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Last results of technological developments for ultra-lightweight, large aperture, deployable mirror for space telescopes

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Abstract—**The aim of this work is to describe the latest results of new technological concepts for Large Aperture Telescopes Technology (LATT) using thin deployable lightweight active mirrors. This technology is developed under the European Space Agency (ESA) Technology Research Program and can be exploited in all the applications based on the use of primary mirrors of space telescopes with large aperture, segmented lightweight telescopes with wide Field of View (FOV) and low f/#, and LIDAR telescopes. The reference mission application is a potential future ESA mission, related to a space borne DIAL (Differential Absorption Lidar) instrument operating around 935.5 nm with the goal to measure water vapor profiles in atmosphere. An Optical BreadBoard (OBB) for LATT has been designed for investigating and testing two critical aspects of the technology:**

1) **control accuracy in the mirror surface shaping.**
2) **mirror survivability to launch.**

The aim is to evaluate the effective performances of the long stroke smart-actuators used for the mirror control and to demonstrate the effectiveness and the reliability of the electrostatic locking (EL) system to restraint the thin shell on the mirror backup structure during launch. The paper presents a comprehensive vision of the breadboard focusing on how the requirements have driven the design of the whole system and of the various subsystems. The manufacturing process of the thin shell is also presented.

Keywords: **lightweight mirror, deployable mirror, active optics, space telescope, LIDAR**.

I. INTRODUCTION

In this paper new developments of technological concepts for Large Aperture Telescopes Technology (LATT) are presented in response to an invitation to tender of European Space Agency (ESA). The aim is to improve technologies of thin deployable lightweight active mirrors. The activity of design and manufacture a demonstrator was carried out during the Phase 2 of ESTEC/Contract No. 4200022321 CCN1 in order to validate the new technologies by a ground test.

New solutions were studied for the "Advanced LIDAR Concept" (ALC) another ESA contract during 2007, for the application of a space borne differential absorption LIght Detection And Ranging (LIDAR) system to measure water vapor distribution in atmosphere at 935.5 nm [1],[2],[3].

To improve the Signal to Noise Ratio (SNR) with LIDAR detection the collecting area of telescope collector has to be increased, so the mirror must be large, lightweight in agreement with space mission mass budget and easily controllable in shape, as presented at ICSO 2006 and 2008 [4],[5]. The developed system was presented at ICSO 2010 and deeply described in [6].

The general concept is based on 1-mm thick glass mirror (Zerodur®), actively controlled to reach the specified shape after initial deployment, and maintained within specs for the entire mission duration, by using an optical wavefront sensor in closed control loop with the mirror surface shape control system.

The structural integrity during launch and operations has to be guaranteed by considering the ALC mission critical points [5].

The resulting concept is based on a primary telescope mirror with segmented geometry (mass/area density goal <16 kg/m^2: and an area of 7 m^2, as reported in the previous ALC study in Tab. 1). The central portion is locked to the bus of the satellite, surrounded by a set of petals stored during launch, and opened before the operational phase in space. In addition, the materials selected must also have adequate thermal characteristics in order to minimize the distortion of the mirror shape.

This paper shows now the activities to overcome the critical points that came out in the previous study, concerning to the verification of the technology and of the improved engineering solutions on the deployment system and on the demonstrator Optical BreadBoard (OBB). In particular this includes: optical quality of the thin shell mirror surface, actuators performances and back-plane – electrostatic locking (EL) subsystem. Also a Deployable Breadboard (DBB) is considered, in order to demonstrate the deployment mechanisms and kinematics.

II. Optical BreadBoard

The OBB was developed to assess the ability of the proposed technology to actively control the shape of the mirror with the required optical accuracy.

The OBB structure obtained with this work is made of an honeycomb sandwich (Carbon Fiber Reinforced Plastic (CFRP) and Aluminum), characterized by a set of 19 large trough holes (60 mm diameter) where the actuators "cups" can be inserted. CFRP has been chosen for the backplane because of its low density, high stiffness, low Coefficient of Thermal Expansion (CTE) and high strength, vacuum compatibility. An improved configuration, with respect to previous one [6], for the magnet puck gluing on the mirror has been designed in order to limit the stress on the thin shell during the launch accelerations.

The final design of the electronic control system of the OBB for LATT includes a central control unit and the actuator control electronics, co-located with each actuator. The central control unit is based on the Microgate Basic Computational Unit (BCU) board and the Signal Generator (SigGen) board, which both have already been successfully implemented in the Large Binocular Telescope (LBT) and Very Large Telescope (VLT) projects.

Fig. 1 shows the OBB structure: thin glass shell, backplane and Electrostatic locking

Main OBB requirements

Component	Requirement	Expected value
Mirror	Mass Areal Density	<16 Kg/m^2
	Residual Wavefront Error	<156 nm RMS (λ/6 of 935 nm)
	Shape, Diameter x Thickness	Spherical, R= 5000 mm, 400 mm x 1 mm
	Material	Zerodur
Backplane	Material	Carbon Fiber Reinforced Plastic + Aluminum (CFRP+ Al)
	Main Dimensions	440 mm max external
	EL axial force	2048 Pa
	El shear force	4924 Pa

The OBB is made of four functional subsystems:

- the thin shell representing the optical element [1 mm thick Zerodur Shell, diameter 400 mm and CR 5 m];
- the backplate or honeycomb sandwich, is the OBB backbone structure where the actuator's cups are placed in and which provides also the substrate to the Electrostatic Locking of the shell;
- the Electrostatic Locking System, which is implemented across the shell and the backplane to hold the shell during launch;
- the actuators plus frontal capsens disk, which are mounted inside the sandwich and are facing to the coated back of the shell;
- the flexures to restrain the in plane motion of the thin shell.

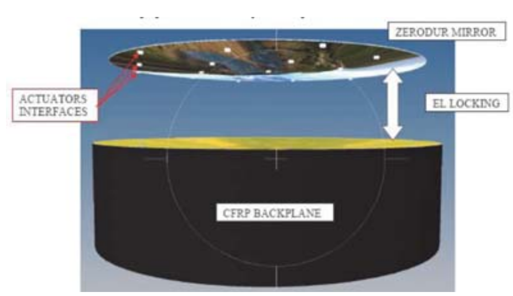

Fig. 1. The OBB concept: the thin shell mirror surface, actuators glued at CFRP back-plane via EL subsystem

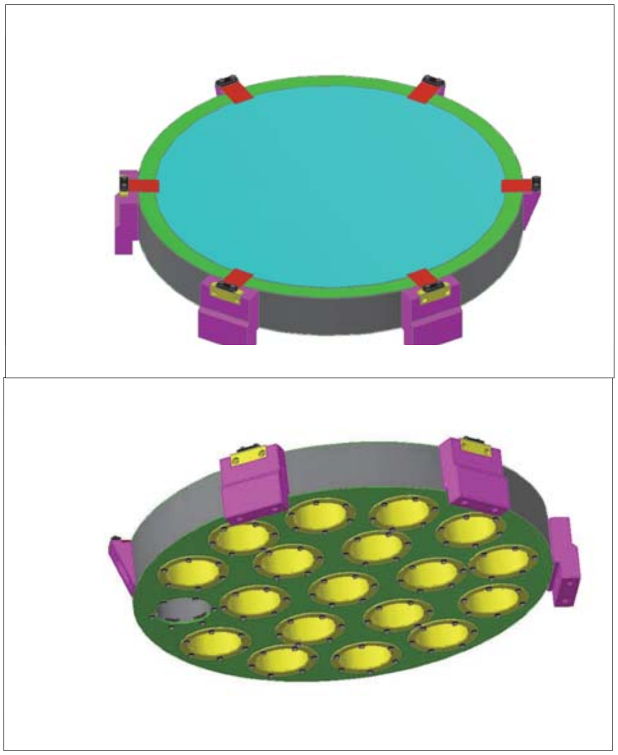

Fig. 2. OBB rendering, view from the thin shell side. Out of the six flexure supports the three in foreground are also used to clamp the OBB during the vibration and optical tests.

III. ELETTROSTATIC LOCKING SYSTEM

The Electrostatic Locking System is implemented directly on the back plate front surface and the thin shell back surface. The armatures are made by evaporation under vacuum conditions of protected aluminum layers on both surfaces (back of the shell and glass inserts).

Protected aluminum coating is made by a first layer of Aluminum on which it is deposited (evaporated under vacuum again) a layer of SiO_2.

This is a quite standard coating process used on mirrors, which has been tailored to match the specific requirements of this application. In particular a pretty thick layer of quartz, namely 5 micron was deposited.

The effectiveness of the locking depends clearly on the shape accuracy of the two armatures.

The low order (large spatial scale) shape errors can be (partially) accommodated by the compliance (flexibility) of the thin shell, while the high order one (local deformations and roughness) shall be kept by fabrication below few microns. On this topic, we proved that by adopting a replica technique the backplane could be properly shaped. Again, this technique is suited to make the backplane of any shape, this not posing any limit on the mirror optical design.

In order to restrain the lateral displacements of the thin shell, a flexure system has been introduced. Moreover, since the Electrostatic Locking efficiency in restraining the lateral displacements is a critical issue, it has been evaluated the possibility of using the flexures system in order to withstand part of the loads induced by the lateral accelerations at the launch.

The obtained mass of the shell is about 0.35 Kg while the equivalent accelerations along X,Y,Z are 59g, 67g and 37g respectively. So for the vertical force we have 127 N corresponding to a required vertical pressure of Pz 2048 Pa (computed on the true area of the backplane, without glass inserts) and Pxy = 4924 Pa. This pressure is intended as a lateral shear force over the backplane area (no inserts).

Fig. 3 shows Pz values at different applied voltage. By assuming μ=1 it results that the required Pz pressure can be achieved by using a voltage of about 120-150 V(cyan line).

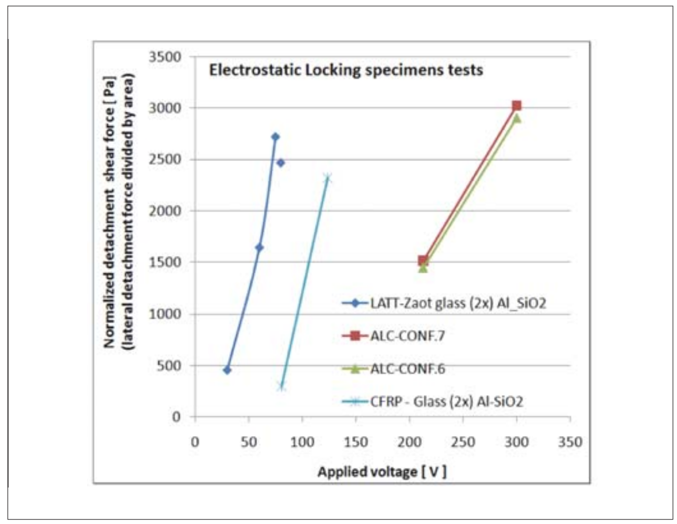

Fig. 3. Pz values at different applied voltage required Pz pressure can be achieved by using a voltage of about 120-150 V (cyan line).

If one wants to hold the shell only by friction it might be needed to increase the operative voltage by a factor of two (minimum). In principle the shell's flexure could contribute to the in-plane stability and thus the voltage level could be limited to what is already needed for the "vertical safety". More tests are needed on prototypes to explore the limits of this technology. Please note that the ALC prototype was vibrated at 300 V (refer to green/brown line of the previous picture) but it was done by using a different technology with respect to what proposed for the OBB

IV. ACTUATORS PATTERN

Previous studies demonstrated that a critical parameter is the actuator density forces in case of:

1. Large deployment errors (i.e. large actuators stroke, large range capacitive sensors)
2. Extremely efficient electromagnetic actuators for minimum power dissipation

These priorities have resulted in the design of a new, highly efficient, large stroke actuator, but at the cost of a considerable actuator mass. One of the primary objectives of development was to reduce the mass of this advanced actuator by at least a factor of two [5].

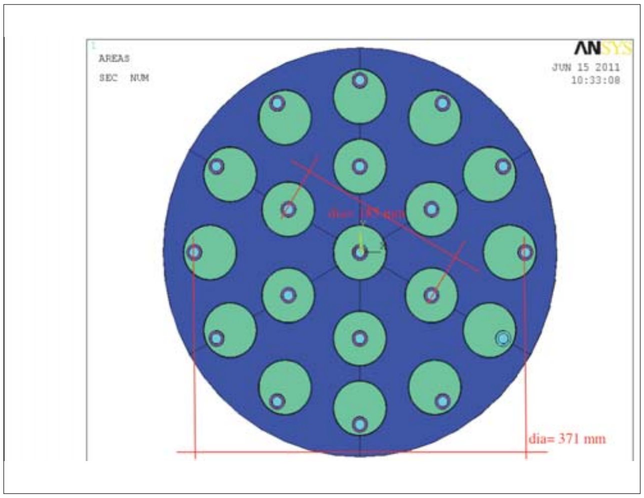

Fig. 4. The new proposed actuator pattern and the diameters of the two reference rings

The new actuators pattern has an average linear pitch of about 92-95 mm. With respect to the previous diamond shaped pattern, in this case the 19 actuators are arranged on two rings having a 185 and 371 mm diameter respectively (top view).

V. SHELL MANUFACTURING

The manufacturing procedure for the construction of two samples of Zerodur is divided in different phases to obtain the final OBB mirror. The first step for the manufacturing of the concave spherical glasses consists in pre-manufacturing all the needed support tools, i.e. the control forms and the marble supports.

Zerodur® is chosen for the OBB since it has a very low (~10^{-8}/K) and uniform CTE, suitable to operate with the CFRP backplane. The thin Zerodur shell (1 mm) is obtained using the same procedure described in [5], but substituting a Zerodur bad quality blank to the marble one, as convex support for the grinding and polishing steps of both the concave and convex surface.

Interferometric measurements are taken for concave and convex surface of the shell and for the final central thickness.

At the end of this procedure the thin glass is unstuck from its support and tested, as is described in next section. Optical tests have to subtract the gravitational quilting effect. Fig. 5 shows the optical manufacturing machine during lap procedure.

VI. THERMO-STRUCTURAL PERFORMANCE OF THE THIN SHELL

Gravitational quilting during optical experiments

When the thin shell is supported on the OBB by the flexure system for the optical ground experiments a gravitational deflection must be compensated by the adaptive optics system to optimize the optical figure.

The deformation under self-weight is not a design driver since the final operation is to occur in space. This allows to reduce the actuator density and the mirror thickness with respect to the traditional ground applications. However this is a major drawback for the laboratory optical tests, because the deformation under gravity (hereafter gravitational quilting) generates an unavoidable bias in the figuring error, increasing the requests of accuracy and dynamical range on the instrumentation for the optical verification of the mirror.

In order to minimize the gravitational quilting, the mirror is tested in a vertical position (Figure 6) i.e. with the optical axis orthogonal to the gravity direction. The resulting PTV deflection is about 0.42 micron before active compensation, as Fig. 6 shows.

Fig. 5. Zerodur blank during polishing step

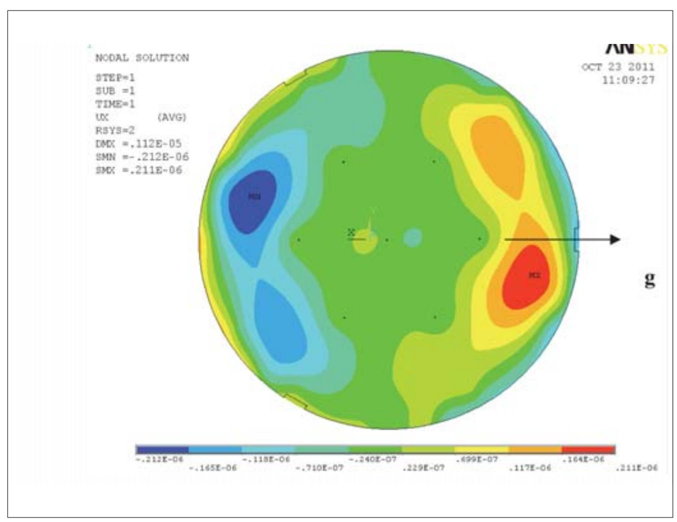

Fig. 6. The deflections of the thin shell [m] in the directions perpendicular to the optical surface. The shell PTV deflection is about 0.42 micron before active compensation.

Thermal deformations

The same considerations can be applied to the thermally induced deflection for the optical ground experiments. The deflection of the thin shell for a

A FE model consisting in the curved thin shell plus a lower "perforated bed" had been developed. A set of surface to surface, non-linear contact elements had been placed between the "continuous" thin shell (equipped with its permanent magnets) and the bed. Applying a vertical static acceleration equal to 100 g in order to squash the shell against its bed the resulting displacement and stress patterns ([m] and [Pa] respectively) are reported in the Fig. 8 and Fig. 9.

temperature variation and the displacement pattern has been reported in the following Fig. 7.

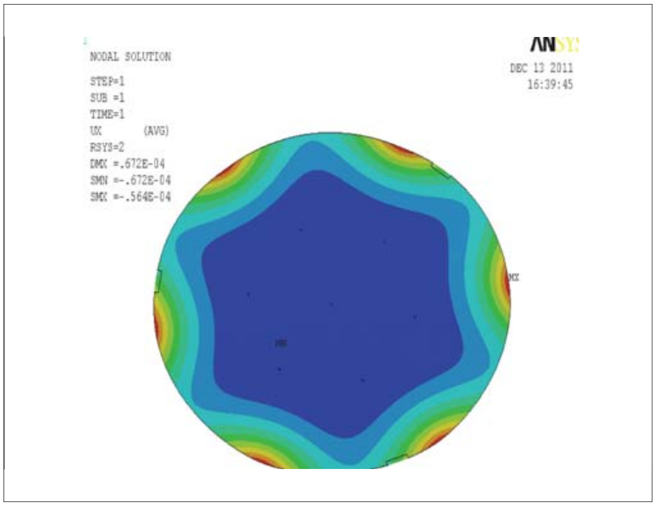

Fig. 7. . Displacements due to the flexure system for 10°C temperature variations. The PTV is about 11 micron.

The integration temperature will be in the range of 20-25 °C it is important to evaluate the thermal effects that could be seen in different temperature laboratory conditions.

The displacement pattern due to a 10 °C temperature difference are measured perpendicularly to the optical surface and the obtained PTV is about 11 micron:

VII. Shell Structural Safety and Performances

A. Shell deflections through the holed reference surface

Fundamental task is the safety of the thin Zerodur shell for the loads experienced during the launch phase.

Because of the particular shape of the OBB backplane there are 19 circular portions of the thin shell free to float and deform under the inertial loads (the rest of the thin shell is clamped by the EL or equivalent system).

A FE model consisting in the curved thin shell plus a lower "perforated bed" had been developed. A set of surface to surface, non-linear contact elements had been placed between the "continuous" thin shell (equipped with its permanent magnets) and the bed. Applying a vertical static acceleration equal to 100 g in order to squash the shell against its bed the resulting displacement and stress patterns ([m] and [Pa] respectively) are reported in the Fig. 8 and Fig.9.

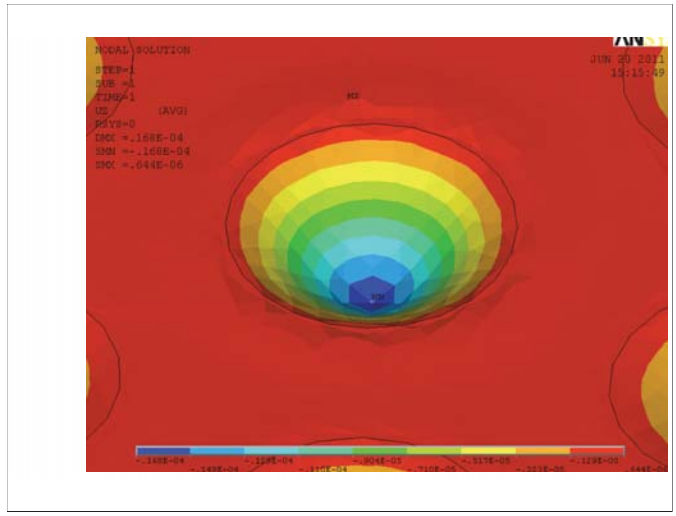

Fig. 8. The displacement of the thin shell (quilting) for a 100 g load. The glass shell tends to fall inside the hole of the CFRP backplane by 16.8 micron.

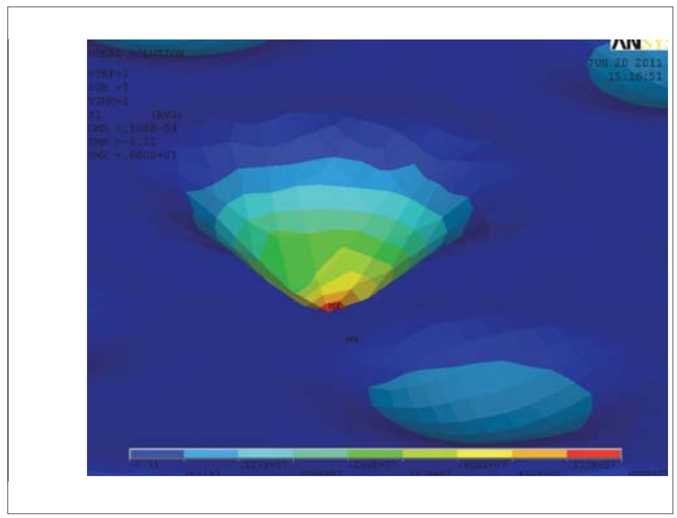

Fig. 9. The tensile stress (s1) in the glass, the maximum stress is about 6 MPa and remains below the admissible value for Zerodur, fixed at 30 MPa.

B. Magnets induced stress for thermal and inertial loads (ΔT=45°C, launch accelerations)

An initial set of kinematic constraints are applied with a -45 °C temperature variation, representative of the worst gradient with respect to the integration temperature (survival @-25°C Vs. integration @+20°C).

The resulting displacement pattern is in the following Fig. 10. As we can see there is a kind of print through of the magnets on the mirror surface. This effect is mainly due to the large CTE of the magnets' material (iron like CTE).

The Z direction displacement pattern [m] caused by a -45 °C temperature variation in Fig. 10 is shown. The print through due to the magnets is very limited and the PTV deflection over the entire surface is smaller than 33.5 nm. It must be noticed that in the worst operative condition the ΔT is limited to 20°C, thus the effect here computed must be scaled down to about 15 nm (surface).

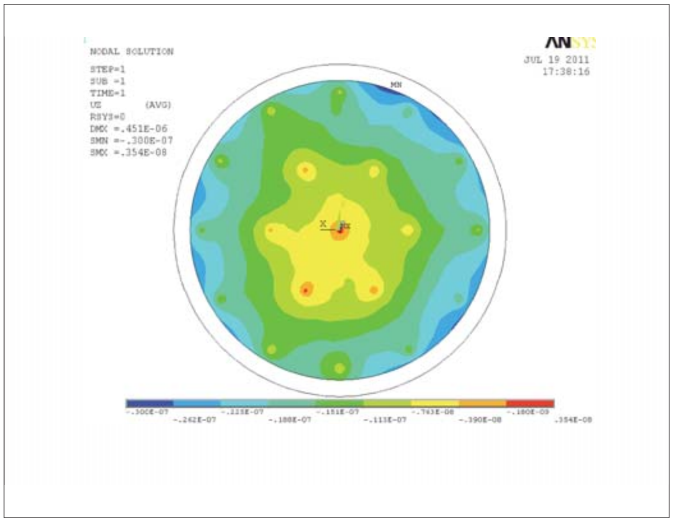

Fig. 10. The Z direction displacement pattern caused by a -45°C temperature variation

VIII. DEPLOYMENT MECHANISM

The primary mirror deployment configuration identified in the trade off analysis is the FWD/REAR folding petals configuration [3],[4]. A stable structure with high stiffness, based on the available hinge and latches technologies, leaving the task of achieving very high precision to the active optics of the telescope e is proposed. The main advantage of the selected configuration is to maximize the mirror aperture with respect to the forward one. Nonetheless, the drawback is that the kinematics for the FWD petals cannot be equal to the REAR petals one.

Each petal is constrained to the main structure by means of two hinges and stiffed by an Adjustable CFRP strut. This strut is constrained both to the petal and the main structure by hinges. The main structure hinge is mounted on the latching device, which can slide up and down on a guide. Simulations and error in deployment mechanism shows the latching plays an important role in the determination of the deployment accuracy. Hence, the deployment breadboard has been developed with the aim of measuring the latching accuracy and of verifying its repeatability. The deployment breadboard (DBB) is made of 3 main devices: Drive device, Latching device, Latching release device and Support Structure. The actuator stroke allocated for the correction on the displacement error is 250 µm. The worst petal tip displacement obtained is about 148 µm.

IX. CONCLUSIONS

Future space-based telescopes with large aperture mirrors, for scientific or LIDAR remote sensing applications must be lightweight and deployable (due to launcher fairing limitations). LATT is developed to validate the ALC technology with the OBB manufacturing and testing to be in agreement with space mission mass budget and controllable in shape.

All the activities performed till now during the Phase 2 of ESTEC/Contract No. 4200022321 allow drawing the following conclusions:

The proposed sandwich backplane structure (CFRP skins and Al honeycomb) fulfills all the functional requirements, both in terms of opto-mechanical stability (during optical tests) and in terms of ability to survive to the launch loads. Thanks to the new gluing solution, the MoS with respect to the RVLFs are now positive. The resulting OBB areal density is about 18 Kg/m^2, a very similar value can be assumed if the LATT petal is fabricated with the proposed technology. Standard PC and communication board, high voltage supply unit are used to control the tests in the test phase. The actuators control electronics (Smart Actuator Control board) is specifically designed and therefore it is thought to be as much as possible representative of a future 'flying unit', both in terms of interfaces, size, weight, power dissipation and control performances.

The required final space optical figure, obtained by means of the proposed OBB optical test setup, cannot be read directly but shall be estimated after removal of the gravity effect. The deformed shape of the mirror, under 1 g load, foreseen by the FE analysis, will be subtracted to the optical test results.

As for the EL, it has been demonstrated that the in-plane restraint offered by the flexure system is reliable integration for what concerns the safety of the shell. The flexures on their own can withstand the full lateral inertial load. Test prediction has been performed to evaluate the safety aspects related to the vibration test.

The deployment error estimation performed in the detailed design of the DBB shows an error of 75.9µm while the actuator stroke allocated for the compensation of the deployment error is 250 µm. It seems that good margins can be achieved for the deployment errors. Nonetheless, this estimation does not consider the effects linked to the accuracy of the latching device.

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