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Apertures for Segmented Coronagraph Design and Analysis

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ABSTRACT

The Astrophysics Division and the Exoplanet Exploration Program (ExEP) Office wish to determine the scientific performance of candidate coronagraph instruments for large space telescope with segmented, obscured apertures. This whitepaper defines 7 segmented aperture architectures and 6 obscuration architectures, and provides a ranking of their relative merits with respect to segmentation, backplane configuration, stability, launch complexity, and secondary mirror support. These architectures are intended to be used by coronagraph designers in their evaluation of system level performance under SCDA task funded by ExEP.

I. Introduction

In support of possible future mission concepts, ExEP would like to understand the ability of coronagraphs working with segmented and obscured telescope apertures to probe the habitable zones of a large sample of nearby stars and directly image exo-Earths. Reaching contrast ratio levels of 10^{-10} at close inner working angles (IWA) to detect the reflected visible light of exo-Earths is an extremely challenging undertaking that has never been achieved experimentally with segmented, obscured apertures in either narrow-band or broadband light. The first step in achieving this goal is to identify coronagraph designs that work with realistic apertures. For this study, we are considering only filled apertures (with the necessary segment gaps and secondary obscurations). Other forms of direct imaging, e.g. distributed aperture interferometry, are not part of the considered trade space.

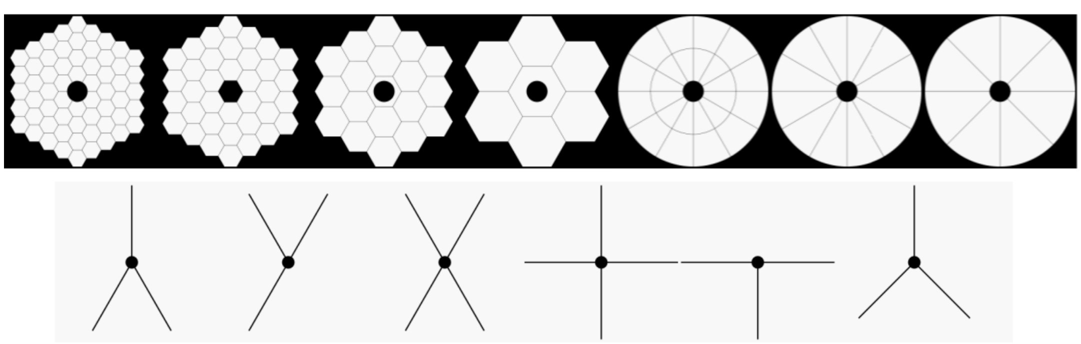

Figure 1 Apertures and secondary support structures selected for the study include four composed of hexagonal segments, one with keystone segments, and 2 with pie wedges. All are 12 m flat-to-flat or 12 m in diameter with 1.68 m diameter secondary obscurations (except the missing hex segment in the 3-ring hex). All segment edge gaps including edge roll-off are 20 mm wide. Secondary support strut widths are 25 mm and 100 mm. Aperture names, from left to right, are: 4-ring Hex, 3-ring Hex, 2-ring Hex, 1-ring Hex, Keystone-24, Pie wedge-12, and Pie wedge-8. Secondary supports are referred to as “Y”, “y,” “X”, and “T,” with two versions of “X” and “Y” for the respective hex and circular apertures.

This whitepaper provides the rationale behind the selection of these segmented, obscured apertures, and discusses their relative merits based on the current state of the art. The selected architectures are intended to be representative of demonstrated large segmented aperture telescopes ranging from the James Webb Space Telescope (JWST) to the Large Advanced Mirror Program (LAMP, Appendix A). The seven apertures defined for this study are shown in Figure 1. To facilitate an "apples to apples" performance comparison and because the "Cosmic Birth to Living Earth" report (http://www.hdstvision.org/report/) called for a 12-m class telescope, all apertures are assumed to be 12 m wide.

The primary mirror (PM) is designed with an f/# of 1.25 and is nearly parabolic (k=-.9929). The secondary mirror is 13.1 m from the PM, leading to Cassegrain f/# of 9.8 and secondary diameter of 1.68 m (=14 % of the primary diameter). The PM f/# and SM diameter were chosen to balance the strong sensitivity of coronagraphs to the size of the central obscuration and to polarization aberrations, with the need to support wide-field imaging for astrophysics instruments. At f/1.25, it is expected that two separate polarization channels will be needed, each with its own wavefront control system. At faster f/#, cross-polarization (one linear polarization being coupled into the orthogonal one) becomes significant and limits performance at small working angles even in single polarization coronagraph channels.

The Cassegrain focus (where the coronagraph would exist) has a 10 arcsec x 10arcsec FOV, over which it has diffraction-limited performance. We imagine the coronagraph would view the central portion of that, say ~1.5 arcsec x 1.5 arcsec. The UV instrument(s) would use the rest of that FOV. The entire TMA focus FOV is ~12 x 8 arcmin, over which it has diffraction-limited performance.

It is recognized that segment gap size is a critical parameter for the performance of many coronagraph designs. A review of the state of the art in mirror fabrication led to the conclusion that segment gaps, inclusive of segment spacing and edge roll-off to optical quality surfaces, could be as narrow as 20 mm.

Table 1 Relative challenges of designs under consideration. Green to red designates least to most challenging. No absolute scale of difficulty is implied, and the relative challenge scale of each row may be different.

	APERTURES						
	4 ring	3 ring	2 ring	1 ring	Keystone 24	Pie wedge 12	Pie wedge 8
Segment Shape	Hex	Hex	Hex	Hex	Keystone	Pie wedge	Pie wedge
Max Segm. Dimension	1.54 m	1.98 m	2.77 m	4.62 m	2.5 m x 3.14 m	5 m x 3.14 m	5 m x 4.71 m
Segments							
Backplane							
Stability							
Launch Configuration							
SM Support							
Overall Ranking							

Likewise, many coronagraph designs are highly sensitive to the width of the secondary support struts. The designs shown in figure 1 are considered with two widths, 2.5 cm, and 10 cm. Obviously the 2.5 cm width will lead to improved coronagraph performance. The 10 cm struts are similar to JWST construction while the 2.5 cm struts would be deeper. The 2.5 cm have been analyzed through an integrated modeling run of the 9.2 m ATLAST reference architecture to show there are no significant changes in line of sight or wavefront performance compared to their nominal JWST-like strut design. However, additional study will be needed to verify the performance for a 12 m aperture.

The SCDA aperture design group used their collective expertise in the field to compare the apertures in the areas of segment configuration, backplane configuration, stability, secondary mirror support, and launch configuration. Table 1 shows a “stop light” comparison of the perceived relative challenges of the seven apertures. This whitepaper discusses these challenges. All apertures are deemed “buildable” though some will require significant new infrastructure including fabrication, assembly & integration, and test facilities, to address the space environment and deployable aspects. Some will be significantly more challenging to build, test, and deploy.

Finally, it should be noted that this work is quantitative and judgement-based without detailed engineering assessment. Its purpose is only to show on a comparative basis, the expected difficulty of building the chosen apertures to the expected requirements for the purpose of informing coronagraph designers of the aperture challenges. It’s an attempt to bridge the gap between coronagraph instrument designers and segmented telescope designers. It’s not a detailed engineering study and it only represents a sampling of opinions from this group and not the larger astronomical community.

II. Segment Configuration

The segment configurations (Figure 1) define a range from JWST-like hex segments of various sizes to keystone and wedge shapes. For the purposes of this initial study, the team has assumed that Corning ULE® glass or a glass ceramic such as Schott Zerodur or Ohara Clearceram-Z are the most likely material choices for the mission. It is believed that these materials are compatible with the high quality mirror surfaces, very low CTE and high stability characteristics required for these types of mirror assemblies.

The various configurations all have advantages and disadvantages from a manufacturability and existing infrastructure standpoint. These issues will be briefly discussed below:

4-ring Hex: This mirror configuration consists of segments 1.54 m tip-to-tip. Mirrors of this type have been manufactured and tested through several development programs since 2001. Mirrors as light as 10 kg/m^2 have gone through shock and vibration testing. A parabola has been completed at 8nm rms surface quality. Some production level development is required but this configuration offers the lowest overall risk for manufacturing.

Trades have compared the sensitivity of wavefront error to decentering, clocking, tilts, and Radius of Curvature (RoC) control as a function of the size for semi-rigid segments. Wavefront sensitivity is large for large mirrors and decreases with size with diminishing return as mirror size gets smaller. For a JWST optical prescription, wavefront sensitivity and pose resolution indicate a sweet spot in the 1 to 2 meter size range. The RoC stability does not couple to backplane stability. However, the pose stability does and leads to constraints on backplane stability.

An alternative that alleviates the sensitivity to pose errors of rigid or semi-rigid mirrors is high-authority control of the mirror surface. Implementations of high-authority control which place actuators between the mirror and backplane will require very good backplane stability. Other implementations which use in-plane actuation in the mirror substrate are less sensitive to backplane stability. Both cases require a stable adaptive wavefront sense and control system with its concomitant added complexity.

3-ring Hex: This configuration consists of 2-m tip-to-tip segments. These are slightly less mature than the 1.54m segments and are likely to require some minor engineering development prior to production.

Gravity testing would also be more challenging due to gravity-induced quilting and the ability to analytically back this error out to a few percent modeling error uncertainty during verification testing. However, this concern is mitigated by the demonstrated ability on HST to back-out gravity sag on a 2.4-m mirror to an uncertainty of 1.4 nm rms.

Concepts for load distribution and mounting interfaces to a backplane reaction structure for rigid body pose control are similar to the 4-ring hex, but will require stiffer design to compensate for the larger size to achieve the same level of mirror distortion for equal loads such as 1-g sag during ground operations. The increased sensitivity to rigid body pose and RoC stability due to size will increase the requirements on mirror stability (RoC) and backplane stability (pose). The increased size also leads to increased mass that is supported by the backplane which factors into the dynamics of the integrated system.

2-ring Hex: At 4m tip-to-tip, these large segments will need engineering development in order to survive launch loads. Also, it will be harder to back-out gravity sag error. Both challenges require stiff, *(i.e*. deep) mirrors. The ability to make closed-back ULE mirrors to at least 40 cm depth has been demonstrated. Open-back Zerodur mirrors can also achieve this depth, but the manufacturing process has added risk. Finally, 4-m is reaching the limit of current infrastructure for both closed-back ULE mirrors and open-back Zerodur mirrors.

Concepts for load distribution and mounting interfaces to a backplane reaction structure are different for a 2-ring or 1-ring or even petal architectures than for the 3 or 4-ring hex architectures. Therefore, analysis is required. However, preliminary point designs have been produced that show how existing technology and design principles produce a backplane capable of supporting a mirror with mass ranging from 2 metric tons (mt) to 20 mt during launch and providing a 20 Hz first-mode reaction structure on-orbit. As a point of comparison, the JWST backplane structure first mode frequency is ~16 Hz. One reason that the backplane for fewer segments can be stiffer than a backplane for many segments is because it does not need to be as large. It does not need to be larger than the maximum interface attach point. However this advantage is offset by the more demanding limitation on the amplitude of the 6 DoF response of the segments, which in turn leads to a more difficult rigid body pose control problem. These rigid body errors are low-order, i.e. piston, tilt, astigmatism, and can be mitigated with in-plane actuation or warping harness. The alternative is to move to a high-authority architecture with multiple actuators between the mirror and backplane to alleviate the stiffness demands, but a high-authority architecture requires a more intertwined and interactive system between mirror and backplane. The stability of the backplane becomes integral to the stability of the mirror surface and not just the pose, resulting in a more complicated high degree of freedom control problem.

1-ring Hex: These are very large segments at 4.6 m tip-to-tip that may require new infrastructure for manufacturing and coating of large ultra-lightweight mirrors. Comments for interfaces and pose sensitivity for the 1-ring Hex are similar to the 2-ring Hex, but are amplified by the size, with the semi-rigid concept being less likely.

Keystone-24: The keystone shape with its near 90 degree corners adds a layer of complexity to the processing. But, the National Ignition Facility optics also had 90 degree corners. The size, with segment arc lengths of up to 3.14 m, is also challenging to the current infrastructure. Again, open backed mirrors would be very deep.

The asymmetry of the segment shapes complicates the load distribution and mounting interfaces, forcing a higher degree of authority for contact points on the substrate. For example, for studies done for JWST (NGST), keystone segments required 5-point mounts whereas the hexagonal segments used 3-point mounts. Also, the simple concept of a single floating RoC actuator for the hexagonal symmetry is not possible with the keystone shape. The rigid body sensitivities also increase. The larger area and shape will likely lead to a higher degree of authority of active control reacting to the backplane. The high authority control with the asymmetric shape is more complicated with cross-talk among actuation modes. Stability will depend on the integrated stability of the intertwined system of mirror, mounting, and backplane.

Pie wedge-12 and Pie wedge-8: These large segments with asymmetrical shapes will challenge the manufacturing and processing technology required to meet the stringent optical requirements. New infrastructure would be required for closed back designs and extreme machining depths for the open backed designs. Gravity testing would be equally challenging.

The comments about interface complexity for these two options are similar to those given for the Keystone design.

It is important to emphasize the impact of segment size on the ability to test on Earth in 1-g. Measuring the 0-g figure is often done by rotating the segment to apply the gravity load in opposite directions, either face-up/face-down or rotation with the mirror surface normal horizontal. The horizontal rotation test is more amenable to symmetric segments. A small gravity-induced deformation is desired because this type of test is essentially a subtraction method. To attain a small self-induced gravity deflection requires a stiffer mounting structure and stiffer mirror. This is harder for larger segments, requiring more wavefront allocation to this metrology when conducting ground testing. This can be mitigated by stiffer, more massive mirrors, mounting, and support structures, but these complicate gravity offloading and test complexity. Further, to be able to move the mirrors in the presence of gravity requires actuators with higher force capability and more actuation range.

Segment size and shape further impacts the ability to control the overall surface figure. Testing of individual smaller segments allows a higher degree of control due to the greater spatial sampling. Because of their length, pie shape segments have limited spatial sampling in the radial direction. To achieve a high Strehl ratio for large or pie shaped segments requires higher spatial resolution metrology, tighter I&T, deployment requirements, and accounting for end-of-life effects. Warping harnesses or deformable mirrors could overcome these issues, but these increase the overall complexity or require significant actuation range for the deformable mirror. This defines a significant trade space for the system architecture.

III. Backplane Configuration

The backplane/metering structure is used to support, align and deploy the segmented apertures. For this initial study, we have not assumed a particular material for the backplane but a composite or otherwise high-stability backplane construction is needed. It is assumed that some level of backplane deployment is required to fit within current or planned (SLS) launch vehicle shrouds. It is further assumed that, unlike JWST, the LUVOIR-type telescope will not be cryogenic and thus the very difficult cryo cooldown, cryo stability, launch and gravity load combination is relaxed.

As a guideline the backplane needs to have the mechanical strength to withstand launch loads and must have sufficient stiffness to react against the forces needed to control the segment's positions. This stiffness may vary depending upon whether segment position is controlled via passive, active, or fully adaptive means. The dynamic reaction loads of a fully adaptive primary may require a stiffer structure than the other positioning methods. In addition a stiff structure is needed to avoid structural coupling between mirrors.

To achieve diffraction-limited performance at 500 nm wavelength requires a primary mirror surface figure error of <10 nm rms of surface error. The driving backplane issue is that the mirror will suffer static and dynamic distortion due to loads from the backplane. Careful mounting of the segments through kinematic or quasi-kinematic arrangement is needed to avoid these loads. Symmetric mounting of hexagonal mirrors may induce less distortion and lower spatial order distortion and may thus be easier to correct with less residual error than the asymmetric mounting needed for the keystone and Pie wedge mirrors. It is technically possible (*e.g.,* Keck, LAMP, ALOT, AOSD, etc. see Appendix of this whitepaper) to correct distortion with warping harnesses or actuators. But this approach has a downside in terms of complexity, mass, and residual uncorrectable distortion. The backplane scaling rule carries over to pre-launch testing. The backplane gravity sag must be small enough to avoid undue distortion or require large actuation range.

Independent of architecture, to achieve on-orbit UVO performance, the backplane needs to be as stiff as possible. Backplane state of the art is represented by JWST and LAMP. Both of their backplanes had a first mode frequency of less than 20 Hz. To first order, all structures have the same scaling relationships. The natural frequency of the mirror and backplane roughly scales as the sqrt(stiffness/mass). Or frequency scales inversely with diameter squared, proportional to thickness to the 3/2 power, and inversely with square root of areal density. Thus, to maintain constant frequency: as the backplane becomes larger, it needs to become deeper; or, if mass is needed to provide sufficient support to the mirrors to survive launch, then it needs to become deeper. Additionally, the effect of higher mass is amplified when the moment of inertia of larger mirrors is considered. Architectures which require more massive mirror segments may require more massive launch support structure, but the exact nature of this structure will vary depending upon design details.

In summary, this is a very complicated systems engineering problem. In the case of JWST, both 18-segment and 36-segment architectures were considered. And, it was decided to go with an 18-segment design. For a potential Large UV-Optical-IR telescope, careful analysis is required to determine which opto-mechanical architecture will achieve the desired performance. Larger mirrors are more difficult to support by the backplane and their rigid body motions produce larger wavefront errors. But they are less influenced by backplane motion which may minimize the amplitude of their rigid body motion. And, their rigid body motions produce lower spatial frequency errors that may be easier to control by downstream correctors. Conversely, smaller mirrors are easier to support and are less sensitive to rigid body motion. But, they are more sensitive to backplane motion and they produce higher spatial frequency errors.

IV. Stability

Stability requirements are critical to the performance of high contrast segmented telescopes. To detect planets at a contrast levels 10^{-10}, 10^{-11} contrast stability is required. This level of stability equates to approximately 10 picometers of uncorrected residual wavefront error over the bandpass of the control system, and this is required for timescales of minutes to hours depending on the target star. A somewhat conservative approach is to set the system level specification of approximately 4 hours for the stability bandpass to assure robustness and margin. This stability bandpass duration includes thermal stability, dynamics stability, and other material-related property stability terms. Given that different coronagraph instruments may have different sensitivities to different types of wavefront error, analysis will determine the required amplitude for each error type. The spatial frequencies of greatest concern are based on the desired IWA to OWA range of 1-10 λ/D. To avoid aliasing, we assume stability over 1-30 cycles across the full primary aperture.

Fortunately, there are sense and control schemes that can be very fast. One method is to use feed forward type control algorithms with a segmented or continuous DM. Others are laser metrology or edge sensors. However, the speed and complexity of the control loop is a function of the number of degrees of freedom. DMs have a limited number of segments or actuators which also limits the controllable spatial frequency band. They do have the capability to control at least some rigid body motions of segments and this looks like a feasible approach for some forms of stability (*e.g.,* thermal changes of the backplane). Higher order changes in the primary mirror (PM) segments cannot be corrected easily and therefore are best controlled at the PM. Mirrors that can achieve better segment stability will make the overall sense and control problem easier (and probably feasible).

With this in mind, we assess the different mirror architectures based on how well they can achieve segment level stability, especially with respect to aberrations that would be in the 1-30 cycle range. Several considerations include:

1. Thermal stability of an individual segment is dominated by front-to-back gradients and the resulting wavefront varies with the radius^2. The wavefront due to these gradients also varies linearly with bulk CTE and the delta T used.
2. Thermal stability of an individual segment depends on the thermal mass and thermal time constant of the segment. The longer the segment's thermal time constant relative to the thermal control system's bandwidth, the less the wavefront will change due to fluctuations in the thermal control system. Increasing thermal mass and hence thermal time constant yields exponential stability improvement. (see Brook, Stahl and Arnold, "Advanced Mirror Technology Development (AMTD) thermal trade studies", SPIE 2015.)
3. Dynamic stability is such that the first mode frequency varies inversely with radius^2 and with thickness^3 (this assumes a simple circular plate; see "Space Telescope Design Considerations" Feinberg et al, Optical Engineering, Feb 2012 for more details).

For thermal stability, we have chosen a 1mK control temperature range in part because sensor resolution is 10-15X better than that. For dynamics, we typically want the first mode of the mirror to be well above the highest reaction wheel speed and look at harmonics at 6x the disturbance frequency. For this reason, we have initially set 500 Hz as a goal for segments. However, this drives not only the development and cost of increasingly large segments, but also the challenges of the whiffle trees and actuators behind the mirror segments. Input disturbances will also affect the stiffness and cross section needed by the secondary mirror supports to avoid harmonic coupling, leading to solid body displacements of the secondary mirror at perhaps 10 Hz. A trade is needed between reducing the disturbance level and developing large, stiff structures driven by the disturbances.

Based on these considerations, for constant mass mirrors, the most stable mirror segments will be the smallest. Work studying mirror stability and published in SPIE ([1] "ATLAST ULE Mirror Segment Performance Analytical Predictions Based on Thermally Induced Distortions" (Eisenhower, Park, Feinberg et al.) has shown that 1-2 picometers RMS WFE is realizable with 1.5-m class ULE mirrors using a bang-bang thermal control approach (in terms of sensor resolution and architecture). Similarly, work studying mirror stability and published in SPIE (Brook, Stahl and Arnold, "Advanced Mirror Technology Development (AMTD) thermal trade studies", SPIE 2015) shows that an equal level of stability can be realized for a 4-m class ULE mirror with appropriate thermal mass using a proportional thermal control approach. A potential challenge to using thermal mass is to maintain the mirror at its set point with longer stability durations. This problem may be eliminated via the use of a predictive thermal control algorithm.

Because the thermal stability goes with radius squared, a large segment (say 5 meters) can have 10x larger changes than a small segment (say 1.5 meter). But, then one must also consider the spatial frequency of these errors, their impact on coronagraph performance and the ability of the DMs to correct them.

Other architecture-specific considerations for stability include how mounts and lightweight ribs print-through the thin face sheets at the picometer scale. If not over constrained and properly flexured, mirrors will move as rigid bodies. However, the use of actuators that react with the backplane makes this more challenging, as is the case for larger segments which require actuators for removing gravity sag. Gravity distortion of the JWST mirrors is 100-200 nm RMS and there is a 5-10% model uncertainty associated with that. In order to meet a 10 nm total segment WFE budget for general class science, segment gravity error will have to be below 50 nm which means roughly 2x less than JWST segments. Since stiffness scales inversely with radius^2, the JWST segment size (4-ring Hex) is already challenged to improve stiffness to achieve this.

In summary, for any of the segmented apertures, achieving picometer stability is going to be extremely difficult. Preliminary assessment indicates that the higher the mirror's stiffness, the better it will be for dynamics stability and for avoiding gravity actuators.

V. Launch Complexity

The launch complexity for the primary mirror and secondary support structure is a function of mass, volume and overall number of deployments. This discussion presumes that the mass function of the deployment mechanisms is largely independent of segment size because larger mirrors require more massive actuators whereas an aperture of smaller segments requires more actuators. However, depending upon how the segments are attached to the backplane and the control-authority architecture, there may be differences in the volume and mass of the backplane structure. For a small segment architecture, to achieve stable on-orbit performance, the backplane needs to be very stiff and thus very deep. This depth could place significant constraints on packaging volume. Conversely, for large segment architecture, the backplane needs to be able to react to launch loads and thus needs to be more massive.

For volume considerations, if the launch vehicle is large enough to accommodate the full volume without folding then there is no preferred aperture. But in general, as we push to larger diameters to improve resolution and collecting area this is not the case. So, we assume some level of deployment of the primary mirrors and secondary mirror (Figure 2). There are also many deployment schemes from table-fold (JWST-like), fold-forward/fold-aft (Lockheed JWST concept), segment stacking (HARD-like, see Appendix A), 'Sunflower' (see Appendix A), segment hinged clam shell (AOSD-like, see Appendix A), and multi-fold (multiple table folds). As segments grow in size approaching the launch vehicle diameter, non-table fold arrangements must be considered. But at this time for optical imaging and coronagraph quality telescopes, these arrangements are speculative (although they have design heritage for radio telescopes and optical communication.) Mechanical engineers are clever in the myriad ways of considering deployments, but for the purpose of this discussion only table and multi-folds are considered further because they have JWST design heritage. There is heritage for other deployments, but they are not considered in this whitepaper. On-orbit assembly is not considered due to the low TRL level and space infrastructure needs.

Folding requires space either in front of the aperture or behind it. Folding the front of the aperture complicates the secondary mirror support, while folding behind requires allowance for the spacecraft volume, backplane, and instruments. In order to maintain a stable platform for the secondary, it is desired to not have fold lines between the base supports. Table-folds that require the mirror to be unsupported over much of its area are a drawback to stability and gravity sag. But additional strongback structure between the mirror and the backplane could be considered. This is likely a drawback to overall performance.

Any radial segment architecture, such as the pie-wedge design, requires either fold-forward/fold-aft or clam shell or even 'sunflower' deployment. If there is a central mirror, then deployment occurs at the boundary between that mirror and the outer segments. Given the small central obscuration, folding aft doesn't allow much room for backplane or other structure. Folding forward provides very little room for a secondary support structure. A non-90 degree fold could be accomplished and this may provide enough room to package the petals. It is possible to have the backplane hinge further out from the inner edge to ameliorate this problem.

The hexagonal shape is most well-suited to a 'table-fold' style as there is the most support for each mirror along lines parallel to the fold. Each chord of segments can have a fold in this style. Smaller mirrors or a more segmented aperture offer more options for folding and then deploying to transition from launch configuration to operational configuration. The minimum fold spacing is set by the spacing of the

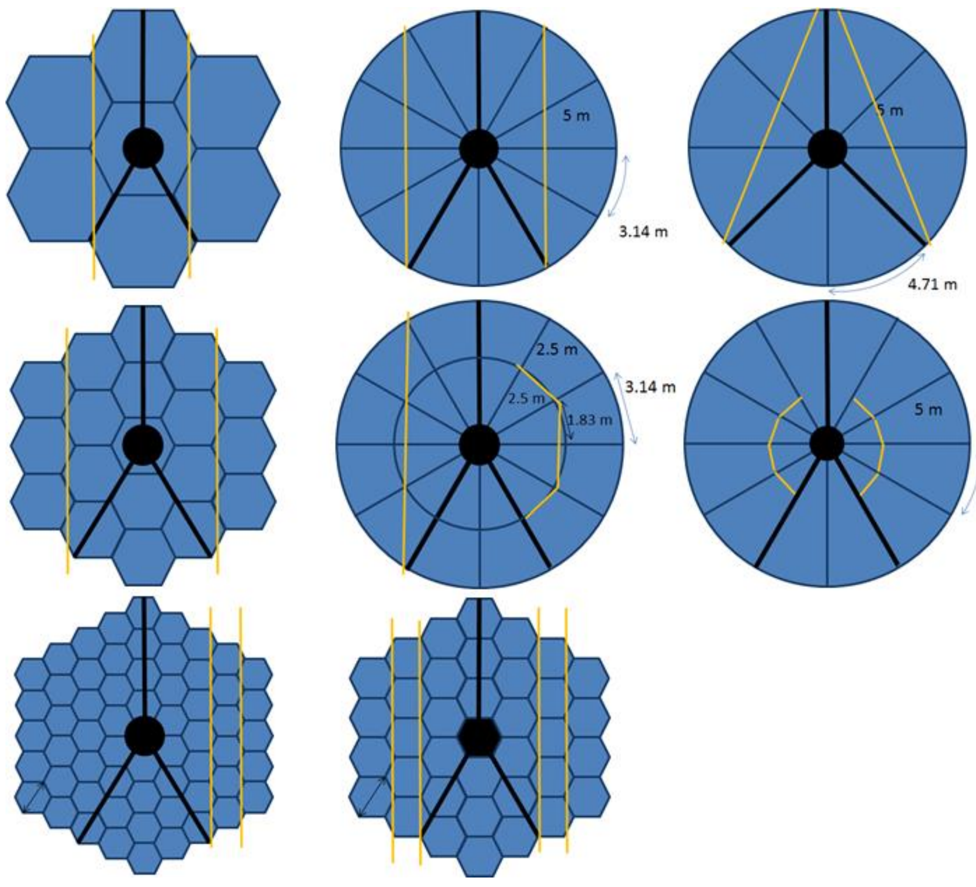

Figure 2 Some possible fold lines.

secondary mirror struts. The apertures with 3 or more rings can have multiple folds to improve packaging at the expense of backplane stiffness.

From Figure 2, the pie wedge using a compound fold is likely preferable to single parallel folds and allows a combination of forward and backward deployments. The pie wedge designs do not appear suitable for a single table fold because of the difficulty of supporting segments with a large cantilever. As drawn, each of the apertures delivers similar stowed width except the 8 pie wedge aperture which has wider secondary stance.

It is assumed that each segment and hinge are deployed; this includes mechanisms for launch lock and deploying segments off of snubbers. For segments, only a single actuation is counted (even though in some cases a mechanism such as a hexapod may be used), and for the hinge only a signal actuation is counted as well (Table 2). This underestimates the number of actuators and hinges and latches actually required, but the table is useful for a relative comparison.

Table 2 Deployment actuator count

	Segments	Hinge Lines	Total
1-ring Hex	6	2	8
2-ring Hex	18	2	20
3-ring Hex	36	2	38
4-ring Hex	60	2	62
24 Keystone-1 fold	24	2	26
24 Keystone-3 fold	24	6	30
12 pie 1 fold	12	2	14
12 pie 4 fold	12	8	20
8 Pie wedge	8	2	10

VI. Secondary Support

Given the assumptions on obscuration and primary mirror prescription, the secondary needs to be positioned more than 10 meters away from the primary. Since this is larger than most launch configurations, deployment of some type is assumed. Four structures were considered for supporting, aligning and deploying the secondary mirror: 'X', 'Y', 'y', and 'T' as shown in Figure 1. More complex shapes like the WFIRST 6-strut system were not considered due to deployment complexity. A single tower style was also not considered at this time.

Only those approaches requiring hinges and latches integral to the support system have been considered; exotic deployments such as free-floating legs that latch post-deployment may offer some advantages but are left for future studies. It should be noted that for the purposes of this initial study, the team has not assumed a particular material for the secondary support but composite struts or otherwise high-stability support construction are needed.

As with the backplane, the secondary support needs to have the mechanical strength to withstand the loads during launch and provide a stiff enough reaction force structure to allow the secondary to be positioned passively, actively or fully adaptively. For the fully adaptive case, the dynamic reaction loads require a stiffer structure than the other positioning methods. The stability of the secondary is driven by the connection to the backplane and the inherent stiffness of the support structure geometry. For example, a Hubble-style truss-tube secondary structure is stiffer than a JWST-style 3-leg secondary structure.

The 'X' and 'Y' supports provide a symmetric load where the forces can be balanced. This aids both on-orbit and with testing in 1-g. In this regard the 'X' and 'Y' are preferable to the 'y' and 'T' configurations.

The 'Y' and 'T' configurations allow single degree-of-freedom hinges and latches. The 'y' configuration requires a multi-axis hinge on the single strut; this is more complex and likely less stable and repeatable. The 'X' configuration requires either deployable booms or multiple hinges and latches on each leg.

The 'T' configuration has the longest effective baseline which should provide higher geometric stiffness and thus better stability assuming that the backplane deployment hinge lines do not disrupt the backplane stability for this mounting.

The table-fold designs have a stiff, monolithic center section and have a stable platform for the secondary mirror attachments. This may not be the case for the keystone and pie wedge apertures with multi-fold deployments (Figure 2). For the keystone and pie wedge, either a narrow support baseline or accordion-folding with additional hinges can be employed; both may reduce stiffness and stability of the secondary support depending upon the backplane design.

VII. Additional Comments

Due to time constraints and the wide experience base of the co-authors, the team did not reach consensus in some areas. This assessment was not able to fully analyze the detailed questions associated with large segments, particularly with respect to higher mass. While this issue may not necessarily change the color codes provided, it has the potential to necessitate new categories be included and would warrant further study if large segment solutions are to be fully understood. The rationale for this goes as follows: For constant stiffness, large segments will be thicker and, with backing structure, will weigh significantly more but the implications of this additional mass are not well understood. Even using JWST stiffness, a large (example 4m meter) segment will be approximately 3-5x high areal density than a 1.3m mirror and the backplane will add an additional 1.5-2x factor (so total of 5-10x more areal density). On a 12m mirror, this will have implications in the 1000's of Kg's. While the rocket itself may be able to handle considerably more mass in the case of SLS, the additional mass possibility is beyond heritage and introduces many new risks that require study.

A key lesson learned from JWST was how mass drove so many of the difficult technical issues. A few examples of key recent issues for JWST are launch restraint mechanisms which had to accommodate larger loads than previously used on launch restraint devices and thus a whole new larger device was developed that has been challenging to manufacture. This issue has been the JWST Top issue for several years. Another key technical issue is the new larger shakers required (beyond anything NASA already has) which have been difficult to build and are required to environmentally test the system. Another key area are 1-G deployments on the ground which now would have to be done with far more mass, perhaps even exceeding crane capabilities in some cases. JWST was able to get by with minimal offloading which would be extremely complicated to implement during testing and/or deployments. JWST latches and hinges were able to leverage systems used for Chandra and since latches, hinges, and the backplane structure all have to hold mass in the 1-G environment and then during launch itself, the requirements on these could grow considerably outside of heritage with larger mass. These are just a few examples of how larger mass impacted JWST and justify the point that handling the large masses in the case of larger mirrors requires extensive study. More generically, higher mass causes larger launch loads which drive strength requirements, racking strain due to larger mass, more offloading which adds more uncertainty, more low frequency modes which impacts pointing, more self-induced gravity on mirrors which makes them harder to polish to 0-G, means larger reaction wheels and cause more jitter, and can even mean less reserve mass for fuel and thus lifetime.

Our expectation is that we will find engineering solutions to the new issues, but the costs and risks of dealing with larger mass could be considerable and are unknown and not well quantified in this assessment. Our experience from working with cost modeling teams is that mass plays a significant role in the cost of the observatory when structure and deployments are included and our experience is that this relationship is justified.

Other areas where consensus was not reached include: whether the backplane would be easier or harder for many small segments versus fewer large segments; the significance of the technology difference associated with launch configuration and SM support between each architecture; and finally, while there is agreement that the current ability to make ULE or Zerodur mirrors is approximately 4 meters – which is why 5-m class mirrors are 'red' – mirrors of both materials have been made as large as 8 meters and could be made again at this size. This is more of an infrastructure issue than a technology issue and hence maybe should not be red.

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APPENDIX A: Survey of Historical Segmented Telescopes

Given the cost and risk of space telescopes, it is generally considered good practice to use concepts which have been proven on the ground. Figure A-1 shows a compilation of historical, existing and planned telescopes. It is instructive to observe that, while some of the apertures are sparse (e.g. MMT and LBT), most are either monolithic or filled with hexagonal segments. Also, one can observe that telescopes have moved back and forth between monolithic and segmented. Historically, segmented apertures are used when the technology does not exist to affordably produce a monolithic mirror of the desired size and with the desired performance.

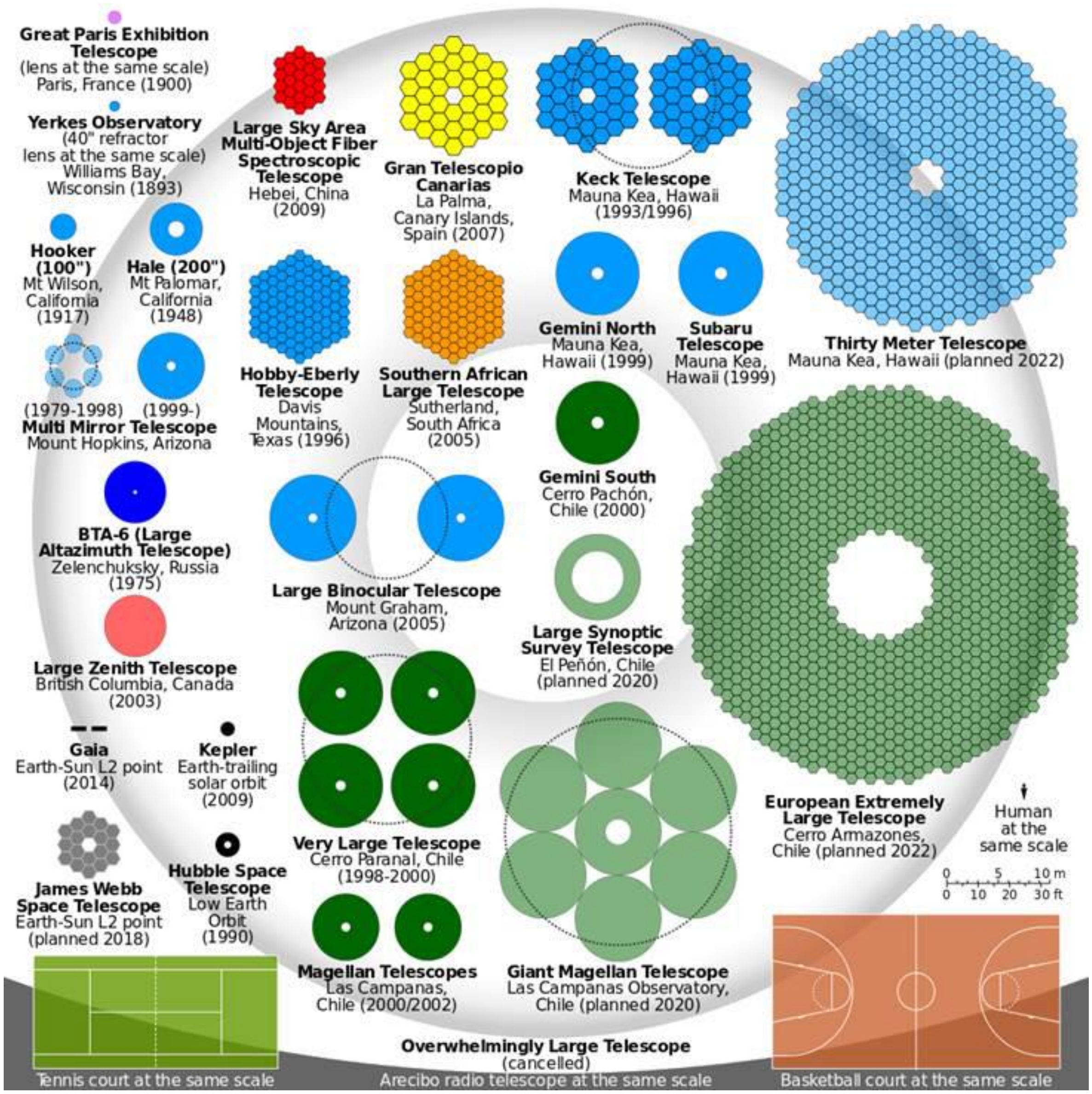


Figure A-1 Relative size and segmentation of selected astronomical telescopes (from Wikipedia

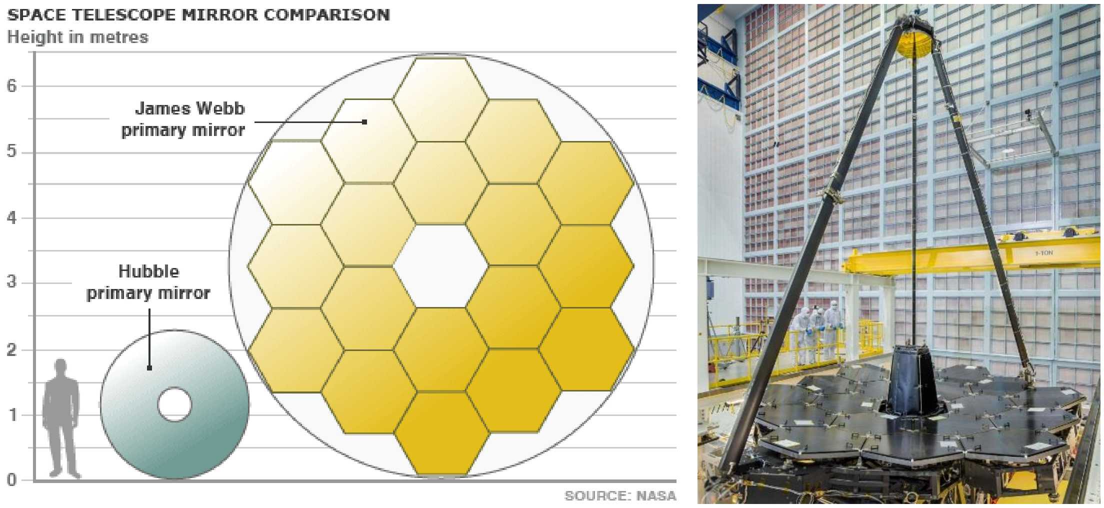


Figure A-2 James Webb Space Telescope

It is important to note that this graphic is not complete. It does not include segmented sub-millimeter telescopes such as Segmented Mirror Telescope (SMT) and 12-m Reflector, which tend to use trapezoid segments and several Department of Defense (DoD) telescopes and test beds, including: Large Advanced Mirror Program (LAMP), Adaptive Large Optics Technologies Project (ALOT), Advanced Optical Systems Demonstrator (AOSD), Sunflower and High Accuracy Reflector Demonstration (HARD). These are all viable architectures for potential large aperture space telescopes. Both LAMP and A LOT were considered for JWST.

James Webb Space Telescope

The James Webb Space Telescope (JWST, Figure A-2) primary mirror is 6.5 meters in diameter consisting of 18 1.3 meter hexagonal segments (in two rings). The maximum gap size between optical surface areas is 30 mm. The secondary mirror is 0.74 meters diameter and is supported by three legs. Each segment has a surface figure error < 20 nm rms. Total primary mirror surface figure error is ~ 25 nm rms. Segment phasing is controlled to ~ 20 nm rms via passive vibration isolation. The telescope is diffraction limited at 2 micrometers. Areal Density of the Primary Mirror Assembly is 70 kg/m^2.

Keck

The Keck Telescope (Figure A-3) primary mirror is 10 meters in diameter consisting of 36 1.8-meter hexagonal segments. Segment edges are 2-= mm and the gap between segments is 3 mm. Segments are 'figured' via warping to < 80 nm rms (Keck Telescope Wavefront Errors, 13 March 2007). Segment phasing of ~100 nm rms is controlled by edge sensors. Total primary mirror surface error is approximately 100 nm rms (5X JWST). The telescope is diffraction limited at 10 micrometers. Areal density of the mirror assembly is 190 kg/m^2.

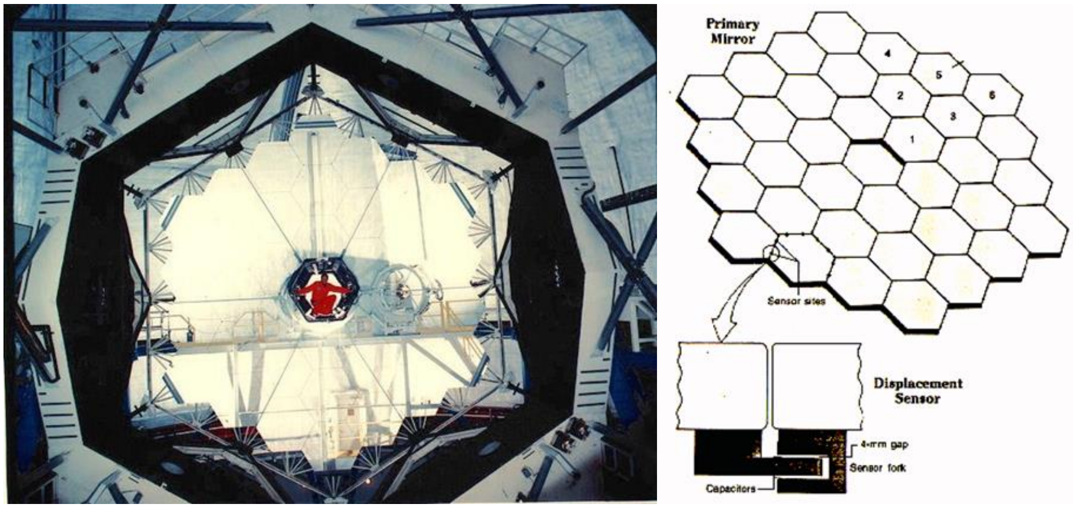


Figure A-3 Keck Telescope

Large Advanced Mirror Program

The following passage is extracted from "*A Scientific Assessment of a New Technology Orbital Telescope*", National Academy (1995):

"The Large Advanced Mirror Program (LAMP) was a ground demonstration of a 4-meter, actively controlled, segmented mirror. Each of its seven, 2-meter, quasi-hexagonal segments was approximately 17 mm thick and attached to surface control actuators mounted in a stiff, lightweight graphite-epoxy back-up structure. A total of 312 surface control actuators and 42 segment position actuators enabled the LAMP mirror to be controlled so as to yield a wavefront accuracy of better than 100 nm rms. The LAMP mirror was subsequently installed as the beam expander for a hydrogen fluoride laser at the San Juan Capistrano test range in California."

The below images show a schematic and photo of LAMP located in the Capistrano test facility. The LAMP primary mirror figure was controlled via a center of curvature wavefront sensor. The gold circular patches on the primary mirror are holograms which directed a portion of the light into a Hartmann sensor for active wavefront control. Segment phasing was controlled via edge sensors with a resolution of 60 nm. Areal Density is 140 kg/m^2. LAMP saw first light in 1996 and was operated in vacuum over 24 times.

Adaptive Large Optics Technologies Project

The following passage is extracted from "*A Scientific Assessment of a New Technology Orbital Telescope*", National Academy (1995):

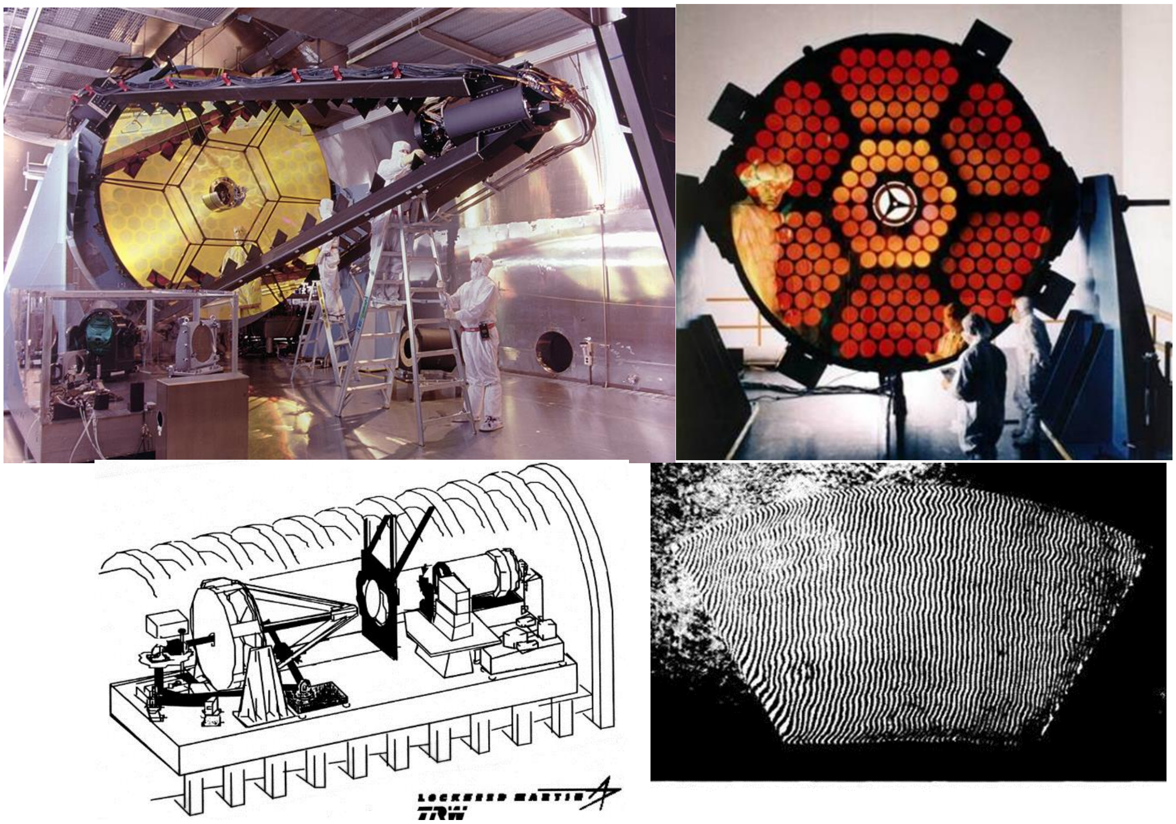


Figure A-4 LAMP Telescope

"The Adaptive Large Optics Technologies (ALOT) project—a 4-meter, lightweight, segmented-mirror telescope—was designed and built by Itek to test the technology for autonomous capture, phasing, and figure control of a fully adaptive primary mirror by sensing an extended scene in real time. The telescope consists of a central 2.6-meter annular mirror, with 144 actuators, surrounded by a number of 0.7 × 2.1-meter radial mirror segments (only one, however, was built) each equipped with 43 actuators. Testing of ALOT in Itek's thermal-vacuum chamber revealed that the active control system could yield a residual wavefront error of 70 nm rms in the presence of active disturbances to the beam.

"All of ALOT's support structures are made of graphite-epoxy composite, including the tripod supporting the secondary mirror, the Cassegrain baffle, and the reaction structure supporting the segmented primary mirror. All components, except the control electronics, are space qualifiable and compatible with launch by a Titan IV booster. The principal modifications required for space qualification of the existing ALOT hardware would be upgrading the electronics, replacing the control computer with one that is space-qualified, modifying the software, and adding thermal insulation and an external shroud."

Segment phasing was controlled by edge sensors and phasing of 35 nm rms was demonstrated. Areal Density was 70 kg/m^2.

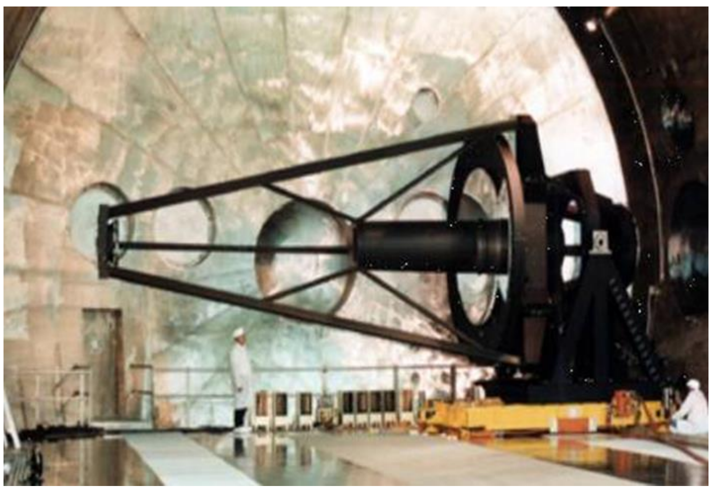
Additional reference: Cox, Charles D. and Mark E. Furber, "Four-meter diameter adaptive optical system technology demonstration", Proc. SPIE 2807, 132 (1996); doi:10.1117/12.255095.

Large Optical Segment Project

The following passage is extracted from "*A Scientific Assessment of a New Technology Orbital Telescope*", National Academy (1995):

"The Large Optical Segment (LOS) project used the technology developed for LAMP to build two of the thirteen 4-meter segments required for an 11-meter mirror. Unlike the quasi-hexagonal structure of LAMP's primary, LOS's will resemble ALOT 's in that it will consist of a central annular mirror surrounded by a number of radial segments. Each of the segments is ground from a 4-meter blank of Corning ULE glass."

The central mirror was to be 4-meter diameter. It was to be surrounded by 13 identical 3.5-meter long keystone petals.



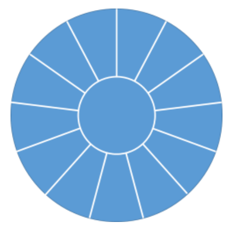


Figure A-5 Large Optical Segment Project

Advanced Optical System Demonstrator

Advanced Optical System Demonstrator (AOSD) test-bed is a segmented 2.6-meter primary mirror with a center mirror and a single outer petal. It demonstrated both deployment and active phasing control at < 30 nm rms.

Figure A-6 AOSD

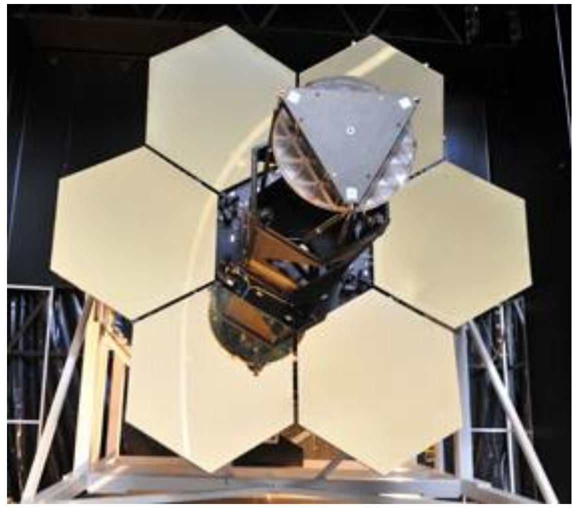


Figure A-7 SMT

Segmented Mirror Space Telescope

The following passage is extracted from http://www.nps.edu/About/News/NPS-New-Home-for-Giant-Segmented-Mirror-Space-Telescope-.html

"The Segmented Mirror Space Telescope (SMT), designed and developed for the National Reconnaissance Office (NRO) as a technical demonstrator and experimental testbed for cutting-edge space imaging technologies." It is 3-meter diameter with 6 hexagonal petals. Each segment has "more than 100 actuators for surface control as well as three fine and six coarse actuators to bring the segments into alignment after deployment". "Like the Webb telescope, the SMT employs a large, lightweight deployable mirror system to increase optical resolution on-orbit while reducing telescope weight. The mirror segments of such telescopes collapse into a small volume to fit into their launch vehicles and then open to their full diameter in response to a wireless command after launch. The segments must be very accurately aligned after deployment, and their surfaces must be actively controlled using hundreds of tiny actuators. Adaptive optics systems work by measuring the distortion in an image and using "adaptive" optical elements – usually deformable mirrors – to restore the image by applying an opposite, cancelling distortion."

SMT segments are composed of a nanolaminate reflective coating epoxied on to a SiC substrate. The SiC substrate uses in-plane actuators to correct the surface shape. SMT was initially designed to be diffraction limited at 0.5 micrometers, but only achieved 5 micrometer diffraction limit.

NRAO 12 meter telescope, Kitt Peak Observatory | Sub Millimeter Telescope (SMT), Mt. Graham, AZ

Figure A-8 NRAO 12 m and Sub-mm Telescope

Sub-Millimeter Telescope

The sub-millimeter telescope (SMT) is 10-meter in diameter consisting of concentric rings of identical trapezoidal panels. Panels are fabricated from carbon fiber reinforced plastic (CFRP) skin with aluminum honeycomb sandwich core. Each panel weighs 110 kg. The structure is fabricated using CFRP tubes with invar steel joints. Its total weight is 3040 kg. The reflector surface is 15 micrometers rms.

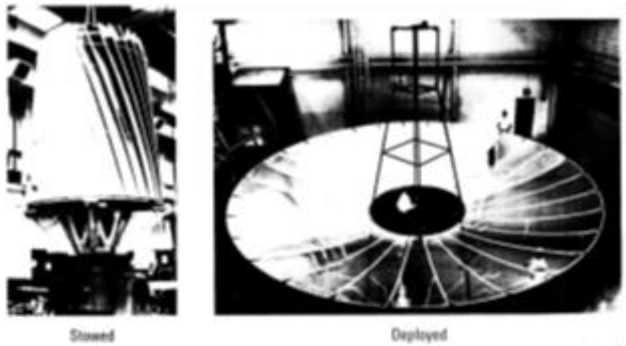
12-Meter Telescope

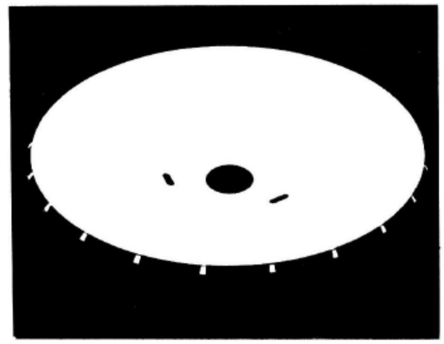
The Arizona Radio Observatory 12 Meter Telescope was installed in 1984. It is constructed from multiple rings of identical trapezoidal panels. Surface accuracy was < 60 micrometers rms. In 2014, it was replaced by an Alma Prototype Antenna designed by ESO.

"Sunflower" Reflectors

Source for information and figures: Lillie, C. F., "Large Deployable Telescopes for Future Space Observatories", Proceedings of SPIE Vol. 5899 (2005); doi: 10.1117/12.624231

From 1960 to 1986 several deployable segmented reflectors ranging from 4.5 to 15.2 meters were developed, fabricated and in some cases, qualified for flight. The 10-meter "Sunflower" Solar Reflector (developed in 1963) had an areal density of 1.5 kg/m2 and an RMS surface accuracy of ~ 1.5 mm. The 4.6-meter "Sunflower" Microwave Array had an areal density of 2.9 kg/m2 and an RMS surface accuracy of ~76 micrometers. The Microwave Array was flight qualified in 1970. Between 1976 and 1986 several Advanced Sunflower Precision Deployable Reflectors were designed. These solid reflector efforts demonstrated the packaging efficiency, areal density, deployment accuracy and stability, and RMS surface accuracy required for the reaction structure for optical and infrared telescopes





Parameter (units)	SunFlower		Advanced SunFlower			HARD Reflector
	Solar Mirror	μ-wave Antenna	15-foot	30-foot	50-foot	
Year Developed	1963	1970	1976-1986			1987-1992
Mass (kg)	109.7	48.2	48.2	212.7	530.9	36.4
Diameter (m)	9.8	4.6	4.6	9.1	15.2	4.6
Area (m^2)	74.8	16.4	16.4	65.7	182.5	16.4
Areal Density (kg/m^2)	1.5	2.9	2.9	3.2	2.9	3.0
Surface Accuracy (μm)	1524	76	76	76	54	203

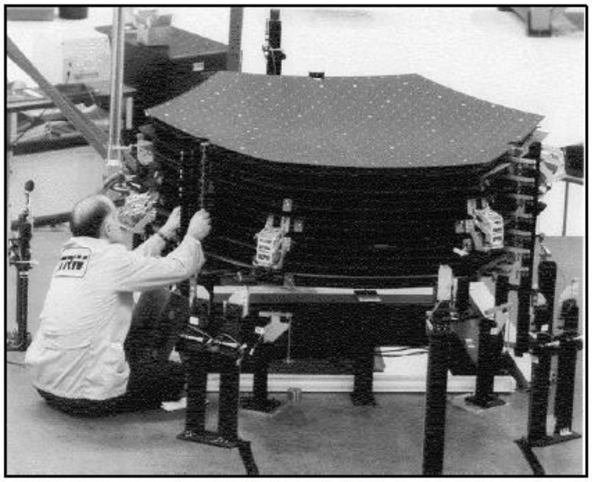
Figure A-9 Top left: 10 m "Sunflower" solar reflector. Top right: 4.6 m "Sunflower" microwave antenna.

High Accuracy Reflector Demonstration

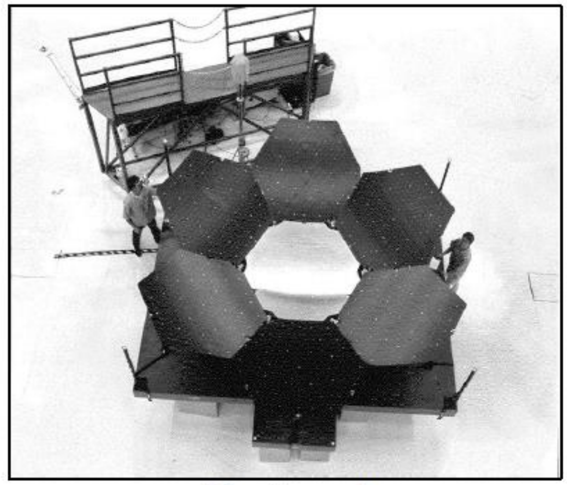
The High Accuracy Reflector Demonstration (HARD) was a 4.5-meter reflector composed of 6 hexagonal reflectors.

The following quote and figure are extracted from Lillie, C. F., "Large Deployable Telescopes for Future Space Observatories", Proceedings of SPIE Vol. 5899 (2005); doi: 10.1117/12.624231

"The HARD reflector was designed for RF communications and demonstrated less than 1.2 dB loss at 60GHz, consistent with its rms surface accuracy of 200µm. Its performance is currently limited by the surface accuracy of the RF panels, since preliminary measurements indicate the repeatability of the panel position from one deployment to the next is approximately 12.5 µm rms. By upgrading the HARD reflector panels' accuracy and figure to optical quality (10Å rms) we can obtain a large aperture light collector for UV and optical spectroscopy. This reflector has significant potential for other applications, however. In the visible and near-IR it can be used as a light collector for optical communications and solar-thermal power generation. At wavelengths longer than ~60 to 100 µm it can provide diffraction-limited performance for far infrared and sub-millimeter imaging and spectroscopy. It also has potential applications as a collector for soil moisture radiometry. The HARD design concept can also provide apertures much larger than 4.5 meters, since panel diagonals up to ~4.5 meters can be accommodated by current launch vehicle fairings, providing apertures up to 12-m for a 7-segment reflector, or 20-m for a two-ring design with 19 panels. The launch, deployment and on-orbit performance of HARD depends on three basic mechanisms: a restraint mechanism to cage the panels during launch, a Rotational-Translational Joint (RTJ) to deploy the panels, and a latch mechanism to stabilize the panel-to-panel position on orbit."



Stowed



Deployed

Figure A- 10 HARD reflector