Adaptive optics correction over a 3km near horizontal path

Ruth Mackey and Chris Dainty

Applied Optics Group, Department of Experimental Physics, National University of Ireland,
Galway, Ireland

ABSTRACT

We present results of adaptive optics compensation at the receiver of a 3km optical link using a beacon laser operating at 635nm. The laser is transmitted from the roof of a seven-storey building over a near horizontal path towards a 127 mm optical receiver located on the second-floor of the Applied Optics Group at the National University of Ireland, Galway. The wavefront of the scintillated beam is measured using a Shack-Hartmann wavefront sensor (SHWFS) with high-speed CMOS camera capable of frame rates greater than 1kHz. The strength of turbulence is determined from the fluctuations in differential angle-of-arrival in the wavefront sensor measurements and from the degree of scintillation in the pupil plane. Adaptive optics compensation is applied using a tip-tilt mirror and 37 channel membrane mirror and controlled using a single desktop computer. The performance of the adaptive optics system in real turbulence is compared with the performance of the system in a controlled laboratory environment, where turbulence is generated using a liquid crystal spatial light modulator.

Keywords: Adaptive optics, strong turbulence, scintillation

1. INTRODUCTION

We are interested in applying adaptive optics (AO) correction to laser beams propagating through strong turbulence with application to line-of-sight (LOS) optical communication. Free-space optical communication is an alternative to wireless communication at radio frequencies that offers the possibility of high bandwidth communication that is secure due to the narrow footprint of the beam and with a communication system that is low in mass, making it ideal for Earth-satellite or portable terrestrial communication links.

One of the limiting factors in the communication bandwidth and maximum link distance is the fluctuation in signal caused by fluctuations in the refractive index of the atmosphere. We have established a 3km optical link across Galway City in order to investigate the effects of atmospheric turbulence on laser beam propagation and also to investigate the effects of AO correction using a simple low-order AO system.

The strength of atmospheric turbulence has been measured using a 127mm optical receiver with a Shack-Hartmann wavefront sensor (SH WFS), from which the coherence length and coherence time have been estimated by looking at the variance of angle-of-arrival fluctuations of the SH WFS subimages. Due to wind buffeting of the launch system a differential image motion method has been used.

Concurrent with the measurements of atmospheric turbulence, we have been developing an AO system in the laboratory that can be added to the 127mm optical receiver. The AO system has been designed with off-the-shelf components and uses a desktop computer for wavefront sensor processing and closed-loop control. The AO system has been tested in the laboratory using a liquid crystal turbulence generator capable of generating real-time evolution of the atmospheric turbulence.

Although the design of the AO system and the components used have left much to be desired, the development of the AO system has served as a useful tool to get hands on experience of the requirements necessary for AO correction in strong scintillation conditions. Initial trials of the AO system on the 3km link have shown partial correction of the turbulence degraded wavefront. However, the performance of the AO system was limited to weak turbulence conditions with higher wavefront sensor sampling and faster mirror response required for strong turbulence conditions.

Further author information: (Send correspondence to R.M)
R.M.: E-mail: ruth.mackey@nuigalway.ie
C.D.: E-mail: c.dainty@nuigalway.ie
The layout of this paper is as follows: A description of the 3km optical link and atmospheric turbulence measurements is given in sections 2 and 3. A description of the AO system and its performance in the laboratory using the liquid crystal turbulence generator is given in sections 4 and 5. An example of the AO correction in weak turbulence conditions using the 3km optical path is given in section 6. A summary of the paper and discussion of the limitations of the system is given in section 7.

2. 3KM HORIZONTAL PATH AND BEACON LASER

The 3km optical link consisted of a 635 nm beacon laser that was launched through a 90mm Meade ETX telescope. The laser beam was transmitted from the roof of the seven-storey Eircom Building on the edge of Galway City towards an optical receiver in the second floor meeting room in the Applied Optics Group at NUI Galway. The beam height was approximately 10–20 m above the ground and crossed varying landscape; including roads, commercial buildings, open grassland and the River Corrib (Fig. 1).

![Figure 1. Laser propagation path across Galway City.](image-url)

The beam was made to diverge slightly so that the diameter at the receiver was approximately 3 m. The large beam diameter was used to try to overcome the effects of beam wander as there was no active tracking on the launch telescope. The housing of the launch system was on an exposed roof and subject to wind buffeting. This caused the beam to move several metres off target to the right or left between each measurement, requiring remote realignment of the beam pointing direction.

3. ATMOSPHERIC TURBULENCE MEASUREMENTS WITH A SHACK-HARTMANN WFS

3.1. The optical receiver

A 127 mm diameter Maksutov-Cassegrain with Shack-Hartmann wavefront sensor (SHWFS) and high speed CMOS camera sampling at a frame rate of 1023Hz was used as the optical receiver for turbulence measurements. The wavefront sensor consisted of a square lenslet array with pitch of 100 µm and focal length of 2.7 mm. An optical relay was used between the lenslet array and the detector with a magnification of 1.5. There were 21 lenslets across the pupil diameter with a total of 196 useable subapertures within the pupil and a lenslet pitch in the pupil plane of 5.7 mm.
3.2. Measurement analysis

Each measurement set contained 3000 frames of data measured at 1023Hz with an exposure time of typically 180$\mu$s. After flat-fielding and dark frame removal, the frames were combined to create an average image and used to define the reference spot positions. Examples of the SH spots in an averaged frame and in a scintillated single frame are shown in Fig. 2. A centroiding algorithm was used with intensity thresholding to find the reference centroid positions. These positions where then used to define search regions. In each frame of data the sum of pixel values in each search region was compared with a minimum threshold intensity and a saturation intensity. Search regions with the sum of pixel values falling outside this range were marked with an identifier so that this element could be removed from subsequent analysis.

3.3. Differential angle-of-arrival

Due to wind buffeting of the launch telescope system, it was necessary to remove the effect of global tilt from WFS measurements using a differential image motion (DIMM) approach. The variance of differential angle-of-arrival of the SH WFS subimages was used as a measure of the turbulence strength. Following Sarazin and Roddier\(^1\) the longitudinal and transverse variance of angle-of-arrival for subapertures separated by a distance, $d$, for a plane wave are given by

$$
\sigma^2_{\alpha,L}(d,0) = 2B_{\alpha}(0,0) \left[ 1 - \frac{5}{9} \left( \frac{d}{D} \right)^{-1/3} \right] \tag{1}
$$

$$
\sigma^2_{\alpha,T}(0,d) = 2B_{\alpha}(0,0) \left[ 1 - \frac{10}{12} \left( \frac{d}{D} \right)^{-1/3} \right] \tag{2}
$$

where the variance of the angle-of-arrival of a single subaperture, $B_{\alpha}(0,0)$ in one dimension, is approximated by using the structure function of the phase for a plane wave to define the phase variance between two points, separated by the diameter of the subaperture, $D$. In the near-field approximation (for circular lenslets) this is given by

$$
B_{\alpha}(0,0) = \frac{6.88}{4\pi^2} \left( \frac{D}{r_0} \right)^{5/3} \left( \frac{\lambda}{D} \right)^2, \tag{3}
$$

where $r_0$ is the Fried parameter and $\lambda$ is the wavelength.

In Fig. 3, examples of measured probability distributions of differential angle-of-arrival over a 3 second period are plotted for strong and weak refractive index fluctuations at different times during the day. There is a large fluctuation in turbulence conditions during the day, in terms of the spatial coherence length and in terms of the degree of scintillation.
Figure 3. Differential image motion with Shack-Hartmann lenslet separation of 5 subapertures. Figure (a) is an example of turbulence strength in the middle of the day with an estimated $r_0$ of 1.4 cm. Figure (b) is an example of turbulence strength 1.5 hours after sunset, with an estimated $r_0$ of 4.4 cm.

3.4. Temporal correlation

In order to measure the temporal coherence time the differential motion for each lenslet pair with a given separation was compared versus increasing time delay $\Delta t$ for a time delay of 0 to 200 frames.

$$C_{\alpha_d\alpha_d}(j\Delta t) = \frac{1}{n-j} \sum_{i=0}^{n-j-1} \alpha_d(t+i\Delta t)\alpha_d(t+[i+j]\Delta t)$$

The ensemble average of the temporal correlation of all pairs in a set with a given separation of a sample measurement is plotted below in Fig. 4. This is the temporal correlation of the data given in Fig. 3 (a) with strong refractive index fluctuations. The $1/e$ coherence time was found to be on the order of 5ms for this data set, indicating that an AO system would need to operate with a sampling rate on the order of 2kHz in order to keep up with the evolution of the atmospheric turbulence.

4. ADAPTIVE OPTICS RECEIVER

A low-order AO system was developed to add to the 127mm optical receiver used on the 3km optical link. The main components of the AO system comprised a Melles-Griot tip-tilt mirror, a 37-channel OKO membrane mirror and a Shack-Hartmann wavefront sensor with CMOS camera (Photonfocus MV-D752) and Silicon Software framegrabber. The wavefront sensor consisted of a lenslet array with 200$\mu$m square lenslets of focal length 7.5mm and sampled the pupil with 10 lenslets across the diameter of the receiver, giving a total of 72 lenslets in the pupil and a lenslet diameter on the order of 12.7 mm in the pupil.

The layout of the AO receiver is shown in the schematic in Fig. 5. A fibre-coupled diode laser and flip mirror are used to generate a reference for the WFS. Both the tip-tilt and OKO mirror are optically conjugate to the telescope pupil using relay lenses. A beam splitter is used before the wavefront sensor to reflect 33% of the light towards an Andor LUCA camera where the point spread function is monitored.

5. PERFORMANCE OF THE SYSTEM IN THE LABORATORY

The AO system was tested in the laboratory by generating dynamic Kolmogorov phase screens with a ferroelectric liquid crystal spatial light modulator (FLC SLM) from Boulder Nonlinear Systems. The SLM is a pixellated device with 512 x 512 pixels capable of binary phase modulation of 0 or $\pi$ radians. It has a maximum refresh rate of 1015 Hz, which allows simulation of real-time evolution of the atmosphere.
Figure 4. An example of the temporal correlation versus time delay in terms of camera frame time for the differential angle of arrival fluctuations. The $1/e$ point is $\sim 5$ frames, which corresponds to a correlation time of $\sim 5$ms.

Figure 5. A 127mm optical receiver with adaptive optics.

As the device is only capable of binary phase modulation a technique from computer generated holography is used to generate complex fields using a binary phase grating.\textsuperscript{2} The method for generating phase screens follows that of Neil and Booth.\textsuperscript{3–5} The SLM is used as a reconfigurable diffraction grating and phase screens are produced by spatial filtering of the first diffraction order using a 4-f lens system. To generate the diffraction grating a linear phase tilt is added to the desired field $g(x, y) = e^{i\phi(x, y)}$ and the result is binarized by taking the sign of the real part of the field to give a square wave function. The linear phase tilt acts as a carrier frequency.
in the Fourier plane and serves to separate the diffraction orders.

5.1. Performance of the system

The tip-tilt mirror was tested by applying linear phase tilt screens with a sinusoidally varying tilt amplitude to the SLM. The screens were applied at the maximum frame rate of the SLM (1015 Hz) and the frequency of the oscillation was controlled by adjusting the number of frames in one period of the sine wave. The amplitude of the tilt waves was chosen to correspond to the standard deviation of tilt for turbulence strength with $D/r_0$ of 10, where $D$ is the telescope diameter and $r_0$ is Fried’s coherence diameter.

The aperture-averaged angle-of-arrival for Kolmogorov turbulence has a Gaussian distribution with variance, which can be defined in terms of the ratio $D/r_0$. For motion in a single direction (e.g. in the x or y direction) the variance of angle-of-arrival is given by:

$$\sigma_a^2 = 0.18 \left( \frac{D}{r_0} \right)^{5/3} \left( \frac{\lambda}{D} \right)^2$$

(5)

with a standard deviation of

$$\sigma_a = 0.424 \left( \frac{D}{r_0} \right)^{5/6} \left( \frac{\lambda}{D} \right).$$

(6)

For a turbulence strength of $D/r_0 = 10$, this results in a tilt amplitude with a standard deviation on the order of $\pm 3\lambda/D$.

The percentage residual tilt error during correction was measured by finding the centroid displacement of the image on the point spread function camera and comparing with the centroid displacement without adaptive tilt compensation. The plot of percentage tilt correction error versus tilt frequency is shown in Fig. 6. At a frequency of 25 Hz, it can be seen that RMS tilt error with correction has increased to 50% of the tilt error without AO correction. Increasing to a tilt oscillation at 30 Hz, there is only 30% correction. There are several reasons for this poor response. The mirror exhibits a resonant frequency at around 300 Hz, which limits the correction to small or slow variations in tilt when driven at higher frequencies. The mirror also exhibits hysteresis on the order of 14%, which causes a delay in the tip-tilt correction and decreases the correction bandwidth further.

![Figure 6. Tip-Tilt correction of a sinusoidal tilt with amplitude of 3 waves. A plot of the percentage tilt error versus increasing tilt frequency with tip-tilt correction using a gain of 0.2 and with a WFS sampling rate of 1kHz. The error bars are $\pm$1 standard deviation of the percentage tilt error.](http://spiedl.org/terms)
5.1.1. Evolving turbulence correction

The temporal evolution of wavefront perturbation due to turbulence is often simplified by making use of Taylor’s hypothesis of frozen flow, where the decorrelation of structure in atmospheric turbulence is slow compared with the velocity of the wind, \( v \), blowing the turbulence across the telescope aperture. The phase screen generator was used to measure the bandwidth of the AO system in terms of the number of \( r_0 \) crossing the aperture per second, \( (v/r_0) \). The SLM frame rate, which triggers the WFS camera, was used to control the speed of the turbulence evolution relative to the WFS sampling period, \( T \), so that the AO correction could be compared in terms of a normalised frequency, \( (v/r_0) \times T \).

In Fig. 7 a comparison is made between the performance of the AO system in terms of the Strehl ratio, when operated at a frame rate of 1015 Hz and 507 Hz for dynamic turbulence with strength of \( D/r_0 = 4 \). The Strehl ratio was calculated by determining the ratio of the on-axis intensity of the corrected point spread function (PSF) to that of a reference source in the AO system and was used as the metric of AO performance. Although the relative motion of the turbulence is the same for both WFS sampling rates, it was found that the performance of the AO system was severely degraded when operating at a frame rate of 1 kHz. This was unexpected as the processing time for both the WFS frame transfer and control computer used to convert WFS signals to an output voltage were measured to operate at a sampling rate \( > 1 \) kHz.

It was discovered that the OKO mirror is designed for operation below 500 Hz and when operating at a sampling rate of 1 kHz, it introduces instability in the closed-loop operation of the system. This effect can be reduced by lowering the gain of the closed-loop system but this has the effect of slowing the correction rate and reducing the correction bandwidth.

![Figure 7](image_url)

**Figure 7.** Normalised Frequency response of the AO system in response to moving Kolmogorov turbulence with \( D/r_0 = 4 \). The OKO mirror gain = 0.2 and TT mirror gain = 0.25.

### 6. INITIAL TRIALS OF AO CORRECTION ON A 3KM HORIZONTAL PATH

Preliminary testing of the AO system in the laboratory showed the limitations of the system in terms of temporal response. The AO system described in section 4 was tested on the 3km link with low expectations for AO
correction. Figure 8 shows an example of improvement in the long exposure PSF with adaptive optics on when compared with no adaptive optics in weak scintillation conditions. It can be seen in Fig. 8 there was a reduction in the width of the long time averaged point spread function, indicating a partial correction of the turbulence degraded wavefront. However, this is one of the better examples of AO correction. Often there was no visible improvement in the long exposure point spread function as the AO system was not fast enough to correct the turbulence and the degree of turbulence and scintillation was too strong for the WFS sampling and stroke of the mirrors.

![Figure 8](image)

(a) AO off (b) AO on

Figure 8. (a) Long exposure without adaptive optics and (b) with adaptive optics. With ‘AO on’ the full-width-half-max (FWHM) of the long exposure PSF has been reduced by half. The yellow bar in the top left hand corner marks the FWHM of the diffraction limited reference beam for comparison.

7. DISCUSSION

A 635nm beacon laser transmitting over a 3km horizontal path has been used to estimate the effect of atmospheric turbulence on laser beam propagation. An optical receiver with Shack-Hartmann wavefront sensor was used to sample the received laser beam and used to estimate the strength of turbulence in terms of the variance of angle-of-arrival fluctuations. During measurements the problems associated with using a Shack-Hartmann wavefront sensor became obvious, namely how restrictive the sensor is due to its inflexibility in sampling. The atmospheric turbulence strength can change dramatically during the day, even over short periods of several minutes, depending on the weather conditions. Ideally a wavefront sensor for strong scintillation conditions should be able to cope with a large variability in scintillation index and a large variability in atmospheric coherence length, $r_0$.

Concurrent with the atmospheric turbulence measurements, a low specification adaptive optics receiver with Shack-Hartmann wavefront sensor and membrane deformable mirror has been built and tested in the laboratory using a liquid crystal turbulence generator. The system was found to perform poorly due to the delay between the output from the control computer and the mirror response time. The wavefront sensor was also limited in terms of spatial resolution due to the processing time required for each frame of data from the WFS. Ideally the WFS sampling should have been 4 times as dense across the telescope diameter for the type of turbulence conditions expected on a 3km horizontal path. As the time scale for computation is at maximum on the order of a few hundred microseconds, the ideal wavefront sensor is one that requires little or no wavefront reconstruction. One possibility is the use of the point-diffraction interferometer, as suggested by Barchers et al. This has recently been implemented by Notaras and Paterson in laboratory simulations with strong scintillation conditions with promising results. A similar AO system using a Twyman-Green interferometer and a 1.5µm laser propagating over a round trip path of 1.35 km has been demonstrated by Baker et al., showing the feasibility of such a high order AO system in real turbulence conditions.
ACKNOWLEDGMENTS

This work was funded with an Embark scholarship from the Irish Research Council for Science Engineering and Technology (IRCSET) and by Science Foundation Ireland (SFI) under grant numbers SFI/01/PL2/B039C and SFI/07/IN.1/1906.

REFERENCES