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High Resolution Observation Instruments: How to reach the best performance

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HIGH RESOLUTION EARTH OBSERVATION INSTRUMENTS - HOW TO REACH THE BEST PERFORMANCE

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I. INTRODUCTION

Thanks to development heritage of High and Very High Resolution earth observation optical instruments, Thales Alenia Space has mastered the structural stability of large telescopes for many years (National and Export programs). This has raised earth observation performances in Europe.

The very high stability of structure and optical components is key to ensure image quality, and line of sight stability for accurate images geo-localization.

Telescopes pupil diameter increases in order to reach higher resolutions. Associated optical layouts then become more sensitive. So size of these telescopes increases in same time as their stability requirements become more stringent. Moreover satellite agility requirements are more and more severe and instruments shall be compatible with quick evolutions of thermal environment.

Considering all these constraints, each telescope architecture shall be optimized to master developments for each mission in terms of performances, cost, schedule and risks.

This is why Thales Alenia Space uses materials with very a low Coefficient of Thermal Expansions :

- For mirrors : Zerodur®
- For structures : Carbon/Carbon; Silicon Nitride and Carbon Cyanate panels.

II. HIGH AND VERY HIGH RESOLUTION INSTRUMENTS DESIGN AND SENSITIVITY

A. TELESCOPE OPTICAL DESIGN

The optical architecture of the telescope results from the optimization of radiometric performances compatible with volume restrictions, respect to the broad field of view and spectral range required. The **three mirrors Korsch telescope, including folding mirrors, appears to be the best choice**. The following figures show the optical principle of a typical HR telescope (Fig.1) :

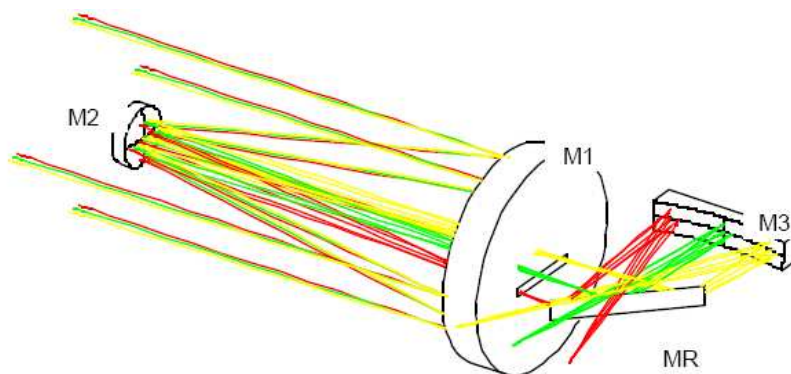


Fig.1 : 3D view of HR telescope typical optical layout

B. HIGH and VERY HIGH RESOLUTION INSTRUMENTS OPTOMECHANICAL DESIGN

Instruments are constituted of a **front cavity** which includes

- Secondary mirror (M2) and its refocusing system
- Supporting structure of M2 (cylinder or truss)
- Primary mirror (M1)
- The associated baffling and thermal control

And a **back cavity** which includes

- Optical bench and panels constituting a stiff “box”
- Tertiary mirror (M3) and folding mirrors
- Detection unit and its focal plane
- 3 support bipods which constitute the isostatic interface with the platform
- The associated baffling and thermal control

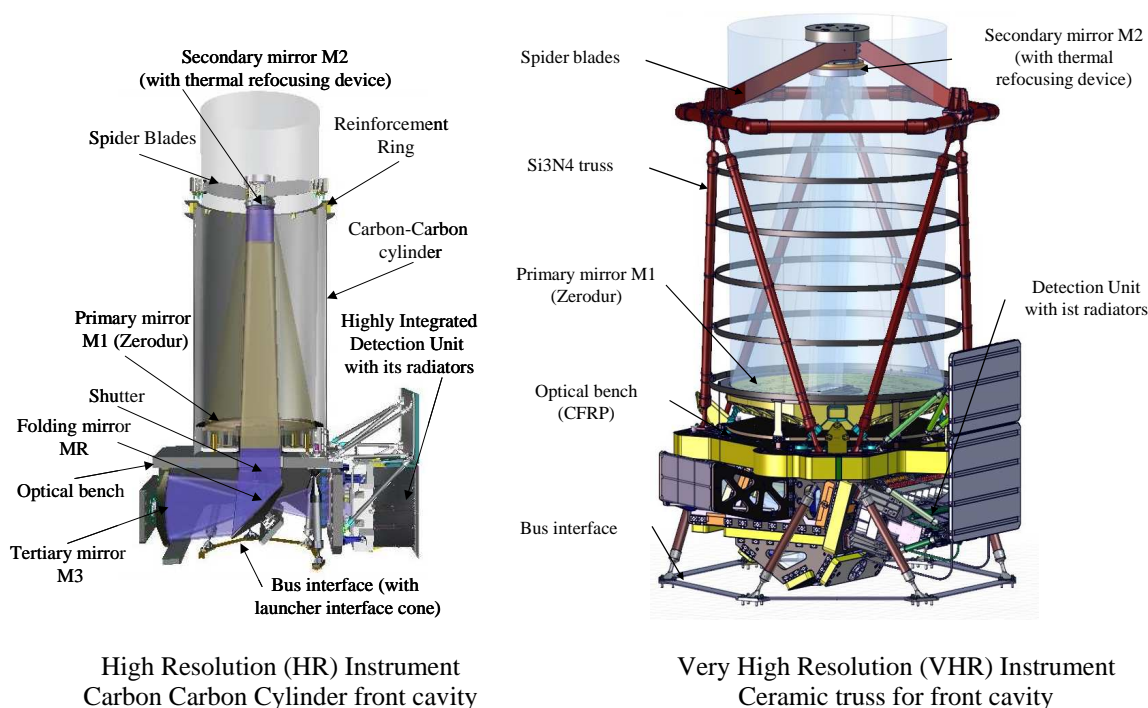


Fig.2 : Opto-mechanical designs of HR and VHR telescopes

C. MAIN PERFORMANCES AND IN FLIGHT STABILITY SENSITIVITY

The main optical typical performances of HR and VHR telescopes are:

- Modulation Transfer Function (MTF) >0,18 (native MTF without detector performance)
- Ground Sampling Distance (GSD) <1m for HR, <0,5m for VHR
- Field of View >15km
- Geo localization <15m

Mainly considering MTF and Geo localization performances, the following opto-mechanical requirements are deduced :

- M1M2 distance stability in flight (between each refocusing calibration) < 3 μ m
- Mirror M1 WFE in flight < 30nm RMS
- Instrument Line of Sight stability wrt Star Trackers Interface in flight < 5 μ rad / axis
- M3 and MR stability < 100 μ m

The telescopes magnification (around 100) implies that back cavity (including MR and M3 mirrors) is far less sensitive to stability than front cavity (including M1 and M2 mirrors). This means that M2 translation of $1\mu\text{m}$ along optical axis is equivalent to $100\mu\text{m}$ translation of M3 mirror along optical axis.

The stability specifications shall be ensured every time the satellite is on top of day lit lands in the range of $\pm 45^\circ$ in roll and $\pm 45^\circ$ in pitch. It means that system shall be operational just after eclipse out coming, and shall not be affected by all satellite maneuvers.

The following figures illustrate how telescopes are submitted to thermal fluxes variations along the orbit due to agility of satellite and albedo variation.

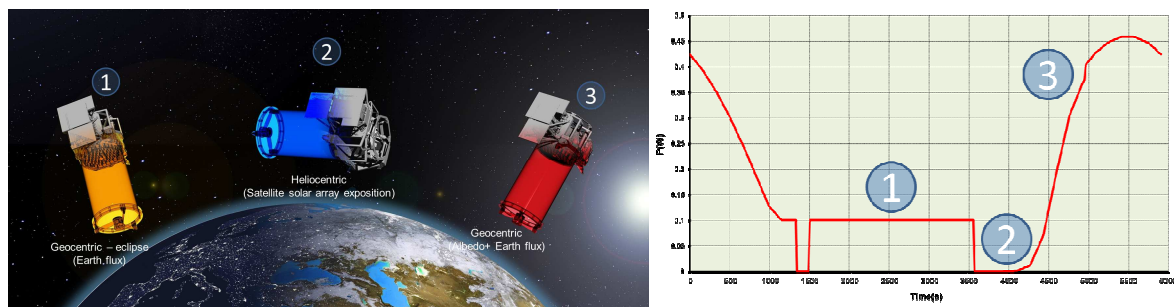


Fig 3 : External thermal Fluxes absorbed by Telescope Primary Mirror (Albedo+Earth) along one typical orbit

On phase 1, satellite is geocentric and in eclipse, telescope cavity receives constant Earth flux.

On phase 2 (cold case), at polar position, satellite is heliocentric, fix solar arrays in front of sun in order to charge batteries. Telescope cavity do not receive any thermal flux and see only deep space.

On phase 3 (hot case), satellite is geocentric in operational conditions, with large pointing capabilities ($\pm 45^\circ$ in Pitch or Roll). Telescope cavity is submitted to variable Albedo and Earth flux up to south pole position.

III. PRIMARY MIRROR

A. Primary mirror stability

The primary mirror shall be stable in order to maintain its own Wave Front Error of 30nmRMS and to have no Radius of Curvature Variation in order to not modify M1M2 optimal distance. **This means that the primary mirror is the most sensitive part of the telescope in terms of stability.**

In order to select material for M1, the thermal steady state factor (Thermal conductivity/Coefficient of Thermal Expansion (CTE)) is often used (cf. [2]). This factor gives the same importance to CTE as to thermal conductivity. However, for very highly lightweighted mirrors, most of the material is removed, therefore actual conductivity is limited. As described in previous paragraph, thermal heat transfer is mostly radiative in orbit. Temperature gradients appear in the mirror, **so CTE dominates and thermal conductivity has a poor influence on mirror stability.**

Table 1 : CTE comparison of main polishable materials for space mirrors.

	CTE ($\mu\text{m}/\text{m}/\text{K}$) @20°C	
Zerodur® Class 0 (Schott)	<0,02	0,007 measured on last procurements
ULE® (Corning)	<0,03	
Silicon Nitride (Si_3N_4 - FCT)	1,4	
Silicon Carbide (SiC Boostec or FCT)	2,2	
Beryllium	11,3	
Aluminium (6061)	23	

This approach is confirmed by worldwide earth observation industry as recalled in following extract of [3] : “NASA’s Navigator Program Office with contributions from JPL, Goddard and industry have indicated that extremely light-weight open-back silicon carbide optics that have comparable areal densities to a passive closed-back ULE® mirrors cannot maintain the same thermo-elastic stability as their glass counterparts. This is because SiC has a relatively high CTE, and when most of it is removed for light-weighting leaving thin ribs which increase structural efficiency , the benefits of the high conductivity are negated. Hence, a small thermal gradient can be generated which could significantly impact the mirror figure”.

This leads to a maximum Wave Front Error of 240nm RMS (without focus) and a focus variation of 500nm RMS around the orbit. For an equivalent Zerodur® mirror, Wave Front Error is only 1,6nm RMS (without focus) and a focus variation of 12nm RMS.



For large mirrors used on active telescopes a faster control loop is required in order to compensate high temperature variation of the mirror.

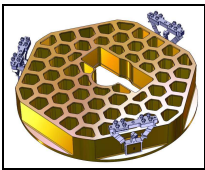
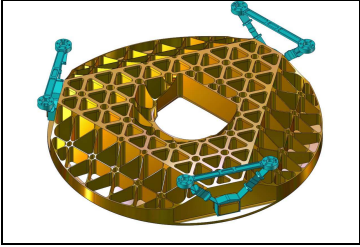
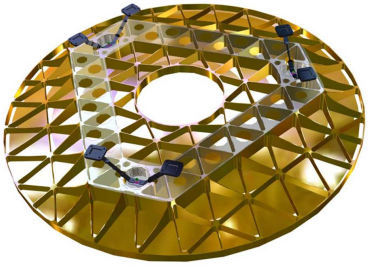
This orientation is also valid for future very large mirrors associated to active optics. With this type of architecture active optics mainly correct ground to flight instability and mid-term evolutions. Moreover, a real time thermo elastic correction of the primary mirror is not necessary.

Therefore, active optical instruments are fully operational at all times for imaging and do not necessitate any high frequency corrections.

B. Primary mirror mass

The primary mirror mass is often presented as a major parameter for space telescopes. Vitroceramics Zerodur® or ULE® are intrinsically less efficient - in terms of stiffness and density - than ceramics like SiC. Nevertheless a mass comparison is hereafter established on 3 typical mirror sizes for High and Very High Resolution telescopes.

Table 2 : Mass comparison of Zerodur® and SiC mirrors

Zerodur® mirrors design			
Active optics required	No	No	Yes
Pupil Diameter	0,65m	1,1m	1,5m
Zerodur® equipped mirror Mass	21kg	65kg	45kg
Thermal Control Mass for Zerodur®	9kg	13kg	0kg
SiC equipped mirror Mass	15kg	42kg	35kg
Thermal Control Mass for SiC	15kg	23kg	25kg
Delta Zerodur®/SiC including thermal control	0kg	12kg	-15kg
Satellite Total Mass	900kg	1300kg	1300kg

This table shows that **primary mirror mass differences between SiC and Zerodur® technologies is negligible regarding satellites total mass.**

SiC mirrors are always lighter but they necessitate an heavier thermal control to create an inertia thermal barrier at the entrance of telescope.

In Zerodur® mirror progress developments, assembly technologies which will be used with active optics, show that Zerodur® technology becomes more competitive than SiC.

Moreover mass which is near the satellites Center of Gravity (CoG) has a poor impact on satellite agility performances. This is the case for primary mirror mass and for Zerodur® thermal control located just behind the mirror. This is not the case for a part of SiC thermal control which is located in the front cavity.

Mass of mirrors (in the range of table presentation) do not have any collateral impact on the telescope structure mass. Optical bench and back cavity are mainly sized by the required stiffness of the instrument (back cavity coupled with high inertia of the front cavity) and not by the M1 mass.

Since the primary mirror brings most of the observation systems performances and while the Zerodur® or ULE® stabilities are 2 orders of magnitudes better than ceramics, Thales Alenia Space selects Zerodur® for its earth observation telescopes.

IV. FRONT CAVITY STRUCTURE

One main requirement of the front cavity structure is to stabilize M1M2 distance with an accuracy of about $3\mu\text{m}$ between 2 refocusing calibration. The M1M2 distance is in the range of 1,5m.

Meanwhile the stiffness of this structure shall be sufficient to limit mechanical loads on M2 and its refocusing mechanism. The mass of this structure shall also be reduced to the minimum because it is quite far from the satellites Centre of Gravity. Its impact on Satellite Inertia and Agility is important.

Materials which have sufficient stability properties are listed on following table.

Table 3 : Stability and mechanical properties of potential materials for front cavity

	Carbon/Carbon	CFRP	SiC	Si ₃ N ₄
Stability				
CTE @ 20°C ($\mu\text{m}/\text{m}^\circ\text{C}$)	0,4	-1	2,2	1,4
CME ($10^{-4}\text{m} / \text{m} / \% \text{ moisture release}$)	0	23	0	0
Mechanical properties				
Young modulus (GPa)	60	90	420	330
Density (kg/m^3)	1,7	1,8	3,12	3,26
bending strenght (MPa)	150	100	350	520
Fragility (K1C)	NA	NA	4	7

CFRP is not selected for front cavity in order to avoid moisture release impacts on M1M2 distance. This effect is a drawback for keeping stability between ambient and vacuum environment. Vacuum is used on ground to characterize telescope performances and ambient conditions are used to block M2 position.

Silicon Carbide has the highest CTE. Moreover, it is not possible to manufacture tubular beams for truss and M2 frame with this material. Only “U” or “T” shape section can be made.

Despite its good mechanical properties, the global stiffness and mass performance of SiC is not as good as the one achieved with Silicon Nitride (Si_3N_4) which allows tubular beams manufacturing. To reach the same torsion inertia with “U” shaped section beam (SiC manufacturable), 4 times more material is required.

For a VHR front cavity, the truss and M2 frame mass is 70kg in Silicon Carbide and 45kg with Silicon Nitride tubular tubes, which is 35% lighter.

The standard specific rigidity E/p factor is not sufficient to compare materials, the manufacturable shapes shall also be considered.

Moreover SiC is more fragile than Si_3N_4 (K1C parameter near twice lower), so breaking risks during all AIT phases of the structure is the most important of all the compared materials.

Carbon/carbon is used for HR telescopes. For these middle size instruments, the global benefit is as good as Silicon Nitride. So it is selected for its higher stability.

For smaller telescopes, tubes between M1 and M2 offer a natural structure for optical baffling. They can be made either in Carbon/Carbon or Si_3N_4 .

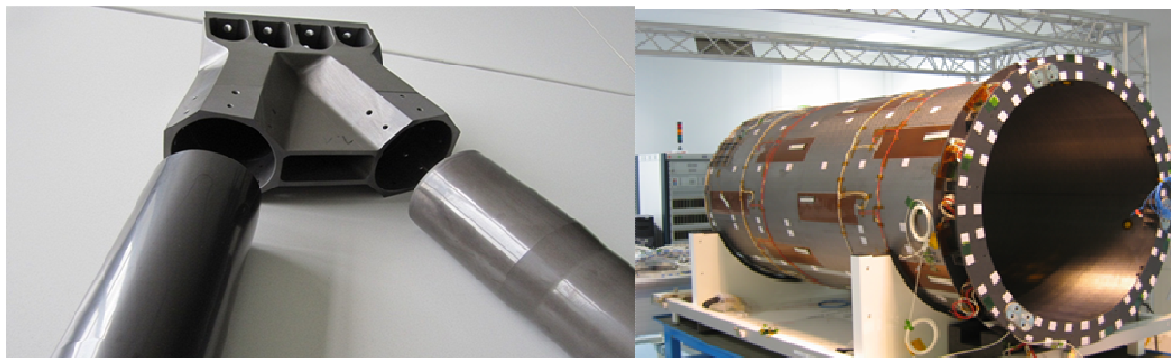


Fig 5 : Part of Silicon Nitride (Si_3N_4) truss and Carbon Carbon cylinder

V. BACK CAVITY STRUCTURE

Optical design of Korsh telescopes naturally leads to constitute a “box” for the back cavity. On the top of the box (main optical bench panel), the M1 mirror, the front cavity and the star trackers, are fixed. Inside the box are put all the mirrors (M3 + foldings), and on one side is mounted the detection unit with the focal plane.

This box has the advantage of being very stiff and procures easy adjustable positions of panels by simple washers adjustments. The box also procures a natural baffling of the optical path, no specific secondary structures are required, simple MLI s or SLIs are used to close the residual holes.

The back cavity is constituted of honeycomb panels. This technology has been used for many years in aerospace industry and it does not have to demonstrate its very high Stiffness/Strength-to-Weight Ratio and high reliability.

Carbon Fiber Reinforced Polymer (CFRP) with Cyanate-Ester resin skins are used to get a low Coefficient of Thermal Expansion ($1\mu\text{m}/\text{m}/^\circ\text{C}$). They also allow limited sensitivity to moisture release (contraction of $20\mu\text{m}/\text{m}$ from ground to vacuum environment).

This relative instability from ground to space environments is fully acceptable by back cavity since M3 and folding mirrors are far less sensitive than the M2 mirror (cf. II.C). Only the thermoelastic stability after calibration in flight is key to ensure star tracker stability with respect to instrument line of sight. Therefore, the initial moisture release of the structure does not affect geo-localization performances.

Panels are directly manufactured by Thales Alenia Space. This allows optimization and mastering the properties of the sandwich and especially the moisture release behavior. For instance, it is better to make panels with CFRP skins coming from same manufacturing batch in order to get a full symmetric behavior of the panel and to avoid any bending.

Thales Alenia Space's skills for sandwich panel manufacturing are demonstrated by in-flight structures of optical instruments performances (Hélios 2, IASI, Planck, Pléiades).

Moreover CFRP panels brings the following industrial constraints compatibility,

- They can be modified late during project development :
 - An insert can be added at the end of manufacturing
 - A skin reinforcement can be glued after panel manufacturing if a late negative safety margin is discovered by mechanical analysis.
- The CFRP is not fragile and can be repaired by local machining.
- There is no size limitations for satellite applications.

All these advantages of CFRP are also retained by most of instruments developed in the world. For instance it is used to constitute the Integrated Science Instrument Module (ISIM) of the James Webb Space Telescope[5].

In case optical design leads to a simpler optical bench instead of a back cavity, Si_3N_4 material may be used for the same advantages as for the front cavity.



Fig 6 : CFRP large back cavity produced by Thales Alenia Space

VI. CONCLUSION

Thales Alenia Space, through more than 30 years of experience, presents how the observation telescopes architectures are optimized in order to reach the best performances.

This optimization shall also consider the best material choice.

In the last years, the development of new technologies for materials like composites, ceramics and vitro-ceramics allow to use several high performances solutions.

Architecture and material trade-off shall be done by considering the full system performances. The material is like a tool to the service of the telescope performances and is not a design driver.

Thales Alenia Space has the advantage to master the design, the sizing, the assembly and the tests of all architecture and material solutions in order to propose the best instruments performances.

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