The Giant Magellan Telescope AO Program

A.H. Bouchez[1,a]

[1]Giant Magellan Telescope Organization, 251 S. Lake Ave., Pasadena, CA 91024, USA

Abstract. The Giant Magellan Telescope adaptive optics system will be an integral part of the telescope, providing laser guide star generation, wavefront sensing, and wavefront correction to most of the currently envisioned instruments. The system will provide three observing modes: Natural Guidestar AO, Laser Tomographic AO, and Ground Layer AO. All three modes will use the telescope's segmented adaptive secondary mirror to deliver a corrected beam directly to the instrument foci. We will describe the system requirements, overall architecture, and innovative solutions found to the challenges presented by high-order AO on a segmented extremely large telescope. The GMT AO system is currently in the preliminary design phase, and is expected to see first light in 2020.

1. Introduction

The Giant Magellan Telescope (GMT) is a 25.4 m diameter ground-based optical and infrared telescope being developed by a consortium of universities, research institutions, and national governments [1]. Some of the GMT's highest science priorities require adaptive optics (AO) observing modes, which can provide improved spatial resolution, sensitivity, and contrast over that allowed by natural seeing. Adaptive optics on extremely large telescopes is very challenging, however, as the alignment and vibration tolerances become tighter with the smaller diffraction limit, and the required number of actuators, wavefront sensor subapertures, and guidestars increases. The GMT AO performance requirements have deliberately been kept somewhat less ambitious than those of other extremely large telescope projects, and a comparatively simple and cost-effective AO system design can meet those requirements.

This paper begins with a brief description of the GMT and its proposed instrument suite. Section 3 presents the AO system performance requirements, and Section 4 describes the major AO subsystems. Section 5 describes our approach to phasing the doubly-segmented telescope. Sections 6 and 7 describe the AO control system design, and the design of the AO integration and testing facility. Finally, we conclude with an update on the GMT project schedule.

[a] e-mail : abouchez@gmto.org

2. The Giant Magellan Telescope

2.1. Telescope Design

The GMT has a Gregorian optical design, with an f/0.7 primary mirror composed of 7 8.4 m diameter circular segments, and an identically segmented concave secondary mirror. The area of the primary mirror is equivalent to that of a 21.9 m filled circular aperture with the same central obscuration. The huge primary mirror segments are spin-cast of borosilicate glass at the Steward Observatory Mirror Lab at the University of Arizona. The figuring and polishing of these segments is a challenging process, as the aspheric departure of the off-axis segments is several centimeters. Nevertheless, the first off-axis segment is nearing completion, while the second was cast in January 2012. Raw materials for the third and fourth have been ordered. The production of the primary mirror segments forms the critical path to the first light of the telescope, and completion of the 7th segment is expected in 2022.

The optics are actively supported in a compact alt-azimuth steel telescope structure which, including its 12 m high concrete pier, has a mass of 1,125 metric tons and a lowest resonant frequency of 4.5 Hz. A large enclosure surrounds the telescope and protects it from wind disturbance and inclement weather. Many aspects of the telescope, enclosure, and facilities are based on the design of the twin 6.5 m diameter Magellan telescopes at Las Campanas Observatory.

Fig. 1 : *(Left)* Rendering of the Giant Magellan Telescope on its pier. *(Right)* The first off-axis GMT primary mirror segment on the polishing table at the Steward Observatory Mirror Lab.

2.2. Instruments

Conceptual design studies for 6 instruments were recently completed, and the selection of a first-generation suite composed of 2 to 4 of these will be made in March 2012 (see Fig. 2). Three are diffraction-limited AO instruments (TIGER, GMTNIRS, and GMTIFS), while NIRMOS is a wide-field infrared imager and spectrograph which uses ground-layer AO (GLAO) image quality improvement. In addition to these instruments, a multi-instrument fiber-feed system (MANIFEST) which may benefit from GLAO correction has also been proposed. The instruments are all mounted on a single large mechanical rotator, with narrow-field instruments fed by a tertiary mirror on its upper surface while wide-field instruments are located below and translated to the direct Gregorian focus.

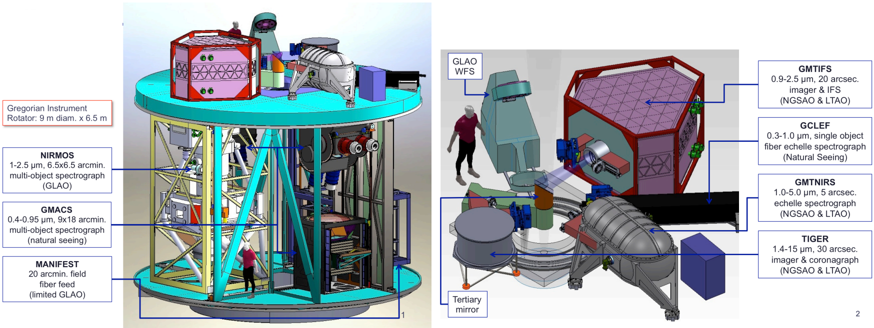

Fig. 2 : *(Left)* Proposed GMT wide-field instruments, mounted in the Gregorian Instrument Rotator (GIR). *(Right)* Proposed GMT narrow-field instruments and other components mounted on the upper surface of the GIR.

2.3. Site

The GMT will be built on Cerro Las Campanas at 2,525 m altitude, the highest telescope site at Las Campanas Observatory in Chile. The site is well characterized and has extremely good seeing (median r_0=16.4 cm) and weather statistics (photometric conditions 64% of the time). Site clearance work to create a 300 m × 100 m platform sufficiently large to accommodate two GMT-sized telescope began in February 2012.

Table 1 : GMT AO observing modes and performance requirements.

Mode	Description and Performance Requirements
Natural Guide Star AO (NGSAO)	High Strehl over a narrow field of view using bright guide stars. SCI1883: >75% K Strehl for R<8 stars. SCI1882: >10^5 contrast at 4λ/D in L' band (goal: 10^6 at 2λ/D)
Laser Tomography AO (LTAO)	Moderate Strehl over narrow field of view with high sky coverage SCI1884: >30% H Strehl over 20% of sky near the galactic pole. SCI1885: >40% K ensquared energy in 50x50 mas over 50% of sky near the galactic pole. SCI1886: >50% K ensquared energy in 85x85 mas with K=15 on-axis NGS.
Ground Layer AO (GLAO)	Seeing improvement over a large field of view SCI1887: >0.30 arcsec image FWHM at K band over >6.5 arcmin.

3. AO Requirements

The GMT AO system will support 3 operating modes, listed with their top-level performance requirements in Table 1. Each challenges the current state-of-the-art in a different way. The NGSAO mode must provide very high-order correction and low calibration errors, leading to tight alignment tolerances and a design which minimizes the number of optical surfaces. The LTAO mode must provide high sky coverage in the presence of significant wind-induced structural vibration, requiring AO-corrected tip-tilt reference stars. Finally, the GLAO mode must provide image improvement over a particularly large field of view (>40 cm in the focal plane), requiring challenging optics.

4. AO System Design

4.1. Design Overview

The GMT AO system design is based on an adaptive secondary mirror (ASM), and wavefront sensors assemblies replicated for each instrument [2]. All narrow-field AO instruments (those using the NGSAO and LTAO observing modes) are located at a folded Gregorian focus provided by a steerable tertiary mirror. Each instrument cryostat window is a long-pass dichroic, and all visible-light wavefront sensing (LGS and NGS) is performed in the beam reflected by the window. Having eliminated the common « AO relay », this design provides very high throughput and low emissivity, with only 3 optical surfaces between the sky and the science instrument. Fig. 3 shows a block diagram of the NGSAO and LTAO observing modes.

The GLAO observing mode is only used by wide-field instruments which can be translated to the direct Gregorian focus. The AO system therefore provides a single GLAO wavefront sensing assembly, intercepting laser guidestars and natural guidestars with a large dichroic and pick-off mirrors ahead of the instrument entrance window.

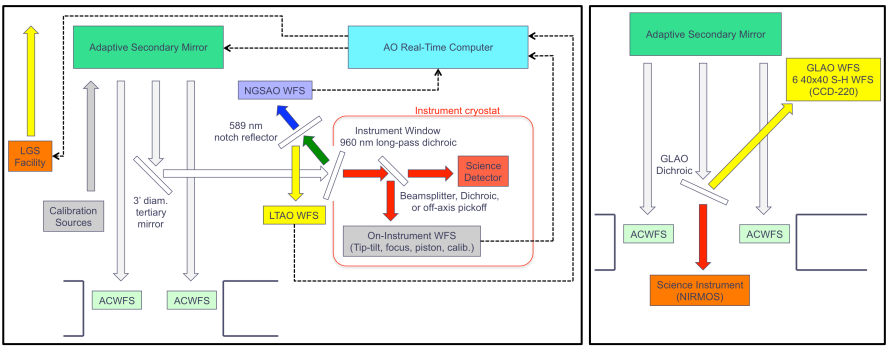

Fig. 3 : *(Left)* Block diagram of the NGSAO and LTAO modes. Light paths are shown with wide arrows, control signals with dashed arrows. *(Right)* Block diagram of the GLAO mode.

4.2. Adaptive Secondary Mirror

The GMT AO system is an integral part of the telescope, being based on an adaptive secondary mirror (ASM). The segmented design of the GMT leads to specifications for each segment of the ASM which are very similar to those of present-generation telescopes (eg. LBT and VLT). The design of the GMT ASM, based on a Phase A study by ADS International and Microgate Corp., is illustrated in Fig. 4. Each 1.04 m diameter segment has 672 voice coil actuators (4704 total), actuating a 2 mm thick zerodur face sheet at up to 1 kHz update rate. Capacitive sensors maintain the shape of the face sheet with respect to a lightweighted Zerodur reference body with ~5 nm precision. The actuators are coupled magnetically to the face sheet, leading to the very desirable property that failed actuators exert no force and can be removed from the control with little reduction in performance.

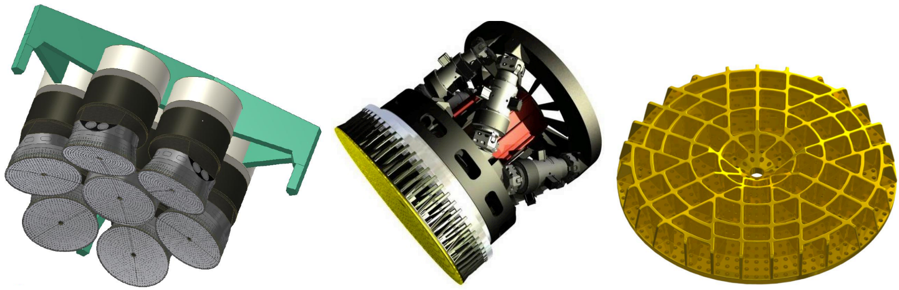

Fig. 4 : Renderings of the GMT adaptive secondary mirror. *(Left)* The 7-segment assembly. *(Center)* The center segment with wind shield removed. *(Right)* The lightweighted Zerodur reference body.

4.3. Laser Guidestar Facility

High-order wavefront sensing in the LTAO and GLAO observing modes will be provided by 6 sodium laser guidestars. We performed an extensive trade study comparing the expected performance of on-axis and off-axis LGS launch architectures [3,4]. We concluded that the additional readout noise due to the greater elongation in the off-axis case was compensated by the fact that each wavefront sensor observes the LGS elongated in a different direction at a given location in the pupil. Slowly-varying calibration errors due to changes in the structure of the sodium layer, which are amplified by greater elongation, can be mitigated by measuring centroids with a larger number of pixels in each wavefront sensor subaperture. In the absence of a significant performance penalty, we selected the off-axis launch architecture because it allows a huge simplification in the design of the beam transfer and launch systems. Thus our baseline design uses six 20 Watt Raman fiber lasers to be coupled directly to six 38 cm refractive launch telescopes, located at the ends of the stiff primary mirror cell connector frame (Fig. 5). The laser and launch telescope designs follow closely the Very Large Telescope AO Facility design [5].

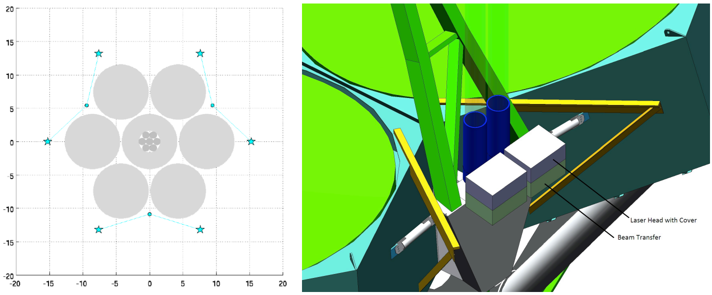

Fig. 5 : *(Left)* Schematic of the 3 launch locations and 6 laser guidestars, projected onto the pupil. Scale is in meters. *(Right)* Conceptual layout of two of the 6 Raman fiber lasers heads and refractive launch telescopes.

4.4. Natural Guidestar Wavefront Sensor

Wavefront sensing in the NGSAO mode wil be provided by a 90×90 pyramid natural guidestar wavefront sensor (NGSAO WFS, see Fig. 6) closely based on the LBT First-Light AO system design [6]. The pupil sampling matches the average actuator density of the ASM, leading to an atmospheric fitting error of ~70 nm RMS for bright stars in median conditions. The NGSAO WFS includes an atmospheric dispersion corrector, modulation of the image on the pyramid using a tip-tilt mirror, and a K-mirror rotator and pupil steering optic to stabilize the pupil on the E2V CCD-220 detector. The sensor has a 180 arcsecond diameter unvignetted patrol field.

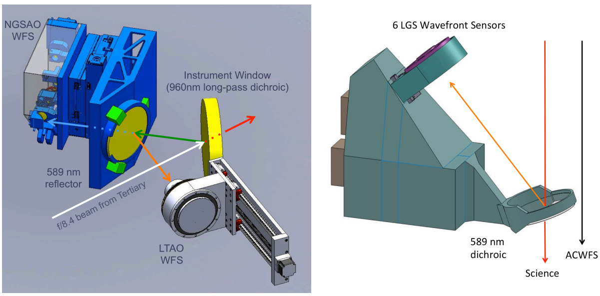

Fig. 6 : *(Left)* Conceptual design of the wavefront sensor assembly supported by each NGSAO and LTAO instrument. It houses the NGSAO WFS (blue), LTAO WFS (gray), and calibration sources (not show). *(Right)* Conceptual design of the ground-layer AO wavefront sensor assembly.

4.5. Laser Tomography Wavefront Sensor

The laser tomography wavefront sensor (LTAO WFS) will provide high-order wavefront sensing in the LTAO observing mode. It consists of 6 50×50 Shack-Hartmann wavefront sensors co-mounted in a rotation bearing and on a long-travel focus stage to track the LGS asterism, which remains fixed with respect to the telescope pupil and change in range from 80 to 200 km. The design uses 840×840 low-noise CMOS detectors currently under development by E2V to provide 10×10 pixels and a field of view of 7 arcsecond in each subaperture. The detectors will be read out at 500-800 Hz framerate, depending on sodium layer conditions.

4.6. On-Instrument Wavefront Sensor

An infrared on-instrument wavefront sensor (OIWFS) housed within each science instrument is the sole natural guidestar sensor required for the LTAO observing mode. Its design is modular to accommodate instruments requiring only on-axis LTAO reference stars (TIGER and GMTNIRS) and off-axis guidestars (GMTIFS). The off-axis version includes a 489-actuator micro-electro-mechanical (MEMS) deformable mirror to compensate anisoplanatism for guidestars located more than 30 arcseconds from the science target. This MEMS DM is controlled in open-loop, using an independent tomographic reconstruction. The OIWFS will consist of a simple tip-tilt guider operating in the K band, and an infrared pyramid wavefront sensor operating in the H band. The pyarmid WFS chanel will measure focus and higher-order wavefront errors including segment piston at 1-10 Hz.

Stars as faint as K=19 can be used to for tip-tilt, focus, and high-order calibration, over a 180 arcsecond diameter unvignetted field of view. Detailed performance simulations with randomly-generated starfields indicate that this design should easily meet the LTAO performance requirements, providing >90% sky coverage at the galactic pole for AO spectroscopy with large (50 mas) spaxels and diffraction-limited performance to J band with more modest sky coverage [3].

4.7. Ground Layer Wavefront Sensor

A facility wavefront sensing assembly can be deployed ahead of any of the wide-field instruments located at the direct Gregorian focus. A 73 cm diameter dichroic reflects 589 nm light to an assembly consisting of 6 40×40 Shack-Hartmann wavefront sensors co-mounted in a rotation bearing and on a long-travel focus stage. Tip-tilt, focus, and calibration of quasi-static aberrations is performed using the facility active optics wavefront sensors (ACWFS), which patrol the anulus outside of the dichroic.

5. Segment Phasing

Achieving the diffraction limit of the 25.4 m GMT will require the primary and secondary mirrors to be phased to <50 nm RMS. Due to the large separation between primary segments (30-40 cm) and their construction of borosilicate, capacitive or inductive edge sensors alone are not expected to be sufficiently stable over timescales longer than a few minutes. In the NGSAO observing mode, the NGSAO WFS can sense and correct segment piston at up to 1 kHz. However, only faint natural guidestars are generally available in the LTAO mode. We have therefore designed a 3-stage phasing system consisting of a coarse optical phasing sensor with a large capture range to initially phase the telescope, primary and secondary mirror edge sensors to maintain alignment over short timescales, and a high-sensitivity optical sensor to correct long-term drifts in the edge sensors. Since the primary and secondary segments are matched one-to-one, errors can be rapidly compensated using the agile adaptive secondary mirror, then off-loaded to the primary or secondary segment positioning actuators as appropriate.

The coarse phasing sensor will be a dispersed Hartmann design, with 2 m subapertures spanning the 12 inter-segment gaps. The light from the two segments passing through each aperture interferes, forming fringes on a Hawaii-2RG detector in the K band. A grism disperses the fringes at low spectral resolution (R~60), increasing the sensor's capture range to ~100 μm. A prototype of the coarse phasing sensor in being integrated at the Smithsonian Astrophysical Observatory, and will be tested on the the Magellan Clay telescope in June 2012 (Fig. 7).

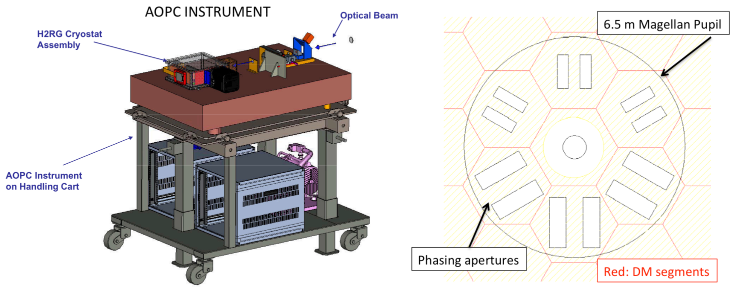

Fig. 7 : *(Left)* Prototype AO coarse phasing camera mechanical model. *(Right)* Layout of the phasing apertures on the Magellan Clay pupil.

The baseline design for the primary mirror edge sensors uses distance measuring interferometers to sense the relative motions of mirror segments due to structural flexure and wind buffeting. More compact capacitive sensors will be used to sense relative displacements between the adaptive secondary mirror reference bodies. These sensors will maintain the relative path length between segments to <50 nm RMS over periods up to ~5 minutes.

The OIWFS infrared pyramid channel will provide phasing feedback on longer timescales, forming the third component of the LTAO phasing system.

6. AO Controls Design

With a large number of wavefront sensors and a deformable mirror integrated into the telescope, the GMT AO system can greatly benefit from a distributed controls architecture. Each wavefront sensor will have associated with it a slope computer which converts pixel values into local wavefront slope measurements. The slope vectors will be transferred to a central real-time computer (RTC) using a commercial low-latency switching network such as Mellanox Infiniband. The tomographic phase volume reconstruction and DM projection from the 6 LGS wavefront sensors is the most computing intensive task performed by the RTC. However, GPU technology has advanced to the point that it appears likely that the operation could be performed on a single GPU board. Communication between the RTC and ASM is again over the low-latency switching network. Closed-loop control of the ASM actuators with their associated capacitive sensor at 30 kHz is performed onboard the ASM, using custom DSP boards.

7. Integration

A test tower is being designed to facilitate optical testing of the ASM segments, and integration of the full AO system, prior to shipment to the observatory (Fig. 8). A retro-reflector can be inserted at prime focus, and illumated by an interferometer at the Gregorian focus. Alternately, fiber sources can be inserted at prime focus (including 6 sources mimicking the LGS asterism) and used to close the control loops on the wavefront sensors. Interfaces replicating those of the telescope will be provided, allowing all AO and instrument functionality to be tested during the integration phase. Once integration is complete, the test tower will be shipped to the observatory and installed in a purpose-built room in the base of the telescope enclosure. If extended maintenance or recalibration of the ASM is necessary, the ASM frame can be lowered directly from the telescope onto the tower.

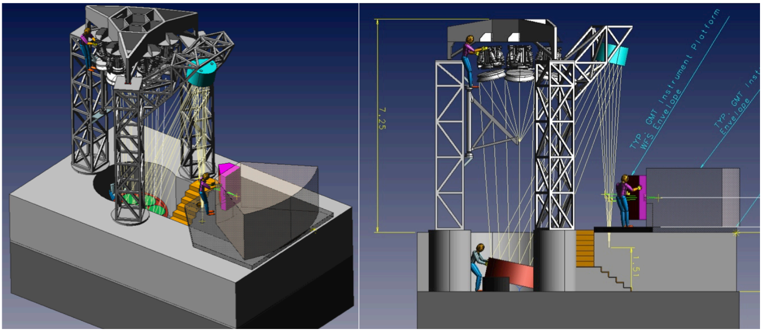

Fig. 8 : Conceptual design of the ASM test tower, which will also be used to integrate and test the full system, including AO instruments.

8. Conclusion

We currently expect the begin commissining the GMT in the natural seeing mode in mid-2019, with 4-5 segments installed in the telescope. Commissioning of the AO observing modes should begin in 2020 with 5-6 segments installed. While some uncertainty remains in the design of certain subsystems (particularly the OIWFS), we believe that the conceptual design presented here meets the GMT AO performance requirements. We are further developing the design, working towards an AO preliminary design review in November 2012.

9. References

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