Solar Orbiter EUV Spectrometer (EUS) Proto-Consortium Meeting
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Optical characteristics of the EUV spectrometer (EUS) for SOLO

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Stigmatic spectrometers for extended regions

The spectrum acquired by a grating spectrometer has information on the spatial distribution of an extended source only in the plane perpendicular to the plane of spectral dispersion (i.e. parallel to the entrance slit)

In a **stigmatic spectrometer**, optical aberrations are corrected both on the plane of dispersion and on the plane perpendicular to this

⇒A point-like source on the entrance slit is imaged on the focal plane as a point

⇒Two-dimensional images are built scanning only in the direction perpendicular to the slit

The **stigmaticity** is guaranteed in an extended field-of-view parallel to the entrance slit only in **normal-incidence** configurations

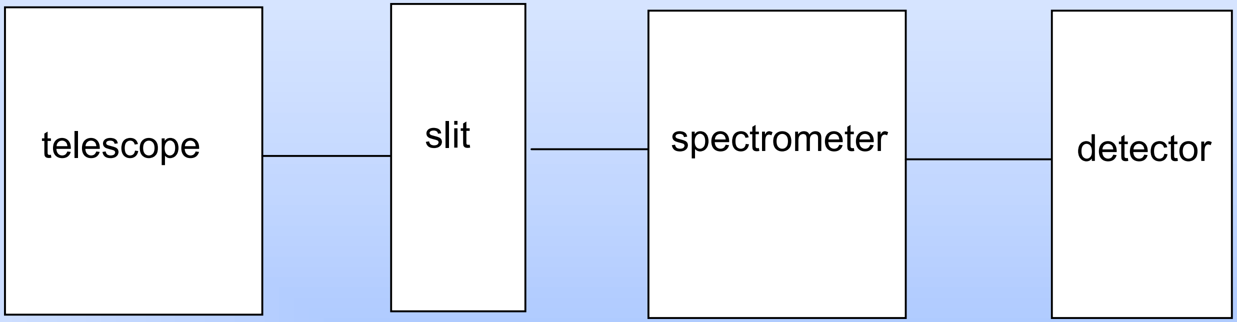
⇒Stigmatic spectrometers with a **single optic**, namely the grating, are being successfully used in EUV space applications (e.g. UVCS/SOHO)

A single-element optic, even at normal incidence, has off-axis aberrations that can not be eliminated, but only reduced by minimizing the subtended angle.

The grating spectrometer introduces off-axis aberrations that have to be carefully analyzed.

Telescope-spectrometer for extended regions

A telescope-spectrometer consists mainly on four blocks:
- the telescope
- the entrance slit
- the grating spectrometer
- the detector



Three optical parameters have to be calculated in the evaluation of the performance:
1) **the spatial resolution in the direction perpendicular to the entrance slit**
2) **the spatial resolution in the direction parallel to the slit**
3) **the spectral resolution in the direction parallel to the slit**

PARAMETER NO. 1 DEPENDS ONLY ON THE OPTICAL PROPERTIES OF THE TELESCOPE.

PARAMETERS NO. 2 AND 3 DEPEND ON THE PERFORMANCE OF THE WHOLE INSTRUMENT (TELESCOPE + SPECTROMETER)

Spectroscopic instrumentation on the Solar Orbiter

The EUV spectroscopic instrumentation proposed for the Solar Orbiter consists of a **NORMAL-INCIDENCE HIGH-RESOLUTION SPECTROMETER** (EUS - EUV Spectrometer)

- The optical layout is a **normal-incidence telescope** that feeds a **toroidal-grating spectrometer** with very high spectral and spatial resolution in the **58-62 nm spectral range** (He I 584, O III 599, Mg X 610)
- Spectral images in the **29-31 nm region in the second diffracted order** are expected (Fe XII 291, Si X 293, Si IX 296, He II 304)

Since the reflectivity of conventional coatings at normal incidence is few % at 30 nm, **the detection of radiation below ≈35 nm at normal incidence requires multilayer coatings**

⇒ **The severe thermal environment of SOLO makes it very difficult to use multilayer coatings on optics looking at the solar disk** (the average solar intensity at 0.2 AU is ≈34 kW/m^2)

⇒ **EUS without multilayer optics is limited to the normal-incidence region** (>≈40 nm)

EUV spectrometer for SOLO

Three different configurations have been analyzed:

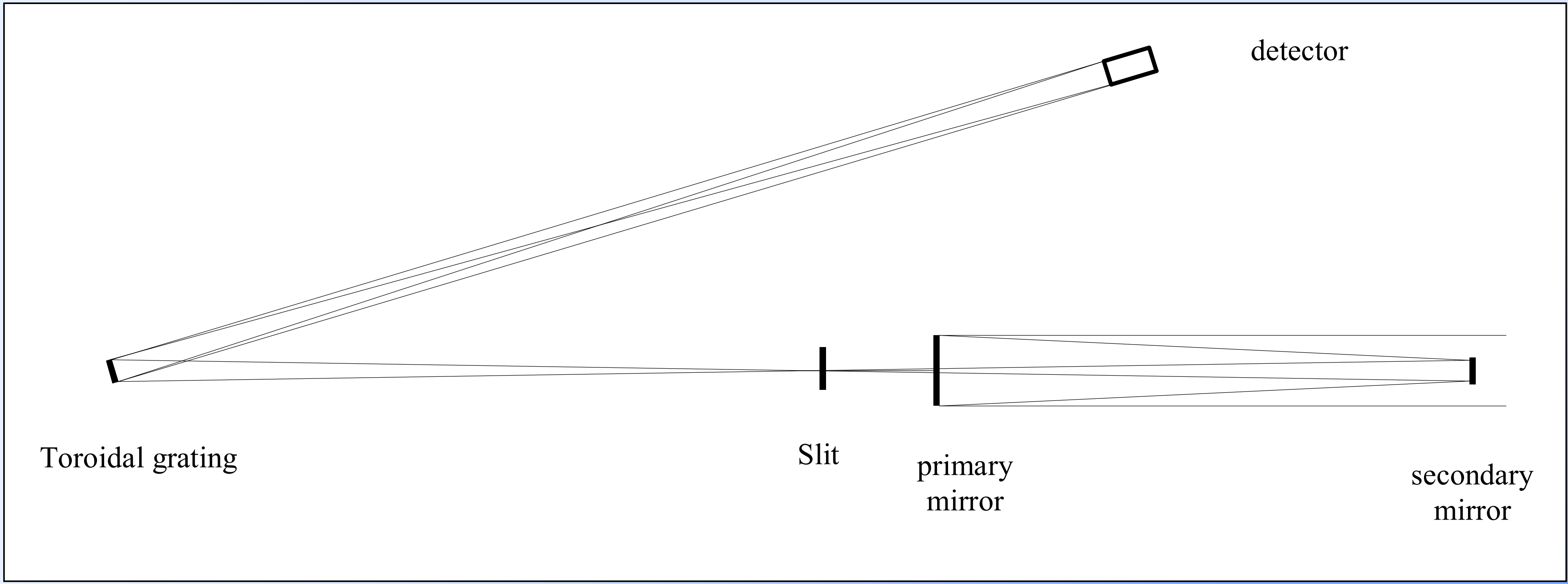
Configuration A. A normal-incidence telescope feeding a normal-incidence toroidal-grating spectrometer;

Configuration B. A normal-incidence telescope feeding a normal-incidence variable-line-spaced-grating (VLS) spectrometer;

Configuration C. A grazing-incidence telescope feeding a normal-incidence VLS-grating spectrometer.

The spectral range of operation is the region 1160-1260 Å (first order) and 580-630 Å (second order)

Configuration A: normal-incidence telescope and normal-incidence toroidal-grating spectrometer (1/3)

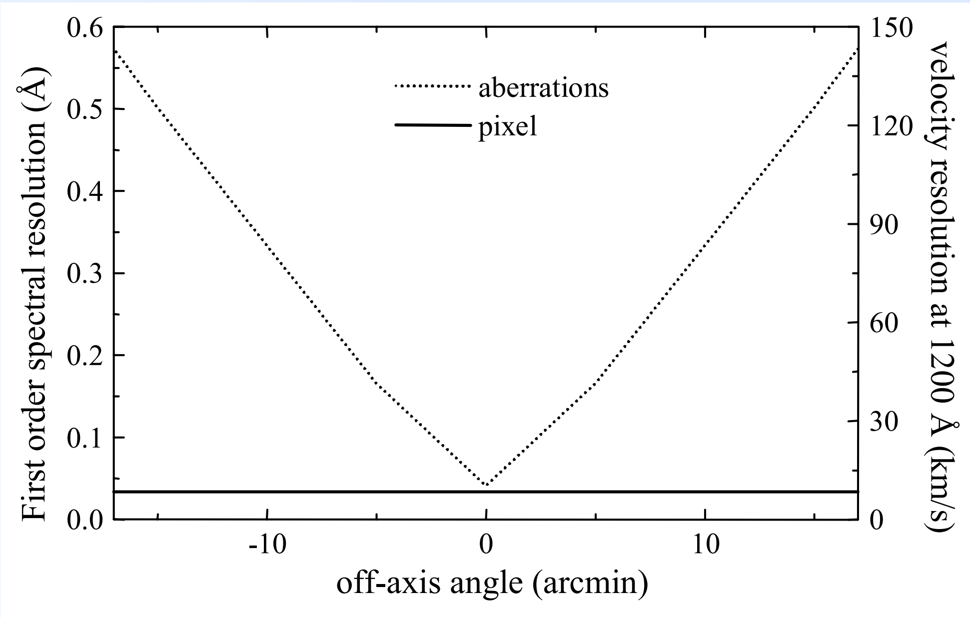


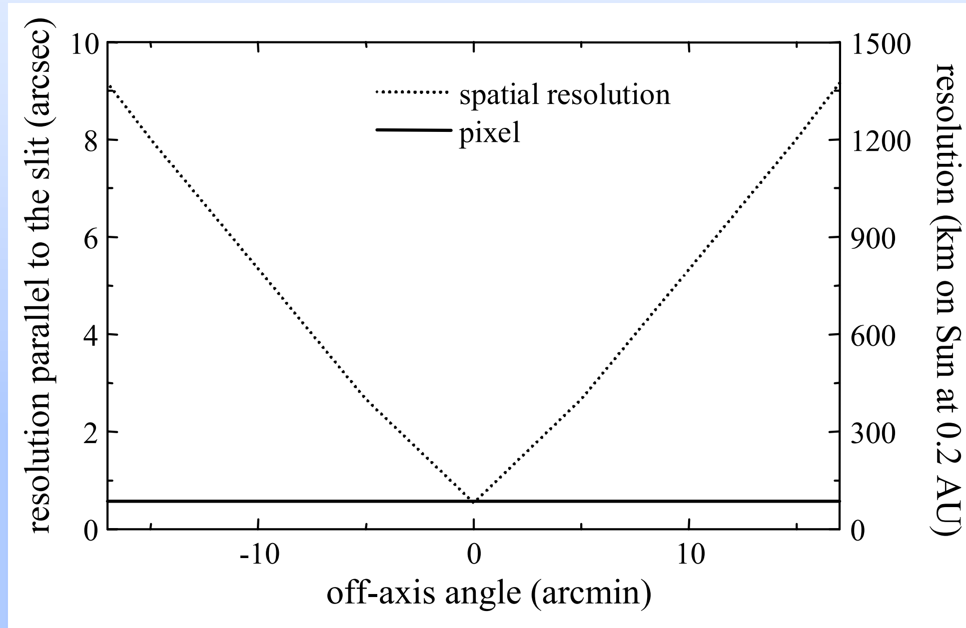
Configuration A: normal-incidence telescope and normal-incidence toroidal-grating spectrometer (2/3)

Telescope	Ritchey-Chretien
Field of view	34 arcmin (‖ to the slit, simultaneous)
	34 arcmin (⊥ to the slit, to be acquired by rastering)
Telescope tube	
Diameter	130 mm
Length	1000 mm
Primary mirror	
Diameter	120 mm
Secondary mirror	
Distance from the primary	900 mm
Extraction length	200 mm
Diameter	45 mm
Focal length	3700 mm
Slit	
Size	9 μm × 36 mm
Resolution ⊥ to the slit	0.5 arcsec

Grating	Toroidal
Groove density	2400 lines/mm
Wavelength	1160-1260 Å (I order)
	580-630 Å (II order)
Entrance arm	1200 mm
Exit arm	1760 mm
Incidence angle	16.88°
Tangential radius	1470 mm
Sagittal radius	1397 mm
Size	40 (⊥ to the grooves) × 105 mm
Coating	SiC
Detector	
Pixel size	15 μm
Format	2800 × 3600 pixel
Area	42 (⊥ to the slit) × 54 mm
Spectral resolving element	36 mÅ (I order)
	18 mÅ (II order)
Spatial resolving element	0.55 arcsec

Configuration A: normal-incidence telescope and normal-incidence toroidal-grating spectrometer (3/3)

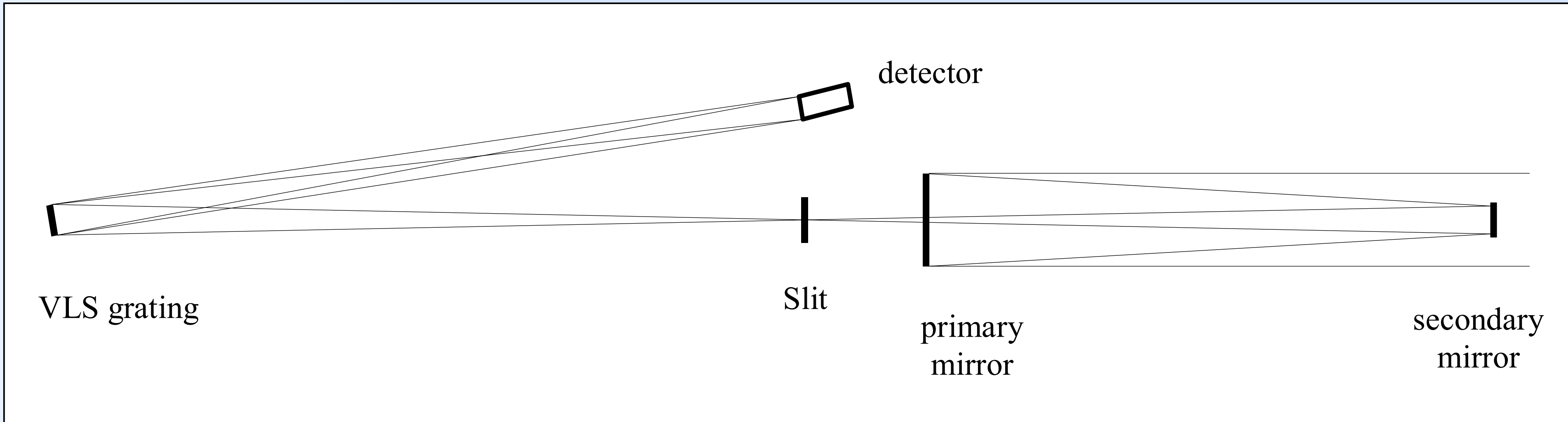




Spectral resolution and spatial resolution parallel to the slit.

The resolutions have been obtained by a simulation of the whole instrument

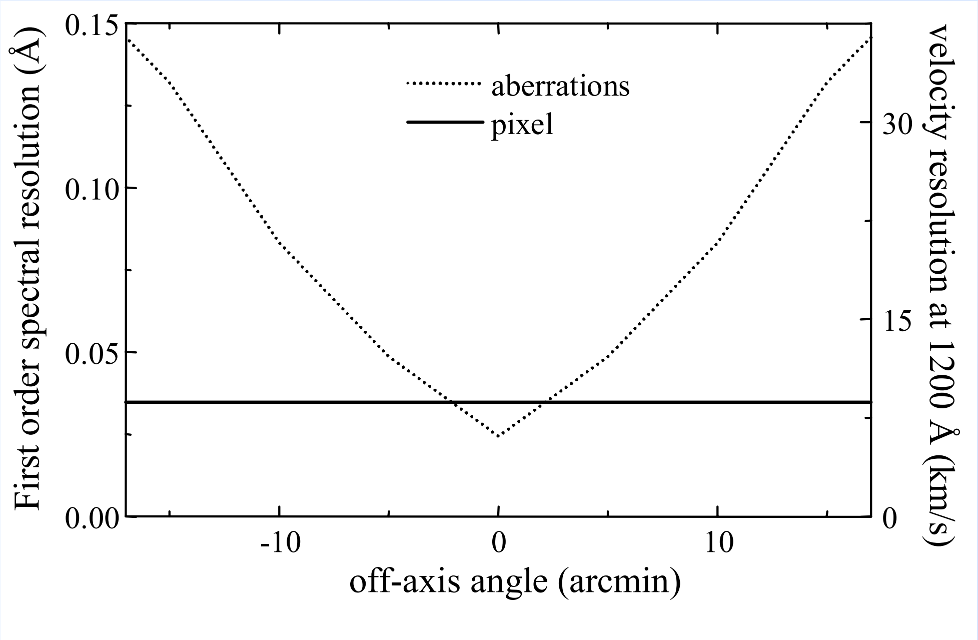
Configuration B: normal-incidence telescope and normal-incidence VLS-grating spectrometer (1/3)

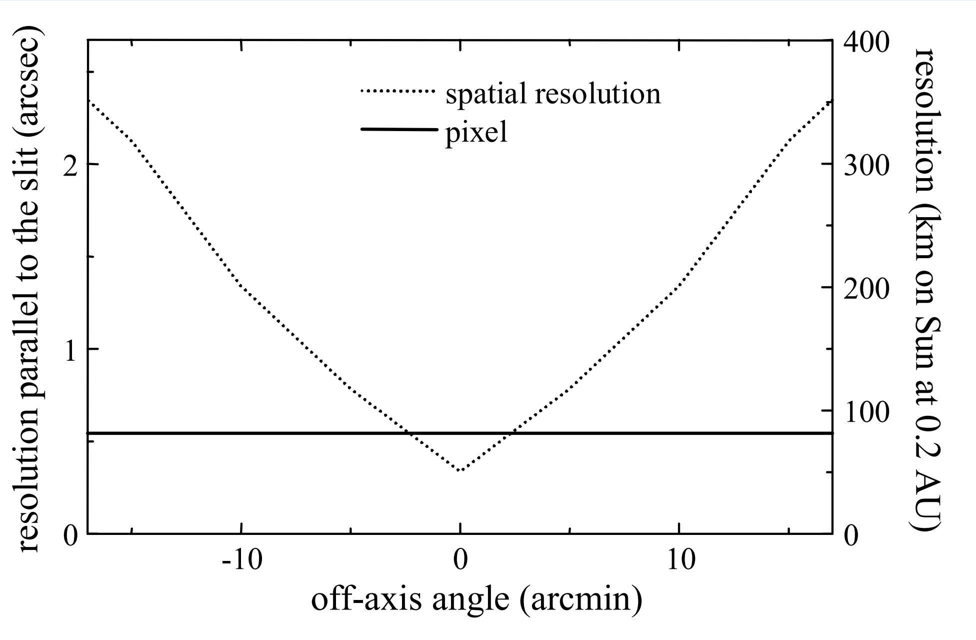


Configuration B: normal-incidence telescope and normal-incidence VLS-grating spectrometer (2/3)

Grating	VLS
Groove density	2400 lines/mm
Wavelength	1160-1260 Å (I order)
	580-630 Å (II order)
Entrance arm	1225 mm
Exit arm	1205 mm
Incidence angle	11.89°
Radius	1200 mm
Size	40 (⊥ to the grooves) × 105 mm
Coating	SiC
Detector	
Pixel size	10 μm
Format	2900 × 3600 pixel
Area	29 (⊥ to the slit) × 36 mm
Spectral resolving element	36 mÅ (I order)
	18 mÅ (II order)
Spatial resolving element	0.55 arcsec

Configuration B: normal-incidence telescope and normal-incidence VLS-grating spectrometer (3/3)

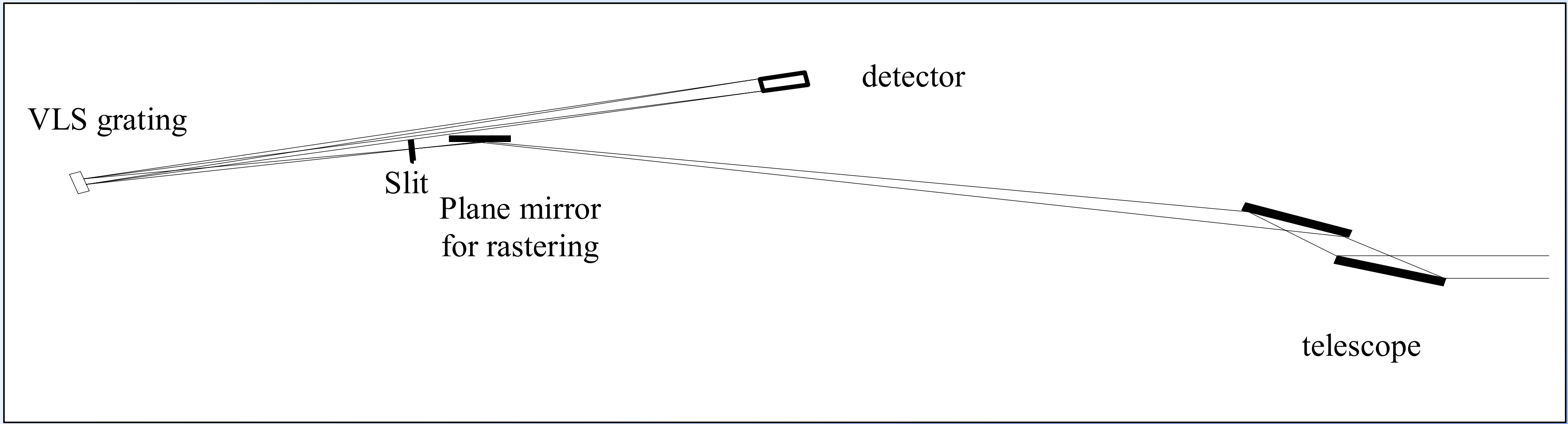




Spectral resolution and spatial resolution parallel to the slit.

The resolutions have been obtained by a simulation of the whole instrument

Configuration C: grazing-incidence telescope and normal-incidence VLS-grating spectrometer (1/3)

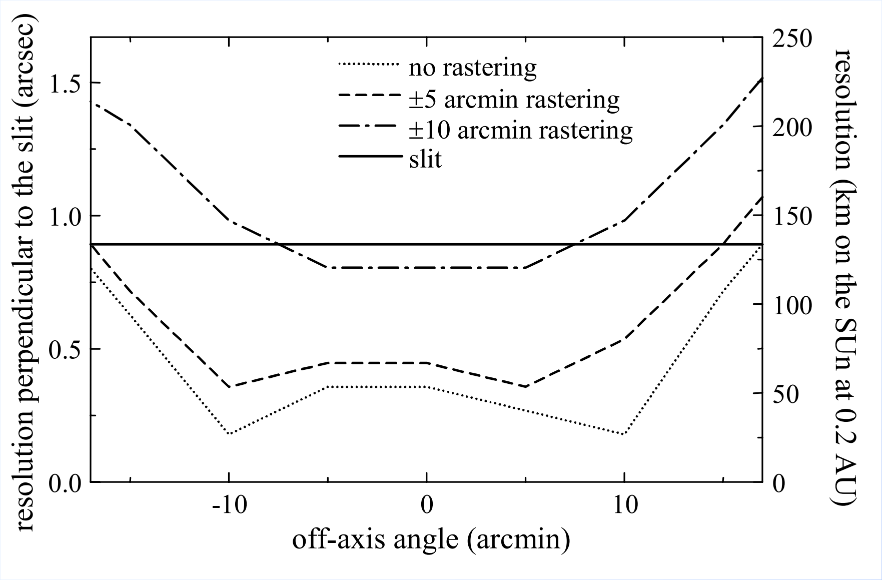


Configuration C: grazing-incidence telescope and normal-incidence VLS-grating spectrometer (2/3)

Telescope	Wolter II
Field of view	34 arcmin (‖ to the slit, simultaneous) 20 arcmin (⊥ to the slit, to be acquired by rastering)
Entrance aperture	
Size	55 mm × 55 mm
Primary mirror	Paraboloid
Size	200 mm × 55 mm
Incidence angle	74°
Secondary mirror	Hyperboloid
Distance from the primary	200 mm
Distance from the slit	1550 mm
Size	190 mm × 40 mm
Incidence angle	78°
Focal length	2310 mm
Mirror for the rastering	Plane
Distance from the slit	100 mm
Size	110 mm × 24 mm
Incidence angle	82°

Slit	
Size	10 μm × 23 mm
Resolution ⊥ to the slit	0.9 arcsec
Grating	Spherical VLS
Central groove density	2400 lines/mm
Wavelength	1160-1260 Å (I order) 580-630 Å (II order)
Entrance arm	600 mm
Exit arm	1200 mm
Incidence angle	10°
Radius	790 mm
Size	15 (⊥ to the grooves) × 45 mm
Coating	SiC
Detector	
Pixel size	18 μm
Format	1600 × 2600 pixel
Area	29 (⊥ to the slit) × 47 mm
Spectral resolving element	62 mÅ (I order) 31 mÅ (II order)
Spatial resolving element	0.8 arcsec

Configuration C: grazing-incidence telescope and normal-incidence VLS-grating spectrometer (3/3)

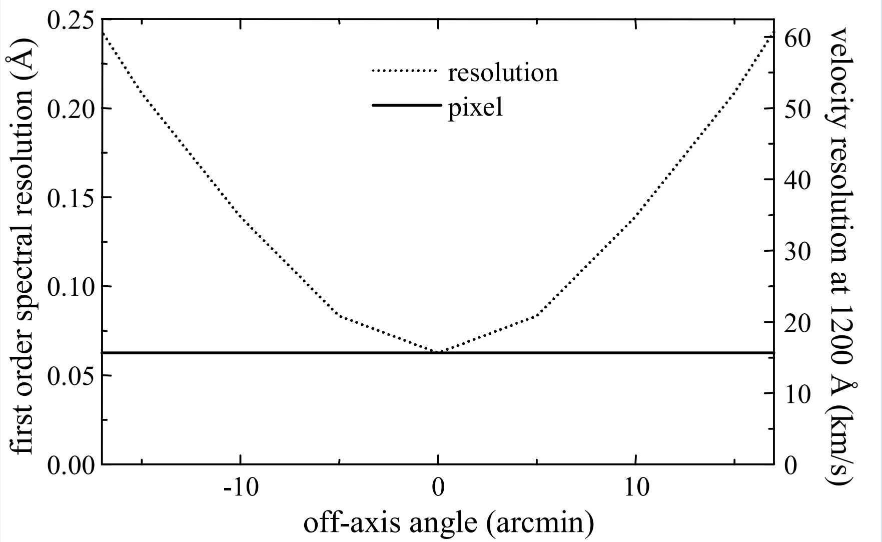


1)

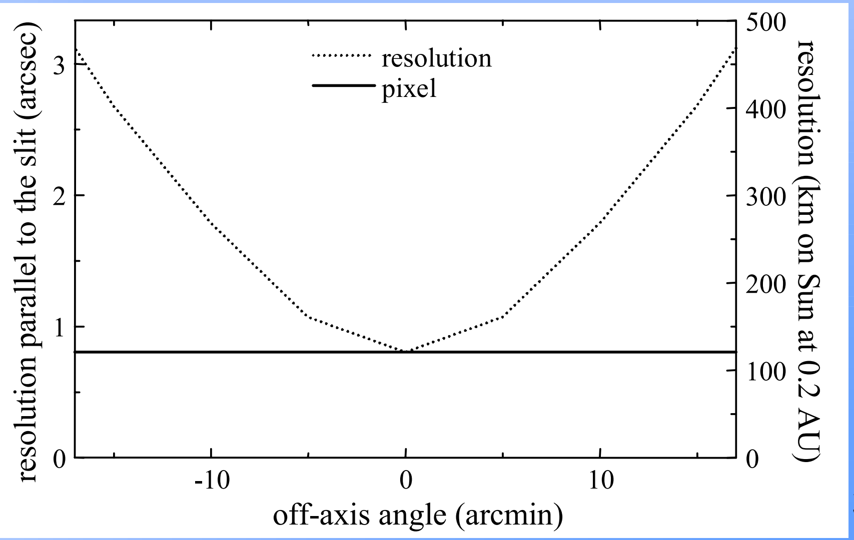
1) Spatial resolution perpendicular to the slit

2) Spectral resolution

3) Spatial resolution parallel to the slit



2)



3)

Effective area (1/3)

Coating	Reflectivity at 600 Å	Eff. area at 600 Å (cm^2)	Reflectivity at 1200 Å	Eff. area at 1200 Å (cm^2)	Total absorption
Au	0.13	0.10	0.16	0.15	0.21
Ir	0.20	0.23	0.18	0.19	0.28
Pt	0.21	0.26	0.21	0.26	0.34
SiC	0.33	0.63	0.48	1.34	0.80

EUV normal-incidence reflectivity, effective area of configurations A and B and total absorption of different coatings. The grating and detector efficiency have been supposed to be respectively 0.15 and 0.4.

Coating	Flux at 600 Å with 10^{13} photons/cm^2/sr/s (counts/pixel/s)	Flux at 1200 Å with 10^{13} photons/cm^2/sr/s (counts/pixel/s)
Au	7	10
Ir	15	12
Pt	14	17

Fluxes collected by a pixel (0.5 arcsec × 0.55 arcsec) in configurations A and B with metallic coatings. The whole spectral line is supposed to be sampled by a single pixel.

Effective area (2/3)

Coating	Reflectivity at 600 Å (74°)	Eff. area at 600 Å (cm^2)	Reflectivity at 1200 Å (74°)	Eff. area at 1200 Å (cm^2)	Total absorption at 74°
Au	0.40	0.23	0.40	0.23	0.19
Ir	0.48	0.32	0.40	0.21	0.33
Pt	0.52	0.41	0.45	0.27	0.38
Si (200 Å) + Au	0.80	1.11	0.80	1.09	0.22

EUV grazing-incidence reflectivity, effective area of configuration C and total absorption of different coatings. In the calculations of the effective area, the grating and detector efficiency have been supposed to be respectively 0.15 (both in first and second orders) and 0.4.

Coating	Flux at 600 Å with 10^{13} photons/cm^2/sr/s (counts/pixel/s)	Flux at 1200 Å with 10^{13} photons/cm^2/sr/s (counts/pixel/s)
Au	40	40
Ir	54	35
Pt	70	45
Si (200 Å) + Au	190	185

Fluxes collected by a pixel (0.9 arcsec × 0.8 arcsec) in configuration C. The whole spectral line is supposed to be sampled by a single pixel.

Effective area (3/3)

Despite the large illuminated area (≈100 cm^2), the effective area of a **normal-incidence** configuration is low (≈0.2 cm^2) because of the low reflectivity.

The effective area of a **grazing-incidence** configuration is higher (≈0.4 cm^2) even with conventional metallic coatings.
The area can be maximized up to 1 cm^2 with a different coating (silicon on gold), Fluxes of the order of 200 counts/s on a whole spectral line are expected with 10^{13} ph/sr/cm^2/s.

Thermal load on the telescope

	NORMAL-INCIDENCE TELESCOPE	GRAZING-INCIDENCE TELESCOPE
Primary mirror		
Flux stopped by the tube	8 %	0%
Entrance aperture	133 cm^2	30 cm^2
Illuminated area	97 cm^2	110 cm^2
Thermal load at 0.2 AU	303 W (3.1 W/cm^2)	102 W (0.9 W/cm^2)
Absorption at 0.2 AU	Au: 64 W (0.7 W/cm^2) Ir: 103 W (1.1 W/cm^2)	Au: 19 W (0.2 W/cm^2) Pt: 34 W (0.3 W/cm^2) Si: 22 W (0.2 W/cm^2)
Secondary mirror		
Flux arriving on the mirror	70 %	95 %
Illuminated area	16 cm^2	76 cm^2
Thermal load at 0.2 AU	Au: 167 W (10.4 W/cm^2) Ir: 140 W (8.8 W/cm^2)	Au: 79 W (1.0 W/cm^2) Pt: 65 W (0.9 W/cm^2) Si: 80 W (1.1 W/cm^2)
Absorption at 0.2 AU	Au: 35 W (2.2 W/cm^2) Ir: 48 W (3.0 W/cm^2)	Au: 13 W (0.2 W/cm^2) Pt: 21 W (0.3 W/cm^2) Si: 17 W (0.2 W/cm^2)
Plane mirror for rastering		
Flux arriving on the mirror		10 %
Illuminated area		26 cm^2
Thermal load at 0.2 AU		Au: 6.6 W (0.3 W/cm^2) Pt: 4.4 W (0.2 W/cm^2) Si: 6.3 W (0.2 W/cm^2)
Absorption at 0.2 AU		Au: 0.9 W (0.04 W/cm^2) Pt: 1.4 W (0.05 W/cm^2) Si: 1.2 W (0.05 W/cm^2)

Thermal load on the telescope: normal-incidence case

The thermal loads are particularly severe in the **normal-incidence** case: **the secondary mirror absorbs 2.2-3.0 W/cm^2** !

The power absorption is about 16 solar constants for gold and even more for other coatings.

This gives some serious drawbacks:

- the **stability of the coating** and the **deformation of the optical surface** have to be carefully analyzed
- the **dissipation of such an high thermal flux** is very problematic.

CONTAMINATION PROBLEMS

It is well known that under high irradiation, particularly in the ultraviolet, any contaminant deposited on an optical surface polymerizes, so the reflectivity of the surface drastically decreases.

The amount of the effect depends on the irradiation exposure and on the partial pressure of the contaminant.

Even with the tightest procedures in handling and assembling the optics, under the extreme irradiation conditions of the 0.2 AU orbit, there is a risk of a serious rapid degradation of the reflectivity.

Thermal load on the telescope: grazing-incidence case

In the **grazing-incidence** case **the absorption is 0.2-0.3 W/cm^2** both in primary and in secondary.

The power absorption is 1.5-2 solar constants, about three times lower than the absorption in the primary mirror of a normal-incidence telescope**.**

CONTAMINATION PROBLEMS

The degradation of the reflectivity due to the residual contaminants is **much less severe when the optics are operated in grazing incidence**

- the portion of the optics illuminated at grazing incidence is much larger than in normal incidence (for the same aperture) and correspondingly the flux decreases (this is beneficial also for cooling the optics)
- the effect of polymerization results in a much less decrease of the reflectivity than in normal incidence.

Conclusions (1/2)

- **Three configurations for an imaging spectrometer at 1200 Å (600 Å)**
  - **A) normal-incidence telescope and toroidal-grating spectrometer**
  - **B) normal-incidence telescope and VLS-grating spectrometer**
  - **C) grazing-incidence telescope and VLS-grating spectrometer**

- **The high resolution of a double-element telescope is degraded by the single-element spectrometer.**
  - **The lower the subtended angle on the spectrometer, the better the off-axis performance**
  - **VLS gratings can operate at lower incidence angle than toroidal gratings, then they give definitely better performance**

- **From the optical point of view, configuration B is preferable to configuration C. The spatial and spectral resolutions are higher, the field-of-view in the direction perpendicular to the slit is larger, and the off-axis performances are better.**

Conclusions (2/2)

- **The effective area of configuration C is higher even with conventional metallic coatings.**
  - **The area can be maximized with a different coating (silicon on gold), that we are going to test in the near future.**

- **The grazing-incidence configuration is definitely preferable when analyzing the thermal load on the optics.**
  - **The flux on the secondary mirror of a normal-incidence telescope is particularly high (≈70 solar constants)**
  - **It is very difficult to operate the Ritchey-Chretien telescope without degradation of performance in time due to coating degradation and surface contamination**

- **Considering the severe environment of SOLO, we retain that grazing-incidence optics could satisfy the scientific requirements in a more robust and effective instrument.**