LSST Telescope Mount & Pier Design Overview

Douglas R. Neill and Victor L. Krabbendam
National Optical Astronomy Observatory
950 N. Cherry Avenue, Tucson AZ 85719

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 summit of Cerro Pachón in Chile. The survey mission requires a short slew and settling time of 5 seconds for a 3.5 degree slew. This is significantly faster than similar aperture telescopes. Since the optical system does not include a fast steering mirror the telescope has stringent vibration limitations during observation. Meeting these requirements is facilitated by the compact mount riding on a robust pier which produces high natural frequencies, an advanced control system to minimize vibration excitation and reaction mass dampers. The telescope mount design is an altitude over azimuth welded and bolted assembly fabricated from mild steel. It supports the primary / tertiary mirror cell assembly, the secondary mirror cell assembly and the camera assembly. The mount design enables the removal of these optical assemblies for servicing and recoating. Retractable / deployable platforms have also been provided for accessing the camera on telescope. As a result of the wide field of view, the optical system is unusually susceptible to stray light consequently the mount must incorporate substantial light baffling. The dynamic characteristics of the steel reinforced concrete pier were enhanced by utilizing two different wall thicknesses, an unusually large diameter of 16 meter and anchoring the foundation in unweathered bedrock. The entire pier and mount assembly has been designed to be invariant with azimuth and elevation angle to enhance the effectiveness of the advanced control system.

1. INTRODUCTION

The Large Synoptic Survey Telescope (LSST), ref 1, is a proposed 8.4M diameter, 3.5 degree field of view telescope dedicated to a 10 year, 6 band, optical survey of the entire visible sky. This deep, fast, and wide survey requires a large aperture, wide field of view, and highly agile telescope to accomplish roughly 5.5 million 15 second observations in a decade of operation. For the telescope mount, the most significant science driven requirements are the stiff support of the optical system, including a massive 3.3 billion pixel camera, and a short slew and settle time of 5 seconds for a 3.5 degree slew. A stiff compact mount riding on a robust pier with high natural frequencies is necessary to maintain the optical alignment without a corrective fast steering mirror and to efficiently re-point the telescope to achieve the rapid image cadence. An advanced control system minimizes vibration excitation and reaction mass dampers will also be incorporated to help meet these dynamic requirements. Maintainability also demands that the mount allow for the efficient removal of the optical assemblies for servicing and recoating.

The LSST has a very unique, compact, optical arrangement, fig 1. The tertiary mirror resides within the 5 m diameter central hole of the primary mirror. The two mirrors will be a monolith, sharing the same single cast borosilicate substrate which improves the stiffness, ref 2. The camera (instrument) assembly is positioned directly below the secondary mirror. Although the optical design is unique, the resulting mount concept utilizes a conventional elevation over azimuth structural arrangement, fig 2. A single mirror cell supports the primary / tertiary mirror monolith. The top end assembly supports both the secondary mirror assembly and the camera assembly.

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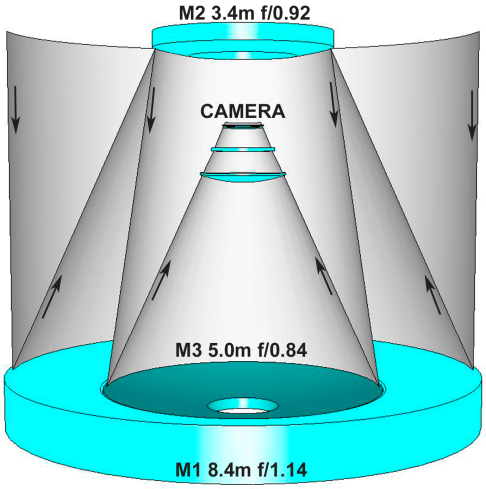


Fig. 1. LSST optical layout.

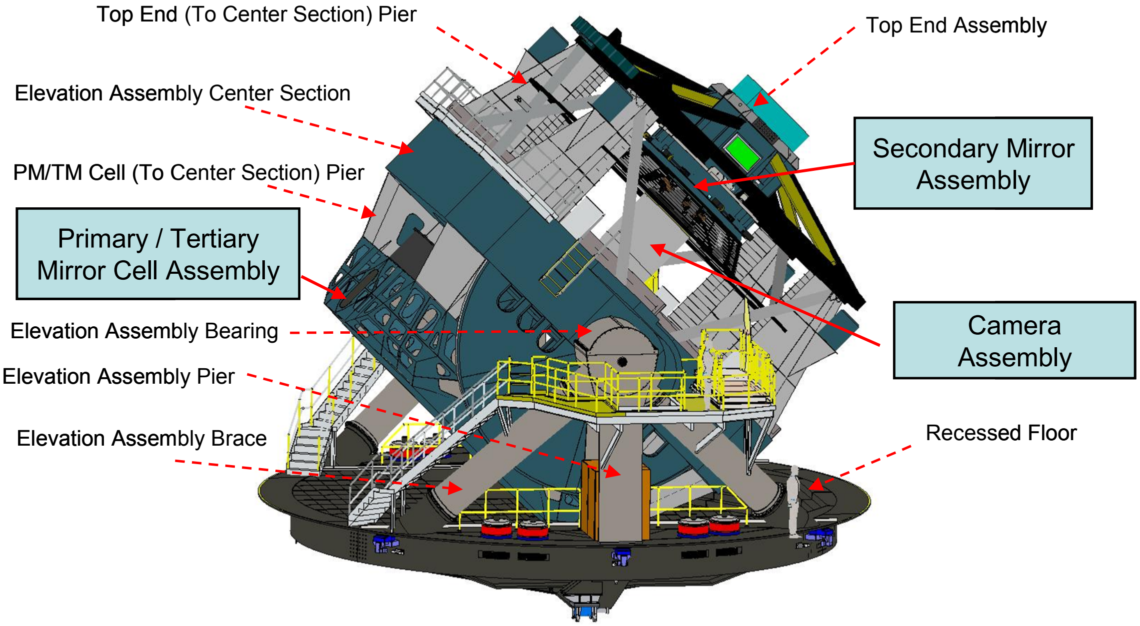


Fig. 2. LSST Configuration

The purpose of the "mount" is to acquire and track fields on the sky by providing motions about the azimuth and elevation axes. The azimuth axis is parallel to the gravitational axis and the elevation axis is perpendicular to it. The mount includes all the moving mass excluding the camera support assembly, secondary mirror assembly (SMA) and primary / tertiary mirror cell assembly which are considered separate components. The mount also includes all the equipment attached to the telescope pier that is required to operate the mount. This specifically includes the hydrostatic bearing assembly, limit switches, hard stops, azimuth encoder system, cable drape, etc. To minimize the variation in dynamic properties as a function of azimuth angle, the azimuth drive system, an integral part of the mount, will be attached to the azimuth assembly rather than the pier.

2. MOUNT CONFIGURATION

The telescope mount is an altitude over azimuth welded and bolted assembly fabricated from mild steel, A36 or equivalent. It supports the primary/tertiary mirror cell assembly, the secondary mirror cell assembly and the camera assembly. Both the camera assembly and secondary mirror assembly are attached through hexapods to facilitate active optical alignment. A rotator resides between the camera and its hexapod to provide image de-rotation during tracking.

The LSST mount must incorporate all systems typical of a large telescope. These include cable drapes, mirror cover, balancing systems, axis bearings, drives and controls required for motion, cable and utility handling, access and safety system. Figure 3 shows the major elements of the mount.

In addition to these typical systems, the unique mission of the LSST requires unique systems as well. The LSST has substantially more baffling than is normally encountered on an 8 meter class telescope due to the position and wide field of the camera. Since the optical system does not include a fast steering mirror for image stabilization, meeting the vibration requirements (wind shake, dome vibration coupling, etc), and the stringent slew and settling requirements will be aided by tuned mass dampers strategically located on the top end assembly piers, ref 3. Accessing the camera for servicing also requires retractable / deployable platforms.

The LSST structure was designed to facilitate maintainability. The primary / tertiary mirror cell is only structurally connected to the elevation assembly at four pier flange locations. This facilitates removal of the mirror cell assembly for coating, etc. The camera assembly and the secondary mirror assembly will be removed as complete intact units. All the hydrostatic bearing surfaces are enclosed which reduces contamination and damage susceptibility.

Unlike most telescopes, the LSST mount incorporates a recessed floor. This 0.8 meter recess reduces the mass and increases the stiffness of the elevation assembly piers and the elevation assembly braces. This feature increases the natural frequency which improves the vibration characteristics.

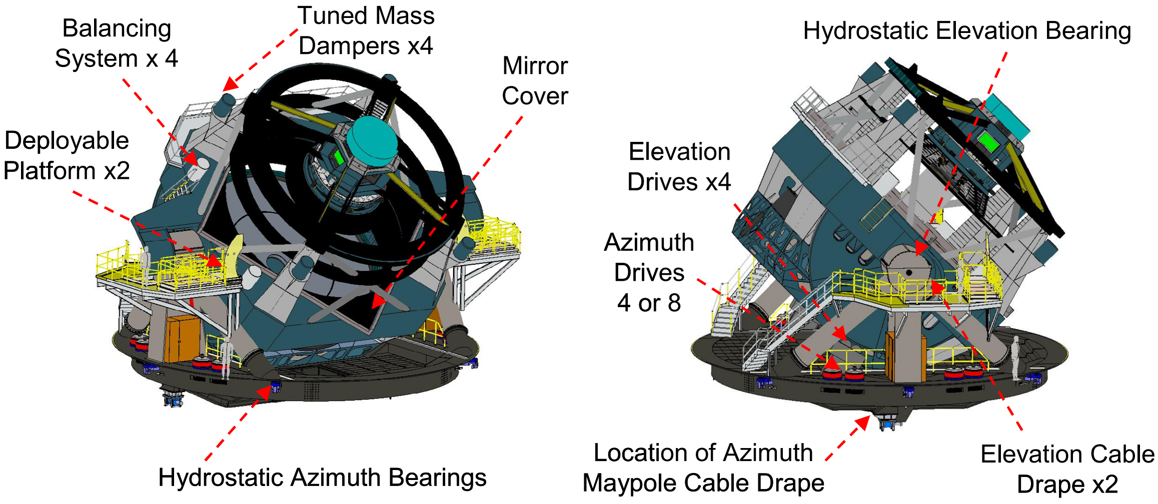


Fig. 3. Telescope systems.

3. PRIMARY TERTIARY MIRROR CELL ASSEMBLY

The primary / tertiary mirror cell assembly, fig 4, consists of the primary / tertiary mirror, its active and passive support systems, its thermal control system, a light baffling ring, a laser tracker and the mirror cell structure. At a mass of 47,300 Kg (104,150 lbs) it is the principle payload of the telescope mount, ref 4.

The primary / tertiary (PM/TM) glass mirror is actively supported by a set of figure control actuators and a hexapod. The active figure control actuators both distribute the load to safely support the monolithic mirror and actively control its shape (active optics) to maintain adequate image quality. The position of the mirror relative to the mirror cell is controlled by a set of six hardpoints (position controlled actuators) that form a large hexapod. The center of the mirror cell supports a laser tracking head which through the use of retro reflectors on the PM/TM mirror, camera and secondary mirror controls the relative position of these optics by the motion of their hexapods.

The mirror cell assembly with a height of 2 meters was designed to provide ample internal clearance for servicing the complex support systems required to operate the PM/TM mirror. Besides the active and passive support systems, the mirror cell also supports an extensive thermal control system to manage the thermal deformations of the mirror, ref 5.

To limit the risk to the borosilicate mirror all routine service must be accomplished without removing the glass from the cell. For coating, the mirror cell must also function as the bottom of the coating chamber, ref 4. Since the coating must be applied in a vacuum, the mirror cell must also function as a vacuum chamber. Consequently, to withstand the vacuum induced stress the PM/TM mirror cell will be fabricated from higher strength steel, A572 Grade 60, than the mirror mount. The vacuum induced mirror cell deformations must be isolated from the mirror support system to prevent overstressing the mirror. This is accomplished by tailoring the structural interaction between the top deck, which supports the PM/TM mirror and the truss systems which supports the vacuum boundary.

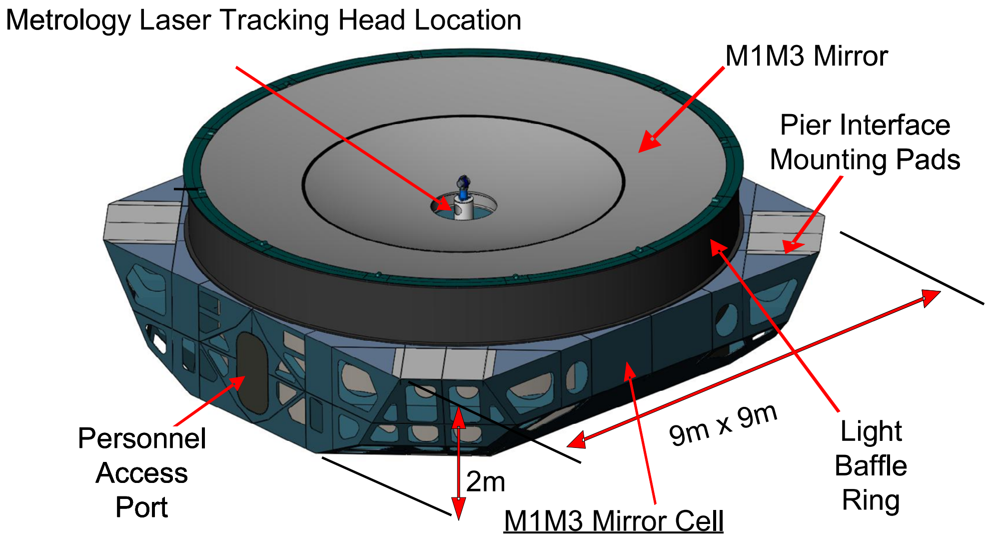


Fig. 4. Primary Tertiary Mirror Cell Assembly.

4. TOP END ASSEMBLY

The top end assembly, fig 5, is principally composed of the secondary mirror assembly, the camera assembly, and the spider and ring assembly. The spider and ring assembly is considered part of the telescope mount and the camera assembly and the secondary mirror are considered separate unit. Both the secondary mirror assembly and camera assembly contain hexapods to facilitate optical alignment to the primary / tertiary mirror. Geometric considerations preclude the use of a conventional hexapod arrangement for the secondary mirror. A rotator resides between the camera and its hexapod to facilitate tracking. Both assemblies attach to the spider spindle of the spider and ring assembly. Both the camera assembly and the secondary mirror assembly must be removable for maintenance.

The main component of the integrating structure, the spider spindle, is attached to the top end ring through 16 hollow rectangular spiders. These spiders have exterior dimensions of 300 mm x 50 mm, and interior dimensions of 210 mm x 36 mm. The hollow spiders are more structurally efficient than solid spiders, and the interior provides a convenient location to route the many cables and hoses required by the camera assembly, the secondary mirror assembly, the hexapods and the rotator.

The spiders are arranged in a parallel / perpendicular arrangement that was determined to be the best compromise between optical and structural performance. Optically this configuration produces only two diffraction spikes. The spider arrangement also provides direct load paths between the spider spindle and the pier mounts and resists payload rotation. The spiders are not preloaded with tension.

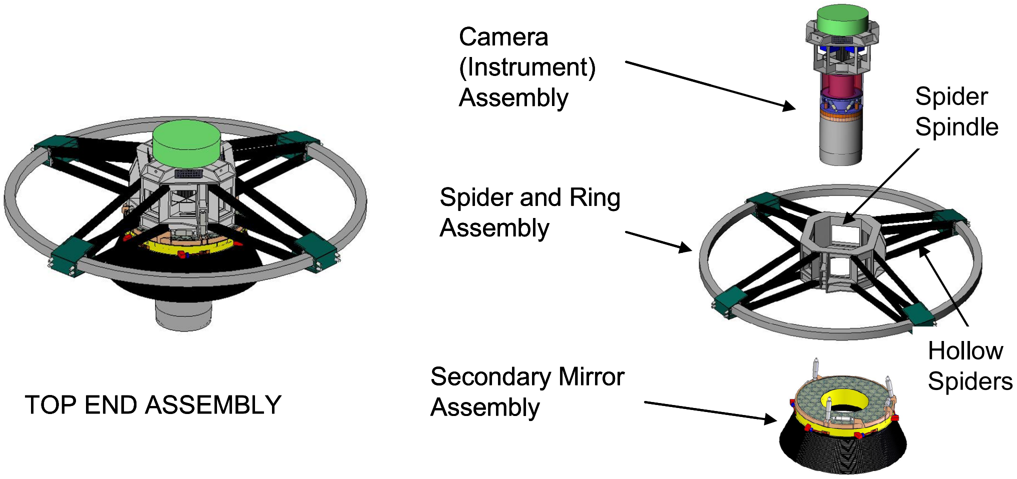


Fig. 5. Top end assembly

5. INSTALLATION AND REMOVAL OF OPTICAL ASSEMBLIES

For maintenance and repairs, the three principle optical assemblies must be removable from the mount. These systems include the camera assembly, secondary mirror assembly and primary / tertiary mirror assembly. The telescope dome (rotating enclosure) and building are all compatible with these removal and reinstallation procedures.

5.1 Primary / tertiary mirror cell removal

Optical coating for the primary / tertiary and secondary mirrors will be accomplished through sputter coating, ref 6. This coating method allows the utilization of more advanced optical coatings than evaporative methods. These advanced coatings have higher reflectivity over the wavelengths of interest, and offer protective materials for extended life spans.

The sputtered coating must be applied with magnetrons in a vacuum. The mass and complexity of the magnetrons, required for the sputter coating, make in-situ coating of the optics on the telescope impractical. The primary / tertiary cell assembly will need to be removed from the telescope and moved to the coating facility in the maintenance and support building reachable with a high capacity reciprocating conveyor (equipment elevator)

The primary / tertiary mirror cell assembly will be removed by a cart, fig 6. The same cart will be used to transport the mirror cell assembly to the coating facility. During the entire transportation and coating process, the primary / tertiary mirror monolith will remain in the mirror cell, and the mirror cell will remain on top of the cart.

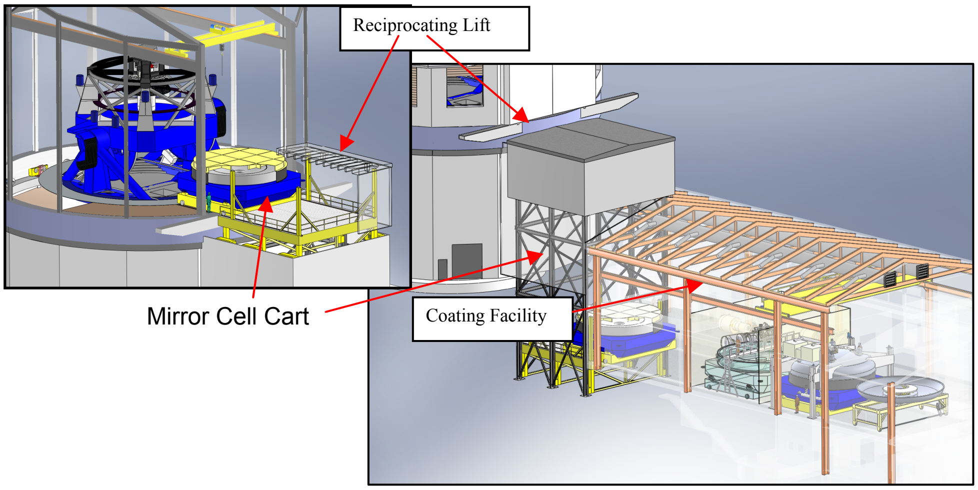


Fig. 6. Mirror cell removal.

Although the dome incorporates an overhead crane, utilizing this crane for the removal of the M1/M3 mirror cell assembly would require a very large increase in capacity from the present 20 tons to 60 tons. This would add substantial mass to the dome increasing its cost, size, mass and moment of inertia.

5.2 Camera assembly removal

The entire camera assembly will be removed as a single unit through the top end assembly, fig 7. The camera assembly includes the camera, ref 7, rotator, hexapod, cable wrap and part of the integrating structure. For this operation the telescope needs to be pointed toward the horizon. The camera assembly can then be removed by the aid of the crane and secured to a cart. During the removal process, the motion of the camera assembly will be controlled by guide rods, which are not shown in the figure.

A lifting fixture with a counterbalance will be attached to the integrating structure of the camera assembly. This counterbalance shifts the assembly's center of gravity away from the elevation axis to a location that can be aligned with the crane hook. The dome is sized to achieve this operation with the shutter closed.

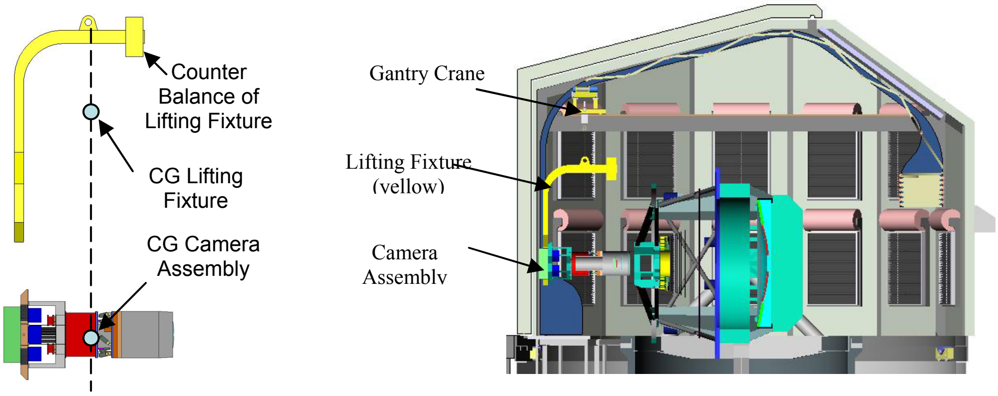


Fig. 7. Camera assembly removal

5.3 Secondary mirror assembly removal

The secondary mirror (M2) is removed from the telescope after the camera has been removed, see previous section, and while the telescope is still pointed horizontally. To prepare for the M2 removal, a section of the telescope top ring will be removed and replaced with a temporary support. The M2 assembly is then removed vertically by the crane, moved to the front of the telescope, and placed onto a cart. Since the secondary mirror faces down it will require less frequent recoating than the upward facing primary / tertiary mirror and is not expected to be removed as often as the camera or PMTM mirror assembly. Individual mass simulators for the camera assembly and the M2 assembly will allow the telescope to be rebalanced so the elevation assembly can be rotated back to vertical for primary / tertiary cell assembly removal.

6. LIGHT BAFFLING

The LSST is very susceptible to stray light rays impinging directly and indirectly on the 64 cm detector because of the wide field of view and camera position. This is prevented by substantial light baffling optimized through stray light analysis, fig 8, ref 8. The incoming light is first baffled by the rotating enclosure which limits the clear aperture and provides light baffling louvers over the vents. The light path is next baffled by three annular baffles. The first is attached to the top end ring (upper top end baffle), the second is attached to the top end pier (middle top end baffle) and the third resides on the top of the mirror cover. The inner diameter of the elevation assembly center section, and all similar flat surfaces adjacent to the light path, have scraper vanes to prevent glancing reflections. The outer edge of the primary mirror, which is not optically figured, is covered by a aperture stop baffle. A conical baffle resides on the secondary mirror assembly. The top end assembly (TEA) to center section piers and the PM/TM cell to center section piers utilize scraper vanes.

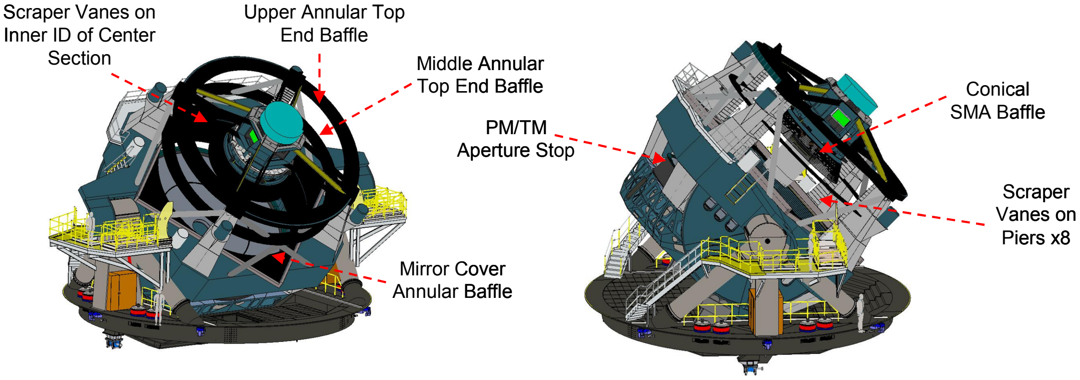


Fig. 8. Light Baffling.

7. BEARINGS AND DRIVES

The LSST will utilize hydrostatic bearings for both the azimuth and elevation axes, ref 9. These types of bearing can provide the stiffness and smoothness required for the LSST operation. For the structural analysis, bearing stiffness near the limits of hydrostatic bearings were assumed, table 1, however, these values had minimal effect on the natural frequencies of the telescope structure. Adequate system stiffness can be achieved even with a reduced bearing stiffness.

LSST Telescope Mount Drive Stiffness

N/mm	lateral		lb/in	lateral
Elevation	7.00E+06		**Elevation**	4.00E+07
Azimuth	1.05E+07		**Azimuth**	6.00E+07

LSST Telescope Mount Hydrostatic Bearing Stiffness

N/mm	Axial	Radial		lb/in	Axial	Radial
Elevation	7.49E+06	1.00E+07		**Elevation**	4.28E+07	5.71E+07
Azimuth	1.19E+07	7.49E+06		**Azimuth**	6.80E+07	4.28E+07

Table 1. LSST drives and bearing stiffness

The azimuth axis utilizes 6 bearing assemblies, fig 9. Each bearing assembly is located adjacent to one of the principle structural supports. Four of these locations are where the elevation braces meet the azimuth ring, and two of these locations are where the elevation piers meet the azimuth ring. Each of the bearing assemblies is assumed to have both axial and radial stiffness.

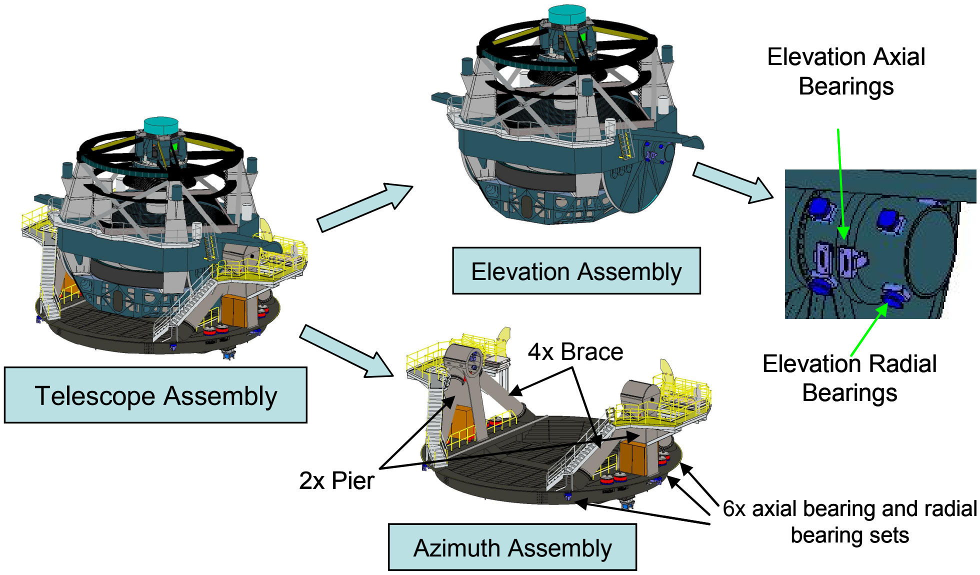


Fig. 9. Hydrostatic bearing configuration and locations on the telescope structure

Both sides of the elevation axis use identical bearing assemblies. Two sets of 2 load-carrying bearings for each of the elevation assembly trunnions provide both force and moment resistance. Preloading bearing on top of the axis increase the stiffness. For each bearing assembly, two axial pads are attached to one side of the collar and two bearings placed opposite them keep the elevation assembly in position along the axis.

The azimuth drives are attached to the azimuth assembly. This configuration allows for their positioning in structurally optimal locations adjacent to the elevation braces. This minimizes the variation in dynamic properties with azimuth angle. However, it also adds the complexity of routing the drive electrical cabling and cooling lines through the azimuth cable drape. The baseline is to utilize 4 azimuth drive motors although 8 motors may be incorporated if it allows the utilization of off-the-shelf components. The elevation drives are attached to the azimuth assembly and act on two large C rings to minimize the effect of drive stiffness on the vibration response of the telescope. Each C ring reacts two drives.

Preliminary analysis showed that either direct drive or gear drive systems would provide adequate performance for this application. The baseline is to utilize frameless motors directly driving geared pinions. This appears to provide the best balance of stiffness, complexity, backlash etc. Drive stiffness from similar projects were used.

8. TELESCOPE PIER

The telescope mount resides on top of the telescope pier, fig 10. Although this concrete telescope pier is not considered part of the mount, its design and characteristics fundamentally affect the performance of the mount. The added flexibility of the pier, its foundation and the substrate the foundation resides on all affect the overall system flexibility and therefore the mount's dynamics characteristics, ref 10.

The telescope pier height was established to have the primary mirror above the predominant ground layer of the local topography. A height of ~22 m is consistent with LSST analysis of local seeing effects on El Peñón, the site for LSST on Cerro Pachón, and is consistent with the height that was established by site testing for the 8m Gemini Telescope on the adjacent peak. The LSST pier height is 15.65 m, slightly higher than the original concept. Analysis of the overall system stiffness revealed an advantage to a more compact telescope structure and a higher pier so the overall height remained constant. The LSST telescope center of gravity is now very low relative to the bearing race on the top of the pier providing enhance dynamic performance.

To prevent the transmission of vibrations, the telescope pier must be separate and isolated from the rest of the observatory. These facility vibrations result primarily from the enclosure (dome) motion, but also from wind shake on the enclosure and excitations from the various support equipment. This isolation requires that the telescope pier have its own foundation separate from the rest of the summit facility. The lower enclosure may not be attached to or in contact with the pier. A physical gap of ~100mm must reside between the observatory deck and the pier to insure vibration isolation, prevent impact during seismic events and provide for thermal control of the pier This specifically precludes supporting the observatory floor off of the pier. Any intermediate or partial floors cannot span between the telescope pier and the lower enclosure. All conduits, piping, cabling etc for the telescope must run up the telescope pier and may not cross from the observing deck of the lower enclosure to the telescope pier. Likewise, the conduits, piping, cabling etc for the dome and lower enclosure may not traverse up the pier and cross over at the upper levels.

To improve the dynamic performance of the pier, it will be constructed of two different thicknesses. The lower half of the pier has a wall thickness of 1.25 and the upper half has a wall thickness of 0.5 M. This reduced the mass of the upper half and increased the stiffness of the lower half, which significantly improved the natural frequency of the pier.

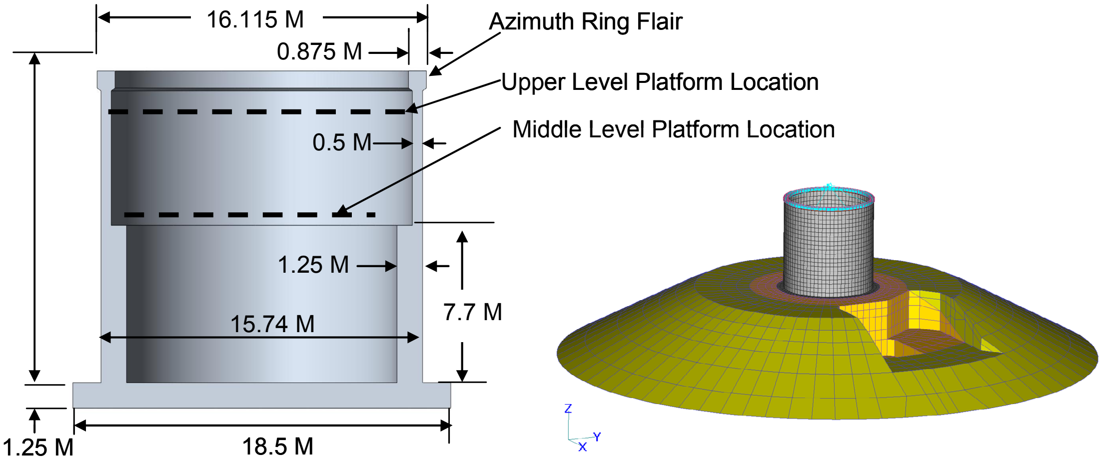


Fig. 10. Telescope Pier Section (left) and FEA Model of Telescope Pier on Mountain (right)

The dynamic performance of the pier was further improved by utilizing an atypically large diameter of 16 M. This is significantly larger than the 9 M pier diameter used on the similarly sized Gemini telescope or the 6.0 diameter pier used on the SOAR 4.3 M aperture telescope. Both of these telescopes are located adjacent to the LSST location. As has already been demonstrated by on-site borings the piers foundation will rest on very rigid, unweathered rock substrate, ref 11.

Finite element analysis was utilized to verify the properties of the pier and foundation when installed, fig 10. In this model the telescope is represented by a lumped mass. The fraction of steel reinforcement in concrete is small (less than 1% by volume) and has minimal effect on the piers dynamic properties. The vibration characteristics of the mount and pier system were determined without including the effects of the steel reinforcement. The FEA model included the variations in substrate properties between the weathered and unweathered rock substrate. Adequate steel reinforcement will need to be incorporated into the pier design to provide adequate strength to support the telescope.

For azimuth motions, the telescope mount slides on hydrostatic bearings on top of the azimuth bearing ring. This ring and its attachment to the top of the telescope pier are close copies of the Gemini Telescope's system. The ring is also used to attach the earthquake clips which prevent the telescope from leaving the ring during a seismic event. A flair from 0.5 M to 0.875 M is required at the top of the pier to accommodate mounting of this ring.

The pier must also counteract the azimuth drive torque, and provide mounts for the encoders, brakes, limit switches and hard stops associated with azimuth motions. Initial analysis indicates this single pier is sufficient but further study will address if the encoder read heads need to be supported from a separate independent central pier unaffected by the drive loads. For accessing this equipment from inside the pier, an upper level platform must be provided under the telescope, inside the pier and attached to the pier, fig 10.

A significant quantity of cabling from the facility to the telescope is required to operate the various systems that move with the telescope. These cables, which include power, control and cooling are connected along the azimuth axis in a maypole type cable drape to allow +/-270 degrees of azimuth rotation. A second middle level platform half way up and internal to the pier will be required for supporting and servicing the cable drape. A reduction in wall thickness of the pier is located at this height for dynamic reasons discussed previously. The resulting lip will facilitate the support of this middle platform.

The principle access to the internal space of the pier will be provided by a door at the pier's base, residing on the ground floor. The internal wall of the pier on the ground floor and the mid level will be utilized for mounting a large number of electrical cabinets etc. Stairways will be provided from the ground floor to the mid level platform, and from the midlevel platform to the top platform. A ladder will be provided from the top level platform to the floor of the telescope. This ladder will move with the telescope and must be accessible regardless of the telescope orientation.

9. MOTION REQUIREMENTS

To maximize the time available for the actual exposures, stringent slew and settling time requirements were set for the LSST mount. For both axes, the slew and settling time requirements were set at 5 seconds for a 3.5 degree motion on the sky, consistent with pointing to adjacent fields. The telescope must be ready for the exposure after 5.0 seconds. A 1 second buffer is set aside for active optics convergence and camera initialization leaving 4 seconds available for slewing and settling.

For the elevation axis there is a direct relationship between telescope motion and on-sky telescope pointing. A 3.5 degree change in elevation angle produces a 3.5 degree change in FOV. For the azimuth axis there is NOT a direct relationship between the telescope motion and the field of view (FOV) change. As a result of spherical geometry, as the zenith angle decreases, the amount of azimuth motion required increases relative to the change in FOV. This relationship can be expressed by simple trigonometry.

Delta FOV = sin (φ) * Delta Az angle. Where φ is the zenith angle.

As the zenith angle approaches zero ($\varphi \rightarrow 0$), the sine of the angle also approaches zero. Consequently, the change in azimuth angle required, for the 3.5 degree azimuth change in field of view, would approach infinite. To limit power requirements to reasonable levels the 3.5 FOV change in 5 seconds is limited to zenith angles greater than 30deg (30 to 90deg). Since sin(30deg) is equal 0.5, at 30 degrees zenith angle, the azimuth drives must produce twice the performance as elevation drives. For azimuth motions, when the zenith angle is smaller than 30 degrees, the telescope mount will not be able to meet the 5 second slew and settling time. Some deficit will result. For azimuth motions, when the zenith angle is larger than 30 degrees, the slew of the telescope mount and the dome will be less than the 5 second slew and settling time requirement. Since the mean viewing zenith angle is near 30 degrees, if the telescope meets the motion specifications at this angle, it will approximately meet the motion specifications on average.

To minimize vibration excitation, the actual acceleration profiles of the mount will be complicated nonlinear functions. “Jerk” is the time rate of change in acceleration. Discontinuities in the acceleration produce infinite jerk. These spikes tend to excite all the vibration modes. By smoothing out the acceleration profile the jerk can be minimized which reduces the vibration excitation of the telescope.

Although the actual acceleration profiles will be smoothed out, for telescope cadence simulation purposes, the accelerations can be represented by constant values. The time profile of the simplified acceleration is therefore a square wave step. When the profile is modified as described above, the maximum accelerations and peak velocities are ~50% higher than the theoretical step values. Theoretical Step Performance Requirements:

Elevation:	Peak Velocity:	3.5 Deg/sec	Acceleration:	3.5 Deg/Sec^2
Azimuth:	Peak Velocity:	7.0 Deg/sec	Acceleration:	7.0 Deg/Sec^2

Although observing will take place only between zenith angles of ~3 to 75 degrees, to simplify servicing the elevation assembly is required to allow motion from elevation angles of 0 to 90 degrees. The azimuth axis will allow for +/- 270 degrees of motion.

10. THERMAL MANAGEMENT

Extensive thermal management is required for adequate performance of the LSST optical system. This is required to both limit thermal distortion of the optics and to control dome and mirror seeing produced by convection. This thermal management requires maintaining the temperatures of the various components to within close tolerances to ambient air temperature, not just the removal of heat. Overcooling also produces detrimental effects. All heat sources will have temperature sensors and temperature control systems.

Heat loss will be controlled from all heat sources on the telescope and in the enclosure. The telescopes heat sources include the azimuth and elevation drives, the fans of the primary / tertiary mirror thermal control system, the active optics control systems for the primary / tertiary and secondary mirrors, the hexapods, the rotator, the camera, and all the associated electronics. The principle means of cooling for the LSST will be glycol / water liquid cooling.

Smaller heat sources may be air cooled where the air is conditioned by centralized glycol water heat exchangers. This reduces the chances of coolant leaks which can be detrimental to electronics and the mirrors optical coating. The camera will also implement a separate cryogenic system necessary for the operations of the detectors.

11. STRUCTURAL DESIGN AND ANALYSIS

Meeting the stringent vibration specifications will require a stiffer mount with higher natural frequencies than is normally utilized by an astronomical telescope. The natural frequencies of the major components (camera 12.6 Hz, secondary mirror 15.9 Hz, Primary / tertiary mirror 14.7 Hz) were also tailored to prevent vibration coupling with the 8Hz natural frequency of the telescope when mounted on the pier. The settling characteristics will also be improved by incorporating an advanced control system that minimize the excitation of the natural frequencies and by adding damping with reaction mass dampers.

The unusual optical design of the LSST allows for a mount configuration with superior dynamic characteristics. By locating the tertiary mirror within the primary mirror, the overall length of the optical system was minimized. This results in a stiff structure and a low moment of inertia, relative to the telescope mass, table 2. The stiffness increases the natural frequency which reduces the settling time, and the reduced moment of inertia reduces the power requirements for slewing the telescope. The high natural frequency also generally reduces the magnitude of vibrations regardless of the source.

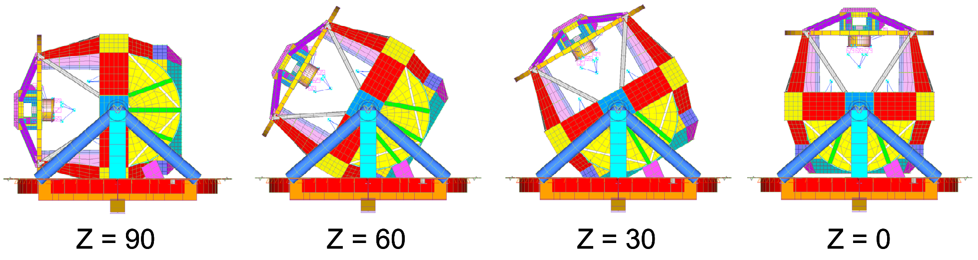
LSST Mount		
MASS AND INERTIA ABOUT ELEVATION AXIS		
W 20% Structural Mass Added	Mass (Kg)	I (Kg m2)
Elevation Asm (About Elev Axis)	149,202	2,225,041
Optics	25,936	294,816
Primary/Tertiary Mirror	17,682	145,752
Secondary Mirror Assembly	5,222	121,709
Instrument	3,032	27,354
Structure	123,097	1,930,226
Mirror Cell w Added Mass	31,106	541,086
Mirror Cell Piers	4,145	71,655
Center Section	46,930	354,888
Top End Structure	14,349	552,401
Top End Piers & Braces	10,304	258,753
C-Rings	13,949	140,273
Balance Masses	2,313	11,171
SUBTOTAL	**149,202**	**2,225,041**

LSST Mount		
MASS AND INERTIA AZIMUTH AXIS & TOTAL		
W 20% Structural Mass Added	Mass (Kg)	I (Kg m2)
Azimuth Assembly	149,105	5,898,472
Elev Bearing Housing	5,941	262,958
Elev Bearing Pier	15,421	678,074
Elev Bearing Brace	38,746	1,806,693
Elev Drive Structure	1,532	49,229
Azimuth Keel	16,736	276,554
Azimuth Frame	28,687	1,037,538
Azimuth Ring	30,983	1,508,708
Azimuth Braces	7,763	212,093
Azimuth Gussets	3,295	66,625
Elevation Asm (About Azimuth)	149,202	3,105,184
TOTAL	**298,306**	**9,003,656**

Table 2. LSST mass and inertia, with 20% structural added mass.

Finite element modeling was used to develop a mount design that meets the vibration requirements. The fundamental vibration modes are a transverse displacement of the elevation assembly along the elevation axis, and the elevation assembly locked motor rotation. Further increasing the frequencies would be limited by the stiffness of the bearings and drives. Most telescopes are heavier and more flexible than predicted. To account for the extra mass the analysis was conducted with 20% added parasitic mass attached to all the structures.

The structure was analyzed at multiple zenith angles, fig 11. To minimize drive torque the center of mass of the elevation assembly must reside along the elevation axis. Unlike most telescopes, the inertia of the elevation assembly is similar in all direction. Consequently, the zenith angle has minimal effect on the vibration properties.



LSST Telescope Inertia (Kg-M^2) As a function of Zenith Angle (degrees)				
	0	30	60	90
IXX	6.80E+06	6.80E+06	6.80E+06	6.80E+06
IYY	1.08E+07	1.07E+07	1.05E+07	1.04E+07
IZZ	8.96E+06	9.05E+06	9.24E+06	9.33E+06
IXY	-4.25E+00	4.36E+01	7.92E+01	9.28E+01
IYZ	-2.77E+04	-1.86E+05	-1.84E+05	-2.25E+04
IZX	-9.25E+01	-8.06E+01	-4.64E+01	9.57E-01
Note: Azimuth Assembly Coordinate System (X,Y,Z)				

LSST Telescope - Natural Frequencies Variations with Zenith Angle					
#	Mode Shape	0	30	60	90
1	Elevation Axis - Locked Rotor	8.7	8.8	8.4	8.0
2	Elevation Axis - Axis Displacement	8.8	8.8	8.7	8.69
3	Optical Axis - Pumping	12.3	12.2	11.7	11.36
4	Elevation Axis - Axis Displace 2nd	12.0	12.0	12.0	11.97
5	Elevation Axis - Locked Rotor 2nd	13.6	13.5	14.0	14.5
6	Main Azimuth Ring	13.7	13.7	13.7	13.7
7	Main Azimuth Ring	13.8	13.8	13.8	13.8

Fig. 11. Finite element model at various zenith angles.

12. CONCLUSION

By supporting the unique LSST optical arrangement in a compact version of a conventional mount, all the telescope's configuration and performance requirements can be met. This compact design coupled with a robust pier results in 8Hz natural frequencies. The stringent dynamic requirements are met by a combination of the high natural frequencies, advanced controls, and moderate levels of added damping. The mount concept also incorporates all the necessary systems and components to support the operational and maintenance needs. The telescope allows for convenient removal of the optical systems for off-telescope re-coating and maintenance as well as on-telescope access for routine cleaning and minor maintenance. The telescope also supports the inclusion of the extensive baffle system and thermal management that are critical to the telescope optical performance.

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