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LARGE APERTURE TELESCOPE TECHNOLOGY: A DESIGN FOR AN ACTIVE LIGHTWEIGHT MULTI-SEGMENTED FOLD-OUT SPACE MIRROR

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I. ABSTRACT

Large aperture telescope technology (LATT) is a design study for a differential lidar (DIAL) system; the main investigation being into suitable methods, technologies and materials for a 4-metre diameter active mirror that can be stowed to fit into a typical launch vehicle (e.g. ROKOT launcher with ~ 2.1-metre diameter cargo) and can self-deploy – in terms of both leaving the space vehicle and that the mirrors unfold and self-align to the correct optical form within the tolerances specified. The primary mirror requirements are: main wavelength of 935.5 nm, RMS corrected wavefront error of $\lambda/6$, optical surface roughness better than 5 nm, areal density of less than 16 kg/m² and 1-2 mirror shape corrections per orbit. The primary mirror consists of 7 segments – a central hexagonal mirror and 6 square mirror petals which unfold to form the 4-metre diameter aperture. The focus of the UK LATT consortium for this European Space Agency (ESA) funded project is on using lightweighted aluminium or carbon-fibre-composite materials for the mirror substrate in preference to more traditional materials such as glass and ceramics; these materials have a high strength and stiffness to weight ratio, significantly reducing risk of damage due to launch forces and subsequent deployment in orbit.

We present an overview of the design, which includes suitable actuators for wavefront correction, petal deployment mechanisms and lightweight mirror technologies. Preliminary testing results from manufactured lightweight mirror samples will also be summarised.

II. INTRODUCTION

This study is part of an ESA contract to develop large deployable space apertures for a future concept DIAL mission that would monitor water vapour distribution in the atmosphere. However it is also relevant for other applications requiring large, lightweight mirrors such as space-based astronomical telescopes. Our work is based on a previous ESA study [1, 2] commissioned to address a similar aim and uses their design as our baseline. We have used the same aperture shape and arrangement but have investigated alternative mirror substrates, actuators and deployment mechanisms. One of the key technologies is the lightweight mirrors and this was a focus of our 9 month investigation. To enable an increase in sensitivity for future DIAL missions without increasing the lidar laser power, an increase in aperture (the collecting area for the back scattered photons) is required; however the areal density and launch size needs to be minimized to keep the mass within a viable mission envelope. This is best achieved in the near future by using a fold-out mirror consisting of multiple segments that can self-align once deployed in orbit. Roll-up membrane type mirrors are beyond the technology readiness level for this study.

A review of new and future technologies suitable for this mission concept was undertaken; those deemed most suited to this mission were further analysed using computer modelling software and some small mirror samples were manufactured for investigation. There are many system components in a design such as this and there is not enough scope in this paper to discuss them all; discussion of support structures, baffles and wavefront sensing systems are not included. This paper looks in more detail at the mirror technologies chosen for our investigation, actuator and deployment mechanisms that will enable the mirror shape to be controlled. The findings of this short study are discussed in further detail in the following sections.

III. MIRROR TECHNOLOGIES

Current and developmental substrates were reviewed for the mirror panels. All types of mirror system were considered: very stiff static mirrors (tip/tilt and piston only for petal alignment), very flexible mirrors with a high density of actuators to control the shape (such as those used for adaptive optics in astronomy) or an active system which is a balance between the two. The latter was chosen as it provides more options for system optimisation and provides scope to correct for any low order mirror aberrations that may arise (manufacturing

residuals, thermal distortions, unaccounted for system misalignments after deployment etc.) The trade-off for this active mirror is between mass, stiffness and actuation; i.e. flexible enough to actuate and yet stiff enough to minimize supports and number of actuators (which also reduces system complexity). Mirror stiffness, support points and gravity sag must be assessed to ensure that adequate ground-based testing can be conducted on the full size mirror segments and gravity deformations also have an impact on manufacturing. The mission requires the mirrors to provide a corrected wavefront error of $\lambda/6$ (RMS, $\lambda = 933$ nm), a surface roughness of better than 10 nm (5 nm goal) and an areal density of < 16 kgm⁻² (this mass budget includes mirror panels, actuators and backing structure). The mirrors must also be robust enough to withstand the launch environment and other potential shocks associated with deployment. Ideally the mirror technology should be scalable to metre-plus sizes to provide the largest possible aperture with minimum design complexity; the mission baseline aperture is 4 m in diameter consisting of a 1.8 m central hexagonal mirror surrounded by six 1.1 m square petals. Consideration was also given to the expertise of the consortium members and studies which had also assessed similar issues. Given the mission requirements, carbon-fibre reinforced polymer (CFRP) mirrors and metal mirrors were chosen to be most favourable in the trade-off compared to the alternatives. These were investigated further in finite element models (FEM) and small technology demonstrator pieces manufactured for laboratory analysis.

A. CFRP Mirrors

The benefits of using a carbon-fibre composite are its high strength and stiffness, low density and low coefficient of thermal expansion (CTE). As an example, compared to glass, there is up to 25% mass reduction, a stiffness increase factor of 1.6 and an approximate average strength increase of a factor of 20 in using a typical carbon-fibre composite (e.g. Toray M55J fibre in 60% volume fraction). The main problems associated with CFRP are form errors compared to the replication mandrel and surface roughness issues from the fibre print-through. The form errors are of a low order (either defocus or astigmatism) and in the case of an active or adaptive mirror system can be corrected for by use of the actuators. For longer wavelength and/or rigid mirror applications the form error may be at an acceptable tolerance or can be significantly reduced by use of a stress mounting system. CFRP dishes and mirrors are already used in space for satellite communications and more recently the primary mirror of the Planck telescope for observations of the cosmic microwave background; the challenges are reducing the discussed errors to optical (visible/near-IR) tolerances.

UCL has been conducting research into CFRP mirrors for over 5 years, most recently into solid thin sheets of CFRP material coated in nickel which can be polished to optical (visible wavelengths) quality without fibre print-through [3, 4]. An example of a Ni-CFRP mirror is shown in Fig. 1; the surface Ra is ~ 3 nm, nickel can be polished to sub-nm if required. Another benefit of the nickel coating is that it seals the CFRP to moisture changes which can affect the mirror shape, useful for ground-based operation where fluctuations in humidity may occur; nickel however does add some extra mass and slightly increases the CTE. For this ESA project we investigated some alternative CFRP constructs and new processing techniques that may produce very lightweight and stiff substrates and an acceptable surface finish without a nickel coating.

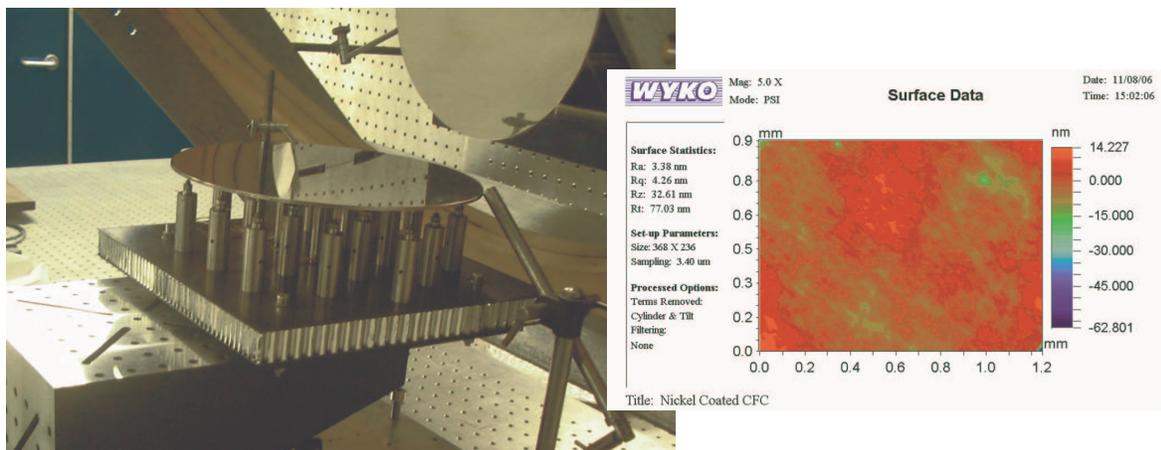


Fig. 1. A 300 mm diameter, spherical form Ni-CFRP mirror mounted on a set of dummy actuators and a CFRP-aluminium honeycomb backing plate (UCL, STFC funded).

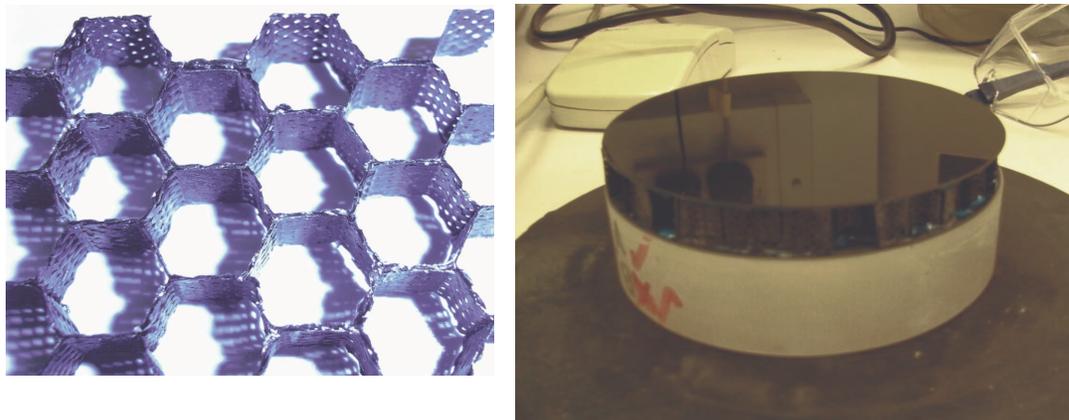


Fig. 2. Construction of a carbon-fibre honeycomb mirror showing an open-weave CFRP honeycomb suitable for vacuum applications and the completed mirror on the glass mandrel.

The alternative constructs considered were an open-backed waffle mirror panel and an all-CFRP honeycomb sandwich structure. FEA showed the honeycomb mirror to have the most favourable properties (low mass, high fundamental frequency, increased stiffness) and so some small honeycomb mirrors were manufactured. Due to the limited timeframe and budget only two 100 mm diameter mirrors could be manufactured. The materials used for the CFRP honeycomb mirror had to be taken from those in stock with our manufacturer rather than a custom material specification. For the pre-preg material (to manufacture the face sheets) this meant that we had the fibre (M55J) of our choice but not the most suitable polymer; a remnant piece of CFRP honeycomb was the only option for immediate availability, an open weave honeycomb of T300 fibre shown in Fig. 2. The honeycomb face skins were formed over polished glass mandrels (flat form, $R_a = 2$ nm). Each face skin had a thickness of ~ 1 mm and consisted of 16 plies of unidirectional pre-preg CFRP material in a standard $[0/90/\pm 45]_s$ lay-up. The honeycomb core was nominally 10 mm thick and was bonded to the face skins using a suitable film adhesive under standard pressure and heat cured. The poor form error on the first mirror demonstrated that the thickness control on the honeycomb material was not adequate for our purposes; a simple grinding process to flatten the honeycomb resulted in a factor of 3 improvement on the second mirror and a form error of 3.6 μm . Although not to specification, we believe a more accurate shaping of the honeycomb insert and a better bonding process (low shrinkage adhesives under room temperature cure) will yield a significant improvement and bring the mirror form to within acceptable tolerances.

An acceptable surface roughness of the CFRP honeycomb mirror (with resin only enhancement of the surface) was not achieved during this short development and some honeycomb print-through was observed. The print-through issue is likely to be resolved with the better processing/adhesives discussed for the form error improvement. At the time of writing a CFRP material with a more favourable polymer has been acquired; some small-scale tests will be performed to investigate the surface roughness improvements that can be made.

The density of the manufactured CFRP honeycomb mirrors was measured to be 309.45 kgm^{-3} (3.71 kgm^{-2}), keeping the system within the mass budget. Mechanical testing backed up with FEM indicates that the Young's modulus of the skins is 100 GPa and the honeycomb core 100 MPa.

Honeycomb mirrors of this format are a promising technology for future lightweight mirror applications. Recent work on similar CFRP honeycomb structures [5] has demonstrated improved optical tolerances, however more research is required to bring the mirrors within optical specifications.

B. Lightweighted Aluminium Mirrors

In general, metal mirrors are relatively inexpensive in terms of material costs, have well defined properties and can be manufactured rapidly. Beryllium is superior in its mechanical and thermal properties but is hazardous to work with. Magnesium is also a good material due to its machinability and low density but is susceptible to corrosion. On this basis aluminium alloy was chosen for further development in this project. As for the CFRP mirrors, three constructs were investigated: open-backed waffle design, honeycomb sandwich and thin-plate mirror. All three designs were taken to the manufacturing stage, the waffle-back and thin-plate mirror are shown in Fig. 3. The primary aim was to reduce mass whilst retaining as much stiffness as possible.

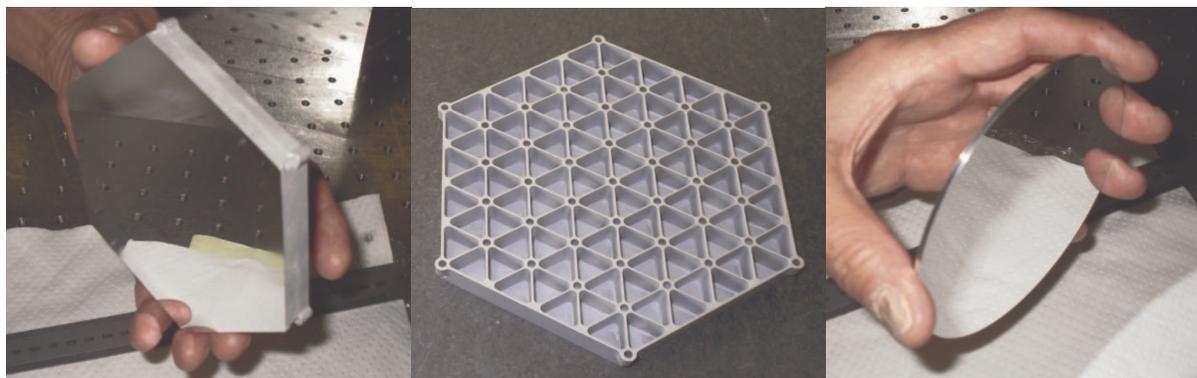


Fig. 3. The aluminium waffle-back mirror (front and rear view to show lightweighting), and the thin-plate aluminium mirror.

The waffle-back mirror was machined from a solid billet of material. The lightweighting in the rear of the mirror and the approximate curvature of the front were produced using conventional machining techniques. The front surface was then diamond turned, supported by three mounts on the rear and the pockets filled with wax to reduce tool chatter. The properties of the waffle-back aluminium mirror are summarised in Table 1. The waffle-back mirror was tested whilst still attached to its machining mount and then in a “free” state. While mounted a pocket print-through effect was measurable on the surface, however this effect disappears when removed from the machine mount. The surface form error increases from 100 nm to 350 nm RMS on release from the mount; a trefoil distortion is observed due to residual stresses caused by the 3-point support during manufacturing. Finite element models have been constructed to better understand the stresses experienced by the mirror during manufacturing and an improved mounting structure is envisioned for future work.

The aluminium honeycomb and thin plate mirror exhibit better surface roughness than the waffle-back mirror but both have a poorer form error. Both these mirrors utilise a different alloy (Al RSA6061-T651) than the waffle-back, better suited to diamond turning and is the alloy of choice for future work.

IV. DEPLOYMENT AND ACTIVE CONTROL

The mirror must be folded to fit inside a small launch vehicle (e.g. ROKOT with cargo bay diameter ~2.1 m). During launch the petals are folded and locked in position as shown in Fig. 4; three petals fold upwards and are locked to each other whilst the other three fold downwards and are locked to the sides of the spacecraft. After launch the locks are released and the petals moved into position using the deployment mechanisms (one per petal). The petal deployment mechanism must be capable of certain level of accuracy so that any remaining misalignments of the petals are within adjustment range of the actuators.

A. Deployment Mechanisms

Various types of launch locks were considered in the trade-off, two types are currently envisioned for this mission: the MHRM (multipurpose hold and release mechanism) by Dutch aerospace, these will be used to lock the petals at their tips; the second is a pin puller positioned near the hinge to improve stowed stiffness and reduce the loads transmitted through the bearings during launch.

Table 1. Properties of the aluminium waffle backed mirror

Property	Value
Overall shape and size	Hexagonal form, 105mm across flats, 13mm thick (at outer edges).
Front surface	3m radius of curvature, Ø100mm diameter, face sheet thickness 1.5mm
Rear surface	Flat surface with pattern of equilateral triangular lightweighting pockets (side length 15mm, wall thickness 0.5mm). Edge 0.8mm thick.
Mounting points	Tapped holes (M3) at vertices of lightweighting pockets, 120° apart on 60mm PCD (on lines joining centre to vertices of hexagonal profile).
Material	Aluminium alloy grade 6082
Mass	85g (8.9kg/m ² , 74% weight relief)

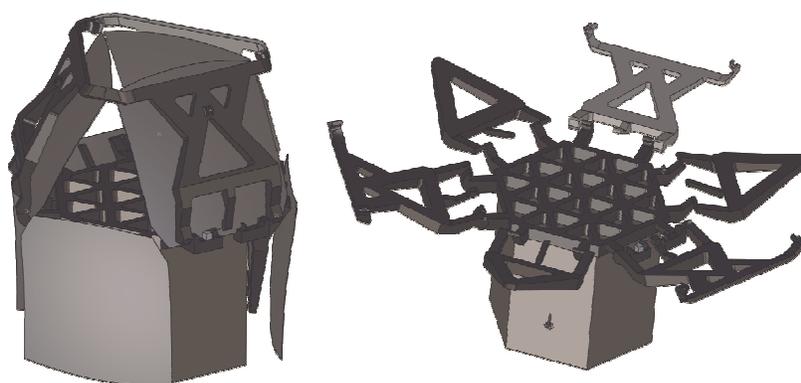


Fig. 4. Petals showed for launch (left) and deployed position (mirrors not shown).

For the petal deployment three types of mechanism appear to be the most promising:

- Elastic memory composite hinge (EMCH)
 - This hinge can be folded for launch then straightened in orbit by the application of heat.
- Stepper motor
 - The motor drives a hinge causing rotation and deployment of the petal.
- Tape spring roller hinge (TSRH)
 - This hinge can be folded and locked for launch. Release of the lock allows the spring to straighten out and deploy the petal.

On further investigation considering mass, accuracy of deployed position and heritage, a stepper motor with a harmonic drive gear box was selected. A conceptual design is illustrated in Fig. 5. This allows an accurate control of the angular position of the petal.

B. Mirror Actuators

A number of different types of actuator were identified as potential candidates for the DIAL mission; the most promising appears to be the piezo driven “Squiggle motor” [6]. The squiggle motor is essentially a threaded rod passing through an elongated nut the faces to which piezo ceramics have been bonded. The piezos are driven so causing the nut to vibrate in a manner that drives the thread through it. The threaded rod is not directly attached to the load and a pre-load is required for correct operation. Tests would be required to confirm reliability under vacuum conditions.

The benefits of this type of device are its relatively high actuation force, low mass and the ability to hold position when unpowered. To satisfy the mode of operation that the actuator needs to perform in requires the squiggle motor to be mounted in a mechanism such as that illustrated in Fig. 6. The mechanism acts to magnify the output force which may be required if very stiff mirror panels are used, the consequence of this is a scaled-down displacement which provides a greater positional accuracy. It also provides a non-rotating contact point to couple to the mirror and if needed could be locked in its mid-point slider position to ensure that launch loads are not carried by the Squiggle motor. The connection between this and the mirror is a design in progress and if needed could incorporate a release mechanism for failure-mode operation.

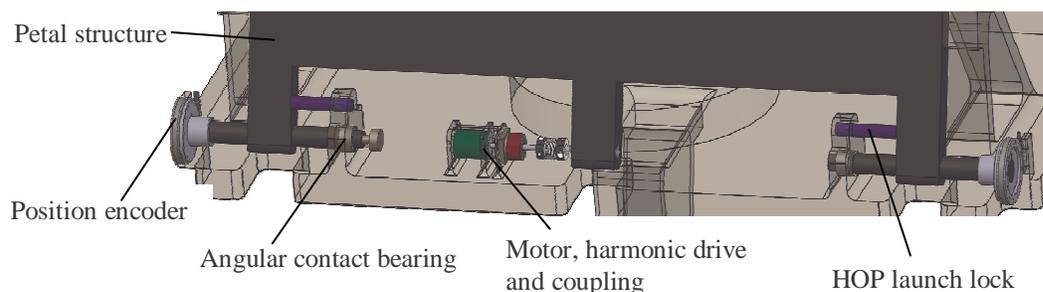


Fig. 5. Conceptual design of the petal deployment mechanism

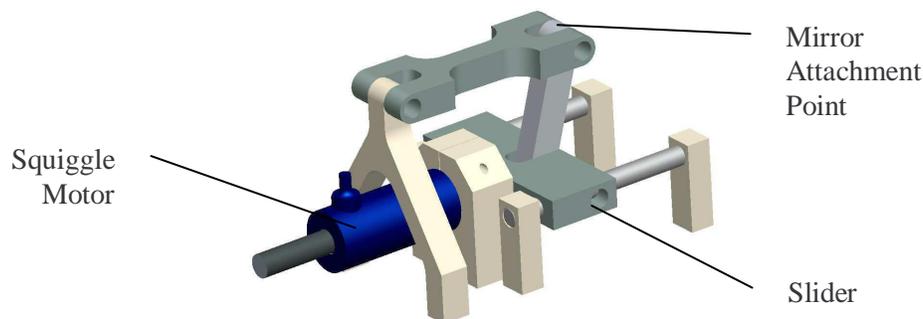


Fig. 6. Concept for the mirror actuator showing the key components.

C. ActuatorArrangement

A number of support configurations were analysed for the mirrors, both the square petal and the central hexagon. Gravity sag needs to be minimised to allow accurate ground-based measurement and testing and a minimum number of actuators is required to correct for optical aberrations arising from manufacturing errors, thermal distortions and deployment misalignments. The number of support points needs to be sufficient to raise the fundamental frequency (f_1) above 100 Hz. More actuators allows the correction of higher-order errors but also increases mass, system complexity and power consumption. The use of a whiffle tree supporting the mirror, provides a greater coverage of support points with the actuators acting on a lower part of the tree, this has not been ruled out as an option. However, we are currently proceeding with the actuators directly coupled to the back face of the mirror. The arrangement of the actuators will be matched to the mirror geometry to provide best support in the corners e.g. square grid for the square mirrors, triangular grid for the hexagon and allow the number of actuators to be minimised. As an example for the 1.1m square petal a 3 x 3 grid is sufficient on initial analyses – for an Al waffle-back mirror in this case, $f_1 \sim 140$ Hz and low order aberrations can be corrected to the tolerances required (a more in-depth analysis is required to validate that the magnitude of system errors expected are within initial estimates).

VI. CONCLUSIONS

We have summarised a design study for a future DIAL mission requiring a large, deployable, lightweight mirror. Further research is required to meet the mission specification in all areas, however, our research to date and the identification of manufacturing problems (for the mirrors) leads us to believe that these problems are surmountable. Depending on further funding these concepts will be expanded and tested at a breadboard level. The technologies to be investigated in this will be a CFRP mirror, most likely the nickel coated thin-plate mirror; the waffle-backed aluminium mirror; the squiggle motor actuator concept and the petal deployment mechanisms discussed. This will include vibration testing and thermal vacuum testing of the components and/or assemblies where cost and time allow.

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