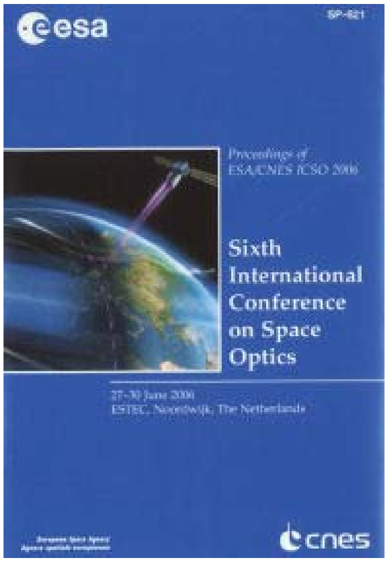

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DESIGN OF A GRAZING INCIDENCE EUV IMAGING SPECTROMETER FOR THE SOLAR ORBITER ESA MISSION

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ABSTRACT

The paper describes the optical design and performance of an extreme-ultraviolet (EUV) spectrometer for imaging spectroscopy to be part of the scientific payload of the Solar Orbiter (SOLO) mission. The main scientific objectives are to study the solar polar region and observe in detail the evolution of corona structures from a favourable point of view at only 45 solar radii from the Sun (0.2 AU).

The instrument concept is based on a grazing incidence telescope, (1200 m focal length, 18 arcmin x 18 arcmin FoV), in Wolter configuration couple to a normal-incidence VLS grating spectrometer, which preserve the stigmaticity in an extended spectral region and in the whole field-of-view.

The spectral range covered by the instrument is the 116-126 nm region at the first order and the 57-63 nm region at the second order. The spectral resolving element is 65 mÅ (I order), corresponding to a velocity resolution of 16 km/s.

1. INTRODUCTION

The Solar Orbiter (SOLO) misson is an European Space Agency (ESA) flexible mission specifically proposed to give a step ahead in unravelling solar and heliospheric physics. The understanding of the solar corona, the associated solar wind and the 3-D heliosphere has advance significantly thanks to solar mission such as Helios, Ulysses, Yohkoh, SOHO and TRACE. Nevertheless in situ measurements closer to the Sun, together with high resolution imaging and spectroscopy from a near Sun and out-of-ecliptic perspective are needed to bring a major breakthrough in present knowledge.[1,2]

The key mission goals and scientific objectives for the SOLO mission are: to study the innermost regions of the solar system so to determine in situ the properties and dynamics of plasma, fields and particles in the near sun heliosphere; study the Sun from close by (0.2 UA), to survey the fine detail of the Sun's magnetised atmosphere using a camera capable of resolving solar features of about 100 km; swing by the Sun, from a quasi-heliosynchronous vantage point, in order to identify the links between activity on the surface and the resulting evolution of the corona and inner heliosphere; observe and fully characterize the Sun's polar regions and the equatorial corona from high heliographic latitude (till about 38°).

SOLO will achieve these ambitious goals via a suite of highly sophisticated and lightweight instruments. The payload will include two instrument packages optimized to meet the solar and heliospheric science objective:

- *Heliospheric in situ instruments*, for field and particle measurement detection;
- *Solar remote-sensing instruments*, high resolution imagers, spectrometers, coronographs, etc. observing the Sun surface and atmosphere from X-ray to visible-light.

The spacecraft (S/C) will be three-axis stabilized and Sun-pointed. Nominal mission lifetime is 5 years, during this period the S/C will experienced several Venus swing-by to incline the orbital plane with respect to solar equator to provide a better view of the Sun's polar region. The S/C will experienced extreme environmental conditions, especially thermal ones, because it will reach the minimum distance of only 45 solar radii from the Sun. Given this issue, the payload has to be design with the aim of saving mass and power as far as possible.

2. EUV IMAGING AND SPECTROSCOPIC CHANNEL FOR SOLO

2.1 EUV imaging and spectroscopy scientific requirements

The scientific requirements for the EUV imagers are, through high resolution imaging, to reveal the fine-scale structure of coronal features and by taking full-disc images of the Sun, to reveal the global structure of the corona, in particular on the inaccessible "far side" of the Sun and for the polar region. These images are required to define the context for spectroscopy and to establish the links between the solar surface and the heliosphere.

Spectroscopic observations of emission lines in the EUV/UV region of the electromagnetic spectrum are critical for the determination of plasma diagnostics from the solar atmosphere, providing the necessary tools for probing the wide solar plasma temperature range, from tens of thousands to several million K. Analysis of the emission lines, mainly from trace elements in the Sun's atmosphere, provides

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information on plasma density, temperature, element/ion abundances, flow speeds and the structure and evolution of atmospheric phenomena. Such information provides a foundation for understanding the physics behind a large range of solar phenomena.

Current S/C instrumentation (SOHO) provides EUV spatial and spectral resolving elements of order 2-3 arcseconds and 0.1 Å, respectively, and UV resolutions of 1 arcsecond and 0.02 Å, and the future solar missions, such as the NASA ones: Stereo, Solar Dynamics Observatory and Solar Probe, will not carry any EUV/UV spectroscopic device [3].

Solar plasma diagnostics is provided by the analysis of a few selected spectral windows with lines coming from ions at different ionizing stages, and thus from different temperature regions. The spectroscopic technique involves using the line profiles, giving via radiance a measure of ion density, and the line shifts in order to derive by the Doppler method values for the ion kinetic temperature and bulk material flow velocity.

Such measurements concern an area of prime science for the SOLO mission. The emphasis will be on the observation of a few bands only. The chosen wavelength range ideally should include strong upper chromosphere, transition-region and coronal lines. Strongly suggested wavelength bands are: 17-22 nm, 58-63 nm and above 91.2 nm [4].

The Solar Orbiter goals demand high spatial, spectral and temporal resolution. The Sun's atmosphere is a truly dynamic, fine-scale environment. Our current capabilities in image resolution (0.5 arcsec pixels with TRACE) and temporal resolution (of order seconds at best) are restricting. Spectroscopic studies show that the true fine-scale structure is much smaller than current pixels sizes, and we are aware that basic processes occur on smaller scales than currently available.

Thus, the target is to provide an order of magnitude better spatial resolution than that available for the current spectrometers, and five times better than the best imager capability. Our target is 150 km on the Sun's surface, which is 0.2 arcseconds from 1 AU. For Solar Orbiter, this translates to 1 arcsecond, since we are tuning the design to the 0.2 AU perihelion.

The dynamic nature of the solar atmosphere certainly demands significantly better temporal resolution than currently available. However, we must be aware of the play off between exposure time and temporal resolution; reasonable counting statistics must be obtained. This means that the actual temporal resolution will be dependent on emission line selection and the type of solar target selected. Thus, the instrument must have flexibility, but we should aim at less than 1 second, and assume that a typical value would be of order 1 second.

Tab. 1 The basic target scientific requirements for the EUV instrument.

Spatial Resolving Element (pixel)	1 arcsec (150 km on the Sun at perihelion 0.2 UA)
Spectral Resolving Element (pixel)	0.02Å/pixel
Field of View (minimum)	Slit Length: 20 arcmin or larger Raster Length: 20 arcmin or larger
Exposure time (minimum)	Ideal: <1 s Maximum acceptable: 1 s
Count Rates	In range 1-100 counts per second per pixel
Wavelength Bands	170-220 Å 580-630 Å > 912 Å

2.2 EUV spectrometer design

To achieve the desired orbit, the SOLO mission puts a severe constraint on the payload mass and size. Thus, whilst recognising that an EUV spectrometer is an essential component of such a mission, we must be aware that it must be compact and light-weight. In addition, it must not be too telemetry 'thirsty' and must be able to cope with the thermal and particle environment of such an orbit.

The EUV spectrometer for SOLO will consist of a telescope making an image of the Sun on the entrance slit of a stigmatic grating spectrometer. In a stigmatic spectrometer, the optical aberrations are corrected both on the spectral dispersion plane, perpendicular to the entrance slit, and on the cross-plane, parallel to the entrance slit. In this way, a point-like source on the entrance slit is re-imaged as a spectrally dispersed point on the focal plane; two-dimensional monochromatic images can then be obtained. The Sun disk can be scanned perpendicularly to the entrance slit using the so called rastering procedure. By moving an element inside the telescope, different strips of the Sun surface are brought to the entrance slit and then monochromatically imaged on the detector; taking a set of consecutive acquisitions the full disk image can be reconstructed.

A normal incidence design was originally envisaged for the telescope, to fit within reasonable length limitation of the S/C. A normal incidence single mirror off-axis parabolic telescope is the simplest choice i.e. only one mirror element for focusing and rastering; in addition it's the best performing one being able to satisfy completely the scientific requirements [6]. However the thermal situation is extreme, especially for a normal incidence design; so an alternative back-up 'grazing-incidence telescope' solution has been studied and will be presented in detail in this paper.

The telescope consists of two grazing-incidence mirrors with surfaces of revolution in Wolter configuration, giving a stigmatic image on the entrance slit plane in an extended field-of-view. The high resolution given by the telescope on the slit plane should be preserved by the spectrometer. This condition can be fulfilled only by a normal-incidence grating which preserves the stigmaticity in an extended spectral region and in an extended field-of-view.

The optical layout of the overall instrument is shown in Fig. 1. It consists of a grazing-incidence section (the telescope in Wolter II configuration and the plane mirror for the rastering), an entrance slit, a normal-incidence section (the spectrometer) and finally a detector. The rastering in the direction perpendicular to the entrance slit is performed by the plane mirror placed in front of the slit.

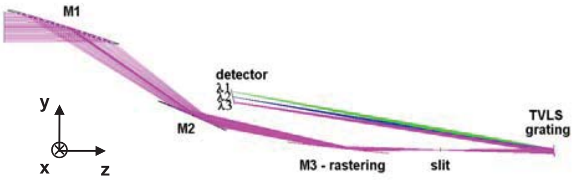

Fig. 1 Instrument layout.

2.3 Grazing Incidence Telescope performance

In the grazing-incidence domain, at least two reflecting surfaces are necessary to give an useful field-of-view, obeying to the Abbe condition. Perfect on-axis images and a large stigmatic field-of-view are given by systems with two confocal conical mirrors, the so-called Wolter configurations [5]. Among the three designs for Wolter telescopes, Wolter II is the more suitable for EUV observations with grazing angles in the range 7-15°. It adopts a paraboloid and a hyperboloid arranged coaxially with a coincident common focus which makes the system focus; the two reflections occur in the internal surface of the paraboloid and on the external surface of the hyperboloid. The main advantage of Wolter II configuration is that the equivalent focal length can exceed the system length substantially, so reducing the size of the instrument.

The main characteristics of the grazing-incidence telescope are summarized in Tab. 2.

The telescope has an equivalent focal length of 1200 mm, corresponding to 6 μm/arcsec on its focal plane. The slit size is 6 μm × 6.3 mm, corresponding to an ideal angular resolution of 1 arcsec (150 km on the Sun at 0.2 AU) and a FoV of 0.3° or 18 arcmin. The spot diagram calculated along the slit (x direction, see Fig. 1 for reference system definition) are shown in Fig. 2, the spots have been displayed only for the +x direction along the slit, being the system symmetric with respect to the zy plane. The central (0°), the middle (0.075°) and the edge (0.15°) positions are considered.

Tab. 2 Grazing-incidence telescope main characteristics.

Field-of-view	18 arcmin (simultaneous) × 18 arcmin (to be acquired by the rastering)
Entrance aperture	50 mm × 50 mm
Telescope	Wolter II configuration
M1	Parabolic mirror
Incidence angle	74º
Size	200 mm × 50 mm
M2	Hyperbolic mirror
Incidence angle	79º
Size	200 mm × 20 mm
M3 (rastering)	Plane
Incidence angle	84º
Rotation for the rastering	±0.35° (off-center)
Size	100 mm × 15 mm
M1 to M2 distance	220 mm
M2 to M3 distance	250 mm
M3 to slit distance	170 mm
EFFL	1200 mm
F/number	F/24 (42 mrad)
Telescope length	770 mm
Entrance slit	
Size	6 μm × 6.3 mm
Spatial resolution on the entrance slit	1 arcsec (150 km at 0.2 AU)

To clearly see the size of the spot, reference boxes of 10 x 10 μm^2 are overlaid. Different symbols (or colors) refer to different rastering position of the M3 mirror, corresponding to different viewing angles in zy plane. Mean root-mean-square (rms) spot radii are of the order of 3-4 μm; the diffraction enclosed energy (EE) perpendicular to the slit (y direction) is of the order of 80% or more, as an example, in Fig. 3 the EE is shown for the central reference position (i.e. no-rastering) for all the FoV (18 arcmin).

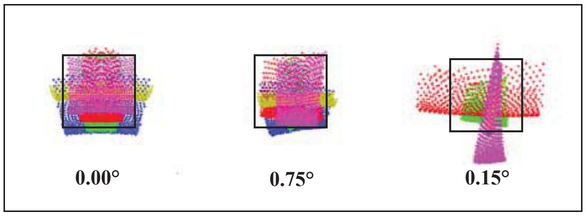

Fig. 2 Telescope spot diagram. Spot diagram along half of the slit (0°, 0.75° and 1.5° FoV) are shown. Different symbols (or colors) correspond to different raster position of the M3 mirror. Overlaid boxes are 10 μm x 10 μm in size.

The rms telescope aberrations on the slit plane, both perpendicular and parallel to the slit, are shown respectively in Fig. 4 and Fig. 5 . Rms spot sizes are varying along the slit height, because of the off-axis angle, and with the rotation of the plane mirror performing the rastering; however, they are ever definitely lower than the slit width, i.e. 6 µm.

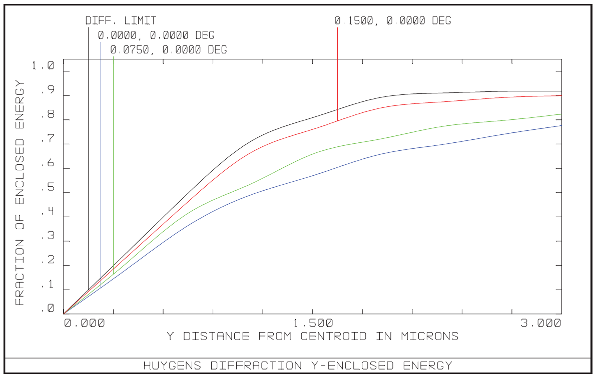

Fig. 3 Diffraction enclosed energy perpendicular to the slit for the central reference position.

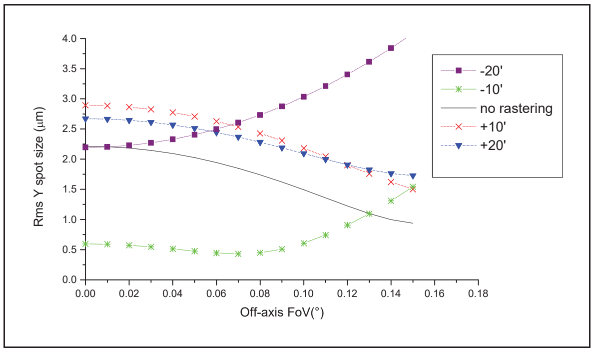

Fig. 4 Rms telescope aberrations perpendicular to the slit for all the FoV.

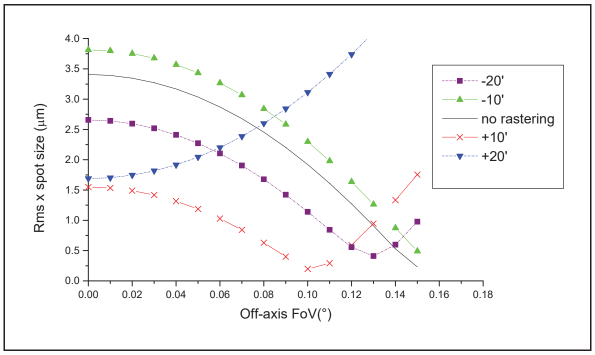

Fig. 5 Rms telescope aberrations parallel to the slit for all the FoV.

2.4 Grating design and performance

The second important part of the instrument is the grating spectrometer, it has entrance and exit arms respectively of 200 mm and 600 mm, giving a magnification of three. To optimized imaging and off-axis aberrations performance a toroidal varied-line-space (TVLS) grating has been chosen [7]. The central groove density is 2400 lines/mm and it is operated at an incidence angle of 4° to fulfil the off-axis condition while having two stigmatic wavelengths within the spectral region to be acquired. The plate factor is 0.65 nm/mm and 0.32 nm/mm at I and II order respectively.

A detector array of 2150 × 1120 10 × 15 µm pixel is presently chosen as baseline (22.1 mm × 16.8 mm useful area), corresponding to a spectral resolving element of 6.5 pm at 120 nm (3.3 pm at 60 nm), a 16 km/s velocity resolution, and to a spatial resolving element of 0.9 arcsec (135 km on the Sun at 0.2 AU). The velocity resolution can be increased over the limit of the detector pixel by a sub-pixel centroiding of the line profile. The length of the overall instrument (telescope and spectrometer) is 1.0 m, that is within the constraints of SOLO.

Overall optical characteristic of the spectrometer are reported in Tab. 3.

Tab. 3 Spectrometer characteristics.

Wavelength range	114-126 nm (I order) 54-64 nm (II order)
Spectrometer	TVLS grating
Central groove density	2400 gr/mm
Incidence angle	4 º
Entrance arm	200 mm
Medium exit arm	600 mm
Tangential / sagittal radii	284.5 mm / 292.7 mm
Size	17 mm (width) × 11 mm (height)
Detector	
Pixel size	10 µm × 15 µm
Format	2150 × 1120 pixel
Active area	25.1 mm × 16.8 mm
Spectral resolving element	6.5 pm/pixel (16 km/s) (I order) 3.3 pm/pixel (16 km/s) (II order)
Image of the slit	18 µm (11.88 pm, 30 km/s I order) (5.94 pm, 30 km/s II order)
Spatial resolving element	1 arcsec/pixel (150 km at 0.2 AU)
Global instrument length	1.0 m

It has been verified that the grating aberrations are negligible with respect to the detector pixel size within the whole spectral range to be acquired and the whole field-of-view, because of the presence of two stigmatic spectral points, of the fulfilment of the off-axis condition and of the low aperture angle (42 mrad).

So the spatial resolution parallel to the slit and the spectral resolution are mainly limited respectively by the telescope aberrations and by the slit width projected on the detector focal plane. In particular, the spectral resolution is constant within the whole field-of-view and limited to 6.8 pm. Also in that case, the velocity resolution can be increased up to few km/s by a sub-pixel centroiding of the position of the line peak. The spatial resolutions on the solar disk, perpendicular and parallel to the slit, are shown in Fig. 6 and Fig. 7 respectively.

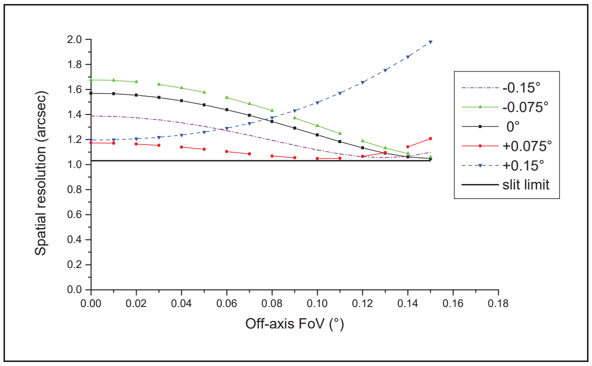

Fig. 6 Spatial resolution perpendicular to the slit.

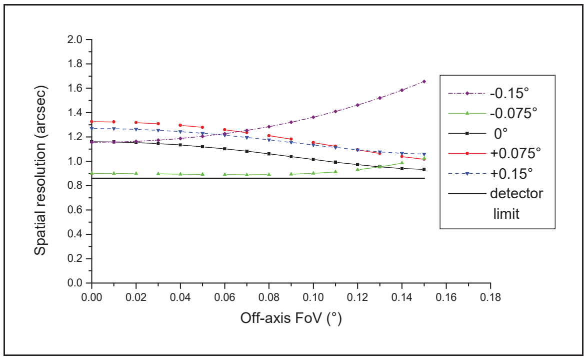

Fig. 7 Spatial resolution parallel to the slit.

2.5 Efficiency

The total efficiency of the telescope-spectrometer at wavelength λ, $E_{TOT}(\lambda)$, is estimated by means of Eq. 1:

$$E_{TOT}(\lambda) = A_{EF}\,[\mathrm{cm}^2] \cdot E(\lambda) \cdot PS\,[\mathrm{arcsec}^2] \qquad (1)$$

where A_{EF} is the entrance effective area, E(λ) is the combined efficiency at wavelength λ of the telescope, spectrometer and detector and PS is the pixel size.

With reference to an existing EUV solar spectrometer, we can calculate the effective area of CDS on SOHO in the NIS2 channel, which operates in the 52-63 nm band, at a wavelength of 60 nm. The numbers to be used in Eq. (1) are A_{EF} = 27 cm^2, E(60 nm) = 0.0005 and PS = 3.41 arcsec^2. The total efficiency at 60 nm results E_{TOT_CDS}(60 nm) = 0.046.

For our grazing-incidence design, the term E(λ) is calculated by taking into account the losses due to the three reflections, the grating efficiency $E_G(\lambda)$ and the detector efficiency $E_D(\lambda)$. It is approximately given by:

$$E(\lambda) = R_{M1}(\lambda, \vartheta_1) R_{M2}(\lambda, \vartheta_2) R_{M3}(\lambda, \vartheta_3)\, E_G(\lambda) E_D(\lambda) \qquad (2)$$

where $R_{M1}(\lambda,\theta)$, $R_{M2}(\lambda,\theta)$, $R_{M3}(\lambda,\theta)$ are respectively the reflectivity at wavelength λ of the paraboloidal, ellipsoidal and plane mirrors of the telescope at angles θ_1, θ_2, θ_3. The exact calculation of the effective area is done considering the local variations of the incidence angle on the optical surfaces, as given by a ray-tracing program. The grating efficiency $E_G(\lambda)$ and detector efficiency $E_D(\lambda)$ will be assumed equal respectively to 0.15 and 0.30 [6].

We can assume to use coatings with high grazing-incidence reflectivity both in the visible and near infrared region, where most of the thermal load is concentrated (⇒ low thermal absorption), and in the EUV region (⇒ high efficiency). Si-Au coatings (a thin silicon film of 20-40 nm deposited on gold) were recently tested with the aim of identify a suitable coating for SOLO. High EUV grazing-incidence reflectivity is given by the silicon layer, while high visible rejection is given by the gold [8]. The following values can be assumed for the reflectivity at 60 nm: R_{M1} = 0.55, R_{M2} = 0.65, R_{M3} = 0.75. The resulting efficiency is E(60 nm) = 0.012. The other numbers to be used in Eq.(1) are A_{EF} = 25 cm^2 and PS = 0.52 arcsec^2. The total efficiency at 60 nm results E_{TOT}(60 nm) = 0.156.

2.6 Thermal consideration

The thermal load at 0.2 AU is 25 solar constant, equivalent to about 34 kW/m^2.

For our telescope configuration, the power on the entrance aperture is about 85 W, that have to be dissipated by suitable radiators. The power density on the first mirror is 0.94 W/cm^2 (7 solar constants). In case of using Si-Au coating, the power absorption on the mirror is about 34 W (0.38 W/cm^2, 3 solar constants). The thermal load on the second mirror is about 48 W. Here, about 18 W are absorbed (0.45 W/cm^2, 3.2 solar constants) and 10 W are reflected towards the plane mirror for the rastering and the entrance slit. Here, about 4 W are absorbed (0.13 W/cm^2, 1 solar constant) and 6 W are reflected to the slit plane, where the power density is about 1.0 W/cm^2 (7 solar constants) and must be reduced by the baffling. Summarizing the results, 56 W are absorbed by the optics and have to be dissipated, 6 W have to be properly absorbed by baffles on the slit plane, the remaining 23 W have to be absorbed by a suitable baffling system.

3. CONCLUSIONS

A grazing incidence configuration for the EUV spectrometer for SOLO have been presented. The instrument consists of a telescope making an image of the Sun on an entrance slit of a grating spectrometer.

The telescope is a grazing incidence Wolter-type telescope. The spectrometer design consists of an aspherical varied-line-spaced grating fulfilling the condition for minimizing the off-axis aberrations while maintaining two stigmatic points within the spectral region to be acquired.

The performance of the telescope and of the overall system all over its FoV, including rastering capabilities, has been presented. The telescope is well corrected with rms spot radii of about 3-4 µm in the whole FoV (18 arcmin x 18 arcmin). The performance of the grating spectrometer is excellent; given the TVLS choice, the grating aberrations are negligible with respect to the detector pixel size within the whole spectral range to be acquired and the whole field-of-view, i.e. spatial resolution is driven by telescope performance.

Efficiency calculation for the system has been done, showing that it is higher than the efficiency of a similar spectrometer flying at present on SOHO.

If we were to compare this design with the normal-incidence one, the normal incidence has a smaller number of optics, only two (an off-axis paraboloidal mirror and a TVLS grating), it gives very good performance in a compact package, in addition, it is simpler both from the point of view of alignment and for tolerances. On the contrary the Wolter-type telescope in grazing incidence has almost the same size but slightly worse performance (although definitely better than the performance on the existing spectroscopic instrumentation looking at the solar disk). Furthermore, it uses four optics and has a more critical alignment procedure and mechanical tolerances.

From the thermal point of view, the constraints for the grazing incidence design are more relaxed and also the degradation of the reflectivity in time can be lower. Finally the optical design presented in this paper can be adopted if the extreme irradiation and thermal load on the telescope makes it difficult to work in normal incidence.

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