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ABSTRACT

The Giant Magellan Telescope Project is in the construction phase. Production of the primary mirror segments is underway with four of the seven required 8.4m mirrors at various stages of completion and materials purchased for segments five and six. Development of the infrastructure at the GMT site at Las Campanas is nearing completion. Power, water and data connections sufficient to support the construction of the telescope and enclosure are in place and roads to the summit have been widened and graded to support transportation of large and heavy loads. Construction pads for the support buildings have been graded and the construction residence is being installed. A small number of issues need to be resolved before the final design of the telescope structure and enclosure can proceed and the GMT team is collecting the required inputs to the decision making process. Prototyping activities targeted at the active and adaptive optics systems are allowing us to finalize designs before large scale production of components begins. Our technically driven schedule calls for the telescope to be assembled on site in 2022 and to be ready to receive a subset of the primary and secondary mirror optics late in the year. The end date for the project is coupled to the delivery of the final primary mirror segments and the adaptive secondary mirrors that support adaptive optics operations.

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

1. INTRODUCTION

The status of the Giant Magellan Telescope Project has been reviewed in SPIE proceedings a number of times.[1, 2, 3, 4, 5 ,6] The basic characteristics and configuration of the telescope are well described in these publications and have not changed significantly since the last publication. A few aspects of the design are under review prior to the start of final design and fabrication while other components and infrastructure are being developed. The motivation for, and logic behind, the key decisions in the design process are reviewed here before we report on the status of the main technical and programmatic areas of the project.

The choice of the large primary mirror segments that lie at the heart of the GMT was motivated by the desire to maximize contiguous surface area within the segmented primary. The choice of the structured mirrors made at the University of Arizona was driven by the excellent image quality provided by the twin 6.5m Magellan telescopes and the other 6-8m class telescopes using the Arizona mirrors. This choice of primary mirror architecture has the added benefit of keeping the production of the primary optics within the GMTO partnership. The secondary mirrors, both conventional and adaptive, are segmented and map one-to-one to the primary segments, making a doubly segmented optical system.

The aplanatic Gregorian design of the GMT has its roots in favorable conditions for designing wide-field spectrographs utilizing refractive collimators [3, 6, 7] and the ease in manufacture and testing of the secondary optics. The Gregorian configuration has an added advantage when used as the deformable element in a ground-layer adaptive optics system as the adaptive elements maps to a conjugate ~160 meters above the primary mirrors.[6] Ground-layer correction was identified as an important goal for the GMT project early on following the first discussions of this mode of adaptive optics.[8]

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Adaptive optics has been integral to the GMT design from the outset. The choice of adaptive secondary mirrors using thin glass face sheets[9] and voice coil actuators early on in the GMT design phase was not without risks. The MMT adaptive secondary[10] was not fully operational in 2003 and during the conceptual design phase of the GMT the LBT adaptive secondary mirrors[11] were still on a long development path, although first-light would quickly demonstrate their power.[12] The choice of the adaptive secondary mirror now looks well justified as similar systems are producing excellent results on the LBT and Magellan AO systems[13] and the VLT adaptive secondary will soon be deployed. As a risk mitigation and operational efficiency strategy, we will deploy a conventional seeing-limited secondary mirror system for commissioning and scientific operations when the AO secondary mirrors are off the telescope for maintenance.

The segmented structure of the GMT secondary mirrors allows us to use much of the engineering and experience from the LBT adaptive secondary mirrors and the VLT adaptive secondary[14] with minimal risk and evolution. As described below and elsewhere in these proceedings, we are progressing through the final design and prototyping of the GMT adaptive mirrors.

The use of small secondary mirrors paired to each primary mirror results in a double-segmented optical system for the GMT. This eases manufacturing and handling and provides additional control paths. The doubly-segmented system and the significant gaps between adjacent primary and secondary mirrors, however, bring additional metrology and control challenges and these have been the focus of considerable analysis and prototyping within the GMT project. These efforts are described in these proceedings.[15,16]

One of the distinctive aspects of the GMT design is its use of a direct focus and deployment of instruments on a platform just below the central primary mirror segment. Some of the convenience of the increasingly common Nasmyth platforms are lost in this configuration. The GMT configuration results, however, in an efficient and highly compact structure with excellent modal performance. Instruments at the direct focus can be fed with only two reflections – primary and secondary mirrors – increasing total throughput.

The selected site for the GMT was first characterized in the 1980s and 90s as part of the site survey campaign for the twin 6.5m Magellan telescopes. The highest peak within the Las Campanas site, Campanas Peak, was recognized as having native image quality that is indistinguishable from excellent seeing at the site chosen for the Magellan telescopes and was recognized even in the early 1990's as a potential site for the next generation large telescope. Carnegie's clear title to the land and good relations with the government of Chile were also recognized as key assets as the development of observatory sites becomes increasingly difficult around the world.

The GMT project entered into the construction phase in 2015 following a System Level Preliminary Design Review and Cost and Organizational Review in 2014. These were preceded by subsystem design reviews in the later half of 2013. The interval between the completion of the PDR and cost reviews and the start of construction was focused on building the legal and financial underpinning of partnership needed to support the construction phase.

2. REQUIREMENTS, DESIGN AND PROCESS

The top-level science goals for the GMT project were drafted early in the life of the project and were reviewed at the time of the Conceptual Design Review in 2006. These were updated periodically and a new edition was prepared in 2012.[17] The project science requirements were closely linked to the science book and were reviewed as part of the system PDR, as were the system level requirements. The traceability of the science requirements to the science book and the system requirements to the science requirements has been documented and captured in a requirements management tool.

As the project moves into final design and fabrication the system and subsystem level requirements are under review and revision for inclusion in fabrication and design-build contracting documents. The level of sophistication and completeness are being improved, as are the underlying analyses that support the system and subsystem requirements and the connection to the science requirements.

The current in-house design and analysis work is focused on supporting critical decisions on the major systems and design of smaller subsystems that are most efficiently carried out by the project office. The large procurements will be contracted competitively worldwide. Procurement packages are being sequenced to support the integrated baseline schedule and project cash-flow profile.

3. TELESCOPE DESIGN STATUS

Papers in these proceedings by Johns et al.[18], Sheehan et al.,[19] and others have described the design of the telescope mount, bearings, drives and other subsystems. The structure follows the design developed by Gunnels, Shectman, Johns and others and is a compact Alt-Az configuration using large “C-ring” elevation bearings and a dual azimuth track. Balancing the loads and maintaining the oil thickness on a structure as large as the GMT offers significant challenges to the design team. The design of the GMT hydrostatic bearings follows the heritage of the Magellan telescope bearing system and is described in Gunnels et al.[20]

The primary mirror cells[21] are integral to the structure and provide some of the overall stiffness of the mount. They are deep enough to allow access by support personnel as their high elevation above the observing floor makes access through other means challenging.

One of the key elements of the GMT design is the highly optimized secondary support truss. This structural element is configured to avoid the beam path to the primary mirror segments and to provide maximum stiffness with minimal thermal mass. The braced hexapod structure has been highly optimized for stiffness and the top-end structure has been configured to reduce focal plane motion in response to gravity- and wind-induced deflections in the secondary support structure. A large number of configurations were analyzed in detail. Additional optimization work is underway in this area.

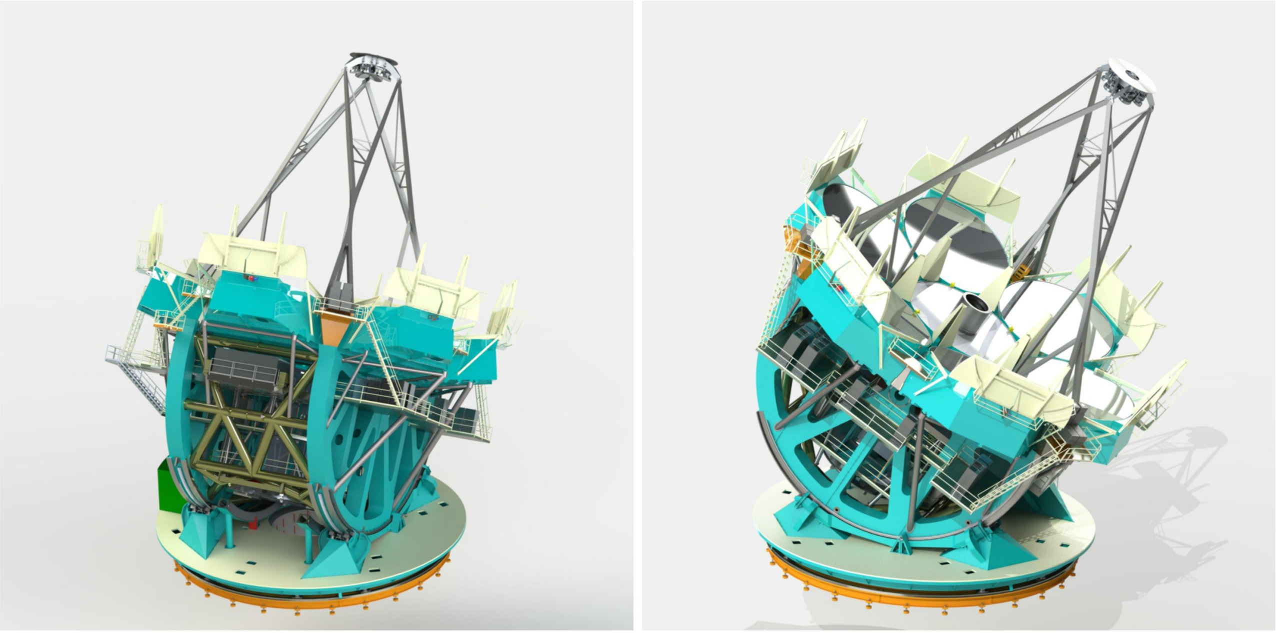

Figure 1. Two views of the telescope structure showing the azimuth track and disk, C-rings, mirror cells and truss.

One significant design concern relates to the response of the mount to seismic disturbances and the large amplifications of accelerations with increasing height within the structure. The unprecedented scale of the extremely large telescope structures and their location in seismically active regions, particularly in Chile, has led to renewed attention to dynamic response to ground accelerations and the amplification of these within the structure. Amplification factors at the level of the primary and secondary mirror are expected to be quite large (factors of 3-10).[22] Under maximum expected earthquake conditions predicted accelerations at the M1 and M2 levels on GMT within the structure reach 3-5g. The GMT design team, working with recognized experts in seismic isolation, is investigating options for isolation, damping, and other approaches to manage the risk to the optics and other elements of the structure during strong seismic events.

While the issues described above are resolved we are developing the procurement documents for the telescope detailed design and fabrication contracting process. A request for proposals will be released in late 2016. The schedule for the telescope fabrication and assembly in the context of the overall project schedule is considered in section 9 of this report.

4. PRIMARY MIRROR PRODUCTION STATUS

Production of the primary mirror segments is one of the pace setting items for the GMT project. The highly aspheric nature of the off-axis segments and tight tolerance on the radius was recognized as the highest technical risk at the start of the project. For this reason, the first off-axis segment was cast in 2005. Development of the necessary infrastructure and the perfection of the testing and polishing techniques required a significant investment of time and resources. The first segment was completed and accepted in 2012. The mirror meets all of its specifications, including the radius of curvature.[23] A number of independent tests were developed to ensure that the mirror figure meets its specifications. These include an enhanced laser tracker test,[24] a scanning pentaprism,[25] and the "Software Configurable Optical Test" (SCOTS). [26]

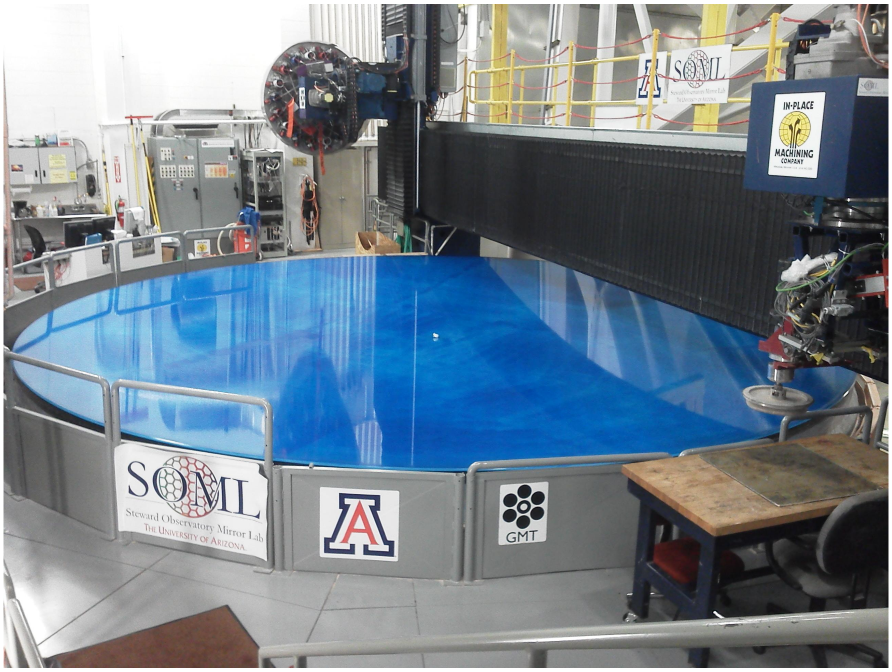

Figure 2. The first GMT primary mirror segment covered with a protective film following acceptance. The rms surface error is 19nm over the clear aperture.

The second off-axis segment was cast in January 2010. The high temperature phase of the casting process went smoothly and the mirror blank contains no significant flaws. The rear surface of this mirror has been fully processed and the load-spreaders needed for support in both the polishing cell and telescope cell have been attached. Polishing of S2 has been slowed due to other contracted work within the mirror lab. The LSST compound M1/M3 mirror was polished following GMT S1. The LSST mirror was challenging due to its compound nature and schedule delays were encountered in getting this mirror to acceptance. The Arizona mirror lab also processed a 6.5m on-axis mirror similar to the Magellan and MMT mirrors following the LSST and this mirror has also experienced some schedule delays. For these reasons GMT S2 is behind its nominal schedule. At the time of this conference the mirror is on the Large Optics Generator (LOG) at the mirror lab and generation of the front surface should be underway.

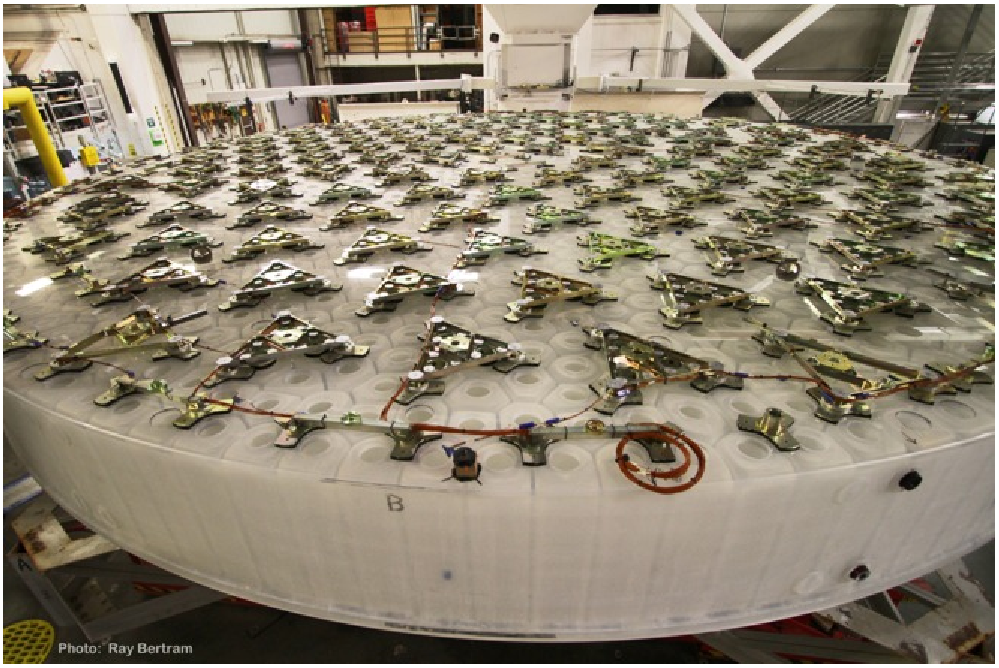

Figure 3. The second GMT off-axis mirror segment, face down, with the load spreaders for the support system attached.

The third GMT mirror segment, also an off-axis mirror, was cast in august of 2013. This mirror has also been processed through the clean out and rear surface generating and polishing phases. The load spreaders will be attached in the coming months and front-surface generation will follow generation of the segment 2 front surface and segment 4 rear surface.

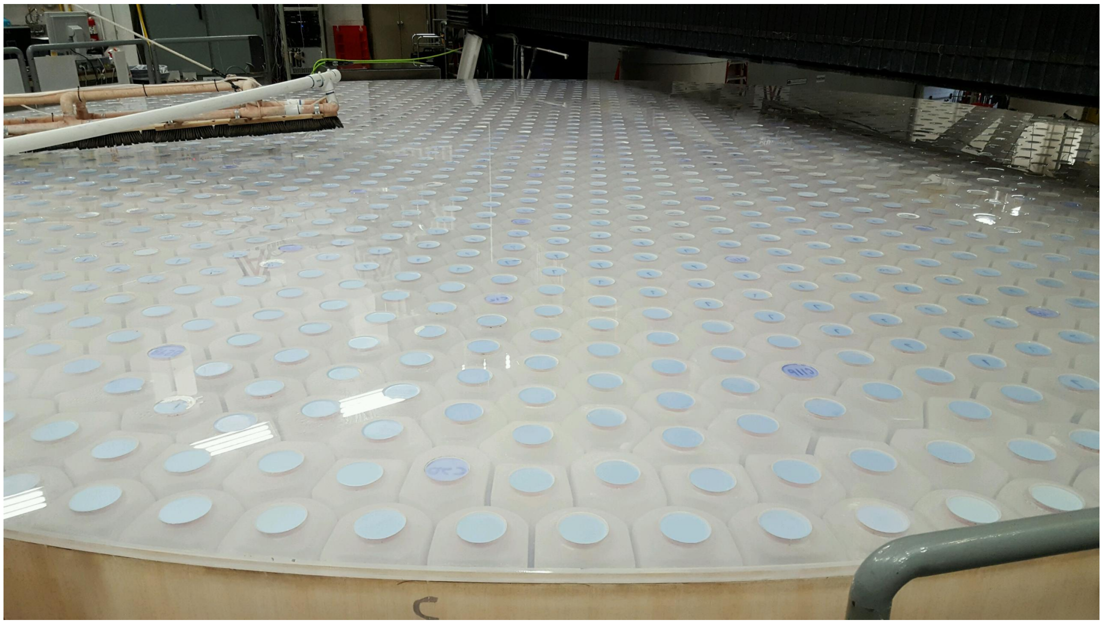

Figure 4. Primary mirror segment 3 following completion of rear surface polishing.

The fourth mirror segment, the central segment, was cast in September 2015. This mirror poses some unique challenges in casting, handling, testing and polishing. The mirror has the largest central hole of any mirror cast at the University of Arizona and is thinner than previous on-axis 8.4m mirrors. Extensive analysis of the structural properties of the mirror during the casting, lifting and polishing phases were conducted before the mold geometry was finalized. The high temperature casting went smoothly and the mirror was lifted from the furnace in December of 2015. The mirror blank has been cleaned and inspected. Further processing of the blank will continue as segments S2 and S3 move through the mirror lab.

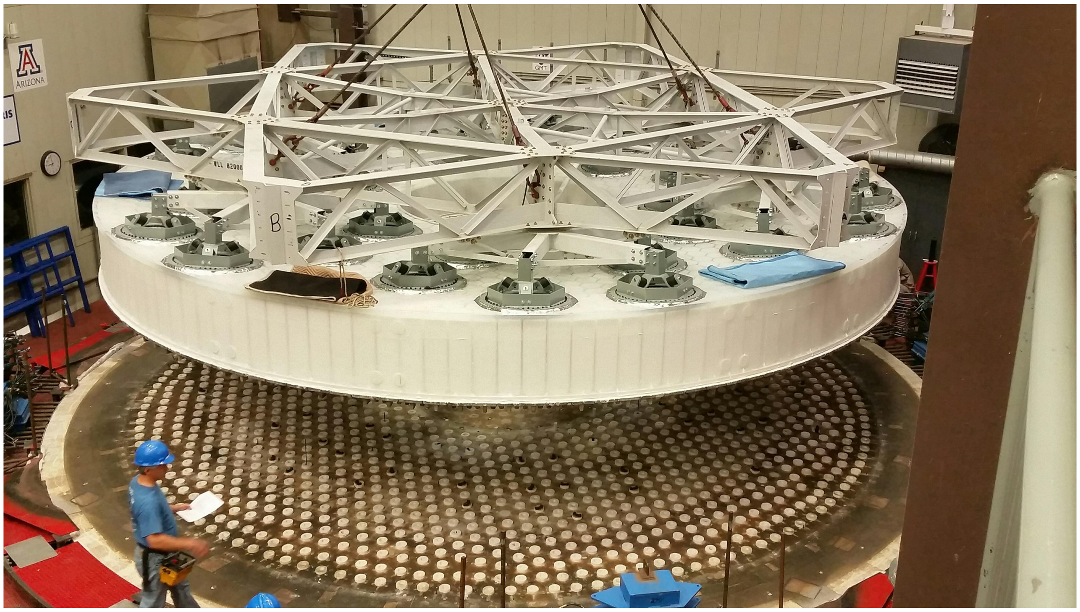

Figure 5. Primary mirror segment 4 being lifted off the furnace hearth at the Arizona mirror lab.

The decision to produce the central segment between the first three and last three of the off-axis segments was driven by the project staging plan. As is described in section 7, we expect to have the telescope mount erected within the enclosure on site before completion of all seven primary mirror segments. Commissioning activities can begin with a subset of the primary mirror segments. Alignment of the optical system will proceed more easily with the central segment in place. Figuring the central segment in the middle of the production of the off-axis segments has schedule implications as the test tower must be reconfigured for the on-axis test.

The glass for the GMT primary mirror segments is produced by the Ohara Corporation of Japan in small batches. The University of Arizona mirror laboratory is one of the largest consumers of Ohara E6 low expansion glass. The lead-time for producing the 20,000 kg needed to produce a single GMT mirror segment is approximately 12 months and interruptions in the production can lead to costly delays and restarts. For this reason, GMTO has secured the glass at a steady rate. At the time of this writing 75% of the glass needed to cast GMT segment 5 has been delivered to Arizona and the remaining glass will be delivered in August 2016. The E6 glass for segment 6 is on order and deliveries will begin in late 2016. An order for the glass for segment 7 will likely be placed in late 2016 or early 2017. This removes the only significant supply risk for the production of the primary mirrors.

5. ADAPTIVE OPTICS AND WAVEFRONT CONTROL

Like all of the extremely large telescopes under development and many of the 8-10m class telescopes, GMT will use a number of wavefront control feedback loops that operate on different time scales. The active optics system that maintains the primary mirror figure, focus and collimation of the telescope builds on the legacy of the Magellan system.[27] The adaptive optics system for GMT has been described by Bouchez et al.[28] It is based on a segmented adaptive secondary mirror and both natural guide star and laser guider star wavefront sensors. Adaptive optics correction will be available to every instruments when the adaptive secondary is installed, using either the telescope guiders for ground-layer correction, or instrument wavefront sensors in the diffraction-limited observing modes.

Development of the adaptive secondary mirror designs has proceeded in close coordination with the AdOptica consortium. At this time GMTO is in the process of finalizing the design and constructing subscale prototypes with the goal of being prepared to enter directly into production when the project schedule calls for this step. AdOptica and GMTO are completing the final design of the electronics for the adaptive mirrors based on designs developed during previous studies. A subscale prototype mirror with 72 actuators will allow full characterization of the actuator and electronics performance. A final mechanical design study will complete the design suite for the adaptive secondary mirrors.

Phasing the primary mirror array is one of the primary technical challenges for the GMT. Some key science areas that call for the highest contrast imaging (e.g. exoplanet detection) are centered on bright stars. Phasing the telescope in these situations is straight forward. Phasing the telescope on high galactic-latitude targets (e.g. galaxies) where bright natural guide stars are less common is more challenging. Our approach to phasing the telescope has been described in a number of publications. [16, 29] An initial prototype phasing sensor using an aperture mask that matched the pupil geometry of the GMT coupled to an infrared wavefront sensor was demonstrated on the Magellan telescopes in 2012. This prototype demonstrated the basic concept and showed that the sensor has sufficient sensitivity in realistic turbulence conditions. A simplified design using a low-noise, fast framerate visible light detector was deployed and tested on the Magellan telescopes in 2015.

6. SCIENTIFIC INSTRUMENTS

The scope of the GMT project includes design and fabrication of a first generation suite of scientific instruments. GMTO openly solicited proposals for concepts for first generation instruments early in the preliminary design phase. Several of these were selected for conceptual design development and a subset of these were selected for further design work or technology development following independent reviews of each instrument. An independent panel of scientists drawn from within the GMT partnership and the astronomical community at large reviewed the candidate instruments in the context of the GMT science goals and the telescope design before making their recommendation.

The diversity of instruments considered and those under development has been discussed in past SPIE conferences by Jacoby et al.,[30, 31, 32] and is also discussed in the current proceedings.[33]

At this time GMTO is supporting a number of instruments at different stages in the development cycle. The G-CLEF high-resolution optical spectrograph [34, 35, 36] passed a preliminary design review in 2015 and is on track to complete a critical design review in early 2017. This spectrograph is targeted at exoplanet research but will also enable fundamental work in stellar astrophysics, stellar and interstellar chemistry, galaxy evolution and cosmology. This instrument is being developed by a team at the Harvard-Smithsonian Center for Astrophysics with collaborators at several other institutions and builds on the HARPS North precision radial velocity spectrograph deployed on the Galileo National Telescope. [37]

A team at the Australian National University is developing an adaptive optics-fed integral field spectrograph and diffraction-limited imager for GMT that builds on the heritage of the NIFS and GSAOI AO-fed instruments at Gemini. The GMTIFS instrument is in the preliminary design phase and is on schedule for a preliminary design review in early 2017.

The principal survey spectrograph under development for GMT, GMACS, has been described in past proceedings along with the design trades under consideration at the time.[38] Most of these design trades have been resolved and a team at Texas A&M University is developing a design based on a single spatial channel with dual red and blue cameras. The instrument mounts at the direct Gregorian focus but will be sized so as to not require the wide-field corrector.

The power of the GMT spectrographs can be enhanced through additional multiplexing with the GMT facility fiber system, MANIFEST.[39] Self-motile fiber heads, “Starbugs”, patrol the full corrected focal plane on a curved glass plate. Multiplex gains as high as ~5-10 compared to the multi-slit approach are possible when coupled to the GMACS spectrograph and on the order of 25 targets are possible with the G-CLEF echelle spectrograph. TAIPAN, a forerunner of MANIFEST is being deployed on the UK Schmidt telescope[40] using the Starbug technology.

The University of Texas at Austin and the Korea Astronomy and Space Science Institute are developing technology to support the GMT Near-IR high-resolution Spectrograph (GMTNIRS). The instrument uses silicon immersion gratings and builds on a number of forerunner instruments, the most recent of which is IGRINS.[41] The first gratings for GMTNIRS have been completed at UT Austin and meet their design requirements.

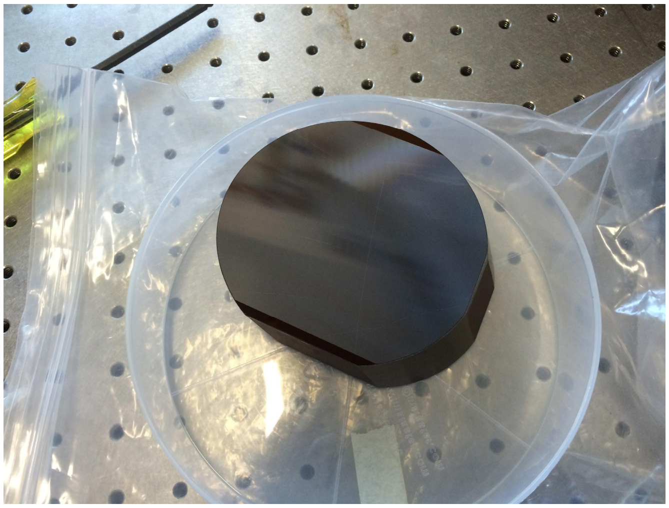

Figure 6. Etched K-band Silicon immersion grating for the GMTNIRS spectrograph before final cutting and processing.

7. ENCLOSURE DESIGN

The design of the GMT enclosure has been reviewed by Teran et al.[42] GMT adopted a cylindrical carousel design early in the project after consideration of a wide variety of architectures. Wind tunnel tests and simple CFD studies validated the design and led to some degree of optimization of the structure during the preliminary design phase.

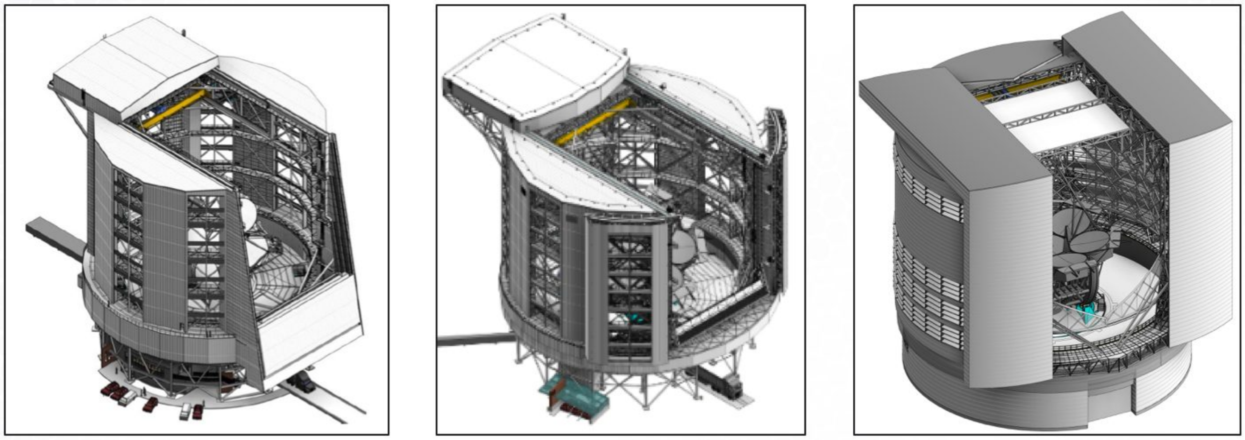

Figure 7. Evolution in concepts for the GMT enclosure. The basic carousel concept has remained, but a variety of approaches to the shutter doors and lower enclosure have been considered.

Following the enclosure preliminary design review in 2013 a number of design modifications have been explored. These involve changes to the enclosure shutters, bogies, vent doors and other elements of the structure.[43, 44] A delta PDR was held in 2014 and these changes were viewed favorably and the baseline design currently includes shutters that move horizontally as opposed to the large vertical shutter door that formed the entrance aperture in the early design. The transition to a form of bi-parting horizontal doors requires an independent windscreen as the previous upper and lower vertical doors served this function. We have developed a sliding windscreen concept that meets our requirements and shields the telescope from the wind while allowing attenuated airflow into the enclosure.

There are a number of design trades that remain open before the enclosure and summit facilities designs can be finalized. Detailed CFD studies of airflow over the summit and around the enclosure that provide input data into these trade studies are described in these proceedings.[45, 46]

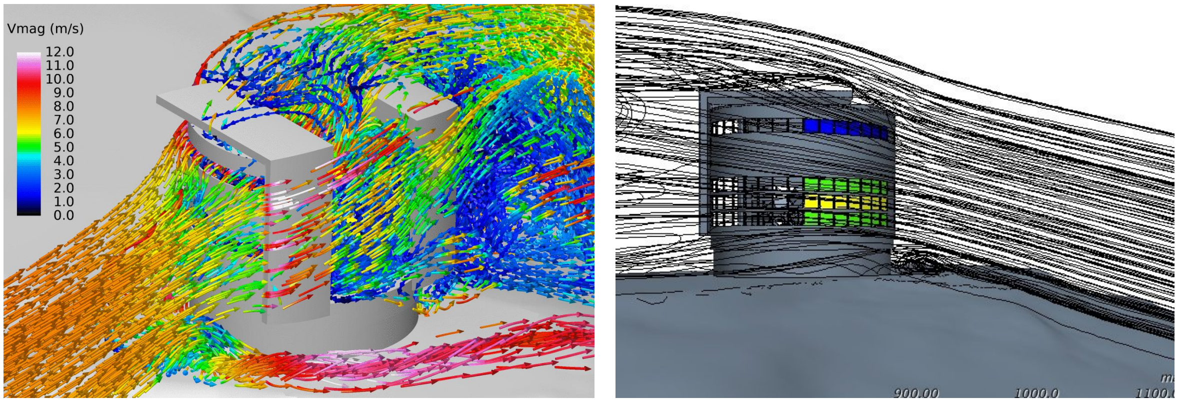

Figure 8. Flow lines around the enclosure in the 90 degree cross-wind case (left) and down-wind pointing (right). Both geometries use a closed lower enclosure and show necklace vortices below the observing level. These figures come from CFD studies by Boeing (left) as reported in Ladd et al.[45] and RWDI (right) as reported in Danks et al.[46]

Figure 9. Instrumentation towers at the GMT site. These host the scintillometer that is being used to characterize the ground-layer turbulence, weather stations, and cameras that will monitor and record construction.

In addition to the CFD modeling we are conducting in situ measurements of the airflow over the summit and the turbulence profile above the baseline enclosure site. LIDAR provides direct measurement of the wind flow pattern over the site and the wind speed at critical elevations. The LIDAR measurements agree well with the CFD models in the basic properties of the airflow. A laser scintillometer measures the turbulence profile between the two towers at a range of heights above the ground. With the transmitter near one tower, pairs of mirrors send the beam horizontally from one tower to the other and then down to the receiver.

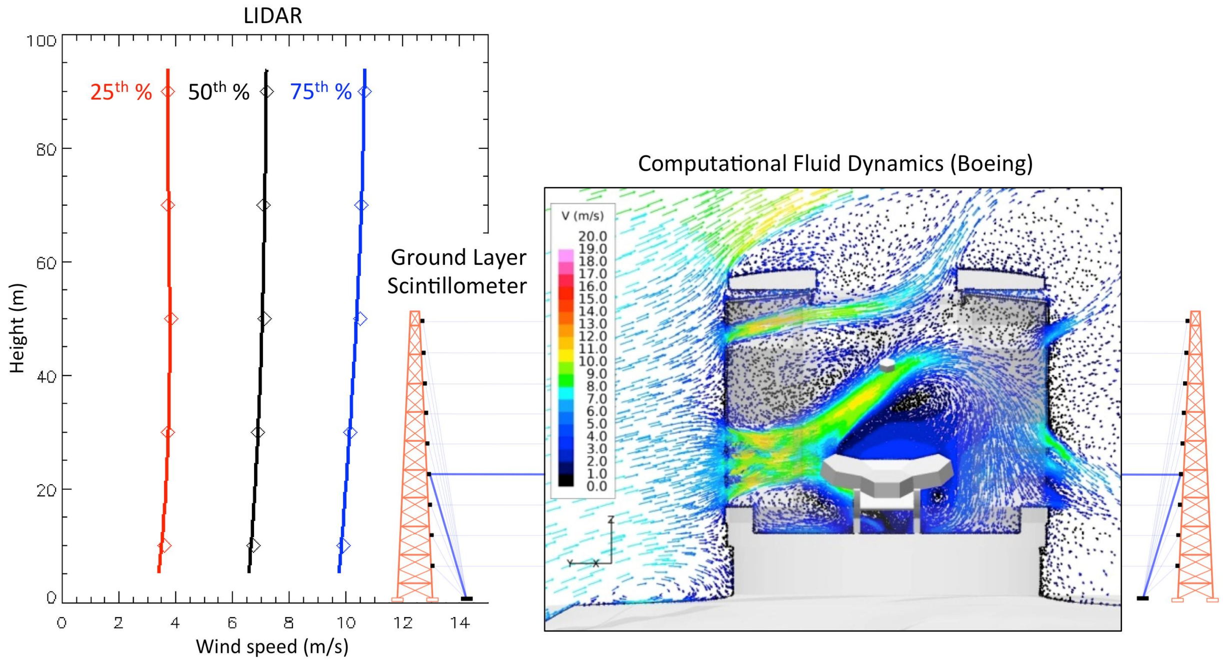

Figure 10. Geometry of the site wind flow measurement program compared to the enclosure. (Left) Wind profile measured in 25th, 50th, and 75th percentile conditions. (Center, Right) Ground layer scintillometer layout. (Right) Wind flow through dome vents from computational fluid dynamics simulations. The LIDAR and scintillometer measure the wind speed, direction and turbulence at critical levels of the telescope and enclosure structure.

8. SITE INFRASTRUCTURE

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. A multi-year site survey was conducted during which several sites were characterized and compared with the site of the 6.5m telescopes.[47, 48] The selected site, Las Campanas Peak, was leveled in 2012 and since that time the basic infrastructure at the site has been under development.

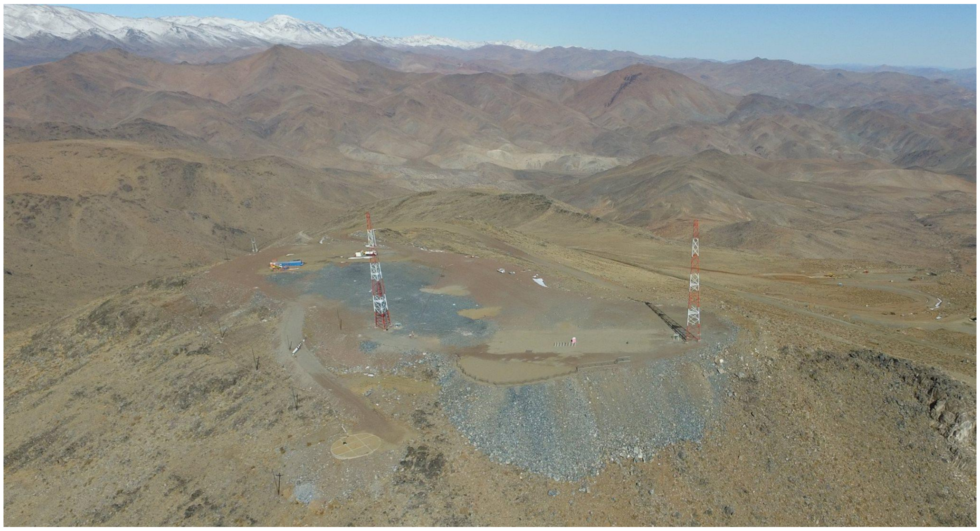

Figure 11. The GMT site seen from the air looking east in March 2016.

In addition to the site development work at the summit, the project team has been developing the infrastructure needed to support the construction and operations team and the transportation of large components and construction material to the site. The road to the summit has been widened and the slopes adjusted to not exceed 10%. Construction pads for two off-summit support sites have been leveled and the housing units are being fabricated in Santiago. They will be installed on site in July-August and should be fully operational in October of 2016. The residence consists of 90 rooms plus commissary and recreation areas. Up to 200 personnel can be supported on site with this facility.

Power is provided to the summit and support sites via an overland connection to Carnegie's power system on the northern side of the Las Campanas Observatory. This supply will support construction on the summit and operation of the residence and construction offices. Before the start of operations the power lines will be rerouted to an alternate supplier capable of providing the power capacity needed for operations.

9. PROJECT STAGING AND SCHEDULE

The GMT project is structured to allow staged implementation. The telescope can be operated in a seeing-limited mode before all of the adaptive optics system hardware has been installed and commissioned. It can operate in the seeing-limited mode with a subset of the primary mirrors. Commissioning the facility in this staged approach will allow us to address a limited set of technical challenges at any time and will retire risk in a sequential fashion. The three stages outlined in the GMT construction proposal are:

> Stage 1: Seeing-limited operations with a subset of the primary mirrors and two visible-light instruments. Most of the basic observatory infrastructure will be developed during this stage.
>
> Stage 2: Completed primary mirror array with seeing-limited operations. During this stage the first adaptive secondary mirrors will be developed and calibrated in the lab.
>
> Stage 3: Completed adaptive optics systems and full suite of first-generation science instruments. This constitutes the full scope of the project.

The project stages overlap in time to a considerable degree. They are intended to allow the stakeholders to manage financial commitments and for the project to address technical and schedule risks sequentially to a greater degree than would be possible if the entire suite of capabilities were to be commissioned at once.

We are reviewing our staging plan and may make adjustments to the timing and sequencing of some subsystems and capabilities.

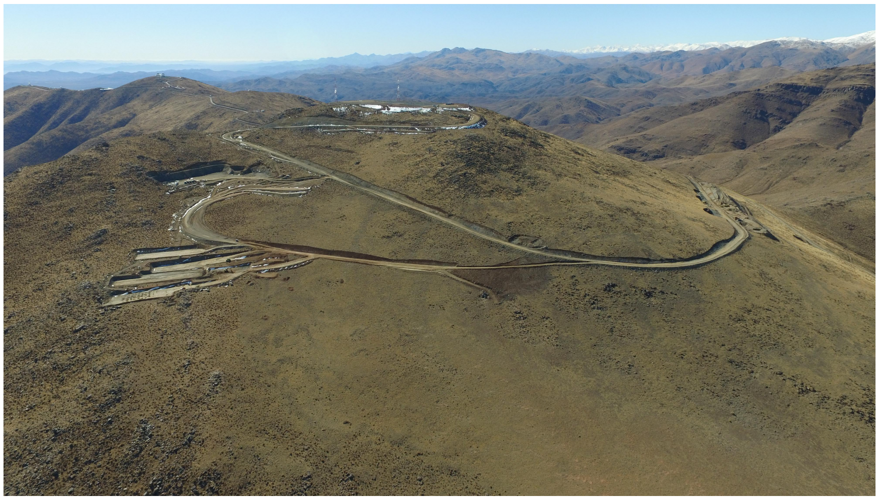

Figure 12. The GMT site in June 2016, from the south showing grading work on the two off-summit support sites at the left.

The summary schedule for the project shown in Figure 13 tracks the primary and secondary mirrors, the telescope structure, construction of the enclosure and other key subsystems. The critical path to first-light runs through the primary mirror cells and the telescope structure. First light could occur with four primary mirrors as early as late 2022; completion of the primary mirror array is projected for late 2024 or early 2025. The critical path to completion of the project runs through the adaptive secondary mirrors and commissioning of the adaptive optics system.

This schedule is purely technically driven; funding issues could lead to a stretch in the schedule. The schedule below is a critical path schedule and does not contain any top-level schedule margin. Some of the elements that are most susceptible to schedule delays (e.g. science instruments) are not coupled to the critical path, while others, such as the adaptive secondary mirrors are on the critical path.

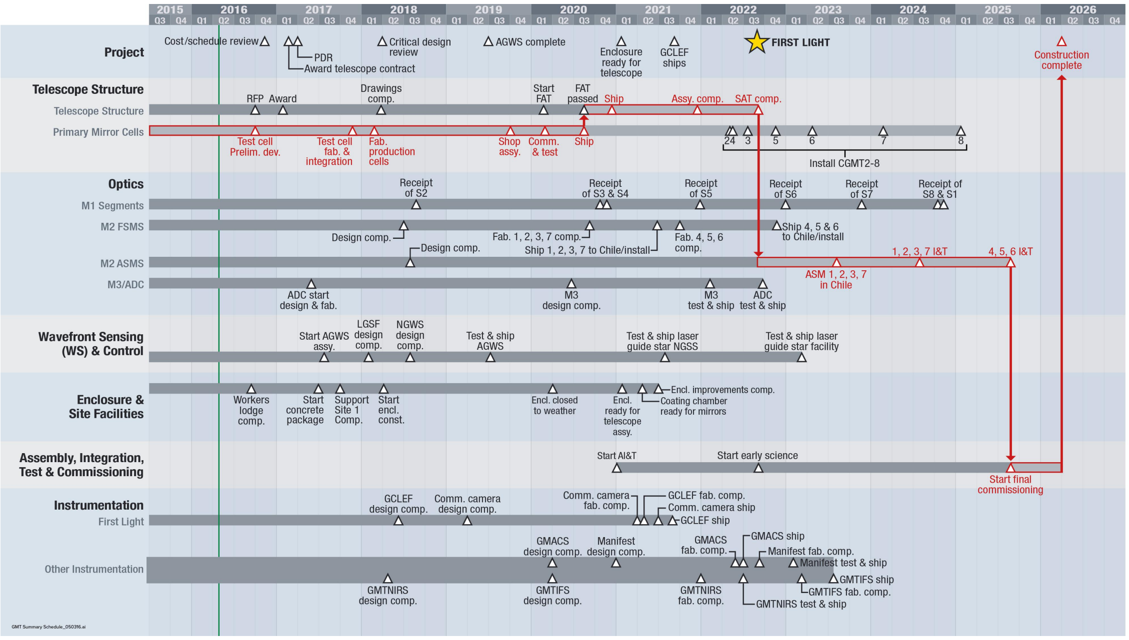

Figure 13. Summary schedule for the GMT Project.

10. SUMMARY

The GMT project is nearly one year into the construction phase. The project is making steady progress in the production of the primary mirrors while advancing other areas of the project through detailed design, subscale prototyping and analysis. The essential infrastructure at the site needed to support construction is nearing completion and will be ready for major activities in 2017.

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