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Large aluminium convex mirror for the cryo-optical test of the Planck primary reflector

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LARGE ALUMINIUM CONVEX MIRROR FOR THE CRYO-OPTICAL TEST OF THE PLANCK PRIMARY REFLECTOR

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ABSTRACT

In the frame of the PLANCK mission telescope development, it is requested to measure the reflector changes of the surface figure error (SFE) with respect to the best ellipsoid, between 293 K and 50 K, with 1 μm RMS accuracy. To achieve this, Infra Red interferometry has been selected and a dedicated thermo mechanical set-up has been constructed.

In order to realise the test set-up for this reflector, a large aluminium convex mirror with radius of 19500 mm has been manufactured. The mirror has to operate in a cryogenic environment lower than 30 K, and has a contribution to the RMS WFE with less than 1 μm between room temperature and cryogenic temperature.

This paper summarises the design, manufacturing and characterisation of this mirror, showing it has fulfilled its requirements.

Key Words: Cryo optical testing and optical manufacturing

1. INTRODUCTION

PLANCK is the third Medium size mission of the ESA long-term scientific plan Horizon 2000. The objective of the PLANCK mission is to image over the whole sky the temperature anisotropy of the cosmic microwave background radiation. The present concept for PLANCK is based on a Gregorian off-axis telescope with a circular projected aperture of 1.5 m. The PLANCK reflectors are 2 CFRP off-axis ellipsoids to be tested separately (Secondary reflector: 1050 mm x 1100 mm and Primary reflector: 1550 mm x 1890 mm). In the frame of the telescope development, it is requested to measure the changes of the surface figure error (SFE) with respect to the best ellipsoid, between 293 K and 50 K, with 1 μm RMS accuracy. To achieve this, Infra Red interferometry has been used and a dedicated thermo mechanical set-up has been constructed [1].

The test lay-out is mainly driven by the fact that the far focus of the PLANCK primary reflector ellipsoid is at about 20 m distance from the reflector. To fit the set-up in a reasonable size it has been decided to operate in double path configuration.

The far focus beam is folded by a large aluminium convex spherical mirror with radius of 19500 m. This configuration made the set-up compact.

The convex spherical mirror has to operate in a cryogenic environment lower than 30 K, and contribute to the RMS WFE with less than 1 μm between room temperature and cryogenic temperature.

The interferometric testing configuration was set up under thermal vacuum in CSL's FOCAL 6.5 vacuum vessel facility (Fig. 1).

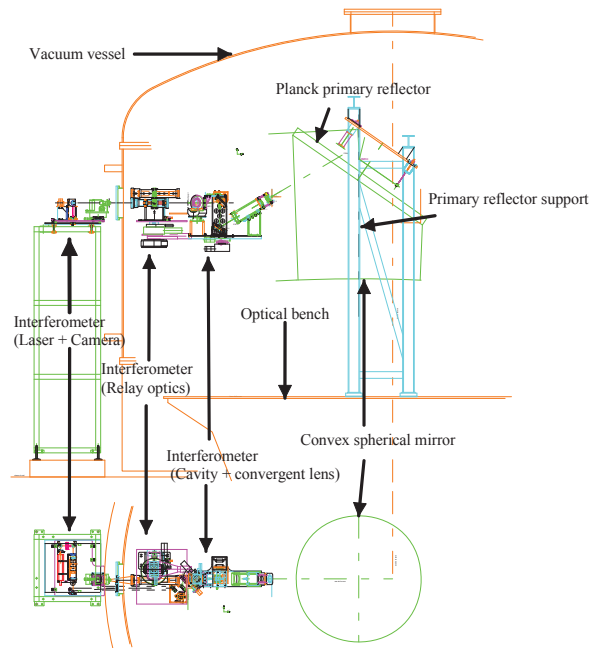


Fig. 1. Stigmatic test configuration for the PLANCK primary reflector cryo-optical test. A convex spherical mirror inside the cryogenic environment reflects the light beam back towards the first focal point

The interferometer head focuses the infrared beam onto the primary focus of the ellipsoidal primary reflector. Light is sent towards the reflector secondary focus. The convex spherical mirror provides an auto-collimation of the test beam in order to fold the configuration within the facility. The convex spherical mirror centre of curvature has to coincide with the far focus of the PLANCK primary reflector.

For adjustment purposes during thermal vacuum testing, tip-tilt and focusing motorised capabilities are implemented as well as an azimuthally motion allowing to calibrate out the non-axisymmetrical defects from the convex mirror.

2. CONVEX SPHERICAL MIRROR DESIGN

The design phase, manufacturing steps and in situ characterisation of this large spherical convex mirror are reviewed here after.

2.1. Material selection

Given procurement time constraints aluminium was imposed for the purpose of this mirror.

From the great number of existing aluminium alloys, for the present application, the alloy 5083 (aluminium-magnesium alloy) was selected for the main following reasons (see also [3]):

- this alloy is recommended for cryogenic applications. It is extensively used for tanks transporting liquefied natural gas;
- this alloy offers excellent forgeability qualities. This is mandatory to obtain a stable and homogeneous product with a good internal structure since severe 3D forging process is applied;
- annealing and cryogenic treatment cycles stabilize the blank;
- these same alloy was also selected in the past for the primary aluminium mirror of FIRST telescope.

The main characteristics (needed for FEM) of this aluminium alloy are given below (other characteristics can also be found in [2]).

- Young's modulus (at RT): $7.033E+10 \text{ N/m}^2$
- Young's modulus (at 30 K): $8.05E+10 \text{ N/m}^2$
- Poisson's Ratio: **0.33**
- Density: 2660 kg/m^3
- CTE at RT: $23.76 \mu\text{m/m}^\circ\text{C}$
- CTE at 30 K: $15.48 \mu\text{m/m}^\circ\text{C}$

2.2. Finite-element study

The convex mirror will be used at horizontal position. A first analysis was performed in order to define the number of axial points required to support the mirror. The blank thickness is 200 mm and has a minimum of

three axial points. In the study, the test mirror is spherical convex with the following characteristics:

- Diameter = 1500 mm
- Thickness = 200 mm
- Radius of curvature = 19500 mm (set at this value for the feasibility study)
- 3 points axial support.

This convex mirror has an isostatic mount.

With a 3 points axial support, under gravity load (along Z axis), at 20°C, the mirror has the following mechanical deformation as shown in Fig. 2.

The effect of temperature variation ($\Delta T = 270$, from 300 K to 30 K) (Fig 3) induces a mirror radius curvature variation of about 78 mm.

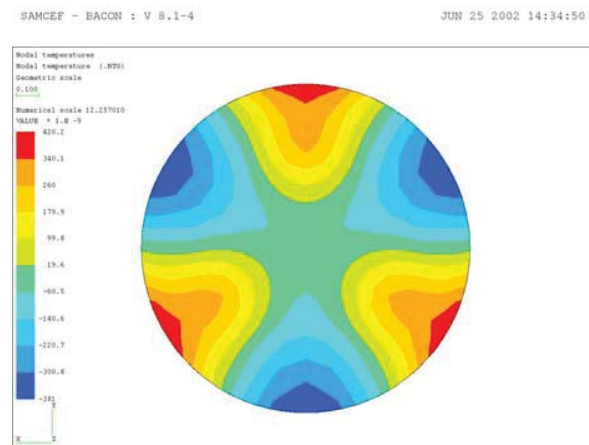


Fig. 2. The surface map of the mirror at 300 K. Piston, tilts and focus aberrations are removed.
SFE: $0.16 \mu\text{m RMS}$

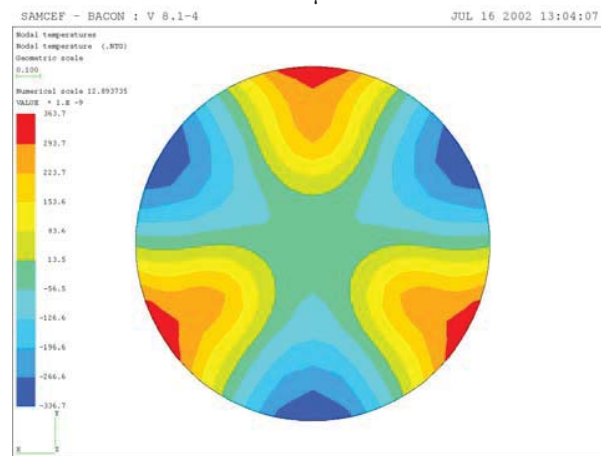


Fig. 3. The surface map of the mirror at 30 K. Piston, tilts and focus aberrations are removed.
SFE: $0.14 \mu\text{m RMS}$

FEM analysis showed also that with a CTE inhomogeneity $< 1\%$ (within the AFNOR norm), the mirror surface quality degradation at 30 K will be lower than 0.1 micron RMS.

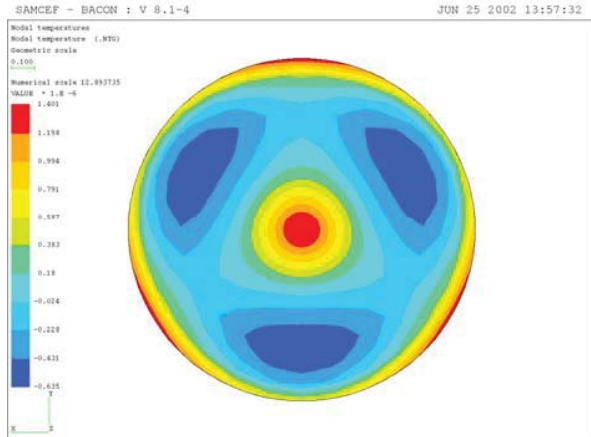


Fig. 4. With a 3 points axial support, under gravity load (along Z axis), at 30 K, with an inhomogeneity of CTE of +5 %, SFE: 0.57 μm RMS

3. CONVEX SPHERICAL MIRROR MANUFACTURING

The forged aluminium blank has been procured by ESA and delivered with following characteristics:

- Grain size ≥ 3 instead of ≥ 5 following ASTM E112 : the mirror roughness specification has been released from 0.1 μm RMS to 0.2 μm RMS.
- Uniformity of thermal expansion coefficient of 0.72 % (measured on one sample) instead of $\leq 0.5\%$: accepted in condition.
- diameter 1520 mm

The blank was transformed into a mirror via the following process:

- Blank machining: the blank is machined with CNC to its final shape (as close as possible, within +/- 25 microns for the best fitting sphere). To guarantee long term stability, annealing have to be foreseen to minimise the induced stresses during machining.
- In order to stabilise its microstructure and keep its shape at cold temperature, the mirror has been submitted to a stress relieving heat and to a cold soaking into liquid nitrogen.
- Spherometry on mirror surface.
- Grinding and polishing of mirror to spherical shape by using classical technique.
- Spherometry on mirror surface.
- In order to stabilise its microstructure and keep its shape at cold temperature, the mirror has been submitted to a second stress relieving heat treatment and to a cold soaking into liquid nitrogen. For the first cold soaking, two steps of mirror cooling have been undertaken.
- Spherometry on mirror surface.

4. CONVEX SPHERICAL MIRROR METROLOGY AT ROOM TEMPERATURE

The final mirror radius of curvature R has been measured with a calibrated (2 μm flatness) spherometer (Fig. 5). The measurement has been conducted with the mirror on its final support.

The measured radius is 19735.7 ± 2.5 mm. In addition, we looked for the radius which minimises the RMS surface error calculated on the whole set of data and it was found to be very near the above value: 19734.8 mm.

A cross-check of the convex radius value has been conducted through the 3D metrology (Fig. 6). Unfortunately, with this metrology machine it was not possible to fix the mirror on its final support.

The accuracy of the radius estimation is:

- 300 mm on each zone of 100 mm size (taking into account a probing accuracy in Z direction of 1 μm for each zone separately);
- of the order of 30 mm on the set of five zones (taking into account a probing accuracy in Z direction of 3 μm for the whole range of measurements).

The values obtained by spherometry and 3D measurement (19735 mm and 19700 mm) are close to each other. The slight mismatch (taking into account the error bars) is probably due to the different ways of supporting the mirror in each measurement configuration.

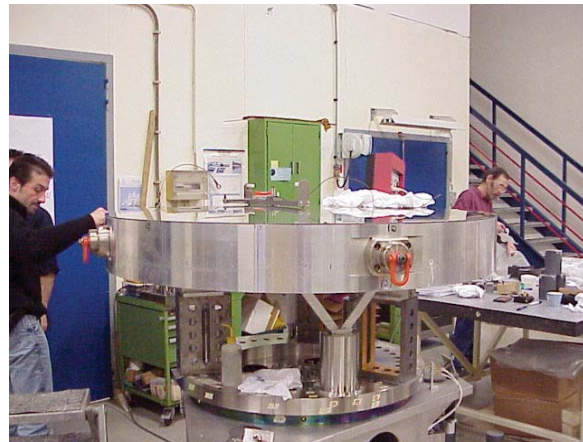


Fig. 5. Surface error measurement with spherometry



Fig. 6. Surface error measurement with CMM

The mirror surface error has been measured by mechanical means. A set of spherometers of different sizes has been used successively along a meridian of the mirror surface. In order to get an optimised RMS departure from the best sphere, the spherometry data have been processed by introducing defocus and tilt.

The results showed that:

- the overall mirror surface figure (SFE) is $1.45 \mu\text{m}$ RMS with respect to the best sphere
- the radius of the best sphere is 19734.8 mm very near the spherometric value
- the estimation of the RMS value for the rotation-symmetrical surface aberrations is $1.2 \mu\text{m}$ RMS (spherical aberration).

The mirror surface figure at room temperature was sufficient to perform infrared interferometry.

The measurement of R_a is performed with a probe roughness-meter (MAHR) every 100 mm along two orthogonal diameters and at 8 locations arbitrarily selected on the mirror. Averaging is made on a 5.6 mm stroke. They show that the mirror roughness varies between 0.017 and $0.083 \mu\text{m}$ RMS and lies well within the specification ($R_a \leq 0.12 \mu\text{m}$ RMS).

The specification required also slopes lower than $5 \cdot 10^{-3}$ rad for spatial frequencies between $1/D$ and $500/D \text{ mm}^{-1}$ where D is the mirror diameter in mm.

For low spatial frequencies ($\leq 1/50 \text{ mm}^{-1}$), the radial slopes have been calculated from the spherometry data and they are well within the specification.

For the high spatial frequencies, the mirror surface has been probed on a 3D machine (Fig 6) with a sampling period down to 5 and 10 mm on several zones on the mirror. From the height data yielded for two adjacent points, the local slope data have been calculated along X and Y directions.

In that case, the measurement method accuracy is limited by the 3D machine accuracy ($\pm 1 \mu\text{m}$ over each measurement zone). This means that with 5 mm inter distance between the measurement points, one can get

till $4 \cdot 10^{-4}$ rad uncertainty and with 10 mm, $2 \cdot 10^{-4}$ rad uncertainty on the slope assessment.

5. CONVEX SPHERICAL MIRROR METROLOGY IN CRYOGENIC CONDITIONS

In order to re-align the spherical mirror during the cryogenic test a support with tip-tilt and focus (3 DOF) is designed. The aluminium mirror can also rotate in order to calibrate out aberrations.

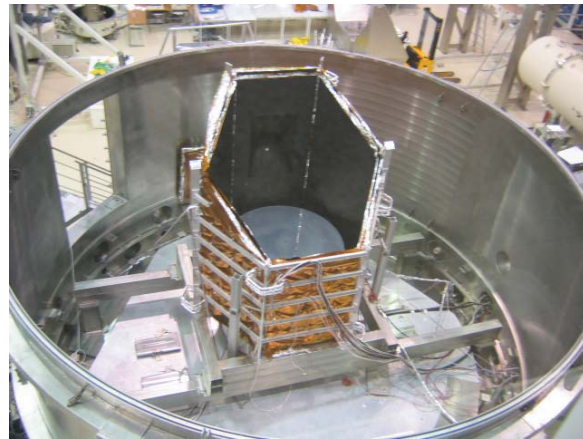
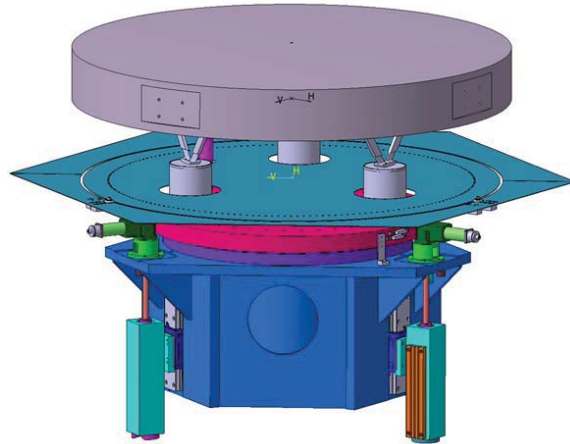


Fig. 7. (Top) Sketch of the spherical mirror mounted on iso-static aluminium blades and stainless steel tubes; (Bottom) Double wall hexagonal shroud surrounding the aluminium spherical mirror in the thermal cavity

The aluminium mirror is integrated on 3 thin iso-static aluminium blades (Fig. 7 top). They are mounted on 3 thin-wall stainless steel tubes. Because the spherical mirror will be cool down to temperatures lower than 30 K, the stainless steel tubes are designed to avoid conductive heat dissipation from the hot environment (the support) to the aluminium mirror.

Between the aluminium spherical mirror and the mirror support a cold panel is mounted. This cold panel is fed with liquid Helium. 90 conductive straps connect the

cold panel to the aluminium mirror. The hexagonal bottom panel rotates with the spherical mirror.

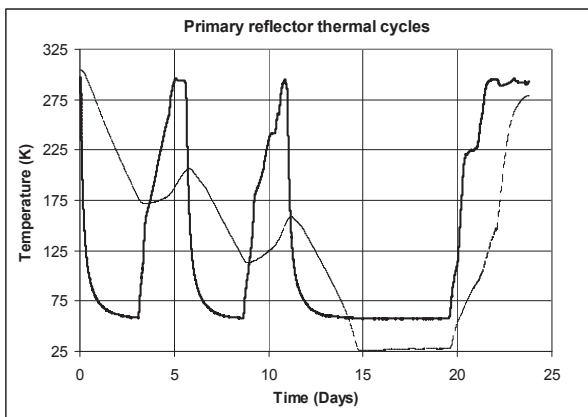


Fig. 8. Temperature cycle of the primary reflector (thick line) and spherical convex mirror (thin line)

Due to timing constraints it was not possible to do a blank characterisation of the spherical aluminium convex mirror in cryogenic environment prior to the primary reflector cryo-optical test. The approach adopted here relies on an in situ characterisation.

One observes on Fig. 8 that the aluminium mirror has large thermal inertia. The primary reflector is reaching its asymptotic temperature quicker. Most of the measurements on the primary reflector during the cycles are done when the spherical mirror is at a higher temperature. Except for the last cycle, there were the thermal capacity drops, the spherical mirror reaches quickly 25 K. In the cycle it was even possible to characterise the spherical mirror with the primary reflector at room temperature.

The homogenous CTE variation will create a change in radii of curvature. Fig. 9 shows the computed spherical mirror relative contraction derived from LVDT measurements, temperature measurements based on a constant CTE model of 0.000024/K and a non-linear CTE model (derived from measurements performed on samples of the same material). One observes a very good agreement between the 3 curves. The LVDT measurement oscillates between the two thermo-elastic models. The uncertainty on the contraction is $5E-5$ at 205 K.

This means an uncertainty of 1 mm on a radius of curvature of 20 m. The LVDT measurements are very sensitive to temperature (the LVDT is nearly in contact with the cryogenic environment). It was decided to use the thermo-elastic model for measurements below 205 K.

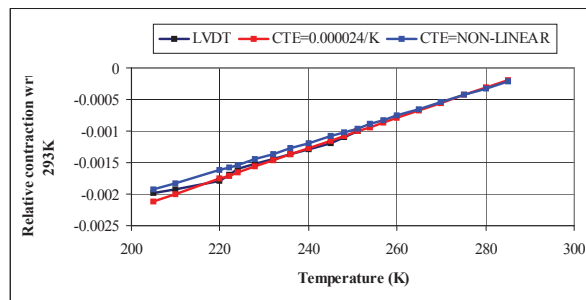


Fig. 9. Relative contraction of the spherical aluminium convex mirror

Non-homogenous CTE variations contribute to the surface figure error of the primary reflector.

The set-up facility is equipped with refocusing capability in order to make the reflector measurement in a stigmatic configuration. It consists in computer aided approach developed at CSL [4] based on the cancelling of the dominant misalignment aberration (Tilt X, Tilt Y, Focus, Astigmatism X, Astigmatism Y, Coma X, Coma Y). These aberration residual terms are systematically removed in all the WFE analysis.

Although many verifications and precautions have been carried out during manufacturing, a verification of this non-inhomogeneous contribution has been performed. This verification is completed in situ. Indeed, at the end of the last cryogenic cycle (Fig. 8), where PLANCK primary reflector was at ambient temperature, the aluminium mirror was still below 100 K.

The verification consists in rotating the spherical aluminium mirror. Four WFE are obtained at 0, 90, 180 and 270 deg. The WFE are summed or subtracted in the following way.

$$prim = \frac{0 \text{ deg} + 90 \text{ deg} + 180 \text{ deg} + 270 \text{ deg}}{4}$$

$$sphe = \frac{270 \text{ deg} - 90 \text{ deg}}{2} + \frac{180 \text{ deg} - 0 \text{ deg}}{2}$$

“Prim” is the WFE of the PLANCK primary reflector with all non-axis symmetrical contributions of the spherical mirror removed.

“Sphe” is the non-axis symmetrical WFE of the spherical mirror.

Fig. 10 and 11 show that the PLANCK primary reflector has not changed before and after the cryogenic cycle.

Moreover; Fig. 10 is computed after averaging 4 WFE maps, removing the contribution of spherical aluminium mirror which is still below 100 K.

The spherical aluminium mirror does not contribute to the SFE with higher order aberrations and consequently it meets its functional goal.

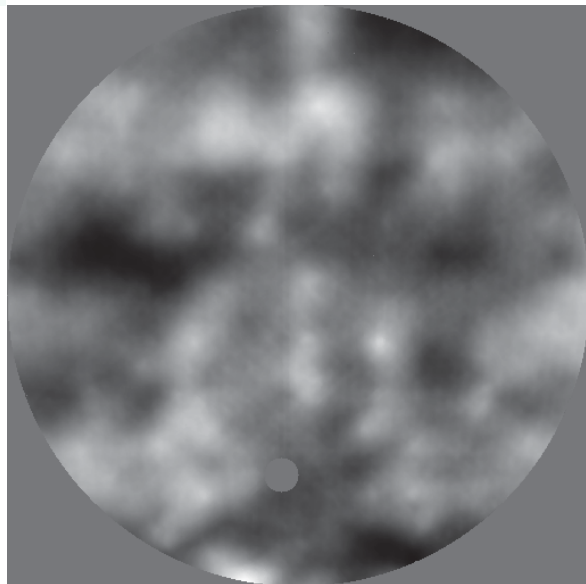


Fig. 10. PLANCK primary reflector WFE at 298 K after the thermal cycles. RMS WFE = 10.2 μm with contribution of spherical mirror removed. The spherical mirror at 100 K

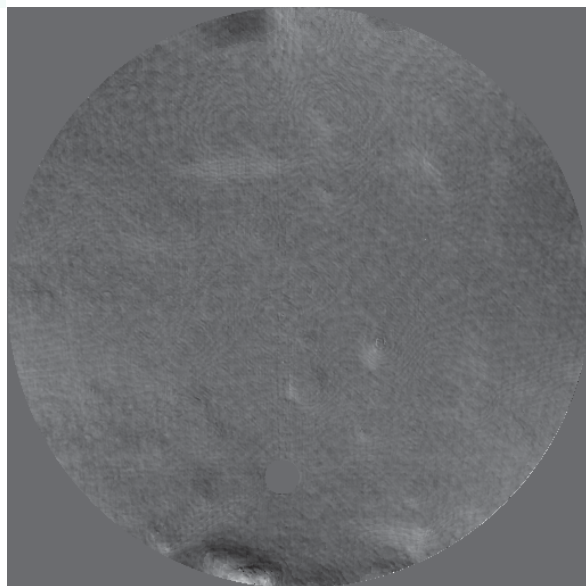


Fig. 11. RMS WFE of the spherical aluminium mirror
RMS WFE = 0.5 μm

6. CONCLUSIONS

A unique large (1500 mm diameter) aluminium spherical convex (19735 mm radius of curvature) mirror has been designed, manufactured and successfully used at an operational temperature of 25 K.

It has been demonstrated that the aluminium spherical convex mirror contribution at cryo temperatures to the WFE measurement of the PLANCK primary mirror is less than 0.5 μm RMS.

7. ACKNOWLEDGEMENTS

The Al spherical mirror and the thermal shrouds have been manufactured by AMOS (B). The reflector has been built by EADS Astrium (D). The tests were conducted in FOCAL 6.5 CSL facility (B). All these works were funded under several ESA contracts.

8. REFERENCES

- [1] S. Roose, Y. Houbrechts, A. Mazzoli, N. Ninane, Y. Stockman, R. Daddato, V. Kirschner, L. Venacio, D. de Chambure, "Cryo-optical testing of large aspheric reflectors operating in the sub mm range", *Proceedings of the 2nd SPIE symposium on Advanced Optical Manufacturing and Testing Technologies*, Xian, Proc. SPIE 6150 (2005).
- [2] Aluminium and Aluminium alloys, Edited by JR Davis ASM international, 1994.
- [3] *Proceedings of the International Workshop on Mirror Substrate Alternatives*, Edited by JP Roselot, OCA/CERGA 1996.
- [4] Y. Houbrechts, S. Roose, Y. Stockman, "Focii determination of an off axis ellipsoid: Theory to practice", SPIE 5190-25 49th annual meeting on *Optical Science, Engineering, and instrumentation*, Denver, 2004.