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HIGHLY LIGHT-WEIGHTED ZERODUR® MIRRORS

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ABSTRACT

Due to more and more stringent requirements for observation missions, diameter of primary mirrors for space telescopes is increasing. Difficulty is then to have a design stiff enough to be able to withstand launch loads and keep a reasonable mass while providing high opto-mechanical performance.
Among the possible solutions, Thalès Alenia Space France has investigated optimization of ZERODUR® mirrors. Indeed this material, although fragile, is very well mastered and its characteristics well known. Moreover, its thermo-elastic properties (almost null CTE) is unequalled yet, in particular at ambient temperature. Finally, this material can be polished down to very low roughness without any coating.
Light-weighting can be achieved by two different means : either optimizing manufacturing parameters or optimizing design (or both).
Manufacturing parameters such as walls and optical face thickness have been improved and tested on representative breadboards defined on the basis of SAGEM-REOSC and Thales Alenia Space France expertise and realized by SAGEM-REOSC. In the frame of CNES Research and Technology activities, specific mass has been decreased down to 36 kg/m².
Moreover SNAP study dealt with a 2 m diameter primary mirror. Design has been optimized by Thales Alenia Space France while using classical manufacturing parameters – thus ensuring feasibility and costs. Mass was decreased down to 60 kg/m² for a gravity effect of 52 nm.
It is thus demonstrated that high opto-mechanical performance can be guaranteed with large highly light-weighted ZERODUR® mirrors.

1. INTRODUCTION

1.1. Scope

Thales Alenia Space France has acquired since several years a strong experience in detailed design and sizing of large glass mirrors on programs such as Helios I and Helios II (French defence programs), ISO and Pléiades telescopes. Moreover, ZERODUR® is a well mastered material with exceptional and unequalled thermo-elastic and optical performances in spite of its relatively low strength and stiffness.
On the other hand observation missions require bigger and bigger mirrors to cope with more and more stringent specifications.
Therefore it was interesting to see to what extent ZERODUR® was still an adequate material while other novel materials are appearing in this field.

1.2. Constraints

Classically, a mirror is subject to a lot of mechanical and thermal solicitations which it has to resist while ensuring a high optical performance. From past experience the main design drivers are found in the following non exhaustive list :

- mass,
- quilting due to polishing pressure,
- gravity effects (which disturb ground performance measurements)
- global stiffness (eigenfrequencies to be decoupled from spacecraft),

2. BACKGROUND

2.1. Lightweigthing manufacturing capabilities

Manufacturing is driven by quilting constraints and walls and facesheets thickness.

Quilting :

As described in [1], quilting effects can be drastically decreased thanks to specific tools such as Ion Beam Figuring as developed by SAGEM.
This allows to increase the cells diameter for a constant facesheets thickness.

Manufacturing features :

Other improvements of classical manufacturing methods enable to reduce walls thickness along higher and wider walls and radius between walls. It is also possible to machine facesheets with constant thickness.

<u>Demonstration breadboard :</u>
As shown in Fig. 1 a breadboard demonstrating feasibility of lightweighting has been made by SAGEM with the following parameters :

- high and thin walls (height = 155 mm / length = 173 mm / thickness = 2.5 mm)
- facesheets with constant thickness (5mm)
- 6 mm radius between walls

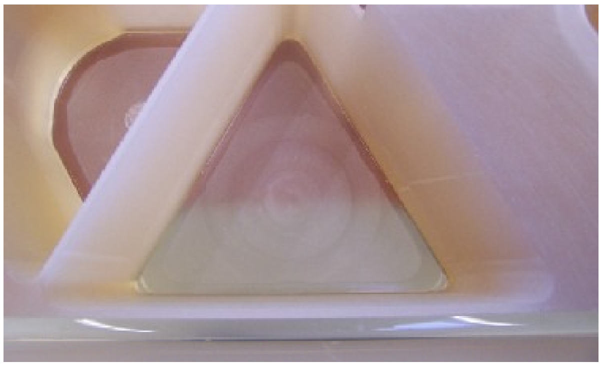

Fig. 1 Manufactured breadboard

More detail about this breadboard can be found in [1].

2.2. <u>Associated design and performance</u>

Taking into account the manufacturing capacities of SAGEM, Thales Alenia Space France designed a 1.5 m² mirror with triangular cells and evolutive thickness (see Fig. 2).

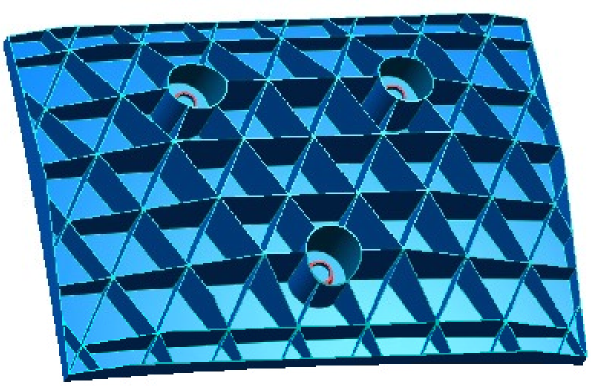

Fig. 2 Highly light-weighted mirror rear view

Mass of this mirror out of ZERODUR® is 54 kg thus **36 kg/m²** which places ZERODUR® mirrors in good position with respect to other materials.
Stiffness of the mirror with iso-static mounts is 183 Hz which perfectly fulfills the need for decoupling from the supporting structure.
Stress under 20g (typical launch loads) is within ZERODUR® admissible values with comfortable margin.

Therefore large size ZERODUR® mirrors are fully compatible with mechanical needs for light-weighting, stiffness and strength.
On the other hand opto-mechanical performance measurements can be disturbed by gravity effects for ground testing. This effect can be minimized thanks to the measurement configuration and to an adequate design. This design provides a wave-front error of about 74 nm (without tip/tilt nor focus) which can be easily subtracted to other measurements with small imprecision.

Fig. 3 Gravity effects (tilts and focus removed)

Full analysis of the mirror performance, with interface definition and validation with breadboards can be found in [1].

This study has demonstrated the competitiveness of ZERODUR® mirrors for space telescopes thanks to optimized manufacturing process aiming at reducing specific mass, even for very large mirrors.
In order to improve the capabilities of such designs, it has been decided to investigate two ways : improvement of manufacturing parameters and design optimisation.

3. IMPROVEMENT OF MANUFACTURING CAPABILITIES

3.1. <u>Target manufacturing parameters</u>

It has been decided to investigate even better manufacturing features than those of § 2.1. This has been done in the frame of a CNES Research & Technology activity [2].

Thanks to a new manufacturing technique using ultra-sound, SAGEM has made a more elaborated breadboard aiming at validating the whole manufacturing process. It confirms lightweighting parameters and demonstrates polishing feasibility.

3.2. Relevance verification

In order to validate the relevance of such parameters, a design study was performed on a large diameter mirror. The goal was to check that it was possible to define a design in order to have less than 50 nm RMS wave-front error under gravity, while keeping a reasonable specific mass close to 35 kg/m².

The first question was to define where the interface points had to be put. There are several solutions and the concept retained here was a three-point isostatic fixation. An analysis showed (with no surprise) that the best position was not on the edge of the mirror but at the back. Fig. 4 shows that there is an optimal radius to put the fixations.

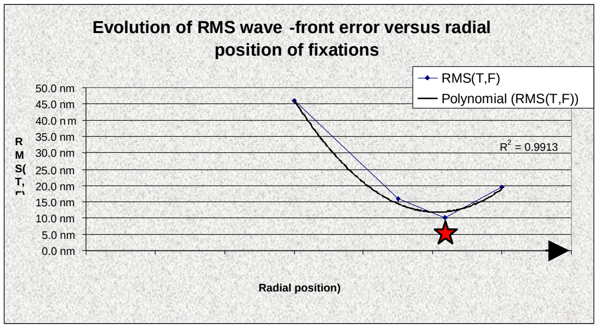

Fig. 4 Optimisation of radial position of fixation

Then a concept optimization was run in order to find out relative best performance of several fixation positions.

Type A consisted in a back fixation, which should give the best results. Type B and C consisted in two peripheral fixation possibilities. See Fig. 5.

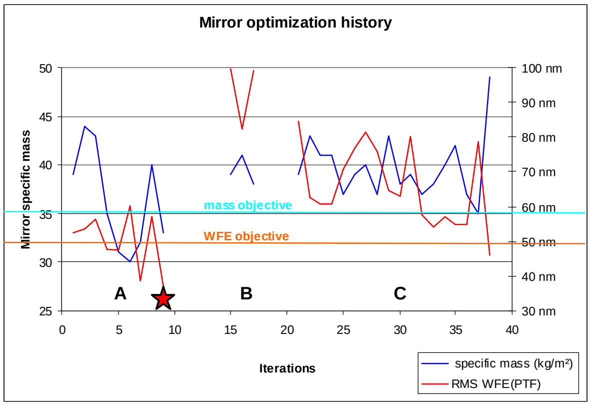

Fig. 5 Mirror optimization evolution

Type A exhibited almost from the start the right wave-front error performance, and optimization was limited to reduction of mass.

Type B was too far out of specification and couldn't be optimized.

Type C was as expected not as good as A because of fixations position. However a limited optimization study was performed with released mass specification. And it was possible to decrease RMS wave-front error in this condition.

The final design, based on A9 solution (red star in Fig. 5) of mirror is shown in Fig. 6.

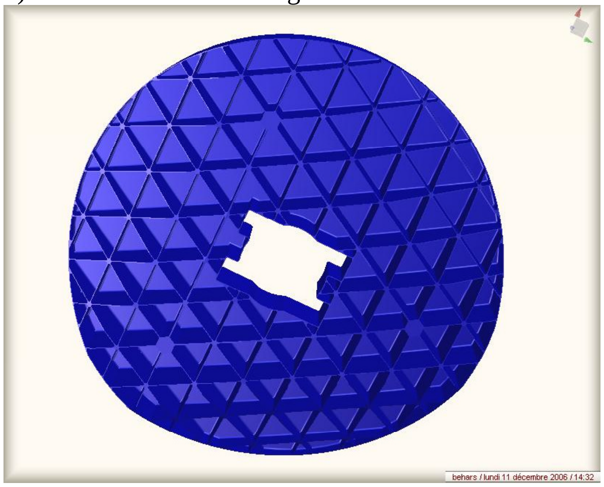

Fig. 6 Optimized mirror design

The final performance of the mirror under gravity is a **wave-front error of 45 nm RMS**. The interferometric view of this effect is shown in Fig. 7.

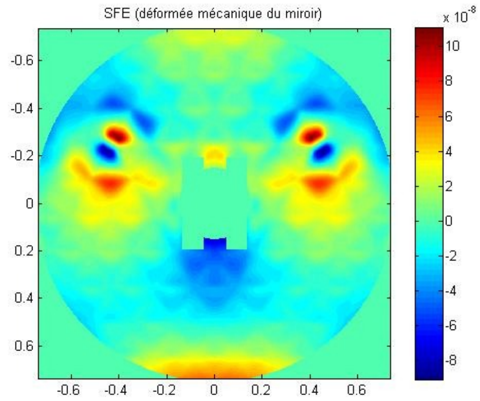

Fig. 7 Optimized mirror under gravity – interferometric view

The decomposition of this effect on Zernike polynomials is given in Fig. 8.

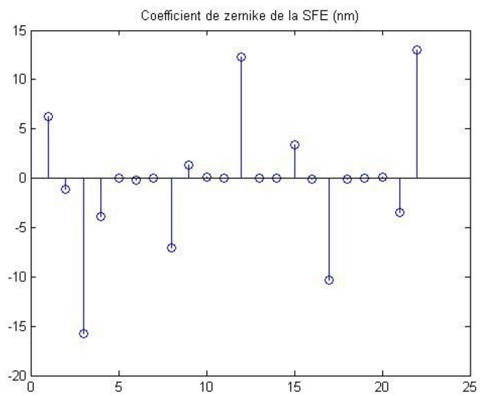

Fig. 8 Optimized mirror under gravity – ZFR Zernike decomposition

Moreover, first eigenfrequency of the mirror is above 120 Hz which ensures a frequential decoupling from the supporting structure.

Strength analysis exhibits more than 30 % of safety margin with respect to a very conservative 10 MPa ultimate value (see [5] and [6] for discussion about ZERODUR® strength).

It is noticeable that the solution with peripheral fixation can provide same order of magnitude for optical performance if mass requirement is released.

3.3. Validation breadboard

The manufacturing process is done in two steps. The first step consists in a pre-lightweighting with classical tools (see Fig. 9) in order to reach a reasonable thickness with a minimum of risks.

Fig. 9 SAGEM second breadboard after rough machining

The second step uses the new machining method with ultra-sound which reduces drastically the machining efforts and enables to reach lower thickness than with usual method. The final breadboard is shown in Fig. 10. Ultra-sound machining for this breadboard longed same duration as pre-machining.

Fig. 10 SAGEM second breadboard after final machining (12 central cells only)

4. DESIGN OPTIMIZATION

4.1. Scope

Two solutions are available to optimize the opto-mechanical behaviour : either manufacturing minimum parameters have to be improved or design has to be reworked. The best solution is of course to perform both in a tuned ratio to minimize costs, schedule and risks.

The opportunity to apply this strategy was offered in the frame of SNAP invitation to tender from CNES in association with US Department of Energy.

The key challenge of the SNAP mission (SuperNovae Acceleration Probe) is to determine the nature of dark energy. Recent measurements carried out by Berkeley's Supernova Cosmology Project and elsewhere made the startling discovery that the expansion rate of the universe is accelerating. The SNAP mission is expected to provide an understanding of the mechanism driving the acceleration of the universe. The SNAP science mission is described at [4].

The French part is to deliver the telescope, with a 2m diameter mirror. Thales Alenia Space France concept has been chosen after the assessment study performed in 2007 for CNES [3].

4.2. Manufacturing parameters

For this study, the manufacturing capabilities taken into account are :

- facesheets minimal thickness = 4 mm
- walls minimal thickness = 3 mm
- walls maximal height = 150 mm
- minimal radius between walls = 6 mm

Walls thickness with respect to height and width, and radius of curvature are less stringent than for the previous breadboards, thus securing feasibility and costs.

4.3. Methodology

Thales Alenia Space France has developed tools to be able to optimize the concept in a minimum of time. The main tool consists in computing the wave-front error from the FEM output (mechanical deformation of mirror's optical surface) and decomposing it on the Zernike basis thanks to an in-house software. This provides the RMS value tilts and focus removed which is the objective function and a visual associated deformation in order to better understand the deformation. This tools gives also an output in interferometric format directly readable by optical tools such as CodeV.
The logic for mirrors design optimization is described in Fig. 11. This illustrates the strong imbrications of optical and mechanical engineering.
It is noticeable that optimization under thermal constraints can also be driven since Thales Alenia Space France has developed tools to directly transform thermal cartography into thermo-elastic loading case for the Finite Element Model.

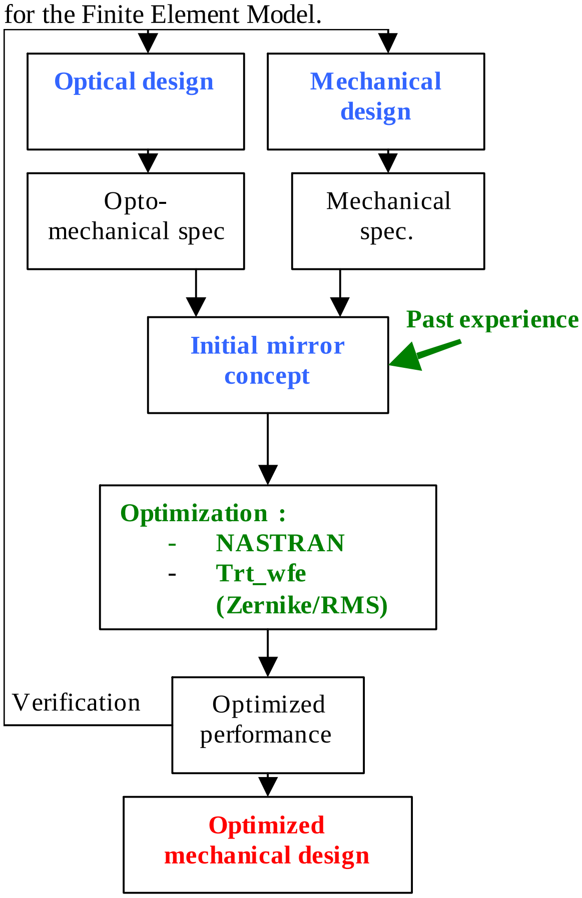

Fig. 11 Design optimization method

4.4. SNAP primary mirror design

The main problem for SNAP mirror was to minimize the gravity effect because it disturbs ground measurements. This can be achieved by an adequate measurement configuration coupled with an adapted design. The objective function was thus the RMS wave-front error under gravity in ground measurements position, after removing piston, tilts and focus.
The target was to have less than 70 nm RMS left, since this is a measurable amount which can be removed from interferometric measurements with small error.
Another constraint was mass which had to be less than 200 kg.
At last, more classical mechanical design constraints had to be taken into account. In particular it was necessary to keep in mind the feasibility and strength of the interface zone.
As shown in Fig. 12, 82 computation steps were necessary for this optimization.

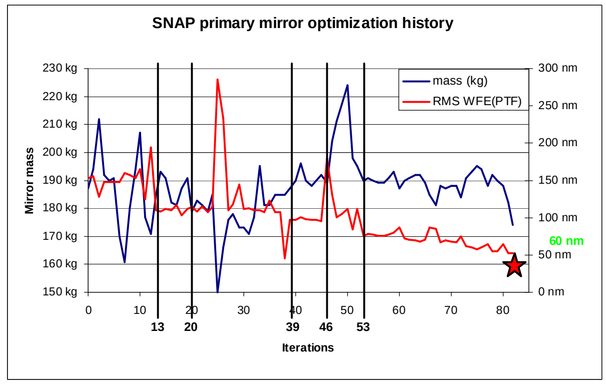

Fig. 12 SNAP mirror optimization evolution

The first 20 steps aimed at testing sensitivities to walls and facesheets thickness all over the mirror, with a first convergence at step 13. Step 20 gave a RMS wave-front error of 114 nm.
From steps 20 to 39 several tests have been performed to understand where the limitations are located in the design, because it was not possible to decrease the wave-front error. This series of tests enabled to find out solutions (cells shape, walls thickness…) to improve the concept.
Between steps 39 and 46 the concept was reworked and a new basis for optimization were created. From step 46 the final basis was chosen. One can see that the optimization direction was not found before step 53 : modifications increased mass when decreasing wave-front error.
From steps 53 to 82 occurred a fine optimization of the concept in order to reach best compromise between mass and wave-front error objectives.

The final design of the mirror is shown in Fig. 13.

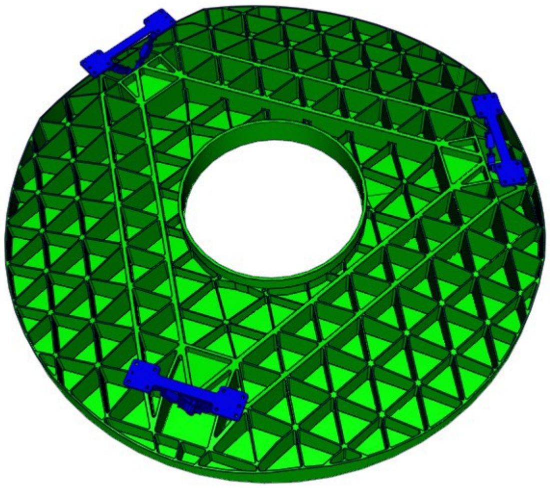

Fig. 13 Optimized SNAP mirror design

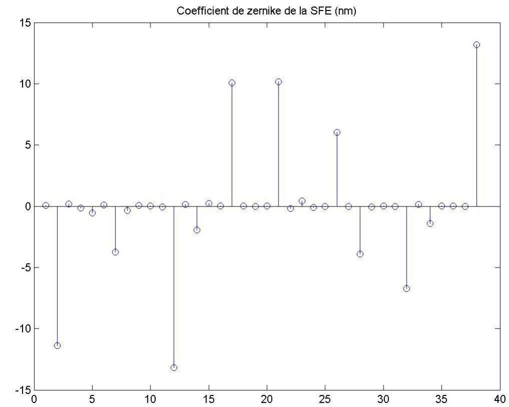

Fig. 15 Optimized SNAP mirror under gravity – ZFR Zernike decomposition

4.5. SNAP primary mirror performance

The final performance of the mirror under gravity is thus a **wave-front error of 52 nm RMS,** for a specific mass of **60 kg/m² (174 kg)**. The interferometric view of this effect is shown in Fig. 14.

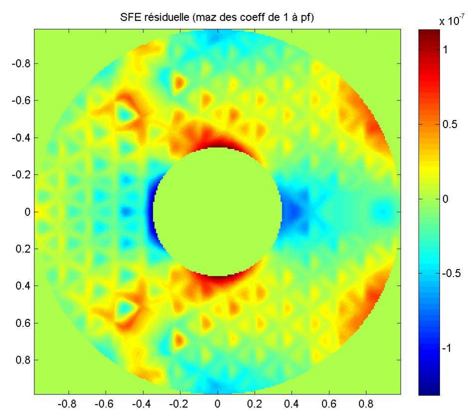

Fig. 14 Optimized SNAP mirror under gravity – interferometric view

The decomposition of this effect on Zernike polynomials is given in Fig. 15.

Moreover, first eigenfrequency of the mirror is above 120 Hz which ensures a frequential decoupling from the supporting structure.
Strength analysis exhibits more than 30 % of safety margin with respect to a typical conservative 10 MPa ultimate value.

Finally, since thermo-elastic performance of the telescope was an important criterion in the study, the wave-front error was computed at worst instants under thermal cartography. Fig. 16 shows the interferometric view of the short-term (after slew) thermo-elastic effect on SNAP primary mirror. The wave-front error is only 0.04 nm RMS which illustrates the very good efficiency of ZERODUR® in such configuration. Another computation was performed for daily stability which gave 0.12 nm RMS, still very low.

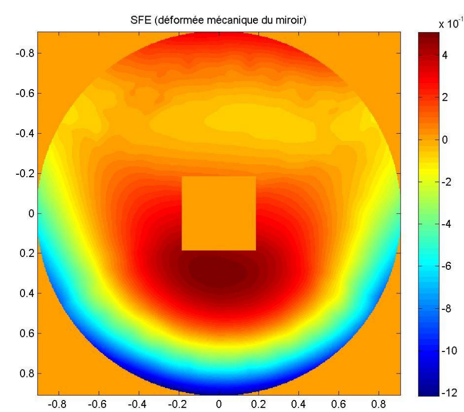

Fig. 16 SNAP – short-term thermal stability (after slew) : WFE = 0.04 nm RMS

5. FUTURE PROSPECTS

Thales Alenia Space has developed several tools in order to manage performance assessment and design optimization of mirrors with respect to RMS wave-front error.

However, this can be improved by automating some steps using FEM optimization modules, associated to more precise objective or constraint functions such as one Zernike term or high frequency residual amount. The implementation of such tools is now in validation phase at Thales Alenia Space France.

6. CONCLUSION

The results described in this paper show that designing and manufacturing large size mirrors out of ZERODUR® is compatible with stringent opto-mechanical requirements. It is now possible to define ZERODUR® mirrors up to 2m diameter, with a specific mass down to 60 kg/m² (174 kg), and a gravity effect on wave-front down to 52 nm RMS. Moreover, its unequalled thermo-elastic behaviour places ZERODUR® among the best candidates for high stability telescopes' primary mirrors in visible wavelengths.

SAGEM has demonstrated with several breadboards that manufacturing mirrors with 90% light-weighting is feasible with existing tools and can be implemented.

Thales Alenia Space France has developed and is still improving a strong ability to design and optimize mirror structures with respect to stringent opto-mechanical requirements.

7. DOCUMENTS

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