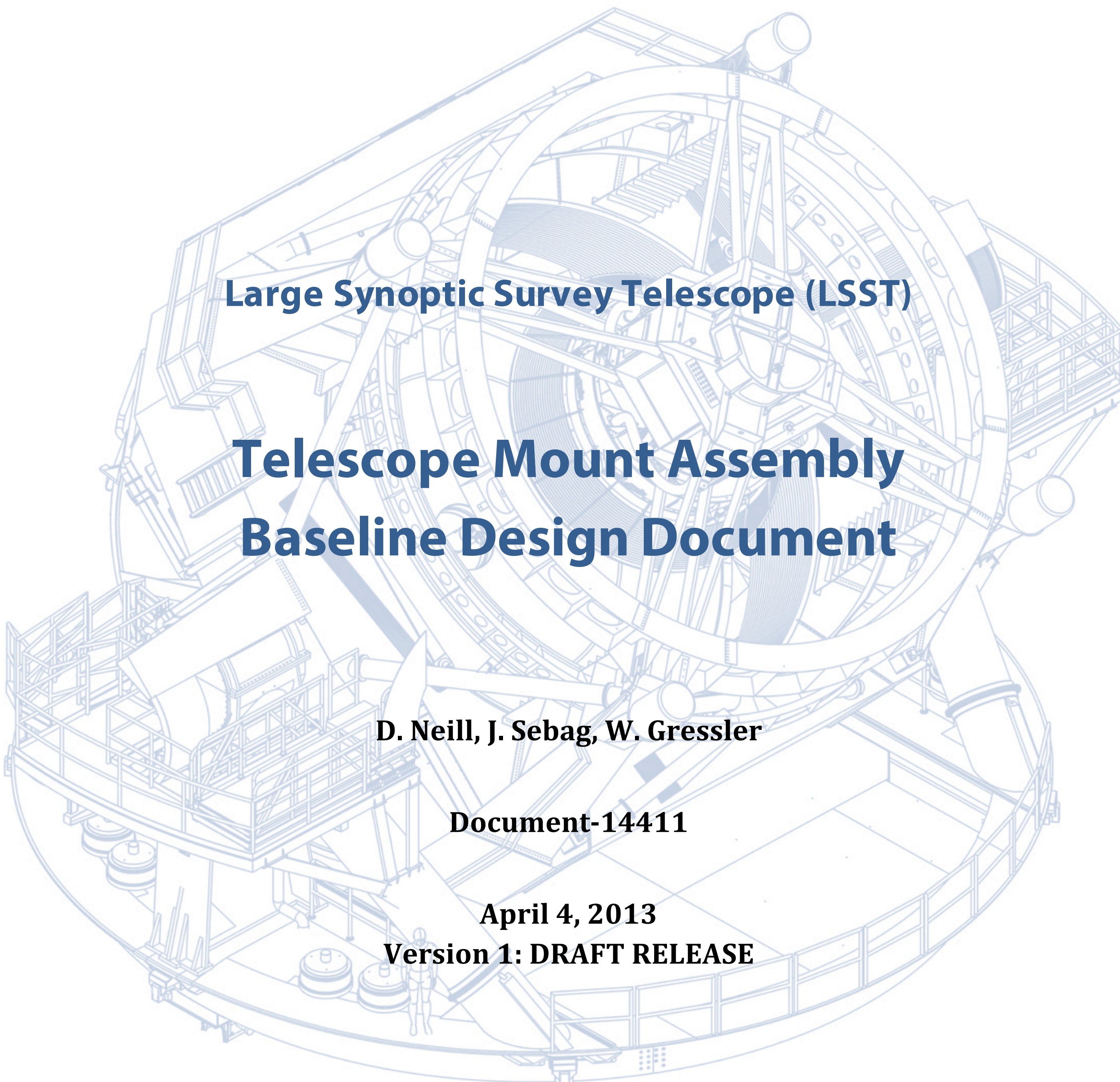
LARGE SYNOPTIC SURVEY TELESCOPE



Large Synoptic Survey Telescope (LSST)

Telescope Mount Assembly Baseline Design Document

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Document-14411

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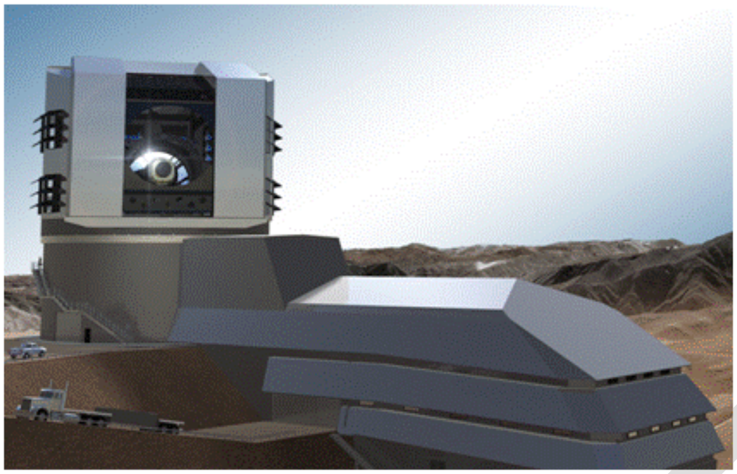
1 INTRODUCTION

This document presents the baseline design of the Telescope Mount Assembly (TMA) for the Large Synoptic Survey Telescope (LSST), document 9549. The purpose of the Telescope Mount Assembly (TMA) 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 roughly 5.5 million, 15 second observations in a decade of operation.

The detailed telescope mount performance requirements are provided in the Telescope Mount Requirements Document (LTS-103). These requirements were flowed down from the Telescope Requirements LSE-60 which itself was flowed down from the overall Observatory Systems Requirements document LSE-30. All requirements provided in this document are for reference only and in case of any conflicts between these two documents the requirements document LTS-103 takes precedent. While there may be some variation between the actual TMA and the baseline described in this document, the TMA is required to provide all the functionalities described in this document.

1.1 TELESCOPE AND SITE INTRODUCTION

The Large Synoptic Survey Telescope (LSST) is a large, wide-field survey telescope, which will be located on the summit of Cerro Pachón in Chile, and can survey the entire visible sky every three nights, fig 1-1. This achievement is accomplished via a three-mirror telescope 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 accommodates a 3.5-degree field of view, feeding a large three-lens refractive Camera.



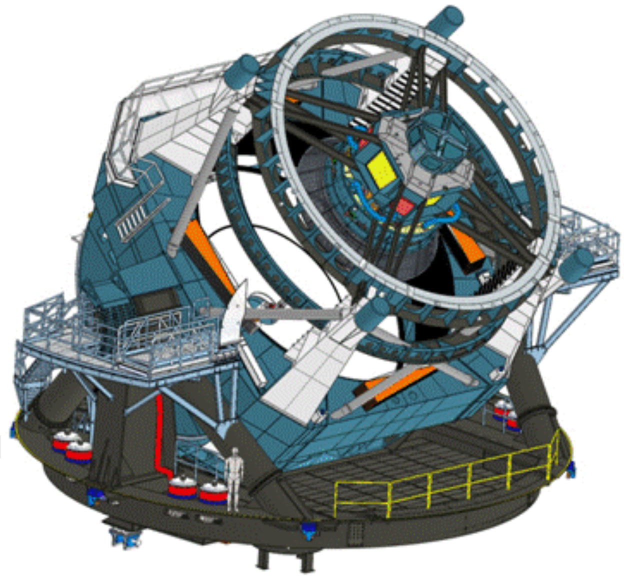


Figure 1-1: LSST Observatory (Left), LSST Telescope (right)

The LSST has a very unique, compact, optical arrangement, fig 1.1-1. The tertiary mirror (M3) resides within the 5-m diameter central hole of the primary mirror (M1). The two mirrors will be a monolith, sharing the same single cast borosilicate substrate which improves the stiffness. The camera is positioned directly below the secondary mirror (M2).

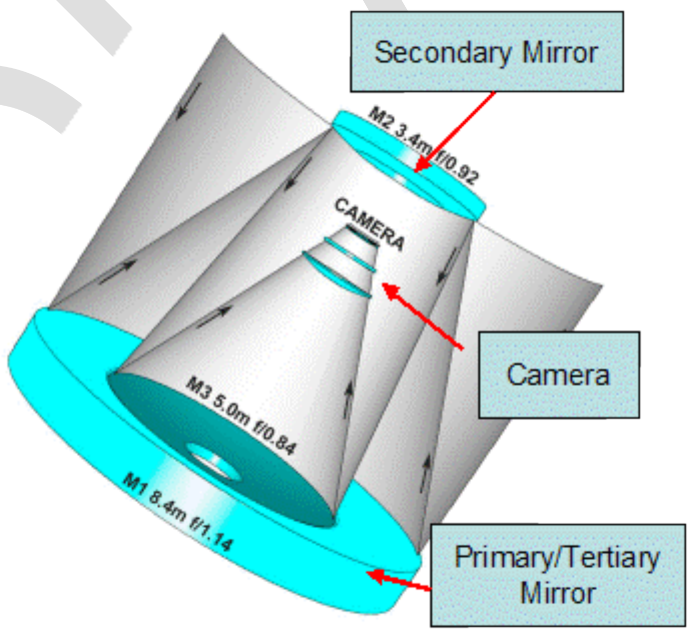


Figure 1.1-1. Optical Arrangement.

The camera and M2 mirror are attached through hexapods to facilitate alignment to the M1M3. A rotator resides between the camera and its hexapod to provide image de-rotation during tracking.

As a result of its wide field of view the telescope 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, meeting the high cadence demands of the LSST requires fully automated operations. This includes the choice of targets which 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 enables local hardware control with a personal computer via the facility network. This interface will report status, and enable maintenance and servicing.

The survey mission requires a short repointing time for the telescope of 5 seconds for a 3.5 degree repointing. This is significantly faster than similarly sized telescopes. The optical system also 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 control system to minimize vibration excitation, and reaction mass dampers. The dynamic characteristics of the steel reinforced concrete pier were enhanced by utilizing two different wall thicknesses, a large top flair, an unusually large diameter of 16 meters and anchoring the foundation in unweathered bedrock.

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

1.1.1 TELESCOPE TOP LEVEL REQUIREMENTS

Operating Conditions (see LTS-54 for more details):

Temperature:	-3 to 17 C
Humidity	<90%
Wind	
(Enclosure)	12 m/s
(Telescope)	3 m/s
Zenith Angle	
(Observing)	20-3.5 deg
(Maintenance)	0-90 deg
Azimuth	+/- 270 deg
Altitude	2650 M

Support optical system.

M1M3	Held in optimum position by hexapod

M2	Actively aligned to M1M3 by M2 hexapod
Camera	Actively aligned to M1M3 by Camera hexapod
Light Baffling	Fixed to telescope

Allow removal of major optical systems as complete assemblies and allow access for maintenance.

M1M3 Cell.
M2 Cell.
Camera.

Provide for all typical telescope subsystems.

Cable drapes.
Mirror cover.
Balancing system.
Etc.

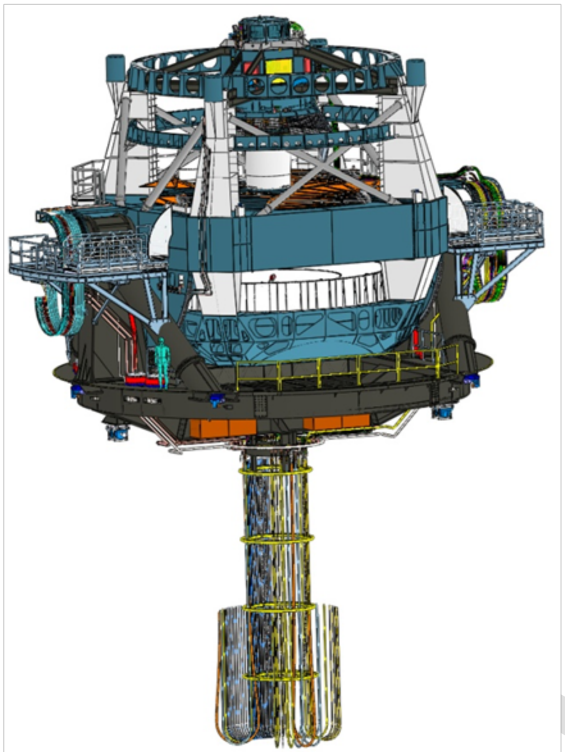
Meet demanding cadence for 10 year survey

Repoints 3.5 degrees (one field of view) in 5 seconds.

Meet image budget allocations (LTS-123).

1.2 TELESCOPE MOUNT ASSEMBLY (TMA) INTRODUCTION

The purpose of the Telescope Mount Assembly (TMA) is to acquire and track fields on the sky by providing motions about the azimuth and elevation axes, fig 1.2-1. A stiff compact TMA 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 settle by avoiding the excitation of the natural frequencies, document 8384. Passive reaction mass dampers, which increase the overall damping by 5% document-2328, will also be incorporated to help meet these dynamic requirements. The entire pier and mount assembly has been designed to have minimum variation in dynamic properties with azimuth and elevation angle to enhance the effectiveness of the advanced control system and the damping system. To minimize the variation as a function of azimuth angle, the azimuth drive system, an integral part of the mount, should be attached to the azimuth assembly rather than the pier.




Telescope Mount Only

Figure 1.2-1. Telescope (Left) Vs. Telescope Mount Assemble (right).

The TMA design, fig 1.2-1, is an altitude over azimuth welded and bolted assembly fabricated from mild carbon steel (A36 or equivalent). It includes all the moving mass excluding the three payloads which are optical systems 1: primary tertiary mirror (M1M3) cell assembly, 2: secondary mirror (M2) cell assembly and 3: the camera. The TMA does not include the optical positioning systems (M2 hexapod and camera hexapod/rotator assembly). However, the TMA does include TMA The baseline design incorporates all systems typical of astronomical telescopes and those unique to the LSST application. Whenever practical, off the shelf drive components are utilized that meet the performance requirements (SKF Hydrostatic Bearings (document-5643) and Kollmorgen Direct drive brushless DC motors (document 12077).

The unusual optical design of the LSST allows for a mount configuration with superior dynamic characteristics. By locating the M3 mirror within the M1 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. The enhanced stiffness increases the natural frequency reducing the settling time. The reduced moment of inertia also reduces the slewing power requirements. The high natural frequency also generally reduces the magnitude of vibrations regardless of the source.

Although the optical design is unique, the resulting TMA utilizes a conventional elevation over azimuth structural arrangement, fig 1.2-2. A single mirror cell supports the M1M3 mirror monolith. The top end assembly supports both the M2 assembly and the camera assembly.

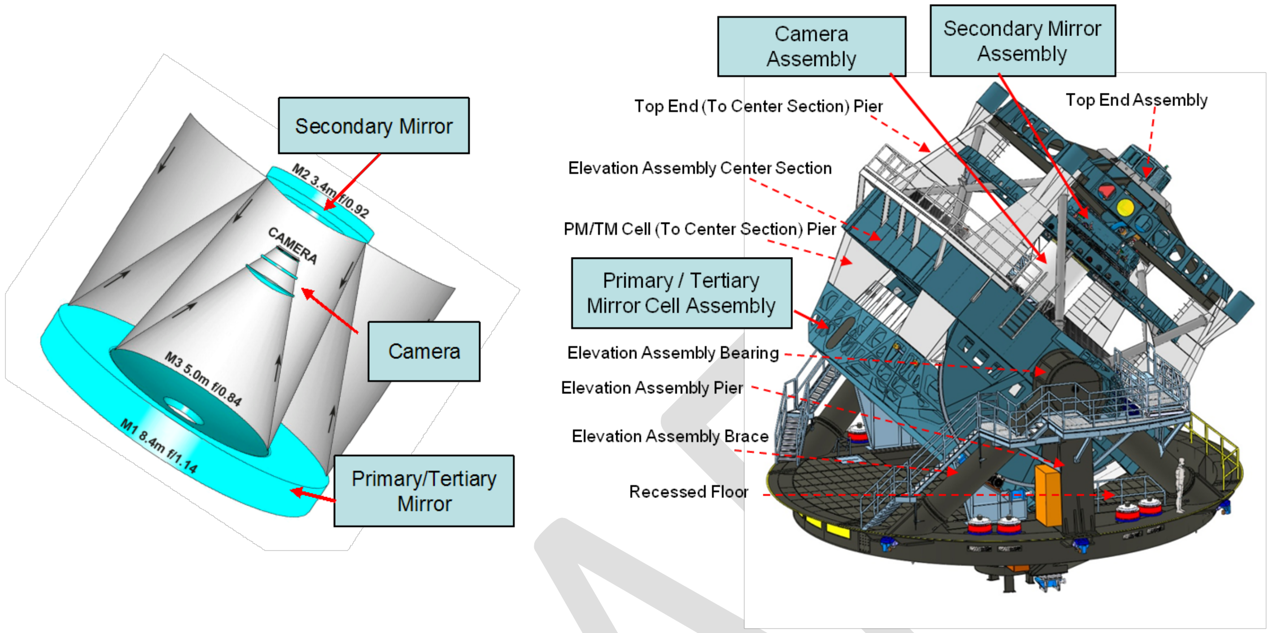


Figure 1.2-2. TMA Accommodation of Optical System.

The Telescope Mount Assembly (TMA), along with the rest of the telescope systems, receives its commands from the Telescope Control System (TCS). The TCS has both a fully automated mode for normal operations and a manual mode for maintenance and engineering.

As a result of the wide field of view, the optical system is unusually susceptible to stray light. Consequently, the TMA incorporates substantial light baffling and vanes, document 11524. However, the most important stray light mitigating element of the overall LSST facility is actually the rotating enclosure (dome). All the dome vents are covered with light baffles and only a minimal clear aperture is provided. The light baffles and vanes on the TMA are only designed to capture the stray light that enters through the dome's clear aperture.

To maximize the time available for observations, the telescope has been designed to minimize and facilitate maintenance. The mount design enables the installation and removal of the three optical payloads as complete assemblies for testing, servicing and recoating, fig 1.2-3. Platforms, ladders and stairways are provided to readily access all components which require servicing, fig 1.2-4. Deployable platforms are incorporated for accessing the camera and M2 optical surface while it is on the telescope. The mount structure has been designed to facilitate the replacement of critical camera components, while it is on the telescope, with the aid of the dome crane and the deployable platforms. The utility floor of the azimuth assembly is removable to provide crane access to the interior or the pier. Cut outs in the main ring of the azimuth assembly allow access to the azimuth drive main gear and brakes. The telescope design locates the M1M3 mirror cell walk-in port level with the telescope utility floor.

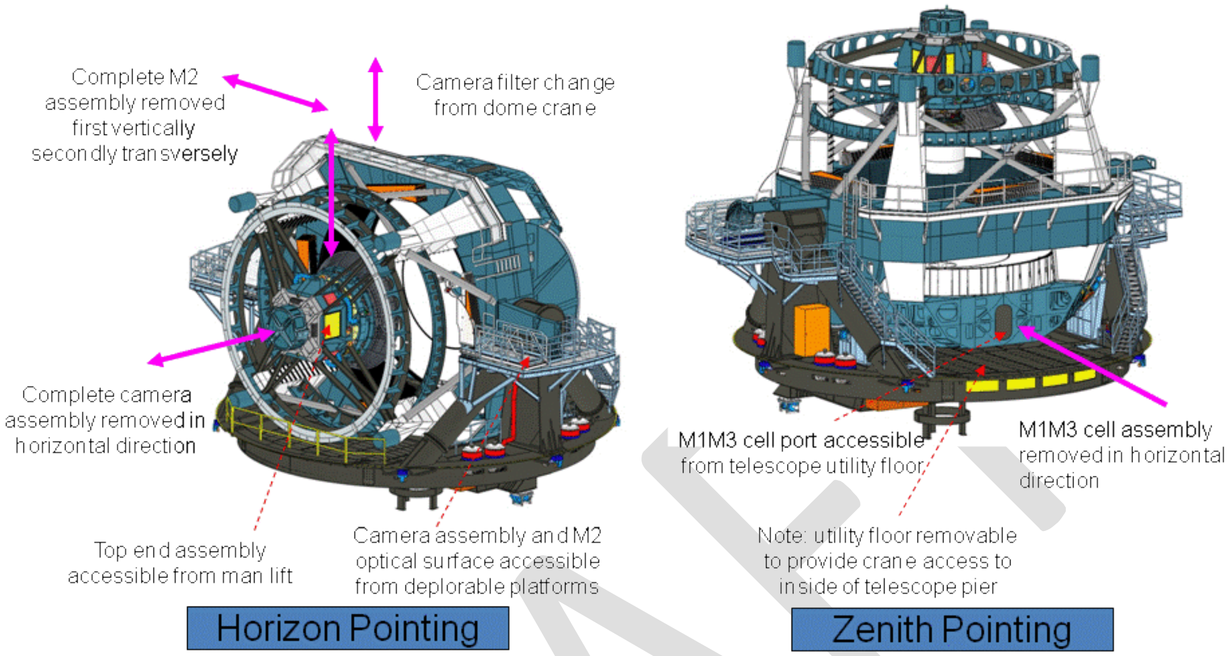


Figure 1.2-3. TMA Designed to Facilitate Maintenance.

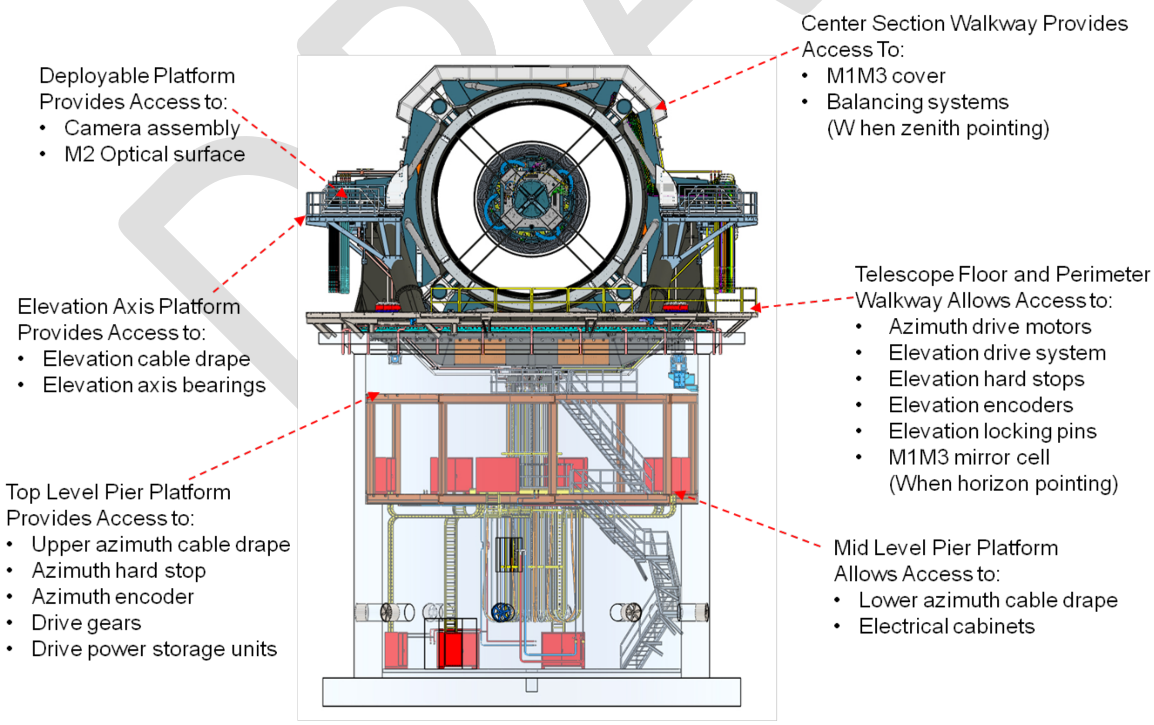


Figure 1.2-4. Platforms, Stairs and Ladders Provide Access to All Critical Components.

1.2.1 TELESCOPE MOUNT ASSEMBLY TOP LEVEL REQUIREMENTS

The detailed Telescope Mount Assembly (TMA) requirements are provided in LTS-103. All three optical systems must be readily removable/replaceable as complete assemblies, and be accessible while on the telescope for minor maintenance (M1M3 mirror cell assembly, M2 mirror cell assembly, Camera with hexapod and rotor). The TMA must possess all systems typical of a large telescope.

- Elevation bearings / drives / brakes / cable drape / stow pins /etc.
- Azimuth bearings / drives / brakes / cable drape / etc.
- Damping system
- Balancing system
- Controls
- Mirror cover
- Utility routing and cable drapes
- Maintenance accesses
- Safety systems (interlocks, etc.)
- Light baffling

It must also possess some unique systems that are required as a result of the LSST unusual optical design, and survey mission.

- Damping system
- Substantial Light baffling
- Deployable camera access platforms.

All this equipment must be readily accessible, easily replaceable, and require minimal maintenance.

The LSST telescope site, Cerro Pachón in Chile, is seismically active, Document-9651. Consequently, the telescope will be required to withstand substantial seismic accelerations.

1.2.2 TMA MOTION REQUIREMENTS

To maximize the time available for the actual exposures, stringent slew and settle time requirements were set for the LSST Telescope Mount Assembly (TMA). For both axes, the slew and settling time requirements were set at 4 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 was set aside for active optics convergence and camera initialization leaving 4 seconds available for slewing and settling.

The theoretical mount motion profile used by the telescope cadence simulator consisted of a 2 second motion profile followed by a 2 second settling time. Preliminary analysis demonstrated that the shortest overall slew and settling time occurs when the slew time and settling time are nearly equal. For this motion profile the acceleration is a simple constant magnitude step square wave (step). To ensure that the telescope mount meets the simulators predicted performance, the mount is required at a minimum to meet the theoretical step performance, document-7784

To minimize vibration excitation, the actual acceleration profiles of the mount will be "Jerk" limited. "Jerk" is the time rate of change in acceleration. Discontinuities in the acceleration produce infinite jerk, which tends 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. Furthermore, an optimum slew and settle is not produced by strictly delineated slew and settling times but by a smooth transition between the two. To allow for more realistic motions, the maximum allowable motions of the TMA were set with velocities and accelerations 50% higher than these theoretical step values. These increased values set the upper limits of the telescope motion. In practice the actual motions must be higher than the step values. Consequently the maximum allowable motions were set 50% higher than these values. The TMA control system must also produce these slews using an optimum trajectory while minimizing the excitation of the natural frequencies.

MAXIMUM ALLOWABLE MOTIONS

- Elevation axis motions (MAX)
  - Angular velocity: 5.25 deg/sec
  - Angular acceleration: 5.25 deg/sec^2
  - Angular Jerk: 21.0 deg/sec^3
- Azimuth axis motions (MAX)
  - Angular velocity: 10.5 deg/sec
  - Angular acceleration: 10.5 deg/sec^2
  - Angular Jerk: 42.0 deg/sec^3

MINIMUM REQUIRED

- Elevation axis motions (MIN)
  - Angular velocity: 3.5 deg/sec
  - Angular acceleration: 3.5 deg/sec^2
  - Angular Jerk: 14.0 deg/sec^3
- Azimuth axis motions (MIN)
  - Angular velocity: 7.0 deg/sec
  - Angular acceleration: 7.0 deg/sec^2
  - Angular Jerk: 28.0 deg/sec^3

The TMA is required to meet stringent pointing and tracking requirements without the aid of a fast steering or deformable mirror.

- Pointing: 1 arcsec RMS repeatability 0.2 arcsec RMS FOV offset
- Tracking: 0.1 arcsec rms / min drift

Stringent thermal control is required to meet the cadence without degrading the image quality by releasing heat (Typically 0.5 C > T > -1.0C), LTS-103 & LTS-106. Hexapods, which are not components of the TMA, are utilized to actively align the optical systems. This reduces the requirements of the TMA. However, the hexapods operate off of a Look-Up-Table. Consequently, the TMA must exhibit a high degree of repeatability for these hexapods to properly function.

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 ($\phi \rightarrow 0$), the sin 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 to 0.5, at 30 degrees zenith angle, the azimuth drives must produce twice the performance as the elevation drives. For azimuth motions, when the zenith angle is smaller than 30 degrees, the telescope mount will not be able to meet the 4 second slew and settling time allocation. 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 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.

Besides the rapid slew and settling time requirements, the telescope mount has stringent pointing and tracking requirements. The specific values are provided in the mount requirement document. These stringent requirements are the result of the wide field of view optical system which precludes the incorporation of a fast steering mirror. A fast steering mirror can normally be utilized to counteract moderate tracking errors.

Although observing will take place only between zenith angles of ~3 to 70 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.

1.3 OPTICAL SYSTEM INTRODUCTION

The LSST has a very unique, compact, optical arrangement, fig 1.3-1. The tertiary mirror (M3) resides within the 5-m diameter central hole of the primary mirror (M1). The two mirrors will be a monolith, sharing a single substrate which improves the stiffness. The 3.2 billion pixel camera (instrument) is positioned directly below and aligned with the secondary mirror (M2). Neither the optics, (M1M3, M2, camera) their support systems, their mirror cells nor their positioning systems (hexapods and rotator) are considered components of the TMA. However, the purpose of the TMA is to orient these optical systems to acquire and track fields on the sky by providing motions about the azimuth and elevation axes.

Figure 1.3-1 LSST Optical System.

The two mirrors utilize significantly different technologies. The M1M3 mirror is a Steward Optical Mirror Laboratory honey comb borosilicate spin casting, document-9689. The pneumatic mirror support system utilizes a set of 6 hardpoints (forming a hexapod) to position the mirror and 156 force actuators attached to various loadspreaders for figure control. The loadspreaders are attached to the flat M1M3 back plate and consist of 8 single, 30 dual, 114 triple, and 4 quad loadspreaders.

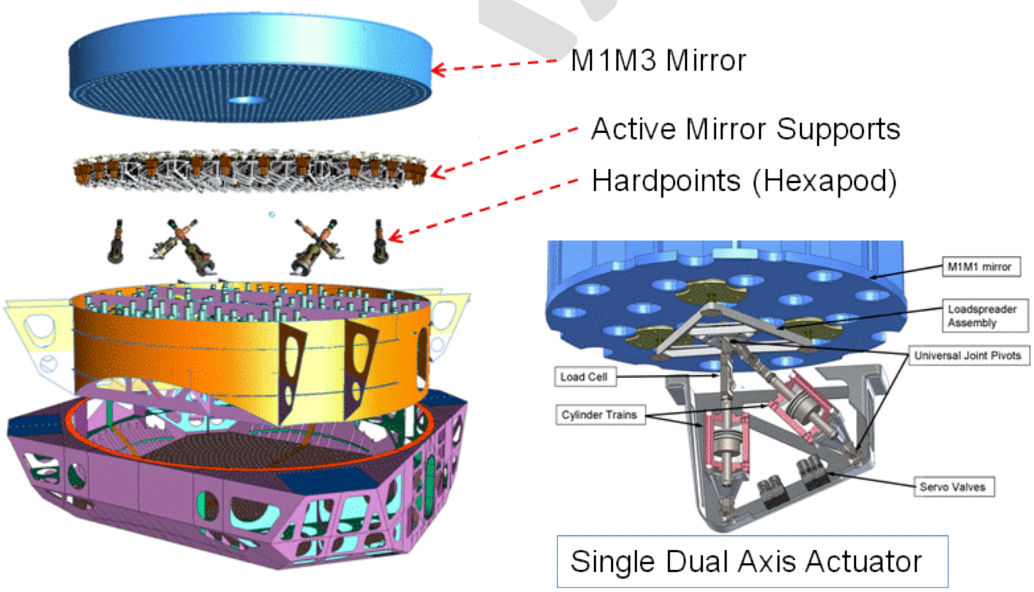


Figure 1.3-2. Primary/Tertiary (M1M3) mirror and support systems.

Since the borosilicate glass has a relatively high coefficient of thermal expansion for an optical glass, an extensive thermal control system is required to maintain the optical figure, document-7574. This system uses approximately 80 glycol/water supplied blower assemblies, fig 1.3-2, to supply temperature controlled air to the interior of the principally hollow cast borosilicate honeycomb mirror, fig 1.3-3.

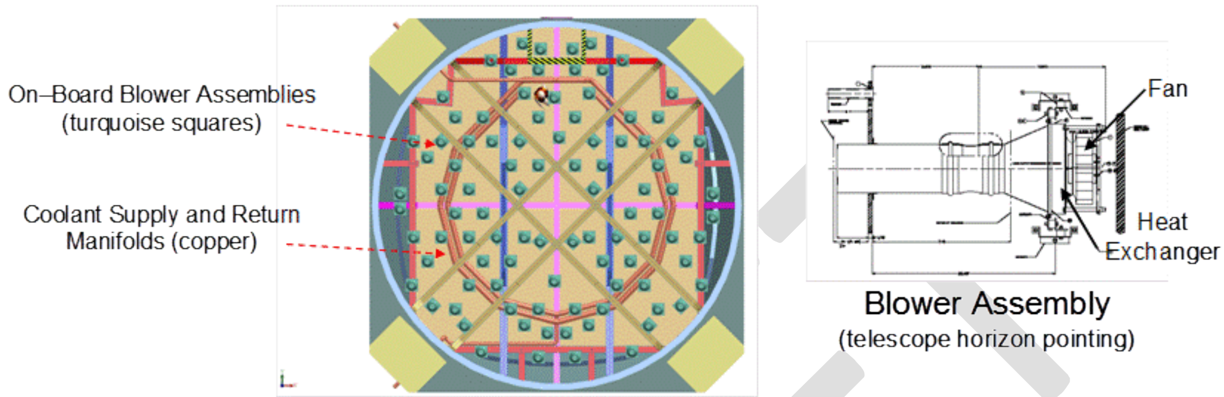


Figure 1.3-3. M1M3 blower assemblies.

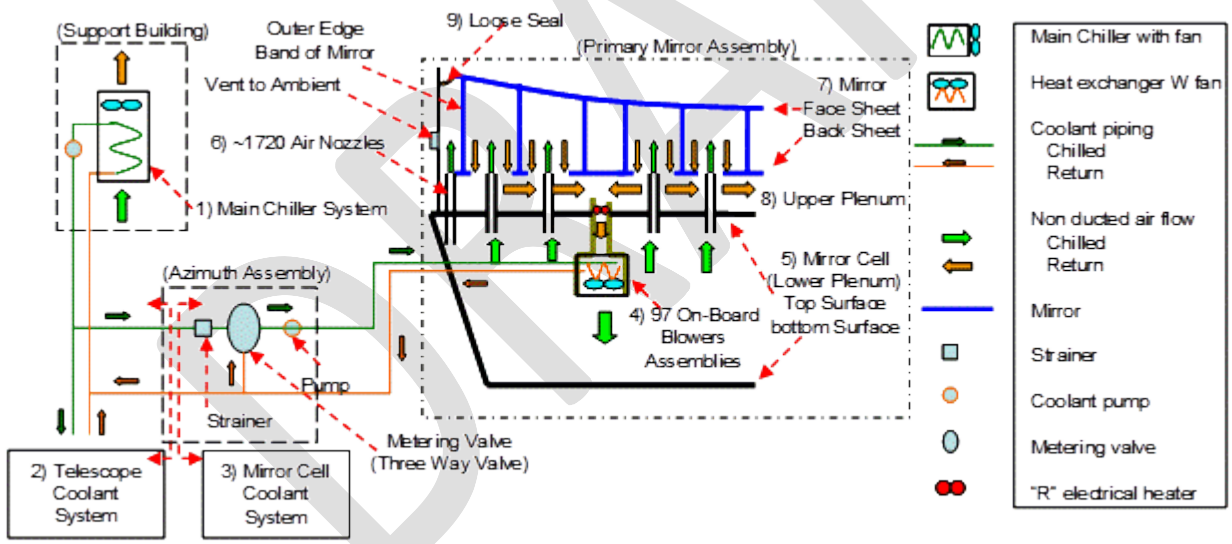


Figure 1.3-4. M1M3 thermal control system.

The M2 mirror uses a corning Ultra Low Expansion (ULE) meniscus substrate. This system uses electromechanical actuators to support the mirror, LTS-193. Separate systems of axial actuators and tangent links are used to provide axial and tangential support. Since the CTE of the ULE glass is two orders of magnitude smaller than the borosilicate systems, no thermal control is required of the mirror.

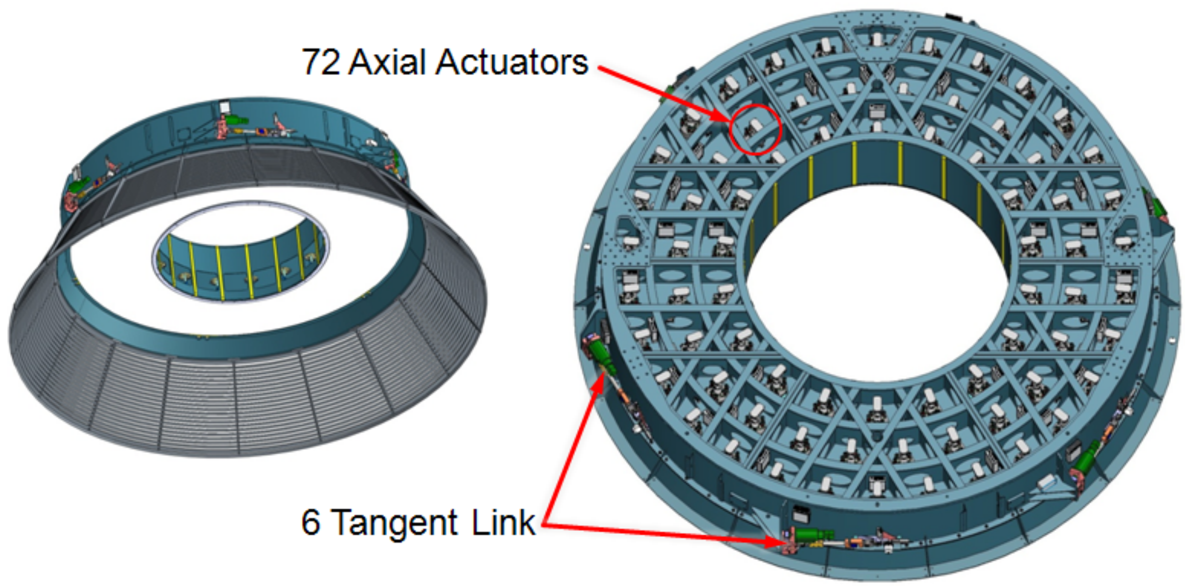
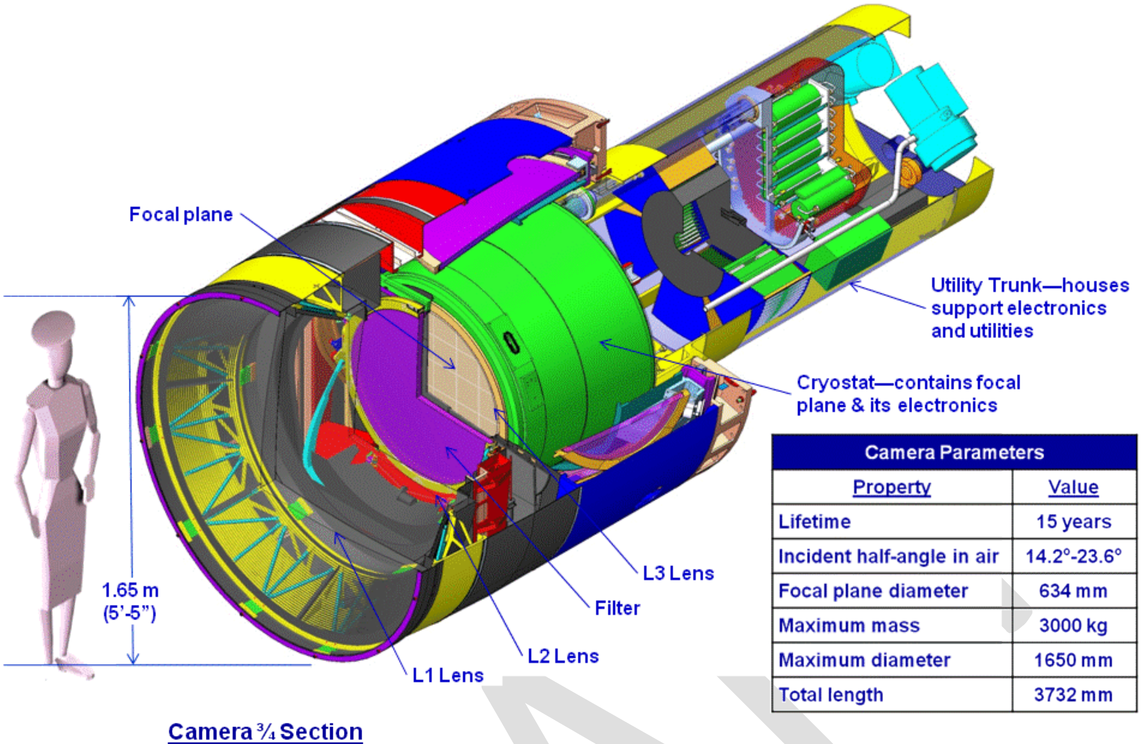


Figure 1.3-5. M2 mirror support systems.

The TMA provides routing for both the large quantity of compressed air required to operate the pneumatic support system and glycol/water required to operate the thermal control system of the M1M3. Since it requires neither compressed air nor glycol/water cooling, the TMA does not provide these utilities to the M2 mirror cell assembly. It does provide for the routing for the communication and power cabling required to operate both the M1M3 systems and the M2 systems.

Unlike most astronomical telescopes, the LSST only utilizes a single camera, fig 1.3-6, document-11431. This camera uses three lenses to direct the light path onto the 634 mm diameter, 3.2 Giga pixel detector plane. To allow operation at cryogenic temperatures, the detectors and their electronics are housed in a cryostat. A utility trunk at the back of the camera, which protrudes through the hexapod/rotator assembly, houses the support electronics and utilities. To allow for surveys in multiple wavelength bands, the camera holds up to 5 optical filters that can be interchanged automatically. To add versatility, these filters can be replaced without removing the camera from the telescope. The mechanical shutter, which is expected to be the most high maintenance component of the camera, can also be replaced without removing the camera. To attenuate stray light, light baffling rings are included within the lens assembly.



Camera Parameters	
Property	Value
Lifetime	15 years
Incident half-angle in air	14.2°-23.6°
Focal plane diameter	634 mm
Maximum mass	3000 kg
Maximum diameter	1650 mm
Total length	3732 mm

Figure 1.3-6. Camera Configuration.

Both the pneumatic support system of the M1M3 monolith mirror and the electromechanical support system of the M2 mirror will be used for active optical figure control. Both the M2 Cell Assembly and Camera utilize hexapods to facilitate optical positioning relative to the M1M3 Mirror, and a rotator resides between the Camera and its hexapod to facilitate tracking, figure 1.3-7. To produce a more structurally efficient configuration, the camera hexapod and camera rotator will be produced as a single assembly (Camera Hexapod/Rotator Assembly), document-13998. The requirements of the M2 Hexapod and Camera Hexapod are very similar; consequently to facilitate maintainability both hexapods will utilize identical actuators.

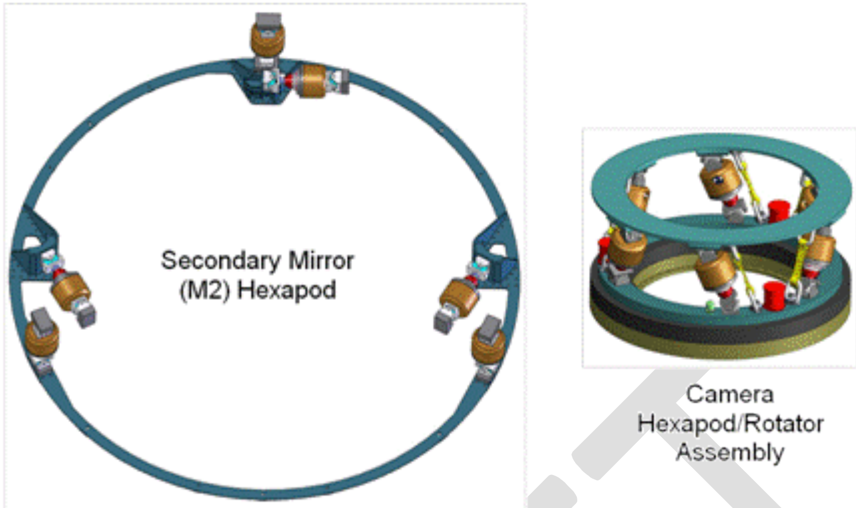


Figure 1.3-7: LSST M2 Hexapod and Camera Hexapod/Rotator Assembly

Both sets of active supports and both sets of hexapod are principally operated off of a look-up table (LUT). Since these systems principally function to counteract the changing distortions produced by changes in the gravitational orientation, the principal input parameter of the LUT is the elevation angle. For these systems to function adequately, the TMA must exhibit a high degree of repeatability (minimal hysteresis). These systems also utilize offsets to the LUT provided by the wave front sensor systems of the camera.

2 TELESCOPE MOUNT ASSEMBLY DESIGN

The telescope mount assembly (TMA) is an altitude over azimuth welded and bolted assembly fabricated from mild steel, A36 or equivalent. It supports the primary/tertiary (M1M3) mirror cell assembly, the secondary (M2) mirror cell assembly and the camera. Both the camera assembly and M2 mirror cell 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 hexapods and rotators are not considered components of the TMA. The secondary mirror assembly and camera do not interface directly to the TMA but rather their hexapods do.

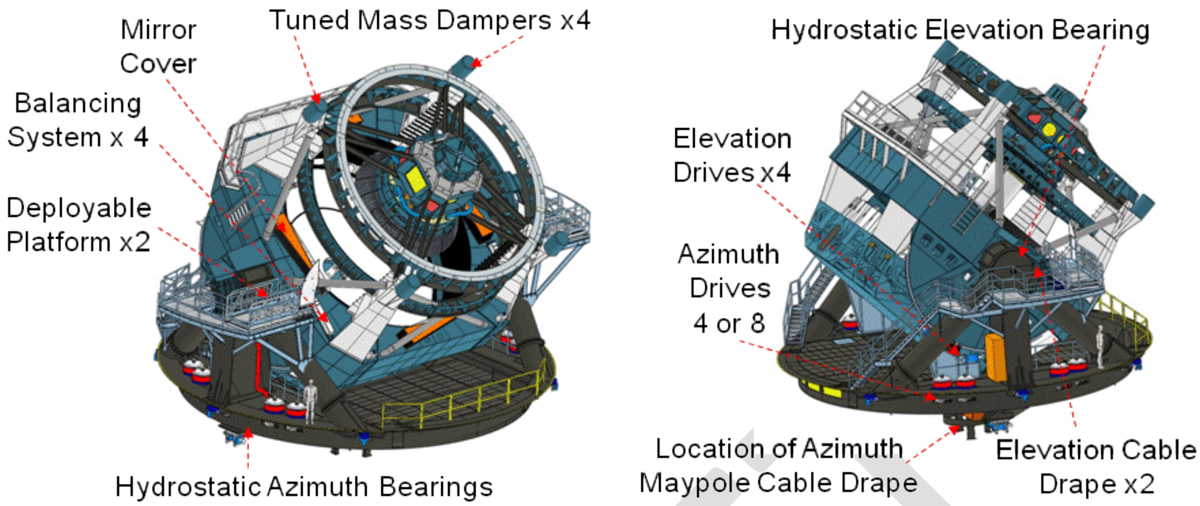


Figure 2-1: LSST Telescope Mount Assembly Overview.

The LSST mount incorporates 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 a safety system. Figure 2-1 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. Accessing the camera for servicing 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.

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.

2.1 DESIGN ENVELOPE AND INTERFACE

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. In a co-rotating configuration the azimuth motions of the telescope and the rotation of the dome are locked together. For a telescope with a high aspect ratio elevation assembly, co-rotation can utilize a more compact dome. However for the compact LSST telescope design, co-rotation would produce minimal reduction in the dome size.

Freeing the dome and the telescope azimuth rotations facilitates maintenance, calibration and thermal control. It also reduces the motion demands of the dome. A large gantry crane rides on the dome. Since the dome and telescope are not locked together, the crane can access any location inside the dome relative to 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. 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, document-2580.

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, fig 2.1-1, document LTS-105. The telescope mount assembly must stay within this envelope while moving through the full range of elevation axis, and while accommodating the envelopes of its three optical payloads: M1M3 mirror cell assembly, M2 combined assembly and camera. It must also accommodate the hexapods and rotator that control the position of the M2 mirror cell assembly and camera.

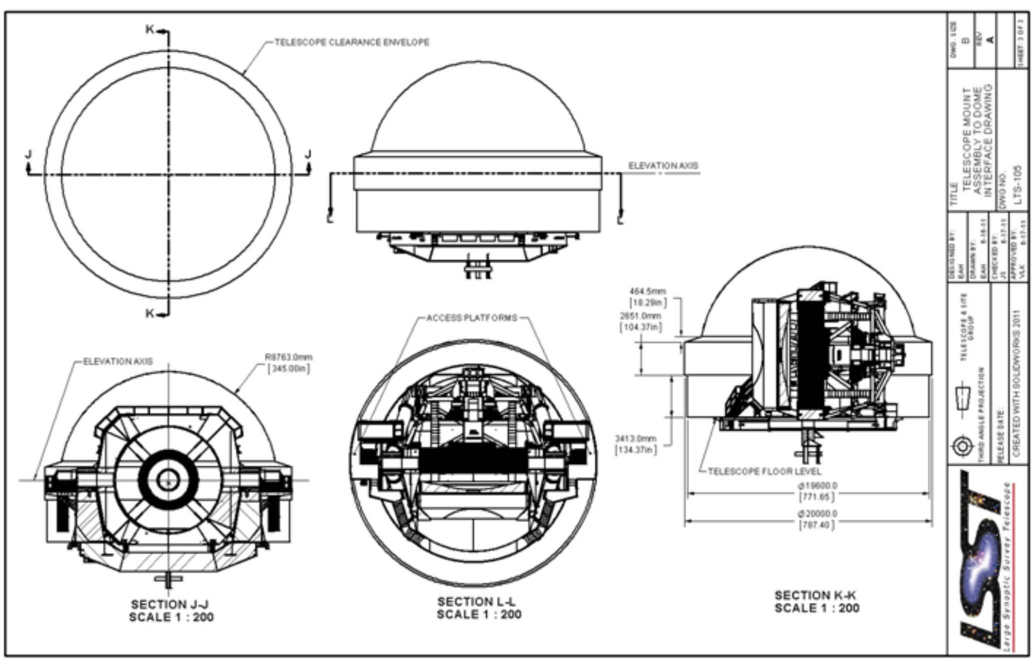


Figure 2.1-1: LSST Telescope Mount Assembly (with payloads) Design Envelope.

Although there are many interfaces that the TMA must provide for the various payloads, utilities and maintenance equipment, the principal physical interface of the TMA to the observatory is its pier, LTS-77. The baseline is for the TMA to utilize a hydrostatic bearing for its azimuth motions. The bearing track design was appropriated from the Gemini Telescope. The resulting interface between the TMA and the observatory is the bolting interface that attaches this hydrostatic bearing track to the telescope pier.

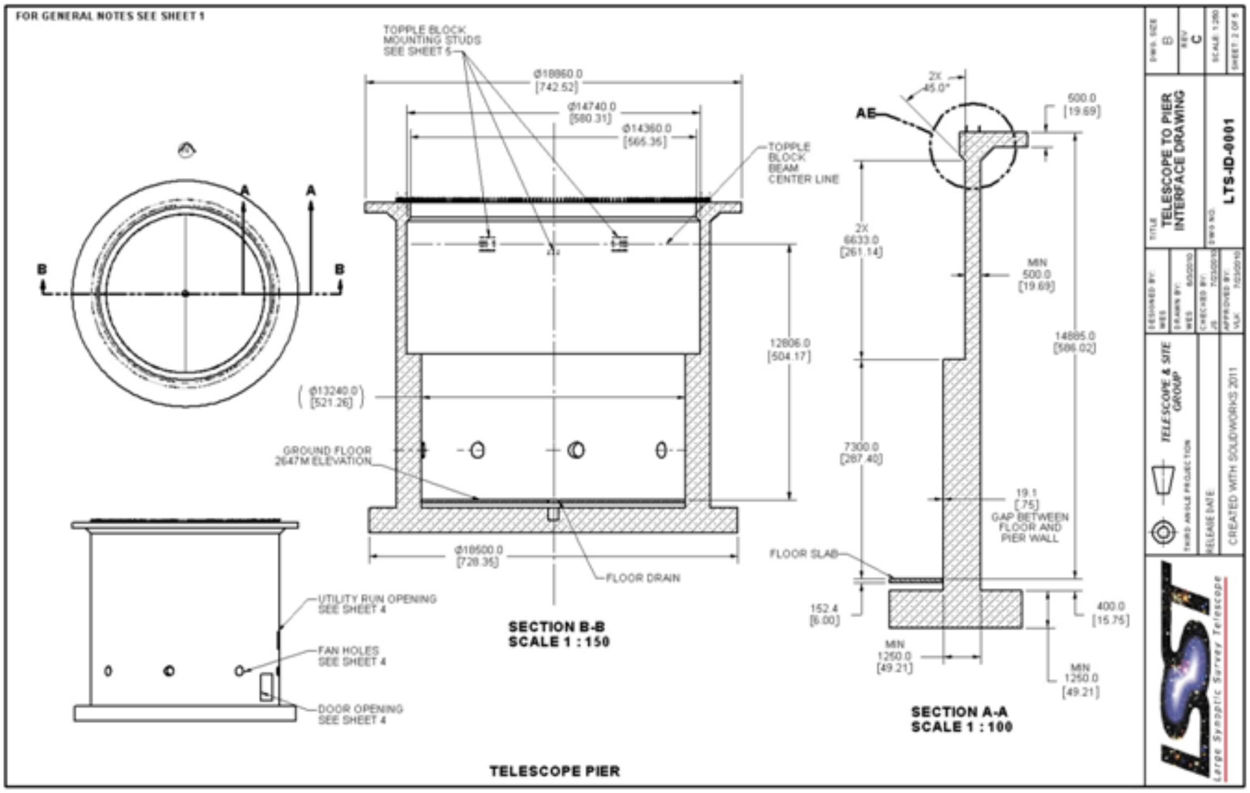


Figure 2.1-2: LSST Telescope Mount Assembly to Pier ICD.

To facilitate alignment, the bearing race is not in direct contact with the concrete pier. As shown in the above figure, two circles of threaded anchor bolts are imbedded in the pier top. The track is initially supported on nuts installed on these bolts. The nuts are turned to change the local bearing track elevation and load distribution. Once the track is properly located, a second set of nuts from the top is used to lock the track in place.

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. 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 topple blocks which interact with the azimuth hard stops requires its own mounting interface also provided in LTS-77. The azimuth encoder tape system will be attached to the pier. However, since this is a very low load item, the interface bolts can be added as needed after the pier construction and are not included in the interface document.

Note: This document presents the baseline design of the LSST mount. The contractor who produces this mount will be responsible for the final design of the azimuth bearing and drive system. Substantial variation between this baseline and the final design may occur.

2.2 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 2.2-1. 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		
W20% 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 2.2-1. LSST mass and inertia, with 20% structural added mass (Values Out of Date).

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.

2.2.1 ELEVATION ASSEMBLY

To minimize motor/ brake torque requirements and to reduce the risk of runaway motion, the elevation assembly axis must align with the center of gravity (CG) of the comprehensive elevation assembly, fig 2.2.1-1. 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. The actual elevation bearing shaft is offset from the center of the elevation axis to utilize some of the center section mass to balance against the M1M3 mirror cell assembly, and to increase the gap between the M1M3 mirror surface and the center section to aid in natural air convection.

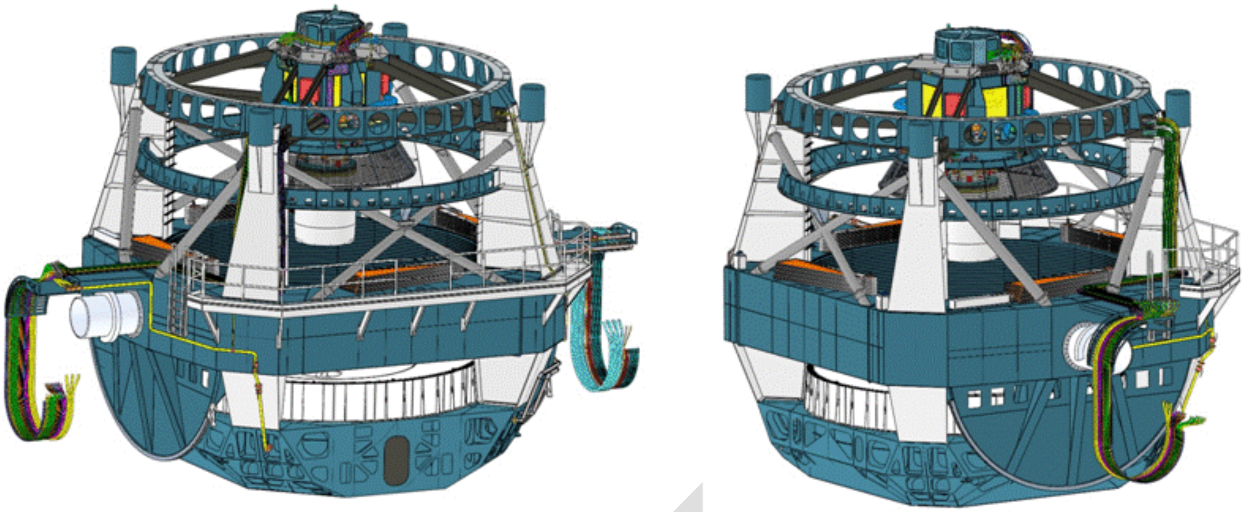


Figure 2.2.1-1. Elevation Assembly (with Cabling)

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. Rectangular cut outs were incorporated to aid in the natural air convection over the M1M3 mirror surface.

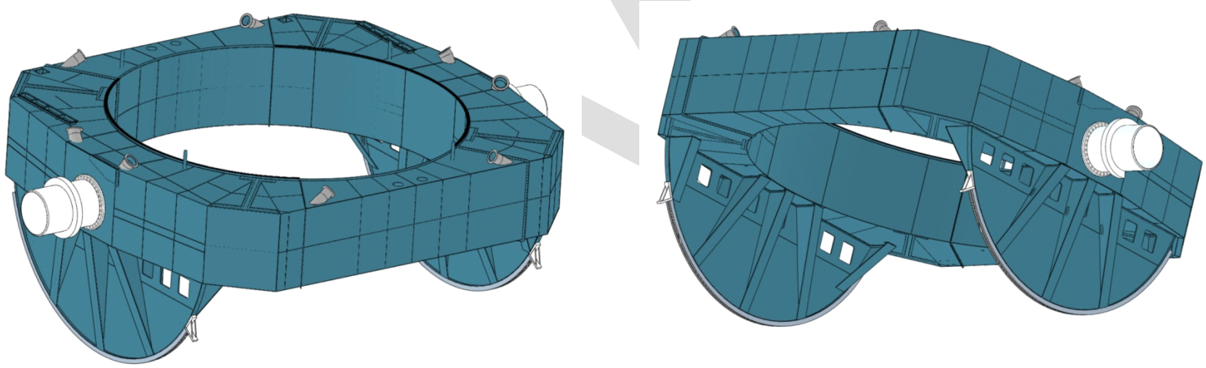


Figure 2.2.1-2. Center Section w Drive Wheels.

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.

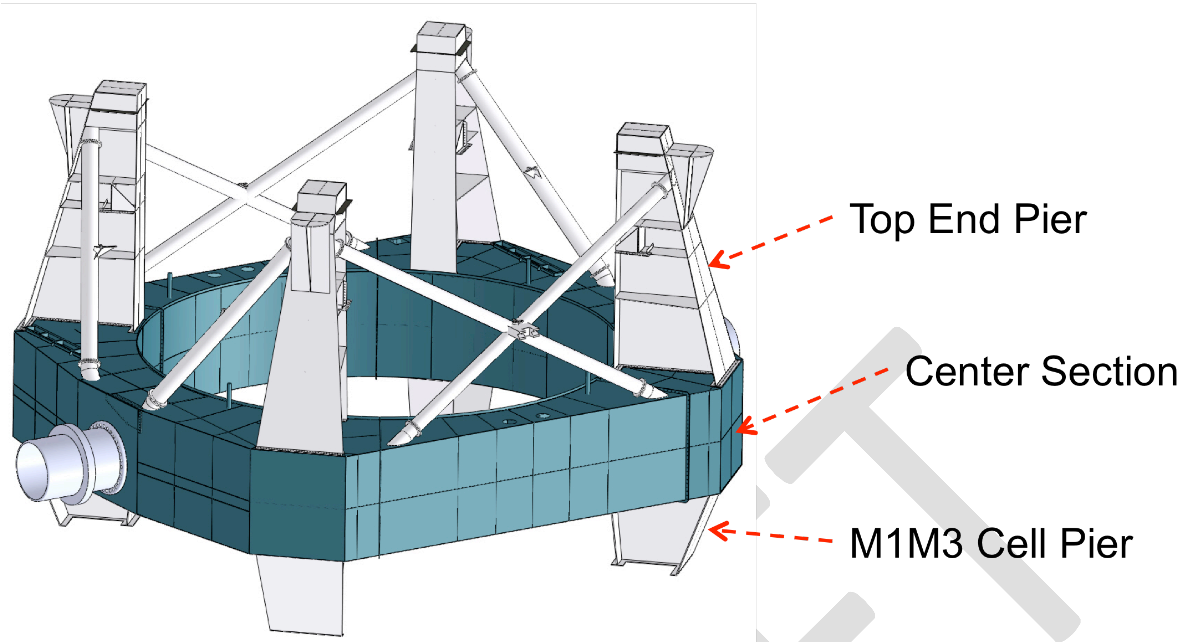


Figure 2.2.1-3. Elevation Assembly Center Section with Piers.

The top end assembly (TEA) is also supported by four TEA piers, which are aligned with the M1M3 piers, fig 2.2.1-3. As a result of their much longer 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. Bracing in the direction perpendicular to elevation and optical axis 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 over an "X" brace. This "V" brace configuration also allows for the incorporation of the deployable platforms that provide access to the camera and M2 optical surface.

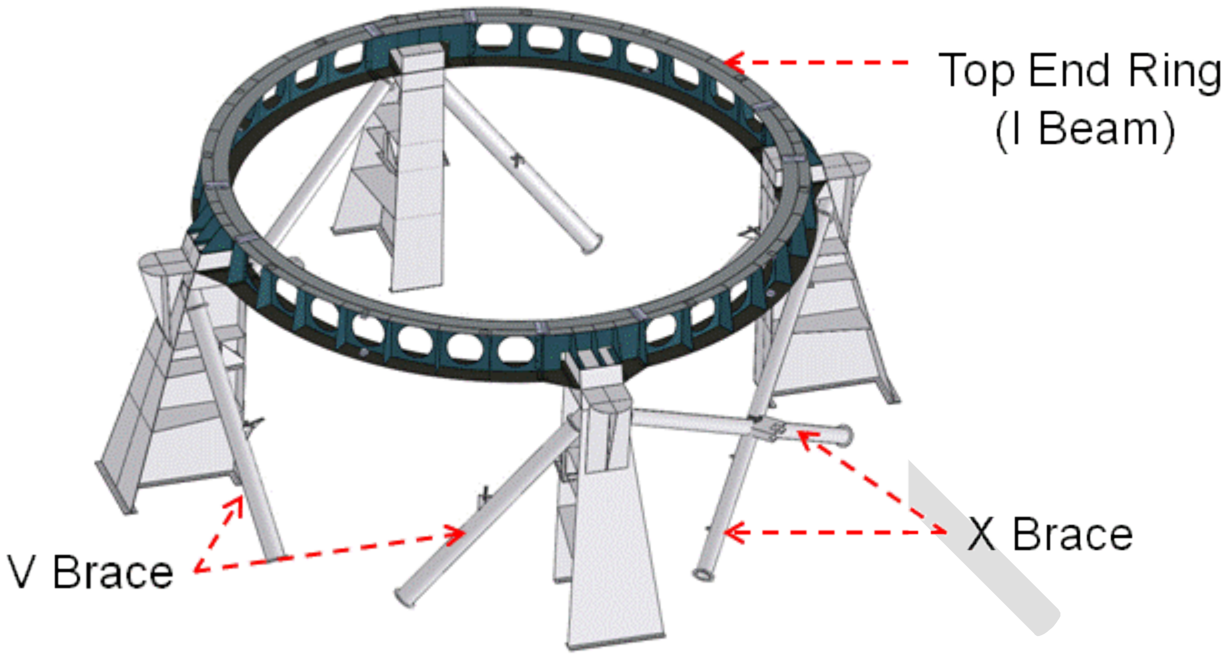


Figure 2.2.1-4. Top End Assembly Structure, TEA Ring, TEA Piers and TEA Braces.

The ring of the top end assembly (TEA) is required to transversely stabilize the tops of the four TEA piers. Since two light baffles were also required at this location, an "I" beam configuration was used to fulfill both requirements simultaneously. The two "I" beam flanges functions as the two light baffles. Another mid-level baffle is required between the center section and the top end ring. However, this is a non-structural member and fabricated from sheet metal. 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, which was chosen as a balance between structural efficiency and optical degradation, is described in detail in the Top End Assembly section of this document.

2.2.2 AZIMUTH ASSEMBLY

The azimuth assembly both supports the elevation assembly and provides for the rotation about the gravitational vector, fig 2.2.2-1. 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.

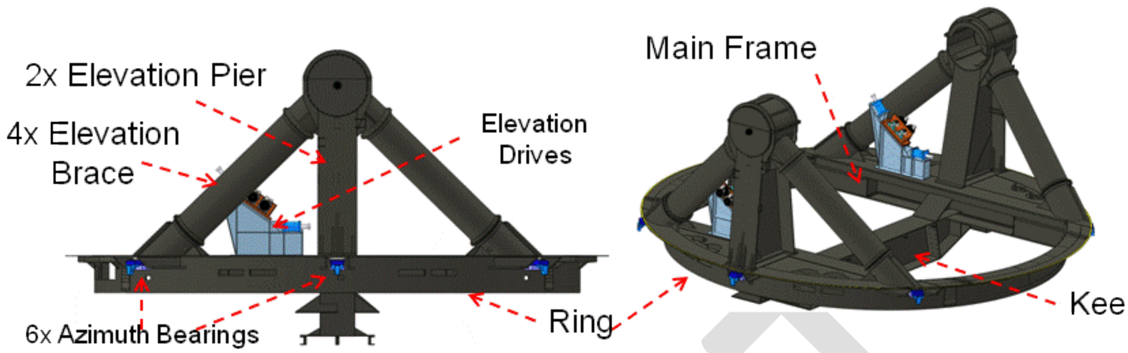


Figure 2.2.2-1. Azimuth Assembly Structure With azimuth bearings and elevation drives.

The azimuth structural assembly must both allow for the elevation axis motion and the removal of the M1M3 mirror cell assembly. This limits the location of the azimuth bearing set end of the braces. Locating them farther from the pier would increase the structural efficiency; however, this would interfere with the above functional requirements. Consequently, to provide adequate support in the direction along the elevation axis, a keel was incorporated connecting the two piers.

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, this height was reduced by approximately 1 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 approximately 16 meters. This large diameter pier also significantly increased the overall telescope and pier assembly stiffness.

An azimuth ring was required to support the floors, support the azimuth drives, and counteract the twisting of the two tripods described previously. Although this is a continuous ring, it 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 to support the floors. These cutouts also provide access to the main gear and brake disk for inspection, maintenance and repairs.

The above described azimuth assembly would have inadequate stiffness between the two tripods without the associated flooring. This flooring, described in the flooring section, was designed to the manufacturing flooring standards and is required both structurally and for maintenance.

2.2.3 MANUFACTURING AND SHIPPING

Both the elevation and azimuth structural assemblies were designed to facilitate manufacturing and shipping. All structural components are designed to 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. Both the azimuth and elevation structural assembly were designed to be fabricated in sections that fit through the tunnel on the roadway leading to the site. This tunnel is the limiting obstruction for component transportation, LTS-54. It was specifically enlarged to accommodate the 8 meter class Gemini telescope. The two largest items that will require shipping are the M1M3 mirror in its shipping container and the M1M3 cell. Both of these components are larger than any component of the TMA.

For the elevation structural assembly, all eight piers bolt onto the center section, fig 2.2.3-1. The top end ring is constructed of four sections that bolt to the top end piers, fig 2.2.3-1. All sixteen spiders and all eight of the TEA braces bolt into place.

The center section itself is fabricated in several sections that bolt together. Each of these components can readily be shipped to the site.

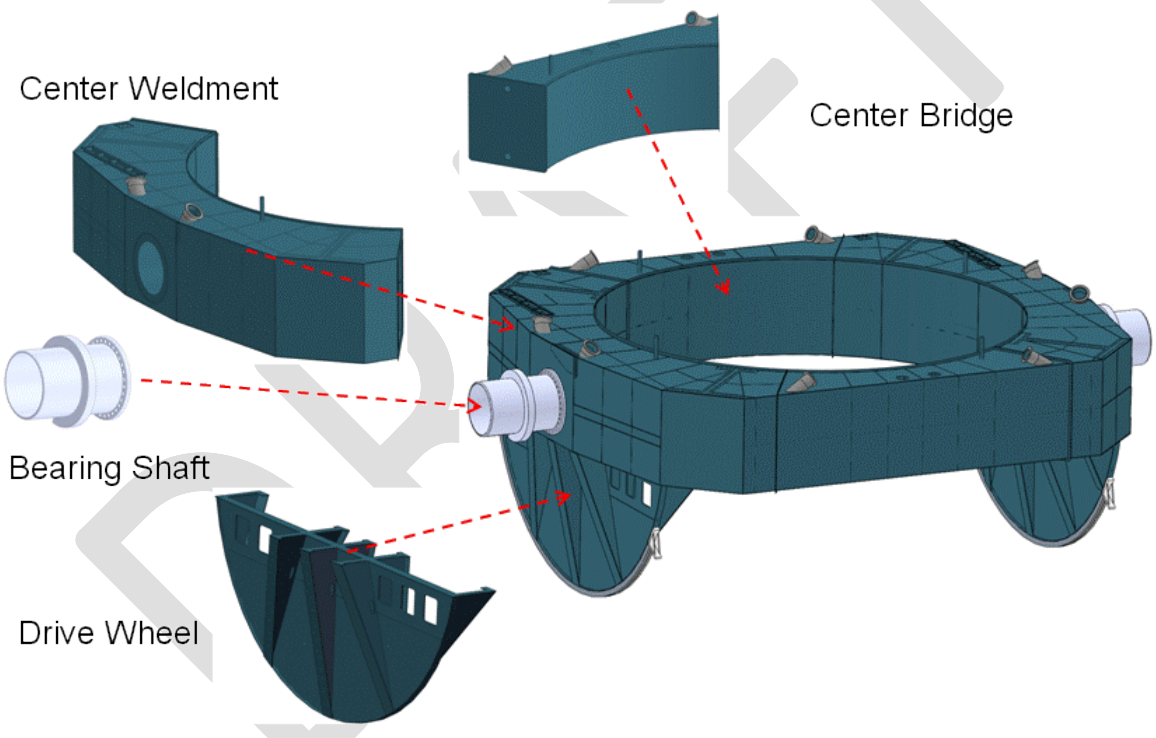


Figure 2.2.3-1. Elevation Center Section Components.

The azimuth assembly has two main weldments that function as the base of the two tripods. These weldments contain the main frames and sections of both the keel and ring, fig 2.2.3-2.

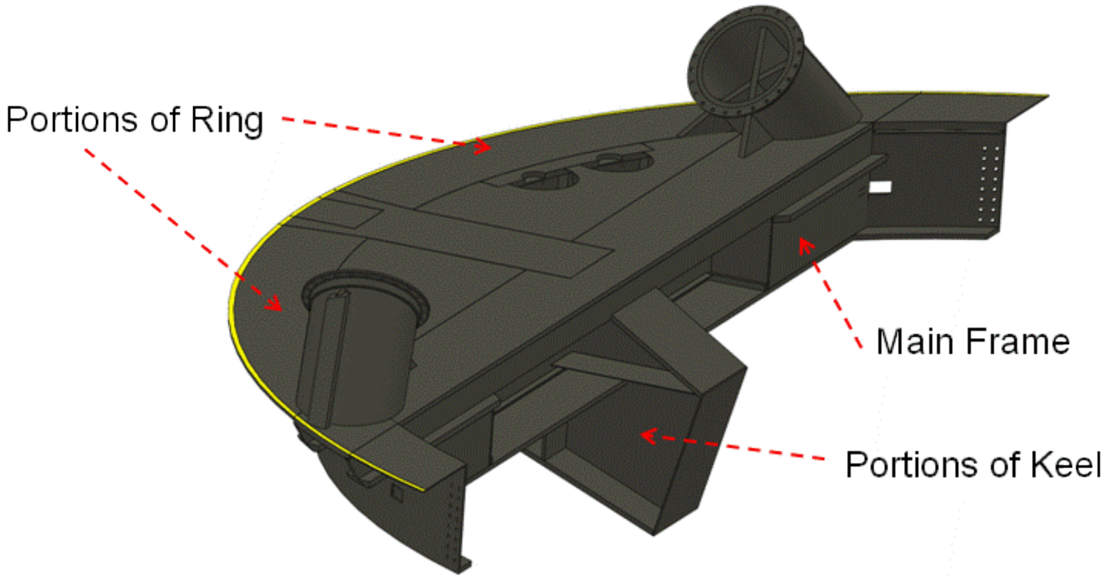


Figure 2.2.3-2. Main Weldment.

The two sections of the azimuth ring, the center of the keel and the flooring that span between the two weldments are all fabricated separately and are all bolted into place. The elevation piers and the braces are also fabricated separately and bolted into place.

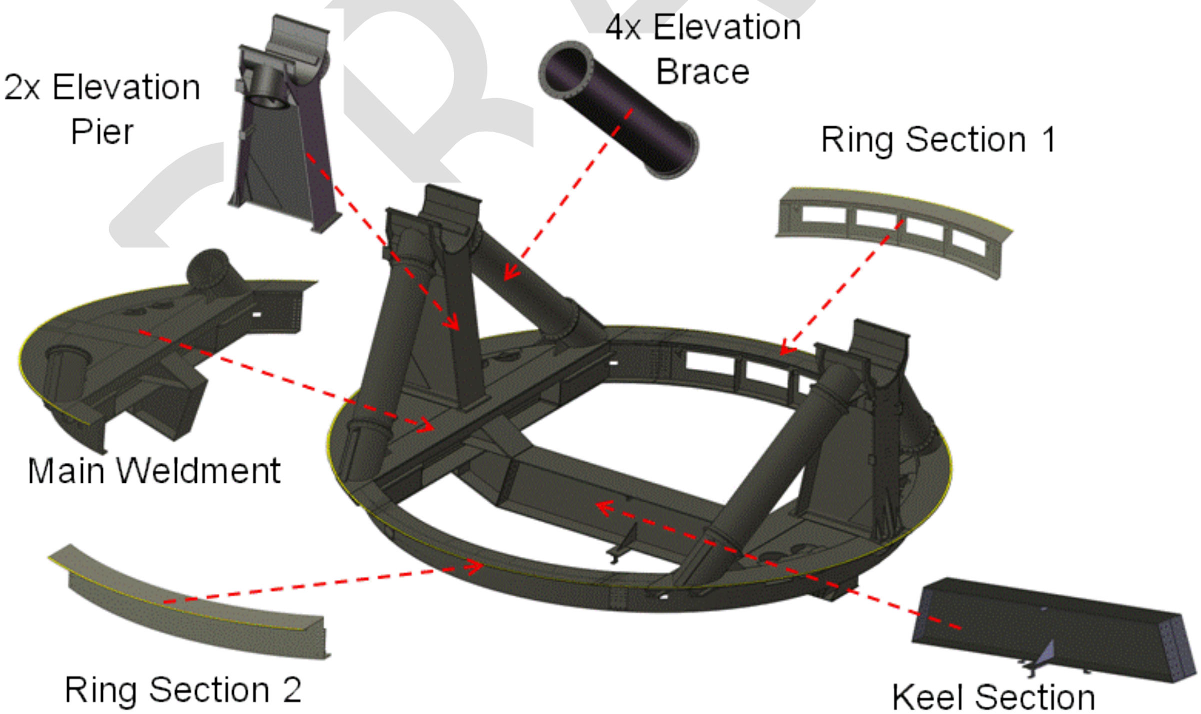


Figure 2.2.3-3. Main Structural Components of Azimuth Assembly.

2.3 BEARINGS

The baseline is for the LSST to utilize hydrostatic bearings for both the azimuth and elevation axes, document 5643. These types of bearings can provide the stiffness, lifetime, and smoothness required for the LSST operation, fig 2.3-1.

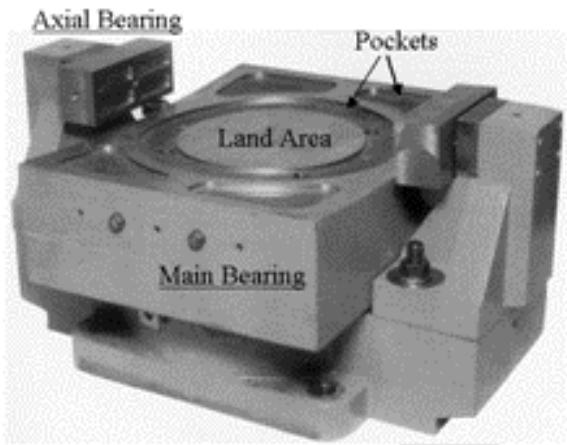


Figure 2.3-1. Typical Hydrostatic Bearing.

For the structural analysis, bearing stiffness provided by a hydrostatic bearing manufacturer were assumed, table 2.3-2, However, these values had minimal effect on the natural frequencies of the telescope structure. Adequate system stiffness may be achievable 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 2.3-2. LSST drives and bearing stiffness

The azimuth axis utilizes 6 bearing assemblies, fig 2.3-3. 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.

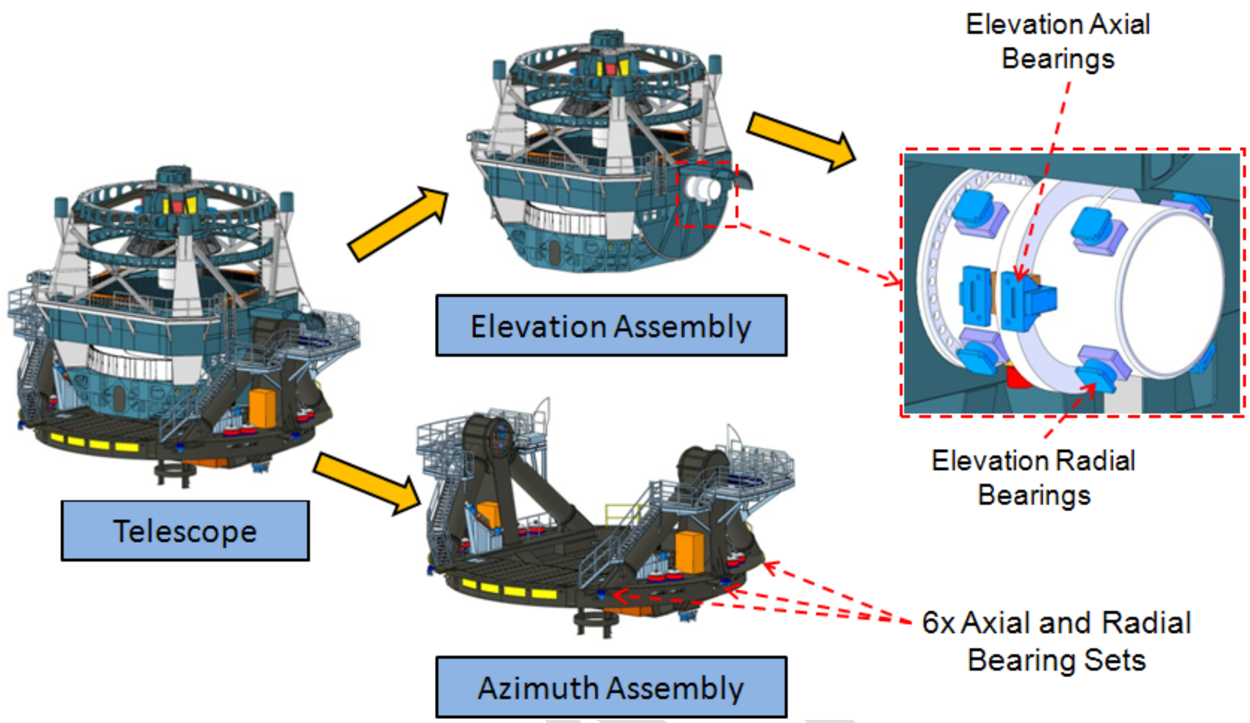


Fig. 2.3-3. Hydrostatic bearing configuration and locations on the TMA

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 bearings on top of the axis increases 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.

Note: Although the baseline is to use the hydrostatic bearing arrangement presented earlier, rolling element bearings may be substituted by the mount vendor for either the elevation axis or the azimuth axis. Hydrostatic bearings were chosen for the baseline because: 1) they have historically been successfully utilized for this type of application, 2) mass and stiffness information was readily available, and 3) hydrostatic bearings require more utility support in the way of pumps and piping, consequently a hydrostatic bearing mount design can readily be modified to utilize rolling element bearings. If the baseline mount was designed for rolling elements, it would be difficult to incorporate hydrostatic bearings. The present facility design has all the utilities required to support hydrostatic bearings which include the hydrostatic oil pump, oil tank and the associated piping.

2.4 DRIVES SYSTEM

For the structural analysis, drive stiffnesses utilized by other telescope projects were assumed, table 2.3-2 above. However, the TMA structure was designed such that the drive stiffness was not the predominant flexibility source. Consequently, moderate deviation from these stiffnesses should not have significant effect on the overall system performance and should have minimal effect on the natural frequencies of the telescope structure. For both the elevation axis and the azimuth axis, the baseline drive system is for direct drive motors to operate pinion/gear systems, fig 2.4-1, ref Document 9485. 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.

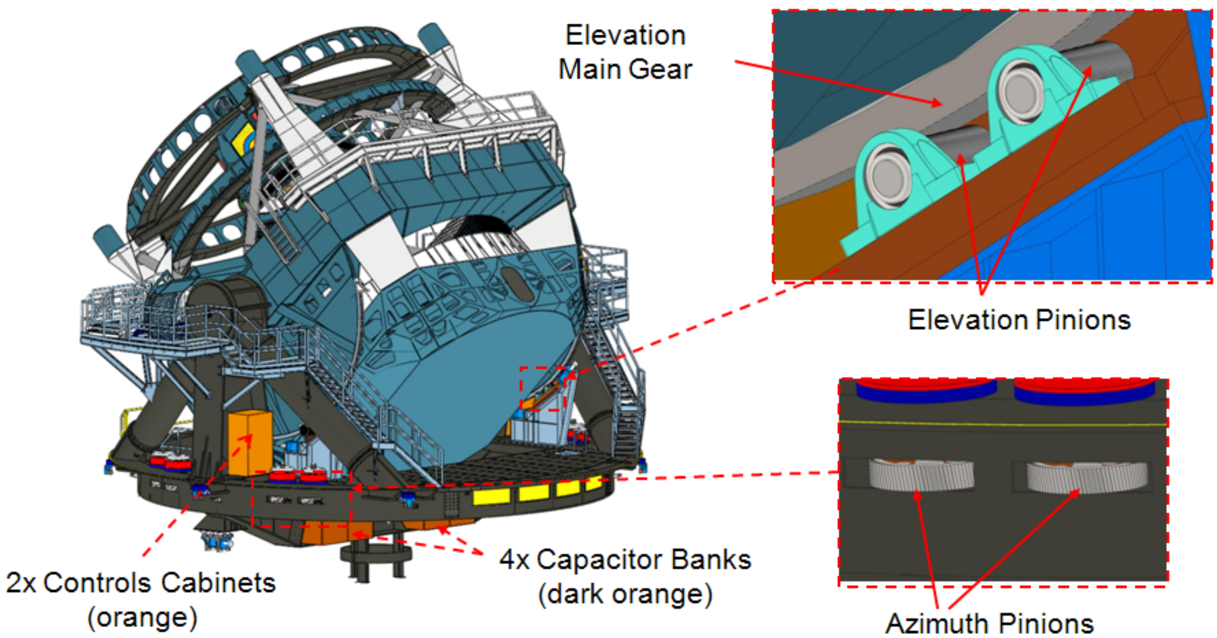


Fig. 2.4-1. Drive System Components

As a result of the rapid acceleration and deceleration of the telescope mount, the inertial effects produce the principal drive loads. Utilizing direct drive motors significantly reduces the rotational inertia load. The motor inertia affects the overall inertia relative to the square of the speed ratio of the drive motor to mount axis. Consequently, if more traditional high speed motor and reductions gear systems were used, a large portion of the motor power would be required to overcome its own inertia.

Even though utilizing direct drive motors significantly reduces the power requirements, substantial motor power is still required (~400 hp azimuth and 30 hp elevation). These power requirements can be met by existing motors available through Kollmorgen, Document 14354.

- Baseline Motors:
  - Azimuth: 8xKBM-260X04 (450 Hp Total)
  - Elevation: 4xKBM-163X02 (28 Hp Total)

For both axes, the motors are arranged to operate in pairs. During slewing, the motors all operate in unison. During tracking, the motor pairs counteract each other to minimize back lash. The elevation axis utilizes four motors. One motor pair is associated with each side of the elevation axis.

For the baseline, the azimuth axis uses eight motors arranged in four pairs of motors. The large number of motors was chosen for greater motor availability and to reduce the pinion size. If only four motors are used, each pinion must transfer twice the power. This requires a larger diameter pinion and a significantly greater motor torque. The combination of the doubled power and increased pinion diameter increases by approximately a factor of four the motor torque requirements which significantly restrict motor availability. If direct drive motors are available with the necessary torque and speed rating for the actual TMA design, it is likely that a four motor system will be substituted.

For the azimuth axis, the 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 control systems and damping systems.

For the elevation axis, the direct drive motors are attached to the azimuth assembly and act on large drive wheels attached to the center section of the elevation assembly center section. A direct drive system acting directly on the axial shaft is more commonly utilized for this type of application. However the shaft drive configuration would significantly reduce the natural frequencies of the telescope. The drive wheels were sized such that the drive system was not the major flexibility source of the system. A shaft drive system with comparable stiffness would require an excessive shaft diameter near that of the drive wheel diameters of the baseline design.

For the elevation axis, since helical gears produce significant axial thrust, the gears on these wheels are double helical. Double helical gears are two adjacent gears with opposite slants. Consequently the axial thrust produced by the two gears cancels and no net thrust is produced. If standard helical gears were utilized, they would produce significant deformation on the drive wheel since they are relatively flimsy in the transverse direction.

As a result of the 30 year design life and the high duty cycle, large diameter pinions are required, document-9485. If the 4 direct drive motor azimuth option is utilized rather than the 8 motor option, twice as much power would be transmitted through each pinion. The combination of the doubled power and increased pinion diameter would greatly increase the motor torque requirement for this option.

- Elevation: 7.0”
- Azimuth(4 drives): 27.2”
- Azimuth(8 drives): 13.1”

For both axes, since the pinions are directly attached to the motor shaft, the motor and pinions will be installed (and removed) as a single unit. The motor/pinion unit configurations have been designed to facilitate replacement. Although the elevation assembly prevents accessing the azimuth drives with the overhead crane, these units can be accessed from the fixed perimeter walkway that surrounds the main floor of the telescope. Since these units are similar in size and mass to an automobile engine, an engine lift (an A frame) can be used to lift and remove the drives. The elevation drives are easily accessible and as a result of their relatively small size can be removed directly by personnel.

2.4.1 DRIVE CONTROL SYSTEM

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, fig 2.4-1. One controller is used for each half of the TMA and operates half the elevation and azimuth motors.

2.4.2 DRIVE CAPACITOR BANK

As a result of the large quantity of power required to accelerate the mount, all the motors are regenerating. Deceleration is provided by the same motors, and the energy is stored in a large capacitor bank, document-12077. If regenerative braking was not used, the power demands would be too large for the utility lines to the telescope facility and excessive image degrading heat would be produced. As discussed in the thermal management section, the motors are also cooled by the glycol/water thermal control system.

The DC capacitor bank (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 the regenerative braking by reabsorbing the regenerated energy for reuse instead of dissipating it in form of heat. This also reduces total energy consumption and thermally induced image degradation.

The capacitor bank is large, heavy, produces heat, and is potentially hazardous; consequently it is located at the bottom of the TMA, below the floor, on the keel that connects the two halves of the azimuth assembly, fig 2.4-1. 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.

The capacitor bank will require significant 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, the ambient air will be blown into the cabinet and then the air will be exhausted through a heat exchanger. Although it is more difficult to control the air temperature with this method, since the cabinet is below the azimuth floor it can be overcooled without degrading the image quality. The overcooled air will sink into the pier and not float into the optical path.

2.5 BRAKES

Although the TMA will utilize regenerative braking in normal operation, for safety the TMA must also have a separate power off braking system for both axes. This system stops the telescope in the event of a drive system failure or power interruption. Since the payloads of the TMA are only designed to operate at the maximum drive accelerations, the braking system has the same deceleration requirements as the drive system.

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.

Since the braking deceleration requirements are identical to the drive deceleration requirements, the braking torque can be safely provided through the motor's gear systems. Since the drive system uses multiple drive motors, the loss of a single motor/brake system would only minimally reduce the overall braking capacity. This allows for the removal of a single motor/brake system for maintenance. Since they would only need to resist static force, the remaining motor/brakes would provide adequate holding torque.

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

2.6 CABLE WRAPS AND ROUTING

Three cable wraps are required to operate the telescope. Although they are commonly referred to as cable wraps they are used to route all types of utilities.

These cable wraps include the azimuth wrap, elevation wrap, and camera wrap. All three cable wraps are considered components of the Telescope Mount Assembly (TMA). These wraps provide for the routing of power cables, communication lines, coolant flow, and compressed air, LTS-217. The coolant lines include both the glycol/water mixture used as the main coolant for the telescope and facility as well as the cryogenic refrigerant used for the camera. The cryogenic refrigerant lines are expected to be the largest, heaviest, and least flexible of these utility lines. All of these types of utility lines will be referred to in this document as cables.

The rigid lines between the cable wraps are very long lasting and low maintenance. The flexible lines traversing through the cable wraps have limited life spans and will need replacing. Consequently, all refrigerant and compressed air lines have shut off valves at both ends of each cable wrap. This facilitates replacement of these items.

A large quantity of glycol/water coolant is required to flow through both the azimuth and elevation cable wraps. The coolant is required to support the M1M3 thermal control system as well as the TMA drives and capacitor bank. The piping main for this system will have approximately a 2-1/2" diameter. It is impractical and undesirable to route such a large flexible line through a cable wrap. Consequently, the single main is divided into three 1-1/2" lines. If a single line develops a leak it can be shut off and the system can continue to operate but at a reduced capacity.

2.6.1 AZIMUTH CABLE WRAPS

Two type of azimuth cable wraps are commonly used for large ground based telescopes. These include the powered cable chain design and the maypole design. For the power chain, the utility lines are run though a power chain that slides on a horizontal surface. A drive system is required to move the power chain. For a maypole design the utility lines hang down from the bottom of the moving telescope in a circular maypole configuration. The other end of the lines are attached to an elevated stationary floor. 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.

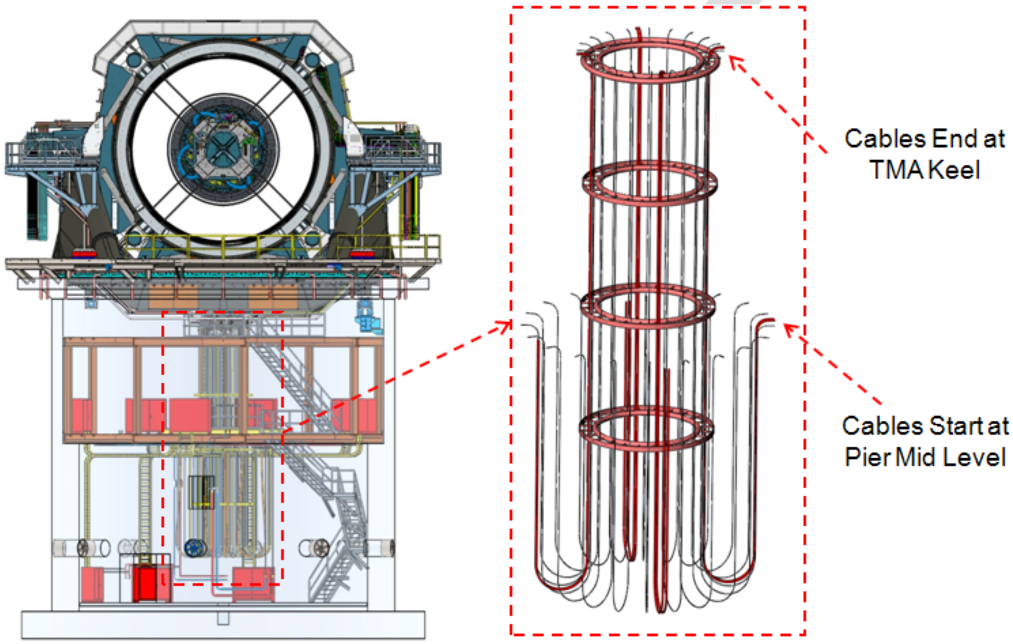


Fig. 2.6.1-1. Azimuth Cable Drape.

There are two other large telescopes located near the LSST site: Gemini and SOAR. The Gemini Telescope utilizes a power chain design and the SOAR utilizes the maypole design. The maypole design is simpler, cheaper, and has been found to be more reliable. The Gemini power chain has been problematic, while the SOAR system has functioned without incident.

The rapid motions of the LSST TMA are also of concern relative 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 SOAR. Its largest and least flexible refrigerant lines are also comparable to the LSST. This cable drape has also operated without incident.

The LSST telescope pier has been designed to accommodate a maypole type azimuth cable drape, fig 2.6.1-1. The pier has two elevated floors, one directly below the telescope and one at the piers mid level. Both floors have circular holes to allow for the maypole. The top floor provides access to the end of the cables attached to the telescope. The mid level floor provides access to the fixed end of the cables. In general, the utilities routed to the pier go directly to this mid level floor. The mid level floor is high enough to provide for the necessary hanging cable section. The ground floor is slanted toward the center of the pier where a catchment is located to contain any leaks or coolant or hydrostatic oil.

The baseline design is to use hydrostatic bearings for both azimuth and elevation motions. Since these bearings are attached to the azimuth assembly, the azimuth cable wrap must also support the hydrostatic bearing oil supply lines. The hydrostatic bearings use a gravity return system that need not traverse through the cable drape. A tray around the azimuth bearing catches the oil escaping from the azimuth bearings. The return from the azimuth assembly discharges into this tray.

2.6.2 ELEVATION CABLE WRAPS

Since the elevation axis only makes a 90 degree motion, the baseline design for the elevation cable wrap uses a simple non powered cable drape system, fig 2.6.2-1. One end of the cables 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 under the effect of gravity and sufficient flexible cable is provided to allow the necessary motion. 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.

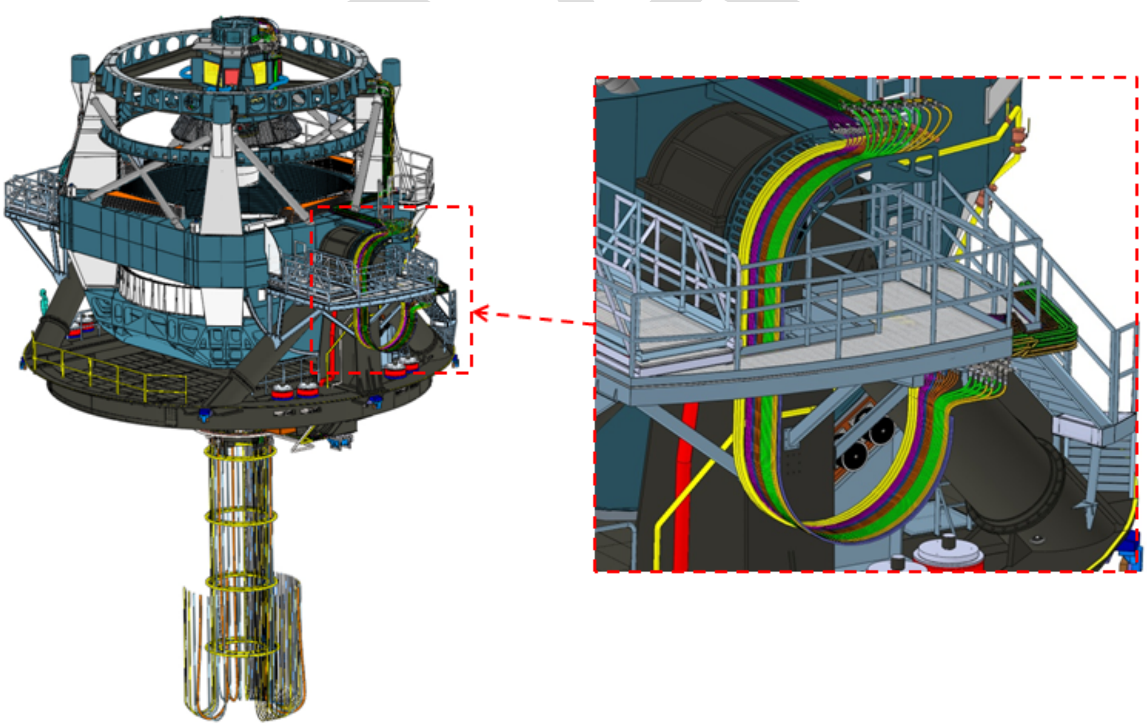


Fig. 2.6.2-1. Elevation Cable Drape

2.6.3 CAMERA CABLE WRAPS

Unlike the azimuth and elevation assemblies which utilize simple passive drapes, the camera cable wrap requires a powered cable chain, document-12460. As the elevation angle changes, the orientation of gravity relative to the cable wrap system changes. This precludes the use of any cable drape systems that requires gravity to control the cables.

As a result of its location on the top end assembly, significant limitations exist on the size and location of the camera cable wrap, fig 2.6.3-1, document-12460. 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 assembly as a single unit. This is described in detail in the top end assembly section.

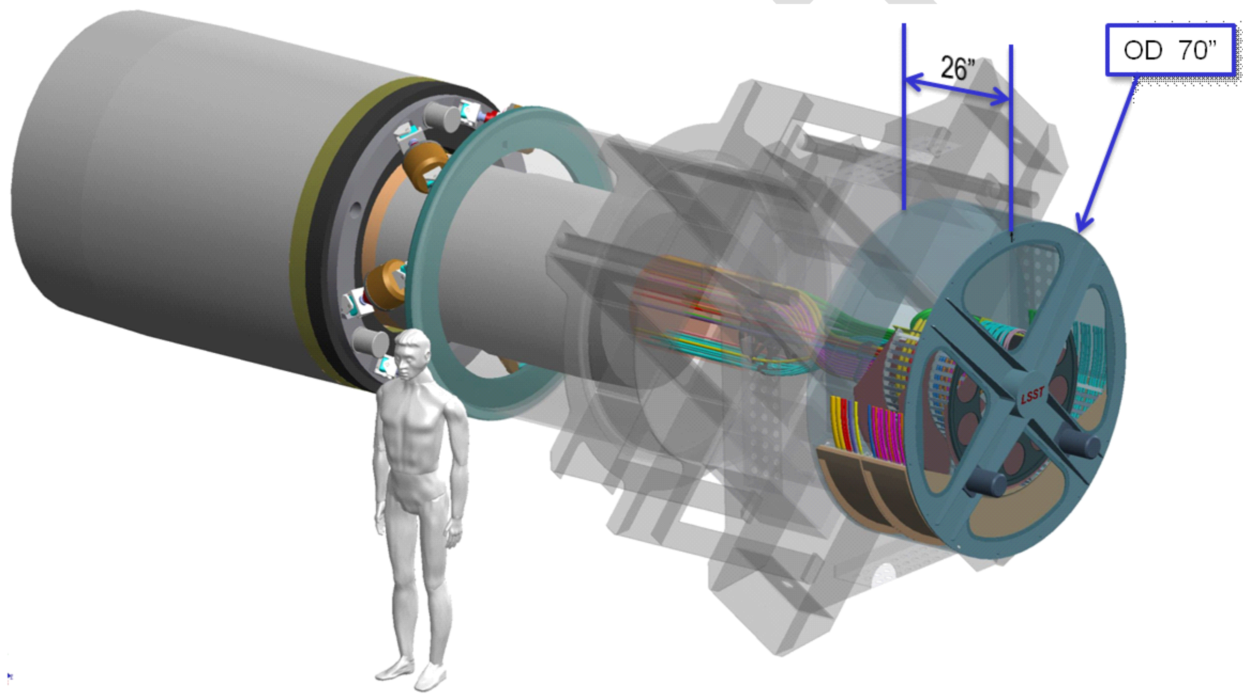


Fig. 2.6.3-1. Location of Camera Cable Wrap.

The camera lift fixture, which is used to install the camera support assembly on the telescope, attaches to the integrating structure adjacent to the camera cable wrap assembly further limiting its design envelope, fig 2.6.3-2.

The camera cable wrap employs four cable chain assemblies arranged in a rotary fashion within the cable wrap drum to handle all the relative rotation travel needed, fig 2.6.3-2 document 12460. 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.

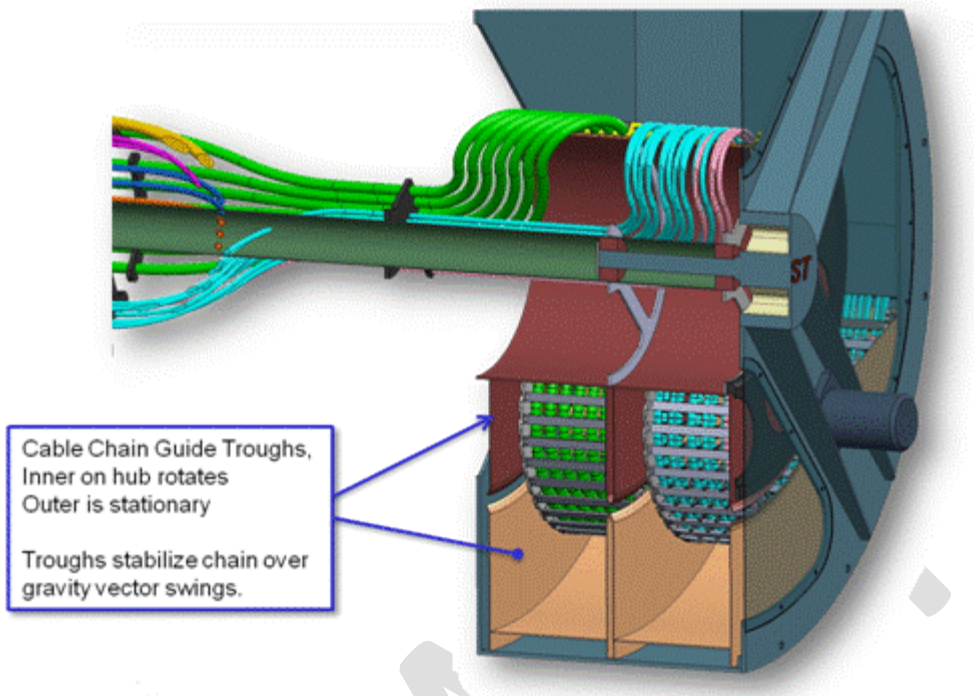


Fig. 2.6.3-2. Section View of Camera Cable Wrap.

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.

Cable guides fixed to a torque tube running down the rotation axis from the hub secure the lines between the hub and camera. This design includes a dedicated active drive unit to offload cable wrap drive torque from the camera and rotator.

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 provided excellent cable organization.

To minimize the effects of a possible disorientation between the camera rotator and the camera cable wrap, a safety pull cord is provided. The pull cord is attached between the camera and the rotating portion of the camera cable wrap. If the camera and camera cable wrap do not move in unison the cable is pulled which activates a safety switch cutting power to both the rotator and cable wrap. For the pull cord to properly protect the cables there must be less slack in the pull cord than any of the cables; consequently, there is a turn buckle in line with the safety switch to allow for adjustment.

In addition to the pull cord, both the rotator and camera cable wrap have torque limiting to limit the cable tension. The maximum torque the drive systems can generate is limited. Consequently, even if the control systems fail and the pull cord fails, it is unlikely that the cables will be damaged.

The camera cable wrap is expected to require a significant amount of maintenance relative to the rest of the camera support assembly. Consequently, it is located on the outermost location of this assembly where it can be readily accessed by a scissor-lift with the telescope at horizon pointing.

2.6.4 CABLE ROUTING

Besides the cable wraps discussed previously, the baseline design of the TMA contains routing for all the major utilities (cables), fig 2.6.4-1, document LTS-217. All the power, communication, coolant, refrigerant, and compressed air up to the 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 drape. From the elevation cable drape, 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 to the TEA cross the optical path through the hollow spiders to the central assembly of the top end assembly. The cables for the various components leave this main route along the way as necessary.

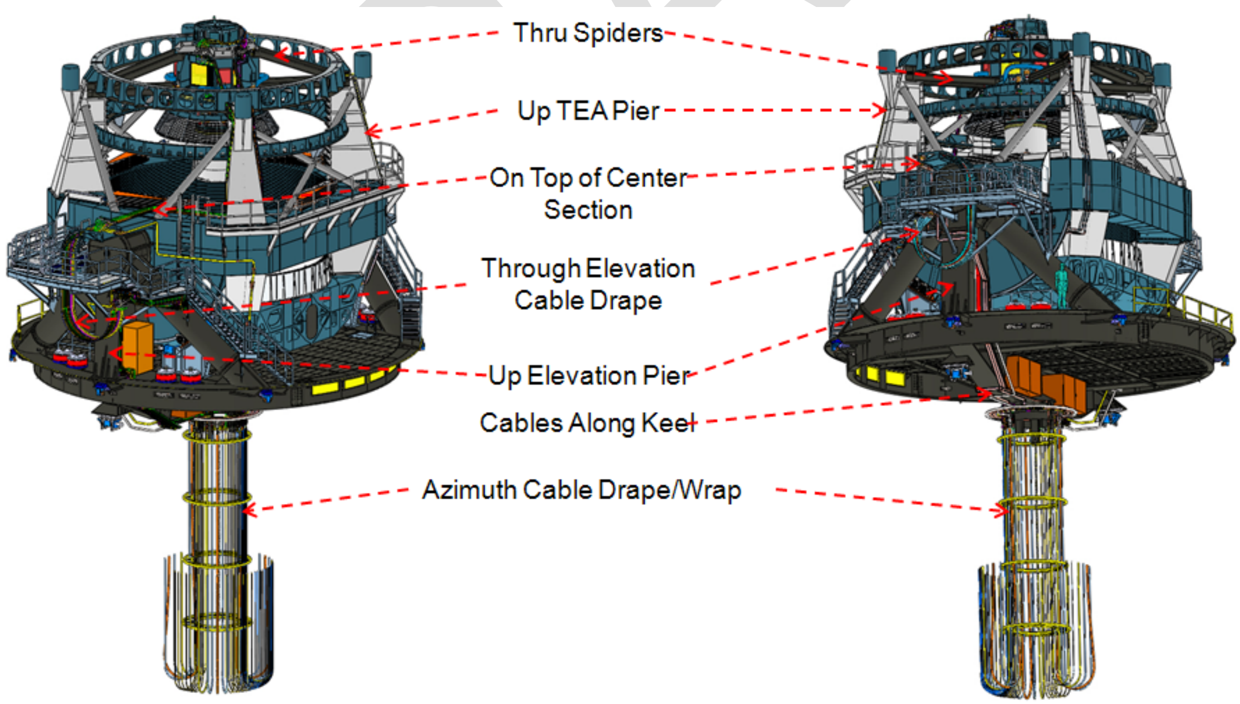


Fig. 2.6.4-1. Cable Routing.

2.7 SOFTWARE LIMITS, LIMIT SWITCHES, AND HARD-STOPS

For both the elevation axis and the azimuth axis hard-stops, limit switches and software limits were included to restrict the travel to safe limits. The software limits interface with the mount control system and are intended to stop the mount motion before a limit switch or hard stop is encountered. The limit switches are intermediate to the software limits and hard stops. They directly remove power from the drives and engage the power off brakes. The hard stops are included to physically prevent any over travel in case of malfunction of both the software limits and limit switches. The software limits will be adjustable to reduce the travel but may not allow contact with the limit switches or hard stops during normal operations. Sufficient motion range will be provided between the software limits, the limit switches and the hard stops such that they do not interfere with each other.

During engineering or maintenance the mount control system can override the software limits. This is required to test the limit switches. It is also required to position the elevation axis in its zenith or horizon pointing maintenance positions. Since they are aided by gravity, uncontrolled elevation axis motions are more problematic. Consequently, the software limits for the elevation axis will likely be set near the normal operational limits of the elevation axis (~3.5 to 70 degrees zenith angle). This maximizes the range available to stop the elevation axis motion in the result of a drive system failure before the limit switches are contacted (0 to 90 degree zenith angle).

The limit switches are required to limit the travel to the required design travel ranges, elevation axis (0 to 90 degrees zenith), azimuth axis (+/- 270 degrees). Motion will be allowable through these ranges before contacting the limit switches. The limit switches will engage as soon as practical afterwards. The limit switches will be configured so that they are not damaged if they are driven past and a hard stop is contacted.

The rotational motions of the mount about its axis are physically limited by energy absorbing shock absorbers commonly referred to as "hard stops." Although they are referred to as hard stops, these devices limit the deceleration to safe levels by absorbing the rotational kinetic energy through either mechanical springs or air charged bladders. Hard stops limit the motion of both the elevation axis and azimuth axis at both ends of travel. Specifically, ITT Enidine HDN series shock absorbers are utilized in the baseline design, fig 2.7-1.

The +/- 270 degree range requirements of the azimuth axis require the use of a topple block system. The topple block system utilized successfully on the Gemini telescope was incorporated into the LSST baseline design, fig 2.7-1

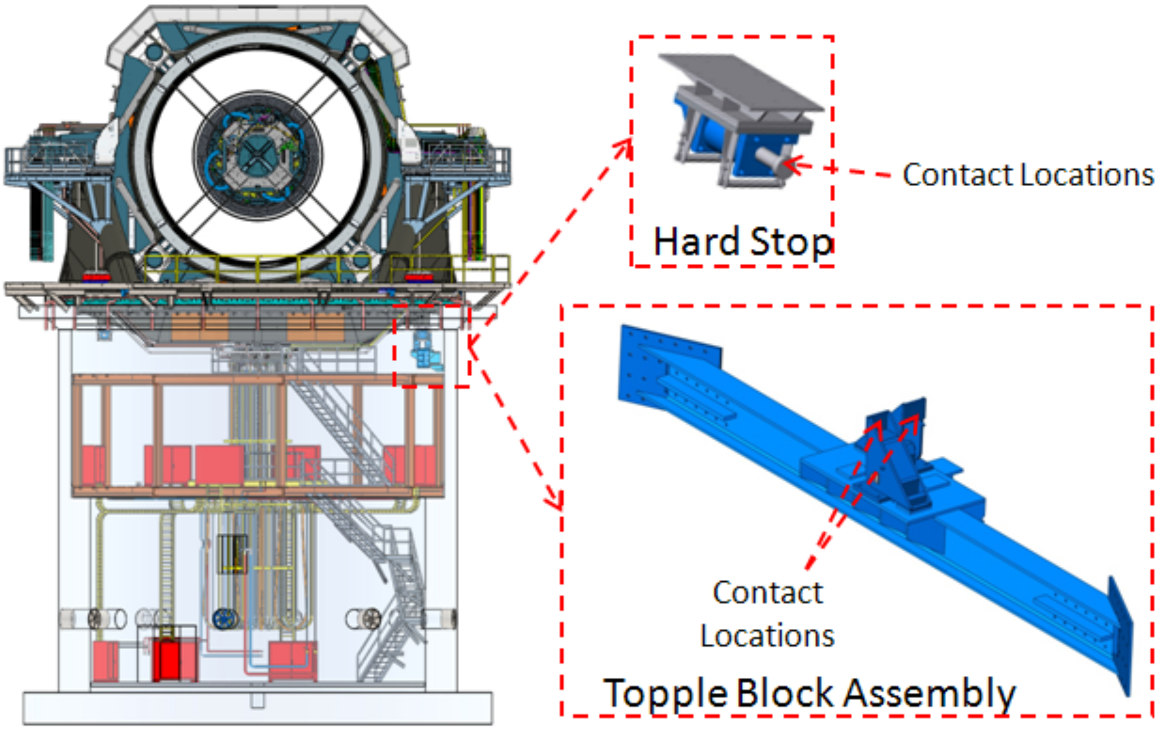


Fig. 2.7-1. Topple Block System

2.8 DEPLOYABLE M1M3 MIRROR COVER

The estimated 3,300 lb deployable M1M3 mirror cover design uses four “Chinese fans", fig 2.8-1, document-12517. The purpose of the cover is to protect the M1M3 mirror from falling object (nuts, bolts and tools), water (leaks through the 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.

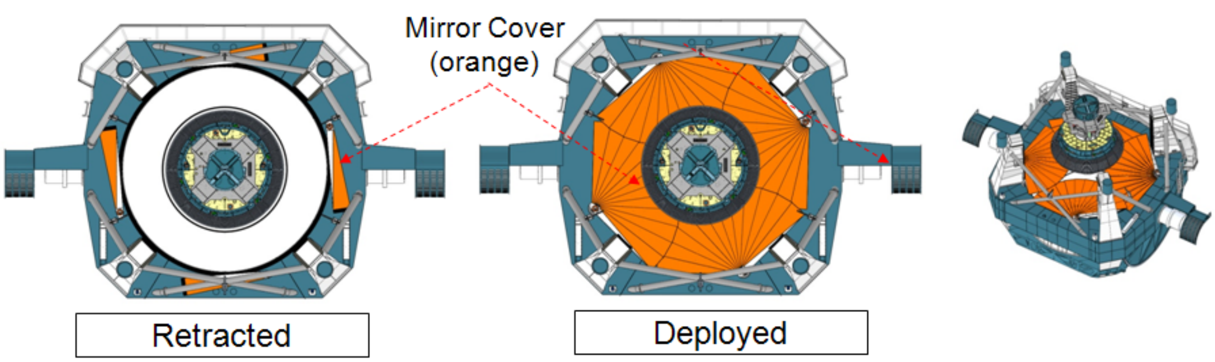


Fig. 2.8-1. M1M3 Mirror Cover shown on TMA elevation assembly

Each of the 4 fans contains 12 blades. The fan blades are consecutively shorter in length to clear the telescope structure when stowed, and to produce a stair step catchment at the end of each petal, fig 2.8-2.

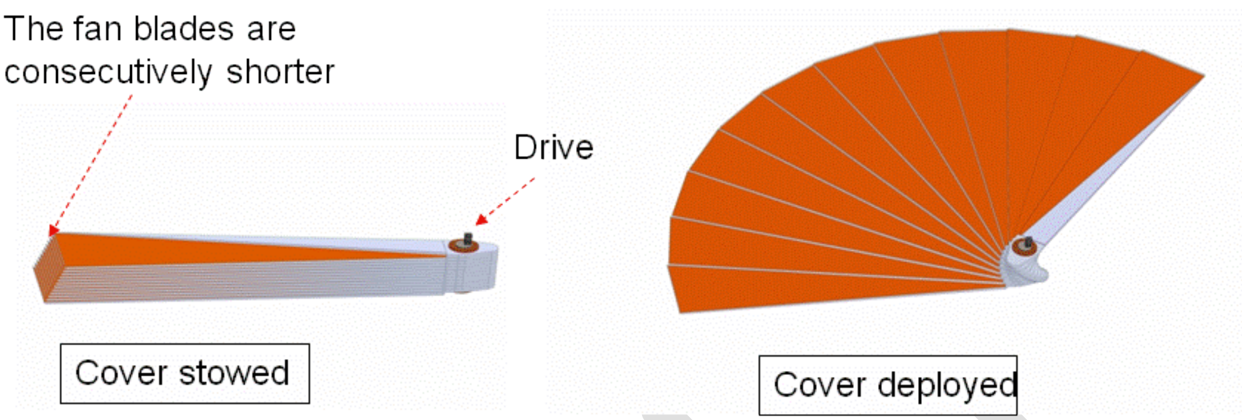


Fig.2.8-2. M1M3 Mirror Single Fan Assembly.

The blade design incorporates a box beam for added strength. Folded edges produce a stair step arrangement, when assembled into a fan, which prevents drips or items from hitting the mirror, fig 2.8-3. 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 design would inherently remove small objects when retracted and would facilitate removal of a larger object with an extension arm .

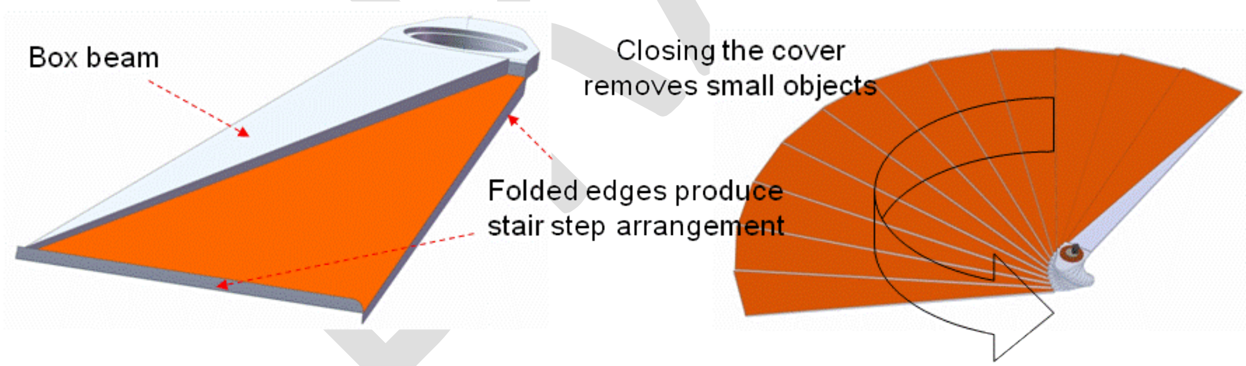


Fig.2.8-3. M1M3 Mirror Fan Blade.

When the M1M3 mirror cover is deployed it does not cover the ~ 2 meter x 2 meter area under the camera, fig 2.8-4. This eliminates any possible contact hazard between mirror cover and first camera lens (L1). Since the cover is slightly higher than L1 it also provides substantial protection for it. When stowed, all of the mirror cover resides over the center section of the telescope mount.

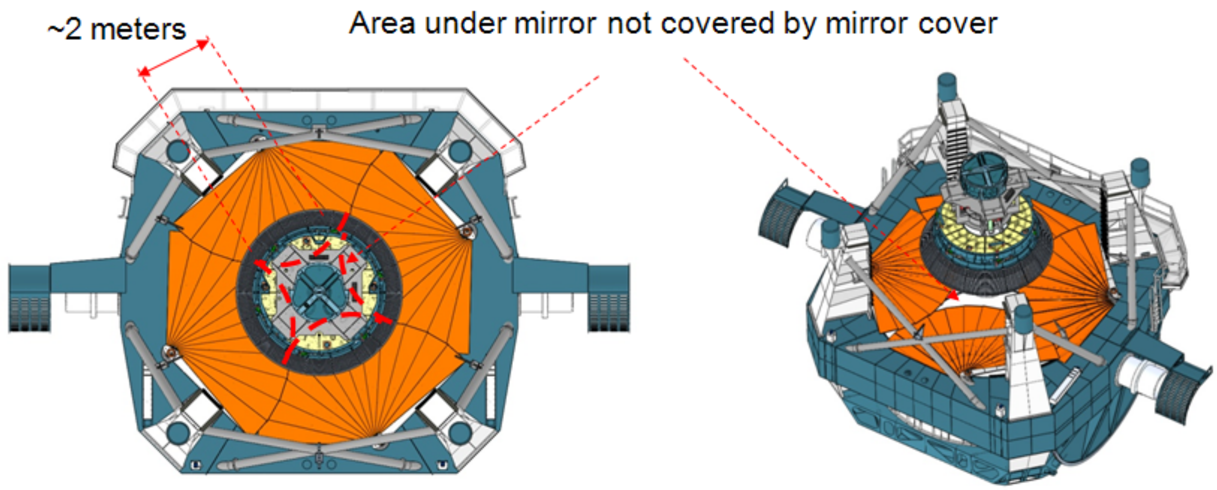


Fig.2.8-4. Area Not Covered by M1M3 Mirror Cover.

Most likely each of the 12 blades comprising each fan will be fabricated from aluminum. Since the design will be strength limited, the high strength to weigh ratio of aluminum will be advantageous. Aluminum with its low elastic modulus of 10e6 psi and high ductility can absorb more energy from a falling object than a comparable steel structure. The softness of aluminum relative to steel produces less of a hazard to the mirror if part of the mirror cover escapes and contacts the mirror.

The simplest drive system would only move the upper most blades and use a slot and pin system to move the rest of the blades. Unfortunately this system would allow uncontrolled motion of the other blades and limit the deployment of the M1M3 mirror cover to when the telescope is in the zenith pointing orientation. Consequently, a gear drive or cam follower system, which will control motion of every blade, is required to allow the safe deployment at any zenith angle. The slot pin system would likely be retained for redundancy. The slot/pin system and a gear drive system are shown in fig 2.8-5.

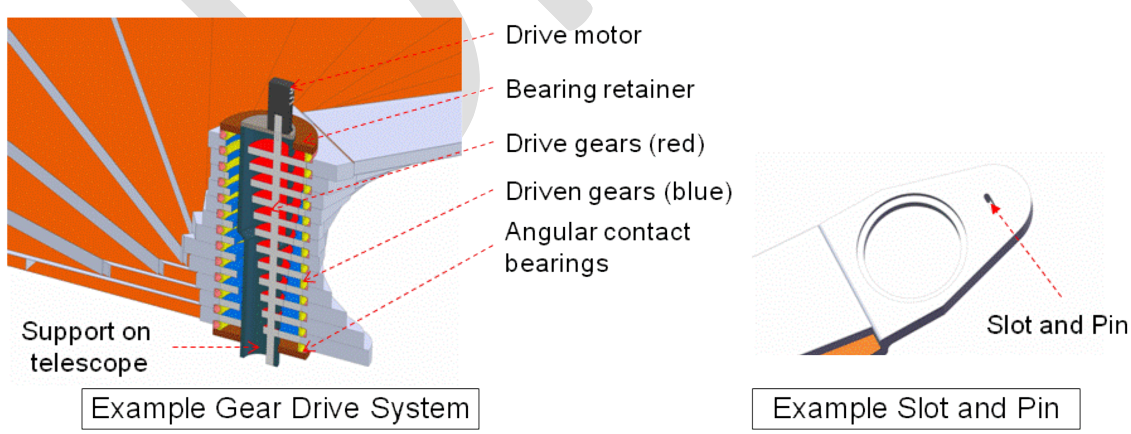


Fig.2.8-5 Drive System of M1M3 mirror cover.

This cover design has the added benefit that when deployed it increases the crane access area available for camera filter changing operation. When stowed it decreases the available crane access area which promotes deploying the mirror cover before filter changing. This reduces the hazard to the M1M3 mirror during this operation. The camera filter changing operation is explained in the Camera Support Assembly maintenance access portion of this document.

This mirror cover design is similar to the one originally utilized on the Large Binocular Telescope (LBT). However, the LBT design apparently did not individually drive each petal and could not be safely deployed except when the telescope was zenith pointing. Consequently the units were removed from the telescope.

2.9 BALANCING SYSTEM

Proper operation of the TMA's elevation axis drive system requires the elevation assembly be balanced about the elevation axis, otherwise unnecessary motor torque must be utilized to counteract the imbalance. The unnecessary torque increases the electrical current demand, produces unnecessary image degrading 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 assemblie'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, fig 2.9-1. The elevation assembly must 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. 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.

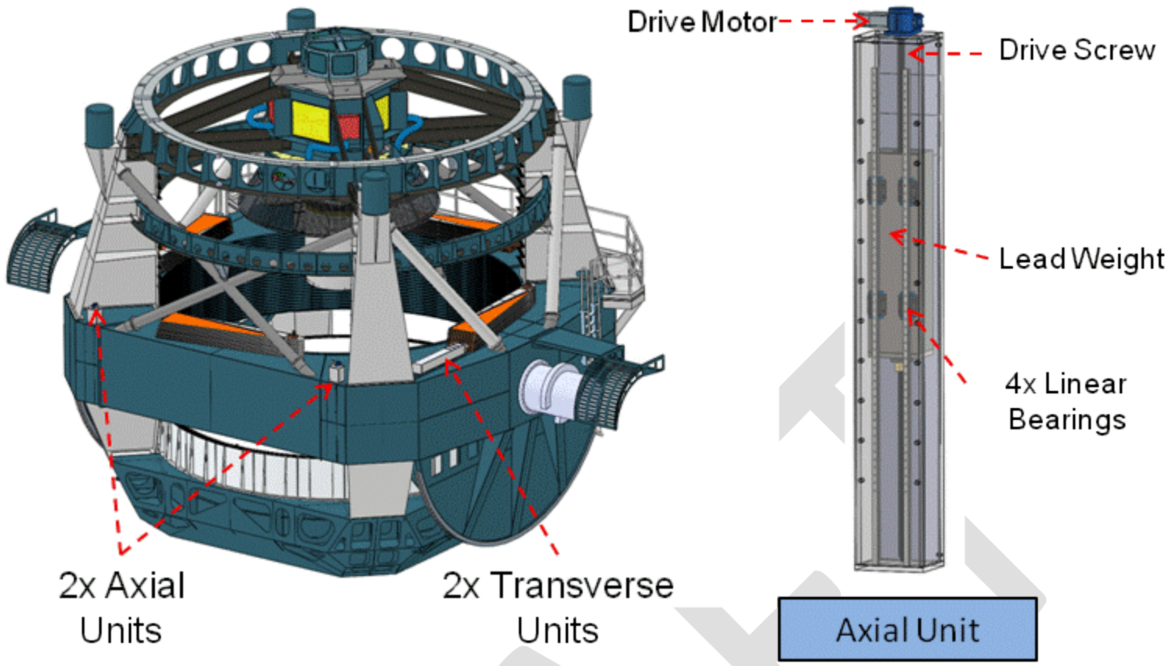


Fig.2.9-1 Elevation Assembly Balancing System.

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, fig 2.9-1. The drive screw motors are operated manually through the telescope control system. Since the purpose of balancing the elevation assembly is to minimize the mount drive motor current, the drive amperage is used by the telescope operator as feedback to adjust the units.

2.10 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%.

It would be difficult to meet the LSST vibration requirements with only natural damping. 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 systems would still be required.

To increase the damping level of the telescope mount assembly, tuned mass dampers (TMD) were incorporated into the design, Document 5721. A tuned mass damper consists of 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 assembly. For the LSST application, the targeting 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 top end assembly, fig 2.10-1. These locations have the greatest displacements other than the actual top end central assembly. As a result of their size and mass, attaching them to the central assembly would be problematic. A study by CSA Engineering, Document 5721, demonstrated that the four 973.5 lb TMD units with a total moving mass of 3894 lbs at these locations could produce 5% added damping at the fundamental frequencies. The actual mass budget for these items is 50% higher (5894 lbs) than just the moving mass to account for the unit's stationary mass.

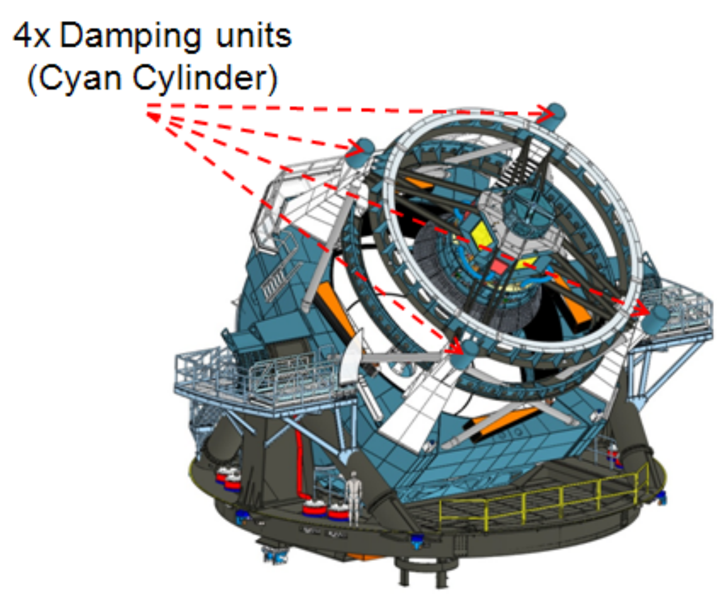


Fig.2.10-1 Location of damping units on telescope.

Although the TMDs only produce significant damping for the specific frequencies, their addition to the overall performance is significant, fig 2.10-2. 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.

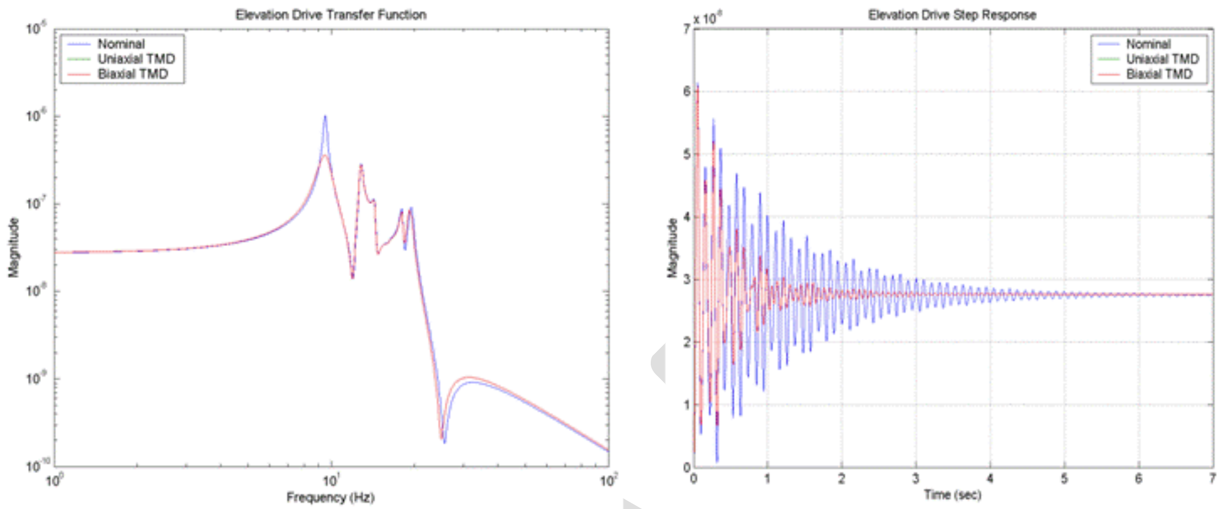


Fig.2.10-2 Effects of Added Damping on TMA Dynamic Performance.

Active damping systems were also considered. Their principal benefits are lower mass and the greater range of vibrations frequency that they will attenuate. However, since both the settling time and the wind induced vibrations image degradation are governed by the lowest natural frequency, the greater range of frequency attenuation produces little benefit. Since the TMA was designed for the larger and heavier TMD system, an active damping system can be readily retrofitted at a later date if necessary.

2.11 LIGHT BAFFLING

The LSST is very susceptible to stray light rays impinging directly and indirectly 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, fig 2.11-1, document 11524.

1. Top End Ring Light Baffle
2. Mid Level Light Baffle
3. Center Section Light Baffle
4. M1 to M3 Transition Baffle
5. Top End Pier Scraper Vanes
6. Center Section Scraper Vanes
7. M2 Baffle

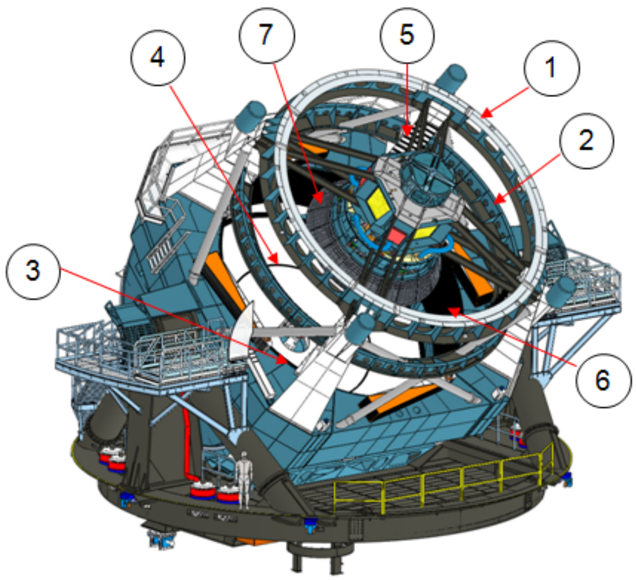


Figure 2.11-1: Light Baffling.

Although the optical field of view is 3.5 degrees, the clear light path in the telescope is slightly oversized to 3.8 degrees (TBR with tolerances) to prevent unintended vignetting. On the telescope, the light path is first baffled by the top end ring which, through its "I" beam configuration, provides 2 light baffles. A second baffle ring is attached mid way up the top end assembly piers. The top of the center section 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 piers and the M1M3 cell piers. The outer edge of the M1 mirror, which is not optically figured, is covered by an aperture stop baffle. The transition surface on the M1M3 between the two optical surfaces is covered by a baffle (paint). A conical baffle resides on the secondary mirror assembly. All of the light baffles and scraper vanes are considered components of the TMA.

2.12 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 standards. All stairs, ladders and platforms incorporate regulation height safety rails. The stair steps are regulation sizes.

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. Consequently, the requirements for manufacturing floors were adopted, which are provided below in their IBC imperial units.

Live loads (L), Manufacturing Floor Load Requirements:

- Heavy
  - Uniform load 250 psf
  - Concentrated Load 3,000 lbs
- Light
  - Uniform load 125 psf
  - Concentrated Load 2,000 lbs

Per the building code the concentrated load was applied over an area of 2 ½ feet by 2 ½ feet.

Since they are all interior floors, the loading is principally seismic and live loads. The slewing loads are all in plane. Not only are the floors much stronger in this direction, but the floors will not experience slewing loads and live loads simultaneously.

To facilitate the motion of maintenance carts and to aid in the directing of air flow, both the observatory level floor and the recessed floor are solid (non perforated). To facilitate air flow, which improves image quality, all the elevated stairs, ladders and platforms utilize perforated grating for flooring.

2.12.1 AZIMITH 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), fig 2.12.3-1, document-8585. This flooring area must be strong enough to sustain substantial traffic during construction, maintenance and repairs. Since the flooring covers a significant area and possesses adequate strength, the resulting mass of ~10.3 metric tons accounts for a significant portion of the overall total telescope mass. Since the flooring was designed according to the international building code, which was in imperial units, this section uses imperial units.

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

Whenever practical to prevent vibration coupling, the natural frequencies of the TMA subassemblies should be at least twice the principal frequencies of the telescope. Consequently all the relevant natural frequencies of the flooring are at least 20 Hz.

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 dividing into three areas, fig 2.12.1-1:

- Recessed Floor. All of the 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.

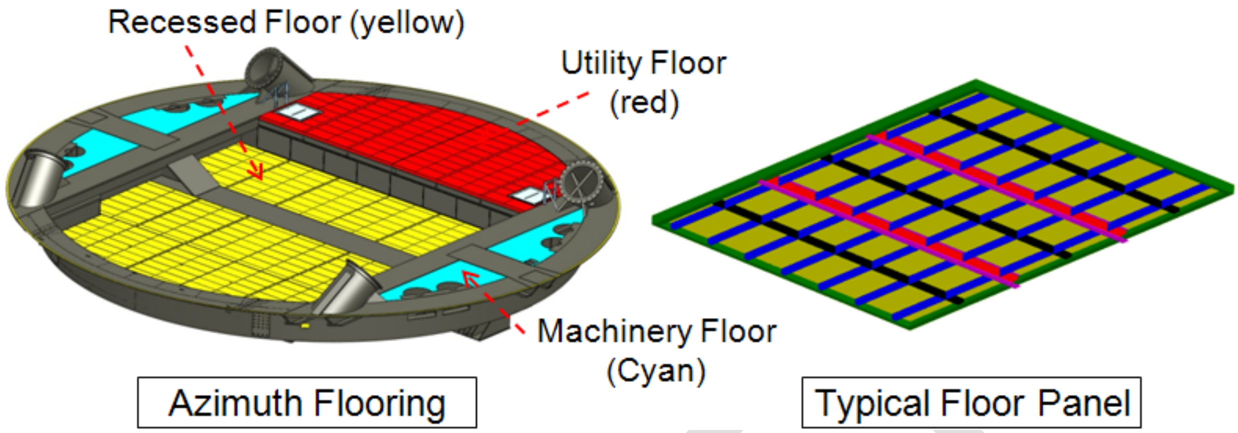


Fig.2.12.1-1 Main Floor of TMA Azimuth Assembly.

The recessed floor will sustain minimal traffic. It will be difficult to access this floor with either the crane or wheeled transportation. Consequently it will experience minimal loading. 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.

An LSST design policy is to minimize on site fabrication. All components, assemblies, etc should be manufacturable off site and only assembled in place by bolted joints. Consequently, all flooring sections and structures are bolted in place and easily removable. Not only does this facilitate manufacturing and installation but increases maintenance access. In particular, the utility floor was designed to be removable, with the dome crane, in two sections. 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.

Unlike most of the TMA structures which are stiffness limited, the flooring is strength limited and will be manufactured from a higher strength steel A572A Grade 60, or equivalent. All floor panels are of similar construction, fig 2.12.1-1. Since the telescope is left/right symmetric, the flooring is also symmetric.

Extensive analysis was conducted on the flooring to verify adequate mass budget and performance, document-8585. This analysis demonstrated that the flooring design meets all the requirements.

2.12.2 STATIONAL 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 with 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, fig 2.12.2-1. 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.

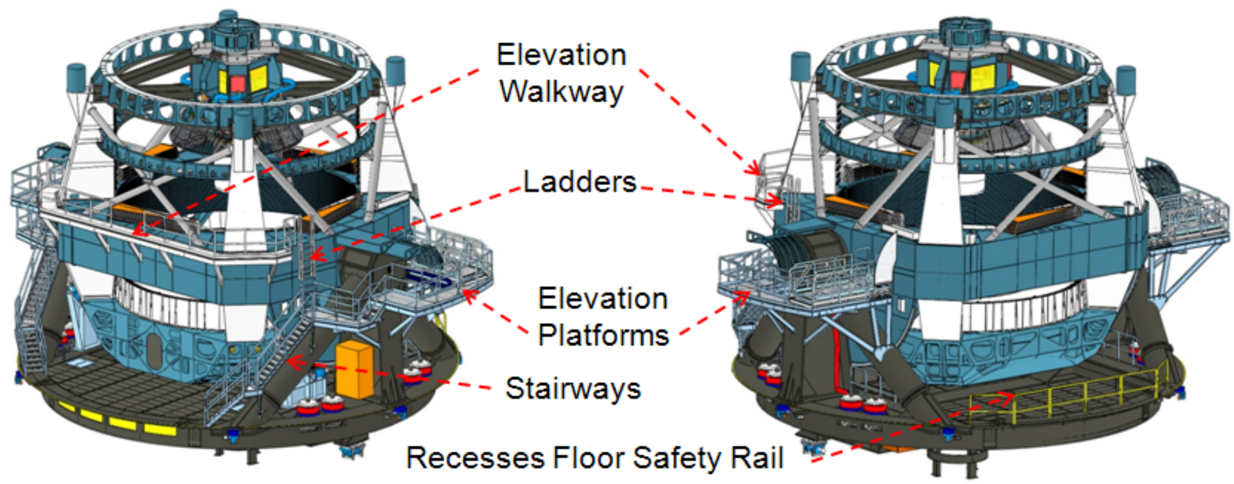


Fig.2.12.2-1 TMA Platforms, Stairways, Ladders and Safety Rails.

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 more appropriate than stairways. To provide safe access to 3 of the 4 mirror cover subassemblies, a walkway is provided around the half of the center section which is elevated when the telescope is horizon pointing. As a result of the compact design 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 are more appropriately accessed when the telescope is horizon pointing, a walkway around this section is also unnecessary and none was incorporated.

As described in the flooring section, there is an approximately 1 meter recess in the main telescope floor. Safety railings circumscribe this recess wherever there is a fall potential.

2.12.3 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 for maintenance, deployable platforms were provided, fig 2.12.3-1, document LSE-18. These two deployable platforms are mounted on the elevation platform of the telescope azimuth assembly. This system was principally developed to access the camera but also allows for access to the camera's hexapod/rotator assembly and the M2 optical surface. It also aids in the cleaning and inspection of the M1M3 optical surface.

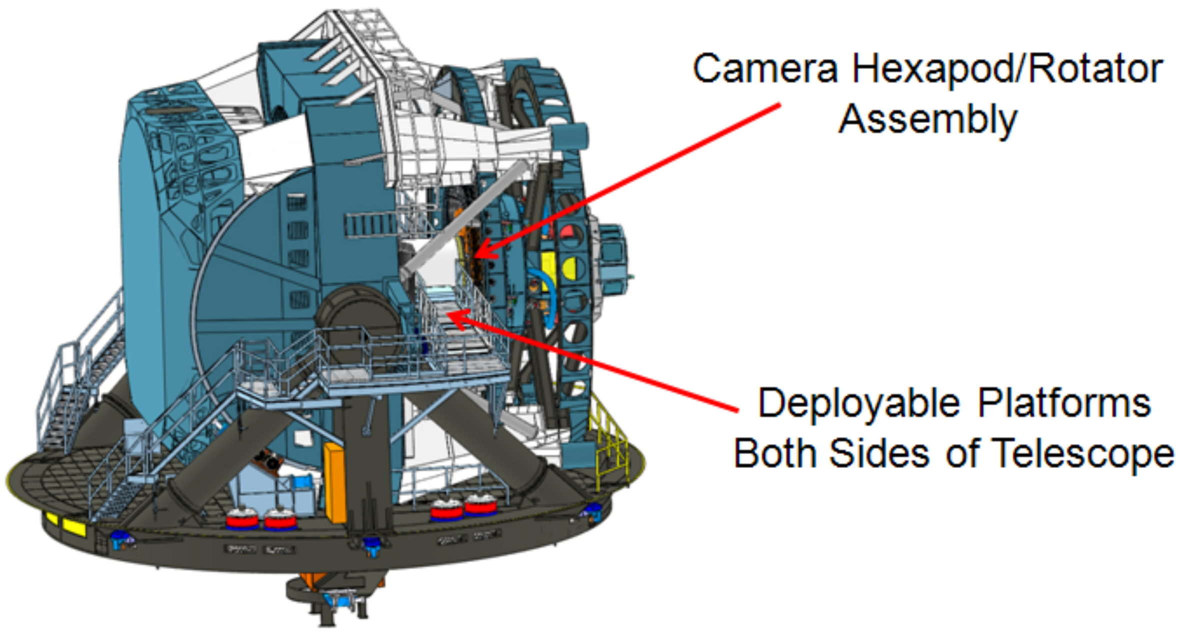


Figure 2.12.3-1: Deployable Platforms.

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 M2 mirror and provides access to 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. Any significant repairs of the hexapod/rotator will require removal of the entire camera support assembly.

2.13 GENERAL MAINTENANCE ACCESS

The TMA, the pier that supports it, and the enclosure that surrounds it have all been designed to facilitate maintenance. As discussed previously, the TMA incorporates stairs and platforms to provide convenient access for general maintenance.

Both the fixed (lower) enclosure and the rotating enclosure (dome) were designed to facilitate TMA maintenance. The lower enclosure provides an elevated maintenance floor aligned with the main TMA floor. The main floor of the lower enclosure provides clear access to the outer perimeter of the TMA azimuth bearings. The dome has a large gantry crane that when combined with dome rotation provides overhead crane access to the TMA.

The telescope pier provides a top floor under the azimuth assembly of the TMA for accessing the azimuth drives, azimuth encoder, limit switches, hard stops and azimuth cable drape. This floor can be accessed by crane by removing the utility floor described earlier. The telescope pier also provides a perimeter walkway surrounding the telescope at its main floor.

3 TELESCOPE MOUNT ASSEMBLY ANALYSIS

Extensive analysis was applied to the TMA design. Finite Element Analysis (FEA) was used to represent the entire telescope, its pier, and the mountain top in a single model. Since this model was compressive, it accurately reflected the dynamic characteristics of the TMA when installed at the site, fig 3.2-2.

This comprehensive model allowed for the optimization of the TMA in regard to natural frequencies. Increasing the natural frequencies improves the overall performance of the telescope. The natural frequencies directly affect the settling time, the effectiveness of the control system and the vibration induced image degradation (jitter). Since the settling time is proportional to the number of vibration cycles, higher natural frequencies reduce the settling time. Since the interactions of the natural frequencies and the control system limit the control system's update rate, higher natural frequencies allow more rapid motions. Jitter is proportional to the displacements produced by vibrations. Since the displacements decrease proportionally to the square of the natural frequency, increasing the natural frequency reduces the jitter.

Not only was the TMA optimized to increase the lowest natural frequencies, but it was also designed to minimize the variation in natural frequency with elevation angle and azimuth angle which optimizes the effectiveness of both the control and damping systems. The lowest natural frequencies and the higher natural frequencies were tailored to minimize vibration coupling. Non-orthogonal vibration modes that could couple and affect the image were staggered in natural frequency by a minimum of 50 %.

Since the natural frequencies are proportional to the square root of the ratio of the stiffness to the mass, they provide a measure of the overall structural efficiency. Consequently, higher natural frequencies not only lead directly to improved performance, but they also imply reduced gravity sag, wind shake, etc.

Only minimal load analysis was applied to the TMA. Since they require extreme rigidity, large ground based telescopes are seldom strength limited. High loads are generally localized and can be alleviated with local reinforcement and by the utilization of higher strength but still commonly wielded structural steels. For example, to meet seismic requirements some components of the Gemini Telescope are fabricated from A 588 rather than the more common A36 structural steel.

3.1 FINITE ELEMENT MODEL

To analyze and optimize the dynamic properties of the LSST telescope, the telescope mount assembly (TMA), telescope pier, and mountain top were all modeled in a single FEA model. Most of the TMA will be fabricated from steel plate. Consequently, it was modeled with plate elements. The hexapods, drives, bearing etc., were modeled with lumped mass and spring elements. The concrete pier and mountain top were modeled with solid elements. The properties for the mountain top elements were from actual locations. This FEA model was utilized in a wide variety of analyses.

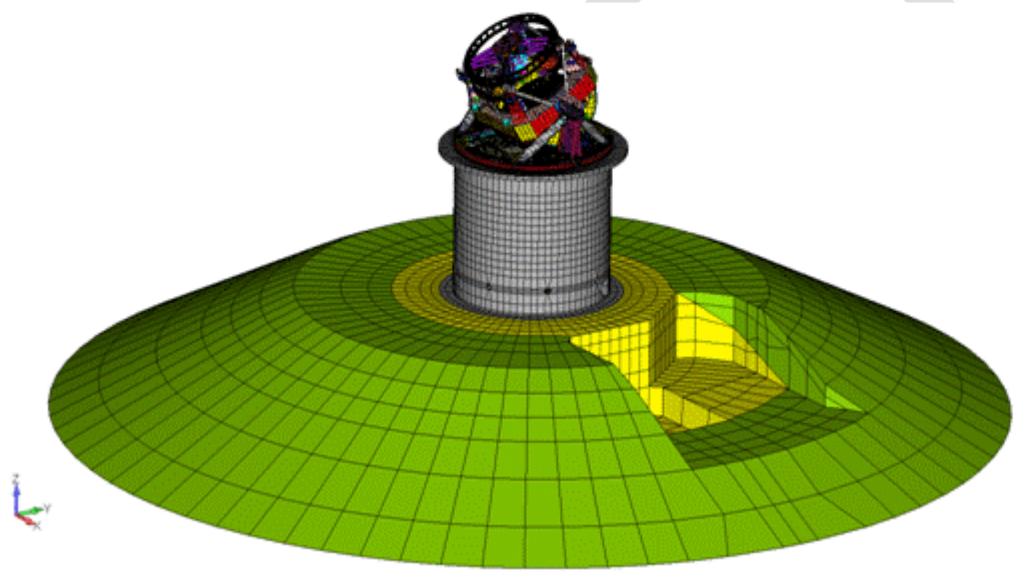


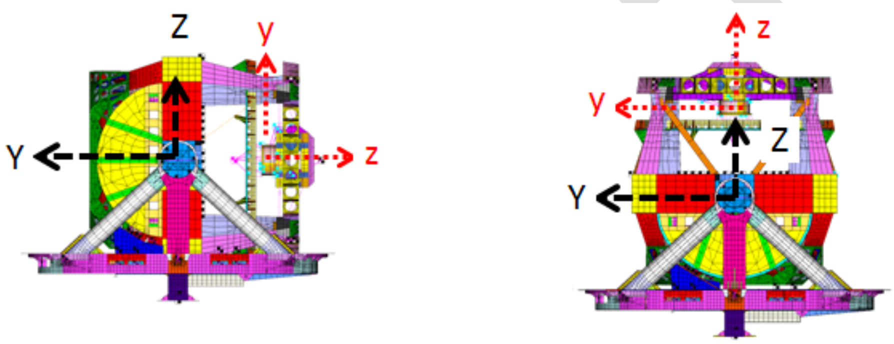
Figure 3.2-1: Comprehensive FEA model of TMA, pier and mountain top.

3.2 DYNAMIC PERFORMANCE (NATURAL FREQUENCIES)

The fundamental vibration modes of the TMA are associated with motions in the three principle directions, fig 3.2-1, document 13381. These are a transverse displacement of the elevation assembly along the elevation axis (x), the elevation assembly locked motor rotation, and a pumping mode along the optical axis (z). The elevation assembly locked motor mode is a combined displacement (y) and rotation about the elevation axis (x). 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 15% added parasitic mass attached to all the structures.

After the lowest natural frequency modes described above, the dominant vibration modes are the displacements of the camera (and M2 mirror cell assembly). To minimize vibration coupling, the TMA was designed to separate these secondary modes from the lowest modes by 50%. A coupling potential does exist for vibrations of the TMA in the gravitational direction (Z) and the camera along the optical axis (z). However, these axes only align when the telescope is zenith pointing. Since the telescope does not image in this orientation, this mode is difficult to excite and has less effect than transverse motions and it is considered tolerable.

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. The structure was analyzed at multiple zenith angles, fig 3.2-2, to demonstrate this minimal variation.



Horizon Pointing: Vibration Modes		
Mode #	Frequency (Hz)	Mode Shape
1	7.53	**Telescope X Translation**
2	8.38	**Telescope Y Trans / X Rot**
3	11.37	**Telescope Z Translation**
4	11.68	Camera X (*x*) Translation
5	12.55	Camera Y (*z*) Translation
6	13.99	Camera X (*x*) Rotation
7	14.74	**Telescope Z Rotation**
8	15.83	Camera Y (*z*) Translation
9	15.87	Camera Y (*z*) Translation
10	16.58	Camera X (*x*) Rotation

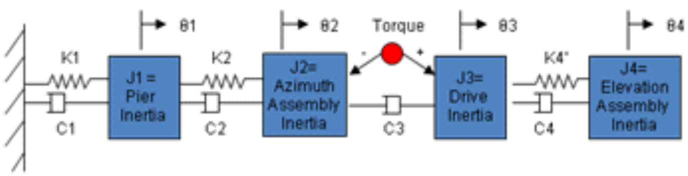
Vertical Pointing: Vibration Modes		
Mode #	Frequency (Hz)	Mode Shape
1	7.51	**Telescope X Translation**
2	8.86	**Telescope Y Trans / X Rot**
3	11.36	**Telescope Z Translation**
4	11.71	Camera X (*x*) Translation
5	12.40	Camera Z (*z*) Translation
6	13.34	Camera Y (*y*) Translation
7	14.70	Camera Y (*y*) Rotation
8	15.37	**Telescope Z Rotation**
9	15.98	Camera Z (*z*) Translation
10	16.32	Camera X (*x*) Translation

Figure 3.2-2: Natural Frequencies of TMA.

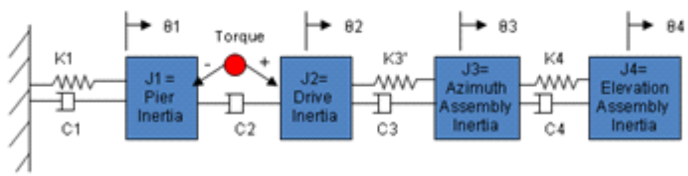
The other natural frequency of significant importance is the azimuth angle locked rotor frequency which has a direct effect on the azimuth drive control system and the azimuth motion settling time. This natural frequency of approximately 15 Hz is nearly twice that of the elevation axis frequency of 8.5 Hz. Spherical geometry requires twice the velocities and accelerations in the azimuth direction as the elevation directly. Consequently, this higher natural frequency is beneficial.

3.3 LUMPED MASS MODEL

The finite element model was used to produce simply lumped mass models of the two axes of the telescope (elevation and azimuth), fig 3.3-1, document-4496. Since there are minimal variations in the dynamic properties of the telescope with elevation angle, the two models are effectively decoupled. Two versions of the lumped mass model were produced. One version represented the locked rotor properties of the telescope and the other represented the applied torque version.



LSST Lumped Mass Model : Elevation Axis : Summary				
	Applied Torque	Spring Const (Kr) N-M / Rad	Effective Inertia (J) Kg-m2	Structural Damping C N-M / R / S
1	Pier	6.49E+11	6.93E+07	1.74E+08
2	Azimuth Assembly	3.36E+10	1.01E+06	2.55E+06
3	Elevation Drive	Infinite	1.17E+06	2.94E+06
4'	Elevation Assembly	9.82E+09	2.34E+06	5.89E+06



LSST Lumped Mass Model : Azimuth Axis : Summary				
	Applied Torque	Spring Const (Kr) N-M / Rad	Effective Inertia (J) Kg-M2	Structural Damping C N-M-S/Rad
1	Pier	8.80E+11	1.76E+07	1.05E+08
2	Azimuth Drive	Infinite	4.48E+06	2.68E+07
3'	Azimuth Assembly	5.95E+11	5.89E+06	3.53E+07
4	Elevation Assembly	6.74E+10	3.06E+06	1.83E+07

Figure 3.3-1: Lumped Mass Model of Telescope.

The models were used to model the drive system characterizes and develop the drive control system.

3.4 SETTLING TIME

Various methods were used to estimate the time required to settle after the baseline 3.5 degree slew. Settling is defined as when the displacement magnitude of the vibrations is within the optical error budget.

In document 7784, fig 3.4-1, the initial elastic displacement of the optics was determined through FEA of the TMA by applying the slewing accelerations. A logarithmic decay of these displacements was then used to determine the decay time. Increased stiffness both reduces the initial displacement and increases the natural frequency which increases the decay rate. This simple analysis demonstrated that the settling time was strongly inverse proportional to the natural frequency and that meeting the 2 second settle time would require approximately an 8Hz TMA. It was also shown that the settling time varied little with azimuth angle. Since the initial displacement is linear with acceleration rate and the decay is logarithmic, the peak accelerations only minimally affect the settling time.

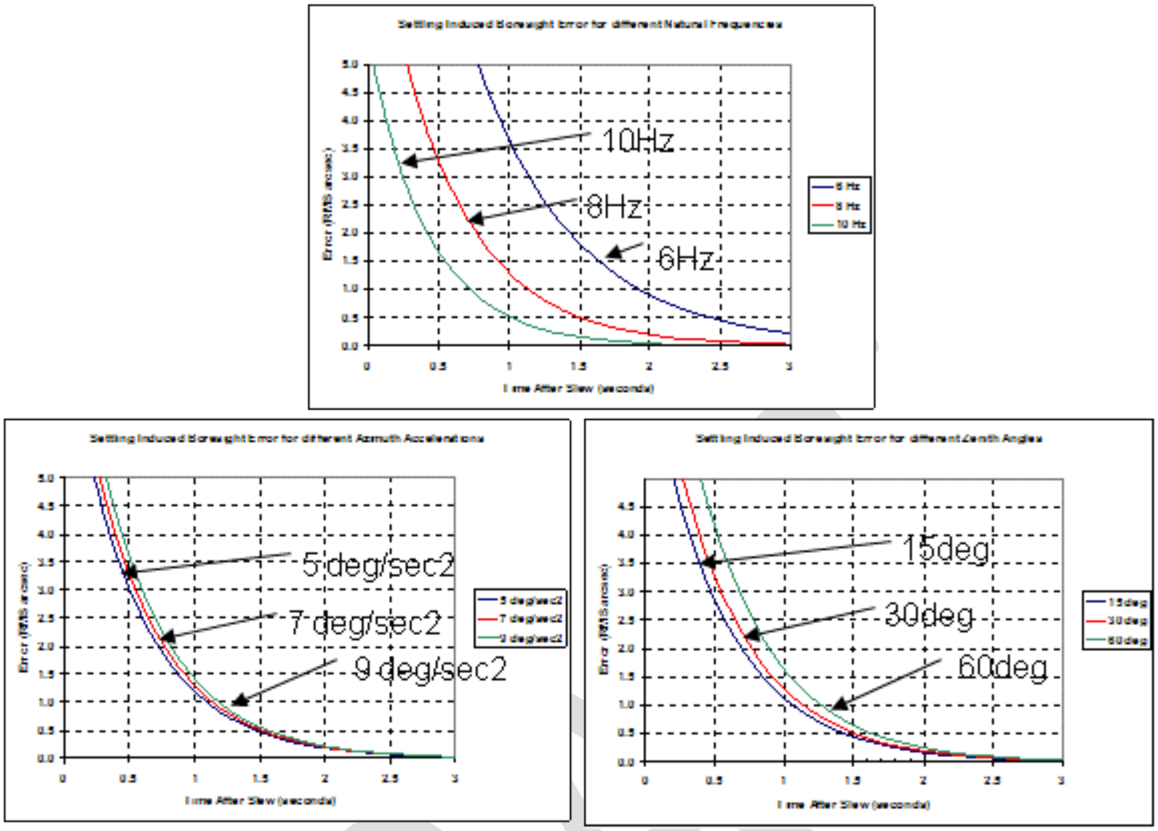


Figure 3.4-1: Settling time as a function of natural frequency, peak acceleration and zenith angle.

The initial analysis utilized only a simple perturbation and vibration decay model. More advanced analysis, document 8284, utilized the lumped mass model to represent the interaction of the TMA and its control systems. In general these analyses all showed that meeting the 2 second settling time allocation will require a TMA with a natural frequency near 8 Hz.

3.5 WIND INDUCED IMAGE DEGREDATION

Since the LSST telescope will not have a fast steering mirror to counteract wind shake, the wind induced vibrations were determined and the resulting image degradation (pointing error) was determined, document-5464. A wind pressure power spectrum was applied to the finite element model of the telescope. The FEA model then determined the resulting response. The predicted motions of the optical elements were analyzed by Zemax software to determine their effects on image quality.

The actual wind speed inside the enclosure is controlled by adjustable vent louvers over the numerous vents in the rotating enclosure. The speed inside the enclosure with all the vents open is approximately half the external wind speed. The best overall optical performance is achieved by balancing the image degrading effects of wind shake with the image improvement that results from dome flushing equalizing temperature differences. This analysis demonstrated that the best balance occurs for wind speeds of

~2.5 m/s which is close to the nominal speed that will result from all the vents open and average external wind speed, fig 3.5-1.

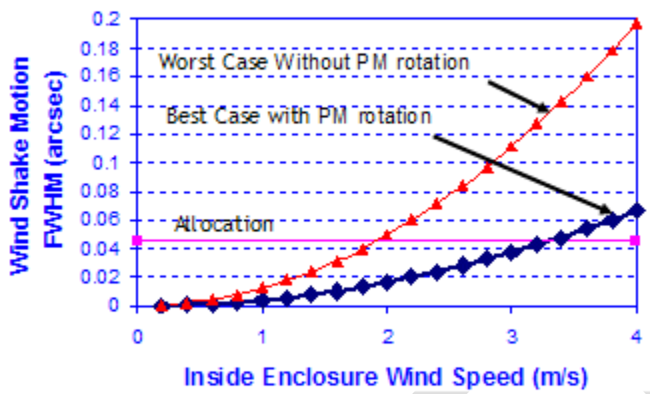


Figure 3.5-1: Pointing error as a function of internal wind speed.

The analysis originally determined unreasonably low image degradation as a result of sympathetic rotations of the M1M3 canceling the motions of the camera and M2. Since it is unlikely that this situation will occur on the actual telescope, this result was non-conservative and the analysis was repeated suppressing the M1M3 rotations to produce a worst case limit.

3.6 DYNAMIC POWER ANALYSIS

A dynamic power analysis was conducted on the TMA to determine the motor drive and power supply requirements, document 14355. This analysis demonstrated that the TMA should utilize a regenerative braking system and a capacitor bank for energy storage, fig 3.6-1.

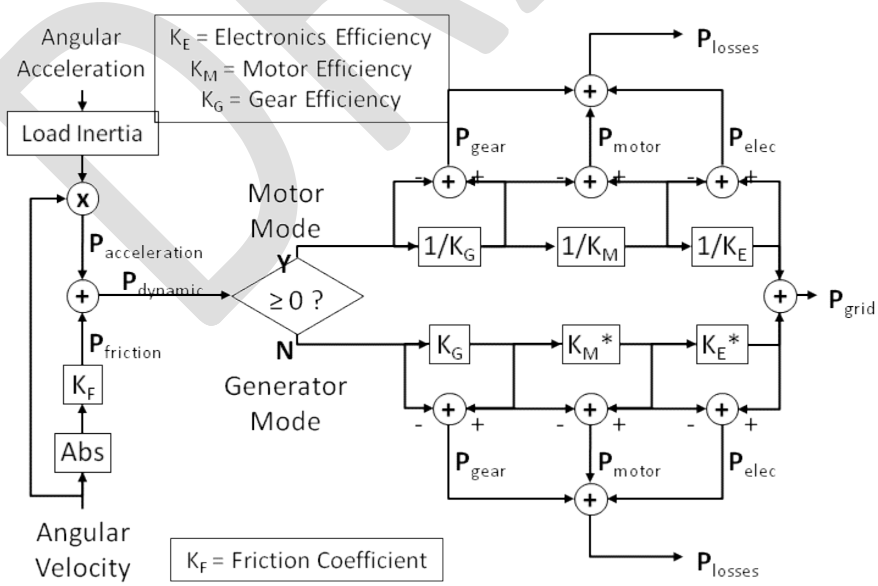


Figure 3.6-1: Schematic of Drive Power Scheme.

The LSST has an observation cycle of 30 seconds: (2 seconds to slew (accelerate and decelerate), 28 seconds to settle and track at sidereal speed). While power required for tracking is relatively small, in the order of a few kW, during slewing a peak power in the order of ½ MW is needed. The existing site power grid doesn't handle such peaks very well and it's not sized for such currents.

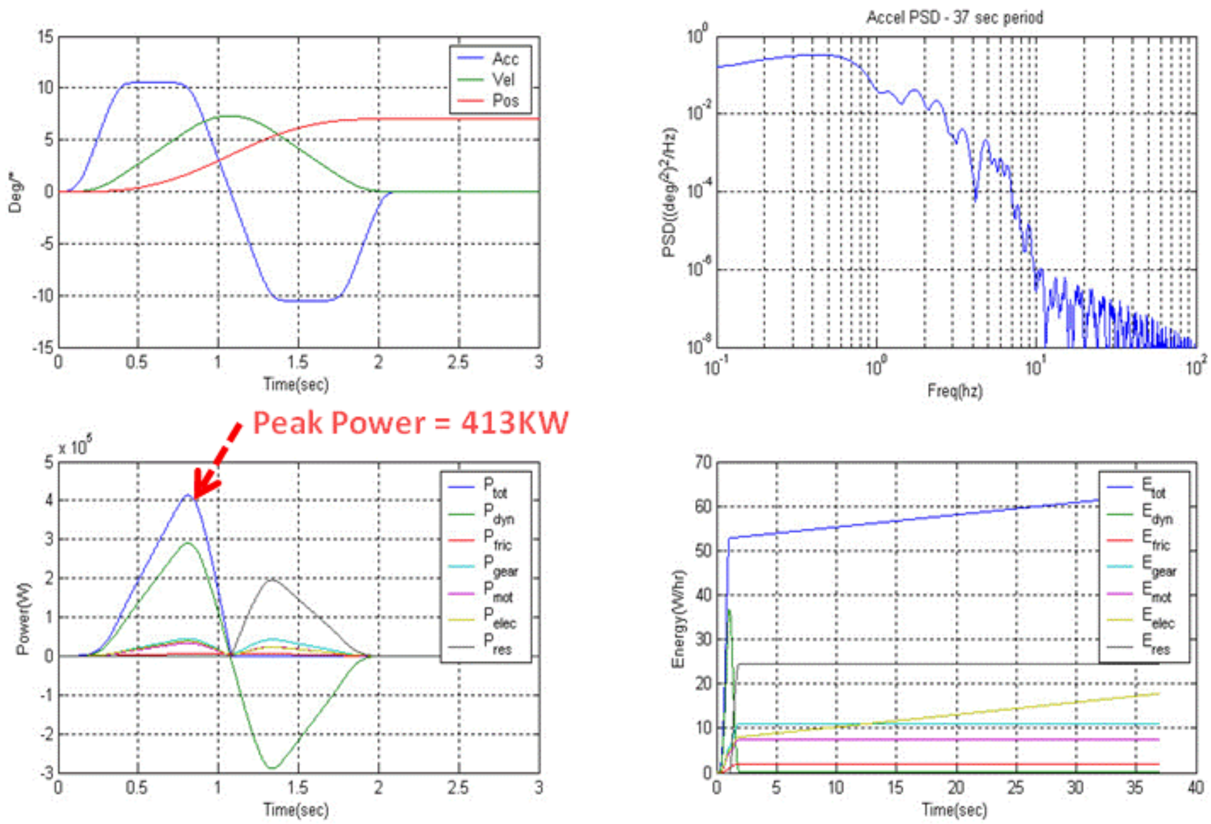


Figure 3.6-2: Drive Power Utilization.

The electrical energy needs to be stored locally so a power surge is not seen globally. The motor controllers are DC fed from the storage device. The energy storage device delivers current surge needed for telescope slewing. The storage device is resupplied during tracking. Given low duty cycle (6.7% = 2 s / 30 s) the power grid basically delivers average power. The motor controllers are regenerative, and most energy is recovered during braking. The capacitor banks were sized to limit the voltage drop during slewing (~10F at 650 Vdc).

3.7 SEISMIC ANALYSIS

The LSST will be located on the seismically active Chilean mountain of Cerro Pachón. The accelerations resulting from seismic events produce the most demanding load cases the telescope and its components must withstand. As a result of the interaction of the erratic ground input accelerations and the dynamic properties of the TMA, the accelerations experienced by the telescope components vary significantly throughout the telescope.

As a result of their locations on the TMA, the camera and the secondary mirror will experience the highest accelerations and are the most likely to be damaged by a seismic event, document LSE-80, table 3.7-1.

Return Period (Years)	Maximum Combined Seismic and Gravitational Accelerations									
	Secondary Mirror Assembly					Camera				
	x	+y	-y	+z	-z	x	+y	-y	+z	-z
300	3.15	2.57	3.99	2.29	2.60	3.60	3.70	5.70	2.04	2.45
150	2.64	2.16	3.52	1.93	2.34	3.03	2.96	4.96	1.71	2.22
75	1.87	1.53	2.78	1.36	1.95	2.14	1.91	3.80	1.21	1.86

Combined Design Accelerations: Peak Seismic and Gravitational (G)								
Design Level	Secondary Mirror Assembly					Camera		
	x	+y	-y	+z	-z	t	+z	-z
Survival	3.15	2.57	3.99	2.29	2.60	5.70	2.04	2.45
Operational	2.64	2.16	3.52	1.93	2.34	3.80	1.21	1.86

Figure 3.7-1: M2 mirror and camera seismic accelerations.

These accelerations were determined by applying seismic accelerations in the form of Power Spectral Densities (PSD) to the FEA model, document 13381. These PSDs were determined from Peak Spectral Accelerations (PSA) provided by the Chilean design codes, fig 3.7-2.

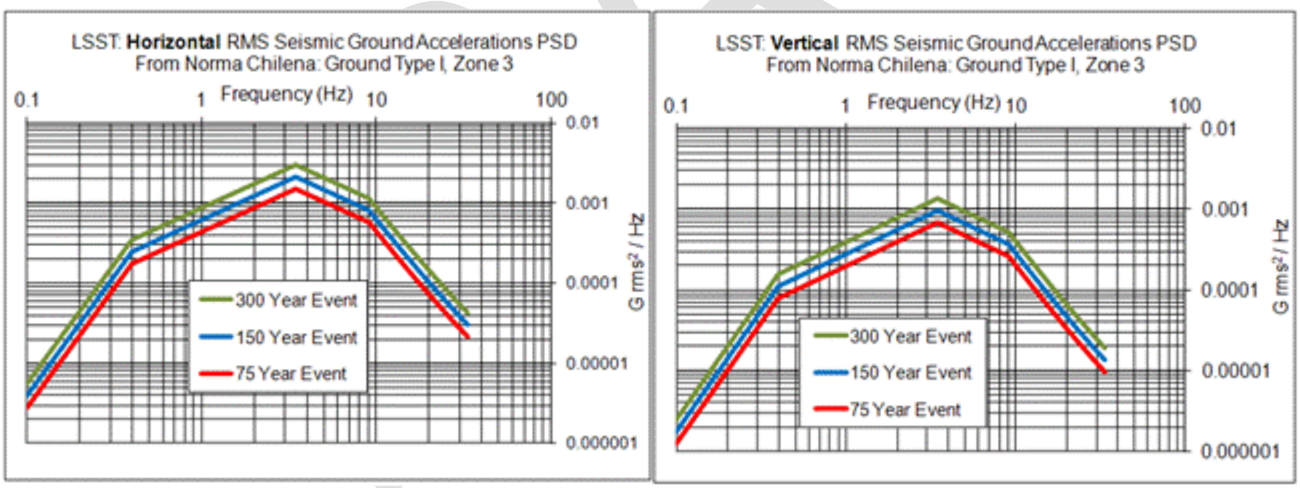


Figure 3.7-2: Seismic Ground PSDs determined from Chilean Building Codes.

The accelerations are also affected by damping level. The LSST incorporates added damping to meets its rapid slew and settle requirements. This added damping also reduces the components' seismic accelerations. The analysis was repeated for the telescope horizon and zenith pointing. Closed form solutions were utilized to verify the results.

4 TOP END ASSEMBLY

The top end assembly is principally composed of the spider and ring assembly, the secondary mirror (M2) cell assembly with hexapod and baffle, and the camera support assembly, fig 4-1. The spider and ring assembly is permanently attached to the telescope and includes the ring, spiders and spider spindle. The TEA ring also functions as two light baffles as described in the light baffle section. The M2 hexapod, M2 hexapod electronics cabinet, and the M2 mirror cell assembly electronics cabinet are attached to the spider spindle. The M2 mirror cell assembly and its light baffle are supported by the M2 hexapod which is attached to the spider and ring assembly. The camera support assembly includes the camera, camera rotator, camera hexapod, camera cable wrap, thermal control system, camera electronics cabinet and integrating structure. Both the camera support assembly and the M2 mirror cell assembly must be removable as complete assemblies for maintenance. When the M2 mirror cell assembly is removed its hexapod remains attached to the spider spindle and the M2 baffle remains stowed within the TMA.

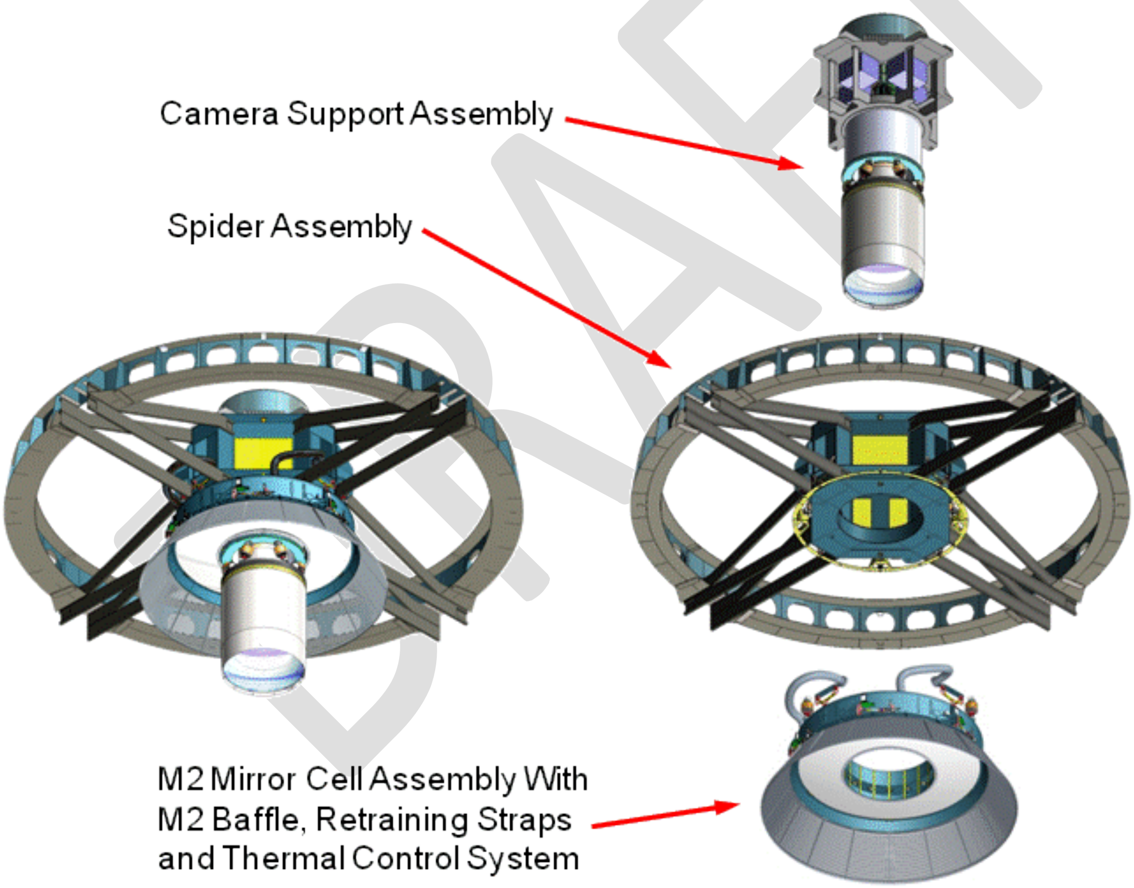


Figure 4-1: Top End Assembly

Since the (TEA) is a tightly intertwined conglomeration of both two of the principle payloads (Camera with hexapod/rotator assembly and secondary (M2) mirror cell assembly with baffle and hexapod) and several components of the TMA, it is described here as a single assembly. All of these components of the TEA except for the two optical payloads are considered components of the TMA. The six thermally controlled electrical cabinets housed in the TEA for support of the payloads are all TMA components. The electronics in these cabinets along with the cabling to the payloads are considered components of the payloads.

Mount Components:

- Camera cable wrap
- Spider Spindle (permanent structure)
- Integrating structure (removable structure)
- 16 spiders
- Ring
- Thermal control system
- Six 19" electrical cabinets

Payload:

- Camera
- Camera hexapod/ rotator assembly
- M2 mirror cell assembly
- M2 hexapod
- M2 baffle

The spider spindle is attached to the top end ring through 16 hollow rectangular spiders, fig 4-2. 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 cell assembly, the hexapods and the rotator.

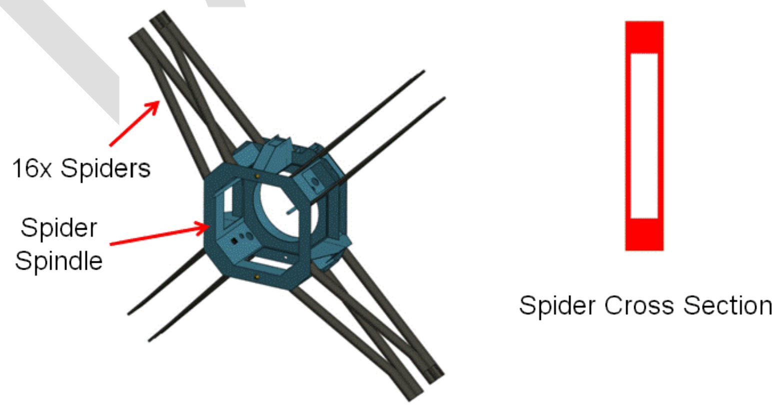


Figure 4-2: Spider Spindle and Spiders

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. As a result of the large mass supported it would not be practical to preload the spiders in tension.

All the components supported by the spiders are referred to as the central assembly and include the camera support assembly, M2 mirror cell assembly (with hexapod, baffle and electronics cabinets) and spider spindle. Consequently, the central assembly includes all top end assembly components except the ring and spiders. When the camera support assembly is installed, its integrating structure is rigidly fastened to the spider spindle to form the central structure, fig 4-3.

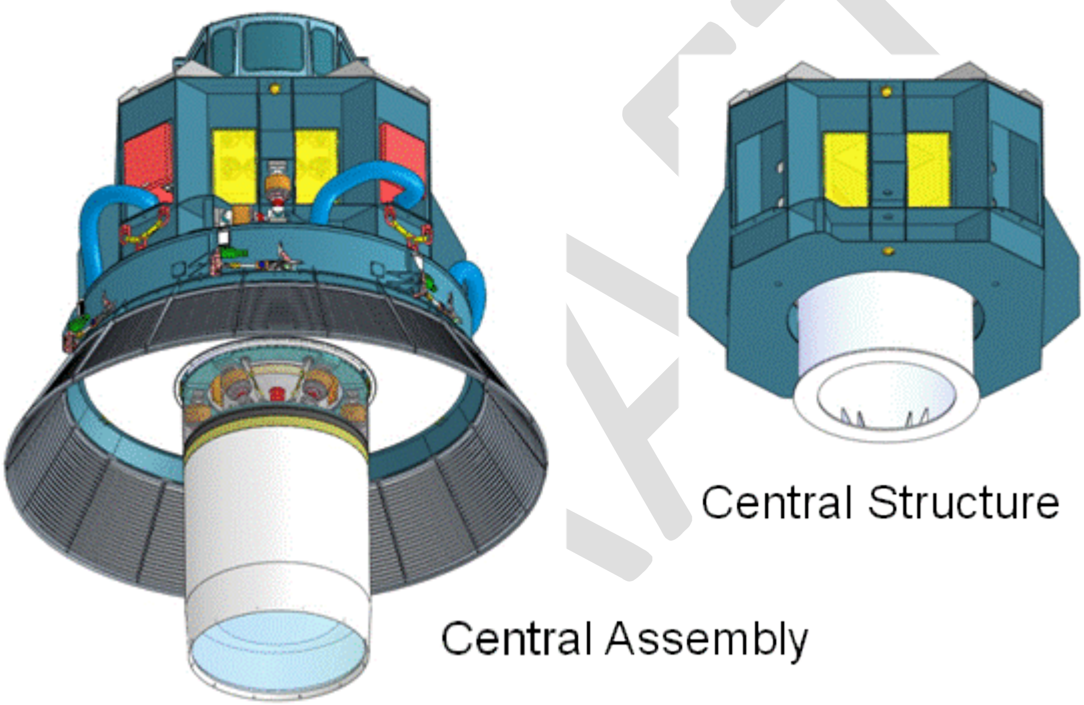


Figure 4-3: Central Assembly and Central Structure.

Both the M2 mirror cell assembly and the camera of the camera support assembly are supported by hexapods to facilitate optical alignment to the primary / tertiary (M1M3) mirror. A rotator resides between the camera and its hexapod to facilitate tracking.

The electronics for the camera hexapod and camera rotator are housed in electronics cabinets attached to the integrating structure fig 8. This allows for testing of all components of the camera support assembly before its installation on the telescope. When the camera support assembly is installed on the telescope, its integrating structure is fastened to the spider spindle, fig 6. This central structure, when combined with a series of covers, is moderately air tight. The enclosed air is thermally controlled central thermal control system which resides with inside the TEA. This thermal control system is described in the thermal management section.

The electronics for the M2 mirror cell assembly and M2 hexapod are housed separately in two of the four electrical cabinets installed on the exterior of the spider spindle, shown as red cabinets in fig 4-3. Consequently, they remain on the telescope when the camera support assembly is removed. Thermal control of these four electrical cabinets and the M2 mirror cell assembly is provided by circulating air to the enclosed central thermal control system inside the central structure, fig 4.1-1. The other two electrical cabinets attached to the spider spindle are not presently formally assigned, however one will likely be used for a bore sight camera and the other will likely be a general purpose electrical cabinet.

4.1 CAMERA SUPPORT ASSEMBLY

To facilitate testing before installation, the camera, camera rotator, camera hexapod, camera cable wrap, thermal control system, electrical cabinets and integrating structure are all installed as a single unit referred to as the camera support assembly, fig 4.1-1. This assembly is held together by the Integrating Structure. The two electrical cabinets of the camera support assembly are dedicated to the electronic for the camera hexapod and rotator.

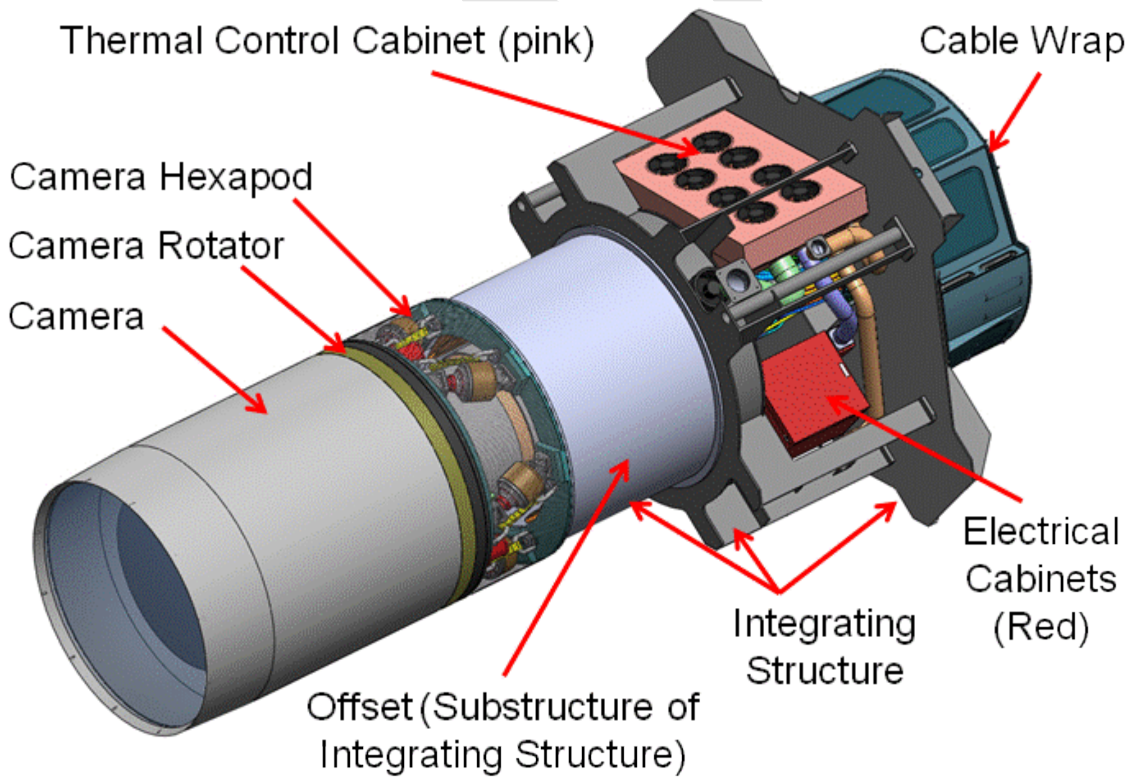


Figure 4.1-1: Camera Support Assembly

The electronics for the camera are contained in the camera utility trunk which is attached to the camera and protrudes through the camera hexapod/rotator assembly. Consequently, since the electronics for the camera are self contained in the camera separate electrical cabinets are not required to support it.

The Camera is mounted to its rotator, and its hexapod is mounted to a substructure of the Integrating Structure know as the Camera Offset, fig 4.1-1. The Camera Offset is a cylinder with a flat annular flange at the end for attaching the Camera Hexapod. Since the Camera, Camera Rotator and Camera Hexapod must be installed through the central hole of the M2 Mirror Cell Assembly their design envelopes are limited by an outer cylinder. Since the Camera extends inside the Camera Rotator, Camera Hexapod and the Camera Offset, their interior design envelopes are also limited by an inner cylinder.

All components of the camera support assembly except for the actual camera and its hexapod/rotator are considered components of the telescope mount assembly. This specifically includes the integrating structure, the two electrical cabinets, the thermal control cabinet, the camera cable wrap and all associated ducting, piping and cabling required to operate the cable wrap and thermal controls system.

The entire camera support assembly is installed and removed as a single unit through the spider spindle of the top end assembly, fig 4.1-2. 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 considered components of the TMA but not shown in the figure.

A lifting fixture with a counterbalance is used to remove the camera support assembly, fig 4.1-2. The purpose of the counterbalance is to align the lifting fixture's CG with the CG of the camera support assembly. Since the two CGs are aligned there is no CG shift when the lifting fixture is attached to the camera support assembly and they are both removed as a single unit. This configuration also aligns the combined CG with the crane hook. If the CG shifted the camera would rotate such that its optical axis would no longer be horizontal and the assembly could not be removed from the TEA. The CG of the counterbalance is adjustable to accommodate small variations from the predicted CG locations. The dome and its crane are configured to achieve this operation with the shutter closed.

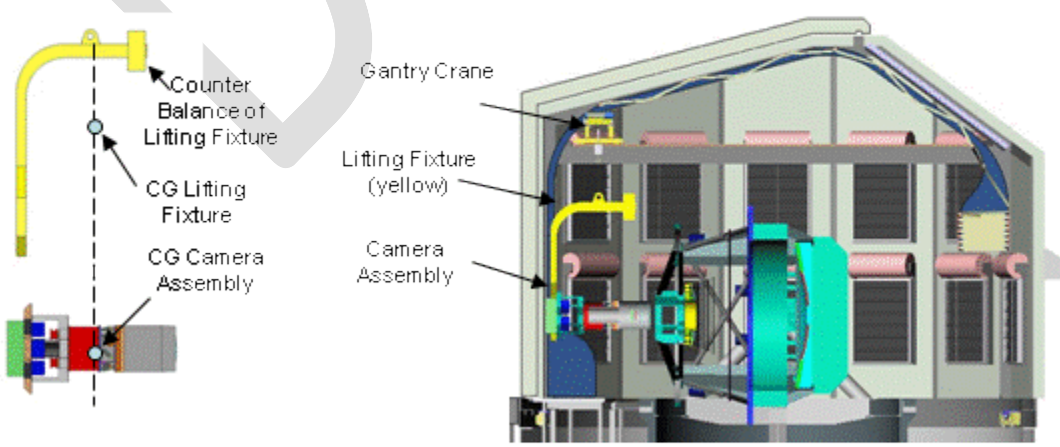


Fig. 4.1-2. Camera support assembly installation/removal

This method of camera installation is nearly identical to that used for installing the camera on the Vista Telescope, fig 4.1-3

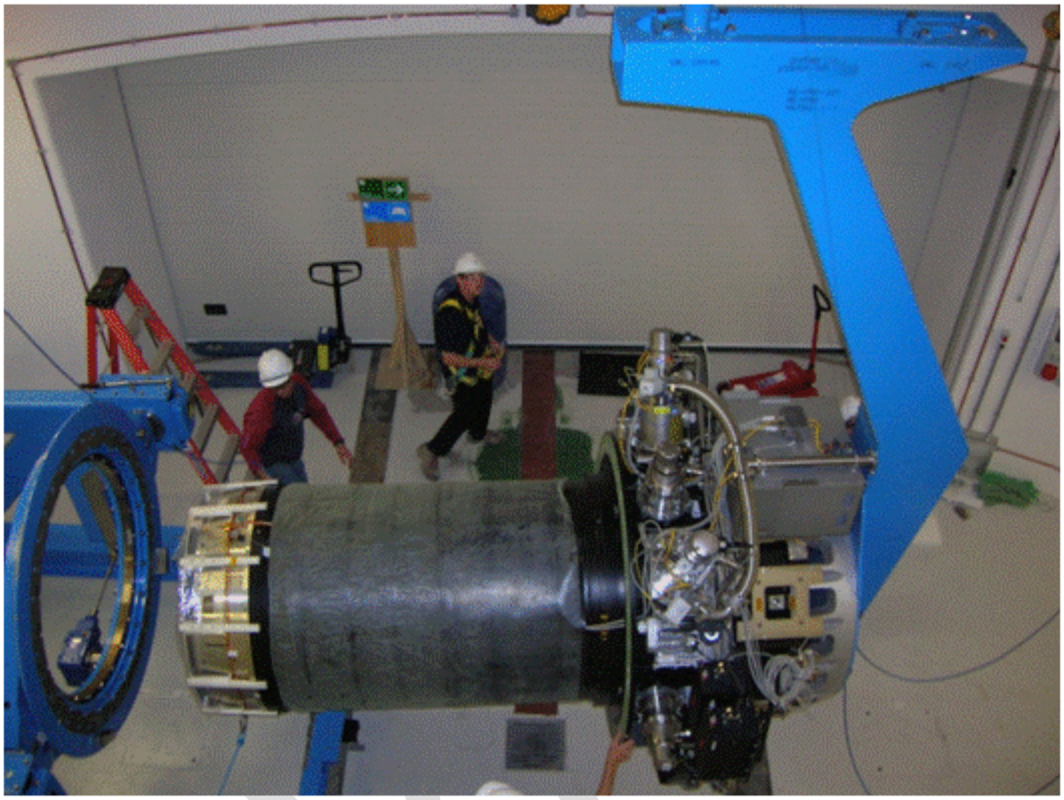


Fig. 4.1-3. Vista camera installation.

4.2 HEXAPODS AND ROTATOR

The Telescope Mount Assembly (TMA) interfaces to the camera and the secondary mirror (M2) cell assembly through hexapods, document 13998. These hexapods are not considered components of the TMA. Consequently, they represent the interfaces to the TMA, LTS-128. The purpose of the hexapods is to maintain proper orientation of the three optical assemblies: (1) camera, (2) secondary mirror (M2), (3) primary/tertiary mirror (M1M3), fig 4.2-1. It is only necessary to move two of the three optical systems to maintain alignment. Since the M1M3 is the heaviest of the optical systems and has the most complicated support systems the M2 and camera are actively oriented toward it with their hexapods. The M1M3 has a hexapod to optimally orient it relative to its support system. However, this hexapod is passive and not normally operated during telescope operations.

The requirements for these components are provided in LTS-206. Although they are demanding, these requirements are within the ability of existing technology as has been verified by multiple vendors.

The disorientation of the optical systems consists of despaces, tilts and decenters. These disorientations are principally produced by variation in gravitational orientation as a function of elevation angle distorting the TMA and the optical assemblies. Other influences include thermal variations, wind and creep. Since these hexapods counteract the disorientations of the optical systems produced by distortions of the TMA, the TMA does not need to be self correcting.

The hexapods will be principally operated by a lookup table. The major input to the look-up-table (LUT) is the elevation angle of the TMA. Bulk temperature changes will also be included.

The initial lookup table will be determined by finite element analysis of the TMA. This lookup table will be refined by measurements from the camera wave front sensor. The wave front sensor produces a measurement of the wave front with every exposure. The wave front sensor will be used to both refine the lookup table and to provide temporary offsets to the lookup table. The temporary offsets will counteract transient effects such as thermal gradients in the structure and mean wind effects.

Besides the wave front sensor, the LSST telescope also incorporates an on board laser tracker system which is not a component of the TMA. The tracker is located in the central hole of the M1M3 and secured to its mirror cell. The laser tracker uses retro reflectors attached to the three optical assemblies to determine their orientation relative to the telescope mount. The laser tracker system has a greater range of measurements and is less accurate than the wave front system, consequently it is moderately redundant. The laser tracker system will also be used to aid in refinement of the LUT, and to determine the initial LUT offset before the start of each nights observing. However, it will not be used during observing.

The demands on the actuators for both hexapods are very similar. Consequently both hexapods are required to utilize identical actuators. This requirement facilitates maintenance and repairs. The three systems (M2 hexapod, camera hexapod and camera rotator) are also required to utilize entirely separate electronics in physically separated electrical cabinets.

4.2.1 CAMERA HEXAPOD/ROTATOR

Positioning and tracking of the LSST camera will be accomplished by the camera hexapod/rotator assembly, fig 4.2.1-1. The hexapod aligns the camera along the optical axis, and the rotator tracks the sky motions by rotating the camera. To optimize mass and stiffness, the camera hexapod and rotator will be produced as a single unit referred to as the camera hexapod/rotator assembly. This eliminates the extra mass and flexibility associated with a bolted interface. The solid models of the telescope present these as two separate components to facilitate modeling.

The rotator is principally used to de-rotate the image inside the camera. Since the TMA is an Alt-Az (elevation over azimuth) configuration, azimuth motions produce a rotation of the image plane relative to the sky. The rotator is required to counteract this rotation during an image exposure which is typically 15 seconds.

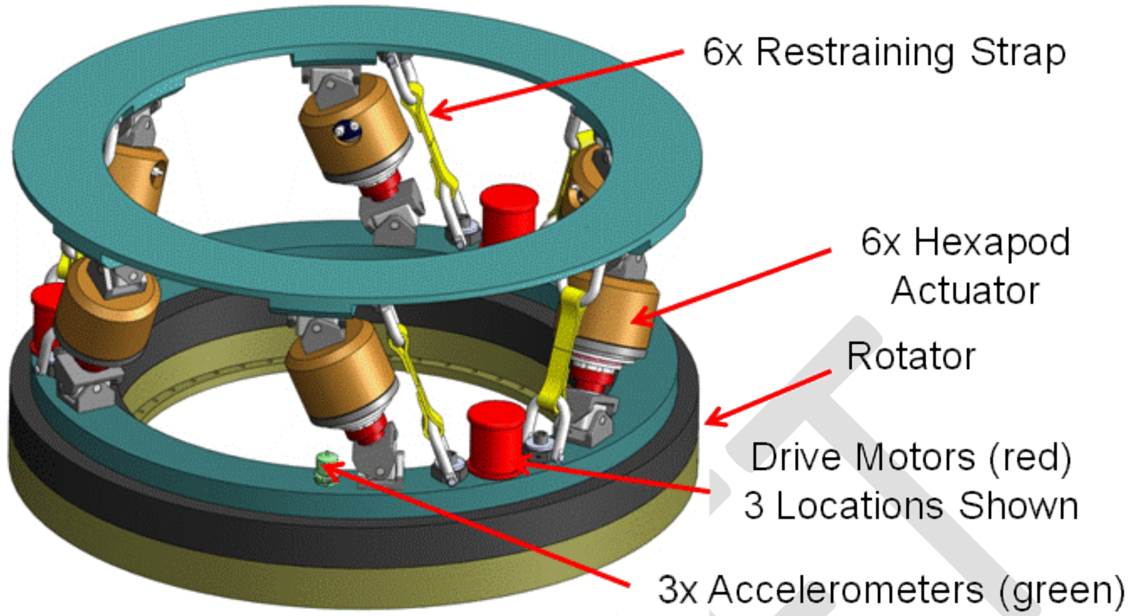


Figure 4.2.1-1: Camera Hexapod/Rotator Assembly

The camera hexapod/rotator assembly is entirely electromechanical. Since the assembly is located over the camera and M1M3 mirror consequently a significant drip hazard exists. This requires that all systems be sealed to prevent lubricant escaping and precludes the use of any hydraulics.

Although it is not shown in the previous figure, a flexible, removable shroud is required around the entire camera hexapod/rotator assembly. This shroud contains the heat produced by the camera hexapod/rotator along with the 200 W of heat escaping from the camera's utility trunk which is located inside the camera hexapod/rotator assembly.

4.2.2 M2 HEXAPOD

Geometric considerations preclude the use of a conventional hexapod arrangement for the M2 Hexapod. The bisymmetric Top End Assembly (TEA) has 16 spiders which connect its spider spindle with the rest of the telescope mount. A conventional three "V" hexapod configuration is geometrically incompatible with this spider configuration. Consequently, the M2 hexapod requires an unconventional actuator arrangement which is provided in LTS-181 and shown in fig 4.2.2-1.

The Spider Spindle of the TEA functions as the base flange for the M2 hexapod. Since the spider spindle is the principle structural member of the TEA, it is permanently attached to the telescope. The TEA was designed to accommodate any hexapod actuator design that can fit within the camera hexapod/rotator envelope. Since the M2 hexapod and camera hexapod utilize identical actuators, the maximum possible diameter of the hexapod actuators of 257 mm is inherently set by the camera hexapod rotator design envelope. Sufficient clearance around each actuator is provided to allow for both the hexapod motion, and the maximum actuator diameter. TEA must also provide sufficient ~ 75 mm clearance for M2 hexapod motions and fabrication tolerances. Sufficient length is also provided for any practical length actuator. Spacing blocks will be required to fill the difference between the actual actuator length and the space available.

A specific hexapod to M2 mirror cell assembly flange is mandated, LTS-181. The M2 hexapod is required to utilize identical actuators as the camera hexapod. Consequently, the M2 hexapod does not have a specific design envelope. Instead the TEA was designed to accommodate the M2 hexapod flange and any hexapod actuator that could fit within the camera hexapod design envelope.

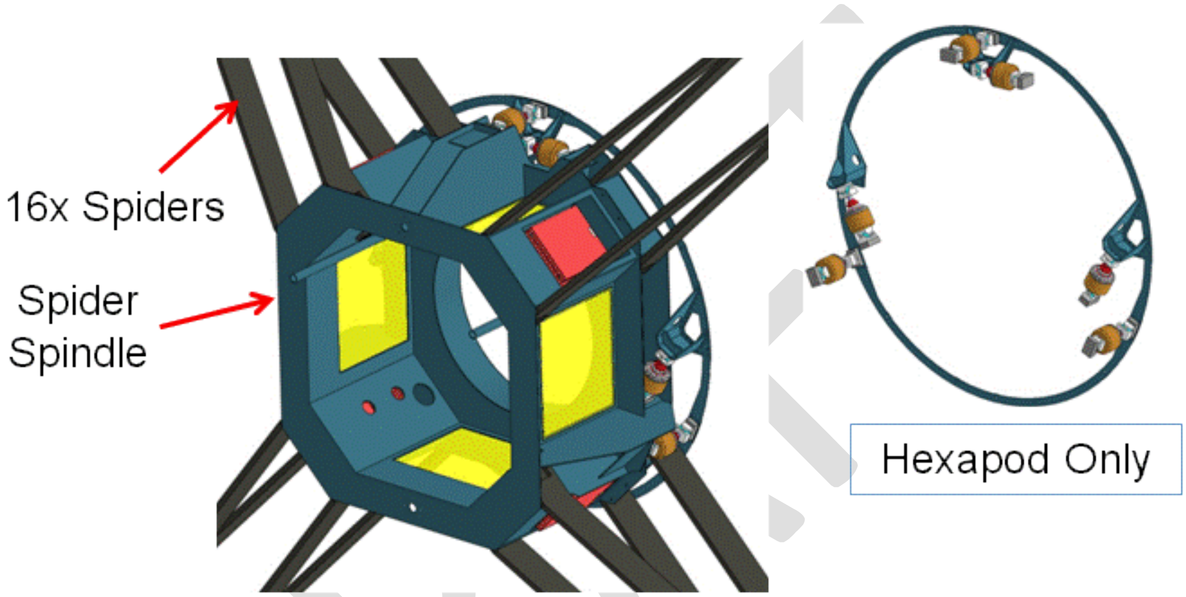


Figure 4.2.2-1: M2 hexapod installed on Spider Spindle.

The mass estimate of the M2 hexapod is 416 kg. Of this total, 151 kg is estimated for the M2 hexapod to M2 mirror cell flange and 265 kg is estimated for the six hexapod actuators.

4.3 MAINTEANCE ACCESS

The top end assembly has been designed to provide access to facilitate maintenance. The spider spindle of the central structure has large removable panels which, when horizon pointing, provide access to the interior, fig 4.3-1. The camera cable wrap is expected to require the most maintenance and is located at the top (when zenith pointing) of the central assembly where it can be easily accessed by a man lift when horizon pointing. The four electrical cabinets that are not removed with the camera support assembly are attached to the exterior of the spider spindle where they are accessible by ladder or man lift. All six actuators of the M2 hexapod are likewise accessible. Deployable platforms are also provide, as described in the flooring platforms and stairs section, to provide access to the camera and its hexapod/rotator.

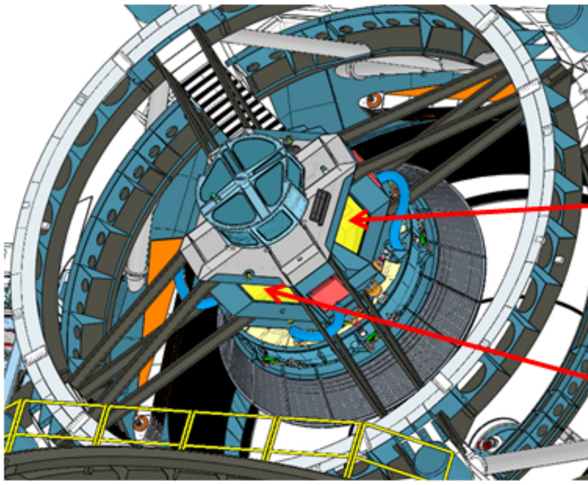


Figure 4.3-1:TEA Maintenance Access.

5 TELESCOPE MOUNT ASSEMBLY THERMAL MANAGEMENT

Extensive thermal management is required for adequate performance of the LSST optical system, LTS106. This is required to both limit thermal distortion of the optics and to control dome and mirror seeing produced by convection. The thermal management requires maintaining the temperatures of the various components to within close tolerances (~+1 to -2 C) to ambient air temperature, not just the removal of heat. Overcooling also produces detrimental effects.

All significant heat sources will have temperature sensors and temperature control systems. These principally include the M1M3 mirror cell assembly, M2 mirror cell assembly, camera and TMA drive systems. The azimuth and elevation drives utilize liquid cooled motors. In general, the TMA does not directly provide cooling for any of these sources except for the drives. However, it does provide the glycol/water coolant plumping, facilities routing for the camera's cryogenic system plumbing and provides a thermal control cabinet in the top end assembly to convert the glycol/water coolant systems to a local air cooling system.

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.

5.1 NATURAL CONVECTION

Natural convection occurs when heat raises the local air temperature which reduces the air density. The lighter air density causes the heated air to float. The variations in air density also produce variations in light refraction and will degrade the image quality if the heated air enters the optical path. The inverse is also true for cooled air increasing the air density, sinking into the light path and degrading the image quality. By minimizing the difference between the surface temperature and the ambient air temperature the image degrading convention is minimized.

Preservation of the image quality requires tight control of surface temperatures (of order 2C) to mitigate the image degrading effects of natural convection. This is achieved by a combination of natural cooling and glycol/water thermal management of the various heat sources as described in the following section.

The entire enclosure that houses the telescope is thermally controlled during the day and maintained at a temperature slightly below the expected initial ambient temperature at the beginning of the nights observing. This prevents the absorption of heat during the day in the telescope, telescope pier and flooring which would be released at night. The lower enclosure is insulated on both its interior and exterior to reduce the absorption and release of heat. At night a down draft system actively ventilates the lower enclosure to remove heat escaping from the ground floor, lower enclosure and telescope pier.

As the ambient temperature decreases during the night substantial heat is released from the telescope as its temperature drops while following the ambient air temperature. By maximizing the natural cooling the temperature difference between the surfaces and the ambient air are minimized which minimizes the image degradation.

Since it is impractical to actively thermally control the entire telescope with glycol/water, the telescope mount has been designed to facilitate natural cooling. The enclosure spaces that would trap air are minimized. Those remaining enclosed spaces, which are not thermally controlled by glycol/water, are ventilated (central structure of elevation assembly and azimuth assembly braces). The stairways, elevation platform, elevation walkway and deployable platforms are all perforated. The top end ring, which provides two light baffles, the intermediate baffle ring and the drive rings all have large holes. The perforations and large holes minimize the obstruction of natural air flow (wind). Natural air flow is the principal means of equalizing the temperature of telescope.

The rotating enclosure which surround the telescope and rotates with it also designed to facilitate natural cooling. It contains numerous vents to allow the wind to penetrate into it. Louvers over these vents are used to regulate the air flow and balance the negative effects of wind shake with the positive effects of natural cooling on image quality.

Although in general the telescope is coated with low reflectivity paint to minimize stray light, those surfaces that face the night sky will be receive a high reflectivity coating. This minimizes the radiant heat transfer from these surfaces to the night sky which can cool these surfaces below ambient which also produces image degrading convection as discussed earlier. These surfaces include the top most surface of the top end ring and the camera cable wrap.

5.2 GLYCOL/WATER THERMAL MANAGEMENT

Except for the heat released by the ambient temperature dropping and the cryogenic cooling of the camera focal plane, all significant heat sources on the telescope are directly or indirectly thermally controlled by the water/glycol thermal management system. 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 can also produces detrimental effects. Each of these heat sources will be monitored by temperature sensors and the temperatures will be controlled by mixing values. Mixing valves control temperature by varying the ratio of the coolant flowing through the component to the coolant bypassing it. This type of system varies from a throttle valve system in that the flow rate remains nearly constant. Consequently, the operation of an individual thermal control system has little affect on the rest of the system.

Heat loss will be controlled from all heat sources on the telescope and in the enclosure. The telescope's heat sources include the azimuth and elevation drives, the fans of the M1M3 mirror thermal control system, the active optics control systems for the M1M3 and M2 mirrors, the hexapods, the rotator, the camera, and all the associated electronics.

The sources that are beneath the optical path are maintained at temperatures slightly below (~1C) the ambient temperatures. Overcooled air will sink away from the optical path and not affect image quality. These sources include the drive motors and the capacitor banks that power them. The sources that are adjacent to the light path must be closely temperature controlled since either over heating or under heating will degrade image quality. This specifically requires tight temperature control on the central assembly of the top end assembly.

5.3 TOP END THERMAL CONTROL SYSTEM

Since it resides within the telescope's light path, the Top End Assembly and all its components must be designed to minimize image degrading thermal convection. This requires that, whenever practical, all components be chosen to minimize heat production, and that the heat produced be containment and removed.

A glycol/water central thermal control cabinet is attached to the integrating structure and resides inside the central assembly. This cabinet principally consists of heat exchanger, fans and a mixing valve control system. Air from the major heat sources which include the 6 electrical cabinets and the M2 mirror cell assembly are ducted directly to the thermal control cabinet. The central structure, when combined with a series of covers, is moderately air tight and functions as the air supply plenum for this thermal control system. Return air is ducted from the main heat sources to the central thermal control system. This thermal control system provides all thermal control for the top end except the camera which requires additional thermal control.

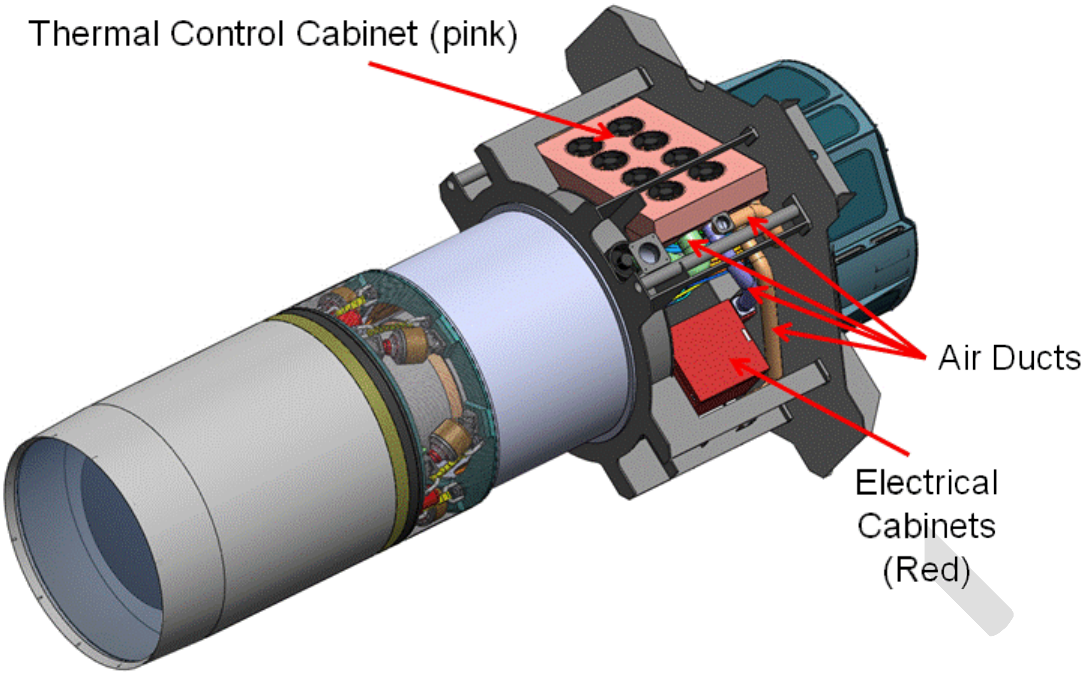


Figure 5.3-1: TEA Central Thermal Control System

Utilizing only a single central thermal control cabinet and ducting the cooling air minimizes the coolant leak potential and allows for effective condensation collection which is critical since the top end assembly resides above the M1M3 mirror. This thermal control system provides all thermal control for the top end except the camera which requires additional thermal control.

The central thermal control system is a component of the telescope mount assembly. Since it is attached to the integrating structure it is installed along with the camera support assembly. Any electronics that are installed on the top end assembly must be housed in cabinets thermally controlled by the central thermal control system.

As a result of its location relative to the optical system, thermal control of the camera hexapod/rotator assembly (hexapod/rotator) is of paramount importance. This thermal control is partially achieved by limiting the heat released by the various components. These components include the six actuators of the hexapod, the rotator drive motors, and the sensors and electronics. However containment and removal of the remaining heat is necessary to preserve the image quality.

Since the heat sources are dispersed, direct cooling off each source is impractical and the air surrounding the camera hexapod/rotator assembly must be contained. Consequently a flexible, removable shroud is required around the entire camera hexapod/rotator assembly. This shroud is shown as a transparent dark gray covering over the camera hexapod in fig 5.3-2. This shroud must be flexible to accommodate motions of the hexapod. It must be readily removable to allow maintenance access to the hexapod, rotator, and camera utility trunk. This shroud also contains the 200 W of heat escaping from the camera's utility trunk which is located inside the camera hexapod/rotator assembly. A simple system of rubber sheeting attached with Velcro is envisioned for this application. Since the most commonly accessed location inside the shroud will be the utility trunk described in the envelope section, these locations will require subpanels so they can be accessed as shown in figure 5.3-2 without removing the entire shroud.

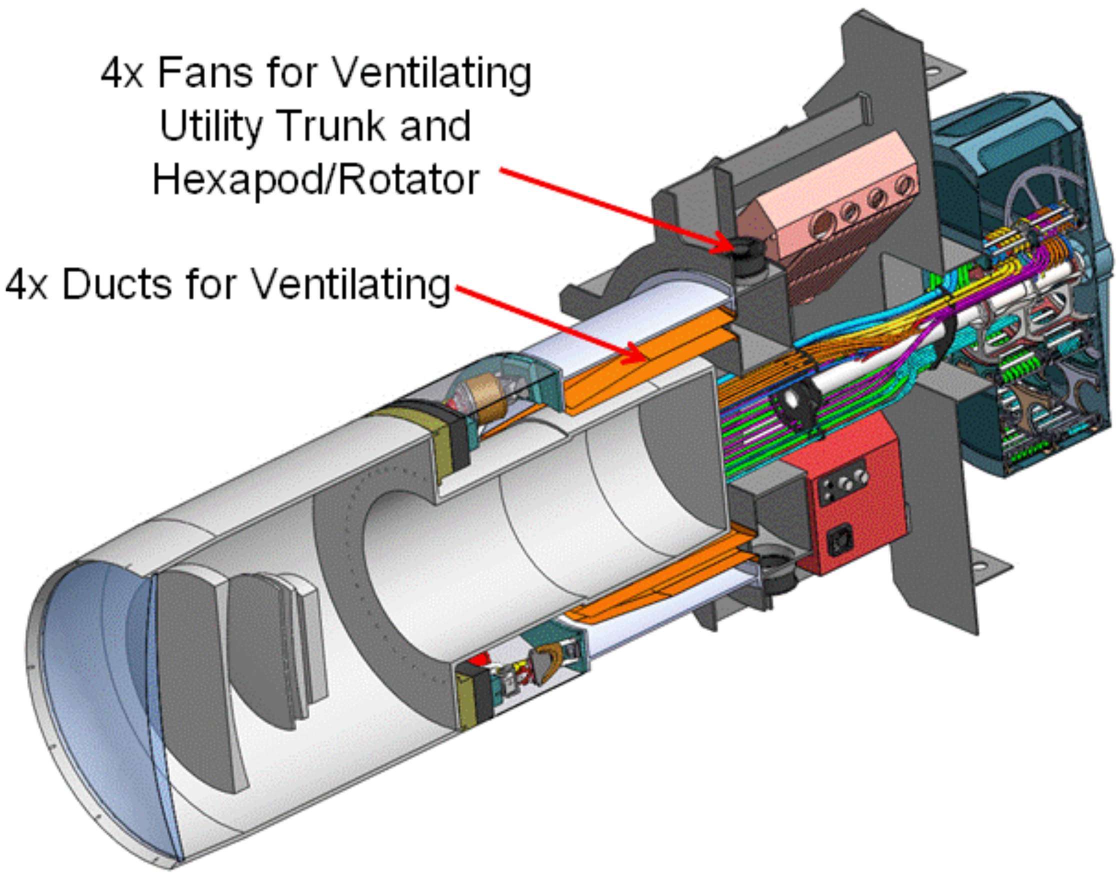


Figure 5.3-2: Thermal Control of Camera Hexapod/Rotator and Camera Utility Trunk.

The heated air contained by the shroud is removed by interactive air circulation with the rest of the TEA thermal control system, fig 5.3-2. Air from near the thermal control cabinet is propelled by four fans though ducts along the inside of the offset of the integrating structure, and is injected onto the utility trunk and toward the camera hexapod/rotator assembly. The return is along the utility trunk and cabling that connects the camera to its rotator.

As a result of its location and lower heat production a covering is not required for the M2 Hexapod actuators. While heat escaping from the camera hexapod/rotator assembly passes through the light path three times, heat from the M2 hexapod only passes through the light path once. Consequently, it is significantly less detrimental to the image quality.

5.4 CAMERA THERMAL CONTROL

The camera has the most demanding thermal control requirements. As a result of its location between the M2 mirror and the M1M3 mirror, heat escaping from the camera may cross the optical path up to 4 times. Consequently, heat escaping from the camera is more detrimental to the image quality than heat from any other source, document-9367. Consequently, the thermal control requirements are also more restrictive. Three separate systems are used to control the thermal control of the camera. A cryogenic system is used for its optical detectors, glycol/water cooling is used of the electronics in the utility trunk, and air circulation from the top end assembles thermal control systems captures the remaining heat escaping from the utility trunk as described previously.

The cameras optical detectors operate at ~-100C, consequently, it would be highly impractical to utilize the telescope mounts glycol/water cooling system for this application. The camera will utilize a separate cryogenic system for the detectors. Since this cryogenic system is only utilized by the camera it is not considered a component of the TMA. However, the TMA is required to accommodate the extensive plumbing that this system requires. Since the refrigerant must transverse from the camera all the way to the facility all three cable wraps must accommodate these lines.

Besides its cryogenic thermal control systems, the camera also utilizes direct glycol cooling for its electronics which are housed in its utility trunk. Although the camera has extensive cooling, significant heat of approximately 200 W will escape from the utility trunk. This heat is removed by the same air circulation system supplied for the camera hexapod/rotator and described in the top end thermal control section.

6 PIER FOR TELESCOPE MOUNT ASSEMBLY

The telescope mount resides on top of the telescope pier, fig 6-1, document-11576 and document-11094. Although this concrete telescope pier is not considered part of the mount, its design and characteristics fundamentally affect the operation, maintenance and performance of the mount. Added flexibility of the pier affects the overall system flexibility and therefore the mount’s dynamics characteristics. Although in general, the telescope pier is not considered a part of the TMA, the azimuth bearing track, dive gear, brake surface, hard stop, topple block and encoder which are attached to the pier are considered components of the TMA. To prevent the transmission of vibrations, the telescope pier must be separate and isolated from the rest of the observatory.

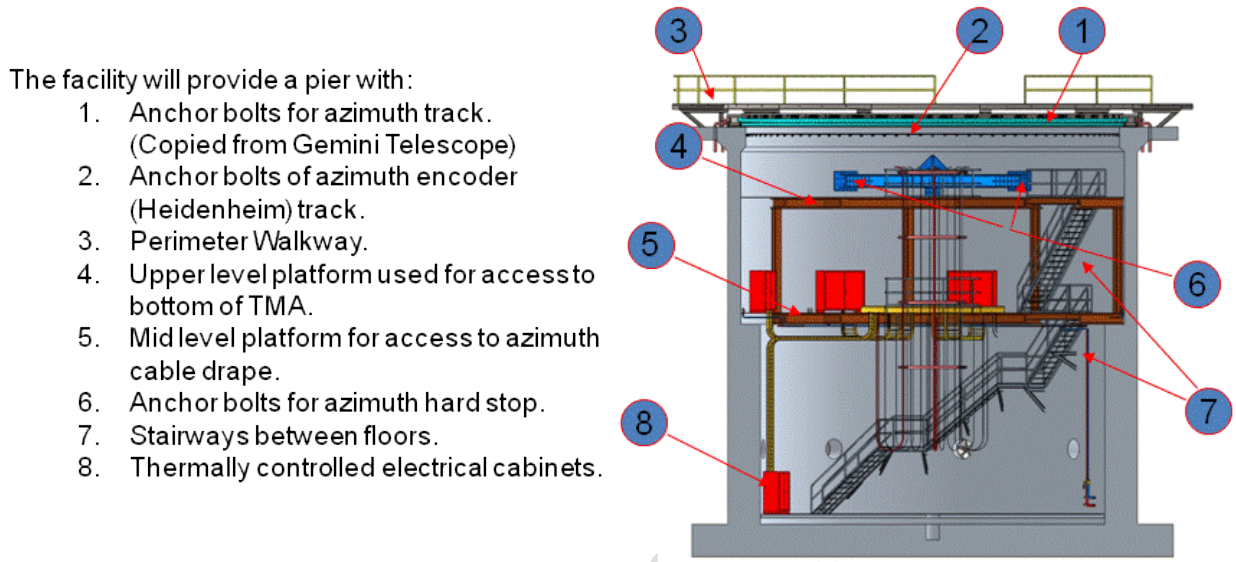


Figure 6-1: Components of telescope pier.

The telescope pier height was established to have the M1M3 mirror above the wind's turbulent layer at the site. This turbulent layer carries heat away from the earth's cooling surface. Consequently, the image quality looking through this layer is poor.

Site testing and analysis of local seeing effects on El Peñón, the site for LSST on Cerro Pachón, determined that the center of the M1M3 should be ~22 m above the ground level to stay above the turbulent boundary layer. This conclusion is consistent with the height that was established by site testing for the 8m Gemini Telescope on the adjacent peak.

Placing the optical system at the desired height requires that the telescope resides atop an approximately 16 meters high pier. The compact design of the TMA leads to a higher pier relative to the axis of the elevation assembly. Effectively the design transfers mass from the TMA to the pier which reduces the moving mass and increases the stationary mass. This is beneficial since the drive power is only affected by the moving mass. The configuration also lowers the telescopes center of gravity relative to the bearing race on the top of the pier providing enhanced dynamic performance.

To prevent the transmission of vibrations, the telescope pier is separate and isolated from the rest of the observatory. These vibrations result principally from the enclosure (dome) rotation, but also from dome wind shake 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 lower enclosure floors and the pier to ensure vibration isolation, prevent impact during seismic events and provide for thermal control of the pier. This specifically precludes supporting the observatory floor or the telescope maintenance floor off of the pier. Rigid conduits, piping, etc cannot traverse between the telescope pier and the lower enclosure.

The dome's drive system utilizes capacitor banks to power its drives analogous to the telescope mount drive system. These capacitor banks will be housed on the middle floor of the telescope pier and their cabling will traverse from the telescope pier to the lower enclosure ring wall. As described above vibration isolation requires that this connection not utilize rigid conduits.

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. To improve the dynamic performance of the pier, it will be constructed of two different thicknesses, fig 6-2. 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.

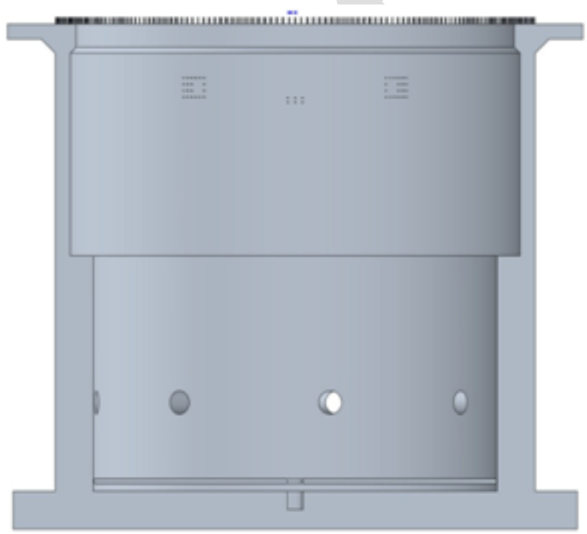


Figure 6-2: Cross Section of the telescope pier.

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 M 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, document-6265.

The pier will also be constructed from higher strength concrete, H40, which also has a greater specific stiffness, document-11094, rather than the more common H30. Specific stiffness is the ratio of elastic modulus to density. Since the natural frequency is proportional to the square root of the specific stiffness this has a direct effect on the overall natural frequency.

Local stiffness of the top of the pier was enhanced by the addition of a wide flat horizontal lip around the outer perimeter. This lip limits the distortion of the pier top (oil canning) and facilitates the installation of the perimeter walkway that surrounds the telescope, document-11094.

Finite element analysis was utilized to verify the properties of the pier and foundation when installed. 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 was 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 track. This baseline track and its attachment to the top of the telescope pier were appropriated from the Gemini Telescope. The drive gear and brake surfaces are attached to this track and do not require individual mounts. The track is also used to attach the earthquake clips which prevent the telescope from leaving the track during a seismic event.

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. For accessing this equipment from inside the pier, an upper level platform is provided under the telescope, inside the pier and attached to the pier, fig 6-2.

A significant quantity of cabling from the facility to the telescope is required to operate the telescope. These cables, which include power, control, and cooling, are connected to the telescope through maypole type cable drape described earlier. A second middle level platform half way up and internal to the pier is provided 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. Two ladders will be provided from the top level platform to the floor of the telescope. These ladders will move with the telescope. At least one will be accessible regardless of the telescope orientation.

7 TELESCOPE MOUNT ASSEMBLY PAYLOADS

The TMA supports the three optical payloads:

1. Primary tertiary (M1M3) mirror cell assembly.
2. Secondary (M2) mirror cell assembly with hexapod.
3. Camera with hexapod/rotator assembly.

Supporting the payloads requires that; they be firmly secured to the interfaces, located at the proper orientations to each other, allow for the necessary utility routing, and provide for the clear optical path. The TMA is also required to facilitate maintenance of all of these payloads. They must also be installable and removable as complete assemblies. The camera is installed and removed in a larger assembly referred to as the camera support assembly which includes the camera (with hexapod/rotator) and several TMA components. See the camera support assembly section for more details.

The three payloads comprise the optical system. These payloads are not components of the TMA. However, since the purpose of the TMA is to support and position them, allowing the optical system to acquire and track field on the sky, descriptions of these payloads are provided in this document.

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 M1M3 cell assembly removal.

7.1 PIMMARY TERTIARY MIRROR (M1M3) CELL ASSEMBLY

At a mass of ~51 tons the primary/tertiary (M1M3) mirror cell assembly, document-9689 & document-9255 is the principle payload of the telescope mount. It supports both on-telescope operations and off-telescope mirror coating. This assembly consists of the M1M3 monolith mirror, the mirror support systems, the thermal control system, a stray light baffle ring, a laser tracker interface and the supporting steel structure. During observing, the M1M3 mirror is actively supported by figure control actuators and a hexapod. The M1M3 figure control actuators distribute the load to safely support the glass mirror and actively control its shape. The position of the mirror relative to the mirror cell is controlled by a set of six hardpoints (displacement controlled actuators) that form a large hexapod. When the active system is not operating the mirror is supported by a separate passive support system. 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.

The center of the mirror cell supports a laser tracker which measures the relative position of the camera and secondary mirror for alignment by their hexapods. The mirror cell design internal height of 2 meters provides ample internal clearance for installation and maintenance of mirror support and thermal control systems. The mirror cell also functions as the bottom of the vacuum chamber during coating. Consequently, to withstand the vacuum-induced stress the M1M3 mirror cell will be fabricated from higher strength steel. The vacuum-induced mirror cell deformations must be isolated from the mirror support system to prevent overstressing the mirror. This is accomplished by utilizing separate truss support systems for the top deck and the vacuum boundary.

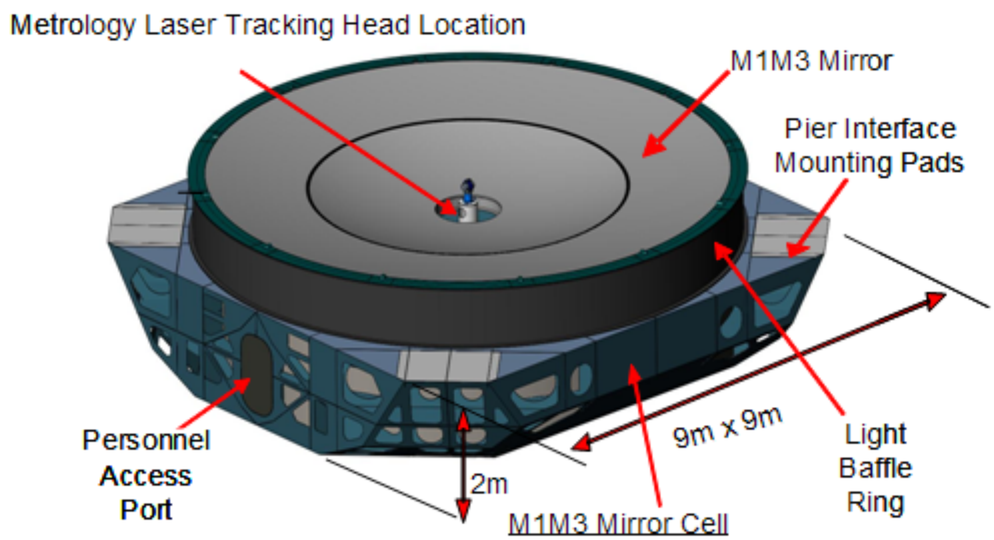


Fig. 7.1-1. Primary Tertiary (M1M3) Mirror Cell Assembly.

To limit the risk to the borosilicate mirror, all servicing and optical recoating must be accomplished without removing the glass M1M3 monolith from the cell. Since the coating must be applied in a vacuum, the mirror cell must also function as the bottom half of the vacuum chamber. Consequently, to withstand the vacuum induced stress the M1M3 mirror cell will be fabricated from higher strength steel, A572 Grade 60, than the telescope 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 M1M3 mirror and the truss system which supports the vacuum boundary. Separate intertwined truss structures are used to support the top deck which supports the M1M3 mirror and the mirror cell bottom and sides which resist vacuum. These two truss structures are not in contact. Consequently, the vacuum induced deformations of the vacuum truss structure does not deform the top plate truss structure.

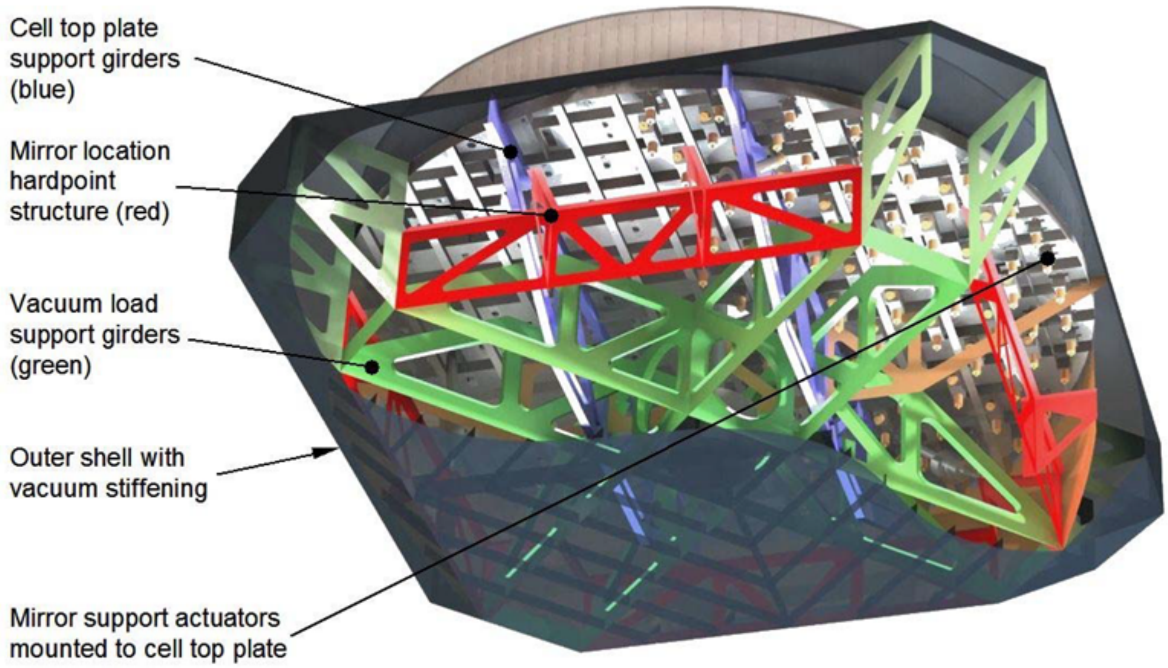


Fig. 7.1-2. Primary Tertiary (M1M3) Mirror Cell Assembly Structure

Not only does the TMA support the M1M3 but it also provides for the water/glycol coolant required for the M1M3 thermal control system. This constitutes the largest load of the telescope thermal control system and hence requires the largest amount of coolant flow. Consequently, the pipe size to the M1M3 will be equal to the plumbing mains supplying the entire TMA of 2-3". The M1M3 also requires high quality compressed air to operate the M1M3, electrical power and controls/sensor cabling. The water/glycol coolant plumbing and the compressed air system will utilize hard piping and are considered components of the TMA up to their interface with the M1M3 mirror cell assembly. Except for those that are required to operate the telescope mount assembly, all other utilities including power and communication cabling are not considered components of the TMA. The TMA provides for the routing of all piping and cabling through the telescope regardless of whether they are considered components of the TMA. This includes routing through all three cable wraps azimuth, elevation and camera.

7.1.1 M1M3 MIRROR CELL ASSEMBLY DESIGN ENVELOPE

As a result of the advanced design state of the M1M3 mirror cell assembly, the design envelope is essentially the exterior of the mirror cell assembly, the M1M3 mirror and the light baffles that surround the mirror. This envelope is provided in 7.1.1-1. The TMA was designed to accommodate this M1M3 mirror cell design. There is able clearance both for the M1M3 to move during the 0 to 90 degree zenith angle changes, and for the installation/removal of the M1M3 mirror cell assembly with the mirror cell cart.

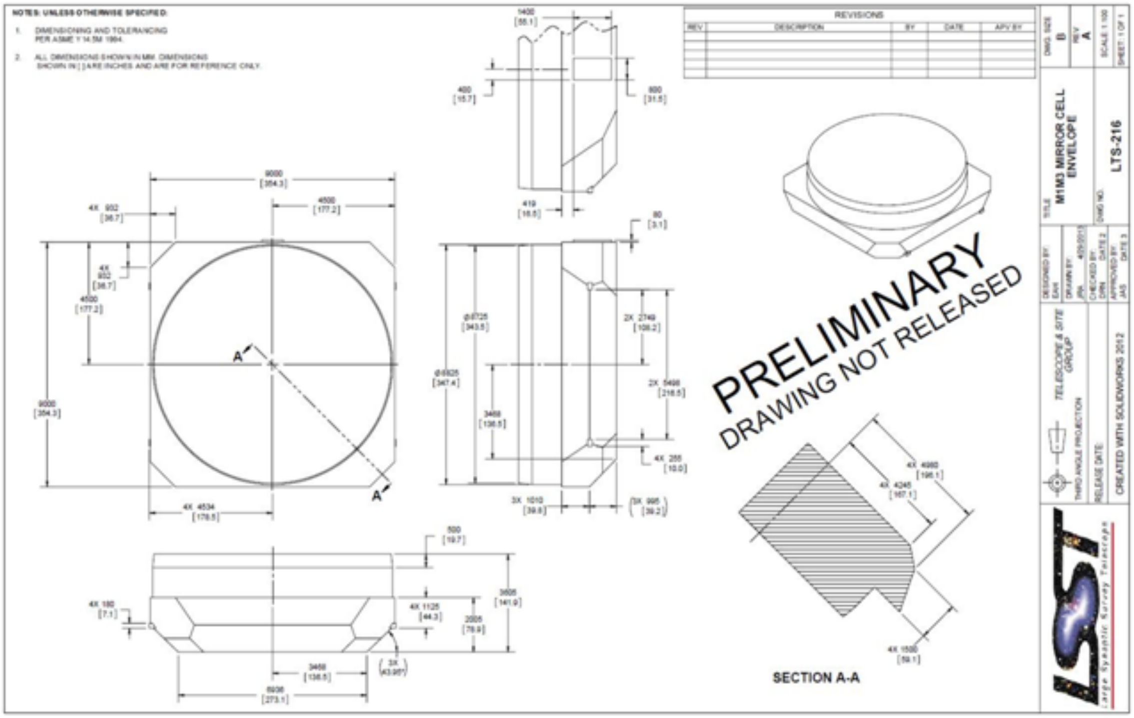


Fig. 7.1.1-1. M1M3 design envelope.

7.1.2 M1M3 MIRROR CELL ASSEMBLY INTERFACES TO TMA

The mirror cell is only attached to the TMA by four piers which attach it to the center section of the elevation assembly. This simplifies the removal of the mirror cell assembly from the telescope and minimizes the transmission of TMA deformations into the mirror cell. The four pier mounting locations are connected by hardpoint support trusses. The M1M3 hexapod actuators (hardpoints) attach to this structure. This configuration minimizes the length of the structural load path from the M1M3 hexapod mounts to the pier mounting locations. Minimizing this path length maximizes the stiffness and the rigid body natural frequency of the mounted mirror.

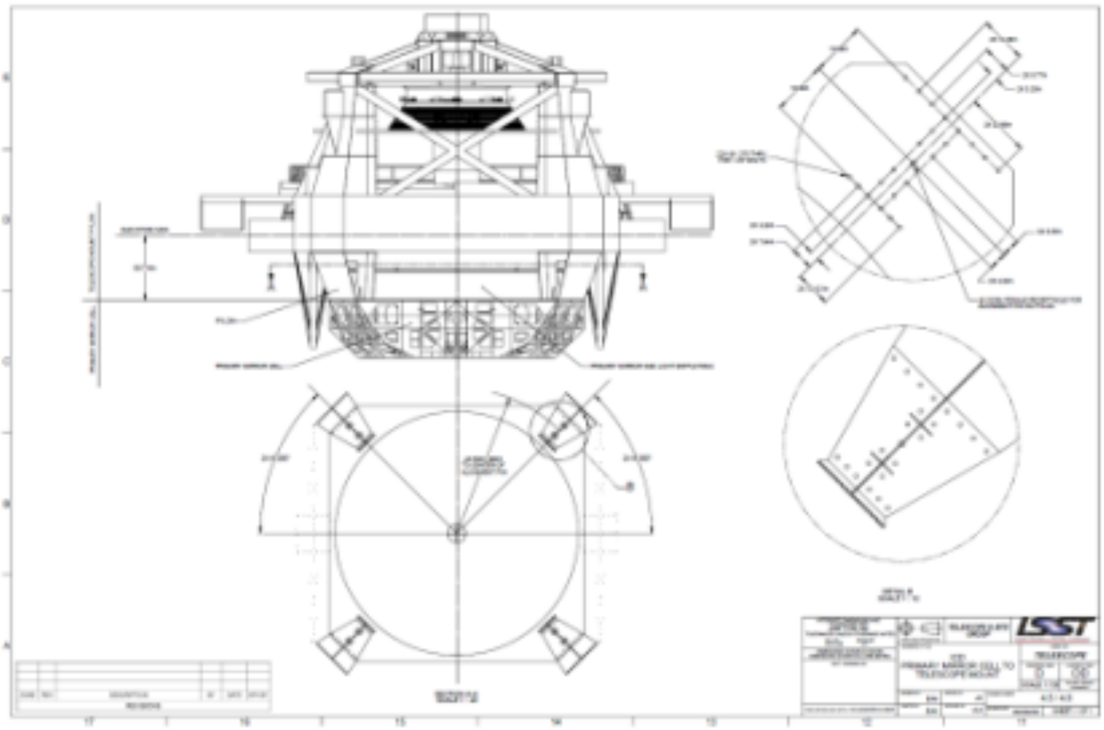


Fig. 7.1.2-1. M1M3 interface drawing.

7.1.3 M1M3 MIRROR CELL ASSEMBLY ON TELESCOPE MAINTENANCE ACCESS

The vast majority of the maintenance required for the M1M3 active mirror support system and thermal control system will occur from within the interior of the M1M3 mirror cell. Consequently, the M1M3 mirror cell and telescope mount have been designed to facilitate access into the interior. A large walk in portal is located on the side of the mirror cell. The portal is also positioned directly above the telescope utility floor. Consequently, all critical M1M3 systems are accessible from the main level of the telescope.

A light baffle covers the outer perimeter of the M1M3 mirror. This baffle will be fabricated from light sheet metal and designed to be removable in manageable sections while the M1M3 mirror cell assembly is installed on the telescope. This allows access to the ~100 mm gap between the top of the mirror cell and the bottom of the mirror.

7.1.4 M1M3 MIRROR CELL ASSEMBLY INSTALLATION AND REMOVAL

Optical coating for the M1M3 and M2 mirrors will be accomplished through sputter coating. 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.

Through the use of a mirror cell cart, the M1M3 cell assembly is installed and removed from the TMA. The cart is self propelled and travels on an embedded rail system from the TMA to the coating chamber in the support facility.

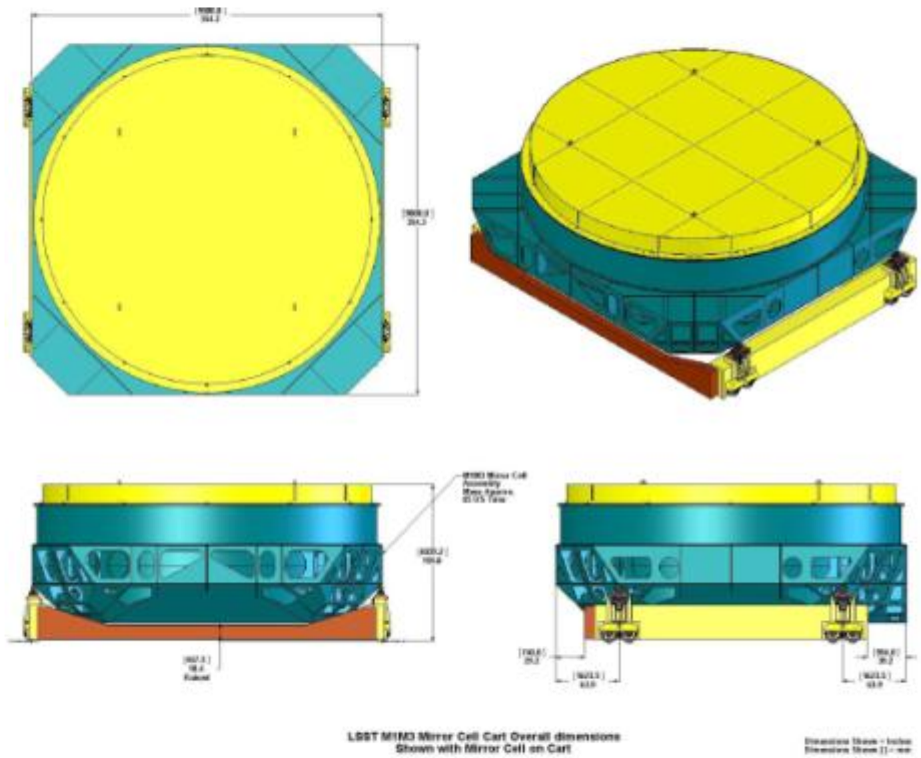


Fig. 7.1.4-1. M1M3 mirror cell assembly on cart.

Although this cart is not a component of the TMA, the TMA must accommodate the use of the cart for installing and removing the M1M3 mirror cell. This requires that the rotating main floor of the telescope be even in elevation with the fixed telescope maintenance floor of the lower enclosure. The TMA must accommodate the tracks that the cart rides on, and provide clearance for the motion of the cart loaded with the M1M3 mirror cell assembly.

The M1M3 is attached to the TMA through four piers. Two of the piers must remain attached to the M1M3 mirror cell assembly until after that assembly is removed from the TMA.

This same mirror cell cart is used to move the M1M3 to the optical coating facility in the maintenance and support building. This requires the combined M1M3 mirror cell assembly with mirror cell cart and mirror cover be lowered to the main floor of the maintained and support building with a high capacity reciprocating conveyor (equipment elevator). During the entire transportation and coating process, the M1M3 mirror monolith will remain in the mirror cell, and the mirror cell will remain on top of the cart.

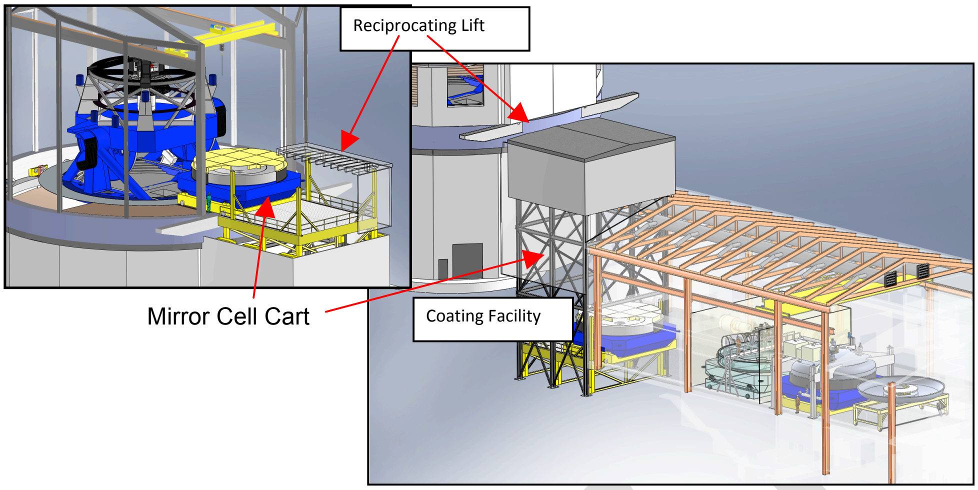


Fig. 7.1.4-2. Mirror cell transportation.

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.

7.2 SECONDARY MIRROR (M2) COMBINED ASSEMBLY

The approximately 6 ton M2 combined assembly includes the M2 hexapod, M2 mirror cell assembly (M2 cell) and M2 light baffle (M2 baffle), LTS-193 and LTS-146. The M2 hexapod is permanently attached to the spider spindle of the TMA and maintained in place. The M2 cell attaches to the M2 hexapod and is installed as a complete assembly. Although the performance of major repairs and maintenance are not envisioned while the M2 mirror cell assembly is installed on the telescope, the M2 cell is designed and its installation configured to allow significant on telescope access. The M2 light baffle attached to the M2 cell and is required for stray light mitigation.

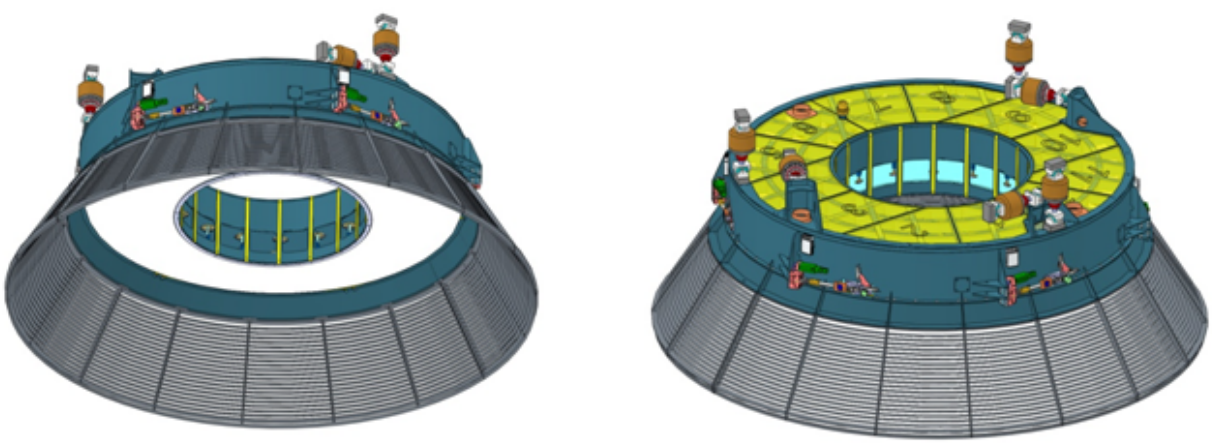


Fig 7.2-1: M2 Combined Assembly: Mirror Cell Assembly, Light Baffle, Hexapod.

The M2 mirror cell assembly, fig 7.2-1, includes the M2 mirror cell structure, the M2 mirror supports (axial actuators and tangent links), the M2 thermal control system, various mirror sensors and the M2 control system, LTS-193. The "M2 mirror" includes both the polished substrate and the invar mounts required for attaching the actuators of the support system. An extensive description of the M2 baseline design of the M2 mirror cell assembly is available in the M2 baseline design, LTS-193. For simplicity, in this document the M2 mirror cell assembly refers to the M2 mirror cell assembly with the mirror installed.

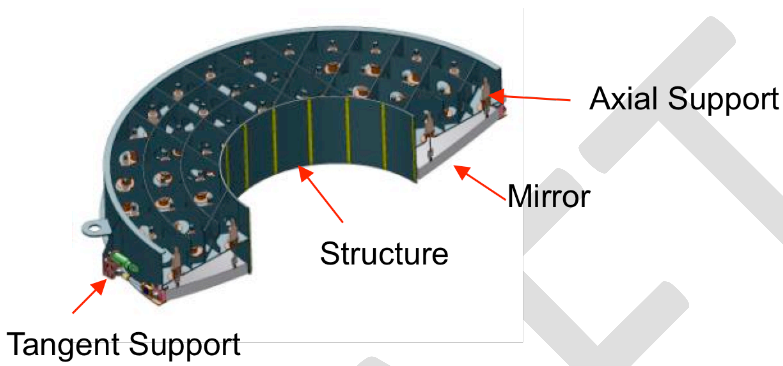


Figure 7.2-2: M2 Mirror Cell Assembly (cover panels and thermal control system not shown)

Except where impractical, all the electrical components of the M2 mirror control system will be installed in the interior of the M2 mirror cell assembly where they can be protected from the elements and thermally controlled. This also facilitates operation of the M2 mirror cell assembly during handling and testing when it is not attached to the telescope.

The power supplies and the controller are located inside of the electrical cabinets attached to the exterior of the spider spindle rather than inside of the M2 mirror cell assembly. One of these four cabinets is dedicated to the M2 active support system and one is dedicated to the M2 hexapod. These components must be readily accessible for replacement and maintenance when the M2 mirror cell assembly is installed on the telescope. The size of these components would have made mounting them interior to the M2 mirror cell difficult. Since the power supplies are a major heat source for the M2 system, mounting them inside these electrical cabinets facilitates their thermal control.

Since the external electronics are housed in electrical cabinets attached to the exterior or the spider spindle, the M2 mirror cell assembly remains operational when the camera support assembly is removed. This allows for the testing and operation of the M2 mirror cell assembly without the installation of the camera support assembly. This facilitates operation of the calibration and engineering instruments when the observing instrument is not installed.

The M2 electronics are designed to minimize the number of connections between the M2 mirror cell (cell) assembly and the electronics cabinet. To minimize the risk to the M2 mirror, the M2 active support system remains operational during installation and removal of the cell assembly from the telescope. This requires that sufficient electronics to operate the system be temporarily installed on the utility mounts located the exterior circumference of the M2 mirror cell, fig 7.2-3. Minimizing the electronics connections facilitates this configuration. Either the electronics located in the electrical cabinets will be temporarily relocated or a separate set of electronics will be utilized.

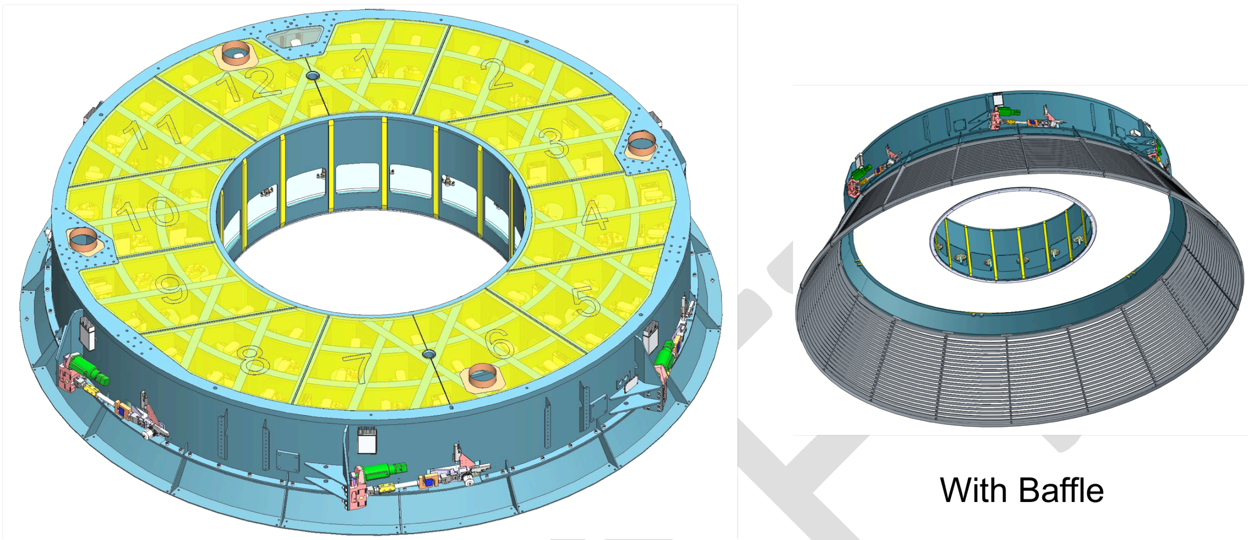


Figure 7.2-3: M2 Mirror Cell Assembly (With and Without Baffle)

The M2 mirror cell is an open back structure to optimize access to the 72 figure control actuators and their associated electronics and cabling. When in operation, 12 lightweight thermally insulated top panels (G10 fiberglass or equivalent) are utilized to enclose the top of the mirror cell to capture heat dissipated by the actuators and to protect the components. These panels are shown as yellow semi transparent in fig 7.2-3. These panels are removable for maintenance both while the M2 assembly is installed on the telescope or on the cart. Utilizing a soft non metallic material for these panels minimizes the danger to the M1M3 mirror in the event of a panel escaping.

The purpose of the open back and panel configuration is to improve access to the M2 mirror cell interior. Consequently, the interfacing between the TMA, the M2 hexapod and the M2 mirror cell assembly are designed to maintain this accessibility.

The M2 baffle, fig 7.2-3, is not considered part of the TMA. However, this baffle mounts to the M2 cell. Consequently, the M2 hexapod must support both the M2 cell and the M2 Baffle. This hexapod permanently mounts to the spider spindle as described in the hexapod section

The entire M2 mirror cell assembly, combined with the M2 baffle, is aligned with the M1M3 by motions of the M2 hexapod. A hexapod by definition uses six actuators to control the motion in all six degrees of freedom. Consequently, there are no redundant load paths and the failure of a single hexapod actuator could allow unrestrained motion of the entire assembly. To prevent unrestrained motion in the case of a

M2 hexapod actuator failure, the top end assembly incorporates a restraint strap system which loosely connects the M2 mirror cell assembly to the spider spindle, fig 7.2-4.

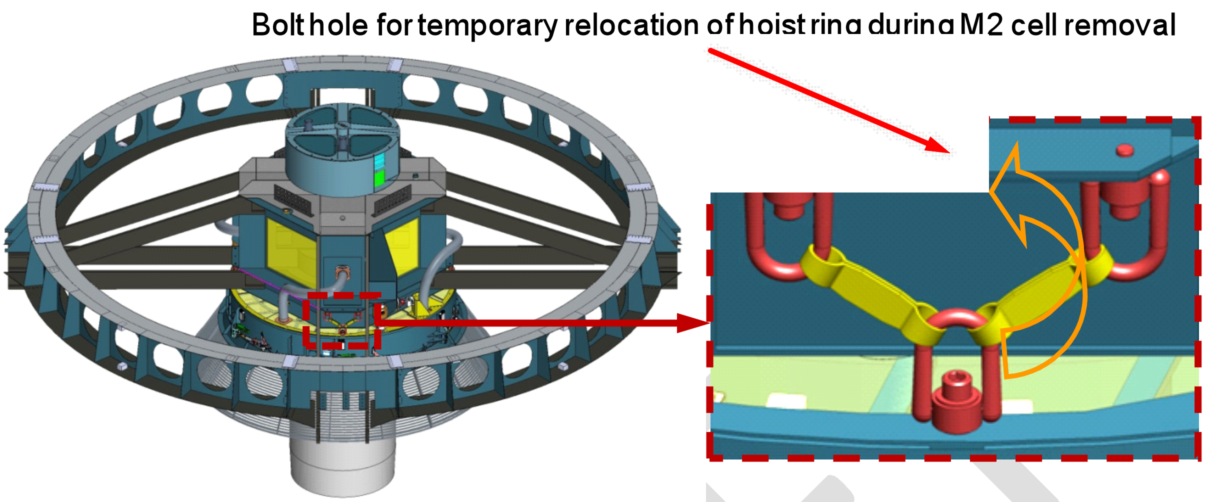


Figure 7.2-4: M2 Mirror Cell Assembly Restraining Straps

Although the purpose of this system is to provide load paths redundant to the M2 hexapod, since it remains permanently attached to the spider spindle it is considered a component of the TMA.

7.2.1 M2 COMBINED ASSEMBLY PRINCIPAL COMPONENTS AND DESIGN ENVELOPES

The Telescope Mount Assembly (TMA) provides adequate space for the M2 hexapod, M2 mirror cell assembly and the M2 baffle. The clearance is sufficient to accommodate the removal and installation procedures described in this document and provide for motion of the hexapod.

7.2.1.1 M2 HEXAPOD

As a result of the complexity of the Top End Assembly (TEA), a formal design envelope was not determined for the M2 hexapod. Instead a specific design was adopted for the M2 hexapod to M2 mirror cell assembly flange, and the maximum size and range of the actuators is set by the requirement that the M2 hexapod and camera hexapod utilize identical actuators. This requirements section is described in detail in the hexapods section.

7.2.1.2 M2 MIRROR CELL ASSEMBLY (M2 CELL)

The design envelope for the M2 mirror cell assembly, ref 3, is an axis symmetric flat ring. In fig 7.2.1.2-1, the M2 mirror cell assembly is shown embedded in views of the design envelope. The outer diameter is limited to facilitate the removal of the mirror cell assembly from the telescope. The inner diameter is required to provide sufficient clearance for the camera installation.

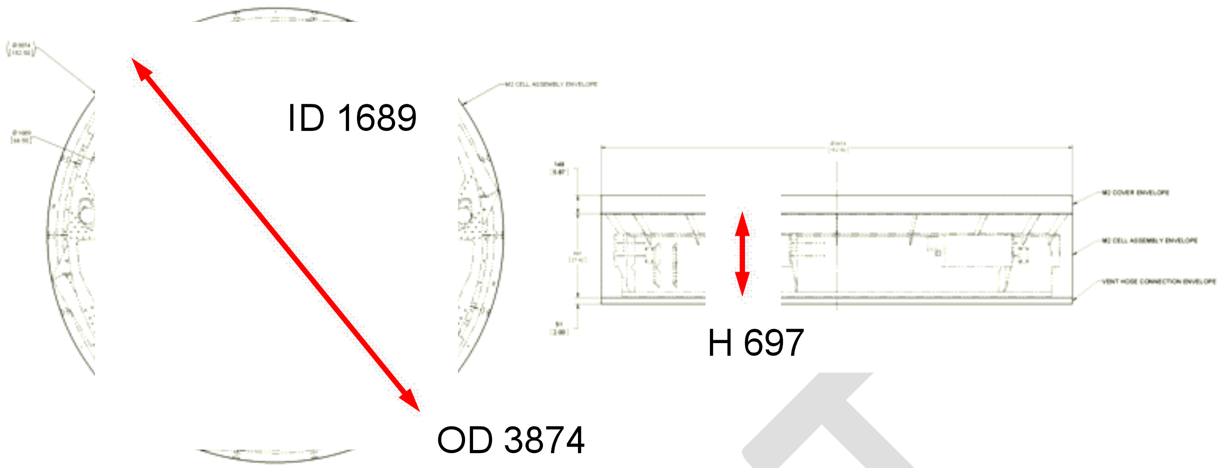


Figure 7.2.1.2-1: Simplified Design Envelope in millimeters.

The important aspects of the design envelope are:

- The optical path to the optical surface and the retro reflectors must not be obscured.
- The inside diameter of 1689 mm must provide at least a 1689 mm clear through hole to install the 1650 mm OD camera. The 1689 mm must include the 10mm thick Delrin sliders.
- The system must attach to the hexapod flange or mirror cart on the top plane.
- The system must attach to the light baffle or mirror cover on the bottom plane.

7.2.1.3 M2 LIGHT BAFFLE (M2 BAFFLE)

Since the light baffle is not in close proximity to any other components, except its mounting to the M2 mirror cell assembly, a formal design envelope is not necessary. This design envelope of this component can be considered a simple truncated cone with height of ??, top diameter of ?? and bottom diameter of ???.

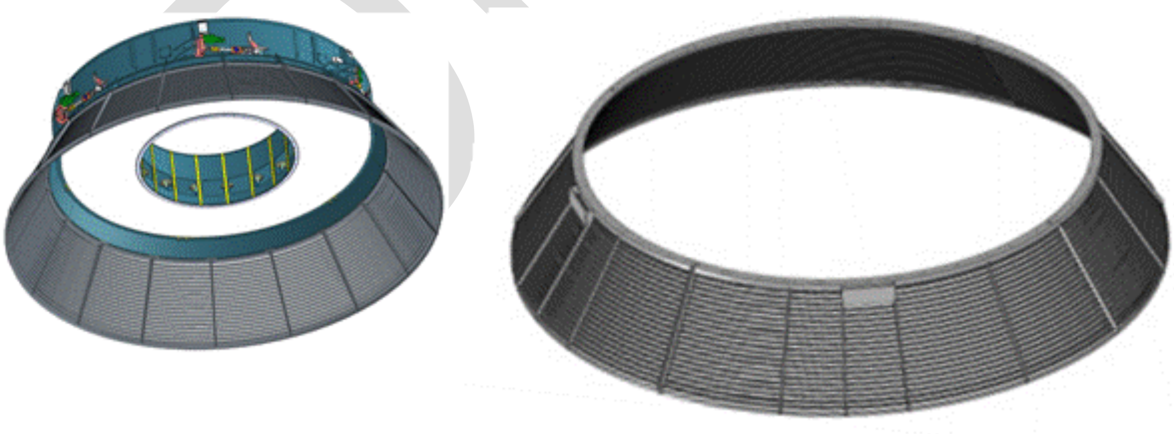


Figure 7.2.1.3-1: M2 Light Baffle.

7.2.2 M2 COMBINED ASSEMBLY INTERFACES TO TMA

Neither the M2 mirror cell assembly nor its baffle interface directly to the TMA. These items are supported by the M2 hexapod. The spider spindle of the TEA functions as the base flange for this hexapod. Each of the six M2 hexapod actuators attaches to a different location on the spider spindle. These locations are provided in LTS-181 and fig 7.2.2-1. These attachment locations represent the principle physical interface between the combined M2 mirror cell assembly with the TMA.

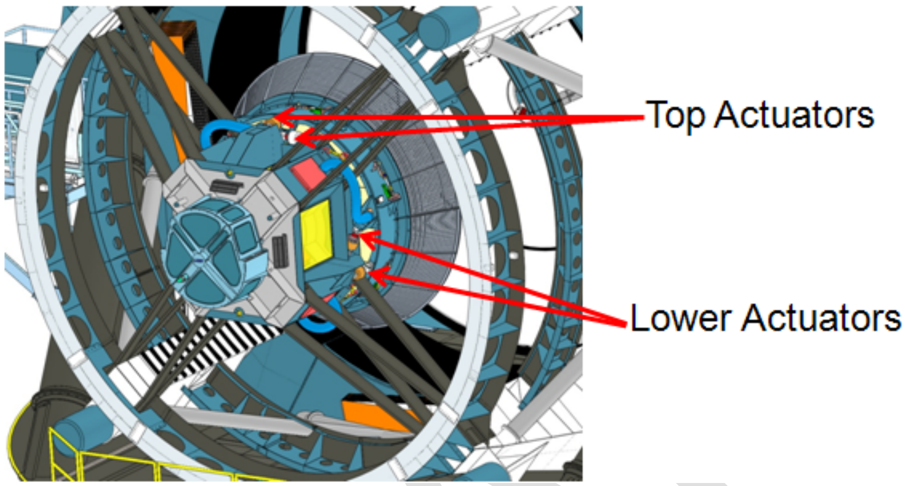
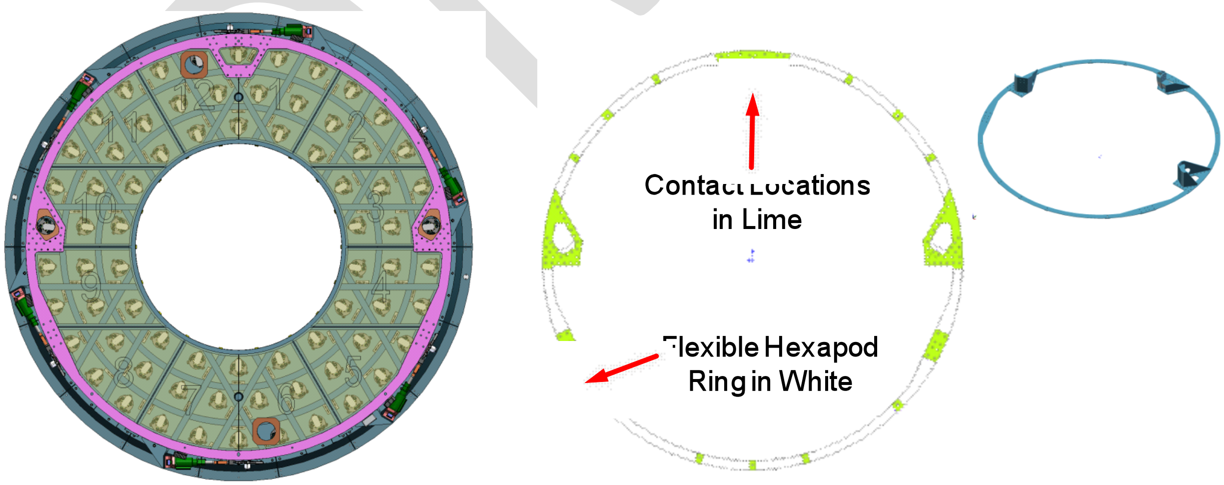


Figure 7.2.2-1: M2 Hexapod Actuator to Spider Spindle Attachment Locations

When installed on the telescope, the M2 mirror cell assembly interfaces to the flange of the hexapod that supports / positions, fig 7.2.2-2. The M2 baffle then interfaces to M2 mirror cell. For removal of the M2 Mirror cell assembly from the TMA the M2 light baffle is removed and replaced with a mirror cover. The TMA is designed to not interfere with the above interfacings and allow for adequate access.



M2 Cell to Hexapod Flange (Purple) Hexapod to M2 Cell Flange

Figure 7.2.2-2: M2 Mirror Cell Assembly to M2 Hexapod Interface

The M2 mirror cell assembly does not have a self contained thermal control system. Thermal control is accomplished by circulating air between the M2 mirror cell assembly and the central assembly of the TEA. This exchange is accomplished by a set of 2 supply ducts and fans along with 2 return ducts and fans. The thermal load of the M2 mirror cell assembly is removed by the central thermal control system of the TEA. Although these fans and ducts are components of the M2 mirror cell assembly, the TMA must interfaces with them. The interfaces are on the spider spindle directly below the electrical cabinets (when zenith pointing). Since the heated air is ducted directly to the thermal control cabinet, the TMA must supply the ducts from these two interfaces for the return ducts to the cabinet.

7.2.3 M2 COMBINED ASSEMBLY MAINTENANCE ACCESS

Access to the M2 hexapod actuators, M2 tangent link assemblies, sensors acting on the tangent links and mounting flanges to the hexapod and baffle are accessible with the M2 mirror cell assembly installed on the telescope, document 13583. This requires the telescope to be in the horizon pointing orientation and is accomplished through the use of the man lift and ladders. The top end assembly of the telescope will be equipped with hand rails and fall protection tie off points to allow access the upper portion of the M2 cell while the telescope is horizon pointing. A step ladder can be place under the M2 cell allowing access to the lower half of the cell, fig 7.2.3-1.

Figure 7.2.3-1: On Telescope Access to the M2 Combined Assembly

The optical surface of the M2 mirror can be accesses from the deployable platforms for inspection and cleaning.

7.2.4 M2 COMBINED ASSEMBLY SPECIAL MAINTENANCE ACCESS CONFIGURATION

As a result of the optical arrangement it is not possible to provide adequate access to the internals of the M2 mirror cell assembly when it is installed on the telescope. Since it requires removal of the entire camera assembly to remove the M2 assembly, it is also not practical to remove the M2 mirror cell assembly for maintenance or minor repairs. Consequently, an intermediate special access configuration was developed to allow access to the interior of the M2 mirror cell assembly, figure 7.2.4-1. This configuration requires that the telescope is horizon pointing and after removal of the top panels provides access to all the internals of the M2 mirror cell assembly.

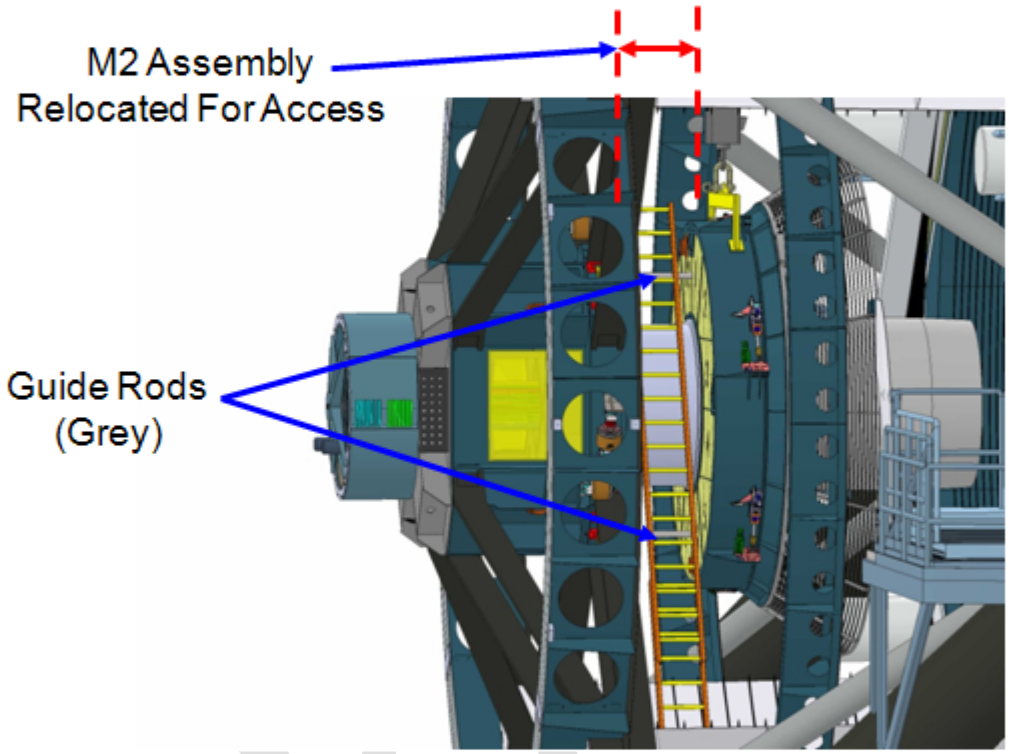


Figure 7.2.4-1: M2 Mirror Cell Assembly Special Access Configuration

After lowering the telescope to horizon pointing, reconfiguring to this configuration requires that the mass of the M2 mirror cell assembly and baffle be offloaded by the overhead crane. Two guide rods are passed through the spider spindle and secured into the top of the mirror cell (back when horizon pointing). Once the M2 cell is repositioned these guide rods are anchored to the spider spindle to hold the M2 cell in position. While in this configuration, the overhead crane must continuously support the M2 mirror cell mass against gravity.

Once the M2 mirror cell assembly is in the special access configuration, and the top panels have been removed, access is readily available to the entire interior of the M2 mirror cell assembly by use of an extension ladder.

The Telescope Mount Assembly (TEA) was designed to be compatible with this special access configuration regardless of whether or not the camera support assembly is installed and whether the M2 baffle or M2 cover is installed. This requires that the guide rods can be installed through the permanently installed spider spindle of the central assembly. Once the M2 mirror cell assembly is in this configuration, the guide rod heads are bolted to the spider spindle to secure the M2 mirror cell assembly in position. The TMA structure was also designed to allow crane access to the TMA throughout this repositioning. Motion of the crane is required to move the M2 cell away from its hexapod flange. Throughout this procedure, the crane and not the guide rods supports the mass of the M2 mirror cell assembly.

7.2.5 M2 COMBINED ASSEMBLY INSTALLATION AND REMOVAL

The M2 hexapod is permanently installed on the TEA through its attachments to the spider spindle. The only maintenance required will either be for its actuators or its electronics. Both of these are readily accessible while on it is installed. Consequently, there is no reason to remove this hexapod.

Although the M2 mirror cell assembly (M2 assembly) design promotes on telescope maintenance, the mirror cell assembly must be installable (or removable) as a complete assembly, fig 7.2.5-1. This allows for comprehensive testing of the M2 assembly before installation. The M2 assembly is removed from the telescope while the telescope is horizon pointing. Since the camera protrudes through the M2 assembly, the M2 assembly cannot be removed without first removing the camera support assembly.

The M2 assembly is removed vertically by the crane. The crane has insufficient hook height to lift the M2 assembly over the top end ring. Consequently, the M2 assembly is lifted to its maximum height and removed transversely from the TMA as show in fig 7.2.5-1. Once the M2 mirror cell assembly is removed by the overhead crane of the rotating enclosure (dome) it is placed on a cart specifically designed to transport, maintain and test the M2 mirror cell assembly, document 13583. The structure of the Telescope Mount Assembly (TMA) that supports the Top End Assembly (TEA) was designed to be compatible with this removal method. Since the M2 mirror cell assembly is transferred to the cart by the crane there is no direct interaction between the M2 mirror cell assembly cart and the TMA.

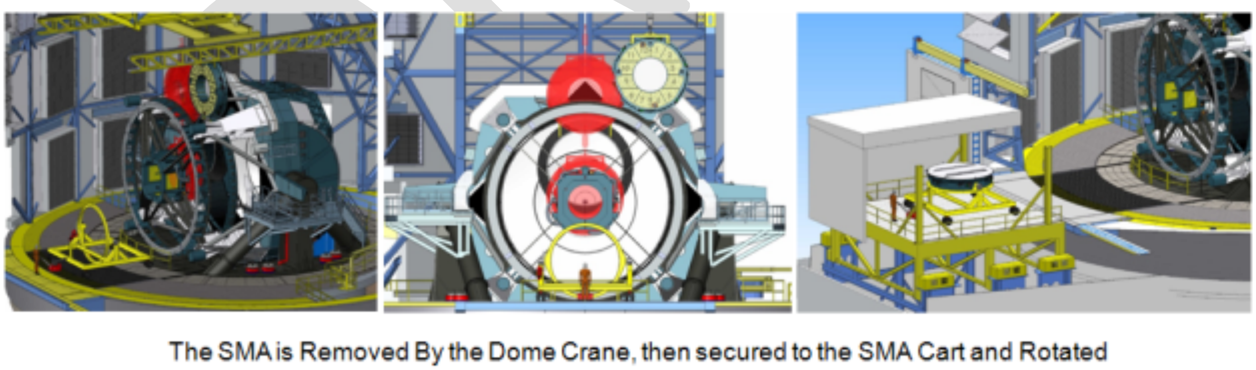


Figure 7.2.5-1: M2 Mirror Cell Assembly Installation/Removal

Since the M2 mirror faces down it will require less frequent recoating than the upward facing M1M3 mirror and is not expected to be removed as often as either the camera or M1M3 mirror assembly. Consequently, the cumbersome removal method described above is acceptable.

The M2 baffle must be disconnected from the M2 mirror cell assembly before removal of the M2 mirror cell assembly. However, this baffle is too large to be removed from the TEA, consequently, it is temporarily stored within the TEA and suspected from the structural cross braces. During installation and removal of the M2 cell the M2 baffle is removed and replaced with an M2 Mirror Cover.

A mirror cover has been designed for the M2 assembly, fig 7.2.5-2, document 13582. Since during installation either this cover or the baffle will be installed, but not both, the mirror cover is designed to use the same mounting flange as the baffle. Lifting interfaces on the cover allow it to be installed or removed in a vertical orientation (on telescope) and horizontal orientation (off telescope). The mounting flange of the cover has a polymer liner to protect the mirror substrate from accidental contact during installation and removal. The combined CG of the mirror cell and baffle is comparable to the combined CG of the mirror cell and baffle. Consequently, only one crane lifting location is required for both configurations.

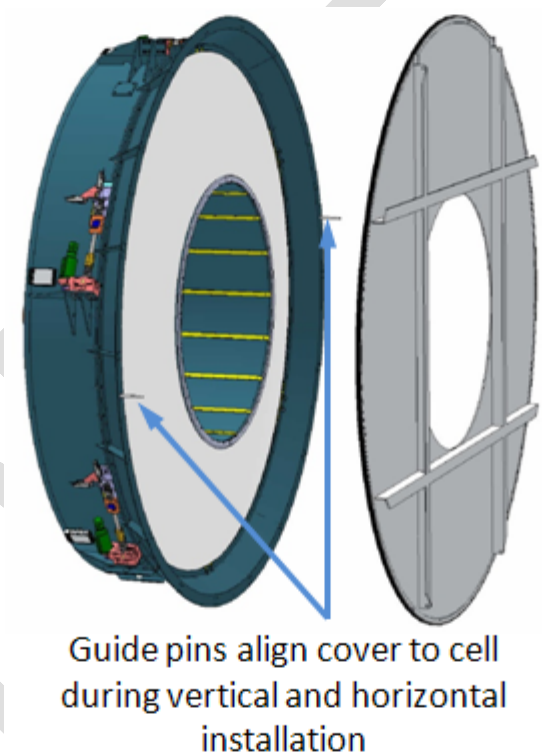


Figure 7.2.5-2: M2 Mirror Cover

7.3 CAMERA AND HEXAPOD/ROTATOR ASSEMBLY

The approximately 3 ton camera along with its approximately 1 ton hexapod/rotator assembly constitutes a major payload of the Telescope Mount Assembly (TMA). However, these items will not be installed directly onto the TMA. The camera hexapod/rotator assembly is first attached to the offset integrating structure and combined into the camera support assembly. This allows for the testing of the entire conglomeration before installation onto the telescope. A detailed description of this assembly and its installation are provided in the Camera Support Assembly section.

7.3.1 CAMERA AND HEXAPOD/ROTATOR ASSEMBLY DESIGN ENVELOPES

The design envelope for the camera hexapod/rotator is available in LTS-208 and in fig 7.3.1-1. This design envelope is applied to the hexapod/rotator assembly with the hexapod in its mean position. The envelope is principally a short, hollow cylinder. The outer diameter is limited by the optical design which requires that the camera hexapod and rotator be installed through the central hole of the M2 mirror cell assembly. The inner diameter is limited by the protrusion of the camera utility trunk through the rotator. Two trapezoidal envelopes are through the cylinder are required to provide access to the cameras utility trunk as described in the deployable platforms section.

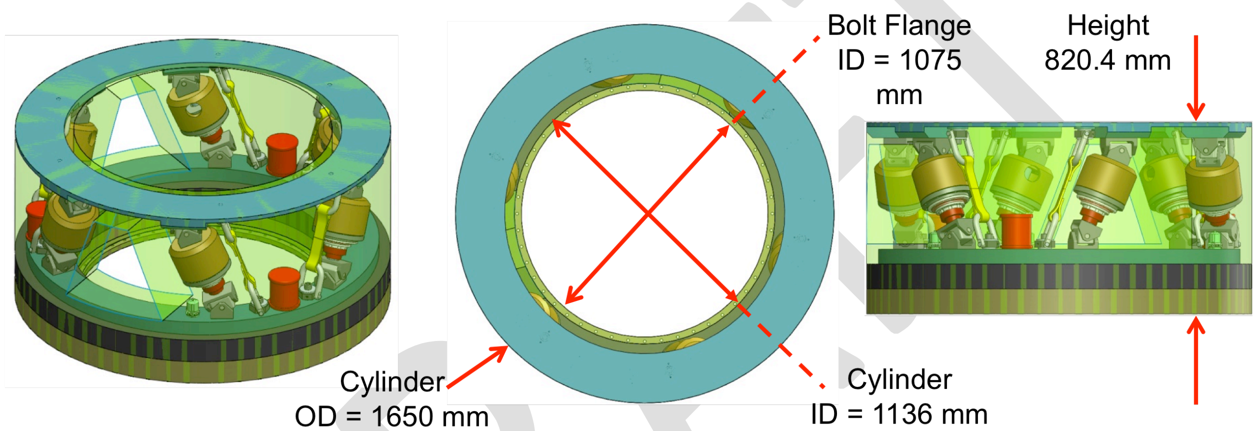


Figure 7.3.1-1: Design Envelope of Camera Hexapod/Rotator Assembly

The camera utility trunk protrudes through the rotator and contains most of the camera electronics, fig 7.3.1-2. The maximum outer diameter of the utility trunk of 970 mm is smaller than the internal diameter of the cylindrical envelope, 1136 mm. Sufficient clearance between the two has been provided to allow for the motion of the hexapod and provide access to the inner ring of fasteners between the rotator and camera as described below in the mechanical interfaces section.

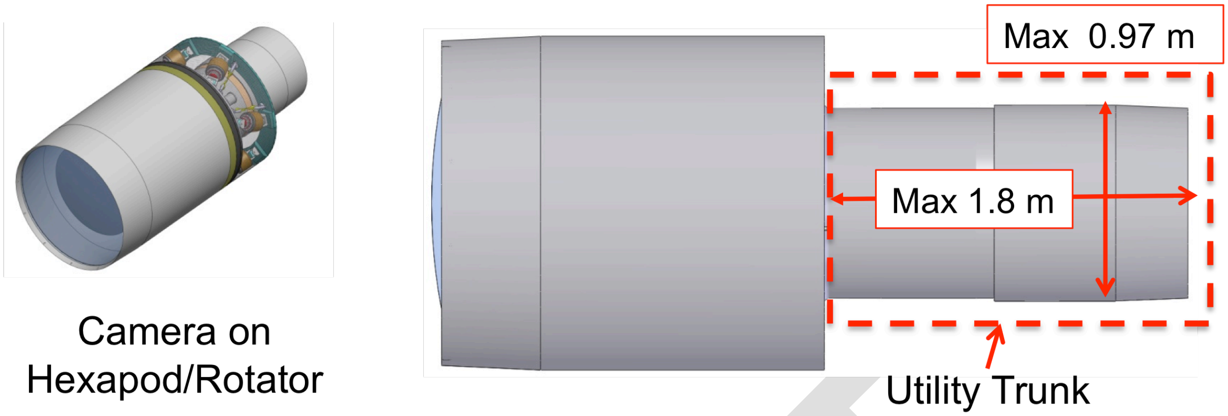


Figure 7.3.1-2: Design Envelope of Camera Hexapod/Rotator Assembly

Although the camera does not interface directly to the TMA, the offset of the TMA must accommodate the camera's utility trunk. The TEA must accommodate the cables from the end of the utility trunk to the camera cable wrap and the deployable platforms must provide access to both sides of the camera.

7.3.2 CAMERA HEXAPOD/ROTATOR ASSEMBLY INTERFACES

The camera hexapod mounts to the offset of the integrating structure, LTS-182 and fig 7.3.2-1. This is a steel structure consisting of two flat rings connected by a straight cylinder. One ring bolts to the rest of the integrating structure, and the other bolts to the camera hexapod. Since the only purpose of this interface is to attach the hexapod, the hexapod contractor will determine the fastener pattern. This connection represents the physical interface between the camera hexapod/rotator assembly and the Telescope Mount Assembly (TMA). Although the baseline offset design is the structure defined above, once the hexapod contractor refines this interface, most likely the design will be upgraded to improve the structural efficiency.

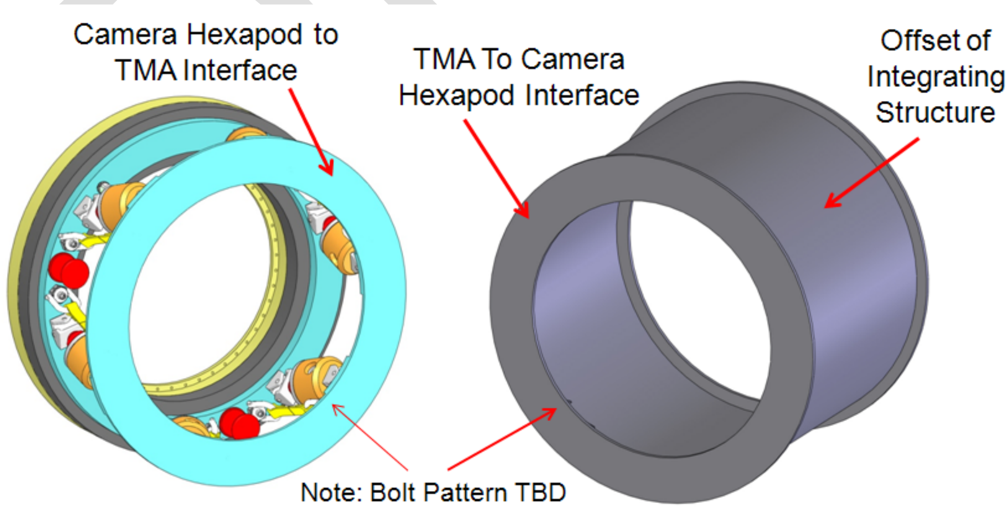


Figure 7.3.2-1: Camera Hexapod To Telescope Mount Assembly (TMA) Interface.

Although the hexapod contractor will have discretion over the fastener pattern, the flange must be fabricated from carbon steel and possess a substantial cross section, which is specified in the interface drawing, LTS-182. The utilization of steel eliminates any significant differential thermal expansion problems. Not only does this interface provide a mounting surface for the hexapod, but it provides substantial radial stiffness to the offset. The required overall stiffness is divided equally between the offset flange and the mating hexapod flange. This stiffness requirement mandates the utilization of a steel flange with at least the minimum cross section. The cross section is not directly specified in the drawing. Instead, a thickness, inner diameter and outer diameter are specified.

The offset has also been designed to be readily modified or replaced to counteract fabrication and assembly errors. These errors are the major component of the hexapod motion budget. By utilizing a minimal error allocation, a significant reduction in motion budget was achieved. This does present a risk that after the initial telescope assembly, the proper location of the camera may be outside of the range of the hexapod. However, if this situation occurs, it can be remedied by modification or replacement of the offset.

7.3.3 CAMERA MAINTENANCE ACCESS

As described in the Deployable Platforms section, two deployable platforms provide access to both sides of the camera hexapod/rotator assembly when it is installed on the telescope. These platform are only available when the telescope is horizon pointing. Through these platform and their extensions access is provided from the base of the hexapod to the first (L1) camera lens. Since the deployable platforms provide access to both sides of the camera and the rotator has a range of 180 degrees, access to the entire outer cylinder of the camera body is available.

A flexible, removable shroud is required around the hexapod/rotator assembly. This shroud is shown as a transparent dark gray covering over the camera hexapod in fig 7.3.3-1. This shroud must be flexible to accommodate motions of the hexapod. It must be readily removable to allow maintenance access to the hexapod, rotator and camera utility trunk. A simple system of rubber sheeting attached with Velcro is envisioned for this application. Since the most commonly accessed location inside the shroud will be the utility trunk, accesses described in the camera hexapod/rotator envelope section, these locations will require subpanels so they can be accessed without removing the entire shroud, fig 7.3.3-1.

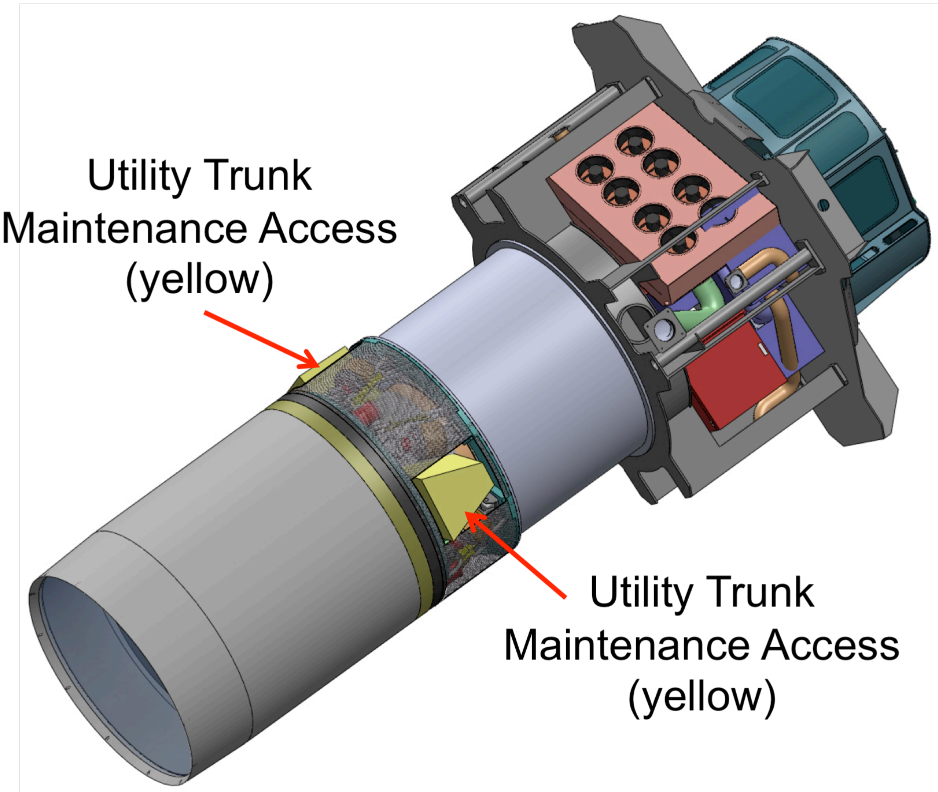


Figure 7.3.3-1: Maintenance Assess Between Actuator Actuators

7.3.4 CAMERA COMPONENTS REPLACMENT

Besides the maintenance access discussed above the TMA must also provide for the replacement of two critical camera components, the optical filters and the shutter assembly. The replacement of these components requires both the use of the deployable platforms and the dome crane, LSE-18 and LSE 80. The TMA cross beams must allow for specific crane access locations to lower these components.

Fall protection is provided during the above operation. When the telescope is still zenith pointing fall protection lines are attached to the cross braces that will be overhead when the telescope is horizon pointing. Consequently, when the telescope is horizon pointing, these lines now hang nearly vertical.

7.3.5 CAMERA HEXAPOD/ROTATOR ASSEMBLY INSTALLATION AND REMOVAL

The entire camera support assembly will be assembled and tested as a complete unit in the telescope support facility before installation on the telescope. A specially designed cart is used both for this assembly and for transporting the assembly to the telescope for installation, fig 7.3.5-1. The integrating structure is first attached to this cart and then the various components are attached to the integrating structure. The hexapod flange of the hexapod/rotator assembly is attached to the offset of the integrating structure and then the camera is attached to the rotator.

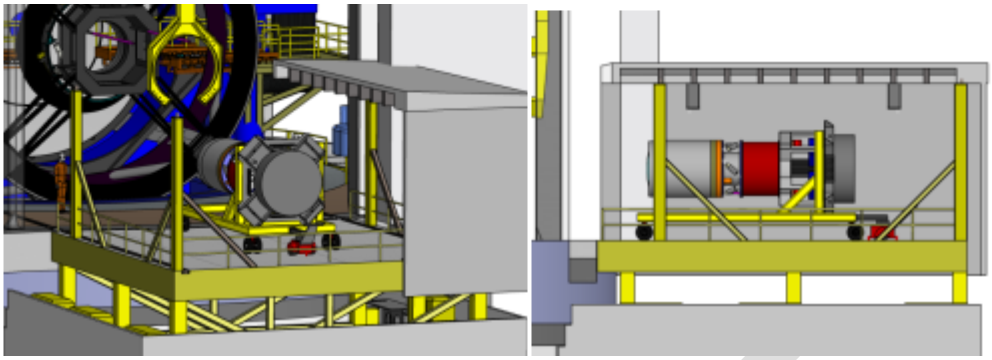


Figure 7.3.5-1: Camera Support Assembly on Cart.

A large number of utilities must be connected to the end of the camera utility trunk at the cable/utility connection area, ref LTS-217, fig 7.3.5-1. As a result of the dense locating of these cables/utilities these lines will be connected with quick disconnects. Since this operation will occur in a climate controlled environment these types of connection will be adequate.

7.4 DUMMY MASSES FOR TESTING AND INTEGRATING

Dummy masses will be required for all three optical payloads during testing and development of the TMA at the vendor's facility. These dummy masses will be compatible with the installation and removal procedures described previously. Consequently, not only must they have masses that are similar to the optical payloads but they will also fit within the same design envelopes and use the same interfaces, etc.

Dummy masses will also be required of onsite TEA testing. As a result of its large mass and size, it would be impractical to transport the M1M3 mirror cell assembly dummy mass used for vendor site testing to the sight. Consequently, the M1M3 mirror cell will be used with a dummy mirror. Neither the M1M3 mirror cell nor the M1M3 dummy mirror is a component of the TMA.

8 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 approximately 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.