LSST Telescope and Site Status
William J. Gressler
Large Synoptic Survey Telescope, 950 N Cherry Ave., Tucson, AZ, USA 85719

ABSTRACT

The Large Synoptic Survey Telescope (LSST) Project received its construction authorization from the National Science Foundation in August 2014. The Telescope and Site (T&S) group has made considerable progress towards completion in subsystems required to support the scope of the LSST science mission. The LSST goal is to conduct a wide, fast, deep survey via a 3-mirror wide field of view optical design, a 3.2-Gpixel camera, and an automated data processing system. The summit facility is currently under construction on Cerro Pachón in Chile, with major vendor subsystem deliveries and integration planned over the next several years.

This paper summarizes the status of the activities of the T&S group, tasked with design, analysis, and construction of the summit and base facilities and infrastructure necessary to control the survey, capture the light, and calibrate the data. All major telescope work package procurements have been awarded to vendors and are in varying stages of design and fabrication maturity and completion. The unique M1M3 primary/tertiary mirror polishing effort is completed and the mirror now resides in storage waiting future testing. Significant progress has been achieved on all the major telescope subsystems including the summit facility, telescope mount assembly, dome, hexapod and rotator systems, coating plant, base facility, and the calibration telescope. In parallel, in-house efforts including the software needed to control the observatory such as the scheduler and the active optics control, have also seen substantial advancement. The progress and status of these subsystems and future LSST plans during this construction phase are presented.

Keywords: LSST, telescope

1. INTRODUCTION

The Telescope and Site (T&S) group for the Large Synoptic Survey Telescope (LSST) Project is based in Tucson, Arizona, and has developed an observatory system designed to meet the 10-year LSST survey mission. The scope of the T&S construction effort is defined in WBS elements and is accomplished by external contract efforts with qualified vendors and internal labor based development activities. The T&S construction WBS elements and vendors on the Project as of this writing are listed in Figure 1.

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Figure 1: Telescope and Site construction WBS and vendors
The T&S team is responsible for the design, analysis, construction, and integration and testing of the summit and base facilities and the infrastructure necessary to support LSST operations. The observatory support facility is shown in Figure 2, highlighting the integrated nature of the elements including a unique tapered pier, concrete lower enclosure, and a large service lift for transport of the mirror and camera systems within the building for clean room access/maintenance and on-site optical coating. A separate nearby auxiliary telescope system provides atmospheric calibration information.

The LSST base facility integrates with and expands the existing Cerro Tololo Inter-American Observatory (CTIO) property in La Serena, Chile. Its design accommodates sufficient building space for 32 offices and 15 work stations to support LSST operations and includes a state of the art Data Center with sufficient rack count and computing power to handle the large amount of data pouring from the telescope, as shown in Figure 3. The inviting circular entryway provides a gallery and general building access. Initial demolition and refurbishment activities are scheduled to commence in late 2016, with facility construction occurring in 2017.
The LSST Project\textsuperscript{1} received its construction authorization from the National Science Foundation in August 2014. All major telescope work package procurements have been awarded to vendors and are in varying stages of design and fabrication maturity and completion. The summit facility is currently under construction on Cerro Pachón in Chile, with major vendor subsystem deliveries and integration planned over the next several years.

2. SUMMIT FACILITY

The LSST Summit Facility\textsuperscript{2} construction effort was awarded to Besalco Construcciones, S.A. in Santiago, Chile, in late 2014, with the site control being transferred on January 5, 2015. The scope included site excavation, concrete foundation forming, structural steel installation, utilities and roads, electrical, HVAC (chillers/compressors), plumbing and special systems. The design firm Arcadis-Chile remains as the LSST architecture/engineering vendor to support the construction effort. Figure 4 illustrates the initial excavation activities and also shows recent progress up to level 3 with protrusion of reinforcing rebar on the summit readying for concrete pouring of the piers for the telescope mount assembly and the dome system. Significant obstacles have been overcome including unexpected fractured rock conditions, harsh/wet weather, and even a substantial seismic event. Progress remains steady with focus towards completion of major interfaces.

Figure 4: Summit Facility early excavation and recent construction status

Pflow Industries Inc., in Milwaukee, WI, is responsible for the custom 80-ton capacity vertical platform lift, which resides between the entrance end of the summit facility and the bedrock footing of the dome lower enclosure. Figure 5 shows workers preparing concrete forms and reinforcing rebar and anchor bolts for the pit of the lift structure. The 88-foot tall steel structure extends up to the rear of the dome and provides the ability to transport the primary mirror assembly on a motorized cart (running on two steel rails) from the telescope mount assembly at the summit down to the lower end of the facility where the mirror strip/wash station and coating plant reside. The lift will also support transport of the secondary mirror assembly and camera systems, each of which will use specialized carts to move within the support facility. The steel column sections for the vertical lift have been completed and are at the site ready for assembly with the remaining moving components of the system in late 2016 as the exterior of the Summit Facility is completed.

Figure 5: Preparation for the Pflow vertical lift structure and cutaway showing building integration
3. DOME (ROTATING ENCLOSURE)

The LSST Dome System contract was awarded to European Industrial Engineering (EIE), Mestre, Italy, in May 2015. The scope includes final design, fabrication, factory testing, shipment, installation, and final acceptance testing on the LSST summit. The LSST Dome System (Figure 6) is similar to the previous EIE VLT dome designs, but includes a separate light/wind screen, comprised of large overlapping light-weighted curved panels along an arc in elevation that provides a controlled aperture to suppress stray and scattered light.

Both the 11-meter wide shutter door opening and the wind/light screen work in tandem to provide the necessary stray light protection required by the LSST wide field of view by actively following the telescope line of sight and limiting the sky angles of direct illumination. In order to keep up with the observing cadence, the dome azimuth drive system will constantly crawl on 14 twin wheeled bogie trucks, minimizing the motor power necessary to rotate the 600 ton structure. The dome system has louvered light baffling vents to provide over 500 square meters of vented area to produce a minimum of 75 air changes per hour with a 5-meter/sec horizontal incident wind. The area between the rotating dome and fixed pier is sealed with both a labyrinth and inflatable seal to provide light tightness and minimize infiltration, thereby reducing air conditioning demand.

The Dome Final Design Review was completed in early June 2016. Early fabrication efforts have resulted in the shipment of the steel plate interfaces to be embedded into the concrete lower enclosure pier as well as the delivery of azimuth motor mounting brackets. Figure 7 shows the fabrication of the embedded plates and the finished hardware being unloaded from its shipping container from Italy on the LSST summit in Chile.
The integration of the embedded plates is scheduled for mid-2016 as the concrete lower enclosure work is completed on the LSST summit facility. By late 2016, the azimuth rails and lower box beam components will be arriving at the summit in Chile. Major integration activities are scheduled during 2017, with the final integration and acceptance testing on the LSST summit planned by the end of 2017.

4. TELESCOPE MOUNT ASSEMBLY (TMA)

The LSST Telescope Mount Assembly (TMA) contract was awarded to GHESA Ingenieria y Tecnologia S.A. and Asturfeito, S.A. in June 2014. The scope includes the final design, fabrication, factory testing, packaging, and on-site installation and final acceptance testing of the TMA in the LSST Summit Facility. Engineering and design activities are based at the GHESA facility in Madrid, with fabrication and integration work occurring at the Asturfeito facility in Asturias. The compact telescope design (Figure 8), provides for a stiff structure that is necessary to achieve the short slew and settling time allocation of less than four seconds for a 3.5-degree slew. Dual deployable platforms while parked at horizon pointing enable access to the camera and secondary mirror assemblies for routine on-telescope maintenance.

![Telescope Mount Assembly design and camera cable wrap](image)

The azimuth and elevation drive systems are designed to use sophisticated dual gap direct drive technology from Phase Motion Control, Genova, Italy, using FeNdB type magnets. The dual gap configuration allows the axial force imbalance to be minimized and provides a more compact layout. Demands for peak power from the local electrical grid necessary to achieve the needed high accelerations are minimized by using a capacitor bank consisting of 360 polypropylene self-healing, film-foil capacitors. This system helps to supply the nearly 1-megawatt demand to slew the 350 ton TMA.

The main axis encoder system uses high accuracy incremental optical encoder technology from Heidenhain, Germany. The azimuth encoder is a complete circular outside-mounted scale tape located in a slot on the azimuth ring, and four scanning heads on the azimuth structure. The elevation configuration uses a segment scale tape and two scan heads. The hydrostatic bearing system uses a custom solution from SKF, Sweden, for both the azimuth and elevation axes to meet the accuracy, high stiffness and low friction requirements, as well as its size, mass, and performance. The TMA subcontractor IK4 Tekniker, from Gipuzkoa, Spain, is responsible for the intelligent mount control system which provides active damping and a complex cable wrap system to provide all camera utilities and services for refrigeration and fiber optic signals, shown above in Figure 8.

The TMA Final Design Review was successfully completed in January 2016 at the GHESA facility in Madrid, leading to the approval of procurements for long lead materials and systems. By March 2016, initial fabrication had commenced at the Asturfeito facility in Northern Spain. Since then, the large azimuth track sections have been welded and are being machined, as shown on the left in Figure 9. The azimuth ring supports the entire telescope assembly and transmits the reaction forces to the pier under all operating conditions. It is anchored via 400 bolts which are grouted into the corresponding embedded pier pockets.
At the time of this writing, a 3-meter tall surrogate pier is being constructed in the Asturfeito facility to enable full system factory testing, as shown on the right in Figure 9. In order to demonstrate the full performance of the TMA in the factory, each optical payload will be substituted by a representative surrogate mass assembly. These surrogates utilize the same interfaces and alignment features to enable installation and maintenance procedures to be verified. In addition, the surrogate masses will have the same center of gravity, total mass, and natural frequency as the optical payloads, within a tolerance range. Factory integration and testing is scheduled throughout late 2016 and early 2017. Upon packaging and shipment, initial installation of the azimuth track sections at the LSST summit is scheduled to commence in early 2018, with final acceptance testing planned by the end of 2018.

Figure 9: Telescope Mount Assembly design and surrogate pier construction for factory testing

5. HEXAPODS AND ROTATOR SYSTEMS

The LSST Hexapods and Rotator contract was awarded to Moog CSA Engineering, Mountain View, CA, in September, 2013. Both the secondary mirror (M2) assembly and the camera positioning systems utilize hexapods to facilitate optical alignment relative to the primary/tertiary (M1M3) mirror optical axis. Geometric considerations preclude the use of a conventional hexapod arrangement for the M2 hexapod, as shown on the left in Figure 10. The camera hexapod positions the LSST camera and a rotator resides between the camera and its hexapod to facilitate tracking, as shown on right in Figure 10.

Figure 10: LSST M2 hexapod (left) and camera hexapod/rotator system (right)

The open loop operation of the optical system requires very low hysteresis from the hexapod, which is achieved by use of flexures rather than traditional end joints. The operational constraints of the LSST combined with supporting a 3060 kg cantilevered camera payload requires high natural frequencies. Consequently to reduce the mass relative to the stiffness, a unique rail and carriage system from THK, Japan, is utilized in the rotator system design rather than the more traditional slew bearing. This system utilizes two concentric tracks and 18 carriages.
Moog has completed the system designs and analysis and has subsequently fabricated the majority of the hexapod components. Assembly and test of the hexapod actuators and rotator will be done in CA, with full system testing (including 200% proof loading via surrogate masses) in their Golden, CO facility which provides the necessary high bay area. Detailed testing plans and procedures have been developed and approved to support the integration and test sequence scheduled for late 2016. Final acceptance testing is anticipated in early 2017, including a second spare rotator which will be provided to the LSST camera team to confirm proper integration features and performance prior to shipment of the system to the summit in Chile.

6. LSST OPTICAL SYSTEM

The LSST optical system utilizes a unique, compact, three-mirror telescope design (Figure 11) consisting of an 8.4-meter primary mirror (M1), 3.5-meter secondary mirror (M2), and a 5.0-meter tertiary mirror (M3). The three-mirror telescope feeds a large three-lens refractive corrector (camera) producing a well-corrected 3.5 degree field-of-view. An active optics system is used to optimize the image quality by controlling the surface figures of the mirrors and maintaining the relative positions of the optical subsystems (M1M3, M2, and camera). The tertiary mirror (M3) resides within the 5-meter diameter central hole of the primary mirror (M1). The M1 and M3 mirrors have been fabricated from single monolith (M1M3) spun cast borosilicate substrate, which improves stiffness. Since the orientation of the M3 toward the M1 is permanent, utilizing a monolith removes six degrees of freedom which simplifies optical alignment and enables a compact, rigid structural packaging design.

Figure 11: LSST optical system layout including compact 3-mirror design and 3-lens refractive camera

6.1 PRIMARY (M1) / TERTIARY (M3) MIRROR ASSEMBLY
The primary (M1) and tertiary (M3) mirrors are two concentric aspheric surfaces on one monolithic substrate, hence they are referred to as the M1M3 optic. The substrate material is Ohara E6 borosilicate glass, in a honeycomb sandwich configuration; produced by the University of Arizona’s Richard F. Caris Mirror Lab. Early private funding enabled the fabrication of this critical long-lead component and effectively removing it from the Project’s critical path—an unusual occurrence for large telescope mirrors. The surface specification is described as a structure function, derived from the equivalent Kolmogorov spectrum associated with the FWHM allocation from the error budget. Both the pointing and centration of the two optical axes are important parameters, in addition to the axial spacing of the two vertices.

The Mirror Lab optical fabrication effort for the M1M3 began with its initial casting in July 2008. The polishing of the M1M3 mirror surfaces was completed, inspected, and accepted by LSST in April 2015. Interferometric measurements confirmed both surfaces met or exceeded their structure function requirements for surface uniformity and figure accuracy over their clear apertures (there is a 50-mm gap between M1 and M3 surfaces which will not be coated). LSST and Mirror Lab personnel confirmed the residual error after synthetic bending mode correction was acceptable given the allowable actuator support force set. Finally, the optical to mechanical position was in tolerance along with all other optical specifications (radii of curvature, conic constants, and other physical parameters).
In May 2015, the finished M1M3 mirror coated with a protective film was vacuum-lifted off its polishing cell and secured in its transport container at the Mirror Lab facility, as shown on the left in Figure 12. After final inspection the transport container top was attached and sealed. In the early morning on May 18th, 2015, the combined 56-ton wide-load was escorted to a secure hanger at the Tucson airport for storage, as shown on the right in Figure 12.

The M1M3 mirror will remain safely in storage while the telescope mirror cell weldment and active mirror support system is fabricated as part of the M1M3 Cell Assembly9. The mirror cell will be populated with the support system components and undergo extensive testing with a surrogate M1M3 to ensure the pneumatic support system is functioning properly. By mid-2017, the M1M3 is scheduled to be removed from storage, mated with the cell and returned to the Mirror Lab for integrated testing with the same interferometric system used to confirm polishing results with synthetic bending mode correction. This optical testing will final testing to verify active optical correction prior to packaging and shipment of the assembly to Chile for optical coating and telescope integration in early 2019.

The M1M3 mirror cell weldment contract was awarded to CAID Industries, Inc., Tucson, Arizona in October 2015, as shown in Figure 13. This 25-ton, 9 x 9 x 2-meter steel weldment supports the 19-ton M1M3 on the telescope and also provides a vacuum boundary for optical coating of the M1M3 as it always remains on its mirror cell. The fabrication of the large weldment is complete and will undergo thermal stress relief before final machining. Final acceptance is scheduled for early 2017. CAID is also under contract for the M1M3 surrogate mirror, which will be used to verify the active support system components are performing as expected.

The M1M3 Cell Assembly positions the mirror on six hard point actuators, being developed in house9, arranged in a hexapod configuration. The mirror is supported and its shape is controlled via 112 dual axis and 44 single axis pneumatic actuators. A dual axis assembly is shown on the left in Figure 14. The Cell Assembly also provides a thermal control system consisting of 96 fan blower units that circulate conditioned air via 1800 nozzles to vent the mirror cores. A section view of the M1M3 cell assembly, on the right in Figure 14, shows a view of the mirror actuators, fan units, core nozzles,
and an ethylene glycol and water cooling loop. The LSST T&S group has completed fabrication of a prototype dual axis actuator assembly, with full production of all units underway in Tucson.

6.2 SECONDARY (M2) MIRROR ASSEMBLY
The 3.5-meter diameter secondary (M2) mirror utilizes a 100mm thick meniscus ULE™ blank completed by Corning Incorporated in 2009. A design/build contract was awarded to the Harris Corporation (formerly Exelis) in Rochester, NY, in March 2013, to polish the M2 convex surface, fabricate the mirror cell and active mirror support system (M2 Cell Assembly), and provide integrated optical testing, shown below in Figure 15. The polished mirror surface figure requirement is described by a structure function, with an allowable force allocation for active optics correction.

The M2 optical fabrication effort has advanced through grinding and polishing of the convex surface, and at the time of this writing, is undergoing full tool smoothing, as shown on the left in Figure 16. Ion figuring will be used to converge the optical surface to meet requirements. Testing the 3.4-meter diameter convex shape of the optic will require a novel technique of stitching of the sub-aperture interferograms developed by Harris to measure the entire surface. In parallel, Harris has advanced the design and fabrication of the M2 cell assembly mechanical elements with completion of the mirror cell (shown with removable service panels), on the right in Figure 16. The M2 mirror cell, surrogate M2, and turnover cart have been completed and delivered to the Harris facility. In late 2016, cell assembly will commence with the integration of the 72 electromechanical axial figure actuators and six tangent links.
Iterative optical measurement and ion figuring correction operations are planned through mid-2017. The M2 Cell Assembly is scheduled to undergo final integrated optical testing at the Harris facility in late 2017 to ensure proper performance of the support system components. Final packaging and shipment of the M2 system to Chile for optical coating and telescope integration is planned for 2018.

7. LSST COATING PLANT

The LSST Coating Plant\textsuperscript{11} contract was awarded to Von Ardenne, GmbH, in Dresden, Germany in March 2016. Von Ardenne is responsible for the final design and fabrication of the Coating Plant including the coating chamber (including pumping system, rotating magnetrons, and steel vacuum vessels) and a separate washing/drying stripping station. These systems are designed to be located on the third floor of the support facility to enable coating of the M1M3 Cell Assembly on its mirror cart and the M2 mirror on the LSST summit, as shown in Figure 17.

The baseline approach defines a fixed substrate and rotating magnetron system, capable of uniformly depositing a wide range of materials, including metallic (aluminum, silver, gold), nitrides (silicon nitride), oxides (silicon oxide), and alloys such as NiCr. The baseline mirror coating is to use a combination of protective aluminum and silver coating: protected
aluminum for the M1M3 mirror surface and protected silver for the M2. This combination allows us to provide a higher reflectivity at shorter wavelengths (u-band).

The coating chamber system has been incorporated into the summit facility design. The area has been sized and configured to receive the M1M3 transport container and support the delicate integration of the mirror with the mirror cell assembly, performing the same tasks demonstrated at the Mirror Lab during packaging. Once integrated, the M1M3 cell acts as the lower coating chamber vessel as the mirror remains in its cell throughout the duration of the LSST survey. The M2 mirror will be removed and coated separately atop a separate whiffletree support and separate coating chamber lower vessel. This 30-month contract effort is planned to conclude with final onsite acceptance testing in mid-2018.

8. CALIBRATION

The LSST T&S group is also responsible for a calibration system consisting of three separate subsystems: (1) the In-Dome Calibration System which is used to calibrate the main telescope; (2) the auxiliary telescope and spectrograph system which is used to monitor atmospheric transmission during LSST operations; (3) the environmental monitoring system which is used to assist the Observatory Control System for target selection and safe operations.

The In-Dome subsystem contains the equipment used to calibrate the wavelength dependent transmission function of the main telescope. This system includes a 9.2-meter diameter calibration screen that may be illuminated with both broadband and monochromatic light. In addition, a collimated beam projector will enable user-defined sub-aperture transmission measurements that are immune to the internal ghosting issues often present in both sky and dome flat fields. The calibration screen and collimated beam projector are mounted on opposite sides of the dome. The light sources used with each system are monitored using fiber-fed spectrographs and a series of NIST-calibrated photodiodes.

The 1.2-meter diameter auxiliary telescope, previously the Calypso Telescope on Kitt Peak in Arizona, will be relocated to Cerro Pachón adjacent to main telescope and used for wavelength dependent atmospheric transmission measurements. The telescope, shown in Figure 18, is currently located at the LSST facility in Tucson and undergoing refurbishment by Astronomical Consultants & Equipment, Inc., prior to shipment to the LSST summit. A slit-less spectrograph will be used to characterize the atmospheric properties based on the variation in the measured spectra of stars with known spectral energy distributions. An imaging mode with an LSST filter set will also be available.

![Figure 18: LSST auxiliary telescope model design, relocated to Tucson for refurbishment](image)

Lastly, the environmental monitoring systems provide data to support the scheduling and operations of the telescope. This subsystem will include a weather station, rain sensors, earthquake sensors, a GPS dual-band receiver to measure precipitable water vapor and numerous anemometers. The Observatory Control System will also receive estimated seeing measurements from a Differential Image Motion Monitor (DIMM).
9. SOFTWARE

The T&S Software team has designed a common component-based design for the software used for controlling the system, defining a component-level state machine and agreed behaviors related to component settings and control request handling. Additionally, the group has developed a custom wrapper around an implementation of the Data Delivery Service (DDS) standard to provide a common API for publish-subscribe communications and logging. The group is responsible for developing, testing, and delivering software and documentation for the Observatory Control System (OCS) reference and the Telescope Control System (TCS) reference.

The Observatory Control System (OCS) is designed in a hierarchical distributed architecture, shown in Figure 19. A specialized communications middleware layer connects the OCS to the Telescope Control System (TCS), Camera Control System (CCS) and Data Management Control System (DMCS), based on the powerful Data Distribution Service (DDS) in a publish/subscribe protocol. The analysis for the Observatory Control system was done in SysML, Enterprise Architect, combining high level requirements flow down, behavior description, structure elements allocation and interfaces identification. The construction plan is described in JIRA, keeping track of individual activities that mark progress towards each release, and it is periodically updated into the overall Project Management Controls System. All the code is under version control, continuous integration and test cycles.

![LSST OCS diagram](image)

The more relevant OCS components are the Application, which controls the operation modes, the Sequencer, which coordinates all the commands involving subsystems synchronization, the Engineering and Facility Database (EFD), which captures and stores the telemetry produced by the observatory and the Scheduler, which produces the targets automatically and dynamically in real-time, and due to its complexity an important effort with detailed prototypes and simulations was performed to achieve a suitable design.

The LSST Scheduler is an autonomous software component from the OCS that drives the survey observations through a sequence of target selection in real time by optimizing a set of science priorities against a dynamic cost function of more than 200 parameters. The scheduler weighs multiple science programs produce thousands of prioritized candidate targets for each observation, while multiple telemetry measurements are received to evaluate the external and the internal conditions of the observatory. The design of the LSST Scheduler started early in the project, providing detailed prototyping and scientific validation of the survey capabilities and the technical performance required to meet the LSST mission. In order to build such a critical component, an agile development path in incremental releases is now employed and integrated to the development plan of the Operations Simulator (OpSim) to allow constant testing, integration and validation in a simulated OCS environment. The final product is a Scheduler that is also capable of running 2000 times faster than real time in simulation mode for survey studies and scientific validation during commissioning and operations.

The Telescope Control System team has designed and implemented test stands to support design of the Inner-Loop Controller electronics board, as well as for functional testing for qualification of each board. The team has implemented a test stand for the M2 axial actuators, and is finishing a test stand for system identification and control optimization of the M1M3 axial actuators. The team has worked with the TMA, Dome, M2, and Hexapods and Rotator vendors through the
interface development and design review phases, as shown in Figure 20. Interface and functional designs for the guider and for the active optics system have progressed. The TCS software team has written and adopted a policy for handling alarms, and has contributed to the development of an operations plan.

Figure 20: LSST TCS diagram

10. LSST CONSTRUCTION PLAN

The LSST Project construction effort is planned for 99 months and began once construction authorization was granted (August 2014). The T&S work package funds the construction effort to provide delivery and acceptance of qualified subsystems in 5.25 years, Figure 21. The effort then transitions to a commission stage, with activities defined and driven by LSST Systems Engineering personnel. First light testing begins with a test Commission Camera (ComCam) system, along with subsystem integration and verification. The LSST science camera is scheduled to arrive in 2020 to begin the final efforts of cadence optimization and science verification, ultimately enabling transition to operations in 2022 and the start of the 10-year LSST survey.

Figure 21: LSST construction schedule including T&S and Commissioning activities
11. CONCLUSION
The Large Synoptic Survey Telescope (LSST) Project received its construction authorization from the National Science Foundation in August 2014. The Telescope and Site (T&S) group has made considerable progress towards completion in subsystems required to support the scope of the LSST science mission. All major telescope work package procurements have been awarded to vendors and are in varying stages of design and fabrication maturity and completion.

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13. REFERENCES