A Phasing testbed for the Giant Magellan Telescope

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ABSTRACT

In this paper we propose a conceptual design for a testbed to be constructed for the purpose of solving several of the challenges that GMT will face to phase its segmented mirrors. With the proper design, this testbed can be used, not only to test all the phasing controls and algorithms, but also its wavefront sensors and instruments. The testbed will therefore play an important role during commissioning of the observatory with a big impact on its productivity. We present the conceptual design of the phasing testbed and its key requirements.

Keywords: Adaptive Optics, image quality, phasing

1. INTRODUCTION

The GMT design consists of seven primary mirrors (8.4 m) and seven matching secondary mirrors. The large mirrors provide a smooth optical surface over a larger area, eliminating most of the correction required by the telescopes that utilize many smaller segments (such as TMT). The smaller secondary mirrors can be used to compensate for some dephasing of the primary mirrors, but too much reliance on this feature can result in field-dependent aberrations. As an example, the tilt of a pair of M1/M2 segment with respect to the other segments will result in field-dependent piston error. Specifically, a 0.12 µrad of tilt (1 µm / 8.4 m) leads to 80 nm of segment piston error at 8 arc-min off-axis.

One key challenge for the large-sized telescope is to minimize the optical aberrations over many Zernike orders to obtain high angular resolution. This means that every ray travelling from the original source to the science camera must have an equal optical path length, down to an accuracy of a fraction of the observing wavelength. This requires the optical alignment of the primary segments with respect to each other to be accurate. Phasing for GMT will be achieved using two wavefront sensor subsystems. The wavefront reflected from the coarsely de-phased mirrors will be measured and phased by the Acquisition and Guiding Wavefront Sensor (AGWS). Subsequently, fine phasing will be achieved through the feedback from the Natural Guide star Wavefront Sensor (NGWS). Positioning the 15-tonne mirrors to the accuracy on the order of 20 nm is an unprecedented exercise in metrology. Additionally, the inter-segment separation of 400 mm is large compared to most other segmented telescopes and makes interferometric edge sensing a challenge.

With so many challenges unique to the GMT optical design, it is imperative to simulate and test as many elements of the phasing strategy as possible. While not entirely novel, the idea of creating a testbed to retire many of the risks associated with phasing is the safest way to guarantee that the telescope commissioning time is not incapacitated by phasing issues. An optical table-sized phasing testbed is therefore a small upfront investment for a next-generation telescope of the scope of GMT.

Looking beyond the phasing challenge, we are also considering that the testbed should be designed to test all the instruments that will eventually be installed on the telescope. This intermediate step, in instrument commissioning is again expected to minimize the engineering time needed to commissioned instruments on sky and therefore optimize the observatory's scientific productivity. All these uses cases impact the technical requirements of the phasing testbed but also its location (hence portability).

In this paper we present the GMT phasing testbed conceptual design as well as its requirements.

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2. THE PHASING CHALLENGE

The full phasing strategy described in [1] relies a several sensors which include a phasing camera, physical sensors on the M1 and M2 segments, on-instrument wavefront sensors. GMT's phasing procedure differs significantly from segmented mirrors like Keck. The phasing system will be run continuously during observations using one of the two available modes of operation: Laser Tomography Adaptive Optics (LTAO) and Natural Guide Star Adaptive Optics (NGAO) modes.

The doubly segmented mirrors provide the advantage of being able to be fine adjusted by the secondary, a much smaller and faster mirror than the primary. However, aberrations arising from the plane of the primary, then corrected by the secondary, produce off-axis aberrations [1]. For instance, any tilt on a primary segment is compensated for by its partner secondary segment which eliminates on-axis tilt but produces a field-dependent segment phase piston error. Consequently, to phase correctly, the relative segment phase piston and segment tilt must be measured at multiple points in the field and corrected [2]. The fine phasing systems will be controlled by the NGWS [3] or AGWS [4].

In the Natural Guide Star observing mode, AGWS will perform the initial phasing, before handing over to NGWS for finer phasing. AWGS will have four multi-channel star probes that have a Dispersed Fringe Sensor to measure segment phase piston error up to ±40 μm in the J-band and Shack-Hartmann wavefront sensor to measure continuous aberrations in the visible [4]. Having four multi-probe channels allows for sufficient coverage over the science field. It will take wavefront measurements at a rate of 0.033 Hz.

Once the phasing is handed to NGWS the closed-loop bandwidth increases to approximately 1 kHz facilitated by a pyramid wavefront sensor. Additionally, AGWS stays active while NGWS is phasing to continue controlling field-dependent aberrations. AGWS also monitors the segment phase piston error in case the aberration is out of the capture range of NGWS, which is approximately ±3 μm.

So far AGWS and NGWS have performed validity and accuracy demonstrations in a laboratory. However, the prototypes have not been tested with the correct pupil geometry of the GMT or demonstrated closed-loop control of segment phase piston [5]. A phasing testbed that is a miniature optical emulation of the GMT presents the opportunity to test the accuracy and robustness of the phasing prototypes (AGWS and NWGS) with the correct pupil geometry.

GMTO has so far developed numerical simulations that capture of the effects of atmospheric turbulence, limits of optical fabrication, dynamical telescope disturbances, adaptive optics (AO) and active optics (AcO) control systems. A testbed would go beyond that and test the control loops in real life conditions. This includes the GMT pupil geometry which has also not been simulated yet. So, the proposed concept plans to emulate the GMT and demonstrate closed-loop controls to resolve and characterize unknowns before the GMT goes on-sky. It is a similar solution to the GMT’s phasing testbed was proposed by the European Southern Observatory (ESO) for the European Extremely Large Telescope (E-ELT), the Minuscule Extremely Large Telescope (MELT) [6]. MELT’s purpose is to introduce the types of aberrations that the telescope is susceptible to in order to characterize them and therefore shape the specifications of their phasing diagnostic instruments. Our concept is a similar solution to MELT and includes the top level requirements Shown in Table 1.

3. THE CONCEPTUAL DESIGN

The concept of the GMT phasing testbed shown in Figure 1 includes several components:

1) A star and atmosphere simulator as input to the telescope.
2) A telescope simulator which captures the characteristics of the GMT pupil.
3) A metrology system to sample the system aberration and optical characteristics of the system.
4) a steerable output beam to feed the telescope light to instruments and wavefront sensors.

At the center of the experiment, the telescope simulator will include an innovative design to simulate the GMT telescope mirrors, and will accurately simulate the real telescope in the following manner: Since the telescope primary mirrors and secondary mirrors have many modes of deformation, our concept relies on a tip-tilt array to recreate the GMT aperture and low order modes (piston, tip and tilt) and a deformable mirror to recreate the higher deformations (the first 12

Zernike modes to be exact). Our telescope will therefore not have individual hardware for M1 and M2 but will divide the functions of the GMT optics by modes. This selection is cost effective and will minimize the footprint of our setup. With this choice, we have selected to center our design around two major components:

- Seven Physikinstrumente S-325 tip-tilt stages, which will be positioned to reproduce the GMT M1 configuration (See Fig. 2). They were selected as the smallest stages capable of giving us the necessary tip-tilt resolution and the physical profile allowing us to match the GMT mirrors size to spacing ratio. Together they allow us to recreate the GMT pupil plane with a 77mm diameter.
- An ALPAO DM-820 deformable mirror. Its actuator density and stroke allows us to input and correct 12 Zernike modes of aberrations. This selection is the result of simulations performed by GMT scientists that analyzed three off-the-shelf deformable mirrors (the other two models were from Boston Micromachines). The DM-820 was found to

Table 1. Requirements and rationale leading the design of the GMT phasing testbed.

Requirement	**Rationale**
The testbed shall reproduce the 7-segment GMT pupil with an f/8.2 focus.	Creates an optical emulation of GMT that is compatible with the prototype wavefront sensors and instruments to allows for them to be tested using the correct pupil geometry.
Introduce a piston error equivalent to >2 μm peak-to-valley, and tip-tilt of >10 μrad peak-to-valley at 60 Hz.	Replicates the combined piston and tip-tilt vibrations of the primary mirror. Values correspond to worst-case displacements in 10 m/s wind.
The testbed shall generate evolving atmospheric turbulence with a Fried parameter range of at least 10.4 cm to 20.6 cm.	Corresponds to 25th to 90th percentile seeing at the GMT site.
The testbed shall include a corrector for segment piston of ≥5 μm peak-to-valley, and tip-tilt of ≥2 μrad peak-to-valley in the telescope pupil, with control bandwidth ≥60 Hz.	Enables control of segment piston and tip-tilt errors, analogous to the secondary mirror.
The testbed shall include a deformable mirror with ≥800 actuators in the GMT pupil with a control bandwidth of ≥500 Hz	Enables the introduction of 12 bending modes for every segment plus control of atmospheric aberrations.
The testbed shall include a near-infrared scoring camera which Nyquist samples the diffraction limit.	Provides independent verification of phasing accuracy.
The testbed shall include an on-axis broadband diffraction-limited light source with brightness variable over the range $5 < R < 18$.	Replicates the range of guidestar magnitudes used by the AGWS and NGWS.
The testbed shall be capable of being deployed at the GMT Folded Port focus, with ≥10 arcseconds diameter transmitted field of view.	Enables the characterization of real telescope segment disturbances and an early on-sky demonstration of phasing.
The wavelength range incorporated by the testbed shall be $0.6\ \mu m < \lambda < 1.35\ \mu m$.	Includes the lower end of the wavelength range of the AGWS and the upper end of the wavelength range for the NGWS.

offer the necessary characteristics, having a larger stroke and inter-actuator pitch. Both of these components will be optically conjugate to one another. The design includes the segmented array of tip-tilt stages and deformable mirror that recreate the GMT optics.

The telescope simulator will be fed by a starlight and atmosphere simulators with realistic characteristics such as star color, brightness, asterism and atmospheric conditions similar to those of the observatory in Chile. This will allow us to accurately verify the performance of the wavefront sensors and instruments. The metrology system is currently under consideration. Since the telescope simulator will work in closed loop with the wavefront sensors, we must use independent metrology for the pupil array and the deformable mirror. For the former, we are studying a low-cost Shack-Hartmann with a custom lenslet array that allows us to interferometrically sense pistons between each segments [7]. The deformable mirror will be sampled by a Zygo interferometer available in our lab.

To make the phasing testbed both cost effective and able to fit a standard 2m x 1m optical table, several considerations had to be implemented regarding the relay optics. While it is impossible on this scale to reproduce the full 20′ field of the GMT telescope, we settled on a 1′′ field of view that maintains the f/8.2 beam over a large waveband. Our baseline relay optics are large custom triplet lenses. Additional field lenses may be required if a wider bandpass becomes necessary. Our preliminary design for the relay optics currently delivers a diffraction-limited spot through the system for wavelengths between 0.60 and 1.35µm.

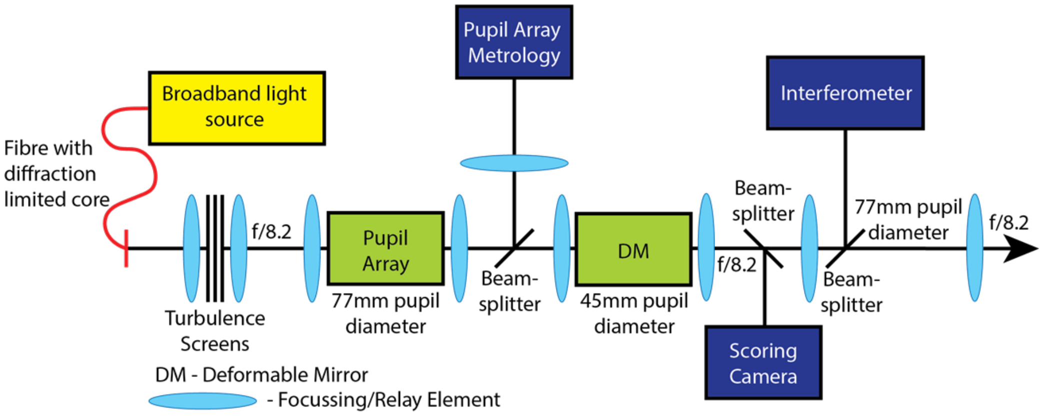

Figure 1. Concept diagram of the GMT phasing testbed. The telescope simulator (green) consists of the tip-tilt array and the deformable mirror (DM) introduced in this section. The metrology components are displayed in blue. The output beam following the steering mirrors lead to the wavefront sensors or instruments to be tested by the system.

The complexity of the optical design entails that the mechanical mounts for the components must be stable but also provide a solid reference for the optical alignment that must be maintained when the testbed is shipped (say between the GMT headquarters to the Observatory in Chile). Considerations such as the degrees of freedom of the optical mounts and the weight of the extra instruments on the table must be taken into account, as the slight bending of the table will affect the alignment. Our preliminary mechanical design fits all the testbed's components on a single 2 × 1 m optical table and delivers an image 60 cm away from the table, which is a sufficient enough distance to incorporate the wavefront sensors and other instruments on an adjacent table.

4. CONCLUSION

Before moving to construction, further study will be necessary to make the optical design compatible with other instruments like GMTIF which will need access to light as red as the K-band. A trade study between cost, band-pass and field of view is necessary to determine to optimum benefit of the testbed for the GMT project.

With the level of cost and complexity that future large observatories face, telescope simulators such as this one become a necessity. Not only they reduces risks during development and construction, but they provide a cost effective solution to the commissioning process of telescope subsystems like instruments and adaptive optics system.

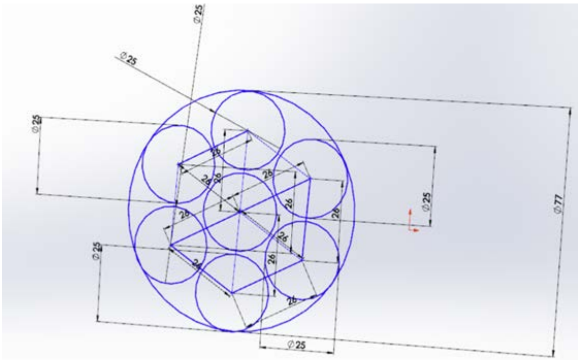

Figure 2. Layout of the seven PI stages reproducing the GMT aperture.

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