On-sky results for the novel integrated micro-lens ring tip-tilt sensor

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We present the first on-sky results of the micro-lens ring tip-tilt (MLR-TT) sensor. This sensor utilizes a 3D printed micro-lens ring feeding six multi-mode fibers to sense misaligned light, allowing centroid reconstruction. A tip-tilt mirror allows the beam to be corrected, increasing the amount of light coupled into a centrally positioned single-mode (science) fiber. The sensor was tested with the iLocater acquisition camera at the Large Binocular Telescope in November 2019. The limit on the maximum achieved root mean square reconstruction accuracy was found to be 0.19 \( \lambda/D \) in both tip and tilt, of which approximately 50% of the power originates at frequencies below 10 Hz. We show the reconstruction accuracy is highly dependent on the estimated Strehl ratio and simulations support the assumption that residual adaptive optics aberrations are the main limit to the reconstruction accuracy. We conclude that this sensor is ideally suited to remove post-adaptive optics non-common path tip tilt residuals. We discuss the next steps for the concept development, including optimizations of the lens and fiber, tuning of the correction algorithm and selection of optimal science cases.

1. INTRODUCTION

In recent decades, improvements in the performance of an increasing number of extreme adaptive optics (ExAO) systems has led to the ability to image near the diffraction-limit using 8 m-class telescopes [1–4]. These ExAO systems focus on achieving the best performance over a small field of view (FoV) and regularly achieve Strehl ratios (SRs) of 80% in the near-infrared (NIR). One of the most prominent goals for these systems is the direct observation and characterization of exoplanets [5], for which high angular resolution and contrast are crucial. The high level of correction provided by these ExAO systems also makes it possible to efficiently couple light from the telescope directly into single-mode fibers (SMFs) [6]. SMFs have a core diameter of the order of ten microns, which can only transport the fundamental fiber mode. As this mode is the only spatial mode transported and has a near-Gaussian intensity profile, the corresponding output beam is very stable and easy to model. SMFs also act as a spatial filter and couple very little sky background [7]. This makes them highly suitable for direct exoplanet spectroscopy [8] and interferometry [9–13]. When coupled to a high resolution spectrograph, SMFs also remove conventional modal noise, allowing
an increase in the achievable radial velocity (RV) precision [14]. A number of SMF-fed spectrographs are currently under development, including iLocater at Large Binocular Telescope (LBT) [7, 15], SPHERE and CRIRES+ at the Very Large Telescope (VLT) [16], RHEA and IRD at SCExAO/Subaru [17, 18] and KPIC at Keck [19].

As the size of the fiber is of the order of the diffraction limit (λ/D, where λ is the wavelength and D the diameter of the telescope), the alignment accuracy is highly dependent on the point-spread function (PSF) stability (see Fig. 1 for an example of relative coupling efficiency as a function of residual tip-tilt position). Any vibrations that occur through the telescope system and influence the position of the PSF in the focal plane can have a large impact on performance. These variations can be caused by electrical and mechanical components such as fans and pumps, but can also be induced by wind, atmospheric distortions and dome seeing [20]. As these variations can have both large amplitude and high frequencies, the adaptive optics (AO) system may not be able to compensate for them sufficiently and, if they can occur outside the path to the wavefront sensor (WFS), they will not be sensed. These variations can effect the performance significantly [21] and turn out to be a limiting factor when coupling into SMFs, with coupling efficiency being degraded by as much as a factor of two [22].

Fig. 1. Numerically calculated theoretical normalized coupling efficiency assuming an optimally coupled diffraction-limited PSF with additional residual tip-tilt variation, plotted in units of λ/D. The measured RMS residuals at the iLocater focal plane are also indicated, without beam stabilization at 0.61 λ/D resulting in a theoretical reduction by 44% (red line), and with additional stabilization with a quad-cell detector improving tip-tilt stability to 0.39 λ/D, leading to a tip-tilt induced coupling loss of 24% (green line) [15].

Besides high-order AO correction, efficient SMF-coupling therefore requires a method to accurately sense and correct induced tip-tilt variations. Traditionally, this is accomplished by detecting the PSF at the focal plane either with a fast quad-cell photo detector [23] or camera, computing the centroid position, and feeding back a corresponding error signal to a fast tip-tilt correction mirror. More advanced systems include feed-forward correction of mechanical vibration measurements with accelerometers [24] and the deployment of complex metrology systems utilizing concurrent alignment lasers [25]. While most of these systems have been adopted at large telescopes, they all have a significant mechanical and optical footprint, throughout loss, tend to become complex in operation, and are vulnerable to non-common path (NCP) effects as the tip-tilt correction is performed at a different optical surface than the SMF face.

Different fiber based photonic sensor concepts are being investigated in the community to complement conventional AO systems [26, 27]. The concept presented in this work draws from Ref. 28, who developed a sensor with multiple single-mode (SM) cores equipped with an micro-lens array to refract the beam at the focal plane for both science instrument and tip-tilt sensing. Our modified concept features multi-mode fibers (MMFs) in conjunction with a micro-lens ring (MLR) [29] for sensing and is called the micro-lens ring tip-tilt (MLR-TT) sensor [30]. We present first on-sky results of this novel tip-tilt sensor with the iLocater acquisition camera at the LBT [15].

In Section 2, we describe the sensor concept and the methods used to design, manufacture and employ it at the telescope along with outlining our simulation approach. In Section 3 we present our on-sky results and supporting simulations and in Section 4 we discuss these results and future developments before presenting our conclusions in Section 5.

2. DESIGN AND METHODS

The MLR-TT sensor concept is depicted in Fig. 2 as both a schematic cross-section of the optics (Fig. 2, left-hand side) and as images of the manufactured components (Fig. 2, right-hand side). The details are re-iterated here, with additional information, for clarity:

1. The sensor consists of a fiber bundle containing six MMFs surrounding an SMF, located at the iLocater focal plane. On the fiber face, an MLR stands 380 µm tall and 355 µm wide with a central aperture of 86 µm.

2. The central part of the beam is injected into the SMF, while the outer edge is clipped and refracted by the MLR. Depending on the alignment of the beam, the proportion of light clipped by the MLR changes, which modifies the coupling into the individual MMFs.

3. The MMFs are separated from the SMF, re-arranged to form a linear array, re-imaged, and read out by a detector.

4. The illumination pattern of the MMFs is processed to reconstruct the original PSF centroid position, which can be fed back to a fast steering tip-tilt mirror for correction.

A. Fiber bundle design

The fiber bundle was manufactured commercially (Berlin Fibre GmbH) and holds the array of seven fibers terminated into an FC/PC connector which is then connected to the iLocater fiber feed mount. The fibers are stripped of their furcation tubing and buffer and are placed in the connector with a pitch of 125 µm. After 30 cm, the SMF and the MMFs separate into two individual 5 m-long fiber cables: 1) the science SMF, which is terminated to an FC/PC adapter to feed the science instrument and 2) the sensing MMFs, which are rearranged into a linear array within an SMA connector.

The SMF (Fibercore SM980) features a mode-field diameter (MFD) of 5.8 µm (1/e²-intensity at 980 nm) and is taken from the same batch of the fiber that will feed the iLocater spectrograph, minimizing any fiber-to-fiber coupling losses further
B. Lens design

Design and optimization of the MLR were performed using the optical design software Zemax OpticStudio. To calculate the coupling efficiency into the SMF, the Physical Optics Propagation (POP) tool was employed, and for MMF coupling the Imaging tool was used. POP uses Fourier and Fresnel propagation, which is crucial when handling the near-Gaussian mode of the SMF and the complex illumination pattern on the MLR. It is computationally intensive however, so to design the shape of the lenses, the Imaging tool was used, which utilizes a ray tracing algorithm to estimate the coupling efficiency into MMFs.

For our technology demonstrator, we aimed to have a strong signal for tip-tilt sensing while also enabling high SMF coupling efficiency. This will both increase the signal-to-noise ratio (SNR) and also provide a signal in all six fibers within a reasonable dynamic range. The diameter of the central aperture was chosen to clip \( \sim 13\% \) of the light, reducing the maximum achievable SMF coupling efficiency with an idealized circular pupil from \( \sim 80\% \) to \( \sim 65\% \). Using this aperture, the surface shape of the MLR was then optimized to maximize the MMF coupling efficiency, weighted to favor on-axis beams with decreasing priority for misalignment up to \( 100 \mu m \) (corresponding to \( \sim 20 \lambda / D \)). The surface shape of the individual lenses needs to provide suitable optical power to focus the incoming clipped part of the beam into the MMF. This was achieved by optimizing the spherical shape and then adding corrections with both Zernike focal sag and separate conical constants in both directions. A strong optical power was necessary to refract the beam from the inner edge of the microlens to the MMF. For this, polynomial corrections were successively applied up to fourth order in the axis parallel to the radial axis, no additional correction was applied in the angular direction.

C. Lens manufacturing

The MLR was manufactured using two-photon polymerization using a proprietary resin on the fiber tip [32], which allows the manufacturing of free-form lenses on small scales. Due to the use of stages in the printing process, these structures can take arbitrary shapes, limited by the need for an appropriate support structure and macroscopic forces. The printing is aided by back-illuminating the fiber bundle and yields sub-micron alignment precision [28] compensating for irregularities in the bundle geometry. The process allows a precision of \( \sim 100 \text{~nm} \) and a root mean square (RMS) surface roughness of \( \sim 10 \text{~nm} \).

The physical size was limited to the maximum build height of approximately \( 400 \mu m \), due to the manufacturing stages and microscope objective numerical aperture (NA).

Once the MLR was printed on the fiber the FC/PC connector was then placed within a bulkhead adapter (Thorlabs HAFC) for mechanical protection.

D. Laboratory sensor response

As the custom lenses belonging to the iLocater acquisition camera were unavailable for laboratory experiments, the MLR-TT sensor’s response was tested using commercial lenses. An SMF illuminated by a 1050 nm SLED source (Thorlabs S5FC1050P),
was apertured and a Thorlabs AC127-025-C lens was used to produce an NA of 0.14, simulating the telescope’s Airy disc. The experimental system provided a lower throughput than the final on-sky experiment, due to lower image quality. The results in Fig. 3 show the sensor’s response to an gradually off-centered beam in the laboratory setup, both as modeled and as measured. The modeled SMF coupling efficiency (Fig. 3, top) includes Fresnel reflection loss of 3.5% at both fiber input and output face. The maximal achievable coupling efficiency within the MLR-TT sensor’s SMF is measured at 59.9 ± 0.6% which is slightly lower than the expected value of 63.2% at the given wavelength. This coupling efficiency then drops off slightly faster than expected with an off-centered beam but features a slightly increased coupling for misalignment of up to 2.2λ/D. The causes of this behavior still to be understood but are likely due to fiber bundle and lens imperfections.

The response of the sensing MMFs (Fig. 3, center) follows the modeled curves well, though the six sensing MMFs are not evenly illuminated when the beam is centered. During alignment we found that the illumination pattern depends strongly on the fiber alignment angle (pitch and yaw) and could not be completely corrected. This can result from asymmetries in the beam or uneven MMF properties such as irregular spacing or different fiber losses. In practice this is corrected by the calibration routine (Sec. F).

Laboratory results show the MLR couples 4.1% of the overall light into the MMFs when the beam is centered, which is 30% lower than the modeled value of 5.8% (this includes 11% reflections and losses from the fiber and 8% from the lens). Interestingly, this loss remains constant with respect to beam position (Fig. 3, bottom) up to a centroid offset of ∼3λ/D. We propose that the remaining mismatch is due to a non-optimally shaped lens surface. The ray approximation as described in Sec. B only considers a central top-hat beam but fails to accurately account for the diffractive pattern that illuminates the lenses outside the central beam.

Theoretical throughput calculations and the corresponding photon, sky background and camera noise associated with the described system show that with this reduced sensor signal, a source with 8th magnitude in the J band can provide a SNR of 14 for each MMF output when running at 500 Hz. Simulations with the same pipeline as described in Sec. H show that this results in an reconstruction accuracy of ∼0.1λ/D in tip and tilt combined. In this limiting case, performance is limited by read-out noise of the detector.

### E. Signal processing

The output of the sensing MMFs was re-imaged with two lenses mounted within a hybrid tube and cage mechanical system and directly attached to the lens interface of a First Light C-Red 2 InGaAs detector. This detector was chosen as it provides both a high frame rate (up to 16 kHz) and low read-out noise (34 e−) with a pixel size of 15 μm. Each MMF illuminates a circular region on the detector with a diameter of 100 μm. For each fiber, the 20 pixels with the highest SNR are selected and used for further processing. In laboratory tests, 20 pixels were measured to provide a steady fraction of 80% of the flux and the best overall SNR. The detector data was then processed by the Durham Adaptive optics Real-time Controller (DARC) [33, 34], running on a consumer grade desktop computer.

![Fig. 3. Modeled (solid lines) and measured (crosses) sensor response as function of centroid offset. Top panel: The coupling efficiency of the science SMF. Middle panel: The response of the six sensing MMF as function of beam offset. Bottom panel: MLR-TT sensor signal summed over all six MMFs.](image)

#### F. Reconstruction and calibration

The reconstruction algorithm (see Fig. 4) calculates the MMF illumination and converts it to a physical centroid position. For this, the six fiber fluxes are ordered with their azimuthal coordinate and a sine function with angular period of 2π is fitted to this signal. Three best fit parameters are obtained by this routine (see Fig. 4):

1. Offset, depending on both background signal and target flux.
2. Amplitude, corresponding to the radial position of the beam. Note, this is an arbitrary flux unit and the amplitude does therefore not directly yield the physical centroid position.
3. Phase, corresponding to the azimuthal coordinate of the centroid position.

Laboratory tests showed that this approach yields the most

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reliable and stable output, less susceptible to noise than a simple center of mass (CoM) algorithm.

A calibration routine is used to correct the reconstructed centroid position for accurate loop feedback and run time diagnostics. It accounts for irregularities in the system such as asymmetries or misalignment of the MLR, transmission variations within the fiber bundle and static aberrations in the PSF. For this, a circular motion is introduced with the tip-tilt mirror. The offset between the introduced and reconstructed azimuthal coordinate and the factor between the respective radial coordinates is approximated with individual best fit discrete Fourier transforms (DFTs) of 5th order as a function of the azimuthal coordinate. The obtained correction function is subsequently applied to the measured centroid position. It should be noted that this calibration routine is repeated for each target in order to remove slowly changing quasi-static aberrations (arising from effects such as mechanical flexure) and to include asymmetries of the source itself such as companions or background sources.

The interaction matrix is constructed by applying a linear signal in both tip and tilt with the mirror and simultaneously measuring the centroid position. The resulting 2x2 matrix is then inverted to obtain a reconstruction matrix, which can be used by the control loop to convert the measured centroid position into an feedback signal to command the tip-tilt mirror.

G. On-sky integration

The MLR-TT sensor was integrated into the iLocater SX acquisition camera [15] that is fed by the Large Binocular Telescope Interferometer (LBTI). The optical path is illustrated in Fig. 5. The iLocater acquisition camera receives the pupil from the telescope (a), passes the wavelengths between 920 nm and 950 nm (c) to its imaging channel equipped with an Andor focal plane camera (ANDOR Zyla 4.2 Plus, d), providing a sampling of 6.1 pixels across the full width at half maximum (FWHM) of the diffraction-limited PSF. This focal plane image is used as reference for the centroid position, i.e. the tip-tilt.

iLocater’s native tip-tilt correction features a quad-cell photo detector (Hamamatsu G6849-01 InGaAs, g), which is fed with light picked off by a dichroic at 1.34-1.76 µm, (e) just before the final coupling optics. The quad-cell system can then feed an error signal back to a fast tip-tilt mirror (nPoinT RXY3-276, b) to correct for tip-tilt. Alternatively, the mirror can be controlled by the MLR-TT sensor to either introduce the required motions for calibration (see Sec. F) or for correcting tip-tilt directly.

The science beam (0.97 – 1.31 µm) is focused by two custom triplet lenses [15] to an f/3.7 beam on the SMF to match its MFD of 5.8 µm (1/e²-intensity at 970 nm). The fiber mount can be moved in 5 axes for alignment and to switch between three independent fibers mounted at the instrument focal plane. These are: the native iLocater SMF, a bare MMF (105 µm core diameter) used for flux calibration, and the fiber port equipped with the MLR-TT sensor (f).

Fiber throughput is determined by measuring the output flux from each fiber with the bare MMF serving as an incident flux reference. Output flux is measured with a FemtoWatt receiver [15]. The fiber bundle holding the six sensing MMFs is routed to a separate opto-electric enclosure, housing the read-out optics and electronics.

H. Simulations of on-sky results

To further investigate the performance of the sensor with our recorded on-sky conditions, we simulated the sensor response for differing AO correction. To do this, an atmospheric wavefront distortion of 1000 modes in combination with a corresponding AO system correcting 500 modes was modeled using the HCIPy high contrast imaging simulation framework [35]. To allow an accurate comparison, the tip and tilt modes of the resulting wavefront are replaced by the centroid positions that were recorded during the on-sky observations.

These simulations are key as they allow us to understand our results and estimate the impact of residual AO aberrations and their dominance with respect to other noise sources.

3. RESULTS

We tested the MLR-TT on-sky in November 2019 at the LBT, using the left (SX) mirror of the telescope [15]. During the run the Large Binocular Telescope Interferometer adaptive optics (LBTI-AO) system was using the SOUL upgrade, which is designed to produce an SR of up to 78% in I-band [36] under optimal conditions. For all observations the AO system was running at 1 kHz closed on 500 modes. Correction for AO non-common path aberration (NCPA) was performed before observations, but otherwise there was no direct interaction between the MLR-TT sensor and LBTI-AO.

We present the results from three on-sky targets, with a total of 8 datasets. All targets were chosen to be bright (< 6th magnitude), marginalizing detector noise from the MLR-TT sensor. Tab. 1 provides an overview of the targets, the AO loop performance, and the associated datasets.

| Target/dataset | J-band mag. | Seeing (") | Est. SR | Additional Tip-Tilt control |
|----------------|-------------|------------|---------|-----------------------------|
| HIP28634 /4   | 5.3         | 1.2-2.0    | 50 ± 6% | MLR-TT                      |
| /5             |             |            | 52 ± 7% | None                        |
| HD12354 /1     | 5.9         | 1.0-1.4    | 67 ± 7% | None                        |
| /2             |             |            | 67 ± 11%| MLR-TT                      |
| HIP7981 /2     | 3.8         | 1.0-1.4    | 66 ± 4% | MLR-TT                      |
| /4             |             |            | 65 ± 4% | MLR-TT                      |
| /5             |             |            | 65 ± 4% | MLR-TT                      |
| /6             |             |            | 65 ± 4% | MLR-TT                      |

Each dataset includes three simultaneous measurements taken using iLocater and the MLR-TT sensor:

- Andor focal plane frames (Sec. 2.G), taken at a frame rate of 250 Hz. A symmetric 2D Gaussian function is fitted to the data in post processing and its calculated centroid used as a reference for PSF position. The SR in Tab. 1 was estimated by fitting a Gaussian to the centroid corrected PSF and taking the ratio between the normalized central intensities of this fit and the expected telescope PSF as described in Ref. 22. Due to the limited SNR of the individual frames, the SR calculations were smoothed by applying a moving median algorithm covering 20 frames.
• The reconstructed centroid position from the MLR-TT sensor (Sec. 2.F). Data were taken at a frame rate of 500 Hz. In post processing the frames were interpolated and cross-correlated to match the time reference of the Andor data.

• The SMF coupling efficiency was measured with the FemtoWatt receiver (Sec. 2.G).

A. Sensor calibration
As described in Sec. 2.F, the calibration pattern was generated by introducing a circular motion on the tip-tilt mirror by issuing open loop position commands. An example of the calibration routine for target HIP7981 is shown in Fig. 6 for (a) the Andor reference centroid position, (b) the raw MLR-TT centroid position and (c) the calibrated centroid position.

During the calibration, the AO loop was closed, but no additional tip-tilt correction was applied. Due to residual vibrations at the telescope, the measured centroid positions show a broadened pattern, which is averaged. The averaged centroid positions are used to correct the reconstructed centroid for static asymmetries.

For HIP7981, the reconstruction without calibration shows an RMS error of $0.33 \lambda/D$ in tip and $0.26 \lambda/D$ in tilt ($0.42 \lambda/D$ combined). After correction, this improves to $0.19 \lambda/D$ in tip and $0.21 \lambda/D$ in tilt ($0.28 \lambda/D$ combined) and appears random. The impact of the calibration on the reconstruction accuracy for all targets is listed in Tab. 2, including the RMS shift that is applied by the calibration. This shift corresponds to the correction that the calibration routine performs on the centroid position which is seen as an improvement of the reconstructed centroid position. The correction is seen to provide a more significant improvement for the datasets with lower pre-calibration RMS reconstruction error. This arises from a more precise measurement of the calibration pattern (corresponding to a thinner ring in Fig. 6) that leads to a more accurate parametrization of the correction function.

For all other datasets listed in Tab. 1, the calibration was also applied but did not provide a significant improvement. These datasets all feature a smaller dynamical range and the applied shift varied between 0.06 and 0.09 $\lambda/D$ in tip and tilt combined. Compared to the overall noise in these datasets (see Sec. D), the impact of the calibration is negligible.

Table 2. Improvement gained through the calibration routine. RMS reconstruction error before and after applying the calibration is listed as well as the RMS shift determined after the application of the calibration routine.

| Target      | RMS error no calib. [\lambda/D] | RMS error calibrated [\lambda/D] | RMS calib. shift [\lambda/D] |
|-------------|---------------------------------|----------------------------------|-------------------------------|
| HIP28634 /cal.| 0.54                           | 0.50                             | 0.23                          |
| HD12354 /cal.| 0.42                           | 0.31                             | 0.27                          |
| HIP7981 /cal.| 0.42                           | 0.28                             | 0.30                          |

B. Closed-loop performance
In the datasets listed in Tab. 1, the acquired PSF centroid positions were used to drive the tip-tilt mirror. While the loop was operating stably, no improvement in SMF coupling was observed. The closed loop transfer function as seen by the MLR-TT sensor (Fig. 7, blue/orange) shows a significant rejection of frequencies below 15 Hz, however this is not seen in the Andor reference camera (Fig. 7, green/red). Above 15 Hz both Andor and MLR-TT show the same behavior, however the loop fails to correct for the faster disturbances. This suggests that the loop is not running at a high enough frequency for correction or the latency is too high.

C. Reconstruction accuracy
This significant mismatch between MLR-TT sensor and Andor reference in evaluating the loop performance needs to be understood. For this, we analyze the accuracy with which the sensor is able to reconstruct the centroid position. Fig. 8 shows the centroid position for the Andor reference and the MLR-TT sensor for HD12354/1, as well as the corresponding reconstruction error. While the scatter of these values does not show any systematic patterns, the time series (cutout, bottom) shows that the
AO simulations as described in Sec. H were performed to reconstruct the sensor operation. Fig. 11 shows the resulting reconstruction error for tip and tilt combined as a function of the retrieved SR and is analogous to Fig. 10. For the lowest simulated SRs of $≈50\%$, reconstruction accuracy is worse than 0.35 $\lambda/D$ and improves to 0.16 $\lambda/D$ for an SR of 80%. As with the on-sky results (cf. Fig. 10), the data are well fit by a linear trend, with a slope of $-0.72 \pm 0.05 \lambda/D$. For completeness, we have also simulated the reconstruction error for a flat wavefront (Fig. 11, yellow marker) which shows a reconstruction error of less than 0.05 $\lambda/D$.

4. DISCUSSION

In the preceding section we presented the on-sky performance of the MLR-TT sensor. Whilst able to track incident beam motions, the sensor was unable to improve fiber coupling performance with our current AO loop. The sensor also shows limitations in the overall performance which can be achieved due to the effects of residual aberrations. The causes and solutions are discussed in this section.

A. Sensor reconstruction limitations

As shown in Fig. 10, the sensor was able to reconstruct the centroid position to an accuracy of 0.27 $\lambda/D$ combined tip-tilt RMS. The majority of this error (50%) originates in frequencies below 10 Hz and depends strongly on the estimated SR. To ascertain the cause of this error, we presented optical simulations with differing SR in Sec. 3.E. The simulations show the same trend with a slightly flatter linear fit. The discrepancy can be attributed to a number of additional noise sources that occur within the measurements. These alternative sources include detector noise, reconstruction algorithm error, NCP vibrations, flux variations, and noise in the measurements of the reference centroid. While we investigated these factors during analysis, the current system is most strongly impacted by the effects of residual aberrations. For future versions of the sensor we aim to understand the exact contributions that these noise terms have on the reconstruction accuracy.
To further investigate the impact of wavefront aberrations on the MLR-TT sensor, in future laboratory testing and on-sky experiments, we intend to acquire additional metrology data to identify other effects driving performance. This will allow us to optimize the MLR-TT reconstruction algorithm to account for the observed aberrations and possibly even reconstruct Zernike modes beyond tip and tilt.

B. Loop performance

As illustrated in Fig. 10, under the best conditions experienced, the reconstruction accuracy of the sensor provided a combined RMS error of 0.27 \( \lambda / D \). Assuming an ideal control system, this would provide correction with an RMS error 1.5 times lower than the existing quad-cell system. With our current control system, this is reduced significantly due to latency and meant the loop was only able to reject frequencies up to 15-20 Hz. The control system therefore needs to be optimized in order to allow a better correction of the tip-tilt disturbance which holds the most power in frequencies between 10 and 20 Hz (see Fig. 9).

As shown in Fig. 9, most of the noise in the reconstruction occurs below 10 Hz. The main goal will be to optimize the MLR-TT sensor software (Sec. A) and hardware design (Sec. C) to improve its performance in this regime. Even without additional precision, the loop can be tuned to filter this frequency range or another sensor designed to suppress vibrations in the range 1-10 Hz can be added. Alternatively, the MLR-TT sensor may be used to only detect slow beam drift below 1 Hz. Any residual aberrations will average out over long timescales (>1 second) and the sensor can be optimized to measure slow mechanical drift resulting from e.g. gravitational flexures. This would focus the sensor on utilizing one of its main advantages, namely that it is virtually free from NCP effects. When running at lower frame rates, the sensor also needs less light for operation, increasing the limiting sensing magnitude and the light available for the science instrument.

C. Sensor optimization

To control the amount of noise that is induced by residual AO aberrations, the lens design can be tuned for future devices. As the shape of the MLR surface is set by the need to efficiently couple light into the MMFs, the height of the lens and the size of the central aperture then become the most important variables. Both parameters control the distance from the focal plane where the telescope beam is sensed and by varying them the impact of aberrations in the system changes.

By sampling the beam closer to the fiber focal plane, the MLR-TT sensor will use an intensity distribution more similar to the PSF for sensing, which depends mostly on the phase of the wavefront at the pupil. As the height of the MLR increases, the beam enters the Fresnel regime and the sensor is therefore also affected by variations in the pupil intensity that arise from scintillation and pupil instability. Fully analyzing this parameter space will be crucial for future sensor optimization.

The size of the lens ring aperture determines how much of the beam’s central core is diverted to the sensor. As the
We presented the first on-sky results of our novel 3D-printed, fiber-based tip-tilt sensor (MLR-TT). The sensor was tested with the iLocater acquisition camera at the Large Binocular Telescope in November 2019. The system consists of a 3D-printed microlens ring that uses six multi-mode fibers to reconstruct the centroid position, while providing an almost unobscured aperture where a science single-mode fiber is positioned. This concept features a very small opto-mechanical footprint and degrades the maximum single-mode fiber coupling efficiency by 15%, which is comparable to typical losses due to beam aberrations.

We showed that the fundamental principle works well and the sensor is able to reach a maximum reconstruction accuracy of 0.19 λ/D in each tip and tilt, however, the system was not able to improve single-mode fiber coupling efficiency. The majority of the vibration was measured in frequencies between 10-20 Hz, but the majority of the reconstruction error was shown to occur in low frequencies between 1-10 Hz. This error in reconstructing the centroid depended strongly on estimated Strehl ratio (SR) and subsequent simulations were able to recreate this trend, suggesting that residual aberrations were the dominating noise source that limited performance.

These findings will help to tune both the optical design and reconstruction algorithm to improve the centroid measurements and to reduce the impact of residual aberrations. Alternatively, the respective frequency range can be filtered or corrected using another sensor to minimize its impact.

We conclude that the MLR-TT sensor is best suited for applications requiring fast correction with low higher-order wavefront distortions while benefiting from its compact nature. This includes extreme adaptive optics systems, compact systems at small diffraction-limited telescopes and space based applications. We also note that the MLR-TT sensor operates very close to the fiber coupling surface, it is free of non-common path aberration and can therefore be used to track drifts and perform guiding in a closed-loop system where calibration between the wavefront sensor and fiber is difficult.
Fig. 11. Synthetic MLR-TT sensor performance derived from AO simulations, plotted to be comparable to Fig. 10. **Main panel:** Reconstruction accuracy as a function of Strehl ratio (SR) for AO simulations with varying residual aberration strength labeled with their RMS wavefront error. Crosses represent overall mean and error for each data set, while the circles correspond to subsets binned by SR, with the size of the circle representing the number of frames in each set. The dashed lines show the fitting error. **Top panels:** Centroid reconstruction error scatter for the individual datasets.

### 6. BACKMATTER

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This research made use of HCIPy, an open-source object-oriented framework written in Python for performing end-to-end simulations of high-contrast imaging instruments [35]. Astropy, a community-developed core Python package for Astronomy [37, 38], Numpy [39] and Matplotlib [40].

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**Data Availability Statement.** Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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