THE PHASING SYSTEM FOR THE GIANT MAGELLAN TELESCOPE

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Abstract. We give an overview of the components of the Giant Magellan Telescope AO system that are responsible for keeping the telescope phased. The segmented nature of both the primary and secondary mirrors, combined with the relatively large size of the gaps between the segments, makes phasing a difficult problem. The phasing components include a dispersed Hartmann sensor, edge sensors for the primary and secondary mirror segments, and phaseweave wavefront sensors. We show on-sky results from a prototype dispersed Hartmann sensor deployed at the Magellan Clay telescope.

1 Introduction

To deliver diffraction-limited images in its natural guide star and laser tomography AO observing modes [1], the seven segments of the 25m GMT must be phased to a small fraction of the observing wavelength. Since both M1 and M2 are segmented, it is the distance between each M1-M2 segment pair that must be equalized. The differing availability of sufficiently bright natural guidestars drives us to use a different phasing strategy for the NGSAO and LTAO observing modes. We begin by considering the overall phasing strategies for the natural and laser guide star cases, and then describe the major hardware components of the phasing system: the phasing camera, and the M1 and M2 edge sensor systems.

2 Natural Guide Star AO

In the NGSAO observing mode [2], the bright on-axis guidestar provides sufficient flux to measure both atmospheric and telescope segment piston at high bandwidth. We have investigated the ability of a pyramid wavefront sensor to maintain the phasing of the GMT, both by simulation and with a dedicated laboratory experiment. Simulations with a single wavelength channel pyramid exhibited occasional “ejections” of segments to integer multiples of the mean wavelength λ, caused by residual atmospheric turbulence across a segment gap exceeding λ/2. This effect is common to any sensor using interference effects, even with broadband light. A second channel at a different wavelength was added to detect and correct these jumps. Based on end-to-end simulations, the phasing performance of the two-channel NGWS is sufficient to meet the 35 nm RMS wavefront error allocated to segment piston in the NGSAO observing mode, with no additional sensors.

However, there remains an initial capture problem as the NGWS has a capture range of only ±3 μm. This can be increased by reducing the wavelength difference between NGWS channels, but at the

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expense of reduced sensitivity to 1\(\lambda\) jumps. We therefore plan to initially phase the telescope at the start of each night using the Phasing Camera. It has a capture range of \(\pm 50\ \mu m\) and no phase ambiguity, allowing rapid phasing from an initially misaligned state (assumed to be as bad as \(\pm 200\ \mu m\) after Laser Tracker alignment) using a bright NGS.

3 Laser Tomography AO

In the LTAO observing mode [3] phasing is significantly more challenging because the wavefront sensor, being a Shack-Hartmann, is blind to segment piston. Segment piston errors must therefore be sensed independently of the high-order atmospheric wavefront error, using either edge sensors or the limited faint off-axis NGS available. Atmospheric segment piston cannot be measured more than \(\sim 10\) arcsec off-axis, so this \(\sim 110\) nm error term cannot be corrected. It is nevertheless critical to correct quasi-static and wind-induced telescope segment piston errors to <65 nm RMS wavefront in order to achieve the performance requirements. The wind will excite mechanical resonances of the telescope, including uncorrelated piston of the M1 and M2 segments. The lowest resonances that contribute segment piston error are at 11.6, 19.6, and 25.5 Hz for M1, and 43-66 Hz for the adaptive secondary mirror (ASM) on the M2 Positioner. While the amplitude of these vibrations in typical wind conditions is not known at this time, it seems prudent to design a system capable of detecting and correcting segment piston oscillations in at least the lowest modes of each mirror. Insufficient starlight is available to measure segment piston errors at this frequency over a significant fraction of the sky. It is therefore necessary to supplement low-bandwidth starlight measurements with high-bandwidth edge sensors, which measure the relative segment piston produced by each mirror array.

In the LTAO mode, the Phasing Camera takes the place of the NGWS to provide continuous updates to the M1 edge sensor setpoints (and thus the M1 segment piston), using a NGS located 6-10 arcmin off-axis. However, the Phasing Camera is subject to potentially significant field dependent segment piston errors, caused by the tilt of an M2 segment compensated by the opposite tilt of its matching M1 segment. This condition results in zero tilt in the focal plane, but a field-dependent segment piston error. Thus the accuracy of the Phasing Camera measurement is a function of the accuracy to which the M2 Edge Sensors can maintain zero relative tilt between the ASM reference bodies. The requirements on the long-term stability of the M2 Edge Sensors have been set such that at most a 30 nm RMS wavefront error results at 10 arcmin off-axis, but it is not yet clear whether this challenging level of stability can be achieved. We have therefore also included in the design a sensitive segment piston sensor in the On-Instrument Wavefront Sensor. This Integrated Optics Piston Sensor (IOPS) [4] is located nearer to the optical axis (within 90°), and thus subject to an order of magnitude lower field-dependent segment piston error. It also has the advantage of measuring the true average segment piston error, rather than the phase difference over a limited region near the segment edges. The IOPS is an optional component of the phasing system, which would provide improved performance at the expense of additional complexity within the instrument. Whether it proves necessary depends on the results of M2 Edge Sensor prototyping in the next phase of design.

4 Phasing Camera

4.1 Introduction

In the phasing camera twelve square subapertures are centered on the segment gaps of a pupil image formed within the camera. Each subaperture forms a Young’s double slit image, and the relative phase between segments can be determined from the phase of each fringe pattern. The M1 segment gap size of 0.3-0.4 m sets a minimum size of the subapertures of 1.0 m. By correcting the tip-tilt of the wavefront in each subaperture, and measuring the fringes in the near-infrared, enough fringe contrast is preserved to make the necessary piston measurement in the presence of atmospheric turbulence. The apertures are sized to be 1.5 m to optimize sky coverage at the K band.

As described, the phasing camera would be prone to the \(2\pi\) phase ambiguity suffered by all interferometric sensors, unable to distinguish an in-phase segment from one \(2\pi\) radians (2.18 \(\mu m\)) out of phase. Grisms are therefore added behind the pupil mask, causing each fringe pattern to be
dispersed parallel to the segment edges with a resolution of $\lambda/\Delta\lambda = 22$. The phase difference between segments then shows up as a tilt in the “barber-pole” pattern of the dispersed fringes (see Fig. 1). The capture range of the sensor is thereby extended to greater than ±50 µm.

Fig. 1. Phasing subapertures superposed on GMT pupil (left), and resulting spectra formed from one subaperture with no atmospheric turbulence. The H and K bands are illustrated, though the Phasing Camera uses only the K band.

### 4.2 Optical Design

Fig. 2 presents an overview of the Phasing Camera optical design. Light from the telescope is diverted by a pickoff mirror and folded into a K-mirror assembly that is used to de-rotate the pupil. A pupil image is then formed on a MEMS segmented mirror that is used for independent fast tip-tilt correction of the subapertures. From there the light goes into a cryostat where it is split into 3 arms, used for fast tip/tip control, pupil imaging (for alignment), and infrared fringe measurement.

An off-axis parabola relay forms a pupil on an Iris AO PT-111 MEMS mirror array. This mirror array has 37 segments, each with 3 actuators that provide ±4 µrad of tip-tilt, or ±2.5 µm piston. Only twelve segments, six in the outer corners of the array and six in the second ring, are used.

After the MEMS relay the beam enters the cryostat, passes through a 2 arcsec diameter cold field stop, and a doublet field lens forms a pupil image on a lenslet array. Just behind the lenslet array is a laser-cut mask that isolates the 1.5 m square phasing subapertures. A dichroic mirror immediately after the lenslet array reflects the K-band light and transmits the visible.
In the IR channel, an array of grisms just after the dichroic disperse the light. The grisms are oriented so that the grating grooves are perpendicular to the tangent line between the segments. Fig 3 illustrates how such an array might be constructed with hexagonal grisms that are epoxied on their edges. The outer-most set of 6 hexagons are not functional but are used as a structural element to attach to a quartz annulus. The baseline infrared detector is a 2048×2048 18 µm pixel HAWAII-2RG. A raytrace of the 12 spectra is shown in Fig 3. The image scale is 0.1 arcsec/pixel, and all of the spectra fit comfortably within a 256×256 pixel region of the detector.

Returning to the dichroic, a beamsplitter cube just after it forms the first element of the tip-tilt arm. Approximately 95% of the visible beam is transmitted to an Andor iXon Ultra 897 EMCCD camera for centroid measurements and the remainder is reflected to a pupil imaging camera used for alignment.

4.3 Data Analysis

The formalism for optimal extraction of the piston information from a noisy undispersed fringe image, as well as sensitivity simulations were derived by Codona [5]. A summary of those results is presented here. To determine the differential piston, \( \Delta \phi \), between two subapertures the long-exposure K-band fringe image is extracted from the larger parent image and Fourier transformed. The resulting transform, \( F(I) \), i.e., the mutual coherence function (MCF), has a region that corresponds to the fringe spacing. A weighting function corresponding to that region, \( O_{\text{AB}} \), is then multiplied by \( F(I) \). The weighting function is a section of the optical transfer function, which may be computed as \( O_{\text{AB}} = F^{-1}(F(P_A)F^*(P_B)) \), where \( P_{A,B} \) are the sections of the pupil corresponding to the 2 adjoining segments. The values in the complex plane are then summed, the phase of the resulting complex number taken, and the result is adjusted for the possibility that the centroid of the image may not be exactly at the center of the image i.e. \( \Delta \phi = \arg \sum O_{\text{AB}} F(I) + \phi_{\text{centroid}} \).

The introduction of dispersion to the images requires no fundamental change to the analysis. As before the fringe image is extracted, before being Fourier transformed. To avoid introducing edge artifacts due to the larger dispersed image, a 30×30 pixel subimage is cut out, apodized at the edges, and pasted into a larger 128×128 array. The padded image is then Fourier transformed. A rough measure of the absolute phase \( \phi_{\\text{est}} \) is computed from the horizontal location of the peak in \( F(I) \). This is accomplished by cross-correlating \( F(I) \) with \( O'_{\text{AB}} \), the weighting function \( O_{\text{AB}} \) multiplied by an additional Gaussian function in the x dimension to reflect the narrower peak seen in the MCF: \( O'_{\text{AB}} = O_{\text{AB}} e^{-x^2/(2\sigma_x^2)} \), where \( \sigma_x \) is the RMS width of the peak seen in \( F(I) \). After the peak location is determined, the fractional phase \( \phi_{\\text{frac}} \) is computed as in the non-dispersed case, using \( O'_{\text{AB}} \) shifted to the location of the peak. The absolute phase is then \( \phi_{\\text{tot}} = \text{nint}(\phi_{\\text{est}} - \phi_{\\text{frac}}) + \phi_{\text{frac}} \). The data flow is shown in Fig. 4.
4.4 Prototype Phasing Camera

A prototype of the phasing camera was built and tested at the Magellan Clay telescope in July 2012 [6]. Key features of the prototype were identical to the design presented above; a HAWAII-2RG detector with 0.1” pixels, an electron multiplication CCD camera, a PT-111 MEMS mirror to correct subaperture tip-tilt, and 1.5 m subapertures. A mask located just after the lenslet array simulated several GMT phasing subapertures within the 6.5m Magellan clear aperture, one of which was dispersed.

The primary experiment was to measure the variance of the piston measurement as a function of seeing conditions and star brightness. These results are shown in Fig. 5. Each of the 6 panels is for a different range of seeing conditions as measured by the Magellan guider. Within each panel, the measurements are binned by R and K magnitude and the RMS is reported for fringe exposures coadded to equal 30 seconds. Colors indicate RMS less than 50 nm (green), less than 120 nm (orange) or greater than 120 nm (red). The key measurement is the bin at the edge of the required parameters R<15, K<12, seeing<0.64”. Due to worse than average seeing on the assigned nights, no measurements were made for the bin 14<R<15, 11<K<12, and 0.6<seeing<0.7. Surrounding measurements suggest that an RMS of <75 nm will be achieved for these conditions, or dividing by √2, <55 nm for 60 s exposures.

4.5 Fringe Capture

The telescope will be brought into phase using a sequence of increasingly precise measurements:

1. Survey the telescope with laser trackers. This will phase the primary segments to less than ±200 µm position error (400 µm pathlength error).
2. Phase the secondary segments using the prime focus AO Retro-reflector and a multi-wavelength interferometer.
3. On-sky, piston the primary mirror segments and hunt for fringes with short exposures using the Phasing Camera. With a ±50 µm capture range, it will only require a few search steps to bring the telescope into phase to a few microns RMS.
4. Refine the Phasing Camera measurements with longer exposures to reduce piston errors to <120 nm RMS.
5. Make final phase measurements using the IOPS or the NGWS.

The prototype phasing camera on the Magellan telescope demonstrated the ability to capture fringes with a large path length error of ±50-60 µm between segments.
Fig. 5. RMS of fractional phase in nm for different observing conditions for 30 s K-band integrations. Points in green meet the goal of 50nm in a 60 sec exposure. Points in orange meet the specification of 120nm in a 60 sec exposure.

5 M1 Edge Sensors

5.1 Introduction

One of the biggest challenges in building a metrology system for M1 is the need to allow for up to 30 mm motion of any M1 segment under seismic accelerations. Any sensor on an M1 segment must therefore be located at least 60 mm from hardware on an adjacent segment. Given that piston values on the order of 10 nm in the wavefront must be measured, an interferometric type sensor is required. The baseline M1ES system is a hybrid metrology system that supplements the interferometric sensors with a more coarse absolute optical position sensor with large capture range. The coarse sensors will make it possible to quickly align M1 to within the capture range of the active optics system (for tip-tilt) and the phasing camera (for piston). Once initial alignment and phasing has been achieved, the interferometric metrology system will maintain the alignment of the M1 segments with high precision and bandwidth, with its absolute reference point updated continuously by the IOPS or the phasing camera.

5.2 Sensors

The fine M1ES sensor is an off-the-shelf Renishaw Distance Measuring Interferometer (DMI). Each sensor consists of a frequency-stabilized 633 nm wavelength laser coupled to a fiber. At the end of the fiber is a small interferometer head which projects the laser to a retro-reflector, mixes the return with an internal reference arm, and reads the interference signal. The nominal precision to changes in range to the retroreflector is 0.79 nm at up to 20 MHz update rate. The actual precision will be limited by the uncertainty in the temperature of the air path. The coarse M1ES sensor is an absolute imaging encoder[7,8]. A special target is attached near one of the boss locations on an M1 segment, and imaged with a simple 8-bit camera from the facing segment, though a 50 mm focal length lens. The target is ~10×10 cm and designed in such a way that analysis of the image can determine the absolute lateral displacement between the camera optical axis and the target, with sub-micron precision. The capture range is several cm. Laboratory experiments demonstrate a P-V noise level of <1 µm over short (~minute) timescales. Over longer timescales, the accuracy of the system will be limited to ~10µm by relative motion of the camera lens with respect to the detector, due to temperature or gravity variations.
5.3 Sensor Locations

The location of the M1 edge sensors is illustrated schematically in Fig. 6. Suites of sensors are mounted at 24 locations, two per segment interface. Two DMIs and 1 imaging encoder are required at each location. The DMIs form a cross pattern across a segment gap, allowing both separation and piston to be measured. This geometry is insensitive to symmetric tilt or distortion of the mirror side walls, as is expected in the presence of a front-to-back temperature gradient in the mirrors. The imaging encoders point across the gap at their associated targets, with a 20° angle between them to allow 2 axes of lateral displacements and the separation between segments to be sensed.

![Fig. 6 (Left) M1 Fine sensor locations. (Right) M1 Coarse sensor locations.](image)

Bosses have been cast and machined on the side walls of the M1 segments to support the M1ES components. They provide convenient mounting surface and can be surveyed accurately with respect to the optical surface during manufacturing. One M1 Edge Sensor Unit is illustrated in Fig. 7.

![Fig. 7. Mechanical design of one M1ES Unit (baffles and covers not shown). The laser beams are shown in red.](image)

5.4 System sensitivity

Table 1 presents the expected error in the measurements of the 6 degrees of freedom of each M1 outer segment, with respect to the center segment. The assumed sensor errors are 3 nm RMS for the DMIs and 10 µm RMS for the imaging encoders.

<table>
<thead>
<tr>
<th></th>
<th>X trans</th>
<th>Y trans</th>
<th>Z piston</th>
<th>θ-X</th>
<th>θ-Y</th>
<th>θ-Z</th>
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<tbody>
<tr>
<td>Coarse sensors</td>
<td>12.5mm</td>
<td>10.5mm</td>
<td>11.5mm</td>
<td>3.0mrad</td>
<td>3.5mrad</td>
<td>2.5mrad</td>
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<td>Fine sensors</td>
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<td>1.5nm</td>
<td>8.4nm</td>
<td>1.5nrad</td>
<td>1.2nrad</td>
<td>0.9nrad</td>
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6 M2 Edge Sensors

The M2 Edge Sensor System (M2ES) must measure the relative displacements between the ASM reference bodies, with sufficient precision and bandwidth to sense wind-induced disturbances of the ASM segments. In addition to segment piston, the M2 Edge Sensors must also accurately measure segment tilt. This is critical because tilt of an M2 segment, if compensated by tilt of the matching M1 segment, leads to zero tilt in the Gregorian focal plane but a field-dependent segment piston (phasing) error.

Fig. 8. M2ES sensor layout with 4 ASM segments hidden. On-axis reference body is yellow.

The M2ES sensor layout, developed by Microgate Corp., is shown in Fig. 8. The required sensor sensitivity is inconsistent with a sensing system in which the capacitive sensor armatures are sufficiently separated to avoid a priori collisions due to relative motion between segments. The design therefore uses a completely different approach, with a break-away system which disengages the sensing plates in case of collision. The M2ES is composed of 24 nearly identical sensor units, two at each of the 12 adjacent segment pairs. Each unit provides two orthogonal measurements of relative segment displacement, for a total of 48 measurements.

Table 2 summarizes the expected RMS error in the rigid body motions of each off-axis segment. The worst sensed modes are X translation, which corresponds to rotation of each outer segment around the center segment, a mode with no optical effect. The Z translation (piston) error of 6.0 nm RMS meets the requirement of 10 nm RMS at 500 Hz. The 0-X and 0-Y segment tilt errors are also well within the specification of 15 nrad RMS. Other modes are far less critical from the point of view of global phasing system performance, and the expected reconstruction errors are all acceptable.

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<tr>
<td>Mean Error</td>
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<td>6.01</td>
<td>3.64</td>
<td>0.49</td>
<td>0.56</td>
</tr>
</tbody>
</table>

7 References

1. A. Bouchez, This conference, (2013)
4. F. Bennet, et al., This conference, (2013)