# Durham MCAO Lab Demo Status

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In this appendix, we describe our work in progress at Durham on MCAO laboratory experiments. The first stage of this experiment has been to produce quantifiable two-layer Kolomogorov turbulence. Our method of multi-layer turbulence generation is described below in section 1, followed by a description of correcting this turbulence with a single conjugate AO system. In section 3 we outline our future plans, up to PDR, for MCAO lab demonstrations.

## 1. Multi-layer LC turbulence generators.

The turbulence generators used at Durham are based on ferroelectric liquid crystal spatial light modulators (FLC-SLMs) used in a holographic arrangement first described by Neil et al[1]. Compared to conventional (nematic) liquid crystals which are generally used for adaptive optics, they have the advantage of high temporal bandwidths (~KHz frame rates), but the disadvantage that they are bistable phase modulators (i.e. they can produce one of only two states - generally 0 or π). The holographic technique is a method to produce analog phase modulation from the binary phase shifters, at the expense of some spatial resolution. The FLC-SLMs used here have 256x256 pixels, so some loss in spatial resolution can easily be tolerated. The technique operates in the following manner.

Consider a wavefront given by $\exp\left(i\boldsymbol{j}(x,y)\right)$, which is binarized, to give $b(x,y)$, where,

$$b(x,y) = B\left(\boldsymbol{j}(x,y)\right) = \begin{cases} +1 = e^{i0} \rightarrow \left|\boldsymbol{j}(x,y)\right| < \dfrac{\boldsymbol{p}}{2} \\ -1 = e^{ip} \rightarrow \left|\boldsymbol{j}(x,y)\right| \geq \dfrac{\boldsymbol{p}}{2} \end{cases}, \qquad [1]$$

where $-\boldsymbol{p} \leq \boldsymbol{j}(x,y) \leq \boldsymbol{p}$. This binarized wavefront can be applied by the FLC-SLM, but clearly the binarized wavefront is not the same as the desired wavefront, $\boldsymbol{j}(x,y)$. We note that the function $B\left(\boldsymbol{j}(x,y)\right)$ can be re-written as,

$$B\left(\boldsymbol{j}(x,y)\right) = \frac{2}{\boldsymbol{p}}\left(e^{if(x,y)} + e^{-if(x,y)} - \frac{1}{3}e^{i3f(x,y)} - \frac{1}{3}e^{-i3f(x,y)} + \frac{1}{5}e^{i5f(x,y)} + \frac{1}{5}e^{-i5f(x,y)} \downarrow\downarrow\right) [2]$$

I.e. the binarized wavefront is a summation of the desired wavefront, $\boldsymbol{j}(x,y)$, along with multiples of the desired wavefront, and their conjugates. In order to separate the individual terms, tilt is added to the desired wavefront, to give,

$$B(\varphi(x,y)) = \frac{2}{\pi}\left(e^{i(\phi(x,y)+\tau(x,y))} + e^{-i(\phi(x,y)+\tau(x,y))} - \frac{1}{3}e^{i3(\phi(x,y)+\tau(x,y))} - \frac{1}{3}e^{-i3(\phi(x,y)+\tau(x,y))} \ldots\right) \quad [3]$$

where $\tau(x,y)$ is the wavefront tilt. If such a binarized wavefront is imaged using a lens, then each term will be diffracted differently to relative displacements of {+1, -1, +3, -3, +5, -5 …}. Each order carries a scaled analog phase modulation with the same relative scaling. The use of a spatial filter allows the selection of only the desired first order term. Thus, in practical terms, the procedure for producing a wavefront is as follows.

1. Numerically produce the desired wavefront, $\varphi(x,y)$. We used a turbulence simulator as described by Lane[2].

2. Numerically add a large tilt to this (typically 70 waves).

3. Binarize the resultant wavefront, using equation [1] above.

4. Apply this binarized function to the bistable FLC-SLM.

5. Pass collimated light through the SLM, followed by a lens. In the focal plane of the lens many diffracted orders can be seen. Select the appropriate order using a spatial filter.

6. Re-collimate the light to give a beam with the desired wavefront.

Neil et al. assessed the quality of the wavefronts produced in this way by a numerical simulation. They define the quality of the wavefronts as the Strehl ratio of phase residual between the synthesised and desired wavefront. They show that the quality varies from about 0.97 for $D/r_0 \leq 5$ to about 0.87 for $D/r_0 = 30$.

By repeating the above optical set-up for each turbulent layer it is possible to produce deterministic multi-layer turbulence, with the correct (Kolmogorov) statistical properties, at different conjugates. In practice, alignment of the spatial filter probably limits real systems to 3 or 4 layers. We applied different $D/r_0$'s to the layers varying from 4 to 13 on each layer. We actually applied tilt removed turbulence, since that mode is reproduced the least accurately by the turbulence generator. However, we can apply tilt, providing it is not so large that it causes the different diffraction orders to overlap.

## 2. Results from 2-layer, 1-DM lab experiments with off-axis beacon.

The aim here is to show that we can produce and correct quantifiable two layer turbulence in the laboratory. The experiment consisted of a 2-layer FLC-SLM turbulence generator feeding the ELECTRA[3] adaptive optics system with 2 illuminating sources. The experimental layout of the turbulence generator is shown in Fig. 1. Both the FLC-SLMs work in reflection mode, hence the need for reflection optics. The beamsplitter, BS, and the two mirrors, M1 and M2, produce a second off-axis beam using the incident on-axis beam from the laser. The angle between the two can easily be controlled by tilting one of the mirrors. The incoming beam is a collimated HeNe laser and the relay optics convert the output to an f/11 beam which then passes on to ELECTRA. The DM is a 228 actuator ThermoTrex segmented mirror with strain gauges to compensate for hysteresis. The WFS is a Shack Hartmann using an EEV-80 CCD chip. The system is controlled by a parallel network of 16 TI C40 DSPs.

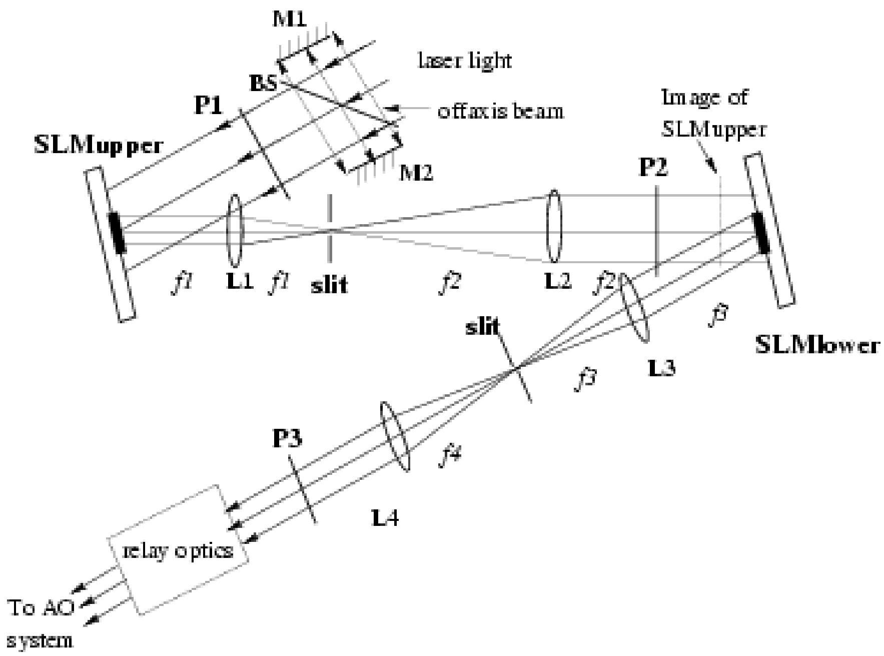


**Figure 1 . Experimetal apparatus used in the 2-layer turbulence generator. P, polarizers. L, lenses. *f*, focal lengths. M, mirrors. BS, beamsplitter.**

The following are key features of the optical design.

1. The beam which is reflected from the full aperture of the upper SLM is then oversized on the lower SLM. Both the on and off-axis beams co-propagate through the lower SLM, whereas they are displaced on the upper SLM. The lower SLM corresponds to a size *D*, projected into the sky, whereas the upper SLM is larger than *D*.
2. The optical design ensures that no vignetting of the off-axis beam occurs, up to some maximum off-axis angle (3.6$^{o}$ in lab. space).
3. Because of the small physical size of the SLMs (3.84mm), it is not realistically possible to design the optics to model an 8m aperture with a 1 arcminute field of view (the large magnification factor required would mean off-axis angles of up to 35$^{o}$ in the turbulence generator). However, the key factor is how large $\theta/\theta_0$ is, and, by adjusting the effective heights of the layers, we can ensure that this is approximately similar to the conditions expected for Gemini, which we outline in Table 1. The system was therefore scaled to simulate a 1m telescope aperture, with a maximum off-axis angle (on the sky) of 49 arcsecs, and a height of turbulence of 3.4km, and a 8m telescope with a maximum off-axis angle (on the sky) of 6 arcsecs, and a height of turbulence of 218km.

| Aperture | $r_0$ | $\bar{h}$ | $\lambda$ | $\theta_{max}$ | $\theta_0$ | $\theta_{max}/\theta_0$ | $D/r_0$ | $\left(D/r_0\right)_{single}$ |
|---|---|---|---|---|---|---|---|---|
| 8m | 20cm | 5km | H | 1' | 6.2" | 9.6 | 16 | 10.7 |
| 8m | 20cm | 5km | J | 1' | 10.1" | 5.9 | 10 | 6.7 |

**Table 1 Expected parameters for Gemini. $\bar{h}$ is a nominal height.**

$\theta_{max}$ is the maximum off axis angle (i.e. half the field of view). $\left(D/r_0\right)_{single}$ corresponds to the $D/r_0$ of the individual layers if the total turbulence is assumed to be equally distributed between two layers. The actual effective parameters which we simulated are shown in the following table, scaled to aperture sizes of 1m and 8m.

| Aperture | $D/r_0$ | $h_{upper}$ | $\theta_{max}$ | $\theta_0$ | $\theta_{max}/\theta_0$ |
|---|---|---|---|---|---|
| 1m | 7 | 3.4km | 46" | 4.7" | 9.7 |
| 1m | 10 | 3.4km | 46" | 3.2" | 14.5 |
| 8m | 7 | 218km | 5.8" | 0.6" | 9.7 |
| 8m | 10 | 218km | 5.8" | 0.4 | 14.5 |

**Table 2 Simulated parameters for the turbulence generator scaled to different aperture sizes.**

The results of correction are shown in figure 2 for 4 different cases of turbulence. In the first 2 cases the turbulence was added only to the lower SLM, which is conjugate the DM, and the correction was approximately independent of the off axis angle. For the other 2 cases we added turbulence to both SLMs, and observed a corresponding decrease in the Strehl ratio with off-axis angle. Strehl ratio is defined here as the peak intensity of the corrected beam, normalised by the peak intensity from a beam propagating through the system with no induced turbulence. The residual system aberrations are small, so this will only slightly underestimate the real Strehl ratio. We fitted the curves to functions of the form,

$$S = A\exp\left(B\theta^{C}\right) + D\,.$$

For curves 3 and 4 the Strehl followed a $\theta^{1.4}$ and $\theta^{1.6}$ dependence, respectively. Roddier[4] states that the curves should follow a $\theta^{2}$ dependence for low values of the order of correction, and $\theta^{5/3} = \theta^{1.67}$ for full correction. We have calculated a $\theta_0$ from the curves, by calculating the angle at which the curve falls to $e^{-1}$ of the peak value. The results are shown in table 3. We needed to account for the fact that our simulated turbulence had no tip/tilt component, which we did by calculating the covariance matrix for angular anisoplanatic Zernike corrections, according to Wilson and Jenkins[5]. Our preliminary calculations indicate that tip/tilt removal can modelled by increasing the value of $\theta_0$ by 30%.

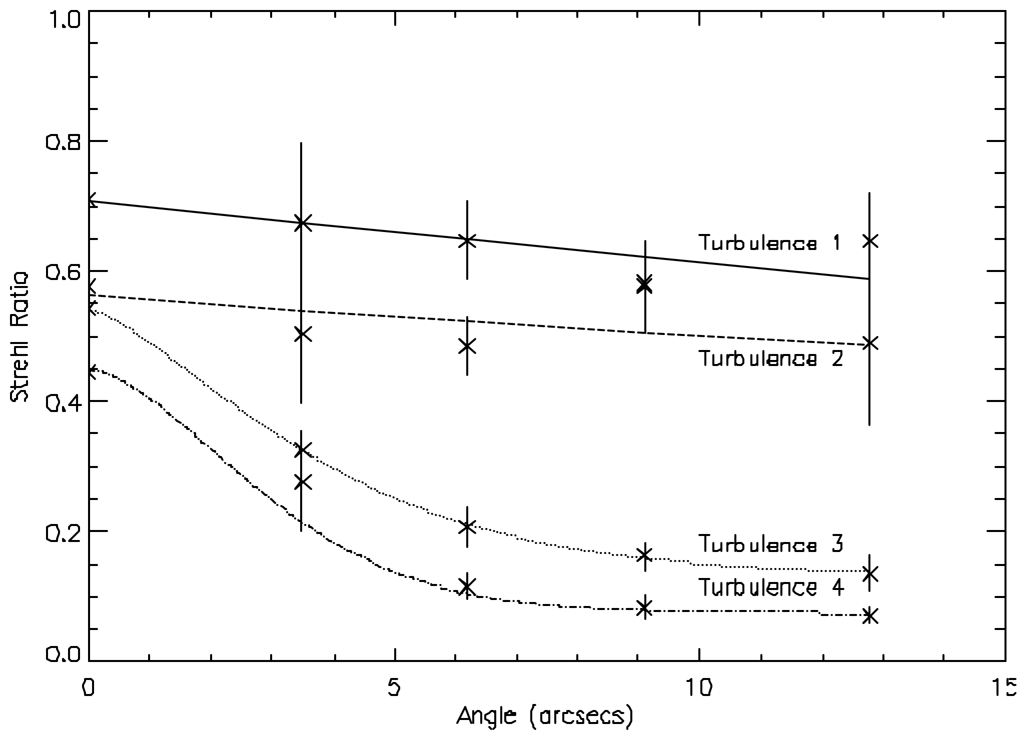


**Figure 2 Strehl ratio vs. angle (assuming 1m telescope) .**

| | |
|---|---|
| Turbulence 1 | Single (lower) layer of turbulence. $D/r_0 = 6$ |
| Turbulence 2 | Single (lower) layer of turbulence. $D/r_0 = 7.7$ |
| Turbulence 3 | Dual layer turbulence. $\left(D/r_0\right)_{lower} = 6$, $\left(D/r_0\right)_{upper} = 4$ |
| Turbulence 4 | Dual layer turbulence. $\left(D/r_0\right)_{lower} = 6$, $\left(D/r_0\right)_{upper} = 6$ |

Note that the cumulative effect of the 2 layers in turbulence 3 is equal to turbulence 2. Hence the 2 lines should converge at zero angle, as shown.

| | Theoretical $q_0$ | Adjusted $q_0$ to Allow for tip/tilt | $q_0$ calculated from figure 2. |
|---|---|---|---|
| Turbulence 3 | 4.7" | 6.11" | 6.6" |
| Turbulence 4 | 3.2" | 4.16" | 4.4" |

**Table 3 Isoplanatic patch size. Theoretical values vs. experimentally measured values.**

We stress that these are preliminary results, and a full analysis is in progress. The main aim of this first experiment was to show that we can precisely generate and correct dual layer turbulence in a controlled laboratory setting.

## *3. Future plans and schedule for a 2-layer, 2-DM system with 4 off-axis beacons.*

During the remainder of this year we plan to decouple the experiments from ELECTRA and generate a standalone AO system using 2 conventional liquid crystal devices as the wavefront correctors. The system will be based on commercially available PC technology, and will not operate in real-time. The following table lists the details of the AO system.

| | |
|---|---|
| DM | 2x 37 actuator modal LC-SLMs |
| WFS | SH |
| WFS Camera | Commercial CCD -TV camera |
| Software | LabWindows |

The following are back-up options

| | |
|---|---|
| DM | Hex69 + 128x128 BNS nematic LC-SLMs |
| WFS Camera | SBIG CCD |

A preliminary set of milestones is as follows…

| | |
|---|---|
| June 2000 | Design and order new optical system. |
| | Install upgraded FLC-SLM controller to allow continuous data streams<br>Design new LC electronic controller. |
| July | Produce simplified system model with dual layer reconstructor |
| Sept. | Complete optical set up with both correctors in place, but with only one operational. |
| Oct. | Close loop with dual layer turbulence and a single DM. |
| Dec. | Close loop with both DMs |

After PDR, we will need to extend the turbulence generator to provide more than 2 illuminating sources. In the current configuration we can only do this if all the sources are lined up (so the light passes through the slit). However, we can remove the first slit completely as long as the wavefront tilts are carefully selected to ensure that the first order diffraction spots from each source do not overlap. The second slit will be replaced by a mask with an appropriate array of holes drilled in it. We can have a set of these to allow for different guide star configurations. Alternatively a conventional intensity modulating LCD could be used. All the sources must be at the same altitude (this can either be at infinity, or some finite altitude). We will then be able to simulate the Gemini 5 LGS geometry on a single camera. Both NGS's and LGS's could be simulated by having two parallel turbulence generators.

# References


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