

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 9 data are given separately by site in the following subsections. This includes discussions on the performance of irradiance standards used for Volume 9 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, which may be given in the section of another site.

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.

<i>Every 5 minutes</i>	<i>Bi-weekly</i>
Temperatures and power checks	System calibration with site standards
Monochromator position check	<i>Monthly</i>
Ancillary sensors measurements	Analysis of calibration and standards stability
Detection of system errors by software	<i>Yearly</i>
<i>Daily</i>	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
<i>Weekly</i>	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	<i>Additionally</i>
System parameter time series and irradiance value checks	Participation in intercomparisons
Website updates	Comparisons with radiative transfer models
	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 calibration scale maintained at Biospherical Instruments by CUCF

The calibration scale of Biospherical Instruments was verified in November 1998 and October 2000 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.

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 $Q(\lambda)$:

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

Here $I_{\text{ext}}(\lambda)$ is the PMT current at wavelength λ during lamp measurements,
 I_{dark} is the PMT dark current, and
 $E_{\text{cert}}(\lambda)$ 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 $\pm 1\%$. 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 $\pm 1\%$. 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.

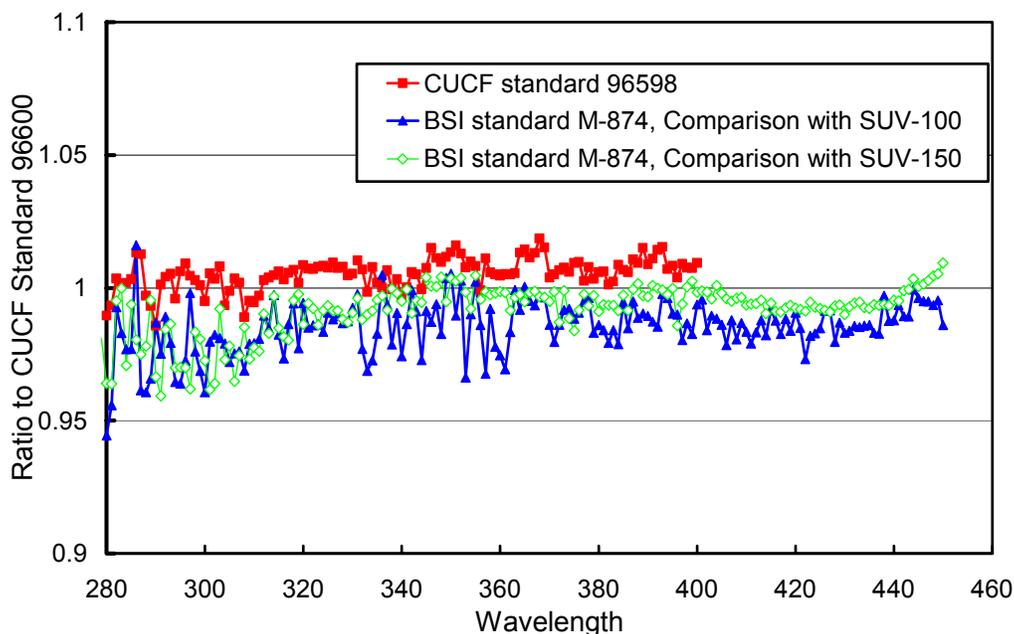


Figure 5.1. Comparison of the BSI traveling standard M-874 and the CUCF standard 96598 with the CUCF standard 96600 in 1998.

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

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

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 $\pm 0.5\%$ 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 $\pm 0.5\%$, 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 $\pm 1\%$ (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.

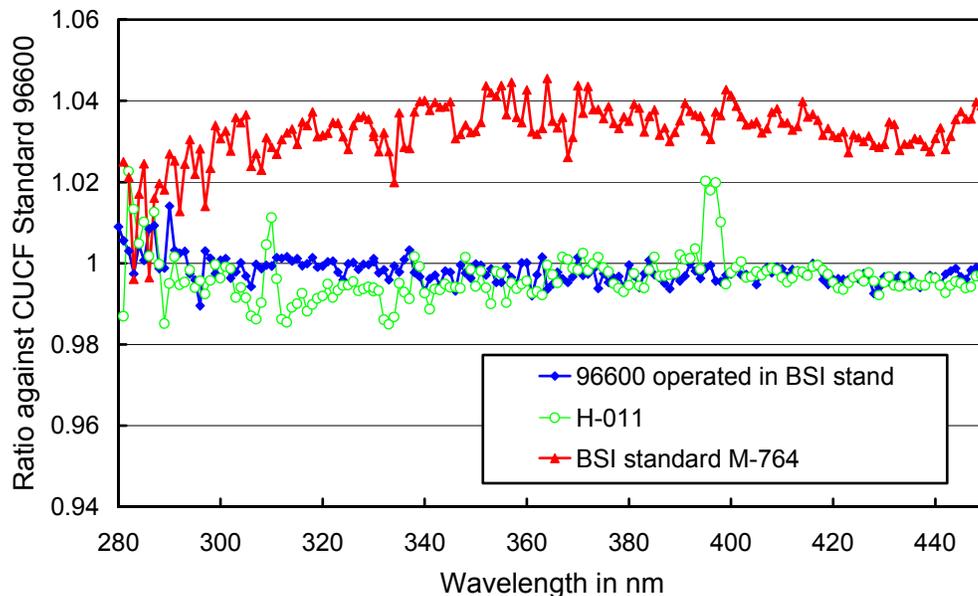


Figure 5.2. Results of the CUCF audit in October 2000. See text for details.

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 recalibration 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.

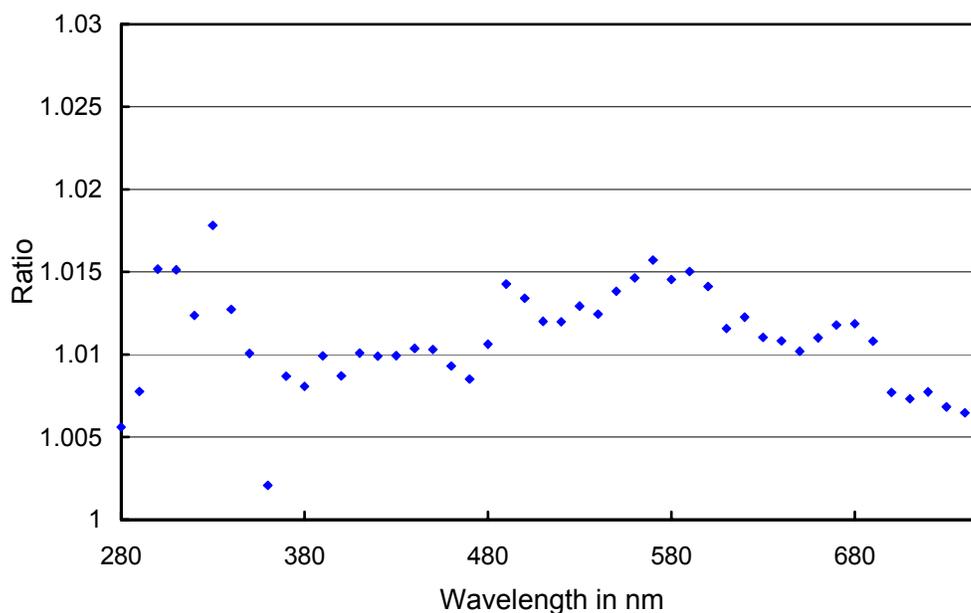


Figure 5.3. Ratio of spectral irradiance of standard M-764 as stated in Optronic Laboratories certificates issued on 3/28/01 and 10/30/92. Values reported in March 2001 are 0.5-1.5% higher than those reported in October 1992.

After return from Optronic Laboratories all 16 200-Watt standards were compared with each other. All lamps agreed to within $\pm 1\%$ (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 of five difference in the irradiance

[#] 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.

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.

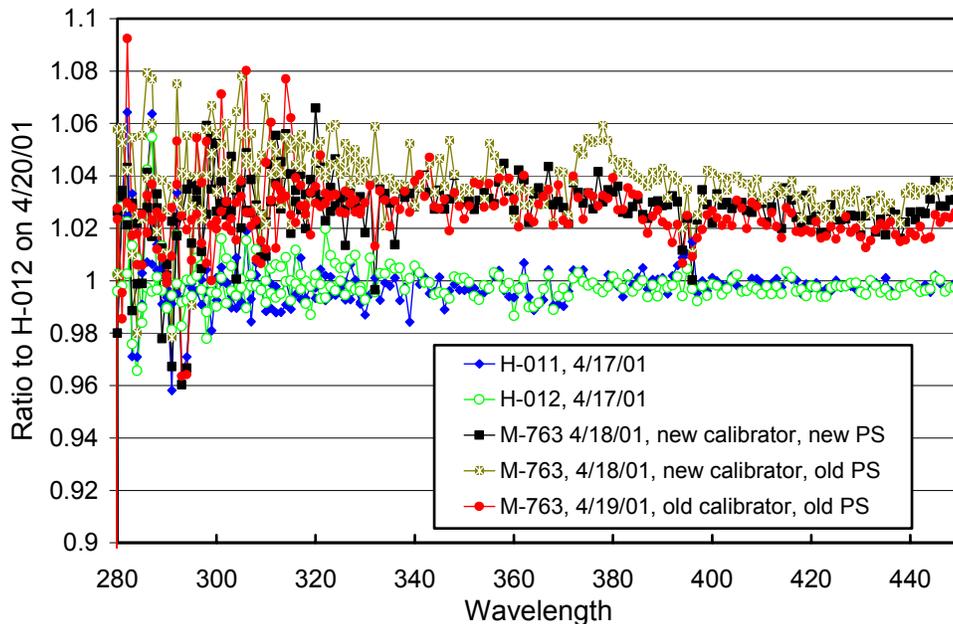


Figure 5.4. Comparison of M-763 with H-012 after M-763 had been recalibrated by Optronic Laboratories in March 2001.

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 the NIST and CUCF scale.

The 5% difference between the results of the CUCF audits in 1998 and 2000 are still unclear. As explained above, it is very unlikely that the BSI irradiance scale has drifted by 5% over two years. Similarly, Patrick Disterhoft has carefully reviewed the CUCF calibration chain and could not find an inconsistency, explaining the discrepancy. As of this writing, the problem is still under investigation.

Volume 9 solar data are based on the Optronic Laboratories irradiance scale.

Irradiance Standards used for Volume 9 Data

Table 5.3 gives an overview of the irradiance standards used in the 1999-2000 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 9, have two or more sets of calibrations. Several lamps drifted during the season. Therefore different calibrations were applied for those lamps during different periods. The traveling standard M-874 was also affected. This lamp was used at all network locations in order to validate the calibration of standards kept at sites. M-874 was in use until June 2000 and was then superseded by M-764.

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 the 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 1999-2000 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-763	BSI transfer from M-874 (Optr. 8/95); establ. 1/98‡	Optr. 3/01	-2.0%	-1.5%	-1.3%
	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				
Barrow	M-699	Optr. 9/98				
	M-762	Optr. 10/92	Optr. 9/98	+1.9%	+1.6%	+1.4%
	200W009	Optr. 9/98				
San Diego	M-881**	Optr. 9/98	BSI transfer from M-874 (Optr 10/92) establ. 4/99‡	+2.5%	+2.0%	+1.5%
	200W010**	Optr. 9/98	BSI transfer from M-874 (Optr 10/92) establ. 4/99‡	+3.5%	+1.0%	-0.5%
	200W016	BSI transfer from M-874 (Optr. 9/98); establ. 11/98‡				
	200W020**	Optr. 9/98				
	200W022	BSI transfer from M-874 (Optr. 9/98); establ. 11/98	Optr. 3/01	-0.4%	-0.4%	0.0%

* 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.

** Lamps M-881, 200W010 and 200W020 drifted significantly during the Volume 9 season, see Section 5.5 for details.

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

Azimuth Asymmetry

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 a 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 $\pm 2\%$ for all wavelengths. The implication of the modification on published solar data will be reported elsewhere. Please contact Biospherical Instruments for specific information.

Figure 5.5 shows the azimuth dependence in Volume 8 solar spectral irradiance data from South Pole Station. The effect is most pronounced at long wavelengths. At 600 nm, the oscillation has an amplitude of about $\pm 8\%$ of the daily average. At 320 nm, the variation almost disappears and is almost completely masked by variations due to clouds. The difference can be explained by the fact that radiation at 320 nm is mostly diffuse with only a small contribution from the direct sun. The position of the sun therefore only has a small influence. In contrast, radiation at 600 nm arrives almost exclusively directly from the sun. Note that the azimuth asymmetry is most evident in data when the sun is low. This is the prevailing situation at South Pole. All other network sites experience higher solar elevations than South Pole Station. Systematic errors in solar data are therefore smaller, even if instrument problem were of the same magnitude.

In Figure 5.6, time-series of spectral irradiance at 380 nm are compared with measurements of total irradiance, measured with the PSP, and readings of the TSI sensor. The period depicted is the same as in Figure 5.5. The measurements at 380 nm show less diurnal fluctuations than measurements at 600 nm, as can be expected. The center wavelength of the TSI is about 370 nm. The amplitude of the variations in the spectral measurements at 380 nm should therefore be comparable to the amplitude in the TSI readings. Figure 5.6 shows however that the variation of the TSI signal is smaller than the oscillations in spectral data. This, combined with the evidence of the two curves being out of phase, are indications that the oscillations are indeed measurement artifacts.

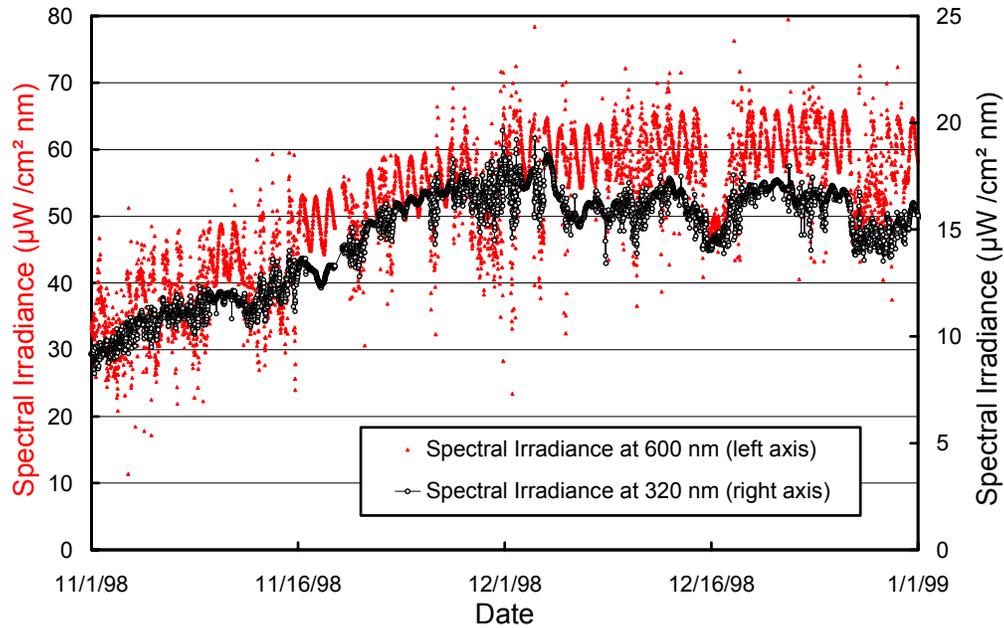


Figure 5.5. Spectral irradiance at 320 and 600 nm measured at South Pole during November and December 1998.

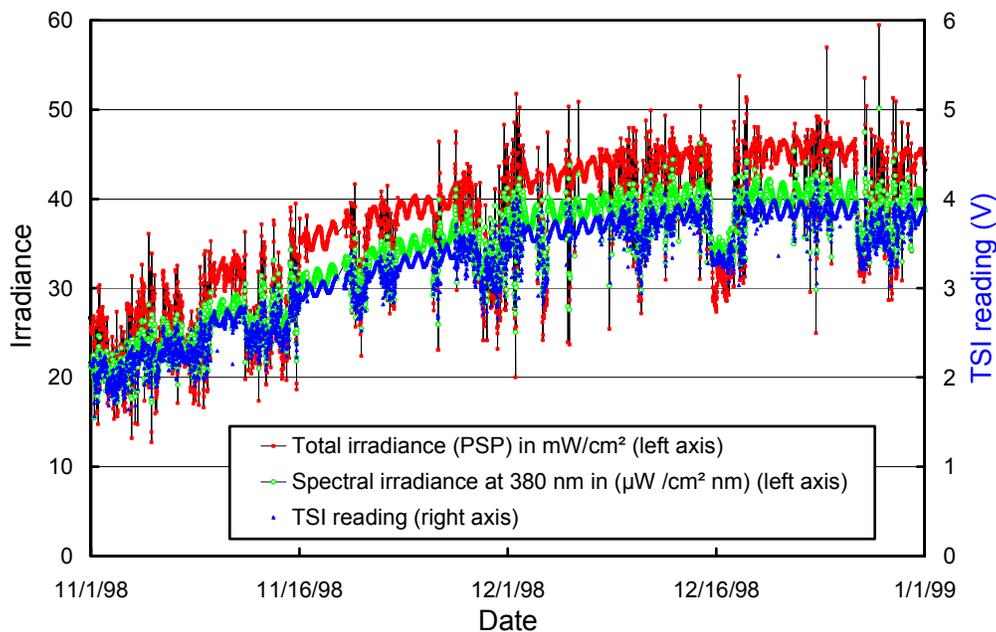


Figure 5.6. Comparison of total irradiance measured by the PSP (highest curve), spectral irradiance at 380 nm (middle curve), and TSI signals (lowest curve).

Note that also the PSP measurements show a diurnal variation of about $\pm 2.5\%$. This is surprising because the PSP is a completely independent instrument, which is not linked to the spectroradiometer's fore-optics. This indicates that the PSP may also be affected by azimuthal errors, or that it was not correctly leveled. Because of the high solar zenith angles prevailing at South Pole, small leveling errors do cause significant effects.

From Figure 5.5 and Figure 5.6 it can be concluded that UV data are affected by the azimuth asymmetry by up to $\pm 4\%$. At shorter UV-A wavelengths or at wavelengths in the UV-B the asymmetry diminishes or almost disappears. The accuracy of daily averages or daily doses is only slightly reduced, as most of the systematic errors cancel out when measurements are integrated over one day.

Final Quality Control of Level 3 Data

The quality of Level 3 data after implementation of all corrections is checked with the following protocol:

- Examination of all irradiance calibrations with 200-Watt standards. This includes intercomparisons of on-site and traveling standards as well as standards with a new calibration. If discrepancies occur, standards are recalibrated or excluded and the corrected dataset is re-processed with the modified scale of irradiance.
- With the Fraunhofer-correlation method, the wavelength accuracy is checked between 300 and 440 nm. If there are systematic wavelength shifts larger than 0.1 nm, the wavelength offsets are adjusted or modified functions used to describe monochromator non-linearity are implemented.
- Based on data from the internal irradiance and wavelength standards, and from measurements of other built-in or ancillary sensors (e.g., TSI, temperature, ground, wavelength-position sensor, PSP, and TUVB) the dataset is screened for drifts and “outliers,” requiring remedial action to be considered.
- Data of the current season are compared with data from previous years. This is done to assess system changes over time.
- On occasion, selected measured spectra are compared with results from radiative transfer models.
- The contents and format of data to be published are checked against those of the internal databases maintained at Biospherical Instruments.