LSST mirror system status: from design to fabrication and integration

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ABSTRACT

In the construction phase since 2014, the Large Synoptic Survey Telescope (LSST) is an 8.4 meter diameter wide-field (3.5 degrees) survey telescope located on the summit of Cerro Pachón in Chile. The reflective telescope uses an 8.4 m f/1.06 concave primary, an annular 3.4 m meniscus convex aspheric secondary and a 5.2 m concave tertiary. The primary and tertiary mirrors are aspheric surfaces figured from a monolithic substrate and referred to as the M1M3 mirror. This unique design offers significant advantages in the reduction of degrees of freedom, improved structural stiffness for the otherwise annular surfaces, and enables a very compact design. The three-mirror system feeds a three-element refractive corrector to produce a 3.5 degree diameter field of view on a 64 cm diameter flat focal surface.
This paper describes the current status of the mirror system components and provides an overview of the upcoming milestones including the mirror coating and the mirror system integrated tests prior to summit integration.

Keywords: LSST, M1M3 mirror, mirror system, integrated mirror test.

1. INTRODUCTION

The Large Synoptic Survey Telescope (LSST)[1] mirror systems includes the specification and construction of the three telescope mirrors including: the purchase of glass substrate materials, the substrate formation, and the optical polish and testing of the mirror surfaces. It also includes the design, fabrication, assembly and integrated testing of the active support systems necessary to safely support and control the shape of the optical surface during operations.

The telescope optical design is a Modified Paul-Baker 3-mirror design. Due to the proximity of the primary and tertiary surfaces, it was possible to fabricate the primary and tertiary mirror surfaces from a single cast borosilicate substrate.[2] The annular secondary mirror is a Ultra Low Expansion Glass (ULE) meniscus.

Private funding allowed the early procurement of the primary/tertiary mirror and the secondary mirror substrate. When the construction phase started in Aug. 2014, the LSST mirrors were already in an advanced state. The M1M3 mirror optical fabrication process was almost completed, and the secondary mirror substrate was ready to start its final optical fabrication process.

The paper reviews the current status of the mirrors and their support systems, and the upcoming subsystem milestones and verification tests required prior to shipment to Chile.

The primary/tertiary (M1M3) mirror and it cell assembly will be integrated and tested in the Richard F. Caris Mirror Lab prior to transportation to Chile. The Secondary mirror (M2) and cell assembly are to be tested in Harris Corp. premises in Rochester, NY prior to shipping to the summit.

2. DESIGN AND FABRICATION

2.1 Primary-tertiary mirror (M1M3)

The M1M3 mirror is the main optical element of the Large Synoptic Survey Telescope (LSST). The mirror substrate is an 8.4 m spun cast, light weighted, Ohara E6, borosilicate glass that supports the two concentric aspheric surfaces of the primary (M1) and tertiary (M3).

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The primary mirror, M1, is an annulus of 8.4 m outer diameter and 5 m inner diameter. The tertiary mirror M1 has a 5 m outer diameter and 1 m inner diameter, as shown in Figure 1. Between the mirrors optical surfaces there is a 50 mm wide annular surface that is not figured to optical quality and will require light baffling to reduce stray light. There is also an M1M3 mirror baffle around the outer perimeter. This outer baffle overhangs mirror surface and blocks the outer 25 mm, which is also not figured to optical quality.

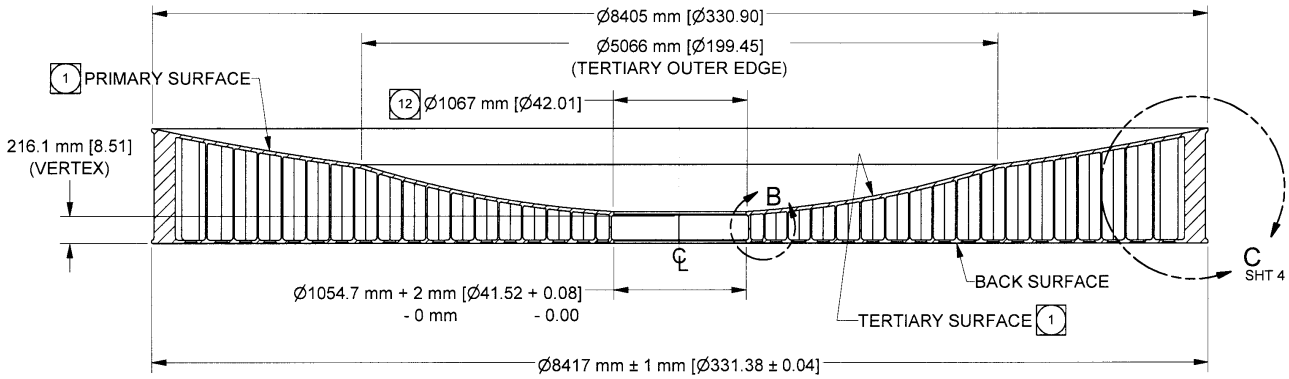

Figure 1: M1M3 monolith mirror design cross section with dimensions. The Primary mirror has a significantly different figure than the tertiary, therefore, the intersection is masked to mitigate any potential scattered light effects.

Identified in the early stages of the project as a critical element, the M1M3 mirror was cast at the beginning of 2009. The polishing process of both mirrors covered the period from April 2012 to October 2014. The M1 was finished in April 2014, and M3 was completed in October 2014. The acceptance tests were conducted from October 2014 to February 2015.[3] The final acceptance test required simultaneous interferometric measurements of both surfaces at two different stages, one for M1 and one for M3, laser tracker measurements and micro roughness measurements. The mirror prescription parameters were measured according to the verification matrix. Table 1 summarizes the nominal and measured prescription parameters.

Table 1: M1M3 parameters

M1M3	**Prescription**	**Measured**
Outside Diameter	8417 ± 1mm	8417.5 ±0.2 mm
Inside diameter	1054.7 +2/-0 mm	1054.8 ±0.1 mm
Substrate thickness at r=4208.5 mm	919 ±2 mm	920.2 ±0.2 mm
Substrate wedge	0 <30 arc sec	6 ±5 arc sec
M1 mean face sheet thickness	28 ±1 mm	28.4 ±0.1 mm
M3 mean face sheet thickness	28 ±1 mm	28.5 ±0.1 mm
M1 vertex to substrate mech. center	0 <1 arc sec	0.4 ±0.25 arc sec
M3 vertex to substrate mech. center	0 <1 arc sec	0.3 ±0.25 arc sec
M3 vertex height below M1 vertex	233.8 ±2.0 mm	234.4 ±0.1 mm
M1-M3 relative tilt	0 <100 μm TIR	20 ±10 μm TIR
M1-M3 axis displacement	0 <1 mm	0.33 ±0.4 mm
Micro-roughness	0<20 A RMS	17 ± 2 A RMS
M1 vertex radius	19835.5 ± 1 mm	8344.08 ±0.15 mm
M3 vertex radius	8344.7 ± 1 mm	8344.08 ±0.15 mm
M1 conic constant (k)	-1.2150 ± 0.0002	-1.215057 ± 0.000021
M3 conic constant (k)	+ 0.1550 ±0.0001	+0.155070 ±0.000005

Interferometric measurements performed on both mirrors show surface errors less than 20 nm RMS over their clear apertures. The optical axes of the two mirrors coincide to better than 0.5 mm at the surface of M3 and are parallel to better than 4 μrad. The parameters of the optical prescriptions, and all mechanical dimensions have been measured and shown to be within their specified tolerances. The measured values of the final mirror substrate were updated in the optical design file.

After final acceptance, the mirror surface was protective coated with OptiCoat in preparation for the transport and storage. The mirror was placed in its shipping container, the same container that will be used for its sea transport to Chile, and moved to its storage place in an airplane hangar at the Tucson airport. It is now awaiting its integration with the mirror cell; scheduled to take place in June 2017.

2.2 Primary-tertiary mirror cell assembly

The M1M3 mirror cell assembly houses the mirror support system that provides support for the M1M3 mirror against wind and gravity.[6,7,8,9] It maintains the position of the mirror and corrects distortion to ensure the mirror's optical surface meets the image quality requirements during operation. Because the mirror's final destination is in Chile, the mirror support system must also be capable of protecting the mirror during a seismic event. A thermal control system is needed to optimize telescope seeing and to minimize the thermal distortions of the mirrors. As a result of the large thermal expansion coefficient of borosilicate glass (2.8 x 10^{-6}/K), large mirrors fabricated from this material require extensive thermal control to prevent excessive thermal distortion.[10,11] The temperature control system is also located inside the M1M3 cell.[10] Figure 2 shows a cut of the mirror cell assembly.

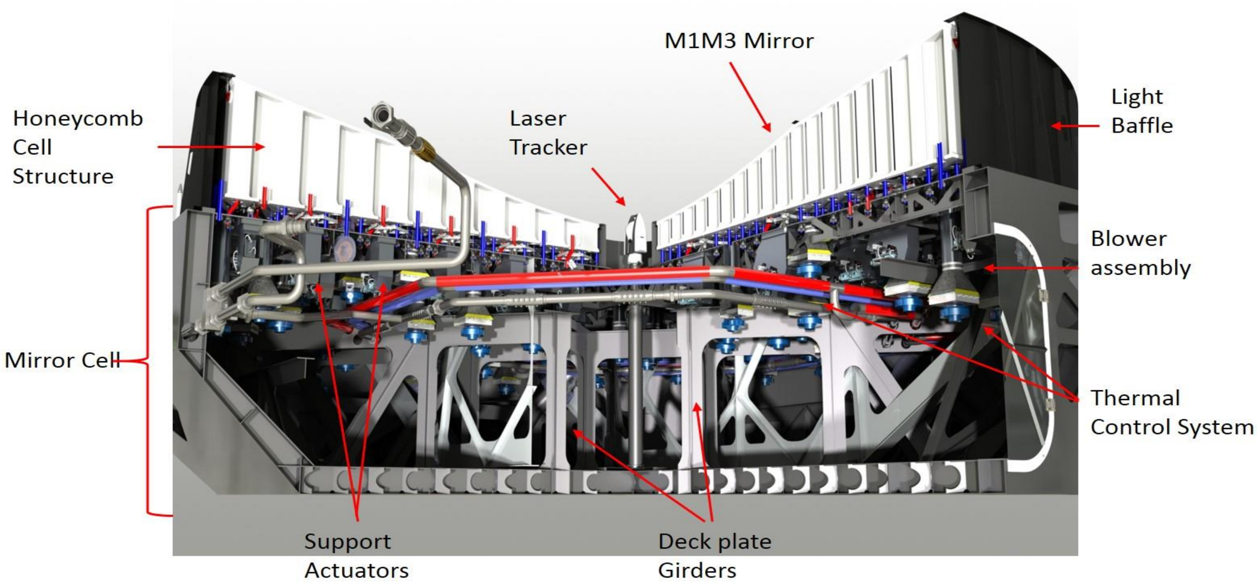

Figure 2: Mirror cell assembly cross-section showing the M1M3 Mirror cell assembly components. There are 112 dual axis actuators and 44 single axis pneumatic actuators (support actuators) used to control the mirror figure. The thermal control system utilizes 96 fan blower units, 1800 nozzles and an ethylene glycol and water(EGW) cooling loop.

The mirror cell also functions as the lower vessel of the coating chamber when optically coating the mirror surfaces.[9] The vacuum in the bottom chamber is separated from the vacuum in the top chamber by seals located on the outer and inner diameters of the mirror. The vacuum performance is dependent upon the out-gassing rate of the various elements contained inside the cell. Therefore, the components located inside the mirror cell are either suitable for use in a vacuum environment, or readily removable.

A laser tracker will be located in the central hole of the M1M3 (Figure 2) to perform alignment of the telescope's optical system. There are 12 spherical mounted retroreflectors (SMRs) are mounted on the periphery of the mirror for this purpose. The mirror support system cell was designed in-house based on a proven support system utilized on 6.5 and 8.4 m class mirrors.[6, 7, 8]

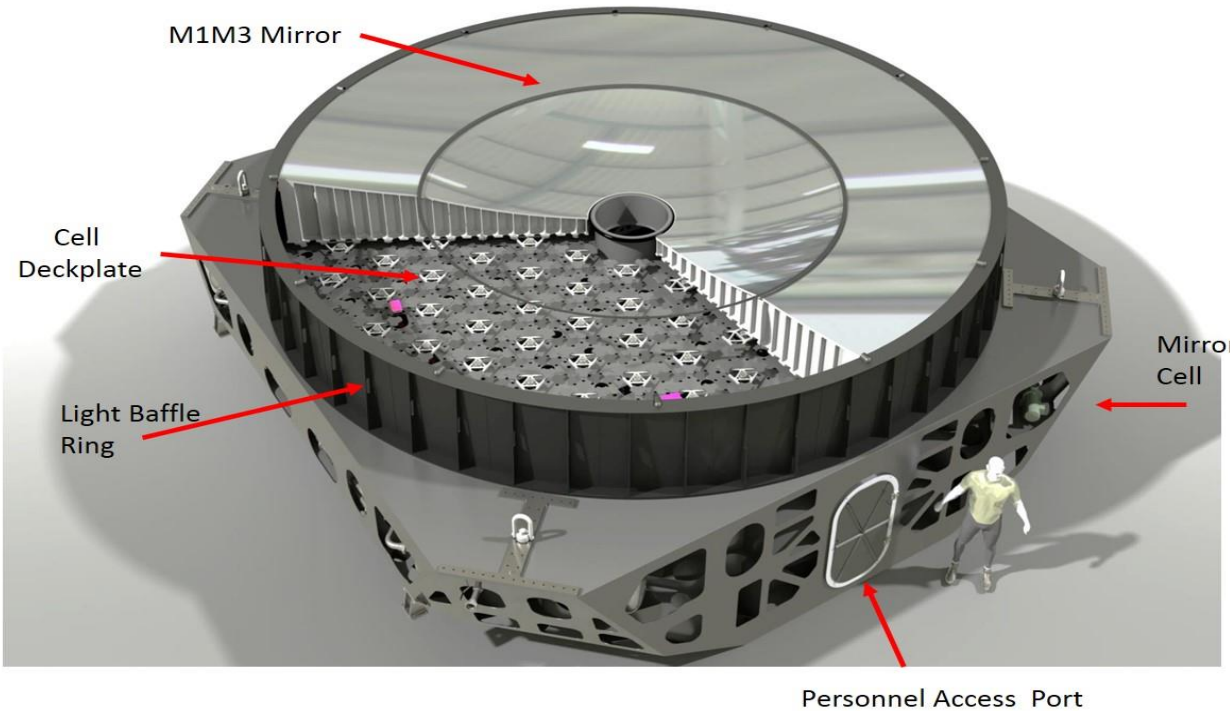

Figure 3: M1M3 mirror cell assembly. The LSST M1M3 mirror cell structure supports the M1M3 cast borosilicate monolith mirror, all of its support systems and its thermal control system. The mirror cell dimensions are 9m x 9m x 2m. Reference figure 1.68 m height.

The position stability of the M1M3 relative to the mirror cell is controlled by six displacement controlled actuators (hardpoints) that form a large hexapod. The hardpoints were developed in-house. They were prototype, tested and the final components procurement are in progress.[8]

The actuators assembly prototypes have been designed and assembled in-house, and are in the process of being tested. Items having long lead times in the mirror support and thermal control system have being identified and are currently being procured. The assembly of the 112 dual axis and 44 single axis pneumatic actuators plus spares will be done in-house and is schedule to start in summer 2016, with the expected completion is Jan 2017.

The LSST M1M3 Mirror Cell contract was awarded in October 2015 to CAID Industries, Inc. based in Arizona. The work includes the final design, manufacturing, assembly, and vacuum testing of the 26,000kg steel cell. Final acceptance is expected in February 2017.

2.3 Secondary mirror

The LSST Secondary (M2) is an annular 3.4 m diameter convex aspheric ULE^{TM} meniscus. The M2 blank was manufactured by Corning Incorporated, using their high-temperature fusion process out of 8 boules of ULE, arranged in a petal-shaped geometry. It was final grind and acid etched within 40 microns of final figure. It was delivered in December 2009.

In November 2014, the mirror blank was transported from its Harvard storage in Cambridge, MA to Harris Corp. in Rochester, NY for the final processing of the optical surface and incorporation into its mirror cell for integrated testing.

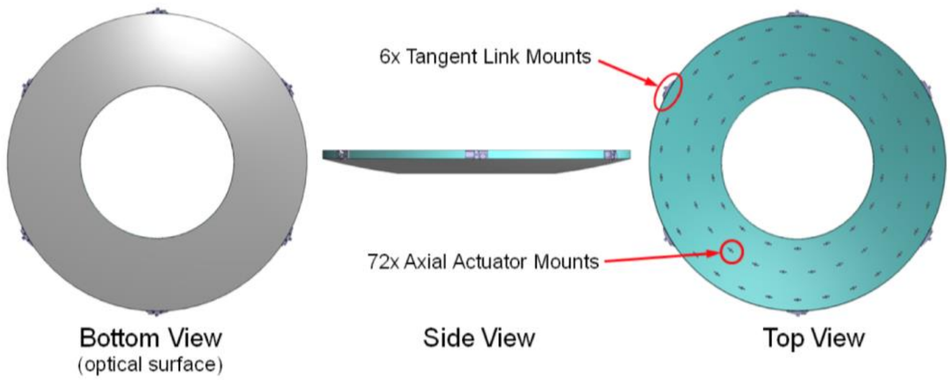

Figure 4: M2 bottom, side and top views showing axial and tangential pad location on mirror.

The optical surface fabrication process started in August 2015 with completion expected at the end of 2017 and final delivery to the summit in early 2018. The process includes grinding, polishing and figuring. Ion figuring will be used for the optical figuring. This process has been demonstrated to finish optics surfaces to exacting specifications with no edge related effects. The M2 mirror prescriptions are summarized in Table 2.

Table 2: M2 mirror prescription

Outer Aperture (Dia)	3470.0 mm
Inner Aperture (Dia	1775.0 mm
Outer CA (Dia)	3420.0 mm
Inner CA (Dia)	1800.0 mm
Convex surface wedge	30 arc seconds
Vertex to center position	0.0 ±0.5 mm
Radius of Curvature, RoC	-6788.0 ± 1.5 mm
Conic Constant, k	-0.2220 ± 0.0001
Fried Parameter, r_0	1.38 m
Scattering (σ) at 500nm	σ = 11 nm
Micro-roughness	2 nm RMS
Full Surface Error	20 nm RMS

The completed M2 includes the mirror substrate, with the optical surface polished to the figuring requirements combined with all 72 actuator support pads and 6 tangent link pads bonded to the glass substrate.

2.4 Secondary Mirror Cell Assembly

The M2 mirror Cell Assembly safely supports the M2 mirror and provides active figure control of the mirror's optical surface through a distributed set of electromechanical actuators attached to Invar pads bonded to the M2 mirror. The cell structure supports the actuator assemblies and interfaces to the telescope mount Top End Assembly (TEA) [12] through the M2 Hexapod Flange. The large diameter Camera Assembly can be safely installed through the center hole of the M2 mirror cell assembly. [13,14]

The Cell assembly is being manufactured by Harris Corp as an additional scope to the polishing contract, and includes the final design and fabrication of the complete M2 Cell Assembly system. This system consists of the mirror cell structure, the mirror support system, electronics and sensors, thermal control, and the mirror control system.

The mirror support system consists of 72 axial actuators, and 6 tangent links (Figure 5). The axial actuators attach to the pads bonded on the mirror's back surface. They safely support and control the shape of the optical surface. The six tangent links attach to mounts on the outer edge of the mirror, and provide support against transverse loads. They provide a repeatable load distribution as a function of zenith angle to minimize stress and distortion in the mirror substrate. All support actuators, both axial and tangential, will experience 1-year of accelerated life testing before integration in the cell.

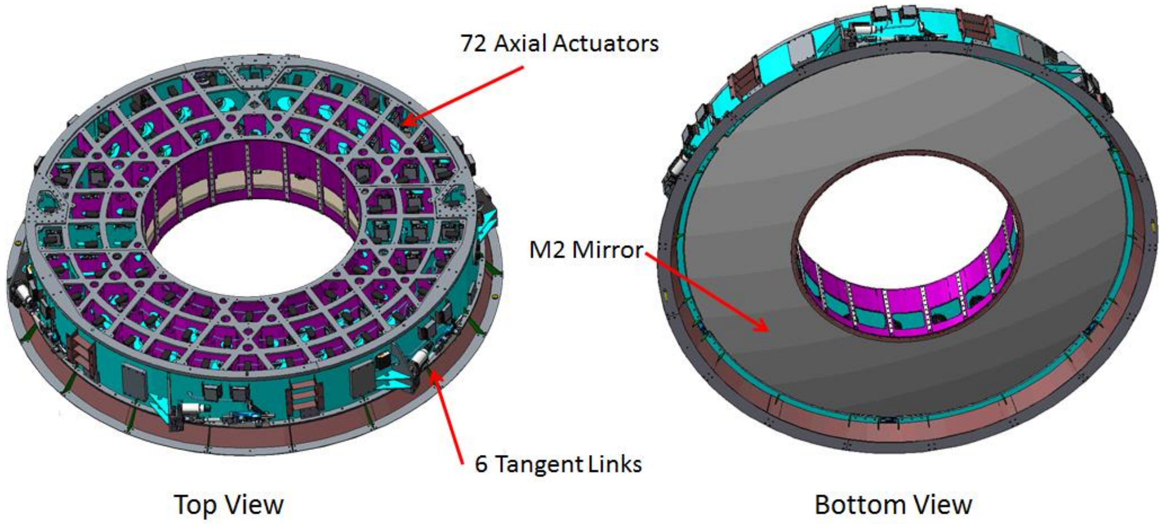

Figure 5: M2 mirror support system top and bottom view showing axial actuators and tangential links position.

The M2 assembly will be initially integrated and tested with an aluminum surrogate M2 mirror. Final acceptance testing will be performed with the actual M2 mirror. The active optics mirror control will be demonstrated and will capture the M2 optical axis location using 12 spherically mounted retro-reflectors (SMRs) permanently mounted to the tangent link mounts on the mirror outside diameter.

3. MIRROR CELL ASSEMBLIES INTEGRATION AND TEST

For both mirror system, integrated cell assembly testing is necessary to verify the active support systems can safely support and control the shape of the optical surfaces. Surrogate mirrors will be used before the glass mirrors for the first integration and test, once these tests are successfully completed the final mirror and cell integrations can take place. The surrogate mirrors will also be used again for initial on telescope testing.

3.1 M1M3 mirror and cell integration

After the Mirror cell acceptance, the subsystems assembly inside the mirror cell that includes actuators, hardpoints and thermal control system will take place. As part of this integration, the surrogate mirror will be mounted in the cell. Approximately 6-months is allocated for the M1M3 cell assembly integration, which will be followed subsequent by 3-months of testing. The integration and test will be performed at the facility of the mirror cell vendor, CAID in Tucson, AZ.

The first fully integrated test of the M1M3 mirror support system will be performed with the surrogate mirror installed on the M1M3 cell. This reduces risk while allowing testing of the mirror support system under realistic load conditions. The mirror support system will initially be tested only at the zenith orientation. Testing at other orientations may be performed as time permits and if the necessary equipment is available. The Mirror cell panic state evaluation (the mirror resting on its static supports) and recovery procedures will be exercised. Once the tests are completed and the criteria successfully met, the surrogate will be dismounted and shipped by sea to the summit for later testing on the telescope. The cell will be prepared for the M1M3 mirror integration and shipped to the mirror lab. The M1M3 mirror will also be transport from its storage place to the mirror lab, where it will be integrated with the cell. As mentioned in Section 2, the actual M1M3 mirror will be integrated and tested with its cell at the Richard F. Caris Mirror lab. This integration is scheduled for the first quarter of 2018.

The integrated mirror cell assembly (Figure 6) will be placed under the test tower. The active optics mirror control will be demonstrated at zenith with the same test tower configuration used during mirror polishing. It will be equipped with both interferometers for the primary mirror M1 and the tertiary mirror M3. [3, 4, 5] We will be able to test the mirror support system with an optical feedback, verify the active optic correction, the mirror figure and the influence matrix then compare results with the M1M3 Mirror FEA model.

Because the Mirror lab is a temperature controlled environment, only reduced thermal control system testing is possible. Tests include image quality degradation and vibrations measurements when blowers are running at full speed. The final thermal control testing will be performed at the summit.

After completion of final lab testing both the cell and the M1M3 mirror will be shipped to the summit for final integration. Once integrated at the summit it is not foreseen that the mirror and the cell will ever be separated as the mirror remains in its cell during coating. The mirror support system will be checked and parameters compared to the surrogate test values.

Figure 6: Integrated M1M3 mirror cell assembly.

3.2 Secondary mirror integrated testing

The M2 integrated testing will take place in Harris Corp premises in Rochester, NY. Prior to integration of the glass, the M2 Cell Assembly will be tested as a complete unit utilizing the aluminum surrogate mirror. The surrogate M2 mirror (Figure 7) was designed with a mass, CG and stiffness comparable to the actual M2 mirror. It also uses interfaces to the axial actuators and tangent links that mimic those bonded to the actual mirror. The surrogate design enables testing of the mirror support system and its control system as required for the M2 cell acceptance. This will also serve as the pathfinder for the integration of the actual M2 optic.

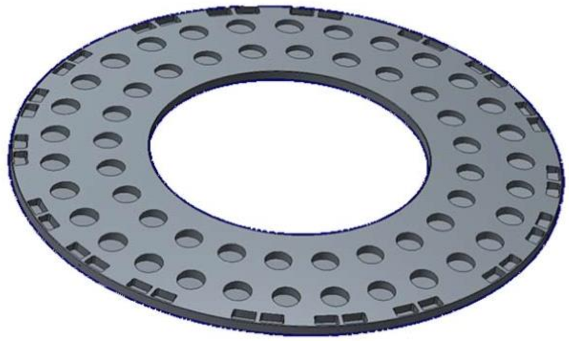

Figure 7: M2 Aluminum surrogate design.

The integrated support system testing shall include at least one orientation with the M2 Cell Assembly downward facing (telescope zenith pointing) and one orientation with the M2 Cell Assembly vertical (telescope horizon pointing). The integrated system testing shall use the M2 Cell Assembly control system to enable remote operation. Optical surface metrology equipment will be used to demonstrate and validate the active optics system performance and correctability.

After completion of the testing and final acceptance, expected late 2017, the M2 mirror, the surrogate and the mirror cell will be shipped to the summit. The M2 mirror will be shipped in its own container that is modified to accommodate the actuators support pads on the back of the mirror.

4. MIRROR COATINGS

A combination of protective aluminum and silver coatings are expected to provide the best performance to meet the current throughput requirements, and also the coating cleaning and extended lifetime requirements. Figure 8 shows the reflectivity of the combined 3-mirror for two possible combinations, M1M3 coated with protected aluminum and M2 with protected silver and vice-versa. The combination of protected aluminum for the M1M3 mirror and protected silver for the M2 mirror provides a higher reflectivity in the blue region (*u*-band) when compared with the other combination. [14]

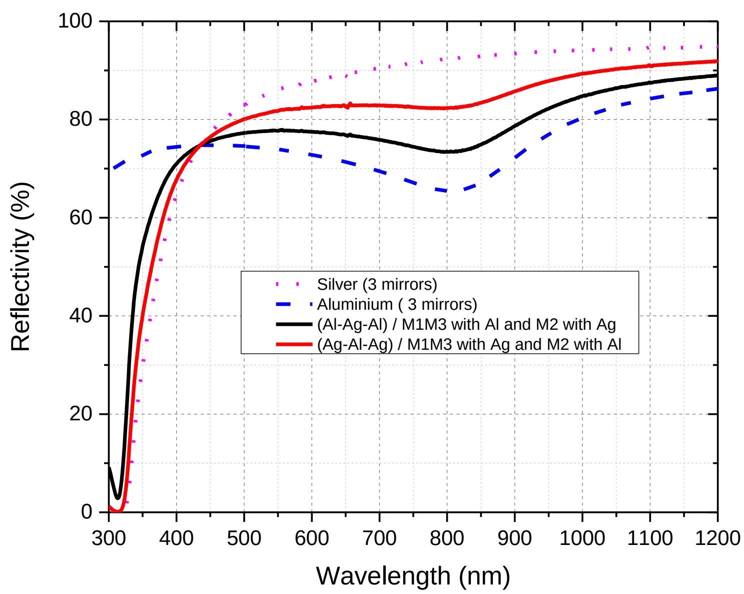

Figure 8: Mirror coating options comparison

To extend the coating lifetime the mirror surface will be periodically cleaned with $C0_2$ snow and less frequently, in situ washing will be performed. The mirror recoating is planned to take place every two years.

The mirrors will be coated on-site in the coating plant at the summit facility. LSST Coating Plant has been designed to coat and strip the M1M3 and M2 Mirrors. The Coating Plant will consist of two standards parts, the Coating Chamber and the Stripping Station. The Coating Chamber can be divided in 3 sub-systems. The Upper Chamber, which houses the Sputtering System with 8 DC planar magnetrons, 4 of them allocated to the M1 mirror and the other 4 for the M3 mirror, each set of those 4 magnetrons will have one Aluminum, Silver, Nickel Chromium and Silicon target. For the M2 mirror coating will use the same set of M3 magnetrons used in another mechanical internal configuration. The second standard part is the Lower Chamber which one can be attached to the Upper Chamber for M2 coating configuration. This Lower Chamber will host the M2 Mirror; and the M1M3 Cell, which hosts the M1M3 Mirror with a separate vacuum system. The vacuum space for the Upper Chamber is a clean vacuum environment for the Sputtering process located above the M1M3 Cell which has a “dirty” or lower cleanliness vacuum. The Stripping Station will host a, “Washing and Drying Boom,” that will be located above the M1M3 Mirror on a rotation system; another specific and smaller system has been designed for the M2 striping.

The LSST coating plant contract was awarded at the beginning of the year 2016 to Von Ardenne GmbH in Dresden, Germany and is expected to be in operations on the summit by mid-2018.

5. SUMMARY

Now two years from the start of construction, the LSST Mirror System is in an advanced state. The primary-tertiary mirror has been polished to specification and it in storage awaiting its integration into the cell. The secondary mirror is being polished and expected to be compled at the end of 2017. The respective mirror cells and support system are currently in fabrication. Testing of the mirror support system will be done with surrogates and later with the glass substrates. After successful completion of the mirror support system tests, the mirror will be shipped to Chile for coating and final telescope integration and test.

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