The Giant Magellan Telescope Phasing System
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ABSTRACT

The 25 m Giant Magellan Telescope consists of seven circular 8.4 m primary mirror segments with matching segmentation of the Gregorian secondary mirror. Achieving the diffraction limit in the adaptive optics observing modes will require equalizing the optical path between pairs of segments to a small fraction of the observing wavelength. This is complicated by the fact that primary mirror segments are separated by up to 40 cm, and composed of borosilicate glass. The phasing system therefore includes both edge sensors to sense high-frequency disturbances, and wavefront sensors to measure their long-term drift and sense atmosphere-induced segment piston errors.

The major subsystems include a laser metrology system monitoring the primary mirror segments, capacitive edge sensors between secondary mirror segments, a phasing camera with a wide capture range, and an additional sensitive optical piston sensor incorporated into each AO instrument. We describe in this paper the overall phasing strategy, controls scheme, and the expected performance of the system with respect to the overall adaptive optics error budget. Further details may be found in specific papers on each of the subsystems.

Keywords: Extremely Large Telescopes, Adaptive Optics, Wavefront Sensing, Metrology

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. Some of the GMT’s highest science priorities require diffraction-limited adaptive optics (AO) observing modes, which can provide vastly improved spatial resolution, sensitivity, and contrast over that allowed by natural seeing. The GMT has a Gregorian optical design, with a primary mirror (M1) composed of seven circular segments, and an identically segmented adaptive secondary mirror (M2 or ASM). To achieve the diffraction limit of the full 25.4 m diameter aperture, the seven M1-M2 pairs must phased such that their optical path length is matched to a small fraction of the observing wavelength. This paper describes the conceptual design of the sensors, actuators, and control loops required to achieve and maintain the segment piston alignment of the GMT.

Current-generation segmented telescopes (eg. Keck Observatory, with only a segmented primary mirror) are phased by observing a bright natural guide star with a purpose-built phasing camera, then maintained in this condition over many nights by closing a control loop between mirror segment edge sensors and position actuators. Our strategy for phasing and maintaining the alignment of the GMT is more complex, due to the doubly-segmented nature of the telescope design and the lack of dimensional stability of the borosilicate glass from which the M1 segments are cast.

The Phasing System is only required for the two diffraction-limited AO observing modes of the telescope: Natural Guidestar AO (NGSAO) and Laser Tomography AO (LTAO). The strategy which we have selected for both modes is similar, and begins with coarse phasing of the telescope using a Phasing Camera with a wide capture range, then maintaining this condition using M1 and M2 metrology systems. In the NGSAO mode, the third stage of control is provided by a pyramid Natural Guidestar Wavefront Sensor (NGWS), which can sense segment piston at up to 1 kHz. No bright natural guidestars stars are available in the LTAO mode, so sensitive measurements of segment piston error

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must be made at low bandwidth by the On-Instrument Wavefront Sensor (OIWFS). These measurements are instead used to update the control points of the M1 metrology system, which is expected to drift on minute timescales.

The following sections introduce the constraints provided by the telescope optical design, describe the sensors which we have designed to phase the GMT, and the phasing control loops. Finally, we derive the requirement flow-down to the various components, and conclude with a brief discussion of the challenges of this design.

2. CONSTRAINTS

2.1 M1 Segmentation

The GMT M1 consists of seven 8.4 m diameter segments spun-cast of borosilicate glass by the Steward Observatory Mirror Lab. The minimum separation between outer segments is 295 mm, while it is 359 mm between the center and outer segments (Fig. 1). Machined bosses are provided on the mirror side-walls 19.6° on either side of each inter-segment gap for mounting metrology systems. Each M1 segment is supported by 165 pneumatic actuators, which also provide active correction to their figure with feedback from the telescope Acquisition, Guiding and Wavefront Sensing Subsystem (AGWS). Each segment is positioned with 6 degrees of freedom using an actuated hexapod positioner, with breakaways in case of earthquake or other dangerous loading conditions.

Fig. 1: (Left) General layout of the GMT M1 mirror segments. (Right) Cross section drawing of 2 segments.

The timescale over which the M1 metrology system can maintain the telescope in a phased state is limited by the thermal expansion coefficient of Ohara E6 borosilicate glass of $2.8 \times 10^{-6} ^\circ$C. Temperature sensor data from the Magellan Clay telescope primary mirror indicate a typical front-to-back temperature gradient of $0.1 ^\circ$C, and a gradient rate of change of $\sim 0.1 ^\circ$C/hr. The larger GMT segments share a similar design, and will be actively cooled in the same way. A $0.1 ^\circ$C front-to-back temperature gradient will lead to an $0.20 \mu$m tilt of the M1 side wall with respect to the optical surface near the edge, after active optics correction of the resulting low-order segment figure errors. This implies that any metrology system cantilevered from the M1 wide walls (either mechanically or optically) will suffer $\sim 5 \text{nm}$ of drift over approximately 5 minutes.

2.2 M2 Segmentation

The Adaptive Secondary Mirror (ASM) is composed of six identical 1.04 m diameter off-axis and segments and one 1.05 m diameter on-axis segment, with 22 to 27 mm gaps between them (Fig. 2). Each segment has 672 voice coil actuators (4704 total), actuating a 2 mm thick Zerodur face sheet at up to 1 kHz update rate with $\sim 120 \mu$m of stroke. Capacitive sensors maintain the shape of the face sheet with respect to a lightweighted Zerodur reference body with $\sim 3 \text{nm}$ precision. Each segment is mounted on a positioner capable of micron-level actuation over 6 degrees of freedom.

The Zerodur reference bodies provide a dimensionally stable location for a metrology system, but the segmented nature of the ASM leads to a different challenge. If the M1 segments tilt with respect to each other (as they will naturally do from flexure due to gravity), and the M2 segments are tilted to compensate, an un-sensed piston variation with field angle will arise. This mode will be invisible to geometric optics (eg. Shack-Hartmann) sensors in the telescope focal...
plane, but will add a potentially devastating error term to off-axis segment piston measurements. This problem is fundamental to telescopes where M1 and M2 are identically segmented. We address this by providing an M2 metrology system which is sufficiently sensitive to relative tilt displacements of the segments, described in Section 3.5.

Fig. 2: Cross section of the ASM, showing the layout of the segments and their Zerodur reference bodies.

3. SENSORS

3.1 Phasing Camera

The Phasing Camera\(^2\) with a large capture range and moderate sensitivity will be located just ahead of the direct Gregorian focus, capable of patrolling a sector of the 20 arcmin diameter telescope field outside of the region vignetted by the tertiary mirror\(^1\). The Phasing Camera fulfills two distinct functions: Its large capture range will be used to initially phase the telescope segments, both during telescope commissioning and at the beginning of each night. It also provides a monitoring capability when fine control of the phasing is performed by the NGWS or OIWFS, which can suffer from phase wrapping.

The current concept for the GMT Phasing Camera is a dispersed Hartmann design, with 1.5 m square subapertures spanning the 12 inter-segment gaps. Each aperture forms a Young’s double slit image, which is tip-tilt corrected using a segmented micro-electro-mechanical (MEMS) mirror and detected with a Teledyne HAWAII-2RG detector in the K band. A grism disperses the fringes at low spectral resolution (R~60) in the direction perpendicular to the gap, increasing the sensor’s capture range to >20 µm in the wavefront\(^10\) (see Fig. 3). The Phasing Camera can access R<15 guidestars with essentially full sky coverage.

A prototype of the Phasing Camera has been designed and built at the Smithsonian Astrophysical Observatory, and will be tested on the Magellan Clay telescope in mid-2012\(^5\). Its purpose is to test the sensitivity and robustness of the dispersed Hartmann sensor’s design, particularly its performance in different seeing conditions.

Fig. 3: Phasing Camera subaperture layout, and simulated dispersed fringes in H and K bands (no noise or turbulence).
3.2 Natural Guidestar Wavefront Sensor

In the NGSAO observing mode, the pyramid Natural Guidestar Wavefront Sensor7 (NGWS) assumes control of segment piston once the Phasing Camera has reduced optical path length differences to <200 nm peak-to-valley (PV). The ability of a pyramid wavefront sensor to sensitively phase a segmented mirror has been demonstrated with the PYPS sensor in the European Southern Observatory’s Active Phasing Experiment11. Simulations performed using the GMT pupil geometry have confirmed that segment piston can be controlled to ~20 nm RMS wavefront when using bright stars. However, we have found that in poor seeing conditions, the segment piston control of the NGWS may be prone to jumps of 2π radian in phase, as the atmosphere briefly imposes a >π radian offset across a segment. Further simulations and a laboratory prototype are planned to test possible alternative control strategies. In the worst case, the Phasing Camera, monitoring segment piston on an off-axis guidestar every 10-30s, would detect the erroneous command and correct it.

![Fig. 4: Pyramid WFS response to segment piston. (Left) Input ± λ/10 piston wavefront error on alternating outer segments. (Right) Resulting pupil plane image when modulating by λ/D, with reference slopes subtracted. The sensing wavelength is λ=750 nm.](image)

3.3 On-Instrument Wavefront Sensor

The On-Instrument Wavefront Sensor8 (OIWFS) will reside within the cryostat of all instruments which use the LTAO observing mode12. It is the sole NGS wavefront sensor in this mode, and must therefore measure all of the aberrations which the LGS cannot. These are: Tip-tilt, focus, slowly-varying calibration errors, and segment piston. To achieve high sky coverage, the OIWFS must operate on guidestars as faint as K=18, up to 90 arcseconds off-axis. Its design has not yet been finalized, but a possible concept is a two-channel device in which tip-tilt is sensed in the K band, and other aberrations sensed in the H band using an un-modulated pyramid WFS (10×10 sampling of the pupil). Both are fed by a MEMS deformable mirror controlled in open-loop, using an independent tomographic reconstruction to correct anisoplanatism.

Simulations of this proposed sensor indicate good sensitivity to segment piston, but also similar problems with phase wrapping when the atmospheric disturbances become large8. Since useable natural guidestars are likely to be well off-axis in the LTAO mode, the OIWFS cannot correct the atmospheric component of segment piston, which decorrelates completely over field angles of ~20 arcsec13. The resulting 110 nm RMS wavefront error in median conditions is one of the largest contributors in the LTAO error budget14.

3.4 M1 Metrology System

The metrology system for M16 must measure displacements of <5 nm, but allow up to ±3 cm of independent motion of each segment during earthquakes or other unexpected loss of control. This motivated the use interferometric sensors, rather than capacitive or inductive designs. The selected design is a hybrid metrology system that supplements the interference based sensors with a coarse absolute optical sensor with larger capture range. The coarse sensors will make it possible to quickly align segments to the capture range of the Phasing Camera (>10 µm of mechanical segment piston). Once coarse optical phasing has been completed, we then rely on the interferometric metrology system to maintain the relative piston of the M1 segments between OIWFS updates.

The M1 fine sensors, Renishaw Distance Measuring Interferometers (DMI), will be located in pairs at 24 locations spanning the segment gaps (Fig. 5). Each of these locations also hosts a single camera/target combination to provide...
coarse sensing of 2 degrees of freedom. The crossed geometry of the DMI beams makes the system insensitive to symmetric distortion of the mirror sidewalls, as would occur with identical front-to-back temperature gradients on all segments. Detailed analysis of the full M1 metrology system indicates that it should have a sensitivity to mechanical segment piston errors of 2.3 nm RMS at 20 Hz. We are about to begin testing the DMI in the laboratory to verify their expected noise performance.

Fig. 5: M1 fine metrology system, which uses 48 off-the-shelf distance-measuring interferometers.

3.5 M2 Metrology System

The metrology system for M2 has a similar sensitivity requirement to that for M1, but must maintain stability over at least a full night, rather than a few minutes. We expect to insert a calibration source at the telescope prime focus before the start of the night, and use the Phasing Camera and NGWS to align the M2 segments. From that point on, any drift in the M2 metrology system resulting in segment tilt will lead to field-dependent piston errors as described in Section 2.2.

The M2 metrology sensors will use pairs of differential capacitive plates mounted directly to the Zerodur reference bodies of the ASM segments (Fig. 6). Their expected sensitivity to mechanical segment piston is 5.9 nm RMS at 50 Hz. The sensitivity to segment tilt is ~0.01 µrad RMS, leading to just 1 nm RMS of segment piston error if the OIWFS NGS guidestar is located 60 arcsec off-axis. Prototyping of the M2 metrology sensors is planned prior to the GMT System Preliminary Design Review.

Fig. 6: M2 metrology system, which uses 12 custom differential capacitive sensors between ASM reference bodies.
4. CONTROL LOOPS

4.1 LTAO Control Loops

The block diagram in Fig. 7 captures the complete LTAO phasing control, and also includes slow Active Optics control loops. High-bandwidth AO control is not shown.

In the LTAO mode, the feedback loops between the M1 and M2 metrology sensors and their respective positioners are closed continuously, making small 6 DOF adjustments to the 6 outer segments to maintain their alignment with respect to the center segment. However, the M1 and M2 positioners have low control bandwidth (~1 Hz) and are not sufficiently precise to meet the segment piston requirement alone. We therefore also feed forward the piston error signal measured by the two metrology systems, with unity gain, to the ASM. The ASM face sheet will compensate rapidly for any detected wind buffeting, errors in positioner actuation, and even segment vibration. This feed-forward control relies on the high precision of the ASM, with its internal closed loop capacitive sensing of the face sheet position with respect to the reference body.

Several outer loops control the set-points of the M1 metrology system, compensating for thermal and gravity-induced drifts in the M1 fine metrology sensors and offloading certain modes from the ASM (segment piston and segment tip-tilt). Most critically, segment piston error measured by the OIWFS will update the M1 metrology set-point, causing the ASM to instantly compensate the segment piston error. The M1 positioner would then slowly take over the piston offset, as the ASM relaxed to its original pose.

4.2 NGSAO Control Loops

NGSAO phasing control loops are illustrated in Fig. 8. The feedback loops between the M1 and M2 metrology sensors and positioners are simplified, since it is no longer necessary to rely on feed-forward control from the edge sensors to
correct transient segment piston errors. Direct detection by the NGWS and correction in closed loop by the ASM is likely to have higher bandwidth and precision. The inputs to the M1 metrology set-points are simplified as well. In this case the fundamental reference for segment piston is the NGWS acting through the ASM. Thus segment piston and tilt offloads from the ASM provide the only updates to the M1 metrology set-points when the loops are closed.

Fig. 8: Block diagram of the NGSAO phasing control loops.

5. REQUIREMENTS AND ERROR BUDGETS

The AO System Requirements governing the performance of the Phasing System are the following:

- **AO-4424**: The AO system in NGSAO mode shall have a telescope Segment Piston error less than 30 nm RMS when using a V=8.0 G2V guide star, over a 120s integration.
- **AO-4422**: The AO system in LTAO mode shall have a Telescope Segment Piston error less than 50 nm RMS over 50% of the sky at the galactic pole, over a 120 s integration [goal: 70 nm over 90% sky coverage].

Both are specified at 15° from zenith median atmospheric conditions (r0=16.4 cm at zenith), and with a conservative assumption of L0=60 m turbulence outer scale. There are currently no requirements on the phasing system in the Natural Seeing or GLAO observing modes, although it is likely that the M1 and M2 metrology sensors could aid in the active alignment of the telescope optics in these modes.

5.1 NGSAO Mode Error Budget

The segment piston error budget in the NGSAO mode consists only of 3 terms: the NGWS piston sensitivity, the ASM actuator position precision, and contingency (Table 1). While the phasing camera is used to initially phase the telescope, and edge sensors to maintain the segment piston and tilt within acceptable ranges, the NGWS fundamentally controls segment piston in closed loop via the ASM actuators. Using a V=8 guidestar, the NGWS control loop would be run at 1 kHz, sufficiently fast to reject any transients due to inaccurate M1 or M2 positioner actuation.

<table>
<thead>
<tr>
<th>Term</th>
<th>Segment Piston Error</th>
</tr>
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<tbody>
<tr>
<td>NGWS piston sensitivity</td>
<td></td>
</tr>
<tr>
<td>ASM actuator precision</td>
<td></td>
</tr>
<tr>
<td>Contingency</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: NGSAO mode segment piston error budget
5.2 LTAO Mode Error Budget

The segment piston error budget in the LTAO mode is shown in Table 2. It includes contributions from most of the sensors described in this paper, and from several actuators which are driven in open-loop in the control scheme described above. The field-dependent segment piston term arises from tilt of the M1 segments corrected at M2. Some of the terms listed evolve at high frequency (~50 Hz, edge sensors precision), while others are far lower (OIWFS and field-dependent segment piston, 0.1-1 Hz).

Table 2: LTAO mode segment piston error budget

<table>
<thead>
<tr>
<th>Term</th>
<th>Segment Piston Error (nm RMS wavefront)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 fine metrology sensors</td>
<td>10</td>
</tr>
<tr>
<td>M2 metrology sensors</td>
<td>10</td>
</tr>
<tr>
<td>M2 positioner piston precision</td>
<td>20</td>
</tr>
<tr>
<td>ASM actuator open-loop accuracy</td>
<td>20</td>
</tr>
<tr>
<td>On-Instrument Wavefront Sensor</td>
<td>25</td>
</tr>
<tr>
<td>Field-Dependent Segment Piston</td>
<td>20</td>
</tr>
<tr>
<td>Contingency</td>
<td>20</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>50</strong></td>
</tr>
</tbody>
</table>

6. DISCUSSION

Segment phasing in the diffraction-limited AO modes is one of the high-risk elements of the GMT project. Two aspects of the telescope design make it particularly challenging: The non-zero coefficient of thermal expansion of the primary mirror segments, and the doubly-segmented optical design. However, it is too easy to focus only on the negative aspects of these design choices. The use of 8.4 m borosilicate segments allows the telescope to deliver high image quality in the Natural Seeing and GLAO observing modes with no active phasing of the segments. This of course reduces the overall complexity and risk to the project. Similarly, the doubly-segmented optical design in fact makes possible an extremely high-performance AO system (4704 actuators, with just 3 reflections before the science instrument) with little risk in terms of the adaptive mirror technology.

The phasing system design presented here, while relying on an admittedly complex control scheme, is built of generally well-understood components. The single item of greatest concern is the noise performance of the differential capacitive sensor, which must be prototyped before this system design can be accepted with confidence. In addition to component prototyping, we are also pursuing an effort to simulate the full control network illustrated in Fig. 7 and Fig. 8. Finally, the preliminary design of the On-Instrument Wavefront Sensor must also be completed.

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