Baseline Design of the LSST Telescope Mount Assembly
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ABSTRACT

The Large Synoptic Survey Telescope (LSST) is an 8.4 meter, 3.5 degree, wide-field survey telescope. The survey mission requires a short slew, settling time of 5 seconds for a 3.5 degree slew. Since it does not include a fast steering mirror, the telescope has stringent vibration limitations during observation. Meeting these requirements will be facilitated by a stiff compact Telescope Mount Assembly (TMA) riding on a robust pier and by added damping. The TMA must also be designed to facilitate maintenance. The design is an altitude over azimuth welded and bolted assembly fabricated from mild steel.

Keywords: LSST, mount, mount assembly, telescope mount assembly, TMA

1. INTRODUCTION

This document presents the baseline design of the Telescope Mount Assembly (TMA) for the Large Synoptic Survey Telescope (LSST). The purpose of the Telescope Mount Assembly 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 LSST's dedicated 10 year, 6 band, optical survey of the entire visible sky will require a large aperture, wide field of view, and highly agile telescope to accomplish 5.5 million observations in a decade of operation. The LSST, located on the Cerro Pachón summit in Chile, can survey the entire visible sky every three nights, figure 1.

As a result of its wide field of view, the LSST is especially susceptible to stray light. Meeting the high observing rate (rapid cadence) requires rapid heat-producing motions of the telescope mount. Consequently, the telescope mount incorporates substantial light baffling and thermal control.

Although operators will be on site to respond to problems, the high cadence demand of the LSST requires fully automated operation. The target choice will be determined by scheduling software. The Telescope Control System (TCS) provides upper level control of all the telescope's systems. In addition to the automated mode, the TCS allows manual operation via an Engineering User Interface (EUI), which will enable maintenance and servicing.

The survey mission only allows 5 seconds for a 3.5 degree on sky repointing. This is significantly faster than similarly sized telescopes. The LSST does not include a fast steering mirror; consequently the telescope has stringent vibration limitations during observation. Meeting these requirements is facilitated by the stiff, compact TMA riding on a robust pier, which produces high natural frequencies, an advanced telescope control system (TCS) and reaction mass dampers.
The characteristics of the steel reinforced concrete pier were enhanced by utilizing two different wall thicknesses, a large top flair, and an unusually large diameter of 16 meters, and by anchoring the foundation in unweathered bedrock.

For testing, maintenance and repairs, the three principal optical assemblies\(^1\) must be installable (and removable) from the TMA as complete assemblies. These include the camera assembly, M2 cell assembly\(^2\) and M1M3 cell assembly\(^3\). The telescope dome\(^4\) (rotating enclosure) and facility are both compatible with these removal and reinstallation procedures.

2. 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 3.4 degree field-of-view, figure 2. The tertiary mirror (M3) resides within the 5-m 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 during fabrication, utilizing a single monolith removes six degrees of freedom, which simplifies optical alignment. The 3.2 billion pixel camera (instrument) is positioned directly below the secondary mirror (M2) and aligned along the optical axis with it. Both the M2 Cell Assembly and Camera utilize hexapods\(^4\) to facilitate optical positioning relative to the M1M3 mirror. A rotator resides between the Camera and its hexapod to facilitate tracking.

Figure 2: Optical Arrangement

3. TELESCOPE MOUNT ASSEMBLY DESIGN

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. The secondary mirror assembly and camera do not interface directly to the TMA but rather interface through their hexapods.

The TMA incorporates all typical large telescope systems. These include cable wraps, mirror cover, balancing systems, bearings, drives, cables/utilities, etc. Figure 3 shows the major elements of the TMA. In addition, the LSST requires substantial light baffling due to its wide field of view. Since the optical system does not include a fast steering mirror, meeting the vibration requirements (wind shake, dome vibration coupling, etc.) and the stringent slew and settling requirements will be aided by tuned mass dampers. Accessing the camera also requires retractable/deployable platforms.
The LSST structure was designed to facilitate maintainability. The M1M3 mirror cell is only structurally connected to the elevation assembly at four pier flange locations. This facilitates removal of the M1M3 mirror cell assembly for coating, etc. The camera support assembly and the M2 mirror cell assembly will be removed as complete intact units. All the hydrostatic bearing surfaces are enclosed, which reduces contamination and damage susceptibility.

3.1 Non Co-Rotating Design

As a result of the compact design of the LSST telescope there would be minimal benefit to a co-rotating telescope and rotating enclosure (dome) configuration, where the azimuth motions of the telescope and the rotation of the dome are locked together. Freeing the dome and the telescope azimuth rotations facilitates maintenance, calibration and thermal control. It also reduces the motion demands of the dome. The dome actually utilizes a slightly (~1m) 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 any location 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 camera's detector system. 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 thermal control systems can function properly while calibration is conducted.

3.2 Design Envelope and Interface

![Figure 4: LSST Telescope Mount Assembly (with payloads) Design Envelope.](http://proceedings.spiedigitallibrary.org/)
Since the LSST telescope and dome are not co-rotating, the design envelope for the LSST telescope is axis symmetric and results from the clearance requirements between the telescope and the rotating enclosure, figure 4. The TMA must stay within this envelope while moving through the full range of elevation axis, and while accommodating its three optical payloads: M1M3 mirror cell assembly, M2 combined assembly and camera.

The principal physical interface of the TMA to the observatory is its pier, figure 5. The baseline is for the TMA to utilize a hydrostatic bearing for its azimuth motions. The TMA to pier interface is the bolting interface that attaches the hydrostatic bearing track to the telescope pier.

The track supported by just the bolts would possess insufficient strength to support the telescope during a seismic event. Consequently, high strength, low expansion concrete grout must be applied to fill the approximately 100mm gap between the pier’s concrete top and the bottom of the bearing track required for installation and alignment. This combination of steel anchor bolts and grout is analogous to the steel rebar reinforcing the concrete pier.

The main azimuth gear and the azimuth brake are both attached directly to the bearing track. Consequently, separate supports for these items are not required. The azimuth encoder tape system will be attached to the pier. However, since this is a low load item, the interface can be added after pier construction and is not included in the interface document.

3.3 Structural Design

The unique 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 with low moments of inertia relative to the telescope mass, table 1. The stiffness increases the natural frequency, which reduces the settling time, and the reduced moment of inertia reduces the slewing power requirements. The high natural frequency also generally reduces the magnitude of vibrations regardless of the source. Although the LSST telescope has a unique optical design and operational requirements, the structural design of the LSST telescope mount is similar to many large ground based telescopes.

The TMA was designed to facilitate manufacturing and shipping. All structural components can be fabricated from easily welded mild steel, A36 or equivalent. Some higher stress areas may require higher strength, but still easily welded, steel (A572 or equivalent) to withstand the seismic loads. All structural assemblies were designed to bolt together in sections that fit through the tunnel on the roadway leading to the site, which is the limiting obstruction.
3.3.1 Elevation Assembly
To minimize torque requirements, and reduce runaway motion risk, the elevation axis must align with the center of gravity (CG) of the elevation assembly, figure 6. Since the purpose of this assembly is to orient the three optical payloads, the location of this axis must be near the CG of these three optical systems (M1M3 mirror cell assembly, M2 mirror cell assembly, and camera). Consequently, the center section of the TMA was incorporated into the design to support the resulting elevation axis bearing shaft.

To minimize the load path, the drive wheels are mounted onto the bottom of the center section. The radius of the drive wheels was set to match the stiffness of the azimuth drives. At this size, the azimuth drives are not dominating the overall flexibility. The drive wheels also add substantial stiffness to the center section.

Four M1M3 cell piers are used to attach the M1M3 mirror cell assembly to the center section. Using only four piers facilitates removal of the M1M3 mirror cell assembly and minimizes the transmission of center section flexure into the M1M3 mirror cell assembly, which can distort the mirror. As a result of the short length of the piers, only minimal moment is transmitted and cross bracing is not required.

The top end assembly (TEA) is also supported by four TEA piers. As a result of their long length, these piers require cross bracing. For resistance along the elevation axis direction, a cross brace, "X", configuration was required. This concentrates the load from the top end into the intersection of the piers with the center section, which is inherently rigid.

Table 1: LSST Mass and Inertia (Best Estimate)

<table>
<thead>
<tr>
<th>Elevation Assembly Mass and Inertia About Elevation Axis</th>
<th>Mass (Kg)</th>
<th>Ix (Kg m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1M3 Etc Payload</td>
<td>52,982</td>
<td>802,374</td>
</tr>
<tr>
<td>M2 Etc Payload</td>
<td>5,489</td>
<td>120,201</td>
</tr>
<tr>
<td>Camera Etc Payload</td>
<td>4,097</td>
<td>44,164</td>
</tr>
<tr>
<td>Elevation Assembly TMA only</td>
<td>92,379</td>
<td>1,592,202</td>
</tr>
<tr>
<td>Elevation Assembly TOTAL</td>
<td>154,948</td>
<td>2,558,941</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LSST Telescope Mass and Inertia About Azimuth Axis</th>
<th>Mass (Kg)</th>
<th>Ix (Kg m^2)</th>
<th>Iy (Kg m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation Assembly</td>
<td>154,948</td>
<td>3,066,281</td>
<td>2,654,003</td>
</tr>
<tr>
<td>Azimuth Assembly</td>
<td>196,578</td>
<td>7,643,131</td>
<td>7,643,131</td>
</tr>
<tr>
<td>Telescope TOTAL</td>
<td>351,504</td>
<td>10,698,038</td>
<td>10,297,134</td>
</tr>
<tr>
<td>(TMA Only)</td>
<td>288,957</td>
<td>10,057,343</td>
<td>9,936,587</td>
</tr>
</tbody>
</table>

Figure 6: Elevation Assembly (with Cabling)
Bracing in the direction perpendicular to the elevation and optical axes is accomplished by a "V" configuration. This concentrates the load from the top end assembly into the intersection of the center section with the elevation bearing shaft. Not only is this an inherently stiff location, but since all the static load is transmitted through this location it also reduces the load path. This "V" brace also allows for the incorporation of the deployable platforms.

The top end ring is required to transversely stabilize the four TEA piers. Two light baffles are also required at this location. An "I" beam configuration fulfills both requirements. The two "I" beam flanges function as the two light baffles. Another non-structural, mid-level baffle is also required between the center section and the top end ring. Both these members have extensive circular cutouts to both reduce mass and enhance natural convection (air flow).

The spider spindle is the central structure of the TEA and indirectly provides the support for the camera and M2 mirror cell assembly. It is attached to the top end ring through 16 hollow rectangular spiders. This configuration was chosen as a balance between structural efficiency and optical degradation. The hollow spiders also provide for the convenient routing of the many cables required for the camera and secondary mirror assembly.

### 3.3.2 Azimuth Assembly

The azimuth assembly both supports the elevation assembly and provides for the rotation about the gravitational vector, figure 7. Since the elevation assembly is balanced about its axis, all of the weight of the elevation assembly is supported by the two elevation bearing assemblies. Each of these bearings is supported by a tripod consisting of the elevation pier and the two elevation braces. Each of these three members is directly supported by an azimuth bearing set. Consequently there are three direct load paths from each elevation bearing into the telescope pier. Each of these pairs of braces is connected by a main frame which is required to provide adequate support for the elevation pier. These main frames are also required to support the M1M3 mirror cell assembly and cart during removal. They are also required to support the utility floor for accessing the M1M3 mirror cell assembly, and for supporting the elevation drives. The azimuth structural assembly must allow for both the elevation axis motion and the removal of the M1M3 mirror cell assembly. To provide adequate support in the elevation axis direction, a keel was added connecting the two piers.

![Figure 7: Azimuth structural assembly with azimuth bearings and elevation drives](image)

The natural frequencies of the telescope are directly affected by the height of the elevation axis above the top of the telescope pier. By recessing the floor of the azimuth structural assembly by 0.8 meter, the M1M3 mirror cell was allowed to swing below the main floor height. To accommodate this configuration, the telescope pier diameter was increased to 16 meters. This large diameter also significantly increased the overall stiffness.

An azimuth ring was required to support the floors, support the azimuth drives, and maintain the proper orientation of the two tripods. The ring has significant light weighting in the form of cutout and thickness variation to remove extra mass between the tripods where the ring’s principal function is floor support. This also provides the flexibility needed to allow the six bearings to remain in contact with the bearing track in what would otherwise be a non-kinematic configuration. The cutouts also provide access to the main gear and brake disk for inspection, maintenance and repairs. The azimuth assembly described above would have inadequate stiffness between the two tripods without the flooring. The flooring acts as a shear web maintaining the proper orientation between the tripods.

### 3.4 Bearings

The baseline is for the LSST to utilize azimuth and elevation axes hydrostatic bearings. These bearings can provide the stiffness, lifetime, and smoothness required by the LSST, figure 8. The azimuth axis utilizes six bearing assemblies.
Each bearing assembly is aligned with one of the principal 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.

Figure 8: Hydrostatic bearing configuration and locations on the TMA

Both sides of the elevation axis use identical bearing assemblies. 2x2 load-carrying bearings for each trunnion provide force and moment resistance. Each of these bearings has a paired bearing to provide preload increasing the overall stiffness. For each bearing assembly, axial pad pairs keep the elevation assembly in position along the axis. This configuration can allow for up to half of the bearings to be used as slaves to prevent binding.

3.5 Drive System

For both the elevation axis and the azimuth axis, the baseline drive system is for direct drive motors to operate pinion/gear assemblies, figure 9. Direct drive motors are low speed, high torque motors that eliminate the need for a reduction gear system. The only gear reduction is provided by the ratio of the pinion to gear. As a result of the rapid acceleration of the TMA, the inertial effects produce the principal drive loads. The motor inertia affects the overall inertia relative to the square of the speed ratio of the drive motor to TMA axis. If high speed motors and reduction gears were used, a large portion of the motor power would be required to overcome its own inertia.

Figure 9: Drive System Components

Even though utilizing direct drive motors significantly reduces the power requirements, substantial motor power is still required (~400 HP for azimuth and 30 HP for elevation). These power requirements can be met by existing motors available through different manufacturers (e.g. Kollmorgen: 8 x KBM-260X04 for azimuth totaling 450 HP, and 4 x
KBM-163X02 for elevation totaling 28 HP). The use of linear motors was also considered, but not further developed due to the higher cost and more limited commercial offering.

For the azimuth axis, the eight drive motors are attached to the azimuth assembly and the gear is attached to the telescope pier. This produces the complication of routing the power and cooling lines through the azimuth cable drape. However, it also eliminated the variation in dynamic properties with azimuth angle, which increases the effectiveness of advanced telescope control system (TCS) and damping systems.

For the elevation axis, the direct drive motors are attached to the azimuth assembly and act on the large drive wheels attached to the center section. A shaft drive system with comparable stiffness would require an excessive shaft diameter near that of the drive wheel diameters.

Both the azimuth and elevation drive motors are attached to the azimuth assembly. The motor controls are attached to the webs of the elevation piers, figure 9. One controller is used for each half of the TMA and operates half the elevation and azimuth motors. These motors are torque controlled within the position and velocity loops. During slewing, the motors all operate in unison. During tracking they operate in pairs to counteract each other and to minimize backlash. The elevation axis utilizes four motors. One motor pair is associated with each side of the elevation axis.

### 3.6 Drive Capacitor Bank

The DC capacitor bank is an energy storage device connected to the DC bus link of the variable frequency drives of the mount motors in order to supply the instantaneous current necessary for fast slewing of large inertia loads and prevent excessive current draw from the power grid. The utilization of a capacitor bank also facilitates regenerative braking by reabsorbing the energy for reuse instead of dissipating it as heat. The capacitor bank is large, heavy, produces non negligible heat, and is potentially hazardous; consequently it is located at the bottom of the TMA, below the floor, on the keel, figure 9. Since this location is below the azimuth bearings and along the azimuth axis, its mass has negligible effect on either the natural frequencies or the rotation inertia of the TMA. The isolated location also prevents inadvertent access.

As a result of its location, the capacitor bank cannot be accessed by the crane once it is installed. It must either be installed before installing the elevation assembly or assembled in place. The bank is designed to not need replacing during the 30 year design life of the telescope. The capacity has sufficient excess to meet the performance requirements within the predictable capacitor failure rate. Although the banks are heavy, the individual components are small enough to be manipulated by hand. Consequently, although not planned, they can be serviced in place if necessary.

The capacitor bank will require cooling. Normally cooling is provided by fans blowing cold air through a heat exchanger and then into the cabinet. Since glycol/water conducts electricity, a coolant leak into the capacitor bank could be catastrophic. Consequently, ambient air will be blown into the cabinet and then through a heat exchanger.

### 3.7 Brakes

Although the TMA will normally utilize regenerative braking, for safety the TMA must also have separate power off brakes for both axes. This system stops the telescope during a drive system failure or power interruption. The braking system may utilize either brakes attached to each motor or an entirely separate braking system. Either option will provide adequate performance and the choice will be made based on the component availability during the final design.

For the azimuth motion, a brake disc attached to the azimuth bearing track has been included to allow for the incorporation of a separate braking system. The brake calipers would be attached to the azimuth assembly main ring. Although disc brakes are not included in the elevation assembly, ample space is available to incorporate them.

### 3.8 Cable Wraps and Routing

Three cable wraps are required to operate the TMA: the azimuth wrap, elevation wrap, and camera wrap. These wraps are used for all types of utilities including power cables, communication lines, coolant flow, and compressed air. For azimuth and elevation, the cable wrap systems chosen are similar to the Space Surveillance Telescope (SST), which has higher accelerations and velocities than the LSST. The camera cable wrap does not need to match the azimuth and elevation drive motions.

#### 3.8.1 Azimuth Cable Wraps

The LSST used a maypole type azimuth cable wrap where utility lines hang down from the bottom of the azimuth keel in a circular maypole configuration, figure 10. The other ends of the lines are attached to an elevated stationary floor in the
telescope pier. A hanging section of cable allows for the change in length required for the circular motion. The cables are organized by a set of loops supported by steel cables. The top of the steel cables are connected to the bottom of the telescope and the lower end is attached to the elevated stationary floor.

The rapid TMA motions were a concern in regard to the azimuth cable wrap. The only other large telescope with motions similar to the LSST is the Space Surveillance Telescope (SST). This telescope utilizes a maypole type azimuth cable drape nearly identical to that utilized by LSST and has operated without incident.

3.8.2 Elevation Cable Wraps

Since the elevation axis only rotates 90 degrees, the baseline design for the elevation cable wrap uses a simple non-powered cable drape system, figure 11. One end of the cable is attached to the elevation assembly and the other end is attached to the azimuth assembly. The operation of the elevation cable drape is analogous to the maypole azimuth drape. The flexible cables hang down and sufficient flexible cable is provided. Although the baseline allows the cable to hang freely, these cables can easily be run through a non powered power chain to provide control and organization.
3.8.3 Camera Cable Wraps

Unlike the simple, passive azimuth and elevation cable wraps, the camera cable wrap requires a powered cable chain, figure 12. As the elevation angle changes, the orientation of gravity relative to the cable wrap system changes: this precludes the use of any cable wrap systems that require gravity to control the cables. The camera cable wrap is attached to the integrating structure of the top end assembly. It is a component of the camera support assembly. Consequently it is installed and removed with the rest of the camera support assembly.

![Camera Cable Wrap](image)

Figure 12: Camera Cable Wrap

The camera cable wrap employs four cable chain assemblies arranged in a rotary fashion within the cable wrap drum. From the drum to the camera, no flexure occurs because the entire array rotates with the camera around a central shaft mounted to the cable wrap drum. The stationary ends of the chains are attached to the drum inner circumference. The driven ends attach to a central hub which rotates on a central shaft around the optical axis. The chain design incorporates both forward bending and reverse bending radii to allow the needed motion.

This design was chosen because no cable twisting occurs during rotation and this type of system is commonly utilized, which reduces risk. The power chains are commercially available, and the systems provide excellent cable organization. Since this cable wrap is expected to require a significant amount of maintenance, it is located on the outermost location of the TMA where it can be readily accessed by a scissor-lift with the telescope at horizon pointing.

3.8.4 Cable Routing

Besides the cable wraps discussed previously, the TMA baseline design contains routing for all the major utilities (cables), figure 13. All the power, communication, coolant, refrigerant, and compressed air up to the beginning (bottom) of the azimuth cable wrap are provided from within the facility.

The main route of the cables starts from where the azimuth cable drape attaches to the bottom of the keel of the azimuth assembly. The cables then run along the keel, through the main floor, and up along the elevation pier to the elevation cable wrap. From the elevation cable wrap, the cables run on top of the center section and then either up the top end pier to the top end assembly (TEA) or down the M1M3 pier to the M1M3 cell. The cables cross the optical path through the hollow spiders. The cables for the various components leave this main route along the way as necessary.
3.9 Deployable M1M3 Mirror Cover
The estimated 3,300 lb deployable M1M3 mirror cover design uses four “Chinese fans,” figure 14. The purpose of the cover is to protect the mirror from falling objects (nuts, bolts and tools), water leaks (through dome and from the thermal control system) and dust. Since the M2 mirror and camera face down they are not susceptible to falling objects, etc., and deployable covers are not required. Moreover, substantial protection of the M2 optical surface is provided by the M2 baffle, and the camera lens (L1) is provided substantial protection by the M1M3 mirror cover described in this section.

It is not possible to produce a mirror cover that would safely support personnel within a reasonable mass budget. Consequently it is difficult to retrieve any object that has fallen onto it. The “stair step” feature of this mirror cover would inherently remove small objects when retracted.

3.10 Balancing System
Proper operation of the TMA's elevation axis drive system requires the elevation assembly be balanced about the elevation axis in both the optical axis direction and the direction transverse to both the optical axis and the elevation axis; otherwise unnecessary motor torque must be utilized to counteract the imbalance. This torque increases the electrical demand, produces unnecessary heat, distorts the mount, and increases the risk of uncontrolled motion.

Gross balance about the elevation axis is achieved by the overall design of the elevation assembly. The top end assembly and the M1M3 mirror cell assembly are attached through piers and brace to the elevation assembly's center section. The center section contains the actual elevation assembly axle for the elevation assembly bearings. The position of the elevation axle was adjusted to intersect the predicted CG location as the telescope design matured. Some variation between the predicted CG and the actual post integration CG of the elevation assembly is inevitable. After initial integration, variations in the CG result from the displacement of the M1M3, motion of the hexapods, maintenance and
modification. Typically these discrepancies are remediated through adding balancing mass to the telescope. Since this mass serves no other purpose it is entirely parasitic.

To both reduce the amount of parasitic mass and allow for rapid rebalancing, the TMA incorporates 4 motorized balancing units, figure 15. The mounting location of these balancing systems can be modified during integration to aid in the initial balancing. These balancing units are modeled after those used successfully on the NASA IRTF telescope.

The heavy 17 ton M1M3 mirror has approximately a 10 mm range of motion relative to its mirror cell. The motorized balancing units have sufficient capacity to balance the elevation axis for any M1M3 mirror location within this range. An approximately 20% reserve is available for minor modifications and for the temporary equipment installations that are common. Traditionally, telescope rebalancing has been accomplished by bolting counterweights to the telescope. This is unnecessarily hazardous, time consuming, and cannot be accomplished in real time.

![Figure 15: Elevation Assembly Balancing System](image)

The axial balancing units are attached to mounts embedded in the center section. These mounts allow for the +/-0.5 meters of axial relocation to aid in coarse adjustment. The transverse balancing units are mounted on top of the center section. If necessary these units can be offset from the mounting surface to counteract a low CG situation, or relocated in the transverse direction to aid in transverse balancing.

Although the balancing units can be relocated for coarse balancing, their principal purpose is to provide motorized rebalancing. These units consist of lead weights sliding on linear bearings and moved by motorized drive screws. The drive screw motors are operated manually through the TCS. Since the purpose of balancing the elevation assembly is to minimize the drive motor current, the drive amperage is used by the telescope operator as feedback to adjust the units.

3.11 Damping System

Effective operation of a telescope requires high repeatability. High repeatability requires low hysteresis, which implies low natural damping. Similar to most large telescopes, the natural damping of the LSST will likely be approximately 2%, which is significantly lower than most similar size structures, which typically have natural damping rates of approximately 5%.

The post slew settling time is governed by the decay of the excitation of the natural frequencies. Since this decay is inversely proportional to the damping rate, meeting the 2 second settling time requirement with only natural damping would be difficult. It should be noted that a theoretically perfect TMA motion control system would not excite any vibration modes and the damping rate would have minimal effect. Consequently, in regard to slewing and settling, the damping system principally functions to counteract the limitations of the control system.

Not only is the damping level important to the slew and settling time, but it also affects the vibrations resulting from wind shake and other vibration-inducing sources. Consequently, even if a control system was implemented that did not produce any appreciable excitation of the natural frequencies, an added damping system would still be required.
Tuned mass dampers (TMD) were incorporated into the design to provide the added damping. A TMD is a mass-spring-dashpot system, and is the most mass-efficient passive means for adding damping to a single mode. The TMD vibrates in sympathy with the structure at a targeted frequency, and energy is extracted from the system by dissipation in the TMD. For the LSST application, the targeted frequencies are the two fundamental frequencies (lowest natural frequencies) whose motions are orthogonal to the optical axis and have the greatest effect on the telescope’s optical performance.

TMDs work best in regions having large displacements. Consequently, they were added to the top of the center section piers supporting the top end assembly, figure 16. A study by CSA Engineering demonstrated that the four 973.5 lb TMD units could produce 5% added damping at the fundamental frequencies. The actual total mass budget for these items is 50% higher (5894 lbs) than just the moving mass to account for the unit’s stationary mass.

Although the TMDs only produce significant damping for the specific frequencies, their addition to the overall performance is significant. The settling time is governed by the decay of the fundamental frequencies. Not only do the fundamental frequencies produce the largest displacement, but since their periods are the longest, they decay the slowest.

3.12 Light Baffling

The LSST is very susceptible to stray light rays impinging upon 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, figure 17.

On the telescope, the light path is first baffled by the top end ring which, through its "I" beam configuration, provides two light baffles. A second baffle ring is attached midway up the top end assembly piers. The center section top provides a third light baffle. 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. This specifically includes the TEA and M1M3 cell piers. The outer edge of the M1 mirror, which is not optically figured, is covered by an aperture stop baffle. The transition on the M1M3 between the two optical surfaces is covered by a baffle (paint). A conical baffle resides on the secondary mirror assembly. All baffles are coated with matte black paint.

3.13 Flooring, Platforms and Stairs
To facilitate maintenance and to maximize the time available for imaging, the TMA was designed with an extensive network of flooring, platforms and stairs to provide access to all components which require routine maintenance. In general these items were designed according to the OSHA safety standards.

All the flooring is expected to experience significant loading and was designed to the international building code (IBC). There are no IBC requirements for telescope floors. As a result of the size and mass of the components expected to traverse them, it was determined that the most similar application was manufacturing floors.

3.14 Azimuth Flooring
With a radius of 315 inches (8 meters), the LSST azimuth assembly has a substantial flooring area of 3.1e5 inches square (201 meters square), figure 18. The resulting mass of ~10.3 metric tons accounts for a significant portion of the overall mass. To facilitate the motion of maintenance carts and to aid in directing air flow, all the azimuth flooring is solid (non perforated).

Since the CG of this flooring mass is very low, it produces minimal effects on the natural frequency of the TMA. Its principal effect is to increase the rotational inertia about the azimuth axis. Since it provides necessary shear stiffness, it is also not entirely structurally parasitic.

Most of the azimuth flooring area, between the elevation pier and brace assemblies, is recessed to reduce the height of the elevation axis relative to azimuth ring. Areas not recessed are at the observatory floor level. The azimuth flooring area is divided into three areas. Recessed Floor: The entire recessed floor was considered a single area and designed to the same requirements. Utility Floor: The flooring between the elevation pier and brace assemblies where the recess was not required will be used to access the primary/tertiary (M1M3) mirror cell assembly. Machinery Floor: The flooring under the elevation pier and braces will provide access to the drive motors, motor controls, etc.

The recessed floor will sustain minimal traffic. Substantial weight savings was achieved by designing this floor to the less stringent “Light Manufacturing” standard. The utility floor will be used to access the mirror cell and is expected to sustain substantial traffic. Consequently, it was designated as a “Heavy Manufacturing” floor. The machinery floor will need to support the installation, removal, repair and maintenance of large heavy drive system equipment and was classified as a “Heavy Manufacturing” floor.

The utility floor was designed to be removable, with the dome crane. This provides dome crane access to the interior of the telescope pier. When the crane and telescope are properly aligned with the hatches on the two interior floors of the pier, this access will clear all the way to the observatory ground floor.

3.14.1 Stationary Platforms, Stairs, Ladders and Rails
To facilitate air flow, which improves image quality, all the elevated stairs, ladders and platforms utilize perforated grating for flooring. This does hamper the movement of wheeled carts. This is generally overcome by temporarily overlaying a flat surface (plywood). As is the rest of the TMA, the stairs, etc., are right-left symmetric.
Stairways lead from the main azimuth floor, at the observatory level, to the stationary elevation platforms, figure 19. These platforms are used for a variety of maintenance applications; consequently utilization of ladders to access this location would be inappropriate. These stairways are supported by the stout elevation pier and braces. Consequently, they add minimal structural mass.

![Figure 19: TMA Platforms, Stairways, Ladders and Safety Rails](image)

The elevation platforms are used to access the elevation cable drape, the deployable platforms, the elevation assembly center section and the elevation axis bearing. These platforms are specifically positioned to allow access to the dome's overhead crane. Consequently, they are designed to the light manufacturing load requirements presented earlier.

The top of the elevation center section is accessed by ladders. Access is only required for maintenance of the mirror cover and the transverse balancing units. Consequently, ladder access is appropriate. To provide safe access to three of the four mirror cover subassemblies, a walkway is provided around the half of the center section which is elevated when the telescope is horizon pointing. It would also be significantly more difficult to incorporate a walkway around the remainder of the elevation assembly center section. Since the remaining mirror cover component and axial balancing units can be accessed when the telescope is horizon pointing, a walkway around this section is also unnecessary.

### 3.14.2 Deployable Platforms

As a result of their location, between the M2 mirror and the M1M3 mirror, providing access to the camera, the camera's hexapod/rotator assembly and the M2 optical surface is inherently difficult. To provide reasonable access, deployable platforms are provided, figure 20. These two deployable platforms are mounted on the elevation platform of the azimuth assembly. These platforms also aid in the cleaning and inspection of the M1M3 optical surface.

![Figure 20: Deployable Platforms](image)

The platforms can only be extended with the telescope in the horizon pointing orientation. Once a platform is deployed, two manually deployed extensions increase the platform width adjacent to the camera. One of these extensions is toward
the camera's hexapod/rotator and the M2 optical surface. The other extension is toward the M1M3 and allows access to the first (L1) lens of the camera for both cleaning and installation of a lens cover. Access to the bottom of the hexapod/rotator assembly is only available from below by a ladder or temporary scaffolding.

While significant access is available to the camera hexapod/rotator assembly, only minimal repairs will be allowed on telescope. Significant on-telescope repair activities would endanger the M2 mirror and the camera and present a hazard to personnel. Access is provided principally for inspection, diagnostics and maintenance.

3.15 TMA Vendor Modifications to Baseline Design

The baseline design presented through this document represents the design utilized for the Telescope Mount Assembly procurement process. Since the procurement is through a design build contract, some modifications to the baseline design are inevitable.

The most notable variation between the baseline design and likely delivered mount is the configuration of the drive system. The baseline design used a system of direct drive motors acting on a main gear through a pinion. This system was chosen because it is the most cost effective method of meeting the mount’s dynamic requirements. Through the procurement process it was determined that a true linear drive system could be incorporated with only a moderate increase in cost. The increased performance warranted the increased cost. The linear drive eliminates all the gearing, which will produce smoother motions and will require less maintenance.

4. REFERENCES


