2003. See color version of this figure in the HTML.

level. For this reason correcting only the calculated products, e.g., erythemally weighted irradiances, is not sufficient: individual channels need to be corrected. The solar comparisons of each channel with corresponding channels of the traveling reference NILU-UV allow the correction of the apparent drift in order to maintain a stable irradiance scale.

3.2. Stability of the Traveling Reference

[26] In order to be able to use one instrument as a reference, the reference instrument itself has to have stayed stable as a function of time. If this is not the case, it must be possible to determine when the change occurred and by how much. In the case of the Antarctic NILU-UV network, a well-maintained NILU-UV is used as a traveling reference. Its stability is checked using both lamp measurements and solar comparisons against high-quality and well-characterized spectroradiometers.

3.2.1. Lamp Measurements

[27] Every Antarctic winter, the traveling reference returns with its three calibration lamps to its home institute, the Finnish Meteorological Institute (FMI). Lamp measurements are also performed there during solar comparisons. The power supply used is of high quality, and the results of the measurements are repeatable. Figure 3 shows the time series of the three traveling lamps, lamps 1, 2, and 3, measured at FMI during 2000–2003. The ratio of each measurement to the first measurement is shown, as well as the mean temperature during the lamp tests. Here also, one measurement means the average of the 13 min of lamp measurement data, where data outside the 3 σ limit were excluded. Channels 3, 4, and 5 show a drift of around 10%, but the slope of the drifts differ. Channel 5 already started to drift after 2000, channel 3 after 2001 and channel 4 after 2002.

[28] During the yearly visits to FMI, four extra lamps are also measured, lamps 5, 6, 8, and 9, in order to obtain a time series with lamps which have not traveled. These lamps also have much less burning time than the lamps which have traveled. The time series of these lamp measurements are also shown in Figure 3. These lamp measurements confirm the results of the channel drift obtained with the three traveling lamps, and therefore the observed drift can be considered to be real.

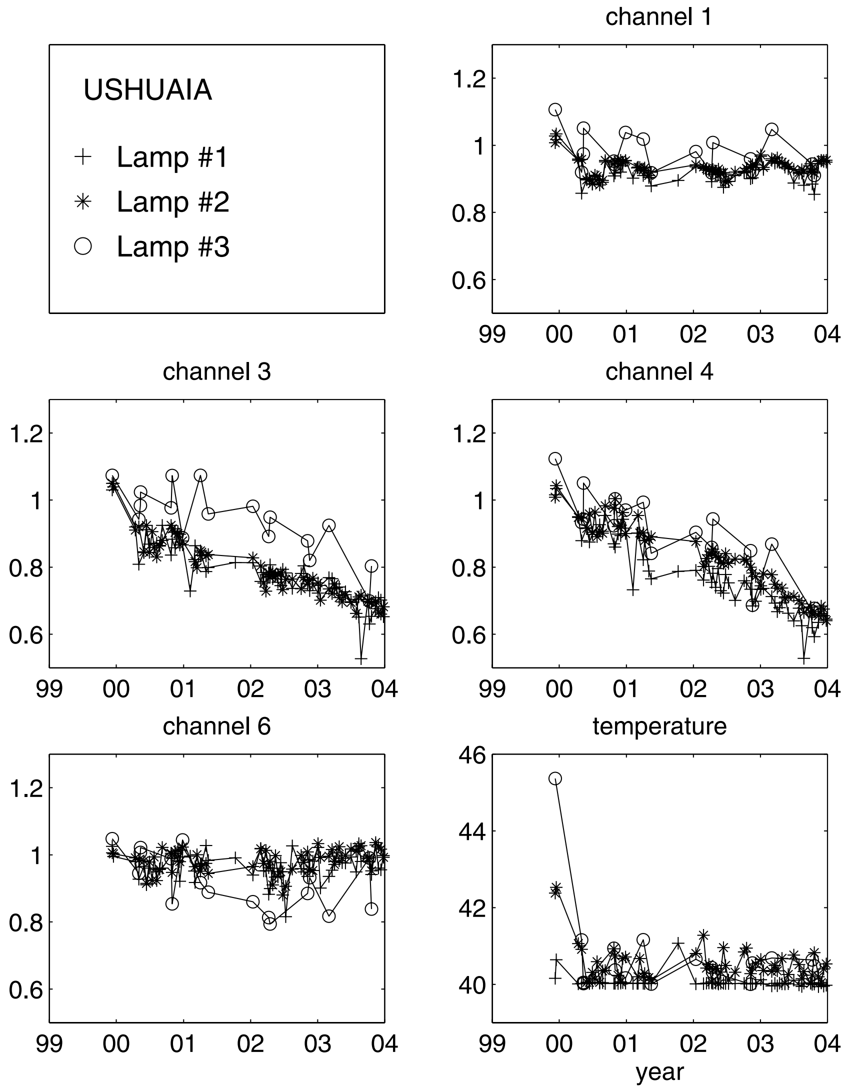

Figure 2. The lamp test time series of the Ushuaia NILU-UV during 2000–2003. See color version of this figure in the HTML.

3.2.2. Solar Comparisons With Spectroradiometers

[29] Every year since 2000, solar comparisons have been made between the traveling reference NILU-UV and one or both spectroradiometers of FMI, the double monochromator Brewer MK-III 107 and the single monochromator Brewer MK-II 037. Both spectroradiometers are well maintained and the data is cosine corrected. Simultaneous measurements with the spectroradiometer and the NILU-UV make it possible to study the stability of each NILU-UV channel as compared to the spectroradiometer.

[30] Following *Dahlback* [1996], a coefficient k can be calculated for each channel i = 1–5 in the following way:

$$k_i = \frac{\int_{270}^{400} I(\lambda)E_i(\lambda)}{V_i}, \qquad (2)$$

where I is the spectral irradiance measured by the spectroradiometer, E_i the spectral response of the NILU-UV channel i and V_i the raw counts of the NILU-UV channel i. As the spectroradiometer uses several minutes to scan the entire spectral range, and the NILU-UV records with a 1-min time resolution, the timing differences have to be taken into account. The NILU-UV records were averaged for the time that it took for the spectroradiometer to scan the wavelength range of the given NILU-UV channel.

[31] The coefficient k gives the relation of the raw signal to the measured irradiation. The time series of the coefficient show the stability of each channel. The relative differences in the coefficients of channels 1–4 compared to the first measurement in 2000 are shown in Table 2. The coefficient for the channel 5 could not be calculated, because the spectral range of the FMI spectroradiometer ends at 365 nm.

[32] The results of the coefficient time series confirm the changes in sensitivity observed using the lamp measurements. The results shown in Table 2 are calculated around local noon and in conditions of low total cloud cover. The differences in SZA, ozone, UV absorbing aerosols and cloud optical depth contribute uncertainties in the calculated coefficients.

[33] In order to perform an absolute calibration, a spectroradiometer with a spectral range covering the whole

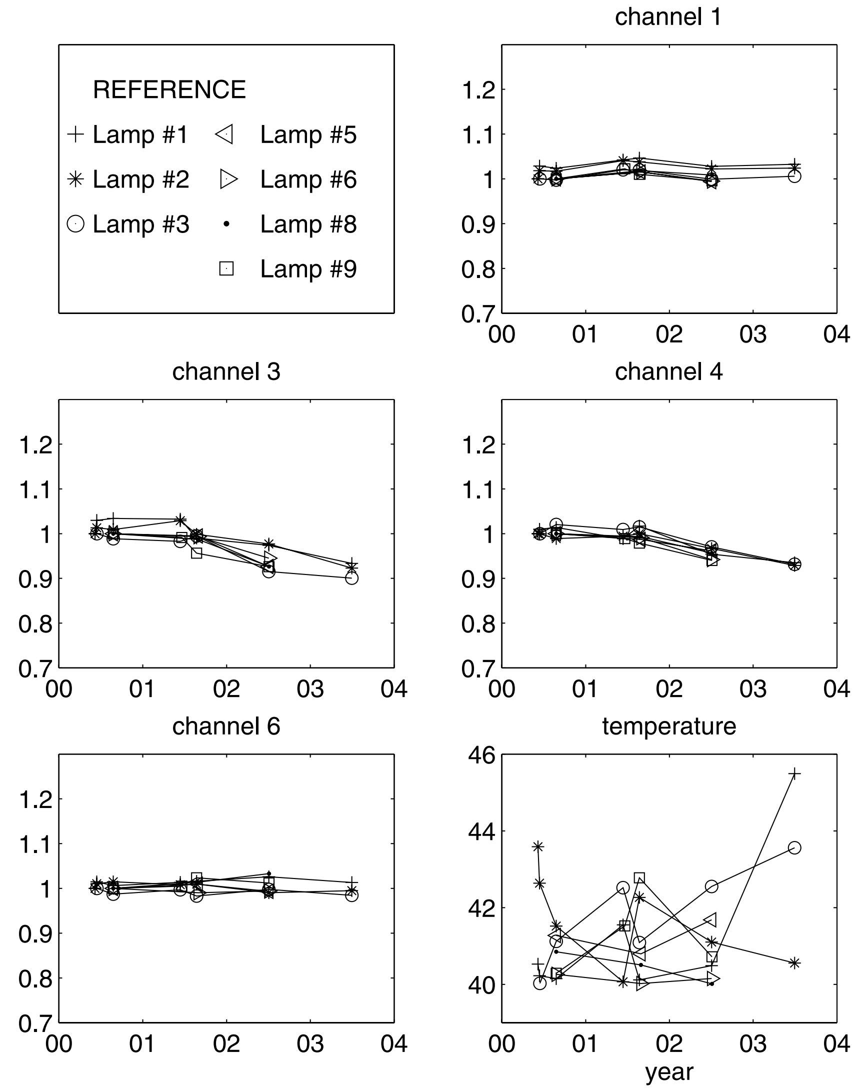

Figure 3. The lamp test time series of the reference NILU-UV measured at FMI during 2000–2003. See color version of this figure in the HTML.

wavelength range of the five NILU-UV channels is needed. For that purpose, the absolute calibration of the traveling reference was carried out by the manufacturer, Norwegian Institute for Air Research (NILU). The first absolute calibration was carried out at Izaña, Tenerife, Spain, in 1999. In 2000, an absolute calibration was carried out during the international solar comparison at Tylösand, Sweden. In 2001 and 2002, the reference NILU-UV instrument was returned to the manufacturer in Norway, where in 2001 a comparison of the traveling reference against a group of three of its own NILU-UV instruments was carried out, while in 2002 an absolute calibration was again made. The total accuracy of the NILU-UV calibration is expected to be better than 5%.

[34] Using the manufacturer's calibrations in 2000, 2001, and 2002, the calculated erythemally weighted dose rates were compared with those measured with the spectroradiometers at the FMI. The results are shown in Tables 3 and 4. The relation with the double monochromator Brewer MK-III 107 is stable during 2001–2002, but a change of a few percent is seen in 2003. Figure 4 shows an example of the relative comparison as a function of SZA. As the spectroradiometer dose rates were cosine-corrected, the NILU-UV shows a good angular response up to an SZA of 70°. The main reason for the divergence seen at larger SZA is the asymmetry between the morning and evening ratios. This asymmetry may be due to a change in the optical properties of the atmosphere, e.g., ozone and clouds, and azimuthal-dependent cosine responses during the day. The results of the comparison with the single monochromator Brewer MK-II 037 confirm that the reference NILU-UV stayed stable during 2000–2002. The differences of a few percent

Table 2. Relative Differences of the Coefficients k for Channels 1–4 of the Reference NILU-UV

Channel	2000	2001	2002	2003
1	1	1.03	1.00	0.97
2	1	0.98	1.02	1.05
3	1	1.02	1.08	1.14
4	1	1.01	1.01	1.10

Table 3. Ratios of Erythemally Weighted UV Dose Rates Between the Reference NILU-UV and the Brewer MK-III Spectroradiometer 107 During 2001–2003

Date	SZA	Brewer/NILU-UV
16 Jun 2001	38	0.96
10 Jul 2002	38	0.95
27 Jun 2003	44	0.99

seen in Tables 3 and 4 are within the uncertainty of the calibrations.

[35] As the absolute calibration of the reference NILU-UV was performed only once a year, lamp measurements, made before and after each solar comparison, were used to pinpoint the dates of changes in sensitivity. E.g., during the 2000–2001 season the drift of channel 5 was regular, during 2001–2002 the biggest drift of channels 3 and 4 was seen after the second trip to Marambio, and during 2002–2003 the biggest drift of channels 3, 4, and 5 was seen after the trip from Ushuaia to Finland. This information makes it possible to use the right calibration throughout the whole period.

3.3. Irradiance Scale

[36] The irradiance scale of the Antarctic NILU-UV network should be based on solar comparison with a well-maintained and characterized spectroradiometer in an area of similar atmospheric conditions to that of the stations of the network. The SUV spectroradiometer of the National Science Foundation (NSF) at Ushuaia was chosen to be the reference for the irradiance scale. The solar comparisons with the SUV spectroradiometer were possible each time the reference NILU-UV visited Ushuaia, i.e., three times a year. The other possibility would have been to choose the double monochromator at FMI, but in that case solar comparisons would only have been available once a year.

[37] Table 5 shows the relative differences between the erythemally weighted UV dose rates retrieved from the reference NILU-UV and those measured by the SUV spectroradiometer at Ushuaia. The results are shown for the lowest SZA in almost clear sky conditions. A cosine correction of 5% has been assumed for the SUV data (Bernhard, G., personal communication, 2004). The results show compatibility within the measurement uncertainties. This means that the irradiance scale given by the manufacturer of the NILU-UV is in agreement with that of NSF. The reference instrument for the manufacturer's calibration of the NILU-UV is the Bentham spectroradiometer of the NRPA, whose irradiance scale is traceable to the National Institute of Standards and Technology (NIST) via the laboratory of SP, the Swedish National Testing and Research Institute [*Johnsen et al.*, 2002]. The irradiance scale

Table 4. Ratios of Erythemally Weighted UV Dose Rates Between the Reference NILU-UV and the Brewer MK-II Spectroradiometer 037 During 2000–2002

Date	SZA	Brewer/NILU-UV
10 Jun 2000	38	0.98
16 Jun 2001	38	0.95
15 Aug 2001	53	0.98
10 Jul 2002	39	0.96

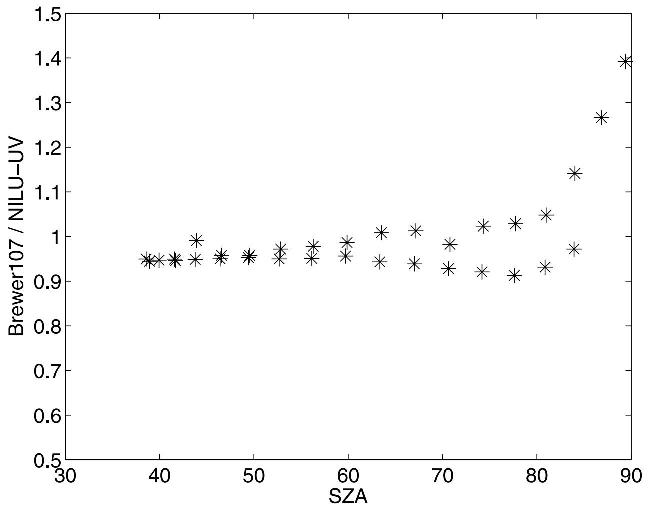

Figure 4. Ratios of erythemally weighted UV dose rates between the reference NILU-UV and the Brewer MK-III spectroradiometer 107 at Jokioinen, Finland, for 10 July 2002.

of the SUV spectroradiometer is also traceable to the NIST via 200 W lamps [*Bernhard et al.*, 2003].

[38] As the relative difference of the traveling reference NILU-UV as compared to the SUV spectroradiometer was lower than 5%, the NILU-UV data were not further corrected, and the irradiance scale of the traveling reference was used as such. Using the same irradiance scale, the results from the international solar comparison held at Tylösand in 2000 showed an agreement of −0.5 ± 3.1% between the traveling reference NILU-UV and the reference Bentham spectroradiometer of NRPA (Dahlback et al., submitted manuscript, 2004).

3.4. Transfer of the Irradiance Scale

[39] In order to transfer the desired irradiance scale to the UV measurements of Ushuaia and Marambio, solar comparisons with the traveling reference were used. One possibility would have been to simply compare the calculated erythemally weighted dose rates to those of the reference NILU-UV, but as we knew that the various channels of the site NILU-UV instruments had drifted at different rates, this would have led to a calibration factor strongly dependent on SZA and atmospheric conditions. We therefore decided to correct channel by channel in order to get more stable results. This was possible because of the known characteristics of the bandpass filters. The bandpass filters of both the NILU-UV at Marambio and that at Ushuaia are made from the same filter series as those of the reference NILU-UV, which means that the channels have more or less the same SZA dependence. This causes the ratio of the channels of two NILU-UV to vary by only a few percent as a function of the SZA.

[40] The corrected Marambio and Ushuaia UV dose rates can be calculated using the same coefficients a_i of the linear combination in equation (1) as the reference NILU-UV. In order for this to be possible, the raw data of any channel of the site NILU-UV should be equivalent to the corresponding channel raw data of the reference NILU-UV. This is brought about by scaling each channel with the

Table 5. Ratios of Erythemally Weighted UV Dose Rates Between the Reference NILU-UV and the SUV Spectroradiometer During 2000–2003

Date	SZA	SUV/NILU-UV
1 Dec 1999	34	0.95
15 Feb 2000	40	0.97
6 May 2000	70	1.03
27 Oct 2000	40	0.99
9 Feb 2001	40	0.98
18 May 2001	74	0.99
17 Oct 2001	34	0.98
14 Apr 2002	65	0.97
11 Nov 2002	40	0.97
22 Feb 2003	45	0.96
17 Oct 2003	45	0.99

ratio between the raw data of that site ($V_{i,site}$) and the raw data of the reference NILU-UV ($V_{i,ref}$):

$$b_i = \frac{V_{i,ref}}{V_{i,site}} \quad (3)$$

An example of the ratios b_i between the raw data of the site NILU-UV and the reference NILU-UV is shown for 11 January 2002 in Figure 5, where the Ushuaia NILU-UV differs from the reference by around 25–30% in channels 1–5. The 3-min moving average is plotted. Figure 5 shows the ratios for the whole day; both cloudless and cloud sky data are plotted, and the impact of changing sky conditions is seen in the scattered values of the ratios.

[41] For the final calculation of dose rates, only one scaling factor c_i was calculated to represent the whole day. This was the average of the ratios b_i near the lowest SZA in clear sky conditions. Thus the erythemally weighted UV dose rate of the site NILU-UV, D_{site}, can be calculated as follows:

$$D_{site} = \sum_{i=1}^{5} a_i c_i V_{i,site}, \quad (4)$$

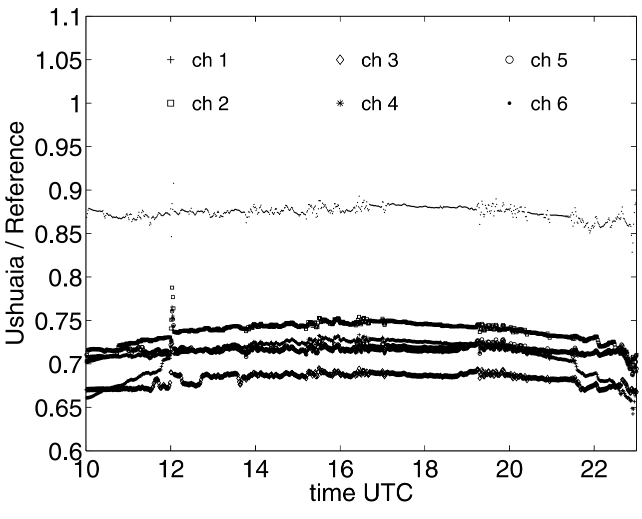

Figure 5. Ratio of UV channel raw data between the Ushuaia NILU-UV and the traveling reference NILU-UV ($1/b_i$ in equation (3)) for 11 January 2002. See color version of this figure in the HTML.

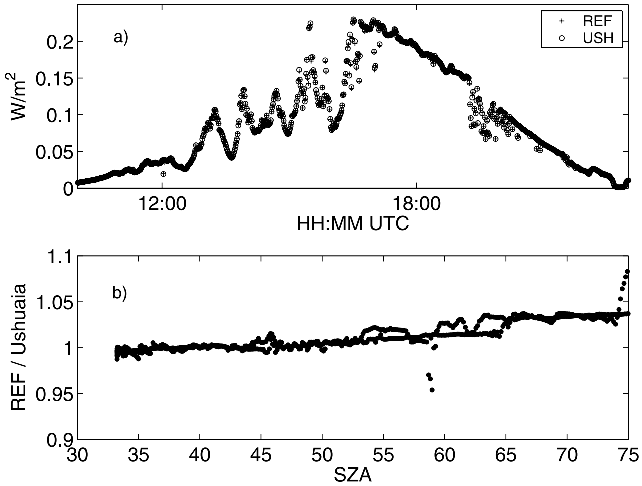

Figure 6. (a) UV dose rates measured with the traveling reference and the Ushuaia NILU-UV for 11 January 2002. (b) Ratios of erythemally weighted UV dose rates between the traveling reference NILU-UV and the Ushuaia NILU-UV for 11 January 2002.

where a_i is the coefficient of the linear combination of equation (1) for channel i of the reference NILU-UV, c_i the scaling factor between the raw data of the site NILU-UV and the reference NILU-UV for channel i and $V_{i,site}$ the site NILU-UV raw data for channel i. Thus each channel of the site instrument was scaled to the corresponding channel of the reference instrument.

[42] Figure 6 shows the result of the corrected erythemally weighted dose rates compared to those of the reference NILU-UV for the example day, 11 January 2002, at Ushuaia. The channels of the site NILU-UV have been scaled with the scaling factor derived from the values of Figure 5. The relative difference of 3-min average dose rates from the lowest SZA to 75° is shown in Figure 6b. The absolute values of UV dose rates are shown in Figure 6a. The small jump in the ratios near SZA 75 is due to a shadow that affects the two NILU-UVs at different times. The mean difference is 0.4 ± 0.9%, when the SZA varies from its lowest value up to 65°, and 1.4 ± 1.8%, when the SZA varies up to 80°.

[43] A corresponding example of solar comparison made at Marambio is shown for 30 December 2002 in Figures 7 and 8, where ratios of raw data and scaled UV dose rates between the Marambio NILU-UV and the traveling reference are plotted, respectively. Here the data for the whole day are also shown, including all sky conditions, from lowest SZA to 75°. The Marambio NILU-UV differs from the reference by around 25% in channels 1, 3, and 4, while in channels 2,5 and 6 the difference is only a couple of percent. The stepped behavior of the ratios in Figure 7 is due to the characteristics of each instrument concerning the instrument gain change, where the new gain is a little different than assumed. The differences in the diurnal patterns between Figures 7 and 5 are most likely caused by the different spectral responses of the instruments. Figure 8a shows absolute values of UV dose rates measured with the traveling reference and the NILU-UV of Marambio during the solar comparison day up to SZA 75°. The mean difference is 0.09 ± 0.5%, when the SZA varies from its lowest value up to 65°, and 0.03 ± 0.5%, when the SZA varies up to 80°.

[44] A similar procedure to that described above was carried out for every solar comparison between the traveling reference and the NILU-UV instruments at Ushuaia and Marambio. This means that for every solar comparison made, a scaling factor (c_i) was calculated for the site NILU-UV. Using this scaling factor to retrieve the UV dose rates at Ushuaia and Marambio, the right irradiance scale was obtained. Figure 9 shows the time series of the scaling factors for channels 1–6 of the Marambio and Ushuaia NILU-UVs. The results shown represent measurements during the lowest SZA in almost clear sky conditions. The ratios between the Marambio NILU-UV and the reference NILU-UV varied between 0.58 and 1.12, while the corresponding ratios for the Ushuaia NILU-UV varied from 0.59 to 0.92.

[45] Even if the raw signal differed from the reference by almost 40% in some channels, the results were good: For all 12 solar comparisons performed at Ushuaia during 2000–2003 the mean ratio (reference/Ushuaia) of calculated erythemally weighted UV dose rates was 1.004 ± 0.009, when the SZA varied from its lowest value up to 65°, and 1.007 ± 0.011, when the SZA varied up to 80°. For all 9 solar comparisons performed at Marambio during the same time period, the mean ratio (reference/Marambio) of calculated erythemally weighted UV dose rates was 1.007 ± 0.009 and 1.012 ± 0.012, when the SZA varied up to 65 and 80°, respectively.

4. Conclusions

[46] The quality control and quality assurance procedures of the NILU-UV Antarctic Network have shown that, when using a multichannel filter radiometer, regular lamp measurements and solar comparisons against a well-maintained reference, both performed by trained personnel, are needed in order to ensure the stability of the irradiance scale. Solar comparisons against a spectroradiometer allow the absolute calibration of the instrument, as well as a follow-up of any changes in channel sensitivity. As for most of the time, the time interval between solar comparisons is long, lamp measurements are needed to pinpoint the time of any possible change in sensitivity. It is essential to use different lamps and different burning times in order to exclude the effect of lamp aging.

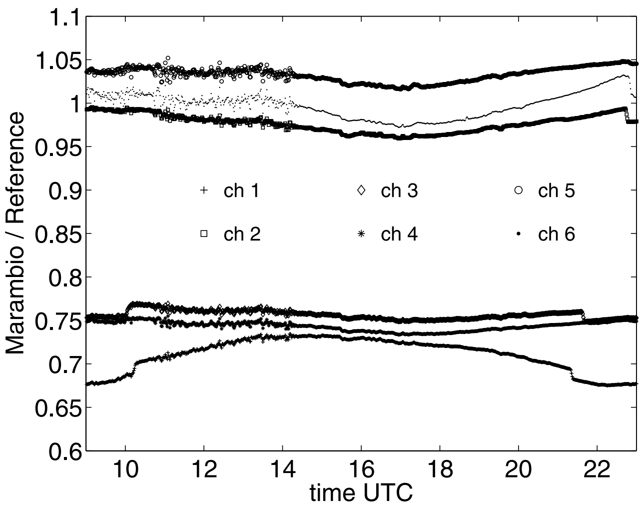

Figure 7. Ratio of UV channels raw data between the Marambio NILU-UV and the traveling reference NILU-UV ($1/b_i$ in equation (3)) for 30 December 2002. See color version of this figure in the HTML.

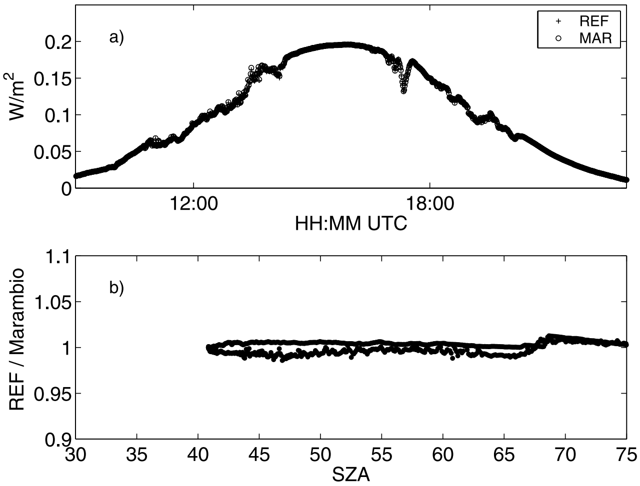

Figure 8. (a) Erythemally weighted UV dose rates measured with the traveling reference and the Marambio NILU-UV for 30 December 2002. (b) Ratios of erythemally weighted UV dose rates between the traveling reference NILU-UV and the Marambio NILU-UV for 30 December 2002.

[47] Using lamp tests, we found that the different channels in a multichannel radiometer can drift at different rates, and that the sensitivity can also recover. The largest observed drift, during 2000–2003, was −35% both for the Marambio and the Ushuaia NILU-UV. This confirms that proper quality control and quality assurance procedures are needed, as well as yearly absolute calibration, to maintain the irradiance scale of a multichannel radiometer network.

[48] For the NILU-UV Antarctic Network stations of Ushuaia and Marambio, a traveling reference NILU-UV has been used to transfer the desired irradiance scale. Each channel of the site NILU-UV has been separately compared with that of the traveling reference NILU-UV during solar comparisons. By scaling the channels with the results of the solar comparisons, the irradiance scale was transferred. Even though the scaling factor could affect the raw signal by as much as around 40%, a linear combination of the reference NILU-UV channels could be used to retrieve the UV irradiances for Marambio and Ushuaia. The mean ratios of erythemally weighted UV dose rates between the reference NILU-UV and the site NILU-UV were 1.007 ± 0.011 and 1.012 ± 0.012 for Ushuaia and Marambio, respectively, when the SZA varied up to 80°.

[49] The results presented above show that, especially under the difficult conditions of the Antarctic, instruments which are generally known to be stable, can have severe drift in the sensitivity of the channels. The use of relative lamp tests was found essential in order to monitor the behavior of the radiometer between yearly solar calibrations, as the drift was found not to be linear. The use of a well-maintained traveling reference, in order to transfer the irradiance scale, was found successful, and can also be

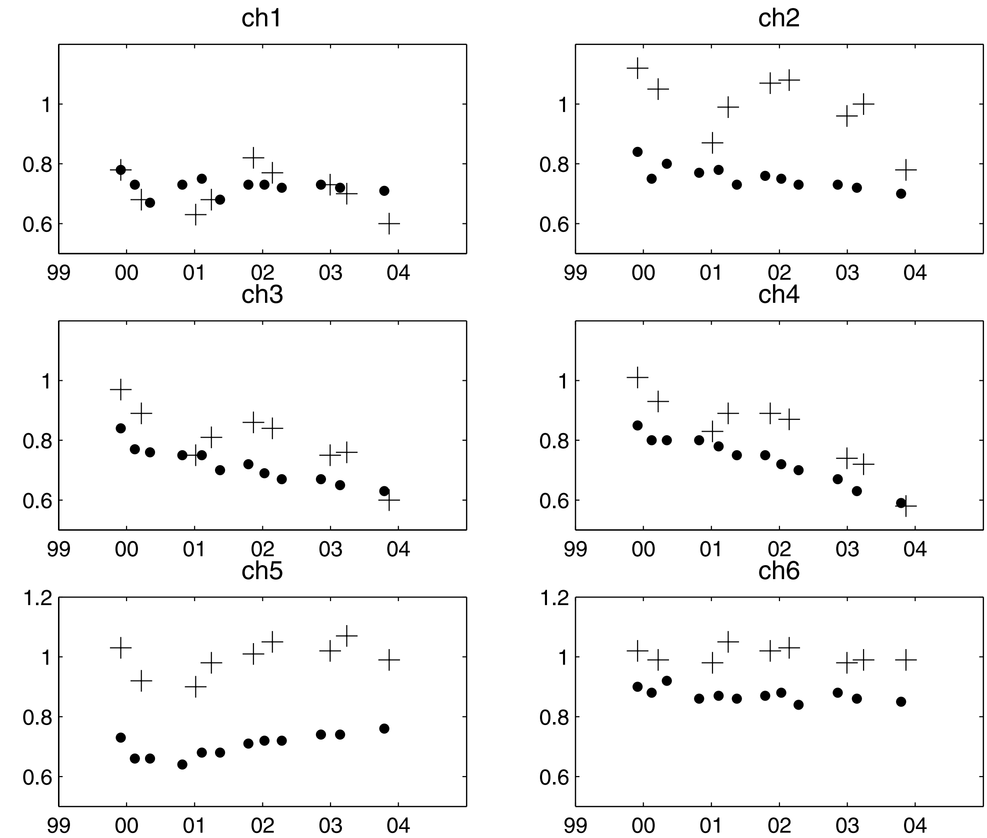

Figure 9. The 2000–2003 time series of the scaling factors of the UV channels of the Ushuaia (dots) and Marambio (crosses) NILU-UV instruments.

recommended for other multichannel radiometer networks. The results show that only proper quality control and quality assurance procedures make possible the reliable scientific use of the data.

[50] **Acknowledgments.** The Academy of Finland has given financial support for this work. The MAR Project is financed by the National R+D Plan of the Spanish Ministry of Science and Technology (National Research Program in the Antarctic) under contract REN2000-0245-C02-01. The SUV spectroradiometer UV data from Ushuaia was provided by the NSF UV Monitoring Network, operated by Biospherical Instruments Inc. under a contract from the United States National Science Foundation's Office of Polar Programs via Raytheon Polar Services Company. We are grateful to Bjørn Johnsen of the Norwegian Radiation Protection Authority for relative response measurements and fruitful discussions. We thank the operators of the MAR project.

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