A HIGH PRECISION SOLAR ULTRAVIOLET SPECTRAL IRRADIANCE MONITOR FOR THE WAVELENGTH REGION 120–400 nm*

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Abstract. There exists a growing need to improve the accuracy of measurement of the absolute solar flux within the wavelength range 120–400 nm. Although full-disk solar fluxes and variations thereof in the 120–400 nm region are required to model the solar atmosphere, current increased interest in the measurements arises from their importance in modeling the terrestrial atmosphere. We describe the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) experiment under development at the Naval Research Laboratory (NRL) for flight aboard the Space Shuttle and the Upper Atmospheric Research Satellite (UARS). SUSIM will monitor the solar flux in the 120–400 nm region with high precision, using an in-flight calibration system to reduce absolute error to < 10%, and error relative to the 400 nm continuum to < 1%.

1. Introduction

There is growing interest in measurements of the absolute solar full-disk flux and its variability, especially over the solar cycle, in the 120–400 nm wavelength region. Astronomers are increasingly interested in evidence of activity in other stars which may be similar to solar phenomena. Long term monitoring of Ca II K emission from late type dwarfs has shown that some other stars appear to go through an activity cycle analogous to the Sun's (Wilson, 1978). The Sun is the only star for which we can make spatially resolved observations of surface activity clearly tied to fine structure of magnetic fields and to global magnetic cycles. Therefore, our understanding of other stars must be based on a comparison of the full-disk solar radiation and the finer scale processes which contribute to it.

The solar radiative output is also important for many processes in the heliosphere, such as interaction with the local interstellar medium streaming through the solar system (see review by Thomas, 1978), physics of planetary atmospheres, and comet chemistry and evolution (see review by Delsemme, 1980). But the greatest spur has come from the importance of accurate solar flux measurements in modeling the terrestrial atmosphere. Although the 120–400 nm region represents a small fraction (< 2%) of the solar constant, it vitally affects some atmospheric chemistry, such as ozone production, and so indirectly may influence terrestrial climate even though representing a small amount of energy.

Existing measurements of the solar irradiance in the 120–400 nm region have important deficiencies. The difficulty of absolute calibration, together with estimated

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errors typically in the 30% range, makes comparisons between different experiments, and even different flights of the same instrument, ambiguous. The most potentially useful experiments, those on long duration satellites, have usually suffered from a large instrumental sensitivity degradation which is difficult to estimate. Great differences within the 120–400 nm range still exist between measurements by different experimenters.

Cook *et al.* (1980) have developed a simple two component model of the solar full-disk flux. They have measured plage-to-quiet region contrast factors for various lines and continua. Together with an estimate of the fraction of the disk covered by plages derived from Ca II plage areas they have shown that a reasonable agreement of flux variation is obtained with a number of published observations. The importance of such a model is to examine in detail the predicted variability following from specific assumptions about its cause, which can be tested against available and future observations, and to provide a plausible estimate of the general magnitude of variability which an irradiance monitor might encounter at different wavelengths in the 120–400 nm range.

The greatest current needs are for an improvement in the accuracy of measurement of the far ultraviolet irradiance, together with a long term program to monitor variability. These needs have been repeatedly expressed by national and international advisory groups on solar-terrestrial relations (i.e., COSPAR Decision 4/77 (IAU, 1978); Report of the Workshop on Monitoring the Solar Constant and Solar Ultraviolet (U.S. GPO, 1978); Upper Atmosphere Research Satellite Science Working Group Report (JPL, 1978)). We describe in this paper the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) experiment under development at NRL, which is meant to meet just these requirements. The SUSIM instrument is now being interfaced to the Space Shuttle pallet together with other scientific instruments chosen for the first Office of Space Science mission (OSS-1). Following this flight, which is presently scheduled for March 1982, the instrument will fly again on Spacelab 2 and then on additional follow-on missions. A pair of SUSIM instruments is scheduled to fly on two Upper Atmospheric Research Satellites currently scheduled for launch in 1986 and 1987, respectively. Because of the long duration of these flights (1.5 years each) daily and 27 day changes of the solar UV output can be monitored with high precision.

2. Scientific Objectives of SUSIM

The main objective of the SUSIM experiment is to measure with high precision full-disk solar fluxes and their changes over a solar activity cycle in the wavelength region 120–400 nm. This task can be broken down into the following subtasks:

(A) Improve the absolute accuracy of solar continuum irradiance measurements in the 140–400 nm region to ±6–10%, wavelength dependent.

(B) Improve the absolute accuracy of solar emission line irradiance measurements in the 120–400 nm region to ±6–10%, wavelength dependent.

(C) Measure with high accuracy the intensities of the continuum below 208 nm relative to the intensities of the continuum above 208 nm to ±1%.

(D) Measure with high accuracy the intensities of solar emission lines below 208 nm relative to the stable solar continuum above 208 nm to ±1–5%, wavelength dependent.

(E) Measure the (wavelength dependent) degree of correlation of the solar fluxes in the 120–400 nm region with the following ground observables: the Zürich sunspot number, the solar 10.7 cm radio flux, Ca II plage index, and full-disk Ca II H and K indices (see White and Livingston, 1978).

A full error analysis shows that the RMS uncertainty of absolute spectral irradiance measurements by the SUSIM experiment should be ±8–10%, depending on wavelength. Previous experiments have achieved solar flux measurements with a ±30% error budget. However, the solar variability in the important 180–210 nm region can be estimated to be approximately 8–20% over a solar cycle (Cook *et al.*, 1980). Therefore, such small variations would be only marginally detectable with the SUSIM experiment in its absolute mode. However, by assuming that the solar output at wavelengths longer than 300 nm is constant within ±1%, one can measure the solar radiation below 208 nm relative to the 300 nm wavelength regime, provided that the instrument sensitivity degradation can be measured with high precision. Scientific goal C is therefore the most important one.

The short wavelength cutoff is imposed by the necessity of environmental control to retard degradation of the sensitivity of the instrument, as explained in the next section. The method of control we have chosen requires a MgF_2 window.

The long wavelength cutoff has been selected to include the Ca II H and K lines in order to establish correlations between their full-disk variability and the variability at other wavelengths. It is also desirable to extend the measurements into the 300–400 nm region for comparison with high accuracy ground-based measurements.

3. Instrument

The SUSIM instrument consists of two identical double-dispersion scanning spectrometers, seven detectors, a UV calibration source, a Sun sensor, a microprocessor system, and associated electronics. Figure 1 shows the optical layout common to both spectrometers. The spectrometers and detectors are sealed in a canister filled with 1.1 atm of argon gas to minimize the effects of contamination of the optics that occur from irradiation under high vacuum outgassing conditions (the absorption cross section of argon is insignificant in the 120–400 nm region). Each spectrometer has interchangeable entrance and exit slits to provide either 0.15 nm or 5 nm spectral resolution over the entire spectral range.

Incident radiation enters the instrument through a MgF_2 window (Figure 2) in front of each spectrometer entrance slit. This window provides the necessary pressure seal for the canister. A diffusing window would be desirable in order to

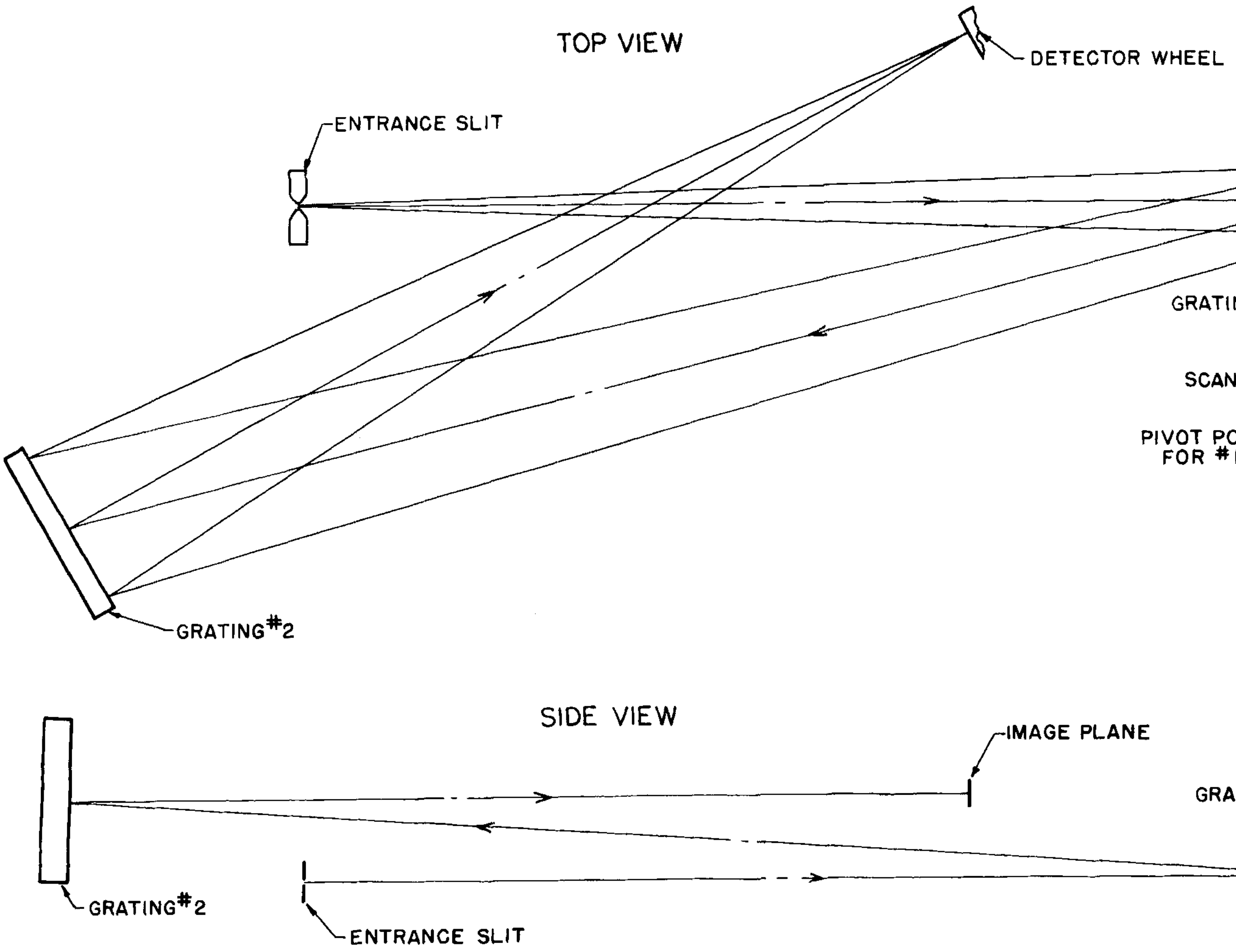

Fig. 1. Optical layout for each spectrometer. 250 nm setting of grating is shown. Side view shows the central ray only.

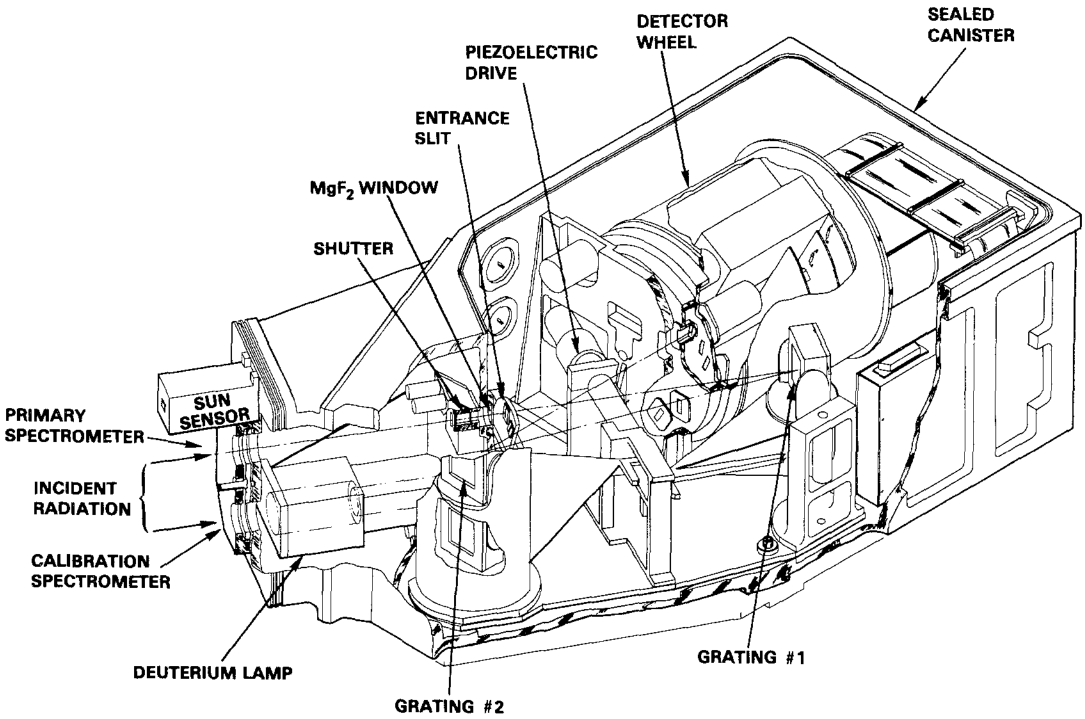

Fig. 2. SUSIM instrument design showing component placement. Light path for primary spectrometer is shown.

make the instrument insensitive to spacecraft pointing offsets. However, an extensive program has failed to develop MgF_2 diffusers with well behaved properties over the 120–400 nm wavelength range (Prinz, 1981). A window which acts as a good diffuser at 120 nm would not diffuse sufficiently at 400 nm; a window which is a good diffuser at 400 nm is nearly opaque at 120 nm. Thus the advantage of a diffuser for reduction of pointing sensitivity becomes a disadvantage because of additional wavelength corrections. Instead, holographic gratings are used since their response across the illuminated area is flat to within ±2%.

Wavelength scanning for each spectrometer is achieved by synchronously rotating the two gratings, keeping the entrance and exit slits fixed. Pivoting the first grating off-center compensates for the changing focal distance as the spectrum is scanned. The out-of-plane configuration is necessary to permit proper baffling between the entrance slit and detector. One spectrometer is used almost continuously during the daylight portion of each solar-pointed orbit; the second is used only infrequently to track any change in the sensitivity of the first.

A deuterium lamp which is used for periodic inflight calibration is located outside of the MgF_2 window. This lamp is being developed by the National Physical Laboratory (NPL) of the United Kingdom and is being calibrated and tested at NBS and NRL. An extensive program (Ott *et al.*, 1980) of development and calibration has already made significant progress in absolute calibration accuracies and in resolving a long standing difference in absolute calibration between NBS and NPL. The lamp is specifically developed to provide highly stable and predictable aging characteristics and to cover the entire wavelength range 120–400 nm. Periodic use of the lamp will allow tracking of the instrument efficiency while not causing undue aging of the lamp. The use of a MgF_2 lens in place of the usual deuterium lamp window together with accurate placement in the optical path allows the lamp to fill the optics in a manner similar to the Sun.

The detectors are mounted on a wheel and arranged so that any of the seven can be moved in front of either spectrometer. Similarly, the calibration lamp can be moved in front of either spectrometer.

Table I summarizes the instrument parameters.

TABLE I

SUSIM instrument parameters

Entrance slits:	0.05×8 mm (for 0.15 nm resolution) and 2.48×8 mm (for 5 nm resolution); MgF_2 windows.
Grating No. 1:	1028 lines mm^{-1}; 480 mm radius of curvature; 16.3×16.3 mm unmasked area; $-1.9°$ out-of-plane tilt of optic axis; 63.1 mm pivot radius for scanning.
Grating No. 2:	1028 lines mm^{-1}; 480 mm radius; $+1.9°$ tilt; pivots about center for scanning.
Exit slits:	0.05×6 mm for 0.15 nm resolution; 2.48×6 mm for 5 nm resolution; 4.6° out-of-plane tilt.
Detectors:	High resolution 0.15 nm mode (two MgF_2 windowed photon counters): Number 1 RbTe photocathode for shorter wavelengths; Number 2 Bi-alkali photocathode for longer wavelengths. Low resolution 5 nm mode (five MgF_2 windowed photodiodes): Number 3 RbTe cathode for shorter wavelengths; Number 4 Redundant RbTe photodiode; Number 5 Bi-alkali cathode for longer wavelengths; Number 6 Redundant bi-alkali photodiode; Number 7 Bi-alkali cathode EMR Type 543P–09–00 calibrated photodiode.
In-flight calibration source:	Quartz-housed deuterium lamp fitted with MgF_2 lens ($f = 100$ mm) placed 100 mm from plasma discharge, calibrated by NBS and NPL.
Overall:	$24 \times 77 \times 86$ cm, with 24×77 cm side to Sun; 55 kg total weight.

Because the solar irradiance increases by five orders of magnitude between 130 and 400 nm, a double-dispersion design is essential for thorough stray light rejection. Experience with similar double-dispersion spectrographs shows that at 140 nm only a very weak stray light level is detectable, even if photographic film that is sensitive up to 500 nm is used. The RbTe cathode used for scanning the 140 nm region has a long wavelength cutoff at 300 nm, which results in even better stray light rejection.

The only region where contamination from second order short wavelength light can be expected is at 243.2 nm if scanned with the RbTe cathode. Assuming that the efficiency of the two gratings in second order is half of the first order efficiency at 121.6 nm (H-Lα), only 10% of the signal at 243.2 nm will be from the second order of Lα. All other strong emission lines have second order intensities that are more than two orders of magnitude weaker than the first order signals. The count rates of the short wavelength second order continuum are less than 2.5×10^{-3} of the first order continuum count rates at all wavelengths.

4. Pre-Flight and Post-Flight Calibration

Highly accurate absolute calibration of this instrument is the critical element necessary for its success. Without the best possible calibration effort, the entire experiment would be of lesser value. For this reason, an extensive calibration program has been developed in close cooperation with the National Bureau of Standards. The calibration methods are not based on artificial restrictions, such as convenience, but are based on the extensive experience and knowledge of NBS, NPL, and NRL.

Pre-flight and post-flight absolute calibration of the instrument will be based on three independent absolute spectral irradiance source standards which have been developed by NBS. The calibration of each of these standards is performed in an independent manner as shown in Figure 3. The tungsten quartz-halogen lamp spectral irradiance standard is calibrated by NBS with an uncertainty of ±3% above 250 nm. This calibration was determined through the use of a gold point blackbody standard and blackbody radiation theory. The argon arc will be calibrated by NBS as a spectral irradiance standard against the high power hydrogen arc primary spectral radiance standard and the tungsten quartz-halogen spectral irradiance standard. The uncertainty in the absolute spectral irradiance of the argon arc will be ±3% between 200 and 400 nm, ±6% between 140 and 200 nm, and ±11%

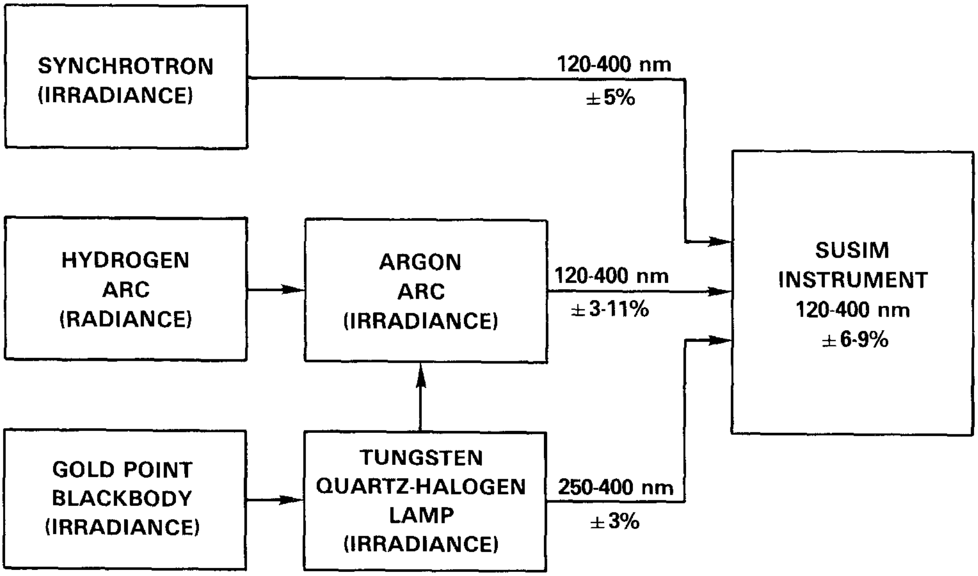

Fig. 3. Absolute irradiance calibration for SUSIM.

below 140 nm. The absolute calibration of the quartz-halogen standard is traceable to blackbody theory while the calibration of the hydrogen arc standard is based on a measurement of the arc length and on atomic theory. Synchrotron radiation from the Surf II storage ring at NBS (Gaithersburg, MD) is known with an uncertainty of ±5% in the 120–400 nm region (Ederer *et al.*, 1975). Its absolute calibration is based on synchrotron theory.

Since the calibration procedure used for each of the above standards is different, this redundant calibration process provides a powerful method of uncovering systematic errors in any one of the calibrations. By combining the argon arc calibration above 200 nm and the synchrotron calibration below 200 nm, an overall calibration standard accuracy of ±3–5% can be achieved.

An EMR Type 543P-09-00 photodiode is included among the seven detectors in the SUSIM instrument. This has been calibrated by NBS as a secondary standard with an uncertainty of ±6% between 120 and 200 nm, and ±10% between 200 and 400 nm. The incorporation of a stable secondary standard within the instrument allows for an additional check of the calibration procedure.

Absolute calibration with the argon arc and tungsten quartz-halogen lamp spectral irradiance standards will be performed by placing the instrument directly in front of the standards at a prescribed distance. This distance will be chosen so that the irradiance of the sources is as close to the expected solar irradiance as possible. In addition, the original calibration of the argon arc irradiance standard will be performed at this same distance.

For the absolute calibration against the synchrotron radiation, the instrument will be inserted directly in the synchrotron beam line immediately behind an orbital plane locator. The spectral irradiance of the synchrotron radiation is known at this insertion point to within the uncertainty stated above.

The instrument low resolution (5 nm) mode photodiode detectors will be calibrated with both the narrow-band and broad-band slits so that the relative spectral response of the spectrometer/photodiode combination can be determined over the range of the broad-band (5 nm) mode.

As a result of this calibration procedure, and under the assumption that the instrument efficiency does not change in orbit, the total expected RMS uncertainty in measured absolute solar spectral irradiance will be ±6–9% over the entire wavelength range.

5. In-Flight Calibration and Stability-Tracking Methods

In the previous section, it has been assumed that the instrument sensitivity would remain the same between the pre-flight and post-flight absolute calibrations. It can be almost guaranteed that this assumption will not hold. Extensive experiences with satellite-borne ultraviolet instruments have demonstrated that sensitivity degradation takes place. To overcome this problem, two approaches will be taken:

(A) Every possible effort will be made to keep sensitivity degradation to a minimum. The spectrometer will be sealed in the argon-filled MgF_2 canister and never exposed to hard vacuum. The window will never be exposed to an oil pumped vacuum system and will be protected during pre-flight testing and during the first day of orbit when most contaminant out-gassing occurs. The throughput stability of the spectrometer and the quantum efficiency stability of the seven detectors will be thoroughly tested over a period of one year prior to flight.

(B) Even with all the above precautions, some in-flight sensitivity degradation must be expected. Consequently, the instrument has been designed with the capability for in-flight stability tracking of its sensitivity. This is accomplished by the following independent techniques:

(i) A deuterium lamp transfer standard is built into the instrument. Periodically the instrument is illuminated with the calibrated radiation from the deuterium lamp and the detector outputs are compared with those obtained during pre-flight calibration.

(ii) Two identical spectrometers are included in the instrument. One is used during the normal solar monitoring mode (primary spectrometer) while the other is reserved for the in-flight calibration mode. By this technique, a loss in sensitivity of the prime spectrometer, due to the combination of contaminants (primarily on the window) and effects of solar radiation, can be detected when compared to the calibration spectrometer.

(iii) Two redundant low resolution (5 nm) mode photodiodes are included among the seven detectors and are used during the in-flight calibration mode. In this way a loss in quantum efficiency of the primary photodiodes can be detected.

In addition, an 'NBS Standard Photodiode' (EMR Type 543P-09-00) is included and used only during the in-flight calibration mode. The shelf life stability of this photodiode has been established by NBS (Canfield *et al.*, 1973) over the past ten years. Since the standard photodiode in the instrument will spend most of its time 'on the shelf' sealed in the argon-filled canister, it is expected that its stability in flight should be the same as on the ground.

Based on the in-flight calibration, the total expected RMS uncertainty in solar absolute spectral irradiance over 120–400 nm will be ±8–10%, and the uncertainty in spectral irradiance relative to the 400 nm continuum should be ±1%.

6. Conclusions

In order to determine the solar UV flux change, it is absolutely necessary to improve existing observations, to extend them over longer time periods, and to measure a variety of solar emission lines and continua that originate from different layers of the solar atmosphere. The instrument design must monitor long-term calibration changes which would otherwise be interpreted as solar changes, and a thorough assessment of errors is necessary.

The SUSIM instrument and observation program have been carefully designed to fulfill these requirements. With the flight of OSS-1 in early 1982, we will enter a decade of solar ultraviolet spectral irradiance monitoring. Flight aboard Spacelab 2 (1983) and follow-on flights at 6-month intervals are now being planned. The first phase of development of two additional SUSIM instruments for the Upper Atmospheric Research Satellite (UARS) Mission has just begun, and will allow longer duration observations of approximately one and a half years from each of two satellites to be launched in 1986 and 1987.

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