Optical Design of Giant Telescopes for Space

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ABSTRACT

Increased performance for optical telescopes has historically come from larger apertures, from technological advances for the telescope components, such as detectors, and from access to better sites, such as space. Little has changed in the basic telescope design for a century. These conventional designs have served us well and will continue to do so with the Next Generation Space Telescope. There is an upper limit to the size of this type of telescope, set by the capacity to launch the required mass. For future space telescopes of 50, 100, 500 meter apertures, we have developed a new type of optical design. We use a primary reflector made from segments of flat and near-flat membranes. The secondary reflector and subsequent optics are supported in separate spacecraft, flying in formation with the primary reflector. In addition, each spacecraft maintains sunshields to keep the optics shaded from the sun. This paper explores optical design issues for this type of giant space telescope.

Keywords: space telescopes, gossamer

1. INTRODUCTION

Planetary science has been limited by the power of telescopes to the study of just our own solar system. Now the presence of numerous planets orbiting stars other than the sun is inferred from stellar reaction motion, but we lack the ability to see these planets directly. We also lack the technology to travel such large distances to investigate these other planetary systems. Our only option for studying these new worlds, as well as the most distant objects in the universe, is to build larger and better telescopes. These telescopes will need to be free from the distorting effects of the atmosphere and far from the thermal emission of earth itself. The next giant steps in our understanding of the universe will require giant telescopes in space.

Some basic requirements for a giant telescope come from the physics of light creation and propagation. The wavelength of interest is defined by the application. The wavelength bands accessible from the ground, from 0.3 – 20 μm will remain of great interest even for space telescopes, since they cover most of the reflected light and thermal emission from exo-planets. The resolution, defined as the smallest angle that the telescope is capable of resolving, is defined by the ratio of the wavelength of light to the largest dimension of the telescope, i. e. its baseline. A telescope with 1000 m baseline is required to resolve 0.002 arc seconds at 10 μm wavelength. Distinct from the base-line is the collecting area, which determines sensitivity, the ability to see dim objects. The light from planets or other distant sources is feeble, so the apertures must be large enough to collect enough light to overcome noise from background, detectors, and from the statistics of the light itself.

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2. HISTORY AND PROSPECTS FOR CONVENTIONAL DESIGNS

2.1 The past

Nearly all large telescopes in the last century were made using the simple two-mirror Cassegrain type of optical design. The high performance and the versatility of this type of optical design make perfect sense for the 20th century telescopes. Glass mirrors with good reflective coatings have enabled telescopes to be used with high efficiency for both visible and infrared wavelengths. This allows a single telescope to be shared by a variety of users. Adding some lenses for field flattening, the optical design can be corrected not only on axis, but for fields greater than 1 degree. Thus, telescopes are frequently used for both imaging and spectroscopy. The "telephoto" nature of the Cassegrain telescope makes the physical length much shorter than its optical focal length. This allows the telescope as a unit to be as small as possible, limiting the volume required for its enclosure and limiting the moment of inertia, enabling fast pointing and slewing. The two mirror telescope has held its prominent status for good reasons.

The development of new technologies is nearly always traced to a heritage defined by the success of previous systems. This evolutionary path for technical advances leads us from the transistor to the Pentium. When we look at the technical heritage for space telescopes, we see the Hubble Space Telescope as the only large, proven observatory in space. This machine is, however, only a modern version of the Hooker Telescope that Edwin Hubble frequently used on Mt. Wilson. (See Figures 1 and 2.)

Figure 1. The 2.4-m Hubble Space Telescope, placed in orbit at 600,000 m altitude in 1990. [1]

Figure 2. The 2.5-m Hooker Telescope, placed on Mt. Wilson at 1742 m altitude in 1917. [2]

Cassegrain telescopes typically have mirrors made from glass, an outer "tube" connecting the secondary mirror to the primary mirror, and a mount which controls the line of sight by moving the entire telescope. This basic design has continued to be used for nearly all 20th century terrestrial telescopes with 0.5 – 10 meter apertures. The stability and ease of polishing of glass have been unequaled for mirror substrates. Advanced glass fabrication and active support technologies have overcome the difficulties of self-weight deflection for the large mirrors.[3] At sizes less than 10 meters, the large mass of the mirrors, supports, and secondary support tube have not been a limitation.

2.2 The present

Telescopes are now being planned for the ground and for space that move beyond the 20th century designs. The special requirements for the Next Generation Space Telescope NGST, a large space telescope that works in the thermal infrared, lead to new design choices. Ground based telescopes of 30 meters and larger are being considered. Both types of systems make evolutionary steps from current and past telescopes.

The difficult requirements for NGST, including the 8-m aperture, infrared optimization, and limitations of existing launch vehicles lead to some new design choices. At the time of writing this paper, there is considerable effort underway to fully optimize NGST for cost and performance[4]. Some new aspects of the NGST design are listed below.

- The primary mirror is too large to fit in an available launch shroud. It must be made from segments which are folded up and stowed for launched, then deployed and aligned in space. On board wavefront sensors will measure phase errors, which will be corrected with actuators.

- Even with its deployment hardware, the mass of the primary mirror is limited to ~800 kg, which requires the mirror itself to be lightweighted to areal density (total mass/mirror area) of about 15 kg/m^2.

- The telescope must operate at temperatures < 50 K, which can be achieved by thermal emission into cold space. This requires the telescope to be operated in shade provided by a sunshield, and in solar orbit to keep the earth from heating it. Also the telescope should be open to the cold sky so it can easily radiate its heat away.

- The use of glass mirrors is still a strong preference, but other materials are being investigated.

- The focal ratio of the primary mirror is faster, $f/1$, to limit the size of the telescope.

- Addition of a fine steering mirror at an internal pupil. Nearly all of the pointing is provided by rigid body motion of the entire telescope, but the fine steering mirror provides compensation for pointing errors of a few arcseconds.
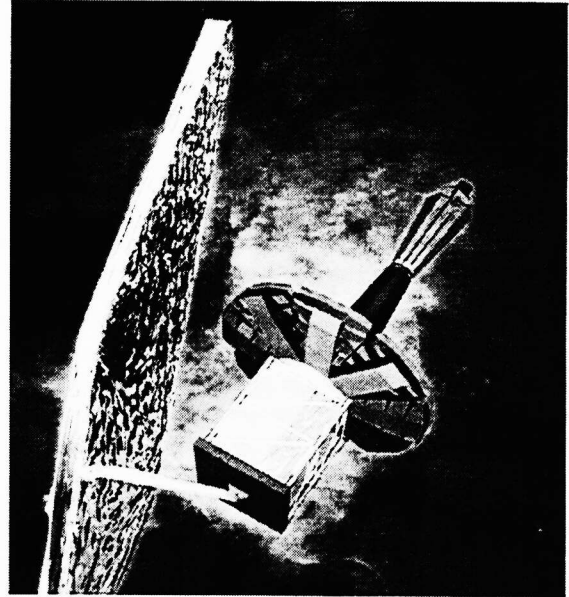
Figure 3. The 8-m Next Generation Space Telescope. To be launched into solar orbit in 2009. (Lockheed Martin design shown).
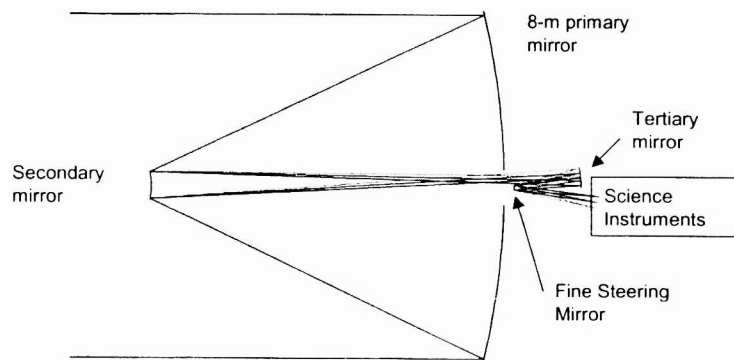
Figure 4. Optical layout for NGST. The 3-mirror astigmatism corrected design gives a 10 arcmin field of view.

The optical design for NGST, shown in Fig. 4, follows from previous systems. The primary mirror is faster, with f/number of 1 (focal length/diameter = 1) to limit the size and the moment of inertia. This basic trend of decreasing the primary mirror focal ratio has occurred for ground based telescopes as well. The shorter telescopes are easier to house and point. The faster primary mirrors are however more strongly aspheric and are more difficult to fabricate. The NGST uses a third mirror with power to correct the design for astigmatism and to provide a real pupil for a fine steering mirror.

2.3 The future for large space telescopes

The natural progression to larger space telescopes begins with the technical heritage. How far can we go by pushing existing technologies? It does not seem economically feasible to develop new launch capabilities for these programs, so we are fundamentally limited to payload masses of a few tons. There are two paths to take from NGST to get larger telescopes. The primary mirror could be made larger as long as its density is decreased. This extrapolation gets to a telescope with hundreds of square meters filled aperture. The details of this type of mirror design and the mass limitations are given elsewhere.[5] Also, multiple individual telescopes can be combined to form a single coherent image. This can get to baselines of a few hundred meters with collecting aperture of tens of square meters.

Using technologies developed for NGST, it seems feasible to make mirrors at 5 kg/m^2 with existing materials. This type of mirror would have a thin (~1 mm) optical surface controlled by actuators. For mass allocation of 1000 kg/launch, mirrors can be flown with 200 m^2 collecting aperture. With new materials and new processes, these mirrors could be a few times lighter, which allows the total area to increase proportionally.

There is certainly a lower bounds for the mass of these types of mirrors. The curved shape of the mirrors must be maintained to a small fraction of the wavelength. Once the optical surface becomes too thin, its shape is entirely controlled by the support and because this surface is highly curved, the support must be distributed over the area. The mass of this support can negate the advantage of the thin optical surface.

The other way to evolve from today's technology is to combine the light from multiple telescopes. This is already done to increase the baseline for interferometry. The Space Interferometry Mission, planned for 2006 launch, combines light from multiple 30 cm telescopes to measure with 10 meter baseline.[6] The Terrestrial Planet Finder or TPF , currently being studied, combines the light from larger telescopes over a larger baseline with the goal of studying planets around other stars.[7]

Figure 5. A preliminary design for the Terrestrial Planet Finder showing 4 free flying telescopes and a combiner.

Some aspects multiple telescope design are listed below.

- Large baselines can be made using several free-flying telescopes that project light to a combiner.

- Multiple telescopes can benefit directly from mirror technology advances, as described above.

- Arrays of telescopes are well suited for optimization for narrow missions, such as TPF.

- It is very difficult to get large collecting apertures with multiple telescopes.

- The field of view is naturally very small for multiple telescopes.

The options for giant telescopes are limited by the system mass, which is dominated by the primary mirror. We are limited to a few hundred square meters per launch with the curved optics weighing a few kg/m^2. To get to the giant space telescopes with tens of thousands of square meters, we need to get the mirror mass to ~0.1 kg/m^2. It appears that there is no evolutionary path that will get there.

3. THE CASE FOR MEMBRANE MIRRORS

The assumption for the optical systems above is that they follow traditional optical designs. The telescope mirrors are curved according to the ideals for the conventional Cassegrain telescope. We now investigate a different scenario that allows the optical surface to be orders of magnitude thinner. What if the optical surfaces are allowed to be flat?

3.1 The physics of flats

The mass limitation for curved mirrors comes from the difficulty of controlling a curved shape to optical precision. If the optic becomes very thin for decreased mass, it cannot maintain its own curvature and the shape must be defined by some other system. The fidelity required by the support adds mass to the system, obviating the advantage from using the thin optical surface. There is one shape that does not have this problem – flat.

A flat surface can be maintained in a membrane by simply stretching it flat, as shown in Fig. 6. This requires no shape stability of the membrane material. The conditions for flatness for membranes are listed below.

1. The perimeter must be defined to be in a plane.

2. Positive tension must be maintained. The membrane will buckle and wrinkle in compression.

3. The membrane must have uniform thickness. The surface variations will be half as large as thickness variations.

4. The membrane must be isolated from external disturbances. These optics are only feasible for space applications. In fact the sensitivity to acoustics and vibration make testing difficult.

Figure 6. A membrane in tension will be flat, except for variations in material thickness.

We have proposed a design that achieves high performance with low mass, shown in Fig. 7 below. The tension is maintained using discrete attachment points. At these points, we define the shape of the perimeter with actuators. Thus, the shape control is reduced from a two-dimensional surface to one dimension along the perimeter. The frame that supports the actuators can be made of stiff, lightweight material. Since the actuators define the perimeter, absolute stability of the support frame is not required.
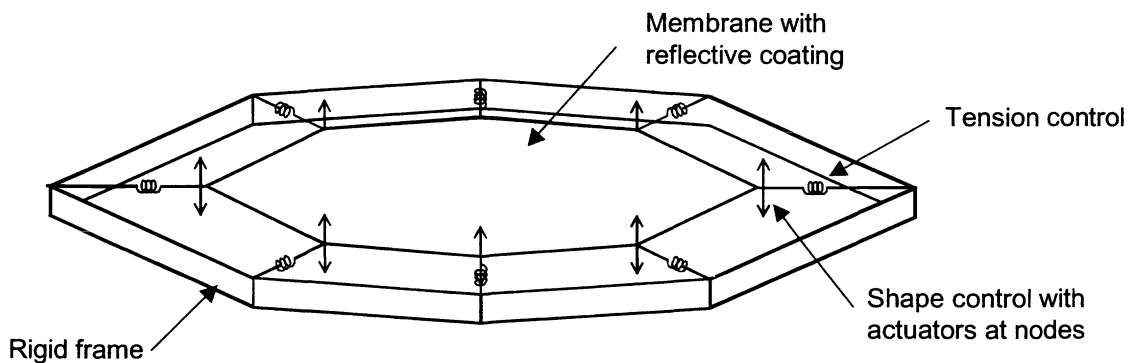
Figure 7. System design for membrane mirrors. Membrane tension and the perimeter shape are is maintained at discrete attachment points.

3.2 Technology for large flat mirrors in space

Engineering and testing of materials and system concepts for these flat membrane mirrors is underway at the University of Arizona.[8] Membrane materials made from several types of polymers, nickel, and silicon nitride have been tested. These materials and the mounting techniques have been evaluated for surface quality from millimeter scale to meter scale. Some representative pictures from this work are shown below in Fig. 8.
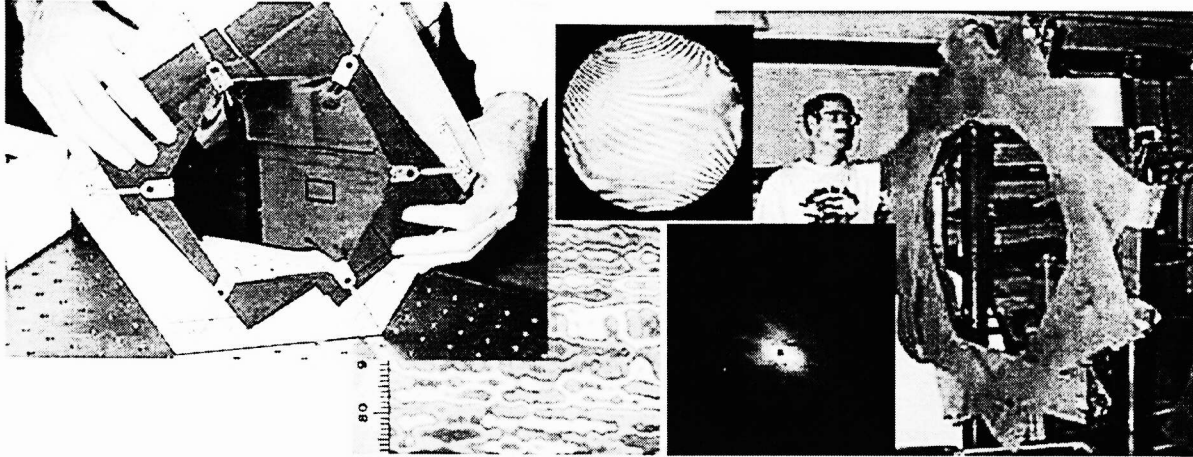

Figure 8. Laboratory tests of flat membranes at the University of Arizona. The details are described elsewhere.

4. OPTICAL DESIGN USING PRIMARY FROM FLAT SEGMENTS

While flat mirrors provide a natural shape that can be maintained with low mass, it is not obvious that this is useful. Flat mirrors have no power and are not used for collecting light, only diverting it. There are three interesting cases that take advantage of flat optics.

1.) A diffractive structure can be applied to the surface to cause the diffracted light to come to focus. This optical design is being developed by Hyde[9] and will not be treated here.

2.) A large mirror can be made from flat facets that achieves an overall focusing ability. The effect of the facets can be corrected with subsequent optics.[10] The design and analysis of this system, which are both quite difficult, are elaborated below.

3.) Slight curvature can be induced using electrostatic fields. A large mirror can be made from segments which are each curved so that the individual optical surfaces coincide with an ideal "parent" surface. This design gives better field performance at the expense of the added complexity of the electrostatic system.

4.1 Design overview for telescope with flat segments

The basic design concept for the telescope with flat segments is illustrated in Fig. 9 below. The primary reflector is made from individual flat segments that lie along a curve approximating a paraboloid. Each flat reflector deflects light into a common secondary mirror, itself somewhat larger than the primary segments. This secondary creates a real image of the seg-
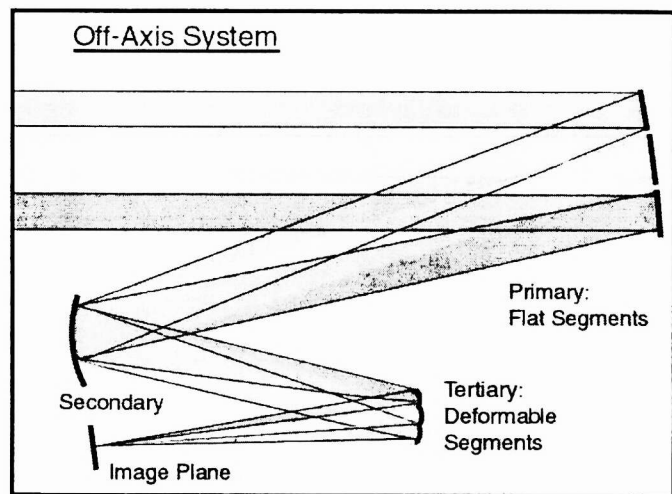

Figure 9. Concept for using an array of flat mirrors as the primary for a large telescope.

mented primary where a tertiary corrector mirror is placed. This tertiary reflects the light from each subaperture to a common phased focus.

There are two different convenient ways of thinking about this optical design. For a conventional ideal telescope, the segments would have curvature. The flat segments can be treated as simply having an error in the shape corresponding to the lack of curvature. So the fact that the primary mirror is made from flat facets is compensated by the tertiary mirror made from concave segments. The spherical aberration in the Hubble Space Telescope primary mirror was corrected by placing the compensating aberration at an image of the mirror.

A different analogy for the optical design is to treat the powered elements as separate off axis telescopes that happen to share the secondary. Each telescope is steered by a flat siderostat membrane mirror so that all telescopes point at the same place. The relative position of the optics is set to co-phase the images and to match the focal lengths. This paradigm for the optical design allows a treatment of the system that follows general rules for multiple aperture imaging systems.

4.2 Design rules

Like any multiple aperture system, there are a few simple design rules that must be followed to obtain diffraction limited performance. The images from the individual apertures must be corrected, they must coincide in the image plane, and they must be in phase. These requirements and the associated optical design issues are summarized below.

4.2.1   Correction of subapertures

For the system to be diffraction limited across a field of view, the images from the individual subapertures must be well corrected. At first glance, it may seem sufficient that the aberrations from the subapertures be non-zero as long as they match. In fact this is not so. For imaging, the light is combined only in the image plane, so there is no benefit to matching the aberrations in the individual pupil planes.

Field curvatures must be considered as aberrations in the subsystems. There is some flexibility to choose the optimum location and tilt for the image plane. Once this is established, the wavefront errors from field curvatures must be considered in the optical design. There is some latitude here because the individual systems tend to have long focal ratios. The depth of focus for each one should be $<< \lambda f_n^2$ where f_n corresponds to the subaperture focal ratio.

4.2.2   Coincidence of images from subapertures

Since the images are combined in the image plane, it is obvious that they must coincide there. For a single on-axis field point this means that the sub-systems must be pointed at the same object to within a small fraction of the diffraction limit for the subaperture. For a telescope with 6 meter subapertures operating at 10 μm wavelength, the pointing should be maintained to 0.1 λ/D or about 0.03 arc seconds.

The situation becomes more difficult when a finite field of view is considered. The images for each field point must coincide to this level, so the telescopes must not only point together, but the focal length and any distortion must match. For the same telescope to perform over a ±10 arc second field of view, the combination of focal lengths and imaging distortion must match to ±0.2%.
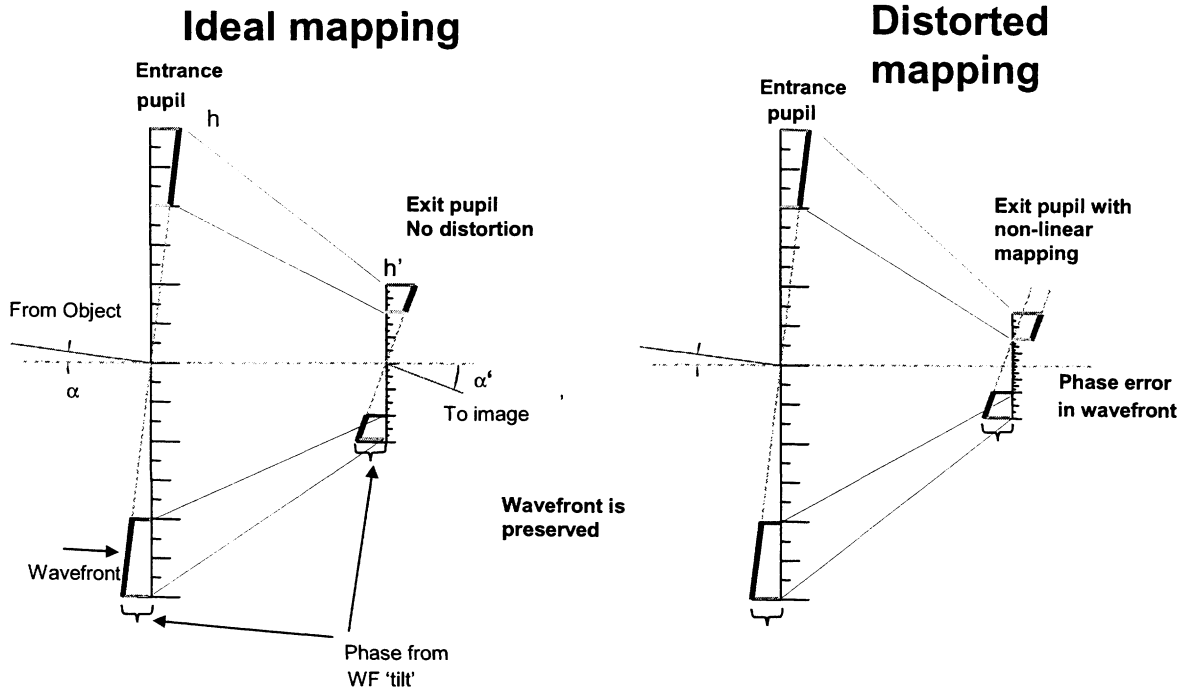
4.2.3   Co-phasing the images

It is critical that the images from the subapertures are combined *in phase* meaning that the path length through the system must be the same for each subsystem. This phasing needs to be maintained to a fraction of a wave over the entire field of view. One can always move a mirror to co-phase the light at a single field point, but it is more difficult to maintain phasing over a finite field.

The phasing across the field can be maintained by enforcing the sine condition, which requires linear mapping from the entrance pupil to the exit pupil. The effect of pupil mapping is seen in Fig. 10 below where a tilted wavefront in the entrance pupil (which corresponds only to a different field point) is mapped to a tilted wavefront in the exit pupil *only for the case where the pupil mapping is linear*. If this mapping is not linear, then the tilted wavefront from the object is distorted at the image.

The magnitude of the dephasing due to pupil distortion is calculated directly by mapping the exit pupil to the entrance pupil. We define the departure from linear mapping as ε_x in the entrance pupil. For field point of α_x, the phase error is simply the product of the two:

$$\Delta W = \varepsilon_x \cdot \alpha_x$$

For diffraction limited operation, the dephasing ΔW must be much less than the wavelength. A 100 meter telescope operating at 10 μm wavelengths and ±10 arc second field of view requires distortion of the entrance pupil less than 10 mm to keep the dephasing below λ/20. This corresponds to pupil mapping of 0.02% over the ±50 meter entrance pupil. This distortion must be maintained for the entire field of view.

Ideal mapping

Entrance pupil h

From Object

α

Wavefront

Phase from WF 'tilt'

Exit pupil No distortion

h'

α'

To image

Wavefront is preserved

Distorted mapping

Entrance pupil

Exit pupil with non-linear mapping

Phase error in wavefront

Figure 11. Violations to the "sine condition" cause phase errors from a coupling between the tilted wavefronts from off axis field points and non-linear mapping between the exit and entrance pupil.

This pupil mapping is frequently referred to as the "sine condition" because the mapping must be linear in terms of the sine of the angle as defined in Figure 11 below for the case of object and image at finite distances. In this general case, the pupils are spherical, centered on the object and image points and the wavefront tilt maps linearly as long as the mapping from exit pupil to entrance pupil is linear in terms of the sine of this angle. The common aberration of coma can be treated as a simple third order distortion of the exit pupil, which couples with the wavefront tilt to cause a third order wavefront aberration.

2 m

18 m

system axis
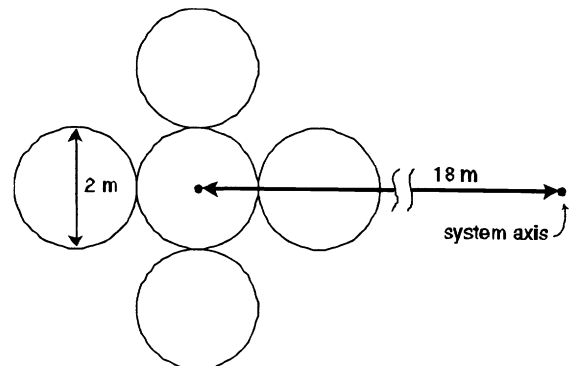
Figure 10. Entrance pupil geometry for simulation of combining for a telescope using a primary made from flat segments
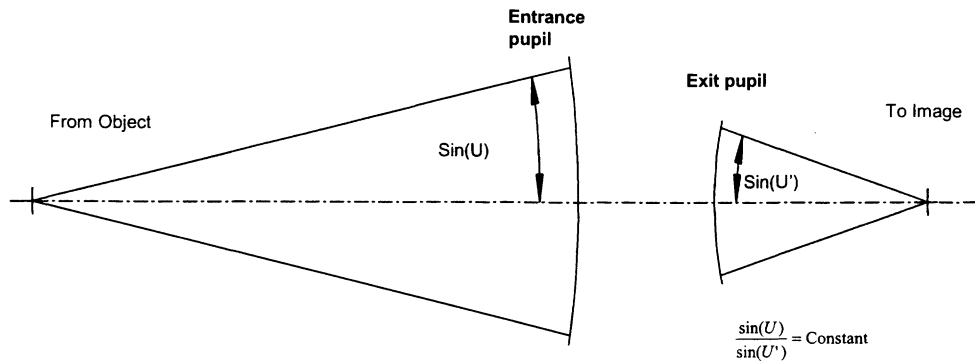
Figure 12. The term "sine condition" is used for the case of finite object and image distances where the pupil mapping must be linear in terms of the sine of the angles as shown.

4.3 Analysis of optical performance

A detailed system model of this type of telescope was developed using *Optima* software provided by Lockheed Martin. One of the specific systems used in our design study is shown below. The system consists of five flats, in an "+" configuration. Each of the flats is 2 meters in diameter, for a total aperture diameter of 6 meters, with a fill factor of 0.44. The entrance pupil geometry is shown in Figure 12.

A complete, phased system was analyzed over a finite field of view. The distance from the primary to the secondary is 1000 meters. The lowest primary flat is 16 meters from the system's axis, and the f/# is 166. Cross-sections of the point spread function of the system are shown in Fig. 13. At zero field angle, the Strehl ratio is 0.99, while at a field angle of 1 arc minute, the Strehl has fallen to 0.93 for 8 μm wavelength. The de-phasing of the telescopes with field angle is apparent in Fig. 14.
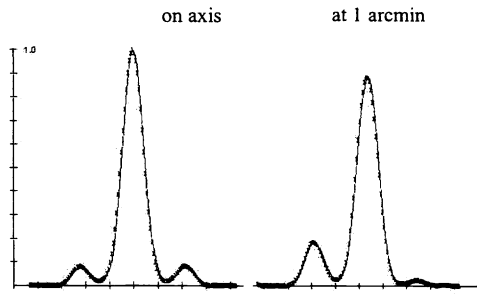
Figure 13. Point spread function for example telescope.
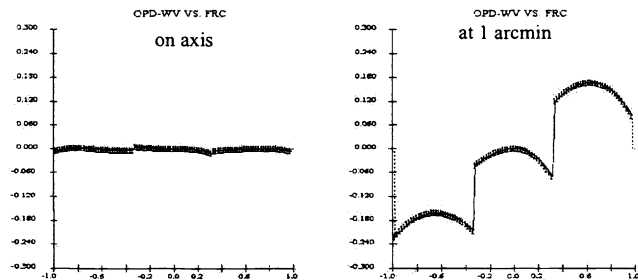
Figure 14. Slice of wavefront errors for example telescope.

The sine condition violation limits the field of view for this system. The mapping is necessarily distorted by off-axis effects from the secondary. The distortion itself is a strong function of filed angle. The effect can be reduced by decreasing the power of the secondary and the angle between the primary and tertiary. For a fixed aperture size, this translates to longer telescopes and larger tertiaries. For a fixed wavefront error, the field of view decreases approximately linearly with increasing size of the primary flats and increasing primary distance from the axis, and decreases quadratically as the primary-secondary distance of the system is shortened.

4.4 Example system design

A basic trade study has indicated that a 100-m flat mirror telescope can achieve diffraction limited observations. The basic design parameters for this telescope are listed below:

100 m overall diameter of primary
6 meter flat segments
2 km length (primary to secondary)
7 m secondary (spherical relay)
10 meter corrector (60 cm elements)
0.3 μm rms wavefront errors for ±10 arc second FOV

It is fundamental to this system design philosophy that the telescope is placed in a benign orbit where the relative position of the primary to the secondary mirror can be maintained to millimeters during an observation. These optics are supported on free flying spacecraft and can be separated by several kilometers.

Also, there is an advantage to providing separate sun shields for each free-flying telescope component which, themselves are free flying spacecraft. By placing the solar shield farther from the optic, the solid angle subtend is reduced and the thermal coupling from the sun shield to the optic is proportionally diminished.[11] Figure 15 below shows a possible layout for one of these giant telescopes with 50-m aperture and 1000 meter separation from primary to secondary.
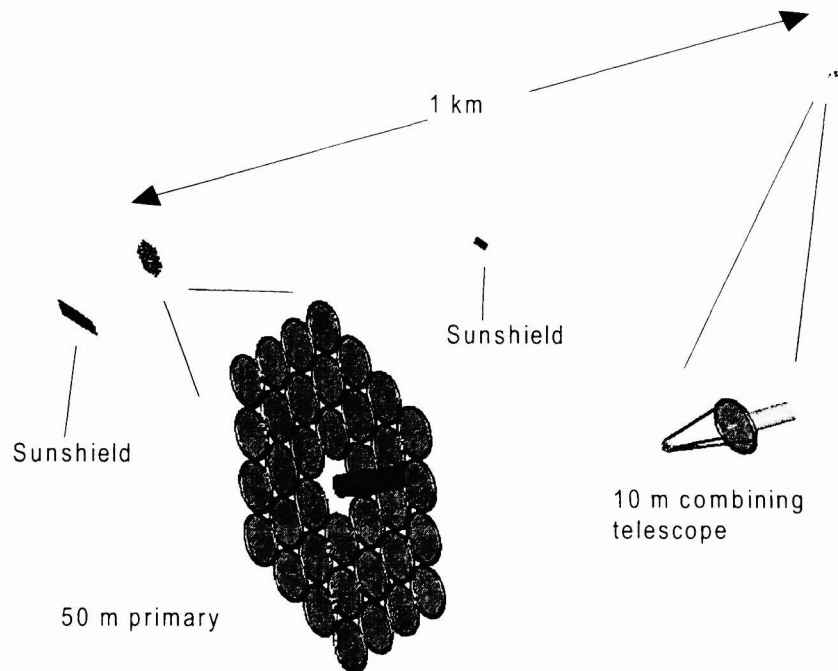
Figure 15. Telescope configuration with 50-m primary separated from secondary by 1000 meters. The sun shields are held by two additional free flying spacecraft.

These giant telescopes become difficult to point and align. Current telescopes are made as short as possible so they can be easily pointed. A 2-km long telescope requires careful station keeping to maintain the line of sight and it would take many hours to re-point to a new place on the sky. The fast, agile telescope of today will have to be used for operations where frequent pointing is required. The long, giant telescope is optimal for maintaining a single pointing angle for a long time.

5. OPTICAL DESIGN USING CURVED PRIMARY SEGMENTS

The optical design for telescopes using arrays of flats has limited field of view. By applying a modest amount of curvature to the segments, an order of magnitude more field can be gained.
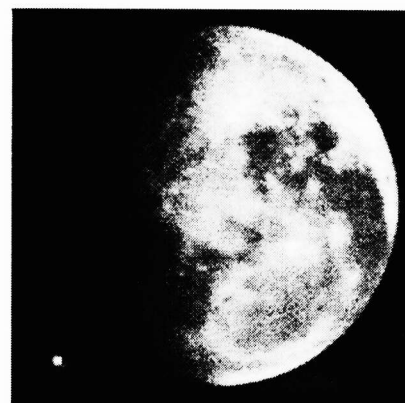
5.1 Applying slight curvature using electrostatics

A small amount of curvature can be created in the membrane mirrors using electrostatic pressure. An electrostatic potential between the membrane and an electrode behind it will cause an attractive force distributed over the area, which can be balanced with the membrane tension to create a concave optical surface, as shown in Fig. 16.
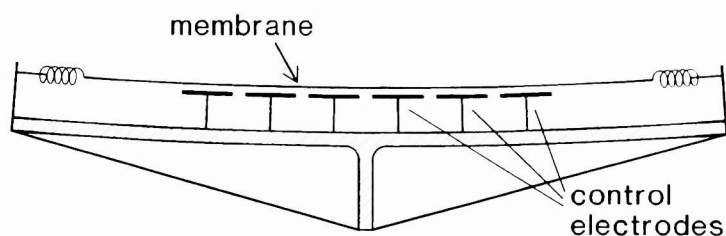
Figure 16. By applying an electrostatic field, a modest amount of curvature can be induced in the membrane.

Mirrors of this type have in fact been demonstrated.[12] Figure 17 shows an image of the moon taken with a telescope made that had an electrostatically deformed membrane as the primary mirror. The aperture for this was only 6 mm, but there is work underway to build a similar telescope with 10 cm aperture.[8]

## 5.2 Optical design advantages for curved segments

The optical design becomes much easier for the case of the primary mirror made from membranes, each with the appropriate curvature that no correction is needed. Thus, the active tertiary is no longer necessary, although it may be useful for accommodating other fabrication and control errors. A baseline optical design for a telescope with primary from curved segments was developed for comparison. The layout of the telescope is shown to scale in Fig. 18 and the design parameters are given below:

Figure 17. Image taken by a telescope with electrostatically deformed membrane as the primary mirror.

> 100-m overall diameter of segmented primary
> 6 meter curved segments
> (The 6 m primary segments have 4 mm sag)
> 2 km length (primary to secondary)
> 10 m concave secondary
> 0.4 μm rms wavefront error for ±150 arc second field

The primary mirror is made from 6 meter segments. Each segment is appropriately curved not only with power, but also with the slight aspheric departure to shape each segment as an off axis piece of an ideal paraboloidal parent. By adding slight variations to the field and to the perimeter points, non-spherical shapes can be made.

This field for this telescope is quite large. In fact the real benefit for the curved primary probably comes for the visible light optimization. Here, a 2-km long telescope described above with 100 m aperture from 6-m flats has 0.04 μm rms wavefront error over a tiny field of ±3 arc second. This is diffraction limited at 0.5 μm. If we apply the curvature to the primary mirror segments, we can achieve the same diffraction limited performance over ±48 arc second field of view. This represents a factor of 250 more sky coverage allowed by the increased performance from the curved mirror telescope over the corresponding flat mirror system.
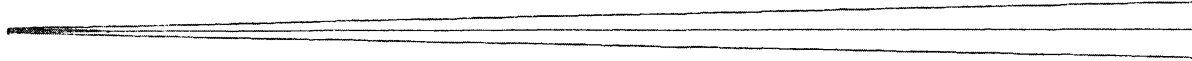
Figure 18. Layout of optical design for a 100m aperture telescope with curved primary segments.

6. CONCLUSION

Telescope advances in the past have resulted from slow, steady evolution of technologies. It seems that there is no way for our current concept of optical telescopes to extend to space telescopes with apertures of thousands of square meters. We present here designs for telescopes that use thin lightweight membranes for the optics and that allow the different components of the telescope to be on separated free-flying spacecraft. We show two types of designs, one that uses an array of flats as the primary collector. This could be used for large telescopes with field of view of a few arc seconds. We show how to improve the field of view by applying a slight curvature to the primary segments using electrostatics.

ACKNOWLEDGMENTS

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