SAFARI optical system architecture and design concept

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ABSTRACT

Spic**A FAR** infrared **I**nstrument, **SAFARI,** is one of the instruments planned for the SPICA mission. The SPICA mission is the next great leap forward in space-based far-infrared astronomy and will study the evolution of galaxies, stars and planetary systems. SPICA will utilize a deeply cooled 2.5m-class telescope, provided by European industry, to realize zodiacal background limited performance, and high spatial resolution. The instrument SAFARI is a cryogenic grating-based point source spectrometer working in the wavelength domain 34 to 230 μm, providing spectral resolving power from 300 to at least 2000.

The instrument shall provide low and high resolution spectroscopy in four spectral bands. Low Resolution mode is the native instrument mode, while the high Resolution mode is achieved by means of a Martin-Pupplet interferometer.

The optical system is all-reflective and consists of three main modules; an input optics module, followed by the Band & Mode Distributing Optics and the grating Modules. The instrument utilizes Nyquist sampled filled linear arrays of very sensitive TES detectors.

The work presented in this paper describes the optical design architecture and design concept compatible with the current instrument performance and volume design drivers.

Keywords: far infrared, optical design, grating spectrometer

1. INTRODUCTION

Along with the reconfiguration of the SPICA mission in the last few years, also SAFARI has been redesigned to fully profit from the low background of the telescope and better profit from the achieved high sensitivity of modern Transition Edge Sensor (TES) detectors. The work presented in this paper is a new grating based concept of SAFARI providing unprecedented sensitivity with the TES performance achieved to date. Other former instrument concept descriptions can be found under references [1] and [2].

SAFARI, is a point source spectrometer providing far infrared spectroscopy and high sensitivity. The SPICA mission, having a large cold telescope cooled to 6K above absolute zero, will provide an optimum environment where instruments are limited only by the cosmic background itself. SAFARI is a grating-based spectrometer and will provide two modes of operation, Low Resolution, or nominal (R~300) and High Resolution (R~2000-11000) With this grating based instrument, the sensitivity of the R~300 mode will be about 5×10^{-20} W/m^2 (5σ, 1hr) for a TES NEP of 2×10^{-19} W/√Hz. Under this design further improvements in TES performance will directly lead to better instrument sensitivity [3].

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2. SAFARI KEY REQUIREMENTS

This section summarizes the main optical requirements that can provide the mission scientific goals allocated for SAFARI.

a) The instrument shall provide point source spectroscopy, with diffraction limited capability in four spectral bands over 34-230µm and over a 2'x2' Field of View (FoV) on sky.
b) The four wavelength bands covered by SAFARI are:
   SW - Short Wave, 34-56 µm
   MW - Medium Wave, 54-89 µm
   LW - Long Wave, 87-143 µm
   VLW - Very Long Wave, 140-230 µm
c) Nominal instrument resolution R~300, named Low Resolution Mode (LR).
d) High resolution mode (HR) is obtained by inserting Martin-Puplett in the signal path (R~2000-11000).
e) 3 spatial positions operated in parallel.
f) The instrument includes a beam steering mirror for spatial modulation and to allow efficient mapping.
g) The instrument shall have an optical interface with the SPICA Telescope defined as an incoming beam of F/5.4, 2.5m entrance pupil aperture. The signal will be picked by a pick-off mirror at an off-axis field position.

3. INSTRUMENT BLOCKS DIAGRAM

An optical blocks diagram of the SAFARI instrument is shown in Figure 1.

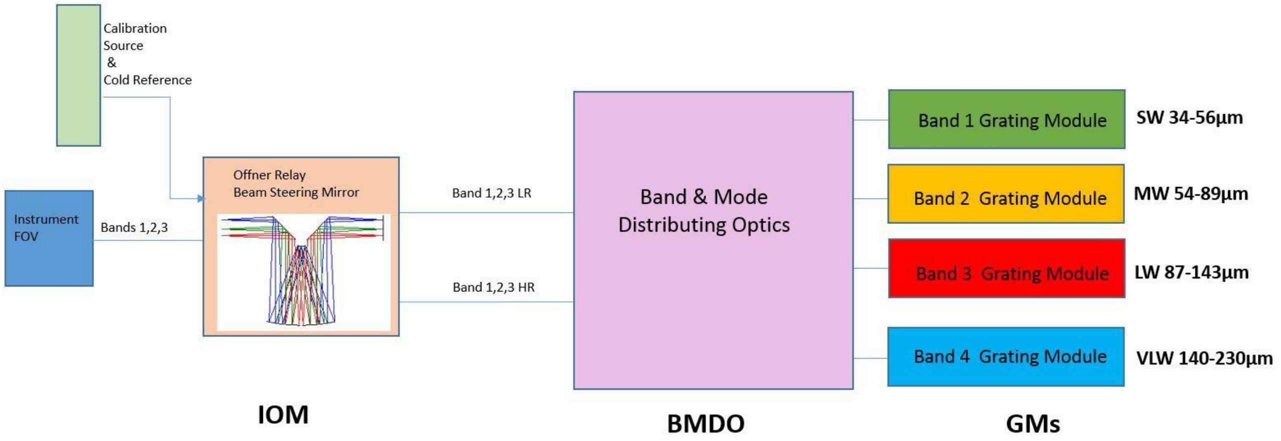

Figure 1. Blocks diagram of the SAFARI Instrument**.**

4. INSTRUMENT UNITS LAYOUT

Figure 2 shows the Instrument Units Layout. As shown in Figure 2, radiation coming from the telescope enters the instrument via the pick-off mirror (POM) and into the Input Optics Module (IOM). The IOM is an Offner Relay of Magnification 1X which includes a beam steering mirror (BSM). After focusing at an intermediate image plane, the radiation enters the Band & Mode Distributing Optics (BMDO), which consists of a set of collimating and focusing optics serving the distribution of bands and modes of operation of the instrument. The BMDO includes a Mode Selector mirror which switches between the two available operational modes. For the high resolution mode the signal is first pre-dispersed using a Martin-Puplett interferometer before entering the grating module, alternative options to achieve this pre-dispersion are being investigated. Also in the BMDO, the radiation bands are split and re-directed to the dedicated grating Modules, four in total, one for each band. The grating modules include a dispersing element which provides the required spectral distribution. The Calibration source radiation (not shown in the figure) enters the instrument at the entrance of the IOM. A dedicated chopping position of the BSM selects the visualization of the calibration sources. The specification of the calibration optics is not fully developed by the time this paper is written.

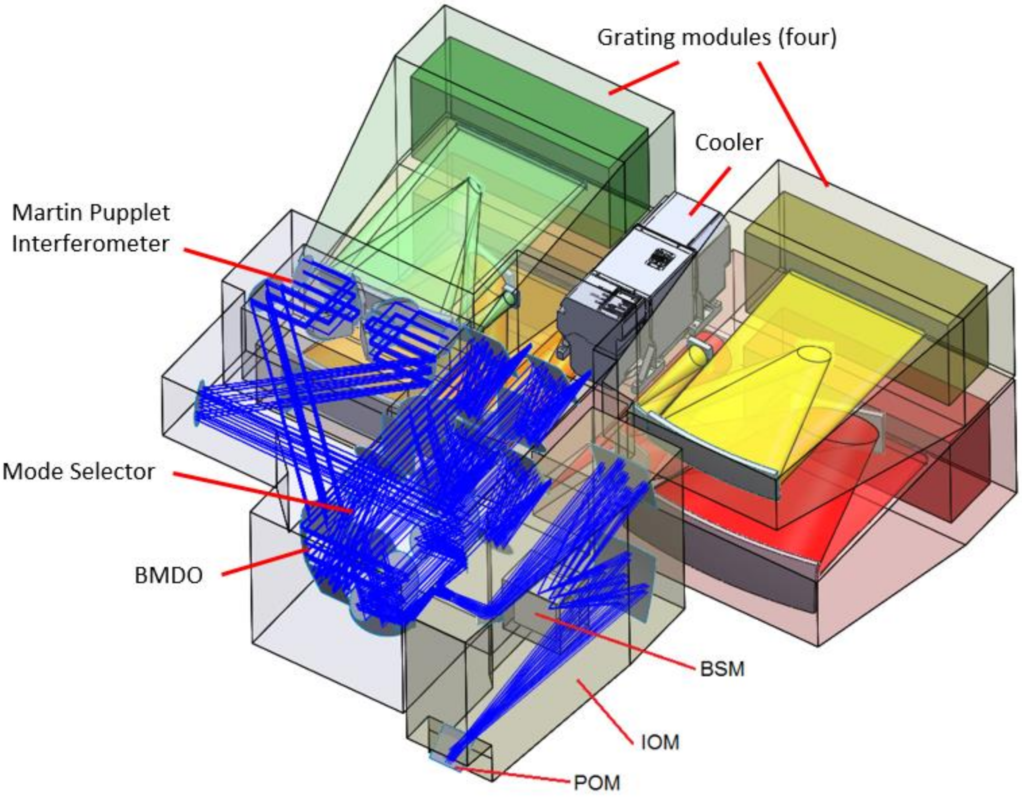

Figure 2. SAFARI Instrument Units Layout.

5. OPTICAL DESIGN DESCRIPTION

The optical design of SAFARI is all reflective (except for the filters, dichroics or beam splitters), and consists of three main optical modules, plus the calibration source optics. The modules represent optical blocks and they are being designed in a modular basis, so that any of them could be individually aligned and/or partially tested. The blocks are named Input Optics Module (IOM), Band & Mode Distributing Optics (BMDO), and Grating Modules (GM).

Each module attends to different optical functions within the whole optical design. The instrument structure including the IOM, BMDO, and mechanisms will be operating at a temperature of 4.5K. The GMs, including the optics, structure and required shielding will be operating at 1.7K. The TES detectors will be operated at 50mK.

The instrument optical concept has been developed based on the one hand, on the requirements derived from the mission scientific goals, and on the other hand, on the boundary conditions set by the satellite. The focal plane architecture and detector current technology are also fundamental design drivers of the SAFARI instrument concept.

The instrument will offer point source spectroscopy in two modes of operation, LR and HR, and for the four wavelength bands stated above. Both modes will allow spatially chopped observations by means of an instrument internal chopper mirror with variable throw; this chopper also is used to alternatively select and pick the signal from the calibration sources into the field of view.

The focal plane sharing of the instrument operational modes is shown in Figure 3

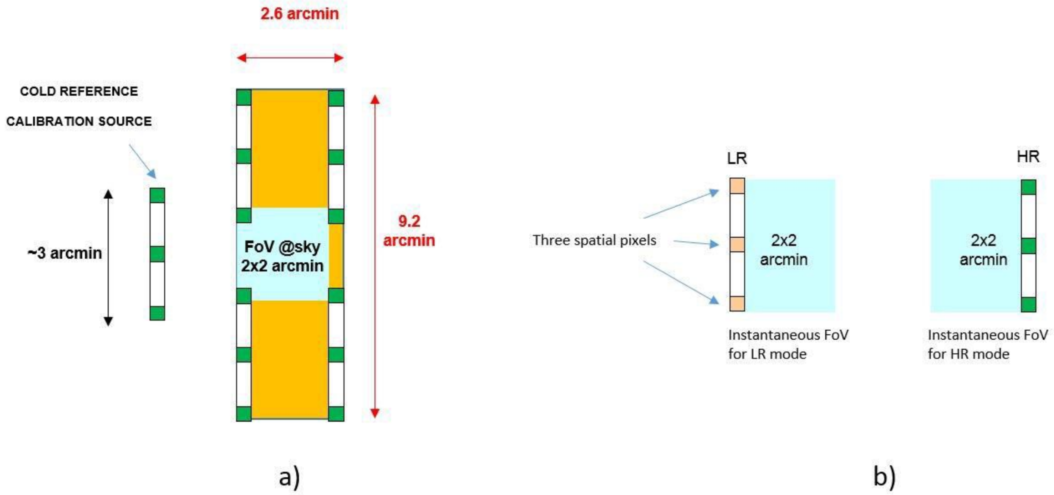

Figure 3. FoV in arcminutes at the entrance of the SPICA telescope

The baseline SAFARI design uses a beam steering mirror (BSM) that forwards the incoming signal through the BMDO and to the dispersing and detection optics. The BSM is used to select sky or calibration signals and forward that to a nominal R~300 (low) resolution optics chain or to a R~2000-11000 (high) resolution optics chain. The low resolution is obtained by dispersion through a diffraction grating illuminating a line of TES detectors. For the high resolution mode the signal is first pre-dispersed using a Martin-Puplett interferometer before entering the grating, alternative options to achieve this pre-dispersion are being investigated. The full 34-230 µm wavelength range is split into four different bands, each with its own dedicated diffraction grating and TES detectors. The baseline design has for each of the bands three separate spatial pixels, to provide background reference measurements, but also to provide some imaging capability. The following sections describe in more detail each module in SAFARI.

5.1 Input Optics Module

The functions of the Input Optics Module (IOM) are to provide:

a) Optical interface with the SPICA telescope at the IOM object space, receiving a beam with an aperture F/5.4, and a telescope focal plane with certain amount of field curvature. The telescope beam is redirected onto the SAFARI instrument via the pick off mirror at an offset of the FoV not determined yet.
b) Spatial chopping of the image in three different spatial positions, to provide background reference measurements, also providing some imaging capability
c) Optical interface with the BMDO Optics which will receive the image of an instantaneous slit-type image of the FoV for each operational mode (LR & HR).
d) A pupil image in transmission at the beam steering mirror.

The IOM contains 7 mirrors including the POM. It consists of 2 common-center powered mirrors, being the primary mirror used as two different off axis sections of the same mirror. This optical layout brings a high level of symmetry into the optical combination and consequently, a high level of aberrations correction. The secondary mirror is the BSM, which is located at a pupil image position and provides the system with a scanning and chopping capability that covers the operational modes needs of the instrument. The input FoV of the IOM is the one shown in Figure 3 a). The output FoV will be a slit-type FoV extension corresponding to the three spatial pixels in one direction and one spectral pixel in the other direction. See Figure 3 b) for a graphical representation of the FoV. The offner relay also makes the system quite compact.

The telescope beam is picked up before the focal plane image which provides internal access to the focal plane, for field stop provision and instrument stray light control. The entrance pupil of the SAFARI instrument is located at the SPICA telescope optical system. The IOM provides an internal and accessible pupil image of the entrance aperture. The IOM is a relay optics system with magnification of about 1X re-imaging the telescope focal plane with F/5.4 to an output image in front of the BMDO with an aperture of F/5.4. In Figure 4, the optics of the IOM is shown.

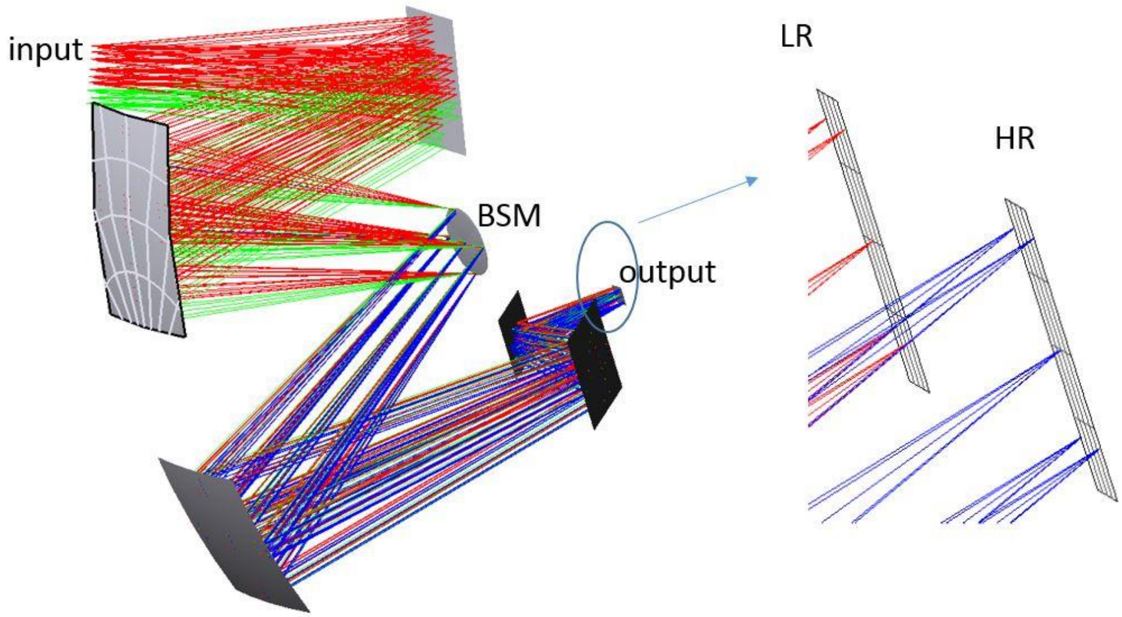

Figure 4. Input Optics Module Layout

5.2 Band & Mode Distributing Optics (BMDO)

The functions of the BMDO are to provide:

a) Optical interface with the IOM receiving a beam F/5.4, and a flat intermediate image in two different slit-type image extensions (see Figure 3 b)).
b) Radiation band splitting into four different bands, by means of dichroics, filters and/or beam splitters.
c) Selection of the operational mode (LR or HR) by means of a Mode Selector Mirror.
d) Optical interface with the four Grating Modules producing a beam F/5.4, and a flat intermediate image in one slit-type image extension, depicting the image of the three spatial pixels by one spectral pixel and to either the LR or HR operational mode.

Figure 5 shows the BMDO optics layout

The two outputs of the IOM entering the BMDO Optics will be first collimated by a collimator mirror (x2, one for each output) and then sequentially filtered and split by the corresponding filters and dichroics dedicated to each band. In this sense, the BMDO will produce four lines of optics corresponding to the four bands. The filter philosophy of the instrument in accordance with the sensitivity budget will determine the sequence and characteristics of the filters and dichroics in the BMDO, optimizing the transmission and polarization distribution scheme of the radiation in this module. The Mode Selector Mirror will select between either the LR or HR modes of operation. When HR is chosen, the Martin-Pupplet interferometer will be operative and the scanning of the OPD will produce the corresponding interferogram and for the desired wavelength band, the desired spectroscopy. The beam is finally focused by a focusing mirror (x4) so that the output consists of 4 slit-type real images, one for each band, which will feed the four grating modules.

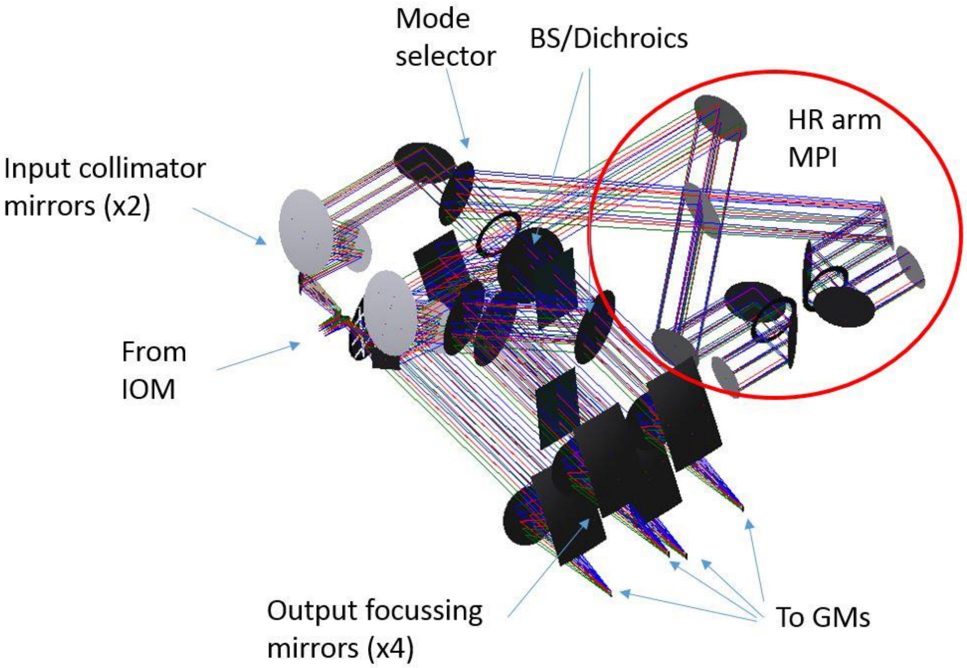

Figure 5. Band & Mode Distributing Optics Layout

5.3 Interferometer Optics

This piece of the optical system will be intentionally selected when operating the High Resolution Mode of SAFARI, being the Low Resolution Mode the nominal operational mode. The HR mode will provide the instrument with a spectral resolving power of R~2000-11000. It can be selected by the Mode Selector Mirror and is part of the BMDO module. See Figure 6 for a layout of the interferometer optics

The optical system is a Martin Pupplet interferometer (MPI) which produces Fourier Transform-based Spectroscopy (FTS).

The use of this type of interferometer, represents a method of interferometric spectroscopy based on polarizing beam-splitters. The modulation efficiency of a metal grid beamsplitter is both high and uniform over a wide spectral range. This allows operation over a wide range of spectral frequency without strong variations in efficiency, and also allows suppression of the mean-level of the interferogram, spurious modulation, which is a major source of error in conventional methods. Martin–Puplett interferometers are set up with two input ports and two output ports. The radiation entering the interferometer is split and polarized in two different paths by the polarizing grid at the entrance of the interferometer. Then the interferometry is achieved by the production of the desired optical path difference (OPD) between both radiation paths and by means of the FTS Roof top mirrors. The optical system also includes the MPI Roof top mirrors in the optical path which retro-reflects and rotate the polarization direction of the beam by 90 degrees. The radiation paths are back to the polarizing grid and finally recombined at the exit of the interferometer.

The configuration of the system produces a folding factor of 8, this meaning that a displacement of Δx in the mechanism will produce an OPD of $8\Delta x$. The concept is then broad band and will serve any of the wavelength bands of SAFARI when operating at the High Resolution Mode. The total stroke of the FTS mechanism will determine the maximum achievable spectral resolution and will be then different for each wavelength band.

The interferometer optics will receive a collimated beam entering the polarizing grid of around 50mm in diameter. See Figure 6 for a layout of the MPI.

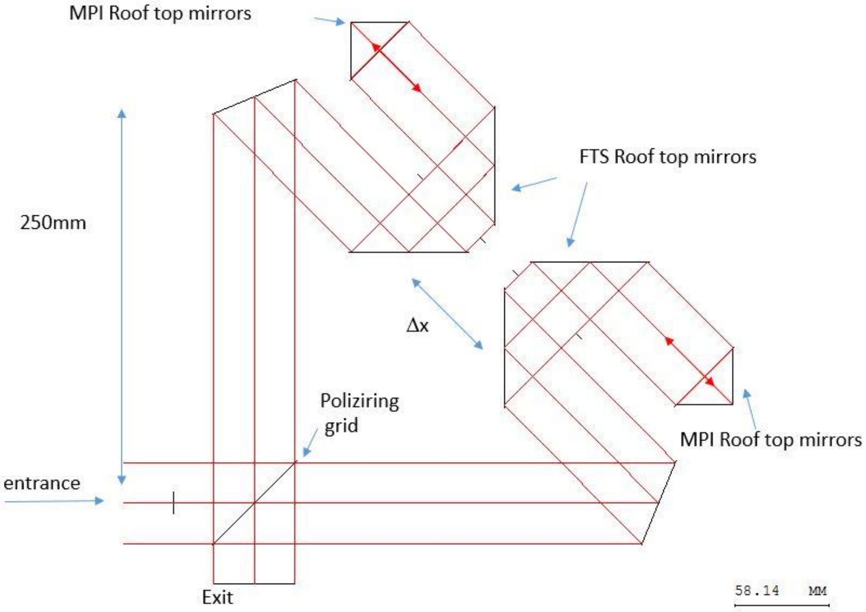

Figure 6. Layout of the Safari interferometer optics (MPI).

5.4 Grating Modules

The functions of the four dedicated Grating Modules are to provide:

a) Optical interface with the BMDO at each of the four output ports receiving a beam F/5.4 at the focal plane of the BMDO, and as a slit-type extension FoV.
b) Provide radiation spectral dispersion by means of a linear diffraction grating and final image onto the detectors for each of the four bands, VLW, LW, MW and SW, at the focal plane arrays (FPA) location, with different final numerical aperture for each band.
c) A pupil image at or near each diffraction grating location.

The final part of the optical train is formed by the Grating Module optics (GM) which starts at a field image in the output of the BMDO. The BMDO provides four output ports as four real intermediate images in a slit-type extension, depicting the three spatial pixels in one direction and one spectral pixel in the other direction. The four modules are very similar in the elements layout. See Figure 7 for a layout of one of the bands GM optical system.

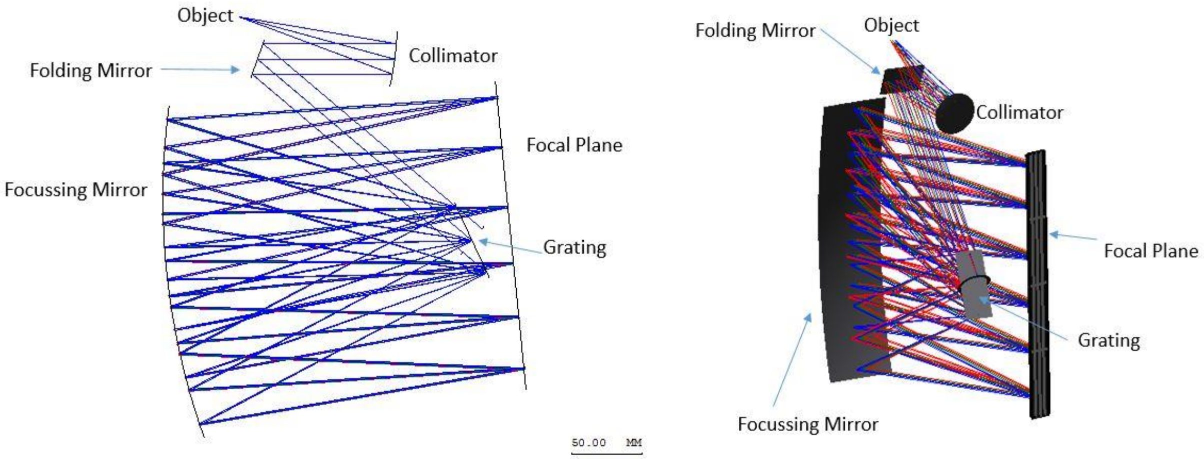

Figure 7. Grating Module Layout

Producing dispersion inherently brings the need of volume allocation in the optical system, being this fact somehow proportional to the wavelength and the desired resolving power. In our case in SAFARI, in the far infrared, the first figures show a quite large instrument. Then, we could say that the key driver in the optical design of the Grating Modules is by far the envelope volume. Sizing the instrument to the interface with the satellite required figures, have been a challenging task and have considerably aimed the Grating Modules design approach. The image sampling and the size of the detector elements are also key drivers in this optical module design.

The main parameters of the optical systems and for each spectral band, are shown in the Table 1, where we can see the current systems parameters corresponding to a pixel size of 1.5Fλ. At the same time, the goal is to keep the physical size of the pixels around 800 µm or larger, as this is a convenient value for the detector manufactures.

Pixel size 1.5Fλ	SW 34-56µm	MW 54-89µm	LW 87-143µm	VLW 140-230µm
Resolving power R min	R227-373 R300 @45µm	R227-373 R300 @72µm	R227 -373 R300 @115µm	R227 -373 R300 @185µm
Resolving element (nm)	150nm	283nm	383nm	617m
Nr. of Spectral points (pixels)	147 (294pixels)	147 (294pixels)	147 (294pixels)	147 (294pixels)
Grating d (µm)/aoi (deg)	38µm/51deg	61µm/51.5deg	110µm/50deg	160µm/60deg
FN coll (spatial /spectral)	5.6/5.9	5.6/5.8	5.6/5.9	5.6/6.2
Focal length coll (mm)	121mm	191mm	357mm	402mm
FN image (spatial/spectral)	17.2/12.8	11.1/7.6	7.1/4.8	5.8/3.1
Focal length cam (mm)	370mm	380mm	460mm	420mm
Pixel size (spatial/spectral) (µm)	1166/805µm	1200/812µm	1216x814µm	1538x803µm
Focal Plane size (spatial/spectral)(mm)	7/239mm	7/246mm	8/247mm	9/251mm
Optics only Volume (mm^3)	320x390x67	322x416x97	430x500x127	530x510x136
Telecentricity (deg)	+4 to -2	+1.7 to -7	+3.8 to -2.6	+4 to-2

Table 1. Grating Modules Optical Systems Main Parameters

The detector manufacturing inputs and the required resolving power have allowed us to make an assessment of the different possibilities that the system could have for the diffraction grating design. We have then studied different configurations for different diffraction grating parameters. The study has assessed and compared the performance and size of the optical systems for different grating figures, in particular the grating period, the grating angle of incidence, and the corresponding diffraction efficiency. In the graphs of the Figure 8, the behavior of the anamorphic ratio, the Total Diffracted Angle /TDA) and the angular resolution are assessed with the band, in order to make known and check the optical system size for a wide range of the grating parameters. This is then an optimizing exercise for which the resulting optimized values are shown in Table 1.

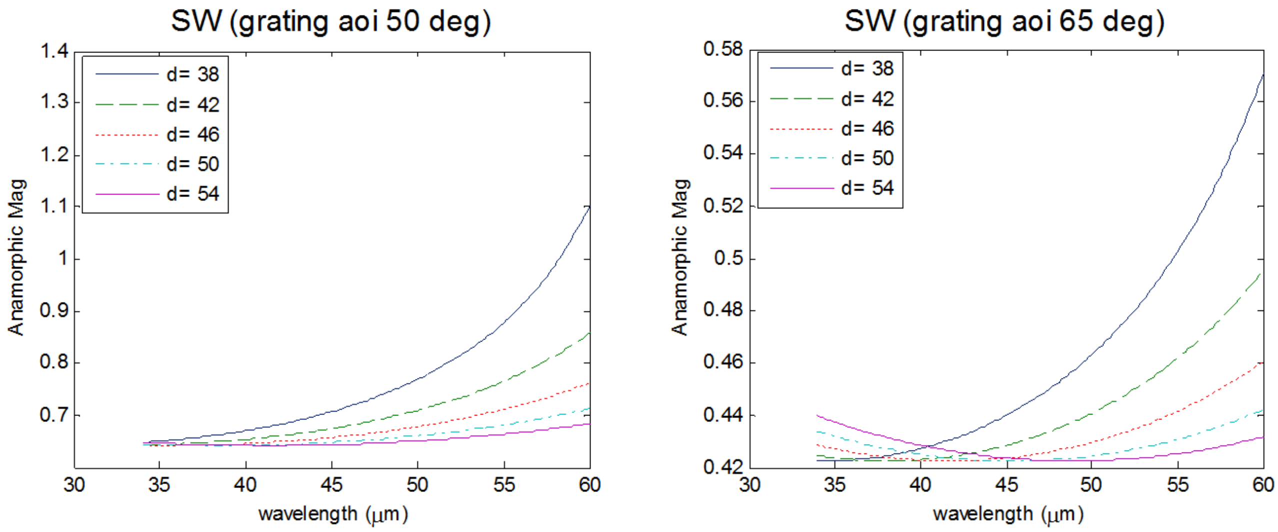

Figure 8. SW band Anamorphic Magnification for different grating constants (d) and different angles of incidence (AOI)

In Figure 8 we can observe how the Anamorphic Magnification varies with the grating constant and the angle of incidence. The anamorphic magnification that comes with the use of a reflection diffraction grating, will nominally produce an elliptical PSF of a point signal, and it will then condition the rectangular shape dimensions of the pixels at the focal plane, so that they match the PSF elliptical shape. In Table 1 we can observe that the different solutions bring different pixel rectangular dimensions, corresponding to the different anamorphic ratios in each band.

Other parameters that have a strong influence in the system volume are the total diffracted angle and the angular resolution, both referred to the focusing mirror in the grating module optical system. For a given grating period and AOI, the dispersed beam in each band, will cover a given total diffracted angle. At the same time and due to the required resolving power, the spectral resolution element will cover an angle which is the limiting resolution angle that our optical system should provide.

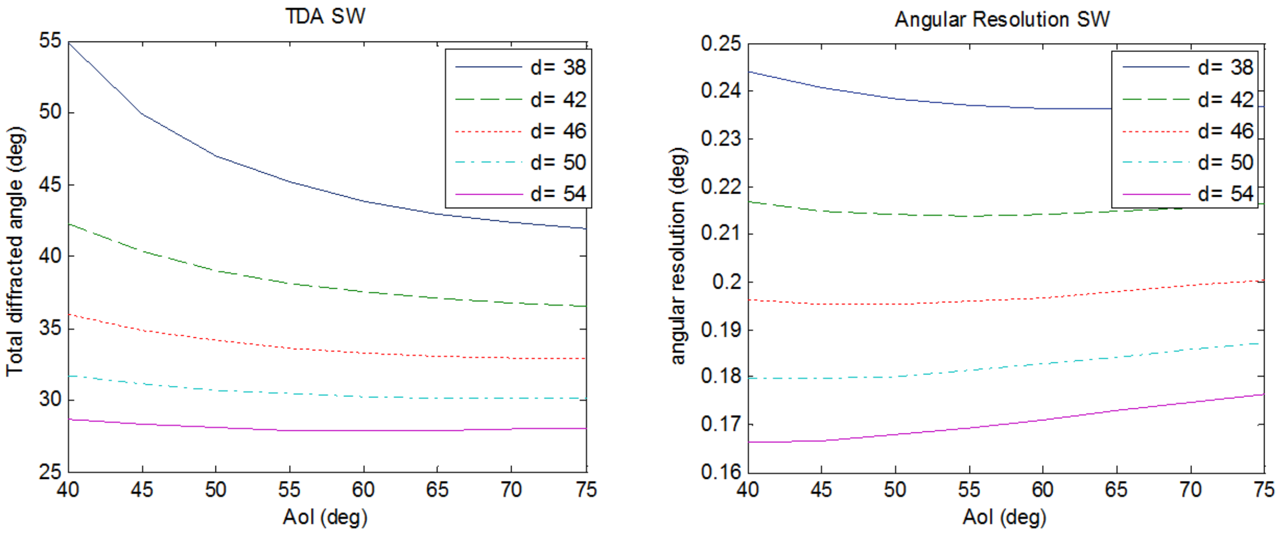

Figure 9. Total Diffracted Angle and Limiting Angular Resolution for the GM Optical System

In the graph on the left in Figure 9, we can observe that smaller grating periods (d) bring larger TDAs, and consequently a larger field of view will enter the focusing mirror, and higher corrections efforts would be needed at the optical design level. A larger TDA would then mean a more demanding optical system.

In the graph on the right in Figure 9, we can observe that smaller grating periods bring larger resolution angles, or in this case, less demanding optical systems attending to the aperture of the focusing mirror. As we can see these results show that we should find a compromise for which a given grating period and AOI, represent a system which is reasonably demanding in terms of aperture on the one hand, and in terms of the acceptance field of view on the other hand. Our aim has been to find an optical system compact enough for our requirements and optically correctable in terms of the FoV.

6. ANALYSIS OF THE GRATING DIFFRACTION EFFICIENCY

A diffraction grating is characterized by the direction of the diffracted beam and by its efficiency (DE) or the ratio of power in each diffraction order relative to the incidence power. While the direction of the beam depends only on the period of the diffraction grating and the material parameters, the diffraction efficiency additionally depends on the physical profile of the grating.

The spectrometer covers the wavelength range from 34µm to 230µm in four bands (SW 34-56µm; MW 54-89µm; LW 87-143µm and VLW 140-230µm). It forces to define four different metallic gratings, one for each channel.

Diffraction gratings has been optimized with GSolver software (Fourier modal method) that is a full vector solution of the diffraction grating problem for arbitrarily complex periodic grating structures [4]. A sawtooth profile is optimized for all gratings with an Aluminum substrate and a different coating (Au, Cu) is used for each grating (See Figure 10) The Drude model is used to estimate the metals index of refraction in the infrared region.

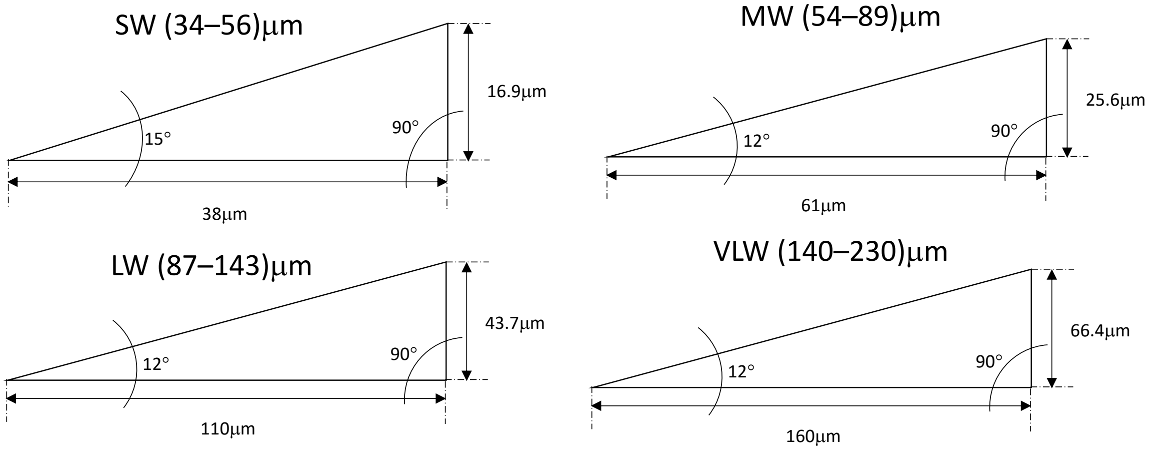

Figure 10. Sawtooth profiles of the gratings

The electromagnetic theory is applied to the grating medium with the corresponding boundary conditions. The analysis is robust for all polarization types and reconstruction conditions. In our case, the efficiency in the -1-st reflected order was calculated in TM polarization as a function of the groove height, grating period and angle of incidence (AOI), and the calculated efficiencies are given in Figure 11. The reflected efficiency in the -1st order depends highly on the polarization.

Additionally, a single parameter sensitivity analysis has been analyzed. The results show that the AOI and grating period are not critical to achieve 90% of efficiency. Groove height sensitivity analysis shows that a ±5µm represent a 10% of DE decrement as can be seen in Figure 12. Depth seems to have a high influence for SW and MW bands.

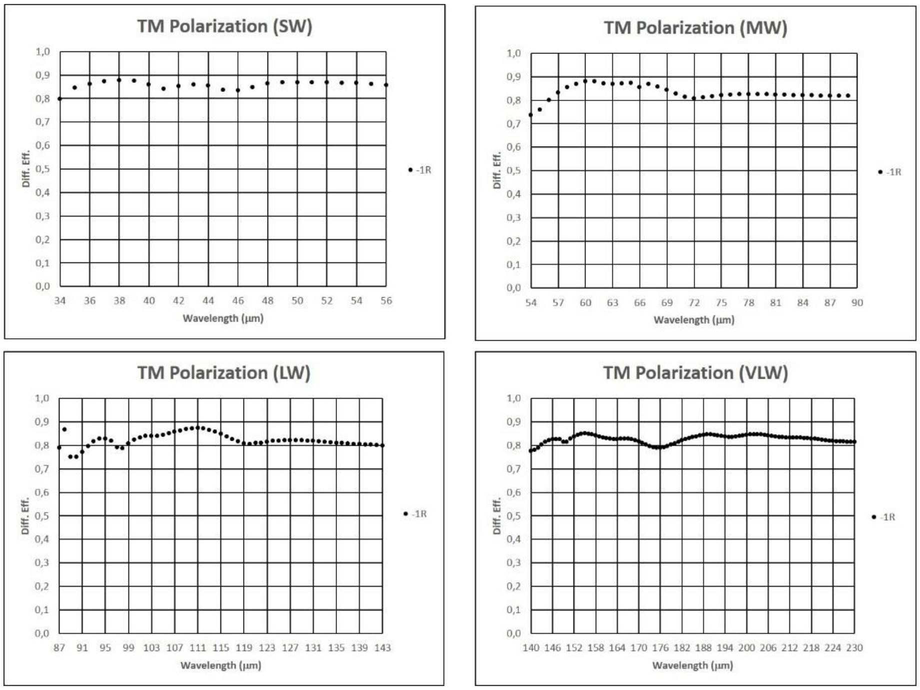

Figure 11. Diffraction efficiency vs Wavelength for each grating. They are optimized for TM polarization

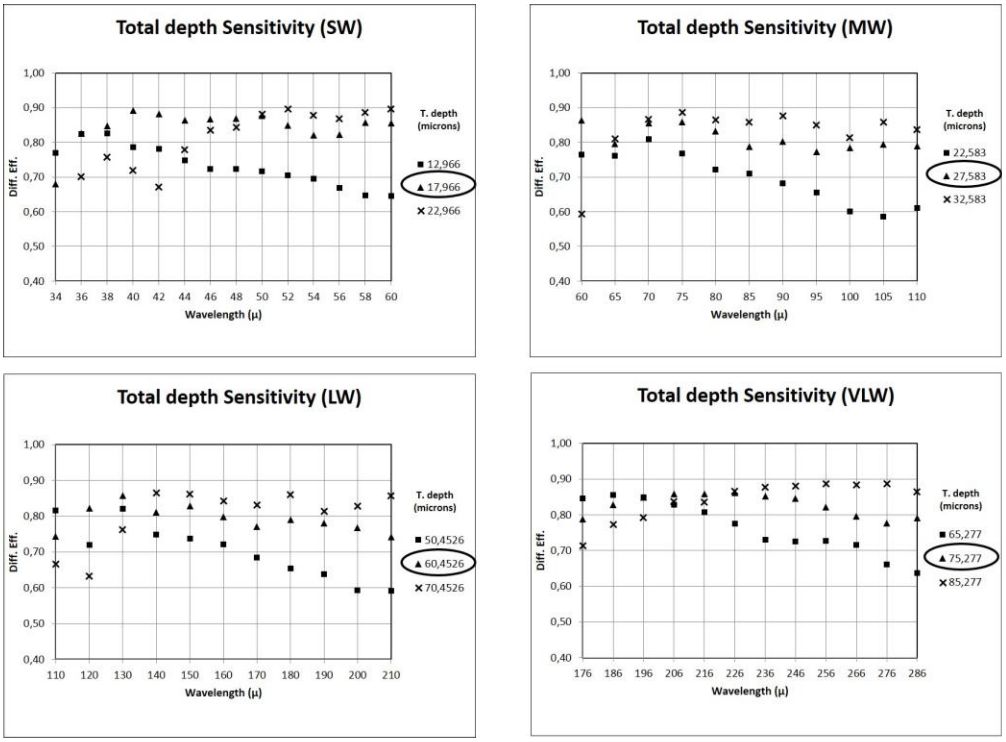

Figure 12. Groove height sensitivity analysis for all metallic gratings.

7. CONCLUSION

A new concept of SAFARI has been studied and developed in a conceptual level. The optical solution responds to the main instrument requirements, being the packaging exercise still on-going.

The optical solution only represents a modelization of the elements in the SAFARI GM-MPI instrument, so that studies involving Interference, Beam propagation, Straylight or Polarization simulations have not been performed by the time this paper is written.

End to end optical performance is limited by the grating modules optics performance, being the IOM and BMDO highly diffraction limited. Further optimization is still foreseen for all the optical design modules.

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