MAGRITTE Optomechanical Design and Mirror Manufacturing

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ABSTRACT

The MAGRITTE telescopes are part of the SHARPP instrument suite, part of the Solar Dynamics Observatory (SDO), a NASA spacecraft to be launched in a geostationnary orbit in 2007. The MAGRITTE instrument package will provide high resolution images of the solar corona at high temporal frequency simultaneously in 5 EUV and in Ly-α narrow bandpasses. The 1.4 R_0 MAGRITTE common field of view compliments the other SHARPP instruments, as well as its spectral coverage with 6 narrow bandpasses located within the 19.5 to 120 nm interval.

The key challenges of the MAGRITTE instrument are a high angular resolution (0.66 arcsec/pixel) with a high responsivity (exposure times smaller than 8 sec), combined with restricted spacecraft resources. The design of MAGRITTE is based on a high performance off-axis Ritchey-Chretien optical system combined with a large detector (4 K x 4 K, 12 µm pixel). The tight pointing stability performance of 1.2 arcsec over the image exposure time requires an active image motion control, using pointing information of a Guide Telescope, to compensate low frequency boresight variations produced by spacecraft jitter. The thermomechanical design and the mirror polishing are highly critical issues in the instrument design.

This paper presents the MAGRITTE design concept with the expected performances based on a realistic error budget. The mirror polishing concept and performances are discussed.

Keywords: EUV imager, off-axis mirrors, solar corona

1. THE AIA FOR THE SDO MISSION

The Solar Dynamics Observatory (SDO) mission is part of the NASA-ILWS program; a solar observatory will be launched in 2007 and sent in a geosynchronous orbit with a quasi-permanent stable Sun pointing.

The Solar Atmospheric Imaging Assembly[1] (AIA) aboard the Solar Dynamics Observatory will be composed of two instruments: the MAGRITTE Filtergraphs, composed of six multilayer EUV / VUV channels (195 to 1216 Å), and the SPECTRE Spectroheliograph[2] (one soft-EUV channel at OV 629 Å). The AIA is part of the SHARPP program[3].

The primary goals of the Atmospheric Imaging Assembly are to characterize the dynamical evolution of the solar plasma from the chromosphere to the corona, and to follow the connection of plasma dynamics with magnetic activity throughout the solar atmosphere. A global understanding of the energy balance (conductive/radiative) and energy flux can only be attained by observing emission from VUV and EUV lines that represent the full range of temperatures present in the solar atmosphere.

The SHARPP/AIA consists of 7 telescopes imaging the following bandpasses: 1215 Å Ly-α, 304 Å He II, 629 Å OV, 465 Å Ne VII, 195 Å Fe XII (includes Fe XXIV), 284 Å Fe XV, and 335 Å Fe XVI.

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The telescopes are grouped by instrumental approach:

(1) **MAGRITTE Filtergraphs**: five multilayer "EUV channels", with bandpasses ranging from 195 to 500 Å and one Ly-α channel;

(2) **SPECTRE Spectroheliograph**[2]: one "soft EUV channel" O_V at 630 Å.

These two instruments, the electronic boxes and two Guide Telescopes (GT) constitute the AIA suite. They will be mounted and coaligned on two dedicated common optical benches. The GTs will provide pointing jitter information to the whole SHARPP suite through an Image Motion Compensation System (IMC). The CCD cameras for the AIA are common to the seven telescopes. The seven AIA cameras will image the Sun simultaneously at a 10 second cadence with a 0.66"/pixel resolution in a field of view extending from the Sun center to 1.4 $R_{\odot}$. The extended FOV is required to have sufficient overlap with the complementary EUV coronagraph observations. This paper is limited to the MAGRITTE instrument.

2. MAGRITTE DESIGN

2.1 MAGRITTE concept

The MAGRITTE requirements are based on quasi-identical specifications for all channels, summarized in table 1. The Ly-α channel entrance aperture is enlarged to compensate the loss of CCD efficiency at 1216 Å and diffraction effect. Photometry imposes the number of mirror (2) and multilayer coating performances impose the maximum incidence angle on mirror (≤ 6°). As all channels have to be acquired simultaneously, the trade-off conducts to a design concept based 6 independent telescopes on the same optical bench. An off-axis optical design was chosen as compromise between the optical performances, the collecting area, the large field of view, the baffling characteristics and the envelope requirement.

Specification	EUV channels	Ly-α channel
Entrance aperture	ϕ 45 mm (unobstructed)	ϕ 60 mm (unobstructed)
Effective focal length	~ 3750 mm	
Spectral range	Quasi monochromatic (Δλ ~ 30 Å) Channel 1: 195 Å (1.5 MK) Channel 2: 284 Å (2 MK) Channel 3: 304 Å (0.06 MK) Channel 4: 335 Å (3 MK) Channel 5: 465 Å (0.7 MK)	Lyman-α (1216 Å)
CCD	4096 x 4096 pixels 12 µm pitch	
Field of view (FOV)	45 arcmin square (1.4 solar radius)	
Envelope	760 mm length	

Table 1: Main requirements for Magritte channels

The EUV channel optical layout is detailed in figure 1. The Ly-α channel is based on the rocket-borne Transition Region Camera[4] design which uses narrow-band interference filters to isolate Ly-α. It has been adapted for compactness by using a scheme nearly identical to the multilayer instruments: an off-axis Ritchey-Chretien design with a 60 mm (resized for throughput and diffraction) aperture. The common conceptual design limits the manufacturing and development cost. All channels are mounted on the same optical bench, as illustrated in figure 2 and 3.

Each channel is composed by a 2 mirrors off-axis telescope, a once opened front door to prevent contamination during test and launch phases, a front aluminium filter to reject IR and visible light, an internal baffling system, a robust shutter (about 10^6 cycles during the lifetime) and a focal plane assembly. Wavelength selection is performed by multilayer coating on optics.

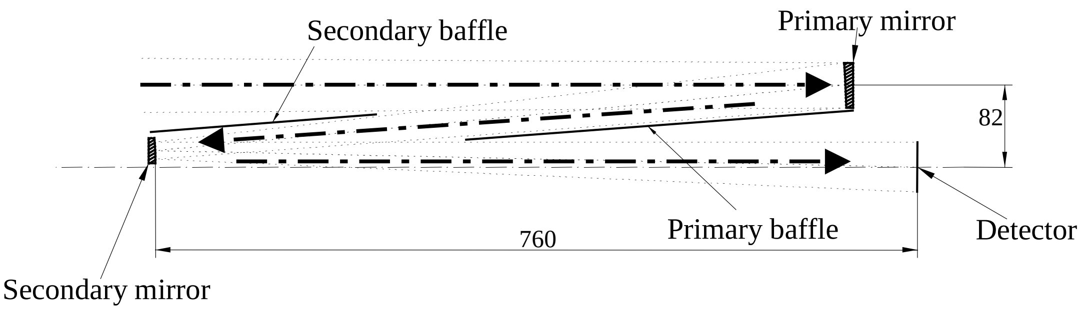

Figure 1: Optical layout of Filtergraph off-axis Ritchey-Chretien telescopes (in mm). Due to the diffraction limit and throughput, the Ly-α channel will be slightly larger

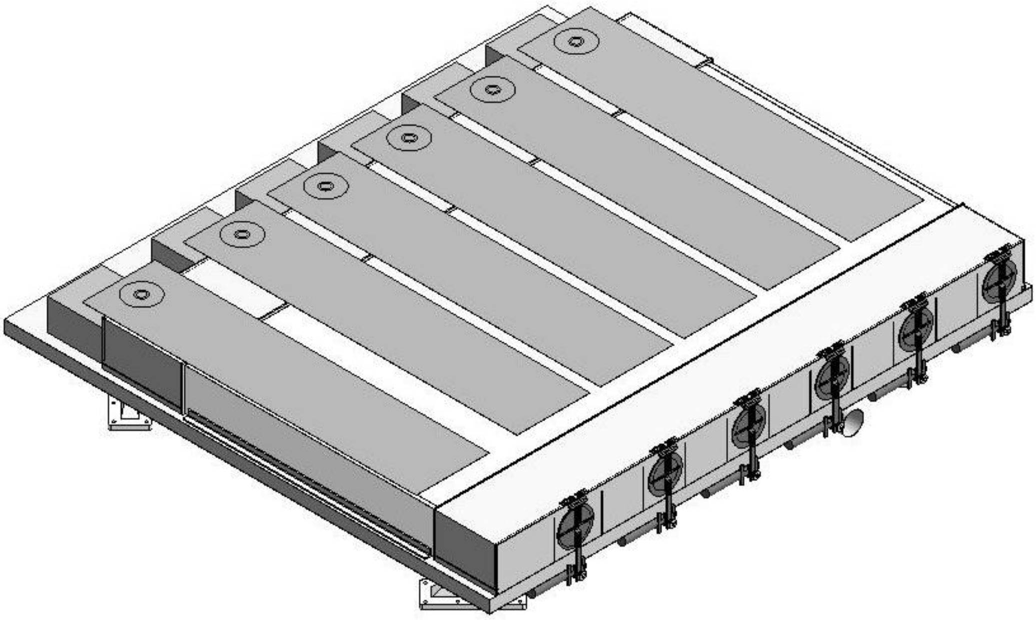

Figure 2: MAGRITTE instrument

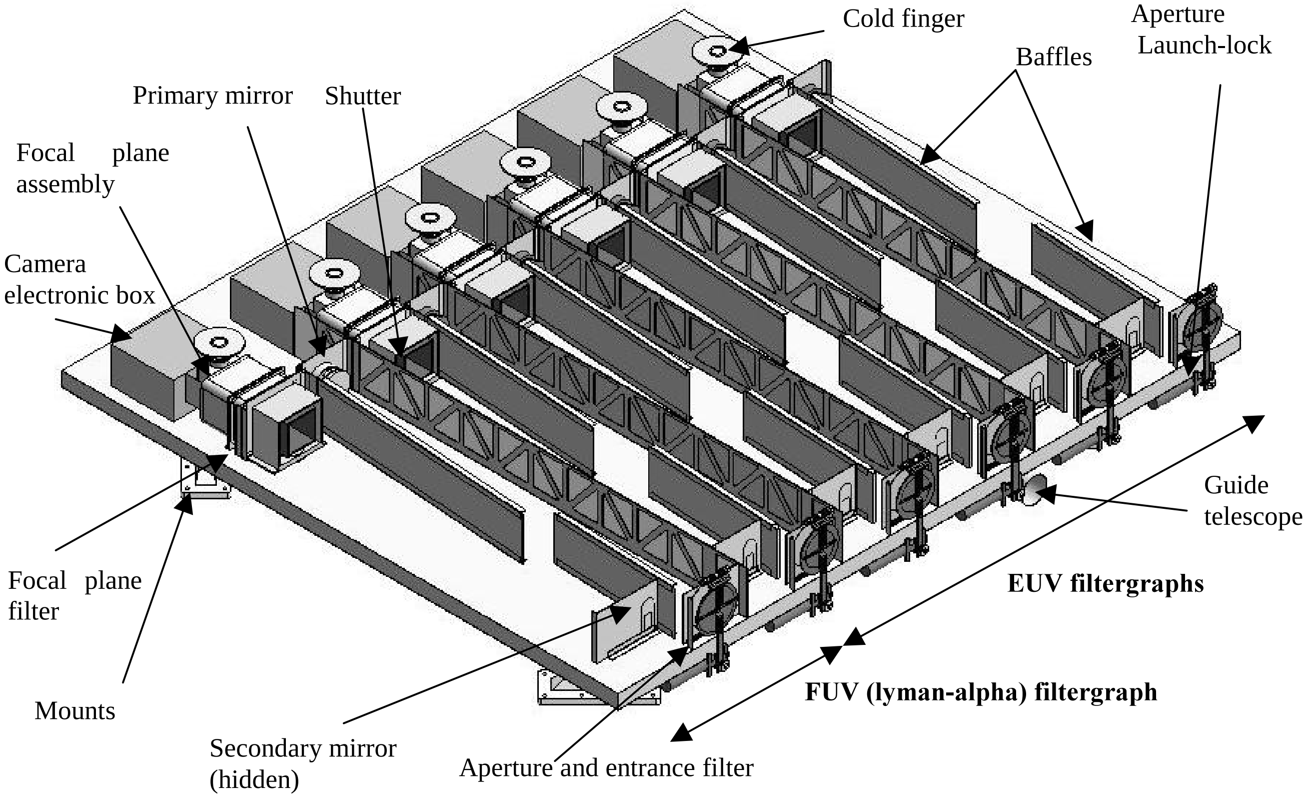

Figure 3: Open view of the MAGRITTE instrument

2.2 MAGRITTE Optics

The optics for all the filtergraph channels will be developed by IOTA. The optical prescription is detailed in table 2. The design has been optimized for limiting incidence angle on mirror and for easy to achieve baffle tolerances while simultaneously avoiding any vignetting in the FOV. The baffling system consists in 2 planar baffle, one coming from the primary mirror and the other coming from the secondary mirror. No front baffle is needed.

Table 2: Optics Definition MAGRITTE Telescopes

Element	**Curvature (mm)**	**Conic**	**Distance (mm)**	**Remark**
Primary Mirror				Circular
EUV	1730.5	-1.01	690	45mm dia. EUV , off-axis 82 mm
Ly-α	1730.5	-1.02	690	60mm dia. Ly-α , off-axis 100 mm
Secondary Mirror				Circular (25mm)
EUV	455.5	-2.75	760	Off-axis: 16.5mm
Ly-α	455.5	-2.70	760	Off-axis: 20.3mm
Detector	Flat	N/A	N/A	Plate Scale: 0.66 arcsec/pixel EUV tilted around θ_x by -0.62° Ly-α tilted around θx by –0.5°

EUV and Ly-α optical system are identical in terms of curvature to limit manufacturing cost with only 2 testplates.

2.3 MAGRITTE Filters

The EUV light enters the instrument through an aluminum filter that suppresses most of the UV, visible and IR counterparts of the solar radiation. Custom Luxel filters with 1500 Å thick aluminum layer supported by a nickel grid are considered for the baseline. The grid will provide mechanical strength and adequate conductive path for heat excess. Alternative locations for the second redundant filter will be considered, taking into account diffraction and shading effects that the opaque supporting grid may produce.

Two narrow-band interference filters will be used to achieve the spectral purity for the Ly-α channel. One filter will be placed at the entrance aperture (where it will reject X-rays and protect the secondary mirror coating with a visible light rejection of 10^{-4}). The second filter will be placed in front of the focal plane and will provide adequate redundancy. The combination of these filters yields a spectral purity of 87% for Ly-α in the quiet sun and higher purity in active regions. It is instructive to contrast this instrument with the Ly-α channel on TRACE that was also based on the TRC design. In order to observe both 1550 Å C IV and Ly-α with a single mirror, TRACE used a coating optimized for C IV combined with a Ly-α filter, resulting in a double-peaked response[5]. The TRACE filtergrams therefore consist of only ~50% Ly-α with the bulk of the residual a mixture of continuum and C IV. Our design, fully optimized for Ly-α, will produce significantly spectrally purer images, similar to the original Bonnet TRC.

2.4 CCD

All the CCDs are individually connected to their respective cold fingers and radiators, which will allow independent thermal control.
The detectors are identical thinned, back-illuminated CCDs with 4096 x 4096 pixels of 12 microns pitch. The CCDs will be passively cooled down to -100°C with radiator facing cold space. This will minimize the dark current and provide a better resistance to radiations.
All the detectors will be closely linked to a heater in order to bake-out periodically the contaminant layer that could build up on the cold surfaces of the sensors.
Additional shielding against important radiation levels seen in the SDO GEO orbit will be implemented and will be part of the housing of the FPA.

2.5 MAGRITTE mechanisms

The six telescopes use identical mechanisms:

1. A one-shot aperture door mechanism: the initial design of the mechanism is based on the INTEGRAL/OMC (launched and successfully operated in space in Oct-2002) and COROT (under development) aperture systems. It uses a spring-loaded hinge with plain bearings, and a paraffin actuated launch lock device (Starsys RL-50C) that was implemented in the SOHO/EIT and INTEGRAL/OMC aperture mechanisms
2. One shutter per telescope used for selecting exposure time (cadence ~10s) and allowing detector lecture. It is developed at MPAe.
3. Possible retractable protection of the thin entrance aluminum filter to avoid breaking of the filter during launch (internal door).
4. Image motion compensation system (IMC) on the secondary mirror (piezo-based system, tilts along 2 axes, small amplitude, no locking mechanism).

2.6 Optical bench and housing

The optical performances are highly sensitive to variations of the distance primary – secondary mirrors. In order to keep an acceptable thermal degradation, the inter-mirror distance variation is limited to ± 30 µm from its nominal (ground alignment) value. This corresponds to increases of 0.25 arcsec (EUV channels) and 0.45 arcsec (Lyman-α channel), as accounted in the budgets of table 4. These constrains dictate one of the main requirements on the thermal design of MAGRITTE in order to define the optical bench material and thermal control.
The internal elements of each unit are mounted on a common optical bench that provides the required thermo-mechanical stability. A CFRP (M55J carbon fibers) optical bench will keep the optics immune from the thermo-mechanical variations. CFRP panels for baffling and envelope purposes will encase each unit. Dismountable panels

will allow easy access to internal elements from the front (instrument entrance: aluminum filters, filter protection, secondary mirrors) and the rear sides (focal plane assemblies, primary mirrors, shutters).
The off-axis optical design has been optimized for large baffle tolerances while simultaneously avoiding any vignetting in the FOV. In consequence, the optical baffles will not require alignment adjustments.
The overall structure will be connected to the spacecraft with a set of isostatic mounts that will reduce stresses and deformations on the optical bench in all the flight conditions., as well as the conductive thermal flux from the spacecraft platform.

2.7 Multilayer coating

Multilayer coating properties are directly linked to the mirror mean incidence angle. The mean incidence angle are represented on figure 4 and 5. Multilayer EUV coatings will be deposited on the primary and secondary mirrors by IOTA and will be optimized for the off-axis system with non-normal incident angles. The coatings for 19.5nm, 28.4nm and 30.4nm channels will be similar to the Mo/Si multilayers developed for the EUVI /STEREO telescope. These new coatings benefits the heritage from EIT/SOHO and were significantly improved by using an ion-beam sputtering process[6]. New developments are being conducted to design, deposit, test and optimize new coatings for the 33.5nm and 46.5nm channels. For Fe XVI (33.5 nm) standard materials (Mo,Si) and recently tested combination of materials based on Mo, B_4C, SiN, Si will be used. The Ne VII (46.5nm) channel will require the use of multicomponents multilayers based on scandium. The experimental study of these new coatings is under progress by using the magnetron sputtering technique.

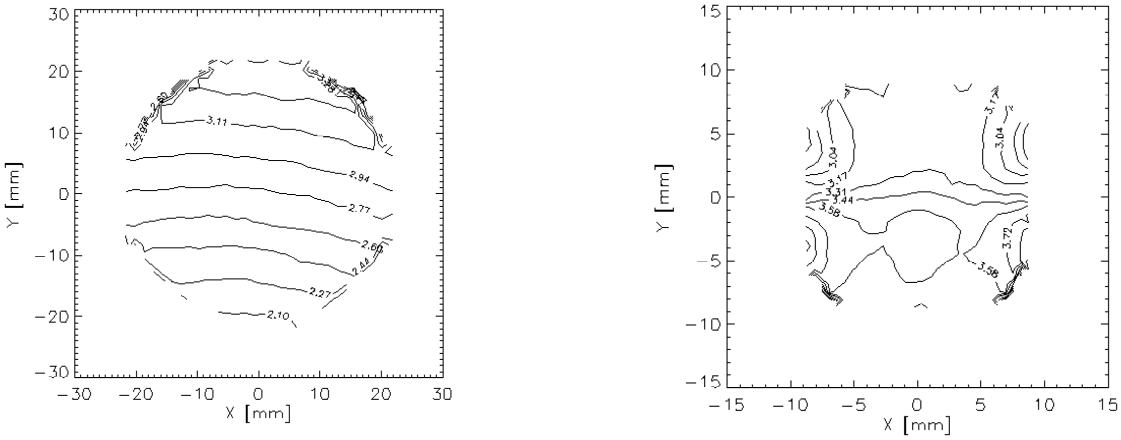

Figure 4: Mean incidence angle on EUV channel primary (left) and secondary (right) mirror.

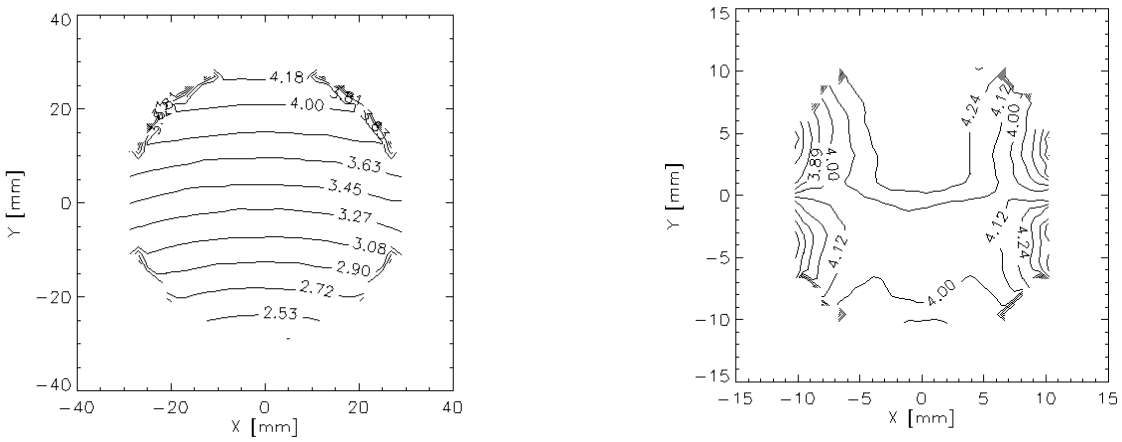

Figure 5: Mean incidence angle on Ly-α channel primary (left) and secondary (right) mirrors.

2.8 MAGRITTE Instrument Performance

– ***EUV optical performances***

The figure 6 shows the optical performances of MAGRITTE, by characterizing the diameter that encircles 70 % of the spot energy. The optical design is diffraction limited over 32 arcmin circular FOV (from –16 to +16 arcmin) for 284, 304, 335 and 465 Å wavelength and design limited outside. The best focus is set at 12 arcmin. The design produces a spot inside the pixel (0.66 arcsec) over a circular 45 arcmin FOV. The table 3 summarizes the range where the design is diffraction limited for each EUV channel.

The table 4 summarizes all degradation contributions. Including tolerances, the 70% encircled energy geometric is included into a 4 pixels area (1.32 x 1.32 arcsec²). The optical system is very sensitive to a variation of the primary – secondary distance and to the irregularities on mirror surfaces. For the first contribution, a distance variation of ± 30 µm (over a 690 mm length) induces a degradation of +0.55 arcsec on the spot size. That imposes a very stable optical bench and mirror mount. For the second contribution, a λ/40 PV optical surface accuracy can induce a degradation lower than 0.338 arcsec. This last estimation depends highly on the kind of residual deviation of the optical surfaces. The high level of the alignment contribution depends mainly on shimming accuracy for the secondary mirror axial location.

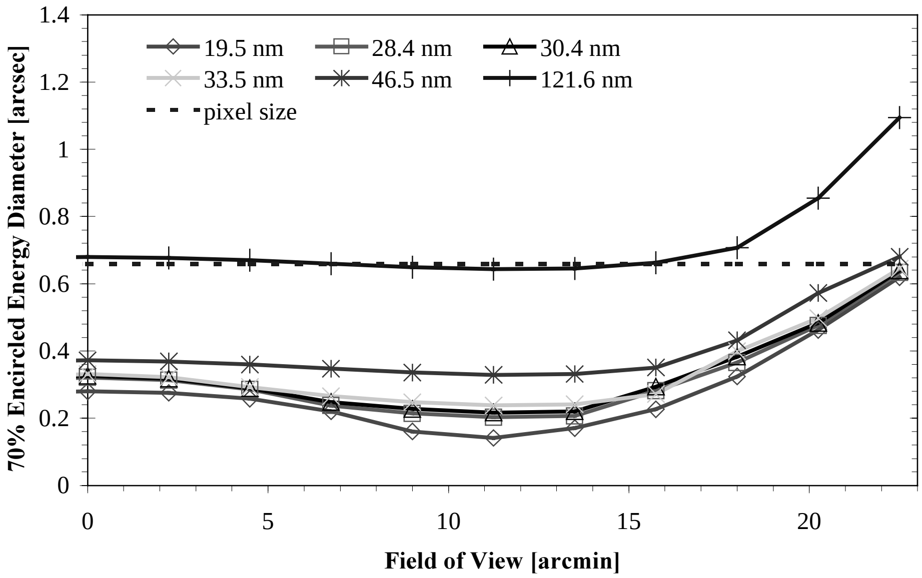

Figure 6: Optical performance of Magritte, 70% encircled energy diameter

Wavelength	Theoretical Airy diameter	Diffraction limited range
195 Å	0.218 arcsec	-16.5 to -4 arcmin 4 to 16.5 arcmin
284 Å	0.317 arcsec	-18 to 18 arcmin
304 Å	0.339 arcsec	-18.5 to 18.5 arcmin
335 Å	0.374 arcsec	-19 to 19 arcmin
465 Å	0.52 arcsec	-21 to 21 arcmin

Table 3 : Theoretical Airy disk and FOV range where the design is diffraction limited

Contributions	EUV channels		FUV channel (Ly-α)	
FOV	**On-axis**	**12 arcmin FOV**	**On-axis**	**At 12 arcmin FOV**
Design	0.26 arcsec	0.08 arcsec	0.31 arcsec	0.13 arcsec
Mirrors manufacturing	0.02 arcsec	0.02 arcsec	0.126 arcsec	0.126 arcsec
Alignment	0.295 arcsec	0.295 arcsec	0.055 arcsec	0.055 arcsec
Mirror WFE	0.216 arcsec	0.338 arcsec	0.44 arcsec	0.605 arcsec
Thermo-optical degradation	0.55 arcsec	0.55 arcsec	0.45 arcsec	0.45 arcsec
Total	**0.921 arcsec**	**0.790 arcsec**	**0.954 arcsec**	**0.896 arcsec**

Table 4: Optical performance contributions in terms of 70% encircled energy geometric degradation ($\Delta\Phi$)

Besides the spot size, tolerances have to be also allocated on the boresight error. As all channels have to be co-aligned on the same optical bench and no adjustment are allowed after alignment, tolerances on the boresight error are particularly stringent on the mirror mount design. The table 5 summarizes the boresight error contributions. The alignment boresight error is lower than 20.2 arcsec while the mechanical distortion of mount and optical bench has to be lower than 57 arcsec. That has a high impact on the mechanical design of the optical bench and the mirror mounts.

Contributions	Boresight error
Interferometer alignment	15 arcsec
Alignment	12.43 arcsec
CCD centering	5.5 arcsec
Micro-setting in mount	12.4 arcsec
Mirror mount	25 arcsec
Optical bench	50 arcsec
Total	**60.8 arcsec**

Table 5: Boresight error contributions

– ***FUV optical performances (Lyman-α channel)***

The figure 6 shows the optical performances of the nominal design in terms of the 70% encircled energy diameter. The optical design is diffraction limited over the 45-arcmin circular FOV. In the corner of the CCD, the spot is larger.

The degradation contributions are also detailed in table 4. Including tolerances, the 70% encircled energy geometric is included into a 4 pixels area (1.32 x 1.32 arcsec^2). Similarly to the EUV telescopes, the main contribution comes from the WFE of mirrors. So polishing and measurement will also need to be accurate.

3. CONCLUSION

A new set of EUV instruments is being prepared for the SDO mission. They will provide simultaneous high angular and temporal images in 6 EUV channels and one FUV channel. The phase B of the project will start in the second half of 2003.

The optical design is a challenge in terms of alignment, polishing and multilayer coating.

4. ACKNOWLEDGMENTS

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