Testable lightweight telescopes for space

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ABSTRACT

The next generation of larger space optics will need lightweight and deployed mirror systems in order to control costs and fit within current and planned launch vehicle fairings. These will require active control based on wavefront sensing to establish and maintain their optical quality. Such control has been the enabling factor for the current generation of 8 m class ground-based telescopes, whose mirrors are either single monoliths with detailed shape control or have multiple rigid segments with control of relative position. They use actuator densities of typically a few per square meter. For active space systems it will be highly desirable to test the full deployed spacecraft in a vacuum test with a scene simulator, to validate before launch the optical performance of the complete system with its closed loop control systems. To enable such testing, the space mirror system must be designed from the start to work in a 1g as well as zero g environment. The orientation we envisage has the spacecraft system pointed at the zenith, illuminated by a downward beam collimated with reference to a full aperture liquid flat.

We consider here two space mirror systems. The first has rigid segments supported by position actuators to control only rigid body motions. Since the segments under test must hold their shape with an axial 1g load and no passive flotation supports, they must be smaller than for ground systems. If made of lightweighted silicon carbide or beryllium for diffraction limited imaging in the optical, they would have to be ~ 30 cm in diameter. A mirror systems made from such segments will require about 40 actuators and wavefront sensor sub-apertures per square meter. The second system is a lightweight 3.5x8 m monolith for very high contrast imaging, as is envisaged for NASA's Terrestrial Planet Finder. High accuracy control of Fourier components down to ~ 0.2 m period is required, requiring a deformable mirror with about 4000 actuators. If the primary itself is the deformable element, and has a 1 cm thick glass meniscus facesheet weighing 600 kg, the gravity-induced quilting during testing would be about 1 nm rms, low enough for ground testing of the complete system at the desired 10^{-10} contrast level.

1. INTRODUCTION

Large aperture telescopes in space are needed for both defense and research applications, diffraction limited at optical and infrared wavelengths. Apertures of 10 to 30 meters or even larger are of interest. NASA is already constructing the James Webb Space Telescope to succeed the 2.4 m Hubble Space Telescope. This 6 m telescope is designed to operate at cryogenic temperature with diffraction limited imaging down to 2 µm wavelength. More advanced telescopes with larger apertures to work at shorter wavelengths will be very much cost limited. It will be essential to find and prove the most efficient and cost effective methods to build and test larger systems.

The experience with optical errors on the Hubble Space Telescope underscores the need for full testing, especially as the preferred location for the JWST and most subsequent space telescopes is the Earth-Sun L-2 point, over 1 million km from earth. Here repair and upgrade missions of the type done for Hubble will be difficult if not impossible. The approach we propose here for design and development of systems that may be tested as fully integrated spacecraft in vacuum offers a solution to this difficulty. In this section we review current design and test strategies as exemplified by ground telescopes and the JWST, as a starting point for the specific testable space systems discussed in later sections.

1.1 Ground based telescopes

Despite the obvious difference in mass between ground and space systems, there are many common elements. Optical quality requirements are similar, and ground systems are more advanced in their use of active controls. A new generation of ~ 8 m aperture ground-based telescopes is now in operation, and plans are being developed for larger successors, in the 20 – 100 m class. These provide useful insights on technologies and system aspects that will likely be

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important in finding optimum solutions in space. Of particular relevance is their use of active and adaptive controls to recover diffraction limited images in the face of constantly changing gravity and wind loads and atmospheric aberration.

Primary mirrors for ground based telescopes need to be much sturdier than for space, to resist wind buffeting. Glass substrates are preferred because of their exceptional thermal and long term stability. But despite their heavier weight, all the large ground mirrors employ active figure control on time scales of a minute or more, using a servo with wavefront sensors and 100 or more actuators.

Single monolithic primaries are used in the telescopes of 6.5 – 8.4 m diameter, with actuators to apply forces to correct for thermal and mechanical bending. Six such mirrors of 6.5 and 8.4 m diameter have been cast and polished by the Steward Observatory Mirror Lab at the University of Arizona, for the MMT, Magellan and LBT telescopes. Before delivery to the observatory site, the complete mirror systems are tested interferometrically to the optical diffraction limit with full aperture illumination. The systems of 100-180 individually controlled force actuators used to optimize the wavefront quality are explicitly tested. In operation, figure control is made in closed loop via Shack Hartmann or pyramid wavefront sensors.

The four 10 m telescopes, Keck, Hobby Ebberly and SALT, use primaries assembled from rigid hexagonal glass segments of 1 – 1.8 m. Three position actuators per segment are used to control relative positions to compensate for distortion in the underlying truss structure. The segments themselves would bend significantly from gravitational moments when the telescope axis moves from vertical to horizontal if the only support was directly at the 3 points. The actuators are therefore act through whiffle-tree supports to spread the segment weight over many evenly spaced attachment points. In operation, these telescope systems correct the full mirror figure extending across the segments using wavefront data from a combination of Shack Hartmann and edge sensors.

Still larger ground telescopes are being planned, for example the Giant Magellan Telescope with the collecting area of a 21.4 m dish and resolution of a 24 m aperture telescope will combine the monolith and segmented mirror technologies (Johns et al., 2004). Its primary mirror will be synthesized from seven 8.4 m circular segments, each one built like the previous honeycomb monoliths. The substrate for the first of the ring of six identical off-axis outer segments has already been cast. Concepts that use a much larger number of smaller rigid hexagonal segments are also being explored, for example the TMT with 1000 1 m segments to form a 30 m aperture, and the OWL with ~ 2500 2 m segments for 100 m aperture.

1.2 Architecture of the James Webb Space Telescope

The most ambitious space telescope for astronomy is the 6.5 m James Webb Space Telescope (JWST), now under construction (Nella, 2002). The primary consists of as 3 rigid hinged panels, one with twelve segments and two with three each, as shown in the figure 1. The panels are folded for launch and are subsequently deployed. The 1.3 m hexagonal beryllium segments are rigidly attached via a hexapod with 6 position actuators to control the 6 degrees of freedom of rigid body motion, plus a seventh actuator to provide adjustment of radius. No whiffle tree support is used or needed for operation in zero g.

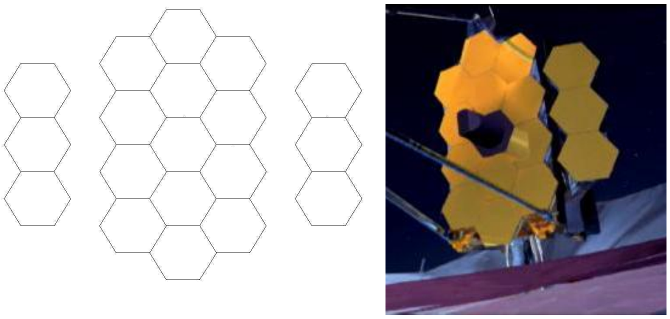

Figure 1. The primary mirror of the James Webb Space Telescope is folded in 3 panels for launch, as shown in the exploded view (left). The hinged side panels each have 3 hexagonal segments rigidly attached, and the center panel has 12. After deployment the segments touch to make a nearly continuous single surface.

The JWST illustrates the features likely to be found in any future deployed space telescope. The architecture is set by three size scales:

1) full diameter of the optical system
2) diameter of the launch vehicle
3) diameter of the optical segments

The first two, optical aperture and shroud diameter (which sets the size of the deployed panels) are inputs to the system design. The segment size remains a choice to be made based on manufacturing and system considerations. For the JWST the adopted segment size of 1.3 m minimizes the number of actuators and the detail of measurements to be made in space. However, the self weight deflection of the 1.3-m mirror segments causes wavefront errors that are large compared to the required limit for operation in space. Thus an end-to-end test with a simulated star field in which the science instruments see a good image formed by the telescope is not possible, neither can operation of the closed loop systems to measure wavefront errors and correct to the diffraction limit be tested directly. To establish even that the optical system should be capable of meeting specs in space, the gravity-bent figure must be measured and a correction applied. Errors in this measurement and correction come from several effects and could be larger than the telescope error budget. They are:

1. Uncertainty in the shape change due to gravity. The absolute accuracy of the finite element modeling for the complex structured segments is limited to about 5%.
2. Uncertainty in the mapping of the measured gravity sag onto the parent surface. Because the gravitational distortion has large slopes, absolute position of the segment distortions must be known to a very small fraction of the segment size.
3. Measurement errors. Second order coupling causes error propagation proportional to the magnitude or slope of the wavefront. When the gravity effects dominate, the measurement errors can be significant.

2. AN OPTIMUM CONFIGURATION FOR GROUND TEST

We believe it desirable, and perhaps essential to take as the starting point for future designs the requirement for a ground test of the fully deployed space telescope that accurately reproduces the operation in space. This approach will lower overall costs and considerably improve system reliability. Not just the optics but the control systems and the control software should all run just as they will in space. An illuminator is needed in the test vacuum chamber to provide a diffraction limited scene that reproduces the angular extent and character of that to be viewed in space.

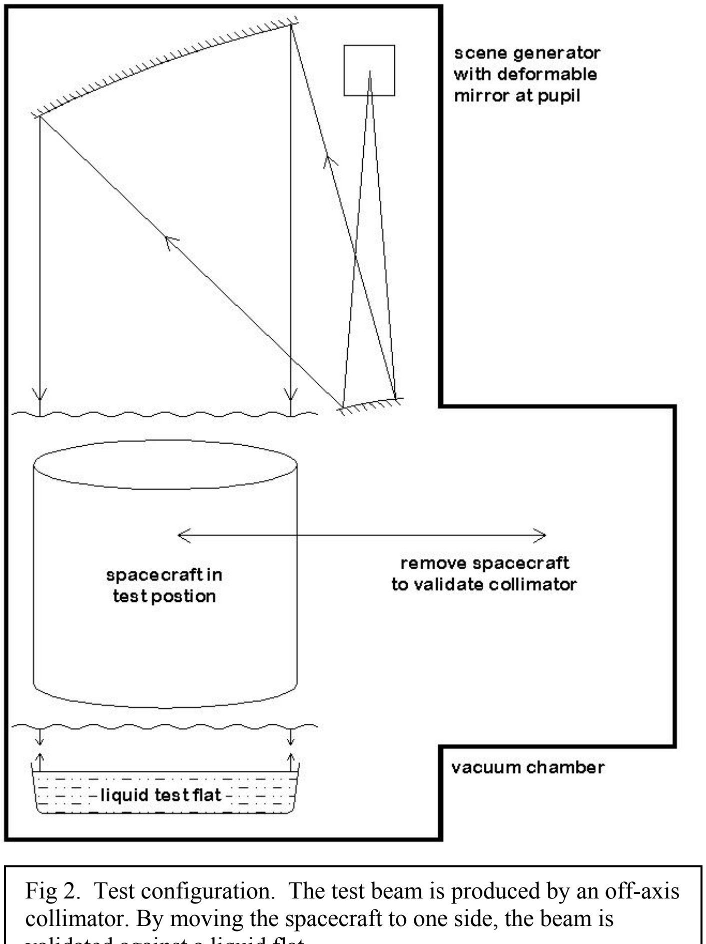

Fig 2. Test configuration. The test beam is produced by an off-axis collimator. By moving the spacecraft to one side, the beam is validated against a liquid flat.

A 6.5 m test collimator for such testing is presently being made by the Steward Observatory Mirror Laboratory for Lockheed Martin. The Cassegrain optical system is implemented with internal metrology elements to establish beam quality and focus without recourse to starlight. While this collimator represents a major step forward for testing space systems to 6.5 m diameter, it is limited to this size and testing of very high contrast imaging systems would be limited by diffraction effects from the metrology elements.

Here we consider a more versatile configuration for future full-aperture tests of still larger spacecraft as shown in figure 2. The illumination system consists of an off-axis collimator that produces a beam pointing directly down. This orientation is chosen so that the beam quality can be verified against a liquid flat, removing the need for any other metrology elements. For test purpose the liquid does not have to be highly reflective, the few percent reflection of a transparent liquid surface is adequate. The liquid should be chosen to have very low vapor pressure and optimum viscosity. Diffusion pump oil is a good candidate. If the system under test has an aperture no larger than 8.4 m, then the collimator could be made using a single off-axis monolith, similar to the one now being manufactured for the Giant Magellan Telescope. Larger systems would require a segmented collimator mirror.

The important requirement set by such a liquid-validated collimator system is that the spacecraft under test must be oriented zenith-pointing. The spacecraft optical system should therefore be able to accommodate operation with or without an axial load of 1g.

3. TESTABLE SEGMENTED ARCHITECTURE

In principle, the rigid segments for a space telescope could be supported as for ground telescopes, from 3 actuators points via a whiffle tree to prevent distortion while testing on the ground. However, such a support would add mass, complexity and potential degradation of performance because of friction. It would be preferable to support simply at three points with direct or hexapod link to the underlying frame. The design criterion for the segments is thus that when supported on three points, their figure change under 1 g load change should not spoil diffraction limited imaging. The deflection should thus amount to some fraction (depending on the error budget) of that allowed for the classic 80% Strehl limit. This is lambda/14 rms for the wavefront or lambda/28 for the surface error.

To a reasonable approximation, the self deflection of a mirror substrate under gravity depends on the overall shape and size and Young's modulus and density of the material, but little on the degree of lightweighting. The rms distortion from flexural bending of a circular disc of radius a and thickness h on 3 optimally located points is given by Nelson, Lubliner and Mast (1982)

$$\delta_{rms} = 6.5 \times 10^{-4} \frac{a^4}{h^2} \frac{\rho g (1\text{-}\nu^2)}{E} \qquad (1)$$

As an example, we take as a requirement 12 nm rms deflection under 1g load (90% Strehl at 0.5 microns wavelength, and find what size disc substrates of different materials will meet this, with a diameter to thickness ratio of 20:1. (Shear effects which increase the actual deflection are small for such aspect ratio). Values of ρ, ν and E, the density, Poisson's ratio and Young's modulus respectively, are given for various materials in table 1, along with the appropriate diameter, thickness and areal density calculated using equation 1.

Table 1. Discs with 12 nm rms flexural bending under 1 g axial load

material	ULE	Silicon carbide	Beryllium
density (kg/m^3)	2210	3017	1848
Poisson's ratio	0.17	0.17	.032
Young's modulus (GPa)	67.6	375	287
diameter for 12 nm rms (mm)	140	285	314
thickness (mm)	7.1	14.3	15.7
areal density (kg/m^2)	15.6	43	29

The results give a guide to the size and the degree of lightweighting that will be necessary to meet a given areal density goal. The low modulus of ULE leads to segments of ~ 140 mm diameter, about half that allowable for silicon carbide or beryllium. On the other hand, the lightweighting need for glass is modest. The high stiffness of silicon carbide allows use of larger segments, but the degree of lightweighting needed is high, and 50% more than needed for beryllium.

The choice of segment size in a specific design must be based on careful optimization of the lightweighted structure using finite element analysis. Preliminary studies indicate that the self weight deflection on 3 points of highly lightweighted substrates of the diameters listed, but with 10% the mass of the tabulated areal densities, can be even less than the targeted 12 nm rms.

Our optimization for a testable telescope meeting the optical diffraction limit indicates a segment diameter about one quarter that used for the JWST. Thus for six meter aperture about 400 segments would be needed. These could be similarly deployed on three rigid panels. Other diameter systems would require numbers of segments in proportion to area, and panel sizes determined by the deployment geometry. Compared to JWST, the main system difference is the higher count of segments and actuators and sensor subapertures, but the required accuracy of measurement and control is not increased. The advantage is that alignment with the spacecraft metrology system could be fully tested before launch. We note that wavefront control systems with large degrees of freedom are already used to recover diffraction limited imaging in adaptive optics systems operating at >100 Hz bandwidth, for monolithic and segmented systems. The almost static control systems needed for space looks easy by comparison.

Consideration of the manufacture of small, off-axis segments is beyond the scope of this paper. We do note, though, that advances in metrology and in direct fabrication, such as precision grinding and magneto-rheological finishing and ion figuring may well allow rapid deterministic fabrication of even highly lightweighted, small substrates. By producing hundreds of small segments, and eventually thousands in mass production, we may achieve the cost benefit of manufacturing learning curves generally not available for one-of-a-kind space systems. Moreover, by building optical systems of many small segments we can expand the manufacturing capability from the very small number of laboratories capable of making and figuring large space-qualified optical systems to a much larger, and less specialized industrial base. Both factors could considerably lower costs.

4. A TESTABLE, HIGH-CONTRAST MONOLITHIC TELESCOPE FOR TPF-C

The goal for the Terrestrial Planet Finder Coronagraph mission (TPF-C) is to image terrestrial planets located only ~0.1 arcsec from a star and ~ 10^{-10} fainter. This is so far beyond the state of the art (~ 10^{-5} at 0.5 arcsec) that it would clearly be very desirable to prove system performance at the desired level before launch. This is especially true because for stability reasons TPF-C will be operated at the inaccessible L2 Earth-sun Lagrange point.

The baseline telescope for TPF-C is an off-axis system with a 3.5 x 8 m primary, as large a monolith as can be squeezed into rocket current fairings. Let us suppose that the telescope and coronagraphic system is designed to be tested in a chamber as shown in figure 3, with the goal of recording images at the 10^{-10} contrast ratio. At first it might seem that the projection system must itself deliver such contrast, an extraordinary burden. But such quality is not necessary because of the active alignment and halo suppression system in the spacecraft suppression optics. This system must be capable of correcting the errors inherent in the telescope primary. As long as the projector's optical quality is similar, then its errors will be corrected along with those of the telescope. It is however necessary that the projector not introduce diffraction effects, so its optical system must also be off-axis and unobscured, as illustrated in figure 2.

As before, the requirement for the full system test is that the spacecraft optical system must be able to reach specification when operated zenith-pointing under gravity. The primary mirror of the current point design would not allow this, but we can envisage an alternate that would. The design builds on the fact that in order to search ~ 1 arcsec search field for exoplanets, TPF must suppress the starlight halo in this region by control of the wavefront Fourier components down to ~ 0.2 m period, on the basis of focal plane measurements (Malbet et al, 1995, Codona and Angel, 2004). Such control could be realized with a small deformable mirror conjugated to the primary, but we will consider the alternate in which the primary mirror system itself would incorporate the necessary actuators, about 200/m^2 for a total of ~ 4000. The density of actuators is high enough that sag under 1g axial load can be made acceptable without the active primary being too heavy. Consider the primary as a thin meniscus mirror connected by a field of position actuators in a triangular grid to a rigid support truss (e.g. Baiocchi & Burge, 2003). The quilting pattern introduced by gravity will depend on the meniscus thickness. If we choose a meniscus of Zerodur 1 cm thick, weighing an acceptable 600 kg, the rms surface quilting would be ~1 nm rms, causing only ~0.1% reduction in Strehl. The high-order, low-amplitude distortion in a regular pattern would not prevent direct ground testing of the complete system at the desired 10^{-10} contrast level. The meniscus could be made by the method currently used at the Mirror Lab for adaptive secondary mirrors, in which the front surface is figured first on a relatively thick meniscus of Zerodur, and the back surface is subsequently thinned and polished to remove stresses (Martin et al, 2000).

The test collimator for TPF-C could be made as a twin of the flight primary, and indeed would be especially valuable if made first as the flight prototype. It would be tested in autocollimation against the liquid flat to validate fabrication and used as a test bed for suppression methods for the flight system.

5. CONCLUSIONS

The argument is sometimes made that ultimately space systems will become so large that it will not be possible to make such full aperture tests, so we might as well accept the inevitable and live with incomplete tests now. However, here we have shown that full system tests of future large active space telescopes can be made prior to launch, provided the telescopes are designed from the start with this in mind. It would appear that the accommodations for such testing need not degrade on-orbit performance, or increase mass. The combination of fully ground-testable integrated spacecraft/optical systems and small, easily manufacturable segments should lower costs and greatly increase on-orbit reliability. The cost of the full system test equipment should be manageable, since ground optical systems have so far always been much less expensive than those of the same aperture built for space.

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