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Compensating Kolmogorov Turbulence with Membrane Deformable Mirrors

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We have reported in the past on experiments in which we compensated Kolmogorov turbulence phase screens in the lab with a membrane deformable mirror. In this application note we are reporting on the results of a model that examined the efficacy of using a membrane deformable mirror (DM) to compensate different strength turbulence.

For this model, we leveraged the KolmogorovPhaseScreen class that is distributed with the AOS software and modeled membrane DM influence functions. (Modeled membrane DM influence functions are available for select DMs on the AOS web-site. For other DMs, the AOS software can generate these influence functions.) For feedback we modeled an oversampled Hartmann wavefront sensor. For this model, we chose an unusual DM that was designed for 45-degree angle of incidence operation. This DM was created using a 2" diameter membrane, but an actuator pad array that spanned an area only 20 x 28 mm in size. The actuator pads were created with such that at 45-degree operation, the actuator pattern was square with 9 actuators across the active area. Figure 1 shows the electrostatic pad array pattern of this 61-actuator DM.

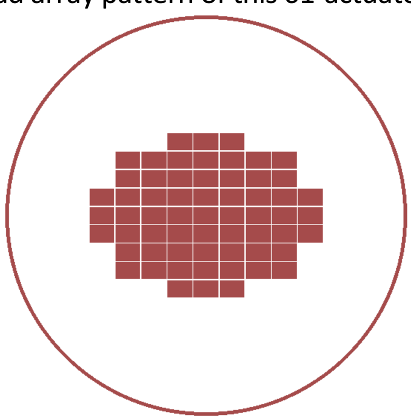

Figure 1 - Pad array for 61-R DM with a 2" Diameter Circle representing the membrane size

For this model, we were interested in compensating turbulence from a 30-cm aperture. To avoid having to model telescopes and to avoid interpolation, we projected all the modeled components (the wavefront sensor, the DM, and the turbulence) into the 30-cm space. Figure 2 shows the overlay of the Hartmann sensor sub-apertures and the 45-degree-projected DM actuators in 30-cm space. We also assumed that the turbulence was in a single screen and imaged perfectly onto the DM and wavefront sensor.

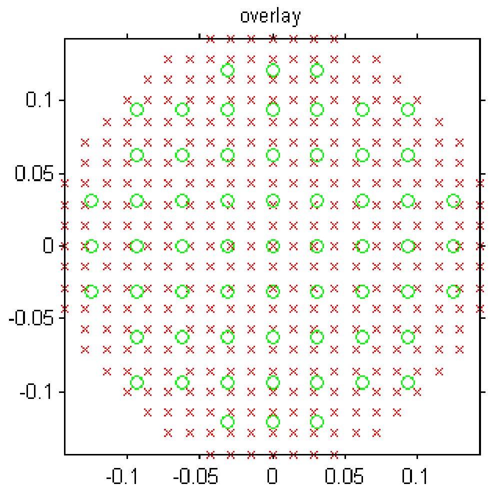

Figure 2 - Overlay of the MDM actuator locations (green circles) and the Hartmann sensor sub-apertures (red x's) in 30-cm space

We began the model by first creating a poke matrix by projecting the modeled influence functions to a 45-degree incidence beam and modeling their effect on a Hartmann sensor. Then this poke matrix was inverted using single value decomposition with no modes removed to create a control (or fitting) matrix. Figure 3 shows the poke and control matrices and the SVD gains from the inversion.

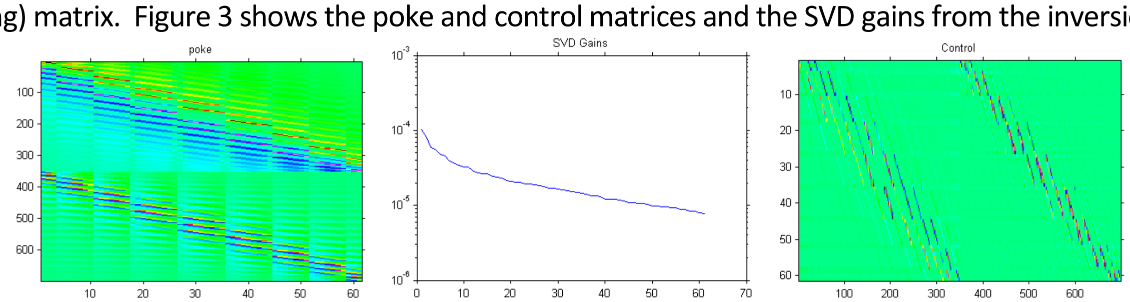

Figure 3 - Poke Matrix, SVD Gains, and Control Matrix

Then we leveraged the AOS KolmogorovPhaseScreen Matlab class to create phase screens on the same sample grid as the DM. The aperture diameter was set to 30 cm throughout, but the D/r0 ratio was varied to vary the turbulence strength.

The limited throw of the DM was modeled by summing all the influence functions together to create the normal focus term and then scaling them all such that that the sum was equal to a user-specified maximum DM throw. During modeling, the DM commands were only allowed to vary between -0.5 and +0.5. One thing we noticed during this actuator limiting setup was that the normal focus bias term when projected at 45-degrees created a significant astigmatism term that would normally use a lot of the DMs throw to eliminate. Based upon this, we recommend using membrane DMs with circular frames at near-normal incidence due to the astigmatic aberration induced by biasing them.

Theory

Robert Tyson's book Principles of Adaptive Optics summarized the relevant theory well. For a Kolmogorov-spectrum phase screen, the RMS wavefront error can be given by,

$$\sigma = \sqrt{\alpha}\left(\frac{D}{r_0}\right)^{5/6}$$

where σ is the RMS wavefront error, D is the aperture diameter, r_0 is the Fried coherence length, and α is a constant that is 1.02 if the turbulence is uncompensated and 0.134 if the turbulence is tilt-removed.

Compensation of atmospheric turbulence was found to follow a similar functional form. The rms wavefront error of a compensated Kolmogorov-spectrum phase screen is given by,

$$\sigma = \sqrt{\kappa}\left(\frac{r_s}{r_0}\right)^{5/6}$$

where σ is the RMS wavefront error, r_s is the spacing between actuators, r_0 is the Fried coherence length, and κ is a constant that depends on the shape of the actuators. The following table summarizes the values that Tyson gives in his book.

Actuator Influence Function Shape	κ
Piston Only	1.26
Experimental	0.39
Gaussian	0.23 to 0.349
Pyramidal	0.28

Results

We first began by setting the maximum throw of the DM to 200 microns, which is significantly beyond the capability of this device in its current form, but allowed us to eliminate the actuator throw limiting and simply look at the effect of the limited spatial resolution. For each case, we ran a single step fitting of the DM influence functions to the Kolmogorov turbulence realization, which is equivalent to a single step of integrator AO with a gain of 100% and no leak. We ran 50 atmospheric realizations and examined the average and the standard deviation of the results.

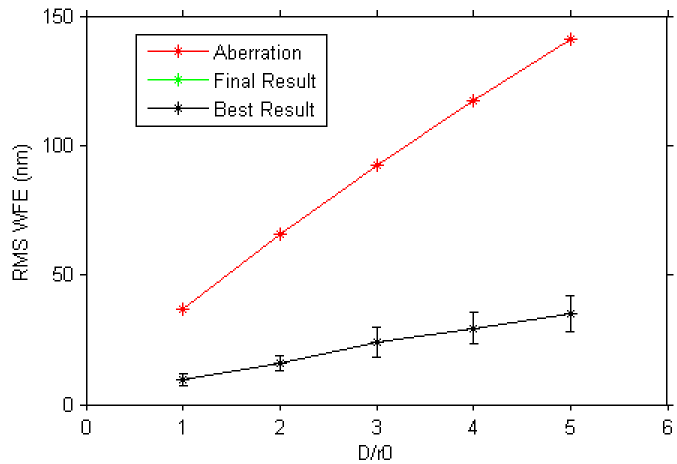

Figure 4 - RMS wavefront error vs D/r0 ratio of the raw aberration, the compensated aberration, and the best model result

Figure 4 shows the results from the simulation. The best and final values were in agreement for each of these cases because the AO system was converged in a single step.

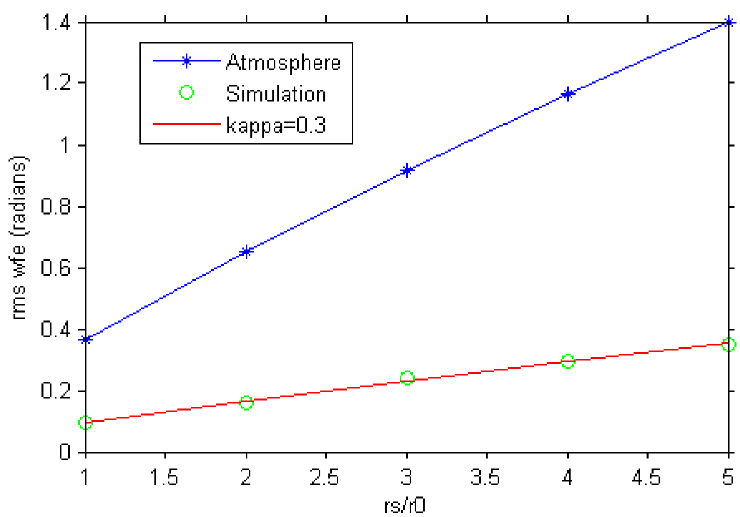

Figure 5 - RMS wavefront error as a function of the ratio of actuator spacing (r_s) to Fried's coherence length (r_0)

Figure 5 shows the results of the simulation plotted against the ratio of actuator spacing (r_s) to Fried's coherence length (r_0) to better compare with the compensation theory presented earlier. The simulation data was shown to fit well to a curve with κ=0.3.

To compare our results to existing results in this space, we repeated this experiment with a Gaussian influence function with a 1/e width equal to the actuator spacing. We found that those results fit well to the theory when κ=0.35, which is close to the .349 result presented in Tyson's Principles of Adaptive Optics.

Conclusions

We found that the membrane deformable mirror fits Kolmogorov turbulence very well. In fact, we found that the membrane influence functions had a κ fit factor of 0.3, which is actually comparable to the pyramidal influence functions and better than the experimental or Gaussian influence function. Repeating our experiment with a Gaussian influence function yielded the same result as was presented in prior work.