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Observations of the solar irradiance in the 200-350 nm interval during the ATLAS-1 mission: a comparison among three sets of measurements - SSBUV, SOLSPEC, and SUSIM

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Abstract. The SOLSPEC, SSBUV, and SUSIM spectrometers simultaneously observed the solar spectral irradiance during the ATLAS-1 mission flown on board the Space Shuttle Atlantis in March 1992. The three instruments use different methods and means of absolute calibration and were each calibrated preflight and postflight. The three data sets are reported from 200 to 350 nm at 1.1 nm resolution. The method of comparing the three independent data sets is discussed. The importance of a common, precise wavelength scale is shown when comparing the data in wavelength regions of strong Fraunhofer lines. The agreement among the solar irradiance measurements is better than ±5%. The fact that the calibrations of the three instruments were based on three independent standards provides confidence that the absolute solar spectral irradiance in the range 200-350 nm is now known with an accuracy better than ±5%. The mean ATLAS-1 solar spectrum is compared with simultaneous solar observations from the UARS SOLSTICE and UARS SUSIM instruments. The two mean solar spectra agree to within ±3%.

Introduction

Solar spectral irradiance data and its changes, particularly in the middle and near ultraviolet (UV) are needed for photochemical studies and understanding the thermal structure, dynamics, and energy budget of the earth's atmosphere. As a result of molecular and aerosol scattering and, to a lesser extent, absorption by trace gases, approximately 50% of the extraterrestrial irradiance in the region between 300 and 400 nm reaches the Earth's surface. Shortward of 300 nm the solar irradiance is strongly absorbed by ozone and molecular oxygen. Tracking solar irradiance changes at these wavelengths can therefore best be done above the Earth's atmosphere. The Upper Atmospheric Research Satellite (UARS) and the ATLAS Space Shuttle missions each carried multiple instruments to measure the extraterrestrial solar irradiance. The two spacecrafts' instruments complemented each other in that the UARS instruments were designed to monitor the sun over time, while the ATLAS instruments were designed to perform periodic checks of the UARS (and other satellite) instruments each time an ATLAS mission was conducted.

In this paper we compare simultaneous ATLAS-1 solar spectral irradiance observations from the Solar Spectrum (SOLSPEC), the Shuttle Solar Backscatter Ultraviolet (SSBUV), and the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) instruments obtained on 29 March 1992. The three ATLAS instruments' solar spectral irradiance measurements are first compared to one another and then the average of the ATLAS data is compared to simultaneous data taken by the UARS Solar Stellar Irradiance Comparison Experiment (SOLSTICE) and UARS SUSIM instruments [*Rottman et al.*, 1993; *Brueckner et al.*, 1993]. This paper complements the results given by *Woods et al.* [1996], where the UARS solar irradiance data are validated by direct comparison and by using SSBUV and SUSIM data from ATLAS-1 and -2.

Observing the sun in the UV is complicated by instrument degradation caused by the damaging space environment and the difficulty in achieving an accurate absolute calibration. In earlier comparisons [*Heath*, 1980; *Mount and Rottman*, 1985; *Nicolet*, 1989; *Lean*, 1991], differences among the measurements were as large as 20% in the middle UV. It is now well known that both solar rotation and solar cycle variability are significantly lower, typically 7-9% at 200 nm, and, except for isolated absorption features, decrease with increasing wavelength [*Lean*, 1991]. The accuracy of solar irradiance measurements has significantly improved during the last two decades. We are now at the point at which the accuracies of the primary standards are no longer negligible with respect to other sources of measurement uncertainty. A unique aspect of the solar observations reported here is that the three spectrometers have different designs, are calibrated with different methods, and employ three different absolute standards. This comparison therefore can determine if the measured absolute irradiance data are consistent. If so, then the absolute value of solar spectral irradiance in the middle UV can be established with much improved confidence.

SOLSPEC

The Shuttle SOLSPEC instrument first flew in 1983 on the Spacelab-1 mission [*Labs et al.*, 1987] and has since flown on the three ATLAS missions. A companion SOLSPEC experiment also flew on the European Space Agency's EURECA platform from August 1992 to May 1993. The instrument was described by *Thuillier et al.* [1981]. SOLSPEC observes from 200 to 3000 nm using three similar double monochromators. The UV spectrometer (200-350 nm) has 1.1 nm bandpass, steps in 0.4 nm increments, and its wavelength positioning, determined from metrology of the grating drive mechanism, is about ±0.01 nm. SOLSPEC incorporates diffusers in front of each entrance slit to minimize the impact of any pointing offset. The UV spectrometer uses a photomultiplier tube (PMT) as its detector. The experiment includes calibration lamps to monitor the responsivity and the spectral characteristics of the optics in space and on the ground. Two deuterium (D_2) lamps were periodically activated to check the spectrometer's radiometric sensitivity. Seven emission lines from a Cu-He hollow cathode lamp were used to monitor the wavelength scale and the instrument slit function. For the 28 spectra used to construct the mean SOLSPEC

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spectrum, the stability of the wavelength scale, determined using the 280 nm Mg II line profile, was found to be ±0.02 nm.

The Heidelberg Observatory blackbody is used as the irradiance source for the SOLSPEC radiometric calibration. The windowless blackbody is heated to approximately 3050 K and its temperature is measured periodically using a pyrometer with an accuracy of ±6 K, including the pyrometer calibration error. The blackbody's irradiance is calculated using Planck's law and the instrument's responsivity determined from the instrument counts recorded when observing the cavity under the same solid angle as is used to view the sun. The estimated 3σ uncertainty of the SOLSPEC radiometric calibration decreases from ±4.3% at 200 nm to ±3.3% at 250 nm and ±2.4% 350 nm. The SOLSPEC wavelength calibration was determined via a least squares regression of the observed positions of lines from argon, krypton, and neon laboratory sources and the internal Cu-He lamp to a second order polynomial dispersion equation. The 2σ uncertainty in the absolute wavelength calibration of SOLSPEC is ±0.1 nm.

Details of the SOLSPEC ATLAS-1 calibration procedures, data processing, and analysis are discussed by *Thuillier et al.* [Observation of the UV solar spectral irradiance between 200 and 360 nm during the ATLAS 1 mission by the SOLSPEC spectrometer, submitted to Solar Physics]. The mean SOLSPEC solar spectrum for March 29 is shown as the blue curve in Fig. 1. The standard deviation of the 28 spectral scan mean was ±1%. The final uncertainty in the derived SOLSPEC irradiance, including the accuracy of the radiometric calibration and precision of the solar measurements, ranges from ±4.5% at 200 nm to ±3.4% at 250 nm and ±2.5% at 350 nm.

SSBUV

SSBUV supports the long-term global stratospheric ozone and solar UV monitoring programs by providing repeated checks on the calibrations of UV ozone and solar monitoring instruments flying on US and international satellites. These include the Nimbus-7 SBUV and Total Ozone Mapping Spectrometer (TOMS) instruments, the Meteor TOMS instrument, and the SBUV/2 instruments on NOAA-9, -11, and -14. SSBUV flew 8 times between October 1989 and January 1996; the ATLAS-1 mission was the fourth SSBUV flight. The instrument consists of a double holographic grating spectrometer with a PMT detector. The SSBUV wavelength range is 200 to 405 nm and the bandpass is 1.1 nm. The instrument is identical to the SBUV/2 satellite instruments except that SSBUV uses a transmission rather than the reflection solar diffuser used on the satellite instruments. An onboard calibration system uses quartz halogen, D_2, and mercury lamps to monitor the instrument radiometric sensitivity and wavelength registration. SSBUV solar irradiance observations from the first four missions were reported by *Cebula et al.* [1994].

The SSBUV calibration approach and results were described by *Cebula et al.* [1989] and *Hilsenrath et al.* [1991, 1993]. Multiple tungsten quartz halogen (FEL) secondary standard lamps, calibrated by the National Institute for Standards and Technology (NIST), are the primary standards used to calibrate SSBUV between 250 and 405 nm. The FEL calibrations are traceable to a NIST gold point blackbody [*Walker et al.*, 1987]. NIST-calibrated D_2 arc lamps also provide calibration data in the 250-350 nm region and are used to extend the SSBUV calibration to 200 nm. The D_2 measurements are normalized to the FEL data in the spectral overlap region [*Cebula et al.*, 1989].

The wavelength calibration of SSBUV as a function of the grating encoder step number is determined via a least squares regression of the observed position of lines from multiple laboratory sources. The estimated 2σ uncertainty of this calibration is ±0.02 to ±0.03 nm. During each mission the stability of the SSBUV wavelength calibration is monitored using the onboard Hg lamp and 13 solar absorption features. Over the first 6 flights, long-term changes in the SSBUV wavelength calibration were less than ±0.02 nm and thermally driven intraflight changes were 0.05 nm or less [*Cebula et al.*, 1996]. The SSBUV solar data were corrected for these changes.

SSBUV observed the sun during 4 solar observation periods on 29 March 1992. Each solar observation consisted of 6 to 8 complete spectral scans of the sun. The arithmetic mean of all scans for each solar observation period was first computed. The arithmetic mean of the mean solar irradiance measured during the second, third, and fourth of the March 29 SSBUV solar observation periods, shown as the red curve in Fig. 1, was then computed. Data from the first solar observation period were excluded in order to ensure that the instrument had fully stabilized. The SSBUV solar data were corrected for a small amount of degradation which occurred during flight. The estimated 2σ uncertainty in the SSBUV solar irradiance ranges from ±2.4% near 350 nm to ±6% near 200 nm [*Woods et al.*, 1996].

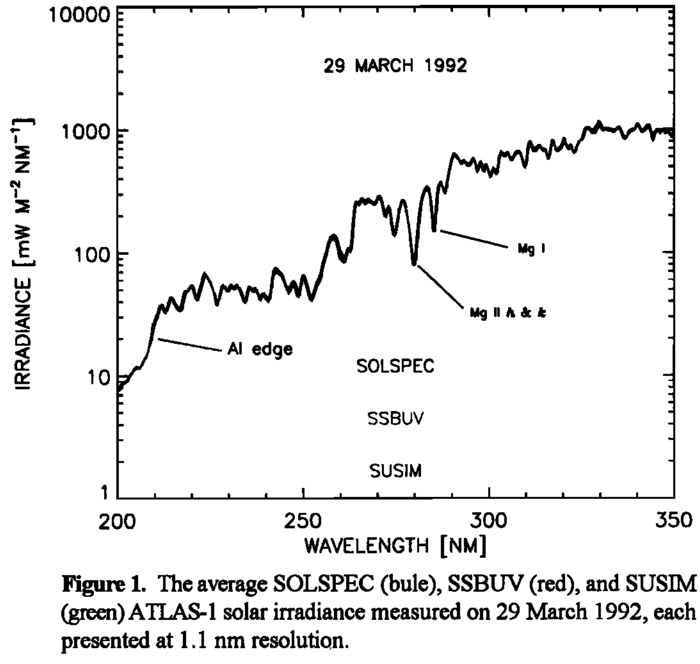

Figure 1. The average SOLSPEC (bule), SSBUV (red), and SUSIM (green) ATLAS-1 solar irradiance measured on 29 March 1992, each presented at 1.1 nm resolution.

SUSIM

The Shuttle SUSIM instrument [*VanHoosier et al.*, 1988] consists of two identical double-dispersion scanning spectrometers which cover the wavelength range 110-420 nm with both 0.15 nm and 5.0 nm resolution, which is controlled by changeable slits. The instrument flew five times between March 1982 and November 1994 on OSS-1, Spacelab, and three ATLAS missions. The Shuttle instrument is the precursor and similar to the UARS SUSIM instrument flying on the UARS satellite [*Brueckner et al.*, 1993]. In-flight sensitivity changes are tracked by using one of the two spectrometers only to view an onboard D_2 calibration lamp in order to characterize changes in the filters and detectors. The second spectrometer is used to make solar measurements and to periodically make D_2 lamp scans to compare with the calibration spectrometer to determine sensitivity changes. The 5 nm resolution is used for the highest accuracy using photodiode detectors, while the 0.15 nm resolution uses PMTs.

The calibration standard for the SUSIM is the NIST Synchrotron Ultraviolet Radiation Facility (SURF), which is a primary standard [*Saloman et al.*, 1982]. The SURF beam irradiance is determined by synchrotron theory. During calibration SUSIM is oriented at 45° and 135° to the plane of the synchrotron; the average of the calibration factors for these two orientations removes almost all the effects of the polarization of the SURF beam. Longward of 250 nm the SUSIM calibration is validated using a NIST-calibrated FEL lamp. The two independent calibrations, SURF and FEL, agree to within 2%. An aging correction to account for SUSIM inflight degradation (4% or less between 200 and 350 nm) was based on a comparison of the preflight and postflight calibrations. The total 2σ uncertainty in the SUSIM absolute calibration, including uncertainties in the SURF irradiance, polarization effects, and instrument degradation during the calibration, is estimated to be ±4% [*Woods et al.*, 1996].

The wavelength scale for the high resolution SUSIM spectrum was derived by a second order polynomial fit to 11 well defined solar spectral lines across the range of the grating encoder positions. These 11 wavelengths were determined by convolving high resolution spectra [*Moe et al.*, 1976; *Anderson and Hall*, 1989; *Kurucz et al.*, 1984] to the 0.15 nm resolution of the SUSIM instrument. Instrument power was cycled several times during ATLAS-1, which necessitated resetting the grating encoder and determining new wavelength coefficients. This made wavelength tracking difficult. The SUSIM wavelength calibration has an estimated 2σ uncertainty of no worse than ±0.4 nm.

The SUSIM solar spectral irradiance used for this comparison, shown as the green curve in Fig. 1, consists of the mean of 2 spectra taken during a 3 orbit period on March 29. This spectrum was computed via a convolution of the observed 0.15 nm spectra with a 1.1 nm FWHM triangular slit function in order to match the resolution of other two instruments. The total 2σ uncertainty in the mean SUSIM solar irradiance ranges from ±5% to ±8% from 200-350 nm. The larger uncertainty applies only in those areas where the solar spectrum is steep and uncertainty in the wavelength registration of the calibration and solar data dominates.

Wavelength scale impact

Each experiment team applied a detailed wavelength calibration to their data. However, small differences in the wavelength assigned to each instrument's solar spectrum can have a dramatic effect when spectra are compared. Particular challenges occur near the numerous solar absorption lines, as well as regions where the spectrum makes large changes in magnitude, for example the Al edge near 208 nm. Each instrument has a slightly different bandpass width and shape, further amplifying sensitivity to wavelength error; SOLSPEC has a gaussian shape while the SSBUV and SUSIM slit functions are nearly triangular. Among the techniques used by the experiment teams to establish accurate wavelength scales for their spectra are comparison to high resolution spectra [*Anderson and Hall*, 1989; *Kurucz et al.*, 1984], which can be determined with higher wavelength accuracy. The high resolution data were first convolved with each of the ATLAS instruments' slit functions, then the resulting spectra were compared to the ATLAS instruments' spectra in 10 nm intervals over the entire spectral region from 200 nm to 350 nm. For each instrument the comparison typically exhibited some scatter with respect to the high resolution data, but no errors greater than ±0.1 nm were revealed, hence no adjustments were made. However, a ±0.1 nm wavelength shift between the spectra can generate differences of about ±5%, which is comparable to the structure observed in the comparisons presented later in this paper.

Comparison of the three ATLAS-1 spectra

In order to compare the data from the three ATLAS instruments, the unweighted average of the three spectra was first calculated, then the ratio of each instrument's spectrum to the mean ATLAS-1 spectrum was computed. These ratios are shown as the dotted lines in Fig. 2. The 1.1 nm instrument resolution ratios demonstrate the impact of small differences in wavelength scale and slit function discussed previously, particularly near strong solar absorption features. To minimize the impact of wavelength misregistration and small differences in slit function, each instrument's spectrum was also smoothed over 5 nm using a running mean. The arithmetic mean of the three instruments' degraded spectra was then constructed, and the ratio of each instrument's spectrum to this mean spectrum computed. The result of this procedure is shown as the solid lines in Fig. 2. While these latter curves show generally good agreement within each instrument's calibration uncertainties, two types of features as a function of wavelength are observed. First, despite the integration over 5 nm, the presence of strong Fraunhofer lines, such as the Mg II line at 280 nm, remains noticeable. Deep lines can generate discrepancies which extend over several nanometers due to the running mean integration effect. Second, variations over tens of nanometers, particularly evident between 240 and 280 nm, are likely due to radiometric calibration errors. Here the differences with respect to the ATLAS-1 mean spectrum are approximately -5% for SOLSPEC and +5% for SUSIM, with SSBUV lying ***roughly*** midway between the other two instruments. This implies an approximate 10% relative difference between SOLSPEC and SUSIM in this spectral region. Taking into account the uncertainty in the two instruments, it appears this difference is real and may be due to a discrepancy in their relative calibrations. At other wavelengths the agreement among the three instruments improves by approximately a factor of two over that seen between 240 and 280 nm. The data presented in Fig. 2 demonstrate the difficulties in measuring the solar irradiance in the middle UV. While at first it might appear that the SSBUV data approximately replicate the mean ATLAS-1 spectrum, this is not the case. The SSBUV irradiances are approximately 2% greater than the mean ATLAS-1 irradiance in the region between 290 and 320 nm and are thus approximately 3% higher than the average of the SOLSPEC and SUSIM irradiances in this interval. Future comparisons of ATLAS-2 and ATLAS-3 data will help identify the source(s) of the differences observed in Fig. 2.

A unique feature of this comparison is that each of the three instruments traces its calibration to an ***independent*** calibration standard: the Heidelberg blackbody for SOLSPEC, FEL lamps for SSBUV, and SURF for SUSIM. Hence, the differences shown in Fig. 2 can arise from errors in correcting for instrument aging during the mission, from errors in transferring the absolute calibrations from the laboratory standards to the instruments, and from fundamental radiometric differences between the irradiance scales of the laboratory standards. The three ATLAS instruments participated in a special NIST-coordinated Round Robin [*Woods et al.*, 1996], which compared calibration standards and laboratory procedures. Further, the comparisons presented herein represent the result of several

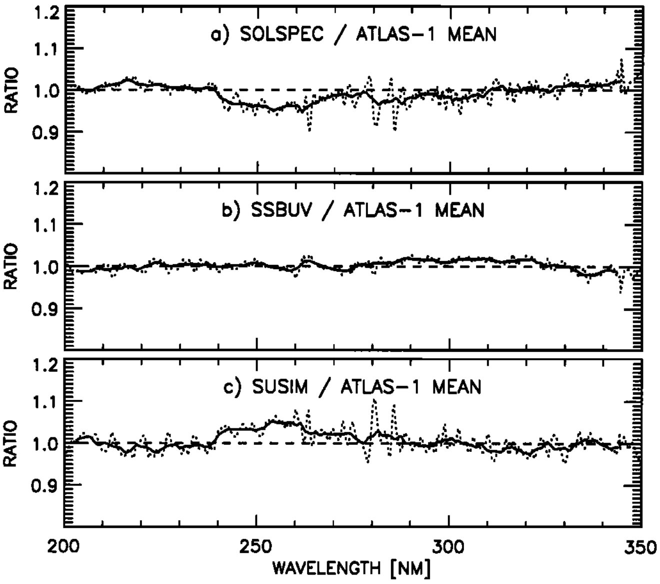

Figure 2. Ratio of the individual spectra to the mean ATLAS-1 spectrum: a) SOLSPEC/ATLAS-1; b) SSBUV/ATLAS-1; c) SUSIM/ATLAS-1. The comparisons are presented at both 1.1 nm (dotted lines) and 5 nm (solid lines) resolution.

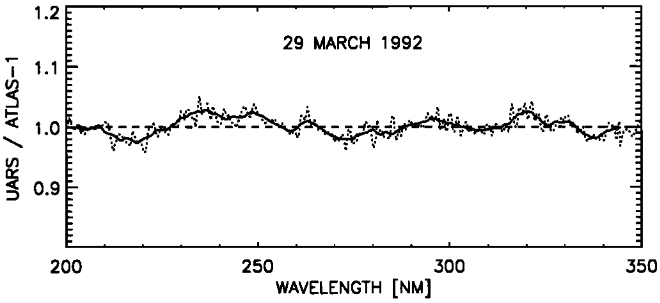

Figure 3. Ratio of the mean UARS spectrum [*Woods et al.*, 1996] to the mean ATLAS-1 spectrum. The comparison is presented at both 1.1 nm (dotted line) and 5 nm (solid line) resolution.

iterations of preliminary versions of these data. As a result of both the Round Robin and the earlier comparisons, individual biases were revealed and subsequently explained. Yet, non-negligible differences remain. The comparison shown in Fig. 2 represents the best agreement to date among three simultaneous, yet independent middle UV solar spectral irradiance measurements. These results suggest that the middle UV solar spectral irradiance can now be measured by independent instruments to an absolute accuracy on the order of ±5%.

Comparison of the mean ATLAS-1 and UARS spectra

The UARS SOLSTICE and UARS SUSIM instruments also measured the solar spectral irradiance on 29 March 1992. A mean UARS spectrum and its validation using SSBUV and SUSIM on ATLAS-1 and -2, is presented by *Woods et al.* [1996]. The ratio between the mean UARS and the mean ATLAS-1 spectra is shown in Fig. 3 at both 1.1 nm and 5 nm resolution. As expected, the effect of the Fraunhofer lines is still present (although reduced in magnitude) in the 1.1 nm comparison. Considering the 5 nm resolution only, the discrepancies are now within ±3%, which is less than the uncertainty in any one instrument's measurement of the middle UV solar spectral irradiance. Between 200 nm and 350 nm the mean ratio of UARS solar irradiance to the ATLAS-1 solar irradiance is 1.0014 ± 0.0020 (2 σ) and no spectral bias is observed. Note that small wavelength errors and differences in slit function have little impact on the 5 nm comparison. This is expected since the mean spectra from the two missions, ATLAS-1 and UARS, tend to average out instrument-to-instrument differences in wavelength assignment and bandpass.

The comparison between the individual ATLAS-1 spectra shows agreement within the calibration uncertainties. Three instruments of different design, calibrated with different techniques using different standards, provided consistent results among themselves and with respect to the UARS solar measurements. The excellent comparisons among instruments on one space platform (ATLAS) and among instruments on another platform (UARS) indicate that the middle UV solar spectral irradiance has now been measured with an absolute accuracy better than ±5%.

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