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ALUMINIUM TELESCOPE FOR FIRST

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ABSTRACT : *The Far InfraRed and Submillimetre Telescope (FIRST) mission is the fourth cornerstone of the ESA long term Space Science Programme. It is an astronomical observatory for imaging spectroscopy and photometry in the submillimeter and far infrared operating in the spectral range of 85 - 600 µm. The proposed optical subsystem is composed of a radiatively cooled Ritchey-Chretien telescope of 3 meters in diameter with a potential extension to 3.5 m diameter.*

To achieve the mission objectives, the image quality of the telescope is diffraction limited at 150 µm wavelength which is equivalent to a total wavefront error lower than 10 µm rms. In addition, an image quality goal of 6 µm rms is defined. The roughness of the mirrors must be lower than 0.6 µm rms to limit the straylight induced by diffused reflection and provide the required transmission.

Under an ESA contract carried out by Aerospatiale, with Neyrpic Framatome Mecanique (NFM) for the primary mirror manufacturing assessment, the following major results have been obtained
- the primary mirror must be machined from a monolithic aluminum blank with an high CTE homogeneity,
- the final manufacturing operation of the front face must be grinding process in order to reach the required surface shape performance,
- with the high thermal expansion coefficient of aluminium, an active thermal control of the telescope is necessary to achieve the image quality and limit the defocus in space. It maintains the telescope temperature around 80 K and limits the thermal gradients between the primary mirror and the tripod which support the secondary mirror.

The main advantages of this solution are the cost and the low development risks. On the other hand, its drawback is the mass. The conclusion is that an aluminium solution is a good candidate for large telescopes covering far infrared and submillimeter wavelength range.

1. INTRODUCTION

The Far InfraRed and Submillimetre Telescope (FIRST) mission is the fourth cornerstone of the ESA long term Space Science Programme. It is an astronomical observatory for imaging spectroscopy and photometry in the far infrared and submillimeter, operating in the spectral range of 85 - 600 µm. The operational orbit is around the second Libration point (L2) in the earth/moon sun system at an average distance of 1.5 million kilometres from the earth.

The proposed optical subsystem is composed of a radiatively cooled Ritchey-Chretien telescope of 3 meters in diameter with a potential extension to 3.5 m diameter, surrounded by a sunshade which protects the telescope from heat loads and straylight coming from the Sun and the Earth, providing a stable thermal environment and minimising the temperature variations across the telescope. To achieve the mission objectives, the image quality of the telescope is diffraction limited at 150 µm wavelength which is equivalent to a total wavefront error lower than 10 µm rms. In addition, an image quality goal of 6 µm rms is defined

Under an ESA contract, Aerospatiale, with Neyrpic Framatome Mecanique (NFM) for the primary mirror manufacturing assessment, has studied the feasibility of an all aluminium telescope.

The following presentation discusses the telescope design, the assessment of the primary mirror manufacturing feasibility, the derived performance budgets and the associated development plan for a 3 m diameter telescope.

2. MAIN TELESCOPE REQUIREMENTS

The telescope is a Ritchey-Chretien type. The following main requirements have been taken into account for this study

- Focal length : 27 m ± 0.05
- Primary mirror diameter : 3 m
- Secondary mirror diameter : 246 mm
- Exit pupil located on the secondary mirror
- Unvignetted field of view : ± 0.25°
- Wavelength range : 85 to 600 µm
- Image quality : 10 µm RMS
- Straylight : for sources inside the field of view, at an angular distance of 3 arcmin from the peak of the point spread function, the irradiance level shall be inferior to 10^{-4} of the PSF irradiance.
- Derived from the thermal self emission requirements, the nominal operating temperature of the telescope is 80K (± 10K)
- Maximum mass for a 3 m diameter solution including margin : 280 Kg

3. TELESCOPE DESIGN

3.1 Mirrors and structure design

The telescope design has been driven by the selection of the primary mirror concept which has been carried out taking into account the following criteria :

- manufacturing constraints
- optical performances : deformation of the optical surface under gravity, during manufacturing and on ground tests,
- mechanical performances : eigen frequency for launch constraints,
- material homogeneity to minimise the optical surface deformation induced by the cooling down of the mirror from ambient to its nominal operating temperature (80K).

The selected solution is a solid machined mirror made in aluminium alloy (figure 1).

The Front face, 3 mm thick, is supported with a main ring which provides interface to the telescope structure via Mirror Fixation Devices (MFD). Twenty four radial ribs are machined to provide the required stiffness of the mirror and additional small stiffeners are located inside the cells delimited by the radial ribs, designed to avoid a quilting effect on the mirror which is induced by machining loads.

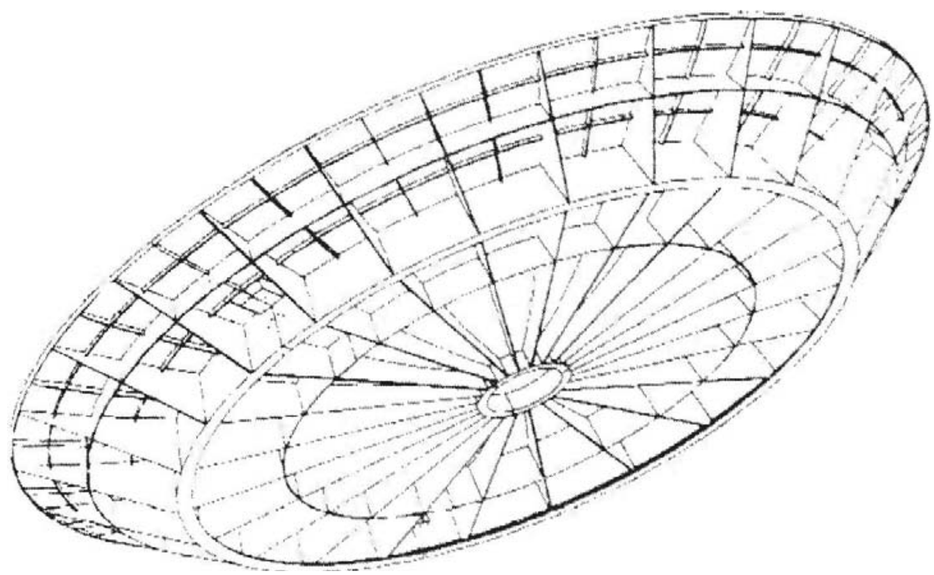

Figure 1 Primary mirror design

Aluminium presents a high reflectivity coefficient in infrared, it is therefore not necessary to apply a coating on the optical surface of the mirror to fulfill the 0.97 transmission requirement.

The primary mirror fixation device provides quasi isostatic mount radial translation decoupling and axial and tangential rotation decoupling are given by the flexibility of the main blade. Radial rotation decoupling is given by the flexibility of the cross blades.

A tripod made with aluminium sandwich structure is fixed on the primary mirror front face with a decoupling interface to avoid distortion on the mirror. This decoupling behaviour is needed for the stiff axis of the tripod legs and is provided by a crossed blades system similar to that of the MFD. The tripod interfaces at its top with the secondary mirror which is made in aluminium alloy with the same processes as the primary mirror. Its support provides the necessary adjustment capabilities to align the secondary mirror with respect to the primary mirror.

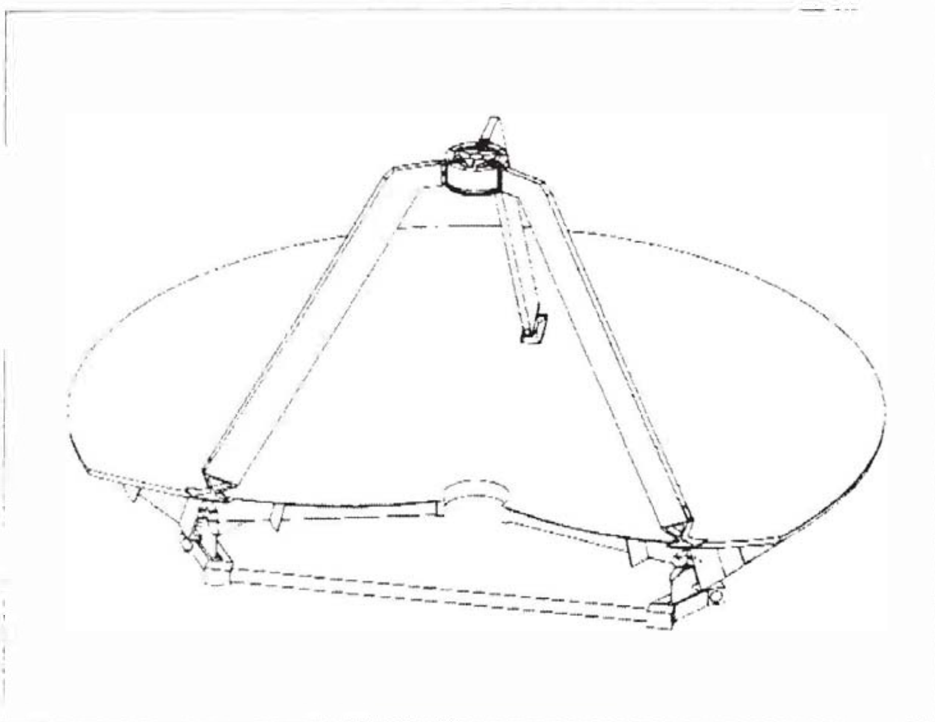

Figure 3 : Telescope design

3.2 Thermal control design

Aluminium has a high thermal expansion coefficient (CTE = 15 10^{-6} K^{-1} at 100 K) so the temperature of the telescope must be controlled to achieve the image quality requirement.

The telescope thermal design is performed to reach a high conductive coupling inside and between the different parts of the telescope and low radiative coupling with the external environment in order to guarantee minimum thermal gradients.

- Heaters are uniformly distributed below the primary mirror rear face to adjust its temperature level and provide a homogenous temperature over the primary mirror. According to the temperature sensed via a proportional integral algorithm, power is sent uniformly to all the heaters. The very low power density needs on these heaters and the high conductivity of the aluminium primary mirror means that its temperature level can be achieved without creating unwanted gradients.

- The temperature level of the tripod is controlled by one heater line one each leg. The sensor for the tripod is placed at the center of each leg. Heaters are applied over the leg surface and the control system provides a uniform heater power density over it, according to the sensed temperature. The large ratio of the conductive heat flow in the leg to the radiative heat flow from the leg to the space at the low operational temperature ensure very low gradients in the legs.

- The temperature level of the secondary mirror is also controlled by one heater line, thus assuring that the remote ends of the tripod legs have the same temperature as at the primary reflector end.

4. TELESCOPE PERFORMANCES

4.1 Image quality

The image quality of the telescope results from various contributors: the optical layout, the manufacturing accuracy of the mirrors, the adjustment accuracy of the secondary mirror with respect to the primary mirror, the on ground measurements accuracy with the gravity effect, the cool-down effect, the stability of the structure under launch loads and the thermal control performance in flight. This is presented on the wave front error (WFE) budget on the figure 4 here after. The total Wave Front Error of the telescope including the telescope defocus is equal to 9 µm rms for 10 µm rms specified :

The optical layout : it induces astigmatism and field curvature. The worst case is at the edge of the field where the WFE is 1.7 µm

Manufacturing accuracy of the primary mirror : it is given by an optimized manufacturing process for that 7 µm rms is allocated.

Assembly, Integration and Tests : the telescope AIT operations starts with the tripod assembly on the primary reflector. The secondary mirror is then adjusted with respect to the primary mirror. The accuracy of this operation is given by the measurement accuracy of the interferometer used to determine the tilt and decenter position of the M2, and the residual positioning error of the secondary mirror induced by the manufacturing accuracy of the shim between the M2 plate and the upper ring.

Cool-down effect : Potential CTE inhomogeneities of the primary mirror blank combined to the large variation of temperature during the cool down of the telescope induce deformations of the primary mirror. The following assumptions are taken into account to compute the corresponding WFE :

- average value of the CTE on the temperature range 300 K 100 K : 20.10^{-6} K^{-1}.
- CTE inhomogeneities ± 0.6 %. This value has been calculated from standard composition variation of the alloy. Calculations carried out from results of chemical analyses performed by the blank supplier give ± 0.2 %. This value has not been taken into account for the budget at this stage of the study
- inhomogeneity distribution linear variation of the CTE along the transverse direction (first order defect in the plan of the mirror)

The WFE of the secondary mirror induced by the cool down and structure effects are extrapolated from AEROSPATIALE experience on other programs.

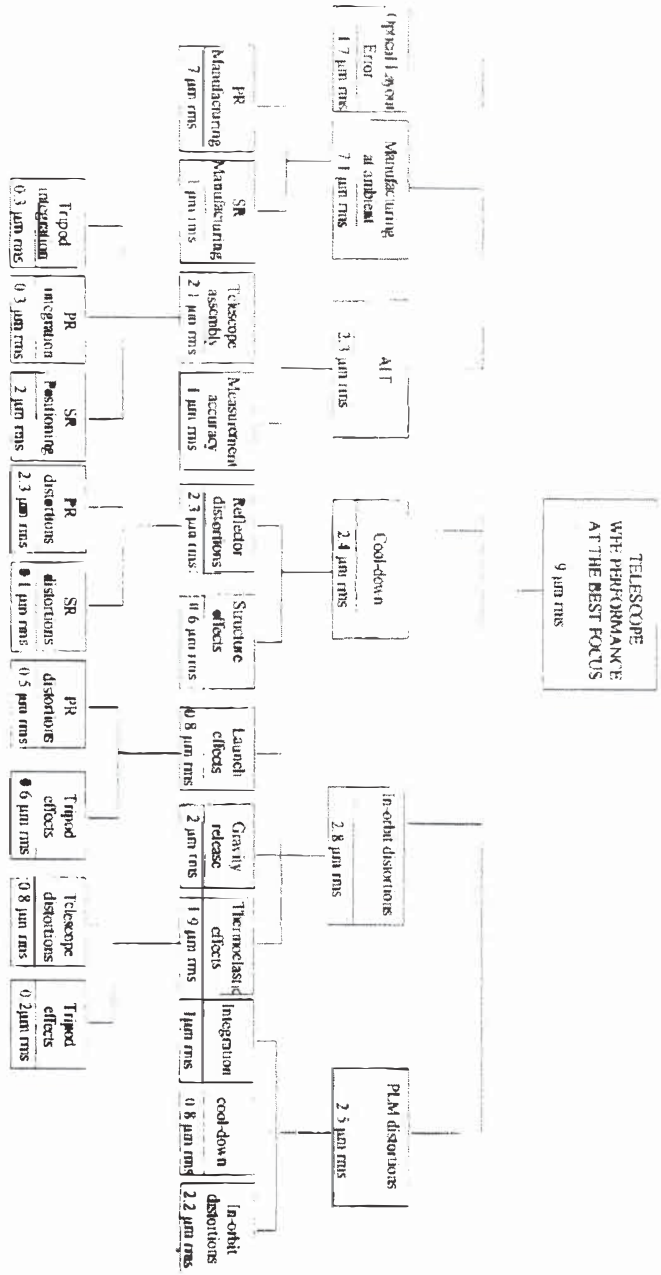

Figure 4 : Image quality budget

In orbit distortions :

- *launch effects*

They induced residual strain of the main parts and micro-sliding instabilities at the interfaces. Finite element analyses of the stress level under quasi static loads have been performed and have shown a positive safety margin with respect to micro yield stress. Associated tilt and decenter induced negligible WFE.

- *Gravity release*

Experience from previous space telescope shows that distortions induced by gravity release is about 10% of the total deformation under gravity.

- *Thermoelastic effects*

The choice of a L2 orbit for FIRST mission has strongly decreased evolution of the thermal environment and consequently the thermoelastic effects on the WFE. The major contributors are the following :

- deformation of the primary mirror induced by the telescope temperature distribution (mirror and tripod effects),
- WFE associated to the tilt of the M2 induced by the temperature distribution along the tripod (difference of temperature level between the tripod legs),
- WFE associated to the decenter of the M2 induced by the temperature distribution along the tripod (difference of temperature level between the tripod legs)

Calculations of the thermoelastic effects at operational temperature have been performed with a CTE = 15^{-6} K^{-1} and taking into account the following temperature distribution resulting from the thermal analysis. These load cases are worst cases with regard to the WFE :

	Mean temperature (K) (cold case controlled to 90 K)	Maximum gradient at the end of life (K)
Primary reflector	90.2	0.17
Tripod	90.3	0.43
Triangular structure	90.3	0.43

PLM distortions :

PLM distortions induce primary mirror deformations and whole displacement of the telescope that produce tilt and decenter.

4.2 Mass budget

The mass budget based on the 3 m diameter design is given on the table here after .

Items	Mass (Kg) Without margin	Margin (%)	Mass (Kg) including margin
Primary Mirror	181	10	199
Secondary Mirror	5	20	6
Tripod	12	20	14
Intermediate Structure	23	20	28
Thermal Control	24	20	29
Miscellaneous	1	20	1.2
TOTAL	**246**	/	**277**

The total mass of the telescope, including margin is 277 kg. It is compatible to the 3 m diameter FIRST telescope mass specification (280 kg) but it is above the value given in the present specification of the 3.5 m diameter telescope in the case of the FISRT/PLANCK merger option (260 kg).

5. DEVELOPMENT

The present analyses gives good confidence in an aluminium telescope to fulfill the FIRST performance requirements. This concept is simple, the thermal control efficiency has been already demonstrated on previous projects. The manufacturing process is the main contributor to the telescope image quality performance and is the main point to be demonstrated.

That is why a manufacturing test on a flat full size mock-up (3 m diameter) has been carried out. The objective of this test was to characterise the image quality that can be achieved with a 3 m diameter mirror.

The manufacturing accuracy involves the machining tool itself, the mirror design and the supporting device.

The tested mock-up is representative of the real mirror for its main rear face structure which gives the structural behavior of the mirror during machining (in particular vibrations induced in the mirror by the cutting tool). The cells of the secondary rear face structure have been designed at different sizes in order to characterize the influence of this parameter on the vibration and quilting behavior.

During the test, the mock-up is interfaced on a supporting device which is also involved in the machining accuracy and vibration behavior. This supporting device has been designed to allow the optimisation of the supporting point position and was in steel to reduce design contraints. It is not representative of the mirror model supporting device which is foreseen in aluminium to reduce differential thermoelastic effects between these two parts during machining.

In addition, the machining could not be performed inside a controlled environment room as it is foreseen for the machining of the mirror model so that the thermal environment was not representative.

The machining operation has started with a mock-up front face thickness of 40 mm. It has been performed in three main steps :
- First machining : the thickness of the front face has been decreased from 40 mm to 20 mm in order to check the machining tool accuracy alone with the diamond cutting tool, without the vibration effects potentially induced by the machining of low thickness.
- Second machining : the thickness of the front face has been decreased to 6 mm to verify if the roughness and again the front surface flatness are achieved with the diamond cutting tool at a lower thickness.
- Third machining : the thickness of the front face reached after this machining is ranging from 2.5 to 5.5 mm. This non uniform thickness has been generated by a surface shape defect induced by mishandling of the mock-up before started the final machining. After the final machining, flatness measurements with the supporting device clamped and unclamped from the rear face of the mock-up have been performed to verify its impact on the manufacturing budget.

In spite of the simplified test configuration, a large experience in different fields of the manufacturing sequence has been gained during the test sequence and from the results and their exploitation

The cutting tool and the cutting parameters defined for this operation are adequate. The life duration of the cutting tool is large enough for the machining of surface larger than 3 m diameter

The surface performances have been characterised after fine machining at different thickness ranging from 22 mm to the final value achieved :

- The roughness is within the 0.6 µm RMS Ra. The maximum size for the rear structure cells has been defined to avoid local vibrations of the front face and reach this performance.

- Some quilting effect has been detected on the surface but it can be reduced by optimized design.

- The surface shape error of the front face could not be measured with sufficient accuracy. The obtained values for the different thicknesses are included between 15 and 100 µm rms. The conclusion is that the accuracy of machine tools used for this test is not high enough to reach a WFE of 7 µm rms which is the required value for the reflector model.

Potential decrease of the surface shape error could be obtained if some improvements on the machining device are performed (machining the surface on a lathe equipped with air or oil bearing for instance). The potential gain is however not quantified presently and not considered sufficient.

So, at this step of the study, the most confident solution identified to perform the final manufacturing operation of the front face is a grinding process (first step of an optical polishing). This could allow to obtain a WFE better than the required performance of 7 µm RMS. This grinding process has not yet been proven on a representative large sample.

6. CONCLUSIONS

The present results give good confidence in an aluminium telescope to fulfill the FIRST telescope performance requirements

The manufacturing test performed on a 3 m diameter flat mock-up has demonstrated that a final grinding operation is required to reach the image quality. The main drawback of this solution is the mass

An aluminium telescope is an attractive solution which presents no major development because it is based on a simple concept.