

# Adaptive Optical System Atmospheric Turbulence Generator Testbed

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## Abstract

At the Naval Research Laboratory (NRL), we have developed a testbed for simulating atmospheric turbulence using Kolmogorov statistics for testing the correctibility of an Adaptive Optical System (AOS). In this testbed, a Liquid Crystal Spatial Light Modulator is being used to induce the atmospheric turbulence and a MEM deformable mirror is being used in the AOS to correct it. This atmospheric turbulence generator can be used to simulate the atmospheric effects on light viewed by an AOS for any telescope aperture with either very poor or very good seeing conditions. This dynamic and expandable system is being used to characterize performance and optimization parameters of our AOS at NRL.

## 1. Introduction

Recent advances in manufacturing capabilities have resulted in many new electro optical devices being developed for us in Adaptive Optics (AO) systems. These devices include MEMS [1, 2], glass thin face sheets [3], deformable secondary telescope mirrors [4] and emerging technologies using composite materials [5]. With so many of these systems coming available there is a significant need to be able to consistently evaluate and characterize the performance of these devices.

Traditionally the performance of an atmospheric compensation device is evaluated either as part of a full AO system using astronomical targets or in static, laboratory tests using lasers and fixed aberrations. What is desired is a system that can consistently and repeatably generate a phase screen similar to the atmosphere but under direct user control.

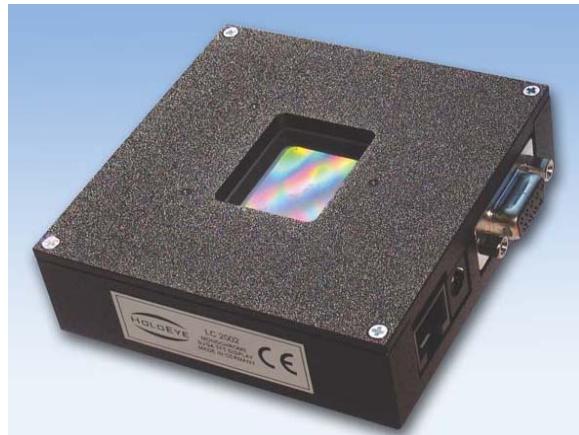
It is also important that the system be able to support a wide range of atmospheric seeing conditions and be scalable to the aperture of the optical system being evaluated. Fried's parameter, also known as the coherence diameter of the atmosphere and represented by  $r_0$ , is a statistical description of the level of atmospheric turbulence at a particular site, related to wavelength. Fried's parameter ranges from under 5 cm with poor seeing conditions to more than 20 cm with excellent seeing conditions in the visible light spectrum [6-8].

In this paper we report on the development of an atmospheric aberration simulator that uses the Zernike polynomial set and seamlessly transitions between aberrations to provide an aberrated wavefront that can be fed into a system or device under test.

## 2. Phase Screen Simulator

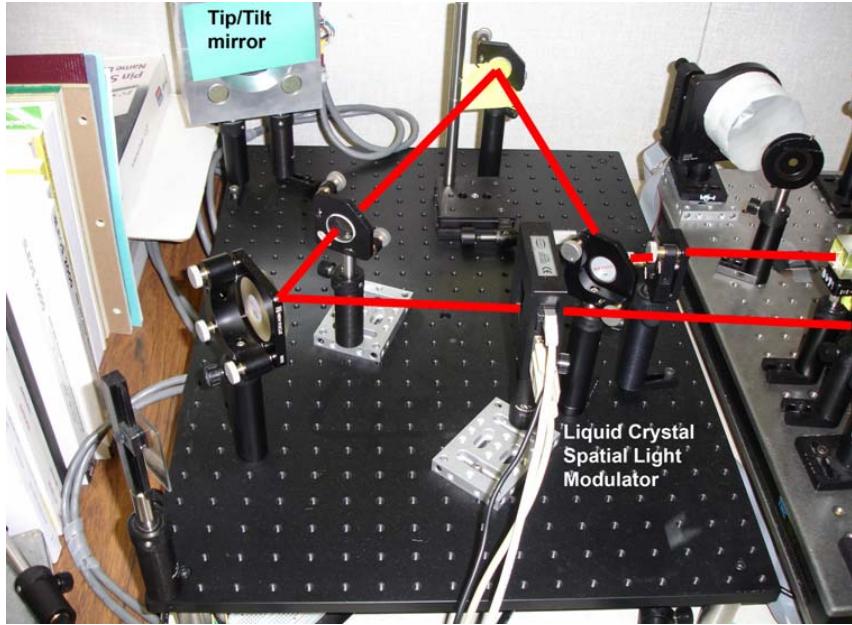
The phase screen simulator being developed is based on a Spatial Light Modulator (SLM) developed by the Holoeye Corporation. This device modulates light in amplitude and phase under computer control allowing the phase of the wavefront to be varied across the aperture.

This specific Liquid Crystal (LC) SLM was manufactured by Holoeye Photonics, AG. It is an 832 x 624 pixel  $2\pi$  phase change device capable of operating at up to 33 Hz. It operates as a computer monitor, allowing software to be written to place an ‘image’ on the device. The images consist of a series of black and white bands that correspond to a phase of either 0 or  $2\pi$ . This device creates a phase-only change allowing wavefront shaping. Fourier filtering is required to block the higher and lower order modes transmitted through the system. The SLM is shown below in Figure 1, and the overall system is shown with relaying mirrors and Fourier filtering and collimating optics in Figure 2.



**Figure 1** – Holoeye Liquid Crystal Spatial Light Modulator. The Liquid Crystal SLM used in this project is the LC2002 SLM.

The Holoeye device has been incorporated into a bench top optical system to provide spatial and phase control over the incoming wavefront which is then relayed into the system under test. The prototype system is shown in Figure 2. The figure shows that the wavefront enters into the system and passes through the Holoeye device before being returned to the system under test.



**Figure 2** – SLM in the optical system. Incoming beam passes through SLM, through relaying mirrors and filtering optics and is recolimated back into the AO system.

### 3. Simulating Atmospheric Turbulence

The Earth's atmosphere is a large, non-linear, non-homogenous medium that is constantly changing in a random fashion that affects light as it propagates through it. The Kolmogorov model is a description of the nature of the wavefront perturbations introduced by the atmosphere. This model was first proposed by a Russian mathematician named Andrei Kolmogorov [9]. It is supported by a variety of experimental measurements and is quite widely used in simulations for astronomical seeing. The Kolmogorov theory of atmospheric turbulence is based on the assumption that the turbulence varies the index of refraction and thus affects the permittivity of the medium throughout it. This affects the light, or electric field, as it propagates through the atmosphere.

Tatarski's model describes the phase variances to have a Gaussian random distribution. So, by taking the sum of Zernike modes and modifying it such that there is Gaussian random noise gives,

$$\text{Wavefront} = \sum_i X_i a_i Z_i(\rho, \theta) \quad (1)$$

where  $X_i$  is the amount of noise for the  $i^{\text{th}}$  mode based on a zero-mean Gaussian random distribution and the  $a_i$ 's are the amplitudes of the aberrations. The  $a_i$ 's are calculated from Zernike-Kolmogorov residual errors,  $\Delta_j$ , measured through many experimental procedures by Fried [10] and calculated by Noll [11] and are given in Table 2 and relate to the ratio of  $D$  and  $r_0$ . Figure 3 is a sample fringe pattern generated.

**Table 2** – Zernike-Kolmogoroff residual errors,  $\Delta_J$ , and their relation to  $D/r_0$  for a Zernike Mode  $J$ .

Zernike Mode	Zernike-Kolmogoroff residual error
Tip	$\Delta_1 = 1.0299 (D/r_0)^{5/3}$
Tilt	$\Delta_2 = 0.5820 (D/r_0)^{5/3}$
Focus	$\Delta_3 = 0.1340 (D/r_0)^{5/3}$
Astigmatism X	$\Delta_4 = 0.0111 (D/r_0)^{5/3}$
Astigmatism Y	$\Delta_5 = 0.0880 (D/r_0)^{5/3}$
Coma X	$\Delta_6 = 0.0648 (D/r_0)^{5/3}$
Coma Y	$\Delta_7 = 0.0587 (D/r_0)^{5/3}$
Trefoil X	$\Delta_8 = 0.0525 (D/r_0)^{5/3}$
Trefoil Y	$\Delta_9 = 0.0463 (D/r_0)^{5/3}$
Spherical	$\Delta_{10} = 0.0401 (D/r_0)^{5/3}$
Secondary Astigmatism X	$\Delta_{11} = 0.0377 (D/r_0)^{5/3}$
Secondary Astigmatism Y	$\Delta_{12} = 0.0352 (D/r_0)^{5/3}$
Larger orders ( $J > 12$ )	$\Delta_J = \sim 0.2944 J^{\sqrt{3}/2} (D/r_0)^{5/3}$



**Figure 3** – Sample fringe pattern of atmospheric turbulence for the phase screen to be applied to the SLM.

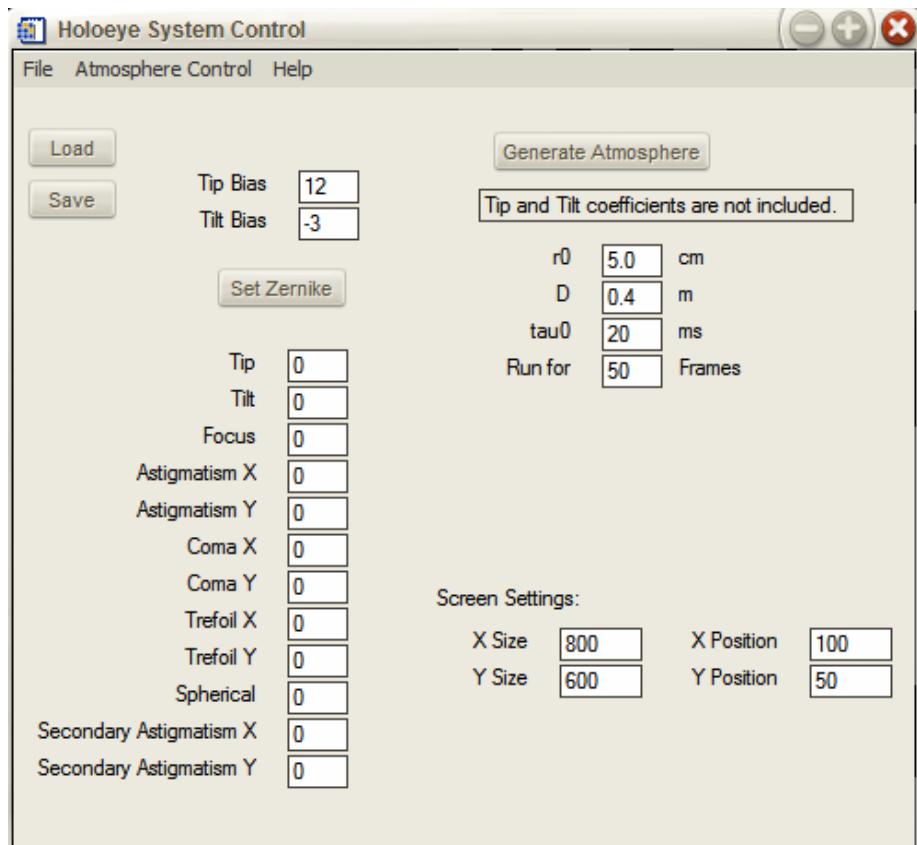
**Table 3** – Zernike coefficients calculated for a 0.4 meter telescope and an  $r_0$  of 5.0 cm.

<i>i</i>	Aberration	$a_i$
<b>1</b>	Tip	-1.0599800
<b>2</b>	Tilt	-0.2295670
<b>3</b>	Focus	-0.7094870
<b>4</b>	Astigmatism X	-0.1323110
<b>5</b>	Astigmatism Y	-0.8104040
<b>6</b>	Coma X	-0.9680100
<b>7</b>	Coma Y	2.1787200
<b>8</b>	Trefoil X	0.7171930
<b>9</b>	Trefoil Y	0.0574078
<b>10</b>	Spherical	-0.0135916
<b>11</b>	Secondary Astigmatism X	-0.5659450
<b>12</b>	Secondary Astigmatism Y	1.6607000

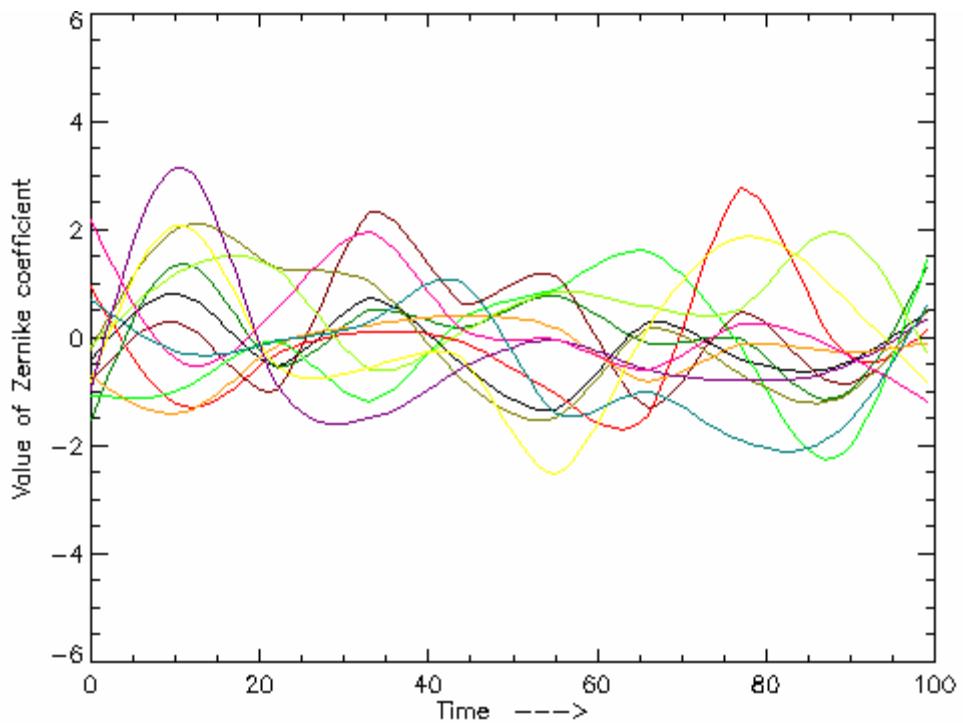
#### 4. Algorithm for the Temporal Progression of Atmospheric Turbulence

Using the methods described in Section 3, software was written in IDL to generate fringe patterns using random Zernike coefficients bounded by the  $D/r_0$  parameter. As shown in Figure 4, a graphical user interface allows the user to enter the number of frames to be generated, the  $D/r_0$  parameter, a  $\tau_0$  parameter and Zernike mode biases. These biases are used in the alignment for the Fourier filtering of the higher order modes and simple misalignments. A large number of frames may be generated, and a splining technique is used to allow a smooth transition between frames. This gives the look of a continuously varying simulated atmosphere.

A vector of only a few elements containing random numbers with a normalized distribution is generated and a spline [12] is fit to it with a resulting vector having the same number of elements as frames desired. This allows for a continuous transition of the wavefront from frame to frame throughout the simulation.



**Figure 4** – Graphical user interface for controlling atmospheric turbulence generator.



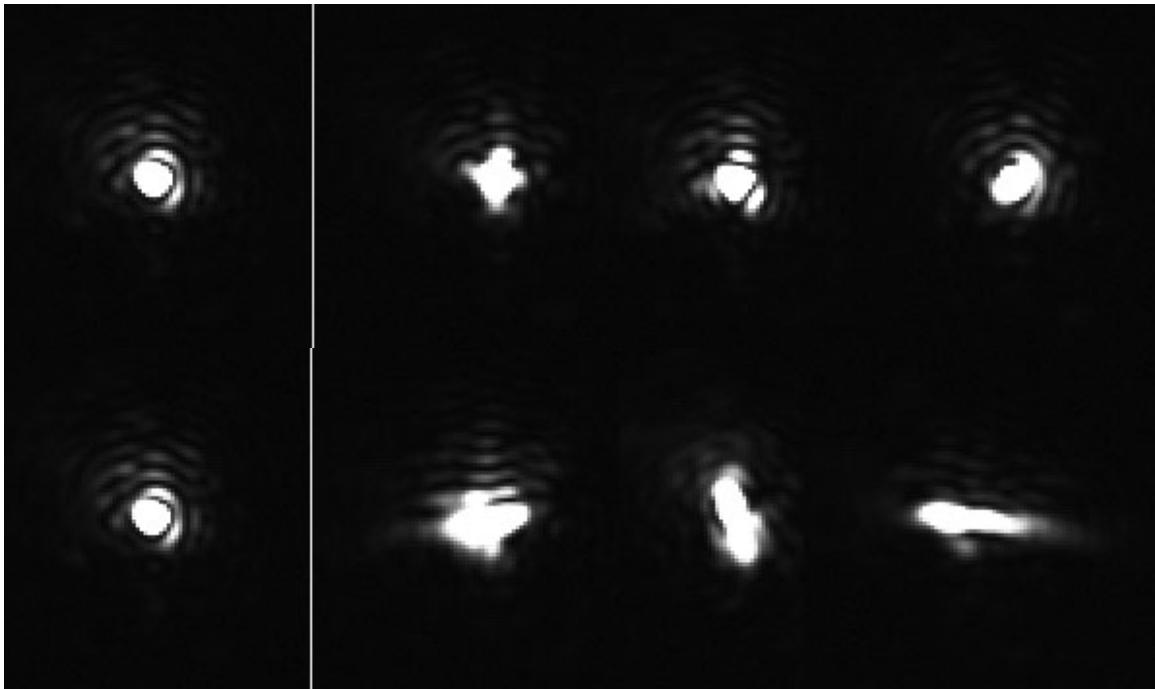
**Figure 5** – Distribution splines for the temporal progression of atmospheric turbulence.

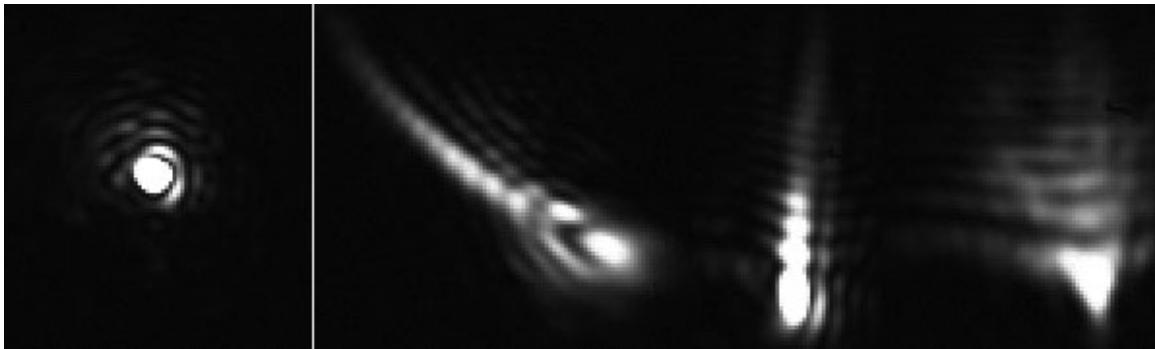
Without this splining technique, the change between phase screens would be discontinuous and would not provide an accurate representation of the atmosphere for testing the adaptive optics system.

## 5. Results

Using the continuously varying splining technique in the IDL software for controlling applied phase screens, the atmospheric turbulence generator is capable of producing aberrations at a refresh rate of up to 33 Hz, which is the fastest the SLM can update. Future efforts may include using faster and more capable devices.

Using the optical setup in Figure 2, sample atmospheric conditions have been calculated and put on the SLM and then measured with an imaging camera. The simulated atmospheric turbulence was calculated for a 1.0 meter telescope with seeing conditions having an  $r_0$  of 20.0 cm, 10.0 cm and 5.0 cm. The results are shown in Figure 6, with the ideal unaberrated point spread function (PSF) on the far left. With a  $D/r_0$  of 5, the variation from round of the PSF is minimal, but noticeable, as shown in the top image. The middle image shows a  $D/r_0$  of 10 indicating more turbulence cells across the aperture and a more aberrated PSF. The bottom image indicates a  $D/r_0$  of 20 where seeing conditions would be beyond the capabilities of many AO systems to correct. The PSFs in this case are extremely aberrated.





**Figure 6** – Point spread functions for various aberrations: (Top) ideal case on left,  $D/r_0=5$ ; (Middle) ideal case on left,  $D/r_0=10$ ; (Bottom) ideal case on left,  $D/r_0=20$

## 6. Summary

This paper reports and describes the development of a testbed that simulates atmospheric aberrations using a Liquid Crystal Spatial Light Modulator using the standard Kolmogorov model for the atmospheric aberrations. This system allows the simulation of seeing conditions ranging from very poor to very good and these aberrations may then be used to test the performance and abilities of any corrective element or entire AO system. Future efforts will include the use of faster devices and/or devices with more resolution.

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