Irradiance Observations from the UARS/SOLSTICE Experiment

By GARY J. ROTTMAN[1], THOMAS N. WOODS[1], ORAN R. WHITE[1] AND JULIUS LONDON[2]

[1]High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO 80307, USA

[2]University of Colorado, Boulder, CO 80309, USA

The Solar/Stellar Irradiance Comparison Experiment (SOLSTICE) is one of the two ultraviolet spectrometers on the Upper Atmosphere Research Satellite (UARS) measuring the full disk solar irradiance. This spectrometer covers the spectral range of 119 to 421 nm and typically makes ten full spectral scans per day. The instrument was designed to monitor changes in the solar radiation with a relative accuracy of better than 1%. To achieve this goal the spectrometer makes repeated observations of a number of bright blue stars; stars that individually should vary by only small fractions of a percent over time periods of thousands of years. The calibration stars are observed with the same optics and detectors used for the solar observations and any drift in the instrument response is directly determined by changes in the ensemble average flux from these calibration stars. The instrument performance and calibration are described and solar data from the first year of the UARS mission are presented. These UARS data show significant solar activity during late 1991 and early 1992 and then clearly mark a decrease as we move off the maximum of solar cycle 22. We are optimistic that an extended UARS mission, perhaps as long as ten years, is now possible.

1. Introduction

The Solar/Stellar Irradiance Comparison Experiment (SOLSTICE) is one of ten complementary instruments on the Upper Atmosphere Research Satellite (UARS). The UARS was launched in September of 1991 and its instruments provide the first systematic, detailed study of the Earth's stratosphere, mesosphere, and lower thermosphere. These satellite data are providing a new understanding of many atmospheric processes, including stratospheric ozone depletion. Ozone levels and other upper atmosphere properties are established by complex interactions of chemistry, dynamics and energy input. Four of the instruments (CLAES, ISAMS, MLS, and HALOE) use remote sensing of atmospheric emissions to measure temperature profiles and concentrations of ozone, water vapor, and other trace species. Two instruments (HRDI and WINDII) employ high-resolution interferometric techniques to measure Doppler shifts and infer the upper atmosphere wind fields. Four instruments (SOLSTICE, SUSIM, PEM, and ACRIM) measure the energy input which strongly influence both chemistry and dynamics. Of these four, three measure the radiation from the Sun, ACRIM measuring the total irradiance and SOLSTICE and SUSIM measuring the ultraviolet spectral irradiance. The PEM instrument, on the other hand, studies the particle influence on the atmosphere by making in situ measurements of charged particles and X-ray images of the atmosphere responding to incoming high energy electrons. This paper describes the observations now being made by SOLSTICE.

Ultraviolet radiation is strongly absorbed by the Earth's atmosphere, in fact shortward of 300 nm it is almost completely absorbed. The solar UV is the dominant energy input to the middle atmosphere and even small changes can have a significant influence.

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Ultraviolet solar radiation can only be detected from space. Early attempts to measure it were sporadic and usually had inherent uncertainties exceeding the amount of solar variability. At UV wavelengths ($\lambda > 120$ nm) the Solar Mesosphere Satellite (SME) (1981 through 1989) and the NIMBUS-7 (1978 through 1989) carried instruments with adequate short-term stability to reliably monitor both short- and intermediate-term solar variations. In the context of this paper, short-term variations have periods of minutes to hours and refer to erruptive type phenomenon, for example flares. Intermediate-term variations have periods of days to weeks and refer to the more slowly varying evolution of magnetic structures on the Sun modulated by the 27-day rotation period. Since both SME and NIMBUS operated for time periods covering a significant portion of a solar cycle they also provided some plausible indications of solar cycle variability. At short wavelengths below 200 nm these data imply solar cycle variations of 10%, increasing to as much as a factor of two at Lyman-α (121.6 nm). At wavelengths longward of 200 nm the solar cycle variation decreases to a few percent or less and is quickly obscurred by the measurement noise and drift in the instrument response. These early instruments had no provision for accurately tracking their sensitivity and their data generally have a relative accuracy growing at a rate of 1-2% percent per year.

The accurate determination of long-term changes in the solar UV output is now coming of age. The SOLSTICE instrument on UARS and perhaps on future missions employs a technique that should adequately detect instrumental drift and provide photometric measurements of the Sun accurate to better than 1% over arbitrarily long time periods. The instrument has been designed to observe the Sun and, using the very same optics and detectors, to observe bright, blue stars. These stars of spectral classification O, B, and A are assumed to vary by only small fractions of one percent over time periods of thousands of years. The strength of the technique, however, is that many stars are used and the ensemble average flux from the stars provides that individual pathological stars can be easily identified and removed from the "calibration" set. The only differences between the solar and stellar observing configuration are: 1) the entrance aperture: 2 cm^2 for the stars and 10^{-4} cm^2 for the Sun, 2) the bandpass or exit slit: 1 to 6 nm for the stars and 0.1 nm for the Sun, and 3) the observing time : 100 to 1000 seconds for the stars and 1 second for the Sun. Figure 1 shows the SOLSTICE solar irradiance data together with the UV flux from the star α-Canis Majoris (amplified by eight orders of magnitude). For these bright blue stars we see that the ratio of solar to stellar flux levels is on the order of five to nine orders of magnitude, and SOLSTICE accommodates this large dynamic range by changing integration time and apertures. Details of the SOLSTICE instrument and its calibration are provided in two papers, Rottman *et al.* (1993) and Woods *et al.* (1993).

2. Observations

2.1. *Solar observations*

The UARS is a three-axis stabilized, Earth-oriented spacecraft with one side always facing the nadir (Reber 1990). From this spacecraft, observation of the Sun or other astronomical targets requires that the instruments be mounted on a pointing platform, decoupled from the satellite motion. In UARS this is accomplished by a two-axis gimbal platform, the Solar/Stellar Pointing Platform, SSPP.

The UARS orbit, at an inclination of 57 degrees and altitude near 585 km, provides a minimum of 60 minutes of daylight in each orbit, although the obscuration of the solar array and other "masks" constrain the effective solar viewing time as seen by the SSPP

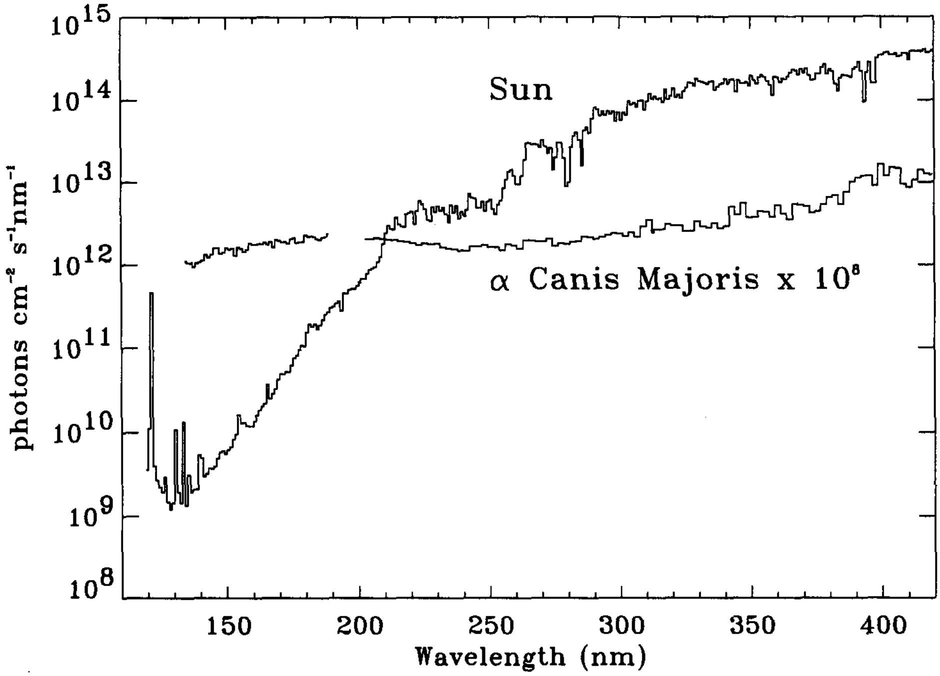

FIGURE 1. Comparison of the SOLSTICE Level 3AS solar spectrum with the UV flux ($\times 10^8$) from the star α-Canis Majoris.

instruments to approximately 35 minutes. Throughout this period the SSPP points the solar instruments at Sun center, and generally the alignment and accuracy of the tracking is better than a few minutes of arc. The solar data reported here were obtained by a scan mode of the spectrometer with a detector integration time at each grating position of either 1 or 0.1 second. A complete spectral scan covers 2048 grating steps while the three instrument channels operate simultaneously. Figure 2 displays a typical full spectral scan and, although compact, it illustrates the spectral coverage and spectral resolution (0.1 nm at the shortest wavelengths up to 0.2 nm at the long wavelength end).

Throughout a calendar day the SOLSTICE obtains a number of full or partial spectral scans. These data are transmitted by the spacecraft and collected at the UARS Central Data Handling Facility (CDHF) at the Goddard Space Flight Center (GSFC). There a processing code corrects the data for all known instrument and observing artifacts and applies a photometric calibration to convert the detector counts to geophysical units (S.I. units of W/m^2). Our primary science requirement is to provide one full spectrum per calendar day, and to achieve this, the data processing algorithm combines all individual observations to form a single spectrum. This daily average spectrum is also "binned" so that a value is reported for each 1.0 nm interval between 119 to 421 nm. These daily spectra are referred to as the SOLSTICE Level 3AS data product, and the solar spectrum provided in Figure 1 is an example.

The pre-flight calibration of the SOLSTICE was accurate to ±3% (Woods *et al.* 1993) but this uncertainty increased through ground testing and launch. We continue to cross-calibrate the SOLSTICE data with the data from the UARS SUSIM instrument (Brueckner *et al.* 1993) and the ATLAS SSBUV and SUSIM instruments. Our current validation

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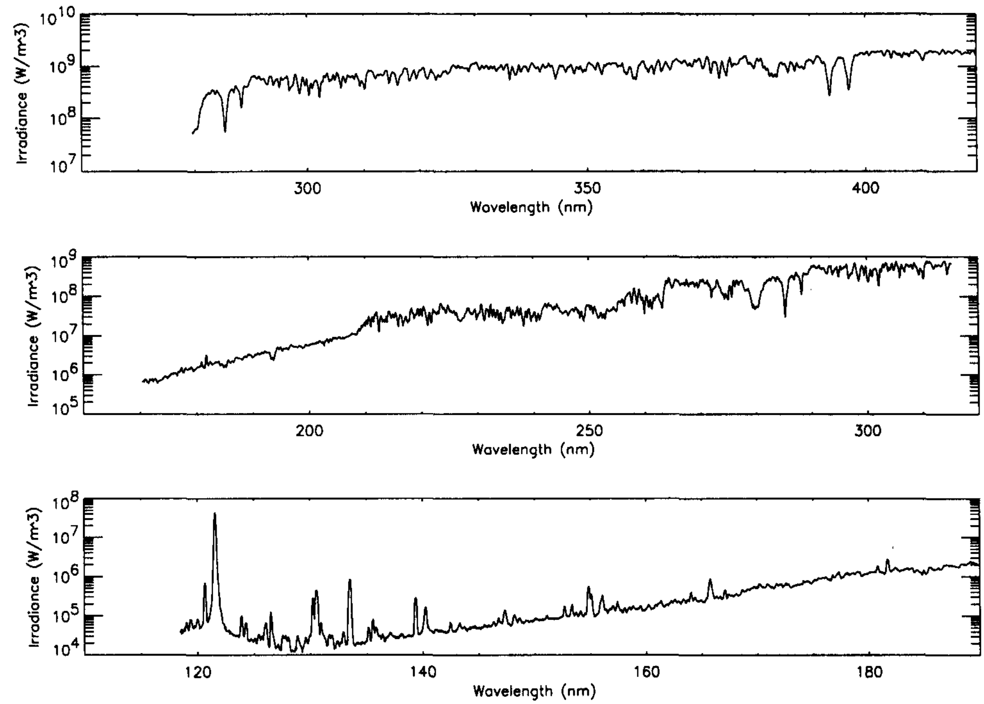

FIGURE 2. Bottom panel: Spectrum obtained from short wavelength channel of the SOLSTICE. Middle panel: Spectral data from middle wavelength channel. Top panel: Spectral data from the long wavelength channel.

efforts indicate that SOLSTICE absolute accuracy is ±2% for wavelengths longward of 200 nm and ±5% for shorter wavelengths.

2.2. *Stellar observations*

As described in the introduction, the SOLSTICE has the unique capability of tracking changes in instrument sensitivity by observing a set of bright, blue stars. The stars used for this in-flight calibration have been carefully selected on the basis of minimal variability (from all known sources of ground based and space observations), on the basis of brightness ($m_{vis} < 3$), and on the basis of their being isolated in the field of view of the instrument (no companion stars brighter than $m_{vis} < 8$ within the instrument field of view).

During each night portion of a UARS orbit, the SSPP is programmed to point SOLSTICE at a selected star and the instrument is configured for a stellar observation. The entrance slit is changed to a 2 cm^2 aperture (four orders of magnitude larger than the solar aperture) and the spectral bandpass, determined by the exit slit width, is increased to at least 1 nm (factor of 10). Usually these stellar experiments are at a fixed wavelength and have an integration or dwell time between 100 and 1000 seconds. The SSPP can only view to one side of the UARS; therefore at any given time, only half of our calibration stars can be observed. However as the UARS orbit precesses with a period of approximately 40 days, all of the calibration stars become available.

The stellar data are also processed at the CDHF with corrections for pointing, dark counts and stray light. As an example, the stellar flux provided in Figure 1 is from the star α-Canis Majoris. Figure 3 is the complete set of observations of this single star

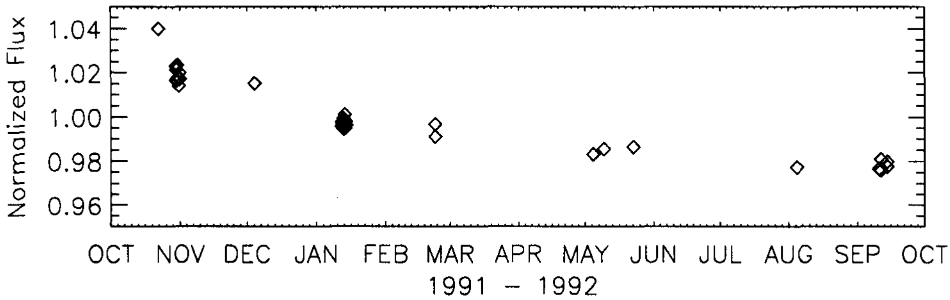

FIGURE 3. SOLSTICE observations of the star α-Canis Majoris and changes are presumed to represent degradation in the instrument sensitivity.

at 153.5 nm and illustrates an approximately exponential decrease throughout the year. In fact it is the combination of similar measurements from fifteen stars that defines the instrument degradation at 153.5 nm. Throughout the first year of SOLSTICE operations the amount of degradation at this wavelength is approximately 3%. Similar analysis is carried out at 54 different wavelengths spanning the interval 118 to 420 nm and the resulting correction factors are then applied to the solar data. The SOLSTICE data, corrected for instrument degradation, are referred to as the Level 3BS data product. These data are transferred from the UARS CDHF to the Distributed Active Archive Center (DAAC) also at the Goddard Space Flight Center, on a fixed schedule and from there they are available to the scientific community. The first year of SOLSTICE data, October 3, 1991 through September 12, 1992 will be available on the Goddard DAAC in the Fall of 1993.

3. Discussion

The Level 3BS SOLSTICE data provide accurate information on short, intermediate, and long-term solar variations. Short-term variations, perhaps associated with flare activity, are identified in the SOLSTICE data and set aside to a special "flare" file for further analysis. It is still premature to consider long-term or solar cycle variations since the UARS has only observed for a short, two-year period, perhaps covering only a portion of the downward trend of cycle 22. In this report we concentrate on the first year of SOLSTICE data and consider primarily the intermediate or 27-day variations.

Figure 4 provides time series for three different wavelengths, Lyman-α, 155 nm, and 240 nm where the ordinates represent a range of $\pm 25\%$, $\pm 20\%$, and $\pm 2.5\%$, respectively. From a solar perspective these three wavelengths represent emission originating predominantly in the chromosphere (Lyman-α), chromosphere/transition region (155 nm), and photosphere (240 nm). From the perspective of atmospheric influences, the Lyman-α is extremely important to mesospheric photochemistry, especially through photodissociation of water vapor; the 155 nm radiation is important to the dissociation of molecular oxygen in the lower thermosphere; and the 240 nm radiation is important to the photodissociation of ozone in the upper stratosphere. All three data sets provide striking evidence of the 27-day variability of the Sun, especially through the spring of 1992. Late in 1991 there appear to be two active longitudes and the time signal has an approximate 13 day periodicity. In mid-summer of 1992, the UARS instruments were turned off in

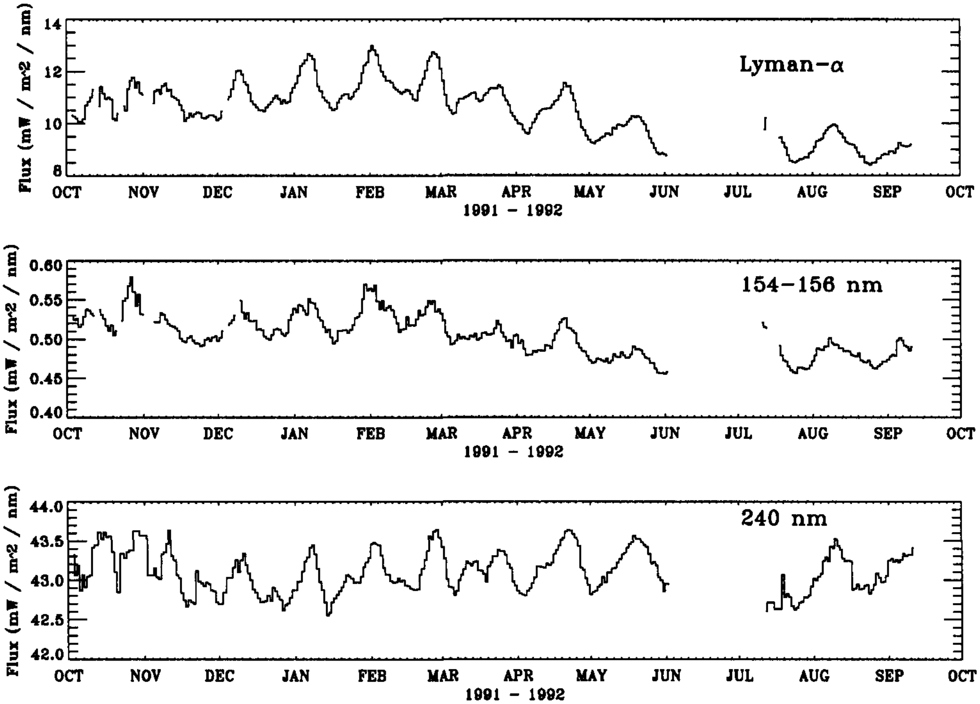

FIGURE 4. One year of SOLSTICE solar data at three separate wavelengths. (The enhanced tick marks denote the beginning of each month.)

order to trouble shoot an anomaly in the solar array drive mechanism and there is a resulting break in the time series.

The magnitude of intermediate term variability is a strong function of wavelength (Rottman 1988; London *et al.* 1993). For example early in 1992 when the 27-day signal is most evident in the SOLSTICE data, a ratio of the irradiance for February 24th (moderately high activity) to March 4th (lower activity) provides a magnitude and wavelength dependence as illustrated in Figure 5. This figure attests to the precision and short-term relative accuracy of the SOLSTICE data. At the shortest wavelengths the emission lines and underlying continuum display strong variability, for example 17% at Lyman-α, and this decreases to only 3% near 200 nm. Near 208 nm, corresponding to the absorption edge for neutral aluminum in the solar atmosphere, the variation abruptly decreases to approximately 1%, and maintains this low level out to 300 nm. Beyond 300 nm the variation is less than 0.5% and approaches the instrumental noise and uncertainty in the two individual measurements. The strong Fraunhofer absorption lines of CaII at 393 nm and MgII at 280 nm stand out in Figure 5 with approximately 2.5% and 3.5% variability, respectively. We emphasize that in spectral regions with both lines and continuum, for example the 1 nm bins including these strong Fraunhofer lines, the reported variations are a function of instrument resolution, and extreme care must be exercised when comparing data sets from two different instruments.

A major scientific goal of the UARS SOLSTICE is to establish the change of the UV irradiance over a solar cycle. The UARS measurements began in late 1991 and we presume that this time period may be representative of solar maximum. Early in 1992 the solar activity decreased precipitously (White *et al.* 1993) and this decrease in

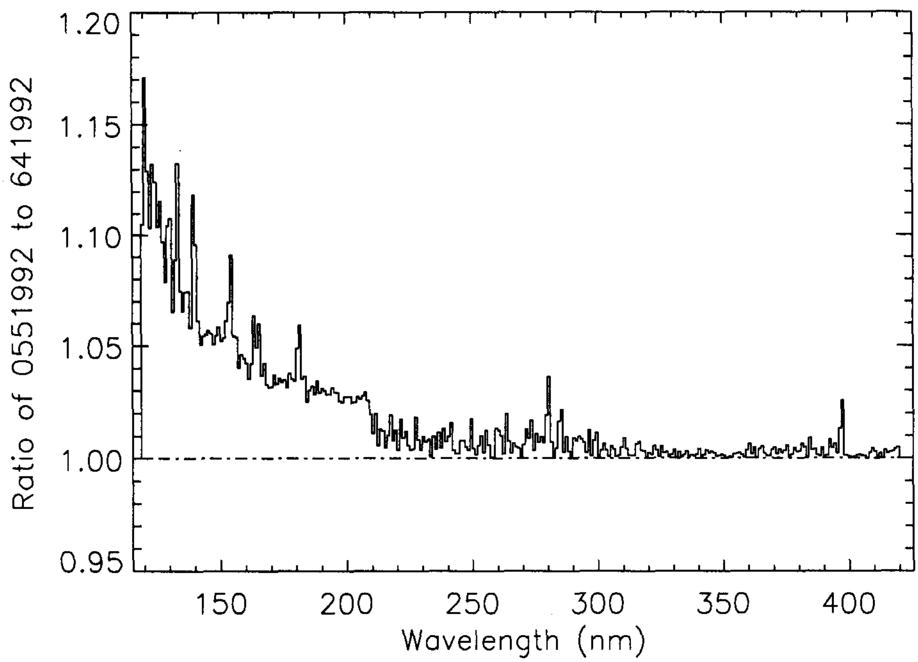

FIGURE 5. Ratio of the solar spectrum for February 24, 1992 to March 4, 1992 as an illustration of typical intermediate term (27-day) variation.

solar activity is attributed to the disappearance of large active regions, especially in the southern hemisphere of the Sun. We are encouraged that the stellar calibration technique of SOLSTICE is working well and that it will provide a final solar data set accurate to 1% over arbitrarily long time periods, in particular over time periods on the order of a solar cycle. Recording the solar cycle variability will require that the UARS mission be continued through solar minimum, now estimated to occur as early as 1995.

If the UARS solar data set extends from solar maximum until solar minimum we will be able to provide a measurement of solar cycle variability. The SOLSTICE data set will have a relative accuracy of better than one percent thereby providing a measurement of solar-cycle variability valid to at least this level. The wavelength dependence of the flux ratio, solar maximum to solar minimum, could be displayed similar to the ratio of intermediate term variability shown in Figure 5. Would the solar cycle variability be a simple amplification of the rotational variability shown in the figure? If so, two-component models with a quiet Sun and active region component may suffice to describe the solar cycle (Lean 1987). A more complicated relation between intermediate and long-term variability requires additional terms, for example an active network component, to fully describe the solar variations.

4. Summary

The UARS SOLSTICE has been in operation since October 3, 1991 and the data reported here cover only the first year. These solar data provide detailed time variations and a precise measurement of intermediate-term solar variability. This information is essential to many of the atmospheric investigations being conducted by the UARS, for it allows an accurate evaluation of the solar effect in the highly variable atmospheric signals. Moreover, these solar data provide important new information on the Sun's variability. Experimental techniques have improved to the point that measurement of intermediate-term solar variability is now straightforward. With proper attention to instrument design, calibration and especially contamination control, spectral photometry at the 0.1% level (relative accuracy) for time periods of one or two months are now routine.

The measurement of long-term solar variations, on the other hand, requires a special technique to accurately and precisely track changes in instrument sensitivity. The SOLSTICE achieves this in a unique way by directly comparing the solar irradiance to the UV flux from a number of bright blue stars. The assumption that the ensemble average flux from these stars is constant now appears valid, certainly to the 1% level and most likely to even a higher degree of relative accuracy. We are optimistic that as UARS continues to operate for several more years, the solar data set will extend from late 1991, near solar maximum of cycle 22, through 1995, the next solar minimum. The resulting time series will provide a first accurate and reliable estimate of solar cycle variability in the ultraviolet spectral range between 120 and 400 nm. Furthermore, the SOLSTICE technique allows that future observations of the Sun, made by comparing solar irradiance to the flux of the same bright, blue stars used by UARS, can be directly related back to today's UARS observations. A second version of the SOLSTICE has been proposed and accepted for the Earth Observing System (EOS). This second version of SOLSTICE is now included as one of the five scientific instruments on the EOS Chemistry Mission, scheduled for launch in the year 2002.

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