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ABSTRACT

The Large Aperture Telescope Technology (LATT) goes beyond the current paradigm of future space telescopes, based on a deformable mirror in the pupil relay. Through the LATT project we demonstrated the concept of a low-weight active primary mirror, whose working principle and control strategy benefit from two decades of advances in adaptive optics for ground-based telescopes. We developed a forty centimeter spherical mirror prototype, with an areal density lower than 17 kg/m^2, controlled through contactless voice coil actuators with co-located capacitive position sensors. The prototype was subjected to thermo-vacuum, vibration and optical tests, to push its technical readiness toward level 5. In this paper we present the background and the outcomes of the LATT activities under ESA contract (TRP programme), exploring the concept of a lightweight active primary mirror for space telescopes. Active primaries will open the way to very large segmented apertures, actively shaped, which can be lightweight, deployable and accurately phased once in flight.

Keywords: Active Optics, Wavefront correctors, Deformable mirrors, Space telescopes, low-weight primary mirrors.

1. INTRODUCTION

It was in mid-80ies when the Nordic Optical Telescope (NOT) and in a more comprehensive way the New Technology Telescope (NTT) paved the way to lightweight solution for the equipment of ground based astronomical telescopes with lightweight primary mirror and adjustable alignment of the optics. So called active optics allows the actual quality of a telescope to be restored in real time. But only with adaptive optics (AO) modern telescopes reached diffraction limited resolution pushing the frequency from few Hz to the kHz.
The adaptive compensation of the atmospheric turbulence induced optical aberrations (the ones causing the stars twinkling) quickly performs the reshaping of the Deformable Mirrors (DM) on the basis of the Wave-Front Sensor device measurements. State of the art ground optical telescopes mount secondaries designed to perform the adaptive correction such as the Large Binocular Telescope First Light Adaptive Optics (FLAO). Top Wave-Front (WF) flattening performance of the telescope are realized using a thin mirror shell (thickness: 1.6mm) shaped by 672 voice-coil actuators controlled in position through capacitive sensor.

Larger the telescope in space larger is the demand for lightweight solutions. Typically such solutions show larger adverse effects due, for example, to thermo-elastic deformations, gravity release, effects of radiation,

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material creep, manufacturing and polishing errors among the others. Of course such inconveniences depend also on the kind of orbit that host the spacecraft because of the different Sun radiation cycles. Cheaper and faster orbits are the ones presenting the largest drawbacks.

The design of space telescopes larger than 4 m foresees deployable primary mirrors which need more demanding metrology and control solution to operate properly. Deployment errors and gravity release may be corrected by moving the available actuators probably of large amount of their stroke and once in telescope lifetime (set and forget). This solution requires *nm* long-term stability of the telescope and of the actuators, and it does not match the condition of LEO/GEO-orbit.

Telescopes which needs continuous correction (1/min, 1/hr) would go towards more active solutions able to compensate at moderate temporal frequency the WF variation on a closed loop fashion. Active optics systems cope the weakness of the lightweight solution. But other weakness points raise: actuators reliability represent a serious risk, although unlikely, for the WF error budget and manufacturing and polishing induced print-through are source of high spatial-frequencies on the deformable mirror because of the variable structural rigidity across the surface.

Within this scenario, LATT is a project funded as an ESA TRP for the study and prototyping of a lightweight active primary mirror. The LATT consortium is composed by the italian industrial companies CGS, Microgate and ADS-International and by the public research institutions INAF (Astrophysical Institute) and CNR-INO (Optics Institute). Within the project a demonstration prototype called OBB (Optical BreadBoard) has been integrated and tested, to assess the technological solutions proposed for the LATT.

This paper is devoted to summarize the features of a LATT deformable mirror, as the primary of an active space-based observatory, together with the findings of the LATT study and OBB experience.

2. THE LATT WAY

The origin of the LATT is traced in the development, test and use of large size adaptive secondary mirrors equipping ground based AO telescopes like MMT and LBT.[1] The main component of such systems is a large format, ultra-thin glass shell shaped at high frequency by contactless voice coil actuators. The concept of adaptive secondary, which has now come to full maturity, has been a breakthrough in ground based AO, because of its advantages: large stroke, low number of optical elements, lower non common path aberrations, all delivered to the entire telescope.

The LATT is a way to apply and extend such expertise (technologies, strategies and knowledge) to space based active optics and develop the concept of the active space telescope. Such effort follows the specific requirements and use cases of an orbiting telescope: reliability, low weight, low power consumption, correction of low-frequency, large-amplitude deformations. In the following we will describe the key elements behind the LATT.

2.1 Active primary

In the LATT the correcting element is the primary mirror, as a natural extension of the square meter sized adaptive secondary. The implementation of the wavefront correction on the primary gives a number of advantages, particularly compared to a deformable mirror (DM) located at a pupil relay; here we will focus on three main aspects. As a first point, an active primary made with the LATT may feature an areal density as low as 12 to 17 kg/m^2 (see Sec.3 for the mass of a 40 cm prototype), with a fundamental impact on mass budget; additionally, pupil relay optics are not longer needed, with a further simplification of the optical design and telescope assembly (and mass).

On a development perspective, primary mirror segmentation shall be taken in mind to deploy a large space telescope: the segments may be folded to fit into the launcher fairing or may be assembled once in orbit. Provided that segmentation is on the largest optics, i.e. the primary, the active correction shall take care of the segments phasing, implying the need for a segmented DM, the primary as the most natural solution.

Finally, if the active correction is performed on the same surface where most of the deformation originates (very likely on the primary, being the largest component), the rest of the optical train will work closer to *as-designed* conditions.

Figure 1. Comparison between the 91 cm LBT TS equipped with 672 magnets (on the left) with the LATT-OBB one (on the right).

2.2 Glass shell and Reference body

The glass thin shell (TS) is the core of the adaptive secondary and of the LATT. So far, 10 shells has been manufactured and their relevant parameters are shown in Tab.2.2. In Fig.1 the TS of the LBT adaptive secondary is shown together with the OBB one. The manufacturing and operating technology has reached its maturity, assessing the following results:

- any optical prescription is possible, including aspheric surfaces, both concave and convex;
- any geometrical shape may be obtained, including those well fitting the segmentation (e.g. the E-ELT M4 deformable mirror[2]);
- the thinning process is able to deliver a 1 mm thin shell up to a linear size of 70 cm and 2 mm for a 1.2 m diameter;
- the optical quality (including actuator flattening) is far better than $\lambda/20$ in V band;
- the LBT shells are in operations since 2008, proofing mechanical reliability and robustness despite their fragility.

As from Tab.2.2, very similar (good) optical quality was achieved on flat, convex and concave, spherical and aspherical surfaces. In facts, the polishing process is standard as for thick mirrors; after polishing the TS is thinned to $\approx$ 1 mm. Because of such additional work, the control of the low order modes (astigmatism, trefoil) is not accurate because of the support structure print-through and self-bending; the residual figuring may be however corrected with negligible loss of stroke budget by the actuators -this is the *flattening* procedure- delivering a typical WFE of 15 to 20 nm RMS. It is of paramount importance that the TS polishing procedure reduces the high orders down to a final (local) WFE of $\approx$ 10 nm RMS. This guarantees that the WF beyond the actuator spatial scale of correction is negligible.

The non-optical side of the thin shell faces a *reference body* (RB), a stiff plate providing a stable mechanical support and a reference for the internal metrology. In the LATT, the RB is an aluminium honeycomb core layered with CFRP sheets on both sides, having a total density of 90 kg/m^3 (which turns into an areal density for the OBB case of $\approx$4 kg/m^2).

Thanks to the actuators, the TS *floats* in front of the RB at the desired position (also known as gap: see Sec.2.3); for safety reasons, however, the RB holds the TS by means of flexures. They are invar springs that provide a very stiff in-plane constraint with negligible vertical rigidity, featuring a minimal interference with the actuators (e.g. without limiting the stroke budget). Flexures are glued on the TS itself: at the central hole (LBT, VLT cases), or at the edge (LATT prototype, M4DP). The curing print-through has been minimized with optimized gluing

Project	n Shells	Size [m]	Shape	Thick. [mm]	n acts	Opt.shape	Opt.quality
MMT	1 (1992)	0.64	Conv.-Circ	1.6	336	Aspheric	na
LBT	5 (2010)	0.91 (OD)	Conc.-Circ	1.6	672	Aspheric	15 nm WF
VLT	2 (2010)	1.2 (OD)	Conv.-Circ	2.0	1170	Aspheric	<28 nm WF
LATT-OBB	2 (2013)	0.42 (OD)	Conc.-Circ	1.0	19	Spheric	See Sec.3
M4DP	2 (2009)	0.3x0.7	Trapezium	1.0	111	Flat	12 nm WF

procedures; the actuators below the flexures may also be operated according to specific procedures (see 2.3) to best manage the residual deformation and the actuator force budget. At last, a flexures detachment mechanism may be implemented to completely release the TS in operating conditions.

The fact that the TS is physically detached from the RB has two fundamental consequences. First, the RB has no optical requirements, so that ultra-lightweight materials may be used (like aluminium honeycomb in the present case). As a second point, the RB thermo-elastic deformations are propagated to the TS (the optical surface) only by the actuators in close loop. Such mechanism may be summarized as follows: the RB bends; the capsens reference is changed; the actuators apply a force to move the TS; the position reading is restored. Now, as the Zerodur TS is almost thermally insensitive, it follows that the wavefront deformations to be corrected are entirely, by design, within the actuator control space, yielding a substantial benefit to preserve the image quality (see also Sec 2.4.1).

One of the concerns about TS and space application is survivability to launch stresses; such issue has been tackled by *gluing* (during the launch) the TS onto the RB by means of an electrical field: the adhesion force is large enough to stabilize the TS against the simulated launch accelerations. In Sec.3 some details about the procedure as demonstrated on the OBB are given.

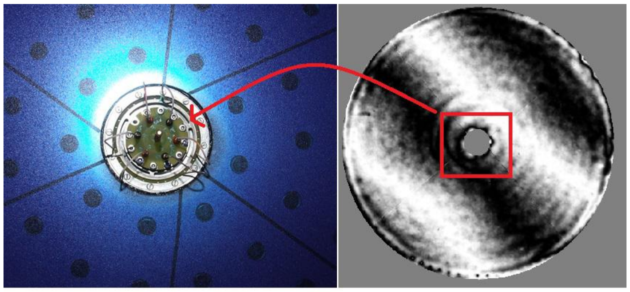

Figure 2. Left: the central flexure used for the LBT adaptive secondary, glued on the TS surface; right: the flexure print-through after flattening the TS with the actuators.

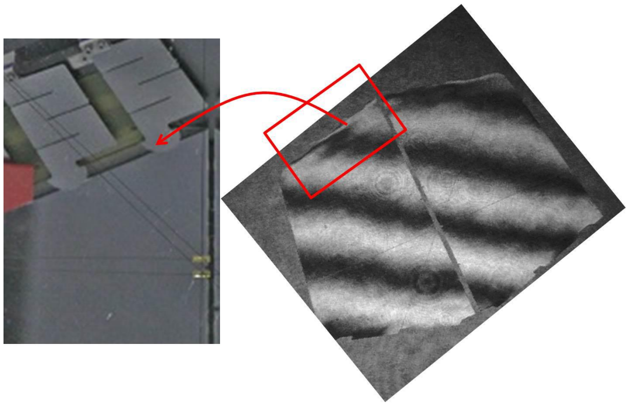

Figure 3. Left: the flexures adopted to constraint laterally the M4DP, glued on the TS; right: the flexures print-through on the TS after applying the flattening command with the actuators.

2.3 Voice coil actuators and *capsens*

In the LATT concept, the actuation is performed by voice-coil motors: the coils are mounted on the RB and the magnets are glued on the back of the TS. The actuators are a modified version of the LBT-VLT ones, an evolution driven by weight and power saving.

The actuator command is controlled in close loop, with the feedback from co-located capacitive sensors: they measure the distance of the TS to the RB by sensing the capacitor made by the two surfaces, which are both coated by aluminium. The achieved precision is typically 5 nm RMS. Such internal metrology works at a frequency much higher than optical loop fed by the WFS, so that the internal loop helps the optical one. The internal metrology is very attractive as the 'real' actuator position is known-not just the command applied. Such strategy allows applying open loop commands accurately, such as initial $flat$ shape, continuous look-up-table corrections, even without (to some extent) the need of a current WF measurement.

Voice-coil motors and capacitive sensors are both $contactless$ devices. The TS is never mechanically constrained by the actuators and in case of failure the broken actuator will not produce a local spot with large WFE. $Contactless$ actuation and metrology is an intrinsic safety feature.

Force actuators are limited by the maximum applicable force to produce a bending on the TS; its stiffness, as for a thin plate, is inversely proportional to the fourth power of the spatial scale of bending. It follows that force actuators may produce low order modes with amplitude as large as hundreds of micron PtV: the stroke is basically limited by the capacitive sensor range which is ≈ 1 mm . Since low orders are most of the thermal deformation, voice-coil force actuators are particularly suited within this context for space active optics.

2.4 Strategies and functionalities from AO experience

The LATT concept inherited 15 years of research from his ancestor the adaptive secondary mirror. Such a legacy, apart from the pure technological development, includes knowledge, debugging and operational strategies. The expertise has been demonstrated to be scalable and applicable to the LATT concept, and is therefore an added value for the development of space active mirrors. In the following we will give a resume of the most relevant points.

2.4.1 FeedForward matrix and mirror modes

The deformable mirror shaped by force actuators is controlled by means of its stiffness of $Feed-Forward$ matrix K. It is the measured coupling among actuators force applied F and displacement P achieved in close loop. The measured K may be orthogonalized by means of singular value decomposition as follows:

$$F = KP; \quad (1)$$

$$K = UWV^T; \quad (2)$$

where V is the eigenvector matrix in the mirror actuators space (each column representing the actuator command to obtain a mirror eigenstate). W is a diagonal matrix where the diagonal elements represent the stiffness value of each of the mirror modes.

2.4.2 Actuators disabling and slaving

Such actuator commands formalization allows defining case-specific control strategies for not-working or saturated actuators. When an actuator fails, it may be removed from the internal control loop (*disabled*) by putting to 0 its force value in Eq.1. The equation may be solved thus reducing the number of degrees of freedom obtaining new (*reduced*) FF and mirror modes matrix. Thanks to this procedure, a dead actuator (more likely from our experience, a misfunctioning capacitive sensor) will work at any time with zero force applied without producing any local shape on the TS.

Similarly as for the disabling procedure, an actuator may be *slaved* by solving Eq.1 for its position when zero force is applied. A new V matrix may be computed, defined over all the active and slave actuators, although with a reduced number of mirror modes. Such procedure is attractive for those actuators where a static (large) force command is requested to compensate a zero shape, so that they cannot participate to the AO loop any longer, yet they can help the neighbors achieving good performances.

2.4.3 Flattening and phasing

The mirror flattening starting from the V matrix has been extensively used for the adaptive secondaries:[3] here, one can build up an *optical interaction matrix* M whose columns are the wavefront maps (measured with a WFS) when the mirror modes in V are applied; the command to flatten the current shape ω may be computed as $c_{flat} = -M^{+}\omega$. Such strategy has been adopted for routine operations on the large format, voice-coil secondaries as mentioned before. For testing and calibration, the flattening command is obtained with the interferometer feedback; for astronomical observations, the on-sky loop is closed with a dedicated WFS, commonly a Pyramid or Shack-Hartmann WFS.

The absolute calibration of the internal metrology gain is a key step in the DM tuning: once the *capsens* are calibrated, one may trust the position reading to apply large stroke open loop command and retrieve the DM differential position in space; such ability is important to solve the intrinsic phase ambiguity of the WFS.

Recently, the accurate phasing of a segmented DM has been successfully tested. Phasing will be also one the goal objectives for the optical calibration of the E-ELT deformable mirror M4. The process consists in three conceptually separated steps. First, the high orders (HO) are removed as in the *traditional* flattening; then the differential tilt between segments is corrected; at last the differential piston is measured and applied to co-phase the segments: this last step may be done in close loop with the interferometer or by applying open loop piston commands on the actuators. The correction capability depends closely from the accurate measurements of the V modes in the interaction matrix M: for tip/tilt and piston, in particular, environment vibration and phase ambiguity issues affect the measurements so that specific sampling strategies have been defined.

The procedures depicted above have been successfully implemented and tested on the demonstration prototype of the E-ELT DM, called M4DP.[4] It is an adaptive mirror composed by 2 trapezoidal segments with 111 actuators each, disposed on a triangular patch over the 30 cm x 70 cm area of each segment, to shape the 1 mm thickness glass shell. The M4DP was flattened achieving a global WFE of 12 nm RMS over the 2 segments area. The steps of the flattening procedure and the final result are shown in Fig.4.

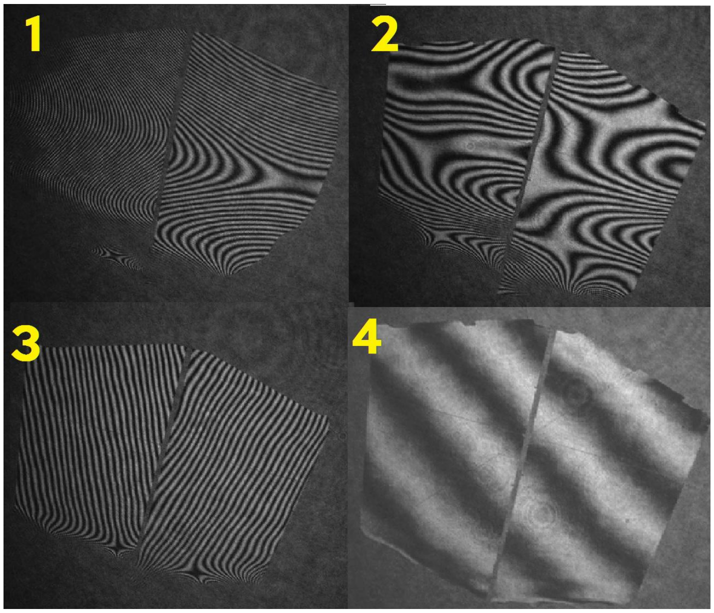

Figure 4. The 4-steps flattening procedure as performed on the M4DP: 1) the first alignment on the optical bench; 2) the preliminary flattening with the first mirror modes to reduce the fringes density; 3) the high orders flattening on the individual segments; 4) the co-phasing, i.e. the correction of differential tilt and piston preserving the high order shape.

The points outlined above indicate that a deformable mirror system composed by a TS and voice coil actuators may reach a final WFE (after flattening) lower than 20 nm RMS, which is $\lambda/20$ in B band. The scaling to the case of a similar mirror shaped by a dramatically lower number of actuators (19 in the case of the OBB) is not straightforward. However we demonstrated with the OBB[5] that a similar result is achieved when considering the same actuator geometry, regardless their actual pitch and global corrected area. In Fig.5 the 20 cm diameter central part of the OBB, corrected by 7 actuators, is compared to a circular portion of 6 cm diameter of the LBT TS, with 7 actuators as well.

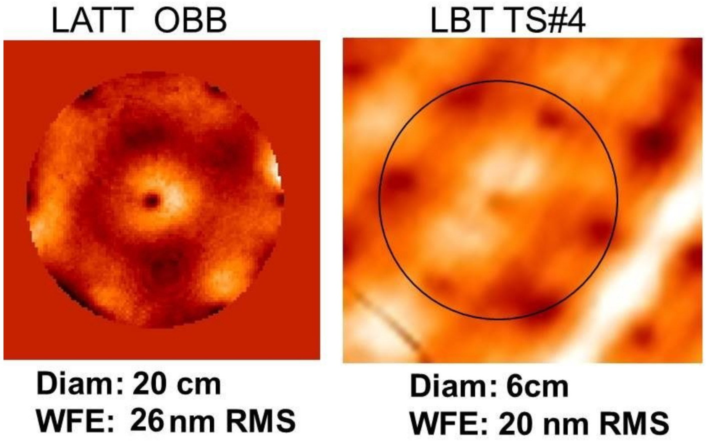

Figure 5. Comparison between the flattening result on the OBB and LBT, measured on a sub-area with the same actuator number and geometry and different size.

2.4.4 Finite Element modeling

The DM system based on TS, RB, voice-coil motors and *capsens* comes with a very accurate model by Finite Elements Analysis. We checked the matching between model and actual system by comparing the actuator Influence Functions measured in the laboratory on the VLT-DSM with those produced with FEA. The relative difference is computed over a significant area, including a grid of 3x3 neighbour actuators; the matching is better than 2%[6] for most of the actuators (see Fig.6), including the effect of residual noise in the interferometric measurements.
Such accurate modelling capability is of great help to predict the system behaviour, assess the fitting error performances and provide the system with synthetic yet accurate aclibrations.

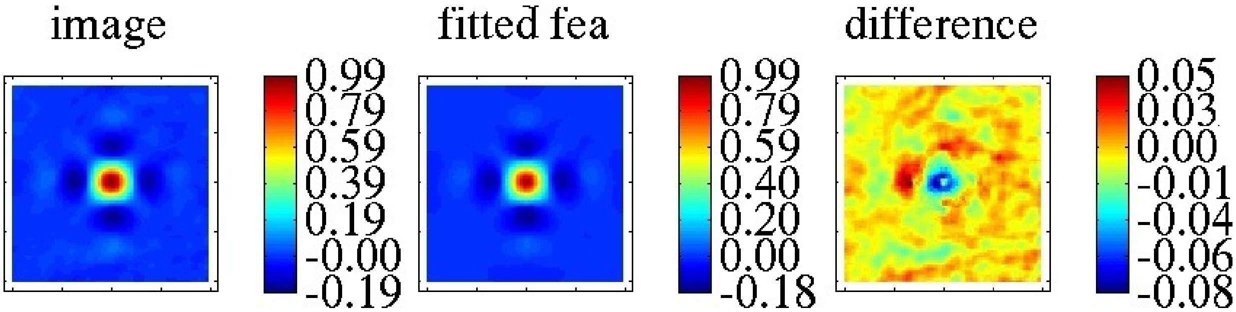

Figure 6. Comparison between the VLT-DSM IF measured on the test bench and Finite Element Model, sampled at the 3x3 actuator scale. The RMS difference is $< 2\%$ for most of the actuators, largely due to convection noise in the measurement.

3. OBB DEMONSTRATOR, FUNCTIONAL AND SAFETY TESTS

The LATT philosophy was technically demonstrated by means of a prototype mirror called OBB, produced under an ESA TRP contract, by a consortium of industrial companies (CGS, Microgate, ADS International) and research insitutions (INAF and INO). In particular, Microgate, ADS and INAF are the team which developed and manufactured the LBT and VLT adaptive secondaries.

3.1 System overview

The OBB[57] is a 40 cm diameter spherical mirror with 19 actuators; the TS is 1 mm thick and the radius of curvature (RoC) of the sphere is 5 m; the RB is composed by a 5 cm thick aluminium honeycomb, layered

Item	**Value**
General	
Mass areal density (as active M1)	<17 kg/m2
ESLocking pressure	axial > 550 N/m2 shear > 550 N/m2
Mirror assembly	
TS Material	Zerodur
TS Diameter	400.05±0.05 mm
TS Thickness	1.013 ± 0.001 mm
TS RoC	5000 mm ± 18mm
RB Material	Al Honeycomb + CFRP
RB coating	Protected Al + SiO_2
Actuators	
Stroke	±500μm
Precision	8nm RMS (typ)
Force budget	± 0.24 N
Control loop bandwidth	1.8 kHz
Power consumption	50-58 mW (per act.)
Mass	80g (per act.)

with carbon-fiber on both surfaces. The honeycomb is partially drilled to house the actuators and capacitive sensor *SAB* (Smart Actuator Board), thus further reducing the total weight of the RB. With respect to the LBT and VLT *capsens*, the SAB were specifically tailored for space application: the sensor circuitry and control electronics was moved close to the sensed area, eliminating the cabling and reducing significantly the noise; such measurement improvement, together with a less demanding specification for the loop correction frequency, allowed slowing down dramatically the sensor clock (set to 1.8 kHz) with an effective impact on the *capsens* power budget: the drop in power consumption is from 1.2W for LBT to 0.06W for the OBB, per *capsens*. The system stability when controlled in local close loop at 1.8 kHz was demonstrated by electro-mechanical and optical test.

The system was equipped with an *Electro-Static Locking* device to glue the TS on the RB and provide a stiff constraint during the launch phase. In Tab.3.1 the main characteristics of the OBB as a demonstrator are summarized.

3.2 Verification by test

The system was subjected to environmental tests: in the thermal chamber the basic electromechanical verification was performed in the temperature range -25° C $< T <$ 55° C; in the vacuum chamber the TS was set and operated at a minimum pressure of 1e-5 mBar. That was a remarkable test, since we learned that the TS may be controlled even with negligible damping from the air trapped inside the gap: differently, on the LBT and VLT adaptive secondaries air damping is of capital importance to balance the very large derivative gain needed for the fast AO loop - this is also one of the reasons why the LBT and VLT TS floats at a $\approx$ 70 μm gap in front of the RB.

The ElectroStatic Locking has demonstrated the TS survivability to the launch accelerations. The TS was stuck on the RB by mean of an electrical field produced a voltage difference between the TS and the RB area (without the *capsens* spots). Such procedure was able to create a $\approx$ 5 kN/m^2 pressure on the front side of the TS. In laboratory, we measured the lateral force needed to detach the TS when changing the amplitude of the electrical field. The entire assembly was then mounted on a vibration test facility and subjected to vibration with a typical launch spectrum, demonstrating the survivability of the TS.

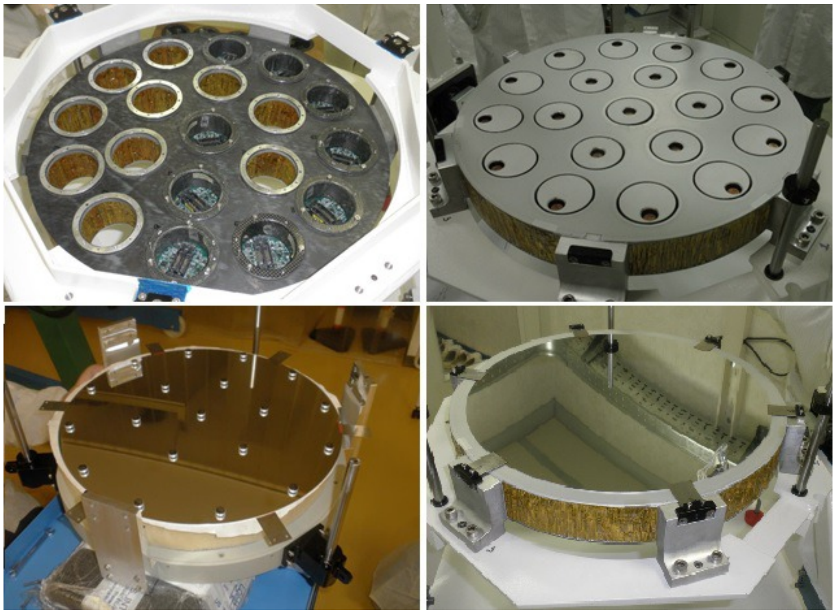

Figure 7. The OBB during manufacturing and integration.

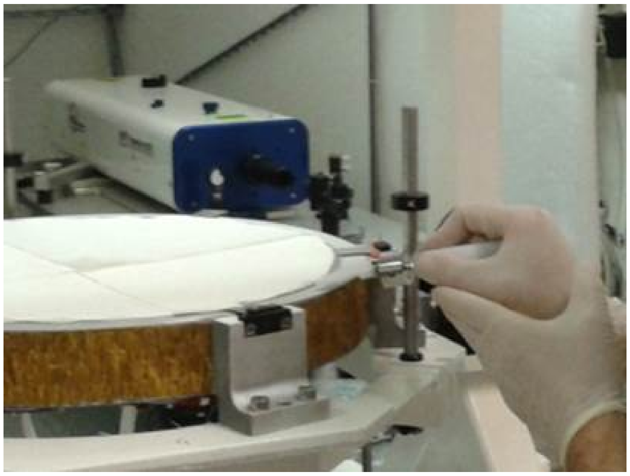

Figure 8. Electrostatic Locking test: an electrical field is applied to the TS to lock int onto the RB. During the test the adhesive force was measured by pushing laterally the TS to check the detaching force.

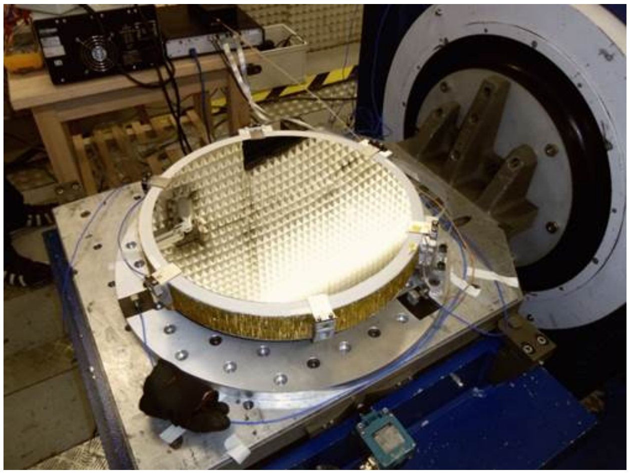

Figure 9. The TS was installed on a vibration test platform and exposed to a launch acceleration spectrum, while the ES locking was engaged. The TS survived the test, proofing the effectiveness of the EL concept.

4. DISCUSSION AND PERSPECTIVES

We have in mind the well established concepts behind the LATT strategy and the results from the OBB; we consider its flexibility to fit an actual space telescope, so that the system recipe (like aperture size, optical prescription, actuators number and geometry) may be tailored for specific science requirements and mission scenarios. We can now envision three possible lines of development for the LATT.

The first possibility is to start from the OBB and produce a parabolic/hyperbolic TS with a similar size. The result is a ≈ 50 cm aperture active telescope, corrected by $15\approx 40$ actuators. The overall performances will be similar to those mentioned above. Such approach may be a *fast track*, gaining the TRL reached with the OBB prototype.

A second chance is to extend the results of the OBB toward the 1m class active primary. The lesson learned with the adaptive secondary tells us that such objective could be at hand: to the first order, it is matter of populating a larger RB with a larger number of actuators, without a demanding design revision. Such approach worked with the scaling from the first 36 actuators prototype of the LBT (the P36[8]) into the final unit with 672 actuators. Also, the manufacturing of 1m class TS (both convex and concave) has been successfully demonstrated with the LBT and VLT AO facilities.

The third, most ambitious chance is to start thinking the space based ELT featuring a segmented aperture with LATT mirror segments. Their individual size may be in the range 0.5 to 1 m as discussed above; the shape may be optimized to be folded together and fit a launcher fairing. The aperture deployment will happen once in orbit. In this case, the deployment system may benefit of relaxed tolerances as the final accurate phasing of the segments may be allocated to the mirror actuators. The large entrance pupil will be fully exploited for high resolution imaging thanks to the high order correction capabilities of the active mirrors.

5. CONCLUSION

We discussed a strategy for space telescopes active optics in the mainframe of the LATT, an ESA funded TRP project. In the LATT we started from the lesson learned with the 1m class, ground based adaptive mirrors to develop a light-weight, low power consumption active primary. A demonstration prototype was integrated and tested to validate the concept, in particular the TS controllability with low power budget and its resistance to the launch accelerations. The LATT way is an attractive concept for space active optics and for space primaries in general, because of its low areal density design, flexibility to fit a specific science goal, restoration of the diffraction limited wavefront. The LATT is also suitable for segmented apertures, as the final segments phasing may be allocated to the actuators, thanks to their large stroke.

REFERENCES

[1] Riccardi, A., Xompero, M., Briguglio, R., Quirós-Pacheco, F., Busoni, L., Fini, L., Puglisi, A., Esposito, S., Arcidiacono, C., Pinna, E., Ranfagni, P., Salinari, P., Brusa, G., Demers, R., Biasi, R., and Gallieni, D., "The adaptive secondary mirror for the Large Binocular Telescope: optical acceptance test and preliminary on-sky commissioning results," in [*Adaptive Optics Systems II*], *Proc. of SPIE* **7736**, 77362C (July 2010).

[2] Vernet, E., Cayrel, M., Hubin, N., Biasi, R., Gallieni, D., and Tintori, M., "On the way to build the M4 Unit for the E-ELT," in [*Adaptive Optics Systems IV*], *Proc. of SPIE* **9148**, 914824 (July 2014).

[3] Briguglio, R., Xompero, M., and A.Riccardi, [*Optical calibration of adaptive mirrors*], Osservatorio Astrofisico Arcetri, Firenze (2016).

[4] Briguglio, R., Xompero, M., and Riccardi, A. & al.., "Optical calibration of the M4 prototype toward the final unit," in [*Proceedings of the Fourth AO4ELT Conference*], (2015).

[5] Briguglio, R., Xompero, M., and Riccardi, A. & al.., "Development of large aperture telescope technology (LATT): test results on a demonstrator bread-board," in [*International Conference on Space Optics*], (2014).

[6] Del Vecchio, C., Briguglio, R., Riccardi, A., and Xompero, M., "Analysis of the static deformation matching between numerical and experimental data on the voice-coil actuated deformable mirrors," in [*Adaptive Optics Systems IV*], *Proc. of SPIE* **9148**, 914840 (Aug. 2014).

[7] Briguglio, R., Biasi, R., and Gallieni, D. & al.., "Laboratory demonstration of a primary active mirror for space with the LATT: large aperture telescope technology," in [*Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave*], *Proc. of SPIE* **9904** (July 2016).

[8] Brusa, G., Riccardi, A., Ragland, S., Esposito, S., del Vecchio, C., Fini, L., Stefanini, P., Biliotti, V., Ranfagni, P., Salinari, P., Gallieni, D., Biasi, R., Mantegazza, P., Sciocco, G., Noviello, G., and Invernizzi, S., "Adaptive secondary P30 prototype: laboratory results," in [*Adaptive Optical System Technologies*], Bonaccini, D. and Tyson, R. K., eds., *Proc. of SPIE* **3353**, 764–775 (Sept. 1998).