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Miniaturized Shack-Hartmann Wavefront-Sensors for ELTs

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ABSTRACT

The miniaturization of wavefront sensors overcomes some of the potential barriers faced by ELTs in implementing large-scale multi-object adaptive optics over large focal surfaces. The Australian Astronomical Observatory is prototyping a compact and lightweight Shack-Hartmann wavefront-sensor designed to be positioned by their Starbug parallel fibre positioning robots. Starbugs perform the critical positioning of optical fibers for the MANIFEST instrument for the GMT. Each wavefront sensor uses a set of polymer bundles to relay the image produced by a microlens array near to the focal plane to a re-imaging module. This allows multiple wavefront sensors to be multiplexed to a single low-noise camera for cost efficiencies per wavefront sensor. The ability to have a large number of wavefronts sensors are likely increase the scientific impact of future ELTs. We illustrate our miniature wavefront sensor concept with a potential design for the GMT.

Keywords: Starbugs, Shack-Hartmann, Miniaturized, Wavefront-Sensors, Adaptive Optics, GMT, MANIFEST

1. INTRODUCTION

Adaptive Optics (AO) [1] is a critical component for each of the planned Extremely Large Telescopes (ELTs). The ability for AO to compensate for the optical wavefront aberrations caused by the atmospheric turbulence improves the image quality and hence the science capability. The ability to measure the wavefront aberrations in real-time is achieved by using a wavefront sensor (WFS). The push towards compensating the image quality for more than one science object can significantly improve the efficiencies for survey work. This is known as Multi-Object Adaptive Optics (MOAO) [2]. This has increased the demand for having multiple WFS spread across focal surfaces covering a large physical area (compared to current telescopes). This requirement causes new challenges, such as the positioning of the WFS to within the accuracy and time constraints. Minimizing the overall cost is also important for the concept feasibility.

To approach the challenge of multiple WFS for ELTs, we present the novel concept of miniaturized shack-hartmann wavefront sensors (mini-WFS) [3] positioned with a 'Starbug' [4, 5] developed by the Australian Astronomical Observatory (AAO). Starbugs provide the ability to simultaneous position optical fibers around the focal with accuracies better than 5 microns and configuration times better than several minutes. Starbugs are a new type of fiber positioner that has been demonstrated in the laboratory and early on-sky tests. Starbugs are a maturing technology that is currently proposed for the TAIPAN [6] and MANIFEST [7, 8] instruments.

The application we propose for our mini-SHWFS are for the GMT, see Figure 1. The reason being that MANIFEST instrument for the GMT is based on Starbugs and therefore a potential upgrade path. The GMT may also benefit from the application that requires a large number of mid-to-low wavefront measurements (for partial corrections), such as Ground-Layer Adaptive Optics (GLAO) [9] and MOAO. The mini-WFS can also be used as an auxiliary diagnostic of the GLAO performance as function of field by observing star clusters.

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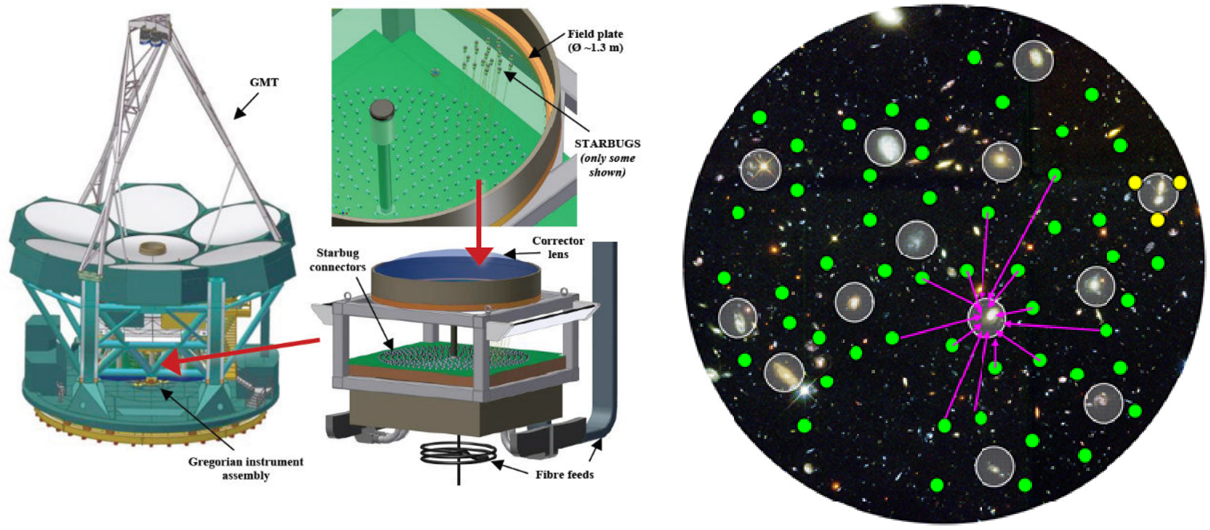


(a) GMT and MANIFEST (Starbugs positioner)

(b) Starbugs mini-WFS (green dots) for MOAO or probe GLAO field positions.

Figure 1: The mini-WFS can be used for MOAO applications, e.g. a possible upgrade option for MANIFEST [3, 7, 8].

2. CONCEPT

The concept of the GMT mini-WFS positioned by Starbugs is shown in Figure 2. The concept is derived from the mini-WFS concept for the Anglo-Australian Telescope (AAT) [3] which has already has some progress with simulations, lab and on-sky measurements. The use of polymer coherent imaging bundles [3, 10] relays the image formed by each Starbug WFS onto a single fast readout, low noise detector. The multiplex of multiple mini-WFS onto a single fast, low noise detector (most expensive component of WFS) is a significant cost savings to the instrument. Therefore, the overall cost per unit WFS is relatively small.

The concept can be described by the following steps [3]: (1) Each Starbug is positioned on a suitable guide star and are held onto the glass field plate by a vacuum force. (2) Each Starbug has fore-optics consisting of a small collimating lens that re-images the telescope pupil onto a microlens array (MLA). (3) The MLA array then images its spot pattern onto the polymer coherent imaging bundle. (4) The bundles from multiple Starbugs are packed together to form a single back-end block. (4) A relay lens then re-images the back-end block (with suitable magnification) onto a fast, low noise detector.

The detector image consists of a multiplexed array of mini-WFS images. The software then processes the detector image to reconstruct the individual wavefronts of each mini-WFS. Flexible operation modes such as higher framerates or improved sensitivity (limiting magnitude of guide star) can be built into the system to adapt to the observing conditions. The modular design allows for scaling up or down the numbers of mini-WFS that are required.

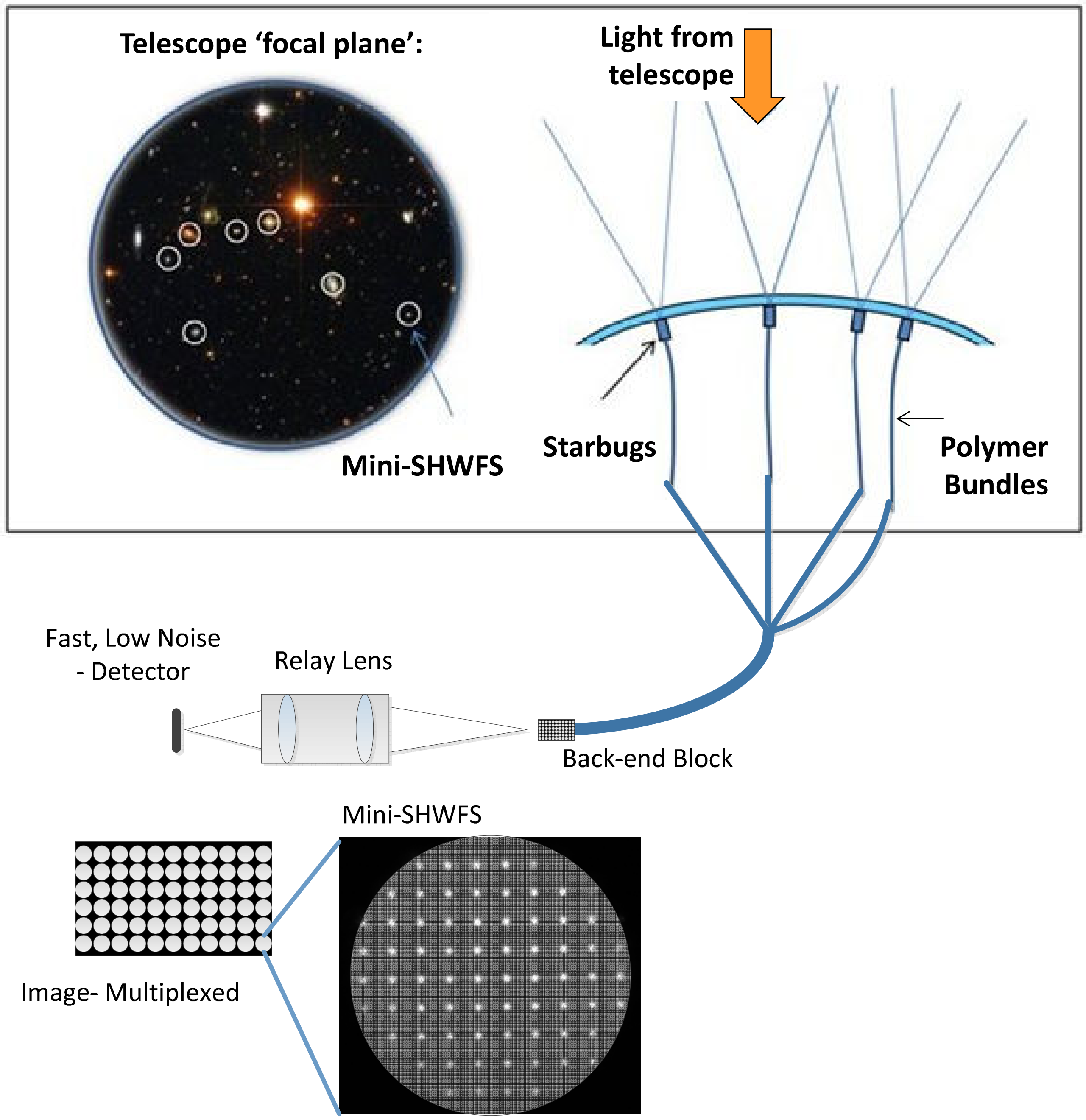
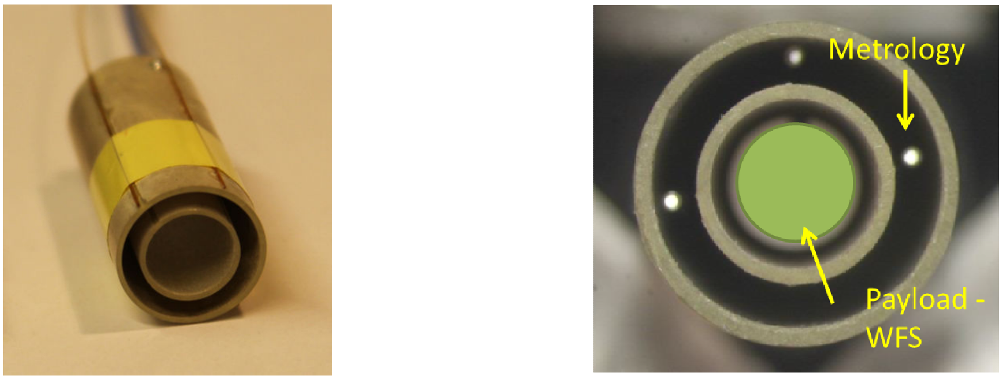


Figure 2: Concept diagram for mini-WFS using Starbugs [3].

3. DESIGN

3.1 Starbug Positioner

Starbugs [4, 5] are parallel robotic positioning to position optical fibres precisely at the focal plane to catch the light from objects and relay them through optical fibers. The AAO has proposed Starbugs as the fiber-positioner for TAIPAN [6]. The goal of Starbugs is to reconfigure typical fields in a several minutes that are typically the downtime between fields to either move the telescope or read the detector. The mini-WFS uses a larger Starbug (Type II), see Figure 2 (a), comprises two piezoceramic tube actuators, joined at one end to form a pair of concentric 'legs' that can be electrically driven to produce a micro-stepping motion. Starbugs are positioned under closed-loop control and are monitored with a camera imaging their back-illuminated metrology fibers; see Figure 2 (b).



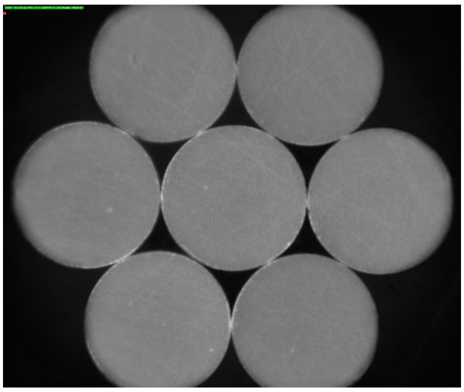
(a) Exterior diagram of the Starbug (Type II) with a tube length of approximately 20 mm and diameter of 12 mm.

(b) Starbug (standard) front surface (contacts with glass field plate to form a vacuum) showing the inner and outer tubes, the metrology fibres and the location for the payload (diameter ~ 3.75 mm) [3].

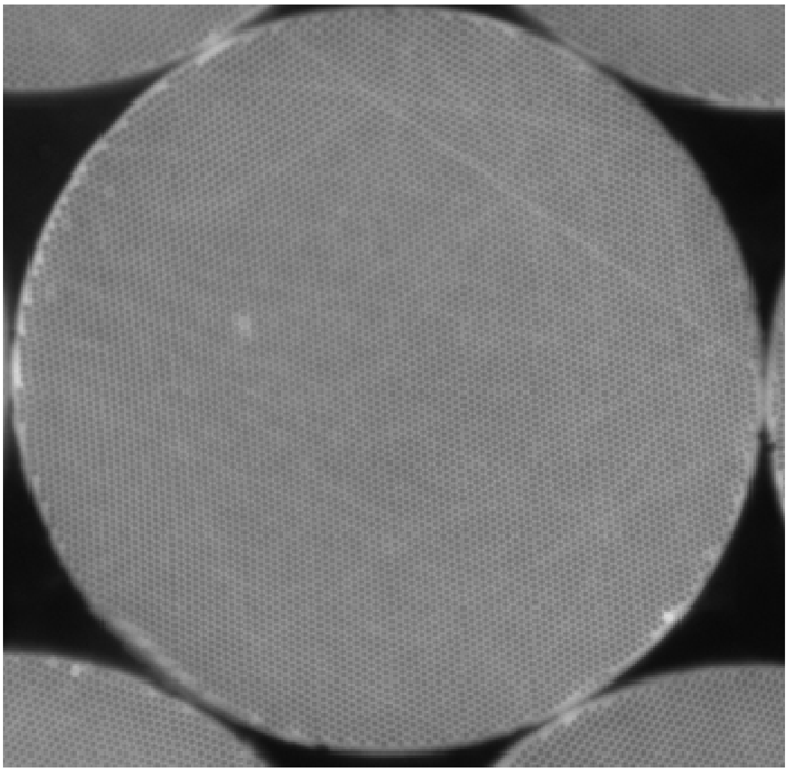
Figure 3: Starbug mechanical (a) and nominal payload position (b).

3.2 Polymer coherent imaging bundles

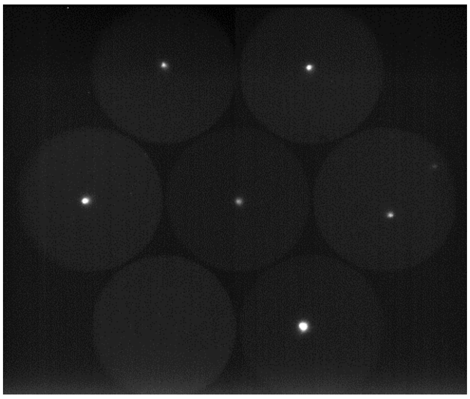
Polymer coherent imaging bundles [3, 10] provide the function of relaying the image of each mini-SHWFS to the re-imaging camera. The bundles that perform this function are 1.5 mm in diameter and contain about 7000 cores that are each approx. 16 microns in diameter. The throughput efficiency has been measured to be approximately 75% with a numerical aperture (NA) ranging from 0.16 to 0.37, allowing the relay of focal beams as fast as F/1.3 to 3.1 [10]. The polymer coherent imaging bundles are used for the SAMI instrument [11, 12] as part of the guide bundle module. The bundles are also proposed for the TAIPAN [6] guide bundle module. The TAIPAN bundle functions include field plate alignment, field acquisition, telescope guiding and as a plate reference for positioning. A TAIPAN prototype module consisting of 7 guide bundles are shown in Figure 4, as tested on the 1.2 m UKST telescope. Tests on the 1.2 m UKST telescope (proto-TAIPAN [6]) provided acquisition of V~10 magnitude stars with exposures approx. 40 ms (25 fps).



(a) flat field illumination



(b) close-up of a single bundle as shown in (a)



(c) imaging V~10 stars with 40 ms exposures

Figure 4: Polymer coherent bundles used for early TAIPAN tests on the UKST 1.2 m. Each bundle is 1.5 mm or 100” field [3].

3.3 Starbugs payload (fore-optics)

The GMT mini-WFS are designed for partial corrections and high-multiplex for median or better seeing conditions. The fore-optics design for the mini-WFS for the GMT focal f/8 beam is shown in Figure 5. The fore-optics is designed in ZEMAX with off-the-shelf components. The components fit into the allowable dimensions of the Starbug’s inner tube clear aperture having diameter of approx. 7mm. The diameter of the collimating lens is 6.25 mm. The length from the telescope focuses to bundle being approx. 75 mm. The MLA array selected to provide adequate number of sub-apertures over the GMT 25.4 m pupil, being 45x45, or sub-aperture length of approx. 56 cm, see **Error! Reference source not found.**. Each GMT mirror segment is aligned with a 1.5mm polymer bundle. Increasing the number of sub-apertures causes spot confusion and insufficient sampling by the bundle cores. The GMT mini-WFS are designed for spot motion range of +/- 0.55”.

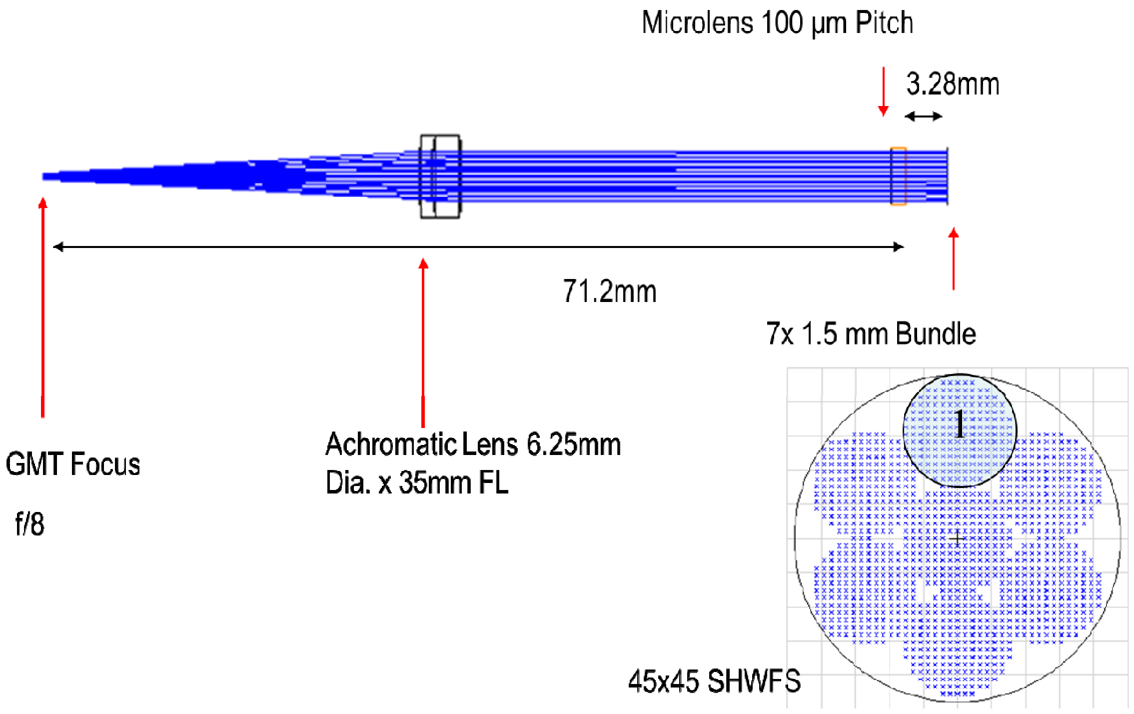


Figure 5: ZEMAX optical design for mini-WFS for the GMT f/8 that fits into a Starbug (Type II).

3.4 Back-end re-imaging module

The purpose of the back-end module is to re-image the back-end block of the polymer bundle array onto the detector, as shown in Figure 6. A telecentric lens with an appropiate magnification and numerical aperture is used to achieve the correct pixel sampling. Camera binning can also be used to achieve the requried sampling. For the design in Figure 6, an aluminium block can be used as a sturdy mount to attach components.

To provide an example of the multiplex gains, consider the Andor Zlya DG-152X-CIE-F1 sCMOS camera [13] with (read noise 1.45-1.80 electrons). The back-end bundle module dimensions 11.73mm x 9.36mm can be re-imaged within the region of interest 1920x1080 pixels using the 0.75x telecentric lens. This allows 6x7 bundles to be re-imaged, or 6x GMT mini-WFS at 200 fps, suffient for partial corrections for wind speeds below 30 m/s (0.56m sub-apertures takes 18 ms crossing time for 30 m/s). Note that the image bundle samples the MLA spots at approx. 1.4x spots per bundle core and then the detector samples the bundle core at 1.5x pixels per core.

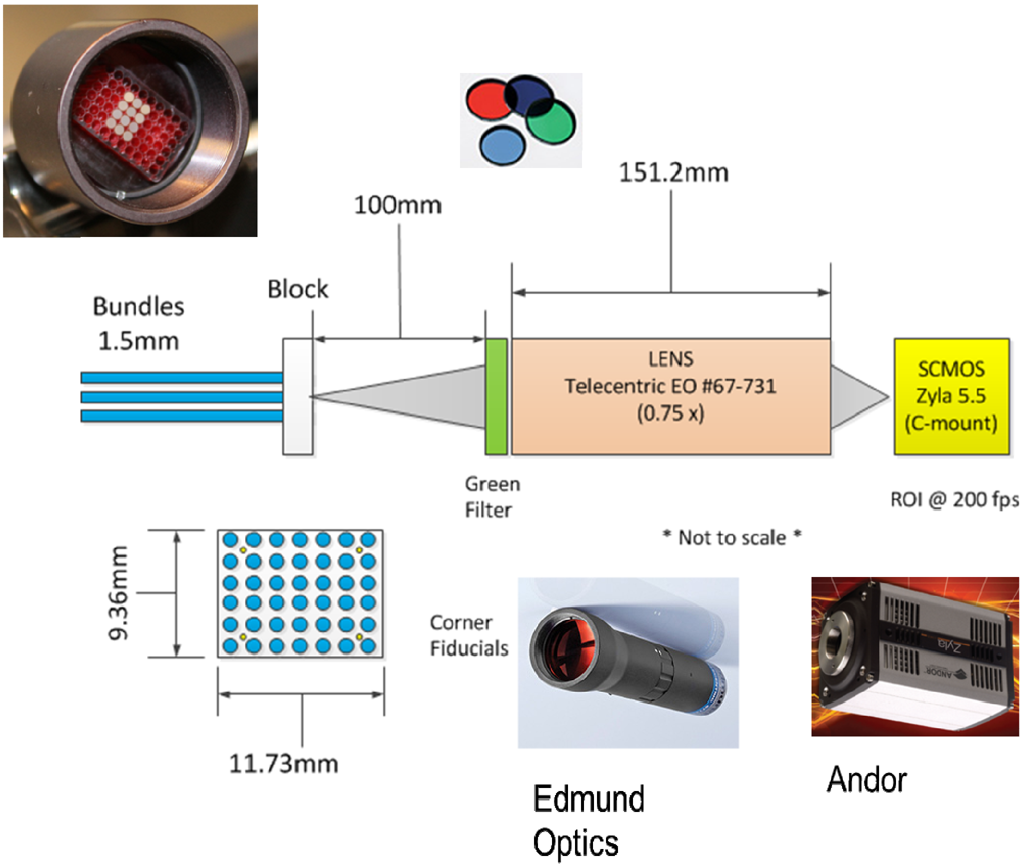


Figure 6: Back-end module concept design to re-image the bundles onto the detector.

4. PROTOTYPE

The prototype of the GMT mini-WFS is shown in Figure 7. The mechanical mount that holds the achromatic lens and the MLA array is 3D printed to specifications. The lens mount fits into the inner tube of the Type II (larger) Starbug. A second 3D printed mount holds the 7 image bundles that are precisely aligned to the GMT segment layout. The bundle mount is polished to have a flat surface for best image quality and fits at the back of the lens mount. A third 3D printed mount hold the back-end block of the bundles to be re-imaged onto the detector. The back-end mount also needs to be polished flat like the bundle front-end. The prototype's length is approximately 95mm and its diameter being 12mm (or a footprint of 12 arcsecs on the GMT focal surface).

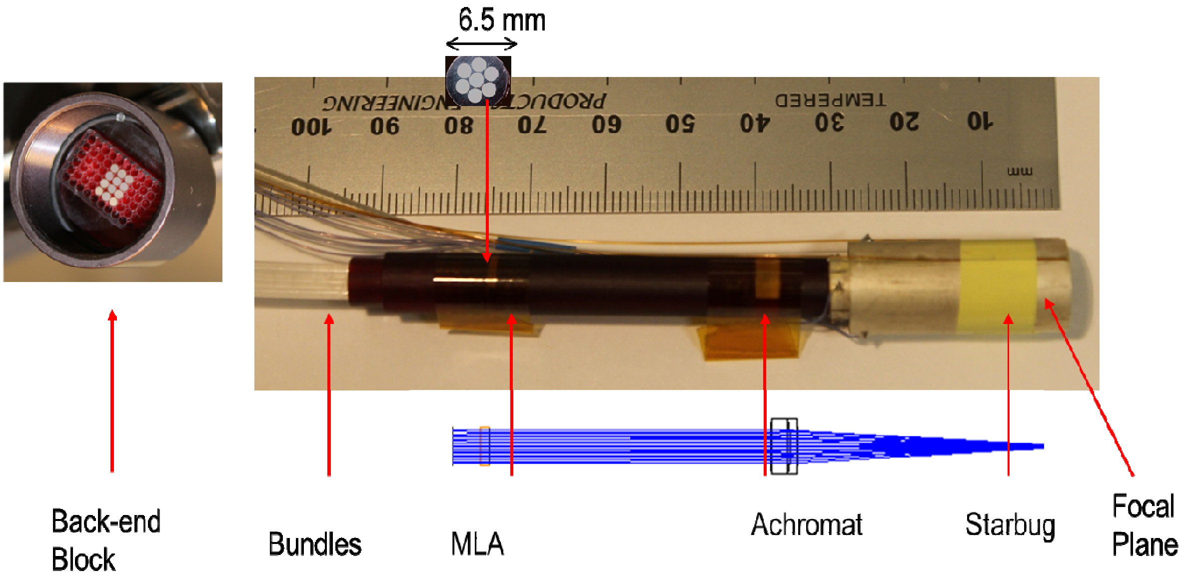


Figure 7: Prototype of the GMT mini-WFS with Starbug positioner

5. EXPERIMENTAL RESULTS

The experimental setup to optical test the GMT mini-WFS prototype is shown in Figure 8. The experiment uses a reference wavefront using a red laser source that is collimated and then passed through an achromatic lens to generate the F/8 input beam. The mini-WFS prototype is then aligned to the F/8 input beam so that the spot pattern is not vignetted on the bundle front-end. The back-end block containing the 7 image bundles of 1.5mm diameter each is then re-imaged by the 2x telecentric lens onto the Thorlabs CMOS detector. The resulting detector image of the reference wavefront is shown in Figure 9. The layout of the re-imaged bundles in Figure 9 can be arbitrary arranged (but are configured in the GMT segment layout).

Example close-ups of detector images for a flat wavefront re-imaged at magnifications of 2x and 0.5x are shown in Figure 10 (a) and (b). The design specification uses 1.5 pixels per core, as shown in Figure 10 (b).

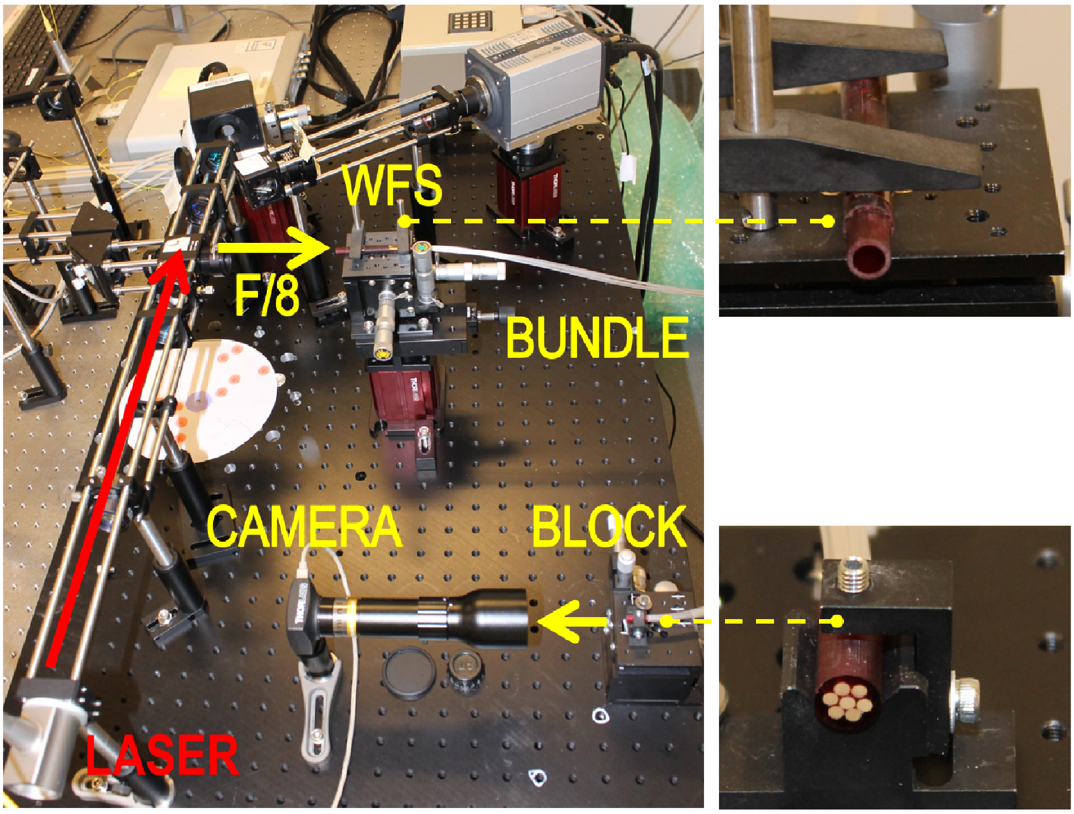


Figure 8: Experimental setup to compare the measured wavefronts using a polymer bundle mini-SHWFS (bottom left corner) with that of a Thorlabs SHWFS using the Thorlabs Adaptive Optics kit.

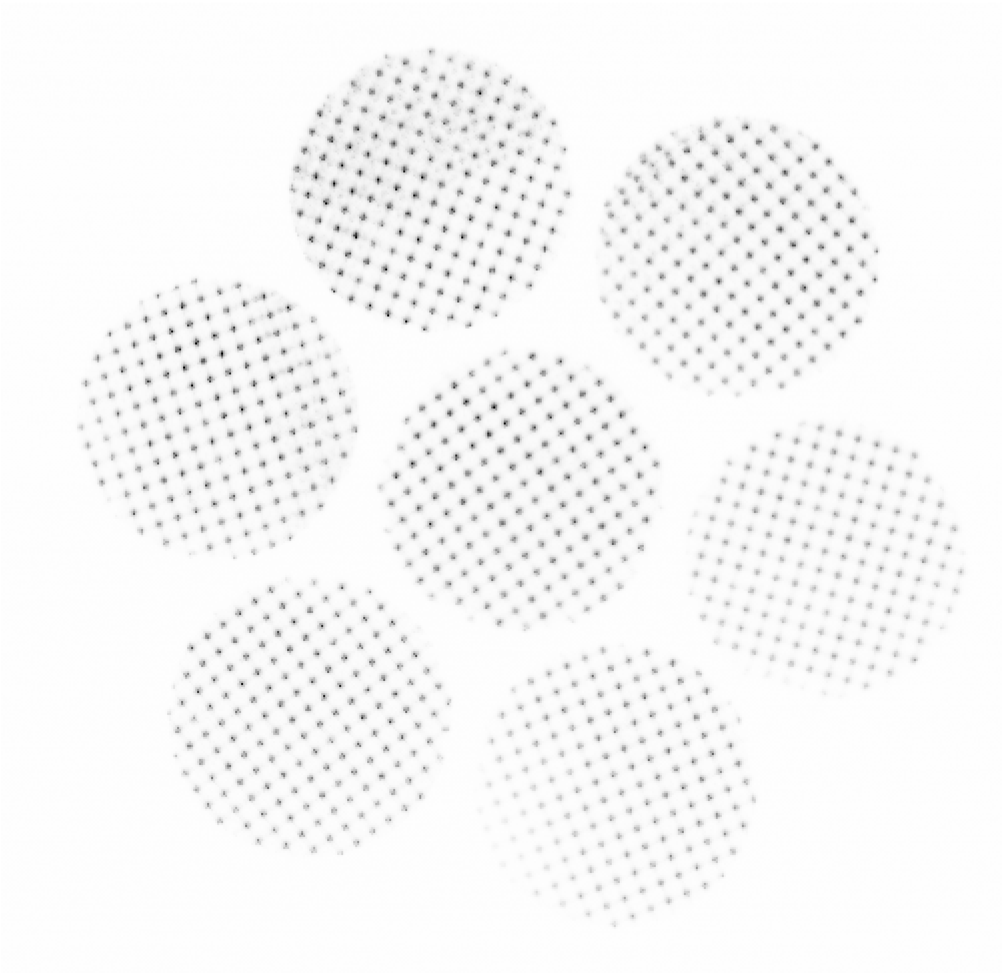
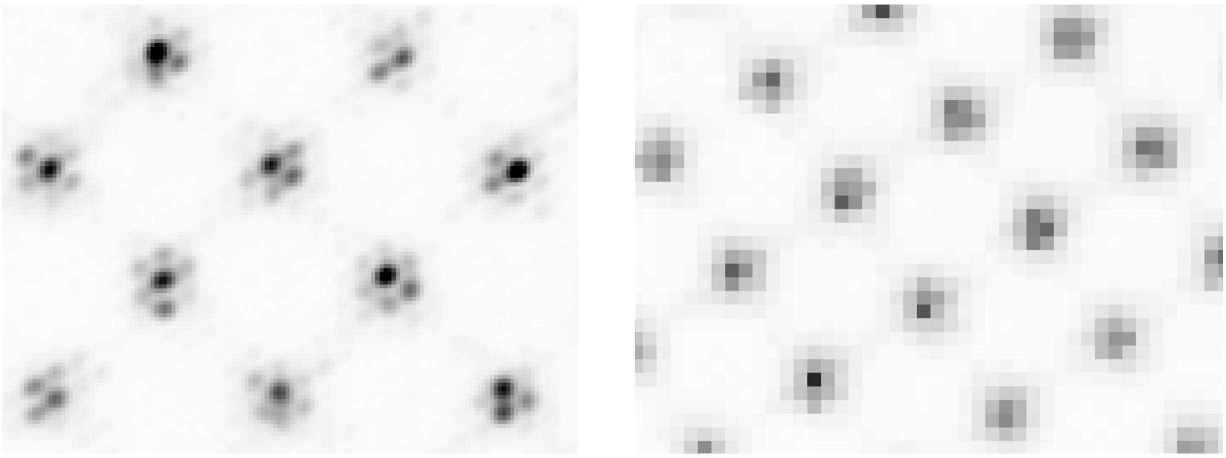


Figure 9: Reference spot pattern image for the GMT mini-WFS prototype.



(a) 6 pixels per core sampling (2x magnification).

(b) 1.5 pixels per core sampling (0.5x magnification – as design).

Figure 10: Sub-section of reference images (flat wavefronts) of the GMT mini-SHWFS using the experimental setup shown in Figure 10. The MLA spot size is approximately 22 microns and sampled on to 16 microns bundle cores.

6. CONCLUSIONS

In this paper we have proposed a concept design for a 45 x 45 mini-WFS system positioned by Starbugs for the 25.4 m GMT at f/8. The concept is capable of simultaneous operating a total of 6 mini-WFS at ~ 200 fps for a 5M pixel SCMOS camera. Verification of the mini-WFS concept design has been shown using a reference wavefront with laboratory measurements. Further work for the mini-WFS includes further AO test-bench work and mechanical positioning with Starbugs. The mini-WFS are a potential solution in providing a high number of WFS across the GMT focal surface for an economical cost. It further extends the versatility of Starbugs positioners for MANIFEST instrument. The ability of the mini-WFS to fit into a larger Starbug (Type II) minimizes both cost and technical risk. Therefore, the mini-WFS can leverage off the many advantages provided by Starbugs. The advantage to multiplex a number of mini-WFS onto a single low-noise fast-readout detector provides a substantial cost savings per wavefront sensor. The advantage of having multiple distributed WFS across the field provides exciting opportunities for new types of AO instruments.

7. REFERENCES

[1] Hardy, J. W., [Adaptive Optics for Astronomical Telescopes], Oxford University Press, New York, 448 (1998).

[2] Rousset, G., Fusco, T., Assemat, F., Gendron, E., Morris, T., et al., “EAGLE MOAO system conceptual design and related technologies,” Proc. SPIE 7736, Adaptive Optics Systems II, 77360S (2010).

[3] Goodwin, M., Richards, S., Lawrence, J., Zheng, J., Leon-Saval, S., Argyros, A., “Miniaturized Shack-Hartmann wavefront sensors for starbugs,” Proc. SPIE 9151, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation, 91514T (2014).

[4] Brown, D. M., Case, S., Gilbert, J., Goodwin, M., Jacobs, D., Kuehn, K., Lawrence, J. S., Lorente, N. P. F., Nichani, V., Saunders, W., Staszak, N., Tims, J., “Starbug fibre positioning robots: performance and reliability enhancements ,” Proc. SPIE 9151, (2014)

[5] Gilbert, J., Goodwin, M., Heijmans, J., Muller, R., Miziarski, S., Brzeski, J., Waller, L. G., Saunders, W., Bennet, A., Tims, J., “Starbugs: all-singing, all-dancing fibre positioning robots,” Proc. SPIE 8450, Modern Technologies in Space- and Ground-based Telescopes and Instrumentation II, 84501A (2012).

[6] Kuehn, K., Lawrence, J. S., Brown, D. M., Case, S., Colless, M., Content, R., Gers, L., Goodwin, M., Hopkins, A. M., Ireland, M., Lorente, N. P. F., Muller, R., Nichani, V., Rakman, A., Saunders, W., Staszak, N. F., Tims, J., Waller, L. G., “TAIPAN: optical spectroscopy with Starbugs,” Proc. SPIE 9147, (2014).

[7] Goodwin, M., Brzeski, J., Case, S., Colless, M., Farrell, T., Gers, L., Gilbert, J., Heijmans, J., Hopkins, A., Lawrence, J. S., Miziarski, S., Monnet, G., Muler, R., Saunders, W., Smith, G., Tims, J., Waller, L. G., “MANIFEST instrument concept and related technologies,” Proc. SPIE 8446, Ground-based and Airborne Instrumentation for Astronomy IV, 84467I (2012).

[8] Lawrence, J. S., et al., “The MANIFEST fibre positioning system for the Giant Magellan telescope,” Proc. SPIE 9147, (2014).

[9] Hart, M., Milton, N. M., Baranec, C., Powell, K., Stalcup, T., McCarthy, D., et al., “A ground-layer adaptive optics system with multiple laser guide stars,” Nature, 466(7307), 727-729 (2010).

[10] Zheng, J., Richards, S., Goodwin, M., Lawrence, J., Leon-Saval, S., Argyros, A., “A miniature curvature wavefront sensor with coherent fiber image bundle,” Proc. SPIE 9148, (2014).

[11] Croom, S. M., Lawrence, J. S., Bland-Hawthorn, J., Bryant, J. J., Fogarty, L., Richards, S., et al., “The Sydney-AAO multi-object integral field spectrograph,” Monthly Notices of the RAS, 421(1), 872-893 (2012).

[12] Bryant, J. J., Bland-Hawthorn, J., Lawrence, J., Croom, S., Fogarty, L. M., Goodwin, M., et al., "SAMI: a new multi-object IFS for the Anglo-Australian Telescope," Proc. SPIE 8446, Ground-based and Airborne Instrumentation for Astronomy IV, 84460X (2012).

[13] Andor, "Andor_Zyla_sCMOS_Specifications," Andor, 20 June 2014, <http://www.andor.com/pdfs/specifications/Andor_Zyla_sCMOS_Specifications.pdf> (20 June 2014).