

**A DEPLOYABLE PRIMARY MIRROR FOR SPACE TELESCOPES**

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# A deployable primary mirror for space telescopes

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## ABSTRACT

NASA Langley Research Center, Composite Optics, Inc., and Nyma/ADF have developed jointly a deployable primary mirror for space telescopes that combines over five years of research on deployment of optical-precision structures and over ten years of development of fabrication techniques for optical-precision composite mirror panels and structures. The deployable mirror is directly applicable to a broad class of non-imaging “lidar” (light direction and ranging) telescopes whose figure-error requirements are in the range of one to ten microns RMS. Furthermore, the mirror design can be readily modified to accommodate imaging-quality reflector panels and active panel-alignment control mechanisms for application to imaging telescopes. The present paper: 1) describes the deployable mirror concept; 2) explains the status of the mirror development; and 3) provides some technical specifications for a 2.55-m-diameter, proof-of-concept mirror.

**Keywords:** precision deployment, hinge joint, latch joint, deployable structures, fabrication, space telescopes, optical instruments, microdynamics.

## 1. DEPLOYABLE MIRROR CONCEPT

NASA Langley Research Center (LaRC), Composite Optics, Inc. (COI), and Nyma/ADF have developed jointly a non-imaging-quality, segmented, deployable, telescope mirror that represents a substantial advancement in the state-of-the-art of space-based telescopes (Figure 1). The 2-to-4-m-class mirror is the lightest-weight, lowest-CTE, most microdynamically stable, segmented optic described in the open literature. The mirror incorporates high-precision deployment and mirror-panel-alignment mechanisms that are expected to provide micron-level stability on orbit. The mirror also incorporates composite mirror panels and metering structure components, and it exhibits an average CTE equal to that of ULE™ glass with an average areal density of about 20 kg/m<sup>2</sup>.

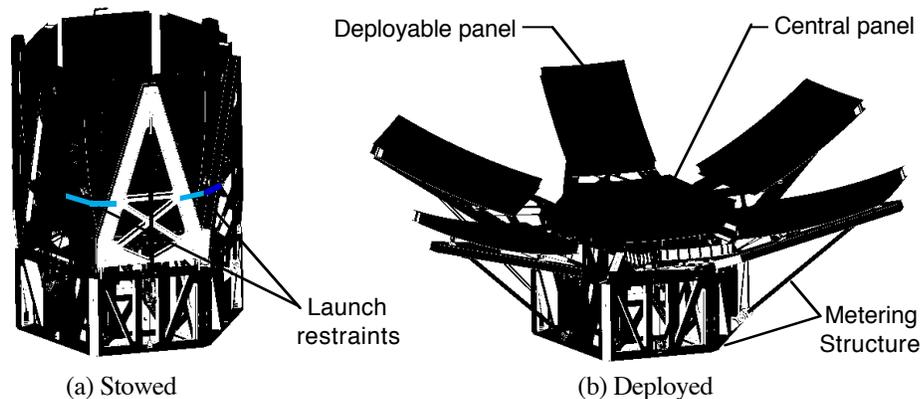


Figure 1. Deployable telescope mirror concept.

### 1.1. Substantial increase in collecting area through deployment

A principal goal in developing the deployable mirror design was to provide a factor of four increase in collecting area as compared to a non-deployable (i.e., monolithic) mirror that would fit in the same payload shroud. This goal was achieved by sizing each of six deployable mirror panels to have one-half the collecting area of the fixed central mirror panel. Hence, the six deployable panels add a factor of three in collecting area to that of the central panel.

## 1.2. Simple deployment kinematics

The deployment kinematics are very simple; the deployable mirror panels rotate through about 75° from stowed to deployed positions. Each deployable mirror panel is mounted on an A-frame-shaped arm that is attached through hinges to a fixed central metering truss (see Figure 2). The outboard end of the A-frame arm is guided through the deployment motion by a hinged strut that connects to a linear, ball-screw actuator. At the end of deployment, the hinged strut engages a precision latch and the deployment actuator drops out of the load path.

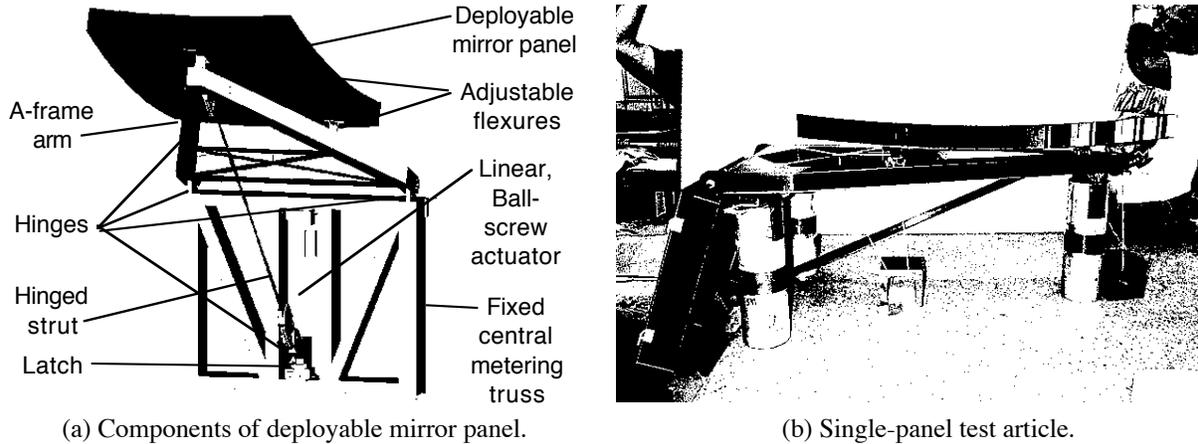


Figure 2. Deployable mirror panel and metering structure.

## 1.3. Low-risk, low-cost architecture

The mechanical simplicity of the deployable primary mirror implies a low development cost and risk as well as low risk of deployment failure. The drawbacks of this architecture are a lower packaging efficiency and collecting-area efficiency than some deployable mirror concepts. Specifically, vertical stowage of the deployable panels requires a packaging volume that is approximately twice as long as its diameter; and substantial gaps between panels in the deployed configuration, which constitute approximately one half of the enclosed physical aperture.

Low fabrication cost is achieved by combining recently developed, low-cost, composite fabrication techniques with the mechanically simple architecture. The six deployable mirror panels are “mass” manufactured using a replication molding process in which a single, optically figured mold is used rather than figuring each individual panel. Hence, composite mirror panels are not only lighter, but are also less expensive to fabricate than conventional (e.g., ULE™ glass and metal) mirror panels. Major components of the deployable metering structure are fabricated from flat laminates using the COI-patented SnapSat™ assembly process that involves minimal hand-touch labor hours and ensures excellent material property uniformity and control.

## 1.4. Robust structural design

As another means of minimizing developmental risk and cost, the deployable mirror structure is designed to be “robust” and exhibit:

- a high stiffness and strength in the packaged configuration in order to simplify the problem of designing for the launch-load environment;
- a high stiffness-to-mass ratio in the deployed configuration in order to minimize distortions under inertial loading that might complicate 1-g testing and exacerbate on-orbit response to slew maneuvers;
- high thermo-mechanical, hygroscopic, and microdynamic stabilities in the deployed configuration in order to minimize or possibly eliminate the need for on-orbit active alignment control.

High strength and stiffness in the packaged configuration are achieved by incorporating substantial cross-sectional depth into the members of the metering structure that will be loaded during launch, and adding secondary launch restraint members to stiffen the stowed segments of the metering structure (see Figure 1(a)). A high stiffness-to-mass ratio is achieved in the deployed metering structure with a relatively deep truss constructed primarily of a high-

specific-modulus (i.e., high- $E/\rho$ ) composite material, and with minimal “parasitic mass” (i.e., non-load-bearing mechanisms, etc.). High thermo-mechanical and hygroscopic stabilities are achieved by tailoring the composite laminates to exhibit extremely low coefficients of thermal expansion (CTE) and moisture expansion (CME). Finally, a high microdynamic stability is achieved by minimizing the total number of mechanisms (24 hinges and six latches), and using mechanisms that exhibit highly linear response to loading.

### 1.5. Applications

The 2-to-4-m-class deployable telescope mirror is designed for application to non-imaging “lidar” (light direction and ranging) instruments whose figure-error requirements are in the range of one to ten microns RMS. In addition, the mirror can be adapted to image-quality telescopes with the addition of active control and higher figure-quality reflector panels. Results from recent analyses and component-level tests indicate that the mirror should exhibit adequate passive stability (i.e., thermo-mechanical, hygroscopic, and microdynamic) for non-image-quality telescopes. This stability will be validated in the near future by tests of a proof-of-concept test article (Figure 2(b)).

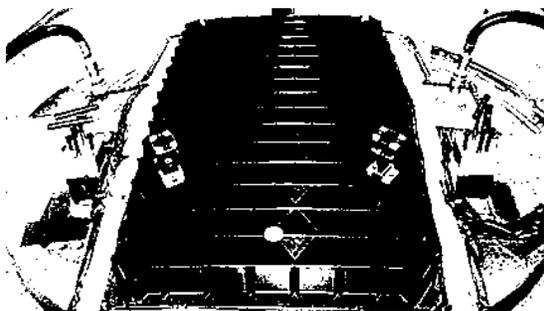
## 2. DEVELOPMENT STATUS

In 1998, NASA LaRC, COI<sup>†</sup>, and Nyma/ADF<sup>‡</sup> completed the detailed design of a 2.55-m-diameter, proof-of-concept, deployable mirror that incorporates a 2.9-m-radius spherical figure, and represents a deployed focal ratio of approximately 0.6. This proof-of-concept design is easily adaptable to any larger focal ratio and scalable to larger diameters (up to about 4 m) without significant mechanical changes. Recently, NASA LaRC and COI<sup>§</sup> fabricated a test article that includes one deployable mirror panel from the 2.55-m-diameter, proof-of-concept mirror (Figure 2(b)). Deployment-repeatability and post-deployment-stability testing of this test article are expected to begin during the summer of 1999 and be completed by the end of 1999.

The deployable mirror design combines over five years of research on the problem of precision deployment by NASA LaRC and the University of Colorado<sup>1</sup> and over ten years of development of fabrication techniques for optical-precision composite mirror panels and metering structures by COI.<sup>2</sup> Specifically, the deployable mirror incorporates numerous, recently demonstrated advancements in the design and fabrication of: 1) composite mirror panels; 2) composite metering structures; and 3) precision mechanisms.

### 2.1. Composite mirror panels

In recent years, COI has: matured composite-mirror fabrication technology; demonstrated numerous designs for non-imaging-quality composite mirrors; and developed viable concepts for imaging-quality, composite mirrors.<sup>3,4</sup> For example, COI has demonstrated: new mold-release techniques to reduce surface roughness; the application of polishable materials (e.g., ULE<sup>™</sup> glass) to molded-composite surfaces to enable optical figuring; and secondary replication and adhesion of an optical-quality surface to a molded-composite surface.



(a) Mirror panel on optically figured glass tool.



(b) Reflective surface of completed mirror panel.

Figure 3. Deployable mirror panel for 2.55-m proof-of-concept mirror.

<sup>†</sup> Phase III SBIR conducted under NASA contract NAS1-97156.

<sup>‡</sup> Task No. GK-14 of NASA contract NAS1-96013.

<sup>§</sup> Phase III SBIR conducted under NASA contract NAS1-98158.

The deployable mirror panel for the 2.55-m proof-of-concept mirror is shown in Figure 3. The panel is an all-composite, isogrid-stiffened construction, and was replication molded using an optically figured glass tool. A flight version of this panel would be nickel plated on all surfaces for moisture control, atomic-oxygen protection, and UV protection, and have a reflective surface (e.g., vapor-deposited aluminum). All aspects of the mirror-panel fabrication process (e.g., replication molding, application of moisture barrier, and application of reflective surface) have been demonstrated either in fabricating this test article, or in other recent COI development programs.<sup>2</sup>

## 2.2. Composite metering structure components

The deployable metering structure is primarily constructed of carbon-fiber-reinforced components (i.e., A-frame arm, hinged strut, fixed central metering structure as shown in Figure 2(a)). To minimize fabrication costs and ensure excellent uniformity and control of material properties, most of these components are fabricated from flat laminates using the COI-patented SnapSat™ assembly process (Figure 4). The SnapSat™ process was developed over five years ago, and has been applied in the design and construction of numerous spacecraft structures in recent years.

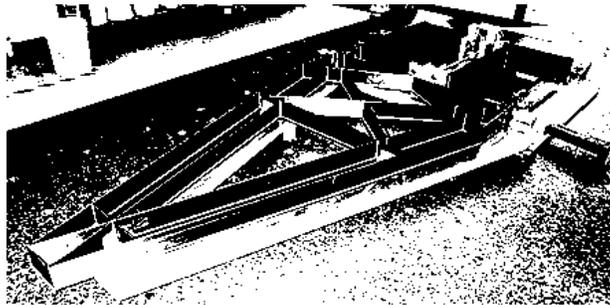
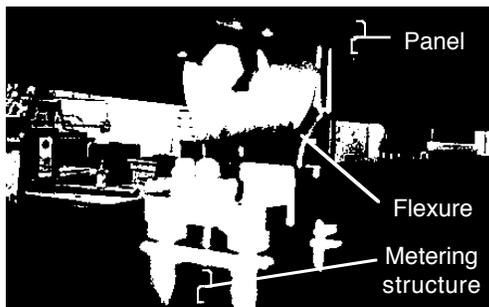


Figure 4. A-frame arm assembled from flat laminates using SnapSat™ process.

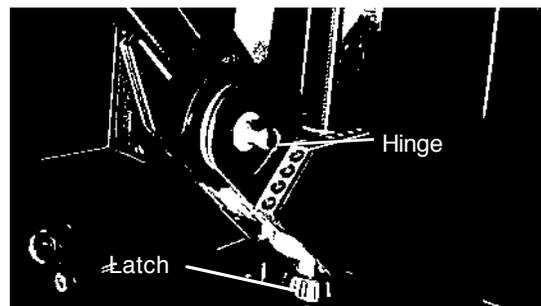
The SnapSat™ process incorporates flat laminates that are precisely cut using a CNC-controlled water-jet cutter, and assembled together using edge-bonded, tongue-and-groove joints. The process involves minimal hand-touch labor hours due to a high degree of automation, and leads to reductions in production schedule and cost, especially for low production quantities. Furthermore, SnapSat™ structures can be fabricated with an exceptionally high level of material uniformity and control (e.g., extremely low CTE) since lay-up errors are easier to control in flat laminates.

## 2.3. Precision mechanisms

The deployable telescope mirror incorporates 24 hinges and six latches (four hinges and one latch per deployable panel as shown in Figure 2(a)). In addition, the mirror incorporates 21 adjustable flexures to mount its seven mirror panels (three flexures per panel) to the composite metering structure and allow for tip, tilt, and piston alignment of the mirror panels (see Figure 2(a)). The designs for these mechanisms were derived from substantial recent research on the problem of precision mechanism design, performed by NASA LaRC and the University of Colorado.<sup>5,6,7,8,9</sup> Photographs of the mechanisms are shown in Figure 5.



(a) Flexure between panel and metering structure



(b) Hinge and latch incorporated in metering structure

Figure 5. Precision mechanisms for deployable telescope mirror.

During the first phase of the deployable telescope mirror development program, NASA LaRC and Nyma/ADF developed concepts for each of these mechanisms and performed load-cycle testing on prototypes. NASA LaRC and Nyma/ADF also worked jointly with COI to adapt these mechanism designs into the COI-developed composite metering structure and mirror panel designs.<sup>10</sup> In fabricating the single-panel, 2.55-m-diameter telescope mirror test article (Figure 2(b)), all issues related to the fabrication and integration of these precision mechanisms were successfully addressed.

### 3. TECHNICAL DETAILS

#### 3.1. Optical design

The design of the 2.55-m-diameter, proof-of-concept, deployable mirror is based on the optical system requirements of the Qzone Research through Advanced Cooperative Lidar Experiments (ORACLE) telescope.<sup>11</sup> A computer-generated rendering of the baseline concept for the ORACLE deployable telescope is shown in Figure 6, and the 2.55-m-diameter, proof-of-concept mirror is shown in Figure 7. The ORACLE telescope primary mirror is aspherical with a collecting area equal to that of a 1.8-m-diameter monolithic mirror, and a deployed focal ratio equal to 0.8. This fast, primary-mirror design is acceptable because of the narrow-field-of-view and non-imaging requirements of the ORACLE instrument. The main benefit of the fast primary mirror is that the secondary mirror can be mounted on a fixed (i.e., non-deployable) structure.

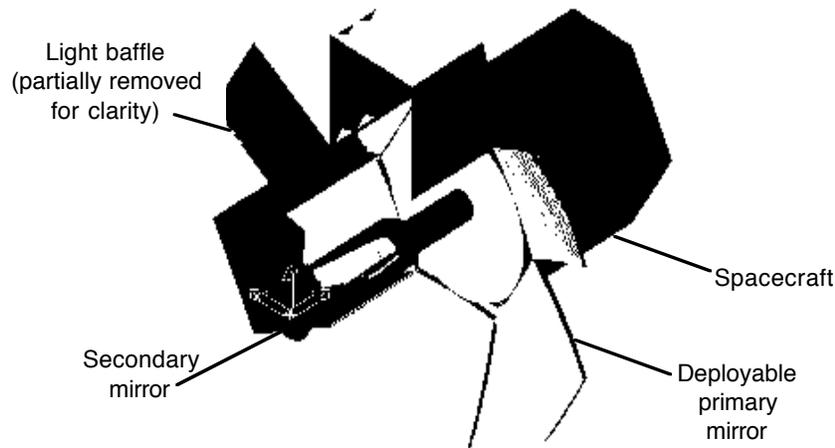


Figure 6. Baseline ORACLE deployable telescope concept.

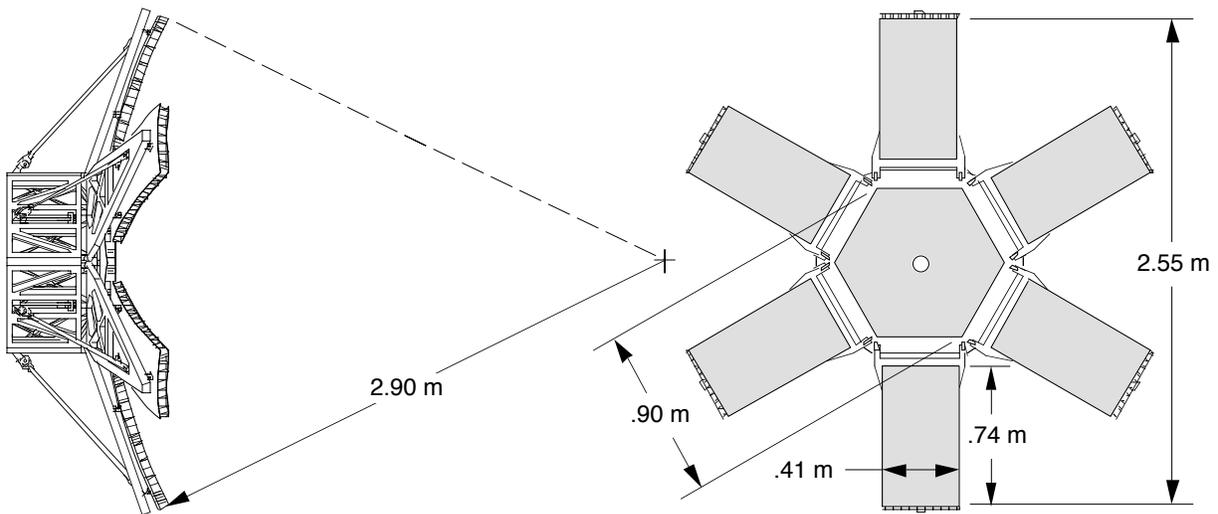


Figure 7. 2.55-m-diameter, proof-of-concept, deployable mirror.

Four physical design constraints were fundamental in developing the geometry of the 2.55-m-diameter, proof-of-concept, deployable mirror. First, the mirror was given a spherical radius of curvature equal to 2.9 m (i.e., close to the ORACLE requirement) to enable an existing polished-glass mold to be used for fabrication. Second, the mirror was constrained to have a total deployed collecting area equal to 2.54 m<sup>2</sup> (i.e., equal to the ORACLE requirement). Third, each of the deployable mirror panels was sized to have one-half the collecting area of the central panel (i.e., a factor of four increase in total collecting area through deployment). Fourth, the maximum stowed diameter of the mirror was constrained to be less than 1.1 m (i.e., the diameter of the Pegasus payload shroud).

### 3.2. Composite mirror panels

The design of the mirror panels for the 2.55-m-diameter, proof-of-concept, deployable mirror is based on two additional optical-system requirements derived from the ORACLE telescope design studies.<sup>12</sup> First, the areal density of the panels was required to be less than 10 kg/m<sup>2</sup>. Second, the surface-figure error of the panels was required to be less than 5 μm RMS. The total surface-figure error was sub-divided into three components: fabrication error, gravity-sag error, and on-orbit errors (i.e., thermal and hygroscopic). For preliminary design purposes, each error component was required to be less than 2 μm RMS.

To achieve these requirements, the mirror panels utilize an all-composite, isogrid-stiffened construction (see Figure 3) with nickel plating on all surfaces for moisture-barrier control and atomic-oxygen/UV-radiation protection. All components are fabricated from quasi-isotropic laminates using a high-modulus carbon fiber and a cyanate-ester resin system. The isogrid cores of the reflector panels are assembled from flat, 0.38-mm-thick, interlocking, slotted ribs. The doubly curved, front and back facesheets are 1.5-mm-thick laminates that are fabricated using a COI-proprietary lay-up technique to enhance thermal stability. The facesheets are replication molded against an optically figured glass mold. The reflective surface (e.g., vapor-deposited aluminum) is applied either directly to the reflector panel or to the mold surface and bonded to the panel during the replication process. For the 2.55-m-diameter, proof-of-concept test article, an existing 2.9-m-radius-of-curvature glass mold was used for lay-up and cure of the reflector facesheets and no reflective surface finish or nickel plating was applied in order to reduce fabrication costs.

The reflector panels were analyzed to determine their figure stability under gravity and thermal loading conditions. The finite element model for a single deployable mirror panel and its underlying metering structure is shown in Figure 8, and the results of figure-stability analyses for this mirror panel are summarized in Table 1. Three analyses were performed: a thermal cool down of 50 °F; gravity sag (gravity vector parallel with optical axis of reflector) with the mirror panel on rigid kinematic (i.e., statically determinant) mounts; and gravity sag with the mirror panel on the deployable metering structure. In computing the RMS values of the figure error, rigid-body motion of the panel (i.e., piston and tilt) was removed from the computed deformations. The results in Table 1 indicate that the mirror panel design is adequate to meet the 2 μm RMS figure-stability requirements for gravity sag and thermal distortion.

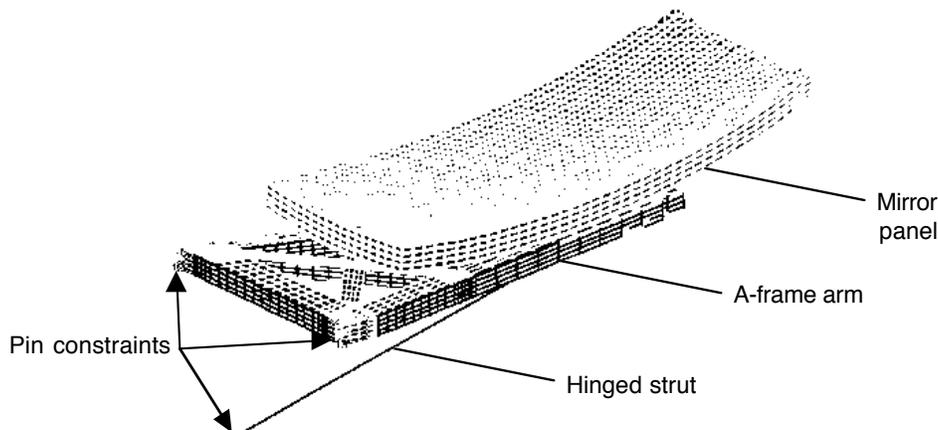


Figure 8. Finite element model of deployable panel for 2.55-m-diameter, proof-of-concept mirror.

Table 1. Results from figure-stability analyses of 2.55-m-diameter, proof-of-concept, deployable mirror panel.

Loading Condition	Support Condition	Figure Error ( $\mu\text{m RMS}$ )
50 °F cool down	Panel on rigid kinematic mount	0.90
Gravity parallel to optical axis	Panel on rigid kinematic mount	0.18
Gravity parallel to optical axis	Panel on A-frame and strut	0.40

Due to cost constraints during development of the 2.55-m-diameter, proof-of-concept test article, no fabrication-error measurements were made on the 0.78-m-by-0.41-m reflector panel. However, as part of the Microwave Limb Sounder (MLS) program (Ref. 2), COI measured the fabrication error of a similarly constructed, 1.6 m by 0.8 m reflector, and results from these tests are summarized in Table 2. Although the total fabrication error of the MLS reflector was nearly 5  $\mu\text{m RMS}$ , approximately one-half of the error was due to mold-surface errors and a significant portion of the error was due to mold-release effects. All remaining steps in the fabrication process (e.g., dry out, thermal cycle, and application of reflective surface) contributed less than 1  $\mu\text{m RMS}$  to the total figure error. A higher quality mold and slightly improved process-control techniques ensure that the composite mirror panels for the deployable telescope mirror will meet the 2  $\mu\text{m RMS}$  fabrication-error budget mentioned previously for the deployable telescope mirror. Furthermore, alternative mirror-panel construction concepts that achieve a higher quality, and more stable surface figure have been developed and demonstrated by COI and could be interchanged with the current mirror-panel concept for deployable telescope applications requiring higher-quality surfaces.

Table 2. Fabrication error measurements for MLS reflector<sup>2</sup>.

Point in Fabrication Process	Figure Error ( $\mu\text{m RMS}$ )
After mold release	4.62
Before dry out	5.23
After dry out	4.69
After thermal cycle	5.69
After application of VDA	4.95

### 3.3. Composite metering structure

Two requirements were placed on the design of the composite metering structure for the 2.55-m-diameter, proof-of-concept, deployable mirror. The structure was required to exhibit: 1) a net CTE equivalent to that of ULE™ glass (approximately  $0.5 \times 10^{-6} / ^\circ\text{C}$ ); and 2) vibration frequencies greater than 20 Hz. The CTE requirement stems from a system-level goal to minimize thermal control and/or isolation of the deployable mirror components. The vibration frequency requirement stems from a system-level goal to maximize the stiffness-to-mass ratio of the structure in an attempt to minimize deformations of the mirror due to inertial loads (i.e., 1-g loading condition during ground tests, and on-orbit slewing). In addition to these requirements, three other system-level goals were identified that affected the design of the composite metering structure. Specifically, efforts were made to minimize fabrication cost and complexity (i.e., part count and hand-touch labor hours), to minimize total system mass, and to provide numerous hard points within the metering structure for attachment of other telescope system components (e.g., secondary mirror, light baffle, focal-plane optics, etc.).

COI was able to satisfy the CTE requirement while keeping fabrication costs minimized by employing their patented SnapSat™ fabrication process in the construction of most composite elements of the metering structure. Like the composite mirror panels, the composite metering structure utilizes nickel-plated, quasi-isotropic laminates of high-modulus carbon fiber and a cyanate-ester resin, to achieve low-CTE, low-CME behavior. Thermal strain data from Ref. 2 are presented in Figure 9 for COI’s plated and unplated, quasi-isotropic composite laminates with the fiber volume fractions tailored to give total strains that closely match that of Zerodur glass (for a cryogenic cool down from ambient to 35°K). These data indicate average CTE’s of approximately  $0.1 \times 10^{-6} / ^\circ\text{C}$ , and confirm COI’s ability to tailor laminate CTE to meet the requirement of the 2.55-m-diameter, proof-of-concept, deployable mirror.

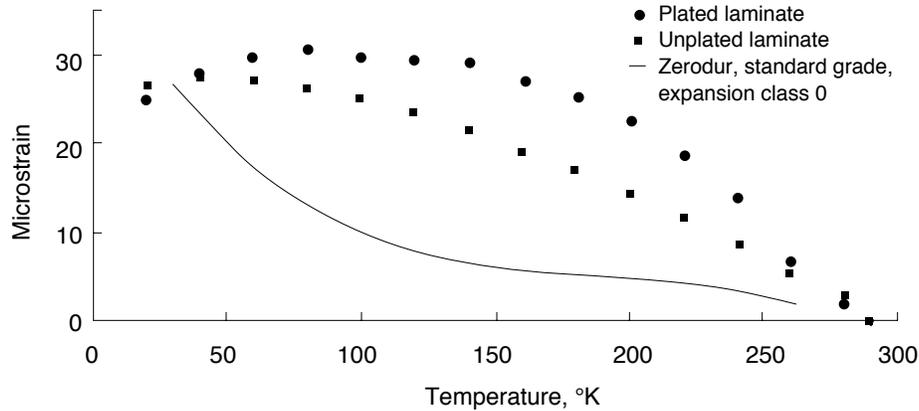


Figure 9. Thermal expansion comparisons for Zerodur glass and isotropic, laminated composite materials<sup>2</sup>.

To date, no analyses have been conducted to determine the natural vibration response of the complete seven-panel reflector assembly. However, analyses have been performed on the single-panel test article using the model shown in Figure 8, and results from these analyses are presented in Table 3. These results indicate that the fundamental vibration mode is four times higher than the requirement of 20 Hz. In these analyses, the base of the A-frame arm and hinged strut were assumed to be pinned to ground, hence elasticity of the fixed central metering structure was not included. Although including the elasticity of the central metering structure will lower these frequencies somewhat, the central metering structure is so much stiffer than the deployable metering structure that the frequencies are expected to remain well above the requirement of 20 Hz.

Table 3. Natural vibration response of 2.55-m-diameter, proof-of-concept, deployable mirror.

Mode	Frequency (Hz)	Description
1	83	Torsion of support structure
2	103	Bending of support structure about hinge axis

### 3.4. Precision mechanisms

Only one hard requirement was established for the design of the precision mechanisms in the 2.55-m-diameter, proof-of-concept, deployable mirror. The mechanisms that must support launch loads in the stowed configuration (i.e., the hinges and the adjustable flexures) were designed to carry a 20-g static load. In addition to satisfying this requirement, three guidelines were followed in developing the mechanism designs. First, the mechanisms were designed to have minimal impact on the net CTE of the composite metering structure. Second, efforts were made to minimize fabrication cost, complexity, and mass of the mechanisms. Third and most importantly, the mechanisms were designed to exhibit a high degree of microdynamic stability.

The fundamental principle involved in designing microdynamically stable mechanisms is easy to state, but is sometimes challenging to follow in practice. Specifically, to achieve a high degree of microdynamic stability, the mechanism must be designed such that the load-carrying mechanical interfaces within the mechanism transfer little or no load through friction.<sup>1,9</sup> This precision-mechanism design principle was followed strictly in developing designs for the hinges, latches, and adjustable flexures. Furthermore, the principle was validated by results from load-cycle tests of the mechanisms that exhibited extremely low hysteresis.

#### 3.4.1. Hinge

A precision composite hinge was adapted by NASA LaRC and Nyma/ADF from an earlier metal hinge design (see Figure 10(a)).<sup>7</sup> The hinge is different from conventional pin-clevis hinges because the rotational element is a set of preloaded angular-contact bearings instead of a pin. The hinge explicitly satisfies the precision-mechanism design principle, because the bearings exhibit minimal internal load transfer through friction. In addition, the hinge is fairly simple and inexpensive to manufacture, because the bearings are commercially available and the other components

require only low fabrication tolerances. The hinge design is detailed in Ref. 10, and its manufacture and use are unrestricted by NASA and Nyma/ADF.

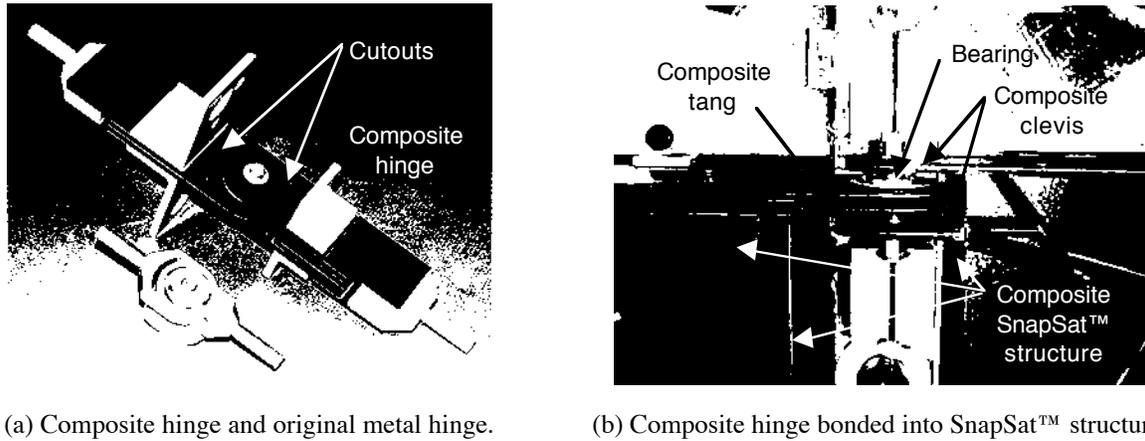


Figure 10. Precision hinge for deployable telescope mirror.

The tang and clevis components of the hinge are made of flat laminated composite materials and bonded directly to flat surfaces within the composite SnapSat™ metering structure (Figure 10(b)). The composite tang and clevis arms include cut-outs (see Figure 10(a), Ref. 7) designed to insure equal tension and compression stiffnesses across the joint. These cutouts, also ensure that the effective CTE of the hinge joint is the same as the CTE of the composite tang and clevis components despite the CTE mismatch between the metal and composite components. Some load-cycle-test results from the composite hinge specimen are presented in Figure 11. The response of the composite hinge to quasi-static load cycling has less than one percent hysteresis, and the hinge is expected to induce much less than a micron of local microdynamic instability into the deployable metering structure.

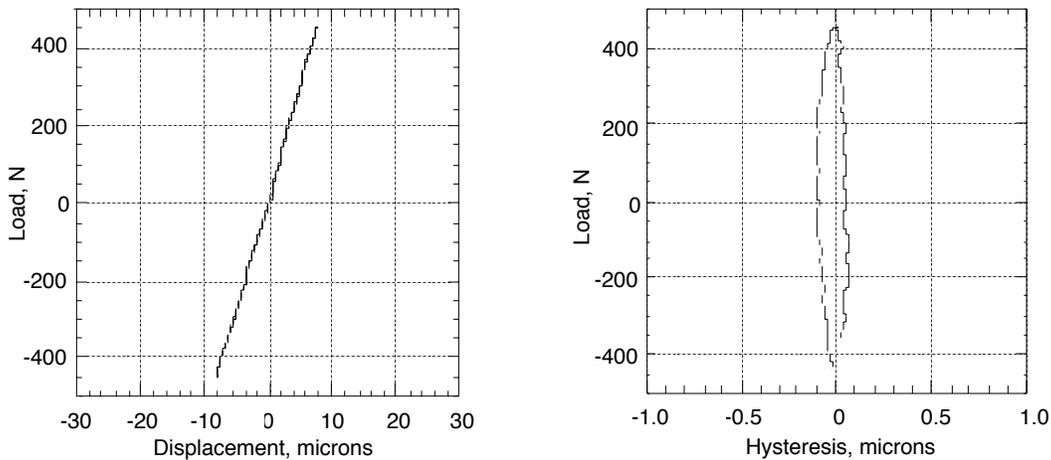


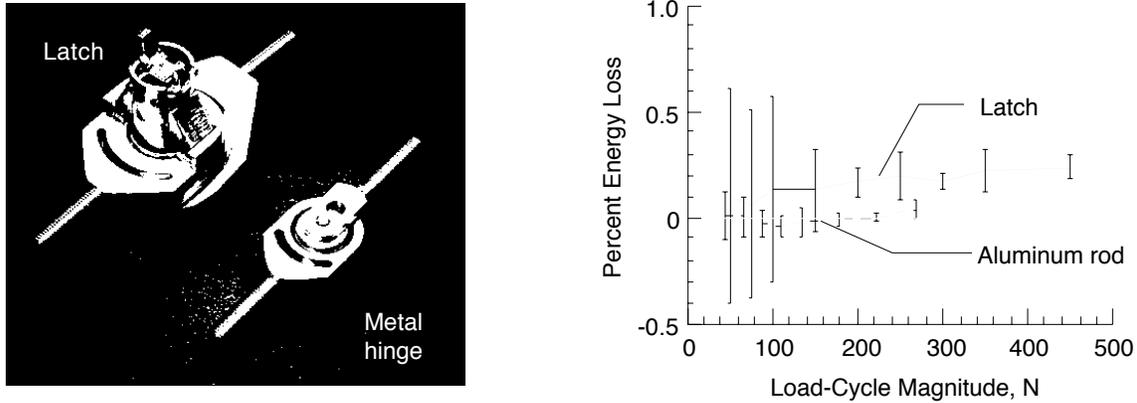
Figure 11. Typical load-cycle response of composite hinge.

### 3.4.2. Latch

The precision latch developed by NASA LaRC and Nyma/ADF possesses some of the same design and internal load-path features as the hinge. A proof-of-concept version of the latch is shown in Figure 12(a), and the latch incorporated in the composite metering structure is shown in Figure 5(b). Some details of the latch design are presented in Ref. 10. However, the design has been submitted for United States Patent protection,\*\* and its manufacture and use are subject to patent license restrictions. Some results from quasi-static, load-cycle testing of

\*\* NASA LaRC Patent Disclosure No. LAR 15763-1.

the latch are presented in Figure 12(b). These data demonstrate that the latch has an even lower level of hysteresis than the composite hinge joint, and indicate that the latch is even more microdynamically stable than the hinge joint. In fact, the average energy loss from hysteresis in the response of the latch joint is substantially below 1%, and approaches that of a monolithic rod of aluminum.



(a) Proof-of-concept latch and metal hinge.

(b) Typical hysteretic response of proof-of-concept latch.

Figure 12. Precision latch for deployable lidar telescope mirror.

### 3.4.3. Adjustable flexure

The adjustable flexures are designed to minimize assembly forces between the metering structure and the mirror panels, and to allow both coarse and fine alignment of the panels in tip, tilt, and piston degrees of freedom. More importantly however, the flexures and the interfaces attaching the flexures to the panel and the metering structure are designed to be microdynamically stable using the same fundamental design principle applied to the design of the hinge and latch.

The major components of the adjustable flexure are shown in Figure 13, and a photograph of one of the flexures is shown in Figure 5(a). The flexure includes two parallel composite blades made of a low-CTE, isotropic laminate, and separated by a set of washers and an adjustment bolt. Torquing the adjustment bolt separates the washers, opens or closes the gap, thus lengthens or shortens the flexure assembly. This procedure effects fine adjustment of the height of the flexure assembly, which, in turn, effects fine alignment of the panel. Microdynamic stability is built into this design because the adjustment mechanism (i.e., the bolt) is not in the primary load path of the flexure (i.e., the composite blades).

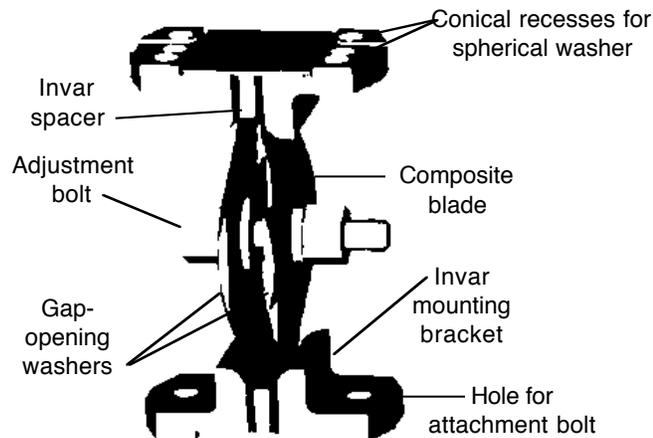


Figure 13. Components of adjustable flexure for deployable lidar telescope mirror.

Coarse adjustment of the flexure height (and panel alignment) is effected by “shimming” the flexure assembly while mounting it between the panel and the metering structure. Mounting brackets on the ends of the flexure assembly are attached to machined receptacles (not shown in Figure 13) bonded within the reflector panels and the metering structure. These mounting brackets and receptacles are machined out of Invar and have conical recesses that entrap spherical bearings as the mounting brackets and receptacles are clamped tightly together. For coarse alignment of the panel, the diameter of the bearings can be selected (e.g., in increments of approximately 25 microns) to compensate for the metering structure fabrication tolerances. In addition to providing for coarse adjustment, the spherical bearings also provide a microdynamically stable interface between the reflector panels and the metering structure.

For the 2.55-m-diameter, proof-of-concept, deployable mirror, the height of the flexure assembly is 6 cm, the nominal gap opening is 4.2 mm, and the nominal gap-adjustment range of 3.2 mm to 5.1 mm gives a total flexure-height adjustment range equal to 1.1 mm. To adjust the gap width, the flexure includes a 28-pitch-thread adjustment bolt (i.e., 0.9 mm per thread). Hence, approximately two complete turns of the adjustment bolt drives the flexure through its entire adjustment range of 1.9 mm, and the adjustment sensitivity of the design is approximately 1.5 microns in height for every 1 degree of adjustment on the bolt. This adjustment sensitivity should be adequate for non-imaging-telescope applications. However, replacing the adjustment bolt with a high-resolution, linear piezoelectric drive motor could result in a more precise, actively controlled version of the adjustable flexure for imaging-telescope applications.

### 3.5. Mass

The mass breakdown for the 2.55-m-diameter, proof-of-concept, deployable mirror is presented in Table 4. Of the 60.33 kg total mass, 23.38 kg is the mass of the reflector panels, and 36.95 kg is the mass of the deployable metering structure. Since the total collecting area of the mirror is 2.54 m<sup>2</sup>, the average areal density of the mirror panels is 9.20 kg/ m<sup>2</sup>, and the average areal density of the complete mirror assembly is 23.75 kg/ m<sup>2</sup>.

Approximately 20 kg of the total mass is from metal parts, many of which are machined from Invar to minimize their contribution to thermal distortion. Although reasonable efforts were made to minimize the number and total mass of metal parts, an estimated 5 kg can be saved by reducing the weight of many of the metal fittings and revising details around the latch assembly. In addition, the mass of the fixed central metering structure is fairly high because it has been over-designed with substantial internal framework for mounting of focal-plane optics and detectors. Some of this mass can be saved with design revisions that accommodate mission-specific focal-plane mounting requirements.

Table 4. Deployable mirror mass breakdown.

Component	Quantity	Unit mass, kg	Total mass, kg
Central mirror panel	1	5.50	5.50
Deployable mirror panel	6	2.98	17.88
Fixed central metering structure	1	11.15	11.15
Deployable metering structure	6	1.43	8.58
Deployment mechanism (metal)	6	0.58	3.48
Precision hinge (metal parts)	24	0.15	3.60
Precision latch (metal parts)	6	1.34	8.04
Precision adjustable flexure	21	0.10	2.10
Total			60.33

## 4. SUMMARY

NASA Langley Research Center, Composite Optics, Inc., and Nyma/ADF have developed jointly a 3-m-class deployable primary mirror for space telescopes which combines over five years of research on deployment of optical-precision structures and over ten years of development of fabrication techniques for optical-precision composite mirror panels and structures. The mirror is the lightest-weight, lowest-CTE, and most microdynamically stable segmented (non-imaging-class) optic device described in the open literature. The deployable mirror is directly applicable to a broad class of non-imaging “lidar” (light direction and ranging) telescopes whose figure quality

requirements are in the range of one to ten microns RMS. Furthermore, the mirror design can be readily modified to accommodate imaging-quality reflector panels and active panel-alignment control mechanisms for application to imaging telescopes. A 2.55-m-diameter, proof-of-concept version of the mirror has been developed and a single, deployable panel test article has been fabricated for ground-based testing. The 2.55-m-diameter design has a total collecting area of 2.54 m<sup>2</sup>, a total mass of slightly over 60kg, and is designed to package in a 1.1-m-diameter Pegasus launch vehicle payload shroud. Testing to characterize the deployment repeatability and post-deployment stability of the single, deployable panel test article is currently underway.

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