

# Normal incidence spectrophotometer with high-density transmission grating technology and high-efficiency silicon photodiodes for absolute solar extreme-ultraviolet irradiance measurements

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**Abstract.** New developments in transmission grating and photodiode technology now make it possible to realize spectrometers in the extreme ultraviolet (EUV) spectral region ( $\lambda < 1000 \text{ \AA}$ ), which are expected to be virtually constant in their diffraction and detector properties. Time-dependent effects associated with reflection gratings are eliminated through the use of free-standing transmission gratings. These gratings together with recently developed and highly stable EUV photodiodes have been utilized to construct a highly stable normal incidence spectrophotometer to monitor the variability and absolute intensity of the solar 304- $\text{\AA}$  line. Owing to its low weight and compactness, such a spectrometer will be a valuable tool for providing absolute solar irradiance throughout the EUV. This novel instrument will also be useful for cross-calibrating other EUV flight instruments and will be flown on a series of Hitchhiker shuttle flights and on SOHO. A preliminary version of this instrument has been fabricated and characterized, and the results are described.

*Subject terms:* magnetospheric imagery; atmospheric remote sensing; free standing transmission gratings.

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## 1 Introduction

Recent developments in silicon XUV photodiode<sup>1–3</sup> and x-ray transmission grating<sup>4</sup> technologies make it possible to construct a normal incidence spectrophotometer (spectrometer) to continuously monitor the solar EUV flux from the space shuttle, SOHO, GOES, and other satellites. This transmission-grating-based spectrometer is not subject to the time-dependent degradation associated with reflection grating contamination, nor to the high background scattered light associated with typical grazing incidence spectrometers.<sup>5</sup> Design, fabrication, and testing of this novel normal incidence spectrometer has been successfully carried out. Specifically, silicon photodiodes with stable, near theoretical quantum efficiency in the EUV wavelength region have been fabricated and their quantum yields measured at the Synchrotron Ra-

diation Facility (SURF II) of the National Institute of Standards and Technology (NIST). A 5000 lines/mm free-standing transmission grating was characterized at 255, 304, and 340  $\text{\AA}$  at the Electron and Optical Physics Division of NIST. The expected performance of the three photodiode elements and the transmission grating that compose this spectrometer was verified at SURF II.

## 2 Normal Incidence Photodiode Spectrometer Description

A schematic diagram of the present EUV transmission grating spectrometer using three isolated silicon photodiodes as detectors is shown in Fig. 1. The photodiodes are of the type flown successfully aboard a sounding rocket at the White Sands Missile Range to obtain absolute integral solar EUV flux.<sup>6</sup> To achieve spectral resolution as well, a free-standing x-ray transmission grating (5000 lines/mm) has been placed on the optic axis between two highly stable (1500- $\text{\AA}$ -thick) Al filters. The Al filters not only limit the radiation that enters the spectrometer to the Al transmission bandpass (170 to 700  $\text{\AA}$ ), but when placed in series with each other also

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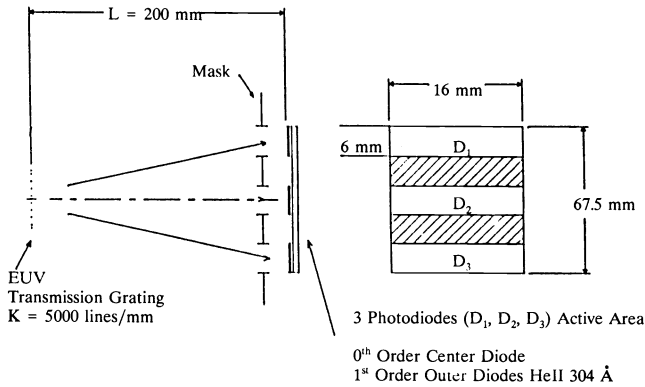


Fig. 1 Schematic diagram of spectrometer optics.

serve to sensibly eliminate the effects caused by any pinholes that may develop.

The spectrometer as shown is configured to isolate the prominent full disk solar He II 304-Å line in first order. Because of the extended source of the sun ( $\sim 1/2$  deg) and finite size of the entrance slit ( $2 \times 10$  mm) the spectrometer will have a bandwidth of  $\pm 40$  Å about the 304-Å line. From this bandwidth and from an EUV spectrum appropriate for moderate solar activity [Heroux Aug. 14, 1979, rocket flight with  $\phi(304) \approx 10^{10}$  photons/cm<sup>2</sup> s], the zero-order and each of the first-order detectors are predicted to register  $\sim 180$  pA and  $\sim 15$  pA, respectively. The first-order 304-Å line is estimated to contribute to a current that is greater than 80% of the total value registered in each first-order detector. In these calculations, we have adopted a representative grating efficiency of 12.5% in zero order and 5% in first order. Measured  $A\ell$  transmission and diode quantum yield data and a triangular effective area function were folded into these calculations. The size of the detector (active area of the silicon photodiode is  $6 \times 16$  mm) was selected to minimize signal loss caused by a maximum external misalignment of 15 arcmin, and to minimize losses resulting from the small dispersion produced by the low-density horizontal support grids (4  $\mu$ m period) of the transmission grating.

Calibration of the complete photodiode spectrometer system was performed in Jan. 1992 at NIST in Gaithersburg, Md., and the results were highly encouraging. Self-consistency tests were performed by independently measuring the absolute efficiencies of the grating, the absolute diode yield, and the quantum yield of the assembled spectrometer at three wavelengths in the extreme ultraviolet shortward of 340 Å. A description of the calibration procedure and the results follow.

### 3 Transmission Grating and Absolute Efficiencies

The free-standing transmission grating used in the normal incidence EUV spectrometer characterized at NIST was procured from Dr. Mark Schattenburg of MIT and Dr. Chuck Hooper of X-Opt Inc. The grating is a high-density periodic array structure of gold rectangular bars. The grating has a bar period of  $p = 2000$  Å, bar width of  $b = 1500$  Å, and a bar thickness of  $t = 3000$  Å. The open spaces of width  $a = 500$  Å are completely devoid of material other than the obstruction caused by the grating support structure. The sup-

Table 1 Absolute grating efficiencies of FS 96 in percentages.

$\lambda(\text{Å})/\text{Order}$	<-3>	<-2>	<-1>	<0>	<1>	<2>	<3>
255	0.43	1.16	2.09	2.50	2.13	1.16	0.48
304	0.34	1.05	2.11	2.74	2.04	1.06	0.50
340	--	0.59	1.87	2.91	2.18	0.81	--

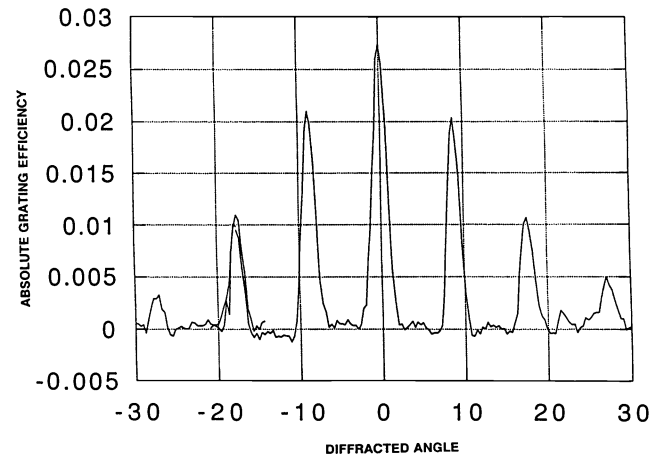


Fig. 2 Absolute grating efficiency of FS 96 at 304 Å as a function of diffraction angle.

port structure is a gold wire mesh ( $4 \times 150$   $\mu$ m) with a geometrical transmission of approximately 40%. EUV radiation at wavelength  $\lambda$  will be diffracted by the grating at an angle  $\Theta$  determined from the grating equation ( $p \sin \Theta = m\lambda$ ) at normal incidence, where the integer  $m = 0, \pm 1, \pm 2, \pm 3, \dots$  is the order of diffraction. Hence, the expected transmission into all orders for the grating is  $0.40a/p = 0.10$  (i.e., 10%). The intensities of the  $m$ 'th orders relative to the incident intensity were calculated to be 2.7 and 2.1% for the zeroth order and  $\pm$  first orders, respectively.

The free-standing transmission grating was calibrated at the Division of Electron and Optical Physics of NIST in Gaithersburg, Md. (October 1991), by Dr. Richard Watts. All measurements were performed with the incident beam normal to and centered on the transmission grating. Absolute efficiencies of the  $4 \times 10$ -mm grating were measured using a beam size at the sample of approximately  $1 \times 2$  mm (the long dimension was parallel to the grating bars). The orders were found to be symmetric about the central order, confirming that the radiation was illuminating the grating at normal incidence and that proper alignment had been achieved. The tests were performed with the electric field of the incident beam parallel to the grating bars. The polarization of the synchrotron beam is  $\sim 90\%$ , at wavelengths near 300 Å, however, polarization effects of the grating at this wavelength are negligible and are briefly discussed in Sec. 4. The results of the calibration are summarized in Table 1, and a representative plot of absolute efficiency versus diffraction angle at 304 Å is shown in Fig. 2.

The uncertainty in the absolute efficiencies is about 10% in the wavelength region 130 to 180 Å and is assumed to be the same at  $\sim 300$  Å. The data indicate that the efficiencies

**Table 2** Average grating efficiencies and calculated transmission.

Order	$\eta_{cal}$	$\eta_{meas}(\%)$	$\sigma$
<0>	2.65	2.71	0.21
< $\pm 1$ >	2.15	2.07	0.11
< $\pm 2$ >	1.08	0.97	0.23
< $\pm 3$ >	0.14	0.44	0.07

at various orders are nearly independent of wavelength between 255 and 340 Å. Averaging over each  $\pm$  order and wavelength we compare the measured and calculated efficiencies and present them in Table 2. The standard deviations  $\sigma$  are also presented. The data were obtained in the least favorable orientation with regard to polarization (electric field parallel to the grating bars), yet the measured efficiencies are nearly the same as the calculated efficiencies of an ideal grating. Thus, polarization effects must be small at these wavelengths, as expected, although physical limitations in the experimental apparatus precluded direct experimental verification.

#### 4 Photodiode Spectrometer Calibration

An optical bench was fabricated so that the spectrometer could be tested and characterized at NIST. The optical bench was fabricated in such a way that each optical element of the spectrometer could easily be inserted and removed. With the diode assembly removed, visual alignment of the instrument optic axis with the incident beam could be realized by a circular screen inserted into the normal position of the grating by viewing the screen through a window located at the center of a 14-in. flange adapted for the NIST calibration chamber.

Calibration of the assembled photodiode spectrometer was performed at the Far Ultraviolet Physics Division, SURF II NIST, calibration facility by Mr. Randy Canfield. Quantum sensitivity measurements were obtained with the incident beam normal to the transmission grating, and unlike the isolated grating characterization, the tests were performed in two mutually perpendicular grating orientations. In one orientation (bars vertical), the grating bars are perpendicular to the electric field of the incident beam, and in the other (bars horizontal), they are parallel. The spectrometer was designed to measure the central and both first-order line intensities at 304 Å. The wavelength response of the spectrometer was thus measured at 255, 304, and 335 Å both with and without the grating installed. Note that without the grating, the absolute quantum yield of the central order diode (Blue 2) is obtained. The absolute flux incident on the diode spectrometer (spectrometer Al filters removed) was known from measurements obtained using a precalibrated Al filter and photoemissive diode beyond the exit slit of the NIST calibration monochromator. The flux level chosen for the characterization was comparable to the solar flux at 304 Å (i.e.,  $10^{10}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ ). The quantum yield  $Q$  (in electron-hole pairs produced per incident photon) was obtained by measuring the current  $i$  produced in each diode and is given by  $i = eIQ$ , where  $e$  is the electronic charge and  $I$  is the absolute number of photons per second that enter the spectrometer. The current  $i_M$  of the precalibrated incident flux monitor of known quantum yield  $Q_M$  is measured immediately prior to each measurement of

**Table 3** Individual photodiode quantum yields at three EUV wavelengths.

Vertical	$\lambda$	Q Blue 1	Q Blue 2	Q Blue 3
	255	0.0039	0.1210	0.0031
	304	0.0556	0.0854	0.0490
	335	0.0150	0.0806	0.0379
Horiz.	$\lambda$	Q Blue 1	Q Blue 2	Q Blue 3
	255	0.0067	0.1614	0.0045
	304	0.0797	0.1249	0.0802
	335	0.0301	0.1129	0.0511
Q Blue 2 w/o grating	$\lambda$	Q Blue 1		
	255	10.0493		
	304	8.0816		
	355	7.537		

**Table 4** Expected spectrometer photodiode current for a flux of  $\sim 10^{10}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ .

$\lambda$	$Q_M$	$i_M(\text{pA})$	Blue 1 (pA)	Blue 2 (pA)	$i_M(\text{pA})$	Blue 3 (pA)	Blue 2 (pA)
255	0.0893	51.6	3.86	92.7	42.3	2.14	76.5
304	0.1019	58.4	45.7	70.7	48.1	37.8	59.5
355	0.1144	58.4	15.4	58.3	48.0	21.4	46.6

the photodiode current  $i$  ( $i_M = eI_0Q_M$ , where  $I_0$  is the incident beam intensity). A summary of the results is shown in Table 3.

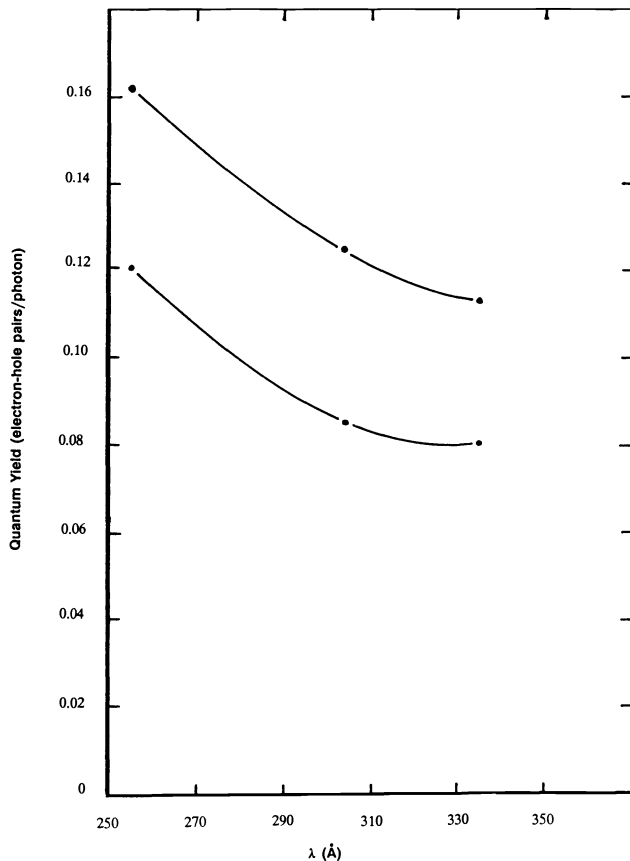
The nomenclature used in Table 3 is

- Vertical      Transmission grating bars perpendicular to the orbital plane of the synchrotron electrons
- Horizontal    Transmission grating bars parallel to the electron orbital plane
- Blue 2        Central-order diode
- Blue 1,3      First-order diodes.

The numbers 1, 2, and 3 are the diode positions. The color blue has no significance other than as a unit identification marker of the particular selected set of three diodes, which were calibrated as a unit.

The  $Q$  values in Table 3 were calculated for  $I = I_0$ , hence are equal to  $(i/i_M)Q_M$ . The calibrated monitor quantum efficiency  $Q_M$  and measured current  $i_M$  measure the absolute incident beam intensity (in photons per second). These values and typical measured photocurrents are presented in Table 4 (grating bars horizontal) and provide an illustration of expected currents from the spectrometer for a flux of  $\sim 10^{10}$  photons  $\text{cm}^{-2} \text{s}^{-1}$  and a 4-mm<sup>2</sup> entrance aperture.

The response of the central-order diode (Blue 2) with the grating in place is shown in Fig. 3. Quantum yields measured with the grating bars horizontal were found to be  $\sim 25\%$  larger than when the bars were vertical. This is an indication that not all of the incident beam passed through the grating. This



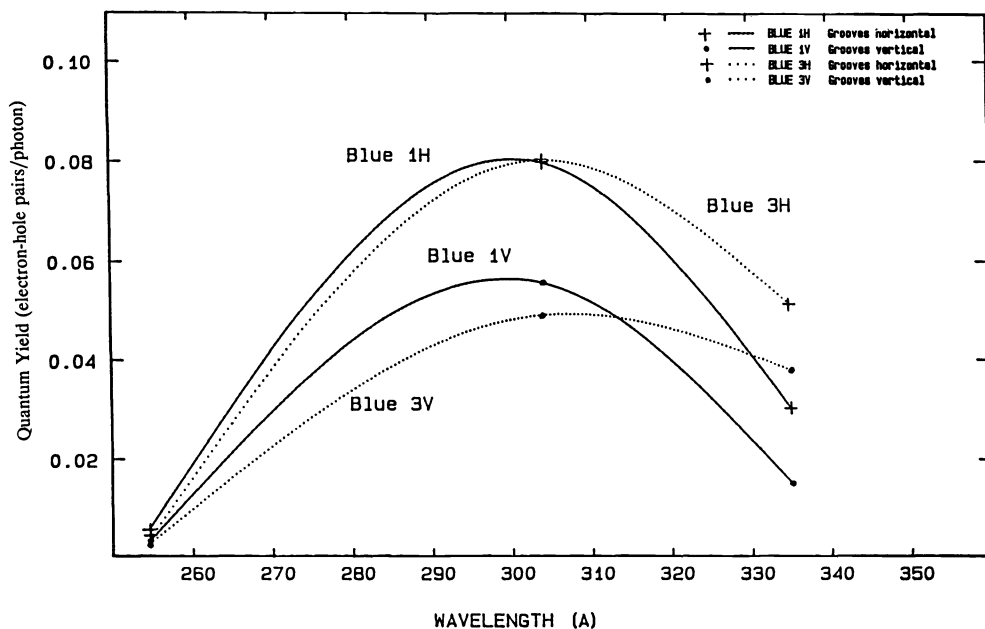
**Fig. 3** Quantum yield of the central-order diode as a function of wavelength using grating FS 96. The upper curve is the zero-order response with the grating lines parallel to the incident beam electric field. The lower curve is the response with the spectrometer rotated 90 deg.

was experimentally verified from detailed analysis of the data obtained from measurements performed with and without the grating. Furthermore, if polarization effects were important, then the expected photocurrent with the grating bars perpendicular to the electric field (bars vertical) would have been larger, and this was clearly not the case.

The measured first-order response of the spectrometer is shown in Fig. 4. A free cubic spline was fitted through the three data points measured for each diode and the centroids of the curves and the estimated full width at half maximum (FWHM) are given in Table 5. If the incident photon beam were perfectly aligned with the optic axis of the spectrometer, one would expect all curves to be coincident, with a peak at 304 Å. However, consistent with the results obtained from the zero-order diode measurements, the quantum yields for Blue V are lower by ~25% from those of Blue H. The general first-order response with wavelength, however, is consistent with the predicted wavelength response. The total bandwidth of the spectrometer was designed to be ~80 Å centered about 304 Å. The response at 255 Å is nearly zero, as expected and shown in Fig. 4, and by the ideal first-order slit function shown in Fig. 5. From Table 3, the ratio of the quantum yields Blue 3/Blue 2 at  $\lambda = 335$  Å for both the vertical and horizontal orientations is within 10% of the expected value. Furthermore, the average FWHM bandwidth of diode Blue 3 is 75 Å and is near the expected 80-Å value.

## 5 Conclusion

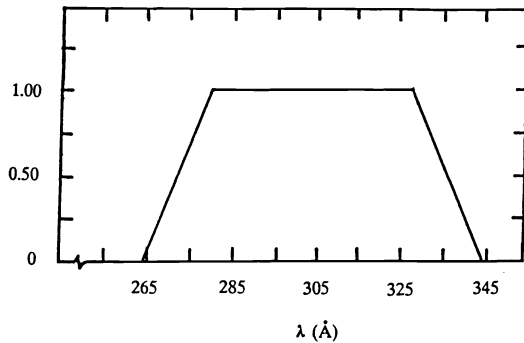
From the preceding, it is clear that the absolute grating efficiencies, bandwidth, and the absolute quantum yields of the central- and first-order diodes are consistent with the theoretical predictions and analyses. In as much as the XUV photodiodes are presently being used by NIST as a secondary standard for photometric measurements within the EUV



**Fig. 4** First-order response: quantum yield of the first-order photodiodes as a function of wavelength. A free cubic spline was fitted through the flux values at the three wavelengths measured. The solid curves are the response of diode 1 and the dashed curves are the response of diode 3. The responses are shown for the two mutually perpendicular orientations measured. The differences in the curves are associated with instrument alignment and are not polarization effects.

**Table 5** Measured first-order wavelength bandwidth of the photodiode spectrometer.

Diode Identification	$\lambda$ (Å)	FWHM (Å)
Blue 1 H	300	62
Blue 1 V	299	60
Blue 3 H	307	71
Blue 3 V	310	79



**Fig. 5** Slit function response of the first-order diodes as a function of wavelength.

wavelength region, we conclude from this work that a photodiode spectrometer would be a strong candidate to provide highly reliable absolute solar flux in the EUV.

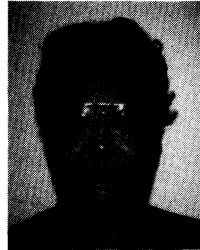
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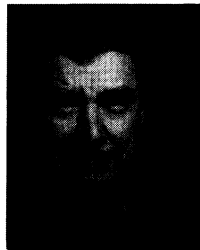


**Howard S. Ogawa** received his PhD in physics from the University of Southern California (USC) in 1978. He has taught physics since 1978 and was involved in experimental research of low-density plasmas at TRW Systems in Redondo Beach, California between 1965 and 1970. At USC he has been active in optics and the study of atomic and molecular physics and their relation to the space sciences. His current interests include investigation into

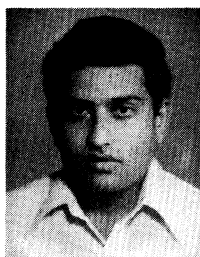
methods of obtaining absolute solar EUV fluxes and their relation to observations of planetary atmospheres and the heliosphere.



**Donald R. McMullin** has been with the Space Sciences Center at the University of Southern California since 1986, and has been involved in a number of solar EUV sounding rocket experiments. His primary interests are mechanical design and data acquisition for space flight instrumentation.



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