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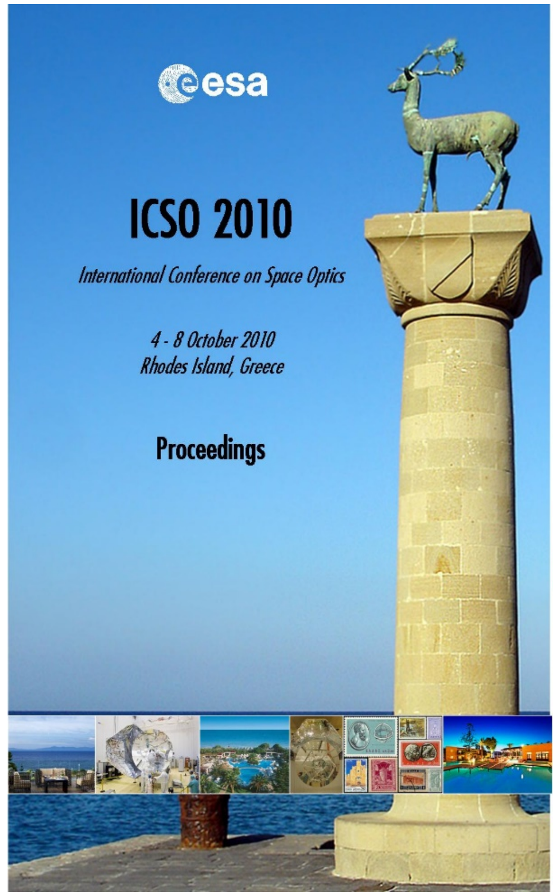

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METIS, THE MULTI ELEMENT TELESCOPE FOR IMAGING AND SPECTROSCOPY FOR THE SOLAR ORBITER MISSION

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I. INTRODUCTION

In 1999 the European solar scientific community proposed to ESA the Solar Orbiter (SO), a mission to explore the circumsolar region, to perform quasi helio-synchronous observations, and to obtain the first out-of-ecliptic imaging and spectroscopy of the solar poles and of the equatorial corona. Presently, SO is one of the three missions under study within the ESA Cosmic Vision 2015-2025 program, and a key ESA-NASA missions within the International Living with a Star Program. SO, to be launched on January 2017, is expected to provide major advances steps forward in understanding the Sun-heliosphere connection.

METIS, the Multi Element Telescope for Imaging and Spectroscopy, is one of the instruments selected in 2009 by the European Space Agency to be part of the payload of the SO mission. The instrument design has been conceived by an international team with the intent to perform both multiband imaging and UV spectroscopy of the solar corona. METIS, owing to its multi wavelength capability, can effectively address some of the major open issues in understanding the corona and the solar wind can be effectively addressed, exploiting the unique opportunities offered by the SO mission profile. METIS observations are crucial for answering some fundamental solar physics questions concerning the origins of the fast and slow wind, the sources of solar energetic particles, and the eruption and early evolution of coronal mass ejections.

METIS adopts an innovative optical design [1] which perfectly adapts to the critical environment that will be encountered by SO, minimizing the radiation flux inside the instrument and thus the thermal problems given by the Sun proximity. Moreover, thanks to the especially suited multilayered mirrors, the instrument will perform coronal imaging in three different spectral ranges: one in the visible, and the others on two intense UV and extreme UV (EUV) coronal lines, the HI Ly-α line at 121.6 nm and the HeII Ly-α line at 30.4 nm. The multiband imaging capability has already been exploited in the recent flight (September 14, 2009) of the Sounding-rocket Coronagraphic Experiment (SCORE) [2]: the flawless performance of SCORE has proved the validity of the multi-wavelength approach to visible, UV and EUV coronagraphy to be adopted with METIS. In addition, accepting a reduced spatial performance over a small sector of the image of the solar corona, METIS will also be able to perform EUV spectroscopy owing to a special reflection grating inserted along the optical path.

Thanks to its capability of combining both imaging and spectroscopic capabilities, METIS will exploit at best the unique characteristics of the SO mission profile. It will indeed image the visible and ultraviolet emission of the solar corona with unprecedented temporal coverage (10 s) and spatial resolution (down to about 2000 km), thus providing information on the structure and dynamics of the full corona in the range from 1.4 to 3.0 solar radii from Sun center (at minimum perihelion). Furthermore, it will simultaneously observe the EUV spectral emission of the two most abundant solar elements in the geo-effective coronal region from 1.4 to 2.0 solar radii from Sun center (still at the closest approach). These measurements will allow a complete characterization of the three most important plasma components of the corona and the solar wind (electrons, protons, helium).

In the following, we will describe some of the most important characteristics of METIS, and the adopted optical layout and performance of both coronagraphic imager and spectroscopic channel.

II. METIS INSTRUMENT DESIGN

METIS is designed to effectively obtain the highest scientific return while minimizing the overall resource allocation. The proposed architecture takes advantage of the commonality between the different elements that constitute the suite, by sharing the great majority of the system optical components to pursue different scientific investigations. In addition, METIS is aimed to provide a very simple interface to the spacecraft (S/C), by internally handling the needs of the various subsystems.

METIS consists of a single optical head which uses a single aperture on the S/C Sun facing thermal shield. The optical head is mounted on an optical bench (see Fig. 1), plus a main electronics and power supply box. The instrument front end consists of the visible-light and UV/EUV coronagraphic imager, which comprises the optics, detectors, proximity electronics and electrical interface. Internally to this coronagraph, in a suitable position, a dispersion grating intercepts a small portion of the solar corona (so that the obtained corona image is actually not complete) to perform UV and EUV spectroscopy. This additional channel does not need any mechanism, and shares one of the imaging coronagraph detectors.

A summary of the METIS foreseen performance, as described in the following sections, is given in Tab. 1.

A. METIS multiband coronal imager

The METIS multiband coronal imager is designed for obtaining broad-band polarization imaging of the visible K-corona (spectral range 500-650 nm), narrow-band imaging of the UV corona in the HI Lyman-α, 121.6 nm line, and narrow-band imaging of the EUV corona in the HeII Lyman-α, 30.4 nm line. The annular field of view (FOV) ranges between 1.4 and 3.0 solar radii, when the perihelion is 0.28 AU, and the attained spatial resolution is 20 arcsec.

A conceptual scheme of the METIS coronal imager is shown in Fig. 2. This is a novel design for externally occulted all-reflective coronagraph [1], in which the external occulter has also the function of system entrance pupil. In such a way, the size of the external aperture is minimized and the thermal flux entering the instrument is greatly reduced, thus allowing to meet the stringent thermal requirements of SO. This novel optical configuration takes the name of *inverted coronagraph* (ICOR) because the diaphragms are inverted with respect to a standard coronagraph design.

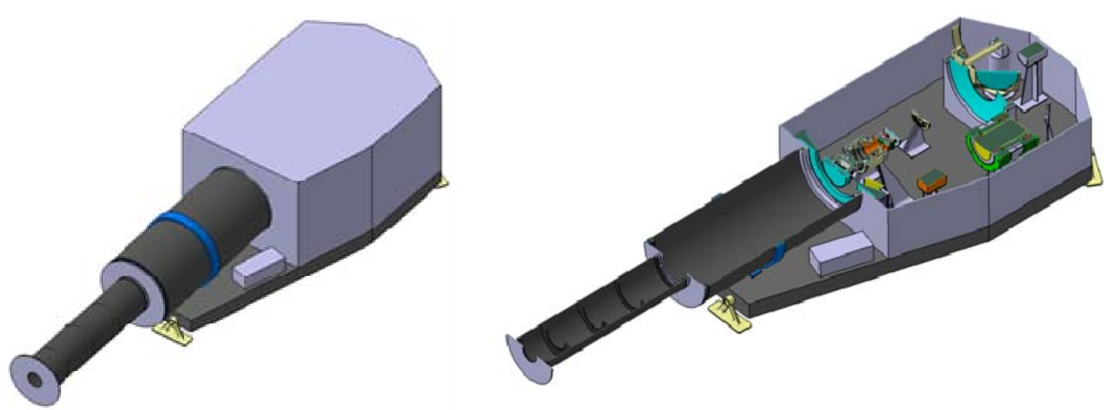

Fig. 1. Two different views of METIS layout. On the left, METIS is shown with its baffling system and enclosure: the thinned external cylinder is the baffling system protruding into the S/C heat shield and supporting the coronagraph external occulter. On the right, a cut-out of the instrument has been done to show the internal optical elements. In this figure, the main electronics box is not included.

Tab. 1. Summary of the main foreseen METIS performance.

METIS Instrument Performance	
CORONAL IMAGING	
Average instrumental stray light (B_{cor}/B_{Sun})	VL < 10^{-9} UV/EUV < 10^{-7}
Wavelength range:	VL: 500-650 nm; UV: 121.6 ± 10 nm EUV: 30.4 ± 2 nm
Spatial resolution	20 arcsec
Field-of-view	1.4° - 3° annular, off-limb corona
CORONAL SPECTROSCOPY	
Wavelength range:	UV: 121.6 ± 0.9 nm EUV: 30.4 ± 0.22 nm
Spectral resolution	UV: 0.054 nm EUV: 0.013 nm
Spatial resolution	34 arcsec
Field-of-view	Slit radial positions: 1.4°, 1.7°, 2.0° Slit extension: 0.8°

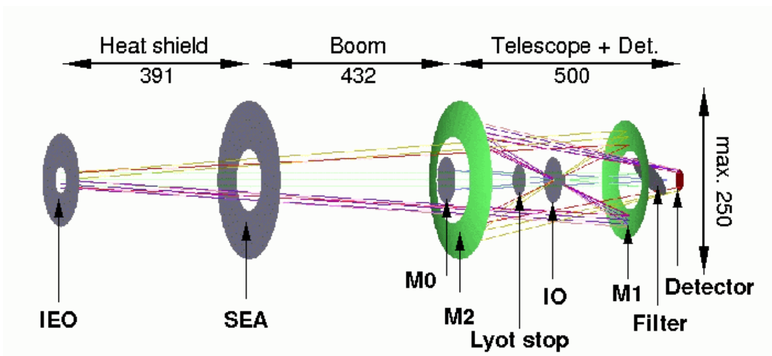

Fig. 2. Optical layout of the inverted coronagraph (only UV-EUV channel). Quotes are in mm. Acronyms are explained in the text.

As can be seen in Fig. 2, the first optical element is the inverted external-occulter (IEO), which is, in this design, a small (∅ 40 mm) circular aperture in the SO thermal shield. Coronal light entering the IEO is then collected by a simple on-axis Gregorian telescope (aspherical mirrors M1 and M2), which makes the coronal image on the telescope focal plane where the detector is located. An internal occulter (IO) is located close to the telescope prime focus with the function of blocking the light diffracted by the edges of the IEO. When METIS is pointing at Sun centre, direct disk light impinges on a small (∅ 69 mm) spherical mirror (M0) which back-reflects it through the IEO. The portion between the IEO and M0 is called "boom" and consists, optically, of three stops: IEO, on the front face of the S/C heat shield, the shield entrance aperture (SEA), on the back face of the S/C heat shield, and the annular aperture delimited internally by M0 and externally by the hole inside M2.

Some of the advantages resulting from this scheme with respect to the classical external occulter design are the following:

- smaller diameter boom (≈ 3 times) through the S/C thermal shield: this implies a smaller aperture on the S/C heat shield and an improved mechanical stability;
- thermal load on M0 greatly reduced (by more than 90%) with respect to a standard externally occulted configuration: this means that there is a smaller temperature inside the instrument, with a consequent easier control of the optical bench;
- on-axis telescope configuration, which yields a better optical performance.

The telescope mirrors are coated with a suitable multilayer coating, optimized to enhance reflectivity in the EUV He line, but still having good reflectivity at 121.6 nm and in the visible (see section C). Hence, it is possible, by means of dedicated band-pass filters, to obtain the solar corona imaging at the three mentioned different wavelength bands. After the secondary mirror, there is a three-position filter mechanism that allows to select either a multilayer filter, which reflects visible light and transmits narrow-band UV HI line, or a low-pass

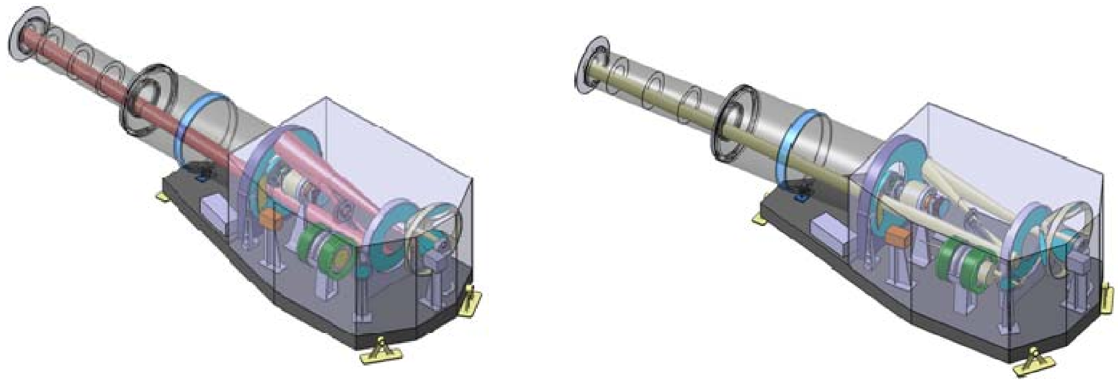

Fig. 3. Optical path inside METIS: ultraviolet (left), and visible (right).

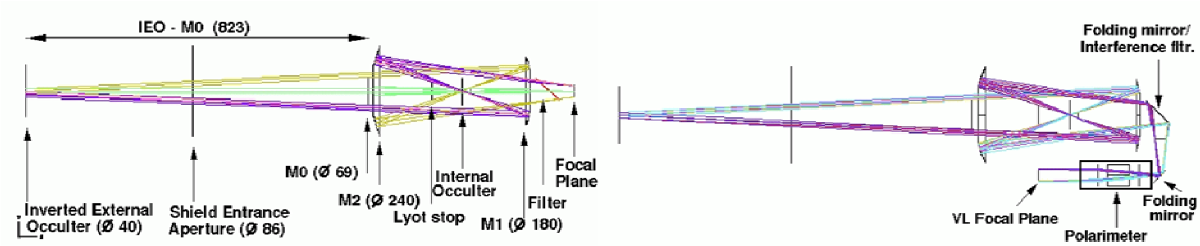

Fig. 4. METIS coronagraph optical ray tracing: ultraviolet path (left), visible path (right).

aluminum filter that transmits the EUV HeII line (the third position on the mechanism selects a neutral density filter). In the first case two coronal images are simultaneously acquired, in the visible and HI line, while in the second case only the HeII image is obtained. As seen in Fig. 3 and in Fig. 4, the transmitted UV light is directly focalized on the UV detector, while the reflected visible light follows a dedicated visible optical path, which includes also an achromatic polarimeter for measuring the linear polarization brightness.

The estimated optical performance of this coronal imager, including the diffraction effect, is shown in Fig. 5. The significant and unavoidable degradation of the optical performance close to the solar limb due to diffraction is evident from the plot. However, the obtained performance is considered rather good, being of the order of 20 arcsec or smaller in a large portion of the FOV.

The polarimeter included in the visible optical path consists of a liquid crystal variable retarder (LCVR) [3] together with a fixed half-wave retarder and linear polarizer in "Senarmont" configuration. The polarimeter is in telecentric mount with collimating and camera lenses.

The suppression of the diffracted light off the edges of the IOE and M0 is achieved, respectively, with an internal occulter (IO) and a Lyot stop in a suitable position. By means of this system, a 10^{-9} rejection factor of direct sun disk light is expected.

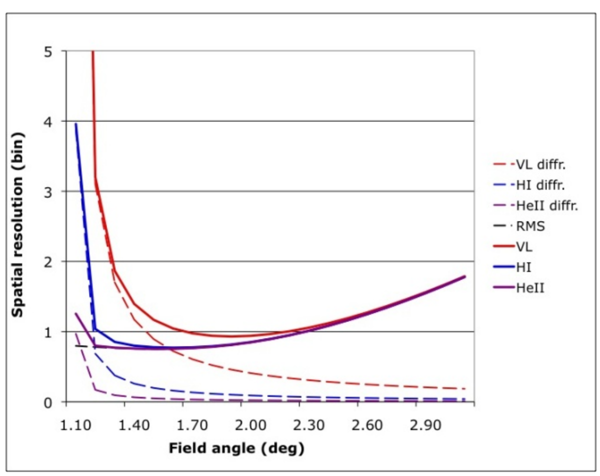

Fig. 5. Estimated METIS rms spatial resolution including diffraction as a function of the field angle. In this plot, continuous lines represent the total aberration, given by the quadratic sum of the rms spot diagram and the diffraction contribution (dashed lines). One bin corresponds to 2×2 pixels (20×20 $arcsec^2$).

B. METIS spectroscopic channel

To optimize the scientific return of this instrument, a spectroscopic channel has also been included in the METIS optical path. In the prime focus of the Gregorian telescope, a three-slit system [4] is located in correspondence of an equatorial region of the solar corona. The slit system inhibits the possibility of doing imaging in this portion of the corona, hence the actual coronal images obtained with METIS will have a small "missing" sector (see Fig. 6). Light passing through the slits is collected by a spherical varied line-spaced (SVLS) diffraction grating located in the aperture of the Gregorian telescope secondary mirror (see Fig. 7). The grating diffracts the HI 121.6 nm radiation at 1st order and HeII 30.4 nm radiation at 4th order, in the same location on the focal plane. The spectrum is imaged on the portion of the detector that is not used to acquire the coronal image. The multi-slit input section selects three FOV's from Sun centre, at 1.4°, 1.7° and 2.0°. Since the spectroscopic channel either shares the same optical components of the coronal imager or replaces some of its parts (the grating corresponds to a sector of M2), without any additional mechanism and with a reduced amount of additional resources it is possible to enhance the METIS scientific return.

The spectroscopic channel moreover is essential for correcting the HeII coronal image which is partially corrupted by the contribution of the close by SiXI 30.33 line. We not that the "missing" portion of the coronal image can actually be partially recovered by interpolating the slit spectra obtained by the spectroscopic channel in the simultaneous three FOC's identified by the multiple slit system. This technique has been extensively used when analysing UVCS [5] data to produce UV coronal images from spectroscopic data [6].

Concerning the optical performance of the spectroscopic channel, the simulations show that at least 50% of the energy is enclosed within 2 pixels for each of the slits in the direction of spectral dispersion, which corresponds to a spectral resolution of 0.054 nm at the HI line, and of 0.013 nm at the HeII line. With regards to the spatial resolution, this is limited to two pixels (34 arcsec) for the slit closest to the disk (1.4°), to three pixels (51 arcsec) for the intermediate slit (1.7°), and to four pixels (68 arcsec) for the external one (2°).

C. METIS mirror and grating optical coatings

Periodic Mo/a-Si multilayers with natural oxide capping layer (see Fig. 8) represents the baseline solution for METIS mirror coating. This type of multilayer coating has already been employed in several space missions and it is well known it provides the long term stability essential for a space mission. However, in order to improve the spectral purity at 30.4 nm an aperiodic design can also be adopted, which in addition allows to depress

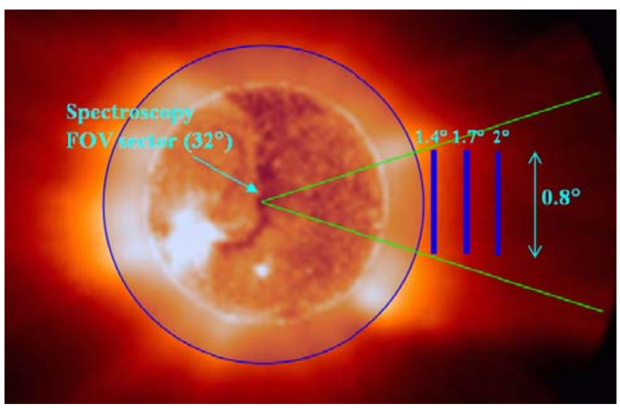

Fig. 6. Example at 0.28 AU of multi-slits FOV for the EUV spectroscopy path. The FOV sector for spectroscopy is about 32° out of the total 360° FOV. The remaining area is used for imaging.

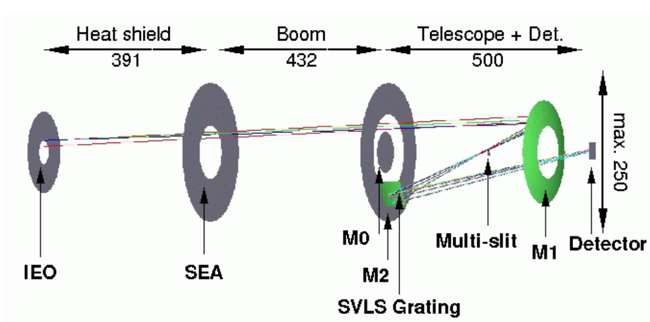

Fig. 7. Schematic layout of METIS spectroscopic channel. All the quotes are in mm.

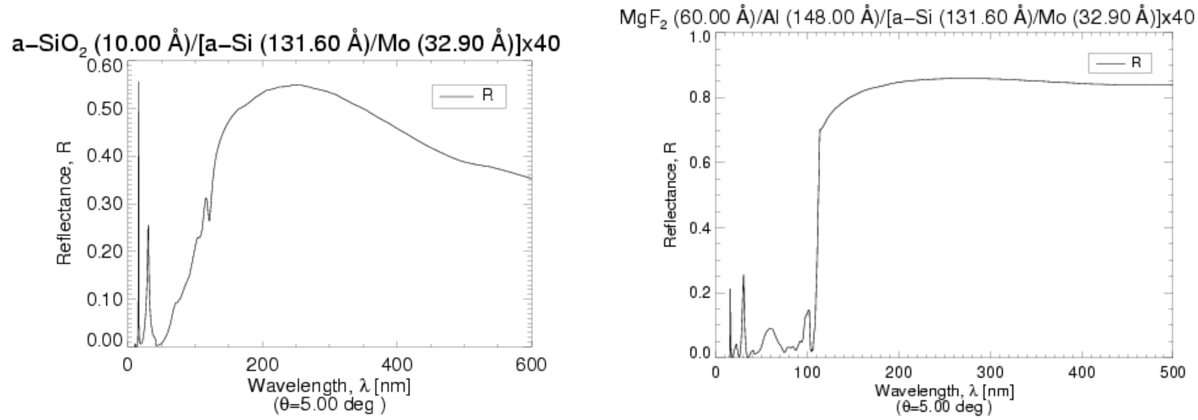

Fig. 8. Reflectivity curves of Si/Mo (left) and of SiC/Mg (right) multilayers as a function of the wavelength.

second order contributions. In order to improve the efficiency in the UV-VIS spectral region, a capping layer can be eventually added on top of the structure; standard single layer material can be adopted, as well as innovative capping layer such as Ru+RuO_2 (recently tested in lithography) or alternatively Al+MgF_2 (see Fig. 8), which provides much higher performance with respect to Mo/a-Si.

III. CONCLUSIONS

METIS, one of the instruments selected by ESA to be part of the payload of the SO mission has been described. The instrument design has been conceived for performing both multiband imaging and EUV imaging-spectroscopy of the solar corona. METIS adopts an innovative optical design which perfectly adapts to the critical environment that will be encountered by SO, minimizing the radiation flux inside the instrument and so the thermal problems. Owing to the especially suited multilayered mirrors, it will realize coronal imaging at three different coronal light spectral ranges: visible, ultraviolet peaked at 121.6 nm and EUV peaked at 30.4 nm. Moreover, reducing the spatial quality over a small sector of the image of the solar corona, METIS will be able to perform also EUV spectroscopy thanks to a special reflection grating inserted along the optical path.

METIS is presently in its definition phase, since the SO mission has not yet been definitely selected. At the moment, the METIS optical design has been defined, as here described, and the first mathematical models (structural and thermal) have been realized. In the philosophy of having a fully reliable, long-lived instrument, only consolidated subsystems are considered. In particular, concerning the detectors, a commercial CMOS will be used for the visible, while a standard intensified APS developed by the team will be used to detect the UV part of the corona. All the optical elements are standard. The only component which needs some development is the liquid crystal polarizer: however, a backup solution with a standard polarization system is also considered.

In conclusion, activities on METIS are in progress under the foreseen schedule, in view of a timely deliver to ESA for the foreseen SO launch on January 2017.

ACKNOWLEDGMENTS

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