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large aperture, deployable telescope for space applications***

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A TECHNOLOGY DEMONSTRATOR FOR DEVELOPMENT OF ULTRA-LIGHTWEIGHT, LARGE APERTURE, DEPLOYABLE TELESCOPE FOR SPACE APPLICATIONS

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ABSTRACT

This work presents the latest results of new technological concepts for large aperture, lightweight telescopes using thin deployable active mirrors. The study is originally addressed to a spaceborne DIAL (Differential Absorption Lidar) at 935.5 nm for the measurement of water vapour profile in atmosphere, as an output of an ESA contract (whose preliminary results were presented at ICSO 2006).

The high versatility of these concepts allows to exploit the presented technology for any project willing to consider large aperture, segmented lightweight telescopes. A possible scientific application is for Ultra High Energy Cosmic Rays detection through the fluorescence traces in atmosphere and diffused Cerenkov signals observation via a Schmidt-like spaceborne LEO telescope with large aperture, wide Field of View (FOV) and low f/#.

A technology demonstrator has been manufactured and tested in order to investigate two project critical areas identified during the preliminary design: the performances of the long-stroke actuators used to implement the mirror active control and the mirror survivability to launch. In particular, this breadboard demonstrates at first that the mirror actuators are able to control with the adequate accuracy the surface shape and to recover a deployment error with their long stroke; secondly, the mirror survivability has been demonstrated using an electrostatic locking between mirror and back-plane able to withstand without failure a vibration test representative of the launch environment.

Keywords: space telescope; active optics; large aperture, deployable, lightweight optics; Schmidt camera; LIDAR; cosmic rays.

1 INTRODUCTION

The main result of this study is the demonstration of the possible realization of a deployable lightweight mirror with mechanical tolerances in agreement with optical specification. This is made possible by the use of a flexible active mirror with a high dynamic wavefront sensor, allowing both the alignment of the optical system after the initial deployment and a constant optimal optical quality during operation. The technology of active mirrors is already in use on ground for compensating slowly varying effects (i.e. orientation changes in the gravity field, thermal effects); it is very promising for space applications such as LIDAR detectors and optical telescopes, although the development requires further efforts.

The LIDAR concept proposed at the ICSO 2006 [1], to which this work is referred as a starting point, is basically a space telescope for monitoring the atmospheric water vapour distribution at 935.5 nm using a DIAL (Differential Absorption LIDAR) technique, retrieving the signal emitted by moderate power laser transmitter. Therefore, the telescope collecting area becomes a key parameter for a LIDAR instrument since laser power transmission is inversely proportional to the aperture size. The key features of the design are: large optics (total available primary mirror surface about 10 m²); lightweight and deployable primary mirror with areal density about 15 Kg/m²; high wavefront quality ($< \lambda/3$). A highly precise deployment is necessary because of the needed dimensions of the mirror, which can hardly be thought as monolithic. It occurs via Elastic Memory Composite (EMC) actuators with the required reliability; any error can be simply recovered by an actuator system beneath the mirror. This active control system guarantees the required wave front quality with low power dissipation.

After the primary mirror deployment, the set of actuators connected to the thin mirror shell recovers the optical

figure minimizing the shape errors, using a closed-loop active control system able to assure a $< \lambda/3$ wavefront quality with low power dissipation (fraction of Watt per actuator). The shape error sources are deployment, mirror manufacturing and thermal deformation. The active control of the segmented primary mirror relies on the interaction between several independent systems that concur to implement a feedback control loop, namely: a) the reference signal collected by the optical system to be controlled, coming from the retro-scattered light of the emitter (a single diode laser with dedicated optics for guide laser star or a diode array laser using the central mirror as collimator, and sent on ground by the telescope); b) the wavefront sensing system (a Shack-Hartmann or a pyramid) measuring the aberration of the collected wavefront; c) the computer where a control algorithm handles the measured optical data into electrical signals driving the actuators; d) the mechanical actuators that apply forces to deform the mirror.

The innovative approach for the primary mirror is based to the coupling of a thin Zerodur mirror optical surface 1 mm thick with a lightweight CFRP (Carbon Fiber Reinforced Plastic) back-plane and supporting structure. A major problem is how to preserve the integrity of the glass shell in the harsh environment of the launch. The use of electrostatic force is here proposed for attracting the glass toward the back plane: applying a 300 V voltage the mirror is practically glued to the CFRP back-plane, withstanding a vibration test simulating the launch environment. This method is particularly promising especially due to the low power consumption.

A special approach to decouple the primary mirror shape optical precision performance from the deployable main structure precision/stability performance, using active optics, is also here presented. Full advantage of standard technology is taken to design deployable high precision and lightweight surfaces suitable for space operation, providing stable structures with relatively high stiffness based on already available hinge technologies and well known materials, and leaving the task of achieving very high precision to the active optics.

In order to demonstrate the feasibility of active optics to meet the requirements also for use in space, two main areas were identified to be investigated in the breadboard phase, with the breadboard development divided in two main processes:

- Actuators performance and power consumption: a critical issue related to the need to re-shape a thin mirror on orbit using a minimum amount of power. An Active Control Actuator breadboard was developed to evaluate the actuation and sensing (capacitive sensor behaviour against long stroke) performances.

- Active mirror survivability to launch: another critical issue, related to locking of a thin mirror during launch by means of an electrostatic locking system. The Electrostatic Locking Back-plane (ELB) breadboard provides information on survivability to mechanical launch environment of the proposed concept. It includes also one active control actuator.

This paper describes the requirements and the design of both breadboards. The most relevant design analyses for the actuator performance are illustrated together with test results showing positive design verification. A further set of structural analyses has been performed to validate the concepts, highlighting that the breadboard can withstand the foreseen vibration environment [2,3].

2. ACTUATOR DESIGN DESCRIPTION

The design of the actuators for the active control of the mirrors surface is here discussed. In the proposed mirror layout, the central part and the deployable set of petals, composed by backplane, actuators and optical surface, are mounted on a deployable truss support structure. The actuators are based on voice-coil actuation concept; they are placed on a 250x250 mm² pattern on all the primary mirror backplane, providing actuating force to the mirror shell (Fig. 1).

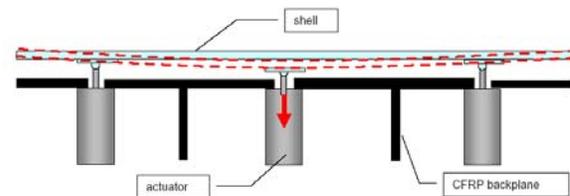


Fig. 1 Actuator concept for mirror motion.

The actuator design comes from experiences with active secondary mirrors on ground-based telescopes [4]: the actuator diameter is set to ~ 25 mm, its overall length is ~ 80 mm and the mass is < 0.15 Kg (Fig. 2).

The actuator mobile part is guided by two axial bearings and it carries a pair of permanent magnets. The coil is wound on the stator and the magnetic circuit is closed by iron polar expansions. The position is measured by a capacitive sensor: the armatures are arranged in cylinders with the axis parallel to the actuator's (Fig. 3). This allows large stroke and sufficient armature surface to get the demanded sensitivity. The interface between actuator head and mirror is made by a magnetic joint, namely two parts kept together by magnetic force which restraints both axial and lateral displacements while leaving the rotations of the two parts free.

The actuator accuracy is < 200 nm, the actuator resolution is < 10 nm and the total stroke is 1 mm.



Fig. 2. Active mirror control Actuator.

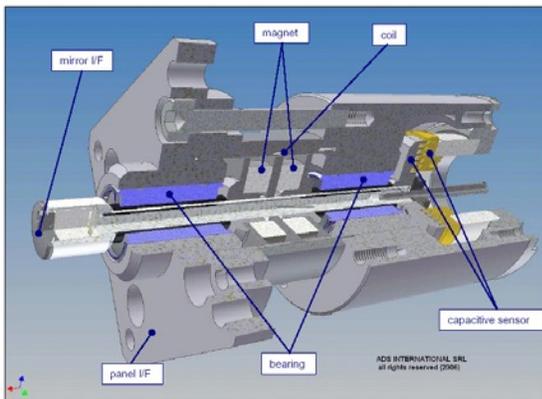


Fig. 3. Active mirror control Actuator: details.

The capacitive sensor measures the variations of capacitance between the two armatures, where one is connected to the actuator body and the other is mounted on the moving part. The armatures are shaped as to increase their capacitance and therefore to improve the sensitivity. One of the two capacitances is solid-state, while the other is the above described moving-armatures capacitance that actually measures the gap.

The capacitor has the following features: (axial) Stroke = 1000 μm ; (radial) Gap = 50 μm ; Capacitance (min, max, functional axial stroke) = 22 pF, 110 pF; (axial) Sensitivity = 0.089 pF / μm .

The resolution and accuracy goals are consistent with the performance obtained developing capacitive sensors for adaptive optics application with similar mechanical constraints, less stringent resolution requirements but significantly higher bandwidth.

The force which drives the design of this interface is the inertia acting on the mobile part of the actuator during launch. The mass of the mobile part is 30 gr and assuming a maximum acceleration of 12 g, the resulting force is ~ 3.5 N.

The same actuator architecture foresees two different types of restraint between actuator and mirror. In all cases the magnetic interface between the actuator tip and the mirror is based on a pair of commercial NeFeB permanent magnets with circular shape and axial

polarization: a soft iron disk is glued on the back of the mirror and another permanent magnet is placed into the actuator mobile frame tip. The most important advantage of using magnetic connection is that this interface design exploits just a pinned connection without introducing rotation stiffness and mechanical hysteresis. The two magnets are packed with the same polarity facing each other in order to squeeze the field out in the radial direction. The coil is placed in this region to exploit the maximum radial field and therefore to maximize the thermal efficiency.

One kind of actuators is meant to restrain mirror lateral movements and in this case actuator mobile frame is directly connected to the mirror; actuator tip and mirror interface disk are machined with a meniscus coupling to leave free relative rotations. The other kind is designed to leave free lateral displacement of the mirror with respect to the actuator itself. This is achieved by interposing a ball between mirror interface disk and actuator tip. Among the two possible types (with or without lateral restraint), the most critical interface is the latter, i.e. when the force shall be transferred through the steel sphere.

The Actuator prototype is designed to be easily machineable and to facilitate its integration, relying on off-the-shelf commercial components compliant or portable to space application:

- Actuator fixed and mobile frames are made of aluminium.
- Polar expansion disks are made of steel (low carbon grade).
- Linear bearings rolling ways are made of steel (surface hardening).
- Capacitor armatures are made of aluminium, while the spacer between the fixed armature and the actuator frame is in ceramic material, an electrical insulator but with the same CTE of aluminium.
- Actuator body and its mobile equipment (through the bearings) are assumed to be the electrical ground reference.

At the current state of the design no critical issues related to thermal vacuum or in general space environment are foreseen, considering that the single actuator sub-components have already been used in space applications. In particular, the selected current space qualified components for the actuator and the used materials already satisfy thermal requirement. Besides, all materials must require proper out and off-gassing properties compatible with space optics. The lifetime of all the foreseen mechanical, electrical and electronic parts must be of 3 years, taking into account that the mechanical components are mainly used with applied loads much lower than their minimum allowable for infinite life, and electrical \ electronic parts can be

selected among typical space qualified components for long space missions.

Actuator current design is consistent with an overall power dissipation of the order of 200 mW/act, including the contribution of about 50 mW dissipated at coil level and 150 mW on the electronics. Other design requirements are in Tab. 1.

Tab.1. Actuator performances summary

	Actuator Performance	VALUE
1	Stroke	> 1mm
2	Accuracy	< 200 nm
3	CL actuator bandwidth	> 1 Hz
4	Actuator Efficiency	$> 0.45 N/\sqrt{W}$
5	Max force	0.2N

3. ELECTROSTATIC LOCKING

A key point of the developed primary mirror is the coupling of a Zerodur 1-mm thin shell with the lightweight CFRP supporting structure; the major problem of this configuration is the glass survival to launch loads. In order to assure the glass integrity after launch, the electrostatic force is used to hold the glass to the back-plane. The glass back face is silver coated and the back-plane is covered with two layers of material: the first one is conductive, while the second is an insulator with high dielectric constant (Mylar). This configuration gives a capacitor with large capacitance (Fig.4).

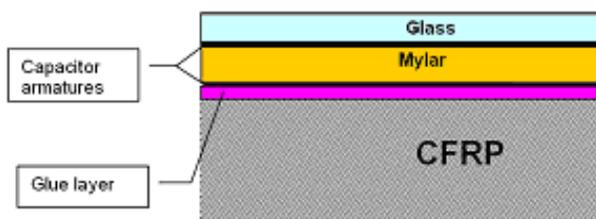


Fig.4. Scheme of Electrostatic Locking.

This method generates high retention forces with low power consumption and low "extra material" budget. For an average insulation thickness of 12 μm , $\epsilon_{\text{MYLAR}} = 3.1$ and 300 V potential difference, the attractive force is more than 6000 N/m^2 , to be applied to a mirror surface density of $\sim 2.5 \text{ kg}/\text{m}^2$. The mirror would (axially) detach from the back plate only with a static equivalent acceleration of $\sim 100 \text{ g}$. For a measured friction coefficient (> 0.5) also the lateral motion would be

prevented for static equivalent accelerations of $\sim 50 \text{ g}$. The electrostatic force depends critically on possible gaps between glass and back plate; it is then important to assure that the insulating layer has constant thickness and is in contact with the conducting back surface of the thin mirror. Fig. 5 shows the Electrostatic Locking developed breadboard.



Fig.5. Electrostatic locking breadboard, top and bottom surface. In the top view the Mylar surface is visible.

4. GROUND DEMONSTRATOR

In order to demonstrate the actuator functionality and the electrostatic locking concept feasibility for the LIDAR concept, a breadboard has been designed, manufactured and tested, considering the most sensitive part (the corner side) of the primary mirror petal. The ground demonstrator is composed by the CFRP panel with a voice coil actuator. To be representative of the final mirror performance, the breadboard has an areal density $< 20 \text{ Kg}/\text{m}^2$, a suitable thermal stability and it is tested at the 1st frequency of $150 \text{ Hz} \pm 50 \text{ Hz}$. Fig. 6 shows the tested ground demonstrator.

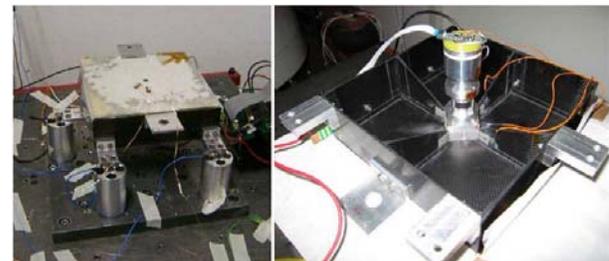


Fig. 6. Tested ground demonstrator, top and bottom view.

The following tests have been performed on the LIDAR breadboard:

- Sine vibration with 10g peak in each axis;
- Random vibration with 11.4 grms input in each direction with a duration of 2.5 min;
- Shock test between 125g and -60g for 0.5 msec each, in the (+ and -) direction perpendicular to the mirror;
- Actuator functional test.

The mirror did not detach from the back-plane surface and an actuator preliminary test showed the goodness of its performance through the vibration tests. However, a more detailed actuator functional test highlighted a damage after the vibration test, but this problem can be overcome by introducing a low-impact actuator design modification. Tab. 2 summarizes the tested actuator performance, showing the actuator expected performance obtainable with a further optimization of the design.

Tab. 2. Developed voice coil actuator performances

Actuator Performance	Measured Value	Achievable Value
Actuator Stroke	1.27 mm	> 1.27mm
Accuracy	25 nm	10 nm
CL Actuator Bandwidth	100 Hz	50 Hz (for 10 nm accuracy)
Efficiency	$0.45 N/\sqrt{W}$	$1.5 N/\sqrt{W}$
Mass	0.15 Kg	0.1 Kg
Fail-safe mode	A failure in actuator does not yield any restraint to the mirror shell	

5. APPLICATIONS

The active / adaptive control technology for the adjustment of the optical surface of mirrors is already used for the thin-glass secondary mirrors of ground-based telescopes [5], via electromechanical actuators to instantaneously correct the atmospheric turbulence effect and therefore for improving the optical performance. The control is made through a wavefront sensing system that measures the aberration of the collected wavefront. However, for space application the disturbances characteristic time is lower, \sim Hz, and is related mainly to in-orbit alignment and compensation of any deformation (i.e. thermo-elastic) of the support. The advancement of this technology can be the key for the improvement of the next generation space telescopes: it can be either competitive or better than the current technological baselines. The potential application range is wide. In particular, Earth observation missions proposed in the ESA Living Planet Programme, which cover a range of environmental issues with the aim of further understanding the Earth system and changing climate (i.e. BIOMASS, TRAQ, PREMIER, FLEX, A_SCOPE and CoReH2O), can take advantage of these technological improvements [6]. For very large telescope diameters, typically above 4 meters, monolithic telescopes can hardly be envisaged

for space applications. A large deployable active primary mirror becomes desirable. In High Resolution astronomy, this technology could be applicable to JWST (James Webb Space Telescope, a large, infrared-optimized space telescope, devoted to several applications in frontier astrophysics), DARWIN (Detection of Earth-like planets around nearby stars), WFI (a Wide Field Imager for Supernovae Surveys and Dark Energy Characterisation). The JWST primary mirror is planned to be composed by deployable optical segments of ultra-lightweight beryllium with an areal density of 16-18 Kg/m² [6].

5.1 Super – EUSO

Super-EUSO (the Super-Extreme Universe Space Observatory) is an international multi-agency mission, led by ESA, whose aim is to investigate the Ultra High Energy Cosmic Particles (UHECPs): charged particles, photons, neutrinos, or yet undiscovered particles, entering the Earth atmosphere with a very low flux of less than 1 km⁻² (sr century)⁻¹, at energies $E = 10^{20}$ eV [7]. These particles are shielded by Earth's atmosphere and their existence is revealed on ground only by indirect effects such as ionization and Extensive Air Showers (EAS) of secondary charged particles covering areas up to many km² (for the highest energy particles). So far, UHE particles have been detected by several independent ground-based experiments, with a correspondence of \sim 1 event km⁻² century⁻¹ with $E \sim 3.2 \times 10^{20}$ eV. Observations from space of UHECP-induced EAS, by collection of the fluorescence light (300-400 nm) [8] and the Cherenkov light diffusely reflected by ground, sea or clouds, are likely to be essential: space-based observatories can in fact reach a very big instantaneous aperture, thus allowing more accurate measurements of the nature, energy and arrival direction of the primaries.

The Super-EUSO mission, an improved version of the EUSO project and included into the ESA Cosmic Vision 2015-2025 program, is a challenging free-flyer experiment that can increase the event statistics by exploiting an instantaneous geometrical aperture of $\approx 10^6$ km² sr that translates in a target mass of more than 10¹² ton, looking downward on the Earth at night. S-EUSO will aim at understanding the highest energy processes in the Universe and testing high energy physics beyond the limits of existing and next generation particle accelerators.

Basically, the apparatus will be a large aperture, large Field of View, fast and highly pixelized digital camera detecting near-UV single photons with high efficiency. Indeed, in order to increase the instantaneous geometrical aperture, the orbit must be high. This makes the signal faint, thus requiring a larger photon collection capability,

which in turn depends on the optics entrance pupil (EP) size and the total photon collection efficiency. The EP is the only parameter affecting the performance which can be dimensioned: the instrument is therefore designed to have the largest possible size compatible with a non-deployable focal surface (FS) for a given launcher. It is assumed that the satellite orbit shall be elliptical with $r_{Average} \approx 1000$ km. The resulting averaged instantaneous geometrical aperture is $AG = 2.0 \cdot 10^6$ km² sr.

In order to cope with the required very large optics it is planned to use a catadioptric system, basically formed by a pseudo-Schmidt camera, i.e. a system made of a big quasi-spherical mirror coupled with a corrector (Fig. 7), which, for this case, is not exactly placed at the centre of curvature of the mirror. This concept has the advantage to be capable of a smaller $f/\#$ than refractive optics, thus helping to limit the size of the FS and hence the obscuration. It is assumed $f/\# = 0.7$, with a goal of 0.6. The lens is planar, with optimization at the higher order of asphericity to account for the spherical aberrations caused by the mirror at the off-axis fields. There are almost no chromatic aberrations and the UV transmission is enhanced with respect to a refractive optics solution.

According to the scientific requirements and for launch with ARIANE V rocket, the main instrument parameters are listed in Tab. 3.

Tab. 3. Super-EUSO: main parameters for ARIANE V.

Main mirror Diameter	11 m
Entrance pupil and corrector plate diameters	≈ 6.7 m
Field of View	$\pm 25^\circ$ half-angle
Angular granularity	DI ≈ 0.7 km at Earth Average
Optics throughput	$\epsilon > 0.7$ Aver. requirement
$f/\#$	≈ 0.6 Current design: $f/\# = 0.7$
Total length of the optics	≈ 8.6 m
Focal Surface Diameter	≈ 4 m
Number of channels	≈ 1.2 M
Size of the pixels of the PD	≈ 4 mm

Due to the lateral dimensions of the corrector and the mirror, these elements must be thought as lightweight and deployable structures: they have to be folded during launch and deployed once in orbit. The mirror will be deployed with a series of petals around a central structure; the corrector plate will be made in segments, with an appropriate deployment design.

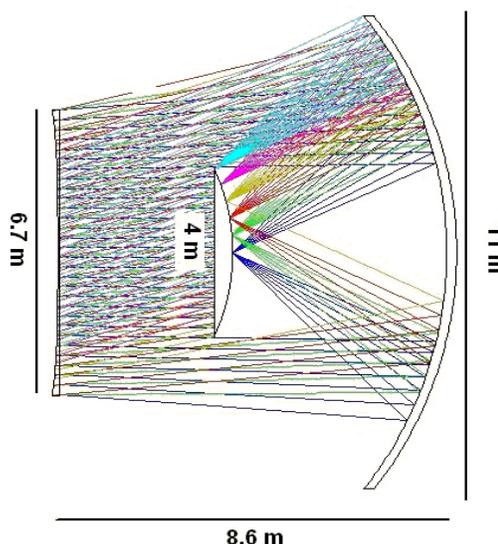


Fig. 7. The Super-EUSO telescope dimensioned for ARIANE V.

Because of the size of this optical system and the difficulty of controlling the temperature and temperature gradients in such a system, the coupling between the thin optical surface of the primary and the stiff lightweight support structure will be made through an array of actuators for the adjustment of the optical surface via active control. Furthermore, the tolerances in the mechanical deployment system are not so stringent, since the spot dimensions are relatively large, and so the active control can compensate fairly well. Active control of the corrector plate will focus on correcting the tilt of the segments because the optical performance is relatively insensitive to small relative translations of the segments.

Super-EUSO will take advantage of the development of the above described technology: currently, the mirror is foreseen to be made of 15 kg/m², 1-mm thick Zerodur mirror and CFRP supporting back-plane

A weak point might be the complexity on all these deployments. The telescope can then be thought to have just the single deployment of the mirror in two visions: by using a bigger launcher (an option already in consideration), or by properly rescaling the whole system and therefore making some modifications to the scientific goals.

6 CONCLUSION

The developed technology presented in this paper is a step forward in the possibility to create well performing large area telescopes to be deployed in orbit. The decoupling of the mirror optical surface from the supporting mechanics improves the optical precision and reduces the requirements

for the tolerances in the deployment mechanism as well as during operation.

The mirror survivability during the launch phase has also been taken into account. The use of electrostatic force is explained for attracting the glass toward the back plane.

The breadboard phase for the proposed technology has been successful, with the following main investigation areas:

- Lightweight primary mirror design and control for space utilization (applications with area range from 0.8 m² to more than 12 m², depending on telescope architecture and deployment/assembly scheme);
- Compatibility with all operation environments, especially the harsh launch phase (tests performed with a general environment for typical launchers).

The built breadboard was successfully tested on a flat geometry with a general vibration environment that simulates a typical launch environment independent from the specific application. The Electrostatic Locking concept has demonstrated its high efficiency providing a retention force that largely satisfies the requirements.

The high wavefront sensor accuracy is guaranteed by the developed voice coil actuator that satisfies all the requirements; additional margins exist to improve the actuator efficiency and to optimize the actuator density.

In the present application for Earth observation, the surface control feedback uses a low power dedicated laser. This can be achieved by any point source in the FOV for astronomical applications such as the study of high-energy cosmic rays from space.

The weight reduction both of the optical surface and the mechanics is improved, thus permitting much larger telescopes to be developed.

In conclusion, the feasibility of the concept of the designed active primary mirror, formed by a thin glass shell coupled with a stiff back-plane CFRP structure reaching a low areal density ($\sim 16 \text{ Kg/m}^2$), has been demonstrated both from performance and Manufacturing – Assembly – Integration Test points of view.

The techniques to obtain the required manufacturing characteristics for the proposed concept are promising, and can positively affect the development of future space-based observatories, such as the Super-EUSO project.

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