Scientific Requirements for Extremely Large Telescopes
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The Giant Magellan Telescope project

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Abstract. The original Magellan partner institutions and the Smithsonian Astrophysical Observatory, Texas A&M University, and The University of Texas at Austin have undertaken to construct an extremely large telescope in Chile. The Giant Magellan Telescope is built around seven 8.4m borosilicate honeycomb mirror segments, six of which are off-axis. The collecting area is equivalent to that of a filled aperture 21.5m in diameter, the angular resolution is equivalent to a filled 24.4m telescope. The telescope mount is highly compact and delivers light to the focal plane in two reflections. Instruments are mounted at either a low-background straight Gregorian focus, or to one of several folded Gregorian foci behind the center primary mirror segment. A set of candidate first generation instruments has been defined and conceptual design studies are underway. The first off-axis primary mirror segment has been cast and will soon be polished as part of a proto-typing program. The current schedule calls for first light in mid 2015. This contribution describes the telescope and the considerations that led to its design.

Keywords. Telescopes

1. Introduction

While the primary purpose of this meeting has been to layout the scientific motivations and challenges for the next generation of large telescopes, some discussion of the telescopes under development is clearly in order. In his introductory presentation Carlberg (these proceedings) provided an overview of all the current ELT projects, including the Giant Magellan Telescope. In this contribution I will attempt to fill in some of the details and outline the thinking that led to the unique design of the GMT. This may help to elucidate how GMT came to occupy its particular place in the parameter space of scientific capability, scope, and technical risk.

The GMT project is being led by a consortium of universities and private research institutions. The partner institutions are: Carnegie Observatories, Harvard University, MIT, Smithsonian Astrophysical Observatory, Texas A&M University, and the Universities of Arizona, Michigan, and Texas at Austin. The GMT consortium has a history of telescope building spanning from the Mt. Wilson reflectors to the most recent generation of large telescopes, including the Magellan and MMT 6.5m telescopes, the Hobby-Eberly telescope and the nearly completed Large Binocular Telescope. The GMT is open to additional partners and discussions with prospective partner institutions are ongoing.

In this contribution I describe work carried out by the GMT project (M. Johns, Project Manager, S. Gunnels, Lead Engineer) and the Project Scientist Working Group (R. Angel, R. Bernstein, D. Fabricant, P. MacQueen, P. Schechter, & S. Shectman). Additional information regarding the telescope, the partners, and the GMT science goals, can be found on our website at www.gmto.org.

2. Lessons from 8m class telescopes

Before embarking on construction of the next generation of facilities it would be prudent to reflect on lessons learned from the 8m class telescopes. All of the ELT projects surely have done this and have drawn on their own, and others', experience and impressions in charting their course towards ELT development. At the GMT project two issues strongly influenced our thinking. First, while all of the approaches to 8-10m telescopes; small segments, meniscus monoliths, and structured monoliths, have produced successful telescopes, the large monoliths appear to have an edge in terms of image quality. Large continuous collecting surfaces free of discontinuities requiring alignment are clearly desirable. While there is no question that a segmented approach will be required for ELT primary mirror construction, the success of the large monoliths and the desire for continuous wavefronts led the GMT group to select the largest possible primary mirror segments.

Current large telescopes not only employ a range of primary mirror choices, they also span a range of mount designs. Some of the current telescopes are very stiff and work passively in high winds. Other designs trade mount stiffness against infrared optimization, or other considerations, and these telescopes require fast guiding secondaries to maintain high image quality. While both approaches work well and are transparent to the user, there are reasons to be concerned about mount stiffness when scaling to the wind area appropriate for ELT-sized apertures. This consideration led the GMT design team to strive for a compact mount with maximum stiffness and minimal top-end wind cross section. The cost savings associated with a compact telescope and enclosure provide an added incentive for this approach. These two considerations, maximum image quality and mechanical stiffness, pervade the GMT design philosophy and are in large part responsible for its unique configuration.

3. Key properties and configurations

By virtue of its dilute aperture the Giant Magellan Telescope is not easily characterized by a single diameter (e.g. 20 meters). The seven primary mirror segments produce a total collecting area equivalent to a filled aperture 21.5m in diameter. For diffraction limited work the edge-to-edge diameter of 25.4m is more relevant, although the small net area at the edge yields an angular resolving power equivalent to a filled aperture 24.4 meters in diameter. Much of the ELT science discussed at this meeting and in the various ELT science cases is AO-driven and predicated on gains that go like D^4, rather than D^2. When comparing the GMT to telescopes of other sizes in the D^4 regime, the appropriate aperture scale is 23m (i.e. 23^4 is the correct factor). This is 1.75× the effective power of a filled 20m aperture, a non-trivial distinction.

The GMT primary mirror segments are 8.4m in diameter with individual focal lengths of 18m, giving a primary focal ratio of $f/0.7$. The optical configuration is an aplanatic Gregorian, the secondary mirror produces a final focal length of 202.7m and a focal ratio of f/8.0. One of the salient features of the GMT design, the lack of Nasmyth platforms, is readily apparent in Figure 1. The very fast primary focal ratio makes it difficult to access a Nasmyth focus above the primary mirror, as the elevation axis naturally wants to fall just below the vertex of the primary mirror. Bringing the beam out below the primary entails increasing the total mass and raising the center of gravity of the mount, resulting in reduced modal performance. Preliminary GMT designs with Nasmyth platforms had lowest resonance frequencies of $\sim$ 2Hz. By foregoing the Nasmyth platforms the GMT design team was able to place the elevation axis where is most efficiently balances the

Figure 1. A rendering of the Giant Magellan Telescope. The mount is of the altitude-azimuth variety and uses two large C-rings to support the primary mirror assembly. The telescope moves in azimuth by rotating on hydrostatic bearings riding on a ring beam. The telescope stands 36m high and is 25.5m wide. Instruments are located behind the central primary mirror segment.

optical support structure. The result is a compact and stiff mount that stands only 36m high and 25.5m wide and has a lowest resonance at 4.5Hz. The moving mass of the telescope is projected to be 1005 metric tons, less than twice that of the Hale 5m telescope. Roughly 1/3 of the total mass of the GMT is in the primary mirror and cell structure alone.

The GMT will use a segmented secondary mirror. The seven secondary segments, as shown in Figure 2, conjugate one-to-one with the primary mirror segments. Segmenting the secondary mirror not only simplifies fabrication, as each segment is only 1.06m in diameter, it allows one to use the secondary segments to make fine adjustments to the alignment of the primary mirror segments, easing the requirements on the primary mirror active supports. The secondary mirror is supported by a hybrid truss composed of steel and carbon fiber composite members. The geometry of the secondary support is such that there is no shadowing from the secondary supports on any of the six outer primary mirror segments. This results in a minimal thermal foot print and reduced diffraction effects in the PSF. Figure 3 shows the telescope as seen from above and illustrates this point.

4. Instruments and their deployment

Foregoing the Nasmyth platforms presents both challenges and opportunities for instrument deployment. The instruments will be in a gravity variable environment and so will likely need active flexure control. Several of the large wide-field spectrographs on

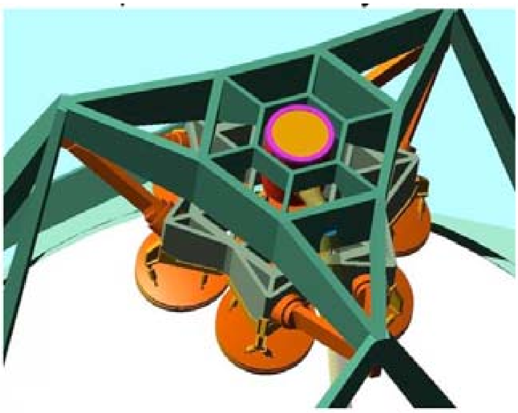

Figure 2. The GMT secondary mirror is composed of seven 1.06m diameter segments, each of which addresses one of the primary mirror segments. The baseline design calls for thin-shell adaptive segments, although conventional light-weighted fast-steering segments might be used for commissioning. The secondary is concave, producing an $f/8.0$ aplanatic Gregorian final focus.

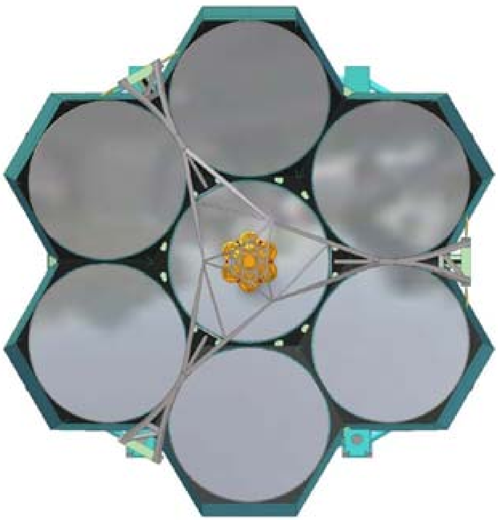

Figure 3. This top view of the telescope shows the small foot print of the secondary supports and shape of the GMT pupil. This secondary configuration results in excellent thermal performance and a PSF free of diffraction spikes associated with conventional secondary supports.

current large telescopes employ active flexure control (even though they are on gravity stable platforms) with great success. Hence we are confident that this is a soluble problem and one that will be with us regardless of the use of gravity invariant instrument platforms. The large wide-field GMT instruments will be deployed at the straight Gregorian focus behind the central primary segment. This instrument bay is roughly 6.5m in diameter and 7.5m deep and can support instruments weighing up to 25 metric tons. The optical and near-infrared multi-object spectrographs will be deployed here and it is likely that the mid-IR spectrometer will also use this focus as it is the minimum background configuration.

The GMT science and operation goals call for rapid response to both changing conditions and time-critical astronomical events. The large instrument bay is not well suited to

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rapid changes. For this reason the GMT design team has developed a second instrument location - a set of folded foci located on a platform just behind the central primary segment, but above the straight Gregorian focus. This area consists of a stationary platform that is 10×20 meters in extent and a rotating platform 8.9 meters in diameter. The rotating platform can accommodate six instruments, each fed by a small fold mirror. Each instrument will likely have a dedicated fold mirror with coatings optimized for the appropriate wavelength range. Instruments at the folded ports will be kept “hot” and be available for rapid deployment.

The layout of the instrument bays is shown in Figure 4. Wavefront sensing and guiding for the folded focal stations can be performed by modules located on the upper platform. The large straight Gregorian instruments will likely have internal guiders and wavefront sensors.

The GMT Science Working Group has identified a set of candidate first light instruments. These are: a wide-field optical multi-object spectrograph, a visible-light high resolution spectrometer, a near-IR multi-object imaging spectrometer, a $1 - 5\mu$m high dispersion spectrometer, a near-IR diffraction−limited AO imaging spectrograph, and a mid-IR diffraction-limited AO imager. Conceptual designs for each of these instruments are underway. While we do not expect to construct all of these instruments as part of the first-light set-up, their development has helped to refine the telescope design.

The wide-field optical MOS (PI: S. Shectman) consists of four double spectrographs covering a field $18' \times 9'$. A full $18' \times 18'$ field can be accessed with some loss of efficiency in the Volume Phased Holographic gratings. Each of the four spatial channels will be wavelength multiplexed and each wavelength channel will address a $4k \times 4k$ detector mosaic. The near-IR MOS (PI: D. Fabricant) has an imaging field $7' \times 7'$ in extent and a spectroscopic field of $5' \times 7'$. This instrument uses VPH gratings and will have a default resolution of $R \sim 3500$, allowing one to work in the dark regions of the OH sky spectrum.

The near-IR Echelle (PI: D. Jaffe) will be composed of two modules, one that addresses the $1 - 2.5\mu$m region of the spectrum, the other covering the $3 - 5\mu$m windows. The spectrometer will make use of Si immersion gratings and will provide resolving powers of $R \sim 50 - 120K$, depending on the entrance aperture. The near- and mid-IR AO imagers will reside on the upper instrument platform and will be optimized for high dynamic range studies, and exoplanet imaging in particular. The near-IR AO camera (PI: L. Close) will likely employ a coronograph, while the mid-IR imager (PI: P. Hinz) will be used for nulling interferometry.

5. Adaptive optics and the GMT

Much of the key science planned for the GMT requires adaptive optics. The telescope will employ a number of different adaptive optics modes, including extreme adaptive optics (ExAO), all-sky laser tomography (LTAO), ground-layer correction (GLAO), multi-conjugate (MCAO), and, possibly, multi-object adaptive optics (MOAO). The GMT science working group has identified ExAO, GLAO and LTAO as the highest priorities as they address the key science areas of exoplanet imaging, galaxy evolution, and cosmology. The adaptive secondary mirror will form the core of the facility AO system. With 4700 actuators driving face sheets only 2mm thick, the AO secondary will correct enough modes for most, and possibly all, AO applications. The Gregorian configuration of the secondary ensures that it will naturally conjugate to a height 200m above the ground, close to the expected height of the turbulent boundary layer.

The GMT facility AO system will use a set of sodium lasers launched from the center of the secondary support structure. Six beams will be directed from lasers located on

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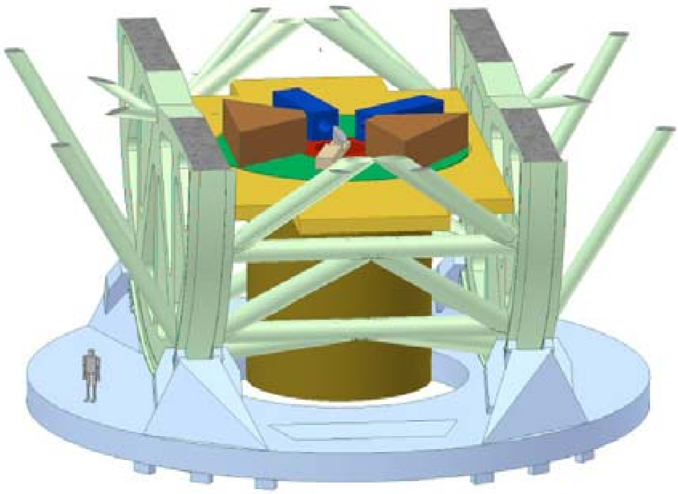

Figure 4. This cut-away view of the telescope highlights the upper instrument platform and shows the large straight Gregorian focus instrument bay. The upper platform will house a number of instruments available for rapid response to changing conditions or time-critical astronomical events. The 8.9m diameter disk rotates to provide field derotation for all of the upper platform instruments.

the rotating azimuth platform to the beam projecting optics at the top of the telescope. This will allow diffraction-limited imaging via atmospheric tomography nearly anywhere on the sky, the limiting factor being the availability of natural guide stars for tip-tilt correction. The segmented pupil design of the GMT lends itself naturally to nulling interferometry. AO corrected beams from each primary-secondary segment pair can be interfered to null out bright stars, allowing sensitive searches for young planets in the nearest star forming regions and hot giant planets in the closest radial velocity detected planetary systems.

6. Site selection and layout

The GMT project has designated Las Campanas Observatory (LCO) in Chile as it's baseline site for planning purposes. Carnegie has more than 25 years of experience at Las Campanas and a long time baseline of data from the Magellan site testing in the late 1980s. The GMT SWG set excellent seeing as it's top site selection criterion (after low light pollution). This reflects their belief in the importance of image quality for seeing-limited applications and the impact of stable atmospheric conditions on the ability to use AO effectively.

The Magellan site testing data (1987 - 1989) gave a median seeing value of $0.6''$ FWHM at the zenith at 550nm (Persson *et al.* 1990). The 6.5m telescopes appear to deliver images with very nearly this same quality, suggesting that the seeing at LCO has not changed in the nearly 20 years interval. Site testing is underway at four sites within the LCO property (Figure 5) with the goal of identifying the best seeing site and characterizing atmospheric conditions and the dependence of seeing on wind direction in particular. The first six months of MASS/DIMM data confirm the median seeing value of $\sim 0.6''$ FHWM and suggest small variations among the four peaks being surveyed. At this time it appears that Las Campanas Peak (elevation 2510m) is the best seeing site available on the mountain.

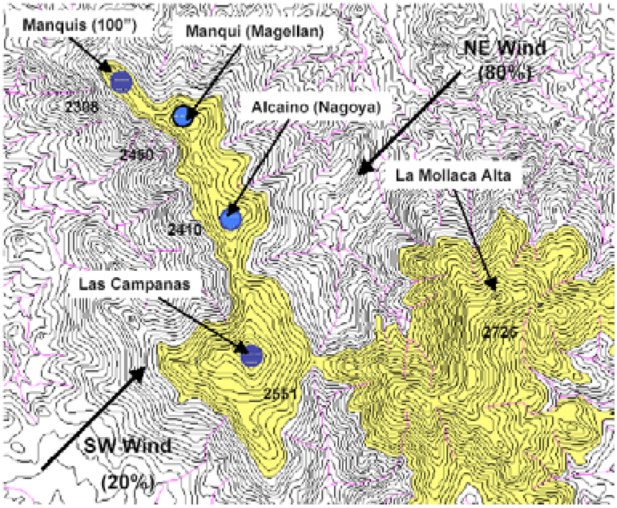

Figure 5. Potential GMT sites at Las Campanas and the location of seeing and weather monitors. The filled circles show the sites being tested. From top to bottom these are: Manquis ridge, near the du Pont 2.5m, Manqui, the site of the Magellan 6.5m telescopes, Alcaino, former site of the U. of Nagoya mm-wave telescope, and Las Campanas Peak. The elevation of each site, in meters, is marked. Manqui is being tested as a reference site since it is currently occupied by the 6.5m telescopes. The prevailing wind directors are noted by the arrows. The wind comes out of the NE most (80%) of the time, for nearly all of the remaining 20% of the time the wind comes from the SW.

Figure 6 shows the layout of the telescope and support buildings on Las Campanas Peak. The primary mirror segments will be removed by an overhead crane and transported on rails to the coating chamber in the support building. Large instruments will also be transported on rails to the support building for servicing.

7. Schedule and progress to date

The current project schedule calls for the start of telescope commissioning in mid-2015 and full science operations in mid-2016. The primary mirror production is the pace setting item and it is possible that the telescope will go into limited operations before all seven segments are in place. The polishing and testing of the large off-axis segments is also viewed as the largest technical challenge in the program. For this reason the project has chosen to cast and polish the first off-axis segment as a prototype. The 8.4m blank was successfully cast in July of 2005 and is shown in Figure 7. The mirror has cooled and is currently undergoing processing in preparation for surface generation and polishing. Test optics required for the off-axis figuring are being manufactured and the project expects to complete this prototype segment in May of 2008.

The next milestone for the project is a conceptual design review, to be held in Pasadena, California, in February 2006. Several members of the review committee are in attendance at this meeting. Site selection is scheduled for mid 2008 and construction will commence in early 2010, pending the outcome of a critical design review in mid 2009.

8. The GMT in context

We have heard about a number of very exciting science programs at this meeting and some very ambiguous telescope projects. It is worth taking a step back and looking at the

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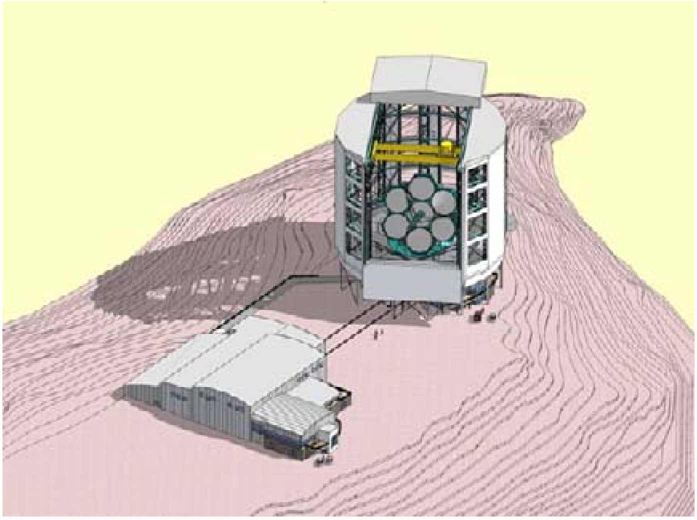

Figure 6. A potential layout of the GMT enclosure and support building on Las Campanas Peak as seen from the east. The primary mirror segments will be removed from the telescope by the overhead crane and transported on rails to the support building for re-coating. Instruments will also be assembled and serviced in this building and moved on rails to the telescope. The enclosure is of the carosel type and has maximum ventilation through a number of apertures that can be configured either for wind shielding or ventilation, depending on the conditions and orientation of the enclosure. The telescope and enclosure rotate independently, allowing access to the secondary mirror from an elevated platform within the enclosure.

Figure 7. The GMT prototype primary mirror segment on the hearth at the Steward Observatory Mirror Laboratory. The mirror is cast in a rotating oven and while it is cast with a circularly symmetric top face, an asymmetric distribution of mold cores ensures that the final off-axis mirror will have a uniform thickness top sheet. The prototype mirror is scheduled for completion in early 2008.

ELTs in the historical context of large telescope development. In the previous century, telescope apertures increased in steps of roughly a factor of two. One can trace much of the history of modern astrophysics through the development of the Mt. Wilson 1.5m, Hooker 2.5m, Palomar/Hale 5m, and Keck 10m telescopes and their similar sized counterparts in other communities. The scientific returns at each of these aperture steps were profound

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and, in most cases, unforeseen. It is somewhat surprising from this perspective then, that the international astronomical community has embraced a plan to move from 8-10m telescopes to 30-100m apertures in a single step. Perhaps the technology is now ripe for such a move. It is certainly the case that our ability to predict solid scientific gains as a function of aperture, particularly with the promise of adaptive optics, is more developed than ever before. I don't believe that anyone would argue that the Hooker, Hale, or Keck telescopes were insufficiently challenging from either a technical or financial perspective, or that, upon completion, they were not worth the effort. Adaptive optics holds the promise of unlocking the full potential of ground-based telescopes and this has impacted the metric for cost-benefit analyses. In this sense the GMT is the most conservative of the currently proposed ELT programs. The scale of the GMT allows us to contemplate large natural-seeing instruments while still realizing large gains in the diffraction-limited regime.

In the US the large telescopes listed above were constructed with private funds and were led by Universities and small private research centers. The scale of the GMT project, while ambitious, is within the reach of a consortium of Universities. We believe that it represents a fine balance between heritage, technical challenge, and scientific return. While we have heard compelling arguments for the expected science return from ELTs of various apertures, we should not lose sight of the discovery nature of our science. The most exciting advances in astronomy are those that were not anticipated. In that sense, planing our facilities with an eye towards maximizing our potential for discovery seems like a wise approach.

9. Acknowledgments

All of the technical work that I have presented is the result of the effort and expertise of others. I thank R. Angel, R. Bernstein, D. Fabricant, S. Gunnels, M. Johns, P. MacQueen, P. Schechter, & S. Shectman for allowing me to present the results of their work. I also acknowledge that the scientific motivation of the GMT was developed with the GMT Science Working Group (W. Couch, X. Fan, K. Gebhardt, G. Hill, J. Huchra, S. Kenyon, M. Meyer & A. Weinberger).

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Discussion

Crampton: We have recently collected seeing statistics from Gemini, Keck, Subaru and Magellan, i.e. 8-10m telescopes on different sites, in different types of enclosures, some segmented and some monolithic. The astonishing result is that they are all essentially identical. The lesson seems to be that there are several paths to success.

Herbst: Can you say more about the Atmosphere Dispersion Compensation? Is it in place for all instruments?

McCarthy: The ADC is intended for visible MOS; it will be removed for IR.

Cuby: What is the cost?

McCarthy: I am not able to discuss cost until after conceptual design review, February.

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