Alignment of the Extreme-UV Imaging Telescope (EIT)

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I. INTRODUCTION.

A global optical survey of the solar corona will be accomplished by observations made with an **Extreme ultraviolet Imaging Telescope** (**EIT**), an experiment on-board SOHO, developed in collaboration with Centre Spatial de Liège (B), IAS at Orsay (F), IOTA at Orsay (F), LAS at Marseille (F) and NRL at Washington (USA). Images in four narrow bandpasses at wavelengths ranging from 17 to 31 nm, will be obtained using normal incidence multilayered optics deposited on quadrants of a Ritchey-Chretien Telescope. They will be recorded on a specific CCD camera especially developped for the EIT instrument.
No sun pointing readjustment possibility is available, thus alignment of the instrument has been emphasized to ensure a good pointing and a good image quality.
This paper reports on how the alignment of the flight instrument was analysed, performed and verified.

II. EIT AND THE SOHO MISSION.

The Solar Heliospheric Observatory (SOHO spacecraft) is part of the international STSP program of ESA and NASA. Launched mid-1995, SOHO will reach the Ll Lagrangian point located between Earth and the Sun, at 1,500,000 km from Earth. It will stay on a "halo orbit" around this location.
SOHO will become a fixed observatory oriented towards the sun. It is a 3 axes stabilized sun pointing spacecraft within 10 arcsec that will provide 2 to 6 years of continuous observations without any eclipse for all the on-board experiments.
The solar corona and the solar wind will be monitored and analyzed from the L1 point by a new package of 12 instruments. The SOHO mission will provide an opportunity for substancial data from solar and heliospheric observations. It is planned for a nominal duration of two years with an optional extension to six year.
The main objectives of the SOHO mission are

- the study and the understanding of the solar coronal phenomena and the solar wind.
- the study of the solar structure and the interior dynamics from its core to the photosphere.

Among these solar experiments attached to a 2000 kg spacecraft, EIT is a medium imaging telescope of the 15 kg class. The EIT experiment is a multi-bandpass Ritchey-Chretien telescope providing in the focal plane images of the solar disk at four wavelengths in the EUV range (He II-30.4 nm-6 10^4 K ; Fe IX-17.1 nm-10^6 K ; Fe XII-19.5 nm-1.6 10^6 K; Fe XV-28.4 nm-3 10^6 K). The experiment is a high resolution, wide field telescope to obtain images of the corona on the disk and above the solar limb.
With its capacity to distribute in real time data to the other coronal instruments on SOHO, EIT will play the role of "conductor" among the instruments on SOHO, dedicated to the corona and chromosphere. With its good corona coverage, EIT will inform the other instruments about the zones to be analysed.

III. THE EIT INSTRUMENT

A. Main components

The Ritchey-Chrétien telescope is made with two Zerodur mirrors, manufactured and coated at IOTA (Orsay). They are attached to a cylindrical structure which is thermally controlled. This structure is mounted in another cylinder, on which several components are fixed. they are as follows:

- ▹ an external front baffle defines the entrance aperture and rejects unwanted rays,
- ▹ an aperture door keeps the instrument under vacuum during launch and is open for observations,
- ▹ an entrance aluminum filter rejects the visible and unwanted light,
- ▹ a rotating mask selects which quarter of the entrance pupil will be illuminated,
- ▹ a filter wheel supports 5 insertable filters,
- ▹ the shutter is used to expose the detector
- ▹ a stray-light baffle with a filter protects the detector from unwanted radiations,
- ▹ a specific CCD camera is mounted at the level of the focal plane.

B. Telescope characteristics

EIT contains a Ritchey-Chrétien telescope with normal incidence Zerodur mirrors. Its main characteritics are summarized in table (III.B.1).

Focal length	1650 mm
Field of view	45 x 45 arcmin
Primary mirror external diameter	115.5 mm
Primary mirror internal diameter	58 mm
Secondary mirror external diameter	46 mm
Secondary mirror internal diameter	7 mm
Space resolution	1 arcsec

Table (III.B.1).

The mirrors have 4 different coatings deposit on four distinct quadrants. A mask selector occults 3 of the 4 quadrants to produce images in one wavelength. A schematic of the design is presented in figure (B.1). This design provides 4 telescopes in one, with the advantages of a unique detector, a mass reduction, a stable and precise alignment of the 4 images in the different wavelengths.

C. Mirrors

The two EIT mirrors have been manufactured and coated at IOTA (Orsay-Fr). They are made of Zerodur, with a light weighted shape for the primary. Both of them have a figure of approximatively $\lambda/20$ in the visible light, with a RMS rugosity of 3 Å.

The first polishing gave them a spherical shape on which a B coating has been applied under vacuum to reach the good aspherical shape. This procedure was applied because substrate of such good quality (3 Å RMS) are more easily obtainable with spherical surfaces.

Four different multilayered coatings are then vacuum deposited on each quarter the mirrors in order to provide four different bandpass depending on which quadrant is illuminated. These coatings use a new type of structures made of metal-oxide sandwiches. These Layered Synthetic Material (LMS) have been previously used extensively in other fields of applications (visible optics, electronic components,...). Due to the moderate absorption coefficient of oxides in the wavelength range of the EIT, extremely sharp bandpasses can be obtained with stacks including a large number of layers. Narrow bandpasses will allow effective selection of the solar emission lines that will be studied with EIT. A periodic stack of pair of alternating material is used: one material is absorbing and reflecting and the other is transparent. The period of stack is adjusted to produce interference by reflection.

For the 284 Å coating, the stack is not periodic in order to reduce the bandpass and to avoid the intense line at 304 Å. A potential crosstalk between these 2 quadrants is avoided by disposing the 304 Å quadrant opposite to the 284 Å one. An additional mask is placed on the primary mirror to avoid crosstalk between adjacents quadrants.

D. Filters.

In order to reduce the chance of data loss due to possible pinholes, radiation must pass through two or three individual filters before reaching the focal plane of the telescope. A third filter may be used if the final test will demonstrate the existence of unadmissible stray-light at the level of the detector.

These filters have been selected in order to reject the visible light, transmit the EUV radiation inthe spectral lines of interest and to reduce the transmission of the intense 584 Å line with respect to the 171-304 Å range.

These filters are mainly very thin aluminum foils that cannot withstand small differential pressure. To prevent their integrity and avoid micro- and macroscopic holes in them, the instrument will be launched under vacuum. It means that the overall enveloppe is hermetic and is pumped before the launch.

Entrance filters

The first filter that is reached by the sun light is made in 8 sectors that cover the overall entrance pupil of the telescope. They are made with 2 thin aluminum films (1500 A each) deposited on each side of a Ni grid and a celluloid foil sandwich.The grid characteristics are as shown in column 2 of table (E.1).

Filters in the filter wheel.

These filters are smaller than the entrance ones. There are 5 insertable filters mounted on a rotating wheel and located at 30 mm from the focal plane. The 5 filters are:

- one "hole"
- 1 type A aluminum filter
- 1 type B aluminum filter
- 2 half field of view type B aluminum filters

The "hole" position is necessary to perform visible light tests. It will also be used to image th esun through only the two remaining aluminum filters. These aluminum filters are needed to improve the suppression of the unwanted radiation. Two types of these filters are used:

-type A have a structure similar to the entrance filters, with a celluloïd film inside 2 thin aluminum foils.

-type B filters have only one aluminum foil without celluloïd.Their transmission is higher than the type B filters.

Type A filters will be selected to record solar events with intense activity.

The "half field of view" aluminum filters are used to take exposure without activating the shutter (shutter in open position). The masked half is used for the data transfer of the CCD pixels.

Stray-light filter

On the stray-light baffle, close to the focal plane, a third aluminum filter will be mounted. It is similar to the type B wheel filters. It is located at 12 mm from the focal plane.

Filter characteristics	Entrance filters	Wheel filters type A	Wheel filters type B
Ni rod diameter	100 μm	40 μm	40 μm
Mesh size	5 mm	0.1 mm	0.1 mm
1st alu layer thickness	100 nm	100 nm	100 nm
Celluloïd layer thickness	30 nm	30 nm	-
2nd alu layer thickness	100 nm	100 nm	-
Transmission for λ>2000Å	10^{-5}	???	10^{-7}
Transmission for 170Å<λ<350Å	10 %	???	40 %
Transmission for λ=584Å	0.5 %	???	15 %

Table (III.E.1).

E. Detector

The detector is a specific CCD of 1024 x 1024 pixels of 21 μm edge. The angular pixel size is 2.6 arcsec.

IV. POINTING

As SOHO is sun pointing within 10 arcsec all the time, the EIT experiment is attached to the spacecraft without any sun pointing readjustment possibility. Thus, special care was taken in the design to ensure a good pointing stability. The instrument is isostatically mounted on a lateral panel by means of three feet. This will prevent any stress coming from -or coming to- the spacecraft. Its optical axis is oriented towards the sun and the close vicinity of the spacecraft fine pointing sun sensor will ensure a good alignment on the payload. This is achieved and verified by means of a reflective cube fixed on the external structure of the experiment that is compared with the spacecraft references. A specific drilling template was used to drill the EIT mounting holes and locating pin holes in the spacecraft.
The pointing budget is shared as detailed in table (VI.1).

Contributor	In-plane	Out-of-plane	Roll	Absolute
EIT	1'	1'		
SPACECRAFT	4' (1'=alignt, 3'=eol)	4'	20'	7' (3'30" achieved)

Table (IV.1)

With these values that include the long term effects, EIT requires the more stringent alignment among all the SOHO experiments.

V. ALIGNMENT

A. Alignment criteria

The angle of view of main scientifical interest is 16 arcmin, it corresponds to the edge of the solar photosphere. Thus the alignment has been optimized for this angle. The criteria are defined in table (V.1).

Spatial resolution (circle of 80% energy)	1" at 16' FOV or 2.6" for all FOV
Wave front error (at 633nm)	$\lambda/15$ at 16'

Table (V.1)

The final criterion will depend on the alignment method that will be used.

B. Mirrors mechanical adjustment.

Great attention was taken to the fixations of the primary mirror and to the spacing between the telescope mirrors to maintain the optical quality. The distance between the primary and secondary mirrors has to be stable at 7 µm.
To avoid bending stresses in the mirror blank, the fixing is made by flexible blades and spherical bearings mounted on small invar rods directly glued on the blank of the mirror before polishing. The primary mirror is first attached and aligned using a mechanical reference on the tube. Its back face will be use further as an optical reference.
The distance between the primary and the secondary mirrors is made constant by thermal control of an aluminum tube on which only the mirrors with their respective baffles are mounted. The refocus can be adjusted by changing the tube temperature.
The telescope final alignment will achieved in the mounting of the secondary mirror. Six degrees of freedom will remain to be determined during the fine optical alignment. The final fixing is done with specific shims inserted between the secondary mirror support and its holding tube.

C. Alignment method.

The 4 telescopes combined in one require a non-classical method to achieve an interferometric alignment of the optics. The different thicknesses of the 4 coatings does not allow the use of a standard interferometer technique.
The possible alignment criteria defined previously, depend on the chosen alignment method.

Image quality test in the visible.
The diffraction spot in visible is of the pixel size or larger. Thus image quality test is not possible at this wavelength range due to diffraction.

Image quality in the EUV.
This test has to be performed under vacuum.The alignment of the secondary mirror based on the image quality in the EUV under vacuum in not flexible at all.

Interferometric methods in the visible.
The use of interferometric methods in the visible has been preferred. A phase shifting intereferometer and its associated software has finally been used to align the flight optics.

D. Alignment procedure.

The alignment steps can be summarized as follows:

- ▷ mount a pinhole on the structure, at the location of the center of the CCD detector
- ▷ align and focus the spherical beam (f#3.3) of the Zygo on the pinhole, remove the pinhole
- ▷ defocus the spherical beam (f#3.3) of the Zygo by -150µm
- ▷ align theodolite #1 via a folding mirror on the back face of the primary mirror (PM)
- ▷ the optical axis of the PM is perpandicular to its backface
- ▷ align an autocollimation flat mirror on theodolite #1, this defines the FOV of 0°
- ▷ align theodolite #2 via a second folding mirror on the theodolite #1
- ▷ theodolite #2 is parallel to the optical axis
- ▷ adjust the secondary mirror (SM) (x, y, z) while maintaining it parallel to the PM in order to minimize the WFE
- ▷ the adjustment is monitored with theodolite #2 in autocollimation with the backface of the SM
- ▷ while adjusting the SM, it remains parallel to the optical axis
- ▷ the decenter and the defocus are optimized and monitored with interferometer
- ▷ the adjustments stop when the WFE in the four quadrants is within the desired specifications
- ▷ the temperature of the internal tube has to be checked and in the 20 ± 0.5 °C range during WFE measurements
- ▷ verify the WFE at 16' FOV in 2 perpendicular directions and adjust again the SM
- ▷ measure the gaps between the SM support and its holding tube to define the shim thicknesses
- ▷ mount the shims and verify the WFE:
    - at 0' FOV & z=-150µm
    - at 16' FOV (above) & z=0µm
    - at 16'FOV (left, right) & z=0µm

E. Alignment results and discussion.

The specificity of this alignment comes from the division of the telescope in four quadrants with coatings of different thicknesses; this prevents to make use of Zernike polynomials to interprete the interferograms and to define the required movements of the secondary mirror.
Thus, analysis was performed on each quadrant taken separtely
The Zygo results can be summarized as follows in table (V.E.1)

FOV	**Defocus (µm)**	**Result in the 4 quadrants *before* SM fixation**	**Result in the 4 quadrants *after* SM fixation**
0'	-150	WFE < λ/14	WFE < λ/14
11' 30 (above)	0	-	WFE < λ/11
16' (left,right)	0	-	WFE < λ/10

Table (V.E.1)

The final alignment corresponds to a residual 2" (vertical) and 11" (horizontal) tilt on the secondary mirror, which is due to the torque applied on the SM. This was measured with the theodolite #2. The residual tilt (vertical) observed in the inteferograms is due to a vertical decenter of 11µm. A ray-tracing program simulating EIT showed that with these decenter and tilt the geometrical image quality was better than one CCD pixel .
The rough Zygo data have been analysed in order to deduce the PSF and the encircled energy for each quadrant, at their respective wavelength. They showed that at various points in the field of view, the circle of 80% energy is included in the pixel size.

VI. CONCLUSIONS

The flight instrument with a spare detector has been tested for a photometric calibration using the SUPER ACO synchrotron radiation. This will give substancial data about the combination of the filters, the aligned optics and the detcetor capabilities.
The global transmission of the complete instrument has been analysed and calibrated at the four nominal band passes and at certain points of the spectrum where the transmission should be negligible, for several points of the field of view, for different temperatures of the detector, using a synchrotron beam line from SUPER-ACO (1.27 m storage ring at LURE; Orsay FRANCE), passing through a monochromator at IAS calibration station.
The absolute flux was measured with a calibrated photodiode and the fluctuations in time were corrected by the knowledge of the synchrotron current.
Table (VI.A.1) presents the main results of this photometric calibration.

Quadrant	**Wheel filter**	**Transmission (e^-/photon)**
195	type B	0.15
195	hole	0.8
171	type B	0.17
171	hole	0.56
284	type B	0.001
284	hole	0.09
304	type B	0.033
304	hole	0.25

Table (VI.A.1)

Stray-light tests have also been performed, stray light being all light reaching the CCD, with the wrong wave-length (visible; cross talk between different quadrants, ...) or light of the correct wavelength but reaching the CCD without being reflected by both mirrors (diffraction and/or scattering). After all the qualification tests, EIT has been delivered to ESA for assembly on the spacecraft and undergoes qualification tests at spacecraft level.

Lessons learnt:
Optical references.
- ▹ During manufacturing process of theoretical components (polishing, aspherisation, coating, ...), the vertex and optical axis are known with a very good accuracy. This knowledge must be saved by the manufacturing of mechanical references aligned on these optical parameters (back face of the mirrors, outer diameter, holes for the mountings,...).
- ▹ The design should be established to preserve access to these reference for the alignment.
- ▹ The first steps fo the alignment should make maximum use of these opto-mechanical references by means of classical (mechanical) metrological tools.

Interferometer interpretation with the help of Tatian-Zernike polynomials development
- ▹ Avoid coatings with different thicknesses.
- ▹ Avoid to put the primary mask before alignment.

An EUV collimator test has also been conducted with the flight intsrument. The analysis of theresult is in process.

List of figures