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TOWARD LARGE DIFFRACTION LIMITED SPACE TELESCOPES WITH THE LATT LIGHTWEIGHT ACTIVE PRIMARY

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I. THE LATT WAY: FROM ADAPTIVE SECONDARY TO SPACE ACTIVE PRIMARY MIRRORS

The design of large segmented mirrors, actively controlled both in shape and in differential piston, is one of the challenges space optics is facing, driven by the needs of the astronomical community. Adaptive optics (AO), allowing ground-based telescopes to compensate for the atmospheric turbulence, already coped with some of these challenges (although within a different scenario and different requirements) and is considered a first light facility for the ELTs.

With the idea of cross-contamination in mind, we tried to transfer and extend the results of the adaptive secondary mirror (AS) development toward the field of space active optics. The AS systems mark a breakthrough in AO as they provide wavefront correction, field stabilization and chopping capabilities in common to all focal stations without the cost and the error budget of additional relay optics. AS are currently in operations/commissioning at 8m class telescopes (e.g. LBT [1], VLT [2], Magellan [3]) and are included in the optical design of the E-ELT [4] and GMT [5].

From this starting point, we investigated a strategy to design deformable primary mirrors (PM) with the goal to provide space telescopes with active wavefront controlled optic surfaces able to compensate the in-orbit thermo-elastic bending and the release of the gravity deformations.

Our concept of active primary is the scaled replica of the AS optimized for space: it consists of a Zerodur ultra-thin shell (TS) kept in shape by contactless voice-coil motors, which are controlled in closed loop via the internal metrology based on capacitive sensors (contactless as well), mounted on a carbon fiber support. These key elements present very attractive properties for space primaries, at least for three reasons:

1. contactless actuation [6] is intrinsically fail-safe and allows to mechanically decouple the support structure from the thermally insensitive Zerodur optics (the TS); the actuators provide a 1 mm stroke with a few nm precision;
2. very lightweight design is obtained by such decoupling: the ultra-thin shell has a very low mass and the support is provided by a structure with few optical requirements;
3. AS are successfully controlled both in shape and global phase, including differential piston-tip/tilt, thus allowing full correction of a segmented primary (where the segments may be 1m in diameter as the typical size of the AS); of course, this implies the use of a piston sensitive wavefront sensor. Moreover, the very large actuator stroke (1 mm) may help the initial deployment of the segments, releasing most of the accuracy requirements on the mechanical hinges.

All these elements have been gathered together into the Large Aperture Telescope Technology (LATT) project, an ESA-funded TRP, with the goal to assess the mentioned approach and answer the following questions: will a thin glass shell survive the launch? Can we stably control the optical surface with very limited power budget and actuator density? How lightweight may such a system be?

A quantitative response to these points was given with the LATT optical breadboard (OBB), a 40 cm spherical demonstration prototype controlled with 19 actuators, featuring an areal density of about 17 kg/m^2. Laboratory qualification, including electro-mechanical, optical, thermo-vacuum and vibration test pushed its TRL toward 5 and demonstrated the technological scaling from the AS to space active primary [7].

Within this work, we will start presenting the LATT way through the results of the prototype; we will then further explore the concept, including a qualitative analysis of the system stability; in the end we will outline the possible customization of a LATT primary DM and its integration into a space active/adaptive optics system.

II. LABORATORY DEMONSTRATION WITH THE OPTICAL BREADBOARD (OBB) PROTOTYPE

A. System description
The OBB is a spherical primary mirror prototype, with 40 cm diameter and 5 m radius of curvature, with an areal density (as active PM) lower than 17 kg/m^2; it was designed and integrated to provide a quantitative

answer to the questions raised before. The prototyping and testing allowed us to push the LATT technology toward TRL 5 and to identify its critical points. The prototype was not intended as a flight unit so that some technical solutions were identified only within the scope of the technical demonstration.

The system has been manufactured, integrated and tested by the LATT consortium, namely the industrial companies Microgate (who provided the electronics and the control software), ADS (mechanics) and CGS (environmental testing, project coordination) together with the research institutions INAF (in charge of the optical test and general consulting) and CNR-INO (who produced the TS). A summary of the OBB characteristics is in Tab. 1 and a more extensive description may be found in [8].

The system is composed of three elements: a reference body (RB), the TS, the control electronics.

The TS is a Zerodur 1mm thick spherical sector, 40 cm diameter. The optical surface was first polished then thinned to the desired thickness. Because of the thinning process, the optical shape is poorly controlled at the low orders; the high orders were, on the contrary, corrected down to 38 nm RMS and 72 nm RMS for the first and second TS respectively, when the polishing was stopped after meeting the project specifications. Details concerning the shape and optical quality of the TS produced for AO so far are given in [7]; more on the manufacturing may be found in [9]. On the back surface, a set of 19 magnets has been glued to provide the actuation point for the voice coil motors.
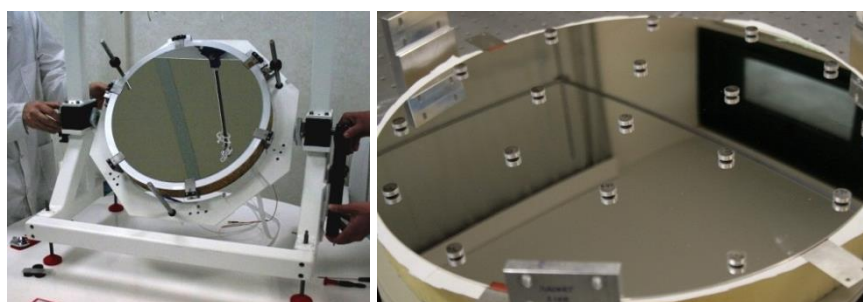

Fig. 1 Left: the OBB assembly on its integration stand. Middle: the back surface of the TS with the 19 magnets.

The control electronics is fully embedded in the Smart Actuator Board (SAB), a co-located system providing the capacitive sensors conditioning/acquisition, the actuator command and the local control loop. The front side (toward the TS) has a thin Zerodur plate, aluminum coated, to act as one of the capacitive sensor armatures.

The SAB concept marked an effective improvement in the actuators control, thanks to its low power consumption and low bandwidth. Moreover, the achieved working range of such actuators is 0 - 1 mm, providing a large stroke which may be partly allocated to the system phasing (in the case of a segmented aperture).

The initial calibration of the actuators consists in measuring the system stiffness or FeedForward (FF) matrix, namely the ratio between the force applied and the corresponding displacement. The system is then commanded via the FF eigenmodes or mirror modes, which are global deformations of the TS. Such modal control offers a number of benefits compared with the zonal one: in particular, allows closing the optical loop with a number of WFS sub-apertures lower than the actuators number.
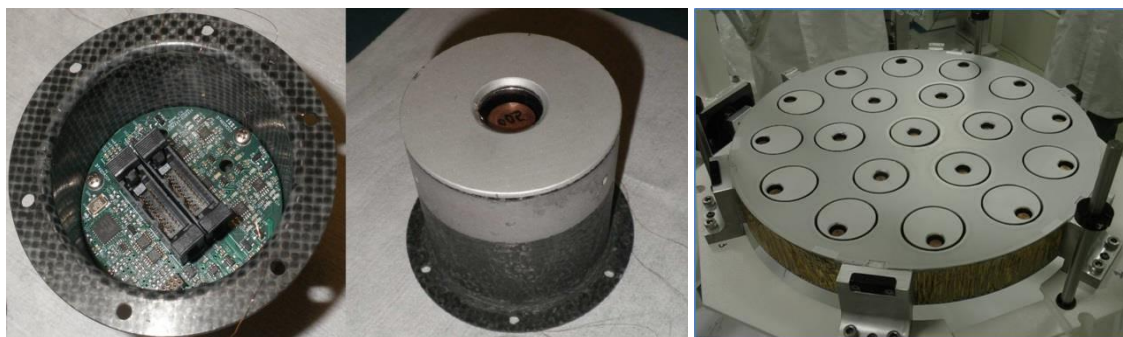
Fig. 2 Left: the SAB, back view, with its CFRP mechanical assembly and the connector; middle: the actuator assembly, top view; right: the RB, front surface, with the 19 SAB installed.

The RB is a 50 mm thick, aluminum honeycomb spherical sector, matching the radius of curvature of the TS. A pattern of 19 holes is drilled to house the SABs and the actuators assembly.

Both surfaces are layered with carbon fiber reinforced plastic (CFRP) and the front is aluminum coated to provide a metallic plate for the electrostatic locking (ESL) mechanism. This is a safety device to preserve the

fragile TS exposed to the launch accelerations. When activated, the ESL generates an electrical field between the RB front surface and the TS back, so that the TS adheres to the RB; such device prevents any lateral and vertical displacement of the glass.

The RB holds the TS via 6 lateral blades glued on the glass, in order to allow the mechanical and optical testing in 1g environment. During the test phase, we found that the TS was over-constrained; this issue was critical during optical qualification, especially because the induced deformation was beyond the actuator correction space. To test successfully the breadboard we devised a way to assess the influence of the blades (see below); in the future a modelling and a depth re-design of the lateral constraint will be a necessary task when addressing a final unit. For instance, we may consider a central membrane (like those used at the LBT/VLT) which exhibits a very low vertical stiffness and a very large lateral one.

Item	Value	Item	Value
Mass areal density (as active M1)	<17 kg/m^2	# actuators	19
TS diameter	400 mm	Act. Density	~100 /m^2
TS thickness	1.01 mm	Act. Stroke	500 um
TS Rad Curvature	5000 mm ± 18 mm	Act. Precision	8 nm RMS
RB thickness	50 mm	Act. Force budget	± 0.24 N
RB Assembly	Al honeycomb + CFRP	Open loop bandwidth	1.8 kHz
RB coating	Al + SiO2	Act. Power consumption	50-58 mW/act
ESLocking pressure axial	> 550 N/m^2	Act. Mass	80 g/act
ESLocking pressure shear	> 550 N/m^2		

Table 1. Overview of the OBB characteristics.

Item	Mechanics	Act assembly	Capsens assembly	Thin Shell	Ref Body
Relative mass	18%	23%	12%	13%	34%

Table 2. Components mass distribution in the OBB

B. Results of the qualification tests

After integration, the OBB has undergone a test campaign for the performances qualification. A more exhaustive discussion may be found in [8]. The test flow may be summarized as follows:

1. electromechanical tuning: calibration of actuator response, lateral blades regulation
2. functional verification and dynamic response
3. optical qualification: actuator influence functions, quality of the optical flattening
4. thermal-vacuum cycle test
5. functional verification and dynamic response
6. vibration and electrostatic locking test
7. functional verification and dynamic response

The electro-mechanical tuning consisted in two steps: first, measuring the system FeedForward FF (or stiffness) matrix, indicating the ratio between the actuator force applied and the displacement measured with the capsens; second, the setting of the control loop parameters, namely proportional and derivative gains.

Thermal testing in air spanned the temperature range 0°C – 40°C and no significant change in the capsens noise, power consumption and FF matrix was observed. The modal step responses, measuring the system settling time after a command is applied, were also demonstrated to be stable and in spec (<0.8s) within the temperature range.

During vacuum test, the unit was exposed to an external pressure as low as 1e-5 mBar. The loop parameters should be re-optimized to compensate for the lack of air damping and no significant drop in performances was observed, apart from an expected slowdown of the system response. Air damping is a key element to allow the ground-based AS to achieve sub-millisecond settling time. Here we aimed solely at demonstrating the optical controllability in vacuum, with no tight requests on settling time.

For the vibration test, the unit was installed on a shaker to transmit in plane and vertical accelerations. The OBB was subjected to a maximum acceleration *a* compliant with the following: 1.5g< *a* <7.9g for in plane, 2.4g<a<10.9g for vertical test, both with sine oscillation levels and random spectra up to 2 kHz. During the vibration test the unit was powered off with EL on. The EL was able to prevent the TS to oscillate against the RB and in general to safely hold the TS during the test. During the post-test inspection, we found some scratches on the TS back which however did not affect the system performances.

The optical test was aimed at assessing the optical controllability with low power budget and actuator density. The OBB was installed on the bench with its optical axis horizontal and measured with the interferometer at the radius of curvature; the TS was suspended on 3 blades only to reduce the over-constraint. Because of the lack of a fine regulation of the blades position, we observed a large residual deformation at the outer edge of the optical surface. We proceeded with the optical test computing the flattening command on an inner area: in particular we tested a sample of diameters in the range 180 to 400 mm. With such a strategy, we flattened the TS to a residual WFE of 26 nm RMS considering an active area of 20 cm diameter controlled with only 7 actuators. Such result may be compared with the typical performance of an AS, where a patch of 6 cm diameter is controlled by 7 actuators as well and the final WFE is typically 20 nm RMS.
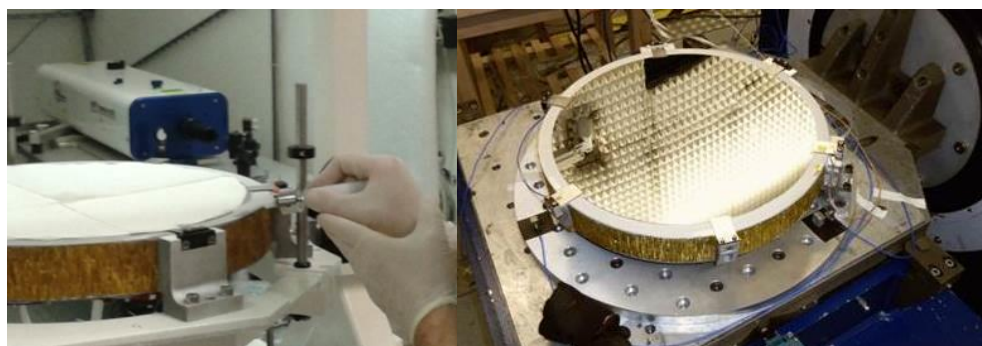
Fig. 3 Left: the OBB during the EL test: a reference force is applied to the TS to measure the EL adhesion. Right: the OBB on the vibration stand.

III. FURTHER ASSESSMENT OF THE LATT CONCEPT

A. Primary active mirror
In ground based AO systems, the DM is often located at a pupil relayed position; this option is pretty convenient as a pupil DM is typically a compact system housing hundreds of actuators thanks to micro-electronics. In the LATT, the active element is the primary mirror, which is the telescope largest optical element, expected to be responsible for most of the wavefront distortion (both from thermal bending and manufacturing/gravity release). Under this assumption, the most natural implementation of a wavefront corrector for space optics is at the primary, provided it is also the optical pupil.

Such approach provides a number of benefits, compared to a solution where the DM is at a pupil relayed position:

- a corrected wavefront is delivered to the rest of the optical system, allowing it to work closer to as-designed conditions;
- the system is simplified as no pupil relaying optics are required, this leading also to volume, mass and complexity reduction;
- an active segmented PM may contemporarily take care of shape control and phasing, while for a (monolithic) pupil DM an additional segments control is required.
- a larger degree of correction is achieved with the same number of actuators.

This last point may be explained by considering that, because of the pupil plane distortion, the aberration seen at the relayed pupil has a higher order compared with that at the primary. Such additional aberration depends on the amount of distortion, which in principle may be controlled with an optimized design. DMs with a very large number of degrees of freedom can compensate for such extra aberrations; on the contrary, system with a few actuators (which is a typical study case for space active optics) cannot correct the higher orders.

As a last point, the LATT approach comprises in a single system both a lightweight primary mirror solution and an active optics system. The current manufacturing technology of TS is able to realize the desired optical prescription for a PM; moreover, the manufacturing WFE may be as low as 12 nm RMS on meter-sized systems [10]. In Table 3 an overview of the existing TS with the relevant parameters is given.

B. A stable system?
Optical stability is an important requirement for the next generation space telescopes, to allow coronographs achieving high contrast images. In AS systems the stability is guaranteed by design with thick, rigid support structures, low actuator pitch, large power budget and suitable control loop bandwidth. For space active mirrors,

severe mass and power requirements shall be taken into account, so needing a different control strategy. In the following we will summarize qualitatively our approach, starting from the AS and the OBB experience.

In Fig. 4 we consider spatial and temporal scales together with the relevant controls and disturbances of the optical surface. The space domain is divided into a controllable area (scales larger than the actuator spacing) and an un-controllable one (beyond the pitch); within the time domain, we identify a not sensed band, the internal metrology band (TS controlled by the actuators in close loop on the capsens), and the optical loop band (where the actuators are externally controlled by the WFS). The disturbances are summarized as follows:

- TS and RB free vibrations;
- thermal bending of the optical assembly, inducing misalignment Zernike modes;
- thermal bending of the RB, whose deformation is transmitted to the TS as the capsens reading is changed;
- high-order thermal features (e.g. glue shrinkage);
- vibrations propagated from the payload to the RB.

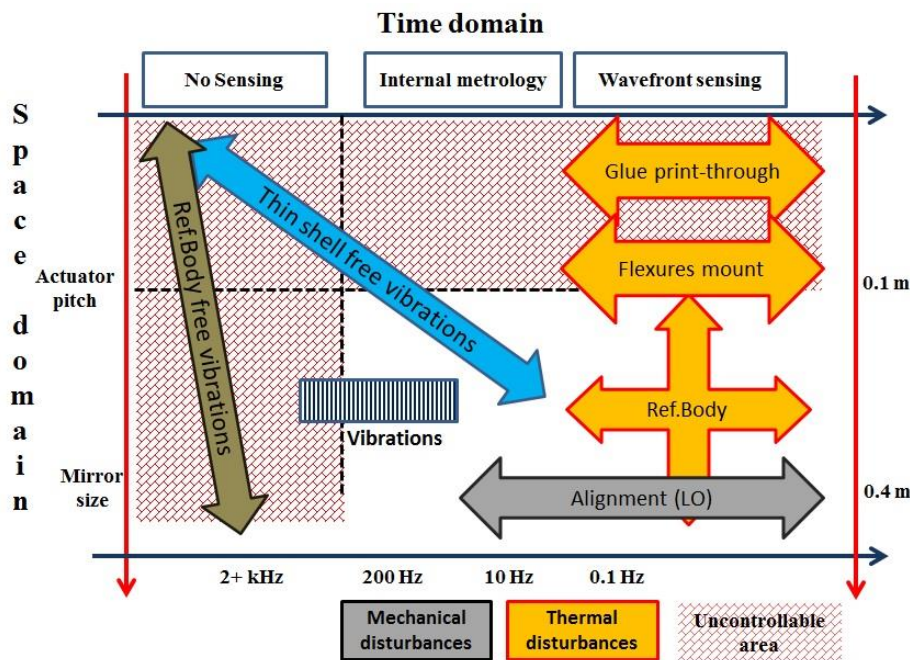The OBB values are taken as reference and are indicated in the chart.

**Fig. 4** Disturbances and controls diagram.

As first, the RB shall be stable at all the spatial scales to act as a good reference for the capsens. Stiffness shall be traded off with the mass budget, provided that the RB contributes a 34% to the OBB areal density. For the OBB case, the RB is a 50 mm thick aluminum honeycomb spherical sector, with a diameter of 40 cm; its lowest eigenfrequency is higher than 800 Hz.

As a second step, we investigated the TS stability: we considered the free oscillation modes of a glass disk with thickness τ and radius r (for the OBB: $\tau = 0.001$m, r=0.2m). The lowest resonant frequency of the thin shell (analytical computation) is lower than 20 Hz so that an active control is required. This task is accomplished by the internal loop closed on the capsens reading, provided that it has a suitable bandwidth. Under this assumption, the TS is constrained by the actuation points and its free oscillations are only those relative to the inter-actuator spacing α.

An interesting point here is that the lowest resonance frequency is proportional to the ratio τ/α^2: such a number is very similar to a thin shell controlled with (sparse) actuators and a traditional rigid mirror relying on passive stability. Moreover, the actuator density/geometry and the TS thickness may be tailored to increase the system stiffness at the uncontrolled scales.

The results the Finite Elements Analysis (FEA) are shown in Fig. 5, where we plot the frequency versus TS thickness for a sample of modes, for two actuators pattern. These values shall be considered as an input for the rest of the system, for instance, the internal loop shall be designed in order to not excite such frequency. For the OBB case, the FEA indicates a lowest resonant (undamped) frequency of ~300 Hz.

As a third step, we considered that the TS is not attached to the RB and is held in place in front of it by means of the internal control loop. As a consequence, the disturbances on the RB (for instance, the vibrations from the payload) are not mechanically transmitted to the optical surface; however when they are within the control band they are read by the capsens as a misplacement of the TS and corrected, so affecting the stability of the optical surface. Such effect may be mitigated with an optimized design of the internal control loop, for instance with notch filters to suppress known noise frequencies.
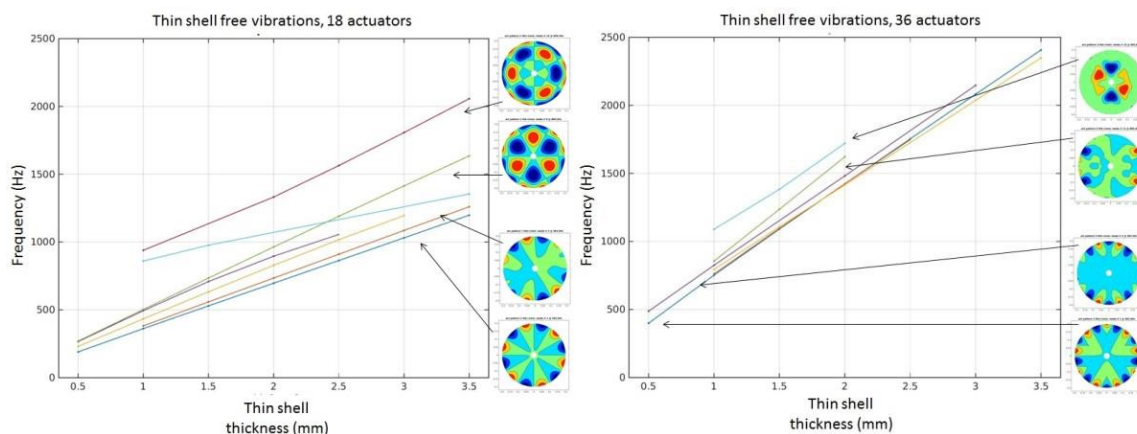
Fig. 5 Free oscillation frequencies for a subset of modes versus thin shell thickness. Left: TS controlled with 18 actuators. Right: TS controlled with 36 actuators.

C. Beyond the OBB

The OBB worked as a technical demonstrator and some degree of re-designing will be needed when considering an actual primary mirror for a space telescope. An interesting feature of the LATT approach is that it may be effectively tailored to fit different science cases or mission scenario. In the present scope, we discuss 3 elements which shall be adapted to the mission design: the TS (shape and optical prescription), the aperture topology (monolithic vs segmented) and the actuator count.

Regarding the TS (see Table 3), it has been widely demonstrated that large, flat or aspheric surfaces may be manufactured with a typical optical quality (correcting with the actuators the low order modes after thinning) below 30 nm RMS WF. The thickness varies in the range 1 mm to 2 mm: a thicker TS offers a larger robustness and stability at the cost of reducing the actuator stroke with the same power budget.
To integrate very large apertures, one may consider a segmented system where the TS are 0.5 m to 1 m in size and are arranged according to a honeycomb or petal-like geometry. The latter choice would provide a lower degree of segmentation and a lower number of boundary areas which are by definition the least controllable ones. Another possibility is to consider two segmentation levels: the actuators are arranged on a segmented RB, where each segment holds in place a number of smaller TS.

The degrees of freedom density for space applications is generally considered to be low: for instance, rigid body motion plus curvature on each segment, as it is implemented on the JWST; the task of keeping the optical shape is fully allocated to the mirror stiffness. In the LATT approach, the actuators are in charge of maintaining both the mirror position and shape against external loads. The system stiffness may be improved with the actuator control, by increasing their areal density. We have two constraints here: on the larger density end, we are limited by the area allocated to the EL mechanism; on the lower end, the resonance frequency of the inter-actuator areas will be too low to get a stable system. The local control loop and the optical one should be also carefully tuned to achieve such result. The larger actuator count grows the system mass and cost: the actuator design should be improved to reduce the individual mass, especially when considering the actuator assembly is responsible for approximately 1/4 of the system mass (see Table 2).

AS system	MMT	LBT	VLT	M4DP	M4 (design)
# of actuators	336	672	1170	2x111	6x886
TS size	640mm (OD)	911mm (OD)	1200mm (OD)	300x700 mm	1270 x 1000mm
TS geometry	Circular	Circular	Circular	Trapezium	Petal
TS optical shape	Aspheric-convex	Aspheric-concave	Aspheric-convex	Flat	Flat

Table 3 Summary of TS characteristics

III. TOWARD AN ACTIVE/ADAPTIVE SPACE TELESCOPE

As a last remark, we suggest the implementation of a wavefront sensor (WFS) as the pyramid one (P-WFS) into the LATT design. The P-WFS [12] is basically composed of a glass pyramid, a camera and a lens. The glass pyramid splits in 4 quadrants the telescope focal plane, while the lens produces 4 images of the pupil on the detector. Combining the 4 pupil images we obtain a signal proportional to the local derivative of the wavefront. The PWFS, as adaptive optics WFS, is now extensively employed in ground based telescopes of 6-8m class, delivering science data since 2012 [13], using reference guide stars up to magnitude R=17.

The P-WFS is particularly attractive for segmented systems, being at the same time sensitive to continuous aberrations and phase steps [14][15]. The PWFS has already demonstrated to be an excellent phasing sensor [16] for segmented mirrors in laboratory experiments and on-sky tests [17] at ground based telescopes.

Moreover, differently from the Shack-Hartmann WFS, the PWFS can tune easily its dynamic range and number of sub-apertures. The dynamic range can be modified by modulating the guide source on the pyramid tip. A broad dynamic range (with poor sensitivity) is required for the initial deployment and alignment of the optical system; then the P-WFS may be configured with high sensitivity to fine-sense the primary surface. The number of sub-apertures may be changed by binning the detector, allowing the use of fainter stars as reference or run the system faster. Such strategy is routinely used for the mentioned ground-based AO systems and matches well with the modal control (see Sec. II) embedded in the LATT, allowing a further customization of the control loop during deployment and science integration.

At the cost of some increase of complexity, the implementation of a PWFS into the LATT design will transform it into a real AO system, allowing the full control of the wavefront in terms of continuous aberrations and differential piston. Then, the total cost of the complexity should be considered system-wise. Beyond improving the image quality, the AO allows relaxing the tolerances of various sub-systems and accomplishes different control tasks within the same device.

IV. CONCLUSIONS

Through the LATT project, we successfully investigated and demonstrated the evolution of the AS technology toward space active primaries. The control of the optical shape at the primary mirror allows delivering a corrected wavefront to the entire telescope and simplifying the optical design, because pupil relaying optics to feed the DM are no longer required. At last, a primary DM is a natural solution for segmented apertures.

The OBB is a prototype of a 40 cm, active primary mirror; it was integrated and tested and the laboratory qualification pushed its TRL toward 5. It is a lightweight system, featuring an areal density lower than 17 kg/m^2, with the option to further reduce the mass with an update of the design. The optical surface of the OBB is a spherical TS controlled via 19 voice-coil linear motors that provide fail-safe contactless actuation of the glass. The laboratory activity demonstrated that the fragile TS survived the simulated launch accelerations, thanks to the electrostatic locking mechanism; the optical controllability of the TS was also demonstrated to be comparable with larger AS equipping AO facility at 8 m class telescopes. The actuators are controlled in local close loop through an internal metrology fed by capacitive sensors. Internal metrology allows system diagnostics and the application of pre-calibrated correction commands. Such features shall be integrated with a wavefront sensor in order to guarantee the low frequency stability of the optical surface.

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