SPICA Telescope

Assessment study

Executive report

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The validations evidence are kept through the documentation management system.

1. INTRODUCTION

In the frame of ESA Cosmic Vision assessment study, Thales propose a 3.5m diameter Ritchey-Chretien telescope in HB-Cesic ceramics. The evaluation of it's performances demonstrate that the proposed design perfectly fulfils the mission requirements.

The objective of this paper is to provide to the reader an overview of the telescope design and performances of the HB-Cesic SPICA Telescope. The development plan is also addressed. It has been established to minimize risks and schedule. The last point is a sensitivity analysis to pupil diameter reduction: an interesting way to further reduce development schedule.

2. SPICA MISSION OVERVIEW

SPICA is an infrared observatory developed by the Japanese Space Agency JAXA, in cooperation with ESA. This mission is a follow-on of ISO[1] and Herschel[2] , developed for ESA by Thales Alenia Space.

SPICA, with its 3.5 m diameter cryogenically cooled (<6K) telescope, is optimized for mid- and far-infrared astronomy. Because of its high spatial resolution and unprecedented sensitivity, SPICA can address a number of key problems in modern astrophysics, ranging from galaxy and star formation, history to formation of planets and detection of exo-planets.

The ESA contribution to SPICA mission, mainly entailing the provision of the cryogenic telescope, the SAFARI instrument and support to ground segment, is an M-class candidate in the Cosmic-Vision 2015-2025 Plan

The spacecraft is composed of a hot Service Module (SVM), in charge of power management, data handling, attitude control and interface to the launcher. The payload module (PLM) is interfaced to the service module via a truss, which decoupling thermally the two modules .

The PLM includes the large telescope (STA) , an instrument optical bench (IOB) holding the instruments at telescope focus, and radiative shields which protects the telescope and instruments from the Sun, maintaining them cold. Active telescope and instruments cooling is achieved by a two stage Stirling cooler, coupled to a Joule-Thomson compressor.

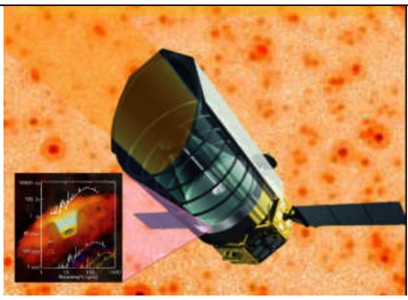


Figure 2-1: SPICA S/C, artist view
This figure illustrates how the large telescope is encapsulated in the payload module shields and baffle. This provides a very cold and stable environment to the telescope

Figure 2-2: Overview of the telescope.
The telescope is composed of HB-Cesic mirrors and structure. This homogeneous ceramic architecture is perfectly suited for diffraction limited image quality in cryo.

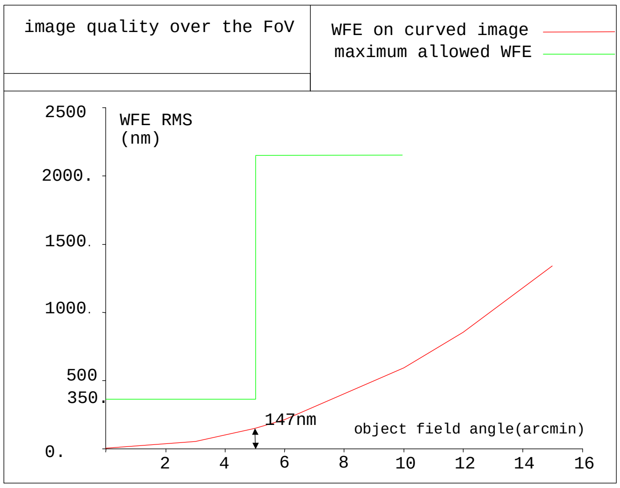
3. SPICA TELESCOPE MAIN REQUIREMENTS AND DESIGN JUSTIFICATION

The main requirements, presented in this section, are the design, performance and development drivers of the SPICA Telescope Assembly.

The telescope is a Ritchey Chrétien, working between 5K and 10K. It's primary mirror (M1) has diameter of 3.5m, and its focal length is 20m. This large size drive the material selection to be HB-Cesic, for the mirrors and the structure, the tests configurations and the schedule. It's circular FoV has a minimum radius of 12arcmin

Optical performance shall be diffraction limited, at 5µm wavelength over a 5arcmin radius Field of view, and at 30µm wavelength over a 10 arcmin field of view. Shortest wavelengths instruments, like the coronagraph, are located at the field center, while long wavelength instrument like SAFARI are located on the side of the telescope FoV. Because of the astigmatism inherent to the Ritchey-Chretien configuration, the driving FoV is at 5 arcmin. Image quality requirements drive the material selection, the development plan, and the optical tests configuration

Like ISO (and contrary to Herschel), SPICA observatory is background limited. To keep this key performance, straylight level at telescope focus shall remain below 20% from unavoidable zodiacal background. This drives the baffles and quadripod legs design, the pupil position, and telescope cleanliness until end of life. Placing the pupil on the secondary mirror, like Herschel, enables a better interface to instruments, and also mitigates the risk from unexpected straylight coming from M1 surroundings. The quadripod legs, providing to the PSF a 4 axis symmetry, is favorable to the coronagraph performance (compared to a classical tripod).



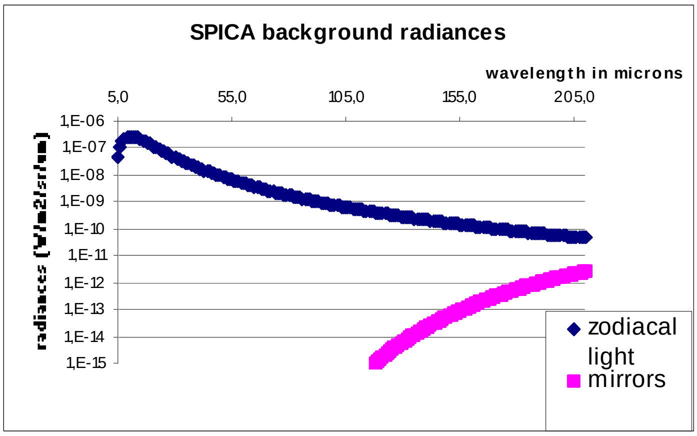


Figure 3-1: WFE theoretical value is driven by astigmatism. Background is dominated by zodiacal like, like ISO.

The telescope shall remain below 10K, with a cryo-cooler at 5K+/- 0.5K. This is the key requirements to achieve low background ,and thus high sensitivity. In order to be compatible with instruments chopping, gradients in the pupil shall be below 0.5K at operational. These thermal performance requirements drive the structure material choice, the HB-Cesic having a quasi null CTE between 100K and 5K, and the passive thermal control design.

Maximum telescope mass is 700kg, including 20% margin. Here again, the HB-Cesic stiffness and lightweighting capabilities is the best material for such a low mass. Its Eigen frequencies shall be

- larger than 30Hz lateral and 70Hz axial, when mounted on a rigid support
- Larger than 18Hz lateral and 36Hz axial, when mounted on the SVM truss

The interfaces, namely the service module (SVM) truss (8 points on a 2700mm diameter circle) and the instrument optical bench (IOB) bipods (6 points on a 1700mm diameter circle), drive the telescope optical bench design.

In principle, the instruments could have been directly interface to the telesopce optical Bench. However, the presence of a specific IOB, holding all the instruments, secures the overall design and development approach.

A 3 degree of freedom mechanism, enables an adjustment of the secondary mirror in axial translation (for focus compensation) and rotation (for coma compensation).

The following figures explains how the main requirements are derived, by trade-offs, to the main design features:

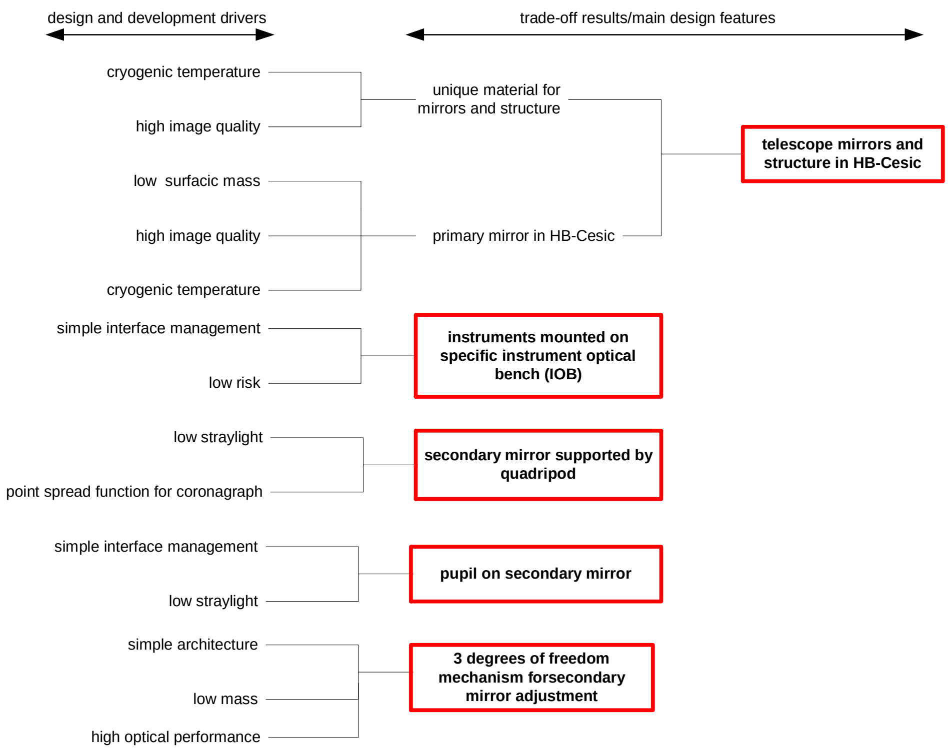


Figure 3-2 design trade-offs logic.
starting from driving requirements, early trade-offs enable to define the optimum design features of the SPICA telescope

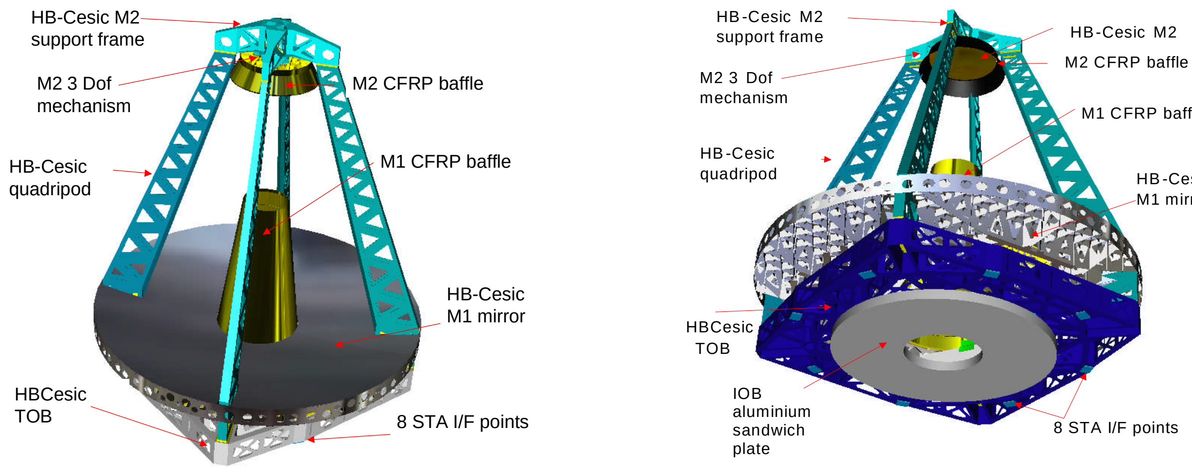


Figure 3-3 telescope and instrument optical bench (IOB) views, without SLI.
HB-Cesic unique material properties enable to build a smart lightweight telescope structure.

4. HB-CESISC, THE BEST MATERIAL FOR SPICA

HB-Cesic unique material properties and manufacturing capabilities make it the ideal material for the SPICA telescope mirrors and structure.

4.1 HB-Cesic material properties

HB-Cesic has very good mechanical properties, as listed in the next table

Mechanical Property	**Value**
E modulus	350 Gpa
Density	2.98
Strength	320Mpa
Damping	1.5 to 2%

Table 4-1 HB-Cesic high mechanical properties are ideal for large space mirrors.

HB-Cesic manufacturing properties are attractive as well:

HB-Cesic monolithic blocks can be manufactured up to a 4m size. This enable have homogeneous thermal extension on a single block. For the primary mirror, this is of major importance to ensure a low deformation at cryogenic temperature, and hence a good telescope image quality.

HB-Cesic can be polished down to a few nanometers, without cladding layer. This avoids the bi-metal effect at cryo between cladding layer and substrate, which would lead to surface shape change at cryogenic temperature.

Very thin ribs, typically 1.5mm/200mm can be manufactured, leading to a very good mass/stiffness ratio.

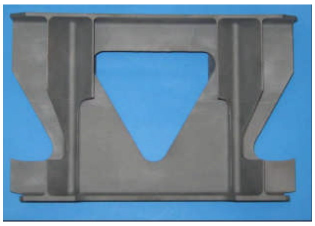


Figure 4-1 pictures from manufactured representative ribs: 1.5mm thick, 200mmheight. Skin thickness is 3.8mm. These ribs demonstrate the capability to manufacture the mirror stiffeners.

5. SPICA TELESCOPE DESIGN

The proposed SPICA Telescope design is the result of extensive trade-offs on material, architecture and interface accommodation, with the objective to reach the performance requirements with low development risks. This low risk is reached by maximizing the heritage in the design, performing detailed analysis already in phase 0, and including design margins in the critical areas.

5.1 optical design

Ritchey Chrétien optical design is the best on-axis two mirrors configuration. The design parameters (focal length, back focal length and inter-mirror distance) are chosen to be compatible with PLM interfaces (shadow from the baffles and instruments accommodation). Straylight prevention is a key element of the optical design, including baffles and quadripod legs shaping (ISO like).

The SPICA telescope has the following optical characteristics:

- stop is on M2, and entrance pupil diameter 3300 mm
- Focal length 20m
- Back focal length (distance between M1 vertex and focus) 828mm
- FoV angular radius 15arcmin
- Inter-mirror distance : 2986mm

Straylight prevention features are a key element in the telescope design. Thales benefits from a strong heritage in this domain, for Earth observation payload to Planck and Herschel. ESA Infrared Space Observatory (ISO), developed by Thales, had the same wavelength domain as SPICA and was also zodiacal light limited. Thanks to proper design prevention features, similar to what is proposed for SPICA, ISO successfully meets the performances in flight..

M1 and M2 baffles are classically sized to avoid direct illumination of the focal plane by out-of-field-of-view sources. Baffles are coated low emissive on their external side to limit radiative exchange with outer baffle, and temperature increase. They are black painted internally, to limit the specular reflection from zodiacal light and outer baffle, respectively at short and long wavelengths.

Quadripod legs are covered by single layer insulation (SLI) to limit their self emission, and are shaped with angles, in order to reject the specular reflection from outer baffle and natural sources outside the instruments field of view.

In addition, instruments working above 70µm wavelength shall be equipped with a cold stop, which is classical at such wavelength (Herschel-like).

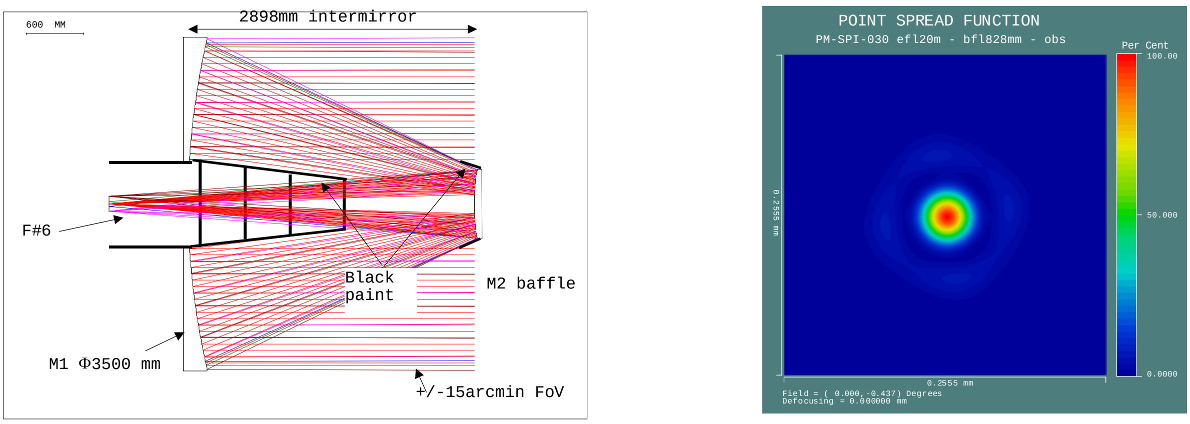


Figure 5-1 The compact Ritchey-Chretien design is the best configuration for imaging quality and accommodation into the payload. Straylight prevention features, like baffles (black painted in their internal side), vanes, and quadripod legs shaping, limit the straylight reaching the focal plane. On the right, the quadripod impact on PSF side lobes symmetry is visible (side lobe peaks at 5% from PSF maximum).

5.2 mechanical design

Mechanical design is based on homogeneous material telescope, mirrors and structure being in HB-Cesic. HB-Cesic mechanical and manufacturing properties make it perfectly suited for SPICA mission. Moreover, ECM heritage on ceramics and especially HB-Cesic , combined with Thales heritage on high resolution telescopes guaranty an optimum design of mirrors and structure, in view of meeting requirements with margin.

The telescope structure is made out of only 3 elements:

Telescope optical Bench, holding the quadripod, and the primary mirror, via 3 isostatic mounts, the telescope optical bench also has the interfaces to the payload truss and to the instrument optical bench, The quadripod structure,

The M2 support structure, linking the 4 quadripod legs and holding the M2 assembly (mechanism and mirror)

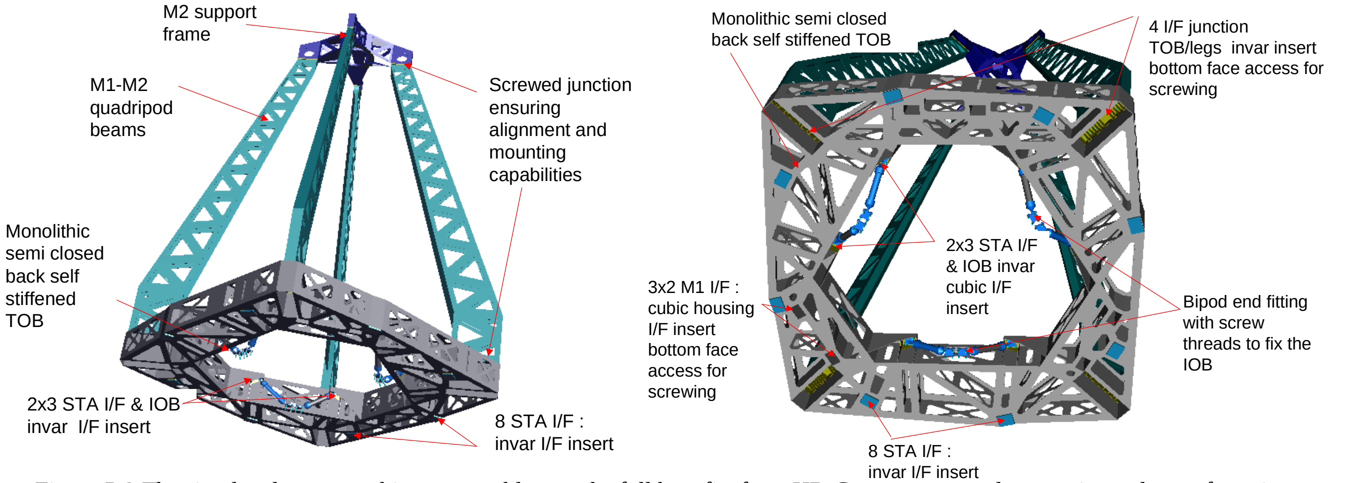


Figure 5-2 The simple telescope architecture enables to take full benefits from HB-Cesic mechanical properties and manufacturing capabilities.

The mirrors design has been optimized versus mass, stiffness, and optical quality (low quilting). Three isostatic mounting devices (MFDs) have been designed, to withstand launch loads, while still being soft enough to minimize interface loads, form integration and cryo-temperature.

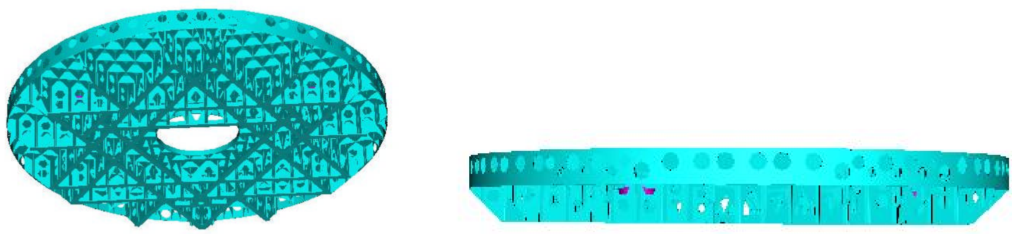


Figure 5-3 This benefits from the large Thales heritage in optical telescope design and realization. Primary mirror mass (with MFD's) is only 240kg (25kg/m2), with Eigen Frequency above 95Hz.

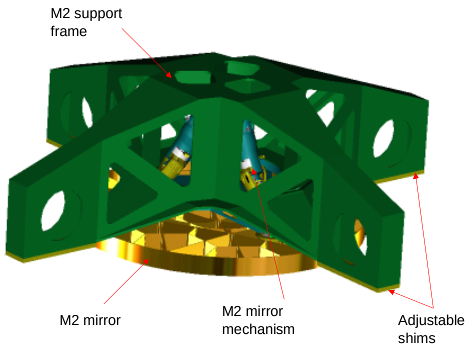
M2 design is very similar to the already manufactured Ultra-light mirror (ULT). Mirror weights only 6kg (17kg/m2)

Figure 5-4 as designed M2 rear face as manufactured HB-Cesic ULT mirror

5.3 Secondary mirror mechanism

The mechanism is eld by the mirror support structure. The simple architecture is based on 3 linear actuators.

It provides piston movement for focus rotation, and pure rotation around the mirror vertex.



5.4 Thermal design

The thermal design is based on a maximization of radiative decoupling from the surrounding outer baffle, at 11K, and thermal straps, internal to the STA linking the cold finger interface bracket on TOB (at 5.3K) to the M1 fixation devices.
The thermal passive control is driven by three concurrent constraints :

1. decouple radiatively the STA from the outer baffle at 11K and shell at 20K, in order to minimize heat flux to cooler,
2. have only low emissive surfaces seen by instruments, in order to lower the straylight by self emission,
3. minimize gradients for scientific performance.

These three objective lead to isolate the telescope structural part by low emissive kapton foils, as single layer insulation (SLI). SLI covers the quadripod legs, the M2 support structure, and a SLI tent encapsulates M1 edge, M1 back face and telescope optical bench.

Thermal straps (copper) are also implemented inside the telescope, to optimize the conductive link between the mirrors and the cold-finger. They are implemented
between the cold finger interface on the TOB edge and the top of M1 fixation devices,
between the M2 support structure ad the M2 triangular platform, shortcutting the M2 mechanism.

Thanks to HB-Cesic high conductivity, there is no need of thermal straps between the cold finger interface and the M2 support structure.

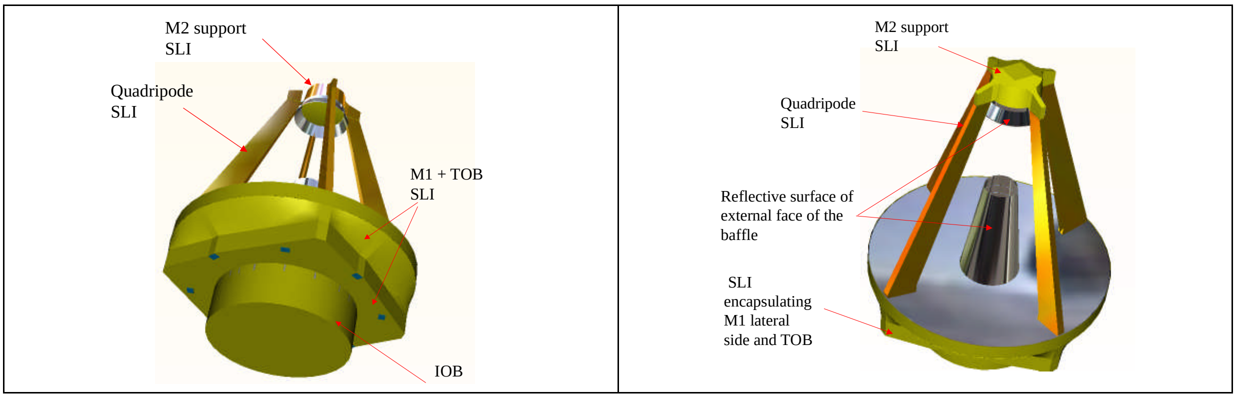


Figure 5-5 The telescope structural elements, present a low emissive surface to the surrounding environment, to maximize the decoupling.

6. SPICA TELESCOPE PERFORMANCES

The SPICA telescope has been designed in order to meet all the performance requirements. An extensive modeling and analysis have been performed to justify this compliance, including margins, covering future refinement of the design and interfaces. These analysis justify that the proposed design based on HB-Cesic material is perfectly suited for SPICA mission.

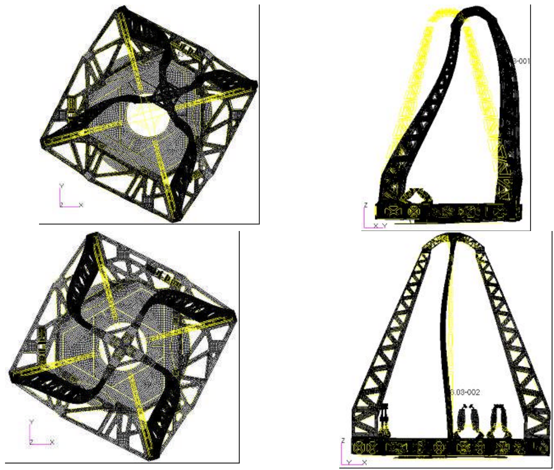
6.1 Mechanical performance.

The overall telescope mass budget is at 700kg, including 20% margin.
This mass is from CAD model, and confirmed by the finite element model. This fits to the payload needs.

First Eigen Frequencies are compliant with margin to the payload needs:

- 48Hz lateral, above the minimum 30Hz required
- 70Hz longitudinal, above the minimum 60Hz required
- 38Hz lateral, above the minimum 30Hz required

Strength evaluation also exhibits positive margin, including a safety factor of 3 for ceramic parts.



6.2 Optical performance

Image quality

WFE budget is built, considering load cases coming from theoretical performance, manufacturing (polishing), assembly integration and tests accuracy, and loads from the structure, mainly thermo-elastic loads from cool-down, and interface loads from the payload supporting truss and the instrument optical bench. Classical RSS summation rule is applied.

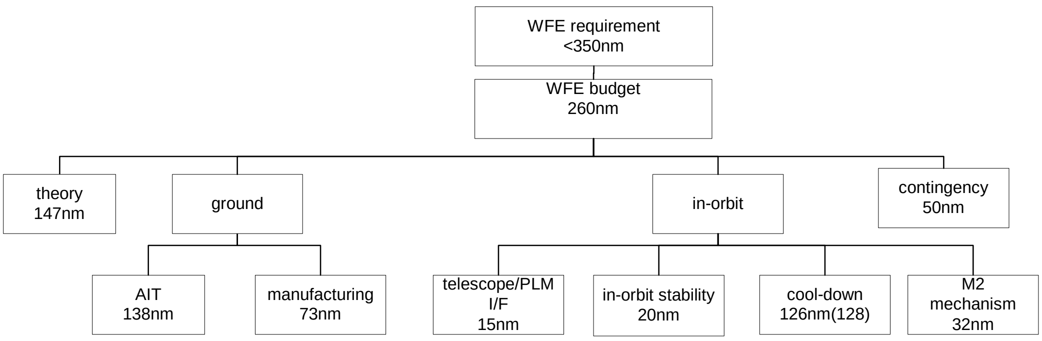


Figure 6-1 WFE budget meets the requirement with margin. The effect of interface loads from IOB and SVM truss are included. The margin comes from the fact that mirrors polishing accuracy is driven by high frequency errors for the coronagraph

Medium and high frequency requirements for coronagraph are also met, with respectively 90nm RMS and 42nm RMS. This is mainly due to the accuracy to which the monolithic primary mirror can be polished.

Straylight

The key requirement for straylight is that the observatory shall remain background limited. Straylight, coming from observatory elements and reaching the telescope focal plane shall thus remain below 20% from zodiacal background.

Thanks to the straylight prevention design features presented above, the straylight level remains below 10% from zodiacal light, as shown in the next picture.

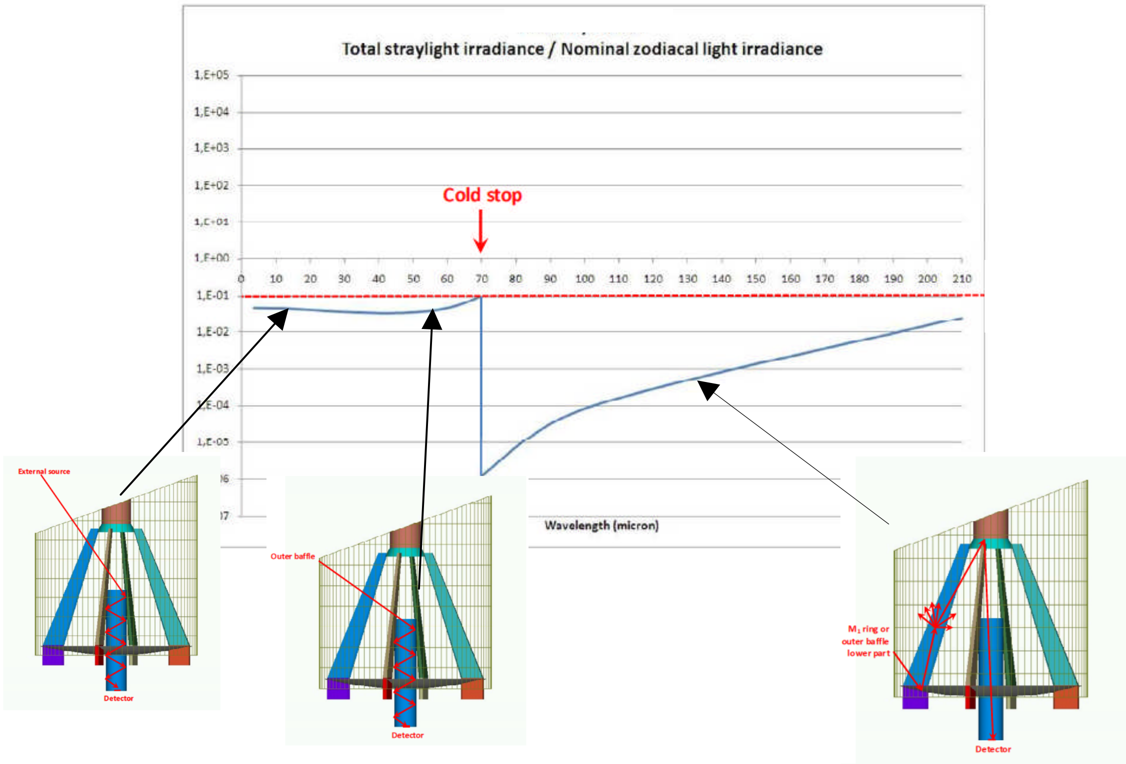


Figure 6-2 straylight rejection performance

Thanks to design optimization and cold stop in instruments working above 70µm wavelength, the straylight rejection of the telescope meets the requirement (horizontal red dashed line) of straylight level below 10% of unavoidable zodiacal light

The driving mechanism depends upon wavelength:

- short wavelengths are driven by zodiacal light, scattered inside the M1 baffle
- medium wavelength (between 30µm 70µm) are driven by outer baffle self emission, scattered inside M1 baffle
- large wavelength performance is driven outer baffle self emission, scattered by quadripod legs.

6.3 Thermal performance

The thermal model predicts a maximum temperature of 6K on the telescope, and a maximum gradient of 0.2K, well in line with science needs.

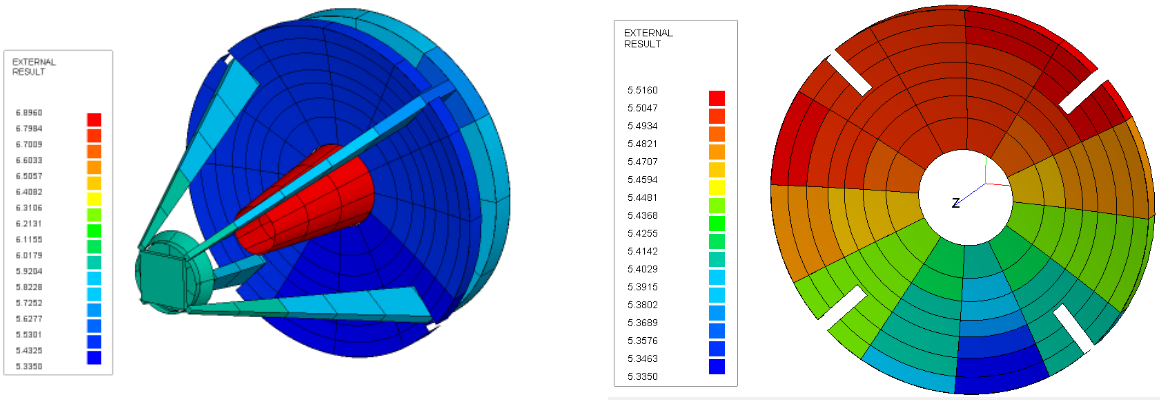


Figure 6-3 temperature distribution on the STA, and gradients on M1

Thanks to perfect decoupling of the STA from its radiative environment, temperature of 6K maximum is reached on the optical and structural elements, which is well in line with the scientific needs

7. DEVELOPMENT

After selection within the Cosmic Vision programs, early 2010, phase A/B1 will be led until end 2011. In parallel to this study phase, technological development activities (TDA) will tackle the main technological open points, breadboarding the primary mirror and an actuator of the refocusing mechanism. The objective of these activities is to have a technology readiness level of 5 by the end 2011. The results of the TDA will feed the implementation phase.

Implementation phase will then start by mid 2012.

The telescope development has been optimized considering Thales Alenia Space heritage in cryo-optical Payloads (ISO, Herschel, Planck) and HB-Cesic structures and mirrors design, ECM heritage in HB-Cesic manufacturing, and CSL heritage in cryo-optical tests.

SPICA Telescope could be delivered in 2016 to ESA/JAXA, M1 manufacturing/polishing/coating being on the critical path.

8. CONCLUSION

In this paper, we describe the HB-Cesic SPICA d the baseline design and performances.

SPICA telescope design is optimised versus the driving requirements. HB-Cesic ceramic is found to be the best material telescope structure and mirrors. Its provides high mechanical performances and quasi-optical image quality at cryogenic temperature.

In depth analyses of the key performances show the compliance of the telescope for optical, mechanical and thermal performances.

Thales Alenia Space have a full commitment to support ESA and JAXA in the future SPICA telescope development.

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[2] Pilbratt, G., "Herschel mission overview and key programmes," Proc. SPIE 7010, (2008)