LSST Secondary Mirror System Final Design

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ABSTRACT

The Large Synoptic Survey Telescope (LSST) has a 10 degrees square field of view which is achieved through a 3 mirror optical system comprised of an 8.4 meter primary, 3.5 meter secondary (M2) and a 5 meter tertiary mirror. The M2 is a 100mm thick meniscus convex asphere. The mirror surface is actively controlled by 72 axial electromechanical actuators (axial actuators). Transverse support is provided by 6 active tangential electromechanical actuators (tangent links). The final design has been completed by Harris Corporation. They are also providing the fabrication, integration and testing of the mirror cell assembly, as well as the figuring of the mirror. The final optical surface will be produced by ion figuring. All the actuators will experience 1 year of simulated life testing to ensure that they can withstand the rigorous demands produced by the LSST survey mission. Harris Corporation is providing optical surface metrology to demonstrate both the quality of the optical surface and the correctability produced by the axial actuators.

Keywords: LSST, secondary mirror, mirror cell, mirror supports, actuators

1. INTRODUCTION

The LSST secondary mirror cell assembly (M2 assembly) is one of the three major optical components\textsuperscript{1} of the LSST telescope\textsuperscript{2}, which is presently under construction in Chile\textsuperscript{3}. This paper presents the final design of the M2 Assembly which includes the M2 mirror, the M2 mirror support system, M2 mirror cell, M2 mirror cell sensors, aperture ring, mirror support control system, associated electronics, and the thermal control system. Fig. 2. This document emphasizes the changes that have occurred relative to the baseline design\textsuperscript{4}. This mirror cell system is presently under fabrication at Harris Corporation. The actual M2 mirror is a polished ULET\textsuperscript{TM} meniscus mirror. For interfacing with its support system invar mounts are bonded directly to its back surface and perimeter. The M2 assembly attaches to the LSST telescope mount assembly\textsuperscript{5} (TMA) through the M2 hexapod flange\textsuperscript{6}. Neither the M2 hexapod flange, M2 baffle (which attaches to the M2 mirror cell), nor the M2 cover (which is used to protect the M2 when it is not on the telescope) are considered components of the M2 assembly.

The M2 mirror support system has been adapted from the primary mirror support systems for the SOAR\textsuperscript{7} and DCT\textsuperscript{8} telescopes. These mirrors are similar in size, thickness, material, and operation as the LSST secondary mirror. The LSST axial actuators mimic the DCT axial actuators, and the LSST tangent links mimic the SOAR active tangent links. These systems have been chosen since they have been demonstrated to be reliable, low maintenance and they meet the stringent slew and settling requirements of the LSST.

In this paper, directions (top, sides, bottom) refer to the direction when the M2 mirror cell assembly is installed on the telescope and the telescope is zenith pointing. In this orientation the M2 optical surface faces down, Fig. 5.

For information on the M2 cell assembly design envelope, mass estimate, telescope interfaces, and thermal control see reference 4, “LSST Secondary Mirror Assembly Baseline Design,” These aspects of the design have not significantly changed from the baseline design. The M2 control system final design is in progress. The M2 is actively operated by the Active Optics System\textsuperscript{9} \textsuperscript{10} which both actively controls the shape of the mirrors and the positioning of the optics which include the M1M3 mirror, the M2 mirror and the camera\textsuperscript{11}. 

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2. M2 MIRROR DESCRIPTION

The M2 mirror is an aspheric convex ellipse (conic constant = -0.2220) with a 6.788-meter radius of curvature. The blank has been completed by Corning Incorporated and is being optically finished by Harris Corporation. The large convex diameter dictates sub-aperture stitching interferometry to accurately guide polishing to final requirements. The mirror optical surface specification is described by a structure function shown in Fig. 1. The quantity plotted in Fig. 1 represents the rms wavefront difference between points in the clear aperture diameter as a function of their spatial separation \(x\) at zenith pointing after active optics bending mode removal.

Active optic correction forces up to \(\pm 62.3\) N from any axial actuator may be applied to correct large-scale figure errors. The residual surface error after removal of the bending modes shall be less than 20nm rms and meet the structure function requirements shown in Fig. 1. The optical axis coordinate geometry of the mirror will be captured during optical testing via laser tracker fiducials attached to the tangent link support pads to aid in M2 telescope alignment.

![Structure Function for M2 Fabrication](image)

*Figure 1. M2 Structure Function Residual Error Requirements.*

3. M2 MIRROR CELL ASSEMBLY

As mentioned in the introduction, the M2 assembly shown in Fig. 2, includes the M2 mirror, M2 mirror cell, the M2 mirror supports, the M2 thermal control system, various mirror sensors, the M2 control system and the associated electronics. The M2 mirror includes both the ULE™ meniscus and the support mounts bonded to it for interfacing to the mirror supports. The M2 mirror cell includes the main structural elements and several minor components. The M2 mirror supports include 72 axial and 6 tangential electromechanical actuators. Various sensors monitor the air and glass temperatures within the mirror cell assembly, the forces transmitted by the mirror supports and the position/motion of the M2 mirror. The M2 control system is comprised of all the electronics and software required to safely operate the mirror support system and monitor the sensors. Details regarding the incorporation of the M2 assembly into the overall telescope are provided in reference 1.
3.1 M2 Mirror (with Bonded Invar Mounts)

The 3.5-meter diameter, 100mm thick solid mirror has been manufactured from Corning ULETM material and is shown in Fig. 3. The near net shape substrate was acid etched. Invar mounts will be bonded to the mirror, with high strength vacuum compatible epoxy (3M 2216) to provide attachment locations for all 72 axial actuators and 6 tangent actuators. Invar 36 is used to match the very low CTE of the ULETM. All of these actuator mounts are considered part of the "mirror", and remain on the mirror during recoating.

3.2 M2 Mirror Cell

The M2 mirror cell includes the main mirror cell structure, aperture ring, safety stops, removable top panels and center hole sliders. The M2 mirror cell assembly is attached to the top end assembly at the interface between the M2 hexapod flange and the mirror cell. This mounting interface is also utilized by the M2 mirror cart. A large M2 light baffle mounts to the aperture ring of the mirror cell. Consequently, the mirror cell must support the loads transmitted from this baffle. When the baffle is not attached to the mirror cell a mirror cover is attached to the baffle mounts.
3.2.1 M2 Mirror Cell Main Structure
The welded steel M2 mirror cell structure, Fig. 4, is the main structure of the M2 assembly. Its design is stiffness limited, and so was fabricated of A36 and A516 low-carbon structural steel.

![M2 Mirror Cell Structure](image)

Figure 4. M2 Mirror Cell Structure.

All major components of the M2 mirror cell assembly, except for the actual M2 mirror, bolt to the mirror cell structure. The M2 mirror is attached to the mirror cell structure through the axial actuators and the tangent links. The M2 baffle attaches to the mirror cell through the aperture ring which is attached to the mirror cell structure.

The M2 mirror cell structure is principally comprised of a face plate, an outer shell, an inner shell, two intermediate rings and ribs. The axial figure control actuators mount to the mirror cell face plate in the voids between the ribs and rings. They protrude through the face plate holes and attach to the mirror. The tangent links attach to mounts on the outer shell, as does the aperture ring and the hexapod flange.

The mirror cell is an open back structure to optimize access to the 72 figure control actuators. This actuator configuration was chosen partially because it allows the utilization of continuous, straight ribs. This greatly increases the structural efficiency of the mirror cell and partially offset the inefficiency of the open back design. These continuous ribs provide both local stiffening for each actuator and global stiffening for the overall mirror cell structure. The steel structure is structurally efficient and contains significant light weighting. The ribs and intermediate rings have light weighting holes between each intersection to reduce mass, provide for the routing of cables, improve access to the axial actuators, and provide for the air flow required for thermal control.

3.2.2 M2 Mirror Cell Aperture Ring
A steel aperture ring attaches to the bottom flange (telescope zenith pointing) of the mirror cell, Fig 5. This ring limits the optical aperture to only the surface of the mirror figured to the optical requirements. The outer ~20mm of the "optical surface" is not required to be figured to optical standards and will be covered by this aperture stop to attenuate scattered light. This optical aperture stop is provided by the inner diameter of the aperture ring.
Since it covers the outer radial 20 mm of the mirror blank, once installed this aperture ring also captivates the mirror blank, fig 5. In the unlikely event of complete support system catastrophic failure the mirror cannot leave the mirror cell.

![Aperture Ring Installed](image)

Figure 5. Section View of Aperture Ring Entrapping M2 Mirror, and mirror safety stops.

### 3.2.3 M2 Mirror Cell Safety Stops

Mirror safety dictates that the M2 assembly provide safety stops, Fig. 6. These are fabricated from soft material (Delrin®) and limit the motion of the M2 mirror relative to its mirror cell to prevent direct contact between the glass and steel. The safety stops are only located in the vicinity of the tangent links. This allows direct measurement of the gap between the mirror and the safety stops.

![Camera sliders and mirror safety stops](image)

Figure 6. Camera sliders and mirror safety stops are made of Delrin® (M2 mirror and Aperture Ring Hidden).

### 3.2.4 M2 Mirror Cell Center Hole Sliders

As a result of the telescope optical configuration, the camera assembly must be installed through the central hole of the M2 assembly. Consequently a contact hazard exists between the aluminum camera and steel mirror cell assembly.
structures. To minimize the effects of a contact, the inner surface of the inner shell of M2 mirror cell has Delrin® sliders attached to its surface and aligned with the optical axis as shown in Fig. 7.

### 3.2.5 M2 Mirror Cell Removable Top Panels
The top of the M2 mirror cell is covered with lightweight thermally insulating G10 fiberglass panels. These panels seal the cell for environmental protection and capture heat dissipated by the actuators and mirror cell electronics, Fig. 8. Panels are light and have integral handles to facilitate on-telescope maintenance. Since the M2 assembly is normally located above the M1M3 mirror cell assembly. Consequently, soft material and retained screws were used to minimize the danger to the M1M3 mirror.

![Top Panels Installed](image1)

![Top Panels](image2)

**Figure 7. Top Panels.**

### 3.3 M2 Mirror Support System

The M2 is actively supported by 72 axial electromechanical figure control actuators (axial actuators) and 6 electromechanical tangent links (tangent links), Fig. 2. The axial actuators support the axial loads and actively control the shape of the mirror. The loads transverse to the optical axis are supported by the 6 tangent links. The load transmitted through each tangent link is actively adjusted to apply a repeatable load distribution which minimizes the stress and deformation imparted into the mirror. The transverse load is principally produced by gravity, but also includes wind, and dynamic loading.

The purpose of the M2 support system is to safely support the M2 mirror while controlling the optical surface error to levels consistent with the image quality error budget. This requires that stress in the glass never exceeds 1000 psi. The optical surface error is the result of interactions of the mirror’s weight with its supports, mirror figuring error, mirror system assembly/fabrication tolerances, thermal distortion, and the limitations of the active optics system.

Both the axial actuators and the tangent links have power off braking. When the system is de-energized the actuators will not back drive. This is accomplished by inherent resistance in the actuator.  

#### 3.3.1 M2 Mirror Support System - Axial Actuators

The 72 axial actuators are force-controlled. The force distribution for these axial actuators is principally determined by elevation angle through a lookup table, however, active optics, static correction and force balance offsets are added to the lookup table values. The force distribution applied minimizes the distortion of the M2 mirror surface.
The axial actuators, Fig. 8, attach to the invar mount pads bonded to the back surface of the M2 mirror. A set of flexures separate the puck attachment from the linear displacement actuator. These flexures allow for differential thermal expansion, fabrication tolerances, and limited motion of the mirror relative to the mirror cell. A load cell resides between these flexures to determine the load transmitted by the axial actuators. Actuator position is monitored by an absolute rotary encoder coupled to the drive motor through a zero-backlash gearbox. This arrangement was necessary to package the actuator assembly within the available height of the M2 cell. A mounting cup provides a base for the actuator assembly that allows it to be replaced as a single unit in the event of a failure, minimizing telescope downtime. The mounting cup also spaces the actuator away from the back of M2 to provide the axial space needed for the flexures and load cell.

<table>
<thead>
<tr>
<th>LSST M2 Axial Actuators</th>
<th>Summary of Key Performance Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force Range</td>
<td>±444 N</td>
</tr>
<tr>
<td>Force Measurement Repeatability</td>
<td>0.09 N</td>
</tr>
<tr>
<td>Force Resolution</td>
<td>0.11 N</td>
</tr>
<tr>
<td>Load Limit</td>
<td>±666 N</td>
</tr>
<tr>
<td>Minimum Stiffness</td>
<td>2.6 N/μm</td>
</tr>
<tr>
<td>Stroke</td>
<td>±3.5 mm</td>
</tr>
</tbody>
</table>

Figure 8. Axial Actuator Baseline Design and Top Level Requirements.

The overall length of the actuator is controlled by commands fed to the stepper motor driving the linear displacement actuator. To provide the required force application resolution of 0.11 N, the effective displacement resolution of the displacement actuator is 0.02 μm. This resolution is required to maintain optical surface errors compatible with the image quality error budget. The displacement actuator is a harmonic drive with a 100:1 reduction coupled to a ball screw with a 2 mm lead. The stepper motor gives 1000 counts per revolution. The actuator’s control system uses feedback from the load cell to convert this motion into the required force.

The load cell chosen is the Interface model SSMF-125 S-Type. It has a non-repeatability specification of 0.01% of the rated load of 445 N (100 lbs) which gives a non-repeatability error of 0.0445 N (0.01 lbs). The load cell is an analog device, therefore the force measurement resolution requirement of 0.10 N is determined by the A/D converter electronics. The maximum operating force is 445 N (100 lbs) and the maximum applied force for these actuators is 667.5 N (150 lbs) lbs. The load cell has a safe overload of 3 times the rated or 1335 N (300 lbs). The linear displacement actuator is rated to a maximum force of 150 lbs. All other components in the actuator stack are sized to handle forces that well exceed the force ratings for this actuator.
Axial actuator assemblies have been fabricated and verified to meet their performance requirements. Measured stiffness of the actuators is 3.1 N/μm, meeting the 2.6 N/μm minimum requirement. This stiffness requirement, when combined with the displacement resolution provides adequate force resolution for control of the mirror optics surfaces. It also ensures adequate natural frequencies of the M2 mirror. Lower actuator assembly stiffness provides greater force resolution because the resulting force on the mirror is lower for a given actuator step size, while higher stiffness provides greater stability of the mirror. Both the required minimum and measured stiffnesses satisfy these requirements. Actuator stroke and force capability requirements are met by internal design of the harmonic drive unit.

The actuator assembly includes a force-limiting mechanism that prevents application of unsafe loads to the M2. The mechanism consists of 3 plates held together by springs preloaded to a load limit of 667 N (150 lbs). The displacement actuator is mounted to one of these plates. When spring preload is exceeded in tension or compression, two of the plates separate and relative displacement between the actuator and mirror produces additional load on the mirror at the combined rate of the three release springs (15 N/mm; 84 lb/in) instead of at the actuator stiffness rate of 3100 N/mm (17,700 lbs/in). This limits the total force that can be applied to the mirror through any actuator to a safe level of 890 N (200 lbs) over the mechanism travel range of ±15 mm. The total mechanism travel allows the mirror to move all the way to its safety stops without exceeded safe load limits. The mass for an entire axial support actuator assembly is 3.1 kg. Force, stiffness, and displacement requirements for the axial actuators were appropriated from the axial actuators requirements for the SOAR and DCT primary mirrors.

The actuators are arranged in a configuration of three concentric rings, Fig. 9. The configuration of the 72 axial actuators was chosen because it requires the minimum number of actuators to meet the optical performance specification, and allows the use of structurally efficient straight rigs in the mirror cell main structure. Nominal support forces at zenith are set to minimize the overall force range of the actuators over the range of telescope elevations, thus maximizing actuator reliability.

<table>
<thead>
<tr>
<th>Ring</th>
<th>Radial Position (m)</th>
<th>No. of Supports</th>
<th>Support Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.002</td>
<td>18</td>
<td>254.4</td>
</tr>
<tr>
<td>2</td>
<td>1.284</td>
<td>24</td>
<td>230.4</td>
</tr>
<tr>
<td>3</td>
<td>1.601</td>
<td>30</td>
<td>190.4</td>
</tr>
</tbody>
</table>

Figure 9. Axial Actuator Zenith Pointing Nominal Force Distribution.

Contrary to the baselined design, the inner ring of actuators, R1, support a greater percentage of the zenith pointing gravitational load, per actuator than the middle, R2 or outer R3 actuator rings. In the baseline design the outer ring of actuators, R3 supported a larger percentage of the load, per actuator. This load distribution was performed to provide greater load capacity to the outer ring of actuators for the removal of mirror deformations and counteracting dynamic effects. More force is required by the outer actuator for the removal of surface deformation. More force is also required in the outer actuators to counteract the moments produced in the mirror by the LSSTs rapid slew and settling time.

### 3.3.2 M2 Mirror Support System - Tangent Links

An active tangent link, Fig. 12 provides transverse support for the M2 mirror. The support system uses six tangent links to control position and distribute support force to the mirror. Each of the six tangent links utilizes an electromechanical actuator and an imbedded lever system working through a load cell and flexure. This tangent link system was originally developed to replace a passive system on the SOAR telescope primary mirror that provided
inadequate performance\textsuperscript{12}. This existing system design has been operational on the SOAR telescope for several years without incident. See reference 12 for more design details.

![Diagram of actuator with encoder and tangent link assembly]

| LSST M2 Tangent Links
| Summary of Key Performance Parameters |
|-------------------------|------------------|
| Force Range             | $\pm 13,764$ N   |
| Force Measurement Repeatability | 2 N         |
| Force Resolution        | 0.11 N          |
| Minimum Stiffness       | 35,020 N/mm     |
| Stroke                  | $\pm 1.0$ mm    |

Figure 10. Tangent Link Assembly and Top Level Requirements. The components in the above figure are described in detail in reference 12.

The lever system reduces the stiffness, strength, and force resolution requirements of the electromechanical actuator and allows more compact packaging. Without the lever system these requirements cannot be met by any reasonable size and mass actuator. This design reduces the strength, stiffness and resolution demands of the actuator by the lever ratio of 6.3 to 1.0.

A relatively simple control system is utilized to operate the active tangent link system. Although all six actuators are nominally identical, three of the actuators are only operated quasi-statically to position the M2 mirror and the other three are force controlled. Each set consists of three equally spaced tangent links. The passive set is comprised of links F1, F3 and F5. The active set is comprised of links F2, F4 and F6, Fig. 11. This type of support system functions as two opposite sets of kinematic supports. Contrary to the SOAR tangent link system and the M2 baselined design, the three active links are operated by a modified axially reflective method. In the method the active tangent links are controlled to match the difference between the mean static link force $f m$ and the force of the passive link opposite each active link. This method was demonstrated to more stable and converge faster than the previous simpler arrangement.
\[ f_m = \frac{(f_{A1} + f_{A3} + f_{A5})}{3} \]

\[ f_{A1} - f_m \]

\[ f_{A2} = -(f_{A5} - f_m) \]

\[ f_{A6} = -(f_{A3} - f_m) \]

\[ f_{A3} - f_m \]

\[ f_{A4} = -(f_{A1} - f_m) \]

3.4 **Mirror cell sensors**

The M2 mirror cell assembly has a large number of sensors. The only sensors that are used directly in telescope operation are the load cells from the axial actuators and tangent links. The rest of the sensors are provided for initiation, diagnostics, and optimization and are the result of experiences on existing telescopes. All sensors are monitored by the control system. There has been minimal variation in the sensor system between the baseline design and the final design.

Position sensors measure the location of the M2 mirror relative to its mirror cell. The mirror is maintained in its optimum position relative to its mirror cell by displacements of the axial actuators and tangent links. Laser tracker retro reflector targets in conjunction with the telescope’s laser tracker determine the position of the M2 relative to the rest of the optical system and aid in optical alignment relative to M1M3.

Except for the load cells, thermal sensors, and inclinometer, all the sensors are attached to or act on the tangent link mounts, Fig. 12. Since the tangent mounts are rigidly bonded to the mirror, these sensors can determine the motion / location of the mirror without contacting the glass which would produce unnecessary risks to the mirror.
The following summarizes the sensing systems of the M2 mirror cell assembly as shown on Fig. 13.

**Actuator Loads:** Every axial actuator and tangent link has a load cell. The control system monitors the forces measured by all these load cells and actively operates these actuators and links to maintain the forces within tolerance.

**Temperature Sensors:** Temperature sensors are used to monitor the temperature of both the actual M2 mirror glass and the internal air volume of the mirror cell.

**Mirror Position Sensors:** Six axial and six tangent displacement sensors sense mirror location relative to the mirror cell. Each tangent link interacts with one axial and one tangent displacement sensor. The redundant measurements allow for the differentiation between mirror motion and mirror cell flexure.

**Vibration monitoring:** Accelerometers are included in the system for measuring motions in all six degrees of freedom. The accelerometers are attached to each tangent link mount.

**Orientation:** An inclinometer is located in the cell to allow the system to operate without elevation feedback from the mount control system. This capacity is required for removing/installing the M2 cell assembly, and it facilitates operational testing of the M2 support system when the M2 mirror cell assembly is mounted on its cart.

**Retro reflector:** The telescope utilizes a laser tracker system for determining the relative location of the M1M3, M2, and camera. Although the laser tracker system is not part of the M2 mirror cell assembly the M2 mirror cell assembly must support 12 retro-reflectors attached to the tangent links of the M2 mirror. Two are attached to each tangent link mount and are measured during optical testing to capture the M2 optical axis coordinate geometry.

### 4. CONCLUSION

The final design of the LSST M2 mirror cell assembly, produced by Harris Corp, meets all of the LSST function and performance requirements. Only minor modification from the baseline design were required during the final development.

### 5. ACKNOWLEDGEMENT

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6. REFERENCES