Invited Paper

The Giant Magellan Telescope Project in 2024: Status and Look Ahead

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ABSTRACT

The Giant Magellan Telescope (GMT) is one of three planned ground-based optical/IR Extremely Large Telescopes (ELTs) that will provide a generational leap in ground-based Optical/IR capability. The GMT is part of the United States ELT Program (US-ELTP) which received the top ranking in the National Academies' ASTRO2020 Decadal Survey. The GMT Project continues to proceed with design, fabrication, and site construction. Our schedule responds to evolving programmatic factors and we are engaged in a process to obtain US federal support for part of the construction and operations scope. Of the seven 8.4 m diameter mirror segments comprising the primary mirror, three have been completed with two in storage and with the third undergoing optical testing to demonstrate figure control with the GMT test mirror cell. The remaining four primary mirror segments have been cast and are in various stages of fabrication. The final design of the telescope mount is complete and fabrication is underway. The first off-axis adaptive secondary mirror system is being tested. Results to date from two adaptive optics and phasing testbeds have demonstrated the GMT phasing strategy and continue to be used for risk reduction and component qualification of our wavefront sensing and control strategy. The first generation science instruments are in various stages of development, from design to early fabrication. Hard rock excavation of the foundations for the enclosure and telescope pier is complete, as is the final design of the enclosure. Residence buildings and other facilities and infrastructure needed to support construction at the Las Campanas site in Chile are complete and in operation.

Keywords: GMT, GMTO, Giant Magellan Telescope, ELT, Extremely Large Telescope

1. INTRODUCTION

The Giant Magellan Telescope (GMT) is one of three planned ground-based optical/IR Extremely Large Telescopes (ELTs). The GMTO Corporation is a member of the United States ELT Program (US-ELTP) which received the top ranking in the National Academies' ASTRO2020 Decadal Survey.[1] The primary intent of this paper is to provide an overview and status update for the GMT Project. For additional perspective on the history and evolution of the GMT design, please refer to References [2] through [10]. Special attention in this update is given to those areas of active construction and ongoing prototyping and qualification testing that are reducing technical risk and informing remaining final designs.

2. PROJECT MANAGEMENT AND ENGINEERING DEVELOPMENT

GMT project management applies standard "best practice" management techniques such as risk management, configuration management, safety (both system and workplace), and quality control/assurance (QC/QA). Project cost and schedule are integrated into a Resource Loaded Schedule, and execution performance is monitored and measured using earned value management (EVM) techniques.

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2.1 Systems Engineering Management Processes and Current Status of GMT Subsystems and Interfaces

The GMT requirements tree is hierarchically divided into the following levels: science (L1); system, architecture-independent (L2); system, architecture-dependent (L3); and subsystem (L4, L5, and L6). Interfaces between subsystems are captured in a standard NxN diagram. We use the IBM Dynamic Object-Oriented Requirements System (DOORS) tool to manage requirements including full linking and compliance tracking. As of June 2024, the fully specified GMT Observatory requirements tree comprises 307 L2, 1824 L3, and 4848 L4 requirements. The NxN diagram defines 101 interfaces that are described and managed using Interface Control Documents (ICDs).

Key requirements are associated to high level Key Performance Parameters (KPPs) and with system level budgets such as image quality (IQ) during both natural seeing and adaptive optics (AO) observing.[11] For transparent and robust configuration management, KPPs are defined and controlled by the GMT Project's Systems Engineering (PSE) group who will also be responsible for their final verification. The GMT KPPs are grouped as follows:

- Image quality (on-axis PSSN, PSSN across the field of view, Strehl ratio, PSSN spatial uniformity, and PSSN temporal stability across the field of view); PSSN is an IQ metric that GMTO SE uses instead of PSF,
- Throughput,
- Target acquisition time,
- Effective collecting area.

A large set of design requirements for a complex large scale precision system such as an ELT requires special techniques to identify and to achieve the truly important performance and capability objectives. A straightforward method to ensure a project does not lose sight of the forest for the trees is to link key requirements linked directly to KPPs, and to link driving requirements directly to design, fabrication, and operational challenges. Design requirements that are both key and driving often require further trade studies and analysis of alternatives to optimize the design. GMTO uses sophisticated end-to-end system-level "integrated modeling" for sensitivity studies, analysis of alternatives, and verification by analysis to continually inform design choices (for example, see References 12 and 13).

From a management perspective, GMT engineering development is currently focused on completing the "leveling" of the Project subsystem engineering design maturity to system-level final design maturity in preparation for a system-level Final Design Review (FDR). As of June 2024, this leveling is more than 90% complete. Table 1 shows the current design maturity for the major GMT subsystems/products.

Table 1. Engineering maturity status for GMT subsystems. The maturity sequence from least to most mature is as follows: Conceptual Design (CoD), Preliminary Design (PD), Final Design (FD), post-FDR First Article Demonstration/Validation (DV), Procurement (Proc) prior to Construction (Procurement begins with RFP preparation and ends with source selection for Construction), Construction (Con), Operational (Op). A design phase ends upon completion of the design review for that phase (CoDR, PDR, and FDR).

Product or Subsystem	**Current Development Phase**
Large Scale Structures/Buildings	
Telescope Structures	Con
Enclosure	Proc
Summit Support Building	PD
Optics and Optics Support Systems	
Primary Mirror (M1) Segments	Con
M1 Subsystem	FD
M2 ASMS	DV
M2 FSMS	PD
M3	PD

C-ADC (14')	FD
C-ADC (20')	PD
Coating Systems	CoD
Instrumentation	
AGWS	FD
NGWS	FD
LTWS	FD
LGSS	FD
Wavefront Control Calibration System	FD
Telescope Metrology System	FD
Instruments (both Science and Commissioning)	
G-CLEF	Con for Spectrograph
GMACS	FD
GMTIFS	FD
GMTNIRS	FD
GMagAO-X	FD
MANIFEST	Mix of CoD/PD
Commissioning Camera	PD
Adaptive Optics Test Camera	PD
Software & Controls	
OCS	FD
GISS	FD
Site Support Facilities and Infrastructure	
Construction Site Infrastructure	Op
Permanent Site Infrastructure	Mix of Design and Con
Support Site 2 (Residential Facilities)	Op
Support Site 1 (Warehouse, Shop, etc.)	Mix of PD/FD

2.2 GMT Design and Development Sponsored by the National Science Foundation (NSF)

Current Design and Development Work Supported by the NSF

GMTO continues to reduce risk and validate segment phasing and wavefront control concepts with testbeds and prototype hardware demonstrations via two NSF awards. The NSF Development (“NSF-Dev”) subaward No NE0651C was received from the Association of Universities for Research in Astronomy Inc. (AURA) as part of NSF Grant No. 2013059. GMTO received an additional award on Oct. 1, 2023 to continue phasing risk reduction, prototyping, and broader impacts efforts. This recent NSF Award focusing on Optical Performance Risk Reduction (“NSF-OPRR”) is supported by NSF Cooperative Agreement Award No. (FAIN) 2332336. Much of the progress reported in this paper and elsewhere in this conference is the outcome of these NSF-sponsored efforts. GMTO takes this opportunity to express its deep appreciation to the NSF for their support.

Additional NSF-related Activities

As of December 8, 2022 the Giant Magellan Telescope (GMT) project was recommended and approved for entry into NSF's Major Facility Design Stage in accordance with NSF's Research Infrastructure Guide (RIG; NSF 21-107, December 2021)1 as part of a United States Extremely Large Telescope (US-ELT) program. It was determined by NSF at that time that the GMT project was sufficiently mature to enter their design process at the Preliminary Design Phase, the second of three phases that comprise the NSF Design Stage.

Following the formal entry of the GMT project into the NSF Design Stage, the NSF convened a formal Preliminary Design Review that occurred in two parts in mid-December 2022 and early February 2023. As determined by the NSF PDR Committee composed of external (non-NSF) experts, the review of the GMT project associated with completion of the Preliminary Design Phase revealed no technical or managerial concerns that could not be addressed during final design.

3. PRIMARY MIRROR OPTICS (M1) AND SUPPORT SYSTEM (M1S)

3.1 Primary Mirror Segment Production

Since July 2022, GMT primary mirror segment production at the University of Arizona's Richard F. Caris Mirror Lab (RFCML) has been focused on the following:

1. The final acceptance of mirror segment S3 see (Figure 1),
2. The beginning of front surface generation of segment S5 (see Figure 2),
3. The casting and post-casting cleanout of segment S7 (see Figure 3).

The GMT activities at the RFCML during the remainder of 2024 and early 2025 will mostly be focused on the optical testing of S3 in the Test Cell under the RFCML Test Tower (see Section 3.2 below).

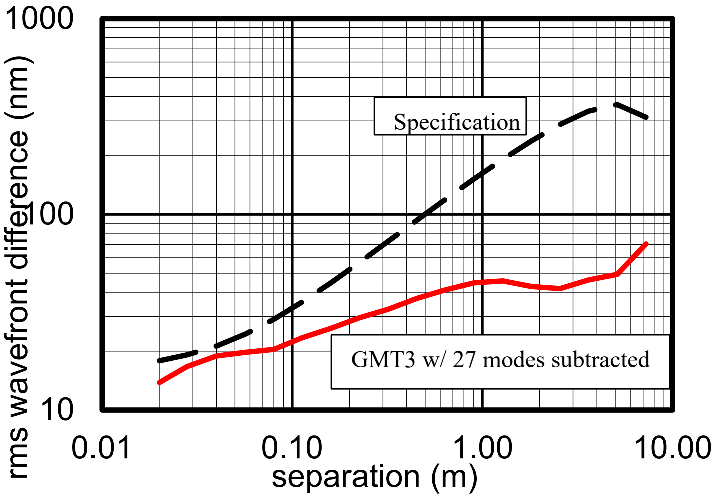

Figure 1. The structure function for S3 showing the excellent polishing performance achieved for the accepted mirror. The subtraction of the 27 modes refers to analytically subtracting 27 bending modes to simulate the primary mirror wavefront corrections that will be applied by the M1S "Active Optics" support actuators when on sky. The structure function above represents the residual mirror figure after this subtraction.

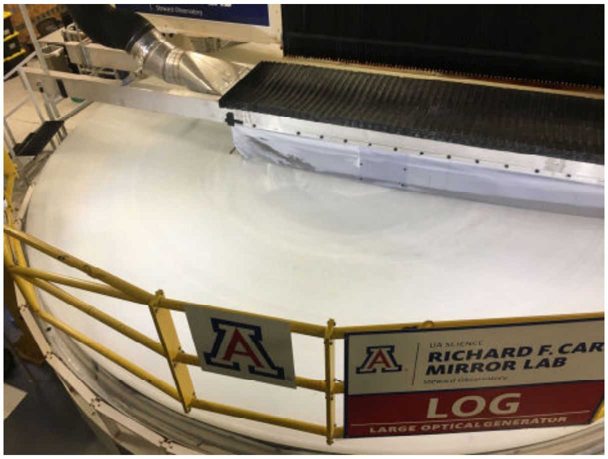

Figure 2. Segment S5 undergoing front surface generation on the RFCML Large Optical Generator. *(Photo courtesy of University of Arizona RFCML)*

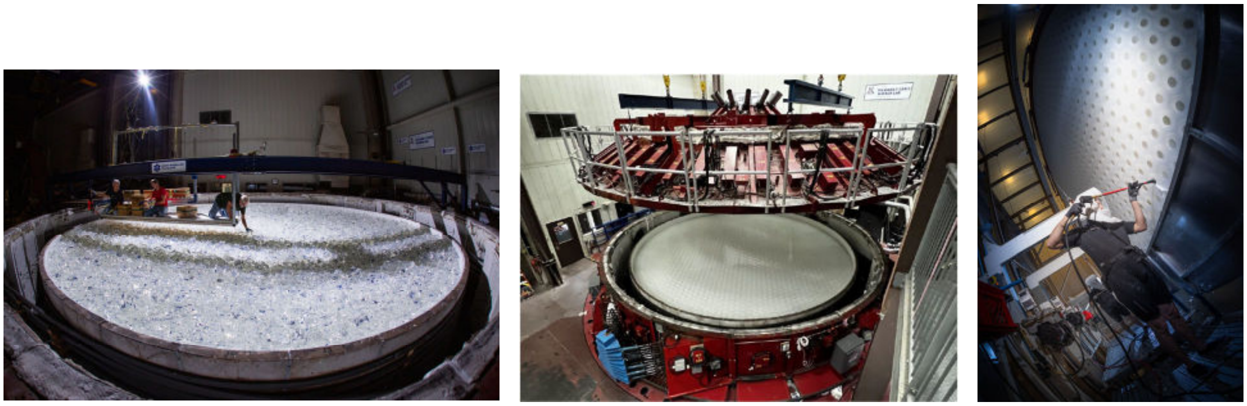

Figure 3. S7 initial production activities: the loading of the glass into the mold (left), the opening of the hearth after the mirror is cast (center), and post-casting cleanout of the cast mirror.

3.2 M1 Support System (M1S)

The GMT requires active optics control to position the primary mirror (M1) segments, actively support the M1 Segment weight, and control low-order M1 Segment figure error using active optics corrections. Mirror seeing and thermal figure error are controlled by actively regulating the M1 Segment temperature to track the ambient air temperature. The M1 Subsystem (M1S) includes the static support, active support control system, and thermal control system of the M1 segments. The active support control system lifts the M1 Segment off the static supports and precisely controls the M1 figure and position. It consists of triple-axis and single-axis pneumatic support actuators that counter the M1 segment gravitational forces and control the mirror figure. The 5-dof bulk position and orientation is controlled by linear actuators known as hardpoints. The mirror segment is cooled by a closed-cycle forced air convection system using air handler units with CO2-based refrigeration to circulate and condition the air.

Since the test plan reported in 2022, the M1S team has conducted functional and performance testing of a complete M1 active support system using a mirror simulator having the mass and center of gravity of an off-axis mirror segment.[14] The objective of these tests was to demonstrate that the control system will be safe and robust in its operation when integrated with the S3 mirror segment. The test results show that the system is safe for integrating with an actual glass mirror segment. The team successfully completed the Safe for Glass Review (SFGR) in May 2023, and this was the last milestone for the M1S testing component of the NSF/AURA Development subaward.

After the SFGR, the M1S team conducted the “Tilt Test” as the first major milestone of the M1S component of the NSF OPRR award. The Test Cell together with the Mirror Simulator was tilted at 13.5 degrees to simulate the cell orientation on the telescope while the telescope is zenith pointing (see Figure 4). Software control of the actuator support system was demonstrated at this orientation. The results show that the active support control system can reliably and repeatedly raise and lower the mirror simulator and recover from a panic event induced by the mirror simulator jammed or twisted against the static supports. The Tilt Test also confirmed that the programmed force distribution calculations are correct as the gravity angle changes.

The M1S team is now preparing to move the Test Cell to the Richard F Caris Mirror Lab (RFCML) for integration with the S3 mirror segment and then conducting optical testing using the RFCML Test Tower.[15] The M1S team has also integrated the air handler units (AHU) of the thermal control system and pressure testing of the CO2 distribution system of the Test Cell. The portable CO2 refrigeration unit (PCRU) that supplies CO2 to the Test Cell has been received and thermal control testing is currently underway.[16]

Figure 4. The GMT M1 Test Cell weldment (white) with a full scale mirror simulator (gray) tilted at 14 degrees which is the angle an off-axis mirror segment will be when the telescope is at its zenith-pointing position. The Test Cell is now fully functional with its mechanical support system and under full software control (an image of the user interface for this control system is shown below in Figure 23).

4. SECONDARY MIRROR OPTICS (M2)

From a technical perspective, the M2 Adaptive Secondary Mirror System (ASMS) represents a key enabling technology due to the GMT AO requirements requiring a new generation ASM relative to the adaptive secondary mirror systems currently in operation. GMTO has contracted with AdOptica, a consortium of ADS International and Microgate, to create what will become the 4th generation of operational adaptive secondary mirror systems and that will possess significantly enhanced capabilities compared to the previous generations (see Figure 5). In order to further inform this technology development, GMTO has been pursuing an Adaptive Secondary Mirror System (ASMS) Manufacturing and Phasing Risk Reduction program. To date, this program has been supported by a combination of GMTO internal funds and funding from the NSF-Development subaward and the NSF OPRR award. The primary objectives of this program are (1) to conduct, assess, and mitigate manufacturing risks as early as possible in the development life cycle, and (2) to use full scale “First Article” hardware to validate and qualify the ASMS design relative to its phasing requirements. For further details see Reference 17.

For the first objective, and specific to the 4th generation ASM for the GMT, the off-axis, parabolic Thin Shell and Reference Body were the first off-axis ASM components to be built. Previous generations of ASMs have had an on-axis parabolic shape. The off-axis optical contour adds complexity in the manufacturing to identify and maintain the vertex through the manufacturing process and complexity to the testing to verify the off-axis shape. Together with other first article opto-mechanical and electro-mechanical HW, assembly and testing has been completed of the ASM components for the primary load path, including testing of the vibration modes and the damping coefficient to verify the mechanical design.

The Thin Shell began as a ~100 mm Zerodur blank supplied by Schott in Germany and then was ground and polished to the final 2 mm thick optic by Safran-Reosc in France (under contract to AdOptica). The manufacturing process removed 98% of the original material to form the Thin Shell, resulting in a 1.05-meter, concave, off-axis, parabolic optic as the deformable surface for the ASM. The deformable nature is due to the 2 mm thickness that can be shaped by the voice coil motors to create a diffraction limited image for the telescope. The Thin Shell is shown in left photo in Figure 6.

The Reference Body was designed by AdOptica and was manufactured by University of Arizona and Korea Research Institute of Standards. The 1.05-meter off-axis parabolic optic is made of Zerodur, has high stiffness, and is 77% lightweighted. It provides the precision surface that matches the Thin Shell contour and provides capacitance sensor armatures for the precise measurement of the Thin Shell position for closed loop control of the image quality. It also provides the pass through for the 675 voice coil motor actuators that provide the non-contact, magnetic force to control the shape of the Thin Shell as well as the mounting for the edge sensors and retroreflectors for the alignment system.

Following manufacturing of ASMS components that undergo comprehensive component-level testing, the ASM phasing risk reduction program integrates these components into testbeds with increasing capabilities as the program advances:

- Mechanical Performance Testbed: Full scale mechanical components comprising a partial single ASM to validate structural performance. Fabrication and assembly is now complete, and ongoing testing will complete in 2024 (funded by NSF/AURA Development Subaward). See photo on the right side of Figure 6.
- Phasing Testbed Stage 1: Additional full scale components comprising a partial single ASM integrated with a test fixture to simulate the interfaces with other ASM segments (funded by the NSF OPRR Award).
- Phasing Testbed Stage 2: Integrate 3 full scale complete ASM segments to demonstrate phasing between ASMs.
- Phasing Testbed Stage 3: Integrate all 7 of the ASM segments mounted in a telescope Top End at the AdOptica factory to demonstrate the fully integrated phasing performance prior to delivery to the GMT site.

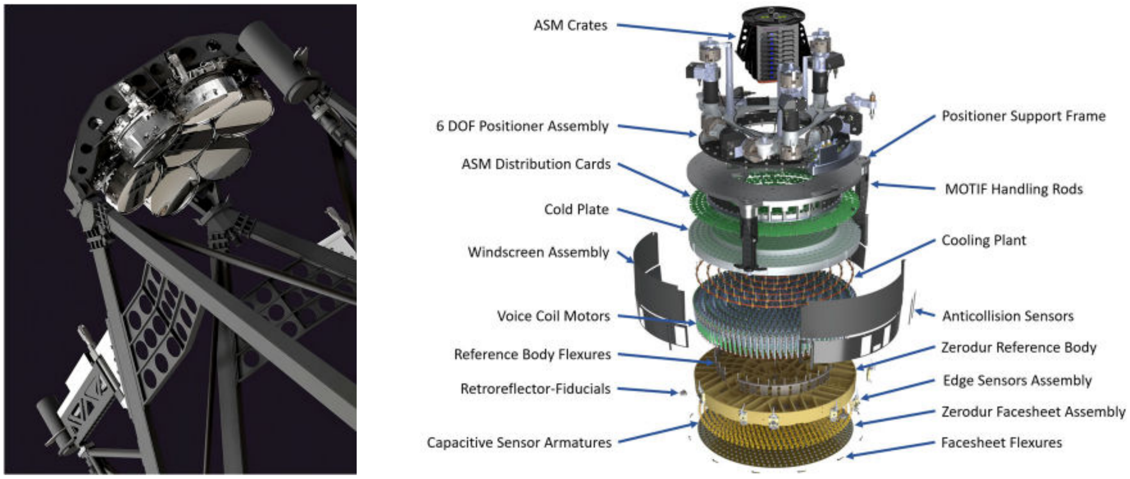

Figure 5. The seven GMT Adaptive Secondary Mirror Systems (ASMS) installed on the Mount's upper truss (left) and an exploded view of a single ASMS (right).

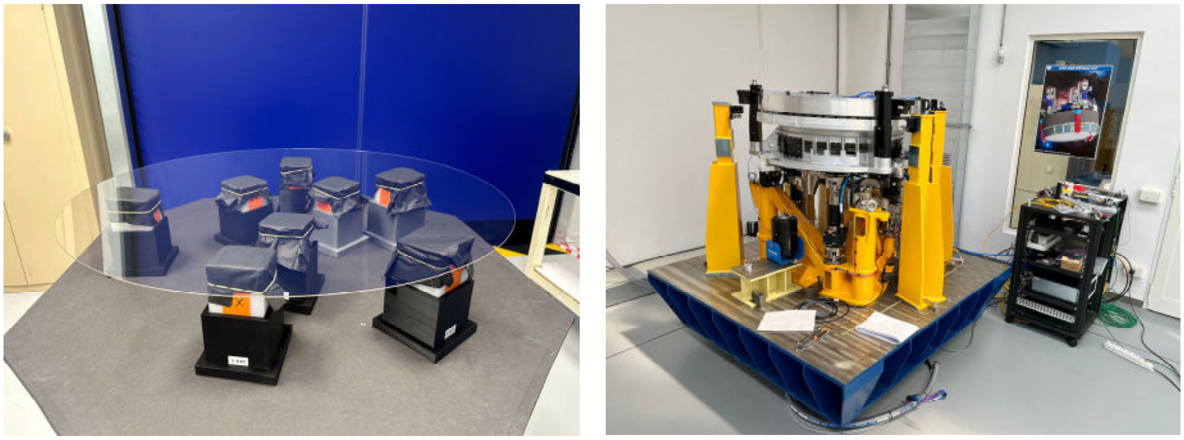

Figure 6. ASMS Thin Shell #1 (left) and associated ASMS hardware in its test stand configuration (right). *(Photos courtesy of Safran-Reosc and AdOptica)*

5. ADAPTIVE OPTICS TESTBEDS

5.1 Wide Field Phasing Testbed (WFPT) Work at SAO

A collaboration between GMTO and Harvard-Smithsonian, supported by funding from the NSF/AURA Development subaward, has completed integration and initial testing of a Wide Field Phasing Testbed (WFPT) (see Figure 7 and for more details see References 18 and 19). This testbed incorporates a prototype Acquisition, Guiding, and Sensing Wavefront Sensor (AGWS-p). To date, the testing has included (i) calibrations and repeatability measurements of a turbulence-generating phase screen, (ii) functional tests and quality checks of the control software in the presence of turbulence, (iii) validation of code for real-time data processing, and (iv) calibration of Shack-Hartmann lenslets.

Of particular note, these tests included the first closed-loop demonstration of a field-dependent piston error being both measured and corrected. This is a required of the Acquisition and Guiding Wavefront Sensor (AGWS) that is so critical to normal telescope operation, and which is necessitated by GMT's unique doubly-segmented telescope design (7 primary-secondary mirror segment pairs). This achievement represents a partial validation of the overall AGWS performance.

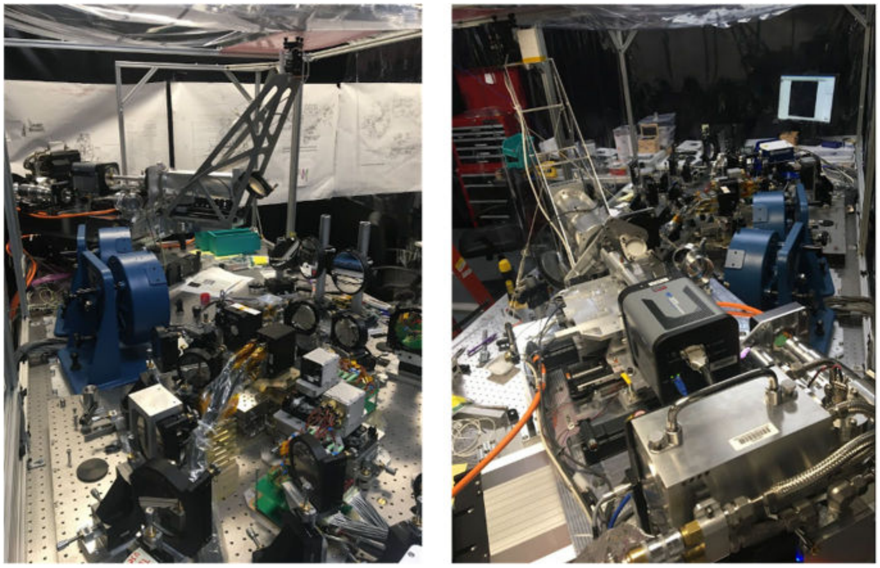

Figure 7. Two views of the Wide Field Phasing Testbed containing the Acquisition, Guiding and Wavefront Sensor prototype (AGWS-p at Harvard-Smithsonian. (*Photos courtesy of Harvard-Smithsonian*)

Another significant milestone was demonstrating closed loop control using a technique known as “modal control”. The test—operated remotely from Pasadena— corrected 98 modes (14 modes per segment) from an initial state of random segment tilts and other modal errors. These results demonstrated a closed-loop steady state residual error less than 100 nm RMS per segment which is considered excellent performance.

5.2 High Contrast Adaptive Optics Testbed (HCAT) and Natural Guide Star Wavefront Sensor Prototype (NGWS-p)

Like the WFPT, the High Contrast Adaptive Optics Testbed (HCAT) currently located at the University of Arizona was developed under the NSF/AURA Development Subaward. GMT’s WFSC team led this effort with technical support from the University of Arizona and INAF Arcetri (see Figures 8 and 9, and for more details see References 17 and 20). Three test runs have been completed with positive results that also indicate what next steps are needed to further mature the GMT phasing capability.

The third and final test run occurred November 2023 in the adaptive optics laboratories located in the Steward Observatory of the University of Arizona. Engineers from GMTO and INAF Arcetri were present working with the UA team. The key accomplishments of this test campaign were the following:

- Demonstration of simultaneous segment-piston phasing and rejection of atmospheric turbulence using the NGWS prototype to sense and control the segmented GMT telescope simulator,
- Demonstration of the ability to recover from segment piston ejections,
- Further validation of the NGWS design and the piston phasing strategy,
- Partial validation of GMT’s wavefront control software and its algorithms.

The optimization of the NGWS-p second channel architecture, which increases the segment phasing capture range and stability in marginal conditions, was a key component of this development activity. The NGWS-p performed reasonably well in the presence of simulated but realistic atmospheric turbulence. Not surprisingly given the initial implementation of a new technical approach, there remains additional work required to fully optimize sensor and control loop performance. It is important to note that there is no indication of any underlying flaw with the GMT phasing approach.

In summary, the HCAT/NGWS-p test runs have demonstrated that GMT’s phasing strategy for NGAO mode is viable and achievable. Furthermore, the results have validated the unique design of the Natural Guide Star Wavefront Sensor Prototype (NGWS-p) by operating two wavefront sensors simultaneously. The test campaign consisting of three two-week runs in CY2023 resulted in significant phasing risk burndown. Future work will include stabilizing and improving the fine phasing performance of the NGWS-p.

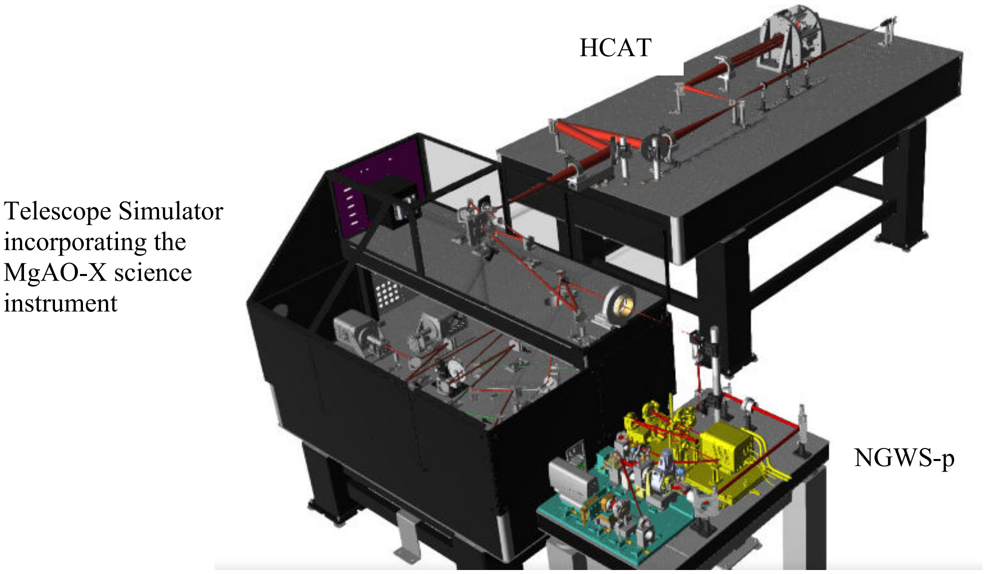

Figure 8. Graphic showing the layout of the three major parts of the GMT High Contrast Adaptive Optics Testbed (HCAT) setup at the University of Arizona: (i) the telescope simulator front end, (ii) the HCAT testbed itself, and (iii) the NGWS-p.

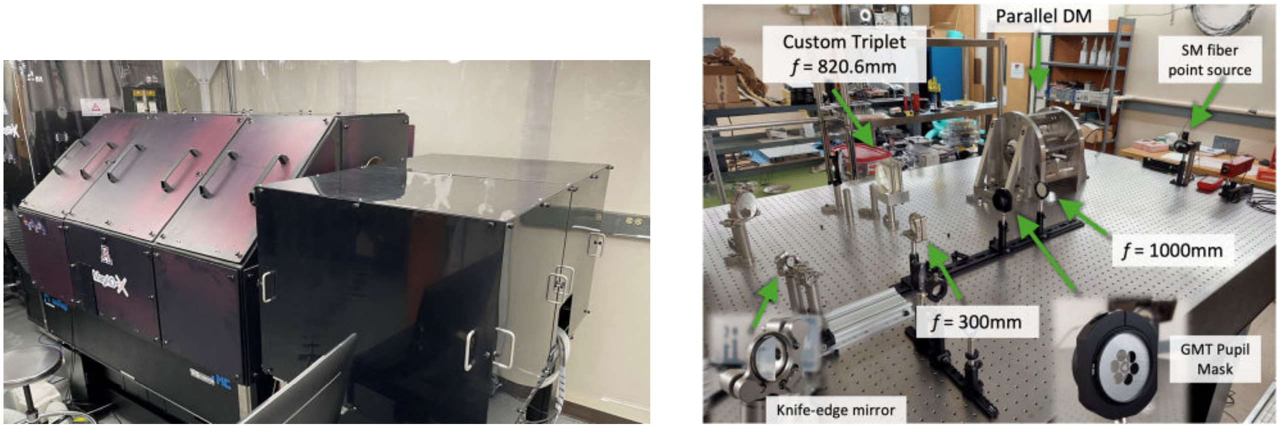

Figure 9a. Graphic showing the layout of the three major parts of the GMT High Contrast Adaptive Optics Testbed (HCAT) setup at the University of Arizona: (i) the telescope simulator front end of which the primary component is the MagAO-X science instrument usually deployed on a Magellan telescope and (ii) the HCAT testbed itself.

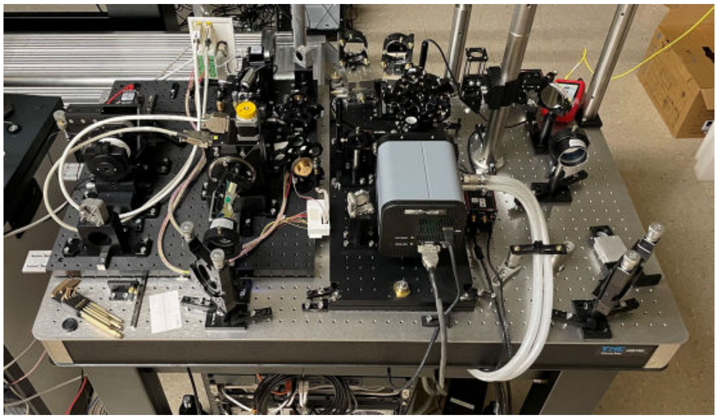

Figure 9b. A photo of the prototype Natural Guidestar Wavefront Sensor (NGWS-p) that is integrated with the HCAT.

6. TELESCOPE MOUNT

As described in our 2022 paper, GMTO selected OHB Digital Connect (ODC, formerly known as MT Mechatronics) of Mainz, Germany and Ingersoll Machine Tools (IMT) of Rockford, Illinois USA to supply the final design, fabrication, and installation of the Giant Magellan Telescope (GMT) Mount.[21] This is the same partnership that designed and built the DKIST telescope structure. The Mount completed Final Design in 2023 and in this section we provide a detailed reminder of its key design features and highlight the beginning of its construction. Further details may be found in Reference 22.

6.1 Selected Technical Features

As shown in Figure 10, the GMT Mount is the structural, mechanical, hydraulic, and electronic system that is required to support, align, point, and track the telescope. The Mount is composed of the following assemblies: Optical Support Structure (OSS), Gregorian Instrument Rotator (GIR), azimuth structure, azimuth track, the Hydrostatic Bearings System (HBS), the mount drives, restrictors and locking pins, M1 conical baffle, primary mirror covers, instrument deployment mechanisms, and the azimuth, elevation, and GIR cable wraps. and is in the initial construction stage.

The Mount design has been optimized through several years of design refinement and extensive engineering analysis that has demonstrated its low-risk technical feasibility. The design approach results in a compact final swept volume that helps minimize the volume of the enclosure needed to support efficient operations. A primary key and driving requirement is that the Mount structure must also explicitly mitigate the challenging seismic environment in Chile.

The Mount possesses 22 interfaces to other subsystems not part of the Mount ("external interfaces"). Some examples of these include the Mount interface to the Enclosure's telescope pier, the interface to M2, the interface to the Telescope Metrology System (TMS), the interface to the AGWS, and the five types of science instrument interfaces: Gravity Invariant Station (GIS), Auxiliary Port (AP), Instrument Platform (IP), Direct Gregorian (DG), and Folded Port (FP). An interesting interface worth noting is the Mount--TMS interface due to the large number of individual TMS lasers, sensors, and communication fibers that comprise the system.[23] A location for a large instrument requiring a stable gravity vector is provided on one side of the azimuth disk, referred to as the Gravity Invariant Station (GIS) which will be occupied at First Light by the G-CLEF instrument. The DG and FP types of science instrument interfaces are located on the GIR. Three DG instruments, two large, and one small, can be stored on the GIR. Three FP instruments, identical in allocated volume and interfaces, can be mounted on the top surface of the GIR. Instruments mounted on the GIR are subjected to a gravity vector varying in two dimensions.

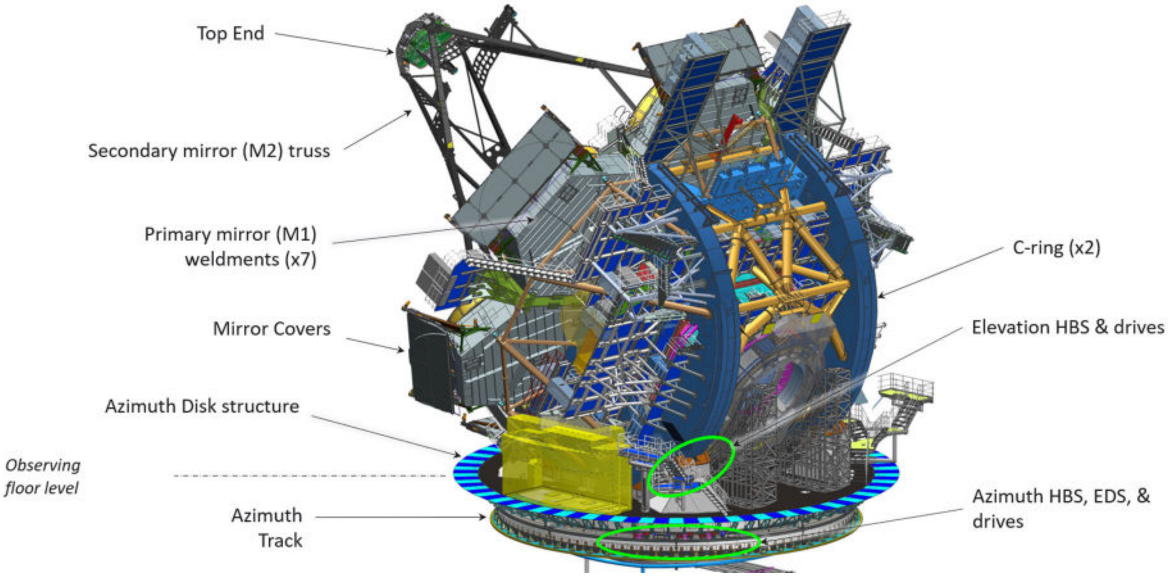

Figure 10. The GMT Mount showing its major components

A high level decomposition of the Mount structures is shown in Figure 11, and will serve as a starting point for presenting the current construction status in Section 6.2. The azimuth track and structures began construction in July 2023 and their construction is fully funded.

The Enclosure's telescope pier features a seismic isolation system (SIS) at its base to reduce the transmission of lateral seismic forces through the pier, but the interface between the top of the pier and the azimuth track must still accommodate significant loading. A key structural aspect of the azimuth track design separates lateral loads from vertical loads to limit stresses at the anchor bolts connecting the track to the pier. While the SIS isolates and damps lateral accelerations, it transmits potentially large vertical acceleration. Vertical loads in the Mount are mitigated by means of an Earthquake Damping System (EDS) which is a proprietary damping system physically incorporated into the azimuth structure.[24]

The azimuth track has an approximately 21.5 meter outer diameter, a weight of 172 tons, a width of 2.4 meters, and is constructed in eight identical segments. The track segments feature both the axial and radial bearing raceways: surfaces in two "orthogonal planes" that must be machined to flatness within 200 microns globally and 20 microns locally. The axial bearing raceway is also the load path for the EDS deployed in seismic, braking, and parked configurations.

The azimuth track is connected to the pier with a combination of anchor bolts, adjustable shim blocks (fixators), and flexures on intermediate base plates that are welded to the steel embedments in the concrete pier. The azimuth track also includes the azimuth encoder tape, azimuth drive magnet rotor forcers, hydrostatic bearing oil collection system (see Figure 12). The azimuth utility wrap is a separate, independently driven, corotating system.

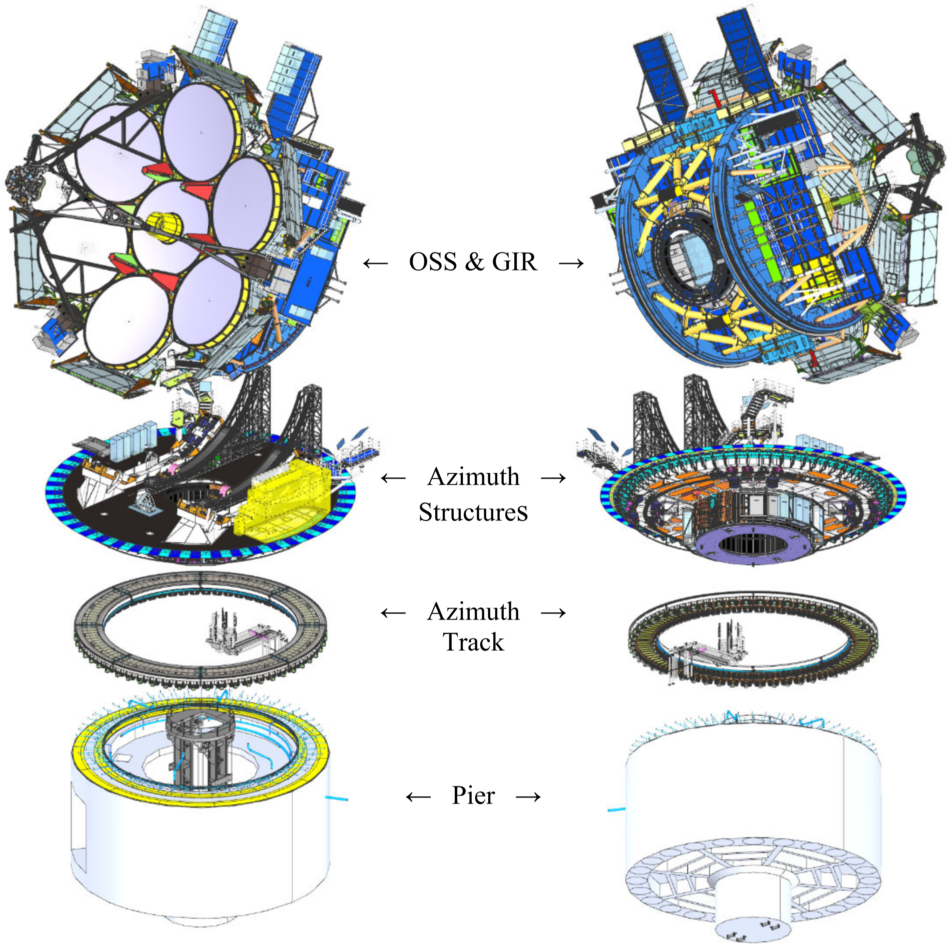

Figure 11. High level decomposition of the GMT Mount and telescope pier (the pier is part of the Enclosure scope, not the telescope).

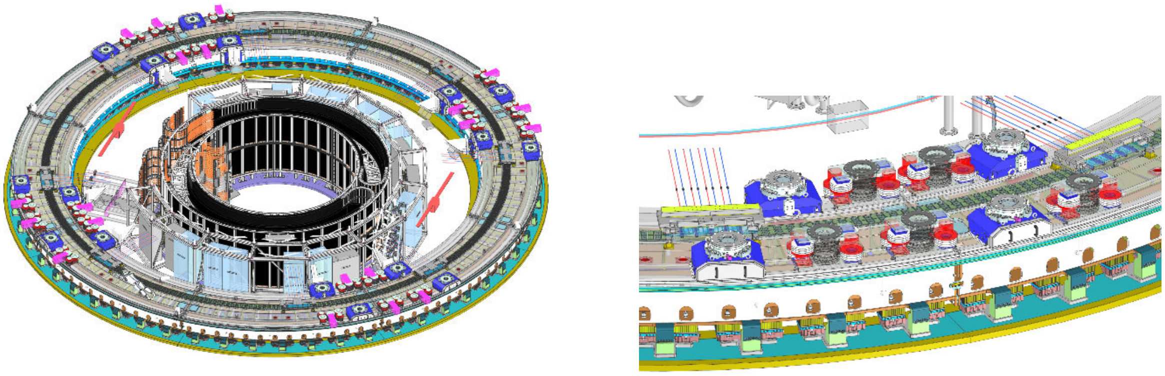

Figure 12. Azimuth track and bearings cross-section (left) and a closeup of the bearings (blue) and EDS (red) on the track (right).

All strength and stiffness FEA and jitter performance end-to-end modeling has been completed to verify analytical compliance. Verification and initial validation will continue during factory testing where actual test values will be compared against the analytical models. The seismic response dynamic analysis continues to be refined to correlate with maturing pier and seismic isolation system design updates.

6.2 Mount Construction Status as of June 2024

After a successful Final Design Review and Manufacturing Readiness Review in June of 2023, the telescope Mount has commenced construction of the fixed Azimuth Track base and the rotating Azimuth Disk structures. The factory construction is split into two phases, Phases 5A and 5B, to coincide with the major sub-assembly groups. Phase 5A consists of the static foundation Azimuth Track and its distributed load connection system to the concrete pier, the rotating Azimuth structure, and the mechanisms and electronics to achieve controlled azimuth motion. GMTO is fully funded to complete Phase 5A with an anticipated completion date of Dec 2025. Photos showing selected parts of Phase 5A construction progress are shown in Figures 13, 14, and 15.

Figure 13. The GMT Mount "test pit" area in the high bay facility at IMT in Rockford, IL. For factory integration and testing, this area represents the top of the GMT pier that interfaces with the Mount's azimuth track. The "springbox" assemblies, just one type of the multiple components and assemblies that are part of this complex interface, are shown here as they are being laid out for the azimuth track integration later this year. *(Photo courtesy of Ingersoll Machine Tools)*

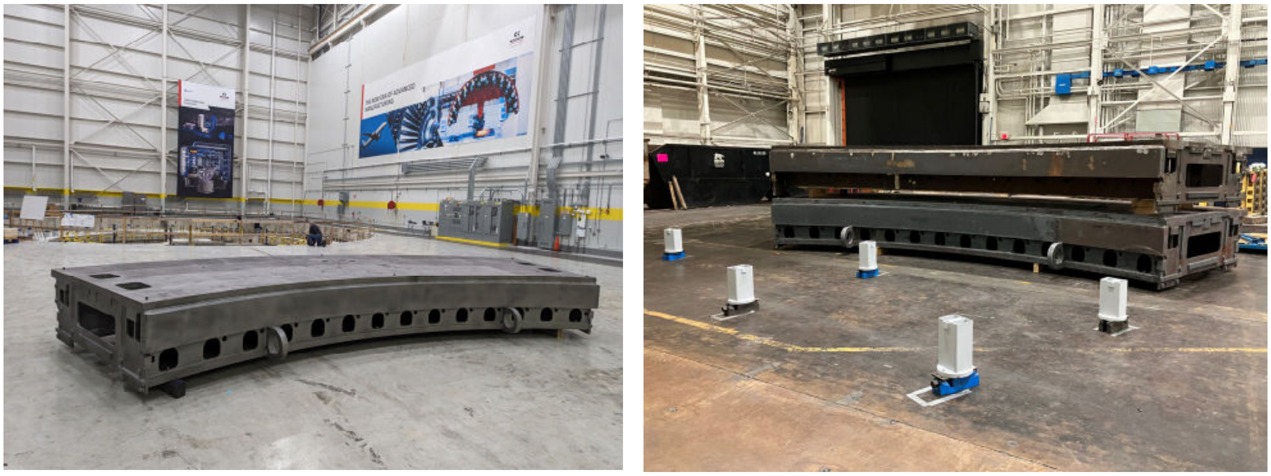

Figure 14. Sections of the Azimuth Track at IMT in Rockford, IL prior to being shipped to Huntsville, AL for rough machining by Teledyne. The section on the left has completed grit blasting while the two sections on the right are awaiting grit blasting. *(Photos courtesy of Ingersoll Machine Tools)*

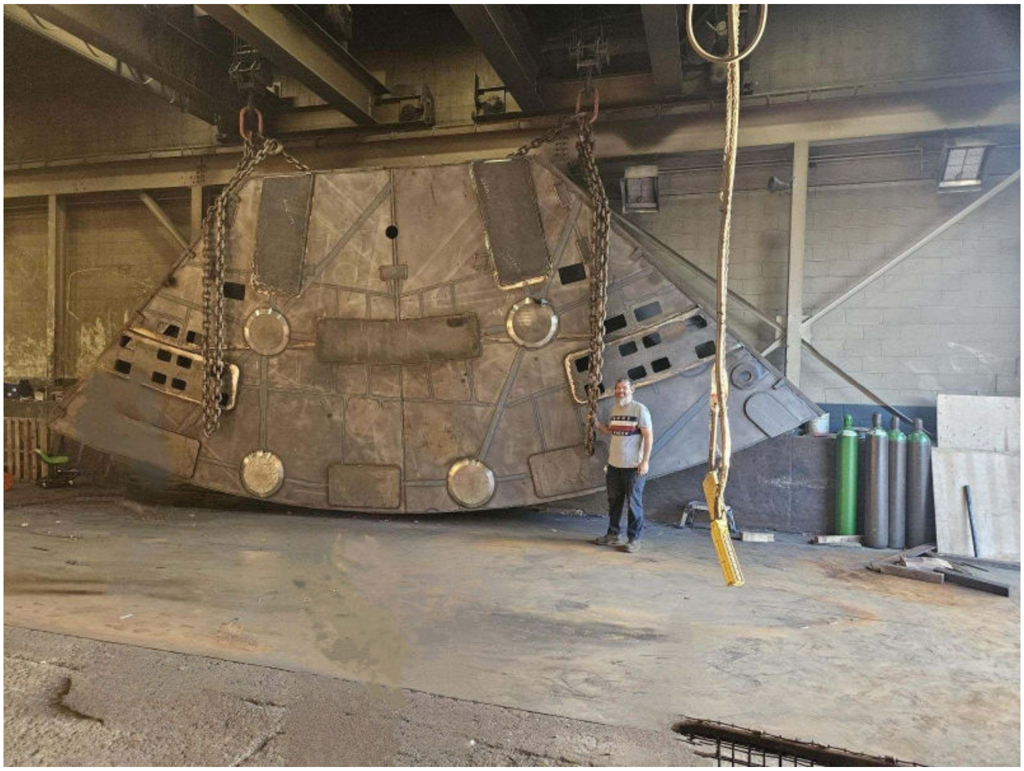

Figure 15. A section of the Azimuth Disk at Dynasty Fab outside Detroit, MI. Once the full Azimuth Disk is completed by Dynasty, it will be shipped to Rockford for integration and testing with the other azimuth structures. *(Photo courtesy of Dynasty Fab)*

7. SCIENCE INSTRUMENTS

As a reminder, the GMT can host up to ten instruments simultaneously that are located at focal stations that accommodate various instrument volumes, masses, and fields of view. Instrument exchanges are designed to facilitate rapid observation of transients and dynamic allocation of observing programs to match changing conditions. The initial suite of first-generation science instruments was identified through an open solicitation for concepts and that passed thorough Conceptual Design Reviews in 2012. Recently, an additional instrument (GMagAO-X) has begun to be incorporated into the baseline configuration (both technically and programmatically). Please refer to Reference 25 for the current status of the GMT first generation of science instruments.

7.1 GMT Consortium Large Earth Finder (G-CLEF)

G-CLEF is a high-resolution visible-light echelle spectrograph with precision radial-velocity capabilities. The instrument is located at the telescope's gravity invariant station and is fiber coupled to a dedicated front-end assembly mounted to the GIR. The G-CLEF spectrograph has completed final design and is in fabrication and initial assembly testing.[26] Once completed, the spectrograph will be deployed for initial observing on one of the Magellan telescopes at the Las Campanas Observatory in Chile (adjacent to the GMT Las Campanas site).[27] The G-CLEF front end electronics specific to the instrument's GMT configuration are in final design. The red camera element of the spectrograph is currently undergoing testing. Key components of the blue camera such as the entrance and exit prisms for the cross-dispenser have been delivered. The composite optical bench has also been delivered. See Figures 16 and 17 for photos of the G-CLEF red camera, echelle gratings, and optical bench.

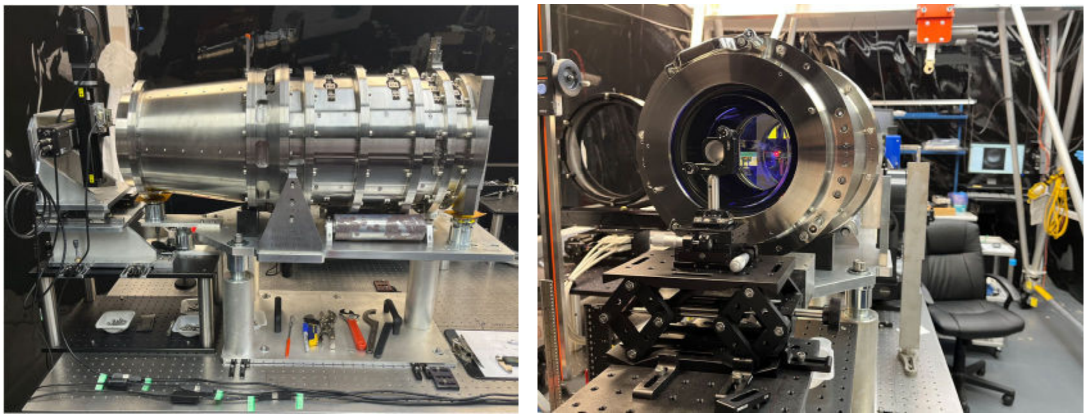

Figure 16. The G-CLEF red camera lens stack viewed from the side (left) and from the rear (right). The red lens stack is made of seven lenses housed in an ultra-stable Invar metal fixture. Following the successful build of instrument's red camera, testing is now underway at the G-CLEF optical test facility. Testing has demonstrated that the optical performance exceeded baseline requirements by approximately a factor of five. (Photos courtesy of A. Szentgyorgyi, Harvard-Smithsonian Center for Astrophysics)

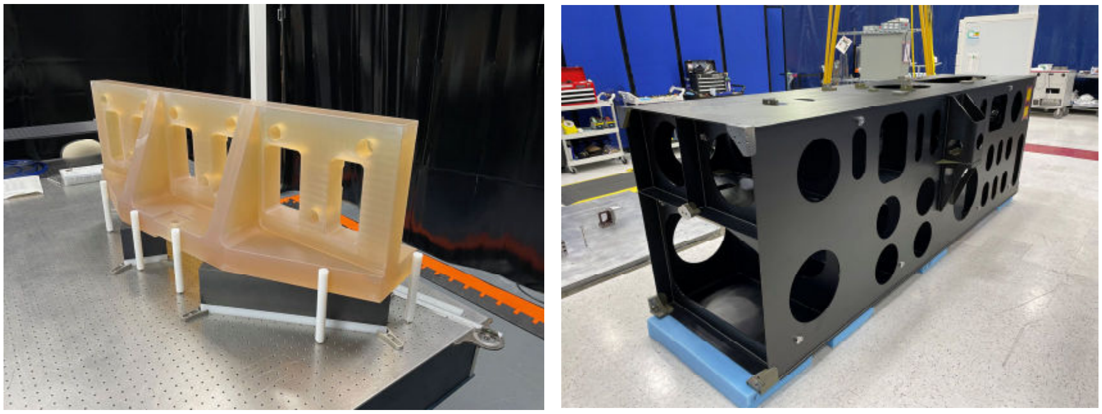

Figure 17. The G-CLEF echelle grating assembly (left) and the optical bench made of composite material to minimize weight while maintaining strength and desirable thermal properties (right). (Photos courtesy of A. Szentgyorgyi, Harvard-Smithsonian Center for Astrophysics)

7.2 GMT Wide Field Multi-Object Spectrograph (GMACS)

GMACS is in development in collaboration with the Center for Astrophysics | Harvard & Smithsonian and the Steiner Institute in Sao Paulo, Brazil. The instrument is a visible-light, moderate-dispersion, multi-object spectrograph. Moderate resolution spectra (R~1,000 – 6,000) can be obtained for multiple targets distributed with a 6.5 x 7 arcminute field of view using 0.7 arcsecond-wide slits in a multi-slit mask. GMACS operates with a wide field corrector and atmospheric dispersion corrector unit (C-ADC-14), where the ADC minimizes slit losses due to spectral atmospheric dispersion and allows long observations of a selected field. Together with the MANIFEST fiber front end, GMACS can perform surveys across the full 20 arcmin field of view of the telescope. The instrument configuration is shown in Figure 18 and currently is in Final Design. GMACS is planned to be the second instrument commissioned on the telescope, and it will likely be our most-used instrument as it satisfies the broadest range of science cases in our first light suite.

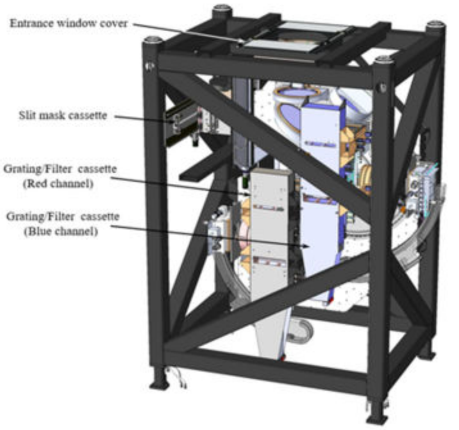

Figure 18. Exterior view of GMACS in its interface mounting frame.

7.3 GMT Near-Infrared Spectrograph (GMTNIRS)

The GMTNIRS is a high spectral resolution infrared spectrograph selected as a first-generation instrument for the telescope. GMTNIRS is a collaborative development effort between The University of Texas at Austin and the Korean Astronomy and Space Science Institute. The six individual spectrographs inside GMTNIRS collectively cover the J, H, K, L, and M spectral bands (1-5 microns) in a single exposure – the highest "spectral grasp" of any existing or planned instrument in the world. Due to the use of silicon immersion gratings developed at The University of Texas at Austin, the design is uniquely compact for its capability. GMTNIRS is currently in Final Design, and similar to G-CLEF, there are plans to deploy the GMTNIRS spectrograph on one of the Magellan telescopes years before it will be integrated into the GMT.

GMTNIRS will be the first diffraction limited instrument for the telescope, operating in adaptive optics modes using natural or laser guide stars. This instrument will be a powerful tool for spectro-astrometry of young stellar objects disks and for characterization of exoplanet atmospheres, as well as additional science cases including galactic evolution through stellar abundances, gas kinematics and physics in star forming regions, and near field cosmology using globular clusters. GMTNIRS is in Final Design.

Figure 19. Immersion gratings for GMTNIRS. *(Photo courtesy of Ben Kidder)*

7.4 Giant Magellan Telescope Integral Field Spectrograph (GMTIFS)

GMTIFS is a diffraction-limited imager and integral field spectrograph (IFS) operating across the YJHK spectral bands. The spectrograph will provide spectral resolving powers of 5,000 and 10,000 over rectangular fields of view with four spatial scales that can fully utilize the diffraction-limited spatial resolution of the GMT, and lower spatial resolution modes that can provide greater sensitivity for extended targets (e.g., galaxies, resolved stellar populations). The imaging channel has a field of view of 20x20 square arcseconds and pixels that Nyquist sample the diffraction limited PSF at 2.2 microns. GMTIFS is in Final Design.

Figure 20. Exterior view of the GMTIFS instrument (left) and cutaway section view (right)

7.5 Many Instrument Fiber System (MANIFEST)

The MANIFEST is a facility robotic fiber positioning system that will make the GMT's full 20 arcminute field of view accessible to any visible or near-IR spectrograph.[32] In its initial configuration, MANIFEST will use the GMT's 14 arcmin diameter FOV Corrector-ADC, and feed the GMACS and G-CLEF spectrographs. MANIFEST is nearly complete with its Conceptual Design.

Figure 21. Exterior view of the MANIFEST fiber positioning system in its interface mounting frame (right) and cutaway section view (right).

7.6 Giant Magellan Extreme Adaptive Optics (GMagAO-X)

GMaAO-X will be the GMT's first-light extreme adaptive optics (ex-AO) instrument containing integrated coronagraphic wavefront control systems. Exceptional high contrast performance is achieved through these advanced coronagraphic techniques. The GMagAO-X requirements are driven in large part by the key science goal to characterize nearby mature, potentially habitable terrestrial worlds in reflected light. Additional compelling high angular resolution investigations: include planet formation (circumstellar disk structures), stellar evolution models (binaries), and spatially resolved mapping (moons, asteroids, or stellar surfaces). The GMagAO-X is currently in Final Design and is shown in Figure 22.

7.7 Telescope Commissioning Instruments

In addition to the science instruments described above, there are two additional cameras that will be used to facilitate telescope commissioning: the Commissioning Camera (ComCam) and the Adaptive Optics Test Camera (AOTC). Although not considered as facility science instruments, these cameras will have significant observing capabilities by themselves.

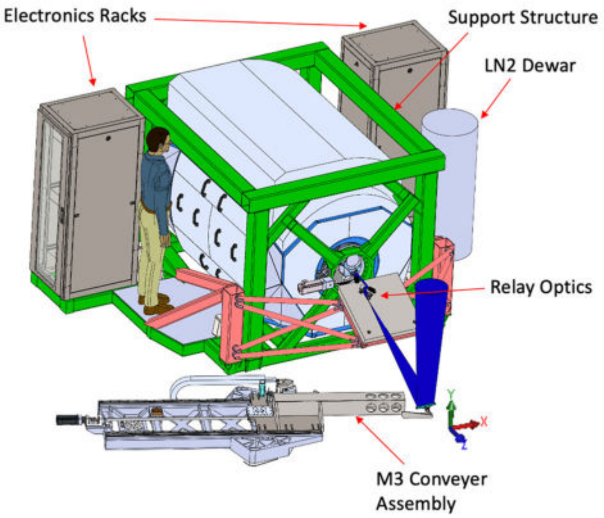

Figure 22. CAD rendering of the GMagAO-X instrument.

Commissioning Camera (ComCam)

ComCam is an all-refractive, focal reducing camera intended for evaluating telescope performance in both natural seeing and Ground Layer Adaptive Optics (GLAO) modes across a six-arcminute diameter field of view. It also provides scientific and public outreach functions by enabling both narrowband and broadband imaging and photometric measurements at wavelengths between 360 and 950 nm. The ComCam is in Preliminary Design.

Adaptive Optics Test Camera (AOTC)

The AO Test Camera (AOTC) will test the interfaces and performance of the GMT adaptive secondary mirror, and wavefront sensors and algorithms in the NGAO and LTAO control modes, prior to the arrival of the AO-assisted science instruments (GMTNIRS and GMTIFS). The AOTC replicates the functions of the GMTNIRS on-instrument wavefront sensor, but not its sensitivity and sky coverage (in order to reduce scope and cost), and it also operates at shorter wavelengths in order to avoid the need for cryogenic optics. The AOTC is in Preliminary Design.

8. SOFTWARE AND CONTROLS

The Software and Controls (SWC) team is currently in the final design phase for both the Observatory Control System (OCS) and Global Interlock and Safety System (GISS), with both final design reviews planned for early to mid-2026. Also see References 28 and 29 for related discussions concerning GMT SWC development of the OCS.

GMT Core Frameworks

The team recently provided a major update to the Software Development Kit (SDK), with the release of version 2.0. This release included switching from CentOS to AlmaLinux as a baseline Operating System, updated build and continuous integration tools, core framework updates, and a new User Interface (UI) Framework. The UI Framework allows developers to create user interface panels with an initial set of widgets that can be seamlessly plugged into the GMT Navigator application.

Observatory Control System

In preparation for the Observatory Control System (OCS) subsystem FDR, the team started working on an End-to-End Prototype, which includes a representative set of hardware and software components that is considered the first implementation of the OCS. The prototype will produce initial versions of all software modules and will be used to verify functional and performance requirements and validate specific architectural choices. One area of focus will be the development and prototyping of the Adaptive Optics (AO) Real-time Controller (RTC) Platform and testing of the Low-Latency communications infrastructure.

Device Control Systems

The Software and Controls team continues to support the design and development of the 28 GMT Device Control Systems (DCSs), refining requirements and maturing Interface Control Documents (ICDs). Two of these subsystems, the Environmental Monitoring Facility (EMF) DCS and the M1 Test Cell DCS, are developed in-house and were recently updated.

The EMF now includes integration with the on-site Seismometer for monitoring and archiving seismic data. This data is stored for long-term characterization of the site, as well as modeling of potential impact on the construction phase on the project. In the short-term, the weather, seeing and seismic data displayed on the EMF User Interface panels are also used by the Site Operations team during day-to-day operations.

The M1 Test Cell DCS continues to be updated with functionality needed for the Optical Test Tower at the University of Arizona later this year. The Active Support system and Local Interlock and Safety System are fully functional and verified. The Thermal Control system implementation is nearing completion and the user interfaces for both the M1 Test Cell and Actuator Calibration Stands have been updated using the new UI Framework (see Figure 23).

Another major accomplishment is the development and integration of the Pyramidal Wavefront Sensor, the Holographic Dispersed Fringe Sensor, and the High Contrast Adaptive Optics Testbed (HCAT) prototypes using the GMT software development kit. This prototype was done as a collaboration between the GMT observatory, Arcetri-INAF, and the University of Arizona. We found that using the GMT frameworks and development process for software development and testing bolstered collaboration and allowed for seamless integration of software components delivered by a multi-disciplinary, geographically distributed team.

Interlock and Safety System

The Global Interlock and Safety System (GISS) passed a Preliminary Design Review (PDR) in January 2023, after which it was moved to the final design phase. The Software and Controls team is currently working with Systems Engineering to review and update the System-level Hazard Analysis, and review system-wide safety concerns such as seismic detection and reaction, zoning, e-stop handling, and muting policy. In addition, the Software and Controls team is leading a series of ISS workshops with GMT subsystem teams to emphasize the role and importance of functional safety on the project, discuss GMTO functional safety processes and deliverables, and elicit the design inputs needed to mature interfaces with the GISS.

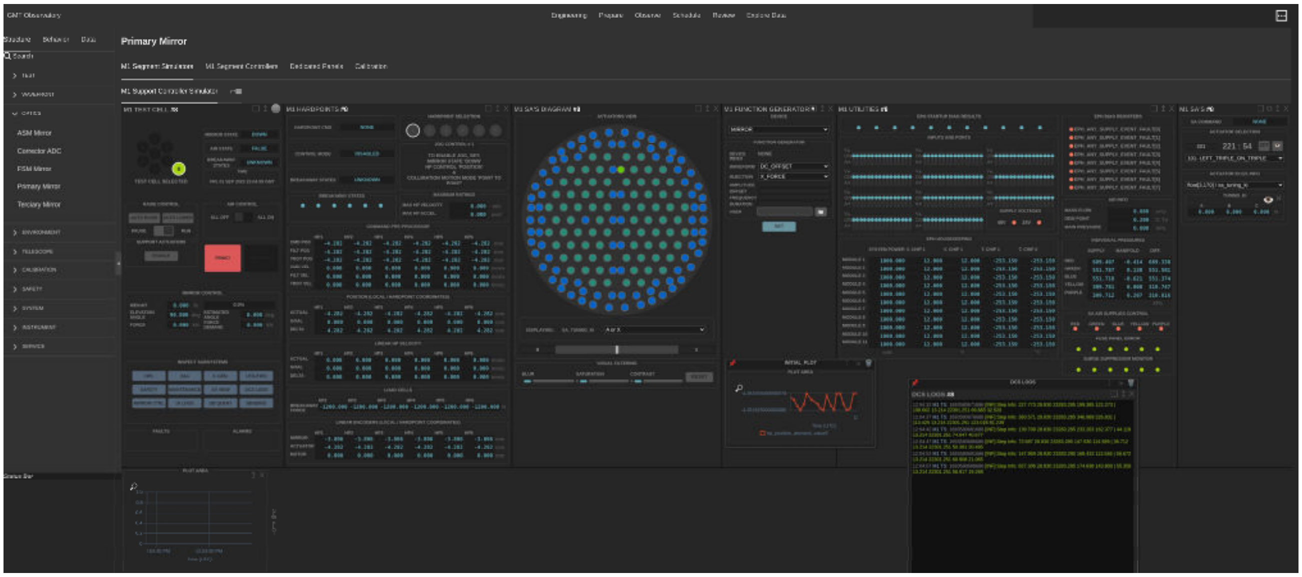

Figure 23. A screenshot of the User Interface for the M1S Test Cell DCS.

9. ENCLOSURE AND SITE FACILITIES

The GMT Site Master Plan shown in Figure 24 has changed only a little since 2022 . Most of the site design and development work since then has focused on completing the enclosure design. Other work has occurred that is related to the permanent site infrastructure that will replace the site's construction infrastructure after construction is complete, and these efforts will ramp up in 2025. A detailed update of the Enclosure design is provided in Reference 30.

The scope of the GMT enclosure final design includes the foundations for the telescope and enclosure, the telescope pier, the telescope pier seismic isolation systems (SIS), the fixed lower portion of the enclosure, and the rotating upper enclosure. Although they are named individually, the Enclosure, Summit Utility Tunnel (SUT), Summit Utility Building (SUB), water pad buildings, dry cooler platform (and the Utility Yard at SS1) have all been designed together under a single contractual statement of work. Beginning in early 2020, the enclosure Designer of Record has been the Architecture & Engineering (A&E) firm IDOM.

IDOM has extensive experience designing observatories including, for example, the upper enclosure for the recently operational Daniel K. Inouye Solar Telescope (DKIST) in Hawaii. Their GMT enclosure design work has been guided by the GMT Site, Enclosure, and Facilities (SEF) team, and they have matured the enclosure reference design (from 2020) through a successful series of design reviews: an initial engineering review (IER) in July 2022, a 60% maturity Critical Design and Constructability reviews in May 2023, a pier and seismic isolation system CDR in October 2023, and a 100% Final Design Review (FDR) in May 2024. Artist's conception renderings of the GMT Enclosure from the FDR are shown in Figures 25 and 26.

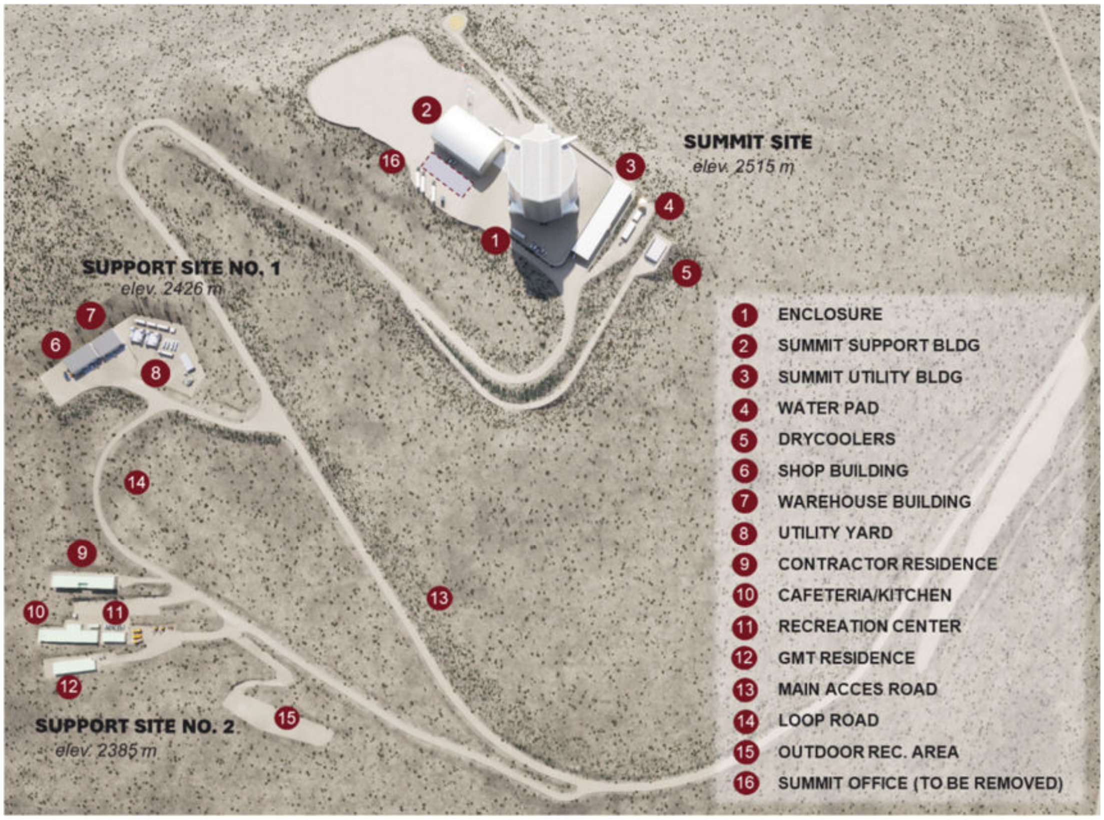

Figure 24. The GMT Site Master Plan as of May 2024.

Figure 25. Artist's conceptions of two exterior views of the future GMT Enclosure and summit support facilities. The Summit Support Building housing the M1 washing and coating facilities can be seen behind the Enclosure in the rendering on the left. *(Renderings courtesy of IDOM)*

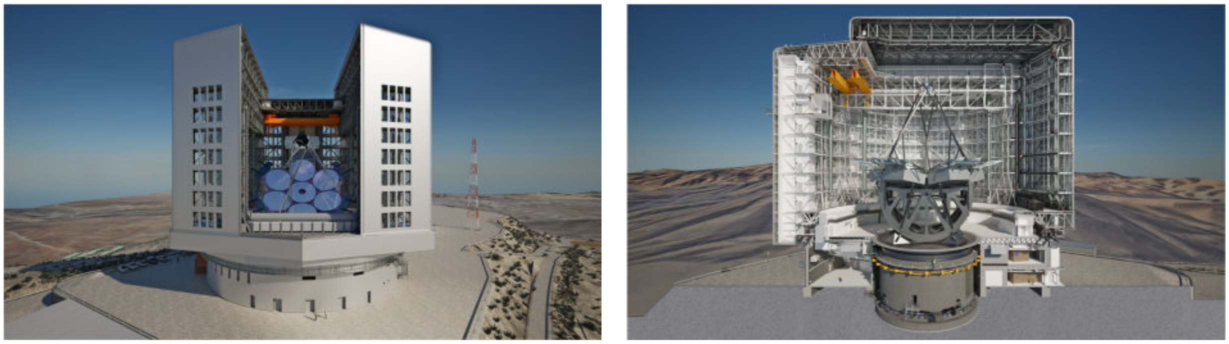

Figure 26. Artist's conception of a face-on view of the open enclosure (left), and a CAD section view showing the full extent of the telescope and pier structure (right). *(Renderings courtesy of IDOM)*

10. CURRENT SITE STATUS AND SITE OPERATIONS

The GMT site at Las Campanas contains fully operational residential facilities, fully operational infrastructure to support major construction, and a summit area ready to begin the next stages of major construction. The GMT summit area proper has not been in major construction since hard rock excavation was completed (see Figure 27). However, other significant construction and maintenance activities continue across the site, primarily related to site infrastructure. These include upgrades to the construction power (e.g., replacing original wooden pole for power lines with concrete poles), water system control, and fiber communication infrastructure. A "green" waste management system is now operational that is just one part of a broader, more comprehensive sustainability for the site. Security measures have also been enhanced although it is an ongoing challenge to fully protect a remote site from theft attempts. GMTO's commitment to a Safety First work culture applies to all who enter the site (GMTO staff, contractors, and visitors). Our Safety Program is driven by proactive continual improvement processes including frequent safety assessments and implementation of measures such as the use of GPS trackers to monitor vehicle speed (repeat violators can be, and have been, banned from the GMT site). We appreciate and accept our responsibilities to be a good tenant for our Las Campanas host, the Carnegie Institution for Science and their Las Campanas Observatories.

Figure 27. A view of the GMT site summit plateau area. The residential facilities at Support Site #2 are in the top center while Support Site #1 is to the top right of center.

11. SUMMARY

This paper has provided an overview of the status of the Giant Magellan Telescope project as of June 2024. Most of the major subsystems are either in Final Design or construction. The Project will be ready for a system-level final design review within the next two years. Technical risk reduction work continues in optics fabrication and optical performance including the optimization of AO phasing. The Test Cell containing the mirror segment's mechanical support system is fully functional and it will be integrated with the completed S3 mirror segment in the next 3 months following which the characterization of bending modes will begin under the RFCML Test Tower. Construction of the Mount azimuth structures is proceeding well and factory assembly, integration, and testing continues. With the completion of the Enclosure design, and the readiness of the GMT site infrastructure to support the beginning of Enclosure construction, it will be possible to pour concrete for the Enclosure foundations as soon as funding is available. Overall, GMT project execution remains focused on achieving GMT's Science First Light as soon as possible while simultaneously controlling risks, minimizing cost growth, and ensuring that system performance will enable the transformative science that the astronomy community expects.

Acknowledgments

The Giant Magellan Telescope is being developed by the GMTO Corporation, a 501(c)(3) nonprofit, and an international consortium of 14 universities and research institutions from the United States, Australia, Brazil, Israel, South Korea, and Taiwan, in partnership with our host country, Chile. GMTO is a partner in the U.S. Extremely Large Telescope Program (US-ELTP).

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