CALIBRATION OF THE EIT INSTRUMENT FOR THE SOHO MISSION

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ABSTRACT.

Optical characteristics in the wavelength range 15-75 nm of the EUV Imaging Telescope to be launched soon on the SOHO mission are discussed. Bandpasses and photometric sensitivity of the multilayered optics telescope have been measured by a dedicated synchrotron light source at Orsay.

Keywords: solar corona, EUV calibration, multilayers, filters, CCD.

1. INTRODUCTION.

The EUV Imaging Telescope (EIT) will image the solar corona in four EUV narrow bandpasses defined by multilayered coatings deposited on normal incidence optics. In order to interpret the future solar data which will be gathered by SOHO, full characterization of the instrument is necessary. The main parameters to be defined are the spatial resolution, bandpasses in the spectral energy domain, and uniformity of the sensitivity within the 1024 x 1024 pixels field of view.

Knowledge of the spatial resolution is necessary in order to identify unambiguously light emitting structures in the solar corona. An exact definition of the bandpasses is mandatory to evaluate the contribution of individual solar emission lines with their own different temperature regimes. Each pixel of the detector defines a 2.6 x 2.6 arcsec volume elements projected on the solar disk. The relative sensitivity of each pixel must be known to convert the data into relative emission intensities (flat fielding). Evaluation of the overall sensitivity is also of interest to predict in-flight exposure times. Despite a development program based on a single proto-flight model and very stringent ESA scheduling discipline, most of the necessary measurements have been completed at component, subsytem or instrument level.

2. IMAGE QUALITY AND ALIGNMENT.

The telescope is a modification of the wide field Ritchey Chretien, proposed by Bottema and Woodruff (1971). This design is very insensitive to a tilt of the secondary mirror which obviously facilitates the alignment. However, to focus the best image on the detector, the distance between the primary and secondary mirror must be adjusted to an accuracy better than 10 μm. The mirrors themselves have been surfaced to an accuracy of $\lambda/50$. The final adjustment was monitored by an autocollimation interferometric method. A pinhole camera located at the nominal central focal point was illuminated by the converging beam of a Zygo interferometer. Interferences of the incoming laser beam with the beam returned by an autocollimation flat mirror normal to the nominal boresight, produced a wavefront error which was mapped by the Zygo. A global wavefront error better than $\lambda/10$ peak to peak was obtained after appropriate shimming of the secondary mirror.

The reference optical cube of the instrument was then measured with respect to the autocollimating flat, thus defining unambiguously the angular tilts required to coalign the instrument boresight with the pointing axis of the SOHO spacecraft.

The wavefront error was used to compute the 2 dimensional point spread function (PSF) at the nominal operating wavelengths. The results can be summarized by the fact that 80% of the encircled energy lies within a diameter of 15 μm for any point inside the 16 arcmin solar radius. Thus the resolution is dominated by the pixel size (21 x 21 μm), see figure (1).

These adjustments were also verified independently using a 3 m Newton collimator accurately focused to produce a parallel beam. The focal plane was found within ± 200 µm of the nominal location by the Foucault knife method and the focal length was measured at 1652 ± 2 mm.

We also tried to check the optical performances at operating wavelengths using a XUV collimator. This collimator consists of a 1 meter off-axis parabola coated by multilayers working at 32 nm in first order and 17 nm in the second order. A Penning discharge light source produced the 30.4 nm line of He II and an aluminum anode Manson X-ray tube was used at 17 nm. However, the divergence of the collimator could not be reduced below 2 to 3 arcsec. The object transmission grid at the focus, proved very difficult to illuminate properly. Thus the EIT mirrors were only very imperfectly covered by the EUV parallel beam. Only qualitative results could be obtained with this device. See figures (2).

This exercise was however very instructive since it provided a convenient way of end to end testing the instrument.

3. THE SYNCHROTRON TEST FACILITY

Optical measurements at the EUV wavelengths of interest to EIT were possible using the calibration facility of IAS (Orsay - F) connected to the synchrotron storage ring light source SUPERACO of LURE. A dedicated beam line includes a grazing incidence toroidal grating monochromator deriving from the LHT30 Jobin Yvon model. A toroidal mirror refocuses the beam on a 2 mm diameter pinhole. This pinhole illuminates a very closely located reflectometer. It also acts as a point source for a slightly diverging beam of 50 m length which can cover one quadrant of the EIT telescope, mounted in a clean vacuum test chamber. Using three different gratings, it is possible to obtain monochromatic light in the range 10-200 nm (spectral resolution 0.2 nm).

4. MEASUREMENTS AT COMPONENT LEVEL.

4.1 The multilayered mirrors.

The Mo-Si multilayered coating fabrication was controlled in situ by monitoring of interferences at 4.4 nm. Fine adjustment of the material thicknesses was the result of an iterative process involving the measurements, at XUV wavelengths, of the reflectivity of test samples, with the synchrotron reflectometer. During the actual deposition run on flight mirrors, witness samples were also coated. These samples obviously occupied different positions than the flight components in the evaporation chamber, and were also measured at an incidence of 5°. However, by measuring these witnesses, it

was possible to deduce the de facto EUV normal reflectivity of the flight mirrors. This work has been detailed before (references [1] and [2]).
A typical measurement is shown in figure (3).

4.2 Filters.

Aluminum thin foil filters are used in the instrument at 3 different positions in order to eliminate completely visible solar light which would be detected by the CCD. Entrance filters block solar visible and IR light before it can enter the telescope, establishing a well controlled thermal environment. In order to minimize diffraction effects in the parallel solar incident beam, very wide supporting grids are used at this level (Ni meshes 100 µm wide on a 5 x 5 mm grid). To improve the mechanical strength, these filters consist in a 60 nm plastic film encased between two 150 nm thick aluminum foils. The plastic material contains carbon which helps to reject light at wavelengths longer than 50 nm.

A pure aluminum stray-light stopping filter is located directly in front of the CCD detector.
A complement of pure aluminum and aluminum/plastic filters is available on a filter wheel to further reduce transmission in the visible if necessary.

All of these filters have been measured in transmission using the same monochromator/reflectometer device.

Typical results are shown in figure (4). They must be carefully interpreted since higher orders of the gratings may appear proeminently at some wavelengths.

4.3 CCD detector.

The detector is a 1024 x 1024 pixels backside illuminated thinned CCD specially processed for XUV sensitivity enhancement by SITE/TEKTRONIX. The CCD is mounted at the end of a cold finger in a vacuum tight compartment. The passively cooled radiator and the pre-amplifiers are outside the vacuum in very close proximity to the sensor head. The whole camera subsystem can be separated from the telescope. The accurate CCD location (± 50 µm) at the focal plane is achieved by trimming the thickness of a spacer. This shim is defined by optical metrology, comparing the flight camera to the pinhole camera used to align the telescope.
A key parameter is the conversion factor between the number of incident photons and the number of electrons collected in each pixel. The output amplifier includes an A/D converter whose readings are expressed in digital numbers (DN). The number of electrons per DN is determined by

the photon transfer method of Janesick (reference [3]) and by observing single events from a Fe^{55} 5.9 kev Xray source. It is about 15 e^-/DN.

When the CCD is cooled to -80°C, the dark current is totally negligible and the read noise of the electronics is a few DN's.

The averaged photometric properties of the camera were measured with two independant XUV facilities: a system using classic laboratory line emission sources and a monochromator at LPARL and the synchrotron test system in Orsay. In both cases, Si diodes calibrated by NIST (reference [4]) were used as reference detector to define the number of incident photons on the camera. The total number of electrons produced in the CCD by these photon fluxes was determined by summing the contents of all illuminated pixels. In the case of the synchrotron, the illuminated area was defined by a 1 x 1 cm square stop which could be interchanged with the 1 x 1 cm calibrated diode. The laboratory light sources did only cover a small irregular area of a few mm^2.

The results can be expressed in terms of the quantum yield (Y) which is the number of e^-/photon or of the quantum efficiency (QE) which is the number of events/incident photon. Since high energy photons can produce several electrons per event, the relation between Y and QE is $Y = QE \times h\nu\ (eV) / 3.6$, where $h\nu$ the energy of the photon is $124 / \lambda$ (nm).

Although measurements at the two places are still slightly in disagreement, sizeable quantum efficiency is found in both cases superior to 25 % which demonstrates that the EUV enhancement processing was quite effective. See figure (5).

In order to be able to "flat field" the solar images, the relative sensitivities of each pixel were determined by the method of Kuhn et al (reference [5]). A photon beam as homogeneous as possible, is used to illuminate the CCD. In order to separate features arising in the CCD and in the beam itself, many exposures at different transversely shifted positions are registered. At Lockheed, a simple beam diverging from the light source and reflected by a flat multilayered mirror produced rather homogeneous illumination at 17 and 30.4 nm. With the synchrotron, Fraunhofer fringes originating from stop edges in the beam line make the processing slightly more difficult. The flat field of the flight camera is shown in figures (6), and the corresponding histogram shows that only reasonnable levels of corrections are required.

5. MEASUREMENTS AT SUBSYSTEM AND SYSTEM LEVELS.

5.1 The optical system.

In order to verify the adequate consistency of potential primary and secondary optics, the flight and spare flight sets of mirrors were mounted on an optical bench. The four possible combinations were tested in the synchrotron facility. A channeltron detector was used to measure the incident flux in the parallel monochromatic beam and the transmitted flux at the focus of the telescope. Scanning the monochromator as a function of wavelength, it was possible to verify the setting of the bandpasses and the throughput, by relative measurements, involving a single and same detector. All four combinations proved to be satisfactory, showing that the wavelength adjustments during fabrication were perfectly controlled.

However, at that time an excessive level of stray-light originating in the monochromator was detected. This resulted in a pessimistic evaluation of the throughput by a factor of two before the necessary correction could be taken into account.
At the end of these measurements, the sets of flight and spare optics were defined.

5.2 The instrument.

The photometric sensitivity of the fully assembled instrument including the camera was evaluated by comparison with a NIST calibrated diode in a way very similar to the calibration of the stand alone detectors. Again, a 1 cm^2 square aperture in front of the telescope was substituted to the calibrated diode. This gave the number of incident monochromatic photons for each setting of the monochromator inside and outside the nominal bandpasses.

Since the "object" pinhole source is only at 50 meters of the telescope, its image is several centimeters behind the focal plane and the CCD surface. Thus 15 x 15 pixels were illuminated on the CCD and their content had to be summed to define the number of electrons detected per incident photon. Several 1 cm^2 square areas on the primary mirror were explored and five points in the field of view of the instrument were controlled by tilting the telescope in front of the beam.

Notice that evaluation of a single point in the instrument bandpass by this method requires analysis of a sizeable part of an image in order to remove the readout noise measured in a non-exposed area Although lengthy, this procedure is quite satisfactory because the radiation from a storage ring decreases very smoothly in time. The four instrument bandpasses are shown in figure (7).
The filter transmission was again measured inside the instrument at the peak of the transmission bandpasses either by using the rotating filter wheel or by mounting and dismounting manually the entrance and stray-light filters.

6. CONCLUSIONS.

Through a complex set of successive measurements, enough informations have been gathered to define the performance of the flight instrument which is now ready for launch. We plan to acquire additional informations by applying this calibration plan of actions, in a more tempered atmosphere than the one which prevailed during the SOHO development, to an additionnal model of the instrument which is under preparation. This model adapted for a sounding rocket program will make use of all available spare optical and mechanical components. Multiple launches of this rocket payload will hopefully provide adequate data to update the characteristics of the SOHO instrument after several years in orbit.

7. ACKNOWLEGEMENTS

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Figure (1): The PSF at 30.4 nm convoluted with the pixel.

Figures (2): EUV collimator results (171 Å and 304 Å).

Figure (3): Reflectivity measurement for the one mirror.

Figure (4): Typical transmission measurement of aluminum/carbon filter.

Figure (5): Flight CCD QE measured at LPARL and at IAS.

Figure (6.a): Raw image (171 Å).

Figure (6.b): Sensitivity map of the CCD (flat field).

Figure (6.c): Corrected image (synchrotron beam only).

Figure (6.d): Histograms of the flat field (nb of pixels versus normalized intensity levels).

Figure (7): The instrument bandpasses.