The Giant Magellan Telescope high contrast phasing testbed


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ABSTRACT

The Giant Magellan Telescope design consists of seven circular 8.4 m diameter mirrors, together forming a single 24.5 m diameter primary mirror. This large aperture and collecting area can help extreme adaptive optics systems such as GMagAO-X achieve the small angular resolutions and contrasts required to image habitable zone earth-like planets around late type stars and possibly lead to the discovery of life outside of our solar system. However, the GMT mirror segments are separated by large $>\,30\text{cm}$ gaps, creating the possibility of fluctuations in optical path differences (piston) due to flexure, wind loading, temperature effects, and atmospheric seeing. In order to utilize the full diffraction-limited aperture of the GMT for high-contrast imaging, the seven mirror segments must be co-phased to well within a fraction of a wavelength. The current design of the GMT involves seven adaptive secondary mirrors, a dispersed fringe sensor (part of the AGWS), and a pyramid wavefront sensor (NGWS) to measure and correct the total path length between segment pairs, but these methods have yet to be tested “end-to-end” in a lab environment. We present the design and prototype of a “GMT High-Contrast Phasing Testbed” which leverages the existing MagAO-X ExAO instrument to demonstrate fine phase sensing and simultaneous AO-control for high-contrast GMT natural guide star science. The testbed will simulate the GMT primary and secondary mirror phasing system. It will also simulate the future GMT ExAO instrument’s (GMagAO-X) “parallel DM” tweeter concept of splitting up the GMT pupil onto several commercial DMs using a reflective hexagonal pyramid. A dispersed fringe sensor will also be implemented into the testbed for coarse piston phase-sensing along with MagAO-X’s pyramid wavefront sensor to measure and correct the fine phasing level of the GMT primary mirror segments under realistic wind load and seeing conditions.

Keywords: Co-phasing, High-contrast imaging, ExAO, ELT, GMT

1. INTRODUCTION

Our galaxy hosts $\sim\,300$ billion stars, each likely to have at least one exoplanet orbiting around it. Out of the $\sim\,4,300$ exoplanets that have been discovered in our galaxy, 60 known nearby exoplanets are found to be in the habitable zones of their solar systems.\textsuperscript{*} If we want to answer one of mankind’s biggest questions, “Are we alone?” we need to detect signs of life by directly imaging these potentially habitable exoplanets in reflected light. This is a difficult task which requires Extremely Large Telescopes (ELTs; $\sim\,30\text{m}$ in diameter) to achieve high angular resolutions and contrasts, extreme adaptive optics (ExAO) to suppress the effects of atmospheric seeing, and coronagraphy to block the starlight.\textsuperscript{1}

These three technologies will all coexist once the 24.5 m Giant Magellan Telescope (GMT) is completed in 2029. With the combined power of ExAO and the future GMT, the discovery of life outside of our solar system may become a reality. However, the GMT’s unique seven segmented mirror design generates a challenge that will make direct imaging of exo-earths difficult.

The GMT consists of seven 8.4 m primary mirror segments (see Figure 1) that are separated by $>\,30\text{cm}$ gaps, essentially creating seven different “telescopes.” In order to combine the power of all seven mirrors into a single 24.5 m telescope,
the segments must be “co-phased,” meaning that the optical path difference (OPD) between all seven mirrors is equal. Temperature changes, gravity load, wind buffeting, and even atmospheric seeing will cause the OPD to fluctuate as much as tens of microns. OPD in the form of piston is of particular concern, since piston cannot be sensed by conventional wavefront sensor methods such as the Shack-Hartmann. Figure 1 shows an example simulation of what the PSF could look like at $\lambda = 656$ nm for the GMT segments co-phased (zero piston error) versus the GMT segments having random piston errors between $\pm 1 \mu m$, assuming no atmospheric turbulence. The result is a reduction in image quality that would not allow an ExAO system’s coronagraph to properly block out the starlight and image an exoplanet. This is why the GMT segments must be co-phased to within a fraction of a wavelength ($\leq 45$ nm RMS) to achieve diffraction-limited performance.

![Figure 1: (Left) The GMT pupil with segments co-phased. (Right) The GMT pupil with off-axis segments having random piston errors between $\pm 1 \mu m$. The resulting PSFs are shown below with a linear color scale to show more detail.](image)

The current design of the GMT involves seven adaptive secondary mirrors, a dispersed fringe sensor (part of the AGWS), and a pyramid wavefront sensor (part of the NGWS) to measure and control the OPD between segment pairs. In NGSAO mode, the DFS phasing camera will be used to reduce the OPD to within capture range of the pyramid wavefront sensor (PWFS), which can theoretically control segment piston errors to within 20 nm RMS. These methods, in particular the PWFS, have yet to be tested with real optics in a lab environment to demonstrate fine phase sensing and simultaneous AO-control for high-contrast GMT natural guide star (NGS) science.

The Magellan Extreme Adaptive Optics system (MagAO-X) is a new visible-to-near-IR ExAO instrument designed for the 6.5-m Magellan Clay telescope in Chile that was recently built (completed fall 2019) in the Extreme Wavefront Control Lab at the University of Arizona (UA). MagAO-X utilizes a PWFS and a 2,040 actuator Deformable Mirror (DM) to produce images with high Strehl ratio (> 70 %), high resolution (19 mas), and high planet/star contrasts ($< 10^{-4}$) at 656 nm to measure and correct atmospheric distortions and image exoplanets with high precision.

We plan to leverage MagAO-X to create a GMT High-Contrast Adaptive Optics phasing Testbed (HCAT) that will test a PWFS’s ability to measure and correct piston co-phasing errors between the GMT segments while simultaneously correcting for atmospheric turbulence. The testbed will involve a DFS for coarse piston phase sensing and test the GMagAO-X “parallel DM” concept using a reflective hexagonal pyramid that will split the GMT pupil onto several piezo-actuated mirrors for fine piston/tip/tilt control. The goal of HCAT is to demonstrate GMT segment piston control at the tens of nanometers level for high-contrast NGS science using a PWFS and show that the parallel DM concept will work for the
future GMagAO-X instrument. Here we show the progress of three different phases of the testbed: the “Proto”-Testbed, the “Proto”-HCAT (P-HCAT), and HCAT.

2. THE PROTO-TESTBED

2.1 Optical Design

The Proto-Testbed was built in February 2020 to create a simple four-segment GMT simulator with one segment variable in piston/tip/tilt. This testbed provided a basic understanding of segment co-phasing and helped pave the way for HCAT. Figure 2 shows the optical design of the Proto-Testbed as well as the lab setup. The design consists of two separate pupil relays. In the first relay, a physical pupil mask is used to define a four-segment GMT pupil that is re-imaged onto the

![Optical Design Diagram](image)

Figure 2: (Top) the optical design of the Proto-Testbed. A physical mask is used to define the GMT pupil, which is optically relayed onto a \( \Phi 3.0'' \) mirror with a hole to allow a single \( \Phi 1.0'' \) mirror to poke through. The GMT simulator is designed to output an F/11 beam for MagAO-X. (Bottom) the lab setup of the Proto-Testbed
surface of a ∅ 3.0” flat mirror in the second relay. The ∅ 3.0” mirror has a hole cut into it, which allows a ∅ 1.0” flat mirror to “poke” through exactly over one of the re-imaged GMT segments so that it may vary in piston, tip and tilt, while the other three segments are fixed piston on the flat ∅ 3.0” mirror. Since the GMT will deploy only four of its seven segments for first light, we decided to simulate only four segments for this testbed. Simulating only four of the seven GMT segments also simplified the optomechanical design and made the cost of the Proto-Testbed cheaper. Commercial off-the-shelf (COTS) lenses were used to create each pupil relay, so there was a large amount of chromatic aberration when using white light. However, we plan to switch these lenses for custom triplets in the future to make the design more achromatic for feeding MagAO-X (see Section 2.5). The size of the pupil mask and the focal lengths of the lenses were designed to output a converging F/11 beam for feeding light into MagAO-X.

2.2 The “Holy Mirror”

The ∅ 3.0” mirror with a hole (nicknamed the “holy mirror”) was fabricated by Tucson Optical Research Corp. to allow a ∅ 1.0” mirror to poke through the hole exactly around one of the re-imaged GMT segments. The ∅ 1.0” mirror was glued to a compact kinematic mount and mounted to a manual differential micrometer to simulate real manual piston/tip/tilt co-phasing errors of one of the GMT segments (see Figure 3).

Figure 3: A conjugate pupil plane is created on the surface of a ∅ 3.0” mirror, which was fabricated with a hole in it to allow a ∅ 1.0” mirror to poke through. (Left) the ∅ 1.0” mirror was glued to a compact kinematic mount and mounted to a differential micrometer to simulate real piston/tip/tilt co-phasing errors of one of the GMT segments. (Right) the image of the pupil overlayed onto the holy mirror.

The holy mirror was specified to have a surface flatness of < λ/10 PV over 90% CA in order to ensure that the re-imaged GMT segments have similar piston values to within a small fraction of a wavelength on the flat mirror. To verify this, we measured the mirror on a Zygo interferometer. The Zygo measurements, shown in Figure 4, show that the surface flatness was not within λ/10 PV due to the hole that was carved. Even when the edges of the hole were masked out, the surface flatness was calculated to be λ/5 PV at best. We did find, however, that the portion of the mirror that was illuminated by the uniquely-shaped four-segment GMT pupil may still be within a λ/10 flat area. The final image results verify this.

2.3 Dispersed Fringe Sensor

To verify the piston alignment of the ∅ 1.0” mirror, we incorporated a dispersed fringe sensor (DFS) into the design. The DFS allowed us to find the “white light fringe,” or zero OPD point, by interfering the light between two segments and dispersing the light. Figure 5 shows the DFS setup in the lab. A beamsplitter was introduced into the final converging beam...
Figure 4: (Left) The $\varnothing$ 3.0” holy mirror Zygo surface measurements (90% CA). (Right) The $\varnothing$ 3.0” holy mirror Zygo surface measurements with edges of the hole masked out (90% CA). The colorbar is in units of waves.

to split the light into a science channel and a DFS channel. The science channel propagates the full four-segment PSF to a CCD, while the DFS channel blocks the top and bottom segments to interfere the light from the variable piston segment and one of the fixed piston segments. A GRISM then disperses the light to create dispersed fringes in the focal plane. As the $\varnothing$ 1.0” mirror drives in piston, the dispersed fringes create a “barber pole” shape, indicating that the segments are not co-phased. As the piston approaches the zero OPD point, the barber pole shape disappears, leaving a straight “line.”

Figure 5: The DFS setup. A beamsplitter splits the light into a science channel and a DFS channel. The science channel propagates the full four-segment PSF while the DFS channel blocks the top and bottom segments to interfere the light between the variable piston segment and one of the fixed segments. A GRISM then disperses the light to create dispersed fringes in the focal plane.

Dispersed Fringes

Out of phase

In phase

600 nm

500 nm

Co-phased PSF

GRISM

BS

Converging F/11 beam

To take this a step further, an undergraduate student, Ritvik Basant, created a Python quasi-real time program which takes the FFT of the dispersed fringes and traces a line through the lobes of the response (see Figure 6). When the slope
of the line is zero, we have reached the zero OPD point (white light fringe) for the $\varnothing$ 1.0” mirror’s piston. This is a useful alignment tool which allows us to perform coarse piston co-phasing of the $\varnothing$ 1.0” mirror while simultaneously observing the four-segment PSF in the “science” channel. See video for a demonstration. We plan to incorporate a DFS with this FFT tool for HCAT to perform coarse piston phase sensing while feeding MagAO-X.

Figure 6: (Left) The dispersed fringes when the $\varnothing$ 1.0” mirror has a large piston error. (Right) the dispersed fringes when the $\varnothing$ 1.0” mirror has almost zero piston error w.r.t. the holy mirror. The truncated FFT responses are shown below with a line traced through the lobes. This allows easy alignment of the $\varnothing$ 1.0” mirror’s piston. See video for a demonstration.

2.4 The Four-Segment PSF

The four-segment GMT pupil creates an interesting PSF that is similar to the seven-segment PSF, however slightly elongated (6 x 9 mas at $\lambda = 656.3$ nm on-sky). It is useful to take the FFT of the GMT pupil to familiarize oneself with the PSF. Figure 7 shows a comparison of the real co-phased four-segment PSF observed on the CCD in the final focal plane of the Proto-Testbed with the simulated four-segment PSF (by taking the FFT of the four-segment GMT pupil in MATLAB). A

Figure 7: (Left) The real co-phased four-segment PSF as observed on the CCD in the final focal plane of the Proto-Testbed. (Right) The simulated four-segment PSF created by taking the FFT of the four-segment pupil in MATLAB. A 550 nm ± 40 nm filter was used in both cases. See video for a “walk through piston” demonstration of the four-segment PSF.
550 nm ± 40 nm filter was used to minimize chromatic aberration from the COTS lenses. The comparison of the real PSF with the simulated PSF is strikingly similar (the only noticeable difference being the stretch), indicating that the segments are indeed co-phased in narrowband white light.

2.5 Custom Triplets

Since we used COTS lenses in the design of the Proto-Testbed, there was a significant amount of chromatic aberration that limited us to working in a relatively narrow bandwidth (± 40 nm BW for the science channel and ± 100 nm BW for the DFS channel). Although using COTS lenses was not ideal, it was necessary to gain a head start on building the Proto-Testbed and gain a basic understanding of segment co-phasing. For feeding MagAO-X, however, an achromatic beam is absolutely necessary. Therefore, we plan to replace the COTS lenses with custom triplet lenses to make the Proto-Testbed suitable for feeding MagAO-X.

The custom triplets were designed to replace the current COTS $f = 750$ mm lenses, but not the COTS $f = 250$ mm lenses. The custom triplet lenses could be designed such that the chromatic aberration from the first two lenses were cancelled. This reduced the cost of adding two additional custom triplet lenses. Figure 8 shows the result of adding the chromatic focal shift plots from the first COTS lens relay with the new custom triplet lenses (x2). Since the custom triplets were designed to have the opposite focal shift curve of the COTS lens relay, adding the focal shift curves together results in a final focal shift curve that is minimized (< 100 µm focal shift from 650 nm – 950 nm at F/11.24).

Figure 8: Chromatic focal shift plots from the first pupil lens relay (top left) and the new custom triplet lenses (top right). The resulting chromatic focal shift plot is shown below.

The custom triplets were designed in Zemax with S-BSM81, S-BSM2, and S-NBH5 glasses from Ohara Corp. Each lens consists of the same design with an effective focal length of 750 mm and an outer diameter of 3.50". Figure 9 shows the Zemax layout of the custom triplet.
3. THE P-HCAT

3.1 Optical Design

To feed light from the Proto-Testbed into MagAO-X, the design was modified to accommodate the new custom triplet lenses and a few other considerations. Therefore, we named this updated design the “Proto”-HCAT (P-HCAT). The P-HCAT will be rebuilt on a new TMC floating optical table in a room next-door to the MagAO-X lab. A hole has been cut in the wall between the labs to allow light to propagate from P-HCAT into MagAO-X.

The MagAO-X instrument was built on a similar TMC floating optical table that has a PEPS-II closed-loop feedback system to lock the position of the floating table. This technique was used successfully on-sky at the Magellan-Clay telescope to allow MagAO-X to sit on the Nasmyth platform separate from the telescope while maintaining a stable alignment. Therefore, we predict that P-HCAT will not need a PEPS-II system, however we can always add one in the future if needed.

The design of the Proto-Testbed was modified to incorporate the new custom triplet lenses and two new COTS lenses for the first pupil relay (see Figure 10). These new COTS lenses (Thorlabs $f = 1000$ mm and Thorlabs $f = 250$ mm) were

![Diagram of P-HCAT](image)

Figure 10: The Zemax layout of P-HCAT designed for feeding MagAO-X. The custom triplets and two new COTS lenses were incorporated into the design, along with a flip mirror to create a “standalone mode” option when MagAO-X is not being used.
used in the design of the custom triplets. A “flip” mirror will be placed after the last lens to allow operation of the testbed in “standalone mode” without MagAO-X if needed. In standalone mode, a beamsplitter will be placed in the final converging beam to create the same DFS/science split as shown previously in Figure 5. When MagAO-X is used, the flip mirror will be removed to allow light to propagate into MagAO-X, and the DFS will be installed inside MagAO-X to simultaneously observe the dispersed fringes while observing the PWFS signal.

Figure 11 shows the solid model of P-HCAT feeding MagAO-X. In the top image, P-HCAT is shown mounted on the new TMC floating optical table on the right, feeding light into MagAO-X through the wall on the left. In the bottom image, a detailed view of P-HCAT is shown in “standalone mode.” In standalone mode, a beamsplitter will be used to split the light into a science channel and a DFS channel, similar to the lab setup shown in Figure 5.

Figure 11: (Top) P-HCAT feeding MagAO-X through the wall in between the labs. (Bottom) a detailed view of the P-HCAT solid model in “standalone mode.”
3.2 PI S-325 Piezo Actuator

The initial design of the Proto-Testbed consisted of a manual piston/tip/tilt alignment of the $\varnothing$ 1.0” mirror. For P-HCAT, we plan to switch this manual setup with a PI S-325 piezo actuator that can piston, tip and tilt electronically with closed-loop strain gauge accuracy. This will allow us to close the loop between MagAO-X’s PWFS and the piezo actuator to properly demonstrate that a PWFS can measure and correct segment piston at the nanometer level. If we can successfully close the loop between MagAO-X’s PWFS and the PI S-325 actuator with P-HCAT, we will move onto the build of HCAT (see Section 5).

To incorporate the PI S-325 actuator into the design of P-HCAT, a custom mount was designed to hold the actuator on the back of the $\varnothing$ 3.0” kinematic mount so that the actuator may stick through the hole in the $\varnothing$ 3.0” holy mirror. A $\varnothing$ 1.0” mirror will be glued to the face of the actuator. The mount is a custom stainless steel disk with an offset hole that will be glued to the back of the kinematic mount (see Figure 12). A Polaris® stainless steel clamp will then be mounted on the disk to hold the actuator securely. This solution allows the $\varnothing$ 3.0” holy mirror and $\varnothing$ 1.0” mirror to be aligned together globally with the $\varnothing$ 3.0” kinematic mount. Then, the piezo actuator will be used to steer the local piston, tip and tilt of the $\varnothing$ 1.0” mirror.

![Figure 12](image-url)

(a) The PI S-325 piezo actuator. (b) The custom piezo mount assembly glued to the back of the $\varnothing$ 3.0” kinematic mirror mount. (c) The completed custom piezo mount assembly.

4. THE PARALLEL DM CONCEPT

The purpose of HCAT is to simulate all GMT segments varying in piston, tip, and tilt using PI S-325 actuators, while also testing the GMagAO-X “parallel DM” concept of splitting up the GMT pupil onto seven commercially available Boston Micromachines Corp. (BMC) 3,000 actuator DMs in a “woofer-tweeter” configuration.6

Figure 13 shows a conceptual model of the GMagAO-X parallel DM concept. In order to create a 21,000 actuator ELT-scale ExAO tweeter DM, the GMT pupil must be split up and optically distributed onto seven commercially available BMC 3k DMs. This could be accomplished using a reflective hexagonal pyramid and PI S-325 actuators to help control the piston, tip and tilt alignment of each segment. Collimated light from a lens would propagate towards the hexagonal pyramid, which would reflect the light from each segment outwards toward a PI S-325 actuator that folds the light onto a BMC 3k DM. The central GMT segment would propagate through a hole in the center of the pyramid and onto a BMC 3k DM. The light from each segment would then reflect back through the system in a double-pass configuration.

This design has a limit to its compactness, since the DM circuit boards interfere with each other. Ideally, we want the optical path length (OPL) to be as small as possible between the hexagonal pyramid and the DMs to prevent any vignetting of the field. To make the design more compact, another configuration could be possible where every other DM is “flipped” in a pattern around the hexagonal pyramid (see Figure 14). This prevents the DM circuit boards from interfering with each other and allows them to move closer to the hexagonal pyramid. In addition, the window chamber of each DM could be removed if the entire assembly is placed in an environmental chamber to control the humidity. This would allow the PI S-325 actuators to be moved closer to the DMs, further reducing the OPL to a total of $\sim$100 mm between the hexagonal...
Figure 13: The GMagAO-X “parallel DM” concept. To create a 21,000 actuator ELT-scale ExAO tweeter DM, the GMT pupil must be split up and optically distributed onto seven commercially available BMC 3k DMs.

Figure 14: A more compact version of the GMagAO-X “parallel DM” concept. Every other DM is flipped upside down with respect to the other in order to avoid circuit boards from interfering and allow the DMs to be closer to the pyramid.
pyramid and the DMs. This would give us an unvignetted 2” x 4” FOV, which would work for GMagAO-X. HCAT will test this concept.

5. HCAT

Figure 15 shows the optical design of HCAT. The design will be similar to P-HCAT with an additional pupil relay added in the middle. This additional pupil relay will consist of a Thorlabs knife-edge prism mirror introduced in the first focal plane to fold the light towards a custom triplet lens designed to form an image of the GMT pupil with $\varnothing$ 18.6 mm segments (the size of the BMC 3k DMs). A custom reflective hexagonal pyramid will split up the four-segment GMT pupil onto three PI S-325 actuators that fold the light onto flat mirrors which represent “BMC 3k DMs” for the GMagAO-X “tweeter.” The PI S-325 actuators will introduce piston, tip and tilt co-phasing errors for each segment except the central GMT segment, which will propagate through a hole in the center of the hexagonal pyramid onto a flat mirror. A small tilt ($\sim 0.1^\circ$) will be applied to each flat mirror to propagate the light back through the system in a double pass configuration, allowing the knife-edge prism mirror to fold the light through the rest of the system. The last pupil relay is where each GMT segment will be re-imaged onto PI S-325 actuators to simulate the “woofer” DM which can introduce additional piston, tilt and tilt co-phasing errors for each segment. Finally, the light will propagate into MagAO-X, where the PWFS will be used to measure segment piston errors. An additional reflective hexagonal pyramid will also be integrated into MagAO-X to split up the light into four GRISMs, creating a DFS for coarse piston sensing of all the GMT segments similar to the DFS discussed in section 2.3.

Since MagAO-X was designed for the 6.5 m Magellan-Clay telescope, the number of actuators on the MagAO-X tweeter DM are fixed. This means that for HCAT, the GMT pupil will have a limited actuator sampling. If we simulated a seven-segment GMT pupil, the sampling would be $< 1$ actuator in between segments, while a four-segment GMT pupil would have $> 1$ actuator in between segments on the PWFS detector (see Figure 16). This is what ultimately deterred us from working with a seven-segment GMT pupil and influenced us to keep working with the four-segment GMT pupil for HCAT to achieve better actuator sampling in between segments for piston wavefront sensing and AO control.
6. CONCLUSION

The GMT design consists of seven circular 8.4 m diameter mirrors that are separated by large > 30 cm gaps, essentially acting as seven separate “telescopes.” In order to combine the power of all seven mirrors into a single 24.5 m telescope, the segments must be co-phased to within a small fraction of a wavelength. The current design of the GMT involves seven adaptive secondary mirrors, a dispersed fringe sensor (part of the AGWS), and a pyramid wavefront sensor (part of the NGWS) to measure and correct the total path length between segment pairs, but we need to test these methods in a lab environment with a real ExAO instrument to demonstrate fine phase sensing and simultaneous AO-control for high-contrast GMT NGS science. This paper presented results from a Proto-Testbed which was built to simulate a four-segment GMT with one segment variable in piston. The Proto-Testbed will soon be modified into the P-HCAT, which will involve custom triplet lenses to feed an achromatic beam into MagAO-X, and will for the first time demonstrate a closed-loop experiment between a PWFS and a segmented GMT pupil with the addition of a DFS. If the P-HCAT proves successful, HCAT will be built to simulate all segments varying in piston/tip/tilt while also simulating the GMagAO-X “parallel DM” concept using a reflective hexagonal pyramid to split up the GMT pupil onto piezo-actuated mirrors. The HCAT testbed will provide us with a deeper understanding of GMT segment co-phasing with simultaneous AO PWFS control that will be crucial for the success of GMT AO/ExAO and the search for life in extraterrestrial solar systems with GMagAO-X.

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