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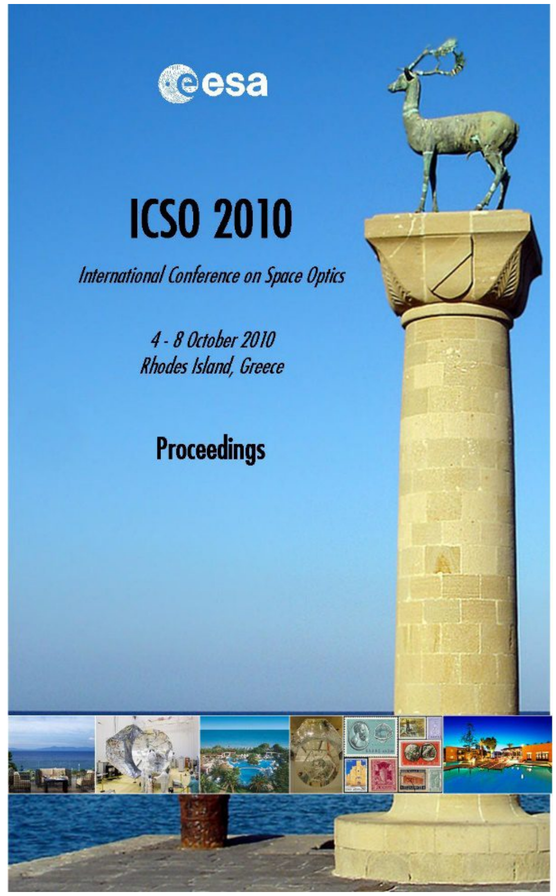

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TECHNOLOGICAL DEVELOPMENTS FOR ULTRA-LIGHTWEIGHT, LARGE APERTURE, DEPLOYABLE MIRROR FOR SPACE TELESCOPES

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ABSTRACT

The increasing interest on space telescopes for scientific applications leads to implement the manufacturing technology of the most critical element, i.e. the primary mirror: being more suitable a large aperture, it must be lightweight and deployable. The presented topic was originally addressed to a spaceborne DIAL (Differential Absorption LIDAR) mission operating at 935.5 nm for the measurement of water vapour profile in atmosphere, whose results were presented at ICSO 2006 and 2008.

Aim of this paper is to present the latest developments on the main issues related to the fabrication of a breadboard, covering two project critical areas identified during the preliminary studies: the design and performances of the long-stroke actuators used to implement the mirror active control and the mirror survivability to launch via Electrostatic Locking (EL) between mirror and backplane. The described work is developed under the ESA/ESTEC contract No. 22321/09/NL/RA.

The lightweight mirror is structured as a central sector surrounded by petals, all of them actively controlled to reach the specified shape after initial deployment and then maintained within specs for the entire mission duration. The presented study concerns: a) testing the Carbon Fiber Reinforced Plastic (CFRP) backplane manufacturing and EL techniques, with production of suitable specimens; b) actuator design optimisation; c) design of the deployment mechanism including a high precision latch; d) the fabrication of thin mirrors mock-ups to validate the fabrication procedure for the large shells.

The current activity aims to the construction of an optical breadboard capable of demonstrating the achievement of all these coupled critical aspects: optical quality of the thin shell mirror surface, actuators performances and back-plane – EL subsystem functionality.

I. INTRODUCTION:

Nowadays, the majority of ground and space-based telescopes is designed in reflective configuration. The main purpose of the studies presented in this paper is addressed to the implementation of the technology for the primary mirror, which is the main driver for the realisation of such big optical structures. Indeed, this mirror must necessarily be large, therefore lightweight, easily controllable in shape, and for space applications it has to be also deployable. For LIDAR applications, this is an efficient way to improve the signal-to-noise ration.

With the intention to proceed on the guidelines of a previous contract with ESA, for the development of an "Advanced LIDAR Concept" (ALC) study [1] completed in 2007, a new contract was issued for carrying on technological improvements on the mirror, and the main results are here discussed.

The general approach adopts a 1-mm thin Zerodur® glass mirror whose segmented optical surface can be actively controlled to reach the specified shape after initial deployment and then maintained within specs for the entire mission duration, via an optical wavefront sensor in closed control loop with the mirror surface. The previous LIDAR study produced crucial experimental evidence on the possibility of protecting this thin mirror in launch conditions by "gluing" it electrostatically to the carbon fibre back structure. Voice Coil actuators drive the surface in order to correct possible deployment errors, thermal drifts, and variations excited by on board motions or orbital manoeuvres.

The ALC study was based on a space mission for the measurement of water vapour profile in atmosphere at 935.5 nm. The optical configuration is an Afocal Cassegrain-Mersenne, with two parabolic mirrors used in double-pass configuration. However, in the frame of the current study an Optical Breadboard (OBB) is designed, representative of the mirror, the EL system, the structure and the actuators (Fig. 1), according to an

Advanced Technology Program (ATP). Also a Deployable Breadboard (DBB) is considered, in order to demonstrate the deployment mechanisms and kinematics to obtain the required positioning accuracy of the petals. OBB and DBB are needed to validate the technology with the future goal of building a petal structure, comprehensive of all these aspects.

For the OBB, basic requirements of the single components, which derive from the previous ALC study, are summarised in Tab.1. In the following sections, a description of the single subsystems of the OBB is given.

Tab.1. Main requirements for the OBB.

Component	**Requirement description**	**Expected value**
Primary mirror	Wavefront error	< λ/6 rms
	Mass areal density	< 16 Kg/m^2
	Material	Zerodur®
	Shape, Diameter x Thickness	Spherical (5m curvature radius), 400 mm x 1 mm
Backplane (EL is part of it)	Material	Carbon Fiber Reinforced Plastic (CFRP)
	Main dimensions	400 mm diameter
	EL axial, shear force	> 400 N/m^2, > 530 N/m^2
Actuators	Quantity	19 (5 on the diameter)
	Power consumption	< 0.2 W /Actuator
	Mass	< 0.15 Kg
	Stroke	1 mm
	Accuracy	< 200 nm
	Resolution	< 10 nm
	Force	> 0.6 N /Actuator
	Closed loop bandwidth	> 0.1 Hz
	Power	80 mW

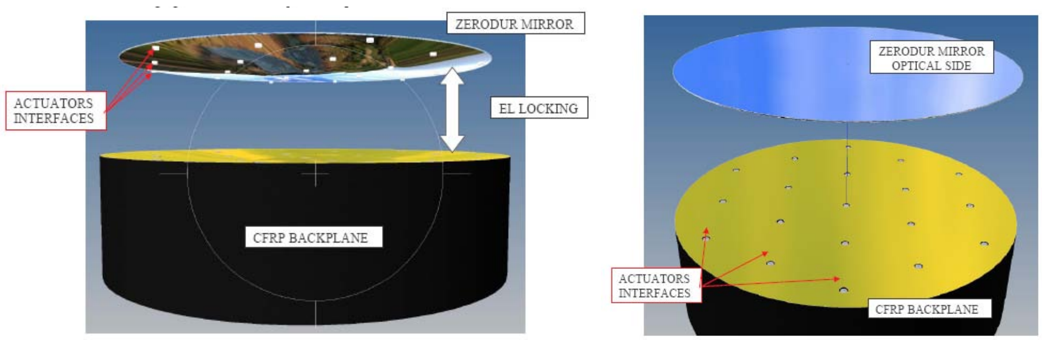

Fig. 1. The OBB concept.

II. CFRP BACKPLANE:

The backplane is the backbone structure where the actuators are mounted on and which provides also the substrate to electrostatically constrain the thin mirror during launch. For the ATP, some specimens of the backplane frontal skin and a specimen of the thin shell have been built and tested. Both are coated to get the capacitor armatures to test the EL system that will offload the shell from launch loads on the final petal design. 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.

The main feature to be proved is to produce specimens with surface smoothness below few µm Peak-to-Valley (PV), in order to make a gap with the shell small enough to allow the proper functioning of the electrostatic locking. An incremental approach was followed to make these specimens: first the goodness of the bare CFRP panel was qualified, then a finishing layer (called surface master) was added to the lamination process and finally the finishing of the panel surface was tested by means of a second replica made after the panel lamination.

A. CFRP backplane specimens

All the specimens have been manufactured using a hot laminating press, able to provide enough temperature for the curing and enough pressure for the homogenization. The material adopted is the CC206 carbon/epoxy.

The manufacturing procedure foresees a preliminary proper coating of the mandrel with debonding material, then the deposition of the plies, the vacuum bagging (with Bag Sealant Tape) and the curing cycle. The lamination technique profiles the holes directly onto the pre-preg plies before the laying up onto the mandrel. After applying the peel ply onto the laminate, a layer of release film is deposited. The last layer before closing the bag is the bleeder cloth, whose purpose is to absorb excess of resin and to act also as a breather. To control the laminate temperature during the cycle, the vacuum port and the thermocouple are then installed. The curing cycle is performed into autoclaves which provide temperature for the polymerization and pressure compacting the laminate, and providing good consolidation and interlaminar bonds.

For each specimen, small scale surface errors (fiber print through) and micro-roughness have been measured, in order to characterise both the flatness of the replicated surface and the quality of the hole. The specimens showed a surface error below 5 µm PV. They have been then coated in order to obtain a fully representative prototype of the overall system and to be tested with the shell specimen to prove the EL. However, during those tests it was noted that front layer of resin is not sufficient to insure the proper insulation. For this reason a layer of insulating resin called “Surface Master” was added during the lamination phase of the composite as first layer of the panel. The surface master film is a sheet of solid resin that can be used as a pre-preg carbon fiber layer. Thanks to its properties, the surface master has been selected to be the baseline solution for the manufacturing of the OBB first and then for the future petal.

During the process of manufacturing of the carbon fiber structure, small out-of-plane displacements may occur on the final laminate. A backup strategy considers a second replica process to the panel front surface using a low shrinkage resin, placed onto the reference surface, then distributed uniformly and then out-gassed, to be applied only if the final reference surface has low order high deformations. This process increments the shape accuracy of the reference surface.

The specimens were coated by Aluminium deposition, protected by 5-µm layer of SiO_2, to make one of the armatures of the capacitor of the Electrostatic Locking System.

B. Shell specimens

Two specimens made of Borofloat® 100x100x1.1 mm^3 glass by Schott have been made to test the EL system. A Silver layer coating gives the two conductive armature of the capacitor: one on the backplane and one on the mirror surface, separated by the dielectric layer made of the quartz on the backplane surface.

III. ELECTROSTATIC LOCKING:

The design of the Electrostatic Locking system is conceived to restrain the thin shell during launch.

The two (previously described) armatures were properly shaped via replica technique, thus maintaining the high order errors below few µm (while the low order ones are accommodated by the flexibility of the thin shell).

A test setup was implemented to measure the detaching force, as function of the voltage, by applying a controlled shear force. The test was repeated at different voltages applied to the EL system specimen, reporting for each test the detaching force. The process to make the armatures on the mirror and the backplane surfaces resulted very effective: it allowed achieving a shear retention force per unit area of almost 3kPa at voltages as low as 100V.

IV. ACTUATORS:

A. Actuators pattern

The actuators are mounted in the backplane and are interfaced to the back of the mirror.

The actuator density of the OBB is driven by optical considerations related to experience on adaptive optics mirrors for terrestrial telescopes [2]. While the OBB embeds 19 electromagnetic actuators with a 95-mm pitch triangular pattern, on the same area it is foreseen that the flight-unit will utilize 7 actuators only, with 190-mm pitch. Indeed, the high density case (red dots in Fig. 2) is required to flatten the thin mirror during ground optical test within the range of the measuring system (interferometer); it also provides 3 actuators along the radial direction of the mirror, thus allowing the control of several optical modes. The low density case (green circles in Fig. 2) is representative of the controllability of a larger mirror segment for flight configuration, typically 1÷1.5-m size, also according to the preliminary outcomes of the dynamics simulations.

The modal characteristics of the OBB were obtained via Finite Element (FE) analysis.

An equivalent static analysis has been performed, considering all the 19 actuators, with the OBB resting “vertically”, in accordance to the simulations of the optical test setup, in order to limit the gravitational quilting of the mirror shell. The maximum displacement is about 36 µm and is clearly located at the rear tip of the actuator. The CFRP structure of the OBB is virtually still, while the displacements at the frontal CFRP reference surface (quilting of reference) are almost negligible (i.e. ± 5.4 µm).

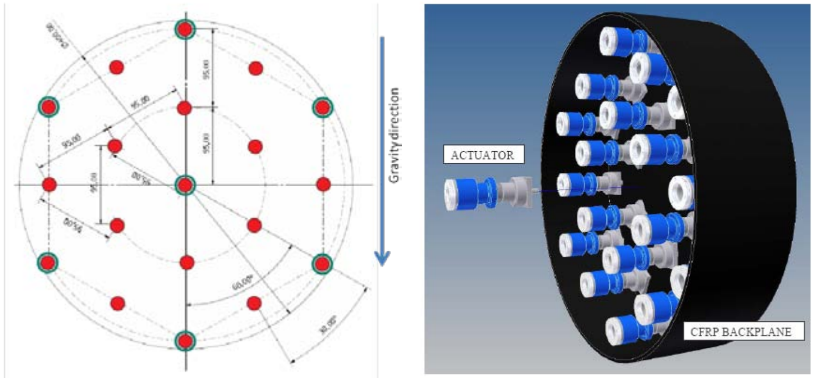

Fig. 2. OBB actuators patterns: low (green circles) and high (red dots) density cases (a); 3-D view (b).

A modal analysis showed that the first 10 modes fell in the range of 93-107 Hz. The 1st resonant mode (93 Hz) in the Optical Experiment conditions is a local pendulum of one of the actuators.

B. Actuator design

The Voice Coil Motor (VCM) actuator has proven experimentally to match most of the initial specifications. For instance, it is fail-safe, i.e. it does not lock in case of failure.

The adopted design is an improved VCM, with the aim of increasing the efficiency w.r.t. the design previously presented [1], using also a closed magnetic circuit. The Voice Coil Motor (VCM) is made by a permanent magnet mounted on the shaft of the actuator; together with the magnet there are two soft Iron polar expansions, used to close the magnets loop around the coil. Considering the high reliability demand on the actuator, a *moving magnet* design was adopted: the coil is mounted on the fixed part of the actuator, with no more fatigue stress. The drawback is an increase of the mover mass w.r.t. a *moving coil* design. However, the relatively low dynamic demand on the actuator and the relatively large mirror mass connected to each actuator mitigate this effect. The computed efficiency amounted to 1.79 $N/\sqrt{W}$.

The actual force required for shell flattening can be estimated starting from actual data measured on the Large Binocular Telescope (LBT) adaptive secondary mirror [2]: for the present application it is 0.3 mN rms. At this level, the VCM topology appears to be significantly favourable. Furthermore, the VCM design allows a quite accurate stability of the motor force constant w.r.t. the mover movement.

A dynamic simulation was performed: its main goal is to provide a quite accurate estimate of the minimum control frequency needed to ensure the system stability, given a certain actuator spacing, shell thickness and moving mass. Moreover, it allows assessing the required actuator force capability. Positioning error rms ranged between 54.5 nm under the hypotheses of 0.5% modal damping and 112.3 nm with 0.1% modal damping.

The actuator is conceived as a self-standing unit: it is made of an Aluminium body which contains the motor and position sensor fixed components packed inside by the front and back taps. The mobile equipments (of motor and sensor) are mounted on a shaft which is guided by two axial bearings (Fig. 3).

At this design stage, the actuator overall weights 230 g (allowing further reductions up to 150g), and is 110 mm long, 37 mm wide, while the mechanical axial stroke is ± 650 µm.

The actuator is screwed to the Invar insert glued into the OBB front skin; on the other side, it is attached to the 1-mm thick deformable mirror by a magnetic coupling.

On the mirror back side, a Zerodur puck and a Fe disk are permanently glued. The interface with the actuator is made by a steel ball embedded into the actuator tip assembly. The bi-lateral restraint between actuator and mirror is made by a permanent magnet, mounted on the actuator mobile equipment tip. This magnet pulls the Fe disk; the interposed steel ball allows decoupling mirror and actuators rotation, while coupling the axial movement. This ball is laterally restrained by an o-ring, which provides a lateral stiffness to the mirror.

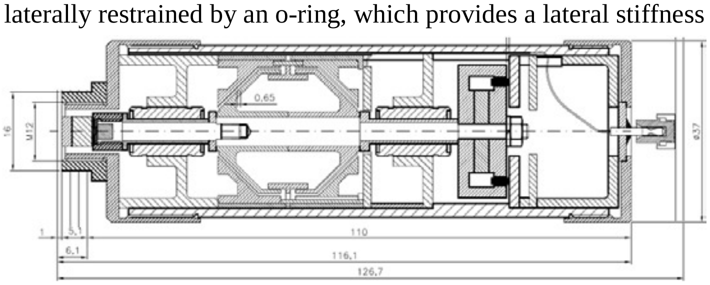

Fig. 3. Actuator assembly drawing.
Mirror interface (left), position sensor (centre), voice coil motor (rear), axial bearings (on axis).

The actuator shaft is restrained by two axial bearings, mounted into the actuator fixed frame.
The position capacitive sensor is made of three sets (two fixed and one mobile) of Invar armatures.

V. DEPLOYMENT MECHANISM:

The preliminary design of the DBB presents the development of the Deployment mechanism for the mirror, with the purpose of proving the feasibility of deployment precision of one mirror segment.

The deployment system must be composed by stable structures with relatively high stiffness, based on available hinge and latches technologies and well known materials, leaving the task of achieving very high precision to the active optics of the telescope.

A stiff structure during launch is important: it simplifies designing for the launch-loads, avoiding coupling with launcher dynamic loads. Moreover, a relatively high stiffness maintained also in the deployed configuration minimises distortions under inertial loading for 1-g testing and reduces on-orbit response to slew manoeuvres. So, the main driver of the selection of the deployment kinematics is the stiffness of the petal in the deployed configuration. The dimensioning of the items composing the kinematics has been performed on the launch loads and is predominant with respect to the on-orbit loads.

It has been calculated that the first frequency of the deployed panel must be higher than 10Hz to avoid negative effects due to on-orbit disturbances and to avoid interference with the control of the actuators.

Modal analyses have been performed on different configurations of petal in deployed arrangement. The best identified configuration is the FWD/REAR folding petals configuration, since it allows maximising the mirror aperture w.r.t the pure forward one. The drawback is that the kinematics for the FWD petals is not equal to that of the REAR petals, although similar. The best design with 1st frequency > 10 Hz indicates that the petal must be constrained to the main structure by means of two high precision hinges. A rod increases the overall stiffness of the panel. Being locked during launch by means of a non explosive, no-shock, low mass release device (NEA Electronic Separation System), the petal is then deployed through the control of the rod, which is blocked at the level of a third hinge. During the deployment, the stiffening strut is kept roughly in the right position by means of a guide. At the end of the deployment a latching device latches the stiffening strut. With this design, the frequency is 18 Hz.

The precision of the deployment is due to the precision of the hinges and the latching device. The estimated deployment error is ±75.9 μm, well below the actuator stroke allocated to compensate the deployment imprecision (i.e. ±250 μm). The FE model of the whole satellite, in launch configurations, was run to extract the forces at the I/Fs of the petals with the main structure. These forces are ~2 KN (axial) and ~3 KN (shear).

The main parts composing the DBB will be: 1) the support structure; 2) the dummy petal; 3) the adjustable strut; 4) the latching device; 5) the guide.

The dummy petal is similar in size of the deployable petal of the satellite (~1m^2), although the material is not representative of the flight one. The adjustable strut will be equipped by rod ends spherical bearings with precision equal or lower with respect to the flight one. The latching device and the guide will be flight like.
The deployment of the petal will be done applying the torque in one of the high precision hinge.

VI. MIRROR MOCK-UPS:

The manufacturing of the thin mirror, for the OBB first and the petal sample then, is not trivial. At this design level, in the frame of the ATP a valid procedure has been provided by building and testing three 1-mm thin BK7 mock-ups, with 100 mm diameter and 400 mm curvature radius. Although the diameter is smaller than the OBB final one, the major complexity consists in fabricating these mock-ups with a curvature stronger than the one foreseen for the OBB. 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 step-by-step procedure guarantees that each passage is well under control, and that the most critical aspects are highlighted and implemented towards safety for the next construction phases of bigger glasses.

A blank of material is firstly sawed to approximately the wanted dimensions. A corner rounding machine provides the circular diameter. Suitable marble supports are fabricated to hold the glasses during manufacturing and for the grinding and polishing steps of both the concave and convex surfaces. First, the concave one is made: a roughing tool is initially used to create a rough plano-concave glass; then, a lapping machine provides the grinding with Carborundium and then the polishing with Cerio oxide; interferometric testing (with horizontal interferometer) shows the goodness of that surface; the concave surface is finished and is finally glued on the plano-convex marble support. The glass is thinned with the roughing tool, which rounds the plane surface to become convex. With similar procedure, grinding and polishing of the convex surface are made, thus defining also the appropriate thickness. Interferometric measurements are taken even for this constrained surface and for the final central thickness. Finally, the thin glass is unstuck from its support: at this level, optical tests are not representative, since gravitational quilting is effective even for these small glass samples. For these mock-ups, the λ/6 rms requirement on the concave surface has been easily achieved. It is important that the concave surface quality (for the mock-ups, as well as for the OBB and the petal) is very high in spatial scales of twice the actuator spacing (i.e. ~10 cm), where actuators cannot provide proper compensation.

VII. OPTICAL TESTS DESIGN:

Once the OBB is completed, optical testing of the deformable mirror (DM) surface quality is required (Tab. 1).

The initial calibration of the position actuators does not guarantee a flattened shape of the mirror, so the OBB is preliminary used to optically calibrate the response of the actuators (optical displacement vs. actuator position commands) and then to define the best (i.e. least wavefront rms error) flattening actuator command vector.

The OBB test layout uses a 3 x 1.5 m^2 optical bench containing the DM with its control electronics, two folding mirrors and the interferometer. For the test layout the DM is set vertical (Fig. 2), to reduce its gravity deformation (gravitational quilting) induced by the glass self-weight, which generates an unavoidable bias in the figuring error. This effect increases the requests of accuracy and dynamical range on the instrumentation for the optical qualification of the mirror.

FE analysis under gravity gives 224 nm rms and 1.6 µm PV when all the actuators are positioned over a common plane orthogonal to the optical axis, while, after calibrating the 19 actuators to minimize the surface error, the analysis gives 115 nm rms (larger than the flattening specification) and 0.94 µm PV. This shape presents an unavoidable bias deformation to be removed from the flattening that will be achieved with the DM to estimate the surface quality in absence of the gravity. The subtraction of the quilting deformation from the flattening data requires high accuracy on the alignment between interferometer measurements and FEA simulation of the gravity deformation.

VIII. CONCLUSIONS:

All the activities presented allow drawing the following conclusions.

The preliminary design of the DBB uses the FWD/REAR folding petal configuration because it allows maximising the mirror aperture with minor complexity. As it was stated, good margins can be achieved in terms of deployment precision, by using latching device and high precision hinges.

The ATP of the mirror manufacturing reports that three specimens, made of BK7, have been successfully built and tested, achieving the required optical quality. Obviously, the feasibility of a diameter bigger than 100mm involves bigger facilities and more accurate procedures.

The OBB has been preliminarily designed and checked under static load. The ATP of the backplane and EL samples demonstrates that the CFRP backplane can be manufactured with the needed roughness, potentially implementable with a second replica. The EL locking is successful with low voltages (100 V max).

The mass areal density of the OBB preliminary design is 20 Kg/m^2, which overestimates the petal density.

The study on the actuators identified the most promising configuration to meet the efficiency/accuracy requirement by limiting the mass and removing wired terminal on the mover. The Voice Coil actuator has been chosen because it is fail-safe, and because of its long stroke, large deployment error correction, good force/power ration and accuracy, good thermal efficiency at low power levels and its significantly good linearity. The capacitive sensor design is compatible with both range and resolution requirements.

The optical figures, obtained by means of the proposed OBB optical test setup, shall be cleaned by the effect of the 1 g load: the deformed shape of the mirror, foreseen by the FE analysis, will be subtracted (as a static bias) to the optical test results. The flattening of the deformable mirror is an iterative process that follows the guidelines suggested by the procedures of the LBT adaptive secondary mirror, which has been under full test for about 1 year and is now ready for final acceptance. That system essentially incorporates all the subsystems considered for the described application (although with some differences): the thin-glass mirror, many electromagnetic actuators, the logic of the control system, a “Pyramid” wavefront sensor. Many assumptions in the presented designs have been based on the LBT experience.

The overall ATP foresees a further development of all these subsystems in order to achieve a bigger and more complex structure formed by petals. Successively, all these considerations can be potentially applicable also for space-based mirrors for scientific purposes other than LIDAR remote sensing.

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