EUVI: the STEREO-SECCHI extreme ultraviolet imager

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ABSTRACT

The Extreme Ultraviolet Imager (EUVI) is part of the SECCHI instrument suite currently being developed for the NASA STEREO mission. Identical EUVI telescopes on the two STEREO spacecraft will study the structure and evolution of the solar corona in three dimensions, and specifically focus on the initiation and early evolution of coronal mass ejections (CMEs). The EUVI telescope is being developed at the Lockheed Martin Solar and Astrophysics Lab. The SECCHI investigation is led by the Naval Research Lab.

The EUVI's 2048 x 2048 pixel detectors have a field of view out to 1.7 solar radii, and observe in four spectral channels that span the 0.1 to 20 MK temperature range. In addition to its view from two vantage points, the EUVI will provide a substantial improvement in image resolution and image cadence over its predecessor SOHO-EIT, while complying with the more restricted mass, power, and volume allocations on the STEREO mission.

Keywords: XUV, Sun, Corona

1. INTRODUCTION

The Extreme Ultraviolet Imager (EUVI) is part of the SECCHI instrument suite currently being developed for the NASA STEREO mission. As an integral element of the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI), the EUVI plays a critical role in addressing the SECCHI science objectives, in particular:

- Investigate the initiation of Coronal Mass Ejections (CMEs): How flux systems interact during the CME initiation, the role of reconnection, and coronal dimming
- Investigate the physical evolution of CMEs: Their 3-dimensional structure, how they are accelerated, and the response of the low corona
- Investigate the 3-dimensional structure of Active Regions

The STEREO mission consists of two identically instrumented spacecraft in heliocentric orbits, drifting away from Earth in opposite directions at 22 degrees per year. The two observatories will provide stereoscopic imaging of the sun as their separation angle increases. The STEREO launch is scheduled for November 2005.

The SECCHI investigation is led by the Naval Research Lab (NRL). The EUVI telescope is being developed at the Lockheed Martin Solar and Astrophysics Lab (LMSAL). The EUVI mirrors are being figured and coated at the Institut

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d'Optique (IOTA) and calibrated at the Institut d'Astrophysique Spatiale (IAS), the focal plane assembly is being developed at NRL and the University of Birmingham, the camera electronics are being developed at the Rutherford Appleton Lab, and the aperture door is being supplied by the Max-Planck Institut für Aeronomie (MPAe).

The SECCHI instrument suite includes five telescopes covering a broad range of fields of view, starting at the solar surface and extending all the way to the interplanetary space between the sun and Earth. The EUVI covers the innermost portion of this range, from the solar chromosphere to the inner corona at 1.7 solar radii. The EUVI builds on its predecessor, EIT on SOHO[1], with several performance improvements including better spatial resolution and a higher image cadence. We present an overview of the design and the capabilities of this new telescope.

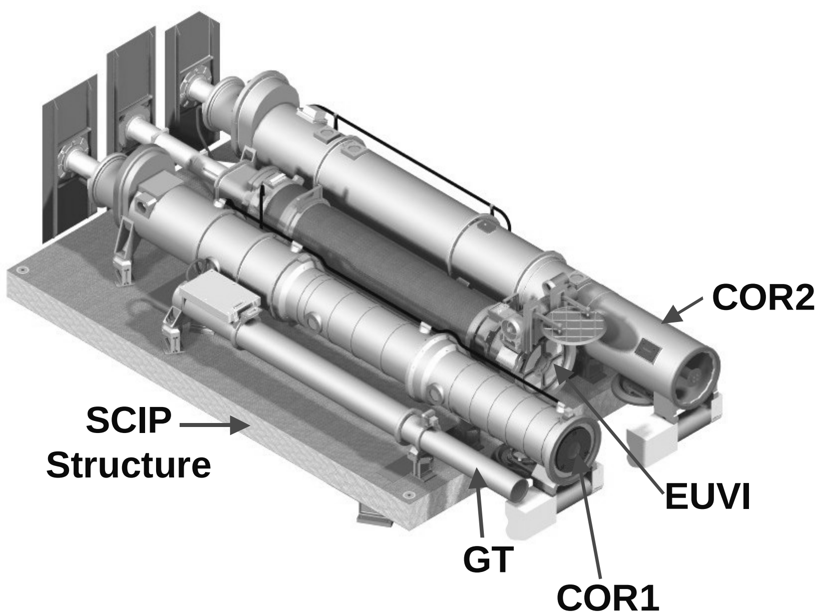

Figure 1. The Sun Centered Imaging Package (SCIP) of SECCHI includes the EUVI.

2. EUVI TELESCOPE OVERVIEW

The EUVI observes the chromosphere and low corona in four different EUV emission lines between 17.1 and 30.4 nm. It is a small, normal-incidence telescope with thin metal filters, multilayer coated mirrors, and a back-thinned CCD detector. Figure 1 shows the EUVI on the SCIP platform and Figure 2 is a cross section through the telescope.

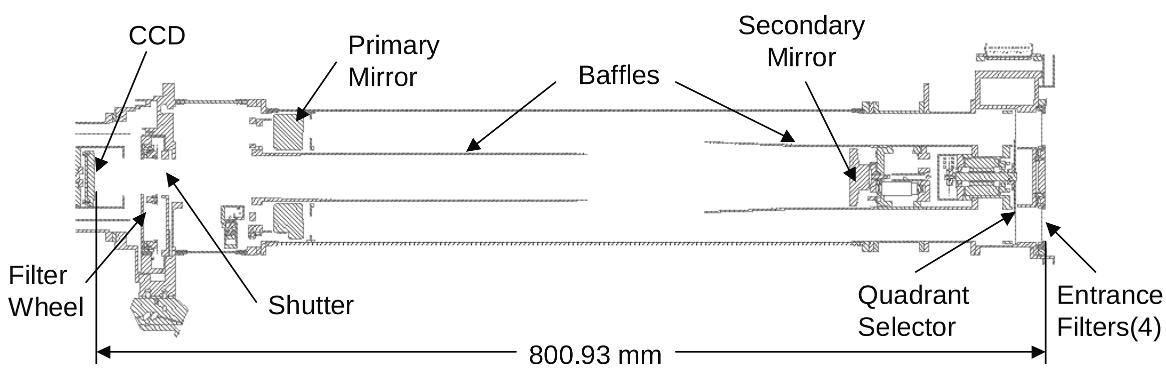

Figure 2. EUVI telescope cross section.

EUV radiation enters the telescope through a thin metal film filter of 150 nm of aluminum. This filter suppresses most of the UV, visible, and IR radiation and keeps the solar heat out of the telescope. During launch, the filter is protected by a door. The radiation then passes through an aperture selector to one of the four quadrants of the optics. Each quadrant of the primary and secondary mirror is coated with a narrow-band, multilayer reflective coating, optimized for one of four EUV lines. The radiation continues through a filter wheel, with redundant thin-film aluminum filters to remove the remainder of the visible and IR radiation. A rotating blade shutter controls the exposure time. The image is formed on a CCD detector. The main parameters for the EUVI telescope are summarized in Table 1.

Table 1 EUVI telescope properties

Instrument type	Normal incidence EUV telescope (Ritchey-Chrétien)
Wavelength selection	Narrow-band EUV reflective multiplayer coatings Four passbands selected by different coatings in each mirror quadrant
Bandpass	He II 30.4 nm Fe IX 17.1 nm Fe XII 19. 5nm Fe XV 28.4 nm
IR/visible/UV rejection	Thin metal film filters
Aperture	98 mm at primary mirror
Effective focal length	1750 mm
Field of View	Circular full sun field of view to ±1.7 solar radii
Spatial Scale	1.6” pixels
Detector	Backside illuminated CCD (e2v CCD42-40), 2048 x 2048 pixels
Mechanisms	1 aperture selector 1 filter wheel 1 focal plane shutter
Image stabilization	Active secondary mirror (tip/tilt)

3. OPTICS

3.1 Optical Design

The EUVI optics is a Ritchey-Chrétien system with a secondary mirror magnification of 2.42. This system provides pixel limited resolution across the entire field of view in all four optical quadrants. The low secondary mirror magnification reduces the telescope’s sensitivity to shifts in the mirror separation and eliminates the need for a focus mechanism. The telescope is fully baffled to prevent charged particles entering the front aperture from reaching the CCD. The telescope pupil is located just in front of the primary mirror and is defined by an aperture mask. The baffles and aperture mask have been designed for an unvignetted field of view to ±1.7 solar radii. The optical prescription of the system is summarized in Table 2. Figure 3 shows ray trace results for a single quadrant, both on-axis and at the edge of the field, and up to 0.15 mm inside and outside of nominal focus. The system has a minor amount of field curvature; the nominal focus location is chosen to minimize the aberrations across the field.

Table 2. Optical parameters.

Parameter	System	Primary mirror	Secondary mirror
Effective focal length	1750 mm		
Mirror separation	460 mm		
Distance secondary mirror - focus	635 mm		
Outer diameter of aperture mask (aperture at pupil)	98 mm		
Inner diameter of aperture mask (central obscuration)	65 mm		
Radius of curvature		1444 mm, concave	892 mm, convex
Conic constant		-1.194	-8.42
Mirror diameter		105 mm	48 mm

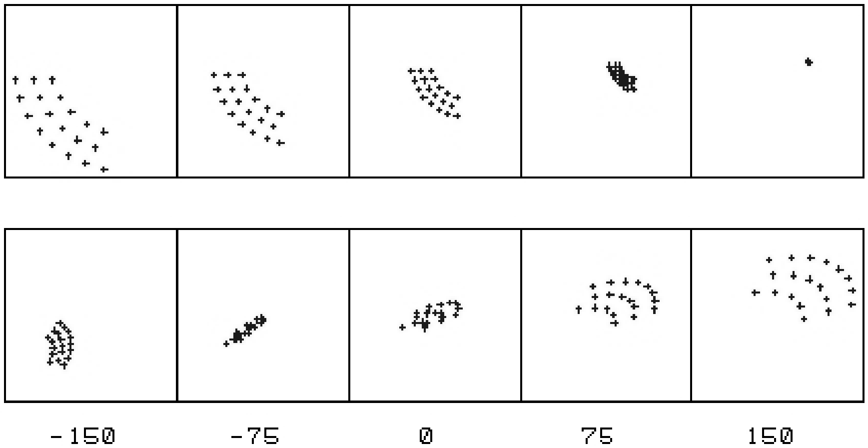

Figure 3. Ray trace results for a single quadrant and two field angles (0 and 27 arcmin) at nominal focus, and up to 150 µm inside (–150) and outside (150) of nominal focus.

3.2 Mirrors

The EUVI mirrors are being figured, polished, and multilayer coated at the Institut d'Optique in Orsay, who also made the mirrors for EIT. The Zerodur mirror substrates are first polished to a sphere and superpolished to the required surface roughness. They are then aspherized using an ion beam etching technique that preserves the superpolished properties of the surface. Finally, each quadrant of each mirror is coated with a narrow passband reflective multilayer, optimized for the specific EUV emission to be observed in that quadrant. All coatings consist of MoSi layer pairs. The coating for the 28.4 nm quadrant has a variable layer spacing for optimum suppression of the nearby 30.4 nm He II emission line. The other coatings use constant layer spacings. Table 3 summarizes the properties of the coatings[2].

Table 3. Properties of the multilayer coatings.

Quadrant/Channel	**17.1**	**19.5**	**28.4**	**30.4**
Principal emission lines	Fe IX, Fe X	Fe XII, Fe XXIV	Fe XV	He II
Center wavelength	17.2 nm	19.4 nm	28.4 nm	30.4 nm
Bandwidth (measured FWHM for single reflection)	1.4 nm	1.6 nm	1.9 nm	3.0 nm
Peak reflectivity (measured, for single reflection)	39 %	35 %	15 %	23 %
Coating materials	MoSi	MoSi	MoSi, var. spacing	MoSi

3.3 Filters

The EUVI uses thin metal film filters at both the entrance aperture and near the focal plane to suppress undesired UV, visible, and IR radiation. We use two types of filters at the entrance of the telescope (Figure 4): an aluminum-on-polyimide foil on a coarse nickel grid for the short wavelength quadrants (17.1 and 195 nm), and a single layer aluminum foil on a fine nickel mesh for the long wavelength quadrants (28.4 and 30.4 nm). Both types of filters use a 150 nm thick layer of aluminum to reject light. The grid supported aluminum filter is backed with a 70 nm thick layer of polyimide for strength. The polyimide layer allows the filter to be supported by a coarse grid with 5 mm line spacing that causes only minimal diffraction at EUV wavelengths. The polyimide transmits only about 50% of the EUV radiation at the observing wavelengths, but this is not a major concern for the strong lines at 17.1 and 19.5 nm. The mesh supported filter avoids the absorbing polyimide layer, which is a major concern at longer wavelengths, especially for the somewhat weaker line at 28.4 nm. The fine mesh with 0.36 mm line spacing causes a noticeable amount of diffraction, especially in the presence of very bright solar features. Both types of filters have been flown on highly successful experiments: EIT used a plastic reinforced aluminum foil on a nearly identical coarse grid for all wavelengths and TRACE[3] used fine mesh supported filters nearly identical to the ones on the EUVI. Near the focal plane 150 nm thick aluminum filters on a fine mesh are housed in a filter wheel. The filter wheel offers redundant filters in case pinholes should develop on orbit. A third filter wheel position contains two filters in series to mitigate against any catastrophic damage to the entrance filters. The fourth filter slot is left open, primarily for ground testing. All filters are being manufactured by LUXEL Corporation.

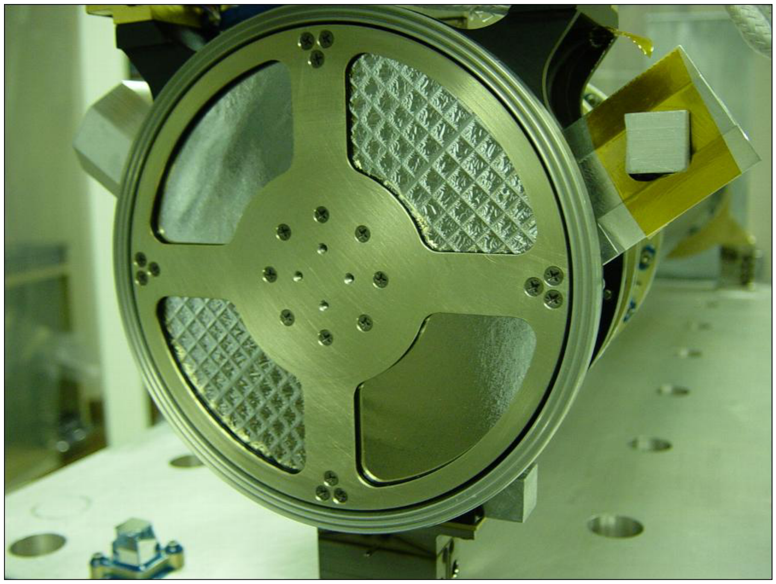

Figure 4. EUVI entrance filters on the structural test model of the telescope. Top left and bottom right are mesh based filters, the others are polyimide backed and supported on a coarse grid.

3.4 Detector

The detector is a back thinned, backside illuminated full frame CCD with 2048 x 2048 pixels. It is a standard CCD42-40 device from e2v technologies with square 13.5 µm pixels. e2v has a long track record of manufacturing CCDs with high quantum efficiency and stability in the XUV. The CCD is passively cooled to below –60 C to minimize dark current and mitigate against radiation damage.

3.5 Aliveness Source

The EUVI telescope contains blue and violet light emitting diodes (LEDs) for testing and calibration purposes. One set of LEDs is mounted in the spider and illuminates the detector through reflection off the two telescope mirrors. A second set is mounted near the CCD. Photons from the blue LED at 470 nm have a similar penetration depth in silicon as EUV photons, while photons from the violet LED at 400 nm provide a diagnostic that is sensitive to CCD surface effects.

4. MECHANICAL DESIGN

4.1 Metering Structure

The EUVI uses a Graphite/Cyanate Ester metering tube as the main telescope structure (see Figure 5). The tube stiffness maintains proper alignment of the optical system through launch. The low coefficient of thermal expansion (CTE) in the axial direction minimizes changes in the mirror separation and keeps the telescope in focus throughout the operational temperature range. This eliminates the need for a focus mechanism. The metering tube is lined with an Aluminum foil on the inside that acts as a vapor and contamination barrier.

Attached to the front of the metering tube are the secondary mirror spider, the quadrant selector spider, and the entrance chamber with the entrance filters and the interfaces to the aperture door and the forward mount. The spider arms are hollow and incorporate separate vent paths for the secondary mirror tip-tilt mechanism and for the quadrant selector motor. Attached to the aft end of the metering tube are the primary mirror mount, and the aft metering structure with the shutter and filter wheel mechanisms, as well as the interfaces to the focal plane assembly and the aft mounts. The aft structure again incorporates separate vent paths for its mechanisms to minimize potential sources of contaminants inside the optical cavity.

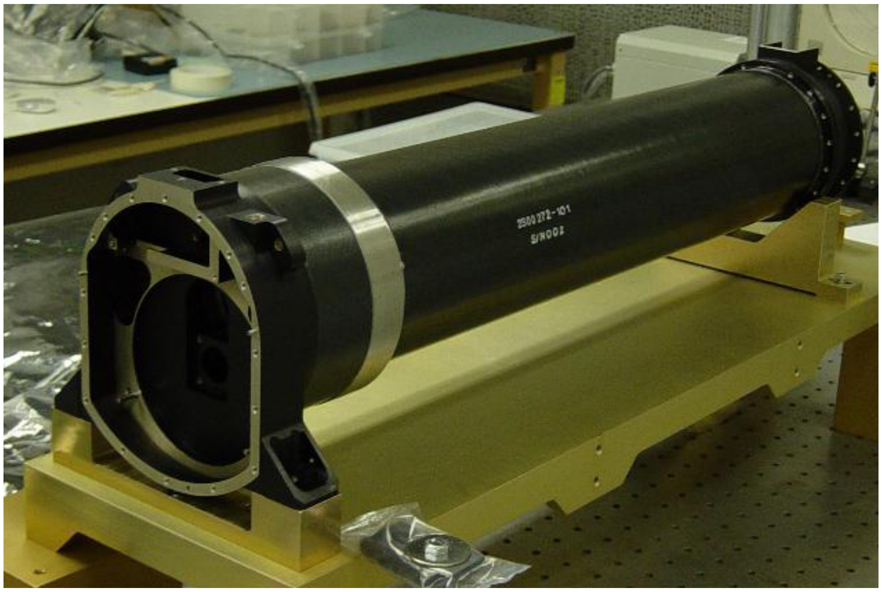

Figure 5. EUVI flight metering tube with filter wheel and shutter housing viewed from the back.

4.2 Mirror Mounts

The EUVI primary mirror and mount are shown in Figure 6. The mount consists of a hexagonal Titanium ring that interfaces to the mirror substrate via three bi-pod flexures. This arrangement is semi-kinematic: each bi-pod strongly constrains two degrees of freedom, but is relatively flexible in the other four, thus isolating the mirror from thermal stresses in the mount. Interferometric tests showed that temperature changes of up to 22 C cause no measurable deformation of the mirror figure. The bi-pods are made of Invar, and attach to the Zerodur mirror through bonded Invar mounting pads. This mirror mount is very compact to fit the tight envelope constraints of the EUVI telescope.

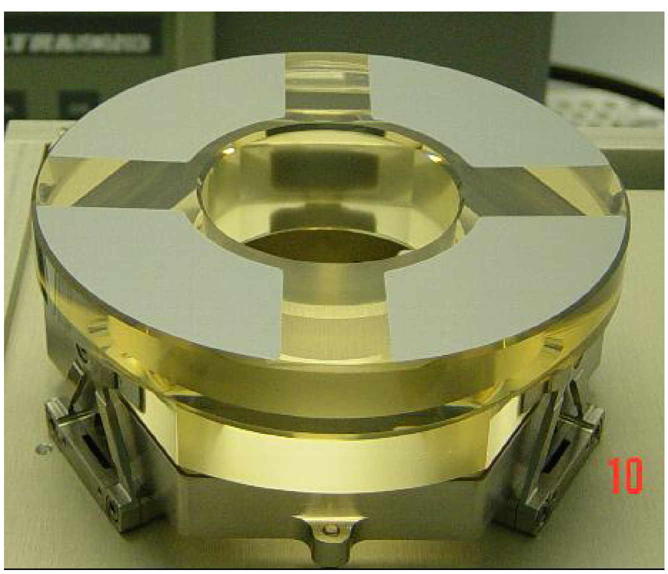

Figure 6. EUVI primary mirror, coated and mounted. the mirror diameter is 105 mm. The regions between the quadrants are deliberately left uncoated.

The secondary mirror mount and the tip-tilt mechanism are shown in Figure 7. The mount is a single piece of Invar with three machined fingers that are bonded to the cylindrical base of the Zerodur mirror substrate. The tip-tilt mechanism is very similar to the one on the TRACE telescope. It uses three piezoelectric (PZT) actuators that push against the Invar mount of the mirror. Software in the SECCHI flight electronics processes fine pointing signals from the SECCHI guide telescope and drives the PZT actuators open loop via a simple digital-to-analog converter and low voltage drivers. The tip-tilt range in the EUVI image space is ±7 arcseconds, sufficient to accommodate worst case spacecraft jitter.

Figure 7. EUVI secondary mirror and tip-tilt mechanism. The mirror diameter is 48 mm. One of the three PZTs (marked "L2...M") is clearly visible inside the housing.

4.3 Mechanisms

All EUVI mechanisms have heritage from previous flight programs. The door mechanism is based on a SOHO-LASCO design and is provided by MPAe. Its primary function is to protect the fragile entrance filters during launch. Previous EUV telescopes used vacuum chambers to protect their entrance filters, but tests have shown that the relatively small EUVI entrance filters survive the launch environment without a vacuum chamber when protected by a firmly closed door lid. The EUVI door is stepper motor driven and recloseable (Figure 8). The door is also equipped with a redundant single use wax actuator mechanism that will open the door in case of failure of the motor drive.

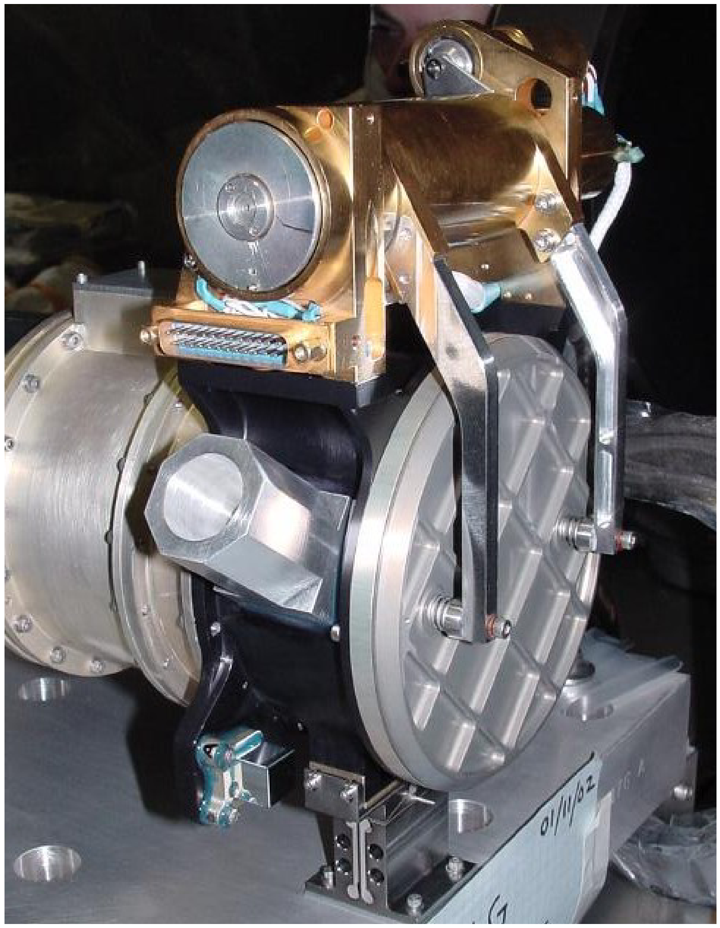

Figure 8. EUVI structural test model door.

The next mechanism in the optical path is the quadrant selector. It is driven by a brushless DC motor with an integral optical encoder. It is highly reliable and represents a major advance over the mechanism used in the TRACE quadrant selector. There are no restrictions in the frequency of changes between telescope quadrants. The EUVI filter wheel and shutter mechanisms use brushless DC motors as well[4]. They are nearly identical to the ones used on GOES SXI-N. The EUVI filter wheel has four slots that accomodate redundant thin metal filters and one open position. The shutter allows exposure times from 60 ms to over 60 sec. Quadrant selector, filter wheel, and shutter are provided by LMSAL.

4.4 Focal Plane Assembly

The EUVI focal plane assembly (FPA) is provided by NRL. It houses an e2v CCD42-40 detector and is passively cooled via an aluminum cold finger and radiator surfaces at the anti-sun deck of the STEREO spacecraft. The FPA is equipped with a heater to keep the CCD warm during the time of high outgassing rates shortly after launch, and for occasional warmups for decontamination purposes if necessary. The FPA has its own vent path along the cold finger and through the radiator.

5. INSTRUMENT RESPONSE AND CALIBRATION

5.1 Calibration Results

In this section we present results of the EUV calibrations of the mirror set for one of the EUVI telescopes, and for one of the flight CCDs.

The EUVI mirrors were calibrated as pairs at the synchrotron of the Institut d'Astrophysique Spatiale in Orsay. The mirrors were arranged in the same geometry as in the EUVI telescope, and illuminated with a nearly collimated beam from a monochromator attached to the synchrotron. Each telescope quadrant was measured individually. Wavelength scans were performed with and without the telescope in the beam; the measured ratio provides the absolute total reflectivity of the mirror pairs[2]. The results for the first flight mirror set are shown in Figure 9 and single reflection coating properties are reported in Table 3. All coatings perform well, both in terms of high reflectivity and proper wavelength of peak reflectivity. The coating for 28.4 nm is optimized for rejecting the strong He II line at 30.4 nm, which results in a somewhat lower peak reflectivity as expected.

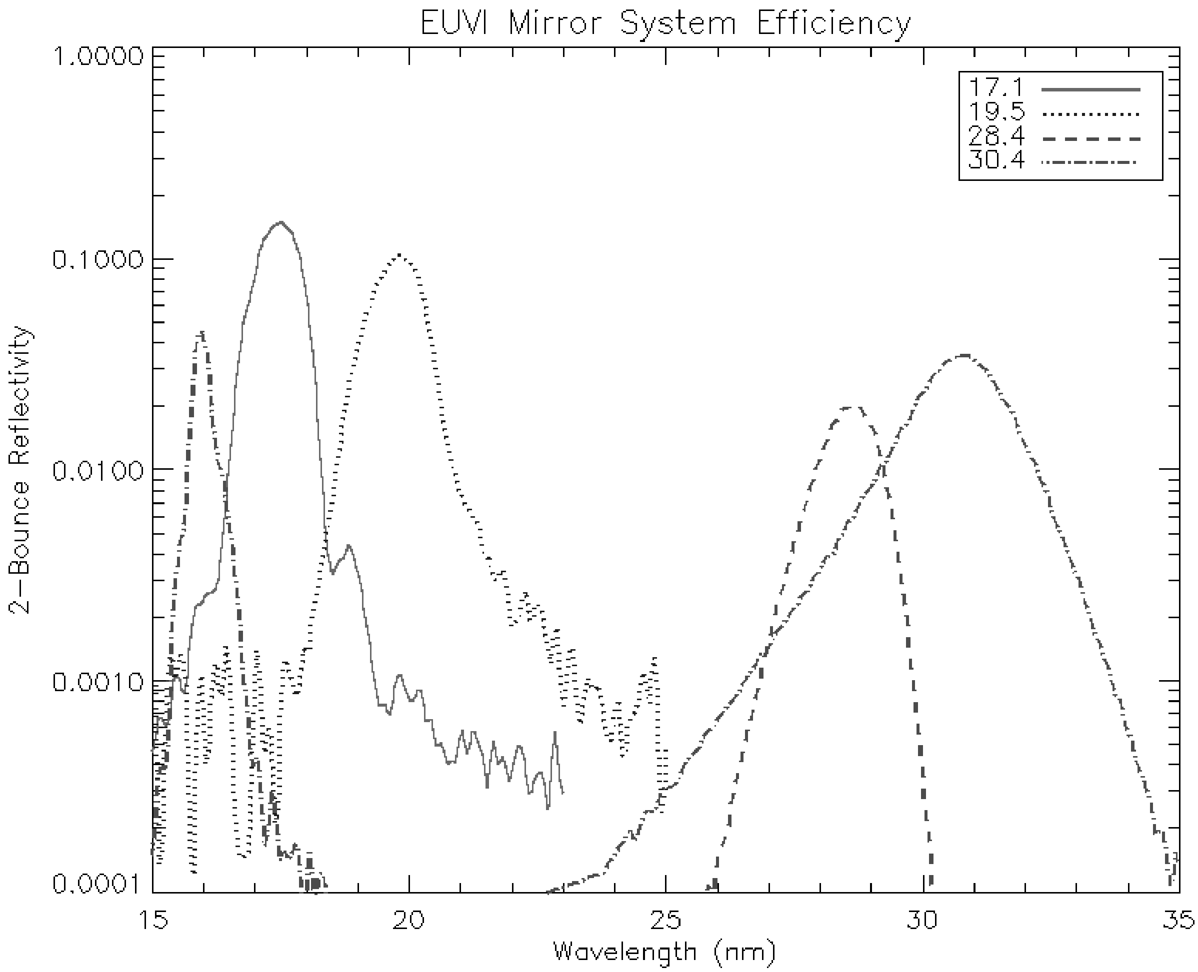

Figure 9. Mirror pair calibration.

CCDs were calibrated at the Brookhaven synchrotron and at the LMSAL XUV calibration facility. Here we report the results from the CCD that was calibrated at LMSAL. The LMSAL XUV calibration facility uses a Manson X-ray source for discrete XUV wavelengths between 1 and 17 nm, and a hollow cathode source for emission lines in the 20 to 122 nm range[5]. A proportional counter is used as a reference detector at the shorter wavelengths, and a NIST traceable Silicon photodiode at the longer wavelengths. Figure 10 shows the measured CCD quantum efficiency (symbols), and a CCD response model fitted to the measurements[6] (solid line). The EUV quantum efficiency is very good and the model provides an excellent fit to the data. This device has the standard (non-enhanded) e2v backside treatment which results in a slightly different response curve in comparison with the CCDs for GOES SXI-N[7].

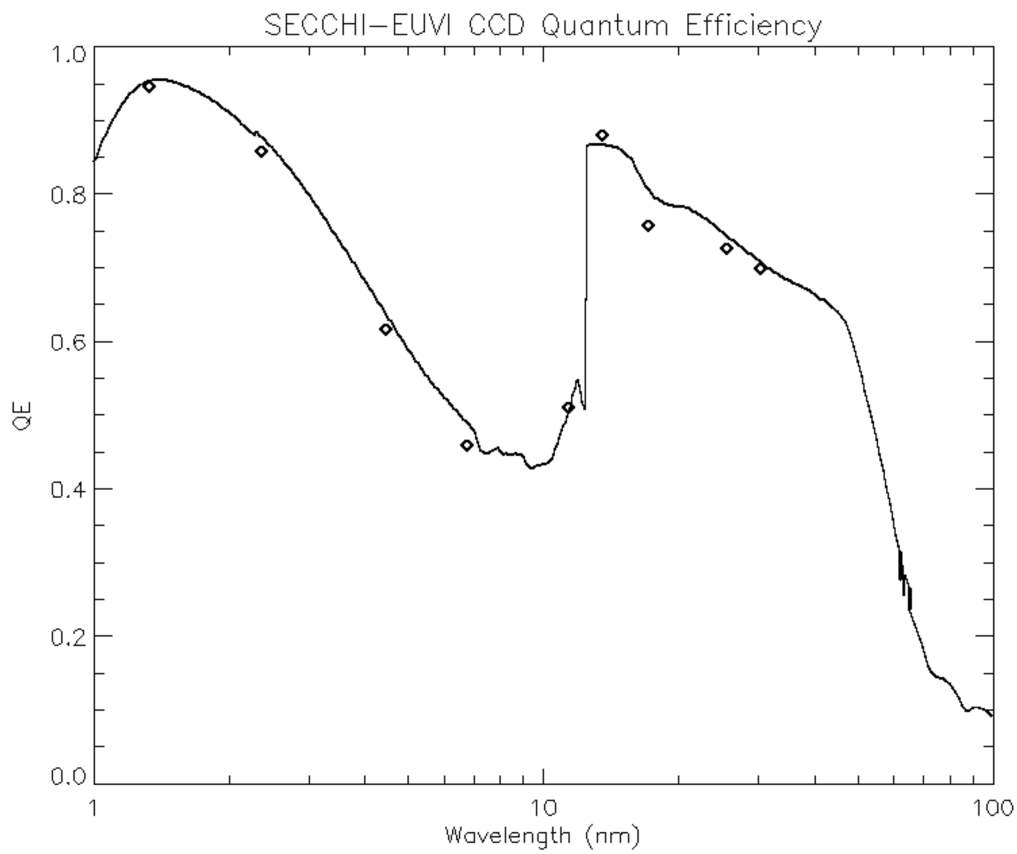

Figure 10. CCD photon quantum efficiency. The symbols represent measurements for device 00462-04-08 and the solid line is the best fit CCD model.

5.2 Predicted Response to Solar Phenomena

In this section, we predict the response of the EUVI to typical solar plasmas using the calibration results. We take typical differential emission measure distributions (DEMs) reported in the literature, predict the resulting solar spectral line emission using the CHIANTI[8] software, and combine the result with our calibration data and with predicted thin filter response curves. Table 4 summarizes the pixel count rates for selected solar features in the different EUVI channels. Note that CHIANTI underestimates the He II flux by typically a factor of three so we have multiplied the prediction by a factor of 3. Figure 11 shows count rates predicted for isothermal plasmas as a function of plasma temperature.

Table 4. Photon count rates (phot/pixel/second) for some solar features predicted with the Chianti code. *The numbers for the 30.4 nm channel have been tripled to adjust for the fact that Chianti typically underestimates the He II flux.

Photons/s/pixel	Quiet Sun	Active Region	M Class Flare
17.1 nm	95	986	25800
19.5 nm	43	852	92100
28.4 nm	3	110	5150
30.4 nm	30*	416*	18200

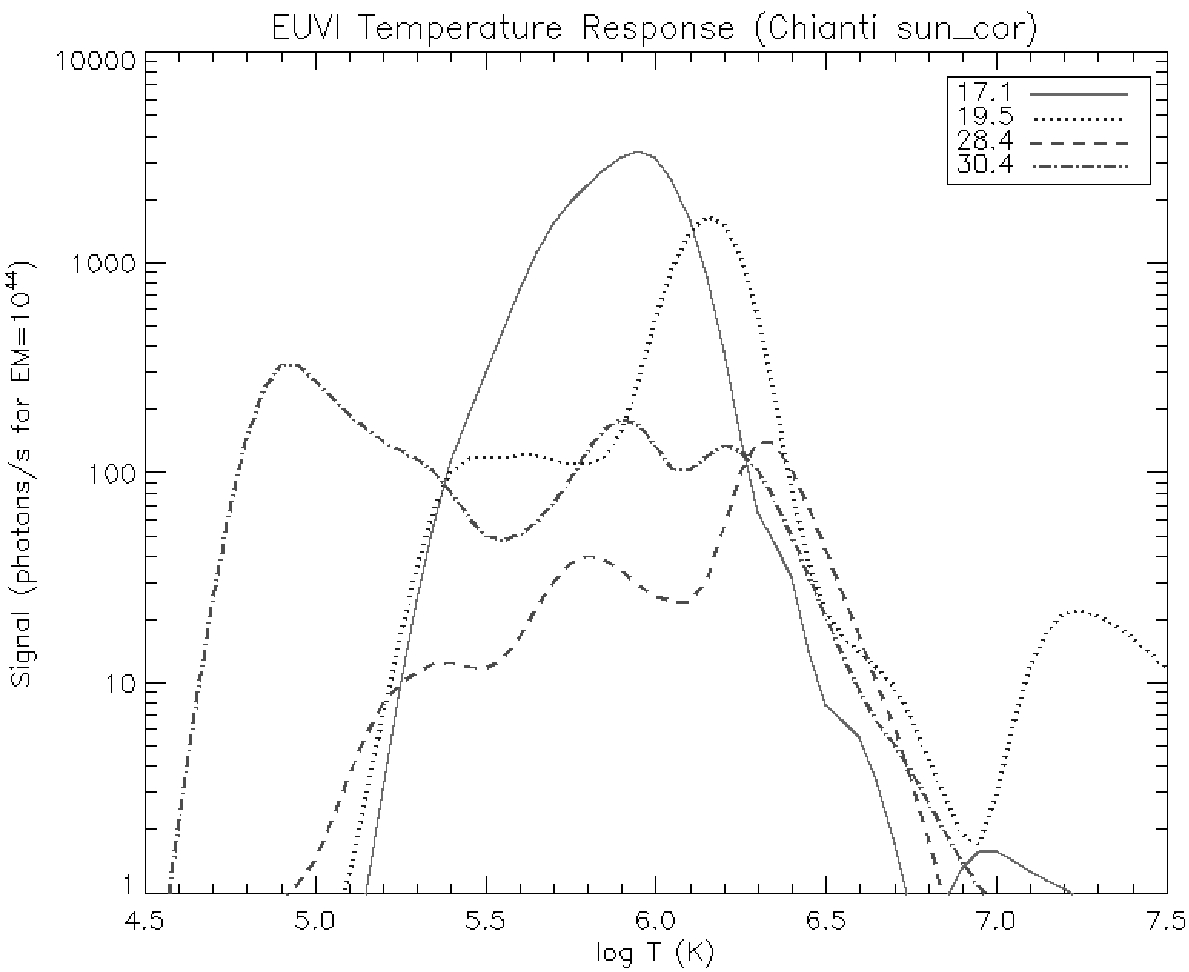

Figure 11. The response of the EUVI as a function of solar plasma temperature.

6. OBSERVATIONAL PROGRAMS AND CONSTRAINTS

The operational control of the SECCHI instrument suite and the EUVI telescope are very flexible. The main constraints are those imposed by the STEREO mission, in particular the limited downlink telemetry and the goal of acquiring simultaneous observations from both STEREO observatories. The latter constraint limits the degree of on-board autonomy for the observing program since the two observatories cannot communicate with each other. The basic observing philosophy for SECCHI consists of two observing programs that run simultaneously on both observatories. The first ("synoptic") program schedules every observation by time, is identical on both observatories, and occupies about 80% of the available telemetry. The second ("campaign") program is more flexible, allowing higher data rates for limited periods of time. It uses a separate, overwritable telemetry buffer that may hold only the most recent high cadence observations. This high cadence buffer can be frozen autonomously by SECCHI based on CME or flare event triggers. Strictly simultaneous observations from both observatories are still desirable in this mode, but are not a requirement. The lower cadence data from the synoptic program from both observatories will remain undisturbed.

It is important to keep in mind that the scientific emphasis of the STEREO mission is constantly changing as the two observatories drift apart. Since observations at a specific spacecraft separation angle can't be repeated, observations must be carefully planned in advance. We expect that the EUVI will provide the greatest contributions to the STEREO science objectives early in the mission, when the separation angle between the observatories is small enough for stereoscopic imaging in the classical sense, and when the STEREO telemetry rate is highest due to the proximity to Earth. During that time, the EUVI will focus on CME initiation studies using high cadence imaging. Later in the mission, when the separation angle approaches 90 degrees, the EUVI of one observatory will observe the low atmospheric effects of CMEs seen off the solar disk by the coronagraphs of the other observatory.

ACKNOWLEDGEMENTS

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