PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Overview and status of the Giant Magellan Telescope project

Fanson, James, Bernstein, Rebecca, Angeli, George, Ashby, David, Bigelow, Bruce, et al.

James Fanson, Rebecca Bernstein, George Angeli, David Ashby, Bruce Bigelow, Glenn Brossus, Antonin Bouchez, William Burgett, Adam Contos, Richard Demers, Francisco Figueroa, Barbara Fischer, Frank Groark, Robert Laskin, Rafael Millan-Gabet, Marti Pi, Nune Wheeler, "Overview and status of the Giant Magellan Telescope project," Proc. SPIE 11445, Ground-based and Airborne Telescopes VIII, 114451F (13 December 2020); doi: 10.1117/12.2561852

SPIE.

Event: SPIE Astronomical Telescopes + Instrumentation, 2020, Online Only

Overview and Status of the Giant Magellan Telescope Project

James Fanson*[a], Rebecca Bernstein[a,b], George Angeli[a], David Ashby[a,c], Bruce Bigelow[a], Glenn Brossus[a], Antonin Bouchez[a], William Burgett[a], Adam Contos[a], Richard Demers[a], Francisco Figueroa[a], Barbara Fischer[a], Frank Groark[a], Robert Laskin[a], Rafael Millan-Gabet[a], Marti Pi[a], Nune Wheeler[a]

[a]GMTO Corporation, 465 N. Halstead St., Suite 250, Pasadena, CA USA 91107;
[b]Carnegie Observatories, 813 Santa Barbara St., Pasadena, CA USA 91101;
[c]Steward Observatory, 933 N. Cherry Ave., Tucson, AZ USA 85719

ABSTRACT

The Giant Magellan Telescope project is proceeding with design, fabrication, and site construction. The first two 8.4m primary mirror segments have been completed and placed in storage, three segments are in various stages of grinding and polishing, the sixth segment is in the initial stages of casting, and glass is in hand to cast the seventh segment. An industry contract is in place to complete the design and proceed with fabrication of the telescope structure. Residence buildings and other facilities at the Las Campanas site in Chile are complete. Hard rock excavation of the foundations for the enclosure and telescope pier is complete. Preliminary design of the enclosure has been completed and final design is underway. Seismic isolation system bearings have been tested. A primary mirror segment test cell that will be used to qualify control system components and software is being fabricated. Prototyping continues in several areas, including on-telescope wavefront sensing and control elements, telescope laser metrology, and a subscale Adaptive Secondary Mirror (ASM). Adaptive optics and phasing testbeds are under development. Construction activities were delayed by the global coronavirus pandemic, but work has now resumed.

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] In this 2020 status update, we concentrate on areas of the project that have undergone significant evolution since the report in the 2018 proceedings. These include the completion of hard rock excavation and other construction at the site in Chile, completion of the second primary mirror segment, and advances in the analysis, design, and prototyping of 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 6.5m 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.[3,5,8]

The scientific motivations for the GMT, and all of the 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 Rubin Observatory and ALMA in the south, and others around the globe and in space.

A new development since the 2018 report is the organization of the US Extremely Large Telescope Program (US-ELTP), which has the goal of providing US nationally funded, all-sky access to the US astronomical community. The GMTO Corporation is a partner in developing the US-ELTP along with the National Optical Infrared Astronomy Research Laboratory (NOIRLab) and the Thirty Meter Telescope International Observatory (TIO).[9]

*jfanson@gmto.org; phone 1 626 204-2231; fax 1 626 510-6645; gmto.org

Ground-based and Airborne Telescopes VIII, edited by Heather K. Marshall, Jason Spyromilio,
Tomonori Usuda, Proc. of SPIE Vol. 11445, 114451F · © 2020 SPIE
CCC code: 0277-786X/20/$21 · doi: 10.1117/12.2561852

Construction at the site in Chile has progressed with completion of hard rock excavation for the foundations of the telescope and enclosure, and improvement of electrical and other infrastructure. A second primary mirror segment has been completed and placed in storage, with three other segments in production, and a sixth planned to be cast in early 2021. Advancement of the design of GMT subsystems has been informed by extensive simulation of seismic response, wind-driven disturbances, and wavefront control. A number of prototypes are being fabricated and tested, and a full-scale test cell is in development to qualify the new designs for primary mirror control systems. Following a two-year procurement process the telescope mount contract has been awarded and the industry team is well along in their design process. GMT's first light science instrument has passed its spectrometer final design review and long lead lens procurement is underway.

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

2. ORGANIZATION, REQUIREMENTS, AND PROCESSES

Figure 1 depicts the organization of the GMTO Corporation, with Board-level functions shown in purple, corporate functions (including procurement) in white, the GMTO Santiago office in orange, the project team in blue, and external advisory bodies in green. Cross-cutting project functions, comprising systems engineering, project engineering, safety, assurance, and the project business office, are shown along the central vertical line. Eight project deliverable subsystems (or project elements) are shown along the lower horizontal line. Technology risk reduction work in the areas of adaptive optics and phasing will be performed with NOIRLab as part of a US-ELTP Development Project funded by the National Science Foundation (NSF). This effort is mainly performed in four project elements, and they have been grouped under the leadership of an assistant project manager. Similarly, we've grouped three elements associated with large scale construction, namely the telescope structure (or mount) manufacture, observatory enclosure and facilities construction, and site operations under a single manager (a deputy project manager). The project business office performs project planning, maintains the resource-loaded schedule, runs the earned value management system, and produces variance and other financial reports. Work is organized within detailed work and planning packages according to a formal work breakdown structure.

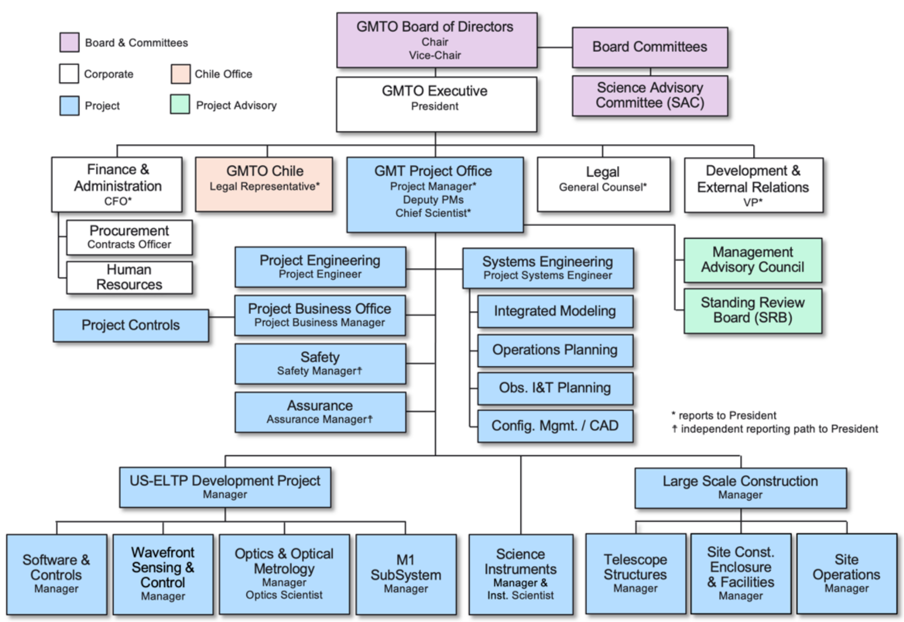

Figure 1. GMTO organization structure.

Systems engineering is responsible for configuration management and change control, requirements management, interface management, integrated modeling, and computer aided design (CAD). The project systems engineer manages technical resources and monitors key performance parameters (KPPs), assisted by the project engineer, who oversees the system level design. Two planning functions—observatory integration (closely related to requirements verification & validation) and the science operations phase—are also led within systems engineering. Risk management is performed in the conventional manner with a risk management board and a detailed risk register. The risk process is administered by a risk manager within systems engineering. Overall project implementation is overseen by the project manager and chief scientist, who report to the GMTO president.

System and subsystem requirements, as well as the interfaces between subsystems, are captured in DOORS Next Generation. Project documentation is implemented through SolidWorks Manage, which provides a unified environment for documents, data, and CAD models. Project maturity is shown graphically in Figure 2. Subsystems representing the majority of total project cost are well advanced. Nearly 80% of project cost corresponds to areas in preliminary or final design, and 20% is in fabrication or construction.

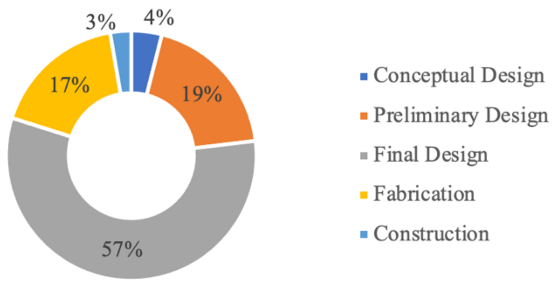

Figure 2. Fraction of project cost in various stages of design and construction.

KPPs are used to assess system level technical performance throughout all stages of the project. They are reviewed quarterly and reported at all project-level reviews. Active management of KPPs allows for early identification and resolution of issues while minimizing budget and schedule impacts. They form an important part of the compliance process. A more detailed description of the KPPs and their use in GMTO system engineering has been reported previously.[10]

An integrated model is used to track compliance with the KPPs during design and construction. It combines the optical, structural, thermal, and control models of the GMT into a single computational framework. The objective of the integrated model is to estimate optical performance from engineering specifications and designs. These estimates constitute the bottom-up budgets for the various Observatory performance modes and configurations. More details on the integrated model are described by elsewhere in these proceedings.[11]

Seismic requirements

The GMT uses large stiff borosilicate mirror segments, and while they offer significant optical advantages, they present a design challenge for a large telescope located in a seismically active environment. In order to trade development costs against project risk and exposure to operational seismic hazards, the GMT seismic requirements have been framed in terms of the probability of failure over the 50-year operational life of the observatory.

As telescopes have grown larger, structural modal frequencies have fallen in comparison to those of the 6-10m class of telescope. In the case of the GMT this leads to unavoidable modal coupling between the telescope mount structure and the mirror segments resting on their supports. This modal coupling, which falls in the most seismically energetic range of frequency, results in significant amplification of an already high level of seismic ground motion. Unmitigated, the probability of failure due to excessive glass stress or support displacement is too great. Given the impracticality of shifting the modal frequencies, GMTO opted to introduce both aggressive damping at the primary mirror supports (to reduce ground motion amplification) and a friction pendulum-based seismic isolation system at the base of the telescope pier (to decouple horizontal ground motion).

In order to evaluate the impact of these measures on the probability of failure we developed a statistical ground motion model, a non-linear seismic isolation bearing model, a dynamic model capturing the telescope structure and primary mirror motion, a primary mirror stress model, and a statistical model describing the probability of mirror failure due to excessive glass stress.[12] In order to calibrate the seismic isolation bearing model, extensive full-scale prototype bearing testing was performed. These tests enabled direct measurement of both friction and static stiffness properties of the friction-pendulum bearings. Seismic fragility has been analyzed and evaluated statistically using methods similar to those commonly employed for other high-value facilities such as nuclear power plants. GMTO has found this arsenal of tools invaluable for developing practical seismic requirements that balance project cost against project risk and operational hazards.

3. TELESCOPE DESIGN STATUS

The GMT is a doubly segmented optical system as shown in Figure 3 (left). Seven 8.4m borosilicate mirror segments form the telescope primary mirror. Two versions of the secondary mirror are being developed: a conventional fast-steering mirror system and an adaptive mirror system. The secondary mirror systems consist of seven 1.05m segments (Figure 3, right), each aligned with its corresponding primary mirror segment. The functional requirements of the two secondary mirror systems and baseline designs have been described in prior reviews.[13,14]

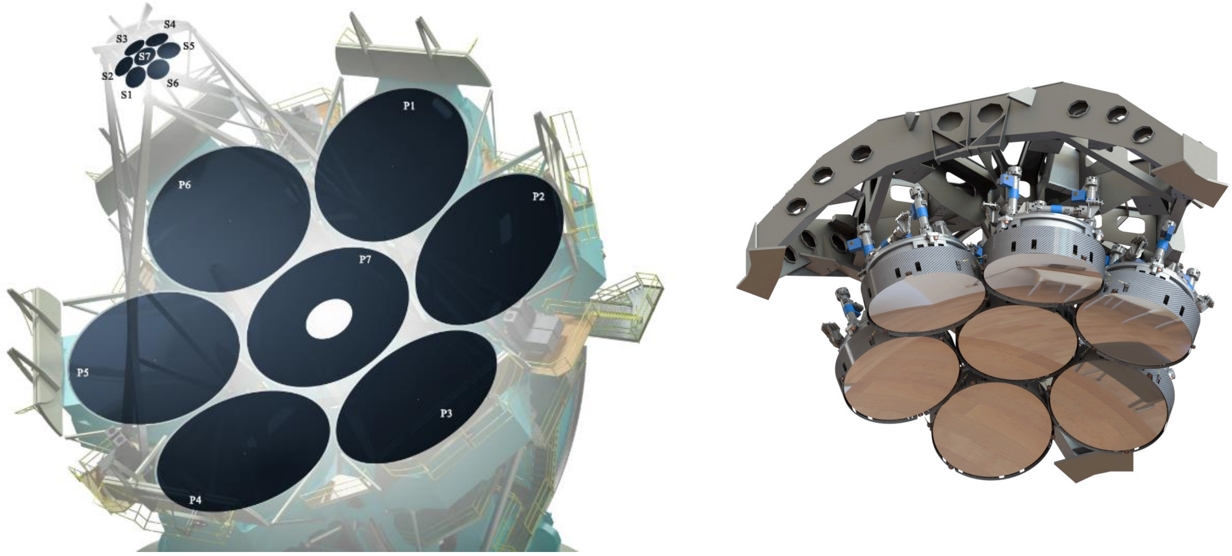

Figure 3. The doubly-segmented structure and conjugation of the GMT primary (M1) and secondary (M2) optics (left). The segmented adaptive secondary mirror (right) is used to phase the telescope and perform adaptive optics wavefront correction to achieve 25m diffraction limited performance of the telescope.

Papers in prior proceedings have described the design of the telescope mount, bearings, drives and other subsystems.[15,16] The structure is a compact altitude-over-azimuth configuration using large C-ring elevation bearings and a dual azimuth track. A third degree of motion is provided by the Gregorian instrument rotator (GIR), which performs image de-rotation for the various science instruments and houses wavefront sensing and control equipment. The design of the mount has not changed qualitatively since the 2014 design review. Modeling of the response of the telescope, primary mirror (M1), and secondary mirror (M2) subsystems to large seismic acceleration led to the incorporation of seismic isolation in the telescope pier and damping elements in the M1 support system. Two additional adjustments have been made to the telescope design: The architecture of the secondary mirror assembly has been returned to a single-stage actuation approach rather than the two-stage concept adopted in 2018. This change resulted from rigorous closed loop simulations of system-level performance in the presence of wind shake. And the GIR is being redesigned to afford the direct Gregorian instruments increased volume allocation.

3.1 Telescope mount

Since the 2018 report on the status of GMT a contract for the design and fabrication of the mount has been awarded to the team of OHB Digital Connect (OHB-DC) of Mainz, Germany, and Ingersoll Machine Tools (IMT) of Rockford, Illinois. This team will complete the design and fabrication of the mount and assemble it at the observatory site in Chile. Figure 4 shows the configuration of the OHB-DC design of the mount.

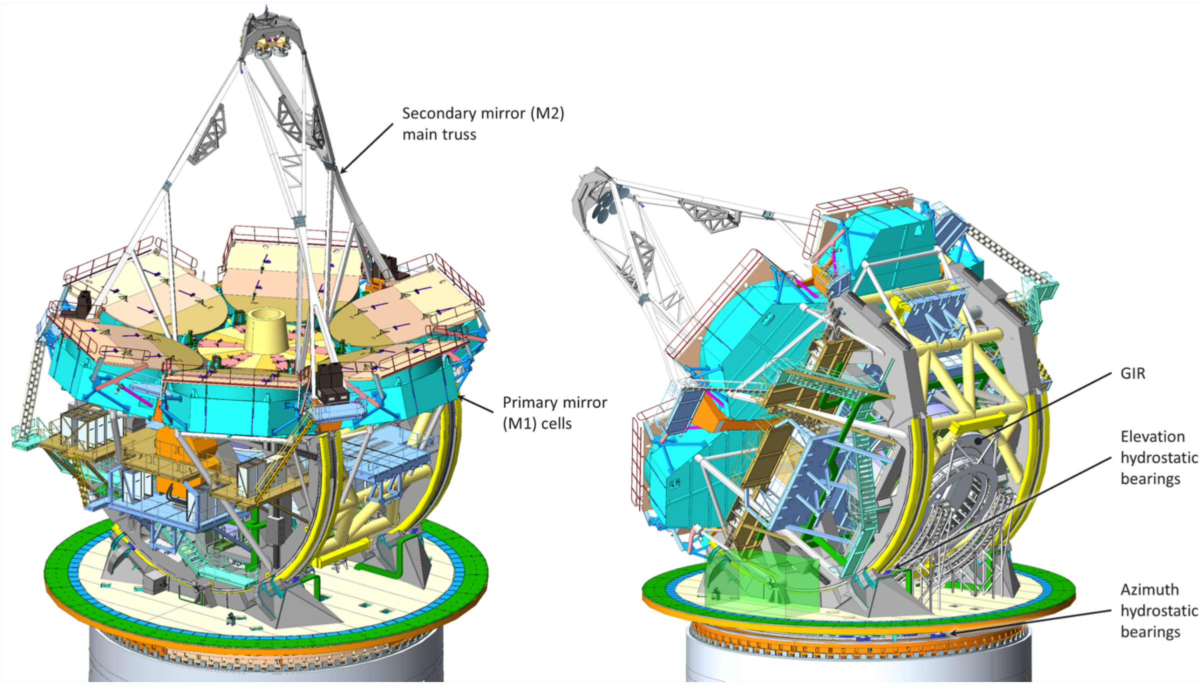

Figure 4. The OHB-DC and IMT team's design of the telescope mount showing the overall configuration of the telescope, its altitude-over-azimuth configuration, the C-ring elevation and azimuth hydrostatic bearings, and the Gregorian instrument rotator.

Several areas of the mount have been the focus of design refinement since 2018.

Azimuth track-to-pier interface. The 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 design separates lateral loads from vertical loads in order to limit stresses at the anchor bolts connecting the azimuth track to the pier. The current design is shown in Figure 5. Qualification tests have confirmed the strength of the steel embedment-to-concrete connection. Further qualification testing will begin in early 2021. While the SIS isolates lateral acceleration, it transmits potentially large vertical acceleration. Vertical loads in the mount are mitigated by means of a proprietary damping system physically incorporated into the azimuth structure.

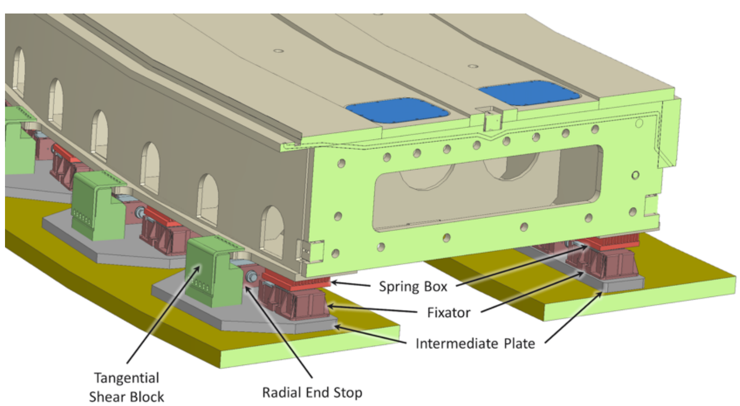

Figure 5. Azimuth track-to-pier interface.

M1 exchange repeatability. The six off-axis primary mirror (M1) assemblies are intended to be interchangeable. As the cell weldments form part of the monocoque mount structure, care must be taken to assure the exchange repeatability at the interfaces between the cell weldments and the cell connector frame. A fixture is currently being fabricated that will be used in verification tests planned for 2021.

GIR. The GIR is a large mechanical assembly on the scale of an 8-meter telescope (Figure 6). The operational requirements demand tight pointing, tracking, and mechanical alignment. These must be met to ensure acceptable alignment of the acquisition, guiding, and wavefront-sensing subsystem (AGWS) and science instruments with respect to the optical axis as the GIR rotates and changes elevation. There are additional critical alignment requirements between the GIR and the primary mirror segments. The GIR is densely packed with science instruments, electronics cabinets, utilities, counterweights and other equipment, requiring careful layout and volume allocations. These considerations make the structural and mechanical design of the GIR one of the more challenging aspects of the mount.

The initial configuration of the GIR accommodated four direct Gregorian (DG) instruments having identical allocated volumes and interfaces. Recent instrument development and new operational considerations led to a change in the DG instrument accommodation. The GIR will now accommodate two larger and one smaller DG instruments. This has in turn led to revised instrument installation, exchange, and deployment concepts and changes to the structural architecture to ensure safe maintenance, repair access, and design safety.

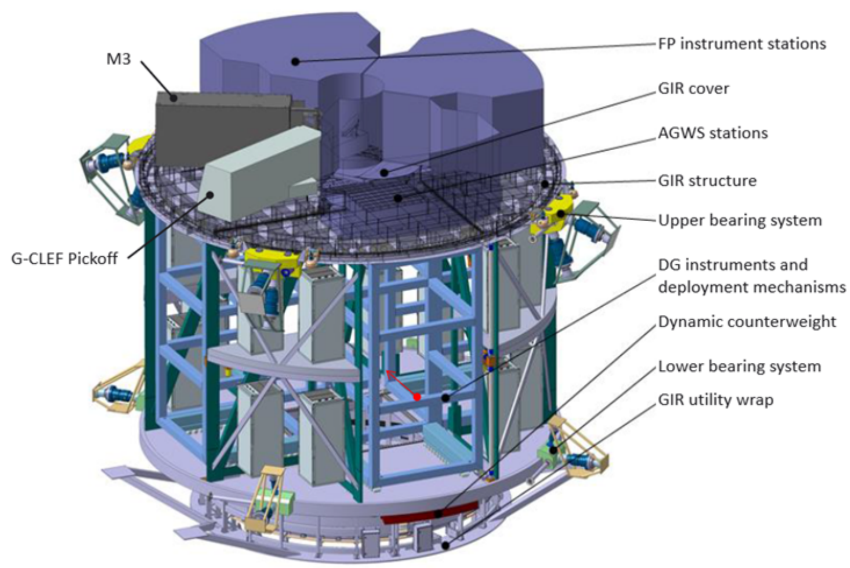

Figure 6. The Gregorian Instrument Rotator, which contains the science instruments and wavefront sensing and control elements. It performs image de-rotation by rotating the entire 6m x 9m assembly. G-CLEF is the first light echelle spectrograph science instrument. M3 is the tertiary mirror. FP are the folded port science instruments mounted to the top plate of the GIR. AGWS is the acquisition, guiding and wavefront-sensing subsystem. DG are the direct Gregorian science instruments housed in the interior of the GIR.

3.2 Adaptive secondary mirror subsystem

Over the past two years detailed trade studies of performance, robustness, mass, and cost were undertaken to optimize the interface between the secondary mirrors and the top-end of the telescope mount. The selected design is now a single-stage interface consisting of one large-stroke hexapod for each segment, which provides six degree-of-freedom position control (Figure 7). Performance analysis of the adaptive secondary mirror (ASM) revealed a control structure interaction issue involving fluid dynamic coupling between the ASM facesheet and reference body. This interaction produced a resonance at about 140 Hz that was limiting achievable performance. Testing of the ASM on the Large Binocular Telescope, which has a similar configuration, confirmed the phenomenon to be real. Further analysis indicated that stiffening the interface between the reference body and cold plate effectively mitigated the issue, and this has been incorporated into the GMT ASM design. Analysis also showed that proof-mass dampers were effective in mitigating the issue, so the GMT design incorporates interfaces for dampers should prototype testing indicate a need for them.

Finite element modeling of the ASMS dynamic performance under various environmental and control system conditions is continuing. In addition, laboratory prototype testing of ASM edge sensor performance is underway, and production of a fully functional prototype ASM is nearing completion. Part of the US-ELTP Development Project involves fabrication, assembly, and testing of optical components and major structural assemblies for the first full-scale off-axis ASM. This includes producing the low expansion off-axis aspheric facesheet and reference body (long lead material), the 6 DOF positioner assembly, the cold plate and all flexures and components necessary to assemble the primary structure. Key objectives of this work include confirming ASM primary structural modes and validating the performance of the 6 degree-of-freedom positioner. The ASM is being developed by the AdOptica consortium in Italy.

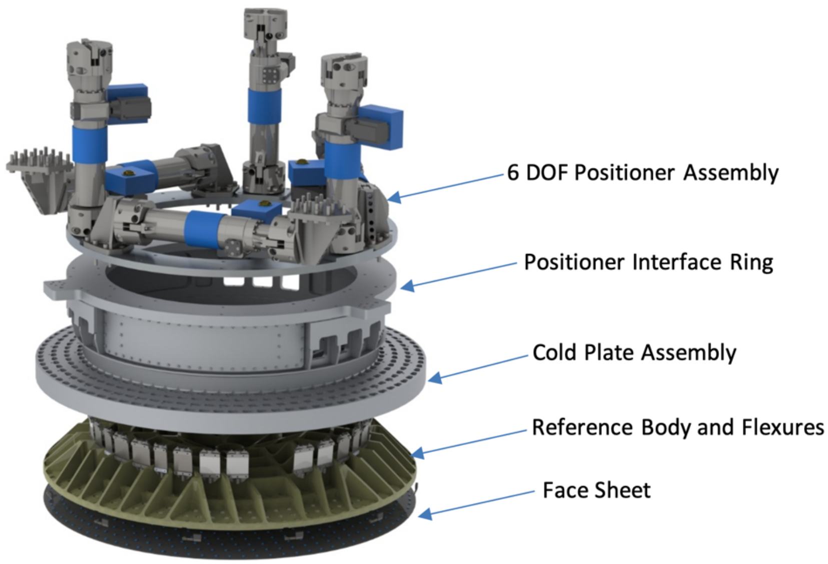

Figure 7. Adaptive secondary mirror (ASM) and positioner assembly.

3.3 Primary mirror (M1) subsystem

Like other modern telescopes, the GMT makes use of an active optics control system for each of its primary mirror segments to maintain collimation and to correct figure errors due to gravity and thermal deformations. The M1 subsystem consists of six position actuators (hardpoints) for rigid body control, a large number of force actuators that carry the weight of the mirror and provide figure control, and a thermal control system. Our M1 subsystem is derived from the successful active optics systems on the twin Magellan telescopes and the Large Binocular Telescope (which also feature large borosilicate mirrors), but several unique requirements drive some design departures. The need to phase the seven mirror segments requires a greater range of motion; the compound angle to gravity of the off-axis segments, and the need for interchangeability, requires that force actuators provide 3-axis rather than 2-axis control; seismic design considerations require the addition of dampers; and the need to achieve diffraction-limited performance over a 25m aperture tightens requirements on vibration. GMTO has chosen to incorporate dampers into the force actuators and is currently developing both eddy current and fluid damper options. The overall arrangement of M1 subsystem components for an off-axis mirror cell is shown in Figure 8.

In order to validate and characterize the M1 subsystem, including control software and algorithms, GMTO is constructing a full-scale prototype test cell.[17] Testing will begin with a steel mirror simulator and progress to testing with a completed mirror segment under the optical test tower at the Richard F. Caris Mirror Laboratory (RFCML) at the University of Arizona. Figure 9 shows the test cell weldment integrated with the steel mirror simulator.

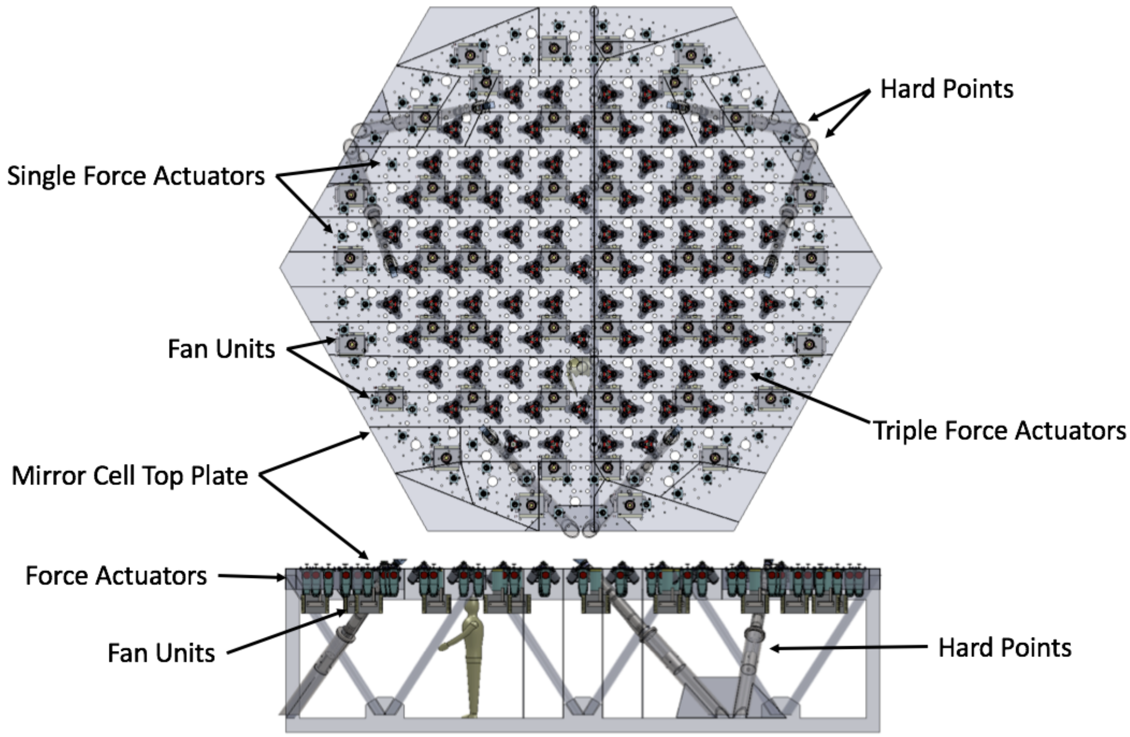

Figure 8. Configuration of M1 subsystem components in an off-axis mirror cell weldment.

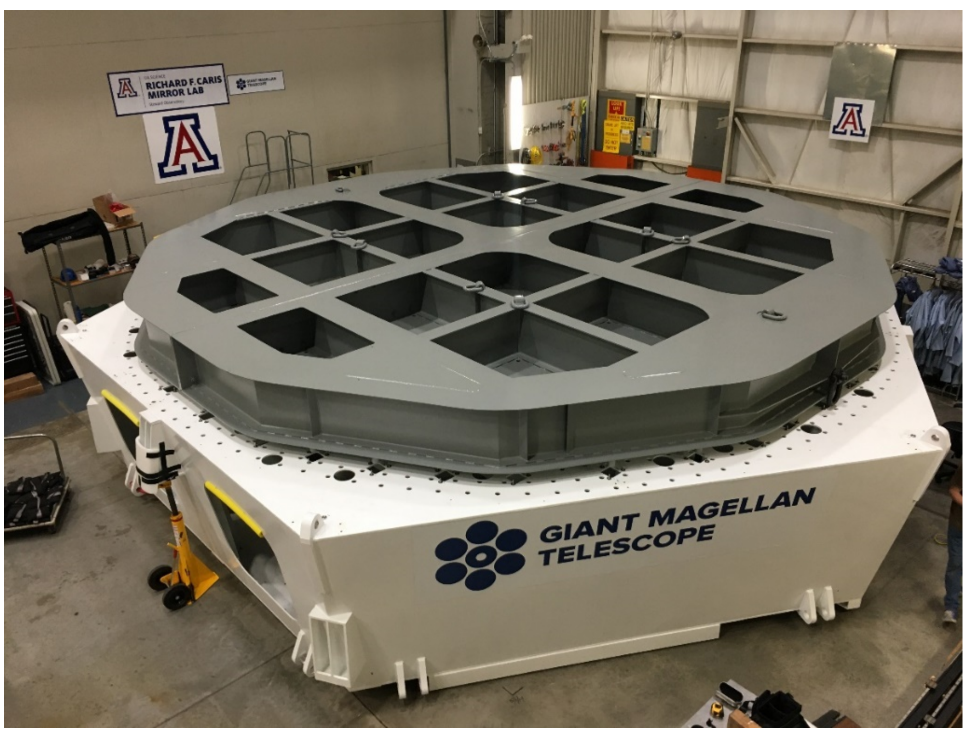

Figure 9. Test cell weldment integrated with steel mirror simulator at the Richard F. Caris Laboratory at the University of Arizona.

4. PRIMARY MIRROR PRODUCTION STATUS

Mirror fabrication at RFCML continues to make good progress. Mirror segment S2 was completed and the mirror formally accepted in June 2019 with a surface figure error of less than 22 nm rms. Segments S1 and S2 are now both completed and in storage awaiting shipment to Chile. Segments S3, S4, and S5 are in various stages of processing at RFCML and the hearth and mold for the casting of S6 are nearing completion. Segment S3 is in the final polishing stage (Figure 10) and has recently achieved a surface figure error of 200nm rms. It is expected to be completed in less than a year, at which time we plan to integrate it with the test cell described in Section 3.3. Segment S4, the center segment, is an on-axis mirror. Before it can be polished the optical metrology equipment used to measure the shape of the mirror's surface must be modified from its off-axis configuration. We plan to polish segment S4 after completing off-axis segment S5. Rear surface processing of segment S5 has recently been completed and the next step is front surface generation. Figure 11 shows segment S5 following completion of rear surface polishing and installation of loadspreaders and hardpoints. Preparation of the furnace and mold needed for casting GMT mirror segment S6 is nearing completion (Figure 12). Refractory cores for the mold are individually machined, numbered, and precisely placed to form the open cell structure of the mirror casting. The silica based refractory material is removed from the mirror cells after casting using a water jet cutter. The casting process is scheduled to reach the high temperature point in early 2021 followed by three months of annealing and cooldown.

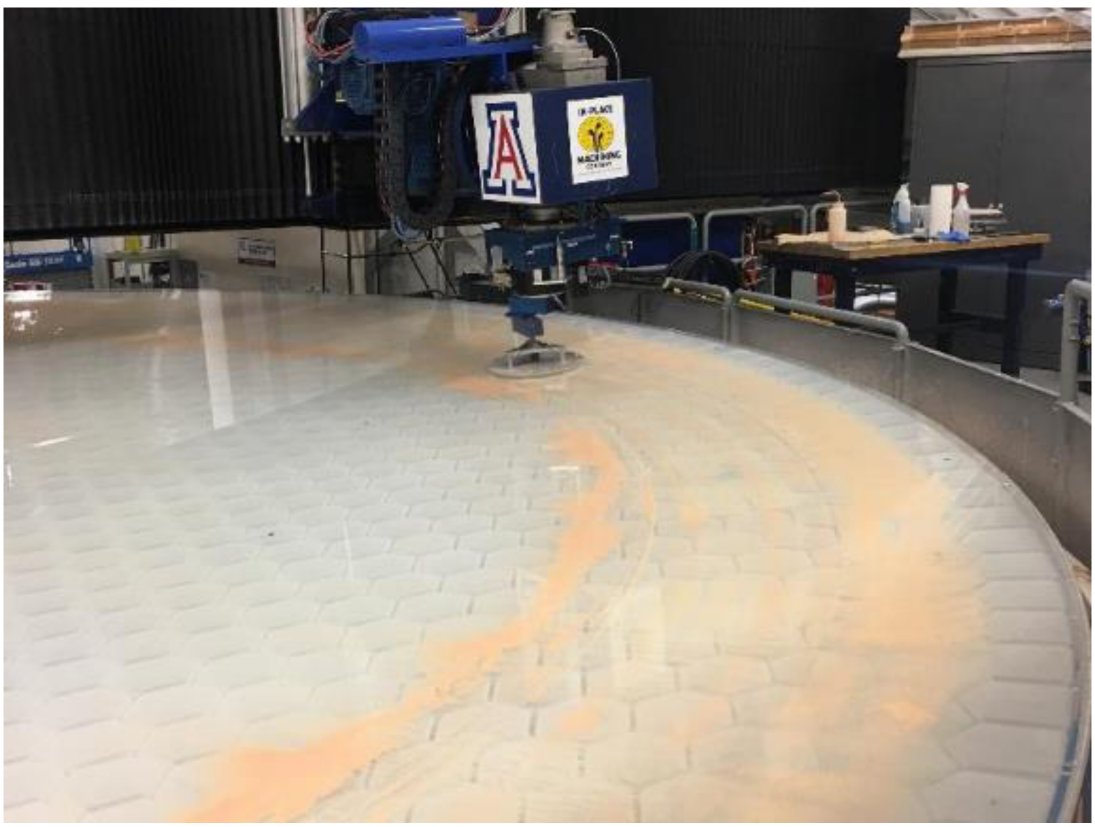

Figure 10. GMT segment S3 being polished using a 40 cm pitch lap.

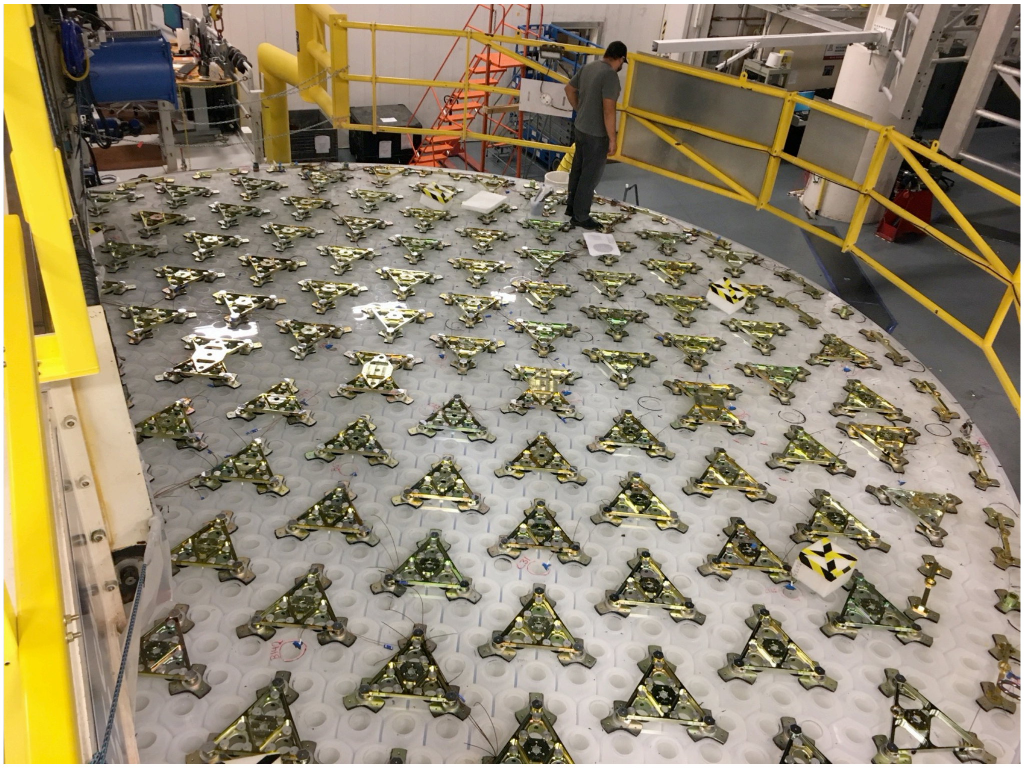

Figure 11. GMT segment S5 after completion of rear surface processing, and loadspreader and hardpoint mount bonding.

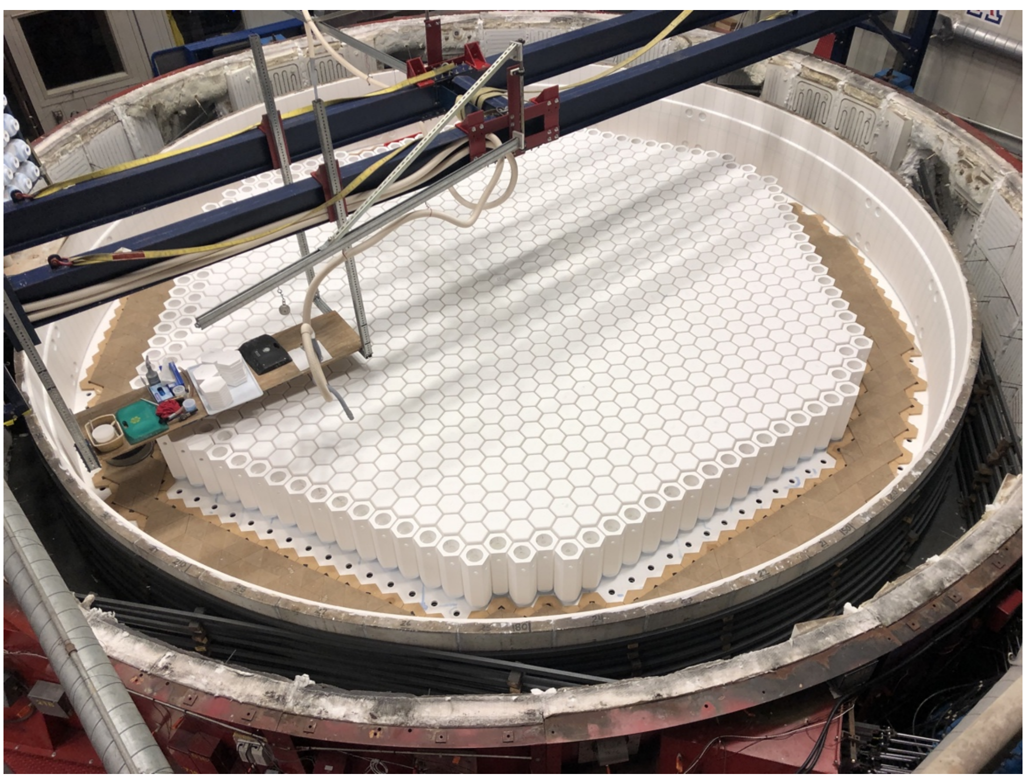

Figure 12. GMT segment S6 mold machining and assembly in the spin-casting furnace is now 2/3 completed.

5. ADAPTIVE OPTICS AND WAVEFRONT CONTROL

GMT will operate in one of four observing modes depending on the field of view, image quality, and sky coverage needs of the scientific program. They are: 1) natural seeing; 2) ground-layer adaptive optics (GLAO); 3) natural guidestar adaptive optics (NGAO); and 4) laser tomography adaptive optics (LTAO). In addition to correcting incident starlight for atmospheric turbulence, wind and observatory vibrations, achieving diffraction limited performance requires the optical control system to correct for position and phase errors in the doubly segmented optical system. The strategy and conceptual design for a segmented telescope phase control system has been developed, and modeling and simulation has informed the development of requirements and performance budgets. The focus of activities over the past two years has been the detailed design of the telescope guiding and phasing system, and the development of two laboratory testbeds to verify control strategies and image quality performance. The AGWS consists of four identical wavefront sensing probes that patrol the periphery of the direct Gregorian focal plane.[18] Each includes an imager for acquisition, a visible Shack-Hartmann wavefront sensor for guiding, active optics, GLAO control, and a near-infrared dispersed fringe sensor for segment co-phasing. The detailed design for the AGWS was completed in June 2020.

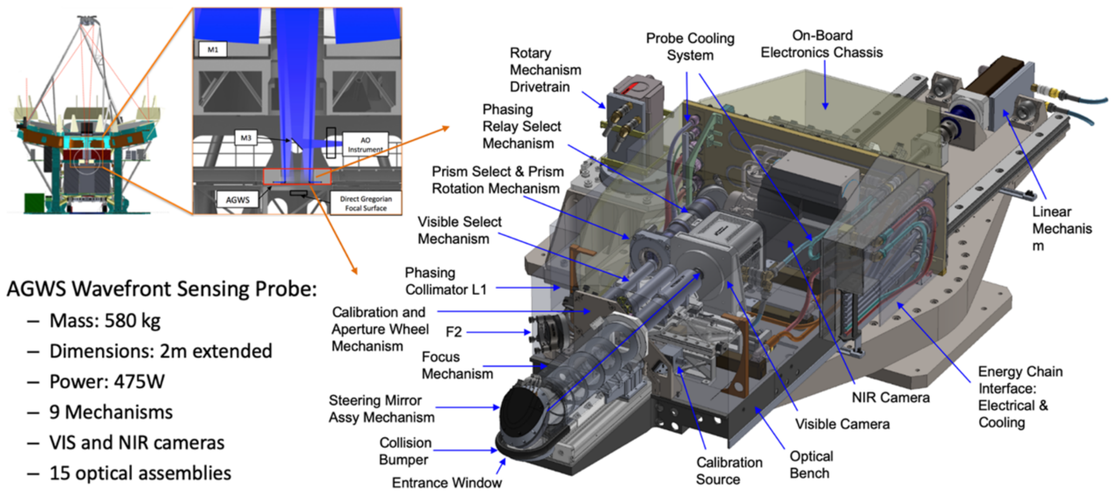

Figure 13. AGWS wavefront sensing probe detailed design. Four identical probes patrol the direct Gregorian focal plan.

Thus far the verification of the GMT wavefront sensing and control system design has relied on detailed end-to-end simulations and measured performance of prototype wavefront sensors tested at the Magellan telescopes. In order to further validate and test the AO design, strengthen the observatory error budget and identify potential unknown error sources, GMT has initiated a program to demonstrate nanometer-level segment phase error sensing and control, and atmospheric turbulence rejection using dedicated testbeds. The objectives of the testbeds include:

- Verification of the sensitivity and accuracy of the AGWS and the natural guidestar wavefront sensor;
- Verification of the performance of current control algorithms to execute active alignment and phase error rejection in a doubly-segmented optical system;
- Testing of calibration techniques for active and adaptive optics.

For practical reasons, these objectives have been partitioned and will be addressed by two complimentary testbeds.

1. The wide-field phasing testbed (WFPT) will demonstrate: i) low order wavefront control using a prototype AGWS; and ii) segment phasing over a wide field in the presence of simulated turbulence. The WFPT configuration is shown in Figure 14.

2. The High Contrast AO Testbed (HCAT) will demonstrate: i) high order wavefront control using a custom-designed pyramid wavefront sensor and deformable mirror; and ii) segment phasing, both over a narrow field in the presence of relevant environmental disturbances. The HCAT will leverage the use of the Magellan MagAO-

X instrument, already well characterized.[19] In a second stage, the reconfigured HCAT will be used to demonstrate pupil splitting, correction using multiple high-order deformable mirrors and coherent recombination in order to achieve science objectives such as high contrast imaging and starlight suppression. The HCAT configuration is shown in Figure 15.

The partitioning of objectives into low and high order wavefront and phasing control systems has two benefits. Parallel efforts will result in greater efficiency and the reduced complexity enables less formidable characterization of error contributions and investigation of unknowns. The WFPT and HCAT are being developed and will be operated in collaboration with GMT partner institutions Smithsonian Astrophysical Observatory and the University of Arizona, respectively. The custom pyramid wavefront sensor for the HCAT will be provided by the Osservatorio Astrofisico di Arcetri in Florence, Italy. Both testbeds are planned to achieve their key milestones in the summer of 2023.

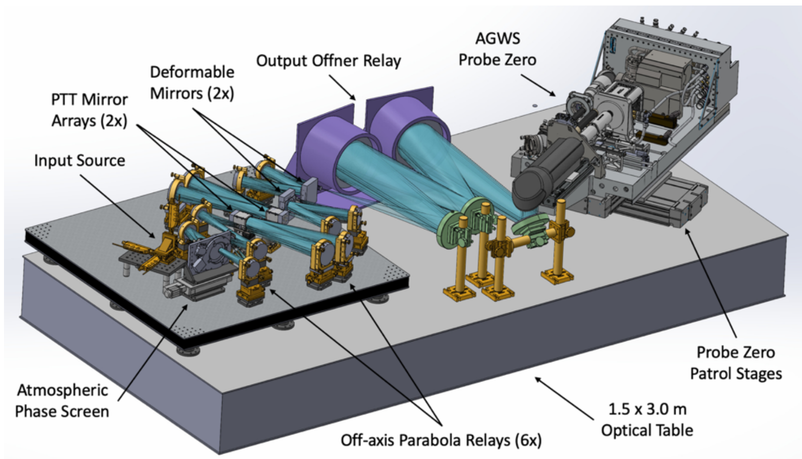

Figure 14. The wide-field phasing testbed concept being developed by GMTO and Smithsonian Astrophysical Observatory.

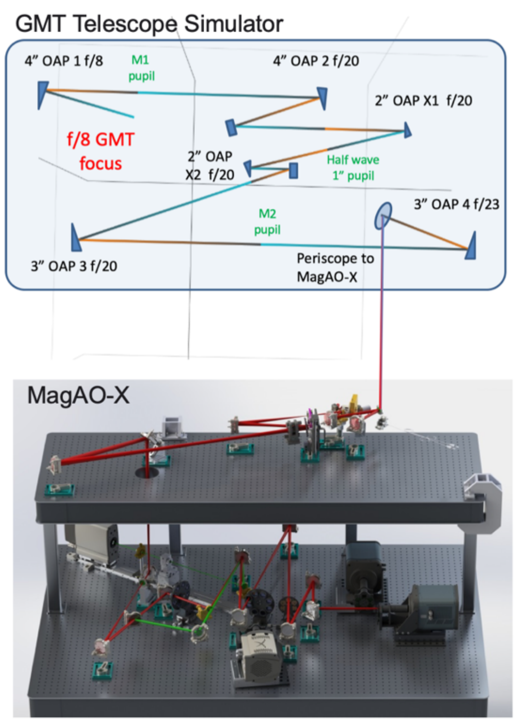

Figure 15. The High-contrast AO testbed concept being developed by GMTO and University of Arizona, which will make use of the existing MagAO-X instrument.

6. SCIENTIFIC INSTRUMENTS

Up to ten scientific instruments can be accommodated on the telescope at various stations. The suite of first-generation instruments was identified through an open solicitation for concepts and passed thorough conceptual design reviews in 2012. The instruments under development at this time include visible and infrared high-resolution spectrographs, a visible-light multi-object spectrograph and an AO-fed combination imager and integral field spectrograph. These instruments are at different levels of maturity as they are planned to be commissioned on the telescope at different times. In addition, a facility fiber optic system is being designed that can significantly enhance the scientific productivity of the two visible-light spectrographs.

The first light instrument for GMT is G-CLEF (GMT-Consortium Large Earth Finder), a high-resolution optical spectrograph. It is a precision radial velocity spectrograph targeted towards exoplanet research, but will also enable fundamental work in stellar astrophysics, stellar and interstellar chemistry, galaxy evolution, and cosmology.[20] G-CLEF is the most mature of the GMT instruments, with the spectrograph having completed final design and long lead optical element procurements placed. G-CLEF is being developed by the Smithsonian Astrophysical Observatory.

Our workhorse faint object, multi-object visible spectrograph is GMACS (GMT Multi-object Astronomical and Cosmological Spectrograph).[21] Its architecture is based on a spatial field of 7.5 arcmins split into red and blue spectral channels. GMACS is in preliminary design and is led by Texas A&M University.

The power of the G-CLEF and GMACS spectrographs can be enhanced by means of the GMT facility fiber system MANIFEST (Many Instrument Fiber System). Self-mobile fiber heads, called "Starbugs," patrol the telescope's focal surface enabling larger fields of view, higher multiplex gains, versatile reformatting of the focal plane via integral-field-units, image-slicers, the capability for parallel observations, and in some cases higher spatial and spectral resolution. An on-sky demonstrator system called TAIPAN is entering science operations on the UK Schmidt telescope at Siding Spring Observatory.[22,23] MANIFEST is being developed by AAO, Macquarie University, and is in conceptual design.

The GMT Near-Infrared Spectrograph (GMTNIRS) will cover the 1.15-5.3 μm range in a single exposure with R=60,000 in the J, H, and K bands and R=85,000 in the L and M bands. It employs the facility adaptive optics system and uses immersion gratings to achieve high spectral resolution and continuous wavelength coverage in a compact package.[24,25] The most challenging aspect of the instrument is the manufacture of the immersion gratings. The team has been proceeding to manufacture these gratings as a risk reduction long-lead manufacturing step. GMTNIRS is being developed by the University of Texas at Austin.

The Giant Magellan Telescope Integral Field Spectrograph (GMTIFS) is an AO-assisted near-infrared spectrograph and Imager. It delivers high sensitivity to low surface brightness extended sources and spectral resolutions (R=5,000 and R=10,000) well matched to a wide range of science cases. GMTIFS will be the first instrument to fully exploit the angular resolution afforded by the GMT.[26] GMTIFS is in preliminary design and is being led by the Australian National University.

7. SOFTWARE & CONTROLS

The observatory software and controls team has remained productive in spite of work restrictions arising from the global pandemic. Software development and testing with hardware systems continues apace, with a focus on delivering capability necessary to support prototype and development testing across the various observatory subsystems.

M1 test cell and ACS device control systems

The software for the M1 device control system is being developed and will be integrated into the M1 test cell in 2021.[27] This software is a crucial component of the GMT control system and its robustness is paramount for efficient and safe operation of the telescope primary mirror and other telescope systems. The low-level functionality for the force actuators, hardpoints, and other EtherCAT & power hub components is completed and has been integrated with the hardware devices and firmware developed at the University of Arizona. Test benches are used to verify the software low-level control components and firmware, and to support multiple instances of each device. We are using software simulators to verify correct software behavior when real hardware is not available to test. The M1 thermal control is under specification and will be incorporated into the software design next year.

The actuator calibration system (ACS) software uses the same low-level components, frameworks, and agile development process as the M1 test cell software. Calibration and qualification software for the M1 actuators is being tested to ensure software robustness, as the first batch of actuators will soon be certified for integration with the test cell. Figure 16 shows the user interface for calibration of the ACS stand. This interface, integrated with the observatory control system (OCS) Navigator, guides the operator in performing all required steps for a successful calibration.

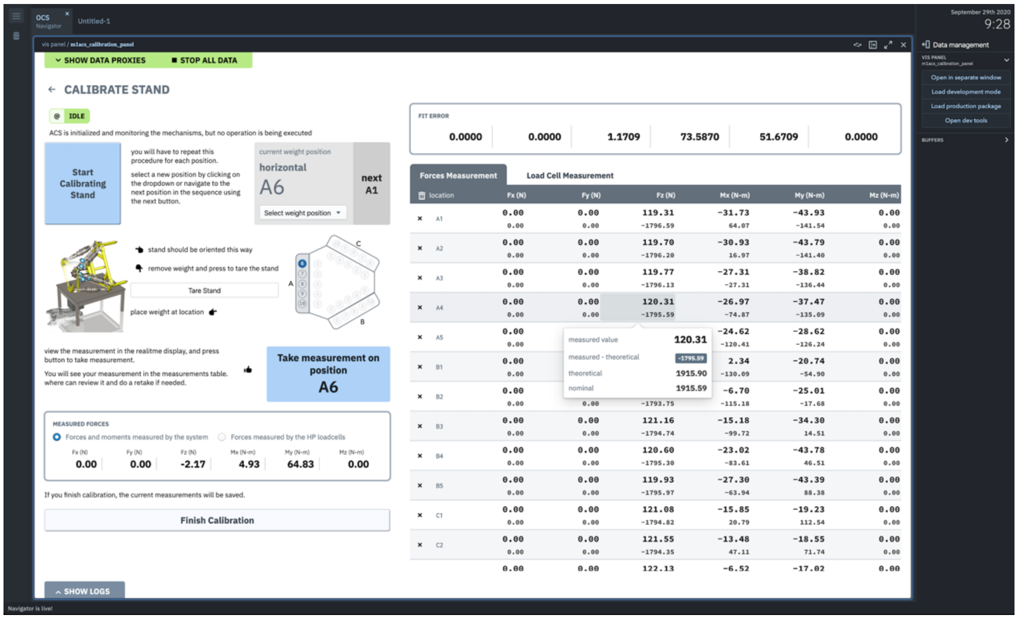

Figure 16. The ACS calibration user interface makes use of the OCS Navigator.

Observatory control system

The software team is completing documentation in preparation for the OCS preliminary design review scheduled for early 2021. This review will evaluate the status of the requirements, architecture, and management plans. A key aspect of the design has been identification and definition of the interfaces with the many controlled subsystems, including the telescope mount, which is approaching contractor preliminary design review. The team is completing the control requirements for all site, enclosure and facilities subsystems. The design of the facilities control system began this year and will include interfaces with several services and utilities at the observatory. Work on low-level controllers for the enclosure is a priority for the months ahead.

SDK Software Releases

The software development kit (SDK) v1.8, which includes the libraries and services to develop device control systems following the reference architecture, was distributed to the external software groups in June. The next SDK version, including core frameworks in Python, is being completed this year. We are supporting these releases and collaborating with the science instrument software teams to implement the instrument control system prototypes.

Interlock and Safety System

The interlock and safety system (ISS), which is responsible for functional safety of the observatory, was successfully reviewed at the conceptual design level in April 2020. A functional safety management plan has been provided and safety interfaces have been defined with major controlled subsystems. These interfaces are based on the safety functions derived from the subsystem hazard analyses. The ISS for the M1 test cell has been designed and is being built to support test cell integration and testing.

Software Collaborations

GMT has begun collaboration with NOIRLab to define interfaces for the high-level operations software, which is crucial for efficient telescope operations. During the last two years the software and controls team has also started a collaboration with the Instituto Mauá de Technology (IMT) in Brazil. The IMT team has already delivered the commissioning camera instrument control software simulator and is developing software components and the user interface for the WFPT, a key activity for 2021.

8. ENCLOSURE DESIGN

The GMT enclosure design has continued to evolve since 2018, based on an on-going series of engineering trade studies, computational fluid dynamic (CFD) analyses, stray light analyses, integrated modeling, and cost assessments. The enclosure preliminary design review was successfully convened in 2019. An artist rendering of the enclosure and other structures at the summit of the Las Campanas site in Chile is shown in Figure 17. Key decisions supporting advancement of the design since 2018 include formal selection of a conventional "closed-soffit" lower enclosure configuration, elimination of the moon-screen (based on extensive stray light analyses), selection of a commercially available windscreen, and revision of the enclosure and shutter door wind vent configurations (based on CFD and integrated modeling results). The preliminary design of the enclosure was performed by M3 Engineering & Technology Corp.

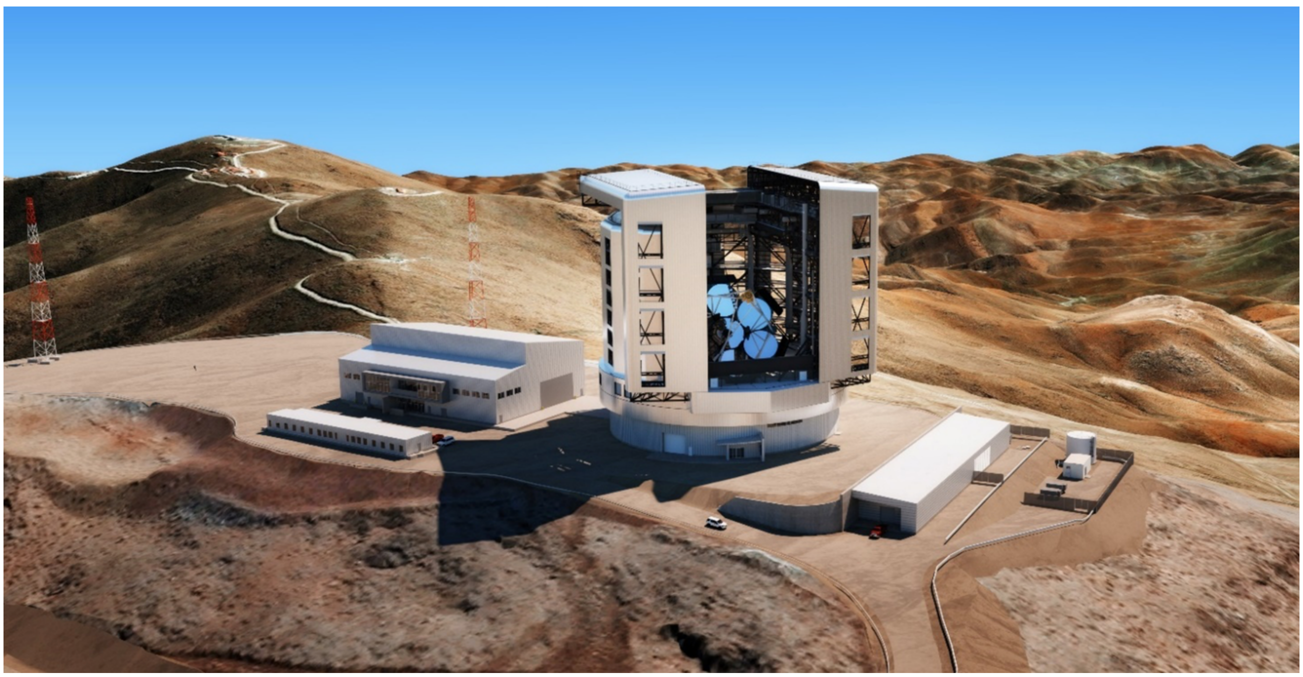

Figure 17. The GMT enclosure design as of November 2020. The summit support and utility buildings are shown to the left and right of the enclosure.

Designs for the major enclosure mechanical systems have also advanced to preliminary design maturity, including the enclosure rotation system, shutters, windscreen, and observing chamber air conditioning systems. Figure 18 shows the enclosure (and telescope) in three common configurations: with shutters and wind vents closed (normal daytime condition), shutters and wind vents fully open and windscreen retracted (nighttime low-wind condition), and shutters and wind vents open, with windscreen fully deployed (zenith pointing under typical wind conditions).

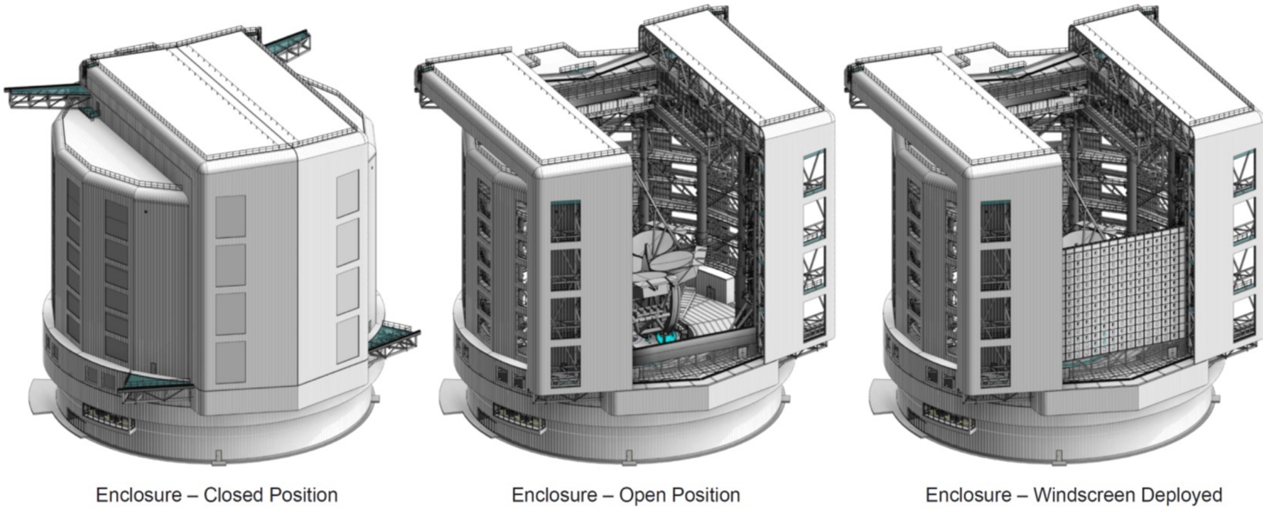

Figure 18. Enclosure shutter, wind vent, and wind-screen configurations.

CFD modeling also established the need for daytime air conditioning of the observing chamber, and preliminary designs for the air conditioning components, including air handling units, ducting, and fans have been developed (Figure 19, left). Daytime air conditioning of the observing chamber will allow the telescope, its payloads, and the observing chamber to be maintained close to the expected nighttime ambient temperature in order to minimize local temperature differences, which would negatively impact image quality.

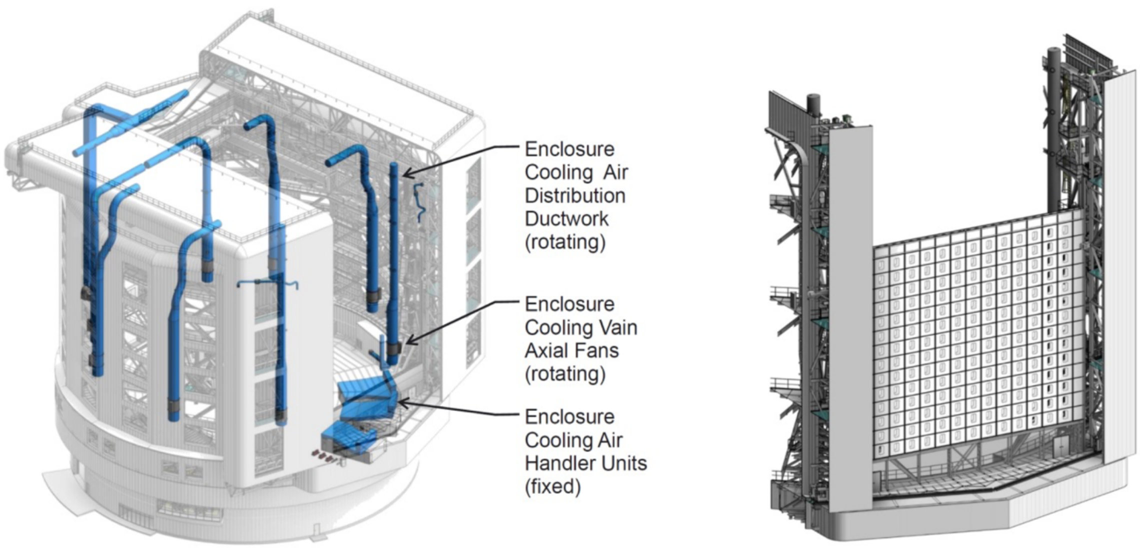

Figure 19. Upper enclosure air conditioning ducting (left) and the enclosure windscreen (right).

A variety of wind-screen design options were developed and compared during the enclosure preliminary design phase, including multiple folding and rotating options, all of which would have required large custom design and construction. However, a structured fabric door was found that could meet the windscreen requirements, with an essentially commercial off-the-shelf product (Megadoor by Assa Abloy). Additional CFD analysis of the enclosure and windscreen together were used to establish the height of the windscreen and a perforation pattern which adequately protects the telescope while allowing some wind-driven ventilation of the observing chamber (Figure 19, right). Additional information is available elsewhere in these proceedings.[28]

9. SITE CONSTRUCTION AND OPERATIONS

The GMT is being built at the Las Campanas Observatory in northern Chile. The site is owned by the Carnegie Institution for Science and is home to the twin Magellan 6.5m telescopes and a number of smaller instruments. The site was leveled in 2012 and construction activities on the summit have been underway since that time. The site master plan is shown in Figure 20.

Completed and operational infrastructure at the site includes the construction offices on the summit, and below the summit, at support site #2, a 68-room residence building to house a construction crew, a 24-room residence for GMTO employees and visitors, and dining and recreation facilities. In addition to electrical power, existing site infrastructure includes backup power generators, wired and wireless internet, potable and firefighting water systems, and waste-water treatment.

Construction accomplishments since 2018 include completion of hard rock excavation for the foundations of the telescope, enclosure, summit support building, summit utility tunnel, and summit utility building, as well as near completion of the underground utility distribution systems for domestic and fire water, electrical power, data network, and cooling fluid. GMTO reviewed the excavation experience of other observatory projects in Chile and incorporated appropriate lessons learned into our plans. The hard rock excavation construction package was awarded through competitive bid to Conpax Montajes S.P.A., of Santiago, Chile. Conpax work began in June 2018 and was fully completed, ahead of schedule, by February 2019. Approximately 7,000 cubic meters of material were removed, including a combination of rock, soil, and fill. All rock removal was accomplished by a combination of mechanical drilling and hammering, with no blasting in order to minimize risk of damage to underlying rock. No substantial voids or other defects were found in the remaining rock; the telescope pier will rest on competent Andesite rock of very high quality.[28] Figure 21 shows the completed work on the GMT summit mesa as of February 2020.

Various other improvements have been made to the electrical and communications infrastructure, including the addition of an automatic transfer switch and load banks for the backup electrical generators, remotely operated reconnectors for the 23kV power line, and expansion of the fiber optics network at the site. Construction was interrupted for a period in 2020 due to pandemic conditions in Chile. With the return of warmer weather conditions have improved and construction has resumed with the addition of appropriate health and safety measures to protect the construction crew and GMTO personnel.

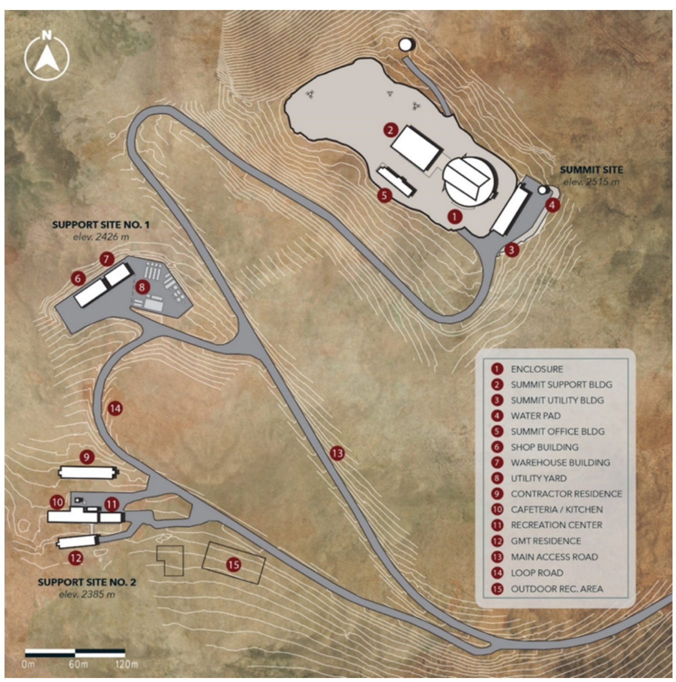

Figure 20. The GMT site master plan, showing the summit site, support site #1 dedicated to shop and warehouse buildings, and the utility yard. support site #2 provides the construction residences, dining and recreation facilities.

Figure 21. The GMT summit site following completion of the hard rock excavation and utility distribution construction packages.

10. SUMMARY

The Giant Magellan Telescope project is progressing with design, fabrication, and site construction. Two primary mirror segments have been completed, three others are being processed, and the sixth is planned to be cast in 2021. The telescope mount contract has been awarded to an experienced industry team. Hard rock excavation for the telescope and enclosure foundations is completed and supporting infrastructure is nearing completion at the Las Campanas site in Chile. A full-scale primary mirror test cell for qualification of control components and systems is approaching integration and test. Two adaptive optics and phasing testbeds are being constructed to verify the wavefront control architecture and simulations. The first light science instrument has reached final design maturity and long lead optical components are being procured. Other science instruments continue in design and risk reduction prototyping. An adaptive secondary mirror prototype is in fabrication and the procurement and testing of components for the first production off-axis adaptive mirror is imminent. Software is being developed and released incrementally to support the work of other observatory subsystems.

This work has been supported by the GMTO Corporation, a non-profit organization operated on behalf of an international consortium of universities and institutions: Arizona State University, Astronomy Australia Ltd, the Australian National University, the Carnegie Institution for Science, Harvard University, the Korea Astronomy and Space Science Institute, the São Paulo Research Foundation, the Smithsonian Institution, the University of Texas at Austin, Texas A&M University, the University of Arizona, and the University of Chicago. In addition, we look forward to working with the NOIRLab under a recent subaward funded by the National Science Foundation.

REFERENCES

[1] Johns, M., “The Giant Magellan Telescope (GMT),” Proc. SPIE 6267, Ground-based and Airborne Telescopes, 626729 (2006).

[2] Johns, M., “Progress on the GMT,” Proc. SPIE 7012, Ground-based and Airborne Telescopes II, 70121B (2008).

[3] Shectman, S.; Johns, M., “GMT overview,” Proc. SPIE 7733, Ground-based and Airborne Telescopes III, 77331Y (2010).

[4] Johns, M. et al., “Giant Magellan Telescope: overview,” Proc. SPIE 8444, Ground-based and Airborne Telescopes IV, 84441H (2012).

[5] Bernstein, R. A. et al., “Overview and status of the Giant Magellan Telescope project,” Proc. SPIE 9145, Ground-based and Airborne Telescopes V, 91451C (2014).

[6] McCarthy, P. et al., “Overview and status of the Giant Magellan Telescope project,” Proc. SPIE 9906, Ground-based and Airborne Telescopes VI, 990612 (2016).

[7] Fanson, J. et al., “Overview and Status of the Giant Magellan Telescope,” Proc. SPIE 10700, Ground-based and Airborne Telescopes VII, 1070012 (2018).

[8] Dressler, A. et al., “IMACS: the wide-field imaging spectrograph on Magellan-Baade,” Proc. SPIE 6269, Ground-based and Airborne Instrumentation for Astronomy, 62690F (2006).

[9] Wolff, S. et al., “The US Extremely Large Telescope Program,” Astro2020: Decadal Survey on Astronomy and Astrophysics, APC white papers, no. 4; Bulletin of the American Astronomical Society, Vol. 51, Issue 7, id. 4 (2019).

[10] Angeli, G. et al., “Performance Parameter based systems engineering for the Giant Magellan Telescope through construction and commissioning,” Proc. SPIE 11450-20, (2020).

[11] Conan, R. et al., “GMTO approach to integrated modeling based system engineering”, Proc. SPIE 11450, Modeling, Systems Engineering, and Project Management for Astronomy IX, 11450-26 (2020).

[12] Schwartz, D. et al., “Protecting A Fragile Giant: Seismic Design, Analysis, Results and Requirements for the GMT,” Proc. SPIE 11450, Modeling, Systems Engineering, and Project Management for Astronomy IX, 11450-33 (2020).

[13] Cho., M. et al., “Development of GMT fast steering secondary mirror assembly,” Proc. SPIE 9145, Ground-based and Airborne Telescopes V, 91451M (2014).

[14] Biasi, R. et al., “GMT adaptive secondary design," Proc. SPIE 7736, Adaptive Optics Systems II, 77363O (July 2010).

[15] Johns, M. et al., “Design of the Giant Magellan Telescope” Proc. SPIE 9145, Ground-based and Airborne Telescopes V, 91451F (2014).

[16] Sheehan, M. et al., “Progress on the structural and mechanical design of the Giant Magellan Telescope,” Proc. SPIE 8444, Ground-based and Airborne Telescopes IV, 84440N (2012).

[17] Fischer, B. et al., “The purpose, plan, and progress of the Giant Magellan Telescope primary mirror off-axis segment test cell,” Proc. SPIE 11445, Ground-based and Airborne Telescopes VIII, 11445-257 (2020).

[18] B. A. McLeod, et al., “The active optics, GLAO, and phasing sensors for the Giant Magellan Telescope", Proc. SPIE 11448, Adaptive Optics Systems VII, 11448-36 (2020).

[19] L. M. Close et al., "Concept for the GMT High-Contrast Exoplanet Instrument GMagAO-X and the High-Contrast Phasing Testbed with MagAO-X", AO4ELT6 Proceedings (2019).

[20] Szentgyorgyi, A. et al. “The GMT-Consortium Large Earth Finder (G-CLEF): An optical echelle spectrograph for the Giant Magellan Telescope (GMT),” Proc. SPIE 11447, Ground-based and Airborne Instrumentation for Astronomy VIII, 11447-388 (2020).

[21] Depoy, D. L et al. “The Giant Magellan Telescope Multi-object Astronomical and Cosmological Spectrograph (GMACS),” Proc. SPIE 11447, Ground-based and Airborne Instrumentation for Astronomy VIII, 11447-395 (2020).

[22] Lawrence, J. S. et al. “Wide field spectroscopy on the Giant Magellan Telescope with MANIFEST,” Proc. SPIE 11447, Ground-based and Airborne Instrumentation for Astronomy VIII, 11447-396 (2020).

[23] Lorente, N. P. F. et al., “Commissioning and initial performance of the TAIPAN Starbugs fibre positioner and spectrograph,” Proc. SPIE 11447, Ground-based and Airborne Instrumentation for Astronomy VIII, 11447-162 (2020).

[24] Jaffe, D. T. et al., "GMTNIRS: progress toward the Giant Magellan Telescope near-infrared spectrograph," Proc. SPIE 9908, Ground-based and Airborne Instrumentation for Astronomy VI, 990821 (2016).
[25] Jaffe, D. T. et al., "MagNIFIES, a high-resolution infrared spectrograph for Magellan with enormous spectral grasp," Proc. SPIE 11447, Ground-based and Airborne Instrumentation for Astronomy VIII, 11447-326 (2020).
[26] Sharp, R. G. et al., "The Giant Magellan Telescope Integral Field Spectrograph and Imager," Proc. SPIE 11447, Ground-based and Airborne Instrumentation for Astronomy VIII, 11447-338 (2020).
[27] Thanasekaran, D. et al., "Device Control Software Design for Active Support System of GMT Primary Mirror Segment," Proc. SPIE 11452, Software and Cyberinfrastructure for Astronomy VI, 11452-140 (2020).
[28] Bigelow, B. et al., "GMT site, enclosure, and facilities; 2020 design and construction update," Proc. SPIE 11445, Ground-based and Airborne Telescopes VIII, 11445-4, (2020).