Phasing the Segmented Giant Magellan Telescope: Progress in Testbeds and Prototypes

Richard Demers[1]*, Antonin Bouchez[1], Fernando Quiros-Pacheco[1], Patricio Schurter[1], Breann Sitarski[1], Marcos A. van Dam[2], Dan Catropa[3], Jan Kansky[3], Brian McLeod[3], Stuart McMuldroch[3], Bill Podgorski[3], Laird Close[4], Victor Gasho[4], Sebastiaan Haffert[4], Alex Hedglen[4], Maggie Kautz[4], Jared Males[4], Guido Agapito[5], Nicolò Azzaroli[5], Luca Carbonaro[5], Anne-Laure Cheffot[5], Simone Esposito[5], Tommaso Lapucci[5], Enrico Pinna[5], Cédric Plantet[5], Alfio Puglisi[5], Fabio Rossi[5] , Guillermo Gonzalez[6], Bijan Nemati[6]

[1]GMTO Corporation, 465 N. Halstead St., Suite 250, Pasadena, CA USA 91107;
[2]Flat Wavefronts, 21 Lascelles Street, Christchurch 8022, New Zealand;
[3]Smithsonian Astrophysical Observatory, 60 Garden St, Cambridge, MA USA 02138;
[4]Steward Observatory, 933 N. Cherry Ave., Tucson, AZ USA 85719;
[5]Istituto Nazionale di Astrofisica (INAF) Arcetri, Largo Enrico Fermi n.5, 50125 Firenze ITALY
[6]Tellus1 Scientific, LLC, 8000 Madison, Blvd., Ste. D102-265, Madison, AL 35758

ABSTRACT

One of the greatest technical challenges of the doubly-segmented Giant Magellan Telescope is the accurate and stable control of segment piston in the diffraction limited observation mode. To address this challenge, in collaboration with the University of Arizona, Smithsonian Astrophysical Observatory and the Istituto Nazionale di Astrofisica, GMTO is executing a project to optimize and validate segment piston control strategies and algorithms using a pair of testbeds. The testbeds provide disturbances to simulate atmospheric turbulence and differential atmospheric dispersion. In addition to the phasing demonstration, the testbeds offer the opportunity to validate hardware designs for the Acquisition & Guiding Wavefront Sensor (AGWS) and the Natural Guide Star Wavefront Sensor (NGWS) and to mitigate their fabrication and assembly risks. Significant progress is reported in the design of the AGWS and NGWS prototypes as well as preliminary test results from the testbeds.

Keywords: Giant Magellan Telescope, adaptive optics,wavefront sensing, segment phasing, segmented telescope, diffraction limited imaging

1. INTRODUCTION

The GMT will operate in one of four observing modes[1] depending on the desired FOV, image quality, and required sky coverage of the scientific observation: 1) Natural Seeing, 2) Ground-layer Adaptive Optics (GLAO), 3) Natural Guide Star Adaptive Optics (NGAO), and 4) Laser Tomography Adaptive Optics (LTAO). The NGAO and LTAO control modes deliver diffraction-limited image quality to the science instruments. To achieve diffraction-limited performance across the entire 25.4-meter doubly-segmented telescope aperture, the WFSC must correct incident starlight for atmospheric turbulence, wind shake, and observatory vibrations; and correct for position and segment piston errors in the doubly segmented optical system. The GMT segmented pupil is shown in Figure **1**-**1**.

During observations in the diffraction-limited observation modes, the wavefronts emerging from the seven telescope segment pairs must be matched in segment piston to a small fraction of the observing wavelength. GMT's large M1 and M2 segment gaps and its M1 borosilicate glass segments pose a unique challenge in correcting for segment piston error. The significant advantages of the GMT architecture include the stiffness of the round segments and simplicity of

*rdemers@gmto.org; phone 1 626 555-1234

Adaptive Optics Systems VIII, edited by Laura Schreiber, Dirk Schmidt, Elise Vernet,
Proc. of SPIE Vol. 12185, 1218518 · © 2022 SPIE
0277-786X · doi: 10.1117/12.2630144

controlling a small number of them. Each of the ELTs must develop wavefront sensing and control systems that will correct and stabilize segment piston error from 10's of microns to 10's of nanometers. Each will arrive at a unique wavefront and phasing control solution tailored to their architecture. The GMT will control segment piston error in closed-loop, using dedicated wavefront sensors observing on- and off-axis natural guide stars and also using intersegment-metrology edge sensors. The phasing corrections are applied to the Adaptive Secondary Mirror System (ASMS), which can be controlled with high bandwidth and precision and later offloaded to slower moving optics. GMT will use the AGWS, NGWS & On-Instrument Wavefront Sensor (OIWFS) to sense and control wavefront error.

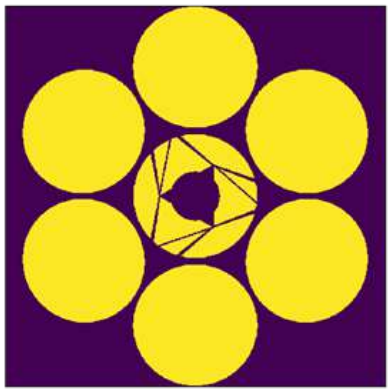

Figure 1-1The true GMT pupil with center segment obscurations caused by the secondary mirror support structure shadows.

GMT's strategy and design for the segmented telescope phase control system has been developed. Modeling and simulation have informed the development of requirements and performance budgets. The wavefront control design for the NS, GLAO, NGAO and LTAO observing modes will be at the preliminary design level by the end of calendar year 2022. The design for wavefront control of all four observing modes is expected to be at final design level by the end of calendar 2024 in time for the observatory construction phase.

In support of the design phase we are addressing our leading technology risks by building and operating two Wavefront Sensing and Control (WFSC) testbeds and two prototypes under an National Science Foundation (NSF)-funded technology development subaward administered by AURA (The Association of Universities for Research in Astronomy). Kicked off in September 2020, the subaward supports a technology development project addressing the leading technology risks of GMTO including the primary mirror (M1) active optics control system, the Adaptive Secondary Mirror Subsystem (ASMS) off-axis segment fabrication and positioner motion control performance, and the WFSC algorithms and sensors for phasing the doubly-segmented telescope and rejecting wavefront disturbances.

The specific WFSC technology development objectives under this program are:

- Demonstration of phasing of a doubly-segmented GMT telescope simulator
- Testing of algorithms to suppress wavefront error induced by atmospheric turbulence, wind and vibrations representative of the GMTO environment
- Advancement of the designs of the AGWS and NGWS which had previously passed Preliminary Design Review
- Mitigation of fabrication and assembly risks of the AGWS and NGWS

Progress and advancement of the Technology Development project is measured by the successful completion of a series of technology milestones that include demonstrations of the wavefront sensor prototypes and staged phasing demonstrations in each of the two fully integrated testbeds. Each milestone, whose completion is evaluated by external independent reviewers, represents a significant technical achievement and is a gate to the next phase of development. At the completion of the NSF Development project by the end of calendar year 2023, GMTO will have an advanced understanding of the design and performance of the WFSC architecture and verification of its performance in the testbeds that will then enable completion of the final design phase.

2. PHASING STRATEGY

Before reporting the testbed progress, we outline the strategy for phasing the GMT. The testbeds are designed to validate this strategy.

The GMT pupil (Figure **1-1**) is perforated by the gaps between the segmented M1 and M2 (ASM) mirror pairs and by the obscurations resulting from the shadows of the ASMS support structure. To eliminate segment piston error the wavefront control system must i) equalize the optical path length from each M1 segment to the instrument image plane and ii) compensate the apparent atmospheric segment piston resulting from the continuous atmospheric phase error viewed through the discontinuous pupil. During the diffraction-limited observation modes, the wavefronts emerging from the seven telescope segment pairs must be matched in overall segment piston to a small fraction of the observing wavelength. We use the term segment piston to mean the difference in optical path length between the seven segment pairs, defined as the average of the six differential piston values. The corrections are applied to the ASMS, which can be controlled with high bandwidth and precision

GMT's unique doubly segmented architecture with 35 – 40 cm M1 segment gaps and high thermal expansion M1 borosilicate glass segments led to a unique segment phasing design strategy. GMT will not rely solely on intersegment metrology edge sensors to maintain segment piston alignment. The GMT will instead control segment segment piston error in a closed-loop, using dedicated wavefront sensors (the NGWS, OIWFS, and AGWS) observing on- and off-axis natural guide stars. The M1 edge sensors measurements will be used concurrently with the WFS measurements in closed loop in the LTAO mode. Phasing in the NGAO control mode is expected to work without edge sensors. The GMT segment phasing occurs in operational steps as follows:

Step 1 – Following a slew to a new target, the Telescope Metrology Subsystem (TMS) Laser Metrology Truss (LMT) is first used to align all segments to ~10 μm accuracy, bringing them within the capture range of the wavefront sensors.

Step 2 – The AGWS carries out coarse phasing and controls field depending segment piston error. It does so by observing 3-4 off-axis natural guide stars over a 20 arcminute diameter field and measures their wavefront and segment piston errors every 30 seconds. This enables the correction of slowly evolving errors such as those induced by gravitational and thermal effects, resulting in residual wavefront error ≤ 100 nm RMS over at least 90% of the observable sky.

Step 3a (NGAO control mode) – GMT will control the on-axis wavefront and segment piston errors at high bandwidth using feedback from the visible light NGWS and will implement corrections using the ASMS. The NGWS splits incoming visible light between a pyramid wavefront sensor main channel and a holographic dispersed fringe sensor[13] (HDFS) 2nd channel. The pyramid wavefront sensor is sensitive to both continuous aberrations across the pupil and phase differences across the segment gaps. Its performance is very robust with typical guide stars in good to median seeing conditions. In poor seeing conditions, however, the pyramid wavefront sensor is susceptible to phase wrapping errors (an ambiguous phase shift of an integer number of waves). The visible HDFS 2nd channel will disambiguate the phase wrap ambiguity in segment piston measurements by interferometrically sensing the segment piston between each adjacent segment pair over a large dynamic range without phase wraps. Simulations of the pyramid WFS with the HDFS 2nd channel using GMT's CEO (CUDA-Engined Optics) ray trace and wave propagation tool show robust segment piston and wavefront control compliant with requirements.

Step 3b (LTAO control mode) – Segment piston errors are measured using an On-Instrument Wavefront Sensor (OIWFS) observing a faint on- or off-axis natural guide star in the infrared and then corrected in closed-loop using the ASMS. The OIWFS measures tip/tilt, focus, and segment piston error at 50-500 Hz using phase retrieval in a diffraction-limited imaging camera at a wavelength of 2.1 μm. Edge sensors between the M1 segments and between M2 segments will be used to supplement the OIWFS feedback at high bandwidth. Simultaneously, the high spatial order wavefront will be measured using six Shack-Hartmann wavefront sensors observing an asterism of six laser guide stars. Shack-Hartmann sensors measure local wavefront slopes and therefore are blind to phase differences across pupil discontinuities and thus are not relied on for segment piston feedback. Both the low-order wavefront errors measured by the OIWFS, and the high-

order errors measured using the laser wavefront sensors are corrected with the ASMS. The OIWFS can only measure segment piston for a subset of the tip-tilt stars, failing for stars that are either too faint or too far off-axis.

Step 4 (Common to both NGAO & LTAO control modes) – Concurrent with the NGWS or OIWFS control of the wavefront and segment piston, the AGWS will provide feedback to control field-dependent wavefront errors at low bandwidth, including field-dependent segment piston error resulting from ASMS tilts implemented to correct M1 segment tilts.

3. TESTBED STRATEGY

We assessed building and operating a single testbed analog to the GMTO WFSC architecture. Accurately simulating the GMT in a single testbed would require a high pitch, large format deformable mirror and a wide field of view. Since the currently available COTS DMs are very small, matching them to a wide f/8 field would be challenging and costly. We opted for a phased technical risk approach. As a first step two testbeds were formulated by partitioning of the technical challenges of both phasing control and rejection of wavefront error due to turbulence and wind. Partitioning the architecture serves: 1) to reduce complexity, thereby enabling easier disentanglement of known and unknown overlapping effects; 2) to progress faster via parallel efforts; and 3) to leverage the broadest possible team of subject matter experts from GMTO and its partner institutions. The GMTO WFSC architecture is therefore partitioned between the two testbeds with complimentary functionality and performance.

The Wide Field Phasing Testbed (WFPT) will demonstrate low order wavefront control using the AGWS and active optics while simultaneously sensing and controlling segment segment piston of a doubly-segmented telescope to 50 nm RMS over a wide field. The WFPT will simulate the active optics control used in the Ground Layer Adaptive Optics (GLAO)[2] observing mode[2]. The AGWS prototype will be integrated with the WFPT. The AGWS utilizes a dispersed fringe sensor[3] and a Shack Hartmann sensor to detect segment phase. The WFPT and AGWS have been designed and are being fabricated, integrated and operated by SAO in collaboration with GMT's WFSC group.

The High Contrast Adaptive Optics Testbed (HCAT) will demonstrate capture and stable control of segment segment piston simultaneously with high order wavefront control over a narrow field. The HCAT benefits from integration with MagAO-X[4], a working extreme AO instrument used on the Magellan telescope in Chile. The NGWS prototype will be integrated with HCAT for the fine phasing demonstration and optimization of the control algorithms developed for the diffraction limited observation mode. The HCAT is being fabricated, integrated and operated by the University of Arizona in collaboration with GMT's WFSC group. The NGWS prototype is being designed, fabricated and integrated jointly by the Istituto Nazionale Astrofisico (INAF) and GMT's WFSC group.

Before initiating major testbed design efforts GMT convened an independent nonadvocate review of the testbed strategy in December 2020. The independent reviewers re-affirmed the wavefront sensing and control (WFSC) testbed strategy while making recommendations and identifying actions for the teams. All actions were closed and all recommendations were evaluated and most were followed.

4. WIDE FIELD PHASING TESTBED

The WFPT was designed by SAO[5] based on an initial design concept from GMT's WFSC group. The WFPT is comprised of three optical sections. The first section contains the starlight source, the sources of the aberrations and the GMT telescope simulator. This is followed by a second section output relay. The final section is the wavefront sensors and scoring camera (aka truth sensor). This WFPT telescope simulator utilizes two custom Piston and Tip-Tilt (PTT) hexagonally-segmented mirror arrays[6] (Figure **4**-**4**) to emulate the GMT segment tip-tilt and piston and two ALPAO high stability deformable mirrors (Figure **4**-**5**) to simulate the GMT M1 and M2 segment shape actuators. The testbed analogs for each of M1 and M2 consist of a PTT array paired with a DM. The PTT/DM pairs are located at M1 and M2 conjugates as illustrated in Figure **4**-**1**. The starlight is provided by a single mode fiber positioned by a precision mechanism replicating stars of R magnitude between 10 and 18. Atmospheric turbulence is introduced by a rotating phase screen and atmospheric dispersion is injected using an Atmospheric Dispersion Compensator to create dispersion. An Offner Relay at the GMT simulator output matches the f-number of the AGWS input beam.

The AGWS (illustrated in Figure **4-2**) is a full-scale engineering model of a single AGWS probe. The GMT Observatory will have four identical AGWS probes patrolling off-axis stars over a 20-arcminute diameter field. The AGWS probe contains a visible Shack Hartmann sensor for acquisition, initial segment pointing synchronization, fast tip-tilt correction and active optics sensing. The GMT image quality requirements can be met using only three probes, but the fourth will be used to exceed required image quality whenever there is an available fourth guide star.

The WFPT will be operated in two test stages. In the first stage the testbed is integrated with the existing Proto3L wavefront sensor which has been used on sky at the Magellan telescope. In this stage—currently in progress—the team is running a series of functional on-axis tests. In the second stage with the AGWS fully integrated we will run functional tests followed by quantitative performance tests first on-axis then off-axis over a 20-arcminute diameter field of view.

The WFPT and AGWS prototype successfully passed independent nonadvocate Preliminary and Final Design Reviews in March and June 2021, respectively. Subsequently all major reviewer actions were completed and all recommendations were addressed.

At this writing we have made significant progress in Stage 1 testing. All testbed subsystems and components and been assembled, integrated, aligned[7] and verification tested. This includes the PTT array, DMs and phase screen. The testbed optical beamtrain was aligned end-to-end. The end-to-end static wavefront error, measured using a commercial 4D interferometer, handily meets its requirement of Strehl ≥50% at 850 nm. A notable achievement was validation of the design for the Dispersed Fringe Sensor (DFS) that will be integrated in the AGWS prototype to carry out segment segment piston control. As discussed earlier, the AGWS will carry out coarse phasing—one of the first steps in the process of phasing of the doubly-segmented telescope mirrors. SAO has demonstrated closed loop operation with sensing from both the Dispersed Fringe Sensor and Shack Hartmann Sensors with correction by both DMs & PTT arrays using GMT's "merged reconstructor" piston control algorithm to carry out coarse phasing of the segmented telescope in the WFPT.

The DFS has a unique design that relies on a precision-machined custom prism array that collects and interferes off-axis light from the edges of adjacent pairs of segments. The DFS accurately senses pure segment piston error between segments but cannot discriminate between a pure piston mode and a segment tilt. The Shack Hartmann which cannot sense phase discontinuity across segment gaps can, however, sense segment tilt and is used to disambiguate tilt from piston. Both sensors are thus fused in closed loop to sense and control piston. The prism array and DFS fringe patterns before and after piston correction appear in Figure **4-6**. There are twelve fringe arrays corresponding to the gaps between adjacent segments and there are six more fringe arrays used for calibration.

The DFS prism array is identical in form, fit and function to the one that will be used in the GMT Observatory. The DFS prism array was demonstrated while integrated into the Proto3L surrogate WFS. The DFS will be removed from the Proto3L sensor and integrated into the AGWS prototype once the latter is fully assembled and ready for integration with the testbed. The demonstration of the DFS functionality in phasing was a significant step in validating both the DFS design and the strategy for phasing GMT.

In parallel GMT is building a full physical optics model of the WFPT and AGWS which will be validated using testbed measurements. The model is based on GMT's custom built telescope optical model, CEO (CUDA-Engined Optics). CEO uses geometric ray tracing from sky to M1 and M2 and diffractive wave propagation from the exit pupil to the wavefront sensors and instrument focal planes. For this analysis the CEO model has been retrofitted with the WFPT optical beamtrain replacing the GMT observatory telescope optics. The testbed uses a wavefront controller identical to the one simulated in the testbed model. Once the model is in reasonable agreement with testbed measurements, the phasing control strategy will be further validated using this model with the observatory telescope optical design.

As part of the current testbed activity the SAO team is engaged in testing PTT actuator range and piston accuracy, validating motion stages accuracy, verification of star source brightness range and fitting Zernike modes to DM commands using an interferometer. In parallel the single-probe AGWS prototype (AGWS-p) is in assembly and integration. The assembly of all six internal mechanisms (Figure **4-2**) is nearly complete and ready for testing. The DFS CRED camera has been bench tested and is ready for integration. The completion of the AGWS-p and its integration with the testbed is expected to take place in August 2022.

The WFPT and AGWS must pass three more NSF milestones before completion of the risk reduction project:

WTB-6: Stage 1 Phasing Tests Complete (using the Proto3L wavefront sensor, functional phasing demonstration)

WTB-8: AGWS-p ready for testbed integration

WTB-10 Stage 2 Phasing Tests Complete (using the AGWS-p, full phasing performance).

These milestones are expected to be completed by the end of 3rd quarter calendar year 2023.

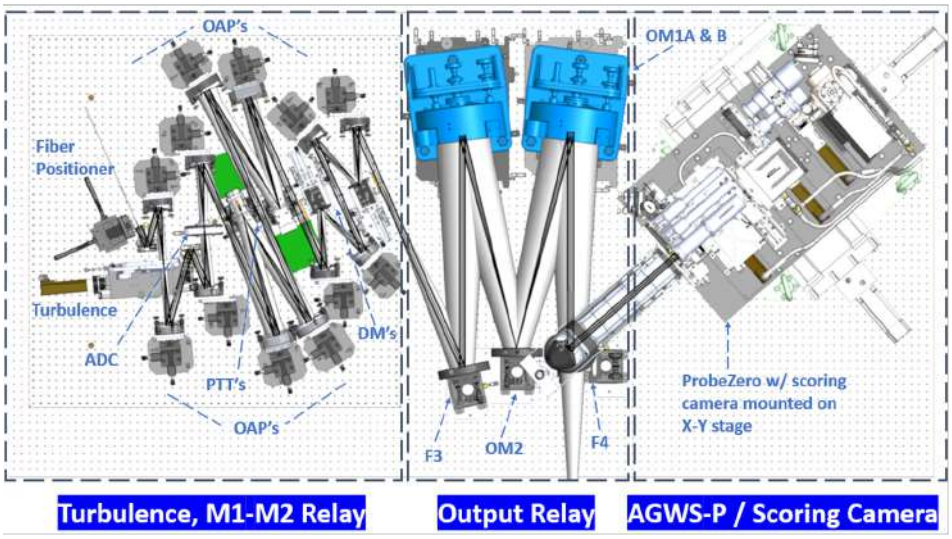

Figure 4-1 The GMT simulator uses segmented hexagonal mirrors and deformable mirrors at both M1 and M2 conjugates.

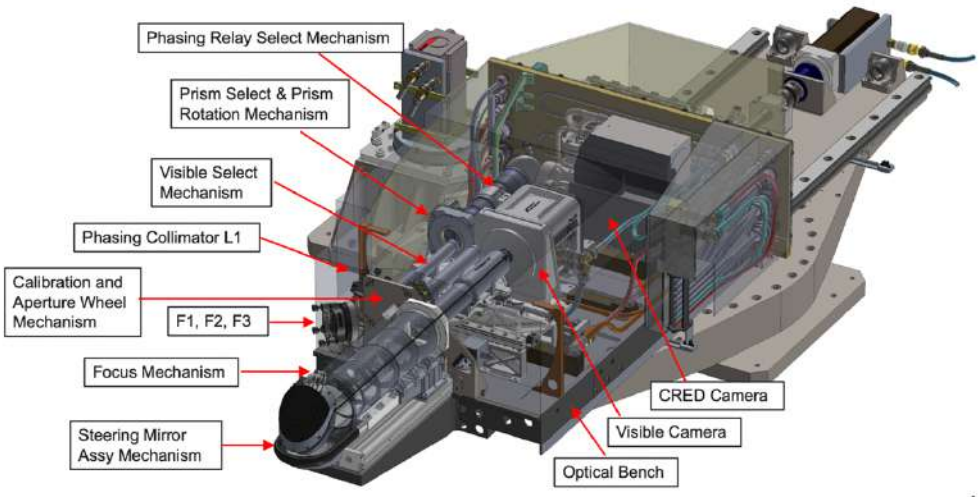

Figure 4-2 The AGWS Prototype is a full-scale engineering model of a single probe following the observatory design.

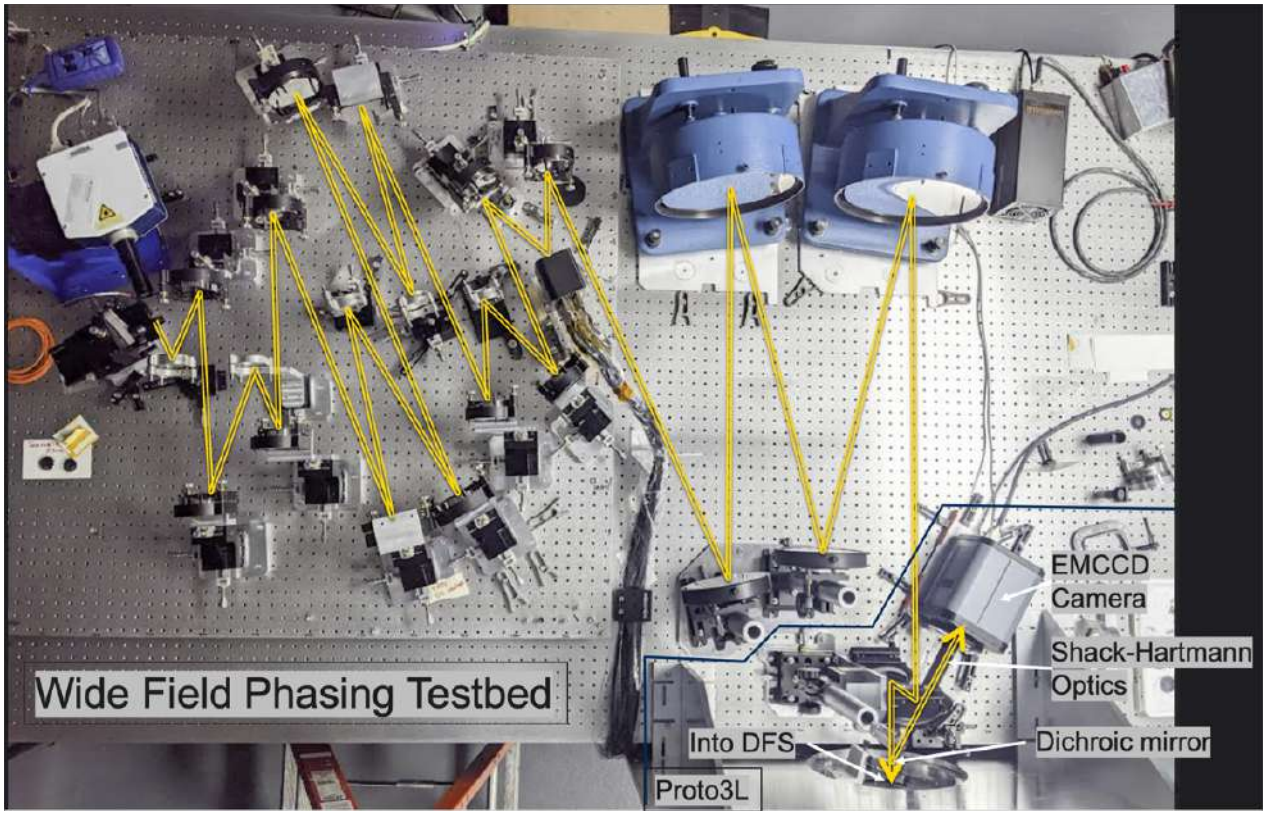

Figure 4-3 Overview of as-built WFPT. Beyond the photograph righthand frame is the Proto3L wavefront sensor acting as a surrogate until the AGWS prototype is ready for testbed integration.

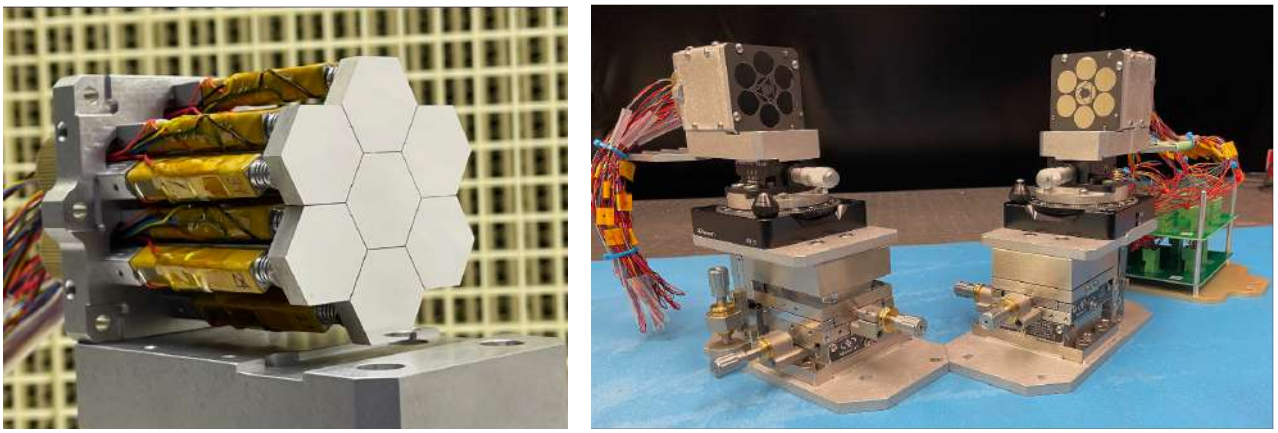

Figure 4-4 An SAO custom-designed and built piezo-driven Piston Tip-Tilt (PTT) Array (left) and the pair of PTT arrays with GMT pupil masks simulating GMT M1 & M2 rigid body positioning in 3 degrees of freedom.

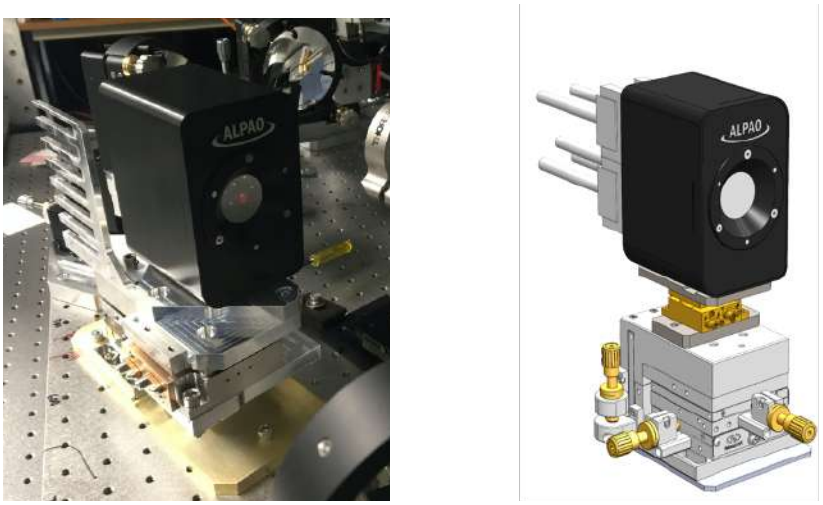

Figure 4-5 A commercial ALPAO High Stability Deformable Mirror on the testbed bench (left) and the CAD model image (right). A pair of DMs are used to simulate the GMT M1 & M2 figure control.

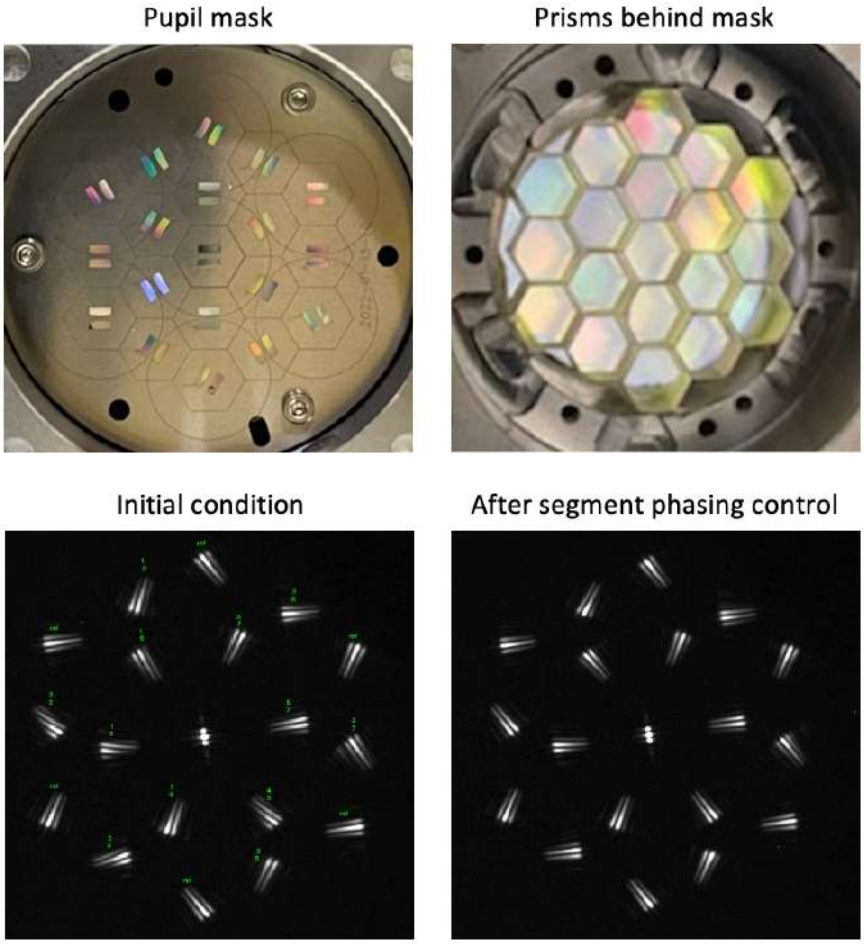

Figure 4-6 Wide Field Phasing Testbed uses a prototype Dispersed Fringe Sensor. The precision-machined prism array (above left and right) was used to demonstrate the closed loop coarse piston phasing of the GMT segmented telescope simulator in the testbed. Fringe

5. HIGH CONTRAST ADAPTIVE OPTICS TESTBED

The High Contrast Adaptive Optics Testbed (HCAT) consists of three optical sections. The first section called prototype HCAT, contains the fiber optic source and collimating optics, the GMT pupil mask, GMT telescope simulator (in two stages), a PSF camera and relay optics. The second section is the Magellan Extreme AO instrument, aka MagAO-X. MagAO-X contains a pair of woofer/tweeter deformable mirrors (ALPAO 97/BMC 2KDM), a pyramid wavefront sensor, a K-mirror, an atmospheric dispersion compensator (ADC), a filter wheel for masks and a pair of EMCCD science cameras. The last section is the NGWS prototype wavefront sensor. MagAO-X was designed to feed a coronagraph but here we use it to feed the NGWS prototype sensor.

HCAT is being tested in three phases. In Stage 0, which was completed in calendar year 2021, a prototype version of the GMT simulator (limited to a subaperture) was used to run pathfinder segment segment piston sensing and control tests. In Stage 1—expected to begin in autumn of 2022—we will operate a testbed-scale telescope simulator of the full GMT segmented pupil with active piston and tip-tilt control of each of the seven segments. We will begin Stage 2 in mid calendar year 2023. In this final stage we will integrate the NGWS prototype sensor with HCAT and will run full wavefront control performance tests using the MagAO-X DMs to correct high order wavefront error. The NGWS prototype will be used to sense piston and all orders of wavefront error.

The HCAT and NGWS prototype successfully passed independent nonadvocate Design Reviews in February and May 2022, respectively. Subsequently all major reviewer actions were completed and all recommendations were addressed.

The objective of Stage 0 was to explore the behavior and limits of the pyramid wavefront sensor (PWFS) as a single sensor for wavefront control and to confirm the predictions of previous analyses on the performance of the PWFS. In this phase we first carried out phasing tests using the MagAO-X PWFS to sense and control segment piston error and high order wavefront error8. The GMT pupil is segmented into seven circular segments arranged hexagonally. The GMT simulator in this initial stage consisted of a subset of four of the seven GMT segments, representing the center segment with obscurations from the ASMS support structure and three outer segments. One segment had active piston and tip-tilt segment motion and other three were fixed coplanar segments (Figure 5-1).

In the first set of tests we found that the PWFS sensitivity decreases with increasing modulation radius, failing at a radius of 5λ/D. Based on earlier GMT simulations Quiros-Pacheco [9,12] found that much of the phase wrap error and resulting segment ejections would be mitigated by a well-constructed controller. Quiros-Pacheco found that optical gain compensation[10] and a modal gain machine integrator [11,12] will stabilize the PWFS piston measurement in the presence of low to medium seeing turbulence. Since the PWFS response is nonlinear, the gain varies with piston. We periodically sample the gain by measuring the response to a few selected segment-mode probes and we can then compensate for optical gain variation. As we had expected, we observed in prototype HCAT that the PWFS suffers phase wrap error in the presence of segment piston errors larger than λ/2. However, our NGAO wavefront controller was not available in time for the prototype HCAT tests and so its results were not directly comparable to Quiros-Pacheco's simulations. We interpreted the results of these pathfinder tests as affirmation of our previous decision to augment the PWFS with a second phase-sensing channel to ensure robust phase-wrap free segment piston control.

As part of the prototype HCAT stage we tested a prototype Holographic Dispersed Fringe Sensor (HDFS) invented by Sebastiaan Haffert[13] of the University of Arizona Center for Astronomical Adaptive Optics. The UA team procured a rapid prototype of the HDFS mask and inserted it into the High Contrast AO Testbed. The HDFS consisted of a phase mask located in the telescope pupil. The prototype phase mask, fabricated by BeamCo in a liquid crystal substrate, was embedded with a custom holographic grating pattern that diffracted and combined the light from the entire area of each pair of GMT segments. The result was an interferometric measurement of the relative piston error between each pair. The phase mask produced a circular array of dispersed fringe patterns on a camera from which seven piston values were numerically extracted and then used to generate commands to cancel out the piston error (Figure **5-2**).

A closed loop Prototype HCAT (p-HCAT) test demonstrated that the HDFS was able to fine phase the small-scale GMT telescope simulator in the testbed and was reported by Haffert[13]. The source intensity simulated a 10th magnitude star. Atmospheric turbulence was injected using the MagAO-X tweeter DM to simulate 0.65arcsecond seeing conditions and an initial piston error of several microns was introduced using the p-HCAT active segment. Five hundred turbulence modes were sensed by the MagAO-X PWFS while piston error was sensed by the HDFS. The NGWS prototype is not yet built, so for these tests the MagAO-X science camera was used to capture the HDFS fringes and sense piston. Since this camera operates at a maximum speed of 20 Hz, the artificial turbulence was injected at only 60 Hz. In order to be able to correct

the ambient laboratory turbulence, the PWFS was run faster than the HDFS camera, while the piston error was sensed at 20 Hz. Using a simpler wavefront controller without the gain compensation and modal gain machine integrator, the steady state residual segment piston error was 50 nm RMS. Results are shown in Figure **5-3**.

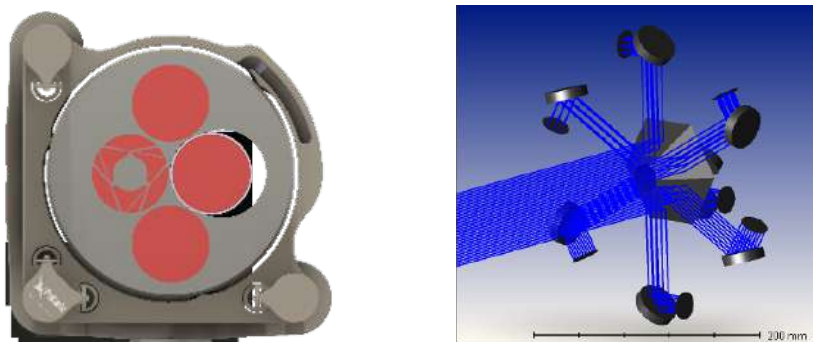

Figure 5-1 Left: Giant Magellan Telescope simulator for the prototype HCAT stage. The center segment and the upper and lower segments were fixed and coplanar. The fourth segment was actively driven by a PI-325 3-degree of freedom piston, tip-tilt actuator. Right: the GMT simulator for test stages 1 and 2 will use a hexagonal pyramid mirror to separate the GMT pupil into seven separately directed and controlled sub apertures which will be subsequently coherently recombined.

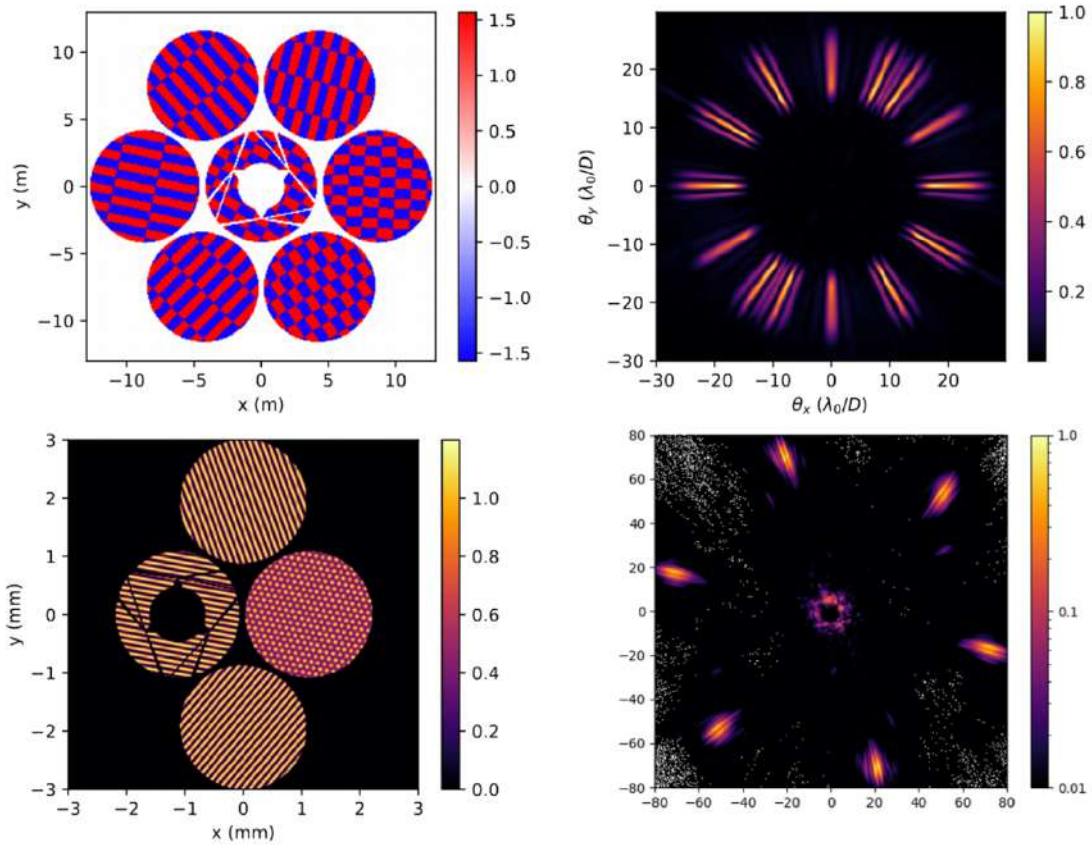

Figure 5-2 The HDFS prototype comprised a holographic grating pattern written into a liquid crystal substrate. The mask designs for both the GMT pupil (top left) and prototype HCAT (lower left) were fabricated. The resulting fringe patterns in the image plane for the GMT pupil (top right, simulation) and prototype HCAT (lower right, measurement) contain pairs of identical fringes along a diameter passing through the center for each segment piston measurement. A zeroth order diffraction PSF is seen at the center.

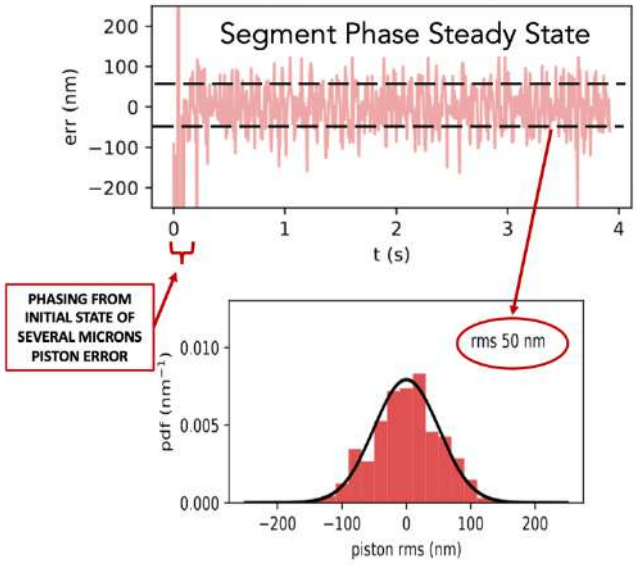

Figure 5-3 Closed loop segment piston residual using the first generation HDFS. From an initial state of several microns piston error the controller achieved a steady state of 50 nm RMS residual piston error.

Having completed Stage 0 testing, HCAT is currently being reconfigured for Stage 1 testing. In this stage a hexagonal pyramid reflector will optically split the GMT pupil into seven collimated beams where actuated flat mirrors will correct tip-tilt and segment piston error (Figure **5-4**, Figure **5-6**). The split beams will then be coherently recombined into the GMT pupil. We will use the PWFS in MagAO-X to sense segment segment piston error and high order wavefront error. We will correct segment segment piston and tip-tilt error using seven active flat mirrors (PI-325 actuators) in the split pupil while using the MagAO-X woofer/tweeter DM pair to both inject and correct high order wavefront error. The pupil splitting and coherent recombination is a precursor for the future GMagAO-X[14] instrument, an extreme AO instrument for coronography currently in its preliminary design phase. In the GMagAO-X instrument, high order DMs will be used in lieu of triple-axis actuated flat mirrors. This configuration will serve as a partial validation of the GMagAO-X pupil-split parallel-DM design.

We will test a second generation HDFS phase mask in Stage 1. Sebastiaan Haffert designed a binary phase mask which was then fabricated at the University of Arizona using a lithographic process whereby the holographic grating pattern was written on a fused silica substrate. The mask is designed for a 600 – 1000 nm wavelength bandpass. Unlike the achromatic liquid crystal HDFS, the binary etched mask is chromatic, however, its overall throughput exceeds that of the liquid crystal phase mask and we expect its performance to exceed that of the former mask. The first fused silica etched mask was printed in a low quality fused silica substrate to rapidly demonstrate functionality (Figure **5-5**). We will fabricate a second binary phase mask using a high-quality substrate for phasing performance tests in HCAT. As in Stage 0 tests, here we will use the MagAO-X PWFS to sense low and high order wavefront error for turbulence correction while the binary mask HDFS will sense segment segment piston. The second stage is expected to be completed in calendar 2022.

In the third and final HCAT test phase, Stage 2, we will integrate and test the NGWS prototype to the output of MagAO-X. Using the split-pupil GMT simulator from Stage 1 and the MagAO-X DMs, we will now use the dual-channel NGWS prototype for sensing and control of piston error and wavefront error. As in Stage 2, the turbulence will be injected using the MagAO-X DMs and piston error will be injected using the split-pupil PI-325 actuators. We will use the NGAO controller with optical gain compensation and the modal gain machine integrator to measure and optimize its performance.

In a collaborative effort INAF Arcetri[15] and GMT's WFSC group have designed the NGWS prototype, which, as previously stated, passed a design review with independent external reviewers in May 2022. The previously existing preliminary design—reviewed in 2013—consisted of a PWFS main channel for AO and a second PWFS 2nd channel sensing at a shifted wavelength to extend the segment piston capture range and to disambiguate phase wrap error. This design was later deemed insufficient to comply with steady state piston error requirements. As part of the recent collaboration, INAF Arcetri and GMT carried out a design trade study in 2021 to determine the best architecture for the NGWS second phasing channel. Several options were evaluated for sensing segment piston including a modulated PWFS

sensing at 1550 and 1650 nm, a visible Zernike phase mask sensor, a dual Zernike phase mask sensor split into 1550 and 1650 nm bands, a visible phase retrieval camera, a NIR phase retrieval camera split into 1150 and 1250nm bands based on the LIFT[16] concept, a prism type dispersed fringe sensor and the holographic dispersed fringe sensor. The design trade and its outcome were documented in a standard decision matrix table. The trade decision criteria consisted of "MUSTS" or compulsory requirements and "WANTS" or discriminating factors. Options that failed one or more MUSTS were removed from the trade. The performance of the surviving options was scored for each of the WANTS which were weighted and scores summed. We used a common set of assumptions and the same analytical tools for evaluation of the performances of the options. We endeavored to use uniform scoring criteria but this is unavoidably subjective. The supporting analysis revealed performance limitations in some of the options with respect to sensitivity to stellar spectral types and the inability to simultaneously recover multiple segment ejections at "bootstrap". The baseline NGWS design calls for sensing of 450 – 920 nm light that is reflected from a dichroic instrument window, however, to explore the benefit from improved AO correction in the IR, in this design trade we considered the use of 5% of the NIR reflected from the dichroic window.

The WANTS or discriminators were categorized into technical performance, system level performance and programmatic criteria. Among the key criteria were piston-sensing dynamic range, ability to sense absolute piston, sensitivity to different spectral types, residual RMS wavefront error for R=12 star, linearity, simplicity of design and implementation, ground-based observatory heritage and adherence to schedule and budget. The utility of the decision matrix is the documentation of the design trade, decision criteria and it provides a process for scrutiny, deliberation and inquiry. We decided on the Holographic Dispersed Fringe Sensor. As a piston sensor it is linear, makes an absolute measurement, does not suffer phase wrap and its design and implementation are simple. The CEO-based simulations of a PWFS + HDFS showed robust phasing performance at bootstrap and in steady state with low piston error residual. In addition we were impressed by the performance of the HDFS rapid prototype on HCAT. In the decision matrix, the dual wavelength phase retrieval sensor (LIFT) was a close second to the HDFS. Since phasing the doubly-segmented GMT is a leading technical risk, we also plan to test a phase retrieval 2nd channel as a backup option on a reconfigured testbed.

The optical layout of the NGWS-p is complete and is shown in Figure **5**-**7**. The NGWS-p is designed to be compatible with the GMT pupil and its f/8.3 fast Gregorian focus. By contrast, the MagAO-X output is a very long f/54. Therefore, we have designed a relay adapter for the MagAO-X interface. Removal of the adapter will allow us to take the NGWS-p to the AdOptica test tower in 2025 to characterize the first ASMS segment. The NGWS-p input after the MagAO-X adapter contains a K-prism pupil derotator, a lens followed by the power beamsplitter which separates the main and 2nd channels. The main channel of the NGWS-p contains the PWFS with tip-tilt mirror for modulation and the 2nd channel contains the HDFS. A technical viewer (TV) camera is located between main and 2nd channels. The MagAO-X input is power split between the PWFS (90%) and the TV + HDFS (10%). A dichroic beamsplitter separates the 10% of light between the TV (450 - 700 nm) and the HDFS (700 - 920 nm). The HDFS beamtrain (Figure **5**-**8**) contains an spatial filter with motorized X-Y positioning, an OAP optical relay to conjugate the pupil to the filter-wheel-mounted HDFS phase mask, a deployable pupil imaging lens and a Teledye-Princeton ProEM-HS 1024BX3 EMCCD camera for fringe imaging. The NGWS-p main channel, the MagAO-X adapter and NGWS-p optical support bench will be provided by INAF Arcetri. The HDFS sub-bench assembly will be provided by GMT's WFSC group. They will be integrated into the final NGWS-p at the University of Arizona in the summer of 2023. We note that whereas in the prototype HCAT tests, the roles of the PWFS and HDFS were cleanly separated between AO wavefront sensing (PWFS) and piston sensing (HDFS), in the Stage 2 HCAT testing with the NGWS-p we plan to test the fusion of piston sensing by both the PWFS and the HDFS.

The HCAT and NGWS-p must pass three more NSF milestones before completion of the risk reduction project:

WTB-7: HCAT Stage 1 Phasing Tests Complete

WTB-9: NGWS-p pre-ship review (PSR)

WTB-11 HCAT Stage 2 Phasing Tests Complete (using the NGWS-p, full phasing performance).

These milestones are expected to be completed by the end of the 4th quarter in calendar year 2023.

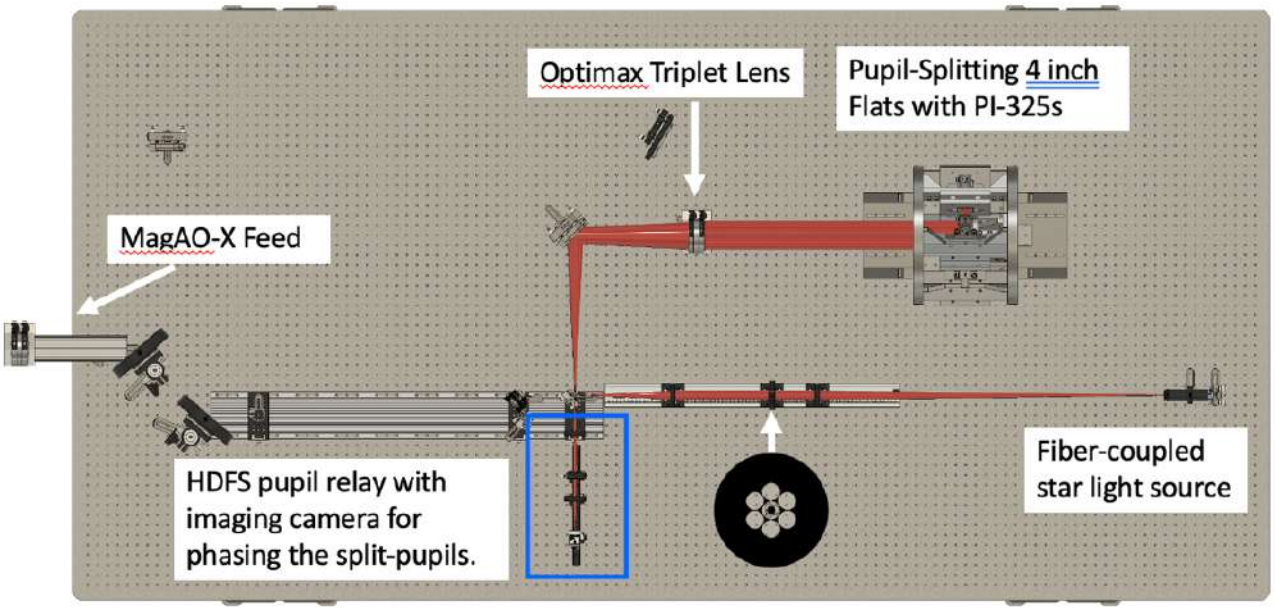

Figure 5-4 Stage 1 HCAT bench optical layout will use an etched mask HDFS and a split pupil with separate segment actuators for phasing tests.

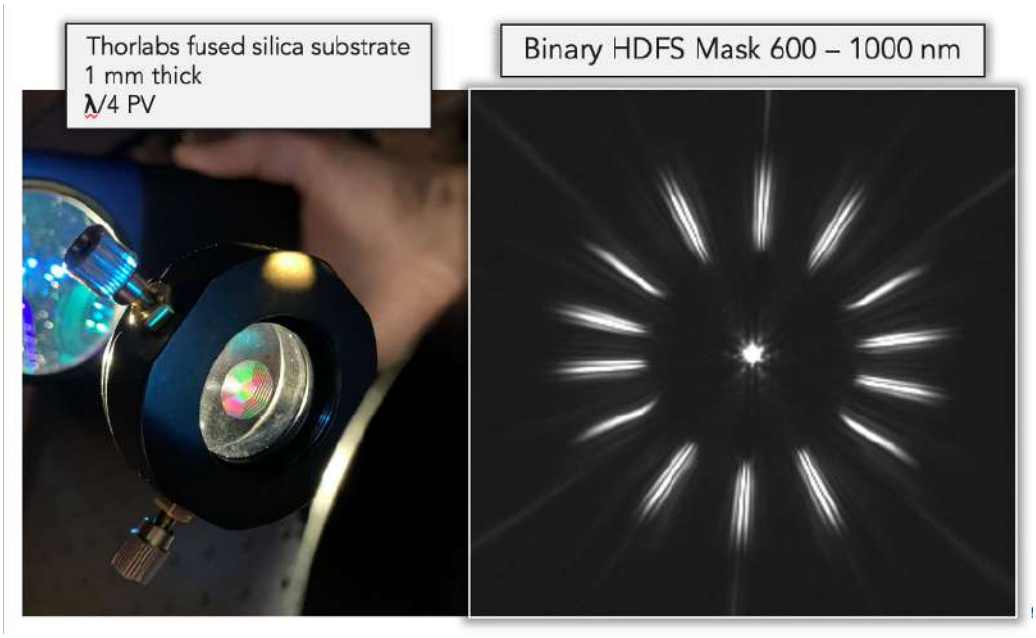

Figure 5-5 The second generation HDFS binary phase mask was fabricated at the University of Arizona by a lithographic process whereby a custom grating pattern was written on a fused silica substrate.

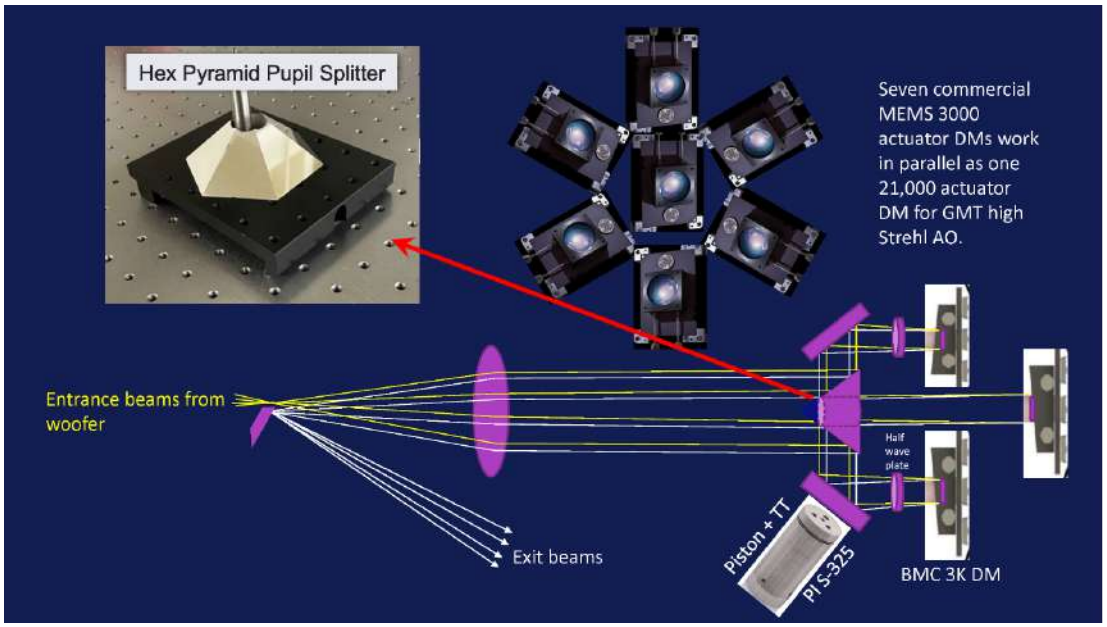

Figure 5-6 Pupil-Splitting Optical Fixture will be used in 2nd Stage HCAT testing

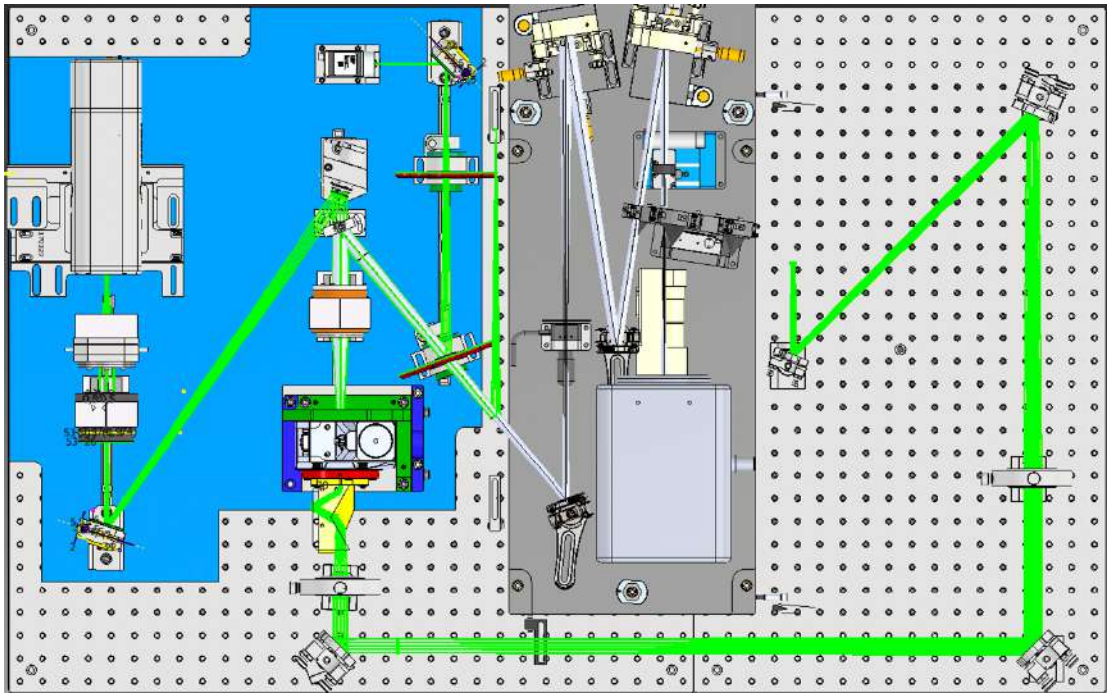

Figure 5-7 The NGWS prototype optical beam train in three sections: PWFS main channel (blue), the HDFS 2nd channel (gray) and the MagAO-X relay adaptor (red). MagAO-X input propagates downward from the top left of the image.

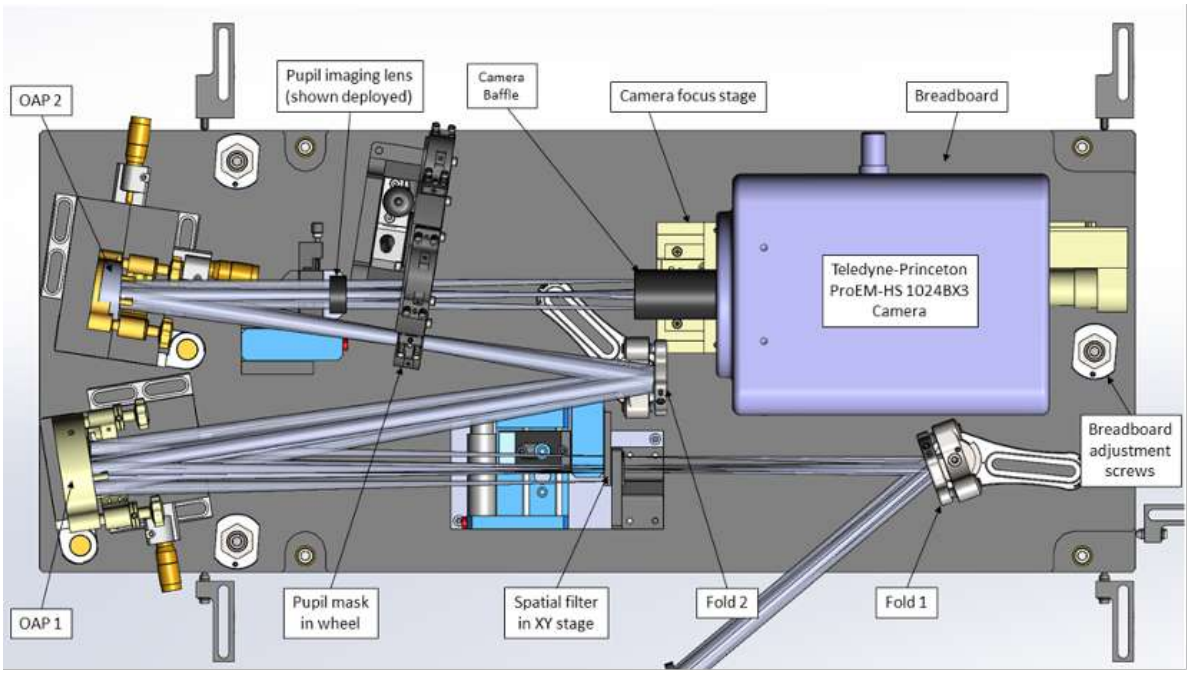

Figure 5-8 The HDFS 2nd channel

6. REMAINING TECHNOLOGY DEVELOPMENT

As a follow on to the current risk reduction program, in 2024 we propose to modify the existing WFPT to become a full analog of the WFSC architecture with all relevant functionalities. We will leverage most of the existing optics, sensors, mechanisms, and support structure including a GMTO telescope simulator, the AGWS prototype and IR camera. In addition we will integrate the NGWS prototype and a new large format deformable mirror with the WFPT. The modified testbed—now having both the AGWS and the NGWS prototypes—will be operated to verify the full WFSC performance in NGAO mode with realistic guide star brightness. The Advanced Testbed will simultaneously sense and control both wide-field low-order wavefront and narrow-field high-order wavefront.

We will also operate the Advanced Testbed to test the Laser Tomography AO control algorithms. In this configuration, a constellation of laser sources will be created at realistic field points and with accurate pupil widths relative to the telescope pupil. Atmospheric turbulence will be artificially injected. Cameras will simulate the Laser Tomography Wavefront Sensor (LTWS) and the On-Instrument Wavefront Sensor phase retrieval camera enabling the demonstration of simultaneous sensing and control of high and low order wavefront and segment segment piston. At the completion of these tests, GMTO will have validated on a testbed the use of the Phase Retrieval sensing technique to phase the GMTO segments in the LTAO mode. We are also exploring the possibility to use the laser facility at an existing observatory to test phase retrieval on sky. In the existing program, since we have partitioned the GMT WFSC architecture into the WFPT and HCAT, we cannot test all wavefront control loops concurrently. The WFPT uses active optics control whereas the HCAT tests adaptive optics control. In the Advanced Testbed we will have the capability to test all the wavefront control loops concurrently enabling us to characterize the behavior of all control loop interactions. The demonstration of the combined functionality and performance will provide a high confidence verification of the GMT end-to-end WFSC performance.

7. CONCLUSIONS

GMT is in the middle of an ambitious testbed and sensor prototype program that we expect to burn down significant risk in the areas of WFC algorithms, non-common path aberrations, sensitivity to piston modes, custom hardware fabrication and assembly and phasing the GMT doubly-segmented telescope. The program

will also serve to validate the advanced designs of the AGWS and NGWS. At the completion of NSF Development program GMTO will have an advanced understanding of the design and experimental validation of the WFSC architecture and verification of its performance in the testbeds

This material is based in part on work supported by the National Science Foundation as a subaward through Cooperative Agreement AST-1546092 and Cooperative Support Agreement AST-2013059 managed by the Association of Universities for Research in Astronomy Inc. (AURA).

REFERENCES

[1] Bouchez, A., et al, "Overview and status of the GMT wavefront control system," Proc. SPIE 12185, Adaptive Optics Systems VIII, 12185-48 (2022).
[2] B. A. McLeod, et al., "The active optics, GLAO, and phasing sensors for the Giant Magellan Telescope", Proc. SPIE 11448, Adaptive Optics Systems VII, 11448-36 (2020).
[3] van Dam, Marcos, et al., "Dispersed Fringe Sensor for the Giant Magellan Telescope," Applied Optics 55.3 (2016): 539-547.
[4] Males, J., et al, "MagAO-X: current status and plans for Phase II," Proc. SPIE 12185, Adaptive Optics Systems VIII, 12185-8 (2022).
[5] McLeod, B., et al, "The wide field phasing testbed for the Giant Magellan Telescope," Proc. SPIE 12182, Groundbased and Airborne Telescopes IX, 12182-7 (2022).
[6] Catropa, D., et al, "Piston-tip-tilt mirror array in the wide field phasing testbed for the Giant Magellan Telescope," Proc. SPIE 12185, Adaptive Optics Systems VIII, 12185-169 (2022).
[7] McLeod, B., et al, "Aligning the GMT wide field phasing testbed optical system using a laser tracker and an interferometer", Proc. SPIE 12188, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation V, 12188-146 (2022).
[8] Hedglen, A., et al., "First lab results of segment/petal phasing with a pyramid wavefront sensor and a novel holographic dispersed fringe sensor (HDFS) from the Giant Magellan Telescope high contrast adaptive optics phasing testbed," Proc. SPIE 12185, Adaptive Optics Systems VIII, 12185-42 (2022).
[9] Quiros-Pacheco, F. et al, "The Giant Magellan Telescope Natural Guide-star Adaptive Optics (NGAO) mode," WFC Workshop, Valpaiso (2021).
[10] Esposito, S., et al, "On-sky correction of non-common path aberration with the pyramid wavefront sensor,", A&A 636, A88 (2020).
[11] Agapito, G., et al., "Advances in control of a pyramid single conjugate adaptive optics system," MNRAS 508, 1745-1755, (2021).
[12] Quiros-Pacheco, F., et al., "The Giant Magellan Telescope natural guidestar adaptive optics system: improving the robustness of segment piston control," Proc. SPIE 12185, Adaptive Optics Systems VIII, 12185-43 (2022).
[13] Haffert, S. Y., et al, "The Holographic Dispersed Fringe Sensor: phasing the giant segmented mirror telescopes," JATIS 21170SSR (2022).
[14] Close, L. M., et al, "The Optical and Mechanical Design for the 21,000 Actuator ExAO System for the Giant Magellan Telescope: GMagAO-X," Proc. SPIE 12185, Adaptive Optics Systems VIII, 12185-76 (2022).
[15] Plantet, C., et al., "NGWS-P: the Natural Guide Star Wavefront Sensor Prototype of the GMT single-conjugate AO system NGAO," Proc. SPIE 12185, Adaptive Optics Systems VIII, 12185-168 (2022).
[16] Cheffot, A., et al, "Differential piston sensing with LIFT: application to the GMT", Proc. SPIE 12185, Adaptive Optics Systems VIII, 12185-196 (2022).