TIMED Solar EUV Experiment

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ABSTRACT

The Solar EUV Experiment (SEE) selected for the NASA Thermosphere, Ionosphere, and Mesosphere Energetics and Dynamics (TIMED) mission will measure the solar vacuum ultraviolet (VUV) spectral irradiance from 0.1 to 200 nm. To cover this wide spectral range two different types of instruments are used: a grating spectrograph for spectra above 25 nm and a set of silicon soft x-ray (XUV) photodiodes with thin film filters for below 30 nm. Redundant channels of the spectrograph and XUV photodiodes provide in-flight calibration checks on the time scale of a week, and annual rocket underflight measurements provide absolute calibration checks traceable to radiometric standards. Both types of instruments have been developed and flight proven as part of a NASA solar EUV irradiance rocket experiment.

Keywords: solar ultraviolet irradiance instrument

1. INVESTIGATION OVERVIEW

The Solar EUV Experiment (SEE) investigation contributes primarily to the NASA TIMED mission goal to characterize the sources of energy responsible for the thermal structure of the mesosphere, the lower thermosphere, and the ionosphere (MLTI). These energy sources include solar radiation, solar energetic particles, Joule heating, conduction, dynamical forcing, and chemical energy release. Of these energy inputs, the solar vacuum ultraviolet (VUV) radiation below 200 nm is the dominant global energy source for heating of the thermosphere, creating the ionosphere, and driving the diurnal cycles of wind and chemistry. The estimated amount of heating by solar VUV radiation as a function of altitude in Earth's atmosphere is shown in Figure 1 for solar minimum and solar maximum conditions. Changes in the amount of solar VUV radiation result in corresponding changes in the energy balance of the upper atmosphere, dynamics, and photochemistry. While solar cycle variability near 200 nm is only about 10%, the solar cycle variability at shorter wavelengths is typically a factor of 2 to 3 for chromospheric emissions and a factor of 10 to 100 for coronal emissions. The variability of both of these emissions are not well understood, especially at the shortest wavelengths below 40 nm. A detailed quantitative understanding of the changes in the solar VUV irradiance and the basic state variables, temperature and densities of N_2, O_2 and O, are essential to detailed investigations of atmospheric energetics, dynamics, and chemistry. The SEE will provide the necessary solar VUV irradiance measurements from 0.1 to 200 nm with about 0.5 nm spectral resolution and with about hourly temporal resolution. These measurement requirements have been established considering the atmosphere's response to the solar radiation and also considering the characteristics of the solar spectrum and its variability. Other TIMED instruments will provide the measurements of the basic state variables over a range of altitudes from 50 to 400 km. The occasional solar occultations by SEE also provide precise measurements of the basic state variables. With the accurate measurements of the energy sources and the basic state variables, atmospheric models of the MLTI can be validated and refined in an unprecedented manner and the response of the upper atmosphere to the various energy sources can be precisely quantified.

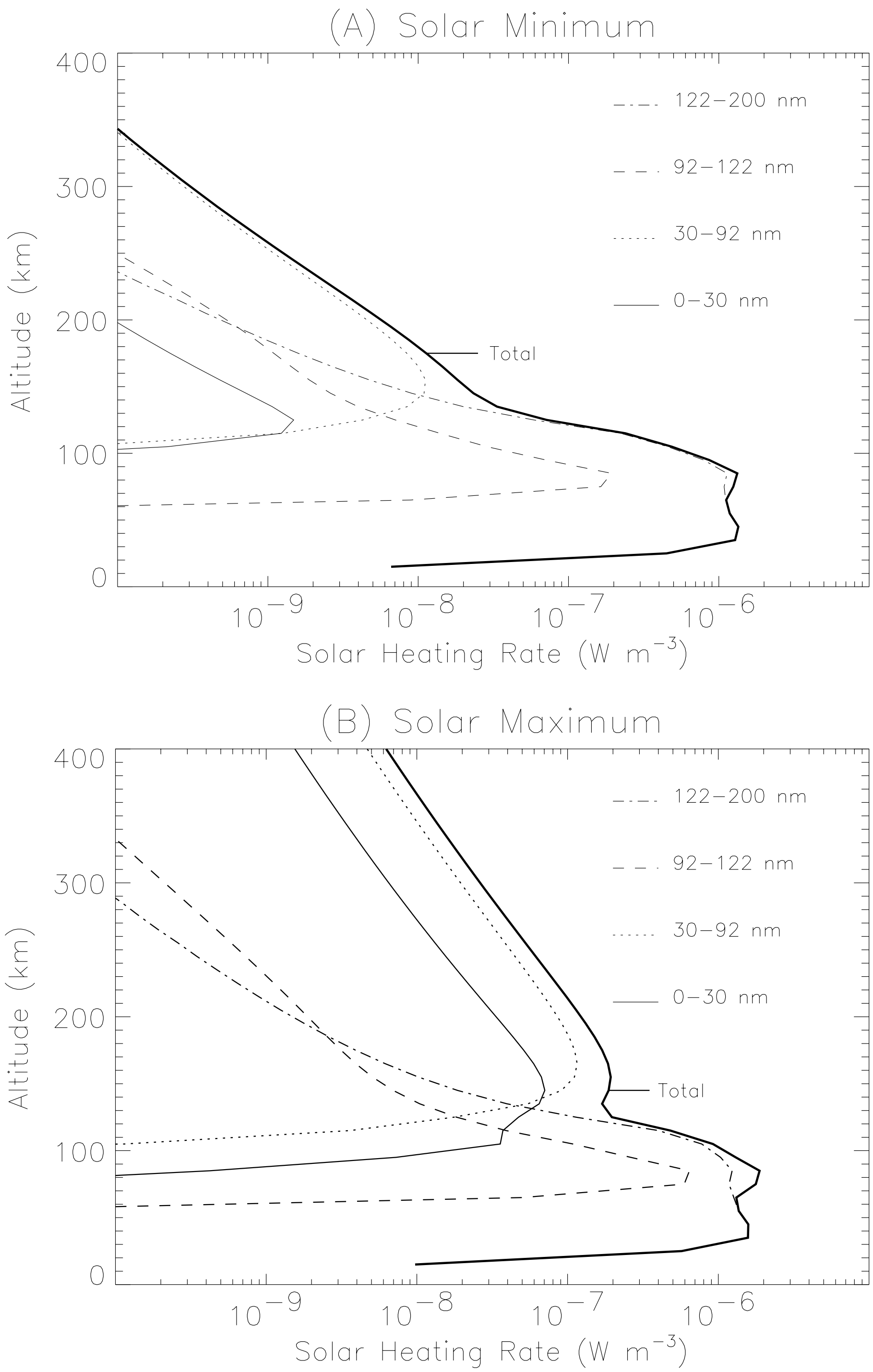

Figure 1. Estimated Solar Heating Rate. Using the MSIS atmospheric model and the Hinteregger proxy model of solar VUV irradiance, the solar heating rate is estimated as a function of altitude for solar minimum (Panel A) and solar maximum (Panel B) conditions.

The SEE investigation also contributes to the TIMED mission goal to improve our understanding of those processes related to anthropogenic influence and to establish a baseline set of observations for future investigations. In order to distinguish between the natural, namely solar variability, and anthropogenic changes in the MLTI regions, a baseline of solar VUV spectral irradiance and basic state variables needs to be established with an accuracy of 10% or better (1-σ value). Existing proxy models that employ ground-based measurement of solar activity to estimate the solar VUV irradiance are highly uncertain and lack the required accuracy for solar connection studies. Therefore, the SEE investigation will also develop improved solar proxy models, based on the TIMED SEE measurements, for future comparisons of natural and anthropogenic effects.

The key elements in data analysis and modeling for the SEE investigation are the analysis of the solar irradiance variability, studying the solar-terrestrial relationships by using the measured solar flux as parameters in models of the atmosphere, verification of atmospheric models and laboratory cross sections for atoms and molecules by using measured solar absorption profiles from solar occultations, and development of a new generation proxy model of the solar EUV flux. The primary atmospheric models are the Thermosphere-Ionosphere-Mesosphere-Electrodynamics General Circulation Model (TIME-GCM)[1] and the MSIS model[2].

2. SOLAR VUV IRRADIANCE BACKGROUND

Solar VUV measurements are only possible above the atmosphere and were first made photographically, and then by photometric detectors, on short duration rocket flights starting after the Second World War. The SOLRAD and AEROS satellites, Air Force Cambridge Research Laboratories rocket experiments, Orbiting Solar Observatory (OSO–3 and OSO–4)[3,4], and Atmospheric Explorer (AE–C, AE–D, and AE–E)[5] conducted survey observations through different parts of the spectrum during the 1960's and 1970's. The revised AE–E solar irradiance data representative for the solar minimum and maximum conditions during solar cycle 21[6,7] are commonly used as reference spectra for atmospheric modeling (i.e. calculating photoelectrons density, heating, etc.). The revised AE–E data set is actually based more on sounding rocket measurements than the satellite instruments because there were no provisions for in-flight calibrations of the solar instruments on AE-E[6]. These previous results have fueled controversy concerning the total solar cycle variation[8,9] because of discrepancies in the absolute irradiance due to the AE-E instrument degradation and the use of several different instruments[6,10,11].

Following the last AE-E measurements in 1981, there has been a long hiatus without daily measurements of the solar EUV irradiance. Donnelly[12] refers to this lack of current solar EUV spectral irradiance measurements as the "solar EUV hole". The few solar EUV spectral irradiance observations during this period include about 20 days during the nine month mission of the San Marco 5 satellite[13,14], six sounding rocket measurements [i.e., Woods and Rottman[15]], and Voyager 1 and 2 measurements made a few days per year. Additionally there have been several integrated EUV flux measurements from Pioneer Venus[16] , PHOBOS, sounding rocket measurements [i.e., Ogawa *et al.*[17]], and SOHO; however, these broadband integrated flux measurements are less useful for solar-terrestrial studies.

The Sun varies on all time scales and the amount of variability is a strong function of wavelength. Our present understanding is that in the visible portion of the spectrum, the intrinsic solar cycle variability is on the order of one-tenth of a percent. Moving into the middle ultraviolet (200 to 300 nm), the amount of radiation decreases rapidly while the variability increases by an order of magnitude and reaches one to a few percent. Further into the FUV and EUV, the amount of radiation decreases further while the solar cycle variability continues to increase with the magnitude of the variation approaching a factor of two, for example at the H I Lyman-α emission at 121.6 nm, and finally to an order of magnitude variations in the extremely high temperature coronal lines. Solar radiation below 200 nm consists of emission lines superimposed on the rapidly declining continuum. These emission lines arise in higher temperature layers of the outer solar atmosphere under non-LTE conditions and are strongly related to the magnetic activity of the Sun as seen, for example, in plage regions. It is known that these emission lines exhibit large amplitude variability during an 11 year solar cycle while the underlying FUV continuum portion is far less variable[11]. The XUV region is dominated completely by emission lines, primarily coronal lines which may vary by orders of magnitude during an 11 year solar cycle. Short term variations, lasting from minutes to hours, are related to eruptive phenomena on the Sun; intermediate term variations, modulated by the 27-day rotation period of the Sun, are related to the appearance and disappearance of active regions on the solar disk, and the more elusive long term variability is related to the 22-year magnetic field cycle of the Sun. The long term variation is poorly determined due to the lack of measurements and to the inadequate long term accuracy of previous satellite solar instruments. Recent reviews about the solar EUV and UV variability with more details include those by Lean[18,19] and Rottman[11].

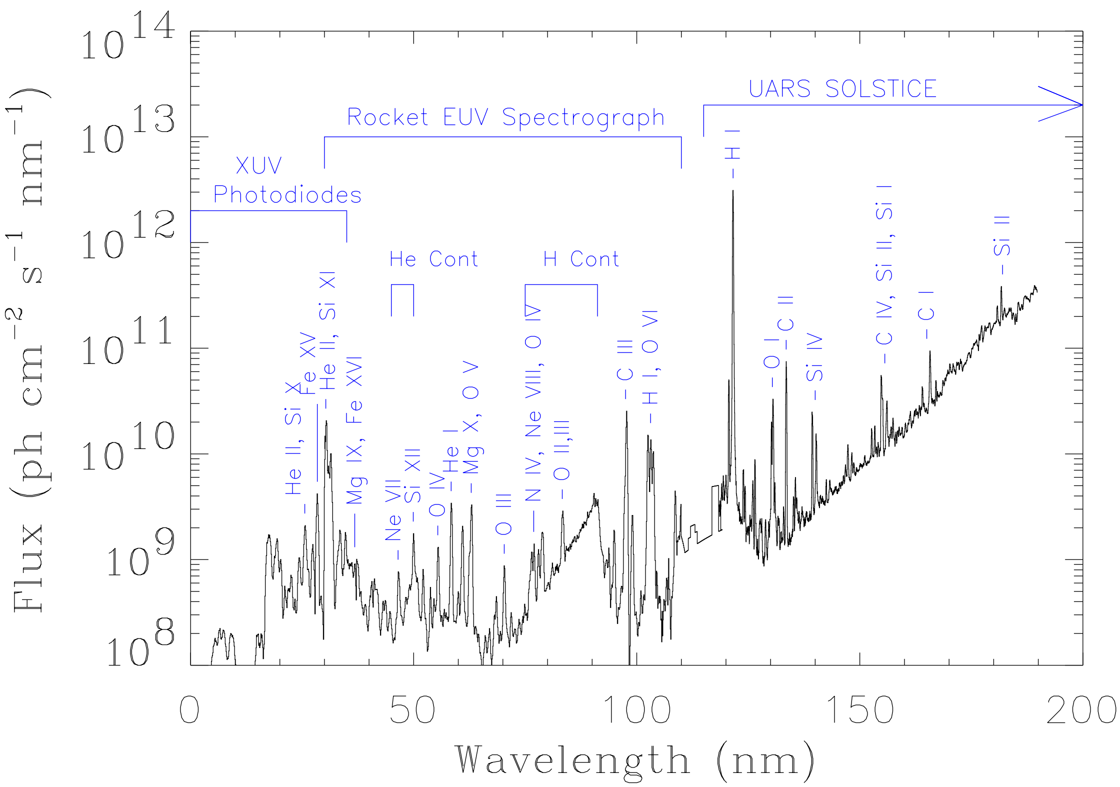

Figure 2. Solar VUV Irradiance Measurement on October 27, 1992. The rocket solar EUV irradiance instruments made the measurements below 110 nm, and the UARS SOLSTICE made the measurements above 119 nm. The SEE solar VUV irradiance measurements will be very similar and will span the entire range from 0.1 to 200 nm.

3. INSTRUMENTATION

The Solar EUV Experiment (SEE) includes two instruments to measure the solar VUV spectral irradiance from 0.1 to 200 nm. The EUV Grating Spectrograph (EGS) is a normal incidence Rowland circle spectrograph and has a spectral range of 25 to 195 nm with a 0.4 nm spectral resolution. The XUV Photometer System (XPS) includes nine silicon XUV photodiodes with thin film filters deposited directly on the photodiode. This XUV photometer set measures the solar irradiance from 1 to 35 nm with each filter having a spectral bandpass of about 5 nm. Additional subsystems to accommodate this solar investigation on the TIMED spacecraft include a one-axis gimbal platform for pointing the solar sensors towards the Sun, and a microprocessor subsystem. For this paper, we focus the discussion on the solar irradiance sensors.

The heritage for the SEE instrument components derives from sounding rocket experiments[15,20] and the UARS Solar Stellar Irradiance Comparison Experiment (SOLSTICE)[21,22] that have made solar VUV irradiance measurements during the past few years. Figure 2 shows a complete solar VUV irradiance spectrum that combines the measurements made from the rocket and UARS on October 27, 1992. This spectrum illustrates the quality and spectral resolution that the TIMED SEE instruments will produce. These SEE solar sensors are fully developed and flight-qualified a few years ago. More recently, the interfaces to the specific TIMED spacecraft have been fully developed over the past couple of years.

The following characteristics are for the entire SEE system. The mass of SEE is estimated to be 27 kilograms. The SEE operating power is estimated to be 27 Watts, and the SEE maximum operating data rate is 4 kilobits per second. These estimates include a mixture of measurements and computer models of the instruments. Because the normal SEE observation scenario is to observe the Sun autonomously every orbit for only two to four minutes, the SEE orbit average power is lower at about 14 Watts, and the orbit average data rate is about 0.2 kilobits per second. The operating temperature range for SEE is 10 to 34 °C. Because SEE has its own pointing platform and Sun sensor, it imposes minimal requirements on the spacecraft attitude control.

3.1. EUV Grating Spectrograph

The EUV Grating Spectrograph (EGS) is a normal-incidence 1/4 m Rowland circle design. The detector is an array detector so that a complete spectrum can be obtained in a few seconds with the grating fixed. This spectrograph has heritage from our solar EUV spectrograph that has flown successfully six times as a rocket experiment [i.e., Woods and Rottman[15]].

The spectral coverage is 25 to 195 nm with a 0.17 nm bandpass per anode on the detector. The effective spectral resolution is 0.4 nm. This moderately high resolution is important for resolving blended lines such as the H I Lyman-β (102.6 nm) and O VI (103.2 and 103.8 nm) lines. To maximize the efficiency at the shortest wavelengths, the grating has a gold coating with sufficient reflectivity down to 25 nm.

The array detector is a CODACON array detector developed by G. M. Lawrence at University of Colorado[23]. The array format is 64 x 1024 anodes. Each anode (pixel) is 25 μ wide (dispersion direction) by 100 μ tall (along slit direction). The CODACON detector uses a microchannel plate (MCP) and coded anode electronics for its readout. The MCP has a gain of more than 10^6 for photoelectrons produced at the front of the MCP, and this output pulse is proximity focused on the anode array. Reverse biasing of an aperture plate above the MCP helps to prevent the CODACON detector from saturating on the brighter solar emission lines. The MCP is coated with gold to provide better MCP characteristics such as larger dynamic range, longer lifetime, better pulse height distributions, and higher gain. In addition, the gold coating serves as the photocathode and is well suited for making solar EUV measurements because its quantum efficiency (QE) is near 10% in the EUV and less than 1% in the FUV where the Sun is much brighter. A small vacuum ion pump is used on the spectrograph to keep the detector evacuated for cleanliness purposes during ground testing but will be removed for flight.

The EGS electronics are primarily the detector electronics, charge amplifiers, photon-detection logic, and memory buffer for photon events. These electronics accumulate each photon event into an image that is stored in double-buffered memory; that is, one memory bank integrates a new image while the other memory bank outputs its image. With no telescope, these images are not solar images but only spectra.

The EUV Grating Spectrograph, which has only one grating and one detector but two slits, is operated in such a way that it has two redundant channels. Specifically, the grating and detector can be illuminated on two separate areas. We use one illumination configuration for daily measurements and the other illumination configuration for weekly calibration checks for the daily measurements. These two configurations are illustrated in Figure 3. To achieve redundant channels from a single grating / detector system, two slits, each being 25 μ wide by 1 mm tall and offset 3 mm vertically from each other, are needed to illuminate the detector differently, and the optical axis needs to be tilted by 2° to illuminate the grating differently. The SEE one-axis gimbal platform provides the means to tilt the optical axis relative to the Sun.

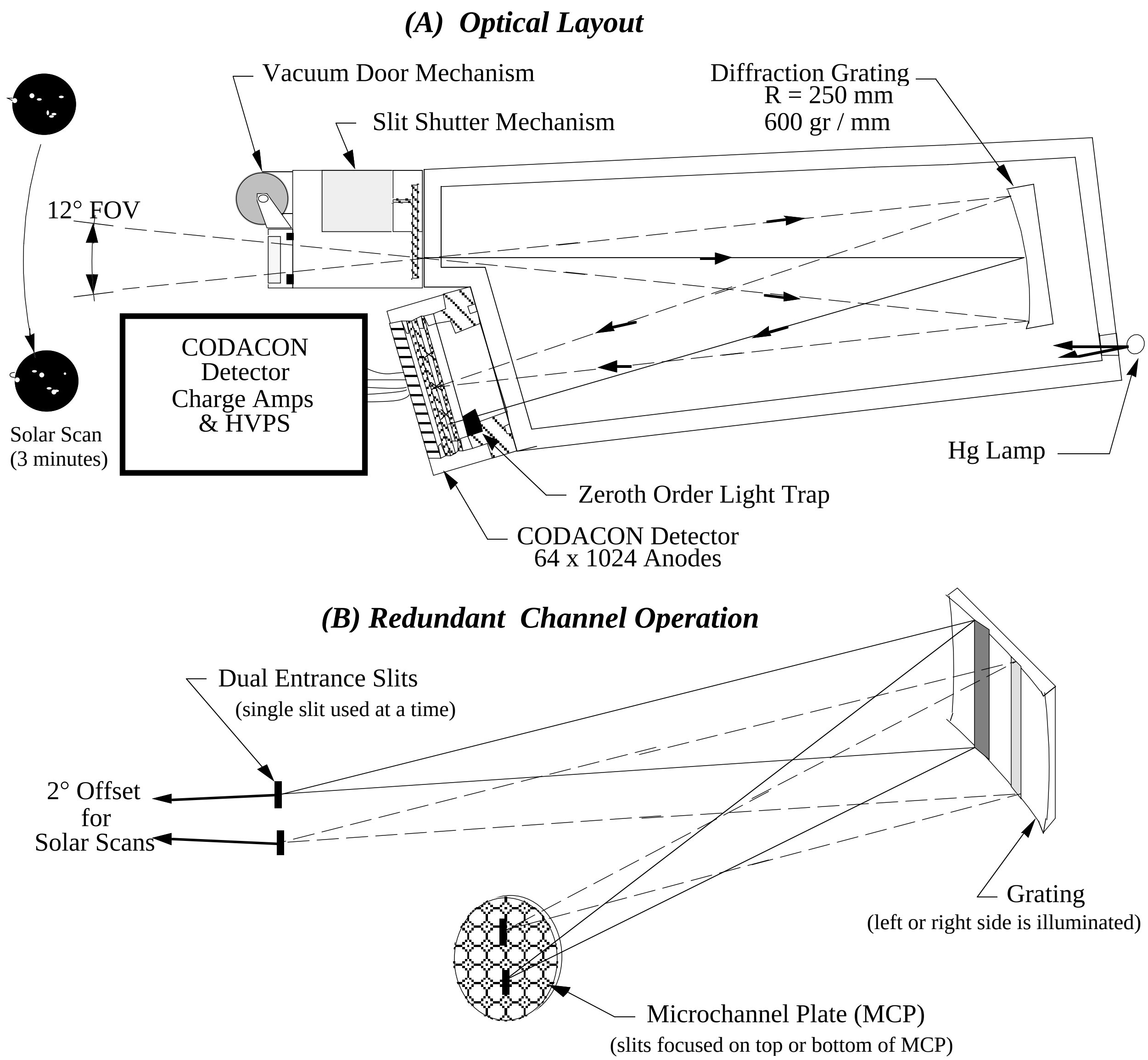

Figure 3. The SEE EUV Grating Spectrograph Layout. The optical layout for the 1/4 m Rowland circle spectrograph is shown in Panel A. It includes a vacuum door, dual slits, fixed grating, CODACON array detector and a Hg lamp. By using a different slit and viewing direction as depicted in Panel B, this spectrograph has redundant channels whereby one channel is used daily and the other channel is used once a week for in-flight calibrations. The Hg lamp is used for flat field calibration of the CODACON detector.

3.2. XUV Photometer System

The XUV Photometer System (XPS) is a package of nine silicon XUV photodiodes for measuring the XUV and EUV irradiance. Each photodiode has a thin film filter to provide an approximately 5 nm spectral bandpass. These thin film filters are deposited directly on the photodiode so that we avoid using delicate metal foil filters which are difficult to handle, prone to develop pin holes, and degrade with time.

R. Korde of International Radiation Detectors has developed these silicon XUV photodiodes with thin film filters to have low-noise and high long-term stability[24,25,26,27,28]. These XUV photodiodes have been adopted by the National Institute for Standards and Technology (NIST) as one of their XUV standard detectors.

The electronics for each photodiode are simple and include only a current amplifier and a voltage-to-frequency (VTF) converter. The VTF converter was chosen over an analog-to-digital (A/D) converter because the VTF converter provides a much wider dynamic range with a significantly lower power consumption. The interface from the VTF converters to a microprocessor is a 32-bit digital counter for each photodiode.

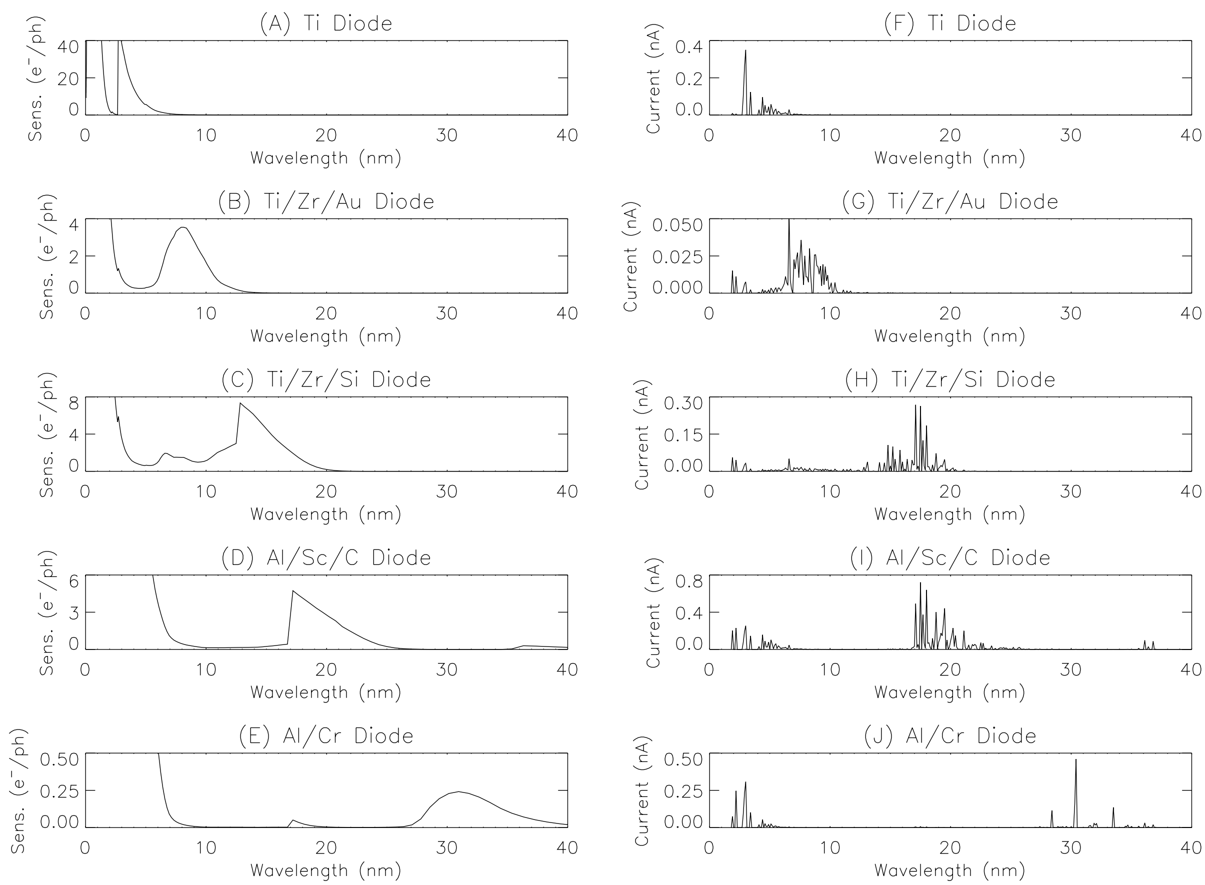

Figure 4. Sensitivity and Expected Current for the SEE XUV Photometers. Panels A-E show the sensitivity, and Panels F-J show the expected current during solar maximum conditions, both as a function of wavelength. The coatings are (1) Ti 5000 Å, (2) Ti/Zr/Au 200/1500/1000 Å, (3) Ti/Zr/Si 200/2000/1000 Å, (4) Al/Sc/C 1500/500/500 Å, and (4) Al/Cr 2000/1000 Å.

There are several suitable metals for use as filters, and the use of multiple coatings on the same diode provides a way of narrowing the bandpass of each diode. Powell *et al*.[29] discuss thin film filters suitable for this wavelength range. In addition to selecting a filter for its bandpass, one must also select a filter that can block the solar visible radiation by a factor of 10^{12} or better; otherwise, the XUV Photometer signal would be dominated by the solar visible radiation instead of the XUV radiation. We have flown as rocket experiments the following XUV photodiode filters: Ti, Ti/Zr/C, Al/Sc/C, Al/C, Sn, and Al/Sn. The detector sensitivities for the silicon photodiodes of the five filters planned for SEE are shown in Figure 4. These five filters are designed to have a bandpass of about 5 nm over the range 0 to 35 nm, a visible light blockage of at least 10^{12}, and a solar XUV signal between 1 and 10 nA. The estimated response of these XUV photometers to solar radiation is also shown in Figure 4. The XUV photometer with the Ti filter measures the irradiance below 6 nm. The photometer with the Ti/Zr/Au filter measures the 6 to 12 nm region. The photometer with the Ti/Zr/Si filter measures the 12 to 20 nm region. The Al/Sc/C filter is designed to eliminate the bright solar He II 304 Å emission so that the 17 to 25 nm region can be measured. Finally, the photometer with the Al/Cr filter measures the 25 to 35 nm solar irradiance. The additional filtered photometer for SEE is a bare XUV photodiode with Acton Lyman-α filters for a redundant measurement of the important Lyman-α irradiance.

A set of twelve XUV photometers is packaged together with a common filter wheel mechanism. There are fused silica windows on this filter wheel mechanism to permit accurate subtraction of the background signal, if any from visible and near UV light. While nine of the XUV Photometers have thin film filters for making solar XUV irradiance measurements, the other three XUV photometers are bare silicon photodiodes to be used in tracking the transmission of the fused silica windows. A typical measurement cycle for the XUV photometers is to measure the dark signal with no aperture, to measure the background signal with the window, and then to measure the solar XUV radiation with a clear aperture. For in-flight calibration purposes, three of the nine XUV photometers are redundant in the XPS. This redundant set will be used once a week for tracking instrument degradation.

3.3. Microprocessor Unit

The SEE Microprocessor Unit (MU) uses a 1750 processor, error detection and correcting (EDAC) memory, a 1553 interface to the spacecraft, and serial interfaces to the SEE components. The serial interfaces to the SEE components are a 32-bit asynchronous command interface and a 64-bit asynchronous telemetry interface, both having even parity checking. The spacecraft +28 V DC power is distributed to the SEE components via the MU. The combination of the +28 V DC power and serial interfaces for command and telemetry between the MU and components is called the Generic Channel Interface (GCI) for the MU. The GCI is identical for each component; however, the command and telemetry formats are specific for each component. The hardware for the GCI inside the MU is truly generic, and only the flight software needs to be tailored for each component. The hardware for the GCI at the component is not really generic as each component GCI has unique requirements for the different component subsystems. However, the component GCIs do share a common design for the DC-DC converters, serial interface logic, printed circuit board layout, and actuator control logic. The unique aspects of each component GCI is implemented primarily in field programmable gate arrays (FPGAs).

3.4. SEE Solar Pointing Platform

The SEE Solar Pointing Platform (SSPP) is a one-axis pointing platform as needed to make a solar observation per orbit. The spin of the TIMED spacecraft to keep its nadir side always pointing towards Earth provides the second axis of control in pointing towards the Sun. The SSPP is mounted on the zenith side of the TIMED spacecraft and faces the Sun-side of the spacecraft. In this configuration and with a 12° field of view (FOV), SEE is able to make at least a 3 minute observation of the Sun each orbit. The TIMED spacecraft attitude control is designed for about 1 arc-minute accuracy, and the SSPP control is also about 1 arc-minute. Schaeffer Magnetics Inc. (SMI) is providing a harmonic drive actuator integrated with a twist capsule, which passes the spacecraft interface onto the SSPP platform, and drive electronics for their actuator. The SMI actuator is the support for one side of the SSPP instrument platform, and the other side of the platform is supported by a spherical bearing, which is suitable for the thermal and mechanical constraints between the SEE instrument and the spacecraft deck. A front view of the SSPP integrated with the other SEE components is shown in Figure 5.

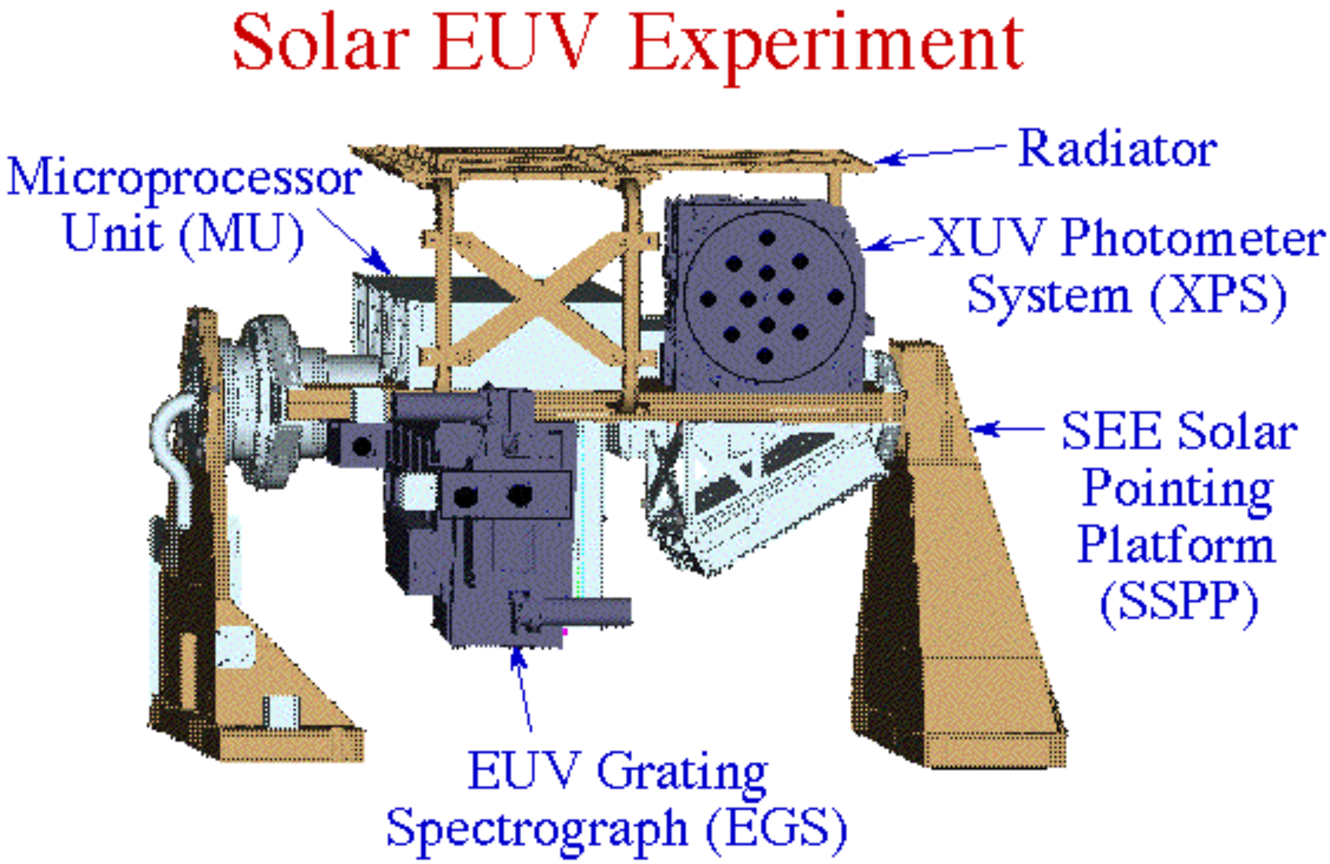

Figure 5. TIMED Solar EUV Experiment Assembled View.

4. CALIBRATION

One of the critical problems with many of the earlier solar VUV irradiance measurements has been the absolute accuracy of the irradiance and the long-term accuracy related to tracking the instrument degradation. The pre-flight and in-flight calibrations are therefore especially important for the SEE program.

4.1. Pre-flight Calibrations

The preflight photometric calibrations of SEE include transferring the calibrations of the National Institute of Standards and Technology (NIST) radiometric standards, such as reference photodiodes, radioactive x-ray sources, and synchrotron radiation, to the instrument[30,31,32]. The current VUV calibration techniques achieve an accuracy of about 3 to 7% (1-σ value).

The individual optical elements, that is the gratings and detectors, will be calibrated at the unit level in order to select the best elements for flight. In addition, the fully assembled instrument will be calibrated and mapped over its aperture to precisely determine the uniformity across its field of view. A careful analysis of the spectrograph's scattered light, which is primarily caused by the diffraction grating, will also be performed using laboratory measurements. A blazed, mechanically- ruled grating from Hyperfine will be used because holographically-ruled gratings appear inadequate to cover such a wide spectral range.

The primary photometric standard for the SEE calibrations is the Synchrotron Ultraviolet Radiation Facility

(SURF-III) at NIST in Gaithersburg, Maryland. We will perform calibrations at the instrument level at SURF, and R. Canfield will perform detailed calibrations of the silicon photodiodes as a function of wavelength at SURF. The Calibration and Test Equipment (CTE) at our facility will also be used for the wavelength and photometric calibrations of the SEE instruments. The VUV photometric standards for the CTE are reference detectors that are calibrated at NIST.

Other pre-flight calibration tests include wavelength calibrations, linearity tests of the detectors and their electronics, scattered light measurements, and detailed mapping of the field of views. The wavelength calibrations incorporate measurements using emission line sources from hollow cathode lamps for the spectrograph. The linearity tests are easily performed using the capability to adjust the SURF electron beam current level over six orders of magnitude, and we have done such linearity tests many times for the UARS SOLSTICE and solar rocket instruments. The scattered light measurements are primarily for the SEE grating spectrograph in order to characterize the scattered light properties of the grating. These scattered light tests include unit level tests and system level tests as performed with UARS SOLSTICE[22,33]. The gimbal tables at SURF have been utilized to make detailed field of view maps for the UARS SOLSTICE and solar rocket instruments[15,20,22], and we will conduct similar tests for the SEE instruments.

4.2. In-Flight Calibrations

In addition to measuring the absolute value of the solar irradiance, determining the long term variation of the irradiance is a fundamental scientific goal; therefore, in-flight calibrations of SEE are required to monitor changes in the instrument response. The in-flight calibration techniques for SEE are on-board photometric standards, redundant measurements by overlapping wavelength regions, redundant optical channels, and underflight calibrations. This variety of in-flight calibration techniques will assure that the SEE long-term accuracy of the solar flux is maintained at or below the desired 10% uncertainty (1-σ value).

Each instrument has redundant optical channels. One channel will be utilized for daily measurements, and one channel will only be used once a week to regularly provide a relative calibration for the other channel. The basic assumption for this technique is that exposure to the space environment and to solar radiation is a major factor determining instrument degradation. By using different duty cycles we can evaluate accurately the degradation related to solar exposure rate. By maintaining a high level of cleanliness for the instruments, as done for UARS SOLSTICE, we expect to greatly reduce the degradation related to contaminates on the optical elements.

Suborbital calibration experiments are of great importance in providing an absolute in-flight calibration on an annual basis. These experiments will be conducted as sounding rocket experiments using the SEE protoflight instrument so that the spectral resolution of the calibration instruments will be exactly the same as the flight instrument. Pre- and post-flight calibration of the protoflight instrument will be performed at SURF for every calibration rocket flight. These SEE underflight experiments will provide an absolute calibration for both SEE channels. From our experience with UARS SOLSTICE and the rocket instruments, we only expect a degradation rate for the SEE instruments to be a few percent per year. This relatively low degradation rate is related to keeping the optics and components free from contaminates (for example, never in an oil-based vacuum system) and to using very small apertures in order to limit the exposure to solar radiation. With the expected low degradation rate and because the solar cycle variability for the majority of the solar VUV irradiance is about a factor of two, the underflight calibrations alone may be sufficient to track the SEE instrument degradation.

Other in-flight calibration tests include wavelength calibrations using the observed solar emission lines as reference wavelengths, scattered light tests using windows on the doors, and field of view relative maps by scanning the Sun across different parts of the optics and detectors. All of the in-flight calibration tests confirm similar pre-flight calibration measurements and insure that the SEE data processing will utilize the most accurate instrumental parameters.

5. SUMMARY

There is a strong need to have well-calibrated and long-term solar VUV spectral irradiance measurements for current and future research of the solar connection to the Earth's upper atmosphere. While our recent rocket measurements provide more accurate solar irradiance reference spectra, new, more accurate satellite measurements made on a daily basis are needed to establish a long-term database of solar VUV irradiance and its variability. While the UARS solar instruments are now creating such a database for the solar VUV irradiance above 120 nm, the daily spectral measurements by the TIMED SEE may be the first satellite measurements since 1981 that are suitable for this long-term database for wavelengths below 120 nm.

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