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Overview and Status of the Giant Magellan Telescope Project

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ABSTRACT

The Giant Magellan Telescope is proceeding with design, fabrication, and site construction. Of the seven 8.4 m diameter mirror segments required for the primary mirror, two have been completed and placed in storage, a third has been polished to specification, three more have been cast and are in various stages of fabrication, and glass is in hand to cast the final segment. The telescope structure is nearing final design review and the start of fabrication. Residence buildings and other facilities needed to support construction at the Las Campanas site in Chile are complete. Hard rock excavation of the foundations for the enclosure and telescope pier is complete. The enclosure is in final design. The first off-axis adaptive secondary mirror is being fabricated, and a primary mirror cell has been fabricated and is under test. Two adaptive optics and phasing testbeds are being fabricated for risk reduction testing and component qualification. Our fabrication and construction schedule is being revised in response to evolving programmatic factors, including the US-ELT initiative, which received the top ranking in the National Academies' ASTRO2020 Decadal Survey.

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

1. INTRODUCTION

We provide a status report on the design and construction of the Giant Magellan Telescope. The goals of the project and the concept for the GMT have been reviewed in past proceedings of the SPIE.[1,2,3,4,5,6,7,8] In this 2022 status update, we concentrate on areas of the project that have undergone significant evolution since the report in the 2020 proceedings. These include the near completion of the third primary mirror segment and casting of a sixth segment, development and initial testing of a primary mirror test cell, the start of fabrication of the first off-axis adaptive secondary mirror, progress in development of two adaptive optics testbeds with prototype wavefront sensors, and advances in the analysis, design, and prototyping of other observatory subsystems and components. A significant number of papers in these proceedings address aspects of the GMT project in depth. In this overview we aim to provide a high-level view of the entire project with an emphasis on process and activities that address risk and tie together the many technical and programmatic aspects of the project. The origins of the GMT concept, its relationship to the twin Magellan 6.5 m telescopes, and the motivations for the use of large primary mirror segments in a fast focal-ratio Gregorian optical design have been described in previous reports of the SPIE.[3,5,9]

The scientific motivations for the GMT, and the other Extremely Large Telescopes (ELTs) under development, remain compelling in all areas of astronomy. Some of the most exciting areas include the growing field of multi-messenger and gravity wave astronomy; the identification and characterization of nearby exoplanets, including those that may be habitable; and progress in understanding galaxy evolution, dark matter, dark energy, and the growth of structure, which will come with the synergy between the ELTs and other observatories in the coming decades, including the Vera Rubin Observatory, ALMA, the increasingly sensitive gravity wave observatories, JWST, and the Nancy Roman space telescope.

A new development since the 2020 report is the release of the Decadal Survey on Astronomy and Astrophysics 2020 (ASTRO2020) by the U.S. National Academies.[10] The report identifies scientific priorities for the U.S. during the decade of the 2020s. The survey's priority for a frontier ground-based observatory calls for significant U.S. investment in the GMT and the Thirty Meter Telescope (TMT) as part of a coordinated U.S. Extremely Large Telescope Program (US-ELTP).

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The US-ELTP has the goal of providing U.S. nationally funded, all-sky access to the U.S. astronomical community. The GMTO Corporation (GMTO) is a partner in developing the US-ELTP along with the National Science Foundation's (NSF's) National Optical Infrared Astronomy Research Laboratory (NOIRLab) and the Thirty Meter Telescope International Observatory (TIO).[11]

In the sections that follow we describe the maturity of our project management and systems engineering approach, along with technical progress on key elements of the observatory.

2. ORGANIZATION, REQUIREMENTS, AND PROCESS

The organizational structure of GMTO is unchanged since the 2020 report. GMTO has followed a "staged development" approach designed to achieve initial operating capability of the observatory at the earliest date. The team has focused on technical progress for schedule critical path and near-critical path activities; retiring technical risk; performing integrated analysis to anchor technical performance budgets and requirements; and maturing the designs, interfaces, and operational behaviors of the observatory. Subsystems are maturing at various rates subject to their criticality for initial operating capability and the availability of funds.

Systems engineering is coordinated by a project systems engineering team led by the project systems engineer, which includes representatives from all deliverable project elements. Approximately 80% of GMT subsystems (by cost) are either in final design or fabrication/construction. One hundred percent of science requirements and 99% of observatory-level engineering requirements have been flowed down to children. About one quarter of observatory-level engineering requirements are derived from the concept of operations. Of 100 interface control documents (ICDs) maintained in a DOORS database, 85% are released, half of which are at a high level of maturity. High priority subsystem ICDs, such as those affecting the telescope structure, are essentially all at a high level of maturity. Configuration management controls the establishment of the technical, cost, and schedule baseline, and changes to that baseline, by means of change control boards. Integrated modeling computational fluid dynamics analysis is used to assess system-level performance.[12,13,14]

In anticipation of possible U.S. federal involvement as part of the US-ELTP, GMTO has matured its project business planning and project controls tools and processes. We routinely manage project execution using earned-value management techniques, and have adopted the methodologies for cost/schedule and contingency estimation documented in the NSF Research Infrastructure Guide (RIG). Our contingency estimation process uses Monte Carlo techniques designed to account for the inherent uncertainty associated with cost/schedule estimates, as well as discrete and discontinuous risks that could result in additional cost or schedule impacts to the project, should those risks be realized.

Project execution is reviewed biweekly in structured tactical meetings with project element teams that focus on schedule status, tracking milestones, problems/concerns, and response actions. Monthly management reviews focus on earned value performance, estimates to complete, variances from plan, recovery plans, and liens on contingency. A risk management board meets regularly to review overall risk posture and changes to the risk register. The risk register is an active management tool and contributes to the Monte Carlo simulations used to estimate needed contingency. Oversight and management of subcontracts is a shared responsibility of the project team (providing a contract technical manager) and the GMTO procurement group (providing the contract officer or manager). Technical oversight and project controls surveillance of subcontractor effort requires close contact with the contractor and good situational awareness. This has been more challenging during the global coronavirus pandemic, where travel has been restricted, but has remained effective via video communication and the convening of remote technical reviews.

3. TELESCOPE DESIGN STATUS

The GMT is a 25.4 m aperture telescope being constructed on Las Campanas Peak (Cerro Las Campanas, 2,550 m altitude) at the southern end of the Atacama Desert in Chile. It features a doubly segmented optical system (Figure 1) with a compact altitude-over-azimuth mount configuration using large C-ring elevation bearings and a 6 m x 9 m Gregorian Instrument Rotator (GIR) to de-rotate science instruments and the guiding system (Figure 2). The telescope features an aplanatic Gregorian optical design that delivers a wide field of view (20 arcmin diameter) with a compact focal surface (1 arcsec/mm). This enables science instruments that are unusually compact for a telescope of this size, allowing them to have higher performance at lower cost and risk.

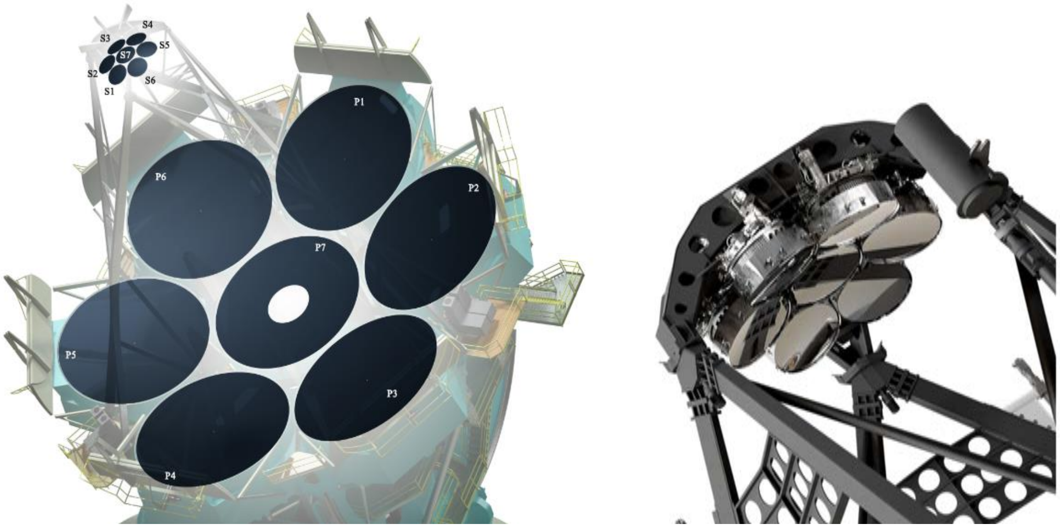


Figure 1. The 25.4 m doubly segmented optical configuration of the GMT (left) consists of seven 8.4 m primary mirror segments (P1-P7) and seven 1.1 m secondary mirror segments (S1-S7). Each active primary mirror segment reflects light to a corresponding secondary mirror segment (P1 to S1, and so on). Two versions of secondary mirror assembly (right) are in development: fast-steering (tip/tilt) and adaptive. The fast-steering version is used during initial telescope assembly and when the adaptive version is off the telescope for maintenance. The adaptive version provides the adaptive optics (AO) function for the ground layer AO and diffraction limited observing modes.

GMTO received an NSF-funded subaward from the Association of Universities for Research in Astronomy, Inc. (AURA) for technology development and broader impacts work over a three-year period of performance that began September 2020. Three main technical activities include: 1) a full-scale primary mirror (M1) control system demonstration involving a 8.4 m steel surrogate mirror; 2) two laboratory testbed demonstrations of optical phasing and adaptive optics necessary to achieve diffraction limited imaging performance; and 3) the partial build and test of an off-axis adaptive secondary mirror (ASM) assembly. These and other areas of progress since the 2020 report are summarized in the sections below.

Telescope mount

The telescope mount provides the overall structural framework for mounting and alignment of optics, science instruments, support payloads and utilities, and provides the three main axes of motion consisting of azimuth, elevation, and GIR rotation.[15]

The team of OHB Digital Connect (ODC) of Mainz, Germany, and Ingersoll Machine Tools (IMT) of Rockford, Illinois was awarded the design and fabrication contract for the telescope mount in October of 2019. The telescope mount successfully passed a preliminary design review (PDR) in February 2021. The PDR design is depicted in Figure 2. A final design review (FDR) is scheduled for Q4 of 2022. Fabrication of the azimuth structure is planned to begin immediately following the FDR.

The azimuth rotation structure supports the pair of C-rings that form the foundation of the elevation rotating structure. The hydrostatic bearing system (HBS) along with the direct drive system provides the guided azimuth and elevation axis motion of the telescope mount. An array of dampers located underneath the base of the azimuth structure, known as the earthquake damping system (EDS), engages during a seismic event to attenuate the vertical seismic accelerations.[16] The seismic isolation system (SIS), consisting of friction pendulum bearings at the base of the concrete pier, attenuates lateral seismic accelerations.

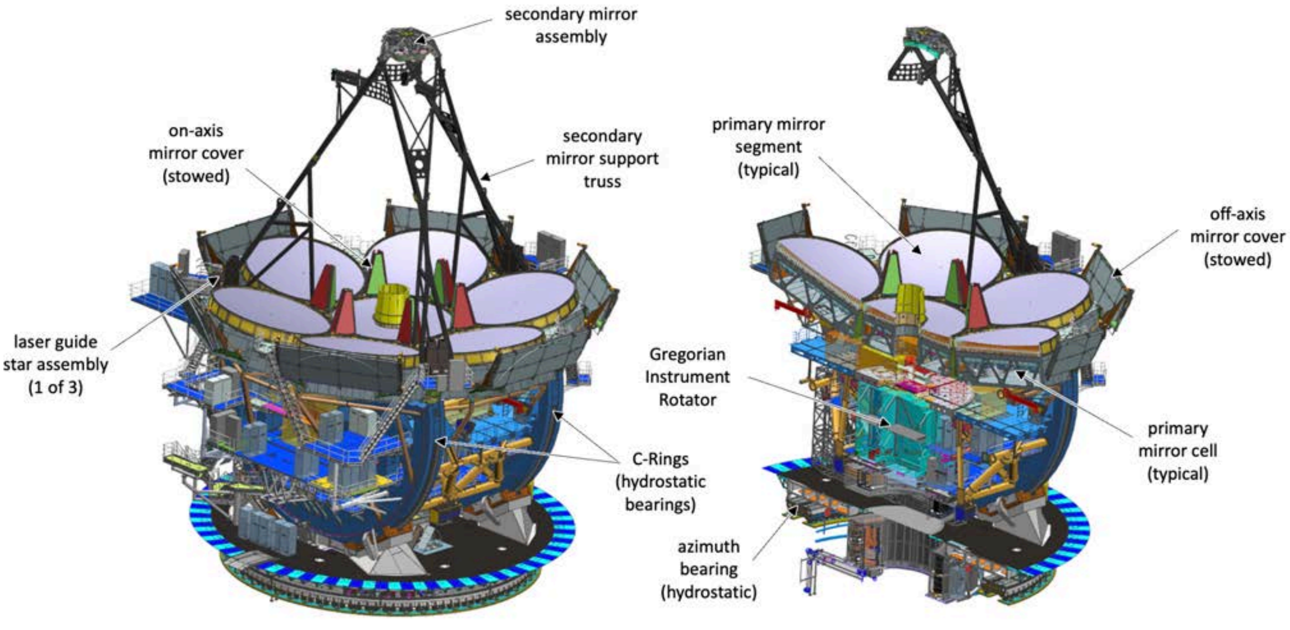


Figure 2. The GMT telescope configuration consists of a compact altitude-over-azimuth mount configuration using large C-ring elevation bearings and a 6 m x 9 m GIR to collectively de-rotate science instruments and the guiding system. The GIR can be seen in the cut away view of the right-hand figure. A three-legged truss supports the secondary mirror assembly for rigidity and to minimize obstructions of the telescope pupil. The primary mirror cells are part of the monocoque mount structure and contribute to overall telescope stiffness. Three pairs of laser guide star projectors are located around the perimeter of the primary mirror.

The seven primary mirror cell weldments are integral to the elevation structure, allowing for a compact structural design. The six off-axis mirror cells are repeatably removable and interchangeable with each other. The upper half of the secondary truss and the top end structure are removable to allow access to remove of the center mirror cell. The GIR is embedded between the C-Ring structures below the primary mirror weldments. The design of the primary mirror covers was optimized with the aid of computational fluid dynamics analysis to minimize wind induced jitter and vortex shedding when stowed during science observations.

IMT has completed construction of a new high bay building with a concrete pit simulating the on-site pier foundation for the telescope (Figure 3). This will accommodate assembly and factory testing of the mount.

Several prototype fabrication and testing activities have been taking place concurrently with final design to inform the design. Prototype versions of the hydrostatic bearing system pads (Figure 4, left) and direct drive motors are being built and tested to validate final design specifications. Full-scale mirror cover (Figure 4, right) structural and deployment tests are underway. Sub-scale utility wrap tests have characterized friction and jitter behavior of the wrap. Sub-scale GIR bearing performance tests (Figure 5, left) will validate assembly and alignment techniques and characterize friction and jitter behavior. Sub-scale primary mirror cell alignment positioner tests (Figure 5, right) have validated the alignment capacity and repeatability of the interchangeable mirror cell weldment mounting final design.

The design of the GIR has been evolved to accommodate two larger direct Gregorian instruments and one smaller instrument, rather than four equal size instruments in the previous design. This permits sufficient volume for more ambitious science instruments such as the GMACS multi-object spectrograph. The GIR is complex, and design changes impact the layout of the guiding system, the MANIFEST fiber front end, utility wraps, and access platforms to service the instruments. All these impacts are being factored into the final design of the mount.

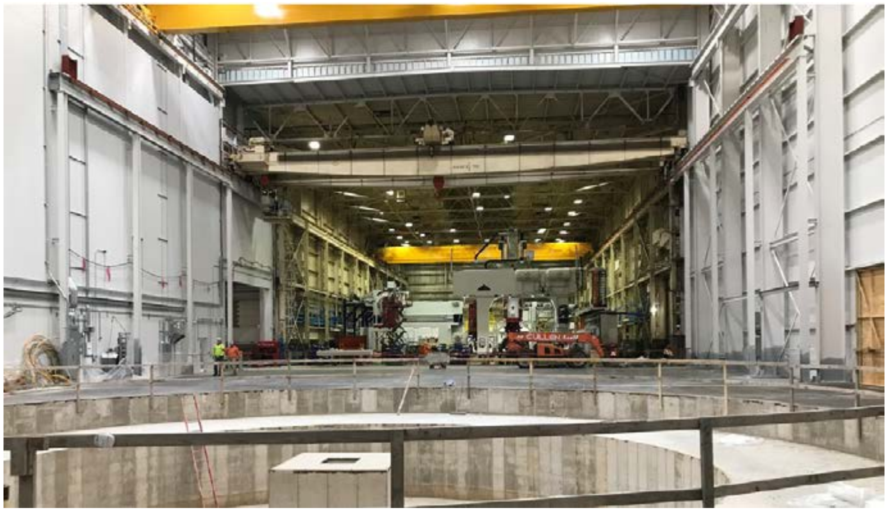


Figure 3. New IMT factory assembly building with concrete pier foundation for the azimuth bearing assembly.

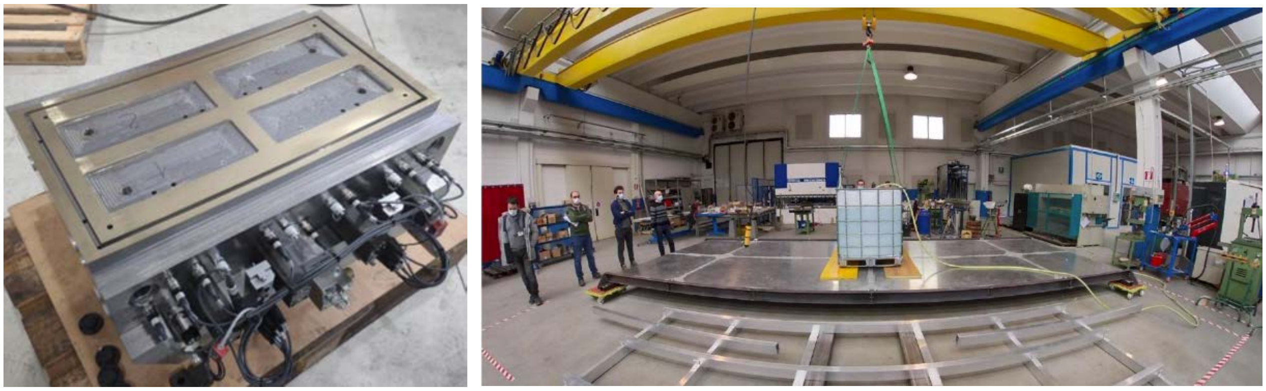


Figure 4. Prototype tests include a hydrostatic bearing pad (left) and full-scale primary mirror cover structural load tests (right).

Figure 5. Prototype testing also includes a GIR bearing segment performance test (left) and sub-scale mirror cell positioner alignment and repeatability test (right).

Primary mirror (M1) subsystem

The GMT requires active optics to position the primary mirror (M1) segments, actively support the M1 segment weight, and control low-order M1 segment figure error. Mirror and dome seeing and thermal figure error are controlled by actively regulating the M1 segment temperature to isothermally track the ambient air temperature. The M1 subsystem includes static supports, the active optics control system, and the thermal control system of the M1 segments. When the M1 segment is at rest, it is supported by wire rope isolators called static supports. These also cushion the segments during earthquakes and limit their range of motion. The active optics control system lifts the M1 segment off the static supports and precisely controls the M1 segment position and front surface figure. It consists of triple-axis and single-axis pneumatic support actuators for figure control, and linear actuators called hardpoints to control segment position. The M1 segment is cooled by a closed-cycle forced air convection system using air handler units with CO_2-based refrigeration to circulate and condition the air. The layout of components is shown in Figure 6.

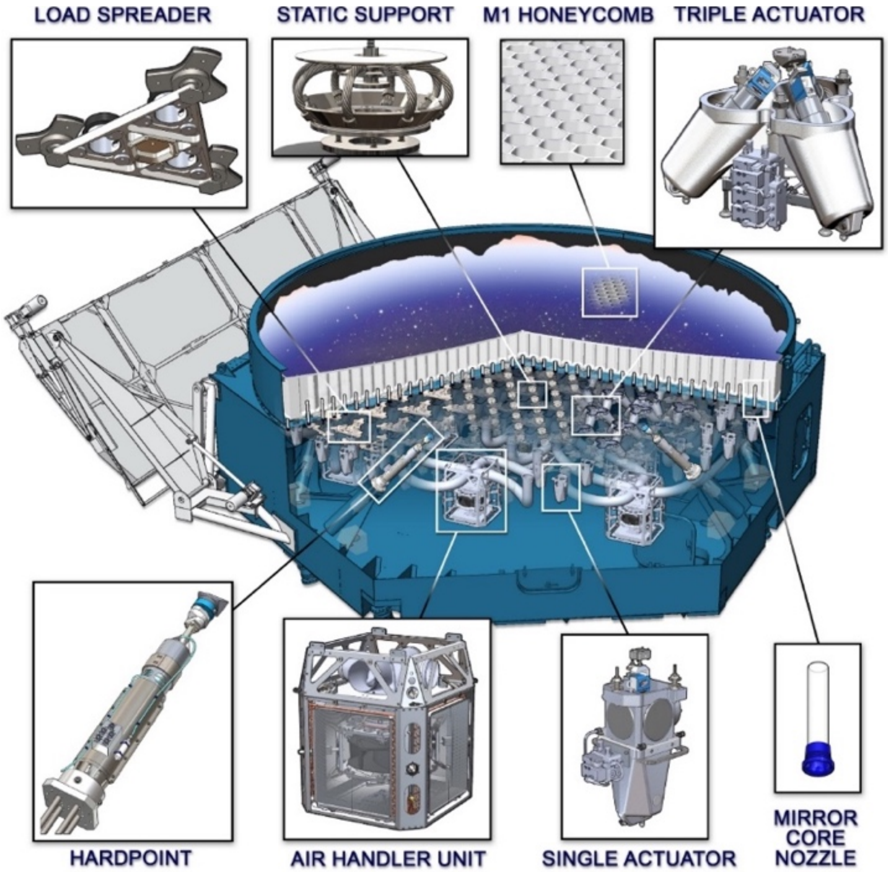


Figure 6. The primary mirror (M1) subsystem controls individual mirror segment position, surface figure, and temperature. Components (clockwise from upper left) include load spreaders that connect support actuators to the mirror back surface, static supports, triple-axis support actuators, air flow nozzles, single-axis support actuators, air handler units, and hardpoints.

The M1 subsystem responds to several requirements that drive design differences from heritage large-aperture telescope mirror control systems. The GMT off-axis segments and mirror cells are positioned at a compound angle to gravity and must be interchangeable. This required the design of three-axis support actuators. The GMT design also seeks to simplify and improve the thermal control system and to minimize exported vibrations. The air handler units are fewer in number and contain integral two-stage passive isolation. The subsystem must accommodate an increased range of motion so that M1 segments can be collimated and phased, while providing seismic protection. Passive fluidic dampers have been incorporated into the pneumatic support actuators to introduce damping that limits M1 segment motion during earthquakes.

And finally, M1 segments are re-coated while remaining in their mirror cells. The entire mirror cell is placed in the coating chamber; therefore, the M1S components must be vacuum compatible. To validate these new designs, a full-scale test cell has been developed.[17] Initial testing using a steel surrogate mirror will validate functionality at various orientations to gravity. Later, a polished glass mirror segment (segment 3) will replace the steel surrogate and the control system will be tested using optical interferometric measurements to validate the ability to control and maintain M1 segment optical figure to the required precision. Prototype support actuators and hardpoints awaiting integrated into the test cell are shown in Figure 7.

Figure 7: Triple-axis support actuators (left) and hardpoint actuators (right) being prepared for integration into the test cell.

The active optics control system in the test cell includes 170 support actuators, six hardpoints, six hardpoint electronics cabinets, an air control cabinet, a power and communications cabinet, a cell control cabinet, air manifold, air distribution lines, and cable routing, as seen in Figure 8. A test readiness review was convened and initial testing has begun. A thermal control system delta-PDR was completed, and the team has assembled two prototype air handler units for vibration and air flow testing.

Figure 8. Test cell with steel surrogate mirror (left) and interior layout of the active optics support system (right). Work is being performed at UA. Photos courtesy of UA.

Primary mirror (M1) production

Mirror segments 1 and 2 have been accepted and remain in storage in their transport containers. Segments 3, 4, 5, and 6 are in various stages of fabrication at the RFCML.[18] Segment 3 has been in front surface polishing since the 2020 report and now meets optical specification. Once final acceptance testing of segment 3 is completed, segment 5 will proceed to front surface polishing. Segment 3 will be integrated with the test cell once testing with the steel surrogate mirror has been completed. Segment 6 was successfully cast in 2021 and awaits access to the grinding machine. Segments 4, 5, and 6 are shown in the stacking rack in Figure 9. Preparations are underway to cast Segment 7, the final segment needed to form the complete GMT primary mirror.

Figure 9. Primary mirror segments 4 (middle), 5 (bottom), and 6 (top) are shown in the mirror stacking rack at RFCML. Segment 5 will be the next to undergo front surface polishing, following acceptance testing of segment 3. Segment 6 is awaiting access to the grinding machine. Photo courtesy of UA.

Adaptive secondary mirror subsystem (ASMS)

An FDR for the adaptive secondary mirror subsystem (ASMS) was successfully convened in July 2021. This review was the culmination of 4½ years of design work by the AdOptica Consortium, comprising A.D.S International, S.R.L, and Microgate, S.R.L.[19] More than 80 documents and many drawings and finite element models were delivered to support the design. Many aspects of the design were verified by construction, integration, and testing of a 72 actuator, 35 mm diameter ASM prototype.[20] An expanded view of the final ASM design is shown in Figure 10.

GMTO has awarded a contract to AdOptica to build and test a full-scale prototype off-axis ASM segment. This prototype is a candidate to become the first production off-axis unit for the telescope. There are two phases to the ASM prototype development. The first is currently underway to produce the ASM components that make up the ASM primary load path and the hexapod positioner. These components will be assembled, and static and dynamic testing will be performed to confirm the performance of the ASM structure and positioner. These tests will reduce the risk of control structure interaction with the support structure, and the results will be used to anchor the finite element models. The second phase will fabricate and integrate other optomechanical components, the CO2 cooling system, electronics, and software to provide control functionality for the thin shell face sheet. The completion of the second phase will provide a complete and operational ASM off-axis segment, which will be tested to verify functional and performance requirements.

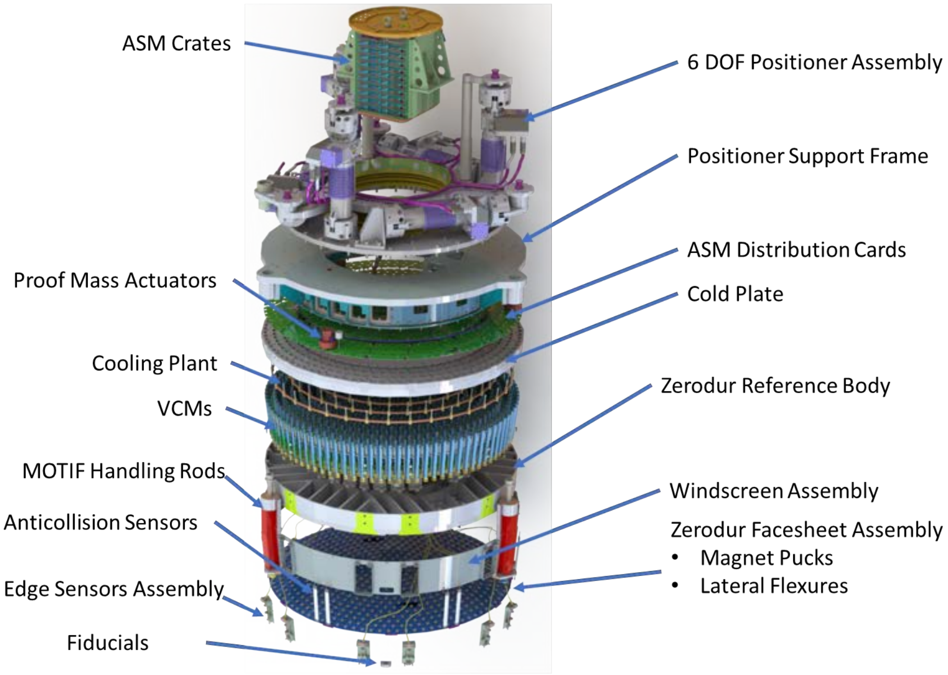


Figure 10. Adaptive secondary mirror (ASM) expanded view showing major components.

A key risk reduction involves the production of the long lead thin shell face sheet and reference body components made of Zerodur, a glass-like ultra-low expansion material. The off-axis thin shell face sheet is being produced by Safran-Reosc under subcontract to AdOptica. The thin shell face sheet is 2 mm thick and 1.05 m in diameter. The large diameter and thin cross section make this a delicate and challenging optic to produce to the required optical tolerances. The reference body is being produced by UA and the Korea Research Institute of Standards and Science. The reference body is a primary structural and metrology element of the ASM. It is in the ASM load path and is an interface for edge sensors, collision sensors, and thin shell gap sensors. The gap sensors are capacitance gages that measure the gap between the thin shell and the reference body in 375 locations to allow internal measurement of the displacement of the face sheet. The reference body is a highly light weighted, 1.05 m diameter structure with a thin-wall pocketed design, and optical quality tolerances on the surface where the thin shell gap measurements are made. Both the thin shell and reference body are produced by reduction machining from a monolithic block of Zerodur. Both long lead items are in the manufacturing stage (Figure 11). Each ASM is supported by a hexapod positioner. A prototype hexapod positioner actuator has been developed by ADS and is currently undergoing testing (Figure 12).

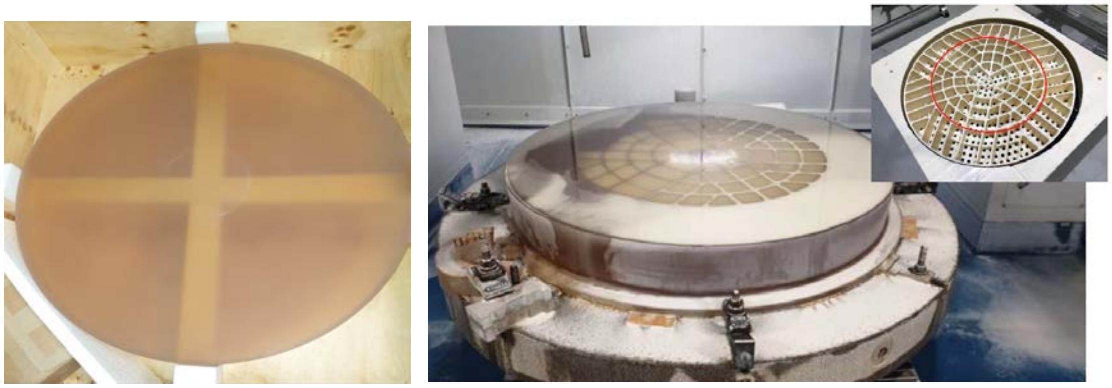


Figure 11. Zerodur blank material for the thin shell (left) and reference body (right, undergoing machining).

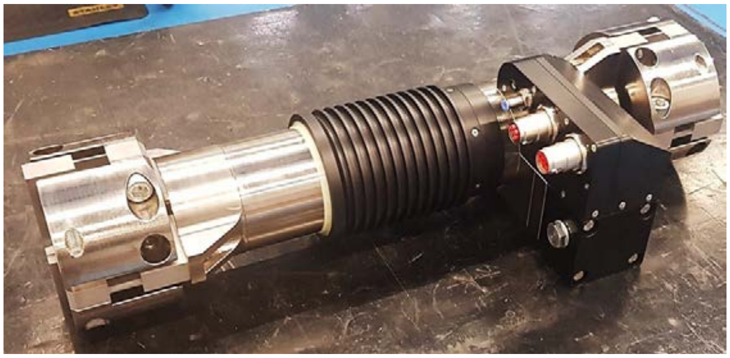


Figure 12. Prototype hexapod positioner actuator is undergoing testing at ADS.

4. WAVEFRONT SENSING AND CONTROL

GMTO continues to develop two wavefront sensing and control (WFSC) testbeds to demonstrate optical alignment, phasing, and adaptive optics technologies for GMT.[21,22,23] The work directly addresses the doubly segmented optical configuration of GMT but has general utility for segmented optical systems. The two testbeds have complimentary functionality and performance to permit efficient parallel development and testing. The wide field phasing testbed (WFPT) incorporates a prototype acquisition, guiding, and wavefront sensing system (AGWS),[24] and the high contrast AO testbed (HCAT) incorporates a prototype natural guide star wavefront sensor (NGWS).[25,26,27] These technologies are key to achieving required image quality for GMT in both the ground layer AO and natural guide star AO observing modes. We have developed plans to extend these testbeds to demonstrate technology for the laser tomography AO observing mode.

Since the 2020 report the WFSC team and its partners at the Smithsonian Astrophysical Observatory (SAO) and the University of Arizona (UA) have made significant progress. SAO successfully validated the design for the dispersed fringe sensor in a prototype AGWS, the system that will be used to achieve coarse phasing of GMT.[28] The dispersed fringe sensor has a unique design the relies on a precision-machined custom prism array that collects and interferes off-axis light from adjacent pairs of segments. SAO recently demonstrated closed loop phasing of a small-scale segmented telescope WFPT using the dispersed fringe sensor and precision prism array. The prism array is identical to the production units to be used in GMT. This is a significant advancement in validating the strategy for phasing GMT (Figure 13).

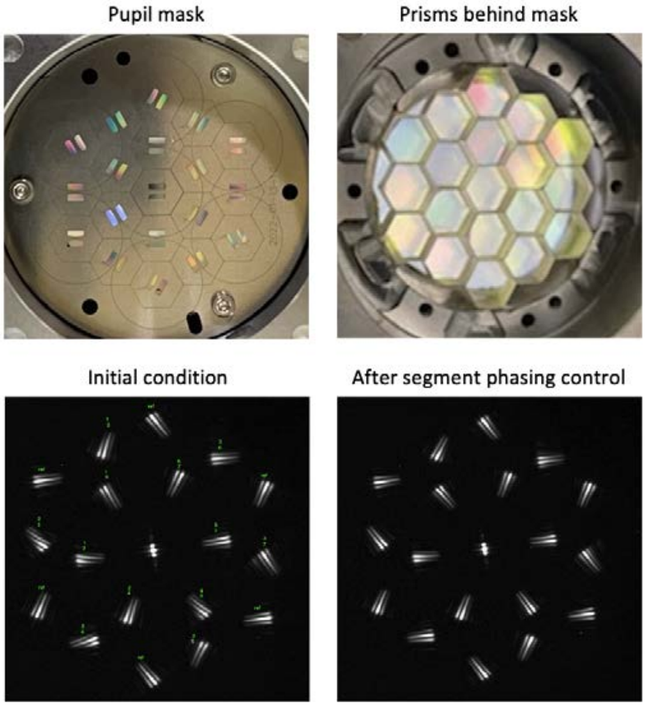


Figure 13. The WFPT uses a prototype dispersed fringe sensor. The precision-machined prism array (above left and right) was used to demonstrate the closed loop coarse piston phasing of the GMT segmented telescope simulator in the testbed. Fringes were aligned in closed loop from an initial unphased state (bottom left) to a final coarse phased state (bottom right). Images taken by SAO.

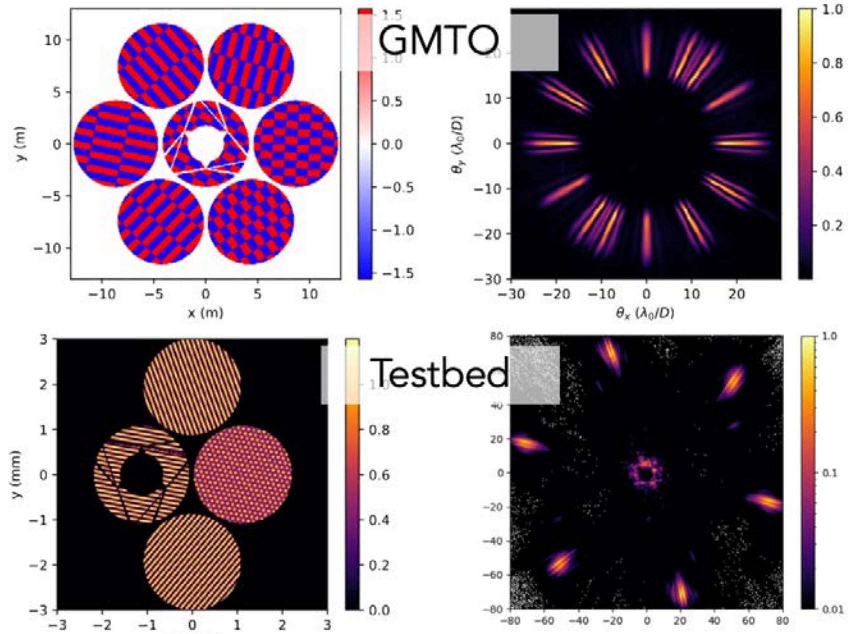


Figure 14. The HCAT uses the recently invented HDFS to carry out fine phasing of the GMT doubly segmented telescope simulator. The four-segment testbed prototype (below left) produces a unique dispersed fringe pattern (bottom right). Each fringe cluster contains the quantitative piston phase difference between a different pair of GMT segments. The mask designs for the testbed (below) and true GMT (above) appear next to their resulting fringe patters. Images taken by UA.

The WFSC team has also made progress demonstrating the fine phasing step of achieving diffraction limited imaging. A new sensor invented by UA, the holographic dispersed fringe sensor (HDFS), is being paired with a pyramid wavefront sensor (PyWFS) to form a prototype NGWS for the HCAT testbed. The HDFS operates on the same principle as the SAO dispersed fringe sensor, but instead of using the precision-machined prism array uses a holographic phase mask to diffract and combine the light from each pair of GMT segments in a such a way as to interferometrically measure the relative piston error between each segment pair (Figure 14). The PyWFS precisely measures low and high order wavefront error, including segment phase piston error, while the HDFS simultaneously measures piston error over a large dynamic range without the phase wrap error observed in the PyWFS. The fusion of the two channels produces robust phase control that avoids segment ejection.

5. SCIENTIFIC INSTRUMENTS

Up to ten scientific instruments can be accommodated on the telescope at various stations (Figure 15). A recent redesign of the GIR was necessary to accommodate the needed instrument volume of the maturing GMACS instrument, and to provide for necessary instrument access during operations. This change permits two larger and one smaller direct Gregorian instruments to be accommodated in the GIR simultaneously rather than four instruments of intermediate size. Instruments can be switched during the night, a flexibility that enables rapid observation of transients and dynamic allocation of programs (queue scheduling) to match changing environmental conditions to maximize scientific return.

The suite of first-generation science instruments was identified through an open solicitation for concepts and passed thorough Conceptual Design Reviews in 2012. We have prioritized the high-resolution visible light echelle spectrograph (GCLEF) as the first light instrument. Portions of the GCLEF instrument are currently being fabricated. The other first-generation instruments are at lower level of maturity as they are integrated to the telescope somewhat later in the commissioning flow.[29]

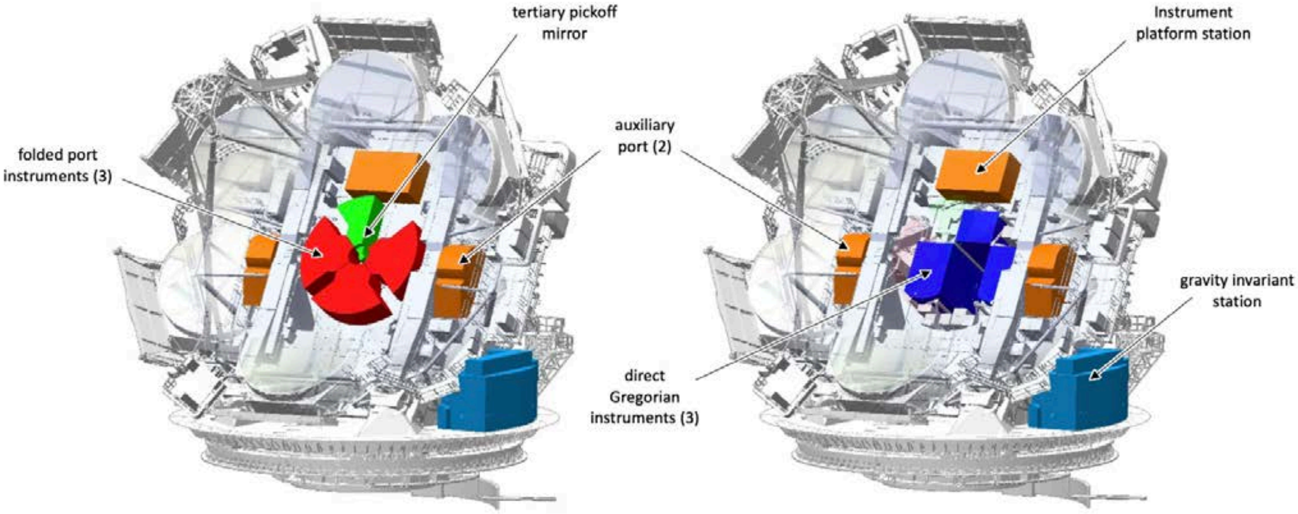


Figure 15: Ten science instruments can be accommodated at various stations on the telescope. These include three folded port, three direct Gregorian, two auxiliary port, one instrument platform, and one gravity invariant (fiber couped to the focal surface). The GIR was redesigned to accommodate two larger and one smaller direct Gregorian instruments.

GMT Consortium Large Earth Finder (G-CLEF)

G-CLEF is a high-resolution visible-light echelle spectrograph with precision radial-velocity capabilities. Portions of G-CLEF are in final design and other portions are being fabricated.[30,31] Long lead red camera lenses have been delivered as well as entrance and exit prisms for the blue camera cross-disperser. The composite optical bench is in fabrication, as are other components. G-CLEF is located at the gravity invariant station and is fiber coupled to a dedicated front-end assembly mounted to the GIR as shown in Figure 16.

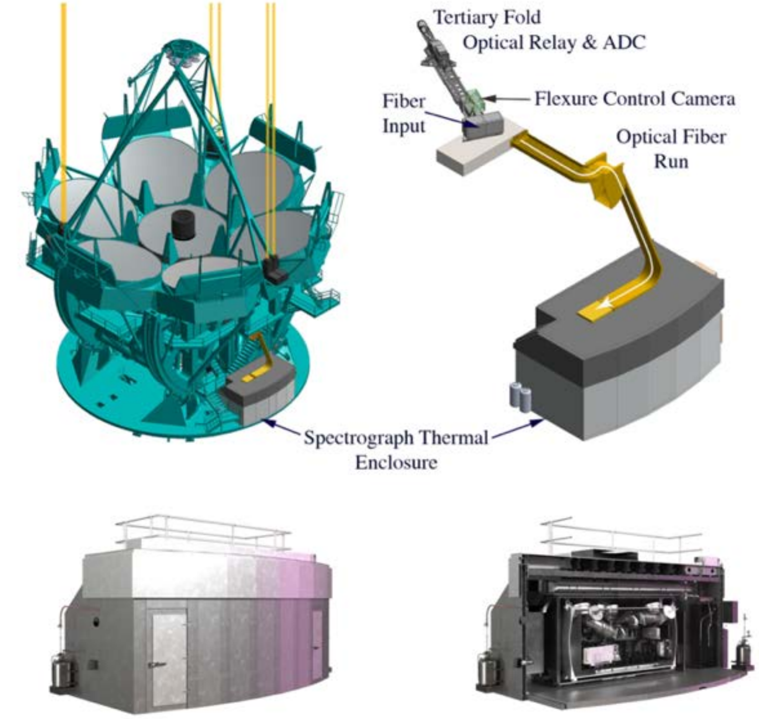


Figure 16. G-CLEF front-end and spectrograph locations in the telescope (top). Spectrograph inside its thermal enclosure (bottom left) and vacuum vessel (lower right), located on the gravity-invariant azimuth platform.

The GMT Wide Field Multi-Object Spectrograph (GMACS)

GMACS is a workhorse 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. Together with the MANIFEST fiber front end, GMACS can perform surveys across the full 20 arcmin field of view of the telescope. GMACS is in Preliminary Design. The instrument configuration is shown in Figure 17. GMACS is planned to be the second instrument commissioned on the telescope.

The Many Instrument Fiber System (MANIFEST)

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] MANIFEST is in conceptual design and is being designed to feed the GMACS and G-CLEF first generation instruments.

The GMT Near-Infrared Spectrograph (GMTNIRS)

GMTNIRS is a single-object, near- to thermal-IR echelle spectrograph. It uses silicon immersion gratings to achieve high spectral resolution (65,000 in JHK; 80,000 in LM) with small (100 mm) beam spectrographs. The optical design provides 5 separate spectrograph channels, so that observations to be made over the full wavelength range from 1- 5µm (J, H, K, L, and M' bands) in a single exposure.[33] GMTNIRS is in Preliminary Design. Long lead manufacture of the silicon immersion gratings is well advanced.

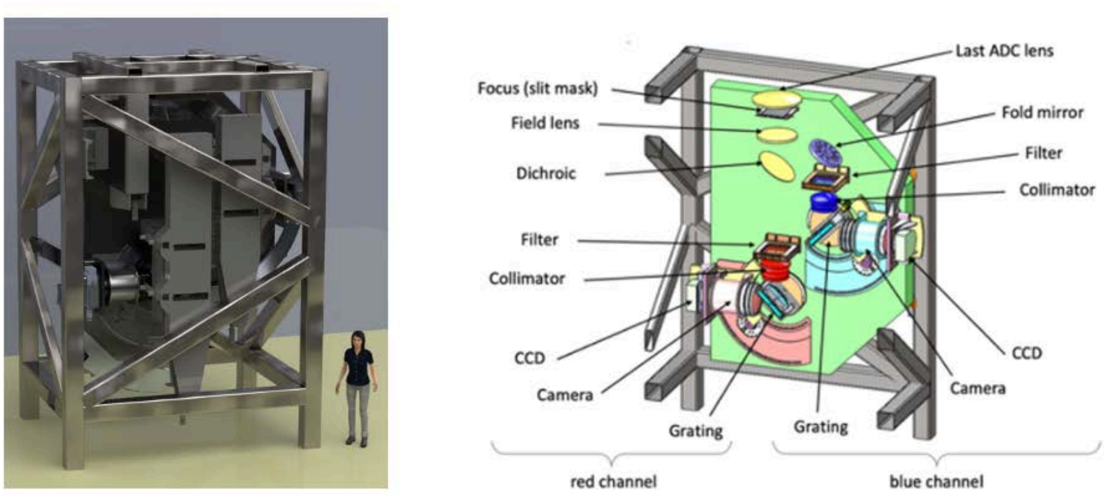


Figure 17. GMACS in its instrument mounting frame, which supports and deploys the instrument in the GIR (left). Detail of optics layout within the instrument (right).

The 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 Preliminary Design.

The GMT 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. ComCam is in Preliminary Design.

In addition to these instruments, a new concept is being considered to fulfill exoplanet characterization science goals at first light. GMagAO-X leverages emerging strategies and technologies that enable very high contrast exoplanet direct detections at inner working angles near λ/D.[34] The GMagAO-X concept is based on a novel tweeter deformable mirror design that uses an optically distributed set of seven pupils (one per GMT segment), allowing the use of high-density deformable mirrors that are commercially available. GMagAO-X is in Preliminary Design.

6. SOFTWARE & CONTROLS

Software Development Kit and Device Control Systems

The software and controls team continues developing the software development kit (SDK), which is used both internally and externally across the observatory subsystems. This software infrastructure allows each controlled subsystem to develop its device control system (DCS) using a common software suite. Eleven versions of the SDK have been released thus far and have been used by multiple teams to develop prototypes and to build software. The SDK includes initial versions of the core, input/output, test and user interface frameworks, and important applications like telemetry, alarms, logs, and configuration services.

The SDK has been successfully used to develop and deploy the environment monitoring facility DCS, currently in operations on-site at Las Campanas, the M1 actuator calibration system DCS, currently used at the UA to calibrate M1 support actuators and the M1 test cell DCS. The M1 test cell DCS is responsible for raising and lowering the primary mirror segment (or mirror simulator) and controlling the forces on the support actuators and hardpoints. Unit tests, functional tests and system tests have been performed to validate the system and software requirements. Having passed an M1 test cell test readiness review the mirror simulator was raised and translated under software control for the first time in July 2022. The test cell thermal control and safety systems are under design and development. The M1 test cell DCS will continue being tested with the software simulators and later with a completed glass mirror segment.

The design of the mount DCS, the enclosure DCS and the ASM DCS is in progress by external contractors following the SWC standards and the defined interfaces with the OCS. The SDK has also been used by external teams to develop prototypes for the AGWS, WFPT, and for ComCam, G-CLEF, and GMTIFS science instruments. Requirements, interfaces, and software designs are being defined for all GMT controlled subsystems under design.

Observatory Control System

The OCS coordinates all the GMT DCSs and supports the GMT operation on site.[35] The OCS passed a Preliminary Design Review in January 2021, and the Final Design Review is planned at the end of 2023. The OCS is responsible for short-term scheduling, observation execution, telescope control and operation and observatory data management. A critical subsystem of the OCS is the telescope control system (TCS) which orchestrates the real-time control loops for all the controlled subsystems. Two main subsystems provide high-level coordination and control functions: the pointing kernel, which relates sky coordinates with mechanical and detector coordinates and vice versa (pointing, tracking, guiding), and the wavefront control kernel, which provides the high-level optical control of the telescope (including active and adaptive optics). Both kernels are being designed and will be prototyped and tested with software simulators.

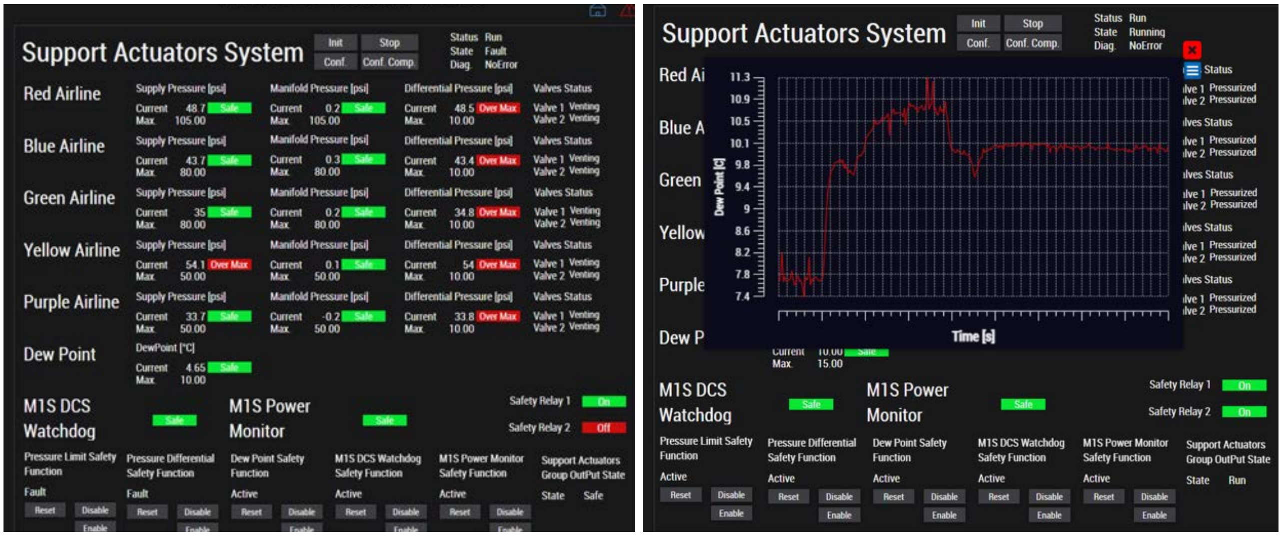
Interlock and Safety System

The interlock and safety system (ISS) is a critical GMT subsystem and is responsible for implementing functional safety. The ISS is separated from the control system and the safety functions may be activated regardless of the control system state. The requirements and the architecture of the ISS are defined, and the system successfully passed a Conceptual Design Review (CoDR) in April 2020. The ISS architecture includes a global ISS, responsible for implementing the global safety functions, and many local ISS, one per each GMT subsystem. The need of a global or safety function is determined by system and subsystem hazards analysis which are being updated by GMT and external contractors. The Global ISS Preliminary Design Review is scheduled for November 2022, and the Final Design Review is scheduled mid 2023.

The team has also integrated and tested the M1 interlock and safety system (M1 ISS) with the M1 device control system (M1 DCS) in the GMT M1 test cell at UA. The M1 ISS is responsible to implement functional safety for the test cell and includes several safety functions (Figure 18) which are independent of the control functionality.

US-ELT Software Collaboration

One of the essential parts of the US-ELTP is the close collaboration with NSF's NOIRLab to develop software for observatory operations.[36] NOIRLab will develop the software used by external astronomers to request observing time and define observations for execution at the telescope. This software will be designed with both GMT and TMT requirements and policies in mind, providing a uniform and powerful product to benefit the US-ELT Program. GMT is working closely with NOIRLab to define requirements and interfaces and will be involved as stakeholders in their software development. Over the last year, GMTO and NOIRLab have had regular meetings defining the division of responsibility between the two organizations represented in the Figure 19.



Support Actuators System

Status Run
State Fault
Diag. NoError

Red Airline
Supply Pressure [psi] Current 48.7 Safe Max. 105.00
Manifold Pressure [psi] Current 0.2 Safe Max. 105.00
Differential Pressure [psi] Current 48.5 Over Max Max. 10.00
Valves Status Valve 1 Venting Valve 2 Venting

Blue Airline
Supply Pressure [psi] Current 43.7 Safe Max. 80.00
Manifold Pressure [psi] Current 0.3 Safe Max. 80.00
Differential Pressure [psi] Current 43.4 Over Max Max. 10.00
Valves Status Valve 1 Venting Valve 2 Venting

Green Airline
Supply Pressure [psi] Current 35 Safe Max. 80.00
Manifold Pressure [psi] Current 0.2 Safe Max. 80.00
Differential Pressure [psi] Current 34.8 Over Max Max. 10.00
Valves Status Valve 1 Venting Valve 2 Venting

Yellow Airline
Supply Pressure [psi] Current 54.1 Over Max Max. 50.00
Manifold Pressure [psi] Current 0.1 Safe Max. 50.00
Differential Pressure [psi] Current 54 Over Max Max. 10.00
Valves Status Valve 1 Venting Valve 2 Venting

Purple Airline
Supply Pressure [psi] Current 33.7 Safe Max. 50.00
Manifold Pressure [psi] Current -0.2 Safe Max. 50.00
Differential Pressure [psi] Current 33.8 Over Max Max. 10.00
Valves Status Valve 1 Venting Valve 2 Venting

Dew Point
DewPoint [°C] Current 4.65 Safe Max. 10.00

M1S DCS Watchdog Safe
M1S Power Monitor Safe
Safety Relay 1 On
Safety Relay 2 Off

Pressure Limit Safety Function Fault
Pressure Differential Safety Function Fault
Dew Point Safety Function Active
M1S DCS Watchdog Safety Function Active
M1S Power Monitor Safety Function Active
Support Actuators Group OutPut State: State Safe

Support Actuators System

Status Run
State Running
Diag. NoError

Red Ai
Blue A
Green
Yellow
Purple
Dew P

Status
lve 1 Pressurized
lve 2 Pressurized
lves Status
lve 1 Pressurized
lve 2 Pressurized
lves Status
lve 1 Pressurized
lve 2 Pressurized
lves Status
lve 1 Pressurized
lve 2 Pressurized
lves Status
lve 1 Pressurized
lve 2 Pressurized

Current 10.00 Safe
Max. 15.00

M1S DCS Watchdog Safe
M1S Power Monitor Safe
Safety Relay 1 On
Safety Relay 2 On

Pressure Limit Safety Function Active
Pressure Differential Safety Function Active
Dew Point Safety Function Active
M1S DCS Watchdog Safety Function Active
M1S Power Monitor Safety Function Active
Support Actuators Group OutPut State: State Run

Figure 18. User interface for the M1 test cell interlock and safety system (M1 ISS).

Figure 19. Flow of the GMT observing process.

7. ENCLOSURE AND FACILITIES

Following a successful PDR for the enclosure, GMTO elected in late 2020 to compete a new contract to complete the final design of the enclosure and produce construction bid documents (drawings and specifications). The contract is structured in three stages, including (1) an initial engineering review; (2) advancing the design from 30% to 60% maturity; and (3), completing the design from 60% to 100% maturity, including bid documents. The enclosure preliminary design is depicted in Figure 20 and the site master plan is shown in Figure 21.

GMTO is planning for a sea-level base facility in La Serena and is in discussion with the Carnegie Observatories over options to incorporate this facility at their compound in La Serena.

Figure 20. A rendering of the enclosure and facilities buildings on the summit of Cerro Las Campanas on property owned by the Carnegie Institution for Science. The summit site includes (from left to right): summit construction offices; summit support building, housing the primary mirror cleaning and re-coating equipment; enclosure; and summit utility building (SUB). The SUB supplies and distributes the telescope utilities, including electrical power, liquid coolants, and gas refrigerants (compressed CO2 and compressed helium). The SUB is connected to the enclosure through the summit utility tunnel (not shown). Additional facilities will include the shop, warehouse, and utility yard at support site #1.

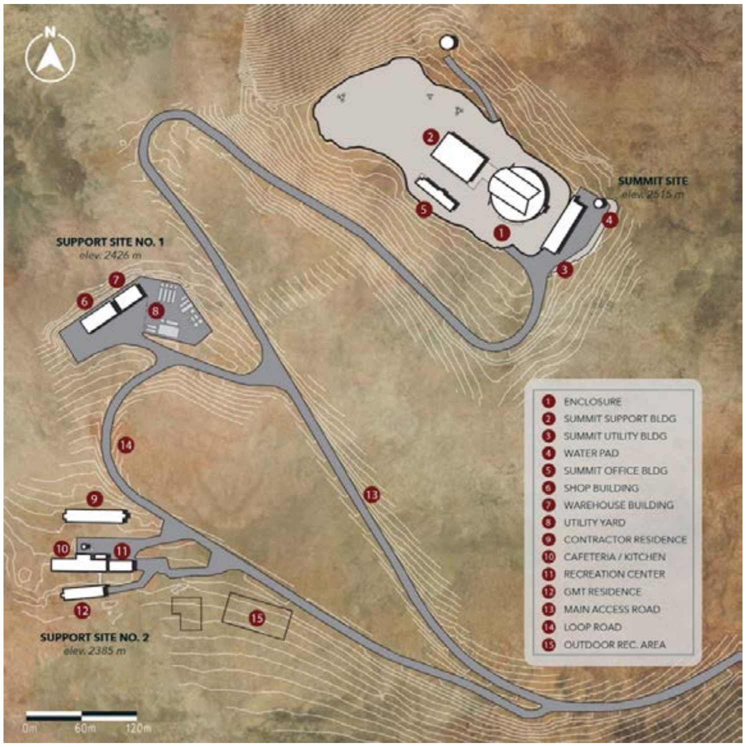


Figure 21. The GMT site master plan, showing the summit site; support site #1 dedicated to shop and warehouse buildings and the utility yard; and support site #2 providing construction residences, dining, and recreation facilities.

8. SITE CONSTRUCTION

Site construction has progressed through hard rock excavation of foundations for the enclosure and telescope pier, the installation of electrical power, data, and water infrastructure, an environmental monitoring facility, and the construction of two residence buildings, and dining and recreation facilities. A small staff has operated the site through the global COVID pandemic, and maintains the roads and infrastructure, awaiting the resumption of major construction. Figure 22 shows a recent drone image of the summit site, with the two support sites visible in the background below the summit. The next step is the concrete package for the lower enclosure, telescope pier, utility tunnel, and building foundations.

Figure 22. The GMT site following completion of hard rock excavation and utility distribution construction packages.

9. SUMMARY

The Giant Magellan Telescope project is progressing with design, fabrication, and site construction at Las Campanas, Chile. Two primary mirror segments have been completed, a third has been polished to specification, three others are being processed, and glass is in hand to cast the seventh needed to complete the telescope primary mirror. The telescope mount is nearing final design review and the start of fabrication. A new contract has been awarded to complete the design of the enclosure. Hard rock excavation for the telescope and enclosure foundations is completed and supporting infrastructure is ready to support a resumption of major construction. A full-scale primary mirror test cell for qualification of control components and systems is assembled and under test. Two adaptive optics and phasing testbeds are being constructed to verify needed wavefront control technologies and are showing encouraging early results. Long lead procurements and fabrication are continuing for science instruments. An off-axis adaptive secondary mirror is in fabrication. Software is being developed and released incrementally to support the work of other observatory subsystems.

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