Uncertainty Budget of Version 2 Data from Barrow

The total uncertainty of Version 2 data from Barrow (BAR) is composed of uncertainties related to (i) radiometric calibration and stability; (ii) cosine and azimuthal error correction; (iii) the finite resolution of the spectroradiometer; (iv) residual wavelength errors after wavelength correction; (v) non-linearity; (vi) stray light; and (vii) photon and electronic noise. All error sources have been discussed in detail by *Bernhard et al*. [2004] for the instrument located at the South Pole (SPO). Since the SUV-100 radiometers installed at BAR and SPO are virtually identical, we adopted the uncertainties of errors sources (i), (iii), (v), (vi) and (vii) reported by *Bernhard et al*. [2004] without modification for the instrument at BAR.

Uncertainties related to (iv) were recalculated and are slightly different from those of the SPO instrument. The detection limit or "noise equivalent irradiance" (NEI) was also recalculated. It varies between 0.0002 µW/(cm² nm) and 0.0007 µW/(cm² nm) for Volumes 2-9; is 0.0010 µW/(cm² nm) for Volumes 10-13; and 0.0007 for Volume 14. The reason for the elevated NEI for Volumes 10-13 is unknown.

1. Uncertainties caused by cosine and azimuthal errors

Uncertainties related to (ii) are site specific, and were recalculated based on prevailing atmospheric conditions, surface albedo, aerosol optical depths, and solar zenith angle (SZA) at BAR. Although the instrument's cosine error changed from year to year, the uncertainty of the cosine error correction is similar for all Volumes. Also the upgrade of the instrument's collector in December 2000 did not have a large impact on the cosine correction and its uncertainty. The upgrade, however, significantly reduced systematic errors in solar data caused by azimuthal errors of the previously installed collector. Up to 11/15/93, the polytetrafluoroethylene (PTFE) diffuser, which is the central part of the instrument's cosine collector, was semi-transparent at wavelengths longer than 500 nm. This led to substantial and wavelength-dependent cosine errors for $\lambda > 500$ nm, which were not corrected. Measurements of Volumes 2-4 at wavelengths above 490 nm should not be used; data at shorter wavelengths are not affected by the problem. The collector with the semi-transparent diffuser was replaced in November 1993.

1.1. Nomenclature (See *Bernhard et al*. [2004] for further information)

SZA	Solar zenith angle in degrees
λ	Wavelength in nm
f_B	Cosine error, expressed as ratio of actual and ideal cosine response
$u_R(f_B)$	Relative uncertainty of cosine error
f_D	Diffuse cosine error, defined as the error in measuring isotropic radiance
$u_R(f_D)$	Relative uncertainty of f_D
R	Ratio of irradiance from the direct solar beam on a horizontal surface to global irradiance
$u_R(f_R)$	Relative uncertainty of R
f_G	Ratio of measured global irradiance affected by the cosine error to true global irradiance
$u_R(f_G)$	Relative uncertainty of f_G
τ	Cloud optical depth at 450 nm
$\tau_A(\lambda)$	Aerosol optical depth at wavelength λ

1.2. Calculation of uncertainties caused by cosine and azimuthal errors

The cosine error f_B was estimated by comparing measured and modeled irradiance at 600 nm. The method and its limitations were described in detail by *Bernhard et al.* [2004]. The relative uncertainty of the cosine error $u_R(f_B)$ was estimated from variations of f_B in different years. For SZAs larger than 70º, the estimate of uncertainty is problematic due to the low frequency of clear sky conditions, which are required for the model-based estimation of f_B. Uncertainties in the measurement of aerosol optical depth further complicate the estimate of f_B at large SZAs with the model-based approach [*Bernhard et al*., 2004]. Uncertainties at large SZAs were partly based on estimates derived from data measured at the South Pole and at McMurdo. For Volumes 2-9, $u_R(f_B)$ was set to <1% for SZA<40º; 1.5% for SZA=50º; 2.0% for SZA=60º; 2.5% for SZA=70º; 5% for SZA=80º; and 7.3% for SZA=85º. For Volumes 10-14, $u_R(f_B)$ was set to <1% for SZA<40º; 1.5% for SZA=50º; 2.0% for SZA=60º; 2.5% for SZA=70º; 6% for SZA=80º; and 8% for SZA=85º.

The ratio of direct/global irradiance $R(\lambda)$ is also estimated from model calculations. The largest uncertainty in these calculations stems from the uncertainty of aerosol optical depth (AOD) used as input to the model. At Barrow, the average aerosol optical depth (AOD) at 500 nm is $\tau_A(500\text{nm}) = 0.09$. This number was calculated from all available measurements of Filter Wheel Normal Incidence Pyrheliometer (FWNIP), and Carter-Scott and Cimel sunphotometers performed between 1991 and 2005 (see main paper for an introduction of these instruments). In most years only FWNIP data are available. These measurements are regarded less reliable than sunphotometer measurements. When FWNIP and sunphotometers were in operation at the same time, the standard deviation of the difference of FWNIP and sunphotometer AODs was 0.03 and the average difference was 0.01. Based on these considerations, the uncertainty $u(R)$ of the direct/global ratio $R(\lambda)$ under clear skies was estimated from the difference of $R(\lambda)$ calculated for aerosol optical depths $\tau_A(500\text{nm})$ of 0.06, 0.09 and 0.12. $u_R(R)$ was calculated to 4% at SZA=50º, 5.5% at SZA=65º, 13% at SZA=80º, and 28% at SZA=85º. These values were also applied to cloudy conditions as the value of the relative uncertainty $u_R(R)$ has little impact on the overall uncertainty $u(f_G)$ when clouds reduce the direct contribution $R(\lambda)$ to near zero.

The uncertainty $u_R(f_D)$ of the diffuse cosine error f_D is mostly caused by the assumption that sky radiance is isotropic. It was estimated from model calculations of sky radiance during clear skies for a variety of atmospheric conditions and surface albedo.

Table 1 summarizes the relative uncertainty $u_R(f_G)$ of global spectral irradiance data for a variety of SZAs, wavelengths, cloud optical depths, and data volumes. The largest uncertainties apply during conditions of variable cloudiness ("τ=?") when it is not possible to determine whether or not the disk of the Sun is visible.

Uncertainties due to residual azimuthal errors in corrected data were quantified by analyzing the amplitude of periodic diurnal variations in the ratio of measurement and model during clear-sky periods. Results are presented in Table 2. The correction for azimuthal error was difficult for Volumes 2 – 4 due to the large cosine error in data of these volumes for wavelengths larger than 490 nm. Uncertainties for these volumes are comparatively high and range between 3% and 4%. Uncertainties of other volumes typically vary between 1% and 2% and tend to be larger at larger wavelengths. Uncertainties related to the azimuthal error of the instrument's collector disappear for cloudy conditions.

Table 1. Standard Uncertainty (k=1) Caused by the Cosine Error as a Function of SZA, Wavelength λ and Cloud Optical Depth τ .

				$\tau = 0$			$\tau = 0.2$			$\tau = 1.0$			$\tau = ?$
SZA [deg]	λ [nm]	f_B	f_D	R	f_G	$u_R(f_G)$	R	f_G	$u_R(f_G)$	R	f_G	$u_R(f_G)$	$u_R(f_G)$
						Volumes 2, 3, and 4							
45	310	1.00	1.000	0.23	1.000	0.6%	0.17	1.000	0.6%	0.06	1.000	0.6%	0.9%
45	400	1.00	1.000	0.51	1.000	0.7%	0.38	1.000	0.6%	0.12	1.000	0.6%	1.0%
45	600	*	*	0.82	*	*	0.61	*	*	0.20	*	*	*
70	310	1.00	1.000	0.05	1.000	0.7%	0.03	1.000	0.7%	0.00	1.000	0.7%	0.9%
70	400	1.00	1.000	0.31	1.000	0.9%	0.18	1.000	0.8%	0.02	1.000	0.7%	1.2%
70	600	*	*	0.72	*	*	0.42	*	*	0.05	1.000	*	*
80	310	1.00	1.000	0.00	1.000	0.7%	0.00	1.000	0.7%	0.00	1.000	0.7%	0.9%
80	400	1.00	1.000	0.11	1.000	0.9%	0.03	1.000	0.8%	0.00	1.000	0.7%	1.2%
80	600	*	*	0.57	*	*	0.20	*	*	0.00	1.000	*	*
85	310	1.00	1.000	0.00	1.000	0.7%	0.00	1.000	0.7%	0.00	1.000	0.7%	0.9%
85	400	1.00	1.000	0.01	1.000	0.7%	0.00	1.000	0.7%	0.00	1.000	0.7%	1.0%
85	600	*	*	0.34	*	*	0.04	*	*	0.00	1.000	*	*
						Volume 5A							
45	310	0.99	1.017	0.23	1.012	0.6%	0.17	1.013	0.6%	0.06	1.016	0.6%	0.9%
45	400	0.99	1.017	0.51	1.005	0.7%	0.38	1.008	0.7%	0.12	1.014	0.6%	1.2%
45	600	0.99	1.017	0.82	0.998	1.0%	0.61	1.003	0.8%	0.20	1.012	0.6%	1.5%
70	310	1.06	1.017	0.05	1.019	0.7%	0.03	1.018	0.7%	0.00	1.017	0.7%	1.0%
70	400	1.06	1.017	0.31	1.030	1.0%	0.18	1.025	0.9%	0.02	1.018	0.8%	1.4%
70	600	1.06	1.017	0.72	1.048	1.9%	0.42	1.035	1.3%	0.05	1.019	0.9%	2.5%
80	310	1.14	1.017	0.00	1.017	0.7%	0.00	1.017	0.7%	0.00	1.017	0.7%	0.9%
80	400	1.14	1.017	0.11	1.031	1.0%	0.03	1.022	0.8%	0.00	1.017	0.7%	1.3%
80	600	1.14	1.017	0.57	1.089	3.1%	0.20	1.043	1.7%	0.00	1.017	0.9%	4.1%
85	310	1.21	1.017	0.00	1.017	0.7%	0.00	1.017	0.7%	0.00	1.017	0.7%	0.9%
85	400	1.21	1.017	0.01	1.019	0.8%	0.00	1.017	0.8%	0.00	1.017	0.7%	1.1%
85	600	1.21	1.017	0.34	1.082	3.3%	0.04	1.025	1.4%	0.00	1.017	0.8%	4.1%
						Volumes 7 and 8							
45	310	0.98	0.963	0.23	0.966	0.6%	0.17	0.965	0.6%	0.06	0.964	0.6%	0.9%
45	400	0.98	0.963	0.51	0.970	0.7%	0.38	0.968	0.6%	0.12	0.965	0.6%	1.1%
45	600	0.98	0.963	0.82	0.974	1.0%	0.61	0.971	0.8%	0.20	0.966	0.6%	1.4%
70	310	0.91	0.963	0.05	0.961	0.6%	0.03	0.962	0.7%	0.00	0.963	0.7%	0.9%
70	400	0.91	0.963	0.31	0.948	1.0%	0.18	0.955	0.8%	0.02	0.962	0.8%	1.4%
70	600	0.91	0.963	0.72	0.928	1.8%	0.42	0.943	1.3%	0.05	0.961	1.0%	2.4%
80	310	0.86	0.963	0.00	0.963	0.6%	0.00	0.963	0.6%	0.00	0.963	0.6%	0.9%
80	400	0.86	0.963	0.11	0.952	0.9%	0.03	0.960	0.8%	0.00	0.963	0.7%	1.3%
80	600	0.86	0.963	0.57	0.905	2.9%	0.20	0.942	1.5%	0.00	0.963	0.9%	3.6%
85	310	0.82	0.963	0.00	0.963	0.6%	0.00	0.963	0.6%	0.00	0.963	0.6%	0.9%
85	400	0.82	0.963	0.01	0.962	0.8%	0.00	0.963	0.8%	0.00	0.963	0.7%	1.1%
85	600	0.82	0.963	0.34	0.916	2.8%	0.04	0.957	1.3%	0.00	0.963	0.8%	3.4%
						Volumes 5B, 6A, 6B, 9, 10, 11, 13, and 14							
45	310	0.98	0.955	0.23	0.962	0.6%	0.17	0.960	0.6%	0.06	0.957	0.6%	0.9%
45	400	0.98	0.955	0.51	0.969	0.8%	0.38	0.966	0.7%	0.12	0.959	0.6%	1.2%
45	600	0.98	0.955	0.82	0.978	1.0%	0.61	0.972	0.8%	0.20	0.961	0.6%	1.7%
70	310	0.89	0.955	0.05	0.952	0.7%	0.03	0.954	0.7%	0.00	0.955	0.7%	0.9%
70	400	0.89	0.955	0.31	0.935	1.0%	0.18	0.944	0.9%	0.02	0.954	0.8%	1.5%
70	600	0.89	0.955	0.72	0.907	1.9%	0.42	0.928	1.4%	0.05	0.952	1.1%	2.8%
80	310	0.78	0.955	0.00	0.955	0.7%	0.00	0.955	0.7%	0.00	0.955	0.7%	0.9%
80	400	0.78	0.955	0.11	0.937	1.0%	0.03	0.949	0.9%	0.00	0.955	0.7%	1.5%
80	600	0.78	0.955	0.57	0.855	3.5%	0.20	0.920	2.0%	0.00	0.955	1.0%	5.0%
85	310	0.69	0.955	0.00	0.955	0.7%	0.00	0.955	0.7%	0.00	0.955	0.7%	0.9%
85	400	0.69	0.955	0.01	0.952	0.8%	0.00	0.955	0.8%	0.00	0.955	0.7%	1.2%
85	600	0.69	0.955	0.34	0.866	3.8%	0.04	0.945	1.7%	0.00	0.955	0.9%	5.0%

* Data from Volumes 2-4 with wavelengths larger than 490 nm have a large cosine error and should not be used.

Table 2. Standard Uncertainty (k=1) of Residual Azimuthal Errors.

Volume	Period	Relative Uncertainty		
		330 nm	400 nm	590 nm
2	Jan 91 - Nov 91	2.7%	4.2%	–[a]
3	Nov 91 - Nov 92	2.9%	2.9%	–[a]
4	Jan 93 - Nov 93	4.2%	4.2%	–[a]
5A	Jan 94 - Jun 94	1.8%	1.8%	4.3%
5B	Jun 94 - Oct 95	2.1%	2.8%	2.9%
6A	Oct 95 - Jun 96	0.7%	0.7%	1.8%
6B	Jun 96 - Oct 97	0.9%	2.1%	?[b]
7	Oct 97 - Aug 98	0.5%	1.1%	1.3%
8	Aug 98 - Nov 99	0.7%	0.7%	0.7%
9	Nov 99 - Nov 00	0.7%	1.0%	1.6%
10	Jan 01 - Oct 01	0.4%	0.4%	1.5%
11	Oct 01 - Nov 02	1.8%	1.8%	1.8%
13	Jan 03 - Mar 04	0.7%	1.1%	1.3%
14	Mar 04 - May 05	0.9%	0.7%	0.4%
Average Volumes 2 – 4		**3.3%**	**3.8%**	**–[a]**
Average Volumes 5A – 14		**1.0%**	**1.3%**	**1.7%**

[a] Volume affected by large cosine error for wavelengths larger than 490 nm
[b] Determination uncertain

2. Combined uncertainty

The combined uncertainty of Version 2 data for Barrow is presented in Table 3. Expanded relative uncertainties (coverage factor k=2, equal to uncertainties at the 2σ-level) vary between 4.8% and 11.4%). For Volumes 2–4, expanded uncertainties of spectral irradiance at 310 nm range between 6.4% and 9.2% and are dominated by uncertainties related to calibration, stability, wavelength errors and unexplained diurnal variations at short wavelengths (listed as azimuth errors in Table 3), which contribute to the uncertainty at large SZAs. For Volumes 5A – 14, expanded uncertainties of spectral irradiance at 310 nm range between 6.4% and 6.8%. Data of several periods have larger uncertainties than indicated above. See document Increased_uncertainty.pdf for details.

At larger wavelengths, the greatest uncertainty arises from insufficient knowledge of the contribution of direct irradiance to global irradiance. This is a problem particularly during periods of varying cloudiness when it is difficult to determine whether the cosine correction factor for clear or overcast sky should be applied. The uncertainty budget presented in Table 3 therefore distinguishes between the cases of "clear-sky", "overcast" and "unknown sky condition". Expanded uncertainties for spectral irradiance at 600 nm range between 4.8% for overcast conditions and 11.4% for periods with variable cloudiness and large SZA. Expanded uncertainties for erythemal irradiance (i.e. spectral irradiance weighted with the CIE action spectrum for sunburn [*McKinlay and Diffey*, 1987]) and DNA-damaging irradiance (action spectrum by *Setlow* [1974]) vary between 5.8% and 6.6% (5.8% – 9.2% for Volumes 2–4), and are only slightly influenced by sky condition.

Table 3. Uncertainty Budget of Version 2 Data Barrow.

Error source	Relative Standard Uncertainty in %									
	SZA=45°					SZA=80°				
	310 nm	400 nm	600 nm	Ery[a]	DNA[a]	310 nm	400 nm	600 nm	Ery[a]	DNA[a]
Calibration, stability	2.7	2.1	2.1	2.7	2.7	2.7	2.1	2.1	2.7	2.7
Spectral Resolution	0.8	0.0	0.0	0.3	0.9	0.8	0.0	0.0	0.3	0.9
λ- shift in UV-B	0.9	0.0	0.0	0.4	0.9	0.9	0.0	0.0	0.4	0.9
λ- shift + Fraunh. lines	0.4	0.3	0.1	0.0	0.0	0.4	0.3	0.1	0.0	0.0
Non-linearity	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Stray light	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Noise	0.7	0.4	0.4	0.1	0.3	0.7	0.4	0.4	0.1	0.3
Additional uncertainties for clear-sky conditions, Volumes 2-4										
Cosine error	0.6	0.7	-	0.6	0.6	0.7	0.9	-	0.7	0.7
Azimuth error	1.0	1.0	-	1.0	1.0	3.3	3.8	-	3.3	3.3
Combined uncertainty	3.3	2.5	-	3.0	3.3	4.6	4.5	-	4.4	4.5
Expanded uncertainty (k=2)	**6.6**	**5.0**	-	**6.0**	**6.6**	**9.2**	**9.0**	-	**8.8**	**9.0**
Additional uncertainties for clear-sky conditions, Volumes 5A-14										
Cosine error	0.6	0.8	1.0	0.6	0.6	0.7	1.0	3.5	0.7	0.7
Azimuth error	1.0	1.3	1.7	1.0	1.0	1.0	1.3	1.7	1.0	1.0
Combined uncertainty	3.3	2.7	3.0	3.0	3.3	3.3	2.8	4.5	3.0	3.3
Expanded uncertainty (k=2)	**6.6**	**5.4**	**6.0**	**6.0**	**6.6**	**6.6**	**5.6**	**9.0**	**6.0**	**6.6**
Additional uncertainties for overcast conditions, Volumes 2-14										
Cosine error	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Combined uncertainty	3.2	2.4	2.4	2.9	3.2	3.2	2.4	2.4	2.9	3.2
Expanded uncertainty (k=2)	**6.4**	**4.8**	**4.8**	**5.8**	**6.4**	**6.4**	**4.8**	**4.8**	**5.8**	**6.4**
Additional uncertainties if sky condition is unknown, Volumes 2-4										
Cosine error	0.9	1.0	-	0.9	0.9	0.9	1.0	-	0.9	0.9
Azimuth error	1.0	1.0	-	1.0	1.0	3.3	3.8	-	3.3	3.3
Combined uncertainty	3.4	2.6	-	3.1	3.3	4.6	4.5	-	4.4	4.6
Expanded uncertainty (k=2)	**6.8**	**5.2**	-	**6.2**	**6.6**	**9.2**	**9.0**	-	**8.8**	**9.2**
Additional uncertainties if sky condition is unknown, Volumes 5A-14										
Cosine error	0.9	1.2	1.7	0.9	0.9	0.9	1.5	5.0	0.9	0.9
Azimuth error	1.0	1.3	1.7	1.0	1.0	1.0	1.3	1.7	1.0	1.0
Combined uncertainty	3.4	2.8	3.3	3.1	3.3	3.4	3.0	5.7	3.1	3.3
Expanded uncertainty (k=2)	**6.8**	**5.6**	**6.6**	**6.2**	**6.6**	**6.8**	**6.0**	**11.4**	**6.2**	**6.6**

[a]Ery, erythemal irradiance; DNA, DNA damaging irradiance. On the basis of individual uncertainties, a combined uncertainty was calculated and multiplied with a coverage factor of 2 in accordance with *ISO* [1993] guidelines. These final uncertainties are the quintessence of the uncertainty budget and are therefore printed in boldface.

References

Bernhard, G., C.R. Booth, and J.C. Ehramjian (2004), Version 2 data of the National Science Foundation's Ultraviolet Radiation Monitoring Network: South Pole, *J. Geophys. Res*., *109*, D21207, doi:10.1029/2004JD004937.

International Standards Organization (ISO) (1993), *Guide to the Expression of Uncertainty in Measurements*, ISO, Geneva, Switzerland.

McKinlay, A.F. and B.L. Diffey (Eds.) (1987), A reference action spectrum for ultraviolet induced erythema in human skin, in: *Commission International de l'Éclairage (CIE), Research Note*, *6*(1), 17-22.

Setlow, R. B. (1974), The wavelength in sunlight effective in producing skin cancer: a theoretical analysis, *Proc. Natl. Acad. Sci. U.S.A., 71*(9), 3363-3366.