Measurement of the Solar Spectral Irradiance from 200 to 3000 Nanometers

Abstract. *The solar spectrum experiment on Spacelab 1 measured 98 percent of the sun's total energy output. It improved the absolute accuracy of solar irradiance data, especially in the ultraviolet and infrared regions. In order to detect any variation in the spectrum on future shuttle flights, the data were obtained in a radiation scale that can be preserved with high precision over many years. The instrument performance and preliminary data reduction are described.*

Accurate solar irradiance data are needed in a variety of disciplines, including aeronomy (earth and planets), meteorology, climatology, astronomy, and solar physics. In particular, it is important to know whether variations in general climatological data are caused by increasing contamination of the earth's atmosphere or by variations in solar radiation. Although solar output variations are known to occur at wavelengths below 200 nm and at radio frequencies and are a familiar aspect of the stream of particles from the sun (solar wind), no reliable information has been available for the spectral region observed in this experiment (1ES016), which covers about 98 percent of the sun's total energy output (except for local variations in active regions).

Indications of slight, global variations came in recent years from precise measurements of the solar "constant" from satellites. As such variations remained below 0.5 percent, very accurate spectral irradiance data are needed to find out which spectral regions are responsible for these fluctuations. It is also evident that the needed accuracy concerns solely the relative radiation scale. It was one aim of experiment 1ES016 to yield the first solar irradiance data in such a relative but very precise radiation scale.

The primary aim was to improve the absolute accuracy in the ultraviolet and infrared. While the irradiance is very accurately known between 330 and 1250 nm—data published recently by Neckel and Labs (*1*) have an internal accuracy better than 0.2 percent and seem to be absolutely correct at least within ±1 percent—the irradiance data outside these spectral limits are relatively poorly known (in ultraviolet, errors up to 20 percent cannot be excluded) and need significant improvement (*2, 3*). As these spectral regions are not accessible from the ground because absorption by the constituents of the earth's atmosphere (O_3, H_2O, and CO_2) is mostly complete, only observations in space can improve the situation.

The space shuttle is the ideal platform for the aims of experiment 1ES016 for the following reasons:

1) It enables observations from outside the earth's atmosphere, so that disturbances caused by the atmospheric constituents are excluded.

2) The instrument is returned safely to the ground, so that it can be flown many times without changing its essential characteristics. The performance of the instrument can be tested soon after solar measurements have been made.

3) A single shuttle mission is long enough to ensure the collection of a sufficiently large number of data and to allow inflight calibrations.

4) The shuttle program is long enough to enable the detection of any variations that are correlated with the solar activity cycle (11 years).

The instrument. Three separate spectrometers, which are double monochromators equipped with holographic concave gratings (f = 10 cm), are used to measure the solar irradiance simultaneously in three channels: ultraviolet, visible, and infrared. The spectrometers form a unique instrument: the six gratings are mounted on the same axis of rotation. This motor-driven axis can be set with high precision at 650 discrete spectral positions. (The intended accuracy of 2 arc seconds, which corresponds to about 0.01 nm, was not quite achieved.)

The profiles of the 1950 passbands, which are defined by the slit widths and the optical characteristics of the gratings and the included optics, are bell-shaped and have a half width (full width at half maximum) of about 1 nm in the ultraviolet and visible and 20 nm in the infrared. As the angular diameter of the sun (~0.5°) corresponds to an aperture ratio of only 1:100, grinds with special scattering characteristics are mounted in front of the entrance slits to ensure full illumination of the gratings. (The grinds also permit easy observation of the so-called inflight calibration lamps, discussed below.) Observations are made in the first-order spectrum of the gratings. Special filters, which change automatically at preselected grating positions, reject the higher orders or reduce the signal to a level that does not harm the detectors (photomultipliers in the ultraviolet and visible and PbS cell in the infrared). A detailed description of the instrument is given in (*4*).

Principle of measurement. The absolute solar radiation data are obtained by comparing the solar irradiance with the irradiance of an artificial light source for which the radiation is known in absolute units. According to the procedure used by Labs and Neckel (*5*) in measuring the absolute intensities in the center of the solar disk, this comparison is done as differentially as possible. The final comparison source, a blackbody with a circular diaphragm, lights the slits under almost the same circumstances as the sun does in orbit—that is, from nearly the same direction, with the same solid angle of the same (circular) shape, without any additional optics. The only differences

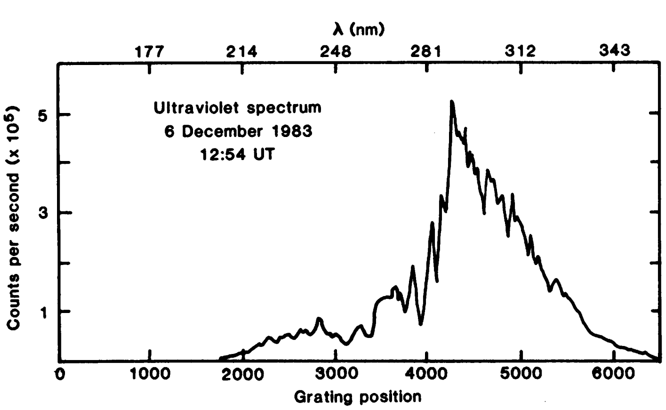

Fig. 1 (left). Ultraviolet spectrometer raw solar data.

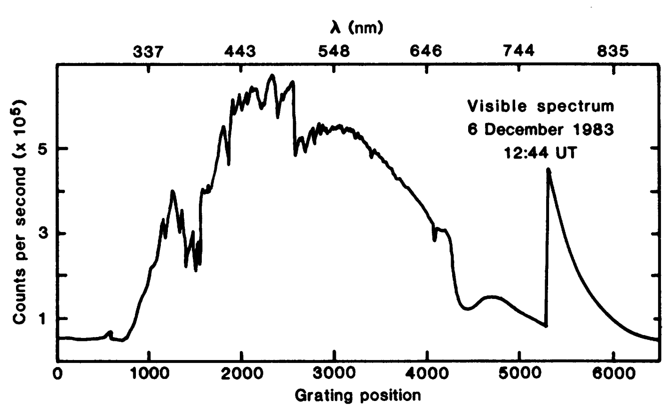

Fig. 2 (right). Visible spectrometer raw solar data.

between the solar and blackbody radiation are that (i) their input directions may be slightly different due to pointing errors of the space shuttle, (ii) the sun shows the well-known limb darkening, while the blackbody diaphragm does not, and (iii) the sun has a line spectrum and the blackbody has a continuous spectrum. According to the scattering characteristics of the grinds, significant errors arising from (i) and (ii) can be excluded. As the profiles of the spectral passbands are not rectangular but bell-shaped, it is point (iii) that requires a time-consuming reduction to obtain optimum accuracy. The reduction requires detailed consideration of the distribution of all absorption lines in the solar irradiance spectrum and precise knowledge of the position and shape of the spectral passbands.

As the blackbody measurements cannot be made in orbit or during integration at Kennedy Space Center but must be carried out in the laboratory of the Heidelberg Observatory, the basic problem is that of knowing very precisely the relative sensitivity of all three spectrometers while the sun or the blackbody is observed. The sensitivity is controlled by two sets of lamps. Ten long-term standard (LTS) lamps are mounted in a special calibration unit, which can be fitted to the instrument as long as it is on ground (and accessible on the Spacelab pallet). The radiation from these lamps enters the spectrometers in the same way as the solar radiation. These LTS lamps make it possible to control the relative sensitivity of the spectrometers with high precision over time intervals on the order of several years. The second set of lamps consists of four inflight calibration lamps (ICL's), which are mounted inside the instrument at fixed positions (*6*). Their radiation can be observed at any time, including time in orbit. The main purposes are (i) to detect any changes in instrument sensitivity that may occur during launch or landing and (ii) to monitor sensitivity in orbit. The ICL's were especially valuable for checking the performance of the instrument during the first and last solar observations.

Although the lamps operated perfectly in orbit, for reasons that are still not known they failed to keep the absolute radiometric scale. However, from the general behavior of the instrument deduced from the LTS data it is clear that this will not have significant consequences.

Finally, the wavelength scale and the passband profiles were carefully determined in the laboratory, using a large number of emission lines from diverse gas-discharge lamps, and were repeatedly controlled in orbit by a hollow cathode lamp inside the instrument. Minor restrictions on the accuracy of the wavelength settings were pointed out above.

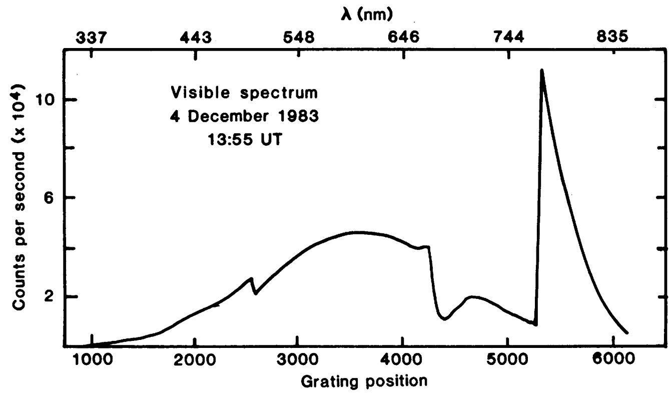

Fig. 3. Visible inflight calibration lamp spectrum recorded in orbit.

Observations in orbit and preliminary results. Measurements of the ICL's and the hollow cathode lamp were made on days 1, 4, 8, and 9 of the Spacelab 1 mission. Solar spectra were recorded for 14 hours on day 8. On all occasions, the instrument performed as well as it did on the ground. About one-third of the data were obtained in real time, one-third by playback; the rest of the data have not yet been delivered.

During day 8 the shuttle orbit was nearly above the terminator between day and night and the sun did not set behind the earth. However, this did not mean that it was possible to record continuously reliable solar radiation data. As the elevation of the sun above the shuttle's "horizon" changed in the course of each revolution, the sun dipped periodically behind the earth's atmosphere. During these phases reliable solar data could not be obtained.

Unfortunately, the first real-time data were received when the distance between the line of sight and the earth's surface decreased from 100 to 25 km, so that the sun was increasingly blurred by the atmosphere and the ultraviolet radiation was completely absorbed by atmospheric ozone. At the time no one was aware of the situation, and since the subsequent ICL runs showed that the ultraviolet channel performed perfectly, the shuttle atmosphere was at first blamed for the failure. Although this was not correct, it raised excitement during the first hour of solar observation.

The total number of solar spectra recorded in orbit was 35. A few of these spectra must be excluded because during the observations the sun was viewed through the earth's atmosphere. Some examples of solar and lamp spectra are given in Figs. 1 to 3.

The preliminary data reduction shows that all undisturbed solar spectra agree within 1 to 2 percent at wavelengths with high count rates. This indicates that a lowering of the sensitivity during the mission, which was indicated by the LTS lamps and was up to 30 percent in the ultraviolet channel, must have occurred during the first minutes of solar pointing. At present, a reduction of the grind-transmission due to solar ultraviolet radiation appears to be the most likely cause. In the ultraviolet, therefore, the comparison between sun and blackbody will be based primarily on the postflight measurements with the LTS lamps.

The postflight blackbody calibration and another accurate determination of the wavelength scale were performed in April 1984. According to the present data analysis, we assume that the intended final absolute accuracy (about 1 percent in the visible and infrared and up to 5 percent in the ultraviolet) will be nearly obtained for most parts of the observed spectral domain. Only for a minor fraction of the spectrum—especially in the ultraviolet/visible and visible/infrared overlap regions—was the sensitivity not high enough to enable equally precise data.

Finally, an effort was made to detect short-term variations of the solar radiation, such as solar oscillations, during the additional day of the mission. For this purpose, the gratings were set in a fixed position and the solar radiation was monitored at three wavelengths (one in each channel). A Fourier analysis cannot be made yet because the data are incomplete. Nevertheless, the available real-time data reveal periodic variations of the signals from the sun and the ICL's, of the order of 0.5 percent. These electronic variations did not occur on the ground before or after the mission. They will not affect the Fourier analysis for short-term variation studies.

In conclusion, the solar spectrum experiment (1ES016) on Spacelab 1 worked without any problem in orbit. Solar spectral irradiance data were obtained successfully. The first mission demonstrated the usefulness of inflight calibration lamps in understanding the behavior of the instrument in space. It also showed the flexibility possible in commanding an instrument on Spacelab from the ground. Solar spectral irradiance values will be published when the missing data are available and the calibration reduction has been completed.

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7. Spacelab experiment 1ES016 was supported by the Centre National d'Etudes Spatiales (France), the Department de la Recherche Scientifique du Ministère de l'Education Nationale (Belgium), and the Bundesministerium für Forschung und Technologie (Federal Republic of Germany). The inflight calibration lamps were specially developed according to our very special requests by the Hanau Heraeus GmbH, Abteilung EQ (J. Schäfer) and they worked in orbit without any problems. We gratefully acknowledge the significant help of the members of the SPICE (Spacelab Payload Integration and Coordination in Europe) group in all phases of integration and during the calibration at Kennedy Space Center. Finally, it is a pleasure to thank the technical team, which built the flight instrument and a large part of the ground support equipment: P. Asscherickx, G. Azria, R. Baedewijns, W. Decuyper, U. Finkenzeller, T. Foujols, H. Jäger, H. Mandel, M. Mathijs, P. Mignon, U. Reichert, C. P. Rieck, W. Rössner, J. P. Rozet, F. Ruzicka, E. Van Ransbeeck, W. Schwarz, J. K. Seeburger, F. Viret, and Th. Ziegler.

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Astronomical Observations with the FAUST Telescope

Abstract. *The far-ultraviolet space telescope (FAUST) was flown on Spacelab 1 to provide wide-field imaging in the wavelength range 1300 to 1800 angstroms. Most of the developed film showed high levels of background exposure. Frames with a lower background included exposures of the Cygnus Loop supernova remnant and an exposure in the direction of the galaxy cluster Abell 2634. Several exposures will be used in a search for hot white dwarf stars.*

Space ultraviolet astronomy has entered the observatory-class era with powerful high-resolution instruments such as the International Ultraviolet Explorer. Next generation high-resolution instruments such as the space telescope are under development. However, there is a large class of scientific problems, as in all branches of observational astronomy, which require instruments with a deep-sky imaging and wide field-of-view capability. These include:

1) Cataloging of the ultraviolet brightness of members of a class of objects in order to provide a basis for understanding these objects and to identify anomalous members that require more detailed study. Such classes include extragalactic objects [quasi-stellar objects (QSO's), BL Lac objects, galactic nuclei] and galactic objects (ultraviolet stars, interacting binaries).

2) Imaging of extended objects to study the spatial distribution of emitting sources. Such sources include supernova remnants, galaxies, and galactic nebulae.

3) Study of the intensity and structure of the diffuse far-ultraviolet background, which may include both an extragalactic cosmological background and more local components that contribute a small-scale structure of great interest. Examples are zodiacal light, reflection nebulae, and high-latitude dust filaments.

4) Support of observational programs of high-resolution instruments, including the study of transient events (supernovae, novae, dwarf novae) and the location of QSO's and galactic objects for ultraviolet absorption studies of intervening matter. In general, deep, wide-field plates will provide valuable primary data on far-ultraviolet intensities of objects to be studied in greater detail.

The far-ultraviolet space telescope (FAUST) was included in the Spacelab 1 instrument complement to provide wide-field (8° diameter) imaging in the far ultraviolet (1300 to 1800 Å). During the Spacelab 1 mission, the instrument was located on a pallet in the cargo bay.

The instrument was operated from mission day 2 to day 6. A total of 47 exposures was taken. Instrument electrical, mechanical, and thermal performance were nominal throughout the mission.

The developed film showed high levels of background exposure on all frames except for a closed-door exposure, which showed the normal unexposed background level. Of the 45 exposures of astronomical objects, all but a few frames are at a density level that prohibits further analysis. An analysis of the source of the background experienced during Spacelab 1 will be published elsewhere (*1*). We present here preliminary astronomical results from some of the frames with lower background.

Experiment description. The FAUST telescope employs a Wynne optical configuration to image the field of view onto a flat focal plane (*2*). The image falls on a frequency-converting image intensifier tube, which transforms the ultraviolet image into an intensified optical image. This optical image is then recorded on 103a-O spectroscopic film.

The telescope has a CaF_2 window for a short-wavelength cutoff and the falling CsI sensitivity on the frequency converter tube as a long-wavelength cutoff. These two factors combine to give a 500-Å bandpass with maximum sensitivity at 1450 Å. The instrument has a measured angular resolution of 2 arc minutes. Preflight calibration showed that the instrument could detect a magnitude 17.5 source against a dark background in 10 minutes, assuming an A0 stellar spectrum.

FAUST observed a total of 22 separate targets on 21 nighttime passes. One dark exposure with the instrument door closed was also taken. An observation consisted of one, two, or three separate exposures from 1 to 15 minutes in duration.

Preliminary results. In Fig. 1 we show a 2-minute exposure of the Cygnus Loop, a supernova remnant (SNR) located about 1500 light-years distant. The age of the Cygnus Loop is estimated to be about 15,000 years, making it a relatively old SNR.

Middle-aged to old SNR's are in the radiative part of their lifetime and emit copious far-ultraviolet line emission. The far-ultraviolet emission spectra are dominated by the C IV 1549-Å and O III 1663-Å lines for shock velocities near 100 km/sec. Collisionally excited, permitted line radiation from these species dominates the cooling in the post-ionization layer of the shock, where gas temperatures are $\sim 10^5$ K. In models of homogeneous, stable shocks in a uniform medium (*3*) the ratio of total emission in the FAUST bandpass to the hydrogen Hβ line intensity is a single-parameter