Investigations of Pre- and Post- Flight Radiometric
Calibration Uncertainties from Surface Based Measurements

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ABSTRACT

Historically SBUV type ozone sounding instruments such as NOAAIS TIROS-N SBUV-2 and the NASA space shuttle SSBUV instruments have used the panel diffuser technique to derive a spectral radiance calibration scale. This scale is based upon a measurement of the scattering properties (BRDF) of a panel diffuser illuminated by a NIST standard of spectral irradiance which is also used for the irradiance calibration. Since 1992 SBUV-2 flight models 2, 5, and 6, the SSBUV and GOME instruments have used an alternate spectral radiance calibration technique based upon an internally illuminated spherical integrator. The accuracy of radiometric calibrations made with the sphere technique has been evaluated through a series of surface based direct sun Langley observations and zenith sky Umkehr observations between SBUV-2 flight models 2, 3, 5, and 6 and the SSBUV instrument against Dobson instruments 83 and 61 in Boulder. The surface based direct sun observations using SBUV-2 and SSBUV instruments yield total ozone values which are 2% larger than those from the Dobson instruments and satellite overpass values from the TOMS instrument. These higher total ozone values are consistent with those obtained with the recent calibration adjustment of a SBUV-2 test data set by the SSBUV instrument using a sphere derived radiance calibration of the SSBUV instrument. Subsequent reductions in bias between a test data set of ozone profiles from the NOAA-11 SBUV-2 and SAGE instruments were observed when the NOAA-11 SBUV-2 instrument was recalibrated by the SSBUV instrument which used a sphere based radiance calibration scale. A previously observed altitude dependent bias relative to SAGE II which varied from 0 to 15% with increasing altitude was reduced to a random bias of less than 3%. A new inversion technique has been implemented for the determination of total ozone from zenith sky umkehr observations. Total ozone inferred from Dobson A-pair wavelengths is about 4% higher than coincident direct sun values obtained with Dobson instrument No. 83. If Dobson AD double wavelength pairs are used, the zenith sky bias is reduced to 1%. A series of Langley plot direct sun observations was inverted to obtain aerosol optical depths at four wavelengths from 318 to 406 nm. An average value of 0.184 was observed on September 8, 1982 with no measurable wavelength dependence.

1. INTRODUCTION

Inversions of ozone profiles and total column are derived from measurements of ultra-violet solar spectral irradiances incident at the top of the atmosphere and resultant atmospheric radiances scattered back into space in the wavelength range of 250 to 340 nm which encompass the spectral regions of ozone absorption by the Hartley and Huggins bands. In order to decrease errors in the ratios of measured atmospheric radiances and solar irradiances the radiometric calibration scales have been tied to the NIST 1000 W quartz-tungsten filament halogen spectral irradiance standards. Initially spectral radiance calibrations were derived from the calculated spectral radiance of a panel diffuser with measured scattering properties (BRDF) which is illuminated by a NIST 1000 W QTH spectral irradiance standard. Since 1990 spectral radiance calibrations of the space-borne ozone monitoring instruments have also been obtained using the internally illuminated spherical integrator technique. This technique yields the spectral radiance of the aperture in terms of its spectral irradiance which is measured relative to a NIST 1000 W QTH spectral irradiance standard provided that the aperture radiates as a uniform Lambertian source over the FOV of the instrument whose spectral radiance sensitivity is to be determined.

Since the very earliest days of the BUV instrument measurements of total ozone from the Nimbus 4 satellite which began in 1970, the satellite observations have provided total column ozone amounts which were larger than the direct sun observations from the network of Dobson instruments. The observations from space which have often been referred to as inverted umkehr observations are compared to the fundamentally different direct sun or Langley plot determination of total column amounts. Over the years fundamental unresolved questions have arisen concerning the BUV, SBUV, SSBUV and TOMS biases of Dobson station overpass total ozone determination with those from the surface based Dobson instruments. Two questions which have persisted are whether the total ozone biases are the result of different observational techniques and whether or not the biases are solar zenith angle dependent, i.e., dependent upon station latitude.

2. SPECTRAL RADIANCE CALIBRATION TECHNIQUES

Since 1990 two spectral radiance calibration techniques have been used in the radiometric calibration of SBUV-2 flight models 2 and subsequently models 3, 5 and 6. The radiometric scale of the panel diffuser and internally illuminated spherical integrator techniques are tied to the radiometric scale of NIST's 1000 W quartz tungsten (QTH) filament halogen FEL lamp spectral irradiance standards.

For the panel diffuser technique, the average spectral radiance (L_λ) of the flatplate Spectralon diffuser illuminated by standard of spectral irradiance (E_λ) in the direction of the SBUV-2 observation is given by

$$L_\lambda = E_\lambda \cos\theta \overline{\text{BRDF}} w(x, y) f(x, y) \quad (1)$$

which is integrated over the field-of-view of the viewing instrument, where

E_λ is the spectral irradiance of the NIST standard;
 θ is the angle of illumination of the diffuser with respect to the normal;
 $w(x, y)$ is the correction for off-axis illumination including vignetting effect;
 $f(x, y)$ is the goniometric variation of the spectral irradiance standard over the projected area of the SBUV-2 instrument on the Spectralon diffuser;
 $\overline{\text{BRDF}}$ is the average value of the BRDF of the Spectralon diffuser in the instrument field-of-view.

The principle source of uncertainty with this technique is associated with the measurement uncertainty of the BRDF of the panel diffuser.

The use of an internally illuminated spherical integrator to provide a known spectral radiance of the aperture of the sphere is based upon a measurement of the spectral irradiance of the aperture of the sphere against a NIST 1000 W QTH FEL lamp standard of spectral irradiance. The spectral radiance of the aperture is calculated using the equation of heat transfer theory for a uniform Lambertian whose spectral irradiance has been measured.

The spectral radiance of the aperture is given by

$$L_\lambda = E_\lambda (d^2 + r_1^2 + r_2^2) / \pi r_1^2 = E_\lambda G^{-1}(d, r_1, r_2) \quad (2)$$

where

E_λ is the spectral irradiance;
 L_λ is the spectral radiance;
 r_1 is the radius of the source aperture
 r_2 is the radius of the detector aperture of a circle with area of the projected SBUV-2 FOV on the Spectralon diffuser;
 d is the distance between the two aperture.

A principle source of uncertainty arises from scattered light which illuminates the panel diffuser which is used to transfer the spectral irradiance scale from the NIST standard to the irradiance of the aperture of the sphere.

Details of comparisons of the panel diffuser and spherical integrator techniques have been given in previously published works by Heath et al., 1993, 1994a, 1994b and 1994c, and Janz et al., 1995.

During 1992 and 1993 the spectral radiance calibration scale of the SSBUV instrument derived with the panel diffuser technique which was based upon NIST BRDF measurements was compared with sphere derived spectral radiance scales for the SSBUV measurement and SBUV-2 flight models 2, 3, 5 and 6. The results of those intercomparison of spectral radiance and irradiance calibration scales indicated that the SSBUV spectral radiance calibration scale based upon the panel diffuser technique was about 7.8% higher than that derived with the sphere technique. Furthermore the uncertainty in the sphere derived spectral radiance calibration scales of the SSBUV and SBUV-2 flight models 2, 3, 5 and 6 were less than 2% over the wavelength range of 250 to 340 nm. The uncertainty in the spectral irradiance calibration scales among these instruments was on the order of 1%. A detailed description of this work is given in the paper by Heath et al., 1994c.

A consequence of this is that the SSBUV instrument measures spectral radiances which are higher than those measured by the SBUV-2 flight model 5 which is on NOAA-14, and consequently the derived ozone profiles will be lower than those from the SBUV-2 flight model 5 operating on the NOAA-14 satellite.

It is becoming increasingly apparent that one cannot assume that the pre-launch radiometric calibration scales for the Nimbus 7 SBUV instrument the Space Shuttle SSBUV instrument and the SBUV-2 instruments on the NOAA TIROS-N series are equivalent prior to the incorporation of the sphere derived spectral radiance calibration scale. Observed differences in spectral radiance calibration scales could affect the assumptions made (E. Hilsenrath et al. 1992) concerning the initial calibration of the SBUV instrument and the recalibration of SBUV-2 instruments in space by the SSBUV instrument using the panel diffuser radiance calibration technique. The current status of the SBUV-2 instrument calibration and data sets is given in Table 1.

Table 1. Status of SBUV-2 Instrument Calibration and Data

<u>Satellite</u>	<u>Calibration</u>	<u>Date Status</u>
NOAA-9	NIST BRDF	V6 NOAA Archive
NOAA-11	NIST BRDF	V6 NOAA Archive
NOAA-9	NASA Sphere and SSBUV	V7 Being Processed
NOAA-11	NASA Sphere and SSBUV	V7 Being Processed
NOAA-14	NASA Sphere	V6 NOAA Archive

3. SURFACE BASED DIRECT SUN COMPARISON MEASUREMENTS BETWEEN SBUV-2, SSBUV AND DOBSON INSTRUMENT NO. 83

During the period between April 1990 and October 1992 a total of 9 days of direct sun Langley type observations were made using SBUV-2 flight models 2, 3, 5 and 6 and the SSBUV instrument coincident with corresponding measurements with NOAA's Dobson instruments No. 83 (world standard) and 61 in Boulder, Colorado. The SBUV-2 and SSBUV observations were made from a clean room solarium at Ball Aerospace which is about 1.5 km from the Dobson instruments.

The SBUV-2 and SSBUV instruments were operated with a mechanical baffle which restricted the total instantaneous field of view to 2.7 deg. Tracking of the sun was done manually, and direct sun observations were made in the solar irradiance mode where the instruments view a solar illuminated diffuser. The SBUV-2 and SSBUV instruments were programmed to make measurements at SBUV, Dobson and Brewer wavelengths sequentially. In this work we report on those made at the Dobson wavelengths. The Dobson wavelengths are: A-pair, 305.5 and 325.4 nm; C-pair, 311.5 and 332.4 nm; D-pair, 317.6 and 339.8 nm. The observations are compared in terms of N-values which are used in the algorithms for the calculation of total ozone and profiles.

$$N = L_0 - L$$

where $L_0 = \log_{10}(I_0 / I'_0) + k$ and $L = \log_{10}(I / I')$ where the prime denotes the long wavelength member of the pair and the subscript 0 refers to the extraterrestrial solar irradiance. The irradiances or radiances (denoted by I) without a subscript refer to the measured radiation at the surface. Total column ozone values are calculated from direct sun observations using double wavelength pairs in order to minimize aerosol effects. The Dobson instrument incorporates an instrument calibration constant k which is derived from extrapolation of Langley plots to zero air mass. The algorithm used to derive total column ozone from direct sun observations and the determination of the extraterrestrial solar irradiance and instrument constant k is discussed extensively by Komhyr et al. 1989.

The extraterrestrial constant L_0 , for the SBUV-2 and SSBUV instruments is calculated from the extraterrestrial solar irradiance measurements made with the SSBUV instrument. The values of SSBUV-3 for 2 September 1992 solar irradiances were used (private communication, R. Cebula). Correction factors for extraterrestrial solar irradiances were calculated from direct sun Langley plots using the technique described by Komhyr et al., 1989. A consistent correction factor could not be determined from the SBUV-2 and SSBUV observations because the statistical sample was too small.

Comparisons of N-values for direct sun observations between SBUV-2 flight model 5 (NOAA-14 instrument) and Dobson No. 83 are shown in Figure 1 for A, C, and D Dobson wavelength pairs. In general for all the direct sun comparison observations the N-values for A-pair wavelengths from the SBUV-2 and SSBUV instruments are slightly higher than for the Dobson No. 83 instrument. For D-pair wavelengths the differences are in closer agreement.

Figure 1. Comparison of N-values for A, C, and D Dobson wavelength pairs between SBUV-2 flight model 5 and Dobson No. 83.

Consequently, the SBUV-2 and SSBUV instrument observations yield total column amounts from the A-D double wavelength pair which are slightly higher than those from Dobson instruments Nos. 83 and 61. Examples of these comparisons are shown in Figures 2 and 3. The average AC, CD, and AD total ozone values in Figure 2 are 253.7, 253.8 and 253.7 DU whereas those from Dobson AD wavelengths are 249.5 DU from No. 83 and 249.4 DU from No. 61. The TOMS overpass value (version 7) is 246.7 DU. The corresponding average total ozone values from the SSBUV and Dobson instruments for Figure 3 are 306.1, 303.5 and 305.3 DU AC, CD, and AD wavelengths from SSBUV, and 297.3 for No. 83 and 296.8 for No. 61. The corresponding TOMS overpass value is 303 DU for version 7.

A summary of the average of total ozone values from the nine direct sun comparisons compared with the corresponding averages from the Dobson Instruments 83 and 61 and the TOMS overpass averages for versions 6 and 7 is given in the upper half of Table 2. The percent differences from Dobson 83 AD double wavelength pairs are given in the lower half of this table. The indications are clear that the SBUV-2 and SSBUV instruments yield AD double wavelength pair total ozone values which are about 2% higher than the corresponding total ozone values from Dobson Instruments No.'s 83 and 61 and the TOMS version 6 and 7 overpass values. Figures 2 and 3 also show negligible change in the bias with air mass or solar zenith angle between the SBUV-2 and SSBUV direct sun values of total zone and those from the Dobson instruments. This constant bias is characteristic of all nine series of direct sun observations.

Other sources of evidence that the TOMS version 7 ozone values are slightly too low comes from large numbers of average coincident measurements between SSBUV space shuttle flights 1-5 using a sphere derived radiance scale and TOMS version 7 coincident data. On the average the TOMS ozone values are 1.4% lower than those derived from coincident SSBUV

Figure 2. Total ozone from direct sun observations for AC, CD and AD double wavelength pairs from SBUV-2 compared with Dobson No. 83 and 61 AD double wavelength pairs.

Figure 3. Total ozone from direct sun observations using AC, CD, and AD double wavelength pairs for SSBUV compared with Dobson No.'s 83 and 61 using AD double wavelength pair.

Table 2.

Average Total Ozone Comparisons (DU) for 9 Days and TOMS Overpass Values

	SBUV-2, SSBUV	Dobson 61	Dobson 83	TOMS Overpass
X_{ac}	284.9			
X_{cd}	284.7			
X_{ad}	284.3	279.2	278.3	
V_6				278.4
V_7				279.3

Difference (%) from Dobson 83 X_{ad} Values

	SBUV-2, SSBUV	Dobson 61	TOMS Overpass
X_{ac}	+ 2.4		
X_{cd}	+ 2.3		
X_{ad}	+ 2.2	- 0.3	
V_6			+ 0.04
V_7			+ 0.4

measurements. Analysis of Nimbus SBUV continuous scan data used to derive total ozone between 20°S and 20°N and 40°N during the period of 1979-1986 indicate that the TOMS version 7 ozone data are about 3% lower (Joiner et al., private communication).

The evidence to date derived from ultraviolet measurements other than Dobson suggests that the TOMS version 7 data are low by about 2% while the TOMS data are in good agreement with the Dobson data. The exception to this is the reported bias between Brewer and Dobson measurements. Results from Kerr et al. (1988) indicate that on the average the Dobson direct sun measurements are between 2 to 4% higher than those from the Brewer. Comparisons of infrared and Dobson total ozone measured from Lauder, New Zealand yielded infrared values which were 4% lower to 2% higher with the lower wavenumber bands yielding lower total ozone (Rinsland et al., 1996).

4. ZENITH SKY UMKEHR N-VALUE COMPARISONS

Whereas the N-value comparisons between SBUV-2 and SSBUV direct sun comparison with Dobson No. 83 and 61 differed by only 1 to 2 units for A, C, and D wavelength pairs, the N-value differences observed in the 11 zenith sky umkehr comparisons were substantially larger. An example of the measured N-values for C-pair wavelengths which are used in the ozone profile inversion of umkehr data is shown in Figure 4 for SBUV-2 flight model 5, SSBUV and Dobson No's 83 and 61. The SBUV-2 and SSBUV measured N-values are nearly equal whereas they are about 15 units higher than those measured by instrument No. 83 and about 7 units higher than those measured by instrument No. 61. Similar N-value comparisons have been made for A-pair and D-pair observations. For the A-pair N-values the differences the SBUV-2 and SSBUV instrument with Dobson 83 are essentially zero for solar zenith angles from 90° to 77° but then begin to diverge with decreasing solar zenith angle. At 60° Dobson No. 83 N-values are lower by about 3.5 units. The Dobson D-pair N-values are lower by approximately 8 units independent of solar zenith angle. These relatively large differences in N-values between the surface based measurements with SBUV-2 and SSBUV instruments and the Dobson instruments are not too serious since the umkehr inversion algorithm uses N-values which are normalized to a solar zenith angle of 60° .

Figure 4. C-pair N-value comparison between SBUV-2 flight model 5, SSBUV, and Dobson No. 61 and 83 for zenith sky umkehr observations.

The small solar zenith angle dependence in the differences between the A, C, D pair N-values between the SBUV-2 and SSBUV and Dobson instruments in both the direct sun Langley type and zenith sky umkehr observations suggests that scattered light is not a significant problem since the range in solar irradiances is about 10^3 and for zenith sky radiances it is about 10^4 .

5. CHANGE IN PROFILE BIAS BETWEEN SBUV-2 AND SAGE II OZONE DATA

A special data set of SBUV-2 NOAA-11 profile data was created which was subsequently recalibrated by the SSBUV instrument incorporating the sphere derived spectral radiance calibration. The profile differences of the selected data set of archived NOAA-11 SBUV-2 data and SAGE II are shown in Figure 5. A strong altitude dependent bias is observed which increases with increasing altitude. At umkehr layer 9 the SBUV-2 ozone values are about 12% less than those from SAGE II.

Figure 5. Ozone profile bias between a selected data set of NOAA-11 SBUV-2 data and SAGE II.

The effect of recalibration of the NOAA-11 SBUV-2 instrument by the SSBUV instrument using a sphere derived spectral radiance calibration which yields spectral radiances which are about 7% lower than those derived with the panel diffuser technique (NIST BRDF measurements) is shown in Figure 6. The NOAA-11 SBUV-2 spectral data when corrected by the SSBUV instrument using a sphere derived radiometric calibration scale has reduced the altitude dependent bias with SAGE II to a random bias of about 3%.

Figure 6. Change in ozone profile bias between a selected data set of achieved NOAA-11 SBUV-2 data and SAGE II after recalibration by SSBUV using a sphere derived radiometric calibration scale.

6. ZENITH SKY TOTAL OZONE

A new ozone inversion has been developed by Ahmad and Heath for the determination of total ozone from zenith sky umkehr measurements made with the SBUV-2 and SSBUV instruments. The derived total ozone values for Dobson A-pair and the AD double wavelength pair relative to the corresponding direct sun AD double wavelength pair values from Dobson instrument No. 83 are shown in Figure 7 for all umkehr measurements. The A-pair ozone values are about 4% higher than the corresponding direct sun values, and the AD double wavelength pairs are about 1% higher which is apparently the result of eliminating the aerosol effect. The use of double wavelength pairs in the zenith sky observations is analogous to the use of double wavelength pairs in direct sun observations which is used to eliminate the effect of aerosols.

Figure 7. Comparison of single and double wavelength pair total ozone values derived from zenith sky measurements from SBUV-2 and SSBUV instruments with direct sun observations from the world standard Dobson instrument No. 83.

7. DETERMINATION OF AEROSOLS FROM DIRECT SUN MEASUREMENTS

The direct sun observations obtained with the SSBUV instrument on September 8 have been used to derive aerosol optical depths at 318, 332, 340 and 406 nm from Langley plots. The slope of linear fits to the data shown in Figure 8 are assumed to consist of a total optical depth which is made up of ozone absorption, Rayleigh scattering for a pressure of 834 mb (Boulder) and aerosol optical depths. Using Dobson instrument No. 83 direct sun determinations of total ozone yields an average aerosol optical depth of 0.184 ± 0.002 which is independent of wavelength from 318 to 406 nm.

Figure 8. Langley plots of direct sun irradiances on September 8, 1992 used to derive aerosol optical thicknesses.

8. SUMMARY AND CONCLUSIONS

A series of 20 surface based direct sun Langley type and zenith sky umkehr observations using SBUV-2 and SSBUV flight models when compared with coincident observations with the world standard Dobson instrument in Boulder have shown the following:

- a) Direct sun observations with SBUV type instruments yield total ozone amounts about 2% higher than the world standard Dobson instrument No. 83. This is similar to the bias in space borne measurements made with SBUV type instruments.
- b) The bias is not dependent on solar zenith angle.
- c) No evidence is found for significant effects of out-of-band scattered light effects based upon negligible solar zenith angle dependence in direct sun and zenith sky N-value comparisons.
- d) The use of sphere derived spectral radiance calibrations removes the altitude dependent bias between SBUV-2 and SAGE II ozone profiles.
- e) Total ozone value can be derived from zenith radiance measurements using Dobson AD double wavelength pairs which are within 1% of the value derived from direct sun observations with Dobson No. 83.
- f) The SSBUV and SBUV-2 instruments can be used to derive aerosol optical depths from direct sun Langley plot observations.

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