Optical space telescope structures: The state of the art and future directions

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ABSTRACT

Future space telescopes will be required to have significantly greater aperture and lower areal density than is currently achievable. Gossamer spacecraft structures have been proposed as a means of achieving this, but the technologies are far from mature. A state-of-the-art review is timely and necessary as new structural paradigms are being considered for the next generation of space telescopes. There is, however, a knowledge gap between the structural engineering community and the additional fields involved in the complete telescope system, leading to the proposal of structures which are unlikely to be launched. It is hoped that, by providing a resource by which structural engineers are made aware of the wider issues in telescope design, this review will serve to overcome this knowledge gap to facilitate productive collaboration.

1.0 INTRODUCTION

Telescopes currently exist in both ground-based and space-based forms. Both have intrinsic advantages, and both require significant design challenges to be overcome. Ground-based telescopes, for example, can be specified with large reflector diameters as they may be constructed in situ. However, a significant barrier to effective observation results from atmospheric interference[1] – the effect that causes the stars at night to twinkle. By contrast, space-based telescopes operate outside the atmosphere, and the observed image is undistorted. They may also be operated at cryogenic temperatures, which permits observation in the infrared (IR) range. However, they operate in an extremely hostile environment, and furthermore, they must be launched into space, which means they must be able to sustain additional vibrational, thermal, and acoustic loading, and which restricts the volume to that which may be enclosed within the fairing. In both ground-based and space-based cases, in order to achieve desired optical accuracy of the reflectors, extremely precise surface tolerances – potentially of the order of nanometers – are required.

The design of telescopes links many fields including optics, control, structures, and it is clear that for a successful telescope to be realised its design must be carried out at a systems level, incorporating all the necessary disciplines. The purpose of this review is to focus on the role that the structures community can play in the design of telescopes by defining the state of the art from a structural perspective. By so doing, it is hoped that future research may be more effectively informed.

1.1 Telescope components and definitions

It is first necessary to consider a broader description of the components of a telescope in order to contextualise the structural aspects. Therefore, in this section a brief introduction to the generalised structure of reflecting and refracting telescopes is provided, and key terminology and definitions are introduced.

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1.1.1 Refracting telescopes

Refracting telescopes consist of two convergent lenses. In this concept, parallel light rays from an infinitely-distant astronomical source pass through an initial convex lens. A second convex lens is placed beyond the focus of the first lens such that its focal plane is incident with the focal plane of the first lens. This has the effect of both magnifying and inverting the image.

There are two major difficulties that arise in the implementation of astronomical refracting telescopes. The first concerns the tendency of a light ray containing many different wavelengths to split into a number of different rays corresponding to the different wave lengths when it passes through a refractive medium. This effect is familiar as the spectrum that is produced when white light is refracted through a triangular prism, and is known as chromatic aberration[2]. This may be mitigated, for example, by the use of a composite lens system known as an achromatic doublet. A second problem, which is the major limitation concerning the use of increasingly powerful refractive telescopes with larger diameter lenses, is the difficulty in fabricating lenses which are perfectly homogeneous. In conjunction with the requirement to manufacture the lens surface to a high level of precision, this is an almost insurmountable problem, and consequently an overwhelming majority (an exception being some proposed nanosatellite constellations, for example the Canadian BRITE program[3]) of space-based astronomical telescopes are based on a second type – the reflecting telescope.

1.1.2 Reflecting telescopes

In this concept, the parallel rays from an infinitely-distant astronomical source are focussed with a concave primary mirror. In more recent designs, further focussing is carried out by means of secondary, (and possibly tertiary etc.) mirrors. All current large astronomical telescopes are based on the reflecting concept.

Many space-based astronomical telescopes incorporate the Cassegrain design[2]. A Cassegrain telescope focusses the parallel rays with a concave primary mirror having a parabolic figure. A convex secondary mirror with hyperbolic reflecting surface or figure is placed before the focal plane of the primary mirror to focus the rays, through a hole in the centre of the primary mirror, to the image plane. A common modification to the Cassegrain system is the Ritchey-Chrétien design[2], in which both the primary and secondary mirrors have a hyperbolic figure. An alternative, less commonly-used, configuration for a reflective telescope is the Gregorian design, in which both the primary and secondary mirrors are concave. In this case the secondary mirror is located beyond the focal plane of the primary mirror.

There are many reasons why reflecting telescopes are preferred for modern astronomical telescopes. The use of mirrors instead of lenses means that there is no chromatic aberration. Additionally the same design may be used over a significantly wider spectrum of light. Less curvature is required for a mirror than for a lens, and substantially brighter images may be produced.

There are also many advantages from a structural perspective. Reflecting telescopes are more compact, which is particularly advantageous in the case of space telescopes which must fit within a specific launch rocket fairing. Only the mirror surface needs to be fabricated to precise optical tolerances, so material inhomogeneities are no longer a concern. It is also possible to provide greater support for a mirror, as opposed to a lens, as the entire backplane may be used for structural support instead of just the perimeter.

1.1.3 Space telescope systems

Although the fundamental telescope concepts consist of very few simply-defined components, it is necessary to remember that several other components are required to realise a complete telescope system. By way of example, a simplified system for a space-based reflecting telescope is considered here. In such a system, the primary and secondary mirrors are supported, connected and relatively positioned by means of a stiff and thermally-stable structure. It may be necessary to make this structure deployable if it is too large to fit inside an available launch vehicle. The focussed rays must be detected, for example with a Charge-Coupled Device (CCD), and sufficiently high-bandwidth control and electronics must be available to ensure that the images are processed and transmitted back to Earth.

Actuators must be incorporated to permit the fine correction of the mirror figure, particularly if elements of the structure are deployed. A distinction is sometimes made between active and adaptive optics[1,4]: a slow correction, such as needed to provide a one-time correction of figure is considered to be adaptive optics; high speed correction is referred to as active optics. The latter is used on ground-based telescopes to correct for atmospheric turbulence, but has applications in space, for example to correct errors due to spacecraft vibration. In a general space telescope system, therefore, both types of actuation may be required.

It is often desirable, for example in the case of infrared (IR) observation, to operate at cryogenic temperatures[5,6]. This may be achieved by means of liquid-gas cryogenic coolers, as in the SIRTF mission[7], in which case observation time is limited by coolant reserves, or passively by means of sun-shields, as is the case in the James Webb Space Telescope (JWST)[8]. It is likely that the latter will need to be deployable owing to the required size relative to the launch vehicle stowage volume. Finally, there must be a connection to the spacecraft bus which contains, among other things, additional instrumentation, a means of propulsion, and a power supply. This connection must provide sufficient thermal isolation and structural stability.

It can be seen that a space telescope system is a complex system containing many couplings between different components. In this article, the focus will be predominantly on the structure of the reflectors and their supports, but it is always necessary to bear the entire system in mind when considering new concepts.

1.2 Requirements

It is worthwhile to define the requirements for space telescopes in a general way in order to assist the assessment of new structural concepts. The environment of space is hostile and materials and structures must be specifically designed to operate within this extreme regime. Temperatures on a single spacecraft can range from several hundred degrees Celsius to a few degrees above absolute zero. Operation *in vacuo* can result in material outgassing, and there is the constant presence of dangerous radiation. It is therefore necessary to use materials that are not only space qualified but also have well-defined properties throughout their operation range.

In order to survive a launch into space, a structure must be resistant to both vibration and acoustic loading, the characteristics of which are determined by the chosen launch vehicle. If the desired size is greater than the available space in the launch fairing, it is necessary for the structure to be deployable, so that it may be stowed for launch, and deployed into the correct configuration when in space. Also, the maximum payload of the chosen launch vehicle may not be exceeded, so it is desirable that the mass of the structure be as low as possible

If we consider the structure of the mirrors, it is possible to specify some further requirements. In particular it is desirable that the reflector diameter be as large as possible a requirement that conflicts with the desire to reduce mass and volume. There are two reasons for increasing the diameter, and hence the surface area, of space-based telescope mirrors: first, to maximise the collecting area i.e. to maximise the number of photons that are collected from faint sources; second, the desire to operate a telescope at the best possible resolution.

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As an effect of diffraction, rays are not focused to a single point, but instead to a circle having diameter d, known as the diffraction limit. In the absence of any imperfections, the diffraction limit represents the maximum theoretical resolution of a telescope[1]. For observation at a wavelength λ, the diffraction limit may be expressed as

$$\text{diffraction limit } d = 1{\cdot}22\,\lambda/a \quad \ldots (1)$$

in which a is the diameter, or aperture, of the reflector. It can be seen that increasing the reflector aperture minimises the diffraction limit, and hence maximises the telescope resolution.

As it is necessary to increase the reflector aperture, the mass must be reduced simultaneously in order to use existing launch capabilities. The most commonly-used metric to measure this is the areal density, defined as

$$\text{areal density} = m/A \quad \ldots (2)$$

in which A is the reflector surface area, and m is the total mass. Areal density is minimised in an optimum design. In order to compare meaningfully between different concepts, m must necessarily include the masses of all the components in the telescope system, including the support structure, and not just the reflector itself[9].

Mirrors must also be manufactured as close to the desired figure as possible. Any defect can result in a degradation of image quality. The majority of image defects are: spherical aberration, coma, astigmatism, field curvature, and distortion. These aberrations are, in part, inherent to particular telescope designs, but may also result from manufacturing defects. For future missions in which telescopes are deployed too remotely to be serviced, the manufacture of the mirrors to correct figure tolerances is of even greater importance. The exact tolerances are mission-specific and depend on the wavelength that is to be observed. Accordingly, geometric tolerances are specified as a fraction of this wavelength.

1.3 'Gossamer' telescopes

Increasing the primary reflector diameter poses severe technical challenges. One possible way of achieving an effective increase in the reflector aperture is by observing with a number of small reflectors flying in formation, and reconstructing a high-resolution image by means of interferometry techniques. The small reflectors may be physically connected by means of a deployable support structure, and larger apertures may be simulated by flying the smaller reflectors on separate spacecraft. This solution is not straightforward, requiring substantial improvements over the current capability to fly spacecraft in formation to very high tolerances. However, the significant advantage is that interferometric missions may be realised using current mirror fabrication technology.

There are, however, some missions for which interferometry techniques are not appropriate, and in addition, it is highly desirable that telescopes with larger aperture primary mirrors than currently achievable be developed[10]. The emergent field of gossamer spacecraft structures provides a possible solution. Possible concepts have been pursued within the Gossamer Spacecraft Initiative which is a long term NASA program promoting the development of 'very large, ultra-lightweight structures and apertures'[11].

Gossamer technologies will allow the specification of missions which are not currently possible. In order to determine the spectroscopic characteristics of an extra-solar-system planet, a tenfold increase in primary reflector aperture over what may currently be achieved is required. Direct low-resolution imaging requires a hundredfold aperture increase. An ideal realisation of a gossamer spacecraft telescope will have an areal density one-hundredth that of the Hubble Space Telescope (HST). Clearly, new reflector technologies must be developed if this is to become achievable. A concept for a gossamer space telescope, in which a membrane reflector is supported by means of an inflatable deployable structure is illustrated in Fig. 1.

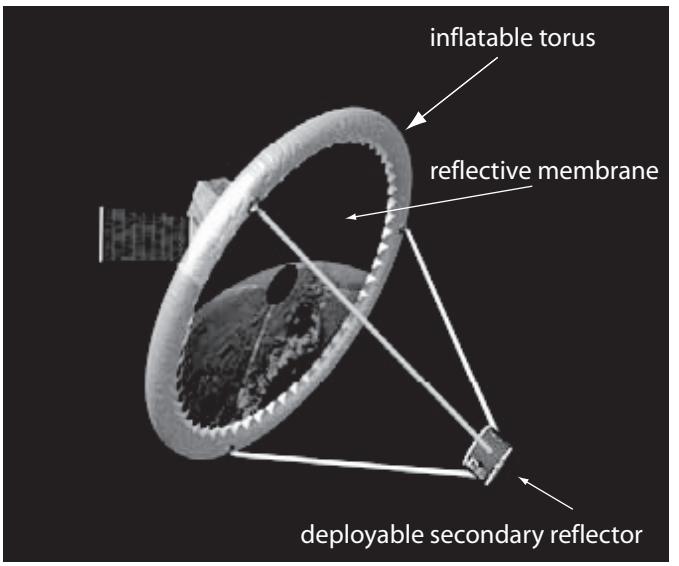


Figure 1. Illustration of a possible realisation of a gossamer space telescope with an inflatable support structure[12].

This review will now focus on lightweight, deployable, 'gossamer' reflector technologies in more detail. The ultimate aim is to develop space-based telescopes with primary mirrors having apertures two orders of magnitude greater than is currently possible.

1.4 Outline

A more detailed review of telescope architectures, specifically the reflector concepts, is now provided. This includes currently-used monolithic and segmented reflector concepts, in addition to the possible lightweight membrane reflectors of the future. In order to demonstrate the current state of the art, a review of recent and near-future space-telescope missions is provided. The list represents a small fraction of all the space telescope missions, but they have been selected to provide a representative overview of the different structures and concepts that are and will be in use.

Following this, gossamer structures are discussed that have particular application to the design of space-based telescope reflectors. These are considered in two parts: shell reflectors, which may be considered as descendants of current monolithic reflector technologies; and membrane reflectors, which are a new technology paradigm, but which potentially offer the greatest increase in achievable reflector aperture. In the next section a review of materials and actuators that are suitable for the fabrication of space telescopes is provided. In addition, suitable metrics for determining their degree of suitability will be introduced.

This article will conclude with a comparison of the concepts, and an assessment of their likely use and potential benefits. Finally, a discussion of mission requirements for future large-aperture gossamer space telescopes is presented.

2.0 TELESCOPE ARCHITECTURES

This section provides a description of different telescope architectures. It is first, however, necessary to define what is meant by 'architecture'. It has already been indicated that space-based telescopes contain a large number of components, each having a different function, and all linked to form a functioning system. In one definition, therefore, the architecture may be considered to encompass the entire telescope system.

A more localised definition of telescope architecture is made by restricting the description to the method by which incident

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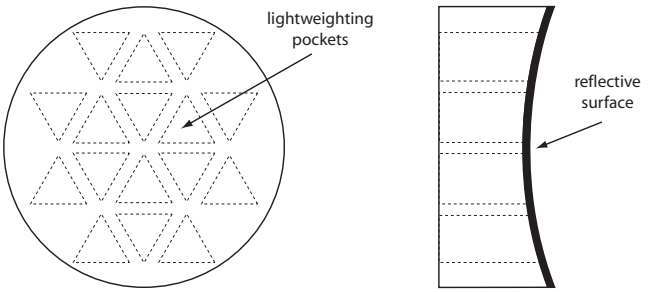


Figure 2. Sketch of a monolithic reflector, illustrating light-weighting.

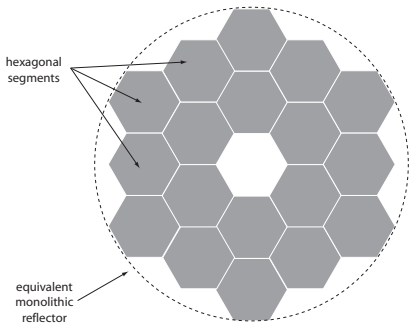


Figure 3. Sketch of a segmented mirror with 18 hexagonal segments.

rays are focussed to form a magnified image: refraction through a lens, or reflection from a concave primary mirror. In order to focus on modern astronomical telescopes, this article is exclusively interested in the latter. From a structural engineering perspective, this is a more useful definition, although it is always necessary to keep the entire system in mind in any design. Therefore, in this article, the architecture of a telescope is considered to be the combination of primary and secondary mirrors in a reflecting telescope, including, where relevant, support structure, and actuators for deployment and positioning.

This section commences with a summary of different reflector technologies, as the increase of reflector aperture, and consequently an awareness of the different possibilities, is of primary importance. In the second half of the section a review of representative space telescope missions provides an opportunity to illustrate appropriate support structure and actuation mechanisms.

2.1 General reflector concepts

In order to provide a road map for future space-based telescopes, it is worthwhile to note that the reflector concepts used in current and proposed missions are based on reflectors and reflector manufacturing technology used for ground-based telescopes. Although the operating environments of the two types are very different, there are important cross-overs between their design requirements.

Examples of these areas of cross-over, in which ground-based and space-based requirements are complementary, include the following. The most important is that reflectors should conform to the desired surface figure, otherwise image aberration will occur. They must also be structurally stable, particularly with respect to temperature. This is as important for space telescopes operating at cryogenic temperature, at which material properties are often not well defined, as for ground telescopes in which temperature gradients between the mirror and the atmosphere may occur. Reflector technology has also been developed to be as lightweight as possible. For ground-based telescopes, this minimises sag under gravity, in addition to reducing the requirements placed on the support structure. For space telescopes this leads to an important reduction in launch mass.

The three general reflector concepts that are now considered in detail are: monolithic reflectors, segmented reflectors, and possible future technologies including thin shell and membrane reflectors. The first two have applications both for ground-based and space-based telescopes, the latter being descended from the former. The future technologies, however, are considered from the beginning to be for space telescopes. Some additional concepts, such as the DART reflector, which differ substantially from existing telescope architectures are presented in a subsequent section.

2.1.1 Monolithic reflectors

Monolithic reflectors are single continuous structures. They are not usually designed to be deployable and consequently they are fabricated in their final configuration. Monolithic mirrors are the oldest and most common type to be used in reflecting telescopes, and have diameters ranging from a few centimetres to metres.

In a monolithic mirror bending stiffness and hence structural stability is often provided by adding depth behind the reflective surface, as shown in Fig. 2. However, this results in a significant amount of added mass. A compromise is made by removing pockets of material behind the reflective surface to reduce the mass with only a limited reduction in stiffness. An example of this is found in Ref. 13 for the reflectors for the Herschel telescope. Light-weighted reflectors may also be constructed as a honeycomb sandwich panel. In general, the fabrication process of monolithic reflectors consists of the manufacture of the light-weighted structure to high, but not optical, tolerances. The mirror surface is then polished to the required optical tolerances, after which a reflective surface and a protective layer are added by means of vapour deposition.

Monolithic mirror fabrication technology is currently mature and, although there are techniques for increasing the achievable diameters it is unlikely that their size will increase significantly in the future. However, there are alternative mirror technologies which offer the possibility of larger reflector apertures and which may still be considered monolithic. One possibility is the use of extremely thin ‘meniscus’ mirrors.

A meniscus mirror is formed from two curved surfaces, one of which is the reflective mirror surface. Lacking a stiffening backing structure it is consequently much lighter than a traditional monolithic mirror at the expense of a substantial reduction in stiffness. The reduction in stability, however, means that optical figure is very difficult to achieve by structural means alone. One possible method of achieving optical figure is to support the reflector on actuators which may be used to provide fine adjustment to the reflector figure[14]. In addition, the use of thin monolithic mirrors with correctable figure allows new deployment techniques to be used which permit large aperture reflectors to be stowed prior to launch. Some of these techniques are discussed in a later section.

2.1.2 Segmented reflectors

In order to increase the maximum achievable reflector aperture, one possible solution is to split the mirror surface area into a number of smaller monolithic segments. This has been carried out, for example, at the ground-based Keck telescope in Hawaii which comprises 36 hexagonal segments, providing an effective aperture of 10m. The segments are tessellated to form an approximately continuous reflective surface. The segmentation of a primary mirror into hexagonal segments is illustrated in Fig. 3.

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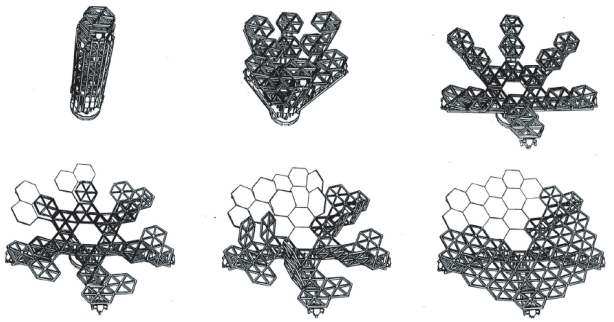


Figure 4. The 'Starburst' segmented reflector deployment process[15].

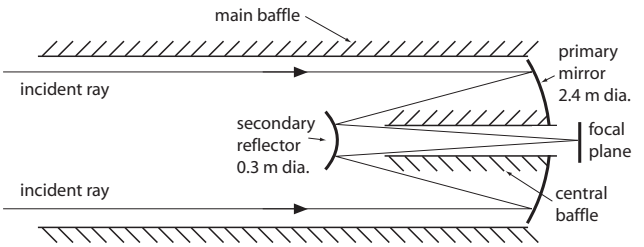


Figure 5. A schematic diagram of the HST. N.B. the Cassegrain reflector configuration.

In the design of a segmented reflector it is desirable to ensure that as many of the segments as possible are manufactured to the same design in order to assist the fabrication process and reduce costs. It is also necessary to ensure that the individual segments are precisely oriented with respect to each other. This may be achieved by mounting each segment on a 6 degree of freedom platform which must have sufficient positioning accuracy to result in the desired optical figure. In order to achieve a diffraction-limited performance, it is also necessary to ensure that the gaps between adjacent segments is a small fraction of the observed wavelength.

Although a large number of segments may theoretically be combined to form extremely large aperture telescopes, the stringent requirements on the relative positioning of the segments means that deployment must be carried out with great accuracy. The deployment method which will be used in the James Webb Space Telescope, which utilises a segmented design, is described below, but for substantially larger effective apertures alternative deployment systems will need to be considered.

Several possibilities are detailed in Refs 16 and 17. One method that has been proposed for the deployment of a 25m aperture segmented reflector is the 'Starburst' launch package concept[15], illustrated in Fig. 4, in which deployment is divided into a number of different stages based on six main deployable booms connected to a central hub. Once the large-scale low-accuracy deployment stages have been carried out, fine positioning is required to achieve optical tolerances. For even larger aperture reflectors having many more segments, assembly could be carried out in-orbit by astronauts[15].

2.1.3 Future concepts

In order to develop the large aperture reflectors of the future, gossamer structures are a viable technology as they are lightweight, deployable, and potentially may be fabricated to the desired tolerances. These include membrane reflectors and thin shell reflectors. The description and assessment of these 'future technologies' is included in the Gossamer Reflector Technologies section below.

An alternative proposed technique for increasing effective reflector aperture – the use of interferometry methods[18] is not covered in great detail in this article, as its effective realisation is largely a control rather than a structural engineering problem. It will be used, however, for the proposed Darwin mission described below. Additional concepts include telescopes based around Fresnel lens systems[19], but are not detailed here.

2.2 Space-based telescopes

In this section five space telescope missions are reviewed. They have been chosen to be representative of the worldwide effort, including United States, European, and Japanese projects. They also serve to illustrate the currently-preferred architectures and materials. At the time of writing, three have been successfully launched and operated. The space telescopes are presented in chronological order, and it will be seen that the trend to increase primary reflector aperture, reduce areal density, and reduce launch volume is followed.

2.2.1 Hubble space telescope (HST)

The Hubble Space Telescope (HST) has been one of the most successful space telescopes, both in terms of the images it has observed, and of public awareness. It is a joint NASA/ESA project and was launched into Low Earth Orbit (LEO) in 1990. Due to the close proximity to Earth, it is possible to service the HST using the space shuttle.

The first service mission was in 1993 and was of critical importance to the successful operation of the telescope. Corrective optics were installed to overcome the spherical aberration resulting from 2μm polishing error on the primary reflector. To date there have been three additional servicing missions in 1997, 1999, and 2002. The lessons learned from HST illustrate the critical importance of correct fabrication as missions are now being planned for deployment and operation at the Lagrange points which are beyond servicing range.

A schematic diagram of the HST is shown in Fig. 5. The HST is based on a standard Ritchey-Chrétien design with a hyperbolic concave primary reflector and a hyperbolic convex secondary reflector. It can be seen that stray light sources are prevented from interfering with the observations by means of cylindrical baffles. The primary mirror has a diameter of 2·4m, and is constructed from Ultra-Low-Expansion (ULE) glass. The mirror is formed from 25mm thick top and bottom plates sandwiching a honeycomb lattice. An Aluminium (Al) reflective layer and a Magnesium-Fluoride (MgF_2) protective layer were placed on the mirror surface by vapour deposition.

The secondary mirror has a 0·3m diameter and is made from Zerodur – a glass-ceramic having extremely high thermal stability – and has the same reflective and protective coatings as the primary mirror. The secondary mirror is mounted on three pairs of actuators which enable fine orientation and positioning. It must be placed relative to the primary mirror with a positional accuracy of 2·5μm.

This relative positioning is retained during operation by means of a Carbon-Fibre Reinforced Polymer (CFRP) truss structure. CFRP is used due to its good thermal stability, light weight and high stiffness. Aluminised Mylar is used to compensate for the temperature variations when the telescope is in the Earth's shadow. It should be noted that the HST was launched in its final configuration and there is no need for a deployment sequence – relative reflector positioning was carried out on Earth.

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Figure 6. The Akari SiC mirror assembly[6].

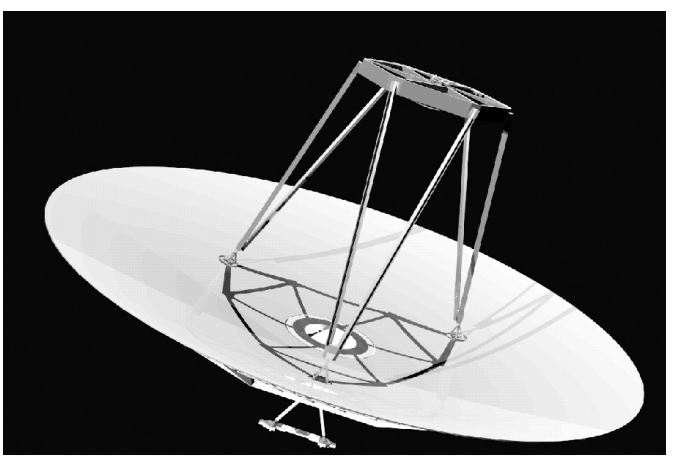


Figure 7. Assembled primary and secondary reflectors of the Herschel Space Observatory[13].

2.2.2 Akari

Akari (designated Astro-F prior to launch) is a JAXA/ISAS space telescope designed for observation at near-, mid-, and far-IR[6,20]. It was launched in 2006 into a LEO. Akari is a Ritchey-Chrétien design with a primary reflector having an effective aperture of 0·67m. In order to observe at IR wavelengths, the telescope is cooled to cryogenic temperatures by a combination of liquid Helium cryo-coolers and mechanical coolers. The former allows an operational temperature of 5·8K, but the latter permit continued observation in the near-infrared when the liquid Helium reserves are depleted following a period of operation.

Both the primary and secondary reflectors are made from Silicon-Carbide (SiC). SiC is chosen as it has very high stability and low thermal conductivity. Two forms of SiC are used: porous, and chemical vapour deposition (CVD). Porous SiC has a density less than 60% of CVD SiC, is more easily machineable, but can not be fabricated to precise optical tolerances. The reflectors are therefore constructed in a multi-stage process, resulting in a stiff but lightweight sandwich-like structure. In this process, first a porous SiC blank is machined to the approximate desired shape. This shape is a concave reflective surface with supporting rear web stiffeners. A thin layer, 0·5mm thick, of CVD SiC is then deposited on the surface forming a stiff surface that is sufficiently strong to be polished to optical tolerances. A Gold (Au) reflective surface (to increase reflectance at IR wavelengths) and a Zinc-Sulphide (ZnS) protective coating are applied, also by vapour deposition. The resulting SiC primary and secondary mirrors are shown assembled in Fig. 6. The trusses separating the reflectors are also shown in the figure. They are fabricated from Beryllium (Be) chosen for its high thermal stability. Stray light is prevented from interfering with the observation by means of a central baffle.

2.2.3 Herschel

The Herschel Space Observatory (formerly named the Far-IR and sub-millimetre Telescope (FIRST)) is an ESA-led telescope that was successfully launched in May 2009. Like HST and Akari, it uses a monolithic reflector design, but demonstrates an order-of-magnitude improvement in overall areal density[13]. It is designed to operate at cryogenic temperatures, of approximately 80K, at the Lagrange Point L2, 1,500,000km from the Earth.

Herschel uses a Cassegrain reflecting telescope design with a primary mirror diameter of 3·5m, made from sintered SiC. Due to manufacturing constraints, which limited the maximum size of component to 1·6m × 1m, it is necessary to fabricate the primary mirror in 12 SiC segments which are brazed together prior to polishing. As is the case for the final assembled mirror, each segment is open-back light-weighted with triangular cut-outs. The secondary mirror, which has a diameter of 308mm, is also an open-backed light-weighted structure made from sintered SiC. The polished mirrors are coated with a thin adhesive layer of Nickel-Chromium NiCr followed by a 150-300nm thick reflective Aluminium coating by vapour deposition.

The secondary mirror is placed relative to the primary by means of an SiC hexapod covered with kapton foil. It provides 10μm stability at the telescope operating temperature. The connection of the hexapod to the primary mirror is by means of Invar (FeNi) attachment pieces. A CAD image of the assembled primary and secondary reflectors is shown in Fig. 7.

2.2.4 James Webb space telescope (JWST)

The Herschel Space Observatory represents the upper end of achievable effective reflector aperture using monolithic reflector technologies. In order to increase the effective aperture it is necessary to adopt alternative technologies. The James Webb Space Telescope (JWST) is the proposed successor to the HST and is scheduled to be launched in 2013. It will be positioned at the Lagrange Point L2, and will be a Cassegrain design, specifically a three mirror anastigmat, with a 6·5m segmented primary mirror. The telescope will observe at the IR wavelength and will operate at cryogenic temperatures. Details can be found in Refs 18, 21, 22 which are summarised below.

The segmented primary reflector will consist of 18 hexagonal Beryllium (Be) 1·32m flat-to-flat segments, using heritage technology from the Spitzer mission[23,24]. Six of these segments are deployable to permit the structure to fit in the Ariane V rocket launch fairing. Beryllium is chosen as the mirror material as its properties are known to 10K, and it exhibits a very small change in Coefficient of Thermal Expansion CTE between 30-80K. The segments are semi-rigid, meaning that a small amount of flexibility is deliberately present to permit in-orbit correction. They are mounted on a rigid and thermally stable CFRP backplane structure.

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The secondary mirror is supported on a tripod structure which locks into configuration once deployed. The tripod will be designed to provide maximum stability against jitter and thermal distortion with minimum beam blockage. Cooling is carried out passively by means of a deployable sunshield. The deployment sequence is as follows Following deployment of the bus appendages and the sunshield, the secondary mirror is deployed on its tripod attachment. Finally the folded segments of the primary mirror are deployed around their two chord lines. Following this low-precision deployment, high-accuracy positioning and phasing of the telescope is then carried out by 6 degree of freedom actuation of the secondary mirror and all the primary segments.

2.2.5 Darwin

As mentioned above, one possible method of increasing effective aperture is to combine the images from several smaller telescopes using interferometry techniques. Interferometry has been successfully used on ground-based telescopes, for example the Keck Observatory in Hawaii. Interferometric telescopes have been proposed for a number of future space-telescope missions – ESA's Darwin mission[25] is considered here.

Darwin is still in the early planning stages, being scheduled to launch in 2015 at the earliest. It is intended to observe at mid-IR wavelengths at a resolution that would permit the detection of planets in orbit around nearby stars. This will require an effective aperture (or interferometric baseline) of approximately 30m. Observation will take place at the Lagrange Point L2. One possible realisation of the interferometer is the Three Telescopes Nulling (TTN) configuration. In this case, three 'collector spacecraft' telescopes each having a single reflector with a diameter of approximately 3m are flown in formation in conjunction with an additional beam-combiner spacecraft, which acts as a communications hub. All the spacecraft would be passively cooled to cryogenic temperatures. It is envisaged that the reflectors used on the collector spacecraft would be based on the sintered SiC reflectors developed for the Herschel mission.

The required interferometric baselines of 10s of meters are thought to be achievable, but it will require advances in formation flying techniques to allow relative positioning to the necessary accuracy. Although the reflectors will be based on Herschel's primary mirror technology, further mass reduction techniques must be developed if the mission goal, that all the component spacecraft are to be launched in a single Ariane V rocket, is to be achieved.

2.2.6 Areal density comparison

For the five space telescope missions described above, it is instructive to compare their areal densities. These are based, not on the mass of the primary mirror as is often the case, but on the total launch mass (real or predicted). This is to enable a legitimate comparison between very different mission architectures. In the case of the Darwin mission it is assumed that the mass is sufficiently low that it could be launched to L2 by a single Ariane V rocket (approximately 5,000kg) and that an interferometer baseline of 30m has been achieved. The areal densities are tabulated below.

Table 1
Representative mission areal densities

HST	2,450kg/m^2
Akari	2,700kg/m^2
Herschel	3,40kg/m^2
JWST	190kg/m^2
Darwin	7kg/m^2

It can been seen that interferometric missions offer the opportunity to improve the areal densities by an order of magnitude compared to segmented reflectors. In the following section gossamer reflector technologies are discussed and evaluated. If they are to be considered as a viable alternative, then their potential areal densities (including necessary support structure) must compare favourably with those made possible by interferometric missions.

3.0 GOSSAMER REFLECTOR TECHNOLOGIES

Gossamer reflector technologies is a general term that includes a large number of possible methods of increasing the effective aperture of a single reflector, whilst simultaneously resulting in a reduction in areal density. Currently, their usage represents a fundamental paradigm-shift in space telescope technology and consequently their benefits have to be clear and overwhelming. They do, however, offer the possibility of orders-of-magnitude increases in reflector aperture and must be seriously considered for space telescope missions in the long-term future. The improvements in resolution that would be achieved, particularly if constellations of large-aperture gossamer reflectors were used in interferometry missions, would be extraordinary. A review of gossamer space structures may be found in Ref. 26: those proposed for space telescope systems are discussed on below.

A goal for gossamer reflectors is the fabrication of deployable space telescopes having apertures of perhaps hundreds of meters. This poses immense deployment, stiffness, stability and accuracy challenges. The current state-of-the-art is far from what is required, particularly with respect to materials, fabrication, and actuation technologies. In this section, two families of gossamer reflector technologies are considered. The first are thin-shell structures, which follow conceptually from monolithic mirrors currently in use but with a substantially reduced structural rigidity. In this case the deployed reflector would have small but finite bending stiffness which contributes to the structural stability and hence the figure accuracy. The second are membrane reflectors. In this case the membrane itself has negligible bending stiffness, and structural stability must be provided instead by the support structure.

As the purpose of gossamer reflectors is to increase the aperture beyond what can be fitted into current launch fairings, it is clearly necessary for stowage and deployment techniques to be considered. Where appropriate this is considered during the discussion of individual concepts, but a unifying discussion including some additional deployment techniques may be found at the end of the section.

3.1 Shell structures

A shell reflector structure is lightweight and thin, and exhibits some bending stiffness. This stiffness may contribute towards the rigidity of the deployed structure, but may restrict the ability of the structure to be tightly packaged for stowage. However, this bending stiffness may be advantageous, as strain energy stored during packaging may assist with the deployment, and consequently may relieve the burden on the driving actuators.

There are two approaches which use shell structures as the basis for a gossamer reflector which will be considered here. The first uses thin glass monolithic reflectors that do not have the substantial bending stiffness that is usually provided by a light-weighted backplane structure. In this case, the backing structure that is adopted must not only provide sufficient structural stiffness, but also contain actuators to enable control of the mirror figure post-deployment. This technology is considered first. The second approach is to consider technologies that have been proposed and adopted for longer wave observation (e.g. microwave or radio wave),

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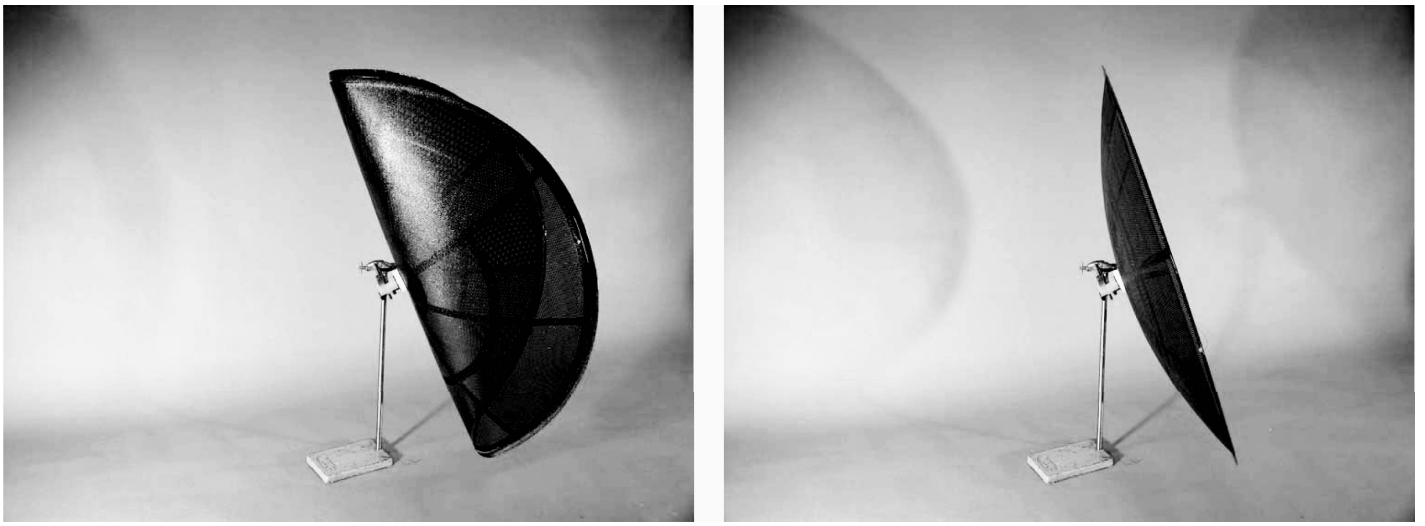


Figure 8. A stiffened spring-back 0·8m diameter reflector demonstration model in its folded (left) and deployed (right) configurations[32].

see for example Refs 27 and 29. Although the surface figure that may be achieved using these techniques is currently far from optical tolerances, the potential improvement in areal density could make their adoption worthwhile in the long term.

3.1.1 Thin-shell mirrors

A thin-shell, or meniscus mirror is a thin reflector having one concave and one convex surface, the former being used as the reflecting surface. Due to the relative lack of stiffness it is necessary for actuators to be incorporated in the support structure which permit control of the surface figure to achieve optical tolerances.

An example of this may be found in Ref. 30 in which a thin Ultra-Low Expansion (ULE) glass mirror is supported by a truss structure containing displacement-control actuators. It has been shown that the actuation may be used to correct surface aberrations typical of those resulting from thermal distortion due to temperature gradients. Similarly it has been shown in Ref. 14 that a 2mm Zerodur mirror, of diameter up to 1m, attached to a stiff, lightweight CFRP support structure may have its surface figure actively corrected at cryogenic operating temperatures by means of fine-pitch screw actuators. These are known as picomotor actuators – the screws are driven by piezo-electric actuators providing a resolution of 6nm. Magnets are used to break the connection between actuator and mirror if the force applied by the actuators becomes too large, risking damage to the mirror. The mass of the actuators must be substantially reduced if the areal density provided by this technology is to becompetitive.

An extension of this approach is to use much thinner shells, for example glass 'membrane', so-called although it exhibits non-negligible bending stiffness, which is commercially manufactured in 50 μm thick sheets. This may be rolled up for stowage during launch. As the reflector becomes thinner it is clearly necessary to design stiffer support structures to compensate for the reduction in reflector stiffness. The deployment of such a reflector would be mostly driven by the strain energy stored during folding. For a more controlled deployment, shape memory composite mirrors have been considered, in which deployment results from heating above a transition temperature[31].

3.1.2 Folded thin-shell concepts

Thin fibre-composite reflectors have been successfully used for long-wavelength observation and communication. In addition, research has been carried out to incorporate piezo-actuators, attached to the surface, in order to improve the shape accuracy. One advantage of fibre-composites is that they can be folded to small radii for compact stowage. The stored strain energy in the folded composite can also be used to drive deployment, as illustrated in both the examples below.

The first example is the spring-back reflector[32]. This is a concave reflector which may be rolled into a stowed configuration, in a manner similar to that which may be observed in soft contact lenses. On release, the reflector deploys to its original configuration. However, an un-reinforced concave reflector is not very stiff and consequently achieving the desired surface figure is difficult. One stiffening technique is to add a reinforcing rib around the perimeter. However, this makes the reflector more difficult to fold, but a compromise has been demonstrated by making slits in the supporting rib, facilitating the folding process, without substantial detriment to the stiffness of the deployed configuration. A stiffened spring-back reflector utilising this technique is shown in Fig. 8.

An alternative deploying reflector concept[33] is shown in Fig. 9. A very high packaging ratio is achieved, and the deployed structure has a two-dimensional parabolic figure. Although the majority of telescope architectures require reflectors having a non-zero Gaussian (double) curvature, there are concepts (such as DART described below), for which this would be sufficient. Additional stiffness in the deployed configuration is achieved with incorporated self-locking tape-spring compliant hinges.

It can be seen that there are many thin-shell concepts that could enable a reduction in areal density for space telescope missions. However, substantial further research would be required to ensure that adequate surface figure could be achieved.

3.2 Membrane structures

Membrane reflectors are the most commonly-proposed gossamer reflector concept for achieving effective apertures of, potentially, hundreds of meters. A membrane is a very thin structure for which the bending stiffness is usually assumed to be negligibly small. In addition, only very small compressive stresses can be sustained without wrinkles forming, and this is usually assumed for practical purposes to mean that no compressive forces can be sustained. They offer the potential of ultra-lightweight, large aperture reflectors with high packaging ratios. The absence of structural stiffness, however, means that stability and rigidity must be provided by the support structure, adding extra mass to the true areal density. Analytical methods to model the structural behaviour of membrane reflector structures may be found in Ref. 34.

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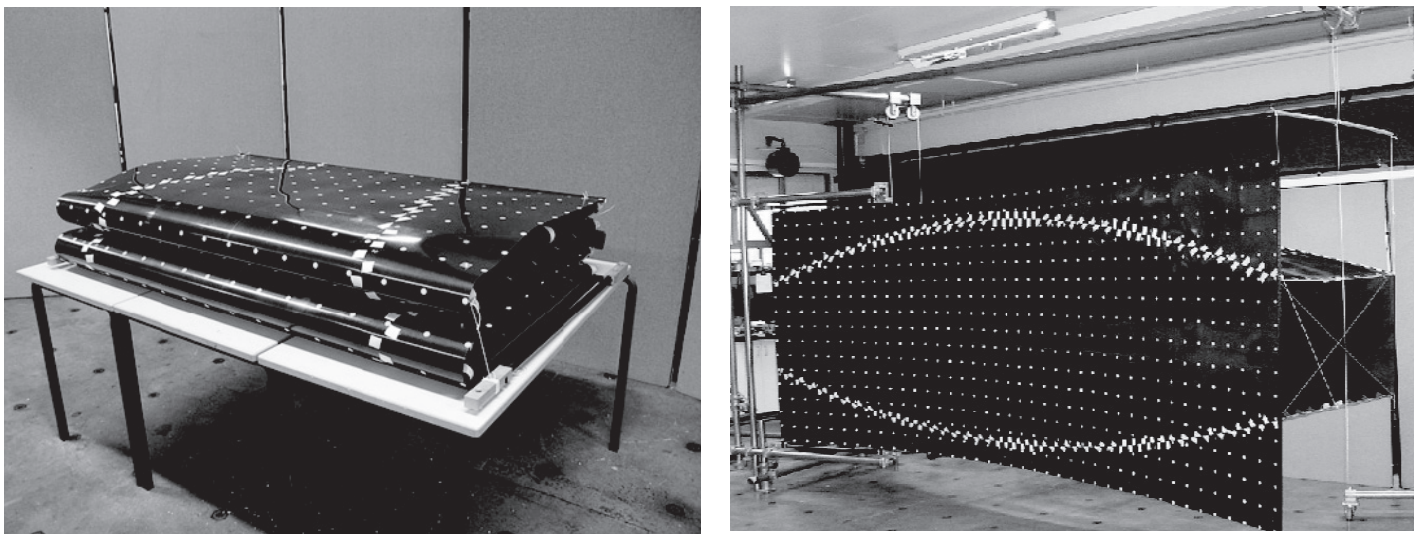


Figure 9. A self-deploying CFRP Synthetic Aperture Radar (SAR)[33] (a) stowed, (b) deployed.

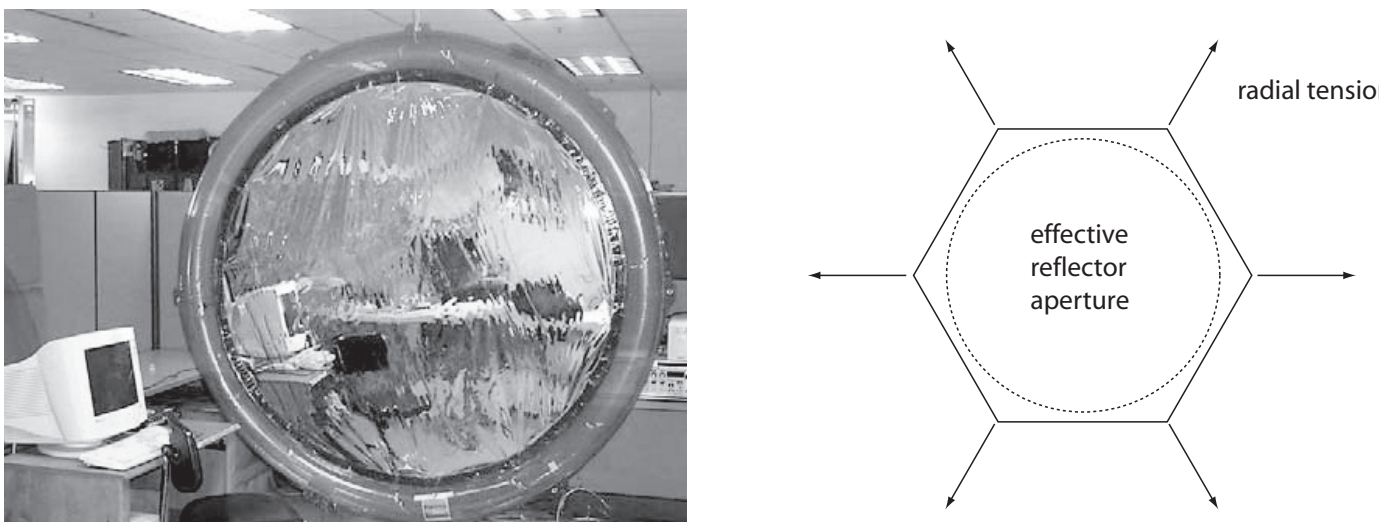


Figure 10. Alternative membrane reflector support structures: (a) Inflatable torus support[42], (b) Discrete attachment points.

Proposed membrane materials include, polyimide and nickel films. They must be manufactured with variations in thickness which are sufficiently small to enable diffraction-limited performance if all other perturbations are corrected. Great care must also be taken during the fabrication and packaging process if irrecoverable material wrinkles are not to be introduced. The thickness of the membrane is also driven by a number of other factors, including: the operational thermal environment; the desired lifespan; and in particular, the required strength to resist the shape correcting and tensioning forces which must be applied at the support structure interface.

A probable deployment sequence for a membrane space telescope reflector would involve a relatively coarse deployment of the support structure and unfolding of the membrane, followed by a precise correction of the surface figure. This coarse deployment could be modelled on processes found in nature[35], and possible schemes are elaborated in Refs 36 and 37. This precise correction could be carried out either by actuators integrated on the membrane surface, or by actuation at the boundary/support structure interface. In the case of the former research has been carried out to integrate PVDF actuation patches, and MEMS actuators, with a polyimide membrane[38,39]. Attempts to model these actuator systems are found in Ref. 40. The actuators are primarily envisaged to control vibration actively, but could additionally be used for fine shape control[41]. Similar patches cold also be utilised as position sensors[42]. It has been observed, that non-contacting boundary actuation may be desirable, as direct contact actuation, in which patches are applied directly to the membrane, only affects small regions[43].

The behaviour of the support structure is of equal importance to that of the membrane[44]. To be effective, it must fulfil a large number of functions. If the packaging advantage of using membrane reflectors is to be retained, the support structure must be deployable. In its deployed configuration, it must be sufficiently stiff and thermally stable to allow the optical figure of the membrane to be sustained. In order to allow a concave membrane reflector that is free from aberration, it must ensure that the boundary is planar. It must also be able to sustain the tensioning forces required to stretch the membrane. Possible deployable support structures for membrane reflectors are an inflatable torus[42], or a deployable truss structure[17,45].

In both cases, a possible deployment technique is to use inflatable-rigidisable technology. The tightly packaged structure is first

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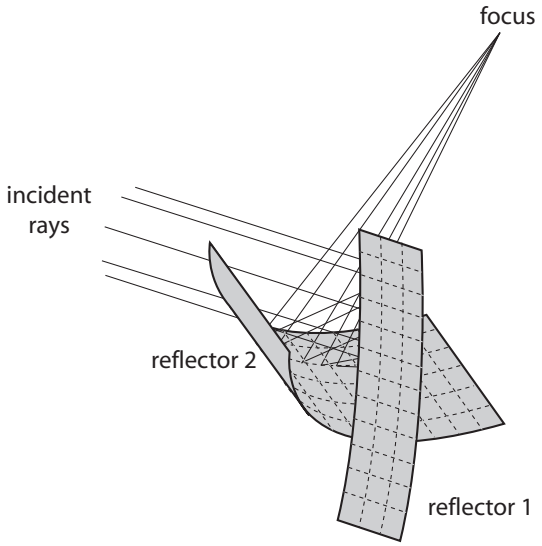


Figure 11. The Dual Anamorphic Reflector Telescope (DART) concept[49].

pressurised, causing it to inflate into a desired configuration. It is possible that a rigidising stage is not required if there are sufficient gas reserves to maintain the pressure, although gas may be lost during operation due, for example, to micrometeorite penetration[46]. If rigidisation is required, however, it may be carried out by a number of methods. The inflated structure may be made of a polymer that cures in response to an external stimulus. Possible stimuli include thermal heating, passive cooling, or UV exposure[12]. Alternatively, the inflation may be carried out by injecting a rigidising foam. These techniques are by no means mature and, although the concept has been broadly

demonstrated, there are a number of problems that must be overcome. In particular, during inflation the structural configuration is undetermined which can lead to undesirable final configurations. If the technology is to be used for space telescopes, the inflated configuration must be sufficiently accurate and predictable to enable the final precise correction to be achievable by the actuators.

If the support structure is an inflatable torus, the membrane attachment can be continuous around the perimeter. This leads to positive biaxial membrane stress. A laboratory example of a membrane reflector with an inflatable toroidal support structure is shown in Fig. 10(a) An absence of negative compressive stresses means an absence of wrinkling and hence a potentially optical-quality surface. With a truss support structure, discrete membrane attachment points, as illustrated in Fig. 10(b), would be more feasible. However, this type of loading leads to wrinkle patterns[47] in the membrane which would need to be corrected by means of additional actuation[48].

Although it is often neglected in current research, a membrane reflector is only viable to be used in a standard reflecting telescope architecture if it has double curvature. This may potentially be achieved by a number of different means. One possibility is by electrostatic pressure[4]. An alternative is to inflate an additional structure to the desired shape behind the membrane. Controlled inflation of this structure could also be used to correct symmetrical reflector aberrations. Achieving a double curvature by means of integrated actuation could also be possible, although would be unlikely to be an efficient method.

A possible alternative is the Dual Anamorphic Reflector Telescope (DART) concept, as considered in Ref. 49, which utilises two singly-curved instead of one doubly-curved reflector. The concept is illustrated in Fig. 11. In this design, the membranes are not subject to additional strain (beyond that required for pre-tensioning) as the reflective surface is developable. The required shape is provided by boundary structures which are attached to the curved edges of the membranes. In Ref. 49, it is envisaged that the boundary structures would be initially straight, but would be formed into parabolic configurations in-orbit by means of forces and moments applied at their ends. With larger effective apertures there is a clear mass penalty as the cross-section of the boundary support must be increased to prevent buckling under the applied end loading.

3.2.1 Deployment

As noted, the deployment of a membrane reflector is likely to be a two-stage process. Methods for the fine correction of surface figure have been described above, but it is worthwhile briefly to consider possible methods for the initial deployment stage in further detail.

In addition to the concept of a deployable torus support structure, research has been carried out into the use of rigidisable-inflatable conical booms[12]. A possible alternative is the use of shape memory alloy (SMA) structures to deploy the membrane, either by forming the support structure itself[37], or by facilitating the deployment of a CFRP truss structure.

4.0 MATERIAL AND ACTUATOR CHOICE

In the preceding sections, reference has been made to many different materials and actuators that have been used, or are proposed to be used, in space telescope structures, but it is not exhaustive. The choice of materials and actuators for any spacecraft depends on the extreme rigours of the environment. These include outgassing caused by vacuum conditions, incident hostile radiation, and temperature extremes from hundreds of degrees Celsius to approaching absolute zero. For space telescopes which, in many missions, operate at cryogenic temperatures, it is therefore necessary to consider how the material performance will effect telescope operation.

Before it may be used, a particular material must be space-qualified, but it is desirable

for a designer to have available performance metrics to assist in the comparison and selection of appropriate materials. In this section, relevant metrics are provided which facilitate the selection of materials and actuators for space telescopes.

4.1 Material metrics

Key material selection metrics for space telescopes are tabulated in Table 2: E (GPa) and ρ (kg/m^2) are Young's modulus and density respectively, k (W/m/K) is the thermal conductivity, and α is the coefficient of thermal expansion (CTE). It is important to remember that these material properties, which are usually considered to be constant, in fact vary as a function of temperature (particularly towards absolute zero) and it is important to consider the behaviour both at the temperature at which the telescope is constructed, and at the (possibly cryogenic) operating temperature.

Table 2
Material selection metrics

Specific Stiffness	E/ρ
Thermal Distortion	$k/\lvert\alpha\rvert$
Strength	σ_f
Toughness	K_{IC}

The specific stiffness relates to the structural stability and minimum natural frequency that may be achieved for a given launch

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mass. Clearly a high value of specific stiffness is desirable as it illustrates the capability to make a lightweight structure for a given mechanical performance. However, structural stability is also effected by the structural geometry. The thermal distortion metric determines the response of a material to both discrete temperature values and thermal gradients across the structure. The Coefficient of Thermal Expansion (CTE) α may be both positive or negative, so consequently the absolute value is used. In order for minimum distortion to occur due the difference in construction and operating temperatures, should be as small as possible. The thermal conductivity, k, indicates the ability of a material to conduct heat. Consequently, a higher value indicates that it is more difficult for temperature gradients to occur and therefore thermal distortions are limited. The combined thermal distortion metric should therefore be maximised for optimum telescope thermal performance.

The material failure strength, σ_f, must be defined suitably for each material – appropriate failure criteria should be adopted. For a monolithic mirror material, in which is usefully defined as the material yield stress, which is related to the material hardness. The harder the material, the better it can be polished to high surface accuracy. The fracture toughness K_{IC} represents a material's ability to withstand the presence of cracks and resist fracture. This is particularly important during launch, during which there is significant vibrational loading. Additional specific strength and specific toughness metrics, in which the strength and toughness are divided by the material density, are also useful to assist with the minimisation of launch mass. An additional material property that should be considered in the design of reflectors is the surface adhesion for reflective and protective layers. It may prove necessary for intermediate adhesive layers to be included if insufficient adhesion can be achieved.

It is also essential that the designer is aware of the variability of the material properties, not only due to temperature and other external effects, but also arising from the manufacturing process. As increasingly fine tolerances are required for optical surfaces, this statistical variability must be accounted for. The method chosen is material specific, but a suitable measure for membranes would be the root-mean-square variation in thickness dimension over the area. For ceramics, a property such as the Weibull modulus (which is an expression of the number of material flaws) would be a more appropriate measure.

4.2 Actuator metrics

For the selection of actuators, similar metrics to those appropriate for material selection may be adopted. However, there are additional characterisations of the actuator performance which must be considered, which include the standard metrics of blocked force, and free stroke, see for example[50]. The former is the actuation force which is produced when all motion is restricted; the latter is the actuation stroke produced in the absence of all resisting forces. In reality, the actuators will clearly operate in an intermediate region bounded by these points. Additional actuator selection metrics may be found in Ref. 51.

It is also necessary to consider the precision and frequency of the actuator performance. When used in space telescopes, these requirements will differ depending on whether deployment or fine correction is being considered. For an initial deployment, precision requirements are not as tight, although a higher actuator stroke is required. The frequency of deployment is also not critical, although low frequency is perhaps desirable to prevent shock loading of the structure. However, for fine correction, the actuator precision must be sufficient to enable optical performance, implying nanometre accuracy. If an active optics system is utilised, for example to cancel out the effects of spacecraft vibration, then high-frequency and high-precision actuation is required.

When actuators are operated cyclically, hysteresis gives a force-displacement relationship that is not constant, but is instead history-dependent. Hysteresis can result from many causes including, for example, viscoelastic material behaviour. A full characterisation of actuator hysteresis is critical in the case of both adaptive and active correction systems as, if hysteresis is present, sensing requirements, and correspondingly the overall mass, are increased. This is because it is not sufficient to sense the actuation force to infer the displacement, or vice versa. One possible way to remove actuator hysteresis is to incorporate multistable structural elements with the actuators in a concept known as binary robotics[52].

A generalised metric that may be adopted for actuator selection for space telescopes is;

$$\frac{\text{control}}{\text{disturbance}} \geq 1 \qquad \ldots (3)$$

in which the 'control' is the available actuator performance, and 'disturbance' is the effect which must be mitigated. An example of this would be overcoming the effects of thermal distortion. In this case the disturbance would be a strain $\alpha\Delta T$, and, following Equation (3), the actuator must be able to produce a strain of greater than $\alpha\Delta T$ when operating at temperature T. This approach may be extended to determine the actuator requirements for mitigating many additional effects.

5.0 DISCUSSION

In this review, the purpose has been to provide a resource for the structures community to give an understanding of the current state of the art of space telescopes and the future design requirements. To achieve this, an introduction to key telescope architectures and terminologies has been given. Two concepts, one based on refracting lenses, the other based on reflective mirrors have been discussed. For many reasons, including the absence of chromatic aberration, relative compact size, and removal of the requirement that lens material be perfectly homogeneous, reflecting telescopes are used for almost the entirety of space-based missions.

A review of different architectures for reflecting telescopes has been carried out. The architecture of a telescope can be considered at several levels of complexity, from complete-system level down to individual components. The focus here has been placed on the reflector and support design. In order to illustrate the evolution of reflecting telescopes, and to demonstrate the increase in reflector aperture for a corresponding reduction in areal density, five current and planned missions were discussed in greater detail. The first of these missions was the Hubble Space Telescope, launched in 1990 which has a monolithic primary mirror with aperture 2·4m. The final mission discussed is the Darwin interferometry mission, which is scheduled for launch no earlier than 2015, and is expected to achieve effective apertures of tens of meters by using aperture synthesis techniques based on a formation of collector spacecraft.

The drive to increase reflector aperture and remove areal density forces the consideration of new paradigms for the primary reflector structure. An alternative to using interferometric techniques is to increase the aperture of a single primary reflector through the use of gossamer structures. Two possible gossamer structural concepts that have been considered are thin-shells and membrane reflectors. The latter in particular offers the possibility of order-of-magnitude increase in achievable aperture. A further discussion and comparison of the different reflector concepts may be found below. Finally, metrics and figures-of-merit which can assist in the selection of materials and actuators for spacecraft in general, and space-based telescopes in particular, have been reviewed.

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5.1 Concept comparison

In order to increase primary reflector aperture, particularly in the case of missions for which interferometry can not be used, such as photon collectors which require a large continuous surface area, it is clear that reflector concepts that provide a reduction in areal density, and which allow stowage and deployment are required. The most commonly-used technology at the present time is a light-weighted, monolithic primary reflector, having a reflective surface which is highly-polished to achieve optical figure. Although the use of advanced materials and fabrication, and light-weighting technology are improving the areal density, it is clear that diminishing returns are being achieved. In order to increase reflector aperture and improve areal density it is clearly necessary to consider alternative techniques.

One possibility, introduced above, is to remove the support structure and retain only the monolithic reflecting surface. In order to achieve optical-precision surface figure with such a meniscus mirror, actuators must be attached to the rear surface to enable precise in-orbit figure correction. If the weight of the actuators is less than the support structure they replace, this would lead to a reduction in areal density. However, the maximum aperture of a monolithic mirror is limited by the available launch fairing space. To increase the aperture further, methods of stowage and deployment must be considered.

Another possibility is the use of segmented mirrors, such as will be used in the James Webb Space Telescope. In this case, the primary mirror consists of a number of hexagonal reflector segments. During launch, these segments can be folded to reduce the enclosed volume and fit into the available fairing volume. They are then deployed when the telescope is in its desired location. Following the large, relatively-coarse, deployment of the primary mirror segments, fine actuation is required to ensure that the segments are correctly relatively-placed and co-phased. This may be carried out by actuators attached to the rear surfaces of the segments providing correction in all six degrees of freedom. To increase the achievable aperture still further, it is conceivable that novel deployment techniques, such as the starburst concept, could be adopted. However, the minimum achievable areal density will still reach an asymptote, as each mirror segment will reach the same limitations as for individual monolithic primary mirrors.

The use of membrane reflectors offer the possibility of significant improvements in reflector aperture and concurrent reduction in areal density. However there are many issues which must be overcome if they are to be successfully used in space telescopes. These are listed below.

- Membranes must be manufactured with consistent thickness
- All stiffness must be provided by the support structure
- Radially-applied tensions can lead to membrane wrinkles
- Nonzero Gaussian curvature of the membrane must be achieved
- Large membrane reflectors are difficult/impossible to test on the ground

It should be noted that membranes are beginning to be manufactured with thickness variation commensurate with optical precision. Wrinkles resulting from radial tension tend to fan out into the membrane. This can significantly reduce the flat area of the membrane, and hence the reflector effective aperture. The difficulties with ground testing are due to the presence of gravity and also to available space constraints.

5.2 Future work

In this final section, proposals are made for work that should be carried out if space telescopes with membrane reflectors are to be realised. With missions planned 15-20 years in advance, it is necessary for several obstacles to be overcome before the use of membrane reflectors becomes a reality. As reflector apertures get larger it becomes increasingly difficult to test the structures on the ground prior to launch. It is therefore necessary to develop increasingly sophisticated analysis techniques which give sufficient confidence in system-level performance. Such analysis would necessarily be multi-disciplinary. In particular, this would require significant improvements in materials technology and testing procedures, to result in materials having properties with minimal statistical variation which are known across the entire band of operating temperatures.

It is clear that the development of feasible support structures for membrane reflectors is crucial. The support must be deployable, thermally stable and sufficiently stiff to allow radial tension to be applied to the membrane. The use of inflatable-rigidisable structures offers a possible solution, but it is necessary for significant improvements in deployment certainty to be achieved to bring the deployed configuration sufficiently close to the desired configuration in order for fine figure correction to be carried out. It is also necessary to prevent or mitigate wrinkle patterns in the membrane resulting from radial tensions, which requires extensions to the analyses used to predict wrinkles in solar sails. It is also imperative that accurate methods for imparting nonzero Gaussian curvature to a membrane are developed. It is possible that this could be carried out either by an applied pressure (electrostatic or otherwise) or by means of actuators incorporated in the membrane surface.

Finally, one of the biggest barriers to the use of large-aperture membrane reflectors in space-telescopes is that it would represent a fundamental paradigm shift from the current state of the art. The importance of using heritage technology in the space industry means that, in spite of potentially large theoretical benefits, membrane reflectors cannot be proposed as the technology currently stands. A solution to this barrier is to recognise that, for example polyimide, membranes are significantly cheaper than monolithic ceramic reflectors. In addition to areal density, another technology driver is the cost density ($/m^2) for which membrane reflectors are very competitive. It will be greatly beneficial for the structures community to focus on developing a, say, 30cm aperture membrane telescope, at which scale the problems inherent to the concept will be more easily solved, and the missions may be flown with less inherent risk. When such a telescope is successfully launched and deployed, it will increase confidence in the technology and will potentially lead to the hundred meter aperture reflectors that have been envisioned.

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