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13. ABSTRACT (Maximum 200 words)

The goal of this research program was development of a method for obtaining daily radiometrically accurately, solar spectral irradiance data at EUV wavelengths. In-orbit radiometric instrumentation recalibration is a fundamental requirement for accurate spectral flux measurements.

We have studied a low-pressure version of the EUV radiance standard and concluded that a substantial redesign of it would be required if a suitable one is to be developed for in-orbit calibration of a solar spectral irradiance monitor. We have reviewed the use, suitability, and the availability of thin film filters for in-orbit EUV calibration. In our opinion, the availability of space-qualified filters has not been verified. We have evaluated and chosen a design of a 4-spectrograph, flat-field package that provides 0.1 to 0.2 nm resolution in the range 5-175 nm with a total weight including detectors of 1.6 Kg.

Several mission concepts, which involve rocket-borne, calibrated spectrometer underflights to recalibrate the *Voyager* spacecraft have been considered.

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FINAL TECHNICAL REPORT: Grant AFOSR-90-0063  
11/15/89 - 11/14/93

**Absolute, Extreme-Ultraviolet Solar Spectral Irradiance Monitor (AESSIM)**

prepared and submitted by

W. H. Parkinson & Peter L. Smith

April 1994

## 1. INTRODUCTION

The goal of this research program was development of a method for obtaining daily, radiometrically accurate, solar spectral irradiance data at extreme-ultraviolet (EUV) wavelengths. These data are required for improvements in U.S.A.F. Air Weather (AWS) capabilities for analysis and forecasting of the space environment for DOD missions (see § 2). In-orbit radiometric instrumentation recalibration is a fundamental requirement for such measurements. AFOSR-90-0063 supported an extension of earlier conceptual studies of an "Absolute, Extreme-Ultraviolet Solar Spectral Irradiance Monitor (AESSIM)" that is compatible with space-flight opportunities and budgets of the 1990's and beyond.

We proposed to investigate, design, and test a smaller, less massive, low-power, in-space version of a 'standard' EUV radiance source, which has been developed for laboratory use, to assess the merits of innovative combinations of rare-gas ionization cells and thin film filters to make absolute measurements of EUV radiation over a number of wavelength bands, to evaluate flat field spectrograph designs that could use array detectors, and to outline a proposed solar EUV monitoring mission

## 2. MOTIVATION FOR THIS WORK

### 2.1 USAF Requirements for Solar EUV Data

The Statement of Operational Need, MAC 05-86, titled *Space Environment Technology Transition (SETT)*, lists and describes Air Weather Service (AWSS) operational deficiencies in analysis and forecasting of the space environment for DOD missions. One area where improvements were sought is in analysis and forecasts of the neutral atmosphere:

*"AFSPACECOM, Consolidated Space Test Center, SAC, and the Ballistic Missile Office require forecasts of the neutral atmosphere (between 50 and 1500 km) to improve atmospheric drag prediction affecting reentry vehicle accuracy, decoy*

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*discrimination, and satellite flight paths. Changes in the neutral atmosphere cause periods of enhanced atmospheric drag and the deterioration of satellite orbits."*

A significant limit to the accuracies of neutral atmospheric models is inadequate data on the principal source of energy for heating and driving the physical and chemical processes in the thermosphere and higher regions of the atmosphere (*i.e.*, above 80 km). This energy source is the EUV radiation from the sun. The status of solar EUV flux data and the need for regular (daily), accurately-calibrated measurements are discussed in Lean 1988; Rottman 1988; Schmidtke 1992.

Section IV. A.5 of MAC 05-86 also addresses requirements for the Integrated Space Environment Modelling System (EEMS) that will, in part, incorporate energy exchanges across the boundaries of models of various upper atmospheric regions. Accurate knowledge of the energy input to the neutral upper atmosphere will be required before energy exchange between the *Neutral Atmosphere Model* and *Magnetospheric, Ionospheric Forecast, and Solar/Interplanetary Models* will have significant validity.

## 2.2 Space Measurement Priority List

In late 1988, a Draft Space Data Priority List was prepared by AWS. Calibrated solar EUV measurements were assigned 13th priority with the following [edited] comments:

*"Another important growth area. Granted[,] solar EUV flux is the driver of dayside ion production and thermospheric heating, but calibrated measurements across the EUV spectrum are needed to improve first principles model calculations. SXI will provide EUV data for 225 - 300 angstroms[,] but [of] limited wavelength interval and measurement accuracy [and], therefore[,] of limited use in 1990 to 1997 time frame. [AWS] [w]ould like accurate measurements to be made by NOAA TIROS or GOES. Development time for calibrated EUV measurements is likely to be at least 5, but possibly 10 or more years, depending on funding. An operational data source for calibrated solar EUV measurements across the entire spectrum in time to provide input to the generation of space models being considered here is unlikely. Given these considerations[,] the # 13 ranking can be considered a strong sign of support for these measurements."*

SXI (Wagner 1990) will have no capability for radiometric recalibration while in orbit.

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The solar EUV data are required for a number of models that are listed below:

**Table 1. - AWS Applications for Solar EUV Data**

<b>Applications</b>	<b>Model Number</b>	<b>Priority</b>
Alerts and Warnings	I	7
Ionospheric Specification Model	II	5
Neutral Atmosphere Specification Model	IV	2
Ionospheric Forecast Model	V	5
Neutral Atmosphere Forecast Model	VII	2

### **2.3 The Need for In-Orbit Radiometric Calibration**

At EUV wavelengths, the output of the sun varies somewhat unpredictably and the detection efficiency of spectrometers changes during use. As a consequence, the record of solar EUV flux measurements is replete with uncertainties and controversies about radiometric accuracies (Lean 1988; Rottman 1988; Schmidtke 1992). Over the past two decades, attempts at similar measurements of solar vacuum ultraviolet, or VUV, flux (nominally 120- 300 nm) have demonstrated that the radiometric fidelity of solar flux observations can only be achieved by incorporating the capability for on-board radiometric calibration into the instrument. This approach is used for the SUSIM, the Solar Ultraviolet Spectral Irradiance Monitor that flew on SPACELAB and has been flown on URAS and ATLAS, to make regular radiometrically accurate measurements of the solar VUV flux (Brueckner *et al.* 1993).

We believe that future measurements of reliable, absolute, solar EUV spectral flux data for AWS applications will require frequent recalibration of the radiometric efficiency of the satellite spectrometer used for the observations, and that such recalibration must be done during the mission, *i.e.*, on board. Only in this way can changes in spectrometer detection efficiency and changes in the solar flux be unambiguously disentangled.

The research supported by AFOSR Grant 90-0063 studied methods for in-orbit radiometric calibration, including a possible small, efficient spectrograph that would be required, and some concepts for solar EUV monitoring missions.

## **3. ACTIVITIES**

### **3.1 Low-Power AESSIM Calibration lamp**

A portable secondary 'standard' of spectral irradiance for EUV wavelengths has been developed at the Physikalisch-Technische Bundesanstalt (PTB) in Berlin (Hollandt, Huber & Kühne 1993; Hollandt, Kühne & Wende 1994). A low-power (10 watts, instead of 800 watts)

in-space version of this standard EUV hollow cathode was designed and built at the Harvard College Observatory (HCO) and then tested at PTB and HCO.

We tested the lamp in laboratory optical systems that had been modified to allow the lamp to be operated in a vacuum. Our studies showed the lamp was stable but not reproducible to the accuracy required ( $\pm 5\%$ ). Our colleagues at PTB and at the University of Hannover believe that the low current of the low-power hollow cathode is not sufficient to maintain the clean, unoxidized, cathode surface that is needed for reproducibility. Therefore, we have concluded that a major redesign of the low-power version of this source will be required if a suitable model is to be developed for in-space use.

### 3.2 Combination of Rare-Gas Ionization Cells and Thin Film Filters

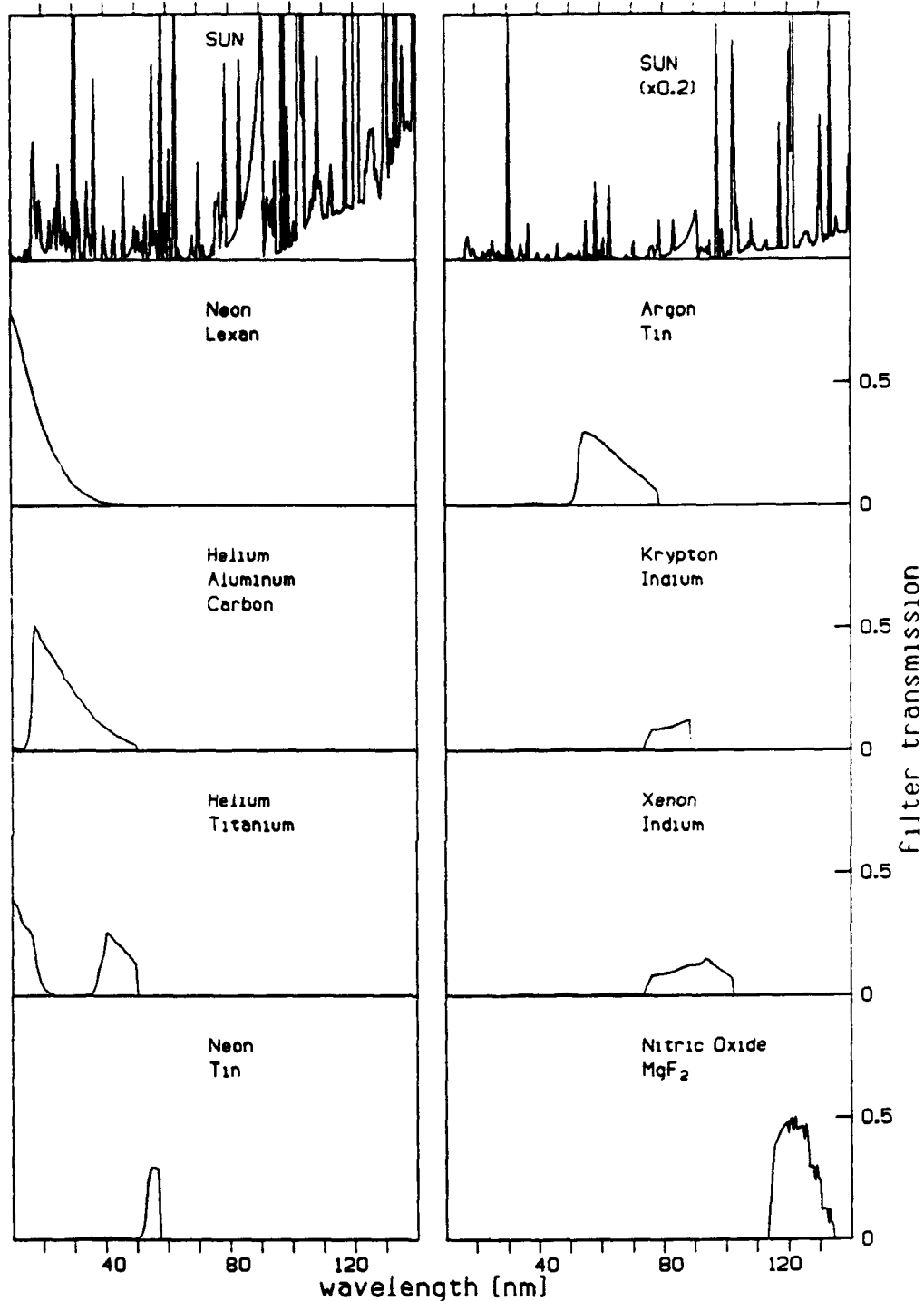
Alternative Absolute, Extreme-Ultraviolet Solar Spectral Irradiance Monitor (*AESSIM*) calibration concepts were also explored, one based on combining the photoionization continuum cross sections of the rare gases and the transmission of their thin film filters to obtain bands of absolute radiometric sensitivity within the EUV range was identified. The concept, originated by Dr. G. Schmidtke (Freiberg, Germany), depends on the rare gas ionization chamber as an absolute detector, allows for the filter transmissions to be monitored, and leads to a 'self-calibrating' EUV photometer.

Schmidtke and we explored various ideas for configurations of ionization chambers, filters, and small spectrometers. Part of our task at HCO was the characterization of the wavelength band and sensitivity that would be available from combinations of rare gases and thin film filters. Our results are summarized in Figure 1. The ionization cross sections and transmission data were available from the scientific literature and trade catalogues.

As a result of our study we concluded that the concept could work but that the availability of space-qualified<sup>1</sup> thin film filters that could be used to define a number of distinct wavelength bands had not been verified. Therefore, we chose not to include those components in an *AESSIM* concept called *ASSET*, Absolute Solar Spectrum in the EUV for *TIMED* the Thermosphere, Ionosphere, Mesosphere Energy and Dynamics Mission. Schmidtke chose to join another, competing team and to avoid conflict of interest, our collaboration with him was ended. Neither proposal was accepted.

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<sup>1</sup>We recently read [EUVE Electronic Newsletter, April 12, 1994] that an Al/Ti/C filter combination on Scanner A of EUVE has become more transparent in the wavelength  $\leq 912 \text{ \AA}$ . Diagnostic observations are underway; one explanation is that a collection of very small pinholes may have developed in the filter. A single hole would result in a catastrophic failure of a radiometry mission.



**FIGURE 1** - The solar EUV flux viewed with various combinations of ionization chambers and thin film filters. The flux data (top two panels) are the *ATMOSPHERIC EXPLORER REFERENCE WAVELENGTH TABLE OF 1659 LINES*, obtained from the National Geophysical Data Center as AES1REF.DAT, binned at 0.5 nm intervals. Full-scale values on the top two panels, which show the same data, are  $10^9$  ph  $\text{cm}^{-2}$   $\text{sec}^{-1}$  (left) and  $5 \times 10^8$  ph  $\text{cm}^{-2}$   $\text{sec}^{-1}$  (right). The lower eight panels, which all have a full scale value of  $0.25 \times 10^9$  ph  $\text{cm}^{-2}$   $\text{sec}^{-1}$ , show the solar flux bands that would be integrated by ionization chambers with various thin-film-filter, 'window' materials (see text). The products of filter transmissions and gas quantum yields are shown by the dotted lines. Filter thicknesses of  $0.15 \mu\text{m}$  were used, except for the  $\text{MgF}_2$  'filter', which was assumed to be 1 mm thick.

### 3.3 Small, Fixed Grating Spectrographs with Array Detectors

We investigated and evaluated designs of fixed-grating spectrographs equipped with array type detectors (Sandel & Broadfoot 1993). In spectrographs with array detectors, the spectral resolution is set by the detector pixel size. We envisioned a CCD based detector (discussed below) with spatial resolution of 30 line pairs per mm, which is approximately equivalent to a line profile width of 33  $\mu\text{m}$ .

Air force solar flux data needs could be met by spectra with 0.1 to 0.2 nm resolution, so we designed a 4 spectrograph, 2 detector package with such resolution over the range 5 to 175 nm. The compact size and grazing incidence configuration allowed the four spectra, which overlap in wavelength to provide redundancy, to be detected by two array detectors (*i.e.* two short wavelength spectrographs share one detector & two long wavelength spectrographs would share another). Total mass, including detectors but not electronics was estimated to be 1.6 kg. No telescopes were used; radiation from the full Sun would enter the spectrographs through small entrance slits. The dimensions, specifications, and performance of the spectrographs, are given in Table 2. A schematic diagram is given in Figure 2. To be conservative, the resolution given in Table 2 is for 36  $\mu\text{m}$  - two pixel widths - at the focal plane.

The gratings would be mechanically ruled in a vacuum deposited gold coating and then ion etched. This process, which ion etches the substrate in a near direct duplication of the ruled surface, is optimum for producing blazed grazing-incidence gratings. The grating substrate may be SiC or fused silica. The first order grating efficiency is estimated to be 5 to 20 percent throughout the *ASSET* wavelength range.

The *ASSET* spectrograph detectors would be intensified charge coupled devices (ICCD) modelled after the successful detectors developed here by our colleagues for the Normal Incidence X-Ray Telescope (NIXT) Project (Golub 1992) and, independently at the University of Arizona. Because our wavelength range of interest is different from that of NIXT, we explored detector parameters to ensure that ones suitable for solar EUV monitoring were possible.

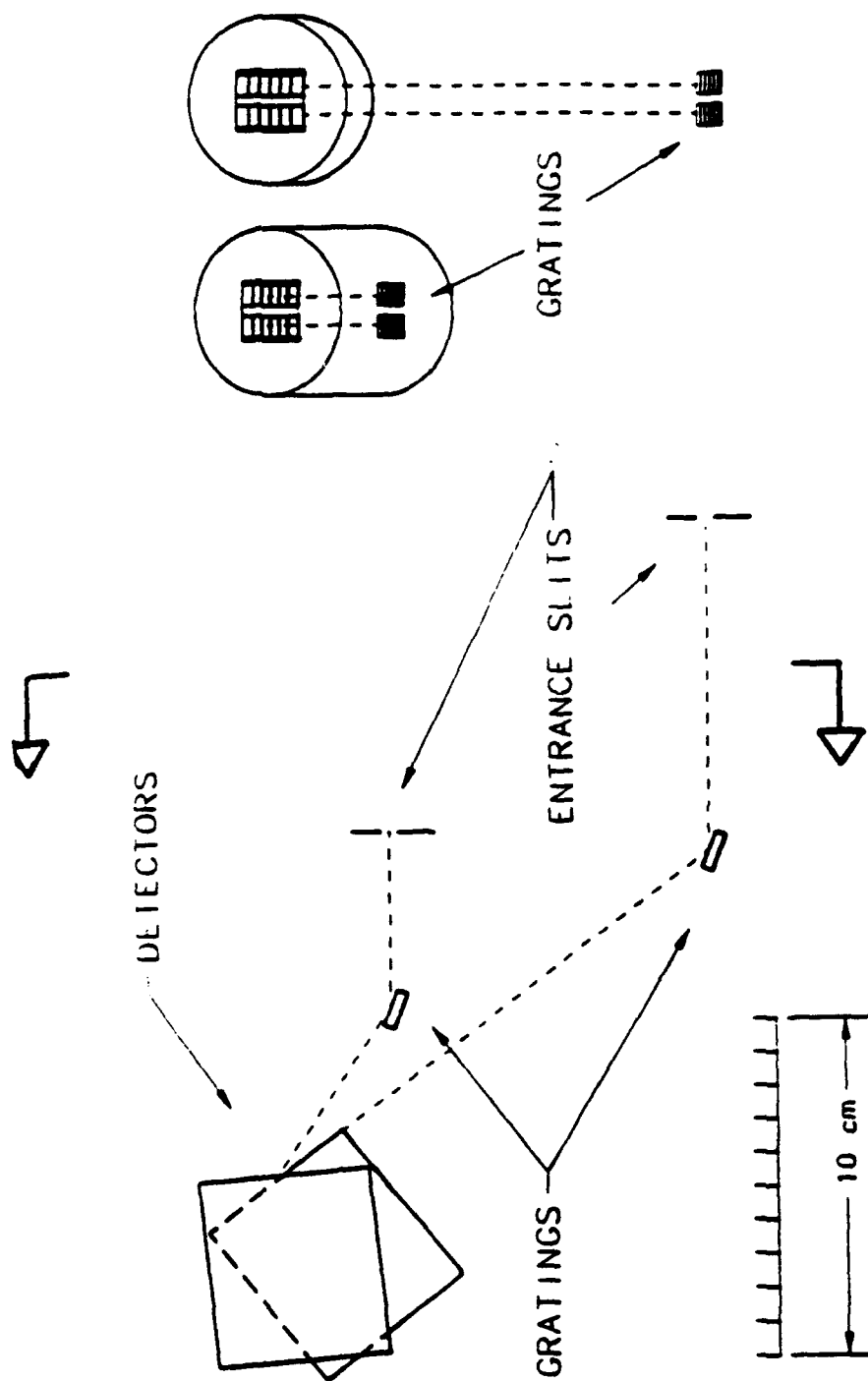
The detector concept is shown schematically in Figure 3. Incoming photons strike a microchannel plate (MCP) image intensifier operated at a gain of  $<1000$ . The charge cloud from the image intensifier is accelerated through  $-5000$  V until it strikes an aluminum-coated phosphor screen on the front of a fiber-optic bundle that couples the photons onto a 1024 x 1024 pixel CCD. To reduce cost and effort, we would use three nearly identical detectors.

The microchannel plate acts as an electronic shutter during CCD readout and as a variable gain stage to increase the dynamic range and allow individual photons to be detected above the CCD readout noise. The spectrum is integrated on the CCD for an interval ranging from tens of milliseconds to tens of seconds and is then read out into the data electronics memory.

Table 2: Parameters and Specifications for ASSET Grazing Incidence Spectrometers

detector width	18 mm			
pixels	1000 × 1000; ~18 μm square			
	short wavelength		long wavelength	
Rowland circle diameter	200 mm		300 mm	
incident angle, α	75 degrees		70 degrees	
exit angle, β	71.9 degrees		58 degrees	
slit dimensions (nominal)	15 μm × 1 mm		10 μm × 0.1 mm	
grating lines per millimeter	600.	300.	800.	600.
minimum wavelength [Å]	40.	80.	952.	1269.
center wavelength [Å]	340.	514.	1146.	1527.
maximum wavelength [Å]	506.	1012.	1349.	1799.
grating grooves illuminated	1111.	556.	2222.	1667.
reciprocal dispersion [Å mm <sup>-1</sup> ]	27.	52.	22.	29.
resolution [Å per 36 μm]	1.	1.9	0.8	1.1
slit to grating [mm]	52.	52.	103.	103.
grating to detector [mm]	65.1	62.1	159.	159.
image size [mm] (see note a)	2.7	2.7	3.6	3.6
minimum β [degrees]	69.3	69.3	56.3	56.3
maximum β [degrees]	74.5	74.5	59.7	59.7
note a: astigmatism plus slit length of 1 mm				





ASSET GRAZING INCIDENCE SPECTROGRAPHS

Figure 2: Schematic diagram of ASSET spectrographs.

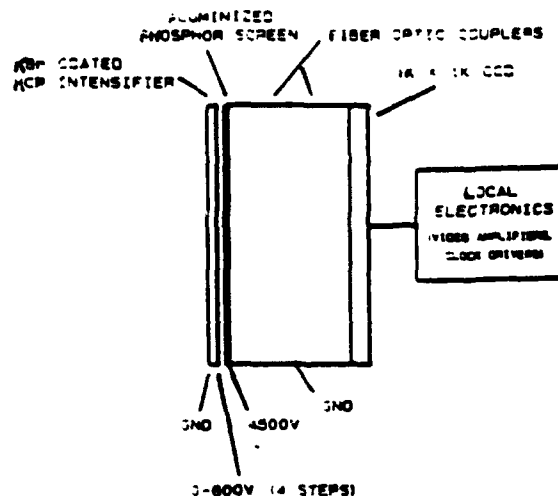


Figure 3: Schematic Diagram of Detector

The EUV photons from a particular grating are incident on the faceplate of a single, flat, microchannel plate. A standard flat plate would be used instead of a cylindrical one in order to simplify the construction of the intensifier and so that the detectors can be made identical. The image spread due to the detector surface not being on the Rowland circle is  $< 6 \mu\text{m}$ . The microchannel plate would have  $> 1 \mu\text{m}$  of deposited photocathode material in order to increase its quantum efficiency at the large angle of incidence of the grating spectrograph detectors and for wavelengths longer than  $1000 \text{ \AA}$ . The photocathode would probably be KBr, which is stable even after being exposed to air for long intervals (weeks to months), but the choice of a specific photocathode would not be made until we could obtain more data on stability.

Detected photoelectrons are amplified by factors of ten to several thousand in the microchannel plate pores and then accelerated onto an aluminized phosphor screen deposited on the fiber optic faceplate. At maximum gain each incident EUV photon would produce an average of  $10^4 - 10^5$  visible light photons at the back of the intensifier. A second fiber optics coupler, tapered to match the image and CCD sizes, is bonded to the  $1024 \times 1024$  pixel CCD with  $15-18 \mu\text{m}$  pixels. The CCD input is grounded to protect it from leakage currents from the phosphor high voltage.

The CCD is operated in the Multi-Pinned Phase (MPP) mode to reduce the dark current down to  $< 25 \text{ pA/cm}^2$  at room temperature, which corresponds to about 1000 electron-hole pairs/pixel/sec at 25 C and about 30 hole-pairs/pixel/sec at 0 C. The full well capacity is approximately  $250,000 \text{ e/pixel}$  and the readout noise will be  $\leq 30 \text{ e}$ .

The active areas of the detectors are larger than necessary in the direction perpendicular to the plane of dispersion, where 12 mm would suffice to image the two spectra from each pair of spectrographs. However because standard components would be used, the detectors would be large enough so that the option would remain to feed a single detector from the four spectrographs.

Signal levels for the grazing incidence spectrographs have been estimated for solar maximum conditions and are presented in Table 3. For  $\lambda \leq 1050 \text{ \AA}$ , fluxes from Torr & Torr (1985) were used; their continuum fluxes are for 50  $\text{\AA}$  bands, which will illuminate about 12,250 pixels in the spectrometers. For  $\lambda \geq 1200 \text{ \AA}$ , flux data are from Mount *et al.* (1980), whose continuum values are for a 1  $\text{\AA}$  band. Such bands, and lines at all wavelengths, would be spread over about 300 pixels. Slits of 15  $\mu\text{m} \times 1 \text{ mm}$  were used for the short wavelengths; 10  $\mu\text{m} \times 100 \mu\text{m}$  were assumed for the longer wavelengths. Grating reflectivities and detector quantum efficiencies of 10 percent were assumed throughout. The final column of Table 3 gives the number of detected photons per pixel per second.

### 3.4. Proposed Solar EUV Monitoring Missions

Our ideas for solar EUV monitoring missions have been described in some detail in the two proposals: *ASSET: Absolute Solar Spectrum in the EUV, an Experiment Proposal for TIMED* (July 21, 1992) submitted in response to NASA A.O. 92-OSSA-1 and *SVELTER: Solar Voyager Experiment for Long Term EUV Radiometry* (September 1993) submitted in response to NASA NRA 93-OSS-01.

We believe that more development is required for the low-power hollow cathode, radiance standard, approach to radiometric accuracy and for the method employing thin film filters and ionization chambers. Therefore our new concepts for solar EUV monitoring missions require radiometric recalibration of the Ultraviolet Spectrometers (UVS) on the *Voyager* spacecrafts. Details on the current status of and potential for using the *Voyager* spacecraft and the UVS's have been reported (Smith, Sandel and Holberg 1993, included as Appendix I).

The Abstracts for each of the above proposals are reproduced here, and thus in conjunction with the Smith *et al.* 1993 paper, will describe in brief our ideas for solar EUV monitoring through full-disk solar spectral irradiance measurements coupled with semi-empirical spectral modelling.

wavelength	10 <sup>-9</sup> ph/cm <sup>2</sup> /s/		slit [cm]	grat. refl.	detr. q.e.	pixs illum.	pix.soni per sec	
	min	max						
50	100	0.38	1.15	1.5E-04	0.1	0.1	12250	0.1
100	150	0.13	0.34	1.5E-04	0.1	0.1	12250	0.0
150	200	1.84	4.85	1.5E-04	0.1	0.1	12250	0.6
200	250	0.92	3.70	1.5E-04	0.1	0.1	12250	0.5
250	300	0.84	4.14	1.5E-04	0.1	0.1	12250	0.5
300	350	0.87	5.63	1.5E-04	0.1	0.1	12250	0.7
350	400	0.21	2.20	1.5E-04	0.1	0.1	12250	0.3
400	450	0.39	0.99	1.5E-04	0.1	0.1	12250	0.1
450	500	0.31	1.67	1.5E-04	0.1	0.1	12250	0.2
500	550	0.51	1.55	1.5E-04	0.1	0.1	12250	0.2
550	600	0.48	1.02	1.5E-04	0.1	0.1	12250	0.1
600	650	0.17	0.48	1.5E-04	0.1	0.1	12250	0.1
650	700	0.22	0.46	1.5E-04	0.1	0.1	12250	0.1
700	750	0.17	0.43	1.5E-04	0.1	0.1	12250	0.1
750	800	0.87	2.18	1.5E-04	0.1	0.1	12250	0.3
800	850	1.93	5.01	1.5E-04	0.1	0.1	12250	0.6
850	900	4.43	13.30	1.5E-04	0.1	0.1	12250	1.6
900	950	4.22	12.03	1.5E-04	0.1	0.1	12250	1.5
950	1000	1.79	4.42	1.5E-04	0.1	0.1	12250	0.5
1000	1050	3.64	8.67	1.5E-04	0.1	0.1	12250	1.1
1200	1250		5.4	1.0E-05	0.1	0.1	300	1.8
1250	1300		1.5	1.0E-05	0.1	0.1	300	0.5
1300	1350		4.8	1.0E-05	0.1	0.1	300	1.6
1350	1400		3.1	1.0E-05	0.1	0.1	300	1.0
1400	1450		3.8	1.0E-05	0.1	0.1	300	1.3
1450	1500		5.4	1.0E-05	0.1	0.1	300	1.8
1500	1550		9.5	1.0E-05	0.1	0.1	300	3.2
1550	1600		12.2	1.0E-05	0.1	0.1	300	4.1
1600	1650		17.6	1.0E-05	0.1	0.1	300	5.9
1650	1700		32.2	1.0E-05	0.1	0.1	300	10.7
1700	1750		56.6	1.0E-05	0.1	0.1	300	18.9
1750	1800		72.6	1.0E-05	0.1	0.1	300	24.2
284.2	Fe XV	0.10	3.17	1.5E-04	0.1	0.1	300	15.8
303.3	Si XI	0.24	2.50	1.5E-04	0.1	0.1	300	12.5
303.8	He II	6.00	11.28	1.5E-04	0.1	0.1	300	56.4
368.1	Mg IX	0.74	1.39	1.5E-04	0.1	0.1	300	7.0
465.1	Ne VII	0.18	0.36	1.5E-04	0.1	0.1	300	1.8
554.4	O IV	0.80	1.59	1.5E-04	0.1	0.1	300	8.0
584.3	He I	1.58	4.87	1.5E-04	0.1	0.1	300	24.3
609.8	Mg X	0.45	1.46	1.5E-04	0.1	0.1	300	7.3
629.7	O V	1.50	3.02	1.5E-04	0.1	0.1	300	15.1
703.3	O III	0.39	0.72	1.5E-04	0.1	0.1	300	3.6
789.4	O IV	0.79	1.59	1.5E-04	0.1	0.1	300	7.9
765.2	N VI	0.20	0.43	1.5E-04	0.1	0.1	300	2.2
770.4	Ne VIII	0.24	0.67	1.5E-04	0.1	0.1	300	3.4
977.2	C III	5.96	13.18	1.5E-04	0.1	0.1	300	65.9
1025.7	H I	4.38	13.13	1.0E-05	0.1	0.1	300	4.4
1031.9	O VI	3.18	9.04	1.0E-05	0.1	0.1	300	3.0
1215.7	Ly-alpha		436.0	1.0E-05	0.1	0.1	300	145.3
1238.8	N V		0.7	1.0E-05	0.1	0.1	300	0.2
1242.8	N V		0.5	1.0E-05	0.1	0.1	300	0.2
1260.4	Si II		0.5	1.0E-05	0.1	0.1	300	0.2
1264.7	Si II		0.9	1.0E-05	0.1	0.1	300	0.3
1302.2	O I		4.7	1.0E-05	0.1	0.1	300	1.6
1304.9	O I		4.6	1.0E-05	0.1	0.1	300	1.5
1306.0	O I		4.6	1.0E-05	0.1	0.1	300	1.5
1334.5	C II		11.0	1.0E-05	0.1	0.1	300	3.7
1335.7	C II		11.0	1.0E-05	0.1	0.1	300	3.7
1355.6	O I		1.0	1.0E-05	0.1	0.1	300	0.3
1393.8	Si IV		7.4	1.0E-05	0.1	0.1	300	2.5
1402.8	Si IV		3.3	1.0E-05	0.1	0.1	300	1.1
1526.7	Si II		4.2	1.0E-05	0.1	0.1	300	1.4
1548.2	C IV		16.0	1.0E-05	0.1	0.1	300	5.3
1550.8	C IV		6.9	1.0E-05	0.1	0.1	300	2.3
1561.0	C I		6.8	1.0E-05	0.1	0.1	300	2.3
1640.3	He II		9.4	1.0E-05	0.1	0.1	300	3.1
1687.0	C I		27.0	1.0E-05	0.1	0.1	300	9.0
1808.0	Si II		13.0	1.0E-05	0.1	0.1	300	4.3
1817.0	Si II		27.0	1.0E-05	0.1	0.1	300	8.7

Table 3: ASSET signal levels.

## PRESENTATIONS

We discussed *AESSIM* at an Air Weather Service Quarterly Space Model Development Review (SMDR) Meeting, Special Science Session on the Atmospheric Impact of Solar EUV and Concepts for Measurement at Peterson AFB, 29 January 1990. A second presentation, which included the ideas and plans for collaboration with G. Schmidtke, was presented at the Quarterly SMDR meeting held at Hanscom AFB, 15 May 1990. We reviewed the needs for regular, accurate measurements of the solar EUV flux and our concepts for in-orbit calibration of such EUV monitoring equipment at a Workshop on EUV Radiometry for Solar and Terrestrial Physics at PTB in Berlin, October 1990. These three presentations were not published.

We presented a paper on the *AESSIM* plan at a USA-Taiwan Bilateral Workshop on Solar Variability Effects on the Atmosphere and Space Processing, Taipei, 15 April 1991. We presented the plan for *AESSIM* and the need for continuous long-term measurements of solar EUV input to the Earth at a workshop on Solar Terrestrial Impact on Global Change, Boulder, 8 May 1991. At the SOLERS22 (Solar Electromagnetic Flux Study for Solar Cycle 22) workshop at Boulder, 3 June 1991, we presented two ideas for in-orbit calibration: *AESSIM* plus an EUV hollow cathode absolute radiance standard and *AESSIM* plus a self-calibrating EUV spectrometer.

Concepts and ideas for regular, radiometrically accurate solar EUV spectral irradiance measurements were presented at the Forth Meeting on New Development & Application in Optical Radiometry, Baltimore, October 1992 and at the Ninth Workshop on the Vacuum Ultraviolet Calibration of Space Instruments, Boulder, March 1993.

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**PUBLICATIONS** (continued)

*In-Orbit, EUV Radiometric Calibration of Satellite Instrumentation*, P. L. Smith, M. C. E. Huber, W. H. Parkinson, M. Kühne & M. Kock, in **EXTREME ULTRAVIOLET ASTRONOMY**, ed. R. F. Malina and C. S. Bowyer (New York: Pergamon), p. 390 (1991).

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## ASSET Abstract

*ASSET* (Absolute Solar Spectrum in the Extreme Ultraviolet for *TIMED*) will provide the solar EUV flux data required to address the *TIMED* science objectives.

The *ASSET* instrument package, proposed in this Experiment Proposal for *TIMED*, will comprise four, small, simple, grazing-incidence spectrographs that will measure the solar EUV spectral irradiance from 50 to 1750 Å with resolution of about 1 - 2 Å, and a transmission grating spectrograph that will provide coverage of the range 20 to 50 Å with a resolution of 5 - 10 Å.

The radiometric detection efficiency of the *ASSET* instruments will be established by extensive preflight calibration, onboard absolute detectors, and contemporaneous observations with existing stable spectrographs on other spacecraft, all of which will be tracked by calibration rocket (or Shuttle) underflights. Specifically, low-resolution solar spectra obtained by the radiometrically stable UltraViolet (UVS) on the *Voyager* spacecraft in the wavelength region 500 - 1750 Å will be used to supplement the radiometric measurements to be obtained by the *ASSET* spectrographs during the periods between underflights.

Two stable detectors, a rare gas ionization cell and an XUV grating photometer patterned after the Solar EUV Monitor on *SOHO*, will provide broadband, radiometrically accurate measurements for  $\lambda \leq 750$  Å. These measurements will be used to calibrate the portion of the *ASSET* EUV spectrographs not monitored by the *Voyager* UVS observations.

The *ASSET* instrument package meets the observational requirements of the *TIMED* mission within the mass and power constraints established by the *TIMED* Science Definition Team. The *ASSET* spectrographs and photometer are based on well established designs with off-the-shelf components; the *ASSET* detectors have a proven heritage. The *ASSET* Scientific and Engineering Team consists of senior scientists and engineers with spacecraft experience, dating back to the beginning of NASA spaceflight programs in 1959, that includes a significant number of solar radiometric measurements, especially at EUV wavelengths.



## SVELTER Abstract

*SVELTER* (Solar-Voyager Experiment for Long-Term EUV Radiometry) will provide, through a program of full-disk, solar spectral irradiance measurements coupled with semi-empirical spectral modelling - each with fundamental emphasis on radiometric accuracy - daily solar extreme ultraviolet spectral irradiance data for use in ITM (ionospheric, thermospheric, mesospheric) studies, and in analysis of data from Space Physics missions.

One of the basic *SVELTER* goals is radiometric calibration of the Ultraviolet Spectrometers on the *Voyager* spacecraft. The UVS's cover the range 50-170 nm with a resolution of 2 nm and are radiometrically stable. Calibration of their radiometric efficiency will correct the radiometric scale of the large archive of UVS solar spectra from the last decade and will provide a regular and routine means of checking the radiometric scale of the *SVELTER* solar EUV data.

The *SVELTER* program comprises two sets of fundamental measurements from space and a modelling program:

- (i) A suborbital 'flight' of a radiometrically calibrated payload comprising, in part, a full solar-disk-viewing EUV spectrometer that will measure the spectral irradiance and a high-spatial, high-spectral-resolution imaging EUV spectrometer that will observe selected portion of the disk. The payload, HiRES Principal Investigator, J. G. Timothy, of Stanford University, will be a *SVELTER* Co-Investigator for these observations.
- (ii) A modelling program directed by E. H. Avrett, a Co-Investigator from the Smithsonian Astrophysical Observatory, will correlate the rocket-spectrometer and ground-image intensity data (eg. daily Ca II K<sub>3</sub> 393 nm images; K<sub>3</sub> is a central peak of Ca II which has been shown to be closely related to intensity in the transition region) to produce a semiempirical model of the solar EUV spectrum that can be used to model the EUV spectral irradiance on all days from which K<sub>3</sub> images are available or can be estimated.
- (iii) The first suborbital flight will be timed to optimize the radiometric calibration of the UVS's. Regular (approximately bi-weekly) observations of the solar spectral irradiance will be made with the UVS's to verify the correctness of the radiometric scale of the semiempirical EUV spectra.

The semiempirical EUV spectral irradiance data will be developed from observed relationships between EUV irradiance and intensity data at all wavelengths and locations on the solar disk, and corresponding K<sub>3</sub> and He II 1083 nm image intensities.

**APPENDIX I**

## Using The Voyager Spacecraft for Solar EUV Spectral Radiometry <sup>1</sup>

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**Abstract.** The ultraviolet spectrometers on the *Voyager* spacecraft are radiometrically stable and presently capable of making long-term, precise measurements of the solar spectral irradiance between 50 and 170 nm. If the detection efficiencies of these spectrometers were confirmed through a dedicated program of underflights, and if a campaign of regular *Voyager* observations of the Sun were instituted, some of the needs for timely, long-term solar EUV flux data could be efficiently met in this decade.

### The Need for Solar EUV Spectral Irradiance Data

Extreme ultraviolet (EUV) radiation from the Sun - considered, herein, to be the solar radiation between 10 and 120 nm - is highly variable on both short (minute) and long (many year) time scales [Schmidtke 1992; Lean 1988; Rottman 1988; Hall *et al.* 1985]. The changes are wavelength-dependent and unpredictable. Solar EUV photons are absorbed in the terrestrial thermosphere and mesosphere, *i.e.*, above about 80 km in the atmosphere, where they heat, excite, and ionize the atomic and molecular constituents [Meier 1991]. This radiation is the principal source of energy for producing and maintaining the complex, time-dependent, thermal and compositional structures and large-scale circulations of this part of the atmosphere [Roble 1987].

There are important, broadly-based, scientific needs for new and improved measurements of the solar EUV spectral irradiance to support aeronomical studies and calculations of global thermospheric and ionospheric dynamics [Meier 1991; Roble 1987]. Many fundamental aspects of the interaction of solar EUV radiation with the terrestrial upper atmosphere are still uncertain: For example, there are discrepancies between the measured photoelectron fluxes in the ionosphere and modelled fluxes based on solar EUV reference spectra [Richards & Torr 1984, 1988]. Accurate and timely solar EUV flux data are also required for improved predictions of thermospheric density and concomitant atmospheric drag on reentry vehicles and satellites in

<sup>1</sup>This work was first presented at the Fourth International Conference on New Developments and Advances in Absolute Radiometry (Baltimore, MD, October 1992) and published in *Metrologia*.

low earth orbit [Davis *et al.* 1987; Marcos 1988]. Experiments that observe EUV radiation absorbed or emitted by planetary atmospheres [Broadfoot *et al.* 1981; Smith *et al.* 1983; Herbert *et al.* 1987; Broadfoot *et al.* 1989], terrestrial aurora and airglow spectra [Meier 1991; Chakrabarti *et al.* 1983; Paresce *et al.* 1983], or radiation backscattered from the local interstellar medium [Chassifière 1986] also require accurate solar EUV flux data. Future space missions that will make spatially resolved EUV observations of the Sun, *e.g.*, the Solar and Heliospheric Observatory (SOHO) [Domingo 1989], will require reliable and timely solar spectral irradiance data in analyses of observations and for evaluations of the radiometric efficiencies of the telescope and spectrometer optics.

As a result of these disparate needs, a number of groups, including a Panel of the U. S. National Research Council concerned with long-term solar-terrestrial effects [Siscoe 1988], a NASA committee concerned with drag on the Hubble Space Telescope and other satellites [Withbroe 1989], and a NOAA study on global change (Avery *et al.* 1992) have recognized the need for real-time, accurately-calibrated, solar EUV spectral irradiance measurements, and, consequently, have recommended that regular, long-term solar EUV spectral irradiance data be obtained. There are many ideas and plans for such measurements, but no instrumentation is being developed at this time.

This paper points out that two spacecraft capable of making modest-resolution ( $\sim 2$  nm) solar EUV spectral irradiance measurements are now in operation. The radiometric efficiencies of their telescope and spectrometer optics are known to be stable. Therefore, these instruments - the ultraviolet spectrometers on the *Voyager* spacecraft - could, if radiometrically calibrated, provide regular, accurate, solar EUV spectral irradiance data until dedicated instruments for such measurements are developed and flown.

### Current Status of Solar EUV Spectral Irradiance Data

No one has yet obtained radiometrically accurate solar EUV flux measurements for a period longer than that of a rocket shot, *i.e.*, a few minutes. Consequently, the history [Schmidtke 1992; Rottman 1988; Lean 1988] of solar EUV spectral radiometry is replete with problematic data. The causes are multiple and, in part, interconnected. For example, many measurements have been attempted without the necessary emphasis on radiometric calibration. In addition, simultaneous measurements using different techniques have been rare, with the consequence that intercomparisons that could provide checks on accuracy have been difficult.

A number of attempts at long-term solar EUV spectral irradiance measurements have been made for  $\lambda \leq 120$  nm [Schmidtke 1992]. One, part of the Atmospheric Explorer (AE) satellite program, provided solar flux data for a number of intervals in the 1976-80 period [Hinteregger 1981]. Questions about the accuracies of the solar flux data from the AE's have led to adjustments, renormalizations, and concomitant uncertainties. Fukui [1990] has recently addressed some of these issues.

Another long term study of the EUV output of the Sun was by the Airglow-Solar Spectrometer Instrument (ASSI) on the San Marco D/L satellite [Schmidtke 1985], which made measurements for eight months in 1988. A solar EUV 'reference' spectrum from ASSI has been published [Schmidtke *et al.* 1992]. The normalization for this spectrum was provided, in part, by comparison with Solar Mesospheric Explorer (SME) data, with data obtained during a sounding rocket flight [Woods & Rottman 1990], and by an internal calibration method.

'Instantaneous' solar EUV spectral irradiance measurements have been made with rocket-borne instrumentation [Woods & Rottman 1990; Ogawa *et al.* 1992]. Judge and colleagues have also made some broad-band (5 - 57 nm) solar flux measurements that appear to be accurate

[Ogawa *et al.* 1990; Feng *et al.* 1989; Ogawa & Judge 1986].

However, because the solar EUV flux is both time and wavelength-dependent, the AE, ASSI, and rocket solar EUV flux data sets cannot – even if concerns about their somewhat uncertain radiometric calibrations are mitigated – be directly used for accurate modelling of current and future properties of, and processes in, the atmospheres of the Earth and planets. Therefore, parameterizations of the solar flux data that employ ‘proxy’ or ‘surrogate’ indices [Lean 1988; Hedin 1987; White 1987; Tobiska 1991] of the EUV flux are used to cover more recent time periods. However, the validities of the proxies are, for the most part, based on their correlations with the problematic AE solar flux data over small portions of a single solar cycle. The imprecise solar-flux data sets produced by using proxies lead to uncertainties when attempting to model conditions in terrestrial and planetary atmospheres and in spacecraft drag determinations.

Researchers in the field of solar vacuum-ultraviolet and ultraviolet radiometry (120 - 400 nm) are hopeful that SUSIM [Brueckner 1993; vanHoosier 1993] and SOLSTICE [Woods 1993; Pankratz 1993] will provide reliable solar flux data for wavelengths longer than those of the EUV. However, there is, at present, no development of instrumentation for long-term – *i.e.*, longer than the duration of a Shuttle flight – solar spectral irradiance measurements at EUV wavelengths. Consequently, we draw attention to the capabilities of the ultraviolet spectrometers on the *Voyager* spacecraft, which could be used to provide, for approximately the next ten years, some of the regular solar EUV flux data that will be required during that time.

### The Voyager Spacecraft and the Voyager Ultraviolet Spectrometers

The *Voyager* spacecraft were launched in 1977 for extensive explorations of the outer solar system. *Voyager 1* is now about 50 AU from the Sun and is leaving the solar system at a rate of  $\sim 3.5$  AU year<sup>-1</sup> along a trajectory inclined +35° to the ecliptic in the direction of the constellation Hercules. *Voyager 2* is now about 40 AU from the Sun and is leaving the solar system at a rate of  $\sim 2.7$  AU year<sup>-1</sup> along a trajectory inclined -48° to the ecliptic in the direction of Sagittarius. If both spacecraft continue to operate as well in the future as they have in the past, they should have sufficient electrical power and attitude control gas to continue transmitting data until at least 2015 [Stone & Miner 1989].

Each spacecraft includes a Wadsworth-mounted, objective-grating, ultraviolet spectrometer (UVS) covering the wavelength range 50 - 170 nm with 2-pixel resolution of better than 2 nm [Broadfoot *et al.* 1977]. Broadfoot *et al.* [1981] have reviewed early in-flight performance of the UVS's. The *Voyager Science and Mission Systems Handbook* [JPL PD 618-128] and the *Voyager Neptune Travel Guide* [JPL Pub. 89-24] give comprehensive general information on the *Voyager* spacecraft.

Since 1990, the *Voyagers* have been devoted, primarily, to the ‘Voyager Interstellar Mission’ (VIM), which is designed: (i), to investigate the interplanetary medium and interstellar wind, and to characterize the interaction between the two, and, (ii), to continue the successful *Voyager* programs of interstellar astronomy. VIM is directed by the Space Physics Division of NASA. Astronomical observations will be discontinued in approximately 1995, when the data rates required for spectroscopic work on stellar sources will no longer be routinely available. However, because of the much larger signal from the Sun, useful solar observations will be possible until about 2005, as will systematic observations of the sky background at the wavelengths of the H I Lyman- $\alpha$  and He I 58.4 nm emissions for interstellar wind studies. After  $\sim 2005$ , there is unlikely to be sufficient power to provide the requisite heating of the scan platform actuators.

The 34-m antennas of the Deep Space Net (DSN) are used to receive most UVS data.

After the year 2000, the 70-m antennas, which are often in demand for a host of high priority space missions, could be required to support a data rate of one UVS spectrum per 3.84 s using the presently available data formats at the rate required for solar observations. As an alternative to obtaining 70-m station coverage, it would be possible to reload a previously used cruise data mode (CR-5) that would provide the required UVS sample rate at lower spacecraft data rates. With this mode, a regular solar observing program could be conducted with the more readily available smaller receiving antennas.

### Solar EUV Spectral Radiometry with the Voyager UVS's

The UVS's were designed primarily to observe EUV airglow from the outer planets and to make stellar- and solar-occultation observations of their atmospheres. The latter observations required the capability to measure the solar EUV spectrum, albeit without concern about radiometric calibration. The *Voyager* UVS archives contain a number of measurements of this spectrum: There were 65 observations before 1991, primarily at the times of planetary encounters, and more frequent measurements thereafter.

The UVS radiometric efficiencies for solar and stellar spectroscopy in the range 91 - 170 nm have been constant for a decade [Linick & Holberg 1991; Holberg *et al.* 1991]. The values - which are not known with the absolute accuracy required for solar EUV radiometry - have recently been tentatively confirmed by the Hopkins Ultraviolet Telescope (HUT) team [Davidsen *et al.* 1992]. Because the UVS's are now 16 years old and no longer exposed to the intense solar radiation field at 1 AU, no future changes in the radiometric efficiencies are expected. The effects of interplanetary absorption on the solar spectrum are rather small [Wu & Judge 1979]. The strong solar Lyman- $\alpha$  line was saturated in spectra obtained when the *Voyagers* were closer to the Sun, but no distortions of the solar spectrum are expected now.

An example of a solar EUV spectrum obtained by one of the *Voyager* UVS's is shown in Figure 1. No absolute scale is given for the spectral irradiance because there has been no confirmation of the *Voyager* radiometric efficiency below 91 nm.

When the SUSIM [Brueckner 1993; vanHoosier 1993] and SOLSTICE [Woods 1993; Pankratz 1993] flux data have been intercompared and validated, simultaneous observations with these instruments and the UVS's will confirm the radiometric efficiency of the UVS's from the long wavelength end of the EUV range, *i.e.*, from 115 - 120 nm, to 170 nm. The agreement between the HUT and UVS radiometric scales provides some confidence in the shape of the UVS efficiencies between 91 and 120 nm. However, there has been no confirmation of the *Voyager* UVS radiometric efficiencies for the wavelength range 50 - 91 nm. Such information could be obtained through dedicated rocket or Shuttle radiometric missions that would observe the sun with calibrated instruments simultaneously with *Voyager* UVS observations. Simple corrections for  $(distance)^2$  and absorption by interplanetary material would be required.

### Discussion

The active region contribution to the solar EUV variability is large, so the EUV radiation is not isotropic. Because the Earth circles the Sun while the *Voyagers* are at relatively constant heliocentric longitudes - about 270° and 310° for *Voyager 1* and *2*, respectively - the *Voyagers* would measure the same solar EUV radiation that is incident on the Earth's atmosphere only during one part of the year, *viz.*, June and July. There could be, at other times of the year, significant differences between the *Voyager*-measured radiation and that absorbed in the thermosphere and ionosphere.

At the Earth, the dominant effect of the radiation anisotropy is modulation of solar EUV fluxes at the 27-day solar rotation period. Because active region lifetimes are, typically, greater than the rotation period of the Sun, first order estimates of the flux at the Earth could be obtained from *Voyager* fluxes shifted in phase by  $\pm 14$  days or less. Modelling techniques [Avrett 1992; Mariska 1992] that would employ 'out-of-phase' *Voyager* spectra and other data, such as ground based images of the Sun, magnetograms [Harvey 1992], etc., could be used to provide corrected solar EUV irradiance data during flares and other energetic events that occur when the *Voyagers* are viewing sides of the sun different from that facing the earth.

*Voyager 1* and *2* observe the Sun from above and below the ecliptic, respectively. Thus, each views extra area at one pole of the Sun but misses part of the other. However, because the poles of the Sun are generally 'quiet', the flux from the unobserved region at one pole is very likely to be compensated for by the flux from the extra area observed at the other. This balance will not be quite valid if there is a large coronal hole at one pole but not at the other. However, coronal holes are stable, lasting for several rotations, and can be characterized by ground-based observations of the He I line at 1083 nm. Thus the necessary small corrections to the radiometry could be made using the modelling techniques mentioned above.

These real, but minor, complications should not obscure the fact that the ultraviolet spectrometers on the *Voyager* spacecraft could be used, starting today and for at least ten more years, for measurements of *relative changes* in the solar EUV spectral irradiance. If efforts were made to determine, or confirm, the radiometric detection efficiencies of these spectrometers through a dedicated series of calibration-rocket or Space Shuttle observations then *absolute* solar EUV spectral irradiance data - required for improved understanding of the properties and processes of the upper atmospheres of the Earth and planets - could be obtained through regular observations of the Sun with these spectrometers. Such observations would likely provide the only method of regular monitoring of the solar EUV flux in this decade.

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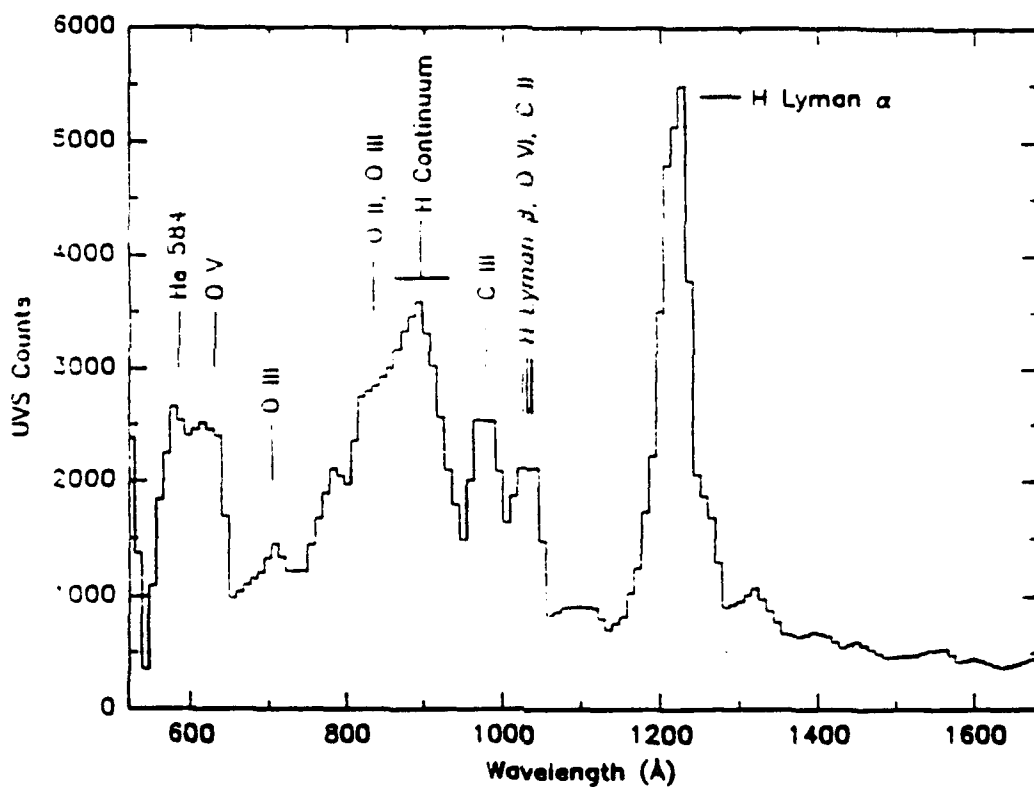
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Voyager UVS spectrum of the Sun.