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Telescope Assembly Assessment Study

Executive Summary Report

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SUMMARY

This document corresponds to the executive summary report of the SPICA Telescope Assembly assessment phase study.

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1 INTRODUCTION

SPICA (**S**Pace **I**nfrared telescope for **C**osmology and **A**strophysics) is a JAXA led astronomical mission. The ESA contribution to the SPICA mission, mainly entailing the provision of the cryogenic telescope assembly, is a M-class candidate in the Cosmic Vision 2015-2025 Plan.

The Cosmic Vision Plan is intended to elaborate and implement the future ESA science missions through an open competitive process involving the science community and within ESA Science Directorate programmatic constraints. The Cosmic Vision 2015-2025 Call for Mission Proposals was issued by ESA in March 2007 and aimed at defining one Medium class mission (M mission) and one Large class mission (L mission). Following this Call for Missions, five new M missions, one of which being SPICA, have been recommended by the Space Science Advisory Committee (SSAC) for further assessment.

These candidate M missions entered a competitive process according to the following schedule :

- Assessment Phase in 2008-2009 and down selection of two M-class missions in 2009
- Definition Phase completed by 2011 for the two M missions
- Adoption of one M-class mission by end of 2011 and Implementation Phase

This document provides a summary of the work performed from August 2008 to september 2009 as required by the European Space Agency (ESA) in the contract for an “Assessment study of the SPICA Telescope Assembly”.

2 SPICA MISSION

SPICA, with its 3.5 m diameter cryogenically cooled telescope, is optimised 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 starformation history to formation of planets and detection of exoplanets.

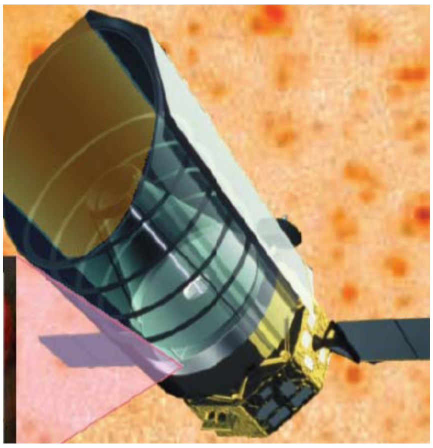
The most important characteristics of the mission is that its telescope is cooled down to 5K, hence the mission is suitable for mid to far infrared observations. A warm launch, cooled telescope design concept (i.e. the telescope and focal plane instruments are “warm” at launch but are cooled in orbit) is baseline for SPICA. The “warm launch” reduces the total size significantly and enables the payload fairing of the H-IIB rocket to accommodate a telescope with a 3.5m primary mirror.

Figure 2-A shows a conceptual design of the SPICA mission with a configuration so that it does not employ a deployable mirror design, but use a conventional “monolithic mirror” design, in order to make the mission technically feasible and reliable.

The core wavelength range of SPICA (5-210 μm) will be covered with two focal plane instruments : Mid-infrared Camera and Spectrometer and Far-infrared Camera and Spectrometer. The main mission specification, applicable to the SPICA telescope, are synthesized in Figure 2-A.

The second Sun Earth Lagrangian liberation point L2 has been chosen as an orbit for the SPICA observatory-type infrared mission. Furthermore, the easy shielding of telescope from the heat sources (Sun, Earth, Moon) enables to make spectroscopic observations with enough photons.

SPICA adopts an entirely new cooling system with a combination system of radiative cooling and mechanical coolers. Radiative cooling of the telescope, down to 11K, is passively achieved through a set of shields. Then, the Focal Plane Instruments (FPI) and the telescope are both cooled with a 5K mechanical cooler. Last cooling of the Ge:Ga detectors installed within the FPI, is performed by a 1.7K mechanical cooler.



Parameter	*Value*
Reflector Size	3.5 m
T reflector in Space	5 K
T Reflector at Launch	300 K
Core Wavelength Range	5-210 µm (diffraction limited @ 5µm)
Orbit	S-E L2 Halo
Cooling	Radiative cooling & Mechanical coolers
Total mass	3600 Kg
Telemetry rate	30 G-bytes/day
Launch vehicle	H-IIB rocket

Figure 2-A : SPICA mission : conceptual design and main specifications

3 ASSESSMENT STUDY OBJECTIVES AND ACHIEVEMENTS

The main objective of the **S**PICA **T**elescope **A**ssembly (**STA**) Assessment Study was to demonstrate both technical and programmatic feasibility of the envisaged ESA contribution to the SPICA mission, and to define the relevant interfaces to the JAXA led project, i.e. STA to **P**ayload **M**odule (**PLM**) and STA to the **F**ocal **P**lane **A**ssembly (**FPA**) constituted by the **I**nstrument **O**ptical **B**ench (**IOB**) and the **F**ocal **P**lane **I**nstruments (**FPI**). The aim was to achieve a consolidated assembly design to the degree required to enter, if selected, the following detailed definition and implementation phases, including programmatic estimates. In view of obtaining this, the following aspects were achieved during the assessment study :

- Critical analysis of the STA requirements with particular regard to their impact on the telescope performance and programmatic aspects.
- Definition of the telescope assembly design, including related trade-off analysis and further refinement of the selected baseline : characterisation of the optimal optical design and establishment of stray-light rejection performances, mechanical design compatible with launch loads and thermal design including cool-down and de-contamination, mechanism design and feasibility assessment.
- Definition of the relevant interfaces to the SPICA PLM and FPA, including trade-off analysis.
- Demonstration of compliance with the performance requirements with the establishment of the related budgets through polisher assessment, AIT error budgets and thermoelastical analysis.
- Identification of the optimal verification approach through the issue of a preliminary AIV/T plan with the identification of adaptations required to existing test facilities.
- Preliminary risk assessment and identification of technological development and risk mitigation activities
- Preliminary development plan including model philosophy, schedule and cost.

4 MATERIAL AND TECHNOLOGY

An all Sintered Silicon Carbide (SiC) telescope design is proposed for the SPICA Telescope using BOOSTEC silicon carbide material for the two mirrors, the telescope optical bench, the secondary mirror support structure. BOOSTEC Sintered SiC provides excellent optical, mechanical and thermal properties : it is a perfectly homogeneous material, mono phase and isotropic (well predictable behaviour). It behaves perfectly homothetically and without distortions when submitted to large temperature changes from ambient down to cryogenic conditions. The BOOSTEC SiC properties are reproducible and homogeneous in time, from batch to batch. This technology is ready for SPICA telescope development :

- high Technology Readiness Level => 9 obtained through on flight HERSCHEL telescope and Remote Sensing instruments
- a perfectly mastered manufacturing processes : achievement of large size (up to ∅ 3.5m) through HERSCHEL and GAIA programs
- production facilities fully validated & qualified and strict quality control from SiC powder to final SiC piece
- dimensioning/verification processes fully mastered and different assembly techniques over a large temperature range

5 TELESCOPE DESCRIPTION AND PERFORMANCES

5.1 OPTO-MECHANICAL ARCHITECTURE AND PERFORMANCES

The **S**PICA **T**elescope **A**ssembly (**STA**) is a Ritchey-Chrétien telescope composed of a parabolic primary mirror (∅ 3.5 m, f-number of 1) and a hyperbolic secondary mirror (∅ 641 mm, f-number of 1.35). The image quality is optimized on the Cassegrain focal plane, leading to some constraints on instruments optical interfaces and the optical design is improved by asphérisation of the primary mirror in order to correct the coma aberration (remaining aberrations are astigmatism and field curvature). The optical combination characteristics are a focal length of 20 m, an aperture stop on M2, a f-number of 6, an axial magnification of 29. The telescope overall dimensions are ∅ 3.5 m x h 3.8 m.

M1 mirror : As for HERSCHEL, the primary mirror M1 is manufactured in 12 petals like pieces, later brazed together, ground and polished then coated (a reflective coating deposited by evaporation was developed for the HERSCHEL telescope in Calar Alto Vacuum chamber and is proposed as the baseline for M1). The backside of each segment is optimized as open back structure for minimum deformation under gravity, under grinding and polishing constraints and for meeting the SPICA mass and stiffness specifications. After brazing, the surface is mechanically ground to a parabolic shape. The design of the primary mirror follows the ∅ 3.5 m Herschel mirrors concept with some adaptations, namely the optimisation of stiffeners and ribs with regard to weight, mechanical and optical performances. As for HERSCHEL, three equally spaced bipods will ensure the iso-static mounting of the primary reflector on the TOB. But SPICA STA WFE performances being 20 times more severe, a particular attention is paid on their design to minimize mirror distortion during cool down.

M2 mirror : Use of same material for primary, secondary reflector and its support structure enable distortions and defocus minimization over the wide temperature range. Furthermore, the secondary reflector mass saving that can be achieved with SiC material will contribute to improve the overall STA stiffness performances. The secondary mirror is made from an alleviated SiC blank obtained in a single compacting and sintering run. The mirror is then ground, polished to shape and reflective coated (with M1 coating, the overall transmission performances are >90% at 5µm and >99% at 110µm with a uniformity better than 0.5%). Fixation of M2 is performed by 3 isostatic titanium bipods which are accommodated underneath the mirror through the same fixation concept already qualified.

Secondary reflector supporting structure : From a purely optical point of view, the tripod is the best solution for obscuration surface and PSF encircled energy, but with the additional constraint for limiting the PSF directions affected by spider diffraction, the quadripod becomes the recommended solution if the coronograph is used. The struts section of the supporting structure is optimized and is selected to offer the best compromise between the conflictual parameters such as obscuration ratio, straylight rejection, stiffness and strength.

Telescope Optical Bench : The TOB is made of 8 SiC segments which are brazed, as for the mirror. The ribs are located to provide stiffened fixation area to the instrument optical bench. Main ribs link the 8 interface fixation points with the cryo-system truss on a 2700 mm diameter. The optical bench design was improved in the frame of the study phase, leading to define an optimized stiffeners height/thickness distribution. Its manufacturing will follow the processes validated through GAIA PLM program.

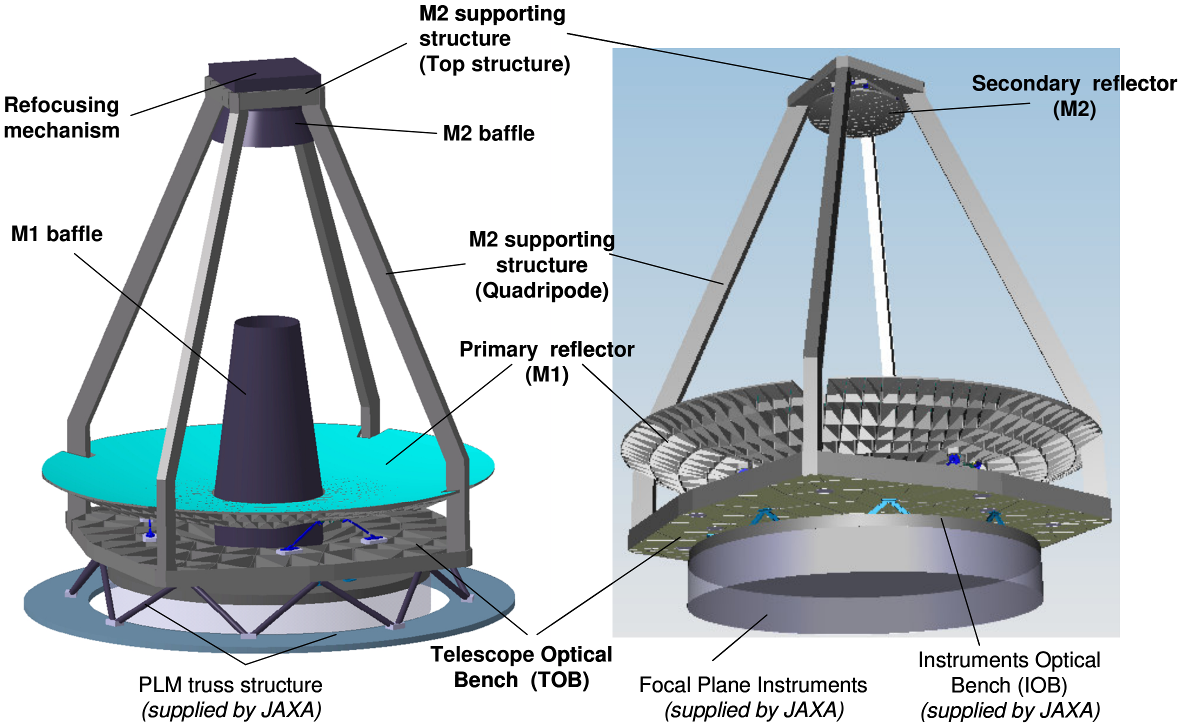
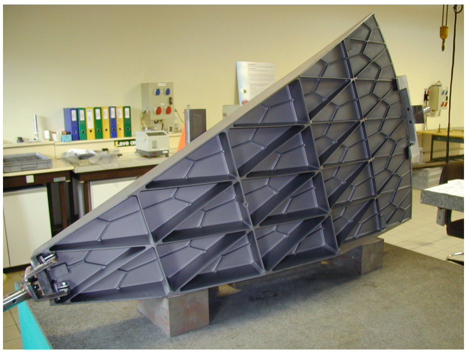
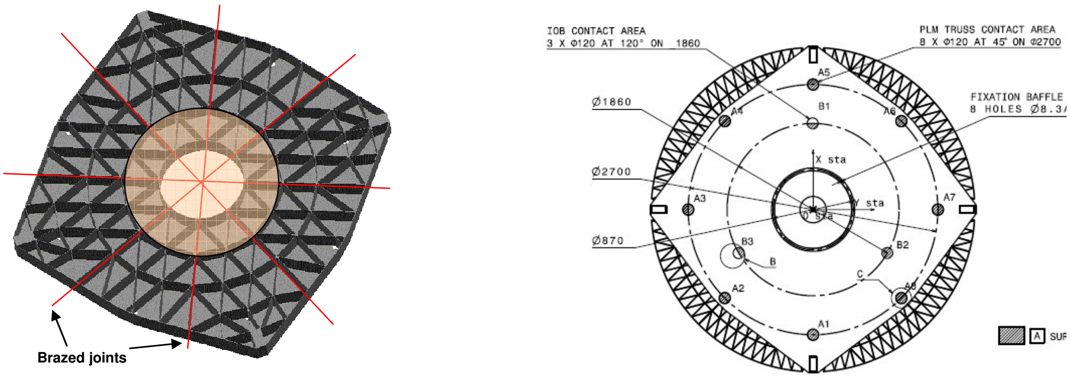


Figure 5-A: SPICA telescope architecture

Herschel telescope



Herschel segment



SPICA TOB design

Figure 5-B: SPICA telescope architecture

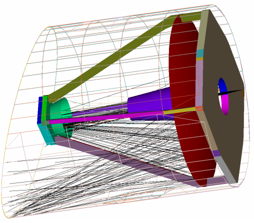
<u>WFE Performances :</u> The WFE budgets have been consolidated for several important aspects : telescope integration errors from AIV Plan, manufacturing and namely polishing from polisher assessment study, cool-down effects from detailed mechanical analysis.

The telescope is diffraction limited at λ=5µm on 5 arcmin radius and respects the specific Coronograph image quality need.

	Performance	*Main contributor*
WFE at 5µm over 5'	**350 nm rms**	M1 Cool down
WFE at 30µm over 10'	**670 nm rms**	Design aberrations
WFE at 5µm (Coronograph)		
3.3 to 12 cycles/D	**50 nm rms**	M1 polishing
12 to 50 cycles/D	**70 nm rms**	M1 polishing

<u>Contamination budget :</u> The particulate cleanliness will be achieved thanks to the HERSCHEL experience (the status before delivery was measured to less than 70 ppm per mirror).

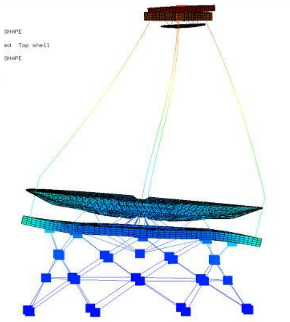
<u>Straylight performances :</u> The preliminary straylight analysis through ASAP modelisation showed that the requirements related to sources located inside and outside FoV are met, considering a) experimental results from ALADIN & HERSCHEL programs and b) optimised M1 and M2 internal baffles. Assuming optimized optical interfaces within the focal plane, the self emission requirements are marginally fulfilled due to the impact of external baffle at 11K



STA mass and modal performances :

The preliminary design leads to a mass of 654kg with 16% contingency included : a commitment on a 700kg specification is realistic.

	Total mass
Primary Reflector (M1) and bipods	280 kg
Telescope Optical Bench	190 kg
M2 support structure, Optical & Thermal & Electrical Hardware	158 kg
Refocusing Mechanism and Electronics	15 kg
Secondary Reflector (M2) and bipods	11 kg
Total	**654 kg**



The modal performances (but also the stability and the strength) of the STA were assessed through a detailed FEM of all constitutive parts, coupled to the PLM truss one. The STA can accommodate, without significant modifications of its modal behaviour, a FPA of 200kg with calibrated IOB I/F stiffness (60Hz lateral, 100Hz longitudinal on rigid I/F) : with the FPA, no modification of the STA first lateral mode (**31Hz** on rigid I/F) and a 2Hz decrease of the STA first longitudinal mode (from 59Hz to **57Hz** on rigid I/F).

Occultation ratio : Considering the optimized struts section, 11.5% is achieved.

STA strength : All Margins of Safety under the specified Quasistatic Loads are positive.

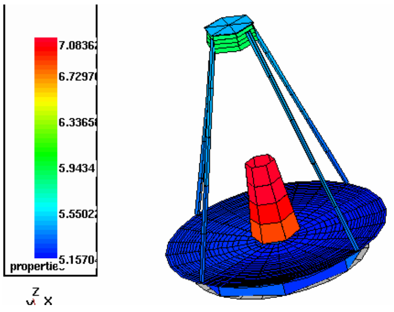
STA stability during cooling down : On top of the calculations of M1, M2 and overall telescope assembly contributions, it was demonstrated that the current JAXA design of the truss respects the radial breathing needed at this interface and that a relative flexibility is mandatory at IOB to TOB interface, allowing to accommodate an aluminium IOB. The overall telescope defocus due to cool-down is well predictable and will be compensated at the FPA/TOB interface level by an relevant shimming.

5.2 THERMAL ARCHITECTURE AND PERFORMANCES

The low operating temperature of [5K-10K] of the telescope and the need of limitation of the spatial gradients within the optical surfaces makes the minimisation and the control of the thermal exchanges with the different elements of the spacecraft one of the main design drivers. The telescope thermal architecture is the combination of passive and active thermal control. The passive thermal control is done thanks to thermal straps and coatings. The active thermal control for decontamination purposes uses thermistors and heaters implemented on the TOB and on the mechanism upper tray, allowing to heat the optical surfaces up to 180 K.

On-orbit performances :

Stabilized temperature	Cooler (fixed I/F temperature)	5 K
	Shell (fixed I/F temperature)	24 K
	Baffle (fixed I/F temperature)	10,4 K
	M1	5,3 K
	M2	5,5 K
	Quadripod	5,4 K
	TOB	5,3 K
	M1 baffle	6,7 K
	M2 baffle	5,8 K
Gradient	Inside M1	0,07 K
Cooler heat load	Cooler heat load	18 mW
In-orbit cooling down duration < 6K	Cooler (fixed duration)	165 days
	M1 and M2	165 days
	Quadripod, TOB , top structure	165 days



The main contribution to the 18 mW of cooler heat load is the direct conductive heat flux from the STA at 5K to the shell at 24K. M1 spatial gradient is very low and is only induced by TOB temperature distribution, which is mainly affected by thermal gradients issued from PLM truss interfaces.

Test cooling down : The 50 K or 10 K temperature can be reached in 2 weeks for all parts of STA.

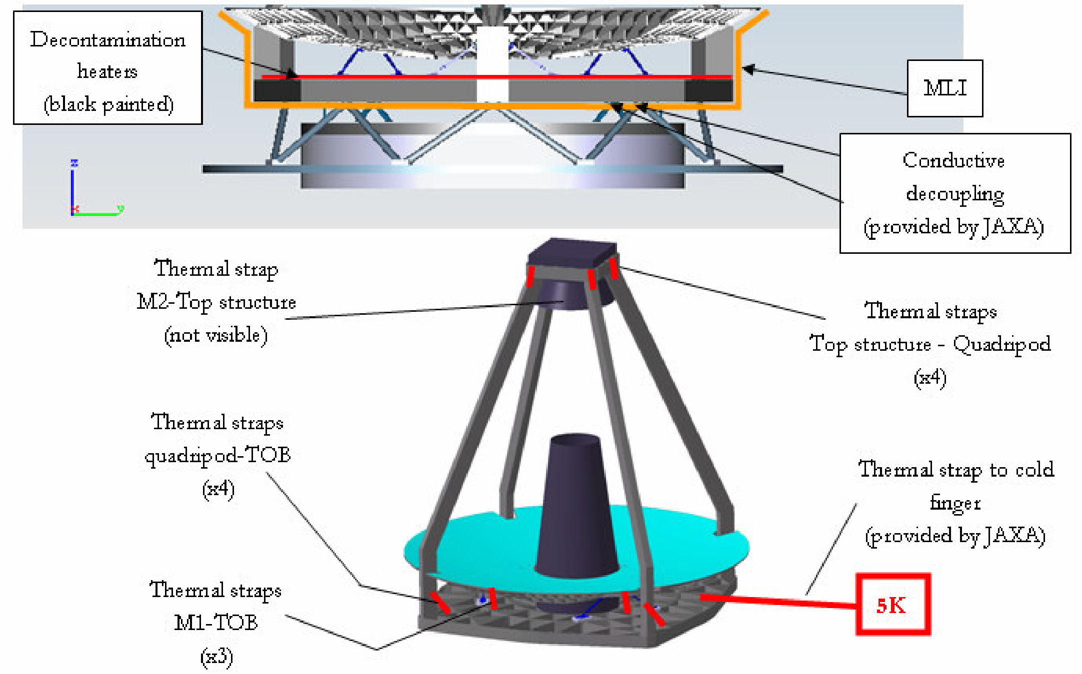
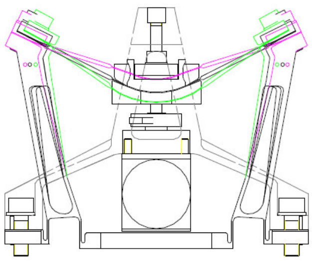


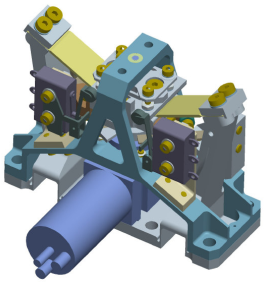
Figure 5-C: SPICA telescope thermal architecture

5.3 FOCUSING / TIP / TILT MECHANISM (FTTM)

Trade-offs on various refocusing mechanism concepts capable of providing piston corrections (range +/- 500.µm) as well as tip/tilt ones (range +/- 100.µrad) were implemented with the selection of an adaptation of GAIA M2MM mechanism to SPICA needs. The proposed design, based on a well-known existing mechanism, considers the development of the actuators with a homothetic design w.r.t. GAIA ones.

Actuator : The linear actuator for the FTTM will provide a 0.1µm resolution over a travel of +/-500 µm with stable positions at any position of the stroke. It also has high load capability to withstand launch loads without losing the launch position (no need of additional Hold Down and Release Mechanism)





Stepper Motor : The actuator is based on the use of a stepper motor and three stages gear reduction, which actuates a spindle-nut, providing a linear displacement in the axis of symmetry of a mechanism. The flexure structure provides a reduction ratio from this linear movement of the nut to the linear movement of the output. The permanent magnet stepper motor has a detent torque that provides stable positions of the spindle-nut when de-energized. The adaptation from GAIA to SPICA leads to select another existing CDA Stepper Motor (type-20 instead of type-12).

Position sensors : The design is open loop, therefore there is no formal need for an absolute sensor which would induce additionnal costs and design complexity. However, a "reference position" sensor (cheaper, simpler design) might be implemented as for GAIA and will allow to obtain an information on the mechanism reference position "zero position" and to estimate the mechanism displacement.

5.4 ELECTRICAL ARCHITECTURE AND DESIGN

One independent electrical unit is used to control the SPICA Telescope Assembly : the M2 mechanism drive electronic (MDE). The Telescope thermal control is managed by a dedicated SVM unit, called “thermal control electronics” and provided by JAXA. Both units are assumed to be connected to a 1553 data handling bus for commanding and observability and supply by a power bus. An interface bracket is located on the TOB.

MDE design : The driver must maintains the current in the windings to ensure the torque capability of the stepper motor even with the significant change in the resistance from ambient to 5K (current control). The need to make the system properly working at ambient and at 5K leads to adapt the GAIA MDE. The advantage is a drastic reduction of the power dissipation of the motor during operation at 5K : the power dissipation in the motor will be lower than 0.1W.

Harness and connectic : The same design as HERSCHEL one is proposed.

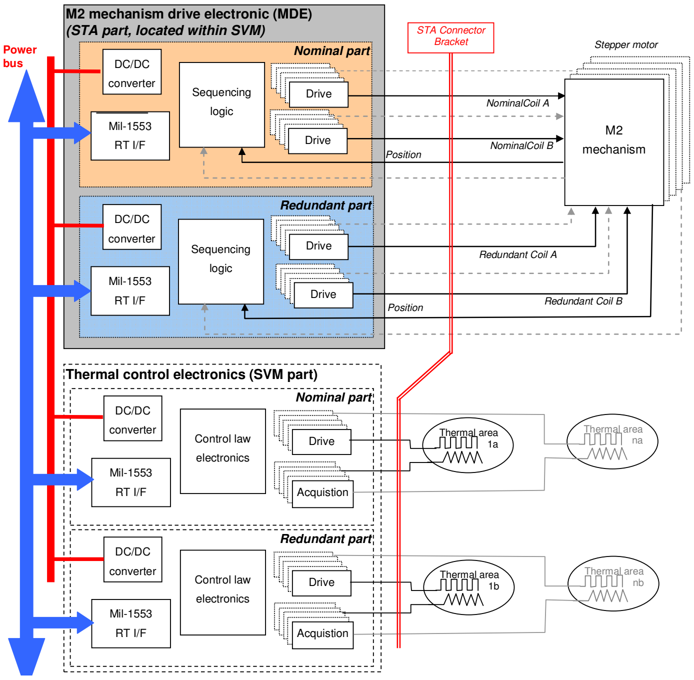


Figure 5-D: Electrical architecture

6 DEVELOPMENT PLAN

6.1 DEVELOPMENT APPROACH

The selected approach is driven by the minimisation of development and qualification risks and the securing of prime requirements early in the programme. The telescope development logic is defined for the complete development flow, from the Phase A/B1 kick-off to the delivery of the proto-flight model and includes a neutralized period of 9 months for down-selection, ITT and telescope contractor selection, as per ESA request.

The major phase A/B1 objectives are basically to freeze the detailed requirements & interfaces, to issue the ITT in order to pre-select the industrial team for the phase B2/C/D, to approve the telescope preliminary design & specification and to implement all identified TDA and risk mitigation activities. The major reviews in Phase A/B1 are the Specification and Interfaces Review (SIR) aiming at freezing the basic hypotheses for the telescope development, and the Telescope A/B1 Phase Final review (FR) aiming at consolidating the preliminary design, performances & development from units suppliers preliminary data, and from all mitigation actions implemented during this phase.

During the Implementation Phase (B2/C/D), the flexibility for different model philosophies is offered :

Baseline model philosophy : SM + PFM

- a Structural Model (SM) structurally representative of the flight model in terms of geometrical interfaces with IOB and PLM truss, and in terms of mass and centering. This model is delivered to JAXA.
- a Proto-flight model (PFM) to qualify the design against mechanical and thermal environment and verify its performances under these environment. At the end of the qualification program, the PFM model is declared flight worthy.
- a spare telescope constituted namely by a M1 blank mirror and by all other items not integrated.

Optional model philosophy :

An upgraded SM will allow a better structural and thermal representativity of the telescope and can be proposed to reduce the development risks at upper level (instrument and/or satellite level). This model can be build from the assembly of M1 blank spare and all other spare items. It can be used as flight spare model in case of failure on flight parts. This upgraded SM will not impact the PFM development schedule.

The major reviews in Phase B2/C/D are :

- the Preliminary design review (PDR) which consolidates the preliminary design, performances and development with the A/B1 results and from selected units suppliers data,
- the Critical design review (CDR) which consolidates the detailed design, performances and development with the units CDR results,
- the qualification review and delivery (QR/DRB), held at the end of PFM program will check the flight model qualification and flight performances and verify that PFM model is flight worthy.

6.2 TELESCOPE VERIFICATION SUMMARY

The verification strategy at STA level is summarised in the table below.

Parameters	SM	PFM
Payload interfaces	**X**	**X**
Functions and operation		**X**
Physical properties	**X**	**X**
Mechanical and Thermal		**PQ**
Electrical		**Q**
Performance		**X**
X : Test and Analysis	*Q : Qualification*	*PQ : Proto-Qualification*

The electronics and the mechanism will be qualified at unit level prior to their integration onto the telescope. Therefore, the EMC qualification will not be repeated at the telescope level. Only auto compatibility will be checked.

The mechanical and thermal verification and qualification follows a standard validation already successfully experienced on previous programme. The mechanical test campaign covers modal signature, quasistatic loads, sine and acoustic vibrations to verify the finite element model and to qualify the telescope and its interfaces against mechanical loads. The thermal test campaign covers operational and non operational thermal environment and mission dynamical environment to be flight representative. During the thermal test campaign, the thermal model, thermal control and optical performances will be verified.

The performances verification (mainly optical and opto-mechanical performances) will be verified under gravity conditions, under thermal vacuum/thermal balance environment and before/after mechanical & thermal environmental tests.

6.3 INDUSTRIAL ORGANISATION FOR B2/C/D PHASE AND HERITAGE

Based on previous programs, the design of the STA has benefited on technologies and components supported by hardware experiment. The selected core technologies have also been utilised on previous space programs. The major following features can be pointed out :

- The telescope is based on ceramic (SiC) technology. The concept benefits from previous space programmes experience in similar size and technology as for STA, namely HERSCHEL, ALADIN and GAIA.
- The mechanism and its electronics, based on a GAIA mechanism
- The other elements as main structure, thermal hardware, can be based on conventional technologies and benefit from numerous program experience.

6.4 LIMITED DEVELOPMENT RISK S

No major technological risks are identified on SPICA Telescope Assembly as other programs have already faced large size mirrors (ϕ 3.5 m on HERSCHEL, ϕ 1.5 m on ALADIN and 1.5 m x 0.5 m on GAIA). However, the main specificity of this telescope is the combination of its large size and its high optical quality.

Basically, there is no major technical and performances risks identified on this project but the combination of a large telescope associated to a good optical quality (better than 350 nm rms) and stability over the cryogenic environment should be validated in advance to the flight model. Moreover, the testing of such large mirror and telescope with a high accuracy implies complex optical ground support equipment and/or verification method that needs to be early analysed in depth.

The following mitigation actions to be implemented during A/B1 phase are then identified :

- improvement of HERSCHEL polishing methods to SPICA needs
- operation of GAIA mechanism at 5K
- detailed characterisation of CALAR ALTO facilities
- local mock-ups for HERSCHEL design adaptations

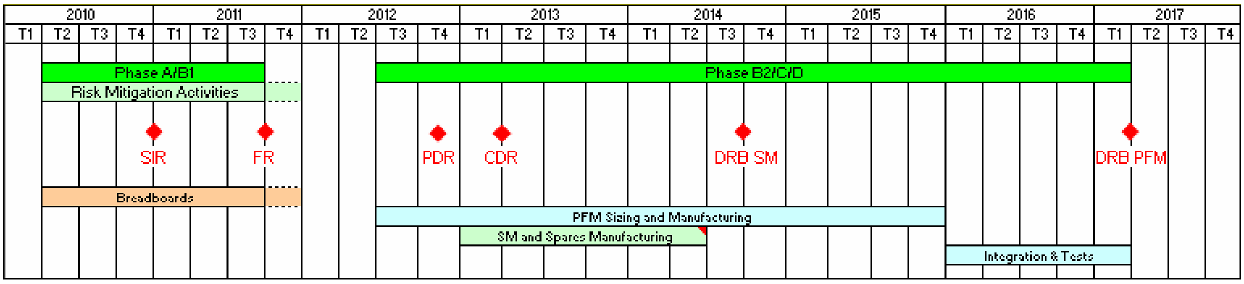
6.5 MASTER SCHEDULE

As per ESA request, the master schedule is compliant with the following boundary conditions :

- Definition Phase (A,B1) of 18 months : nominal kick-off of industrial activities and TDA by Q2/2010, end of industrial studies by September 2011, nominal end of TDA's by December 2011
- Neutralized period of 9 months : final down-selection from October 2011 to January 2012, ITT and contractor selection in Q1 and Q2/12
- Implementation Phase (B2,C,D) : nominal kick-off of industrial activities by Q3/2012

It leads :

- to a development in 18 months for the A/B1 Phase + 57 months for the B2/C/D Phase
- to the following model deliveries : SM by Q3/2014 and PFM by Q1/2017



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