Design of the Giant Magellan Telescope

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ABSTRACT

The preliminary design of the 25 m Giant Magellan Telescope (GMT) has been completed. This paper describes the design of the optics, structure and mechanisms, together with the rationales that lead to the current design. Analyses that were conducted to verify structure and optical performance are summarized. Science instruments will be mounted within the telescope structure. A common instrument de-rotator is provided to compensate for field rotation caused by the alt-az tracking of the telescope. The various instrument stations and provisions for mounting instruments are described. Post-PDR development plans for the telescope are presented.

Keywords: GMT, Giant Magellan Telescope, telescope design

1 INTRODUCTION

The GMT is a 25 m altitude-azimuth telescope (Figure 1) designed for operation over the wavelength range 320 nm to 25 µm[1]. The aplanatic Gregorian optics with corrector provides a 20 arcmin field of view. The segmented primary mirror is composed of 8.4 m diameter circular segments. The alt-az mount provides complete access to the sky above 30 deg elevation angle with a 1 deg diameter exclusion zone for tracking at the zenith. Multiple instrument mounting locations accommodate a wide range of scientific requirements. The GMT is designed to operate in both active and adaptive optics modes. The initial adaptive optics modes are natural guidestar AO (NGSAO), laser tomography AO (LTAO) and ground-layer AO (GLAO). The design and operation of the GMT AO system is described by Bouchez[2].

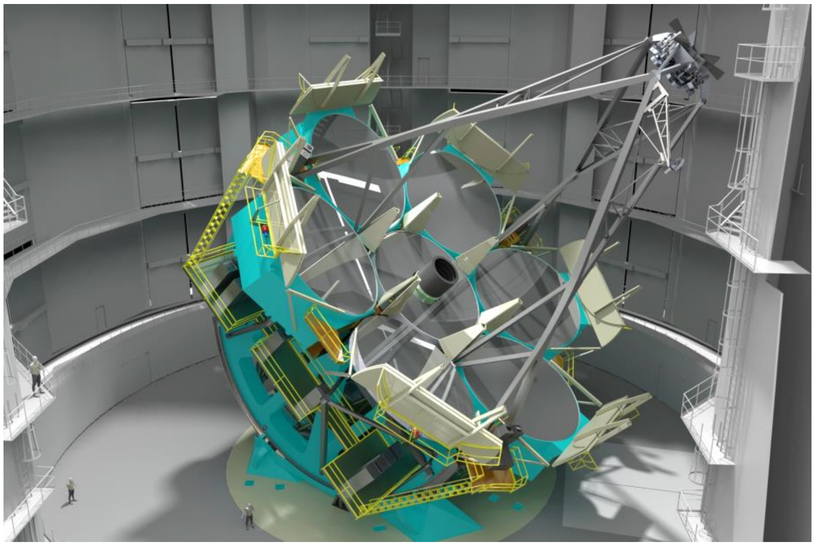

Figure 1. The GMT

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The core design principles that guide the technical development of the GMT are:

1. Design for compactness and stiffness to maximize performance.
2. Capitalize on existing experience, technology and expertise from previous projects.
3. Model critical aspects of telescope performance.
4. Prototype high technical risk components and assemblies.
5. Follow a prescribed process of systems engineering.

These principles drove several of the key decisions early in the project. While the instruments and adaptive optics system may evolve over time, the telescope structure and the primary mirrors must serve for the life of the facility. The decision to use the honeycomb structured mirrors flowed from considerations of performance and experience, while the choice of the direct Gregorian configuration without Nasmyth platforms was based on performance and cost considerations.

2 ARCHITECTURE

2.1 Optical Design

The GMT primary mirror sets the collecting area of the telescope and defines the telescope subapertures. The size and shape of the mirror segments drives the phasing strategy. The largest practical size for monolithic mirrors is around 8 meters. Current generation 6.5-8 m optical telescopes use a single monolithic mirror (Magellan, MMT, VLT, Subaru). The 10 m telescopes (e.g., Keck, GTC) employ a mosaic of small (~1.5 m) segments. The LBT with two 8.4 m mirrors is the only existing telescope combining multiple large-segments in a common mount. The next generation of extremely large telescopes will all have segmented primary mirrors.

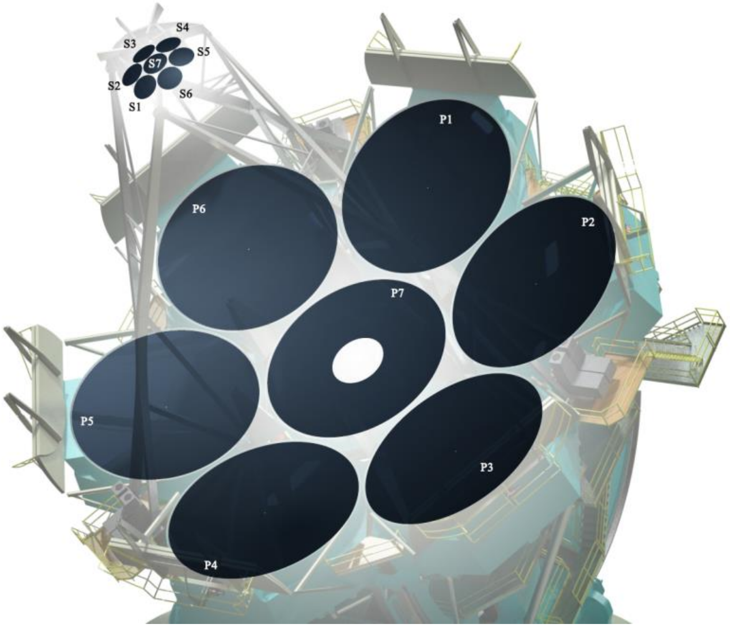


Figure 2. GMT Optical layout

The GMT primary mirror consists of an array of the largest practical (8.4 m) segments manufactured at the University of Arizona Steward Observatory Mirror Lab. The central mirror is surrounded by six off-axis segments as shown in Figure 2. The GMT project considered omitting the central segment in the interest of cost reduction and operational simplicity. The center segment was retained because the six-mirror configuration falls short of providing the desired collecting area and has two other significant performance drawbacks relative to seven segments: (a) the image point spread function is significantly broadened with just the outer six segments and (b) phasing the primary mirror segments would be much more difficult without the center segment to anchor the array.

The seven segments share a common parent optical surface that together deliver 25 m diffraction limited imaging using adaptive optics and a wide field of view for natural seeing applications. The segments provide large subapertures of well-corrected wavefront so that phasing is not required for natural seeing operation or GLAO. The large gaps between segments require special techniques for phasing the subapertures as described by Bouchez[2].

The GMT project settled on an f/0.7 focal ratio for the primary mirror to provide a compact telescope structure. The f/0.7 focal ratio was based on the project's assessment of reasonable limits for extending current mirror fabrication technology. The off-axis segments are highly aspheric: the front surface height around their perimeter varies by more than 14 mm (28,000 waves at 500 nm). These are arguably the most technically challenging mirrors of this size and precision ever attempted.

The segmented secondary mirror provides significant advantages for active control of the optical system. The segments are conjugated 1:1 with the primary segments. Small misalignments of the primary mirror segments can be corrected with rigid-body translations of the more agile secondary segments. This significantly relaxes the precision and bandwidth requirements for the primary mirror support system. Image blur caused by wind shake and telescope structure vibrations can be reduced with fast tip-tilt motion of the secondary segments.

The GMT will be equipped with two secondary mirror assemblies. The Adaptive Secondary Mirror (ASM) segments are based on the adaptive secondary mirror developed for the MMT and now in use on the LBT, Magellan, and VLT telescopes. The ASM will be used by all AO modes. The Fast-steering Secondary Mirror (FSM) uses rigid segments and will be used as the commissioning secondary mirror and whenever the ASM is removed for service. The ASM and FSM are described below.

2.2 Configurations

Science instruments will be mounted on the telescope structure. Direct feeds of the telescope beam to instruments will be provided at various locations. The three principal GMT optical configurations are shown in Figure 3:

- Direct Gregorian Narrow Field (DGNF). This two mirror (M1/M2) combination delivers the beam to the nominal Gregorian focus with two reflections. Vignetting limits the field of view to 20 arcmin but field aberrations become significant outside the central 10 arcmin diameter without the corrector.
- Folded Port (FP). A tertiary mirror directs the beam to instruments mounted on the top surface of the Gregorian Instrument Rotator (GIR). The unvignetted field of view is 3 arcmin. The tertiary rotates about the reference optical axis to feed individual instruments.
- Direct Gregorian Wide Field (DGWF). A 20 arcmin well-corrected field is delivered to the direct Gregorian focus with the Corrector-ADC inserted in the beam.

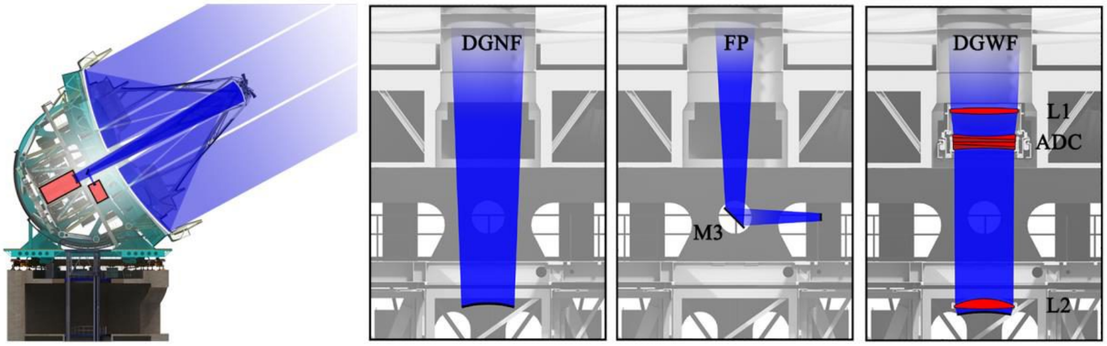


Figure 3. The GMT optical configurations (DGNF, FP, DGWF)

Additional science instruments, not mounted at the principal foci, will be fed with instrument-dependent optical relays, including gravity invariant instruments on the azimuth structure.

2.3 Telescope structure

The three major subassemblies of the GMT are the azimuth track, azimuth structure, and optical support structure (OSS) shown in Figure 4. The telescope mounts on the pier which is part of the base structure of the GMT enclosure.

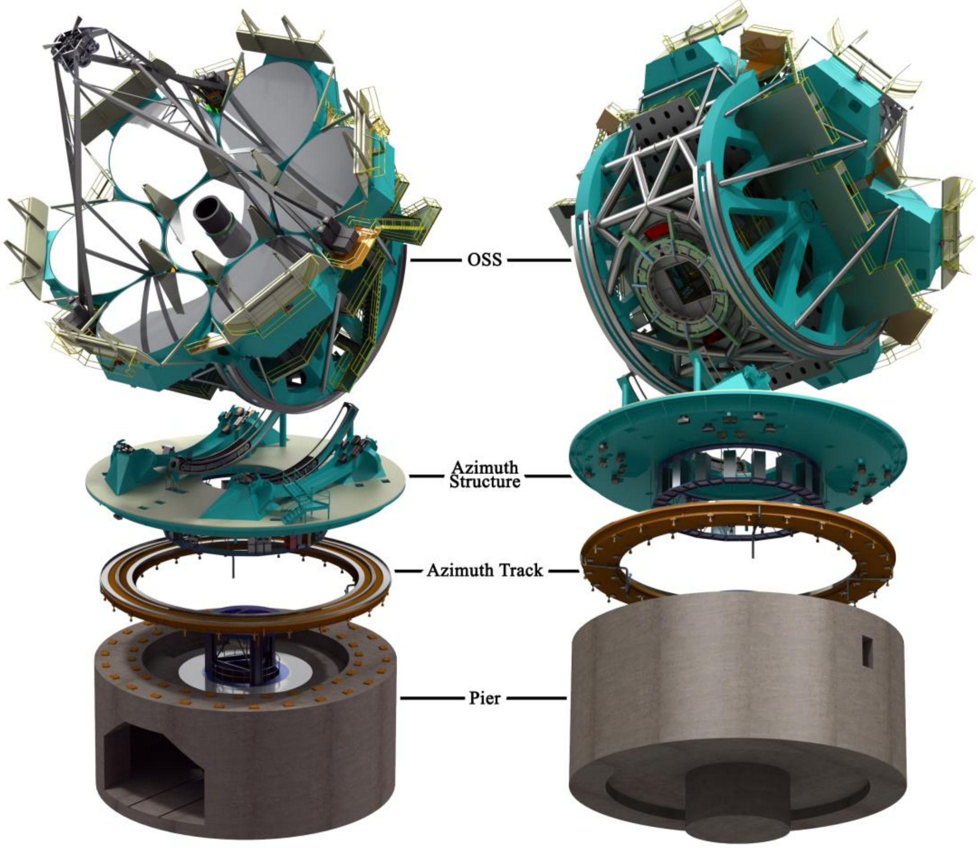


Figure 4. Major telescope assemblies

2.3.1 Azimuth Track

The azimuth track assembly is the stationary structure that forms the interface between the rotating azimuth structure and the pier, as shown in Figure 5. The GMT azimuth and elevation axes rotate on hydrostatic bearings[3]. Two planar runner bearing tracks on top and a single cylindrical radial runner bearing on the 16.78 m inside diameter define the azimuth axis. The azimuth track is constructed from seven segments. Adjustment screws between the track and pier allow for leveling the track.

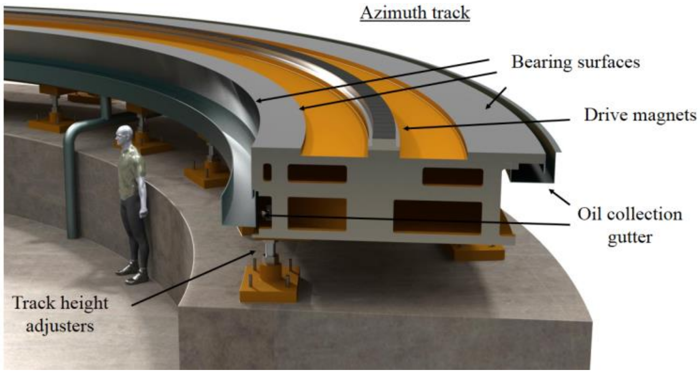


Figure 5. Azimuth track

2.3.2 Azimuth Structure

The azimuth structure is the lower of the GMT's two rotating assemblies. This structure defines the elevation axis with 24 hydrostatic bearings (Figure 6) on its top side that interface with the optical support structure (OSS) runner bearings. It also interfaces to the azimuth track runner bearings with a second set of 24 hydrostatic pads on its lower side shown in Figure 7. The lower azimuth pads and azimuth tracks define the azimuth axis of the telescope. The weight of the OSS is transferred to the azimuth track through the pedestal structures on the top surface of the azimuth structure. The forcer heads for the main axis permanent magnet direct drives are located between the hydrostatic bearing pads in 8 locations.

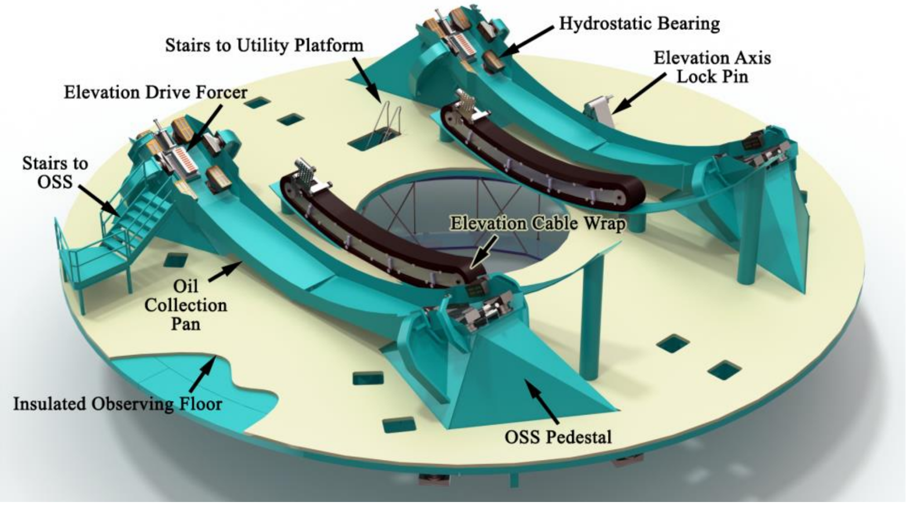


Figure 6. Azimuth Structure (top view)

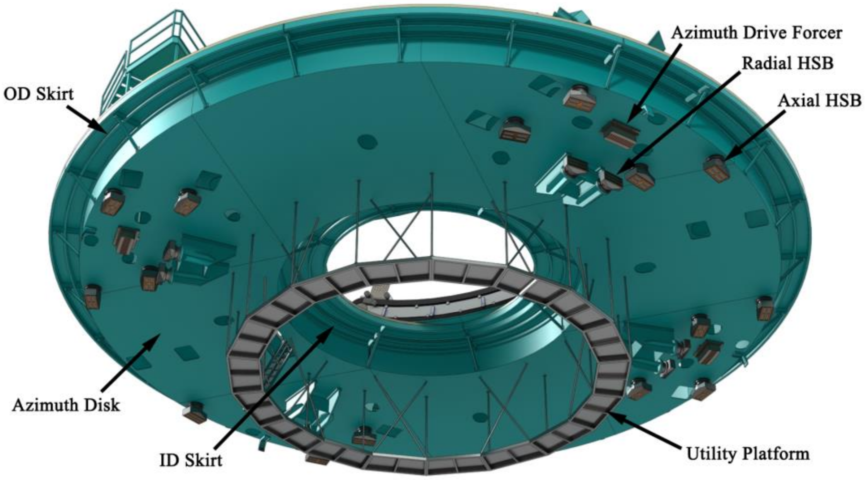


Figure 7. Azimuth structure (bottom view)

2.3.3 Optical Support Structure

The optical systems and science instruments are located, with one exception, in the optical support structure (OSS). The exception is the gravity invariant instrument station on the azimuth structure. The adaptive optics system components are also integrated within the OSS.

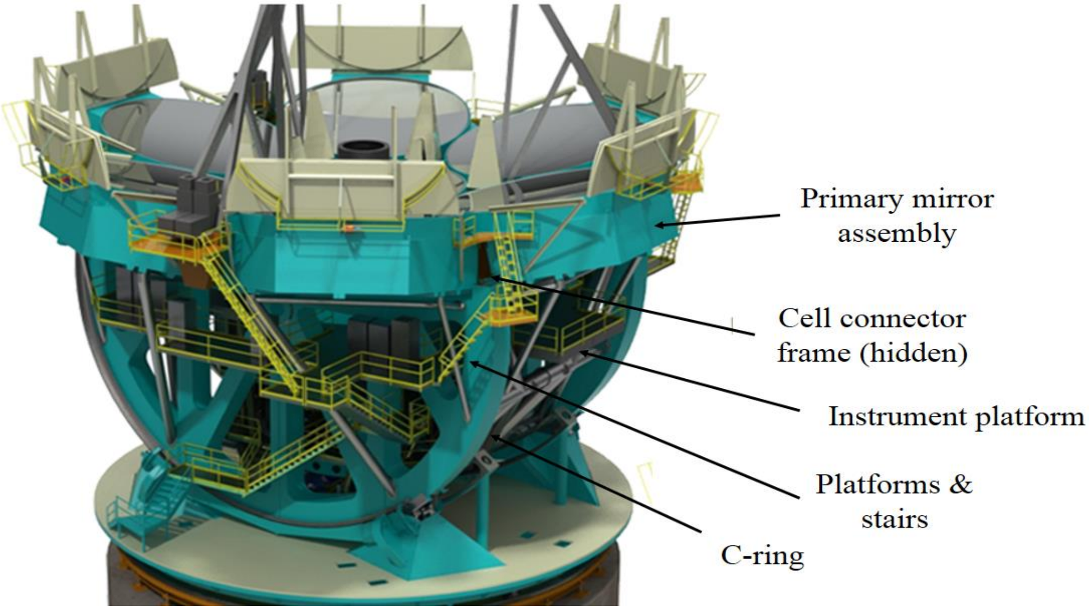


Figure 8. OSS lower structure

Figure 8 shows the assemblies on the lower OSS structure. The C-ring assembly supports the OSS structure and assemblies above. It consists of a pair of C-rings, so called because of their shape, and bracing that connects them. The runners for the elevation bearings are machined into the cylindrical rims of the C-rings. The elevation drive magnets, encoders, and limit switches also mount in this area. The instrument platform (IP) spans between the C-rings and runs their length and provides a deck for mounting instruments within the structure.

The Gregorian Instrument Rotator (GIR) shown in Figure 9 mounts in the center of the C-ring assembly on bearings that allow it to rotate about the OSS Z-axis[4]. The top plate of the GIR is flush with the top plate of the IP. The rotation axis of the GIR defines the Reference Optical Axis (ROA) of the telescope.

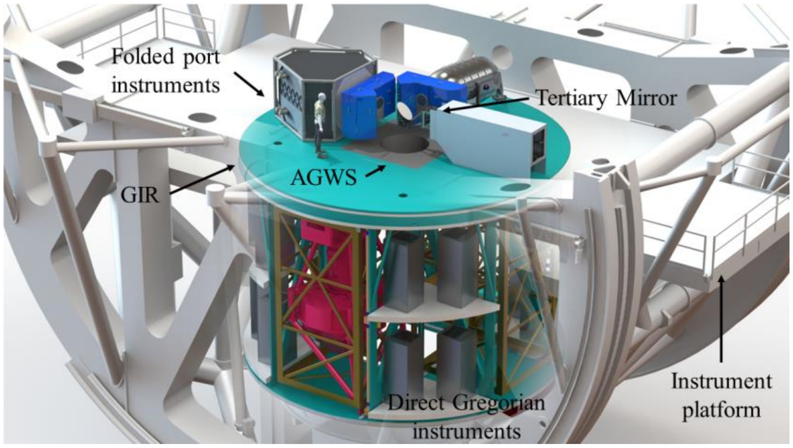


Figure 9. Gregorian Instrument Rotator (GIR)

Direct Gregorian (DG) and Folded Port (FP) instruments are mounted on the Gregorian Instrument Rotator. Field rotation in the instruments caused by the alt-az tracking of the mount is compensated with GIR rotation. The GIR includes instrument bays for four direct Gregorian instruments and three quadrants for mounting folded port instruments. The tertiary mirror (M3) mounts on top of the GIR in the fourth quadrant. The Acquisition, Guide and Wavefront Sensor (AGWS) assembly is recessed into the top plate.

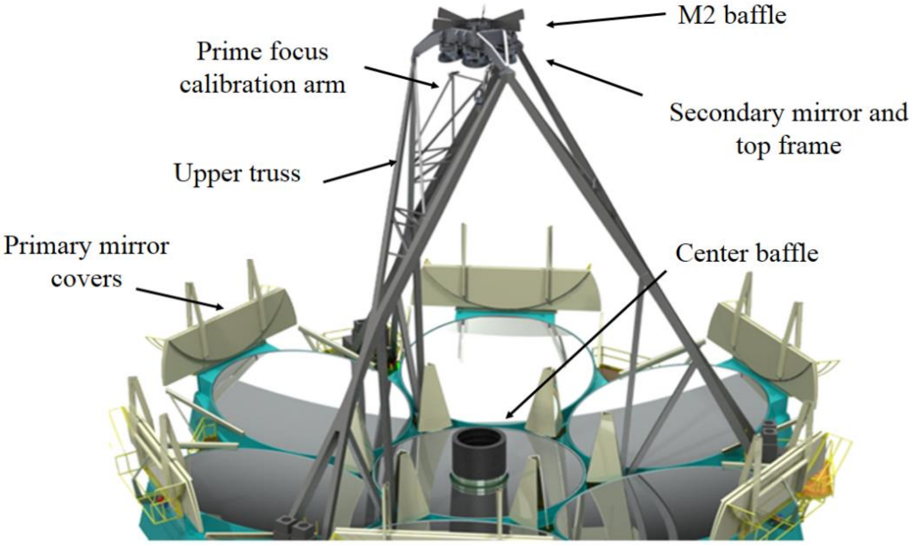


Figure 10. Upper OSS structure and mechanisms

The secondary mirror positioner, seven secondary mirror segments, and the M2 baffle attach to the top frame, Figure 10. The prime focus calibration arm, used to deploy the alignment and instrument calibration sources, is attached to the upper truss near the top.

2.4 Instrumentation

Science instruments are mounted below the primary mirror assembly on the OSS. A number of instrument mounting locations are provided:

- Direct Gregorian (DG)
- Folded Port (FP)
- Auxiliary ports (AP)
- Instrument Platform (IP) station
- Gravity Invariant Station (GIS)

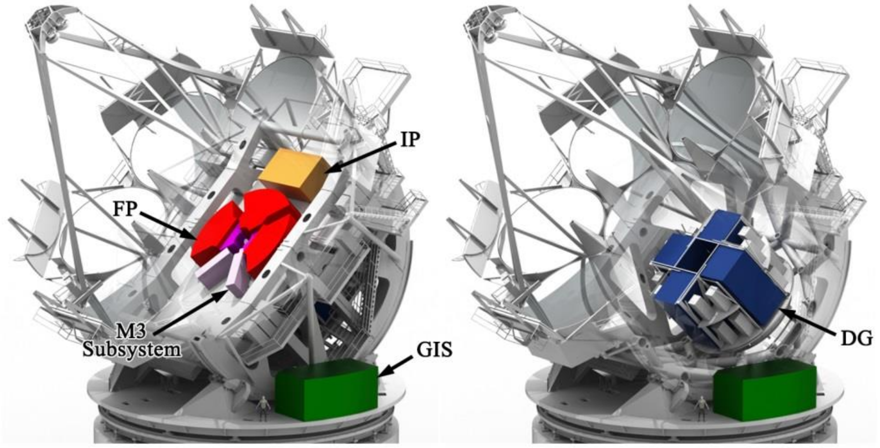


Figure 11. Instrument mounting

Instruments that require the highest stability (e.g., precision radial velocity spectrographs) will mount on the azimuth structure at the Gravity Invariant Station (GIS) and be fed by a fiber or optical relay. Figure 11 shows the mounting locations of the GMT science instruments (Auxiliary Ports not shown).

Science instrument development for GMT is discussed by Jacoby[5].

3 OPTICAL SUBSYSTEMS

3.1 Primary Mirror

The GMT project confronted the choice of primary mirror type early in the conceptual design phase. Various alternatives were considered but the discussion focused primarily on 8.4 m cast mirrors from the University of Arizona (UA). These mirrors offer several advantages.

- Their cell structure allows rapid equilibration with the ambient air much reducing the effects of "mirror seeing".
- They have high internal stiffness making them insensitive to wind buffeting and lowering force accuracy requirements for the support system.
- They allow active correction of low- and mid-order bending modes.
- The technology for casting, generating and polishing mirrors of this size is well developed.
- They can be produced with fast, highly aspheric figures.
- The mirror support and ventilation systems have gone through multiple stages of development and are well understood.
- The means of production resides within the GMT partnership.

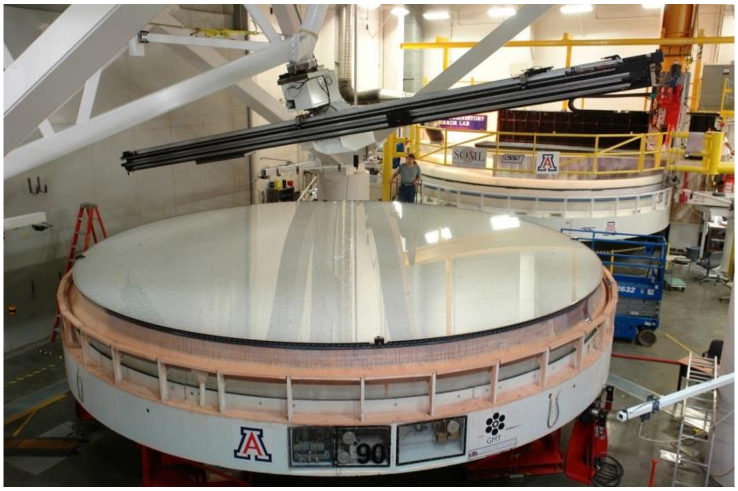


Figure 12. The GMT1 8.4 meter primary mirror segment

The highly aspheric figure of the off-axis segments was clearly a large technical risk for the project. Production of an off-axis segment was initiated early in the conceptual design phase to understand and retire that risk. An extensive program was undertaken to develop the metrology and figuring techniques for these segments[6]. The result was a mirror, GMT1 shown in Figure 12,that fully meets its requirements and validates the process. The prototype becomes the first of seven plus one spare off-axis segment that make up the primary mirror assembly.

Four additional segments are currently in the production queue. Segments 2 and 3 have been cast and are at various stages of completion. Segment 4 will be cast in March 2015 and OHARA E6 glass has been purchased in preparation for casting segment 5. The production of primary mirror segments is described by Martin, et. al.[7].

The primary mirror segments are installed in cells that provide support and thermal control. Once installed, a segment is never removed from its cell. The support system for the GMT primary mirror segments is based on the support systems developed for previous generations of 3.5 m, 6.5 m, and 8.4 m mirrors produced at the University of Arizona[8]. The off-axis GMT M1 cells are designed to be interchangeable to allow a cell assembly in any of the six outer positions to be exchanged with the extra cell for re-coating of the mirror surface. The mirror supports are designed for 3-axis operation to enable swapping.

A set of pneumatic actuators applies lateral and axial support forces to the back surface of each primary mirror segment. These actuators provide continuously varying forces that react gravity, wind and inertial forces and control the figure of the optical surface. The actuators are mounted on the top plate of the mirror cell and attach to loadspreaders that are permanently bonded to the mirror segment back surface.

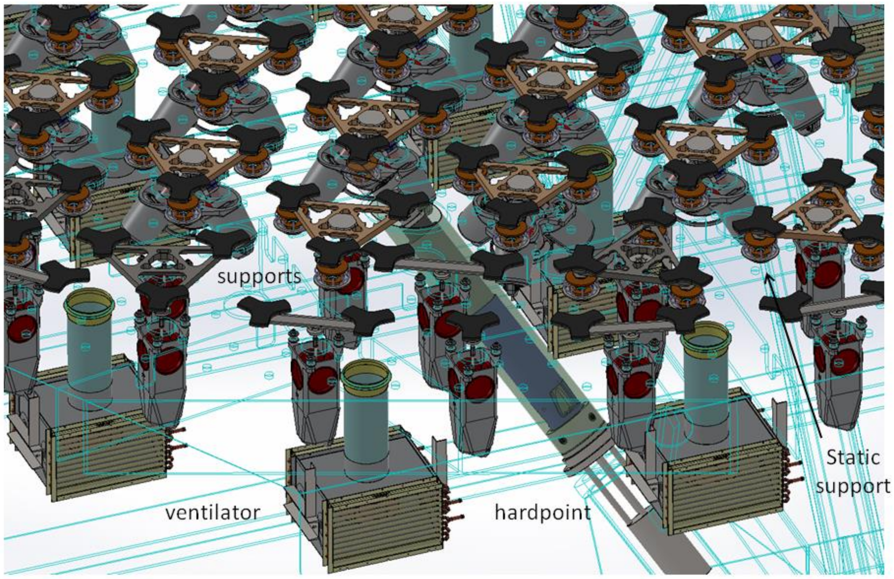


Figure 13. M1 cell components

A hexapod of six motorized hardpoints provides rigid body positioning of the segment. The hardpoints incorporate load cells to measure the forces they apply along their axis and are counterbalanced to apply no lateral forces. The hardpoints are mounted to stiff points in the bottom of the cell, and are attached at the top end to interface plates bonded to the segment bottom surface.

During normal operation, the actuator forces are adjusted to support the segment and maintain mirror figure. The load cells in the hardpoints provide feedback to the control system that adjusts the actuator forces so that the hardpoints carry no load. When the support system is inactive the mirror is supported on a separate set of springs (“static supports”) that passively engage the mirror at load spreader locations.

The temperature of the M1 segments needs to be maintained near the ambient air temperature in order to control the mirror figure and eliminate “mirror seeing” effects. The requirements for temperature uniformity within the mirror blank and temperature difference to the ambient air are on the order of 0.1 C. A thermal control system based on the Magellan design maintains the temperature by blowing conditioned air into each of the cells in the mirror segment. Figure 13 shows the supports actuators, hardpoints, and ventilators in the cell.

3.2 Secondary Mirrors

The GMT will have two independent secondary mirror assemblies: the Adaptive Secondary Mirror (ASM) and Fast-steering Secondary Mirror (FSM). Both consist of seven 1.05 meter segments conjugated to the primary mirror segments as described above. The segments mount below the top frame on actuators (M2 positioner) that provide 6 degrees of motion control for segment alignment and focus control in the telescope. Figure 14 shows the side-by-side assemblies for comparison. The secondary mirrors are exchanged by lifting the whole top end assembly off the telescope by means of an overhead bridge crane mounted in the enclosure.

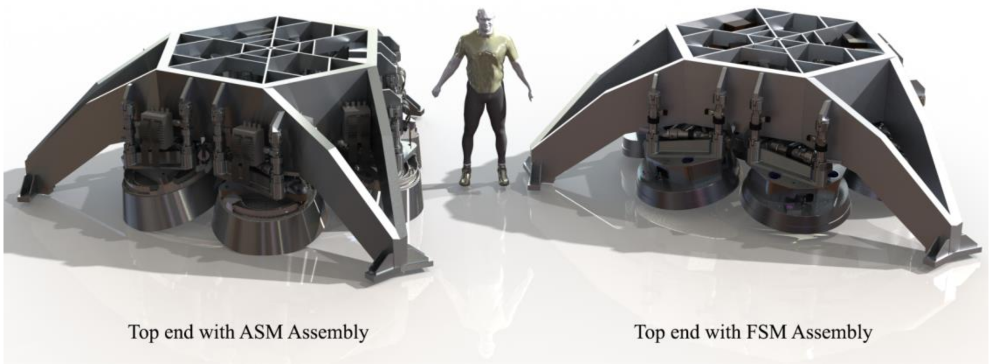


Figure 14. ASM and FSM assemblies

3.2.1 Adaptive Secondary Mirror (ASM)

The ASM is the deformable element in the GMT AO system, providing AO correction to every AO capable instrument on the telescope. The ASM supports the natural seeing observing by passively maintaining a static figure (with or without tip-tilt stabilization). The ASM uses technology developed for the MMT 64 cm and the LBT 90 cm AO secondary mirrors. Adaptive mirrors using this technology have been recently implemented on the ESO VLT and Magellan 6.5 m telescopes. The ASM is described by Bouchez[2].

3.2.2 Fast-steering Secondary Mirror

The Fast-steering Secondary Mirror (FSM) is the commissioning secondary mirror for the GMT and the backup when the ASM is off the telescope for service. The mirror consists of seven 1.05 meter segments in their cells attached to the top frame with positioners that provide six degrees of motion for alignment in the telescope optical system. The positioners have sufficient stroke to accommodate telescope structure manufacturing and assembly tolerances and to compensate for thermal expansion and flexure as the telescope moves in elevation.

The FSM segment axial supports provide short stroke tip/tilt motion to enable high precision stacking of the images from the seven subapertures and to attenuate low bandwidth (<10 Hz) wind shake. The segment and support designs are based on the Magellan secondary mirror. A prototype FSM segment and cell have been fabricated and tested[9,10].

3.3 ADC/Corrector

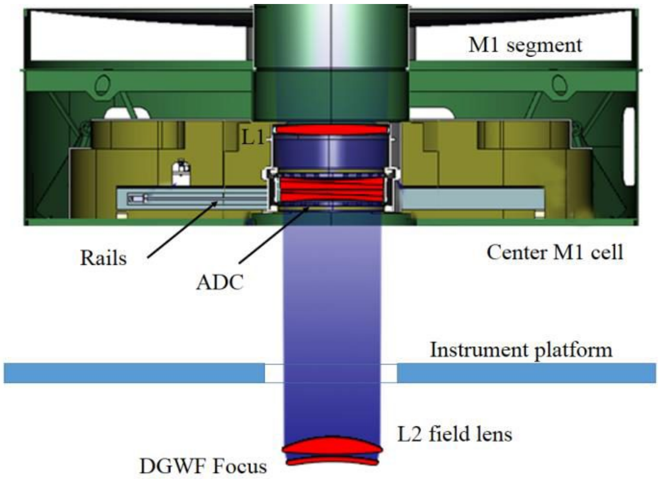


Figure 15. Corrector-ADC

The Corrector-ADC provides a well-corrected 20 arcmin diameter field of view over the wavelength range 370 nm to 1 µm. It also compensates for atmospheric dispersion at those wavelengths. The Corrector-ADC mounts on rails in the center primary mirror cell allowing it to be deployed in and out of the beam, Figure 15. The field lens for the corrector (L2) is located in the science instrument just above the Direct Gregorian Wide Field (DGWF) focus. The wide-field focus is 177 mm below the bare DG focus.

3.4 Tertiary Mirror

A deployable and steerable tertiary mirror 3.9 m below the M1 vertex will direct a 3 arcmin diameter beam to folded port instruments. The tertiary mirror will be mounted on the Gregorian instrument rotator (GIR) as shown in Figure 9. The mirror is retracted for observations at the direct Gregorian ports.

3.5 AGWS guider assembly

The Acquisition, Guide and Wavefront Sensor assembly (AGWS) contains a suite of off-axis acquisition, guide and wavefront sensors located on four “AGWS Units” that deploy and patrol the 20 arcmin diameter technical field-of-view (FOV) outside the 10 arcmin science Direct Gregorian – Narrow Field (DGNF) FOV. The AGWS is located in the GIR with its upper surface co-incident with the GIR top surface as shown in Figure 9. The AGWS structure is 2725 mm square and 610 mm deep.

The AGWS Units are located below the top surface of the Gregorian Instrument Rotator (GIR) and above the DG instruments, Figure 16. The AGWS units patrol the field by moving azimuthally and radially. A separate focus mechanism accommodates the focus required by operational mode and field angle.

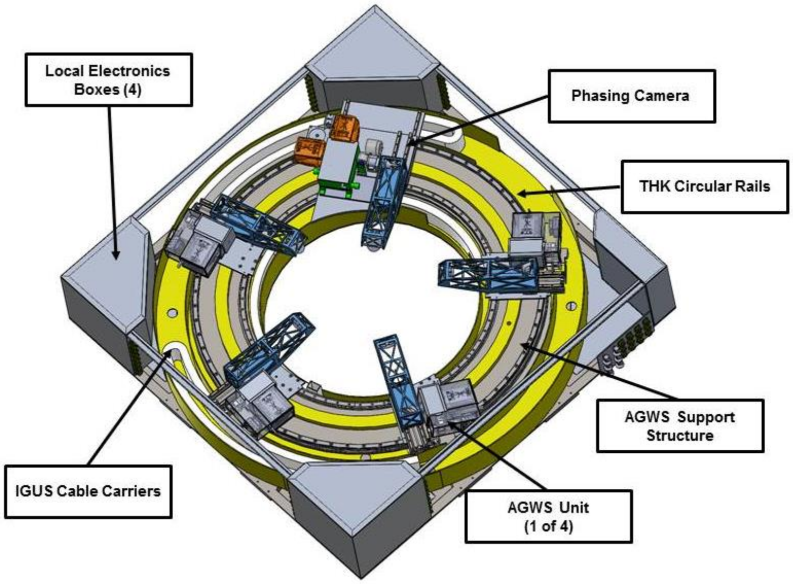


Figure 16. The AGWS viewed from below

These AGWS sensors provide the wavefront and guide star location data used by both the Active Optics (AcO) and (in certain modes) the Adaptive Optics (AO) systems to implement telescope guiding and control functions during operations[11].

The AGWS sensors provide three separate functions with separate optical trains, one function at a time:

1) A *seven-element Shack-Hartmann tip-tilt sensor* (“TT7”) with a 15 arcsec field-of-view provides the capability to acquire and guide images from the seven segments independently. Upon slewing to a new target, this mode will be selected on one of the four units. The seven images are moved to pre-calibrated reference locations by tilting the ASM or FSM to stack the images, and rapid guiding will commence.

2) A backup *initial-acquisition* function is provided by a 30×30 arcsec imaging relay. This mode will be used if the telescope pointing error is larger than the TT7 field of view or if the guide star is too faint to guide the segments separately. It is not expected that this mode will be used under most conditions.

3) After the seven segments are acquired and locked with the TT7, the three remaining units will acquire Shack-Hartmann *wavefront sensor* frames. These frames are fed to the wavefront reconstruction system that generates corrections to the segment positioners and force actuators for primary mirror figure control. After initial corrections are sent, science exposures commence while the AGWS provides continuous data to the guide and wavefront control systems.

The wavefront sensors also support the capability for the Natural Ground Layer Adaptive Optics (NGLAO) mode, which can provide improved image quality for all natural seeing instruments. In this mode, all four units will be configured in wavefront sensor mode following segment acquisition with the TT7. The NGLAO frame rate requirement strongly drives the camera choice in the AGWS.

4 PERFORMANCE MODELING

4.1 Finite Element Modeling

A finite element model (FEM) of the preliminary telescope design was created to analyze telescope performance when subjected to disturbances associated with static gravity deformation, wind buffeting, and seismic events. The model (Figure 17) includes the pier. Non-structural elements are represented by lumped mass attached to the structure with springs of the appropriate stiffness. Counterbalance weights and non-structural mass are applied at defined locations to maintain the center of gravity for the elevation structure at the elevation axis. Optical sensitivity equations in the model provide tip-tilt motion and de-focus of the image at the foci due to static and dynamic motions deflections of the telescope structure to compare against those terms in the GMT image quality budget.

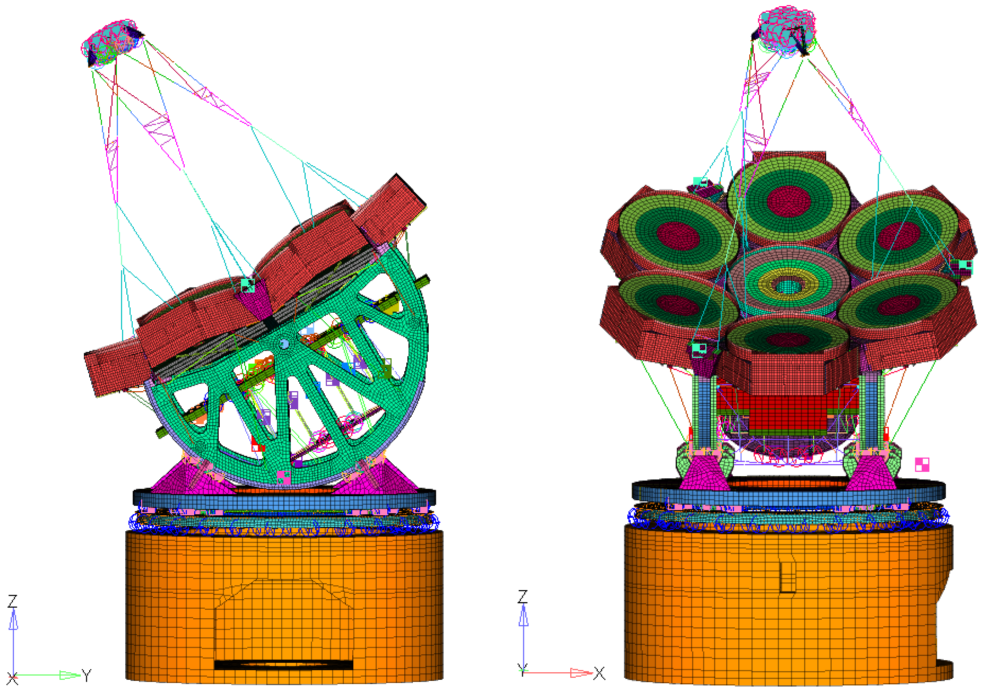


Figure 17. Preliminary design FEM. (Left) side view, (Right) front view

Studies that were conducted include:

- *Modal performance*. The lowest vibration mode of the telescope and pier occurs at 3.6 Hz. This determines the control bandwidth for tracking the mount of around 1 Hz. Fast guiding, including image stacking, relies on the tip-tilt capabilities of the secondary mirror segments.
- *Static Deflections*. Gravity deflection of the telescope structure was modeled over the full elevation range. The results factor into the required range of motion for the actuators on the primary and secondary mirror segments.

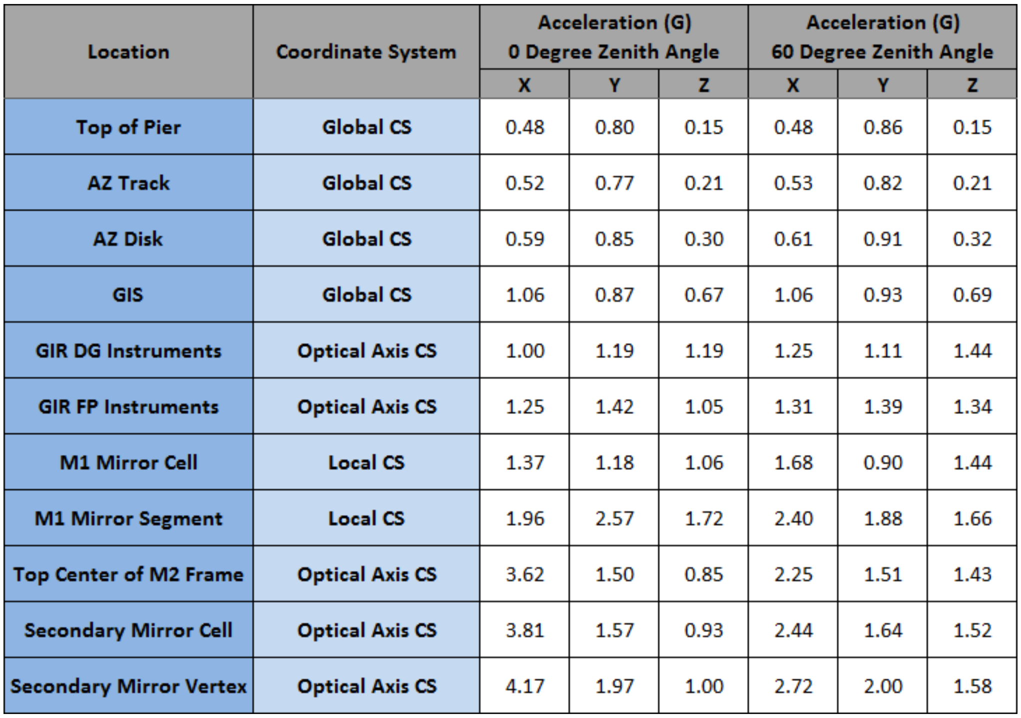
The maximum lateral deflection at the top (secondary mirror) end of the telescope is approximately 2 mm. Deflection for the primary mirror segments and instrument on the IP are under 0.5 mm. The focal plane scale is 1.00 arecsec/mm.

- *Seismic disturbance*. Motions of the ground under the GMT pier were provided in a Site Specific Seismic Hazard Analysis study for two severity cases: operational level earthquake (OLE) and survival level earthquake (SLE). These have been applied to the telescope and pier FEM to obtain forces, stresses and deflections within the structure.

  Responses of interest include accelerations at locations throughout the structure (particularly at sensitive or fragile subsystems), relative displacements at critical areas such as at the edges of optics near support structural elements, forces in all bearings, drives, actuators, M2 supports, and static support springs, and stresses in the major subassemblies. Dynamic acceleration results for the Survival Level Earthquake are summarized in Table 1. Gravity would add 1G to the vertical accelerations in the table.

- *Wind shake*. Wind tunnel testing and CFD modeling of the telescope in its enclosure were conducted to obtain the wind disturbance field on the telescope structure. Both static and time varying effects were considered. Various cases of enclosure opening and wind direction and speed were investigated and the results evaluated against the requirements of the Image Motion Budget. The methodology and results are presented in Irarrazaval, et. al.[12].

Table 1. SLE acceleration summary



Location	Coordinate System	Acceleration (G) 0 Degree Zenith Angle			Acceleration (G) 60 Degree Zenith Angle		
		X	Y	Z	X	Y	Z
Top of Pier	**Global CS**	0.48	0.80	0.15	0.48	0.86	0.15
AZ Track	**Global CS**	0.52	0.77	0.21	0.53	0.82	0.21
AZ Disk	**Global CS**	0.59	0.85	0.30	0.61	0.91	0.32
GIS	**Global CS**	1.06	0.87	0.67	1.06	0.93	0.69
GIR DG Instruments	**Optical Axis CS**	1.00	1.19	1.19	1.25	1.11	1.44
GIR FP Instruments	**Optical Axis CS**	1.25	1.42	1.05	1.31	1.39	1.34
M1 Mirror Cell	**Local CS**	1.37	1.18	1.06	1.68	0.90	1.44
M1 Mirror Segment	**Local CS**	1.96	2.57	1.72	2.40	1.88	1.66
Top Center of M2 Frame	**Optical Axis CS**	3.62	1.50	0.85	2.25	1.51	1.43
Secondary Mirror Cell	**Optical Axis CS**	3.81	1.57	0.93	2.44	1.64	1.52
Secondary Mirror Vertex	**Optical Axis CS**	4.17	1.97	1.00	2.72	2.00	1.58

4.2 Active Alignment

The primary mirror and secondary mirror segments are mounted on six degree-of-freedom actuators that provide focus and alignment control for the telescope optical system. In addition, the primary mirror segments are supported by force actuators that will be used to adjust the mirror segment figures for wavefront control. Closed loop feedback from guide stars is provided by the wavefront sensors in the AGWS. The active optics system operates continuously during observing with a bandwidth of approximately 0.01 Hz. The performance of the system during initial start-up and on-sky operation has been analyzed and reported by McLeod, et. al. [11].

4.3 Servo Modeling

A swept frequency forcing function was applied to various locations on the telescope to provide the transfer functions for the servo analysis of the main axis drives and fast tip-tilt performance of the FSM. These were combined with a servo model of the mount and secondary mirror assembly to obtain tracking and imaging performance for comparison with the Image Quality Budget.

5 CONCLUSION

GMT has completed the preliminary design phase of the project with the design of the telescope and associated facilities[13]. A construction proposal has been submitted to the GMT Board. The next phase of the project is about to start with the final design and fabrication of the telescope.

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