# Horizontal turbulence measurements using SLODAR

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## ABSTRACT

SLODAR (slope detection and ranging) is a technique we have developed to monitor the vertical profile of atmospheric phase distortions, for application to astronomical adaptive optics systems. The technique uses the correlation between slope measurements made using a Shack-Hartmann wavefront sensor observing a binary star. In this paper we describe the principle of SLODAR and then describe our work on using a system for the measurement of horizontal turbulence profiles for application to free space optical communications.

## 1. INTRODUCTION

There has been a large amount of discussion on the use of adaptive optics (AO) to improve the performance of free space optical (FSO) communication systems. Turbulence creates problems for FSO when deployed over long distances, causing high bit-error rates (BER) due to beam wander and breakup. It is also a problem for FSO links at ultra-high BER which are currently constrained by small-area detectors and limited receiver dynamic range. AO has the potential to improve both scenarios by delivering more average optical power to the remote terminal, reducing spot size on the detector, and reducing temporal fading.
A knowledge of the statistical parameters of the atmosphere is of paramount importance when designing an AO system, e.g. the strength of the turbulence directly relates to the number of channels and the profile of the turbulence relates to the position in the optical train of the wavefront corrector. There is not a large amount of published data on horizontal turbulence profiles, and, in any case, the actual statistical parameters will depend very much on the location of the system. With these thoughts in mind, a horizontal turbulence monitoring system has been designed at Durham and is in the process of being tested.

This paper begins by discussing the use of Shack-Hartmann wavefront sensors to determine the total strength and the horizontal distribution of atmospheric optical turbulence between two telescopes. The turbulence profile can be recovered reliably from time-averaged spatial cross-correlations of the local wavefront slopes for Shack–Hartmann observations of double sources. The method, which is referred to as SLODAR, is analogous to the well known SCIDAR scintillation[1-4] profiling technique.
After describing the general operation of SLODAR, the specific details of a system designed to measure horizontal turbulence profiles are descried. Initial results of the turbulence measured at Durham are presented.

## 2. THE SLODAR TECHNIQUE

SLODAR and its application to vertical seeing profiles is described in ref 5. The technique consists of viewing two point sources separated by a small angle which are generate by two closely separated telescopes each launching a parallel beam (or stars in the astronomical case). Each is observed using a conventional Shack-Hartmann wavefront sensor (SH-WFS). The geometry is shown in figure 1. It is well known that by measuring the wavefront gradients of light from a single beacon (star), it is possible to calculate the integrated turbulence strength along the path. However by measuring the cross

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correlations between the slope patterns from two sources it is also possible to infer data on the location of the turbulence and the wind speed. Referring to figure 1, two beams are launched from two transmit telescopes which are closely spaced and directed towards a common receive telescope. Turbulence close to the receive telescope affects both beams in a similar way and if the wavefront gradients measured from each source are cross correlated then there will be a strong correlation at the origin. For turbulence close to the centre of the propagation path, where the beams partially overlap, then each telescope will measure the same turbulence except that each will be shifted by an amount $\approx Lq$ where $L$ is the distance of the turbulence from the receive telescope and $q$ is the angular separation of the beams. The spatial cross correlation of the (time averaged) wavefront gradients will therefore show a peak corresponding to this spacing. For turbulence close to the transmit telescopes, the beams do not overlap at all and there will be no cross correlation in the wavefront gradients.

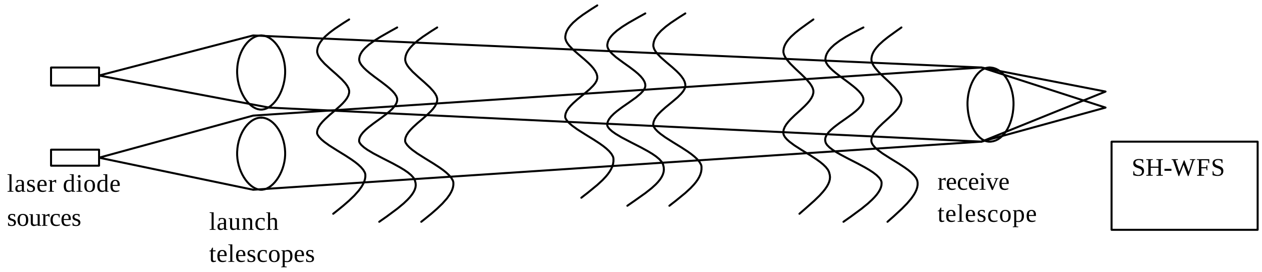



Fig.1 Optical geometry of SLODAR used to measure horizontal turbulence.

Data on the wind velocities can also be found from the cross-correlation functions calculated with a non-zero time delay between the centroid data streams.

## 2. EXPERIMENTAL DETAILS

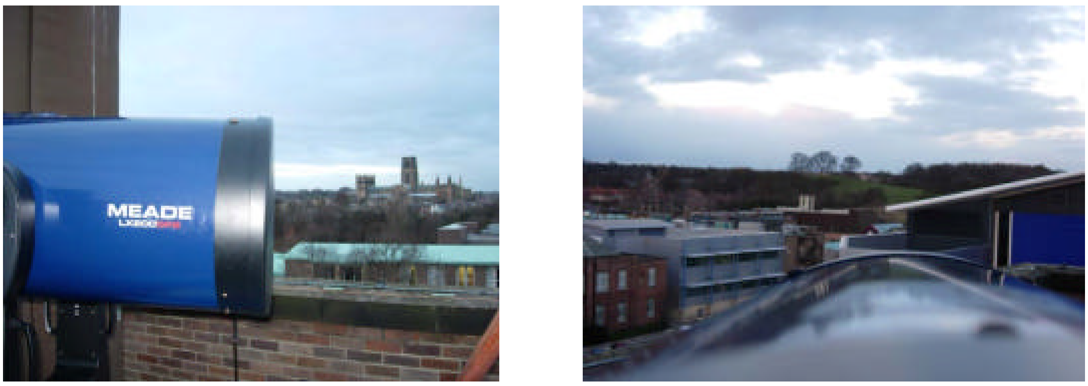



Fig 2. Photographs of the test site in Durham, UK. The left hand photo shows the launch telescope, and the right hand photo is taken down the telescope tube showing the 250m line of sight.

Three 14" (36cm) Meade[6] LX200GPS telescopes were used to launch and receive the beams. The eyepieces in the launch telescopes were replaced by fibre coupled 670nm laser diodes sources, and the eyepiece in the receive telescope was replaced by a 12x12 element lenslet array and re-imaging optics, coupled to a Q-Imaging[7] Retiga frame-transfer CCD camera. Data were taken across the rooftops of the Durham University science campus with the propagation path being approximately 75m or 250m (shown in fig. 2.). Each data set consisted of a sequence of WFS CCD images recorded with a frame of 70Hz, for (typically) 30 seconds. Very short exposure times (~200 micro-seconds) were used, in order to effectively 'freeze' the turbulent motions of the WFS spots in each image.

Centroids were calculated for each frame of data and the wave-front aberration in terms of Zernike modes was estimated via a SVD fit to the local gradients of the Zernike functions. For each sequence of data a value for the Fried parameter, $r_0$, (the spatial coherence length) was found by fitting the resulting spectrum of variances of the Zernike coefficients to the theoretical values calculated by Noll[8] for propagation through turbulence with a spectrum of refractive index fluctuations given by the standard (Kolmogorov) model.

## 3. RESULTS

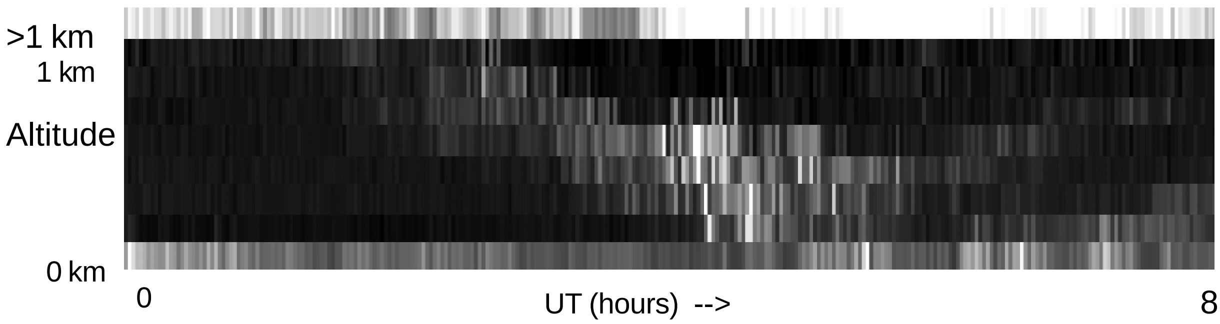



Fig 3. SLODAR results showing the turbulence strength as a function of altitude versus time at the Cerro Tololo observatory (CTIO) in Chile recorded on Dec 1st, 2004. White = strong turbulence, black = no turbulence. There are 8 altitude bins at intervals of 130m (the first bin is centered at the ground), the 9th bin is the integral of all turbulence above 1km.

So far our results for horizontal propagation have been confined to the calculation of the integrated turbulence. However, to demonstrate the utility of the technique we include results below taken at the Cerro Tololo observatory in Chile with a 40cm Meade telescope. Results of a vertical profile are shown in figure 3. which shows the strength of turbulence as a function of height above the ground versus time. The data consists of 8 altitude bins of 130m each below 1KM and 1 altitude bin for the remainder of the integrated turbulence above 1KM. These result were commissioned by the European Southern Observatory, and were compared with data recorded using other techniques, and will be used for the ground-layer and multiconjugate adaptive optics programs. Notice how a layer of turbulence descends through the atmosphere and then tends to rise again.

For horizontal turbulence, measured over a 75m path length in Durham, the values of $r_0$ were typically in the range of 10-20cm, which is relatively large. However there was a large variation in these values over a timescale of minutes. For example, figure 4 shows $r_0$ as measured on the 3rd Nov 2004 as a function of universal time. A summary of values of $r_0$ is included in table 1. 75m is a short path for FSO, and so this may be considered as a benign environment compared to a long range link in a hot country.

We attempted to correlate the values of $r_0$ with weather conditions, and these are shown in figures 5-7. From figure 5 there appears to be a weak correlation between wind speed and $r_0$, (although it is difficult to draw a firm conclusion because of the relatively few data points for higher wind speeds). This correlation is not surprising since turbulence is driven by differential heating and wind motion. From figure 6 it can be seen that there is little correlation between $r_0$ and wetness. More surprisingly, figure 7 shows little correlation between $r_0$ and the temperature, although the range of temperatures here is relatively low. There is, however, a correlation between temperature and the range of r0 taken over a period of time.

Measurements were made using an increased range of 250m over roof tops, in which case the strength of the turbulence increased considerably and the data could not be analyzed. Examples of the raw data are shown in figure 8, where it can be easily seen that the quality of the Shack-Hartmann spots depends on the range of the amount of turbulence.

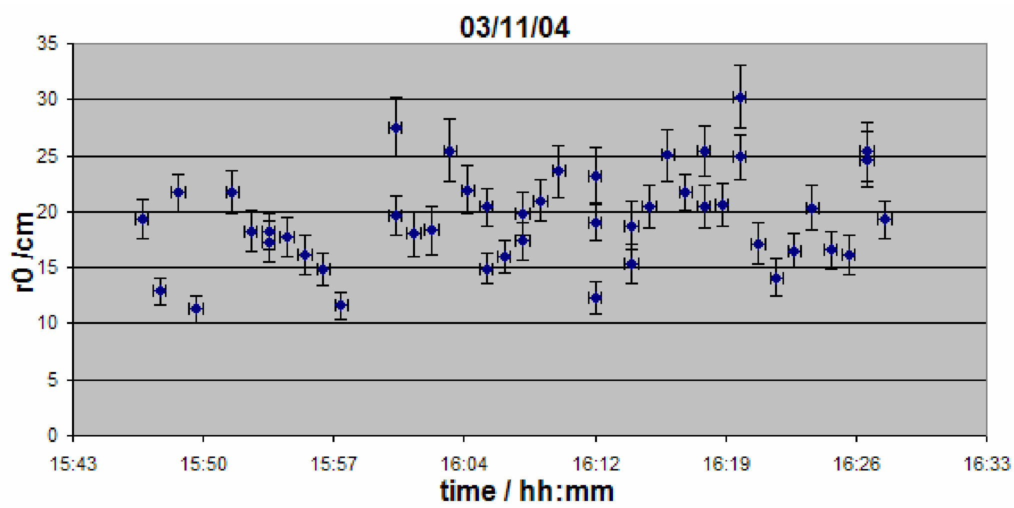



Figure 4. Example set of data showing the Fried parameter, r0, versus time on the 3rd Nov 2004.

| Date | Time (UT) | Mean $r_0$ (cm) | Full range of $r_0$ (cm) | Standard Deviation of $r_0$ (cm) |
|---|---|---|---|---|
| 3 Nov 2004 | 15:45 – 16:30 | 19.4 | 18.9 | 4.2 |
| 4 Nov 2004 | 15:00 – 16:10 | 8.0 | 14.7 | 3.8 |
| 11 Nov 2004 | 14:50 – 16:15 | 11.9 | 22.4 | 5.3 |
| 25 Nov 2004 | 14:30 – 16:00 | 14.9 | 13.6 | 2.8 |
| 26 Nov 2004 | 09:55-10:50 | 12.0 | 16.5 | 3.5 |
| 26 Nov 2004 | 14:55-15:45 | 16.8 | 14.7 | 3.3 |
| 1 Dec 2004 | 14:30 – 16:00 | 14.5 | 11.8 | 2.5 |

Table 1. Measured values of the Fried parameter, *r0*, over a range of 75m in Durham.

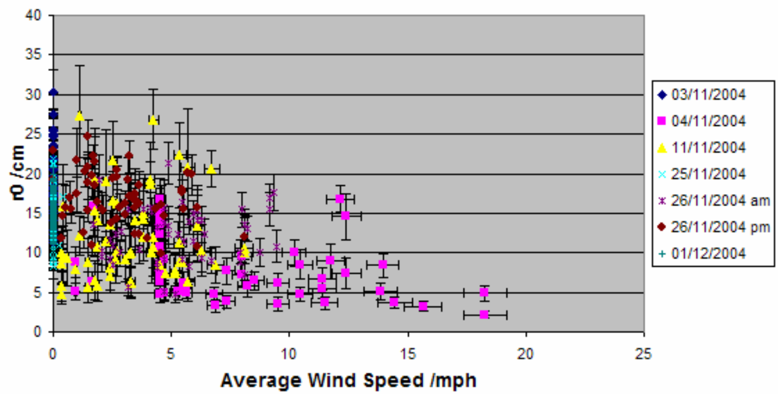



Figure 5. $r_0$ as a function of wind speed.

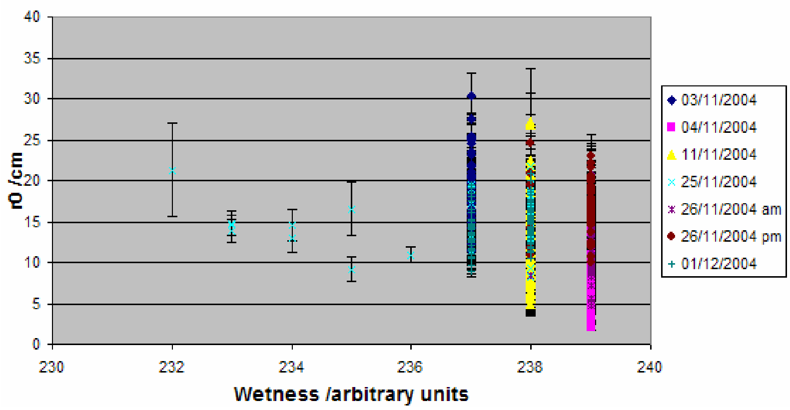



Figure 6. $r_0$ as a function of wetness. (arb units. 239 = dry, 230 = very wet)

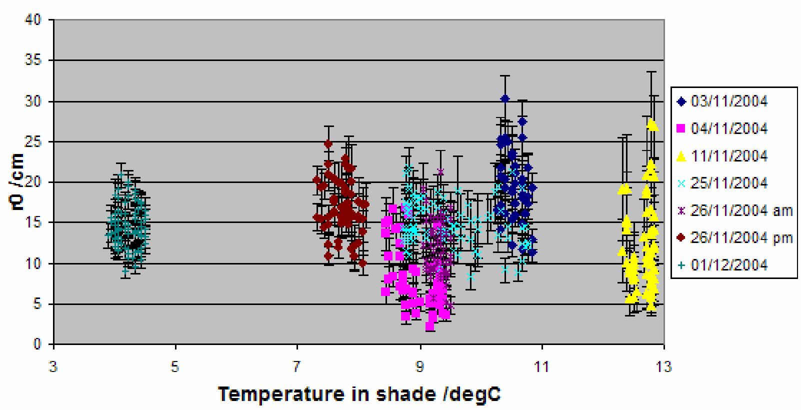
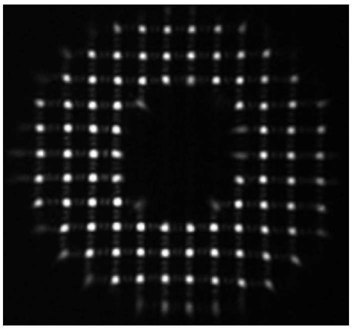
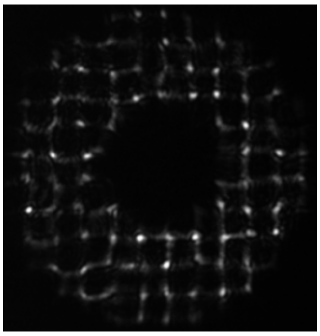


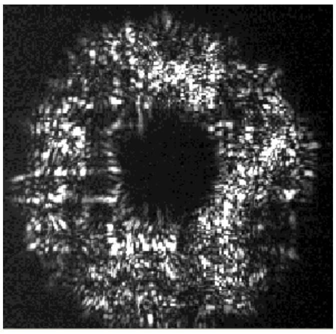

Figure 7. $r_0$ as a function of temperature.



High quality Shack Hartmann data recorded over a 75m path length



Data recorded over a 250m path length. This was one of the best frames, but it would be still difficult to process.



Low quality data recorded over a 250m path length which clearly can not be analyzed.

Fig 8. Frames of raw Shack Hartmann data.

## 4. CONCLUSIONS

We have described the method of SLODAR and shown data of horizontal turbulence strengths as a function of atmospheric parameters. Current work is concentrating on producing full turbulence profiles for horizontal measurements.

In terms of comparing SLODAR and SCIDAR. The advantage of the SLODAR technique is that the impulse response (i.e. the response to a thin single layer of turbulence at a fixed distance) is, to first order, independent of the range of the turbulence. Calibration of the turbulence profile is then much easier. In SCIDAR the response of the system depends on the range of the turbulence. The disadvantage of SLODAR – as these results have shown is that the lenslets need to be approximately matched to the seeing and the technique is more prone to errors from scintillation.


## ACKNOWLEDGEMENTS

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