Producing Large Synthetic Turbulence Plates using MRF Polishing

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Abstract. We have explored the feasibility of using the MRF polishing technique to produce large phase plates such as the 742x386mm phase plate required for NFIRAOS. QED Technologies’ MRF polishing machines can produce phase plates as large as 1100x900mm. This technology allows predetermined phase screen profiles to be polished onto glass substrates, yielding phase plates with well-defined turbulence profiles that are durable enough to be used in the cooled (-35°C) NFIRAOS AO system for TMT. We present the measurements that we have obtained on a 200x200mm pathfinder prototype, manufactured by QED Technologies on a N-BK7 substrate. We find that the synthetic turbulence has the prescribed structure down to a spatial scale of 5mm. For scales smaller than 5mm and down to 0.5mm we measured about 20% less structure than prescribed making the generated turbulence useful even at those scales. Based on these results, we conclude that MRF polishing appears to be a very promising technique for producing large turbulence phase plates for ELT-class AO systems.

1. Introduction

In order to exercise real-time Adaptive Optics (AO) correction without being on the sky or even on the telescope most AO systems include a calibration unit that simulates a number of sky sources as well as atmospheric turbulence. The synthetic atmospheric turbulence can be produced either by physically mixing air masses at different temperatures or by using one or several moving phase plates (in reflection or in transmission) on which the turbulence has been encoded.

The transmitting phase plate design is usually preferred, since it minimizes the space envelope while ensuring that the turbulence has known pre-determined characteristics. Several techniques exist to manufacture such phase plates: micro-machining using semi-conductor technology [1], precision injection moulding [2], applying acrylic paint to a transparent substrate [3], and near index matching [4]. Currently none of the vendors producing these plates can currently produce plates larger than 300mm. This is significantly too small for Extremely Large Telescope (ELT) sized AO systems like the Narrow Field Infrared Adaptive Optics System (NFIRAOS) for the Thirty Meter Telescope (TMT) project. This AO system requires a phase plate of dimensions 742x386mm. Some of the phase plate technology such as

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near index matching may fail when cooled to -35°C due to thermal stress. Other techniques that could be scaled to the size required, such as fluid jet polishing [5], are not commercially available. We restricted search to phase plates produced by commercial vendors, rather than endeavouring to develop in house technology to produce phase plates. Our survey of existing optical production technologies has lead us to the QED Magnetorheological finishing (MRF) as a candidate for producing the phase plate.

2. The NFIRAOS Turbulence Generator
NFIRAOS is the facility AO system for the TMT project. For detailed information on the NFIRAOS system the reader is referred to the paper by Herriot in this proceedings [6]. The earlier turbulence generator concepts for NFIRAOS planned to use an external turbulence generated located at the input to NFIRAOS. This external turbulence generator would need to emulate the telescope focal ratio and exit pupil to correctly simulate the telescope. The system would need laser guide star and natural guide star sources with internal phase plates to simulate the atmospheric turbulence. Conceptual designs of this external turbulence generator showed that such a system would be a complex and expensive system.

![Figure 1: NFIRAOS science path showing the turbulence generator components](image_url)

We opted to incorporate the turbulence generator into the NFIRAOS science path as shown in Figure 1. The NFIRAOS science path is a double OAP relay with two Deformable Mirrors (DMs): a 300mm DM at the pupil (conjugate to the ground layer), and a DM conjugate to the 365mm meta-pupil at 11.2km altitude. At the input to the AO system there is an image formed by the telescope. At this point the natural guide star sources are placed. The laser guide star sources are placed after the natural guide star sources on a translation stage to allow the conjugation altitude of the laser sources to be adjusted. The phase plate is placed in the system at a conjugate altitude of -8km. The phase plate is a 750x390mm racetrack shaped window.
The window is scanned vertically with a motion equal to the meta-pupil diameter for turbulence generation.

The artificial turbulence, for exercising the wave front sensors and control system, is introduced by both the phase plate and the deformable mirrors. The phase plate produces artificial turbulence non-conjugate to the deformable mirrors. The strength of the phase plate is scaled so that the synthetic turbulence of the system matches the Mauna Kea 50% percentile profile coherence length, isoplanatic angle, and the generalized isoplanatic angle (the isoplanatic angle for a two DM multi-conjugate AO system). The phase plate also introduces the non-correctable turbulence (phase errors at frequencies higher than the deformable mirrors can produce). This non-correctable turbulence is observed as speckle in the wavefront sensor lenslet apertures.

The turbulence generator is significantly simplified, with no additional powered optics required. The technical risk is moved to producing one large phase plate. To accurately simulate the atmosphere we also required the phase plate to be produced in a deterministic method so the atmosphere parameters are accurately modeled.

3. Magnetorheological Finishing
MRF was developed into a viable commercial process in the late 1990’s and has revolutionized optical fabrication [7]. MRF is a deterministic polishing process based on a sub-aperture lap formed by a magnetorheological (MR) fluid-optical abrasive slurry. The MR fluid is moved across the work via a spinning wheel and is stiffened at the point of contact using a locally applied magnetic field. This produces a polishing spot or “zone or removal” at the contact between the MR fluid and the work. This polishing spot conforms to the local curvature of the work with a material removal rate that is insensitive to the gap between the wheel and the work, resulting in a predictable material removal rate. The ability of the lap to conform to the part results in a process that smooths micro-roughness and eliminates subsurface damage. A clear advantage over other deterministic polishing processes such as ion beam figuring, which increases micro-roughness and subsurface damage.

Hallock [8] describes in detail the MRF process as applied to large optical windows with similar sizes as required for the NFIRAOS phase plate. For windows, the QED MRF manufacturing process can be applied as an iterative polishing process based on the measured transmitted wavefront error. Our application is an extension of the previous work but requires control of the structure of the optical surface, rather than the form.

4. Phase Plate Pathfinder
As a NFIRAOS risk reduction exercise, we commissioned a technology pathfinder with QED technologies. The goal of the pathfinder was to prove the proposed manufacturing method by prototyping a 200x200mm sub-region of the NFIRAOS phase plate. The final phase screen map with the selected 200x200mm sub-region is shown in Figure 2. This sub-region was selected to give a representative structure, as the local tip-tilt cannot be realized in the
polishing or testing. The wavefront error was scaled so the tip-tilt removed wavefront error was approximately equal to the error of the whole screen.

![Figure 2: Full phase plate phase map with the pathfinder sub-region identified](image)

MRF is a finishing process; the substrate must be pre-polished to an initial figure that forms the starting point for the finishing process. The initial figure used for the pathfinder was 2 fringes on each of the window surfaces to maintain a transmitted wavefront error of less than 1 wave @ 632nm. This figure specification was selected as a compromise between the cost of pre-polishing and MRF finishing based on discussions with the substrate vendor and QED. The substrate vendor Ceravolo Optical Systems elected to polish a circular substrate of 320mm diameter and 25mm center thickness. This was more economical than polishing a square 200x200mm window to the required figure. The pre-polished substrate was shipped to QED’s facilities for 3 iterations of MRF polishing with interferometric metrology at QED.

5. Polishing Results

Three MRF polishing iterations were performed by QED on the substrate. The first iteration was done using a 370mm wheel, while the second and third iteration were done using a 50mm wheel. The size of the zone of removal and the material removal rates are both functions of the wheel size. The 370mm wheel has a zone of removal of approximately 10x20mm, while on the 50mm wheel it is 2x4mm. The 370mm wheel was used in the first iteration to take advantage of the faster material removal rate to remove the bulk of the material.

Figure 3 shows the plate being polishing in the first iteration and the interferometric test data for this run is shown in Figure 4. The loss of high frequencies in the polished phase plate can be clearly seen in the interferogram.
Figure 4: The 200x200mm phase screen provided by HIA (left) and QED measurements after the first polishing iteration (right). All maps are piston and tip-tilt removed.

Figure 5: X and Y cuts of the square-root of the full structure function (scales up to 200mm) for the first polishing iteration. solid line (HIA) is the desired structure function, dotted line (QED) is the measured structure function.
Figure 6: The 200x200mm phase screen provided by HIA (left) and QED measurements after the second polishing iteration (right). All maps are piston and tip-tilt removed.

Figure 7: X and Y cuts of the square-root of the full structure function (scales up to 200mm) for the second and third polishing iterations. Solid line (HIA) is the desired structure function, dotted line (QED #2) is the measured structure function of the second iteration and the dashed line (QED #3) is the third iteration.
To quantify the results we computed the structure function of the test result and plotted the square root of the structure function for the X and Y directions. The square root of the structure function represents the RMS slope at the different spatial scales. The data results are shown in Figure 5. This analysis shows that the RMS slope targets are missed by 30% to 40%.

The results of the second iteration with the 50mm wheel are shown in Figure 6, 7, and 8. The fidelity of the phase plate is greatly improved. At the 5mm scale, which is equal to the NFIRAOS Deformable mirror actuator pitch, the slope is a few percent lower than the desired structure function. At larger scales the phase plate has slightly more structure than specified. For scales smaller than 5mm, the RMS slope is too low with the slope undershooting by about 20% at the 2mm scale. This will result in the wavefront sensor lenslet images appearing less “speckly” than on the sky.

A third iteration was done to attempt to increase structure at the scales less than 5mm. These results are plotted with the second iteration data in Figure 7 and 8. The result was a change in the structure at the larger scales to slightly undershoot. In the 10mm and smaller spatial scales the structure is unchanged from before. The interferogram for the third run has been omitted,
as it is visually indistinguishable from the second run. Although this third iteration did not improve the data, it did improve the understanding of the process control required for phase plates and a modification of the standard algorithms would be required to focus the correction to target specific spatial scales to be improved.

6. Conclusions
The data analysis showed excellent agreement for spatial scales 5mm and larger after the second iteration. This shows the turbulence generator will be able to simulate the atmosphere parameters in terms of turbulence strength and profile. The undershooting of the slopes in the smaller spatial scales will result in the lenslet spots in the wavefront sensor being less blurred than on the sky. A review of the tests to be done with turbulence generator by the NFIRAOS team concluded the slightly less blurry spots are within the required tolerances for the turbulence generator and the phase maps produced in the second and third iteration are acceptable. The results of this study show the QED MRF technology can manufacture phase plates for the NFIRAOS AO system. This risk reduction exercise was successful and NFIRAOS has baselined this technology for the manufacture of the phase plate.

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8. References