Efficient coupling of starlight into single mode photonics using Adaptive Injection (AI)

Barnaby Norris
Nick Cvetojevic
Simon Gross
Alexander Arriola
Peter Tuthill
Jon Lawrence
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Barnaby Norris, Nick Cvetojevic, Simon Gross, Alexander Arriola, Peter Tuthill, Jon Lawrence, Samuel Richards, Michael Goodwin, and Jessica Zheng

Sydney Institute for Astronomy, University of Sydney, NSW, Australia
The Australian Astronomical Observatory (AAO), North Ryde, NSW, Australia
Centre for Ultrahigh bandwidth Devices for Optical Systems (CUDOS), Australia
MQ Photonics Research Centre, Department of Physics and Astronomy, Macquarie University, Sydney Australia
ARC Centre of Excellence for All-sky Astrophysics (CAASTRO)

ABSTRACT

Using single-mode fibres in astronomy enables revolutionary techniques including single-mode interferometry and spectroscopy. However injection of seeing-limited starlight into single mode photonics is extremely difficult. One solution is Adaptive Injection (AI). The telescope pupil is segmented into a number of smaller subapertures each with size $\sim r_0$, such that seeing can be approximated as a single tip / tilt / piston term for each subaperture, and then injected into a separate fibre via a facet of a segmented MEMS deformable mirror. The injection problem is then reduced to a set of individual tip tilt loops, resulting in high overall coupling efficiency.

Keywords: single mode fibres, single mode waveguides, injection, adaptive optics

1. INTRODUCTION

Photonic technologies stand to revolutionise the way astronomy is performed. Photonic interferometers and nullers will allow ultra-high resolution, high contrast imaging, leading to direct imaging of Earth-like exoplanets, at unprecedented levels of performance. Spatial filtering via single-mode waveguides, on-chip beam combination and distribution, and active photonic circuitry enable both long-baseline and pupil-segmenting interferometry to be performed on-chip, leading to increased stability, accuracy, replicability and scalability. Single-mode photonic spectrographs can avoid the problem of modal noise, are replicable and, perhaps even more importantly, have a small physical size independent of the telescope aperture, crucial for the next generation of Extremely Large Telescopes. These and other technologies rely on the use of single-mode waveguides and fibres (as opposed to the multi-mode fibres traditionally used in astronomy for, e.g., transporting light from the focal plane to a spectrograph).

However, the successful use of these technologies faces a major hurdle: the initial injection of starlight into single mode photonics is extremely difficult. Small mode-field diameter (typically less than ten microns) and restrictive numerical aperture means that directly injecting the seeing-limited telescope pupil into a single-mode fibre with acceptable efficiency is virtually impossible. An extreme adaptive optics system is one solution, but these extremely expensive and complex systems are beyond the reach of all but the major 8 m class telescopes.

Here we present an alternative solution - adaptive injection (AI). Analogous to adaptive optics (AO), this system actively adjusts the wavefront in real-time as it varies with the seeing. However rather than attempting to produce the flattest wavefront possible across the whole pupil, AI optimises the wavefront for the best possible injection into an array of single-mode waveguides or fibres.

The key to the efficacy of this approach is that the sub-pupils are sized to be of a size similar to the Fried parameter (atmospheric coherence length), $r_0$. When $1 < D/r_0 < 10$ (where $D$ is the (sub-)pupil diameter),...
the effects of seeing are largely dominated by tip/tilt error, with higher order modes becoming dominant for 
\( D/r_0 > 10.6 \). By dividing the larger telescope pupil into a set of smaller sub-pupils with diameters in this range, 
effective injection can be accomplished by the relatively simple task of correcting just the tip/tilt of each sub-
pupil. In on-sky tests, a projected sub-pupil diameter of \( \sim 50 \text{ cm} \) was used (placed within the Anglo-Australian 
Telescope’s 3.9 m mirror), corresponding to a \( D/r_0 \) of between 1 and 2 for typical site conditions (at the science 
wavelength of 1.6\( \mu \text{m} \)).

The telescope pupil is re-imaged onto a MEMS segmented deformable mirror, and thence onto a two-
dimensional array of single mode waveguides (with matching microlens array (MLA)). The photonic device 
used for the tests described here is a three-dimensional photonic chip manufactured by the femtosecond laser 
direct-write technique,\(^7\) which has a set of waveguides terminating in a two-dimensional array on its end-face. 
The MEMS mirror segments are matched one-to-one with the single-mode waveguides and MLA, thus dividing 
the telescope pupil into an array of sub-pupils. The array is sized such that each sub-pupil is roughly the same 
size as the Fried parameter \( r_0 \). Via a dichroic mirror, the pupil is also imaged into a separate matched MLA and 
camera to act as a wavefront sensor.

For single-mode injection, this system has an advantage over an AO system of comparable actuator count. 
By segmenting the telescope pupil into a series of subapertures with sizes of order \( r_0 \), the problem of injecting 
the complex seeing-induced PSF is reduced to a number of simple, independent tip/tilt loops. Due to the 
absolute sensitivity of injection efficiency on the angle of the incident light, the optimum injection is not achieved 
with a flat wavefront; rather, the beam of each sub-aperture requires an offset applied as a tip/tilt term to the 
corresponding MEMS mirror segment (determined beforehand by way of a raster scan).\(^1\) Since each MEMS 
segment has independent tip/tilt control, the required offset for each waveguide becomes the appropriate zero-
point for the AI loop. Adjacent segments can have entirely opposing tip/tilt values if necessary. A traditional 
membrane DM with the same actuator number would have just over 1 actuator per sub-pupil, and so independent 
tip/tilt control would not be possible. Moreover, a membrane (non-segmented) deformable mirror has limits 
on the absolute difference in piston position allowed between adjacent actuators, so achieving very different 
wavefront tilts over small areas would be very difficult. The remaining coupling losses are due to higher order 
structure within the sub-aperture, which has been found to be small. For interferometric applications, higher 
fringe visibilities can be obtained if the matched wavefront sensor is used in a Shack-Hartmann mode, and the 
appropriate piston terms (and only piston terms) are extracted from the AO solution and also applied to the 
segments.

Here we describe the construction of an adaptive injection system, used to inject light into single-mode 
waveguides of a photonic nulling chip (part of the GLINT nulling interferometer project\(^10\)). We present the 
results of laboratory tests as well as on-sky tests performed at the 3.9 m Anglo-Australian Telescope.

2. EXPERIMENTAL DESIGN AND METHOD

The general layout of the adaptive injection system used for tests is shown in Figure 1. The telescope pupil is 
first re-imaged onto a pupil mask which blocks regions of the pupil not injected into the photonic chip, to avoid 
inserting light into the bulk of the chip and the ensuing stray-light interference problems (see reference \(^{11}\) for 
details). The pupil is then again re-imaged onto the MEMS segmented deformable mirror. After reflecting from 
a short-pass dichroic mirror, near-IR light passes through beam reducing optics to reformat the beam size to suit 
the photonic chip, which also re-image the pupil onto a set of microlenses. Each microlens is carefully matched 
and aligned to a single segment of the MEMS mirror, and to a single waveguide within the photonic chip. The 
face of the chip is placed at the focus of the microlens array such that each microlens injects light at the correct 
NA into the corresponding waveguide, such that a tip or tilt of the relevant MEMS mirror segment translates 
the position of the focused spot. Shorter wavelength (<1\( \mu \text{m} \)) light passes through the dichroic mirror, and 
the pupil is re-imaged onto another microlens array, also matched to the MEMS segments and waveguides. The 
focus of these microlenses are placed onto the detector of an EMCCD camera, in the style of a Shack-Hartmann 
wavefront sensor. The position of each focal spot is determined using a centre-of-gravity calculation, allowing 
the wavefront tilt across each sub-pupil to be measured and then used in the control loop.

Before closed-loop operation begins, the zero-points for each segment – corresponding to maximum injection 
efficiency – must be determined. After acquiring the star, the individual MEMS mirror segments are scanned
(either in a raster or spiral pattern) and the power injected into each waveguide is monitored via the science detectors. A Gaussian distribution is fitted to the measurements and the angles of maximum coupling determined. However in a single scan the random effects of seeing dominate the injected light, so the scan is repeated multiple times and averaged in order to find the true optimum angle.

Also, the relationship between injection angle (and hence coupled power) and position of the focal spots on the EMCCD camera is established beforehand (using a laboratory light source) by a similar scan, to account for drifts in alignment. One advantage is that non-linearities in the relationship can be trivially characterised and used in the control loop by fitting a polynomial function to the scans (a non-trivial problem in the linear algebra approach used in adaptive optics).

In operation, each segment runs in an independent tip/tilt loop using a PID control algorithm. On a low cost computer (Intel i3 processor) loop speeds of 500 Hz were easily obtained, limited by the latency of the camera.

3. RESULTS

The adaptive injection system was first tested in the laboratory, with seeing simulated using a rotating turbulence plate manufactured by Lexitek. The transparent plate has a Kolmogorov phase screen inscribed within it, with a scale chosen to simulate the desired atmospheric $r_0$ for the beam diameter used. The outer region of the plate is placed in the beam at the pupil plane of the system. By rotating the plate, seeing is simulated in the form of a moving atmospheric phase screen, with the speed of rotation determining the simulated wind speed.

Tip/tilt residuals for each sub-aperture were determined by measuring the deviation of the corresponding spot on the EMCCD camera. For comparison, an adaptive optics system manufactured by ALPAO was also used. This adaptive optics system used a a 97 actuator membrane-type deformable mirror, and a Shack-Hartmann wavefront sensor. Laboratory results showing tip/tilt residuals are shown in Figure 2. For this test, simulated seeing with $r_0$ of 10 cm (at $\lambda \sim 600$ nm) and a wind speed of 2.5 m/s was used. Note that the zero milliradian position on the y axis corresponds to the position of a ‘flat’ MEMS mirror with an unperturbed beam, not the optimised positions. It can be seen that while the adaptive optics system yields a major improvement in
Figure 2. Comparison of per-waveguide tip/tilt residuals for no correction (i.e. seeing limited), adaptive optics correction and adaptive injection, from laboratory tests. A rotating Kolmogorov phase plate was used to simulate seeing with $r_0$ of 10 cm (at $\lambda \sim 600$ nm) and a wind speed of 2.5 m/s. The adaptive optics tests were performed using an ALPAO AO system with a 97 actuator deformable mirror and a Shack-Hartmann wavefront sensor. The green dashed line indicates where the data transitions between the correction types. Blue and red lines correspond to tip and tilt respectively. The residuals are plotted in units of milliradians of tilt of a MEMS segmented mirror segment (each of diameter 606 $\mu$m, with the entire telescope pupil being 4.242 mm in diameter at this plane). 8 waveguides (and their corresponding mirror segments) were used, corresponding to the 8 plots above.
the magnitude of tip/tilt residuals compared with the uncorrected wavefront, the adaptive injection performs significantly better. Moreover, it can be seen that the mean position of the corrected tip/tilt is offset from zero (or the mean position of the AO corrected beam) in some waveguides (particularly noticeable in waveguides 1 and 8). This corresponds to the angles of optimum injection into the waveguides, an optimisation not easily performed with a conventional AO system and membrane DM.

On-sky tests were subsequently performed at the 3.9 m Anglo-Australian telescope, at Siding Springs Observatory, Australia, in November 2015. The active injection system was deployed as part of the GLINT photonic nulling interferometer project, which requires efficient injection of (otherwise seeing-limited) starlight into single-mode waveguides. The instrument was placed at the Cassegrain focus of the telescope. Bright stars were observed since the infrared detectors for the GLINT device were relatively insensitive (uncooled PIN diodes), however the EMCCD camera used for the AI system was not at all SNR limited.

Results showing the tip/tilt residuals for an observation of the star alf CMa, for both the seeing-only and active injection cases, are shown in Figure 3. The observation was performed with seeing of approximately 1". A dramatic improvement in tip/tilt residual is seen. In the no-correction data, the fast variation due to seeing is superimposed with slow, global drifts due to telescope pointing error. The adaptive injection loop addresses both of these. The per-waveguide offset required for optimum injection is also clearly seen in these results, with the closed-loop target positions varying significantly between waveguides.

An example of the improvement in injection achieved is shown in Figure 4. Here, waveguide power is shown as a function of time for the star alf Ori, observed with seeing of approximately 1.5" (waveguide power measurements for the previous alf CMa test were not available). In this case, waveguide power for both uncorrected and adaptive-injection corrected cases are shown, along with a third case where a conventional global tip/tilt mirror is added as well. The purpose of this was to remove a large portion of the tip/tilt error (common to all waveguides) to reduce the magnitude of the tip/tilt required for each segment of the MEMS deformable mirror, since the stroke of these segments was limited as an engineering-grade device was used. A further purpose was to roughly cophase the two subapertures (located on either side of the pupil) used for the photonic nuller tests, to improve the average null depth. The adaptive-injection is seen to yield a dramatic improvement over the uncorrected observations, with an average increase in power of approximately a factor of 6. Adding the global tip/tilt mirror increased this by a further factor of 1.1.

However the increase in average power belies the larger advantage gained over seeing-limited injection when used for interferometric applications. A common observable quantity used in such applications is the cophase, which is the sum of the baseline phases around a closed triangle. Unlike the phase of a single baseline, this quantity is largely invariant to seeing. However in order to make a closure phase measurement, a sufficiently accurate measurement of phase has to be made in all three baselines simultaneously. If sufficient light is only injected into two out of the three baselines of the triangle, no measurement can be made. But it can be seen in Figure 4 that the power in the single waveguide shown is approaching zero for much of the time. With these random fluctuations independently occurring on all waveguides, the fraction of time that there is simultaneously a significant amount of power in all three waveguides forming a given three-baseline triangle is small. Thus in an interferometric application, a key advantage of adaptive injection is not just the improvement in average waveguide power but the ability to consistently maintain power in all waveguides at all times.

4. CONCLUSION

Adaptive injection provides a method to improve coupling of starlight into single-mode fibres and waveguides, without the need for expensive and complex high-performance adaptive optics systems. The telescope pupil is divided into a number of sub-apertures, of sizes of a few $r_0$ (such that wavefront error across a sub-aperture is dominated by tip/tilt terms), and injected into separate waveguides or fibres. An individual tip/tilt correction loop is then run on each aperture, by way of a matched MEMS segmented deformable mirror. Since each facet of the MEMS mirror acts as an independent tip/tilt mirror, tip/tilt correction for each mirror can be achieved with better performance than for an adaptive optics system (using a membrane deformable mirror) with similar actuator count. The increased performance (by way of dramatically reduced tip/tilt residuals) of adaptive injection over a similar actuator-count adaptive optics system has been demonstrated in laboratory tests.
Figure 3. Comparison of per-waveguide tip/tilt residuals for the adaptive injection loop open and closed, as measured on-sky whilst observing the star alf CMa with the Anglo-Australian telescope. The green dashed line indicates where the data transitions from loop open to loop closed. These two data sets were taken immediately adjacent in time so seeing conditions remain the same. Blue and red lines correspond to tip and tilt respectively. The residuals are plotted in units of milliradians of tilt of a MEMS segmented mirror segment (each of diameter 606 µm, with the entire telescope pupil being 4.242 mm in diameter at this plane). 8 waveguides (and their corresponding mirror segments) were used, corresponding to the 8 plots above.
Figure 4. A comparison on the power injected into a waveguide for seeing-limited data (orange line), adaptive injection (red line) and adaptive objection in addition to a global tip/tilt corrector mirror. The global tip/tilt correction is intended to remove a large fraction of the error (common to all waveguides) so as to reduce the maximum deflection required by segments of the MEMS segmented mirror (since the engineering-grade device used for this test had limited range). Data is binned into 150 ms bins.
Moreover, efficient injection into an array of waveguides within a photonic chip requires separate tip/tilt offsets for each waveguide, due to the extreme precision required for efficient injection and inevitable microlens misalignment and photonic chip manufacturing tolerances. The adaptive injection approach allows this offset (determined beforehand via a raster scan) to act as the zero-point for each individual tip/tilt loop. Use of a segmented mirror means that adjacent waveguides can have completely different, even opposite, tip/tilt offsets, which would not be possible with a membrane deformable mirror.

On-sky tests at the Anglo-Australian Telescope demonstrated a ∼6 times improvement in injection efficiency in 1.5” seeing. Future improvements to the system will keep the multiple tip/tilt loop approach but also extract phase information by using the existing AI pointing sensor as a Shack-Hartmann wavefront sensor and extracting the phase offset from the reconstructed wavefront, adding these piston terms to the MEMS mirror segments and thus cophasing the waveguides, important for interferometric applications.

REFERENCES


