5. Quality Control and Calibration Standards

Successful operation of a network of complex instruments, such as scanning spectroradiometers, depends upon a well-defined approach to quality assurance and quality control (QA/QC). Standards used to calibrate the instruments must be regularly validated and recalibrated, when necessary. The general network's QA/QC program is explained below. Site-specific results of the QC procedures applied to Volume 10 data are given separately by site in the following subsections. This includes discussions on the performance of irradiance standards used for Volume 10 data, the accuracy and stability of the instruments' responsivity, and the accuracy of the wavelength calibration. Some information is intentionally repeated in these subsections, allowing the reader to focus on the site of interest without missing any background information.

General Quality Assurance and Quality Control program

The QA/QC program of the NSF UV Spectroradiometer Network includes the following elements:

- Uniformity of instruments in the network
- Standardized procedures, parts, supplies, and operator training
- Standardized data processing procedures including calibration review and implementation of correction methods
- Maintenance of a set of calibration standards that are traceable to national standards laboratories, and their regular recalibration
- Scheduled instrument maintenance
- Careful review of recorded data and application of corrections
- Publication of instrument operating history
- Participation in instrument intercomparisons
- Data analysis and publication by independent scientists
- Publication in refereed journals

All site operators are trained at our San Diego facility, and documented operating procedures are used. Instrument maintenance is performed during annual site visits. A more detailed list of the QA/QC activities is presented in Table 5.1.

Table 5.1. Frequency of data acquisition, quality control/assurance, and publication.

Every 5 minutes	***Bi-weekly***
Temperatures and power checks	System calibration with site standards
Monochromator position check	***Monthly***
Ancillary sensors measurements	Analysis of calibration and standards stability
Detection of system errors by software	***Yearly***
Daily	Operator training at San Diego
Responsivity determination	Site visits including:
Wavelength alignment characterization	Scheduled maintenance
Checks by the site operators	Operation audit (testing)
On-site preliminary UV-B calculations	Standards comparison
Weekly	Engineering upgrades
Data transfers	Reprocessing of all calibrations and data
Data archive checks	Final data check
System performance reviews	Report and CD-ROM generation
Preliminary database updates	***Additionally***
System parameter time series and irradiance value checks	Participation in intercomparisons
	Comparisons with radiative transfer models
Website updates	Re-evaluation and testing of methods

Operations reports are annually published by Biospherical Instruments to detail the history of each instrument and present quality control data that can aid researchers in using data from the network. Biospherical Instruments also participates in North American and international intercomparisons of spectroradiometers and standards. Many researchers have had access to these data, conducted their own independent analyses, and published their results.

Verification of the irradiance scale maintained at Biospherical Instruments by CUCF

The irradiance scale of Biospherical Instruments was verified in November 1998, October 2000, and April 2002, when Patrick Disterhoft from the Central UV Calibration Facility (CUCF) visited Biospherical Instruments. The CUCF is part of the Surface Radiation Research Branch (SRRB) of NOAA's Air Resources Laboratory. This laboratory was established in response to the U.S. UV-B Interagency Monitoring Strategy. A major objective of the CUCF is to provide long term, NIST-traceable calibration standards for the U.S. UV-B monitoring activities.

The purpose of the 1998 audit by CUCF was to calibrate the SUV-100 and SUV-150 spectroradiometers in San Diego independently with the CUCF field calibrator and the BSI calibration apparatus; compare the results; and adjust the BSI calibration scale, if necessary. An additional goal during the visit in 2000 was to assess the performance of a new field calibrator, manufactured by BSI during 2000. The design of this calibrator is very similar to that employed by CUCF. In contrast to the calibration stand that is normally used at the NSF network sites (see Section 2.1.3), the new stand accommodates both 200-Watt and 1000-Watt standards of irradiance. The latter lamps are used by CUCF and NIST as transfer standards. The new calibrator enables SUV-100 and SUV-150 instruments to be calibrated with standards provided by CUCF. During the visit in 2000, a discrepancy between the CUCF and Biospherical Instruments irradiance scales was discovered, and the reason of the deviations could be traced to the CUCF apparatus for calibrating irradiance standards. The objective of the audit in 2002 was to verify the consistency of both irradiance scales after modification of the CUCF apparatus. Results of all three audits are described in detail below.

Results of the CUCF audit in 1998

Figure 5.1 shows some of the results from the 1998 audit. The BSI standard M-874 and the CUCF standard 96598 (calibrated on 4/3/98) are compared with the CUCF standard 96600 (calibrated on 6/17/98). Lamp M-874 was calibrated by Optronic Laboratories in September 1998, shortly before the CUCF audit, and this calibration represented the BSI irradiance scale between mid-1998 until mid-2000, when the lamp became unstable. M-874 was also used as traveling standard, see Table 5.3. Figure 5.1 depicts the ratios $Q(\lambda)$:

$$Q(\lambda) = \frac{[I_{\mathrm{ext}}^{(1)}(\lambda) - I_{\mathrm{dark}}] / E_{\mathrm{cert}}^{(1)}(\lambda)}{[I_{\mathrm{ext}}^{(2)}(\lambda) - I_{\mathrm{dark}}] / E_{\mathrm{cert}}^{(2)}(\lambda)}$$

Here	$I_{\mathrm{ext}}(\lambda)$	is the PMT current at wavelength λ during lamp measurements,`
	I_{dark}	is the PMT dark current, and
	$E_{\mathrm{cert}}(\lambda)$	is the certified lamp irradiance.

The superscripts (1) and (2) are placeholders for the lamp serial numbers. For the lamps shown in Figure 5.1, (1) is either M-874 or 96598, and (2) is 96600. Note that the definition of $Q(\lambda)$ is different from the quantity $C(\lambda)$, which was introduced in Section 4.2.1.4 for lamp comparison purposes. In contrast to $C(\lambda)$, $Q(\lambda)$ does not include the irradiance of the internal reference lamp.

Figure 5.1 shows that the two CUCF lamps 96598 and 96600 are in agreement to within ±1%. Lamp M-874 was compared with 96600 both with the SUV-100 and the SUV-150. The results obtained with both instruments agree to within ±1%. The measurements of both instruments indicate a systematic 1-2% difference between M-874 and both CUCF lamps. If solar measurements during 1999 were calibrated with CUCF standards rather than with M-874, published data from the network would therefore be lower by 1-2%. This difference is still within the uncertainties given in the lamp certificates and the uncertainties of the comparison procedure, see Table 5.2.

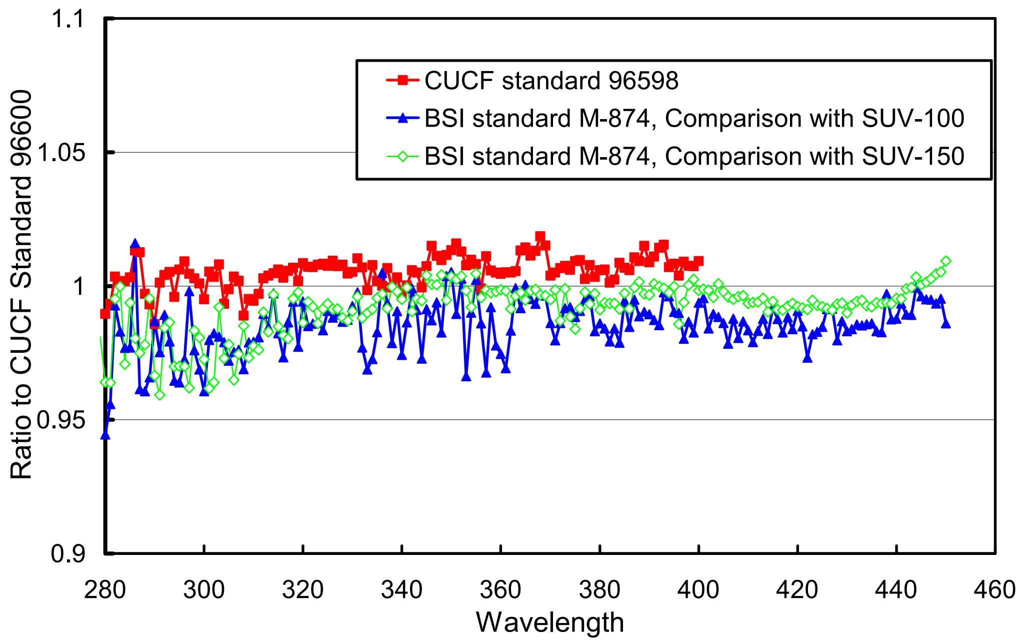

Figure 5.1. *Comparison of the BSI traveling standard M-874 and the CUCF standard 96598 with the CUCF standard 96600 in 1998.*

Table 5.2. Uncertainty estimates by Optronic Laboratories, NIST and BSI.

Target	Standard Optronic	Transfer Optronic	NIST standards F-473, F-474	Compariso n BSI
Uncertainty level	3σ	not specified	2σ	2σ
Uncertainty 280–350 nm	±1.35% – ±2.23%	±1.1%	±1.09% – ±1.82%	±1.5%
Uncertainty 350–650 nm	±1.01% – ±1.35%	±0.8%	±0.91% – ±1.09%	±1%

Remarks: The BSI 200-Watt standards were calibrated by Optronic Laboratories with the standard F-649, which is traceable to the NIST standard F-348. The column "Standard Optronic" gives the irradiance uncertainty of standard F-348 as specified by Optronic Laboratories. The column "Transfer Optronic" gives the additional uncertainties involved in transferring the irradiance from F-348 to the BSI 200-Watt lamps. The uncertainties specified in the column "NIST standards F-473, F-474" are specified in the calibration certificates of those lamps. The column "Comparison BSI" gives an estimate of the uncertainties involved when comparing two standards with the SUV-100.

Results of the CUCF audit in 2000

Objectives of the CUCF audit in 2000 included:

- The validation of the new BSI field calibrator
- Calibration of the SUV-100 with 1000-Watt irradiance standards provided by CUCF. Three of these lamps (S/Ns H-011, H-012, and H-013) were transferred to BSI and are available for use with the new field calibrator.
- The inspection of the BSI irradiance scale.

Figure 5.2 summarizes the results from all three items:

- The curve labeled “96600 operated in BSI stand” is the ratio $Q(\lambda)$ of measurements with the CUCF standard 96600 performed with the new BSI calibrator and with the CUCF calibration stand. Both measurements agree to within ±0.5% with an average difference of 0.3%. This difference is within the typical reproducibility of SUV-100 measurements. It can therefore be concluded that the new field calibrator is suitable for accurate calibrations.

- The curve labeled “H-011” is the ratio $Q(\lambda)$ of the two CUCF standards H-011 and 96600. The measurements were performed with the CUCF field calibrator. Both lamps agree to within ±0.5%, except of a peak between 395 and 397 nm. This peak can be attributed to the emission of Aluminum, which is an unwanted by-product left over from the tungsten sintering process and part of the filament alloy. The lamps H-012, and H-013 were in similar agreement with 96600 and also exhibited Aluminum lines.

- The curve labeled “BSI standard M-764” is the ratio $Q(\lambda)$ of the BSI 200-W standard M-764 and the CUCF standard 96600. For the latter, the CUCF calibration from 08/22/2000 was used. At the time of the CUCF site visit in 2000, lamp M-764 represented the BSI irradiance scale (M-874 exhibited a drift during 2000 and is no longer in use). Figure 5.2 shows that M-764 is too bright by 3-4% as compared to 96600. This means that the BSI and CUCF irradiance scale in 2000 are different by this amount. A comparison of Figure 5.1 and Figure 5.2 suggests that the BSI scale changed by approximately 5% relative to the CUCF scale between 1998 and 2000. The magnitude of these differences is larger than expected, and stimulated further experiments to identify the reasons. The calibration of M-764 in 2000 was less well defined than the calibration of M-874 in 1998. The first step in elucidating the observed discrepancy was therefore the analysis of the calibration history of M-764.

  Lamp M-764 has an Optronic Laboratories calibration from October 1992. It was used as a site standard at McMurdo until January 1999. Season closing calibrations at McMurdo performed on 1/20/99 confirmed that the lamp’s calibration is still valid. It agreed with all three McMurdo standards 200W005, 200W019, and M-543, as well as M-874 to within ±1% (Lamps 200W005 and 200W019 have Optronic Laboratories calibrations from November 1996 and September 1998, respectively). After removal from McMurdo Station, M-764 was used only once until the CUCF 2000 audit. It was therefore presumed that the BSI irradiance scale of the CUCF audit in 1998 was still preserved by this lamp when the audit took place in 2000. A change in the calibration of 5% appears to be unlikely.

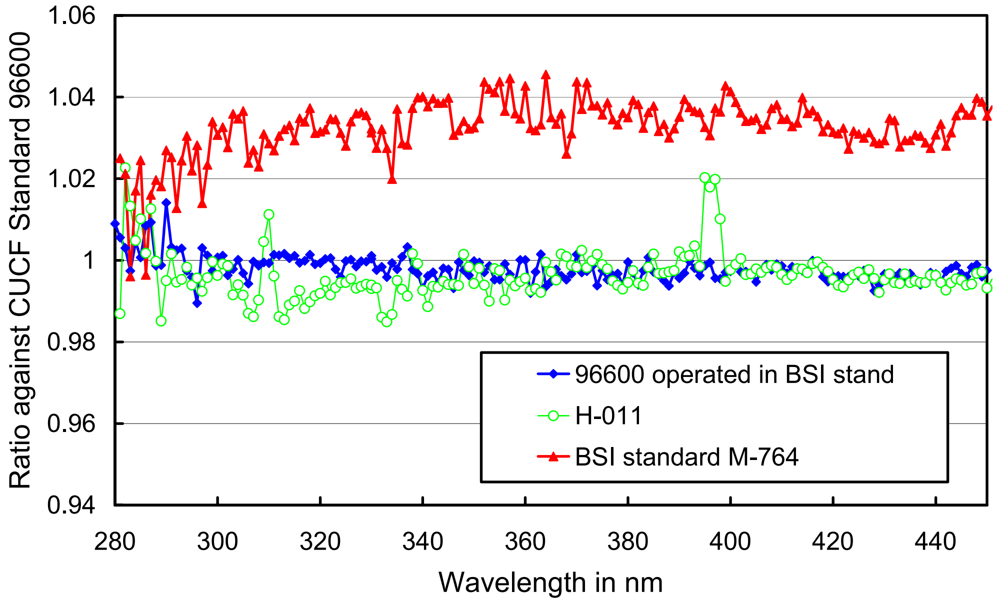

Figure 5.2. *Results of the CUCF audit in October 2000. See text for details. The reference is a scan of CUCF standard 96600, mounted in CUCF field calibrator.*

Recalibration of BSI 200-W calibration standards by Optronic Laboratories

In order to further uncover the discrepancy of both scales, M-764 was sent to Optronic Laboratories for re-calibration in March 2001 together with 15 other BSI 200-Watt calibration standards. The values stated in the new calibration certificate of M-764 were higher by only 0.5-1.5% than those in the original certificate from October 1992, see Figure 5.3. This is a further indication that the BSI scale did not drift by 5% between 1998 and 2000.

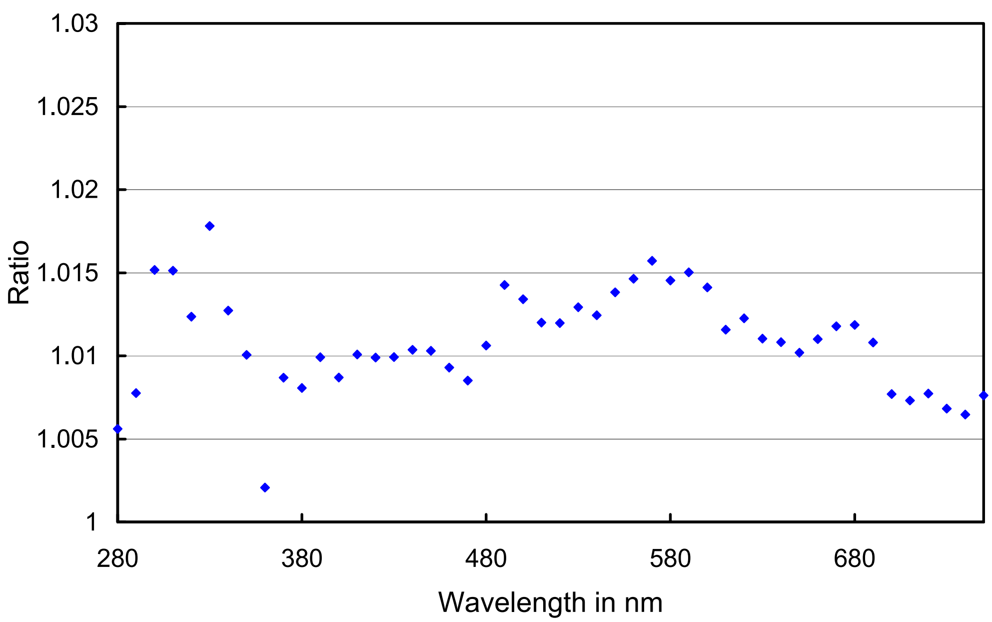

Figure 5.3. *Ratio of spectral irradiance of standard M-764 as stated in Optronic Laboratories certificates issued on 3/28/01 and 10/30/92. Values reported in March 2001 are 0.5-1.5% higher than those reported in October 1992.*

After return from Optronic Laboratories all 16 200-Watt standards were compared with each other. All lamps agreed to within ±1% (i.e. within the calibration uncertainty of BSI, Table 5.2). This confirms the consistency of the calibrations performed by Optronic Laboratories.

A subset of the 16 lamps was then compared with the two CUCF standards H-011 and H-012. Figure 5.4 shows the comparison of M-763[#] with H-011 and H-012. In order to investigate whether the results depend on the calibrator or power supply, M-763 was run three times, once with the new field calibrator, utilizing also its power supply and shunt; once with the new calibrator but with shunt and power supply of the San Diego SUV-100, which are usually used for 200-Watt calibrations; and finally with the standard SUV-100 calibrator, shunt, and power supply. Since the comparison was performed over a three day period, special care had to be taken assuring that the SUV-100 remained stable over this time. As Figure 5.4 shows, measurements of H-012 from 4/17/01 and 4/20/01 agreed, confirming stability of the radiometer. An independent scan with H-011 showed also excellent agreement. In contrast, all three measurements of M-763 were high by 2-3% relative to the CUCF standards, independent of wavelength, calibrator and power supply. This is consistent with the results from the CUCF audit in 2000.

Although unlikely, the discrepancy of M-763 and H-012 could also be caused by non-linearity of the SUV-100, which was used as the transfer spectroradiometer for the comparison. Lamp M-763 is a 200-Watt lamp and H-012 is a 1000-Watt lamp. It is conceivable that the factor five difference in the irradiance produced by both lamps does not lead to exactly a factor of five difference in the measured signal. In order to exclude this possibility, the 200-Watt lamp 200W030 (which also agreed well with M-763), was compared with H-012 both with the SUV-100 and a GUV. The latter is a filter radiometer with four 10-nm-wide channels centered at 305, 320, 340, and 380 nm, and an additional channel in the visible. The results from both radiometers were very consistent. The difference between 200W030 and H-12 as seen by the GUV was 5.4% at 305 nm, 3.5% at 320 nm, 3.5% at 340 nm, and 3.9% at 380 nm.

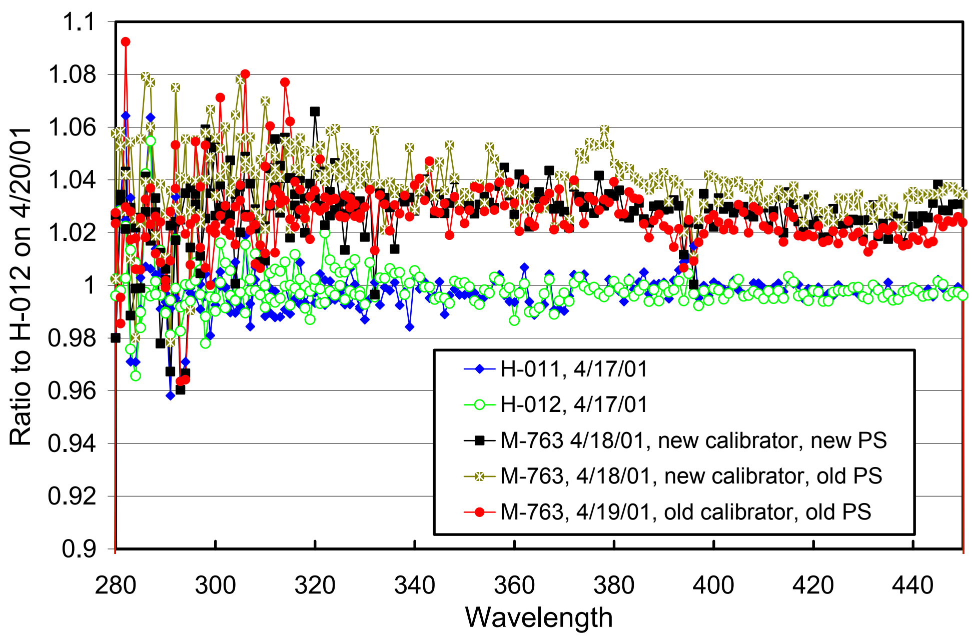

Figure 5.4. *Comparison of M-763 with H-012 after M-763 had been recalibrated by Optronic Laboratories in March 2001.*

[#] Lamp M-764 was not available at that time because it was en route to Palmer Station to serve as the site visit traveling standard. Before shipment, M-764 and M-763 were intercompared using the Optronic Laboratories calibrations from March 2000, and virtually no difference was found.

From these results it can be concluded that the irradiance scale of Optronic Laboratories, which was transferred to the BSI 200-Watt lamps in March 2000, deviates by approximately 3% from the CUCF irradiance scale. This is consistent with the discrepancy observed during the CUCF audit in October 2000.

It cannot be concluded from these results, however, which of both scales is closer to the primary U.S. irradiance scale maintained by NIST in Gaithersburg. In an attempt to determine this, H-012 was compared with two 1000-Watt standards of irradiance (S/N F-473 and F-474), which were calibrated by NIST. F-473 had a total runtime of 10 hours after its calibration; the runtime of F-474 was 6 hours. Both lamps have vertical filament orientation (which is how NIST maintains this scale), in contrast to H-012. It is therefore not possible to compare both NIST lamps directly with H-012, using the SUV-100 (This is also the reason, why both NIST standards are not regularly used to calibrate the SUV-100). The comparison was consequently performed with the GUV. When measuring H-012, the GUV was aligned upright, with the diffuser oriented horizontally; for measurements of the NIST standard, the radiometer was turned by 90°. Since the GUV does not have moving parts, it is unlikely that turning it by 90° changes its sensitivity. H-012 was operated in the field calibrator; both NIST lamps were used in the BSI laboratory.

The difference between F-473 and H-012 as seen by the GUV was 4.9% at 305 nm, 4.1% at 320 nm, 3.3% at 340 nm, and 3.4% at 380 nm. The differences when comparing F-474 with H-012 were 4.4%, 3.1%, 2.7%, and 2.8%, respectively. 200W030 and F-473 were consistent at the 0.5% level; the difference between 200W030 and F-474 was about 1%.

From these results it can be concluded that the March 2001 calibration scale of Optronic Laboratories is consistent at the 1% level with the NIST scale represented by F-473 and F-474. However, there is a 3-4% difference between NIST and CUCF scales.

The results of the before-mentioned experiments were extensively discussed with Mr. Disterhoft. The CUCF apparatus for transferring calibrations of standards with vertical filament orientation to standards with horizontal filament orientation (such as 96600 or H-012) was carefully inspected, which led to the discovery of the reason of the 3-4% bias between NIST and CUCF scales. The CUCF apparatus uses an integrating sphere, which is rotated by 90° for the vertical-to-horizontal transfer. The differences in geometry between both orientations proved to be responsible for the observed discrepancies. The apparatus was consequently modified, several lamps were re-calibrated with the changed setup, and again compared with BSI 200-Watt standards.

CUCF audit in 2002

Objectives of the CUCF audit in 2002 included:

- A comparison of CUCF standard with vertical filament orientation and CUCF standards with horizontal filament orientation, which have been recalibrated with the modified CUCF apparatus.
- A comparison of BSI NIST standard F-473 with various CUCF standards.
- A comparison of 200-Watt standards calibrated by Optronic Laboratories with CUCF standards.

The comparison of all lamps was performed with a SUV-150 spectroradiometer, which was still under development during the time of the audit. Because of problems with the monochromator alignment, measurements were affected by increased noise and sporadic spikes. We were able to mostly eliminate these artifacts by appropriate filtering and smoothing.

The SUV-150 has a new designed entrance optics, which is coupled by fiber optics to the instrument's monochromator. This allows to turn the entrance optics by 90° without changing the instrument's responsivity. This feature makes the instrument ideal for comparison of lamps with vertical and horizontal filament orientation. Because of this advantage, we used the SUV-150 rather than the SUV-100 as the transfer radiometer.

The intercomparison was further complicated by the fact that NIST has recently established a new scale of irradiance [*Yoon et al.*, 2002]. Irradiance values assigned to a lamp that are based on new detector-based scale (NIST2000) are 1-1.5% higher in the UV than values based on the previous source-based scale

(NIST1990). The calibration of all CUCF lamps used during the 2002 audit was already based on the NIST2000 scale.

Results from the CUCF audit in 2002 can be summarized as follows:

- There is no significant difference between the vertical-filament CUCF lamps (S/N 97511 and 96597) and the horizontal-filament CUCF lamps (S/N H-011, 96601, H013, and H-015). It can be concluded that the modification of the CUCF apparatus for lamp transfers led to the elimination of the 3-4% discrepancy of horizontal and vertical lamps, which was discovered during the audit in 2000.
- The signal of BSI's vertical-filament NIST lamp F-473, is high by 1-1.5% in the UV compared to the CUCF standards H-011, 96601, H-013, 97511 and 96597. The calibration of F-473 still refers to the NIST1990 scale. Measurements of the lamp would have agreed with the CUCF standards if we had recalibrated the lamp with the NIST2000 scale. The discrepancy between the BSI standard F-473 and the CUCF standard can therefore be explained by the adjustment of NIST's primary scale.
- The 200-Watt standard M-764, which was calibrated by Optronic Laboratories in March 2001, agrees with BSI's NIST lamp F-473 to within 0.3%. This demonstrates that the Optronic Laboratories irradiance scale as of March 2001 is consistent with the NIST1990 scale to which it is traceable.

<u>Volume 10 solar data are based on the Optronic Laboratories irradiance scale, which is consistent with the NIST1990 irradiance scale, as shown above. It is not yet decided whether we want to employ the new NIST2000 scale for the calibration of solar data in the future.</u>

As of January 2003, the reasons for the 5% difference between the results of the CUCF audits in 1998 and 2000 are still unclear, and it is unlikely that we will be able to solve this discrepancy. However, all our internal quality control analyzes do not indicate a drift of our scale by this amount.

Irradiance Standards used for Volume 10 Data

Table 5.3 gives an overview of the irradiance standards used in the 2000-2001 season and their calibration history. Most lamps were calibrated by Optronic Laboratories. There are also lamps that were calibrated by Biospherical Instruments using the procedure outlined in Section 4.2.1.5. Some of the standards, which have been deployed for Volume 10, have two or more sets of calibrations. The lamp M-874 was used as traveling standard until June 2000 when it became unstable. It was replaced by lamp M-764. This lamp was originally used as site standard for several years at McMurdo. We decided to use it as the new traveling standard because of its exceptional stability. The lamp was recalibrated by Optronic Laboratories in March 2001. The new calibration values differed by less than 1.5% from the original values, which were established in 1992.

The values in the columns "Change between calibrations 1 and 2" in Table 5.3 give an indication of typical changes in the output of lamps during several years. Our observation is that some lamps show abrupt changes, whereas other lamps exhibit uniform drifts.

Analysis of Instrument Stability

In the post-seasonal analysis of instrument performance, stability of both system responsivity and wavelength stability of the monochromator are carefully reviewed (See Chapter 4 for details on calibration and data processing protocols). System responsivity is tracked by analysis of the response scans. There are several events that can occur and will introduce a change into the system sensitivity. Where possible, these events are uncovered and corrected during the stability review:

- Intentional change of the system responsivity (PMT high voltage change) to accommodate changing solar radiation levels throughout a day

- Change of the response lamp due to aging, casualty, or replacement
- Change in instrument temperature
- Drifts of the PMT sensitivity or monochromator throughput
- Changes in the instruments' fore optics
- Any alteration to the system including engineering upgrades and routine or unanticipated maintenance

The wavelength stability of the final data is checked by the Fraunhofer correlation method described in Section 4.2.2.2. Since this method requires substantial computational time, typically only one spectrum per day and per site is checked. However, when there is any doubt in the wavelength accuracy during a specific period, all data scans of a day may be processed.

Table 5.3. Calibration standards used in the 2000-2001 season*.

Site	Standard	Calibration 1	Calibration 2	Change between Calibration 1 and 2		
				@ 300 nm	@ 400 nm	@ 600 nm
Traveling Standard	M-874	Optr. 9/98	Optr. 3/01	+5.0%	+3.6%	+2.6%
	M-764	Optr. 10/92	Optr. 3/01	+1.2%	+1.0%	+1.3%
McMurdo	M543	BSI transfer from M-874 establ. 1/99‡				
	200W005	Optr. 11/96				
	200W019	Optr. 9/98				
Palmer	M-700	BSI transfer; establ. 1/93	BSI transfer from M-874 (Optr. 9/98); establ. 2/00‡	+0.9%	+1.8%	+2.8%
	M-765	Optr. 10/92	BSI transfer from M-874 (Optr. 9/98); establ. 2/00‡	+0.1%	+1.0%	+1.8%
	200W007	Optr. 11/96				
South Pole	M-666	BSI transfer from 200W006 and 200W021 establ. 1/00‡				
	200W006	11/96				
	200W021	9/98				
Ushuaia	M-698	BSI transfer from M-874 (Optr. 9/98); establ. 8/99‡				
	M-766	Optr. 10/92	BSI transfer from M-874 (Optr. 9/98); establ. 5/00‡	-1.3%	+0.0%	+1.3%
	200W008	Optr. 11/96				
	200W026	Optr. 3/01				
Barrow	M-699	Optr. 9/98	Optr. 3/01	+0.5%	+0.4%	+0.3%
	M-762	Optr. 9/98	Optr. 3/01	+0.9%	+0.8%	+0.7%
	200W009	Optr. 9/98	Optr. 3/01	+5.1%	+3.7%	+2.3%
San Diego	M-699	Optr. 9/98	Optr. 3/01	+0.5%	+0.4%	+0.3%
	M-762	Optr. 9/98	Optr. 3/01	+0.9%	+0.8%	+0.7%
	M-763	BSI transfer from M-874 establ. 1/98‡	Optr. 3/01	-1.9%	-1.5%	-1.0%
	200W009	Optr. 3/01				
	200W017	Optr. 3/01				
	200W022	Optr. 3/01				
	200W023	Optr. 3/01				
	200W025	Optr. 3/01				
	200W026	Optr. 3/01				
	200W027	Optr. 3/01				
	200W028	Optr. 3/01				
	200W029	Optr. 3/01				
	200W030	Optr. 3/01				

In March 2001, 16 lamps were recalibrated by Optronic Laboratories. The calibration of all lamps was verified after their return from Optronic Laboratories, see Section 5.5. All measurements also served as absolute calibration scans for the San Diego instruments.

* *Some lamps have more than one calibration. The difference between these calibrations is marked in the three rightmost columns (i.e., positive change means that Calibration 2 revealed higher irradiance values). The calibrations that were actually used in the season are shaded.*

‡ *Date when lamp measurements have been processed to establish a new set of calibration coefficients.*

Cosine and azimuth error of SUV-100 spectroradiometers

It has been noted in previous Network Operations Reports that measurements of solar irradiance at the South Pole Station depend on the azimuth position of the sun. Since the solar zenith angle at South Pole is fairly constant during one day, the azimuth dependence appears as a sinusoidal oscillation in the data with a periodicity of one day. This wiggle is an artifact of the measurement rather than an actual change of solar irradiance with the azimuth angle. It was not clear until the end of 1999, however, whether only the instrument at South Pole or all network instruments are affected. Characterizations performed during the site visits in spring 2000 revealed that the problem exists at all network sites, although to a different extent. In response to this problem, the irradiance collectors of all instruments have been modified in 2000. Measurements with a test apparatus specifically designed for this purpose show that azimuth asymmetries of the modified instruments are generally below ±2% for all wavelengths. The effects of the instruments' cosine error[1] have been extensively studied in 2002, and results were presented at the conference "Ultraviolet Ground- and Space-based Measurements, Models, and Effects II", which was organized by the International Society of Optical Engineering (SPIE) as part of the Third International Asia-Pacific Environmental Remote Sensing Symposium 2002 "Remote Sensing of the Atmosphere, Ocean, Environment, and Space," which took place in Hangzhou, China, between October 23 and 27, 2002. The proceedings paper [*Bernhard et al.,* 2003] is available on the Biospherical Instrument website www.biospherical.com/nsf/presentations.asp. The most important results are summarized in the following. We are planning to reprocess the entire NSF data set based on the method outlined in [*Bernhard et al.,* 2003] in order to correct for the cosine error and azimuth asymmetries, and to remove a step-change that was introduced by the collector modification.

Figure 5.5 shows a photograph of the apparatus for *in situ* measurements of the cosine error[1]. It consists of a light source, which is coupled via an optical fiber bundle into a baffled tube. The tube threads into a black anodized cylinder that rests on the instrument's irradiance collector. The cylinder has precisely machined openings at 0°, 30°, 45°, 60°, and 70° zenith angles, and can be rotated to arbitrary azimuth angles. With a lens (which is located inside the tube about one focal length away from the end of the fiber) an approximately parallel light beam is produced, pointing toward the center of the collector. By coupling the tube to the different openings, the apparatus can be used to measure the angular response at five zenith angels and arbitrary azimuth angles.

Figure 5.6 shows the results of angular response measurements obtained with the test apparatus at Palmer Station, South Pole, and San Diego after the collectors of the instruments had been modified during year 2000. Measurements at all sites agree to within the uncertainty of the test apparatus. Observed variations with azimuth angle are smaller than ±2% at SZA = 70°. Please see [*Bernhard et al.,* 2003] for details on the deduction of the cosine error for incidence angles > 70°.

Apart from the instrument's cosine error, errors in measuring spectral irradiance at a given solar zenith angle (SZA) also depend on the spatial distribution of radiation falling on the radiometer's collector, which in turn depends on SZA, atmospheric constituents (e.g. clouds, aerosols, ozone), and ground albedo. We developed a parameterization of the measurement error depending on these parameters, which also allows to correct for this error [*Bernhard et al.,* 2003]. The correction procedure is rather elaborate, both computational and in terms of quality control. As of this writing, it is therefore not possible to give a complete assessment of the impact of cosine and azimuth errors on published solar data for all sites and seasons. An analysis of South Pole and McMurdo data from Volume 9 (measured in 1999 before modification of irradiance collector) and Volume 10 (measured in 2000 with modified collector) indicates the following:

[1] The cosine error describes the deviation of a radiometer's angular response from the ideal cosine law: if a light source illuminating the radiometer is moved from the zenith (incidence angle = 0°) to larger incidence angles, the radiometer's signal should change proportional to the cosine of the incidence angle. For example, at an incidence angle of 60° the signal should only be 50% of the signal at incidence angle = 0° as cos(60°) = 0.5. If the actual signal at 60° were only 45%, the cosine error of the radiometer would be -10%, as (0.45/ 0.5 - 1) * 100% = -10%. In this case, the radiometer would underestimate the true irradiance by 10%.

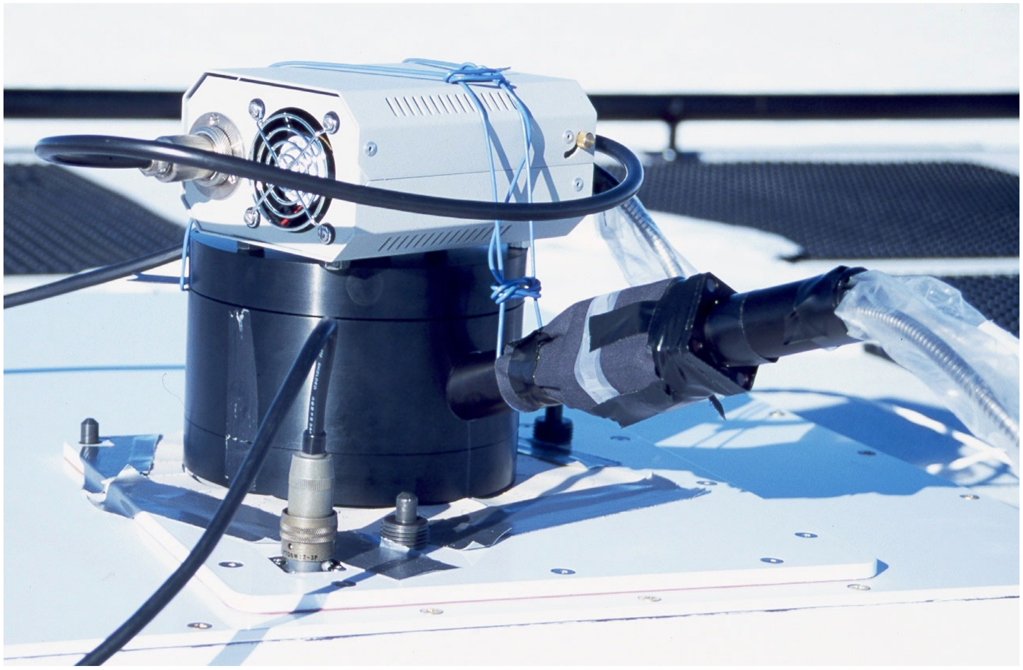

Figure 5.5. *Apparatus for characterizing the angular response of SUV-100 spectroradiometer in operation at the South Pole. The white box on top is a light source, which is coupled via a optical fiber bundle and a baffled tube into the black cylinder shown in the center of the picture. The cylinder has precisely machined openings at 0°, 30°, 45°, 60°, and 70° zenith angles, and can be rotated to arbitrary azimuth angles.*

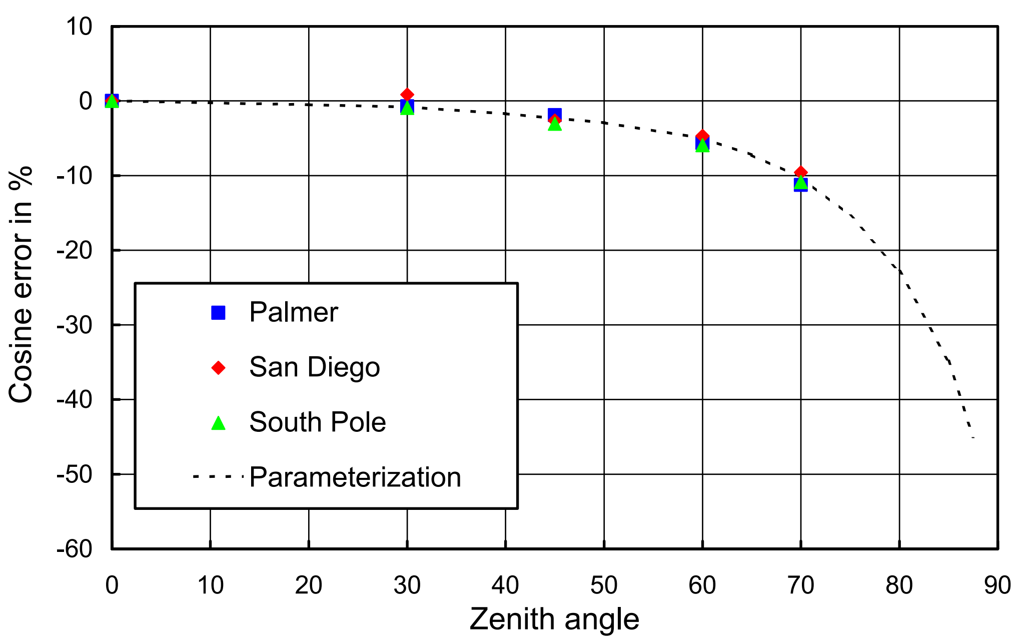

Figure 5.6. *Cosine error of SUV-100 spectroradiometers after modification of the collector. The symbols represent measurements with the cosine test apparatus shown in Figure 5.5.*

- Biologically weighted irradiances calculated from clear-sky solar spectra measured prior to the collector modification are low by 2-5%, and data exhibit a clear variation with the Sun's azimuth angle.
- Dose rates measured during overcast conditions are low by about 3%, independent of solar zenith and azimuth angles.
- Visible data are more affected by the cosine error than UV data because of the larger contribution of the direct solar beam to global (i.e. sun + sky) irradiance. At 450 nm and SZA=75°, the error can be as high as 17%. This value seems large, but is comparable to errors of many other instruments that are employed worldwide.
- Dose rates calculated from data that were measured at South Pole after the collector modification were low by about 5-7%, and show virtually no azimuth dependence, even at long wavelengths.
- The step change in published dose rates introduced by the diffuser change is about 3%, but the difference becomes significant in the UVA and visible.
- Cosine-corrected values of global spectral irradiance at 340 nm measured at the South Pole in 1999 (original collector) and 2000 (modified collector) agree to within ±0.5%. The results suggest that the cosine-correction will improve both the absolute accuracy of all data and the homogeneity of the data from different seasons.

Figure 5.7 compares corrected and uncorrected erythemal irradiance measurements from the Volume 9 South Pole data set in order to better illustrate the effect of the cosine and azimuth error on solar data. For clear sky spectra, the correction varies between 2.2% and 5.5% during the course of one day, and for conditions with thick clouds the correction is 3.1% throughout the day. Note that erythemal irradiance changes from 8.5 μW/cm² on 12/2/99 to 4.5 μW/cm² on 12/5/99. This rapid step-change of almost 50% is caused by the dissipation of the "ozone hole", and is more than 10-times larger than the cosine correction.

In order to illustrate the effect of the collector modification in January 2000, Figure 5.8 compares corrected and uncorrected data from Volumes 9 and 10. The figure depicts spectral irradiance at 340 nm. This wavelength is not affected by ozone absorption, and variations over time are therefore mostly caused by gradual change in SZA, the azimuth error, and cloud variations. As can be seen, uncorrected data from 1999 (Volume 9, before collector modification) show ±2% diurnal variation, which is attributable to the azimuth error. Corrected data from 1999 are in average 3-4% higher, and the effect of the azimuth error is greatly reduced. Uncorrected data from 2000 (Volume 10, measured after the collector modification) show no variation with azimuth angle but are in average 3% lower than uncorrected data from 1999. Corrected data from 1999 and 2000 agree to within 1%.

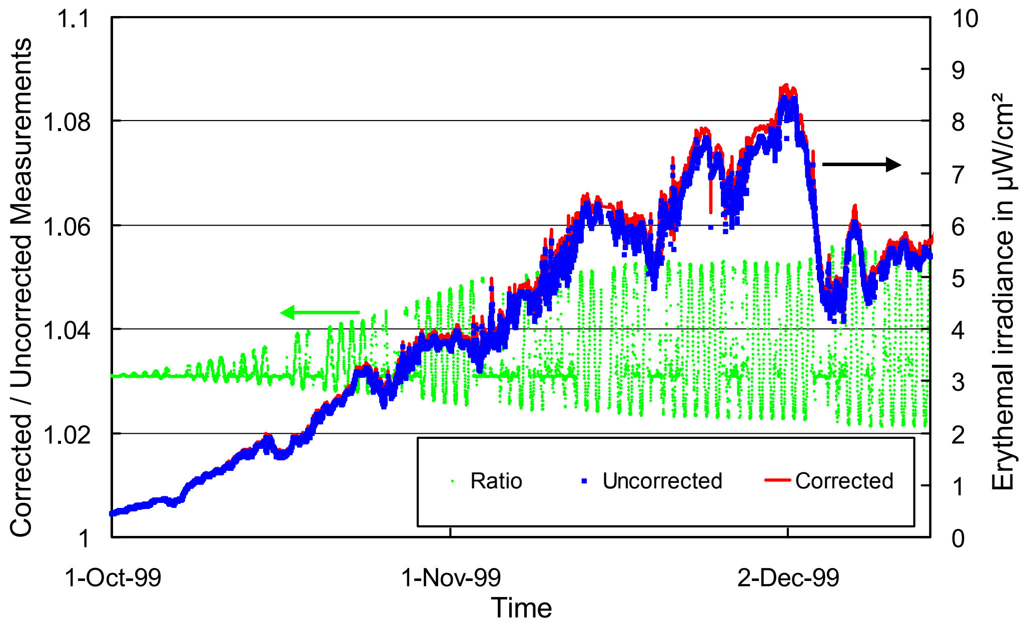

Figure 5.7. *Comparison of corrected and uncorrected erythemal UV measurements at the South Pole, fall 1999.*

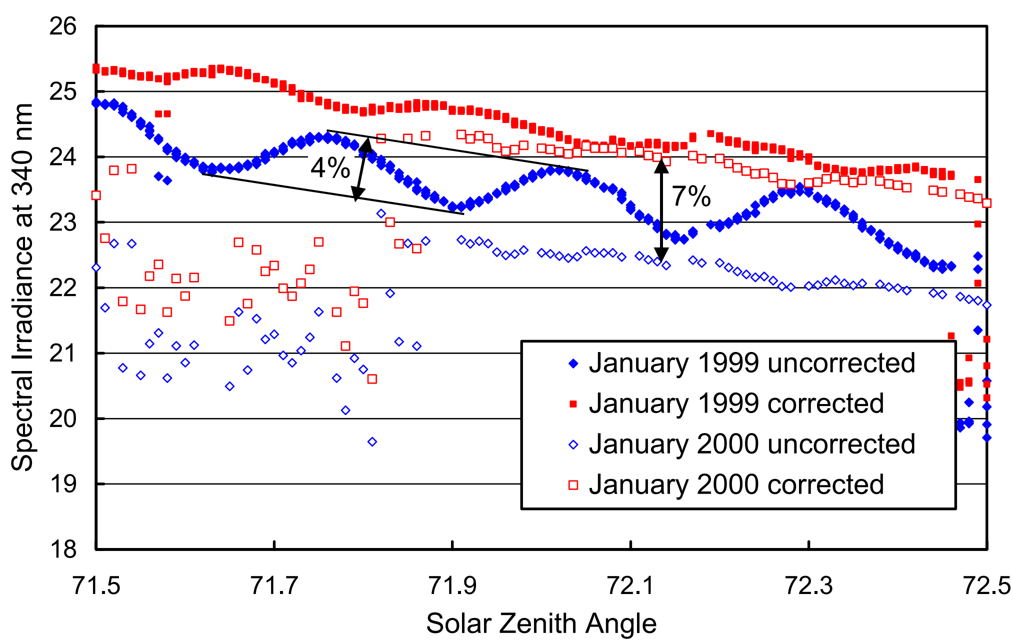

Figure 5.8. *Comparison of cosine-corrected and cosine-uncorrected spectral irradiance at 340 nm, measured at the South Pole in 1999 (Volume 9, before collector modification) and 2000 (Volume 10, after collector modification).*