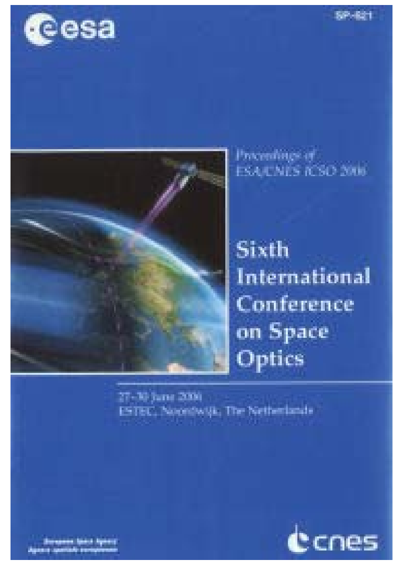
International Conference on Space Optics—ICSO 2006

Noordwijk, Netherlands

27–30 June 2006

Edited by Errico Armandillo, Josiane Costeraste, and Nikos Karafolas



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International Conference on Space Optics — ICSO 2006, edited by Errico Armandillo, Josiane Costeraste, Nikos Karafolas, Proc. of SPIE Vol. 10567, 1056717 · © 2006 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2308175

HIGHLY LIGHT-WEIGHTED ZERODUR MIRROR AND FIXATION FOR CRYOGENIC APPLICATIONS

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ABSTRACT

Space telescopes require large primary mirrors within a demanding thermal environment: observatories at L2 orbit provide a stable environment with a drawback of very low temperature. Besides, it is necessary to limit as far as possible the mirrors mass while withstanding launch loads and keeping image quality within a cryogenic environment.

ZERODUR is a well-known material extensively used for large telescope. Alcatel Alenia Space and Sagem/REOSC have combined their respective skills to go further in the lightweighting ratio of large mirror (**36 kg/m²** on 1.5 m²) through a detailed design, performance assessment and technology demonstration with breadboards.

Based on a large mirror detailed design supported by analysis, a ZERODUR mock-up has been manufacturing by Sagem/REOSC to demonstrate the achievability of the demanding parameters offering this high lightweighting ratio.

Through the ISO experience on mirror attachments, a detailed design of the mirror fixation has been done as well. A full size mock-up has been manufactured and successfully tested under thermal cycling and static loading.

Eventually, the ZERODUR stability behavior within this large temperature range has been verified through thermal cycling and image quality cryotest on a flat mirror breadboard.

These developments demonstrate that ZERODUR is a good candidate for large space cryogenic mirrors offering outstanding optical performances associated to matured and proven technology and manufacturing process.

1. MIRROR STRUCTURE

1.1 Zerodur main properties and advantages

Integrated CTE at cryo-temperature (integrated values from 293K):

α= 0.11 E-6 °K^{-1} at 120K
α= 0.16 E-6 °K^{-1} at 50K

Moreover, Zerodur offers an excellent homogeneity of thermal expansion.

This very stable and homogeneous integrated CTE property leads to a high stability of the optical shape from the manufacturing/polishing at ambient to the operational at cryo-temperature.

Mechanical characteristics (E/ ρ) are high enough to allow the design of rather stiff and lightweight mirror structures.
Density: ρ= 2.53 g/cm3
Young's modulus:
E= 90 GPa at 293K
E= 85 GPa at 50K

Strength: fragile material but very well known and predictable with Weibull distribution. Attention must be paid on the application of the appropriate surface treatment (etching, polishing).
Conservative bending strength value for long term application is 10 MPa, value used for the global mirror.

For the allowable stress at the fixation interface we have considered a D35 surface treatment (especially for the prediction of the bonded fixation strength). This grade qualifies a median treatment in terms of strength performances. Associated weibull parameters are:

$$\sigma_o\text{=78.7 MPa}, \quad \lambda = 15.7$$

Proc. '6th Internat. Conf. on Space Optics', ESTEC, Noordwijk, The Netherlands,

The weibull distribution law gives the following allowables for the interface area:

44 MPa, for a probability of 10^{-4}

1.2 Zerodur manufacturing improvement

IBF (Ion Beam Figuring) allows to decrease drastically the quilting effect of a classical polishing.
This quilting effect is one of the main limitation for the definition of the cells diameter, then for the mirror lightweighting.
The IBF correction has been simulated on different cell shape, tria or hexa, and for several size (inner diameter) and front face thickness.
Globally IBF correction reduces from more than a ratio of 10 the RMS value link to the quilting effect of the classical polishing.
This allows to increase the cells diameter for more than 30% (for a same front face thickness) .

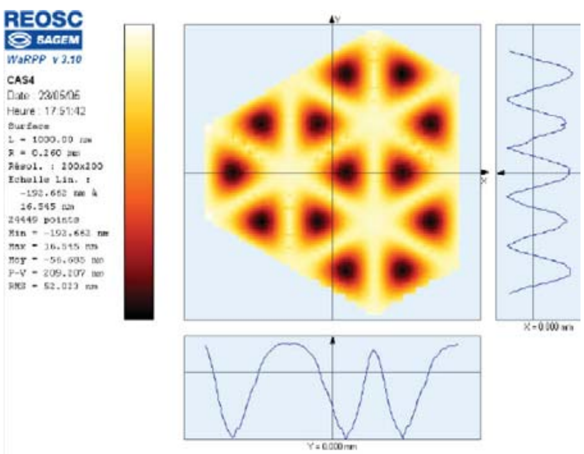


Fig. 1. Quilting on tria cell – 15 g/cm²

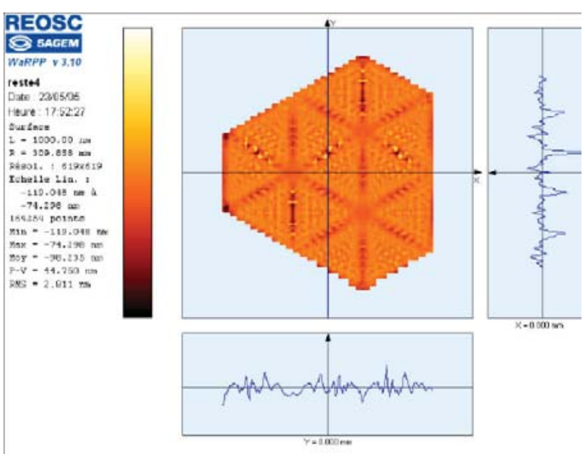


Fig. 2. Residual quilting on tria cell – after IBF

We also push at their limits the ''conventional'' glass manufacturing capabilities by making:

- very thin wall thickness for large cell walls thanks to ultrasound technic.

- cells bottom with adaptated slop to follow the local front face slope.

- very small radius between cell walls, over all the cell

1.3 Mock up for lightening feasibility check

A mock up dedicated to the validation of the glass lightweighting has been developped by Alcatel/Sagem-REOSC and manufactured by Sagem-REOSC.

This activity has validated the feasibility of manufacturing the following geometry:

- thickness of high cell walls (H155mm) of 2 mm (semi closed back) and 2.5 mm (open back) at ±0.2 mm over all the wall surface with a combination of milling, ultrasound machining with constant monitoring of the induced load in glass and etching operation for stress relaxation at the end.

- cells bottom with adaptated slop to follow the local front face slope.

- very small radius between cell walls, down to 3 mm over all the cell depth.

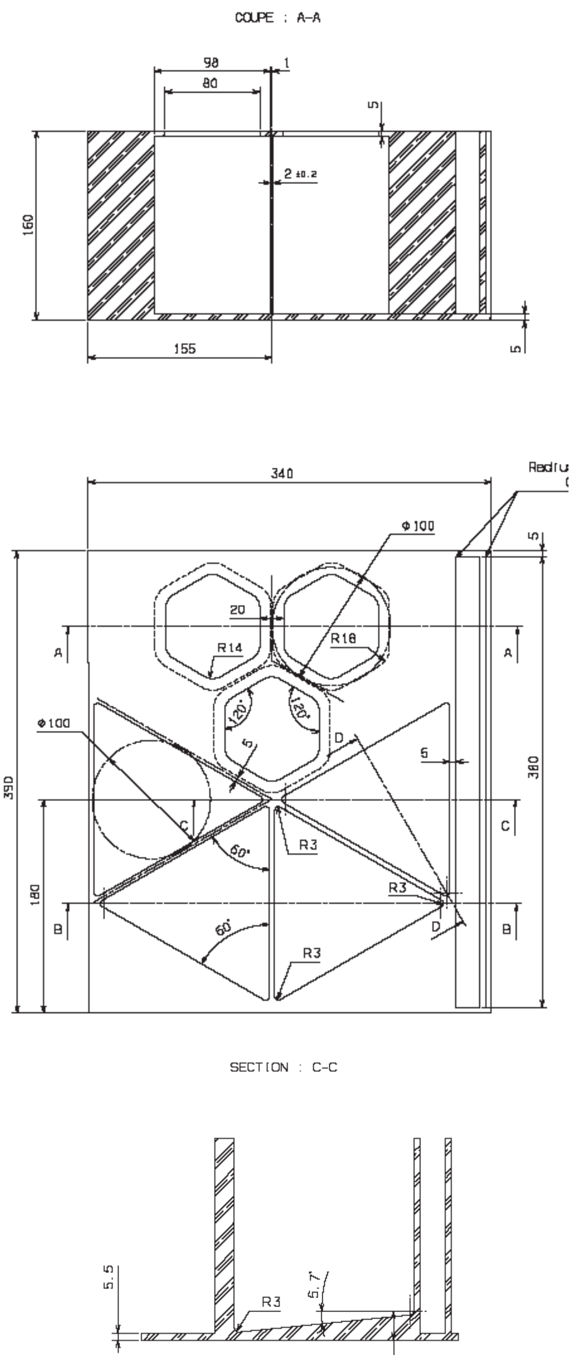
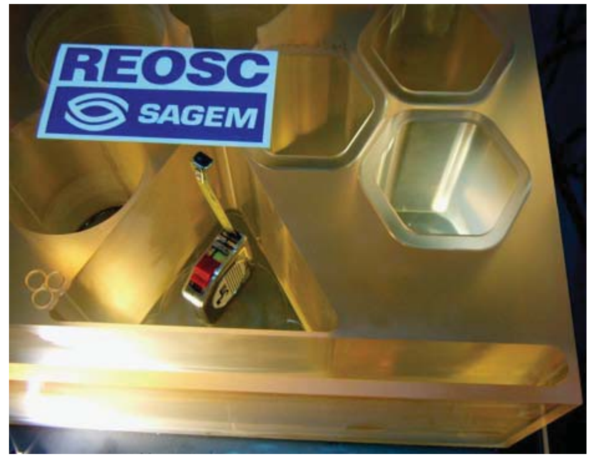
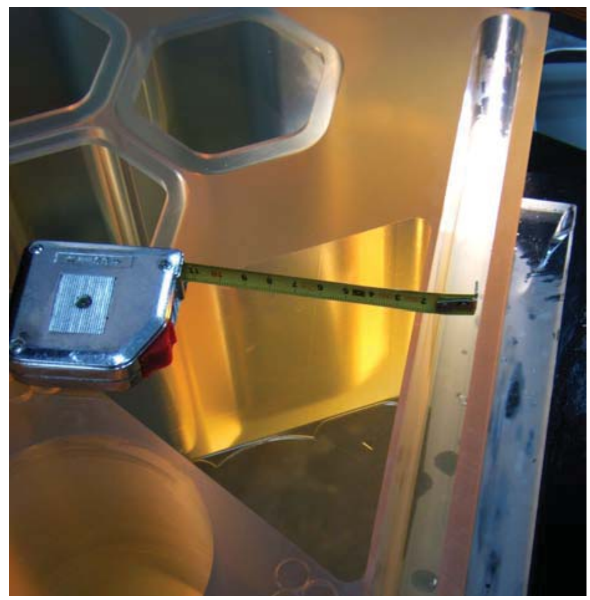


Fig. 3. Mock up definition





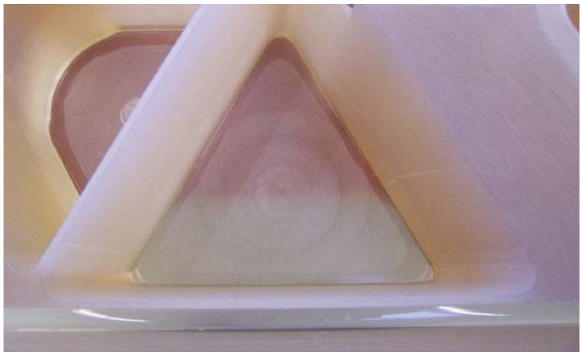


Fig. 4. Manufactured mock up for the lightening

1.4 Test sample and results for the Zerodur behaviour at operational cryo-temperature

A cylindrical flat mirror made of Zerodur have been optically measured at ambient and at cryo-temperature in order to check the good stability of the material: image quality and hysteresis.
Mirror characteristics:
Zerodur class 0, thickness 15 mm, dia 250 mm

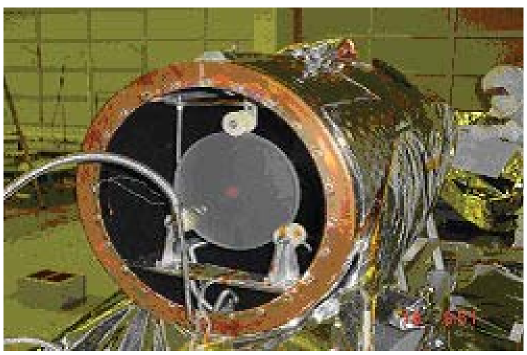


Fig. 5. Mirror mounted into the cooled cavity

Mirror supporting is reduced to the minimum, based on ISO mirror cryo-testing heritage, to avoid constraint induced during cool down and provide a good thermal decoupling (3 permaglass cylinders).

The optical measurement is performed with a Fizeau interferometer. The optical reference surface of the interferometer is accommodated inside the vacuum chamber to have a measurement free from air turbulence and vacuum shroud porthole deformation. This optical reference is mounted on the optical bench and is protected by MLI. This configuration is inherited from ISO experience. The measurement accuracy is close to 5 nm.

The Wave-front error measurements are performed on sub-areas of 100mm diameter. The seven positions selected are sketched on to cover a maximal part of the surface. The five measurements A, B, C, D and E give the mirror material behaviour while F and G monitor the mirror supporting.

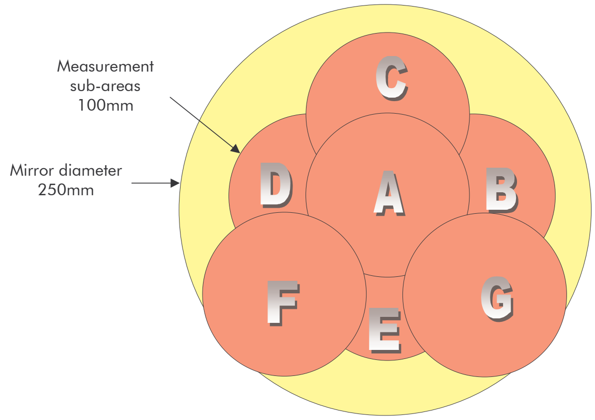


Fig. 6. Measurement areas location on the front face

From wave front error map computations between ambient and cryogenic temperature (105K), it appears that the values are close to the measurement accuracy: between 5 and 8 nm. The residual effects can be assigned more realistically at mechanical configuration (slight residual constraint at I/F) or optical variation on phase reference plate under vacuum.
Moreover, delta WFE computation between room and cryogenic temperature evidences no hysteresis effect.

Zerodur class zero confirms its good behaviour whatever the temperature is (here down to 105K).

1.5 Design and optimization for 1.5m² mirror

Based on the manufacturing performances here above, we designed two rectangular mirrors (primary mirror type for large telescope) which have the necessary level of mechanical and mecha-optical performences to cope with visible wavelengths mission.

1st concept: Evolutive thickness with tria cells:

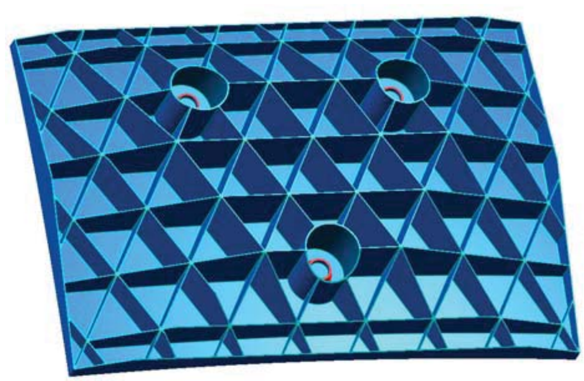


Fig. 7. Evolutive thickness – rear view.

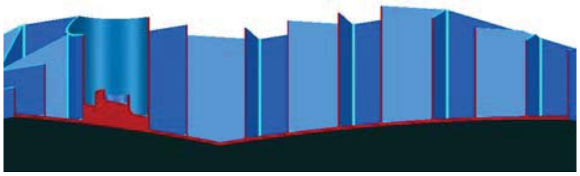


Fig. 8. Evolutive thickness – cross section.

2nd concept: Circular Frame

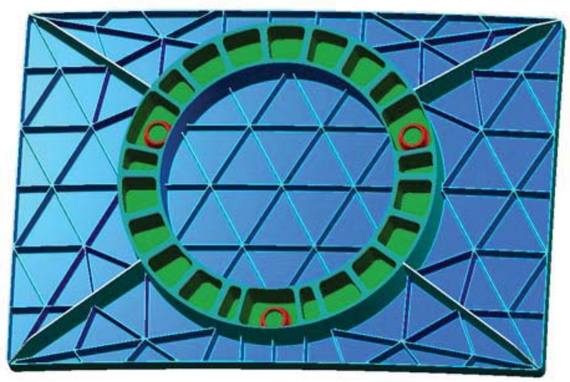


Fig. 9. Circular frame – rear view.

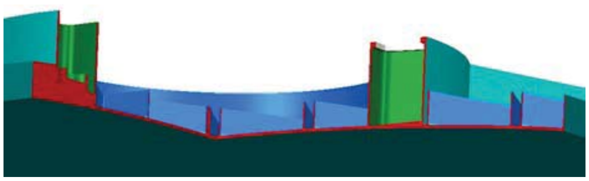


Fig. 10. Circular frame – cross section.

Both concepts have the same mass but:
- the ''Evolutive thickness'' one is stiffer, consequently more efficient.
- the''Frame'' one is less efficient but more compact: global thickness -25% w.r.t ''Evolutive thickness'' one.

The mass and strength for both are:
- mass = 54 kg - thus a mass/surface ratio: **36 kg/m²**
- Q.S loads (allowable) > 20g in-plane and out-of-plane

Here after, an exemple of the performances for the ''Evolutive thickness'' concept, are:
- first frequency: > 200 Hz
- 1g effect on vertical mirror (in-plane direction):
  SFE(-T,-F) = 74 nm RMS
- interface mismatch effect with standard mirror ISM
  SFE(-T,-F) = 13 nm RMS

2. MIRROR FIXATION

2.1 Design and justification

The fixation definition at the interface with Zerodur is very critical since it must be compatible in strength with:

- loads at ambient temperature, derived from the Q.S, ~ 4200 N in plane and up to 8500 N out of plane,

- high thermo-elastic load: ΔT= -193 K,
and also be compatible with the mirror SFE budget at operational cryo-temperature.

A trade-off on different concept of fixation has shown that the best compromise in term of performences is the following one:
An INVAR ring is bonded on a Zerodur boss. The bonding thickness is calibrated by a groove in the metallic ring.
The adhesive was selected for its particular good mechanical characteristics in the working temperature range (100 K to 300 K): it is the best compromise for strength and stiffness vs. low temperature.

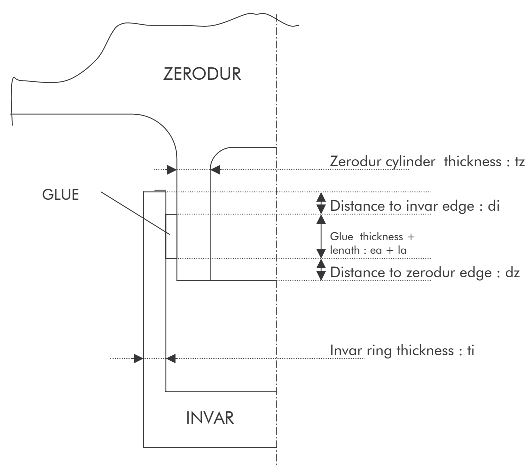


Fig. 11. Fixation – cross section (sketch)

2.2 Main characteristics and capability

Mechanical strength of the bonded interface:
Glue:
- Q.S loads: 4 MPa, MS>100% (avec CS=1.25)
- thermoelastic: 35 MPa, MS=0 (avec CS=1.25)

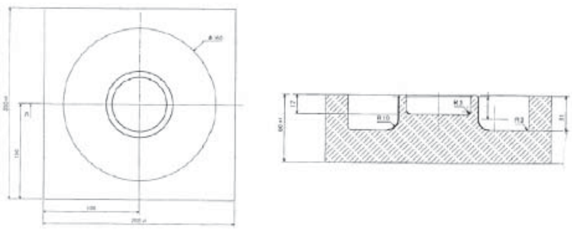
Zerodur:
- Q.S loads : 16 MPa, MS=+10% (avec CS=2.5)
- thermoelastic: 15 MPa, MS=+19% (avec CS=2.5)

WFE impact at Operational temperature:

Thermoelastic effect of the 3 bonded fixations on the mirror optical face at Operational after cool down 293K -> 100K (by analysis with the mirror FEM):

SFE(-T,-F) = 17 nm RMS

2.2 Mock up and test results



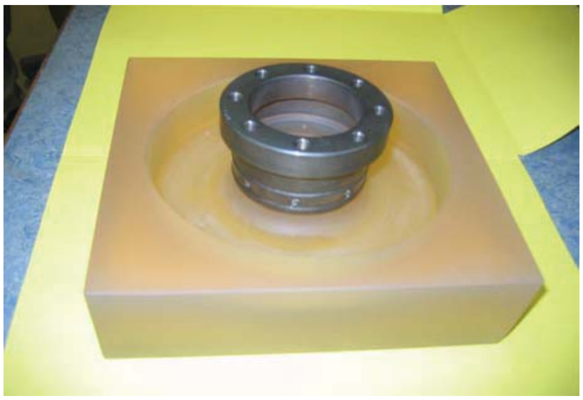


Fig. 12. Fixation mock up

Thermal cycling:

More than 10 thermal cycles from ambient temperature down to 100 K have been performed successfully. The temperature rate was 2° / min which leads to a cycling duration of more than 3.5 days, when including stabilisation time at 100 K and at 313 K.

Static loading, performed after the thermal cycling:

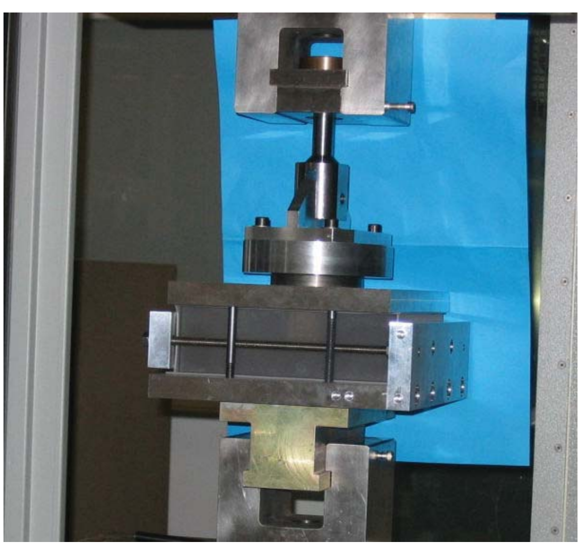


Fig. 13. Fixation mock up during traction test

Out-of-plane direction:
the maximal effort of 6600 N was reached and maintained a few seconds.
That demonstrates a margin of + 56% wrt the highest axial design load.

In-plane direction:
the test was performed in several steps up to 17000 N. At this level (twice the tangential design load) no damage has been detected.

3. CONCLUSION

This study, supported by breadboards and tests, demonstrates that ZERODUR is the good candidate for large cryogenic space mirrors, offering outstanding optical performance at operational cryo-temperature (100K) with a reduced mass.

The main results are:

- a specific mass of **36 kg/m^2** (mirror mass of 54 kg for a size of 1.5 m²) is achieved, with manufacturing feasibility demonstrate thanks to a specific mock up.

- the ‘’on ground’’ and ‘’in orbit’’ stability performances are fulfilled, with a level of performences to cope with a visible wavelengths mission. ZERODUR stability is checked with a specific test mirror.

- Confident margins of safety have been demonstrated in current areas of the mirror as well as in the critical zones of the mirror fixations. The specific fixation mock up have demonstrated the good strength, both for glue and Zerodur, under thermoelastic cycling (Cool down representative) and under static loading (Q.S.L representative)