The LSST Dome final design
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ABSTRACT

The Large Synoptic Survey Telescope (LSST) is a large (8.4 meter) wide-field (3.5 degree) survey telescope, which will be located on the Cerro Pachón summit in Chile. As a result of the Telescope wide field of view, the optical system is unusually susceptible to stray light. In addition, balancing the effect of wind induced telescope vibrations with Dome seeing is crucial. The rotating enclosure system (Dome) includes a moving wind screen and light baffle system. All of the Dome vents include hinged light baffles, which provide exceptional Dome flushing, stray light attenuation, and allows for vent maintenance access from inside the Dome. The wind screen also functions as a light screen, and helps define a clear optical aperture for the Telescope. The Dome must operate continuously without rotational travel limits to accommodate the Telescope cadence and travel. Consequently, the Azimuth drives are located on the fixed lower enclosure to accommodate glycol water cooling without the need for a utility cable wrap. An air duct system aligns when the Dome is in its parked position, and this provides air cooling for temperature conditioning of the Dome during the daytime. A bridge crane and a series of ladders, stairs and platforms provide for the inspection, maintenance and repair of all of the Dome mechanical systems. The contract to build the Dome was awarded to European Industrial Engineering in Mestre, Italy in May 2015. In this paper, we present the final design of this telescope and site sub-system.

Keywords: LSST, Dome, rotating enclosure

1. INTRODUCTION

This document provides the baseline design of the Large Synoptic Survey Telescope (LSST) Dome (rotating enclosure), Figure 1. The development of this design made substantial use of Computational Fluid Dynamics (CFD), as presented in previous documents. The Dome includes both the rotating components and those fixed to the lower enclosure of the facility. The function of the Dome is to:

- Protect the telescope from the environment.
- Provide a clear optical path for the Telescope observing.
- Minimize the effects of stray and scattered exterior light within the Dome interior.
- Provide louvers to control ventilation and flushing of the Dome interior with external ambient air during night operation.
- Facilitate maintenance of both the Telescope and the Dome itself.
- Provide a controlled thermal environment during the day for preconditioning and testing.
- Provide a light tight enclosure during the daytime to enable testing and calibration of the Telescope’s optical system.
- Be compatible with the removal of all three Telescope optical systems as complete assemblies.
- Support equipment for calibrating the optical system.
Figure 1: Summit Support Facility showing rotating enclosure (Dome) atop the fixed lower enclosure

The Dome includes all rotating components, azimuth drive system with capacitor energy storage, brake system, slip ring system and locking mechanism. It also includes the Dome control/interlock system, and the track system on which the bogies ride. The main interface between the facility and the Dome is on the top of the concrete lower enclosure pier on which the bogie track and drive units are located.

GENERAL PROPERTIES: The Dome is approximately 27 meters in height and 30 meters in diameter. The size is defined primarily from the Telescope clearance envelope, required maintenance operations, and space needed for the light/wind screen mechanism. The 12-meter distance between the arch girders is determined by the size of the Telescope aperture. The Dome is supported on the insulated cylindrical concrete lower enclosure pier. This cylinder is ~30 meters in diameter and 17 meters tall. The height of the cylinder was determined by site measurements such that the Telescope would be located above the thermal boundary layer.

NON-CO-ROTATING: The Dome is completely independent from the rotation of the Telescope (non-co-rotating). As a result of the squat aspect ratio of the LSST Telescope there would be minimal benefit to co-rotation. Freeing the Dome and the Telescope azimuth rotations facilitates maintenance, calibration and thermal control.

OVERSIZED SLIT/DOME CRAWL: It would require an unrealistically large amount of power to enable the Dome to match the azimuth motions of the Telescope. This difficulty is overcome by utilizing a Dome clear aperture slit width which is oversized horizontally by approximately 1 meter, Figure 2. This allows the Dome to crawl to the next observing location while the present exposure is underway.

Figure 2: Dome Crawl

VIBRATION LIMITATIONS: Since the Telescope optical system cannot include a fast steering mirror, the observatory has stringent vibration limitations. Since the Dome operates at non-trivial velocities while the Telescope is observing, the Dome motion produces a vibration potential both acoustically and through propagation down the lower enclosure and up the Telescope pier. The lower enclosure is a concrete cylinder rather than the more common steel structure. This eliminates
the variation in load path as a function of Dome azimuth angle which normally produces a “bounding” effect during azimuth motions. There are also no direct structural paths from the lower enclosure into the Telescope pier.

STRAY LIGHT SUSCEPTIBILITY: As a result of its wide field of view the LSST Telescope is very susceptible to stray light and requires a significant amount of stray light baffling. The Dome constitutes one of the most important stray light baffles of the overall LSST system. The numerous vents must provide ample airflow while preventing stray light from entering.

HIGH CADENCE: Being a high throughput survey instrument, the LSST Telescope is designed for rapid slewing with high rotational velocity and acceleration. In order to mitigate the large azimuth drive power needed for the Dome to rotate in sync with the Telescope, the project has adopted a crawling scheme described above, figure 2.

FIXED AZIMUTH DRIVES: The azimuth drives are fixed to the lower enclosure which improves regenerative braking by avoiding the need of slip rings. These drives operate continuously during observing, and they are attached to the lower enclosure where they can be glycol/water cooled to prevent heat from escaping and degrading the Telescope image quality.

CAPACITOR BANKS: During the rapid slewing motions, if the electrical power demand was applied directly to the power grid it would result in excessive current draw. Consequently, a capacitor bank is used to store and supply this power.

AZIMUTH BOGIE AND TRACK: The Dome includes 14 twin-wheeled bogie trucks that are approximately equally spaced around the circumference of the base of the Dome. Each bogie is mounted to a trussed ring beam lying in a horizontal plane at the Dome’s base. A steel azimuth track is mounted to the top of the fixed lower enclosure pier ring wall. This wall provides the mounting surface for the azimuth rail, on which the Dome bogie wheels and the bogie lateral restraint rollers roll.

THERMAL CONTROL: During the day, conditioned air is supplied to the Dome and lower enclosure from air handlers at the interior base of the lower enclosure. The interior air is maintained at a temperature slightly lower than the expected ambient temperature that is predicted for the beginning of observing. During observing, thermal control is principally provided by natural ventilation (wind). The louvers which are placed over every vent are controlled to balance the flushing effects with the wind induced image degrading vibrations. The facility also has a down draft system to aid in dome flushing during periods of low wind velocity.

MAINTENANCE AND REMOVAL OF OPTICAL SYSTEMS: The Dome provides a bridge crane for facilitating Telescope maintenance and the removal of some of the optical assemblies. The crane provides both horizontal and vertical travel which covers the foreseen range required for removal of large optical subsystems from the Telescope. A rear access door opposite the aperture slit provides access to a platform lift (vertical reciprocating conveyer). The platform lift is used for vertical transport during installation and removal of the optical systems.

SUPPORT EQUIPMENT FOR CALIBRATING THE OPTICAL SYSTEM: Since the LSST Telescope is monitoring the sky for time dependent astronomical variations, its optical system must be sufficiently stable to detect these changes. Consequently, the science mission of the LSST Telescope requires a high degree of calibration of the Telescope’s optical system and principally the camera detectors. This requires that the Dome support both a flat field and a collimated beam projector, which are attached to the inside of the dome.

2. TELESCOPE AND OPTICAL SYSTEM

The LSST optical system utilizes a unique, compact, three-mirror design consisting of an 8.4 meter Primary Mirror (M1), 3.5 meter Secondary Mirror (M2), and a 5.0 meter Tertiary Mirror (M3). This system design feeds a large three-lens refractive corrector (Camera) that produces a well-corrected 3.5 degree field-of-view, Figure 3. The tertiary mirror (M3) resides within the 5 meter diameter central hole of the primary mirror (M1). The two mirrors are a monolith (M1M3) sharing the same single cast borosilicate substrate, which improves the stiffness. Since the orientation of the M3 toward the M1 is permanently fixed, utilizing a monolith removes six degrees of freedom, which simplifies optical alignment.

The Telescope Mount Assembly (TMA) is an altitude over azimuth, welded and bolted assembly fabricated from mild steel, A36, A572, etc. or equivalent. It supports the primary/tertiary (M1M3) mirror cell assembly, the secondary (M2) mirror cell assembly and the camera. To facilitate active optical alignment, both the camera assembly and M2 mirror cell assembly are attached through hexapods, which are not considered components of the TMA. A rotator resides between the camera and its hexapod to provide image de-rotation during tracking.
3. DOME (ROTATING ENCLOSURE) NON CO-ROTATING DESIGN

As a result of the compact design of the Telescope there would be minimal benefit to a co-rotating telescope and Dome design, where the azimuth motions of the Telescope and Dome are locked together. Freeing these rotations facilitates maintenance, calibration and thermal control. It also reduces the motion demands of the Dome. The Dome actually utilizes an (~1 meter) oversized optical clear aperture. Consequently, the Dome does not have to match the rapid motions of the Telescope as it repoints between adjacent fields. Instead it crawls toward the next field as the Telescope is imaging.

Since the Dome and Telescope are not locked together, the large overhead bridge crane can access most locations inside the Dome regardless of the orientation of the Telescope. The Telescope must be pointed toward a large screen inside the Dome for frequent calibration of the detector system on the camera. Thermal control during the day requires the Dome be parked in a specific rotational orientation to align the air ducts of the lower enclosure and the Dome. Since the Telescope and Dome are not locked together, the Telescope can move to other orientations for Telescope calibration, while the Dome is parked and the air ducts are aligned for thermal conditioning.

4. DOME STRUCTURAL DESIGN

The base of the Dome is a box section ring beam, Figure 4. The ring beam is supported by the bogies. The ring beam supports all of the columns and the two arch girders that support the rest of the Dome structure. The arch girders carry a major portion of the loads and support the optical slit and rear access door openings. Principal framing for the Dome utilizes standard steel structural shapes, including rectangular tubing and wide flange columns. This framing, along with secondary framing supports insulated aluminum panels for cladding.
The arch girders consist of built-up truss-work. They carry much of the roof load, the entire 20 US ton overhead crane load, the weight of the shutters and light screen, and the Main Dome Platform. A circular array of eight, wide-flange columns are distributed around the base ring beam. These carry a portion of the roof loads, weight of the louvered ventilation assemblies, the calibration screen assembly, and a large portion of the lateral and torsional loads from wind and seismic.

The LSST Dome structure is supported by fourteen bogie assemblies attached to the base of the ring beam. Twelve bogie assemblies are vertically aligned with each of the columns and both ends of each arch girder. This provides the structural benefit of direct load paths from the Dome structure and into the lower enclosure. An additional 2 bogie assemblies are located midpoint between the arch girders to further reduce the overall bogie loads. To help equalize bogie loads even more, structure has been added laterally to the arch girders to off load some of the higher loading on the bogies directly under the arch girders to other surrounding bogies.

The heavy aperture shutter doors open horizontally. Each shutter is supported by traversing horizontal box beams. These box beams are located at both the top and bottom of the shutters. The box beams are supported by the arch girders. The rear access doors are similarly supported. The overhead crane runway is supported by a 21-meter clear span light-weighted box beam.

Secondary structure consisting of horizontal beams and X-bracing connect between the columns and arch girders to provide overall torsional stiffness and distribute the loading. Secondary structure also supports the roof from snow loads. The two halves of the Dome structure are connected together by a transverse, open truss structure running underneath the top shutter support and attaching to main columns at each end. This contributes significantly lateral stiffness and improves the natural frequency of the Dome structure.

5. DOME AZIMUTH DRIVE AND BEARING SYSTEM (ADBS)

Embedded Interface Plates
The azimuth track bolts to the top and inside of the lower enclosure wall. The tracks are secured by interface plates with embedded anchor bolts. The space between the track on which the bogie wheels ride and the drives which rotate the Dome will be mounted on the top and inside of the lower enclosure ring wall and secured by interface plates and embedded anchor bolts. The space between the interface plates and the lower enclosure concrete pier will be filled with a low expansion concrete epoxy grout. Epoxy grout has similar stiffness and higher strength than the concrete. The placement of the anchor bolts will be achieved by using the interface plates as templates during the concrete pour. Concrete secures
the anchor bolts to the pier as the final pour of the pier. The interface plates will also provide features to mount the inflatable azimuth seal around the interface.

**Azimuth Seal**

The area between the rotating Dome and fixed pier is sealed with both a labyrinth and inflatable seal. The labyrinth seal prevents light from entering the Dome, but still allows the Dome to rotate during observing. During this time, the inflatable seal is deflated. The inflatable seal is deployed when the Dome is in its parked position. This seal provides protection for the components inside of the Dome from dust, wind and stray light. By preventing wind infiltration, the air conditioning demand for the Dome is reduced. By mitigating stray light, the inflatable seal allows for calibration activities during the day from inside the Dome.

**Azimuth Drive Units**

The azimuth drive units are fixed to the lower enclosure pier, Figure 5. This makes it much easier to capture and remove the heat generated by the drive units; this also facilitates regenerative braking and negates the need for supplying extensive electrical power through the slip rings. If the drive units were attached to the bogie wheels, a cable wrap would be required to transfer glycol/water to the rotating Dome. To facilitate maintenance, the drive units can be removed as complete assemblies and serviced in place on the Dome floor.

The drive system utilizes bevel rack and pinion gearing. The circular bevel rack gear is comprised of arced segments supported from the base ring beam and extending 360 degrees around the enclosure, Figure 6. Five evenly spaced, independent azimuth drive stations are bolted to the azimuth track. The odd number of drive units reduces the vibrations, which is necessary since the Dome rotates at non-trivial speed during imaging. The even spacing ensures that no net radial force is applied to the rotating Dome by the drive units.
The radially oriented teeth on the bevel rack gear allow the attached pinion gear to move radially with the rack gear as needed for proper continuous meshing of the gear teeth. The rack gear and supporting assembly will be composed of several modular units which are bolted together. This modular design allows relatively easy removal of a local section of track for replacement.

Each drive unit is insulated in an enclosure. The heat is removed by air-to-liquid fan heat exchangers. The skin temperature of the enclosure is measured by thermocouples. The coolant, 35% ethylene glycol / 65% water, is regulated with mixing valves and is supplied from the facility at least 5 C° below ambient for all operating conditions.

The drive units use synchronous servomotors to provide high torque at low speed. This reduces the required gearing reduction. Not only is this simpler and more efficient, but it also significantly reduces the effect of the motor inertia on the overall inertia. The motor inertia combines with the Dome inertia according to the square of the rotational velocity.

This design of the Dome allows for continuous and unlimited range of azimuth motion. The requirement of continuous motion precludes the use of an azimuth cable chain/wrap and requires a slip ring system. Although the azimuth motion does not have travel limits, it does have velocity, acceleration and jerk limits.

**Bogie (Bearing) and Track System**

The LSST Dome is supported vertically and located radially by 14 twin wheel bogie trucks mounted to the Dome base ring beam lower surface and it rides on a steel azimuth track attached to the top of the lower enclosure circular wall, Figure 7.

All bogies are identical. This allows for easier maintenance and minimizes spares. The bogies use a horizontal pivot at the center of the wheel housing to distribute vertical loads evenly to each wheel. A separate frame that reaches around the wheel housing attaches the lateral rollers, which interface with the sides of the azimuth track.

Each bogie mounts to the lower face of the Dome base ring beam on adjustable mounts, Figure 8. Each mount provides the ability to adjust wheel camber while allowing a small range of steering angle compliance. Spherical joints within the bogie assembly provide a few degrees of this steering and camber adjustment.

Bogie wheels are canted such that their rotational axis coincides with the centerline of the Dome at the elevation of the azimuth track rolling surface. This allows the wheels to roll in a circular path without slipping. Spherical roller bearings are used for the wheels to minimize the impact of small misalignments of the bearing centers during fabrication and assembly. Bearings are oversized by a factor of two to reduce the risk of failure and subsequent down time.
The bogie wheel diameter and width are sized to limit the contact stress to below the fatigue limit of the track material. The wheel rolling surface is conical in shape producing a line contact between wheel and track. To ensure uniform loading across this contact width, the bogie design incorporates a means to ameliorate any misalignment by allowing some compliance of the camber angle through a spherical joint within the bogie assembly.

The bogies are relatively large and heavy units with an estimated weight of 2.1 metric tons (4620 lb) each. A single bogie wheel with shaft has an estimated weight of 318 kg (700 lb). Because of their size and weight, removal of an entire bogie assembly would be problematic. Therefore, each assembly has been designed to be maintained, disassembled and repaired in place. Sufficient access to and around the bogie unit is available for routine inspection and maintenance. The wheels and rail are made from medium Carbon chrome-moly steel, and heat treated to give sufficient hardness and strength for good fatigue life.

The bogies provide radial support through separate roller assemblies, perpendicular to the vertical rollers. These rollers contact the sides of the Azimuth rail in the case of misalignment or side loading.

The azimuth track provides vertical and radial support for the Dome. The loads include gravity, wind, snow/ice, seismic and various live loads. The track must also withstand a seismic recoverable event without yielding or local damage, and a seismic survival event without catastrophic failure.

The track top plate overhangs the supporting web plates to provide a structural load path for the uplift restraints.

The wheels and rail are made from heat treated medium Carbon chrome-moly steel to increase hardness and strength to improve fatigue life and to meet the Dome’s design life under normal operational conditions without fatigue, spalling or excessive corrosion. The corrosion requirement precludes the use of plain carbon steel.

As a result of the transportation limitation (Puclaro tunnel) and the large diameter of the track, the azimuth track will need to be shipped in multiple segments. The joints connecting these segments have been problematic at other telescope facilities. Angling of track splices allows some mitigation of the vertical step across the splice, promoting smoother operation.
**Drive Capacitor Bank**

The Dome DC capacitor bank is an energy storage device connected to the DC bus link of the variable frequency drives (VFD) of the Dome azimuth drive motors. It will supply the instantaneous current necessary for fast slewing of the large inertia loads of the Dome. It will also prevent excessive current draw from the power grid. It also allows for some of the azimuth regenerative braking by absorbing the regenerated energy for reuse instead. This reduces total energy consumption and thermally induced image degradation. The Telescope Mount Assembly (TMA) utilizes a similar solution built with the same capacitors.

The capacitor bank is large and heavy, but produces almost no heat. The high voltage at the capacitor terminals is potentially hazardous. Consequently, the capacitor bank cabinets are located inside the Telescope pier together with the Dome azimuth motor drive cabinets, on the pier’s intermediate floor. This provides superior access control, and prevents unintentional contact during maintenance of the Telescope, Dome or facility. Locating the capacitor bank and azimuth drive cabinet(s) in a central location also allows for radial distribution of VFD conditioned power to the motors, reducing losses related to cable length.

Dry electrolytic film capacitors are the type used in the design since they are safer than wet electrolytic capacitors. They are unlikely to produce toxic fumes or fire. At a minimum, the capacitor bank has the capacity to satisfy the Dome azimuth power requirements during a baseline slew cycle with 8% voltage drop or less. To preclude the need for hazardous inspection or disassembly, the system meets its requirement while including the expected failure rate and degradation of the capacitors over the life of the system, at site operating conditions. Surplus capacitors are included in the design to cover any expected failures or degradation. To enhance safety, this system is classified as “non-serviceable equipment”. Components other than the capacitors will be located outside the protected cabinets.

The chosen capacitors have very low series resistance. The schematic configuration for this is an anti-parallel scheme that tends to equalize the duty for all of the capacitors. Because of intermittent electrical load, RMS power draw from the banks will be relatively low. Given these design choices and proper sizing, the capacitor banks will not need to be actively cooled to meet the cabinet surface temperature specification, nor for reliability reasons.

**Slip Ring**

The Dome must have continuous and unlimited azimuth rotation range. This precludes the use of an azimuth cable wrap and requires a slip ring system. Rotating Dome electrical power is conducted through the slip ring. To provide redundancy, it will utilize two identical twin follower assemblies (trolleys) located at 180 degrees apart. Grounding for the electrical systems in the rotating Dome is distributed through the slip ring system. The Dome lightning protection will be connected to the separate facility ground via a dedicated slip ring. For safety purposes, the Dome uses an enclosed slip ring with four copper bars, where one of them is dedicated to grounding and the remaining three feed the rotating Dome. Light fixtures on the rotating enclosure are equipped with emergency kit (batteries) which ensure emergency lighting in case of power off.

Since the slip rings could potentially be damaged during a lighting strike, a means of bypassing the slip rings is available. At least four equally spaced dedicated power receptacles are attached to the rotating Dome. A power reel attached to the lower enclosure is used to provide power to one of these receptacles. This bypass allows for closing the Shutter doors, vent louvers, etc., but does not provide for rotation of the Dome. The Dome will also include an onboard Uninterrupted Power Supply (UPS) with sufficient capacity to operate all controls and communications equipment rotating with the Dome for at least one hour. This not only maintains the controls operable during a power interruption, but also electrically isolates the controls. Observatory raw power is backed up by a standby generator.
Bi-parting aperture shutters (ApS) are used to cover the Dome slit when observing is not underway, Figure 9. When closed, the shutters seal the entire clear aperture over its elevation range, and protect the light/wind screen and Telescope. The motorized bi-parting shutters will open and close horizontally. Since the shutter drive system is not operated frequently or during observing, there are no special requirements in regard to drive system regeneration, braking, thermal control or location. During routine operations the shutters are operated by the Dome Control System (DCS). The Dome and shutters consist of metal cladding over structural steel framing.
Drive pinions and rack gears located at the upper and lower end of each shutter panel control the travel of the shutters. The drive units are synchronized via encoders. The minimum torque and power to close the shutter doors is 2900 N\*m and 1.3 kW per drive (4 drives total).

Each shutter door is supported at the top and bottom by rollers that ride on the Dome shutter beams, Figure 10. There are four rollers per shutter door that constrain each shutter door in the downward vertical direction. In addition, there are a total of sixteen + sixteen (sixteen on each rail side) side rollers that restrain each door laterally. Each door is restrained in the upward direction by a simple bracket in four places in the event of seismic activity.

Weather tight seals are required around the perimeter of each shutter. The overall seal system must also be light tight for daytime optical testing/calibration. All surfaces of the aperture shutters that are adjacent to the optical path or have the potential to reflect or scatter light into the Dome will have a low reflectivity (low-emissivity), flat black coating.

Domes have a history of being difficult to seal. Often the worst leakage comes through the seal between the shutters. This is especially problematic since it can allow leaks onto the mirrors. Consequently, particular attention is given to the seal between the shutters. This includes compressing seals and overlapping members above the seals. Drip gutters will be provided along the inner face of the shutters to capture leakage before it falls into the enclosure and Telescope.

Since the shutter must be closed to protect the Telescope, redundant closure methods have been incorporated. An on-board, UPS isolated, control panel is provided on the rotating Dome to close the shutter if wireless communications are lost. A cable and receptacle system is available to bypass the slip rings and power the shutter drives. Finally, a means of closing the shutters manually will be achieved through use of a pneumatic air wrench.

### 7. DOME LIGHT/WIND SCREEN (LWS)

The purpose of the light/wind screen (LWS) is to block stray light and mitigate the effects of wind, Figure 11. The LWS follows the Telescope’s elevation angle. The LSST cannot operate successfully without this stray light mitigation. Consequently, the LWS must be safe, reliable, low maintenance and robust. Its height and precarious location above the Telescope makes maintenance difficult. It will operate continuously during observing, tracking with the Telescope. The LWS will be controlled by the Dome Control System (DCS).

The LWS configuration consists of multiple overlapping light-weighted curved Aluminum panels. Aluminum was chosen over steel in the shell panel construction to reduce the required operating power. The panels are of bonded and welded construction. These panels overlap on the top and bottom of the LWS, above and below the clear aperture, to allow for the full operation of elevation range. This baseline LWS design was derived, to the extent possible, from the Gemini Telescope windscreen.
Since the major purpose of the LWS is to attenuate stray and scattered light, most surfaces of the LWS have a low reflectivity (low-emissivity), flat black coating. Only surfaces that have no reflected/scattered light potential, or are impractical to coat, are not coated. The outer most surfaces that face the sky will be coated with a highly reflective coating to reduce super cooling. Low reflective coatings are applied to the internal surfaces of the light/wind screen.

The LWS is semi permeable to wind to provide a superior balance between dome seeing and wind shake. The panels have a staggered closed cylinder pattern. The cylinders are interconnected by a series of lateral openings within the panels. This structure within the panels will effectively block stray light and allow for some air to pass through. For both sides of the panel, the holes defined by the open ends of the cylinders represent 15% of the LWS panel’s surface area.

Two drive assemblies are attached to the upper corners of Panel 3. The drives are mounted on top of the panel to minimize any heat dissipation entering the optical path.

The motors are attached to gear reducers. The output shaft of each gear reducer uses a sprocket with two idlers (see Figure 12) to allow the panel to climb and descend two stationary segments of roller chain. The chain segments are anchored to the Dome structure at the upper end. The lower end of the chain is attached to the Dome structure through a tensioner to provide tension on the slack side of the chain below the drives. This prevents the chain from slapping around during use.

The two drives are coincidently driven using electronic gearing. The upper and lower panels are mechanically interlocked with each other in sets of three. The lower panel set is attached by cables to the upper set. While increasing in elevation, the panels are pulled off their respective stops by the mechanical interlocking features. All active positioning is dictated by Panel 3, which is actively driven. When the LWS is decreasing in elevation angle, panels 1, 2 and 4-6 are driven by gravity until they are offloaded onto stops located on the guiderails and Dome. These stops have shock absorbers to reduce the shock loading from the impacts during operation.

Each panel has a roller set in each corner. The roller and guiderail configuration is shown in Figure 12. A combination of rollers and brackets are used to restrain the assembly in every direction except along the guiderail path. The brackets are used for outward radial seismic restraint. One side of the panels differs from the other side in that it allows significant but limited lateral travel in the event of misalignments of the guiderail or seismic events in the horizontal direction.

The drives for the LWS consist of brushless DC motors (BLDC) coupled to gear reduction drives. Brushless DC motors are chosen as the drive motors, for their high efficiency, which will allow for minimal heat dissipation. For the 6900 kg panel payload, the peak power requirement at the output shaft is estimated to be 12kW (16HP) per drive. Since the assembly is located on the rotating part of the enclosure, it will not have glycol/water for cooling but will instead rely on natural and forced convection.

Normally, the drive motors apply motor braking when decelerating. The drive system also has power off / fail safe braking. This braking system is able to stop motion without power and automatically hold LWS position if power is interrupted. Using motor braking retains the power off braking for redundancy and reduces the wear of the brake system.
The light/wind screen has a special slit access configuration. The purpose of this configuration is to provide crane access through the slit for items that are too large or heavy to use the other accesses during Telescope construction. During this configuration, all panels below the aperture are stored at their lowest positions and all panels above the aperture are stowed at their highest position. This is achieved by detaching the two cables that connect the upper and lower panel sets while the lower panels are resting on the Dome floor. The upper panels are then raised to their highest position.

Each panel of the LWS that is above the clear aperture (upper panels) has a manually operated locking mechanism, which locks them in their highest position. Two locking mechanisms on opposite sides secure each panel. During significant maintenance, the lower panels would likely be stowed in the special access configuration. Consequently, they do not require locking mechanisms.

8. REAR ACCESS DOORS (RAD)

Transporting the major optical systems from the Telescope to the support facility is accomplished through the platform lift (vertical reciprocating conveyor). The platform lift runs up the outside of the lower enclosure that supports the Dome. The Rear Access Doors (RAD) are required to transport these optical systems from inside the Dome to the platform lift, Figure 13.

![Figure 13: View of the rear access doors](image)

The RAD is composed of motorized doors that open and close horizontally and collinearly. They are aligned tangentially to the Dome circumference and run parallel with the main shutters. They are located on the Dome opposite of the aperture slit opening. They have weather and light tight seals located around the perimeter. Each door incorporates a louvered light baffling vent (LLBV) discussed in the next section. The doors are supported by V-groove wheels on a track located at the top of the door, Figure 13. A follower track captures the lower end of the doors. They are operated by a drive system accessible from inside the Dome.

The doors are sized to allow the M1M3 mirror cell assembly with protective cover over its mirror and while supported on its cart to safely fit through the opening onto the platform lift, Figure 14. The platform lift can be raised with the doors closed to keep the Dome protected from the outside elements during Telescope maintenance operations.

![Figure 14: M1M3 Mirror Cart Shown Loading onto Platform Lift](image)
Unlike the aperture shutters (ApS) and light/wind screen (LWS), the RAD is locally controlled through an adjacent control panel. The controls will be interlocked to prevent operation of the RAD unless the lift is in its topmost position, and the louvers on the rear doors are shut.

9. LOUVERED LIGHT BAFFLING VENTS (LLBV)
During observing the seeing environment inside the Dome is mainly governed by natural wind flow through the Louvered Light Baffling Vents (LLBV), and the clear aperture of the light wind screen, Figure 15. Since wind also degrades the image quality by vibrating the Telescope (wind shake), the air flow through the vents must be regulated to produce a balance between these two effects. During the daytime the vents must also facilitate thermal control and provide light tightness for optical testing. When the louvers are closed, they are weather and light tight.

These LLBV have the competing requirements of accommodating convection while simultaneously providing light baffling. These dual requirements are met through the use of light baffles with a single sinusoidal profile, and with the entrance and trailing edges horizontal. The single sinusoidal profile provides the least impediment to wind flow while still providing light baffling. The horizontal leading and trailing edges force the wind to flow horizontally inside the enclosure, which improves image quality. All internal surfaces of the Dome vents that have the potential to reflect or scatter light into the Dome have a low reflectivity, flat black coating.

Flow through each vent is controlled through a motorized drive. The opening of the louvers is continuously variable between the open and closed positions to allow control over the volume of air flow during observing. Each drive is independently controlled by the Dome Control System (DCS). The louver’s drive system, bearings, sensors and all other mechanisms are located inside the Dome (on the inside of the louvers) so that they are protected from the environment when the louvers are closed. The light baffles swing open on hinges to allow for maintenance of the vent mechanisms and seals. The sizes of the hinged light baffle sections vary according to the need to clear surrounding components near the opening. All mechanisms are accessible for maintenance from inside the Dome using the lower enclosure man-lift or the mobile scissor lift.

10. OVERHEAD BRIDGE CRANE (OBC)
A variable speed overhead bridge and trolley crane is attached to the Dome. This will be used for lifting and positioning telescope assemblies and components, Figure 16. This crane has an 18 metric ton (20 US ton) capacity over its full range of hook, trolley and bridge travel. It rides on a pair of horizontal support beams that run along the sides of the aperture from the Dome shutter to the rear access door. The trolley moves across the bridge to provide motion in the perpendicular direction. The hoist is supported off of the trolley.
At its maximum height the crane hook is 15.0 meters above the Telescope maintenance platform of the lower enclosure. At this height, the crane does not penetrate the swept volume of the Telescope. The hook travel is 20.0 meters and can reach the Dome floor.

The crane is used during the removal of the camera support assembly and the M2 mirror cell assembly. These tasks are accomplished with the Telescope in the horizon pointing orientation. It is also used during general repairs and maintenance. The horizontal coverage, hook height, and load capacity of the crane are designed to accommodate all these required handling tasks.

During observing, the bridge crane remains in the parked position located closest to the rear access doors and under the main dome platform. This locates the trolley at the location farthest from the clear aperture.

Maintenance to the bridge and trolley can be conducted in the parked position of the crane. All areas of the crane requiring maintenance can be accessed from the main dome platform.

The crane is able to lift and lower loads through the utility hatch in the Dome floor of the lower enclosure. The hoist travel is insufficient to reach the ground level. Lifting from the ground floor to the observatory floor will be accomplished through the aid of slings, etc.

## 11. THERMAL CONTROL

There are two separate thermal control states of the Dome. During the daytime, the interior of the Dome and lower enclosure is maintained at a temperature slightly below the expected temperature at the beginning of the night’s observing. During nighttime observing, the image degrading effects of thermal convection are mitigated by controlling the production and dissipation of heat and providing for natural ventilation (Dome flushing). The Dome is designed to accommodate these two thermal states.

### Daytime: Thermal Preconditioning

To prevent image degradation resulting from convection during the daytime, the temperature inside the telescope building must be tightly regulated to within +0.5 °C to -1.0 °C of the expected ambient temperature at the beginning of nighttime observing. This temperature is principally maintained by four air handling units in the lower enclosure, Figure 17. These units utilize refrigerated glycol/water supplied by chillers located in the mechanical room. These air handling units are not considered part of the Dome. However, the Dome must interact with this system.
The air from each of the air handling units is ducted above the Dome floor where it interfaces with air ducts in the Dome. The Dome ducts are sized and oriented to align with the lower enclosure ducts when the Dome is in the parked position. The ducts on the Dome are aligned with the arch girders to maximize floor area and provide mounting structure for the ducts.

Each of the four ducting systems in the Dome must utilize fans (and silencer to reduce noise) to maintain the flow from the air handling units. This eliminates the need of a seal between the lower enclosure ducting and the Dome ducting. Each of the four ducts branch into two distribution ducts positioned near the Dome’s interior surface. Each branch has multiple exhaust diffusers to uniformly distribute the air. Each diffuser has a balance adjuster to evenly distribute the flow. Each intake port of the ducting system uses a grill or screen to prevent the intake of foreign objects.

An inflatable Azimuth seal is deployed whenever the Dome is parked to minimize air infiltration. The inflatable azimuth seal is deflated during nighttime observing to allow for Dome rotation without damage of the seal.

When the Dome is not in the parked position and the ducts of the lower enclosure and rotating Dome are not aligned, significant air circulation will still result. The conditioned air will be discharged to the Dome floor. The fans in the Dome intake this cooled air and circulate it through the Dome ducts.

Air circulation from the top of the Dome to bottom of the lower enclosure floor is unimpeded as a result of a gap between Dome floor and telescope pier along with vents in the telescope azimuth assembly.

**Night time: Thermal Control While Observing**

During night time observing the wind through the Dome is regulated by adjusting the Louvered Light Baffling Vents (LLBV) to balance thermally induced turbulence with wind induced vibrations, which affect image quality, Figure 17.

Significant air flow is also provided through the clear aperture and the semi permeable light/wind screen. The flow through these is not directly controlled. However, controlling the flow through the louvers also controls the flow through the aperture and light/wind screen. The inflatable azimuth seal is deflated during nighttime observing to allow for Dome rotation without damage of the seal.

A down draft air ventilation system removes air from the lower enclosure. This prevents heat released by natural cooling from rising into the light path. To capture the rising air, the intakes for this system are near the floor of the lower enclosure. The suction from this system draws air downward through the gap between the Dome floor and the telescope pier, and through the vents in the telescopes azimuth assembly. This air flow aids in maintaining temperature equalization of the Telescope and telescope pier with the ambient air temperature. The down draft system is entirely a subsystem of the lower enclosure. None of its components are considered components of the Dome and the Dome does not directly interact with the down draft system. The down draft system is only operated during low wind conditions.
12. PLATFORMS, LADDERS AND STAIRS

To facilitate maintenance and to maximize the time available for observing, the Dome was designed with an extensive network of platforms, ladders and stairs. These features provide access to components during routine maintenance, Figure 18. All access equipment is designed according to OSHA standards. All the flooring is expected to experience significant loading and is designed to the International Building Code (IBC).

All Dome stairs, ladders and platforms, except for the flooring through the Rear Access Doors (RAD), will be perforated or grated to aid in air circulation. The RAD floors use non-skid surfaces that are durable and suitable for personnel access.

Main Dome Platform (MDP)
The Main Dome Platform (MDP) provides access to the entirety of the three upper light/wind screen (LWS) panels, including their drives and bearings, when the panels are in their highest position. Access to the lower three panels is provided from the maintenance platform when the LWS is in its lowest position. Two access ladder systems are provided from the stationary telescope maintenance platform in the lower enclosure to the MDP. Besides these stairways the MDP is accessible by the man-lift of the lower enclosure.

Light Wind Screen Side Access Stairs/Walkway
LWS access is provided by a pair of stairways/walkways either side. Entry to these walkways is from atop the MDP. The side access stairways extend from the MDP to the center of the clear aperture when the light/wind screen is at the 45 degree elevation angle. A man-lift provides access below this height. These stairs/walkways provide access to the tracks and rollers on the LWS.

Top Exterior Platform (TEP)
The Top Exterior Platform (TEP) is provided on the top exterior of the Dome. This platform is located adjacent to the top most edge of the aperture shutter. The purpose of this platform is to provide access to the upper drives, rollers, latches etc., of the aperture shutter. It will also be used to inspect the seal between the aperture shutters. The top exterior platform will extend to the outer edge of both aperture shutters when they are in the fully open position. Access to the top exterior platform will be provided by two sets of stairs or ladders leading from the Main Dome Platform (MDP).
13. CONCLUSION
The design of the Dome system described in this document meets all the requirements. Although the unique nature of the LSST mission produces unique requirements, these requirements can be met with only minor modifications to traditional observatory dome designs. The vents incorporate light baffles to provide simultaneous natural ventilation and stray light attenuation. The light/wind screen limits and follows the telescopes aperture to further attenuate stray light. An oversized aperture alleviates the Dome from needing to mimic the Telescope’s rapid cadence. Relocation of the azimuth drives to the fixed lower enclosure allows for glycol/water thermal control to remove the heat produced by the Dome’s constant motion.

14. ACKNOWLEDGEMENTS
This material is based upon work supported in part by the National Science Foundation through Cooperative Support Agreement (CSA) Award No. AST-1227061 under Governing Cooperative Agreement 1258333 managed by the Association of Universities for Research in Astronomy (AURA), and the Department of Energy under Contract No. DEAC02-76SF00515 with the SLAC National Accelerator Laboratory. Additional LSST funding comes from private donations, grants to universities, and in-kind support from LSSTC Institutional Members.

15. REFERENCES