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Abstract—**METIS (Multi Element Telescope for Imaging and Spectroscopy) is an externally occulted coronagraph part of the Solar Orbiter payload. METIS innovative occulting system, called inverted externally occulter (IEO), consists of a circular aperture, IEO, that acts also as the entrance pupil of the instrument, and a solar disk rejection mirror (M0), placed at the bottom end of the coronagraph boom. M0 reflects back through IEO the solar disk radiation, letting the coronal radiation enter the coronagraph telescope. Light diffracted by IEO enters the telescope and has to be minimized with a proper shape of the IEO edge. The paper describes the theoretical results of the diffraction analysis extended to the scattered light by the primary mirror of the telescope onto the primary focal plane. A summary of the entire stray light reduction capabilities of METIS is also given.**

Keywords: Solar coronagraph, external occulter, optimization, stray light, measurements, Solar Orbiter, METIS.

I. INTRODUCTION

The METIS instrument (Multi Element Telescope for Imaging and Spectroscopy), designed for the Solar Orbiter payload, has the capability to study the solar corona by performing UV imaging, polarimetric imaging in the visible and EUV spectrometry in selected coronal portions (multi-slit concept) [1]. To cope with all these scientific aims, METIS is composed by 3 channels. A UV imaging channel in which the target (the solar corona) will be imaged in the HI 121.6 nm line on a UV/EUV focal plane assembly. A narrow band Al+MgF2 filter is used to select HI line. The visible light reflected by the Al+MgF2 filter is used to feed a visible light (VL) polarimetric channel, designed to measure the linearly polarized brightness. The field-of-view of the imaging channels spans from 1.4 to 3 solar radii when Solar Orbiter is at 0.28 AU perihelion. A small portion of the corona is imaged on a multi-slit element that is placed in a portion of the focal plane of the primary mirror M1 feeding a spectrometer at three heliocentric heights. A grating placed at M2 position is able to disperse on the UV/EUV detector the HeII 30.4 nm line profile. The EUV
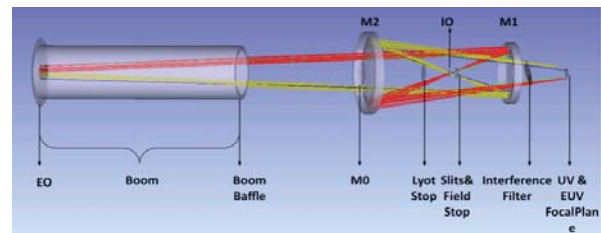

Fig. 1. METIS optical layout for the UV channel.

band is selected by means of a combination of the telescope mirror multilayer coating and of a low pass aluminum filter.

METIS is an externally occulted coronagraph (see Figure 1), that is, the telescope has an occulting system between the Sun and the primary mirror, M1, that puts M1 in the shadow of the Sun disk.

The rejection of solar disk radiation is the most critical issue in a coronagraph design: solar disk radiation that impinges on the coronagraph detectors, no matter how, is called stray light. Traditionally, the external occultation concepts consists of an occulting disk that prevents solar disk radiation from reaching the entrance pupil aperture. METIS operates with an inverted occulted system concept [2]: light from the solar disk and from the corona enters a round external aperture that acts as the entrance pupil and is called inverted external occulter, IEO. Solar disk light is then blocked and rejected through IEO by a Sun disk rejecting mirror, M0. This configuration has the advantage, very important for this mission, of reducing the thermal load inside the instrument. In order to reduce the amount of stray light METIS Sun disk radiation is rejected by means of stardard techniques used in externally occulted coronagraphs:

- a Sun disk rejection mirror, M0, that reflects back the disk radiation through the entrance pupil;
- an internal occulter, IO, that is placed in the conjugate

plane of IEO relative to the primary mirror M1, that blocks light diffracted by the edge of IEO;

- a Lyot stop, LS, placed in the conjugate plane of M0 relative to M1, that blocks secondary diffracted light from the edge of M0.

The stray light sources inside the coronagraph are due to two main contributors:

1) **Sun disk light diffracted by the edges of the entrance aperture IEO** Light diffracted by IEO is mainly taken care by the internal occulter, IO, and by the Lyot stop, LS. Nevertheless, diffracted light impinging on the primary mirror, M1, is partially scattered by its surface and becomes the major contributor to the final stray light level.

2) **Sun disk light entering the entrance aperture IEO** Disk light entering IEO is taken care by the disk light rejection mirror, M0, that re-images the Sun disk back through IEO itself. Scattering from the M0 surface will contribute to the stray light level via diffusion off telescope components: mounts and walls.

Additional contributions to the stray light will be produced by particulate contamination on those components illuminated directly by the Sun (IEO and M0) or illuminated by the light diffracted by IEO (M1, mounts and coronagraph walls).

This paper describes a theoretical analysis of the stray light inside METIS (based on previous experience on the subject [3], [4], [5]) for all three wavelength bands, when the coronagraph is Sun center pointed. The output of the theoretical model is then confronted with METIS requirements on stray light and cleanliness. First, the case of stray light produced by light diffracted by the edge of IEO and scattered off the primary mirror surface intrinsic roughness is taken into account. Second, the stray light produced by Mie scattering off particles deposited on M1 surface is added.

II. STRAY LIGHT REQUIREMENTS

The stray-light analysis has to be done taking into account the different wavelength range at which the instrument is working:

- UV: Narrow band UV (HI 121.6 nm)
- EUV: Narrow band EUV (HeII 30.4 nm)
- VL: Broadband polarized visible light VL (500-650 nm)

The METIS requirement for the stray-light suppression is more stringent in the VL than in the UV/EUV, because the emission of the corona with respect to the disk emission is different in the two cases (see Figure 2). The average requirements on the in-band instrumental stray light (B_{stray}/B_{Sun}) are:

- B_{stray} (VL) $< 10^{-9}$ B_{Sun} (VL: 500 – 650 nm)
- B_{stray} (UV/EUV) $< 10^{-7}$ B_{Sun} (UV: 115 – 130 nm; EUV: 29 – 32 nm)

where B_{stray} represents the stray light irradiance (photons cm^{-2} s^{-1}) measured on the telescope focal plane and B_{sun} represents the solar disk mean irradiance that would impinge
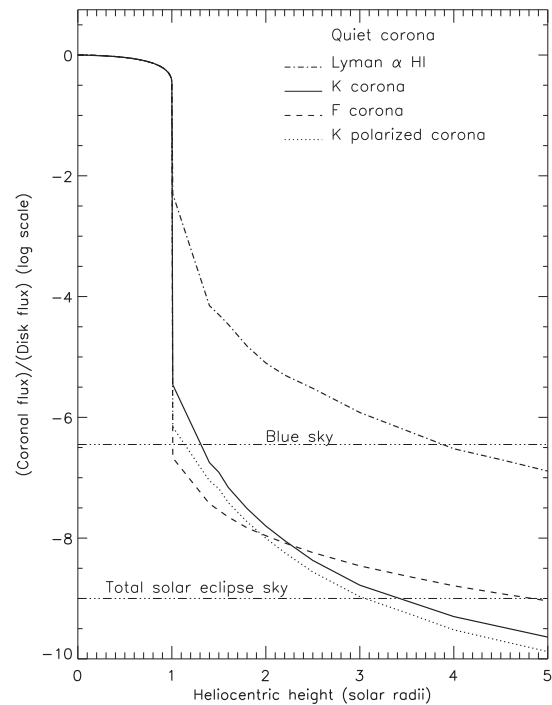

Fig. 2. Ratio of the radiance of a quiet coronal equatorial region to the radiance of Sun-center in Lyα and visible light versus heliocentric height (in R$_\odot$).

on the focal plane as if the solar disk would extend throughout METIS FOV. With this definition, it is useful to quantify the y-axis of Figure 2 in terms of B_{cor}/B_{Sun} where B_{cor} is the coronal irradiance on the focal plane.

A. Cleanliness requirements

The particle cleanliness requirement for the METIS optics is defined such that the contribution to the straylight created by particulate scattering of the IEO diffracted light is less than that scattered by the mirror surface roughness.

III. ESTIMATED STRAY LIGHT

A. Sun disk light diffracted by the edges of the entrance aperture IEO

Radiation from the Sun disk is diffracted by the edge of the IEO aperture. M0 is oversized in order to block most of this light. The part that is not blocked by M0 enters the telescope. The most important effect of the diffraction from an aperture is to brighten up the edge of the aperture. Therefore, the image of the edge of IEO has to be blocked by an occulter, called internal occulter (IO), on the conjugate plane of IEO with respect to the primary telescope mirror M1. A secondary effect is produced by the brightening of M0 edge. This is a second order effect, because the edge of M0 is not directly illuminated by the solar disk light. Nevertheless, in a coronagraph, the brightening of this edge is taken care by a stop, called Lyot stop (LS), placed in the conjugate plane of M0 edge with

respect to M1. Both IO and LS operate after the coronal light and the diffracted light have impinged on M1, therefore IO and LS take care of diffracted light reflected by M1 but not of diffracted light non-specularly scattered by M1. The non-specularly scattered light off M1 mirror surface cannot be separated from the coronal radiation, hence its amount has to be minimized.

A theoretical calculation of the stray light level for the EUV, UV and VL channels has been performed. The computation takes into account the present geometry of METIS internally occulted coronagraph, a Sun angular size at 0.28 AU and a uniform disk brightness of the Sun, and derives the diffraction pattern on the primary mirror surface in the case IEO has a knife edge. In order to decrease the amount of diffraction that reaches the primary objective of an externally occulted coronagraph it is always necessary to optimize the shape of the external occulter edge. The techniques of optimization of the occulter are beyond the scope of this paper and are described in depth in [5], [6], [7]. The diffraction off the IEO edge is computed on the plane of M1, using the Fresnel diffraction approximation.

The light diffracted by IEO impinges on the primary mirror M1 surface. The part specularly reflected by the mirror is blocked by the internal occulter, but the part that is scattered by the surface can reach the focal plane [8]. The surface scattering properties are characterized by the bi-directional scattering distribution function (BSDF) and the total integrated scatter (TIS). The BSDF distribution is related to the roughness spatial frequencies through the formula:

$$BSDF = \frac{dP/d\Omega_s}{P} = \frac{16\pi^2}{\lambda^4}\left(\frac{1+cos^2\theta_s}{2}\right)g(\vec{f}) \quad (1)$$

where $g(\vec{f})$ is the power spectral density (PSD) of the surface roughness, P is the power of the incident radiation, $dP/d\Omega_s$ is the scattered power in the solid angle Ω_s, and θ_s depends on the spatial frequency, f, through the grating formula: $f = sin\theta/\lambda$. TIS is obtained from the BSDF by integrating over the hemisphere, HS, in which the radiation is scattered:

$$TIS = \int_{HS}\frac{dP/d\Omega_s}{P}\Omega_s \quad (2)$$

if the PSD is a Lorentzian function with cylindrical symmetry around the reflection direction, the TIS becomes:

$$TIS = \frac{16\pi^2\sigma^2}{\lambda^2} \quad (3)$$

The range of spatial frequencies of interest is related to the angles at which the scattered light from M1 goes through IO.

M1 specifications related to stray light reduction are: rms roughness: 0.2 nm goal; 0.3 nm acceptable PSD: for spatial freq. $< 0.1 \mu m^{-1}$ TIS $< 5 \cdot 10^{-5}$

Considering that the mirror surface has a micro-roughness, σ, and a typical scale-angle of scattering, θ_0, tied to the PSD
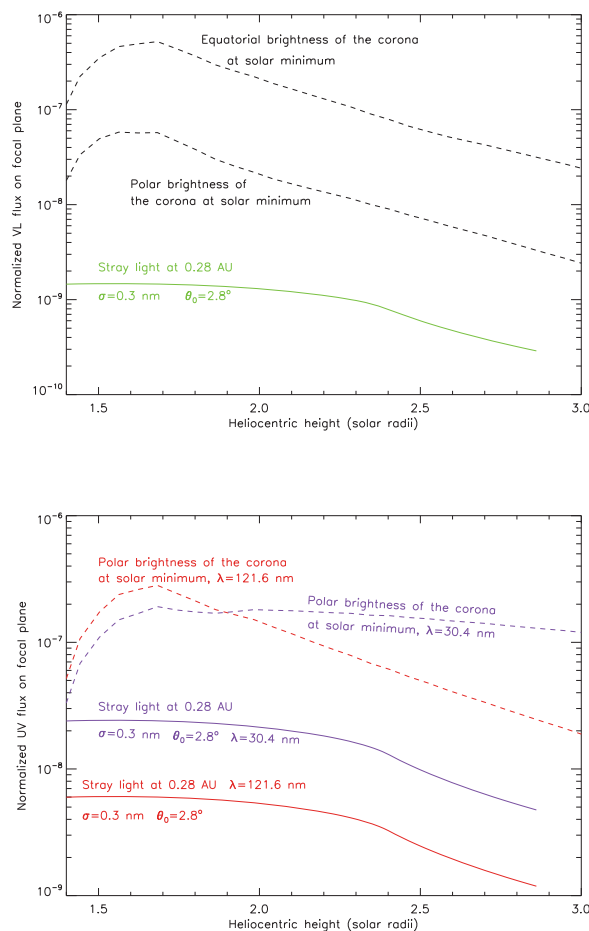

Fig. 3. Computed stray light level in the VL (top) and in the UV and EUV (bottom) wavelength bands. The stray light is computed at the primary focal plane and includes the IO vignetting action.

spatial frequencies, the fraction of scattered light that is distributed on the primary focal plane, once the vignetting action of the internal occulter is taken into account, is plotted in as a function of the heliocentric height for all the three wavelength bands for $\sigma = 0.3$ nm from the mirrors' specifications and $\theta_0 = 2.8°$ which is the worst case scenario, where the scattered radiation fills the IO aperture (Figure 3).

Figure 4 shows how the stray light level increases with increasing the micro-roughness of the mirror.

B. Contribution of contaminants to stray light

A calculation of this stray light contribution by particulate contamination of the METIS mirrors has been conducted using the BSDF for various surface cleanliness classes (expressed in terms of the MIL-SPEC-1246C Classes - whose conversion into obscuration factor (ppm or mm^2/m^2) is given in table H-1 of the ESA-ESTEC ECSS-Q-ST-70-01C *Space product assurance – Cleanliness and contamination control*) derived from Mie scattering theory by Plesseria et al. (2001) [9].
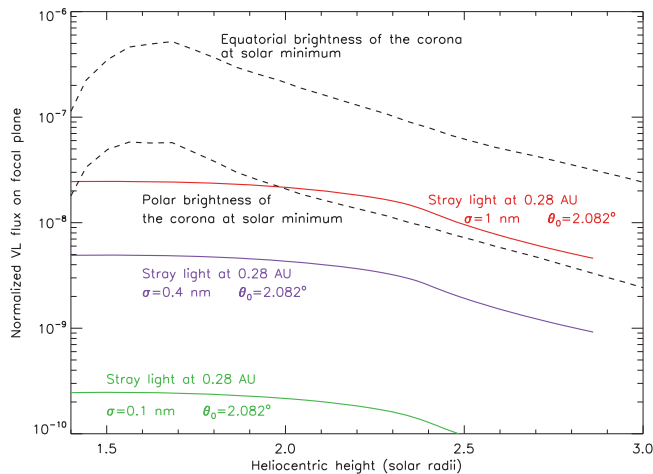
Fig. 4. Computed stray light level in the VL for different values of M1 surface micro-roughness.
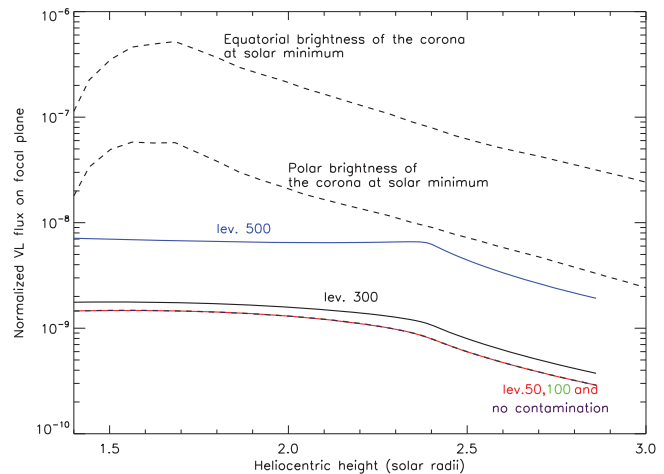

Fig. 6. Computed stray light level in the VL for different classes of particulate contamination and M1 micro-roughness $\sigma = 0.3$ nm.
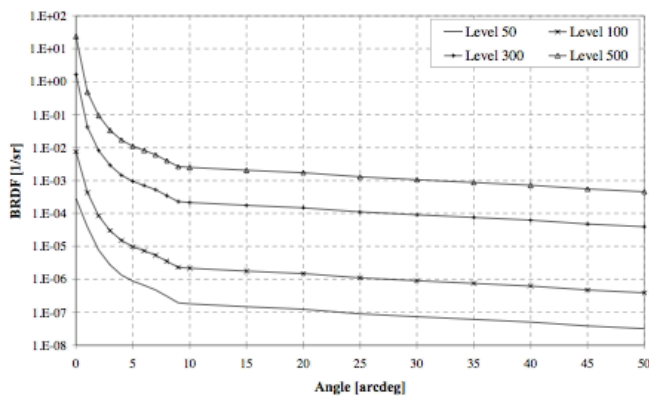

Fig. 5. BSDF for different classes of particulate contamination level at 550 nm (from [9]).

The estimate of the stray light produced by the particle contamination is performed in the most critical visible light band. The BSDF is shown in Figure 5 for 550 nm for different values of cleanliness class.

The contamination generated stray light was added to the surface roughness stray light and propagated through the optical system. The result of this calculation is presented in Figure 6 using M1 micro-roughness $\sigma = 0.3$ nm.

Note that the total stray light level is not perceptibly increased by Class 50 and Class 100 surface contamination levels while Class 300 contamination begins to increase the total stray light.

This theoretical analysis shows clearly that METIS stray light requirement is met in the UV/EUV band, while it is about 50% higher in the VL band below 2 solar radii, where the expected coronal flux is higher. Besides, the M1 particulate contamination class should be no higher than class 300 in order

to meet the requirement.

It must be remembered that an additional reduction of the diffracted light off IEO will be obtained by an optimization of its shape [7].

IV. CONCLUSION

The present theoretical analysis shows that the stray light levels in all three METIS wavelength bands meet the requirements. The analysis is based on an ideal instrument, i.e. it does not include manufacturing and alignment tolerances and also the cleanliness of the optical components, and includes approximations on the shapes on the occulters. The Fresnel diffraction is also an approximation of the diffraction pattern and the optimized shape of the occulter, mentioned above, is also a very complex problem for a theoretical approach. The analysis is therefore necessary to define the specifications of the components, but it is not sufficient to characterize the stray light behavior of the coronagraph. Past experience of previous space-borne coronagraphs has shown that the stray light behavior of the instrument can be very different from the computed stray light.

In order to characterize the coronagraph stray light is therefore necessary to build a laboratory model of the stray light rejection subsystem and test it inside a special facility with the capability of reproduce as close as possible the solar irradiance conditions on the coronagraph. Laboratory tests are important to better characterize the occulting system and find and improve its limits and defects [5], [7].

METIS occulting subsystem called boom-occulter assembly (BOA) has been built and has been preliminary tested at the the Articial Sun facility at Laboratoire d'Astrophysique de Marseille and is presently under evaluation in the Optical Payload System facility (OPSys) for testing space coronagraphs at ALTEC in Turin [10].

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