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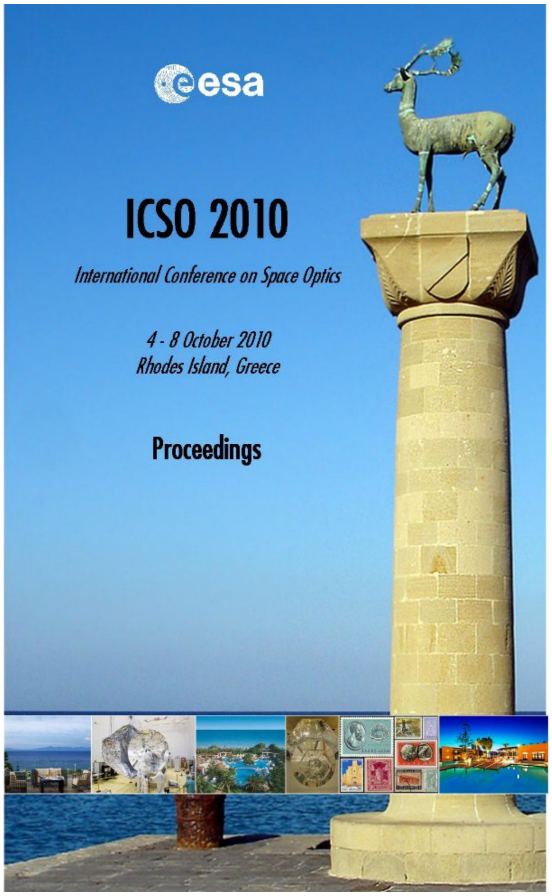

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SUPER-LIGHT-WEIGHTED HB-CESIC® MIRROR CRYOGENIC TEST

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I. INTRODUCTION

Future scientific space missions require ever more demanding large optics that work at cryogenic temperatures. In the frame of a Darwin assessment study conducted under ESA contract by TAS, the need of future very lightweight cryogenic mirrors with superior optical quality has been identified. Such mirrors need to be of size up to 3.5 m in diameter, with a mass of less than 250 kg (i.e. 25 kg/m^2) and possess excellent optical quality at cryogenic temperature down to 40 K.

Furthermore, the Darwin non-planar Emma configuration is composed of three large free-flying receiver mirrors and a central beam combiner on which the light from the receiver mirrors converges. The mirrors create a "virtual" parabola, called the synthesis telescope. The optical integrity of the evolutionary synthesis telescope is ensured by a continual adjustment of the astigmatism and radius of curvature of each of the three receiver mirrors.

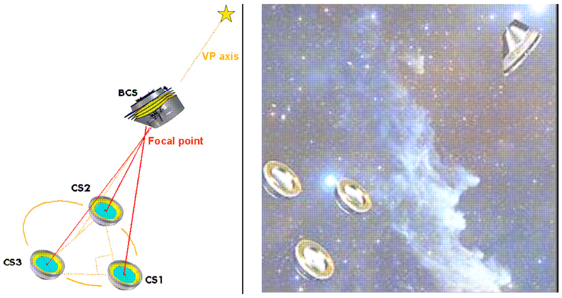


Fig. 1. Darwin free flyer interferometer telescope with mirrors up to 3.5 m in diameter.

Moreover, number of other foreseen missions require also large, very lightweight, and ultrastable mirrors and optical benches, such as the SPICA and FIRI missions.

On this basis, ESA contracted Thales Alenia Space (TAS) for a technical development project, with for main objectives to design, establish the performance of Darwin large receiver mirrors and to design, manufacture, and test a representative optical demonstrator mirror to validate its optical stability under cryogenic conditions, including a system to correct astigmatism.

For large cryogenic optical mirrors, TAS selected ECM's HB-Cesic® optical material for its unique material properties, such as a high specific Young modulus, high thermal conductivity, low CTE, and high strength (especially for a ceramic), and its versatile manufacturing capabilities, which allow manufacturing large monolithic structures from a single homogenous greenbody blank.

First an ultra-lightweighted technological (ULT) 600-mm diameter mirror of high optical quality, made of HB-Cesic®, was designed, its include its isostatic fixations and a special astigmatism compensation device (ACD) for mirror shape control.

The mirror was then manufactured by ECM, polished by SESO to a surface figure error of less than 20 nm Rms, and finally optically tested from ambient to cryogenic temperatures by TAS. The integrated ACD system was then installed on the mirror and activated at cryo temperatures under WFE measurements.

II. DESIGN OF THE ULTRA-LIGHTWEIGHTED TEST MIRROR

The ULT mirror design was optimized to be representatively scaled from the Emma/SPICA flight mirrors. ULT mirror had an external diameter of 600 mm and was constructed of HB-Cesic® with a face sheet thickness 3 mm, strengthened by a rib pattern with ribs thickness of 1.2 to 1.5 mm. The mirror I/F fixations was fully representative of flight fixation I/F.

The ACD beam, also made of HB-Cesic®, allows the adjustment in a single direction of the mirror's astigmatism at 100 K and is a flight demonstration concept. By either heating or cooling the beam, the length is either increased or decreased microscopically and create changes in the mirror's astigmatism.

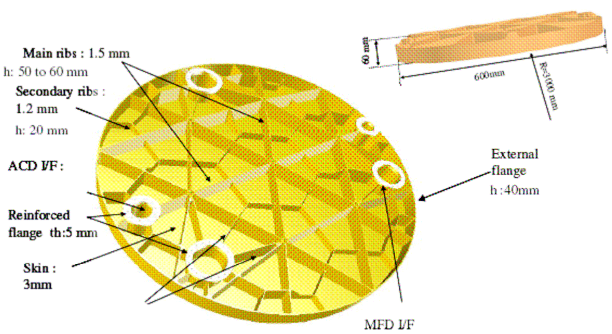


Fig. 2. The ULT mirror design.

The mirror fixation filtering devices have been optimized vs. eigenfrequency, loads, I/F filtering capability, and cryogenic impact. However, the CTE mismatch between glue and HB-Cesic® remains a significant contributor to the mirror WFE at cryo temperatures, especially for such an ultra-lightweighted mirror. The mass of the 600-mm mirror is less than 5 kg (i.e. 17.8 kg/m^2).

The ULT mirror performance was assessed via detailed FE analyses, using a model with 1,400,000 nodes and 950,000 elements. This detailed modeling was necessary to assess the optical performance vs. all nm-scale disruptives, especially at high frequencies.

The ULT mirror optical performance was computed via detailed opto-thermo-elastic modeling for numerous load cases to demonstrate the WFE performance at cryo temperatures with and without the ACD beam.

III. FABRICATION OF THE MIRROR

ECM has manufactured the mirror using directly CAD file, received from Thales Alenia Space. Due to the fact that this mirror will operate at cryogenic temperatures, particular care was taken during the inspection of the raw material to ensure its homogeneity in order to be confident of the thermal stability of the final mirror performance. Homogeneity was verified through the characterization of many samples issued from different random locations of the raw material.
After infiltration, the shape of the mirror surface was measured and the maximum deviation from the nominal shape was only 0,38 mm P-V, which is very small. This result confirmed the very small uncertainty of the shrinkage factor during infiltration (less than 0.05%) leading advantage in producing the optimal oversize of mirrors for grinding after infiltration to shape it to the specified radius of curvature.

After inspection, , I/F mount in the mirror was precisely machined by EDM and surface skin of the mirror was ground with conventional grinding tools, see fig. 3. After just three weeks, the mirror shape was corrected from the original 0.38 mm down to 20 µm P-V.

Fig.3. view of mirror back face after machining

IV. POLISHING OF THE TEST MIRROR

The mirror was polished by SESO directly on bare HB-Cesic®, to validate surface roughness performance for future space missions, and gold coated, to determine impact of gold layer on thin HB-Cesic® face sheet.

The different steps performed by SESO were the following :

- Grinding: This abrasion process allowed lowering the deviation between the measured surface and the theoretical shape to below 3µm P-V.

- Fine grinding: This intermediate step allowed lowering the surface error down to about 1 µm P-V, while starting to get a polished surface.
- Rough polishing: At this level, the mirror was still being polished on its full face at once, and the abrasives we used were getting progressively smaller in grain size.
- Gluing of the Mirror Fixing Devices (MFD) pads onto the mirror and assembly on the Invar frame
- Polishing with the Computer Controlled Polishing Machine (CCPM) up to final performance
- Dismounting of the Invar frame for coating of the mirror.
- Coating of the mirror (equipped with MFDs) with a hard gold coating:
- Remounting of the mirror on the Invar frame.

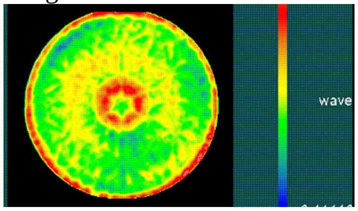


Fig. 4. Mirror SFE after MFDs gluing, frame mounting, and final polishing – 20.2 nm RMS.

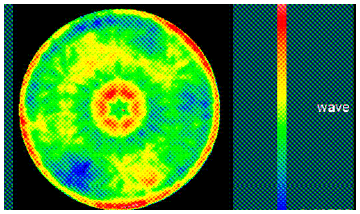


Fig. 5. Mirror SFE after coating and remounting – 20.4 nm RMS.

The main issue of the full-face activities was to avoid generating any quilting effect (also called “print-through”) due to the extreme light-weighting design. The achieved result was satisfactory and allowed us to get down to the required level for CCPM polishing.

The main concern of the MFDs mounting optimization was to minimize the gravity effects during inspection at ambient conditions. The gluing of the pads and the mounting on the frame were done before final polishing to be able to compensate during polishing for any possible effects linked to mounting stresses.

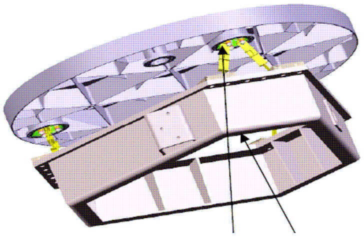


Fig. 6. Mirror mounted with MFDs and Invar frame.

The principal issue of CCPM polishing was the removal rate, due to the use of a very localized polishing tool. To avoid losing too much in rate removal, SESO optimized the polishing compound and its management during the polishing process, the polishing tool support, and the polishing pressure and tool speed to allow a good removal rate while avoiding quilting generation during CCPM polishing.

The final challenge was the gold coating, which we solved by coating the mirror with mounted, avoiding stresses on the mirror which could generate WFE evolution, getting good coating uniformity across the mirror surface, and remounting the mirror equipped with the MFDs onto the Invar frame without altering the WFE as measured after polishing.

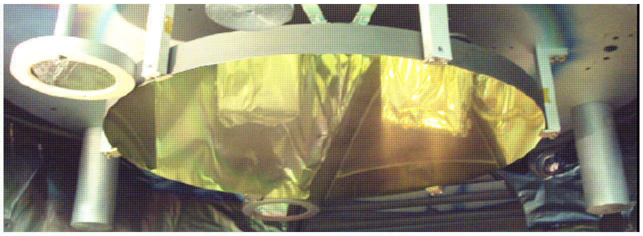


Fig. 7. Mirror coated, in the coating chamber.

The micro-roughness achieved on samples 100 mm in diameter was locally as low as 2.8 nm RMS. According to our experience, with further polishing, the same micro-roughness can be reached on the ULT mirror.

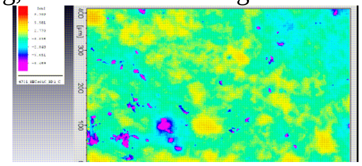


Fig. 8. Micro-roughness measured on a Ø100 mm sample (2.8 nm RMS).

V. DESCRIPTION OF THE CRYO TEST FACILITY

The testing of the ULT mirror's WFE at cryogenic temperatures was performed at the TAS Optical Test Center, Cannes, France. The general test set up configuration is recalled hereafter.

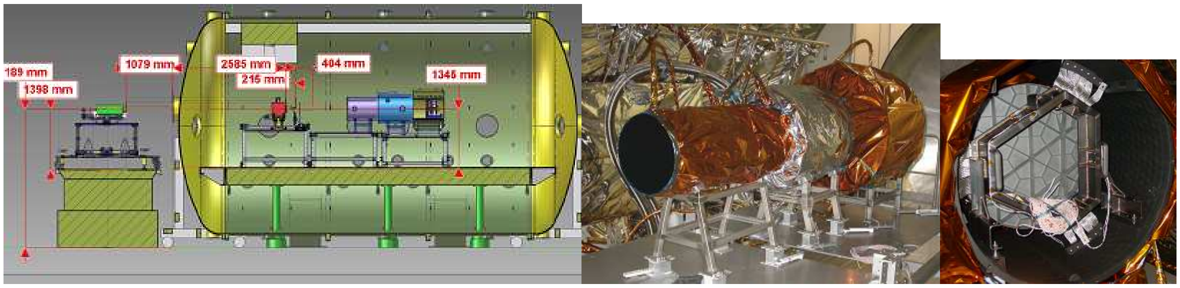


Fig. 9. Constitution of the test set up

For the optical test, the mirror was fixed on an Invar frame located and fixed inside a thermal shroud, cooled to liquid N_2 temperature, shroud being located on an optical bench in a thermal vacuum chamber at ambient temperature. In the ambient temperature area, a lens f/2,25 and a transmission flat stand on a 2 axis motions micro controlled platform in order to place the focal point of the lens at the centre of curvature of the mirror. Measurements are referenced with a movable reference sphere. This sphere stands on a 2 axis motions micro controlled platform in order to have a good positioning of the radius of curvature.

External to the cryo chamber, a fast ZYGO interferometer was used to illuminate through a lens the mirror and measure its surface at the center of curvature.
The interferometer lies on a support outside the chamber on the anti seismic block. The support is equipped with manual alignment device to align the interferometer on the optical axis. The optical beam enters in the vacuum chamber through a high quality glass window.

Such an optical test set-up offers a high accuracy as transmission flat and focus lens are inside the chamber at ambient temperature, and it gives a very high reproducibility. A removable reference calibration sphere allows the suppression of all optical artifacts generated independently of the mirror surface (lens, window, flat, etc.) and produces a very low noise level. A relative accuracy budget between two measurements was established and confirmed by repeatability measurements done on the test set-up before to start the test sequence showing a WFE measurement reproducibility better than 4 nm RMS.

VI. DESCRIPTION OF THE CRYO TEST LOGIC AND CRYO TEST RESULTS

Test logic was established to have a comprehensive behavior of the mirror WFE performance. First, the WFE of the mirror was measured without the ACD at ambient temperature under vacuum, then at 93K cryo temperature and finally at ambient under vacuum after the cryo test.
This measurement showed a very low WFE increase, namely 17 nm RMS, mirror WFE changing from 91 nm RMS to 108 nm RMS.
By subtracting one map from the other, we obtained the "ΔWFE" and determined the impact of the cryogenic conditions on the mirror WFE.
Using precise FEM of the whole equipped mirror on its frame, the mirror WFE evolution during the cryo test was predicted using material data and DL/L data from 300 K to 93 K, mirror core being considered with uniform HB-Cesic® CTE. When we compare the predicted WFE map with the measured one, we observe the same WFE map shape and the same level of ΔWFE between prediction and measurement. This excellent correlation is an indicator of the high homogeneity of the HB-Cesic® mirror.

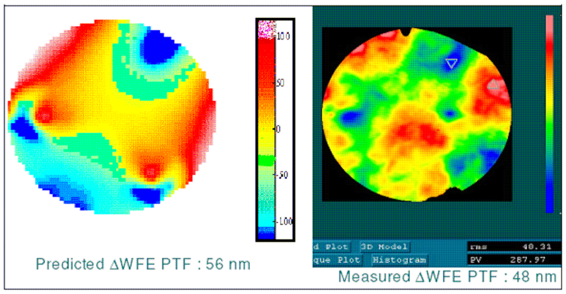


Fig. 10. Illustration of the very high correlation between prediction and measured WFE map.

Comparing the high-frequency WFE terms gives the same level of ΔWFE as for the lower-frequency terms**.** This indicates the high reliability of the FEM prediction vs. the measurements and, therefore, the high homogeneity of the HB-Cesic® material.

There exists some correlation between the ΔWFE (Z<36) map and the rib pattern, showing a very small thermo-elastical cell quilting (less than 10 nm) .

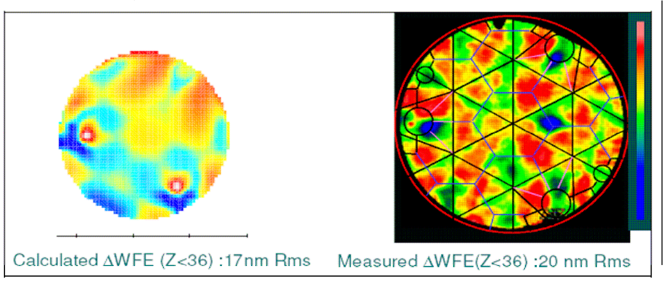


Fig. 11. Illustration of the high correlation between prediction and measured WFE (Z<36) & cells

After the cryo test, the mirror WFE was measured again, this measurement indicated that the WFE is very stable before and after the cryo test, with WFE values of 91.45 nm RMS and 91.46 nm RMS, respectively.

Even for high-frequency terms (Z>36) no change in ΔWFE was measured.

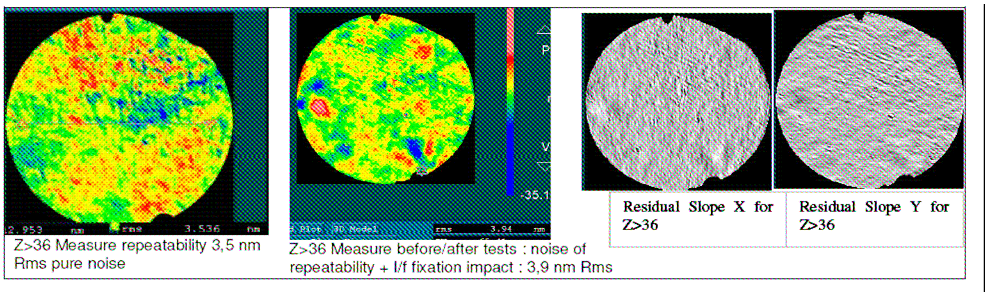


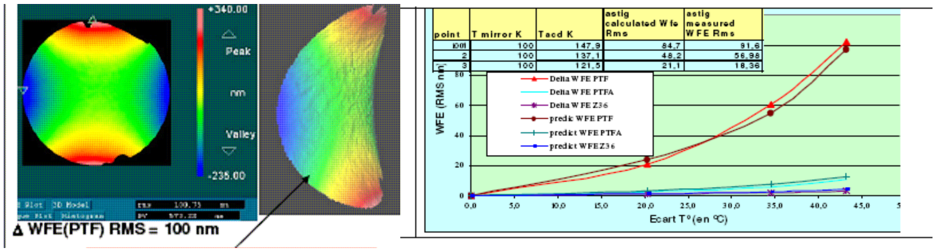
Fig. 18. WFE (Z<36) map evolution 3.9 nm vs. noise level 3.5 nm.

Measurements demonstrate that ULT HB-Cesic® mirror is very stable at nm-level before and after the cryo test.

After completion of this successful test, the mirror was integrated with the ACD beam. WFE of the mirror was then measured at ambient temperature and, finally, at cryo temperature with and without activation of the ACD. Integration of ACD did not degrade mirror WFE (126 nm RMS after integration vs 127 nm RMS before).

The ACD was activated at ambient with the mirror in front of the interferometer. We observed a linear behavior and a perfect correlation with predictions for the astigmatism term and also for the residual terms. We observed no residual terms after the temperature of the ACD had returned to that of the mirror. After ACD activation, the mirror and ACD beam were cooled to 100 K and the ΔWFE (cryo/ambient) was measured and compared the results with prediction. Measurements and prediction were very close. [Predicted ΔWFE (ambient-100K) was 75 nm RMS vs. a measured ΔWFE of 106 nm RMS.] and the ΔWFE maps show close agreement between predictions and measurements.

Mirror WFE was measured when the ACD activated at cryo temperature for different ACD temperatures and results with predictions are compared. As predicted, we obtained a quasi-pure astigmatism and a perfect correlation between the measured WFE (PTF, PTFA, and Z<36) vs. predicted values at cryogenic temperature is observed for different ACD heating steps.



point	T mirror K	Tacd K	astig calculated Wfe Rms	astig measured WFE Rms
1	100	147,9	84,7	91,6
2	100	137,1	48,2	56,98
3	100	121,5	21,1	18,36

Fig. 21. Mirror WFE when ACD is activated at cryo.

Thanks to very precise WFE measurements, this intensive test campaign has allowed us to unambiguously demonstrate the very stable behavior of the HB-Cesic® mirror from ambient to a cryo temperature of 93 K and the perfect performance of the ACD beam in modifying astigmatism at ambient and at cryo temperatures.

VII. FUTURE ULTRA LIGTHWEIGHT LARGE OPTICAL CRYOGENIC MIRROR

Based on this very positive ULT manufacturing, polishing and cryogenic tests results, 3,5 m large and lightweight HB-Cesic optical cryogenic mirror meeting stringent optical requirements has been designed and sized through deep FEM analyses for SPICA project.

Mirror lightweight design has been achieved thanks to the high manufacturing possibilities offered by HB-Cesic technology (Very thin and height ribs including hammer head and lightweighting triangular holes maximising stiffness/mass, Tailored ribs type ensuring optimisation of each ribs function, low shrinkage allowing a mastering of the shape).

The mirror design met the most stringent WFE performances under cryogenic operational environment, limit the deformation under gravity for a proper management of the optical performance on ground, includes secondary ribs to limit quilting effect to meet coronagraph high frequency requirements, and has low sensitivity to I/F and is fully compatible of launch and loads. Its nominal mass is only 240 kg (i.e. 25 Kg/m^2)

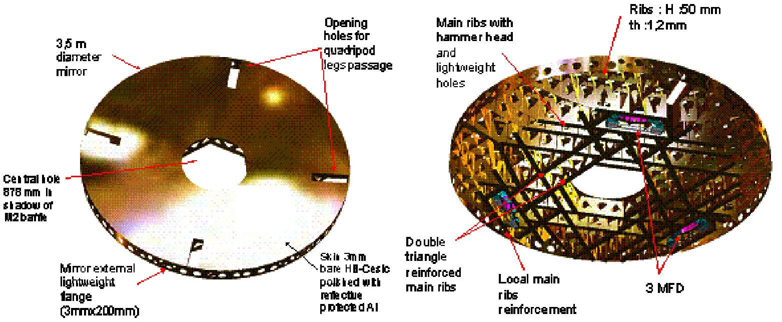


Fig. 23. 3.5 m cryogenic lightweight mirror design

TAS has on its own budget manufactured with ECM a representative breadboard of such large mirror design. This breadboard design is based on SPICA mirror design and is fully representative vs : Skin thickness (3 mm) , main reinforced ribs (Ribs height : 250 mm , th: 1,5 mm, same lightweight opening triangular pattern in the ribs, hammer head on top of the main ribs).

After lightweighting the mirror breadboard has been successfully infiltrated. The obtained skin face shape is very near the 3 CAD model as the deformation of the front face vs the 3D CAD model is only below 0,25 mm.

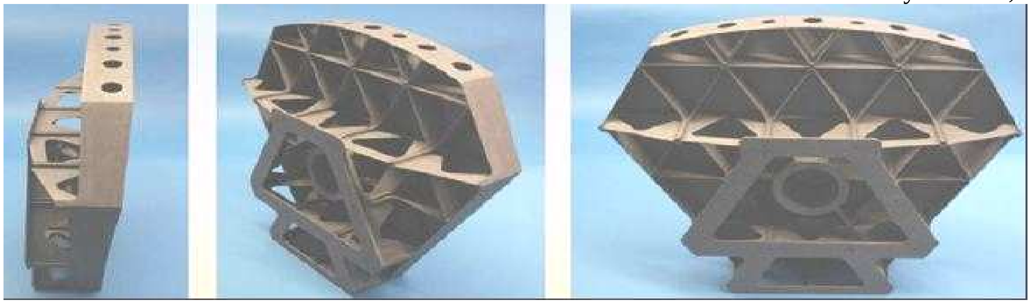


Fig. 24. Successful infiltration of the 2 meter mirror breadboard segment (detail)

VIII. CONCLUSION

Based on our successful ULT optical mirror development and full scale breadboard section, we can state with confidence that the HB-Cesic® technology has reached maturity and is suitable, for large ultra-lightweighted future space optics applications at cryogenic temperatures.

Our mirror demonstration project showed the following capabilities :

- Construction of a 600-mm mirror with an areal density of 17 kg/m^2 and possessing high stiffness and high strength.
- High polishing quality of the mirror to a surface error of 20 nm Rms and a roughness of few nm , with the possibility of further improvements.

Our highly accurate and exhaustive cryogenic WFE test campaign demonstrated :

- Outstanding performance at cryo temperatures of the HB-Cesic® mirror.
- Highly accurate WFE prediction consistent with all of the measurements.
- Very high performance of the ACD beam.

We achieved all of the project requirements – such as mirror mass, mirror optical performance, and mirror-ACD cryogenic performance. Furthermore, we demonstrated with our accurate CAD design and FEM analysis the ability to achieve a very high level of correlation between the test results and modeling, which is fully compatible, including margins and extrapolation through FEM analysis to large-size mirrors, with the specifications of the SPICA and Darwin missions .