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NEW DESIGN AND NEW CHALLENGE FOR SPACE LARGE ULTRALIGHTWEIGHT AND STABLE ZERODUR® MIRROR FOR FUTURE HIGH RESOLUTION OBSERVATION INSTRUMENTS

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INTRODUCTION

Space telescopes pupil diameter increases continuously to reach higher resolutions and associated optical scheme become more sensitive. As a consequence the size of these telescopes but also their stability requirements increase. Therefore, mass of space telescopes becomes a strong design driver to be still compatible with price competitive launcher capabilities. Moreover satellite agility requirements are more and more severe and instruments shall be compatible with quick evolution of thermal environment.
To overcome these challenges, a new generation of space telescopes based on adaptive optics is on the track, allowing to reconsider the requirements of the primary mirror and therefore allowing new innovative lightweight concept as the primary mirror wave front error could be corrected by a small active mirror located at an intermediate pupil.
Nevertheless the mirror wave front error shall remain stable during all satellite maneuvers as active correction can't be instantaneous.
Thales Alenia Space has proven the interest of Zerodur material for the primary mirror. As for previous High Resolution earth observation instruments, its thermal stability is a key advantage**.** Its quasi null Coefficient of Thermal Expansion (CTE) allows it to remain stable (few nanometers) during all mission phases even when it is submitted to quick surface thermal flux evolution.
New concepts of large lightweight Zerodur® mirror have been conjointly developed by Thales Alenia Space and Thales SESO taken into account the adaptive correction of the wave front error. Very challenging density is achievable for a 2 meters mirror : a 17kg/m2 Zerodur hybrid mirror and a 25 kg/m2 closed back assembled Zerodur mirror have been designed. For both concepts, breadboards have been successful manufactured and tested paving the way for future very large, extremely lightweight and hyperstable Zerodur® mirrors.

CONTEXT

More and more space missions require, for visible earth observation or astronomic observation, telescope offering very high spatial resolution leading to telescope with large M1 mirror and with a M2 far from M1. Mass of space telescopes becomes therefore a strong design driver to be still compatible with price competitive launcher capabilities.
Moreover satellite agility requirements are more and more severe and instruments shall be compatible with quick evolution of thermal environment.
To overcome these challenging requirements, space telescope with adaptive optics seems the ideal solution to reduce mirror WFE error requirements and mirror positioning stability, both being correctable thanks to mechanisms.
Since several years and based on its experience on very high resolution optical space instruments (Helios 1, Helios 2, Pléiades, HR instruments for export market), Thales Alenia Space, with different partners, has engaged :

1/ detailed studies to design a space telescope with adaptive optics for low and geo orbit,
2/ detailed analysis to specify the different key elements,
3/ substantial developments to demonstrate and validate the adaptive optics technology for future space telescope.

In the frame of CNES contract, Thales Alenia Space and Thales SESO study and develop a new generation of mirrors dedicated to future adaptive large telescopes.

PRIMARY MIRROR REQUIREMENTS FOR AN ADAPTIVE HIGH RESOLUTION SPACE INSTRUMENT

Following system analysis of space active telescopes, Thales Alenia Space, in relation with CNES, has established the requirements of large M1 mirrors in association with a deformable mirror located in an intermediate pupil.
The use of a deformable mirror to correct M1 WFE allows a drastic relaxation of the M1 WFE requirements.
M1 WFE requirements are strongly linked to the correction performance and capacity of the deformable mirror, and to the in orbit correction period which will define the stability requirements of the mirror.
In the frame of CNES contract, Thales Alenia Space is developing a space deformable mirror based on Madras mirror, **Fig. 1,** mirror initially developed up to TRL 4 by a consortium led by Thales Alenia Space involving also Thales SESO and LAM. Madras has been developed specially for a space use, sized vs launch loads and ensuring a very high stability even in an open loop mode .

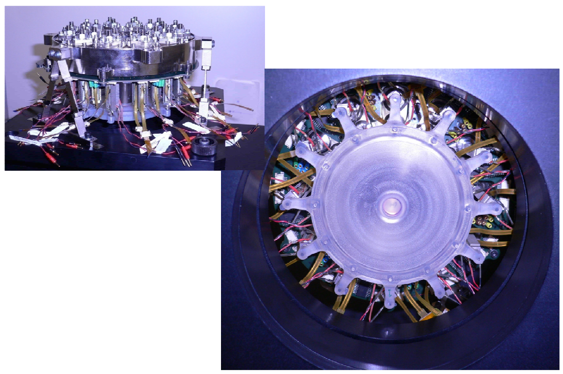

Fig. 1 Madras deformable mirror

Correction performances and stroke of the deformable mirror have been determined and validated by precise WFE measurement allowing to dispose of a consolidated tested available correction data base.

System study has determined the mirror optical performance necessary to fulfil the requested WFE performance of future HR and VHR optical telescopes during all the life in space of the instrument. On ground WFE after correction are also specified to allow a proper integration of the instrument and shall allow the verification of the instrument MTF. Such requirements and correction range shall be also compatible of the stroke allowable by the deformable mirror.

Adaptive optics will permit to strongly reduce the mass of the mirror. A range of an area mass of the equipped mirror with its Isostatic Support Mount (ISM) between 20 Kg and 25 Kg /m2 is then foreseeable for a mirror diameter between 1,5m and 2m. Nevertheless a special attention shall be put on the design and manufacturing process to limit the high frequency terms of the WFE which cannot be corrected by the deformable mirror and which will potentially strongly reduce the image quality of the instrument at some spatial frequencies of interest.

Mirror WFE and focus stability between two corrections is also a key issue v.s. the telescope performances.
Earth observation satellites are now very agile, allowing to point at any moment toward earth scenery of interest and toward anti sun direction to recharge the battery through fixed solar panels. Therefore primary mirror is exposed to very high thermal flux variation along and between orbits .

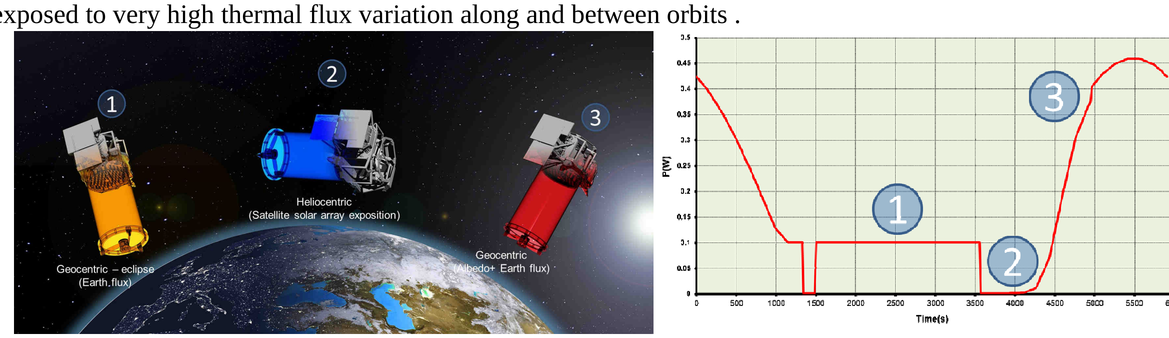

Fig 3 : External thermal Fluxes absorbed by Telescope Primary Mirror (Albedo+Earth) along one typical orbit

If mirror is thermally sensitive, thermal level and thermal gradient affects strongly the focus stability and the WFE variation. To calibrate the telescope and initiate focus and WFE correction of the mirror, today active correction on a space telescope observing earth on push broom mode requires images of good contrast and good spatial frame. The availability of such images, the time to treatment and also the on ground verification for a first mission will limit strongly the frequency of the correction. To be fully robust to any case and to have a system fully operational with a full availability to take operational images at any time, Thales Alenia Space has fixed the minimal correction period of the WFE of the mirror which shall remain large especially for a first operational mission. Therefore despite the use of active correction for the WFE, mirror shall remain ultra-stable between two corrections.
Mirror shall of course sustain mechanical launch loads (QSL, sinus , random) and also notably the acoustic loads which can be a sizing loads case.

LIGHTWEIGHT PRIMARY MIRROR NEW CONCEPTS

On primary mirror, the thermal steady state factor (Thermal conductivity/Coefficient of Thermal Expansion (CTE)) is often compared. This factor accords same importance to CTE as to thermal conductivity. However, for highly lightweight large mirrors, most of the material is removed, therefore actual conductivity is limited and doesn't ensure a thermal homogeneity as thermal heat transfer is mostly radiative in orbit. Temperature gradients appears in the mirror, so CTE dominates and thermal conductivity has a poor influence on mirror stability.
Comparing different materials, Zerodur is far more stable for mirrors than all other polishable space materials (CTE of selected procurement of Zerodur® is 314 times lower than SiC one).

This is why Thales Alenia Space selects Zerodur® for its telescopes and keeps this orientation for future very large mirrors associated to adaptive optics.

With this approach, adaptive optics will correct ground to flight instability and mid-term evolutions but doesn't necessitate to measure and correct very often thermoelastic deformations of the primary mirror. This approach will ensure therefore equivalent availability and reliability to those of a passive telescope, without adding ground operational constraint.

Of course classical Zerodur® mirror concept which has been designed without taken profit of adaptive optical correction suffered in the past from some slight drawbacks linked to the limited Young modulus of the Zerodur® and to limited past stress sizing coefficient. Such concept allows nevertheless already space mirrors with an areal density of 60 Kg/m2 for mirror above 1meter size on board of passive space telescope.

To reduce more strongly the mass while taken benefit of the quasi null CTE of the Zerodur® , Thales Alenia Space associated to Thales SESO has studied and started the development of two new generations of Zerodur® mirror specially optimized thanks to the use of adaptive optics :

- Assembled Zerodur® mirror up two meters diameter allowing an area mass of less than 25 Kg/m2 for 1,5m,
- Hybrid sandwich Zerodur® mirror for application from 2m to 4 m allowing an area mass of less than 17 Kg/m2 for 2 m.

LIGHTWEIGHT DESIGN OF ASSEMBLED ZERODUR® MIRROR

One of the key issue in the design of the primary mirror is to limit the WFE parts which could not be corrected by the adaptive mirror. Therefore High Frequency (HF) terms shall be kept under control during all the phases of the Mirror (from manufacturing up to the end of life). Thanks to the favorable behavior of the Zerodur, it is now possible to totally suppress the generation of quilting by optimizing lightening and polishing sequences. This is also facilitated by the fact that Zerodur needs a polishing pressure 3 times lower than SiC for example.
Therefore skin thickness and cells size are now largely optimized.
In order to increase the mirror stiffness (eigen frequency, dynamic loads response, deformation under gravity) ISM position has been optimized at around 2/3 of the diameter leading to a rear fixation of the mirror instead of lateral one.
ISM has been optimized to filter as much as possible displacement coming from the I/F of the structure of the telescope (I/F flatness, I/F deformation) as on large telescope, for development and mass constraint, it is not possible to polish the mirror already integrated on telescope frame.
To optimize the mass/stiffness ratio, a back plane made in Zerodur® and coming from the same blank in order to have exactly the same CTE, is bonded on the reinforced stiff triangle linking together the 3 I/F points of the mirror. Such back plane allows to reduce strongly the height of the mirror limiting the time and the difficulties of the lightweight sequence and therefore authorizing the machining of thin ribs, see design **Fig. 2.**

Bonding has been strongly optimized to not affect either the extremely low thermo-elastic behavior of Zerodur® mirror and either to not affect after optic adaptive correction the long term stability of the mirror (due to bonding ageing, moisture effect or strain relaxation).

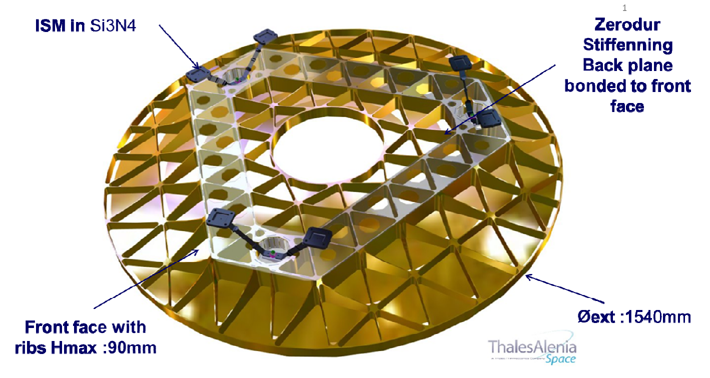

Fig. 2 Assembled Zerodur® mirror design

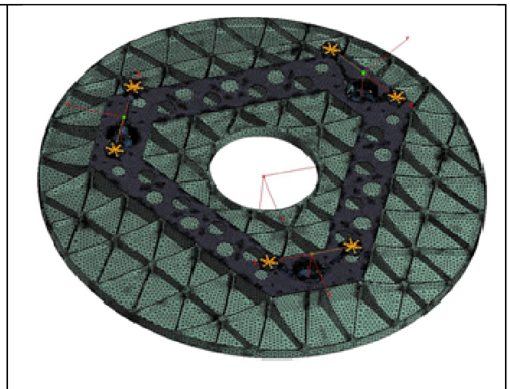

Fig. 3 FEM model

Based on all these design drivers, a 1,5m design has been optimized by Thales Alenia Space through deep opto-mechanical analyses based on very detailed Finite element model (1 million nodes, **Fig**. **3**) , model taken into account all manufacturing industrial constraints determined through CAM tools (corner radius, bottom cells accessibility with tools).
Mass of the equipped mirror including its ISM is less than 46 kg leading to an area mass of less than 25 kg/m2.
All bonding have been also modeled in 3D to take into account the bonding impact on the WFE.
Despite the low mass and large size, the first eigen frequency is above 113Hz and first lateral mode (ISM mode) is at 153 Hz allowing a sufficient decoupling with launchers, **Fig. 4.**

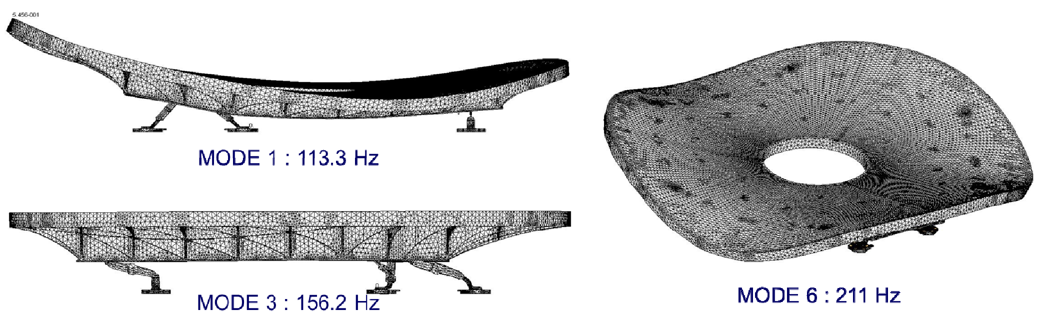

Fig. 4 eigen frequency of the Zerodur® assembled mirror

Mirror, bonding , ISM stresses have been computed under 15 QSL, sinus up to 125 Hz and acoustic, showing positive margins, thanks to the use of new mechanical data base performed on numerous samples having representative surface condition (use of same tools, same acid etching) .
WFE performance has been established using the FEM. For each case the WFE is break dawn in Zernike coefficients. Using Madras correction, the correctable Zernike terms are subtracted taking into account the residual, and corrected WFE performance are then calculated, with a great attention to HF terms .

Thanks to the use of the deformable mirror, the mirror gravity deformation on ground is allowed to be important (WFE range 100 nm Rms, **Fig. 5**), deformation which is well corrected by Madras. After correction by the deformable mirror, the residual on ground WFE performances are slightly degraded compared to performances in orbit. Nevertheless, the on ground instrument MTF performance measurement is still relevant.
Thanks to measurements optimized sequence, gravity effect is removed during the measures, mirror is then polished without gravity impact. Therefore, in orbit WFE performances are not affected by gravity.
Nevertheless, to take into account measurement uncertainties some % of gravity impact is taken into the budget.

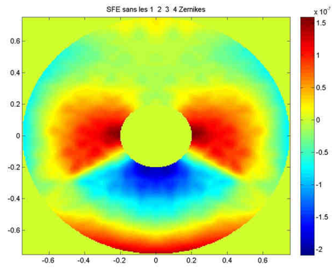

Fig. 5 mirror SFE map under gravity

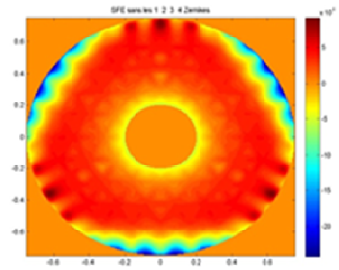

Fig. 6 coating impact on mirror SFE

For large and soft mirror, coating deposition could be an issue for the WFE performance. Thales Alenia Space and Thales SESO have gained large experience to better determine and control the coating impact on the WFE. Characterization measurements on samples and correlated model with the results on actual mirrors are used to predict very accurately the coating impact. The design optimization and the polishing sequence permit to limit drastically this effect. The residual WFE after adaptive correction is less than 6 nm Rms.

I/F deformation during integration and in orbit affects also the WFE of the mirror, for each ISM I/F and for each degree of freedom , bias have been introduced and the mirror WFE is calculated, **Fig. 7**).
After combination of all these loads cases and determination of a worst load case, the WFE is computed to 33 nm Rms, then this WFE is very well corrected by the deformable mirror leading after correction to a residual of only 7 nm Rms.

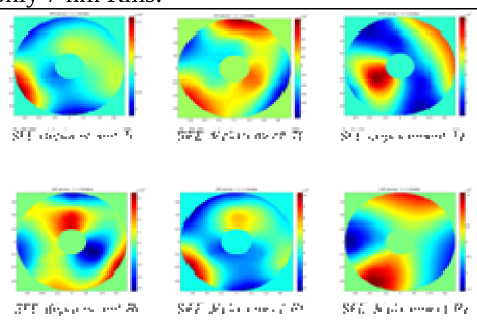

Fig. 7 SFE map of the mirror under I/F loads cases

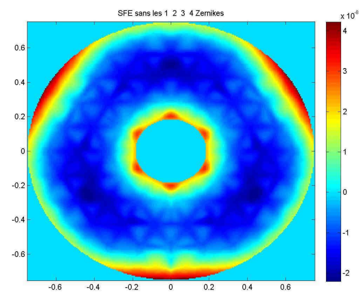

Fig. 8 SFE map of the mirror after 10 year in space due to radiation

Zerodur® mirror of space telescopes are subjected to radiation which can impact the WFE. Thales Alenia Space use dedicated tools to calculate the radiation dose profile in the depth of the mirror and calculate the induced deformation and therefore the WFE impact. On such soft mirror the WFE can reach 33 nm Rms end of life, **Fig. 8.** This deformation is also very well corrected by Madras , leading to only few nm after correction .

Mirror thermo-elastic behavior has been also calculated based on detailed thermal maps all along the orbits taken into account the bonding and ISM CTE effects. Thanks to Zerodur® extremely low CTE and the optimised design, thermo-elastic effect is less than 2 nm Rms WFE in worst case scenario.

Taking into account all these effects and considering polishing performance corrected also partially by Madras, in flight WFE performance of less than 20 nm Rms for low frequency terms and less than 13 nm Rms for high frequency terms is attained. This detailed study demonstrates that such lightweight mirror will meet all the required performances with margins.

FIRST BREADBOARD RESULTS

A 400mm mirror breadboard representative of the technological key elements of the M1 mirror has been designed, manufactured and tested.

The breadboard has a front face, ribs, and a reinforced back plate with optimized thicknesses of few millimeters representative of the flight mirror **Fig. 9**.

Back plate bonding has been optimized to strongly reduce the influence of the bonding on to the mirror WFE and stability and to be compatible with large mirror manufacturing.

This bonding technology has been validated onto Zerodur® representative samples and bonding strength above 20 Mpa have been reached after ageing thermal cycling.

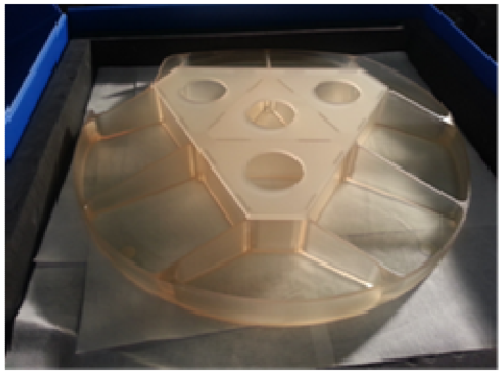

Fig. 9 400 mirror breadboard with assembled reinforcement back plate

The mirror has been then polished and tested under severe environments to check its WFE stability, mirror has been submitted to :

- 10 thermal ageing cycles under humidity [-5°C, +40°C]
- 1 cycle under vacuum
- 1 cycle [+20°C,+80°C] to simulate cleaning process

Between and after all these tests no WFE evolution has been measured showing the great stability of this assembled mirror concept.

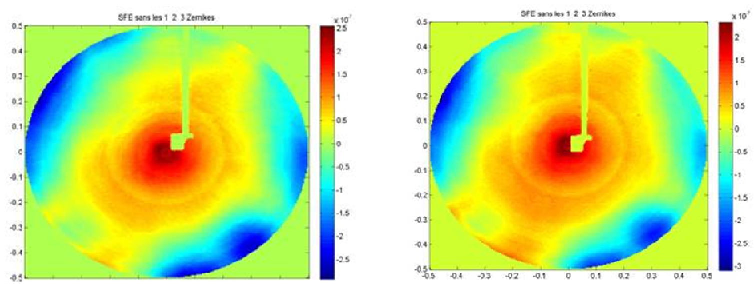

Fig. 10 WFE map before and after cycling showing the high WFE stability

HYBRID SANDWICH ZERODUR® MIRROR

In order to combine very high thermo-elastic stability of Zerodur® and very high stiffness/ mass ratio for very large mirror, a more advanced design has been developed by Thales Alenia Space with Thales SESO support.
The concept consists of a sandwich mirror made of 2 Zerodur® shaped thin skins, one on front face, and one on rear face linked together by an optimized CFRP honeycomb using high Young modulus and conductive Fibbers and cyanate resin. Based on this concept a 2 meter mirror has been designed, **Fig. 11**, and finely analyzed by finite elements models. Such mirror has an area mass of only 17 Kg/m2.
Mirror ISM has been fixed on the rear side inside reinforcements of the Zerodur® back skin and fixed at 2/3 of the diameter to optimize the stiffness under gravity and eigen frequencies.
The honeycomb is homogenous in density and thickness on all the mirror in order to avoid to create inhomogeneity and discrepancy in terms of stiffness, CTE, moisture impact on the mirror surface. Such design allows a soft correction of these effects by MADRAS deformable mirror.
Honeycomb properties and height have been specially optimized to be at an optimum in terms of global performance/mass ratio, giving a height of 80 mm and a very small cell size. Such cells size allows to use Zerodur® very thin front face shell without creating quilting during polishing, coating and/or others effects.

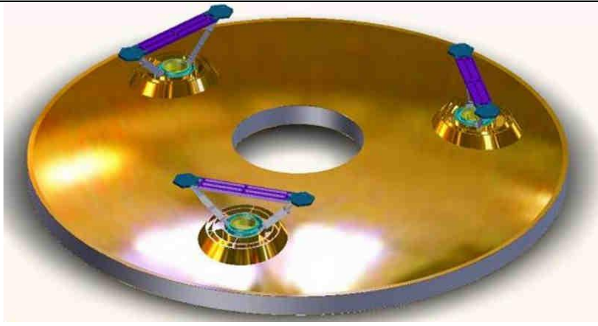

Fig. 11 Hybrid sandwich Zerodur® mirror

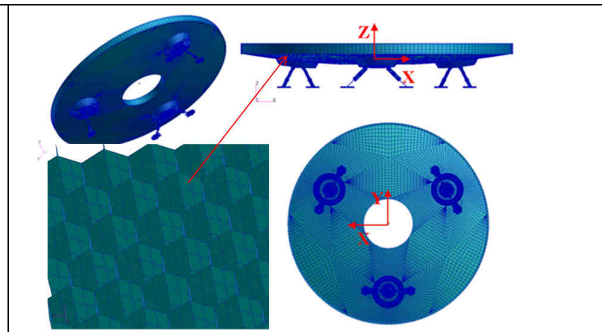

Fig. 12 hybrid sandwich Zerodur® FEM

FEM model takes into account of course the bonding between the core and the mirror and equivalent orthotropic properties. CTE, CME of the sandwich core and bonding have been computed through dedicated models and such properties introduced in the large model, **Fig. 12** .
As for the assembled Zerodur® mirror, full analyses have been performed , showing the conformance of eigen frequency requirement (100 Hz), and showing positive margin vs launch loads.
In orbit, computed thermal and thermo-elastic behaviors show also the great WFE stability along orbit, only focus shall be corrected , one to twice per orbit , this correction being in open loop mode.
On such large mirror, WFE under gravity is rather large (near 200 nm Rms), **Fig. 13**, hopefully essentially with low frequency(LF) terms, terms easily compensable by Madras on ground. Limited LF terms after correction, allow a safe telescope and focal plane integration and alignment. Coating impact has been studied as well and is limited and homogeneous, WFE after anticipation and correction by Madras is only 4nm (**Fig. 14).**

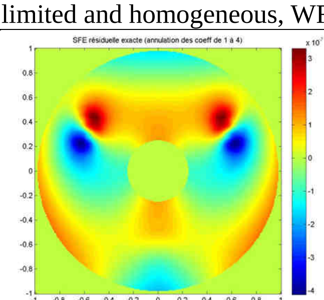

Fig. 13 SFE map under gravity

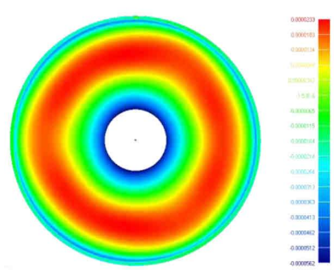

Fig. 14 SFE map due to coating

ISM interface deformation impact on the mirror WFE are very limited : 9nm Rms before correction 3 nm after correction by Madras, as for radiation impact wich is limited to 8 nm Rrms after correction by Madras .
Mirror WFE under moisture effect of the bonding and CFRP has been studied with particular interest. Bonding meniscus has been modeled in 3 D with the honeycomb and skin on local model,Fig**. 15** . Equivalent shell model has been established and the computed properties introduced in goblal model.
Full moisture release remains important on WFE : 150 nm Rms, **Fig. 16**, and even corrected by Madras residual is high: 60 nm Rms as HF terms are high, 50 nms,**Fig. 17.**

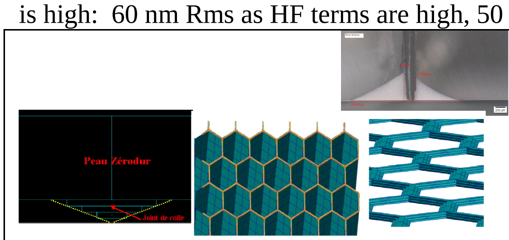

Fig. 15 3D model of bonding meniscus, core & skin

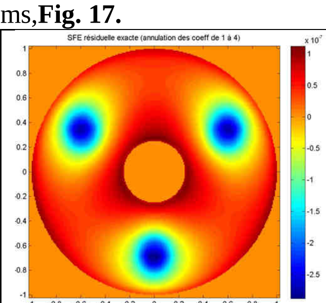

Fig. 16 mirror SFE due to moisture release

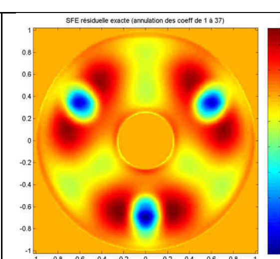

Fig. 17 mirror HF de to moisture release

To cope with WFE requirement, it is necessary to anticipate moisture impact during polishing either by aniticipation by model either by making a WFE measurement under vaccum between a polishing step to determine the moisture WFE map and substract if from WFE measurment done under air.
Under this condition an hybrid Zerodur® sandwich mirror meet the 25 nm WFE performance goal for a 2 m optical mirror during all its life in orbit.

HYBRID SANDWICH ZERODUR® MIRROR BREADBOARD MIRROR RESULTS

Based on the design and analysis performed on the sandwich Zerodur® mirror, Thales Alenia Space has manufactured on own funding a 300 mm sandwich Zerodur® mirror with CFRP core, Fig**. 18** and also characterization sandwich samples Fig**. 19**. Mirror breadboard has been polished at 60 nm Rms showing the convergence of the polishing Fig**. 20**.

Fig. 18 Shaped CFRP honeycomb

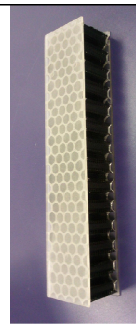

Fig. 19 sandwich sample

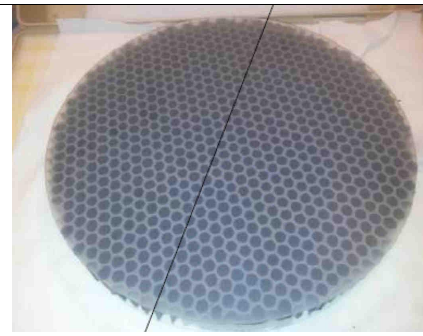

Fig. 20 300 mm sandwich mirror (Zerodur® skin, CFRP core)

The mirror has been then tested under evolutive moisture condition by Thales SESO.
During the moisture test, the WFE evolution has been measured with a good return to 60 nm after the test, showing the long term stability. As predicted, important WFE due to moisture has been measured : evolution from 60 nm to 130 nm Rms. When compared to prediction we can see a good correlation between measures and prediction **Fig. 21**.

variation WFE etat sec etat hydrique	delta mesure^2 WFE etat sec-etat humide SESO (sauf terme power)	delta WFE calculé par TAS
total avec power	131,1	131,7
WFE total sans power	76,6	96,8
WFE power	82,0	89,4
PTF AST coma et sa3	63,6	40,5
WFE HF Z>36	8,3	5,0

Fig. 21 comparison between prediction and measure

CONCLUSION

Thanks to adaptive optics, new extremely lightweight Zerodur® mirror designs have been designed and optimized to meet all requirements. Thanks to its ultra-high thermo-elastic stability, such Zerodur® mirrors allows a safely way to implement adaptive optics for high to very high angular resolution telescopes.
Thales Alenia Space and its partners are paving the way to a new generation of very compact and lightweight telescopes. Unequalled developments in terms of resolution, image quality under cost ratio in orbit are in prospect.
The Team Thales Alenia Space /Thales SESO under CNES contract develop a 1,5 m assembled Zerodur® mirror. First engineering steps sanctioned by mirror PDR has been held with success authorizing mirror blank manufacturing. The design is already consolidated by the manufacture, the tests and the performance characterization of a 400 mm mirror breadboard.
Zerodur sandwich mirror has been also studied, such solution allowing very low mass for high optical performance and short term stability. Such mirror offers a solution for ultra-stable ultra- large and ultra-lightweight future mirrors up to 4 meters. The feasibility of such solution has been already validated through a 300 mm mirror breadboard, which has confirmed the calculated behavior under humidity. Activities to reduce the moisture impact on Zerodur® sandwich mirror have now started.

ACKNOWLEDGMENT

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