

Deep Horizontal Atmospheric Turbulence Modeling and Simulation with a Liquid Crystal Spatial Light Modulator

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Abstract

We investigate the performance of a Liquid Crystal (LC) Spatial Light Modulator (SLM) as an optical device for generating high intensity atmospheric turbulence in the laboratory. The experimental setup represents long range horizontal beam propagation at a low altitude where the conditions of atmospheric turbulence can be most severe. WaveProp is a software package written by the Optical Sciences Company (tOSC) which is used for simulating electro-magnetic field propagation through equally spaced phase screens. This simulation tool provides the cumulative amplitude and phase modulation input signals to a single LC SLM. An SLM is configured at the Naval Postgraduate School (NPS) Adaptive Optics Center of Excellence to modulate both amplitude and phase simultaneously. The SLM reproduces large amplitude fluctuation with branch points and branch forks from the deep turbulence models. Deep horizontal path laser propagation reported herein is modeled and simulated in the NPS laboratory to provide realistic optical disturbances for an adaptive optics wavefront correction system.

Introduction

In order to test an adaptive optic systems being developed at the Naval Postgraduate School (NPS), a Liquid Crystal (LC) Spatial Light Modulator (SLM) is being used to generate atmospheric turbulence in the laboratory on a laser beam. Using a LC SLM in combination with software that generates atmospheric turbulence gives the flexibility to simulate different atmospheric conditions and path lengths in the laboratory. In addition, measured turbulence data can be used to “play back” real-world scenarios to recreate atmospheric conditions in the laboratory for device testing and evaluation. The Boulder Nonlinear Systems (BNS) LC SLM used in our laboratory has a 512x512 pixel format with 15x15 μm /pixel pitch, and can operate at 1kHz. In this experiment, we have configured the LC SLM to impart amplitude and phase on the laser beam simultaneously. Many other research institutions have performed similar tests with phase-only devices. Research at NPS has included modeling atmospheric turbulence including scenarios in a maritime environment and simulating atmospheric turbulence in our laboratory.^{1,2} Research has also been performed in the generation of aberrations with LC devices for simulating turbulence in other institutions³⁻⁶.

Software simulation parameters

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In order to test the LC SLM, a WaveProp turbulence simulation was performed with $C_n^2 = 8 \times 10^{-15} m^{-2/3}$, 4 km propagation range, 30 cm receiver diameter, 1 μm wavelength, 5 phase screens (equally spaced), 2048×2048 propagation array size, x4 Fresnel scale factor, and 5 m/s wind velocity. A Rytov value of 0.35 was obtained for the turbulence generation, assuming a point source target. The WaveProp generated amplitude and phase are shown in Figure 1. This resultant amplitude and phase is what will be applied to the SLM located at a pupil to simulate atmosphere in the laboratory.

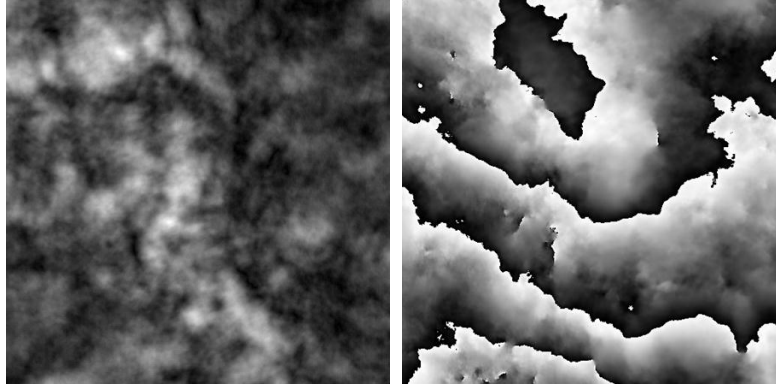


Figure 1. Amplitude and phase simulated

The optical setup

The optical setup shown in Figure 2 is a Mach-Zehnder interferometer set up to characterize the LC SLM⁷. A linearly polarized beam at 45° enters a polarizing beam splitter (PBS1) and the reflected beam is sent to another polarizing beam splitter (PBS2) which reflects light to the BNS LC SLM which rotates the orientation of the linearly polarized beam pixel-by-pixel. At each pixel the device acts like a half wave plate with a voltage controlled rotation of the optical axis (polarization rotator).⁸ The light reflected from the LC SLM goes to a polarizing beam splitter (PBS2) transmitting the light that was rotated by the LC SLM. Using LC SLM, we create a grating in which we vary spatially to introduce the phase modulation in the first order diffracted beam and vary the contrast of the grating to modulate the amplitude. An iris at the focal point of the beam is used to select the first order of the diffracted beam. The re-collimated beam enters the beam splitter (BS) which is combined with the reference beam to produce an interference pattern on the camera.

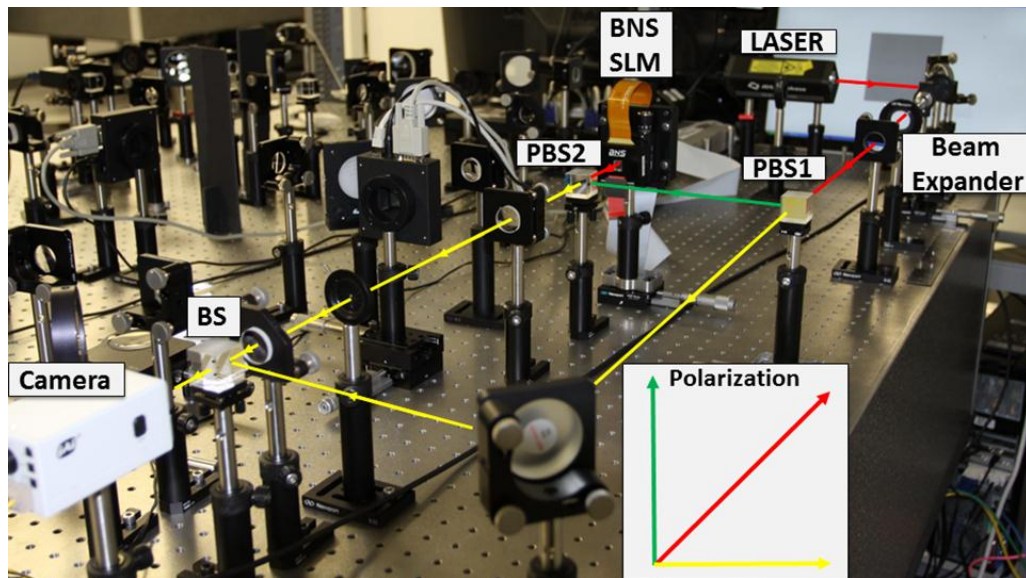


Figure 2. NPS laboratory optical layout with LC SLM

Using the SLM to put Phase on the beam

The phase generated for the atmospheric propagation simulation shown Figure 1 was used to create the image on the left of Figure 3. This was applied to the LC SLM and the measured interferogram is shown on the right of Figure 3. In the interferogram, we can see the branch forks caused by branch points in the phase. The LC SLM is not fully illuminated but the LC SLM is reproducing multiple branch points that were in the phase simulated by WaveProp.

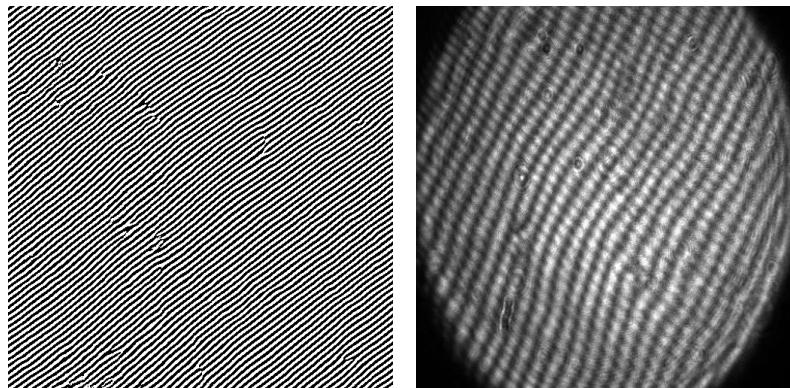


Figure 3. (Left) Simulated phase only applied to LC SLM device (Right) interferogram

Characterizing the LC SLM to change the beam's irradiance

The reference beam was blocked to look at the irradiance of the beam reflected from the LC SLM. The top two images in Figure 4 show the image applied to the LC SLM. The bottom two images are the camera images of the reflected beam from the LC SLM. The irradiance on the camera image is changed by adjusting the contrast in the images applied to the LC SLM. Low contrast leads to low irradiance and large contrast leads to a high irradiance.

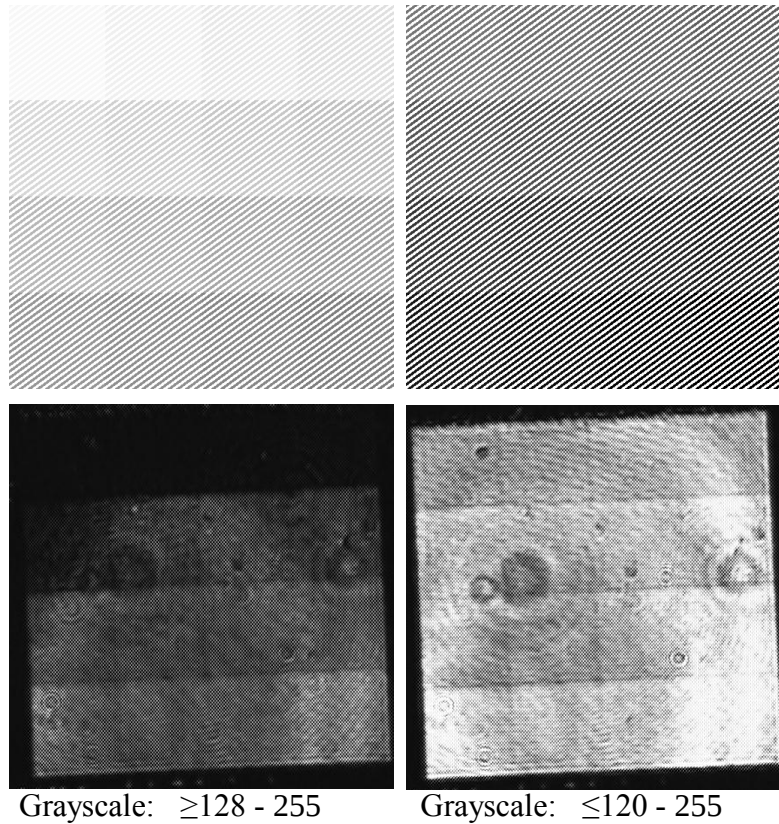


Figure 4. LC SLM amplitude characterization and response

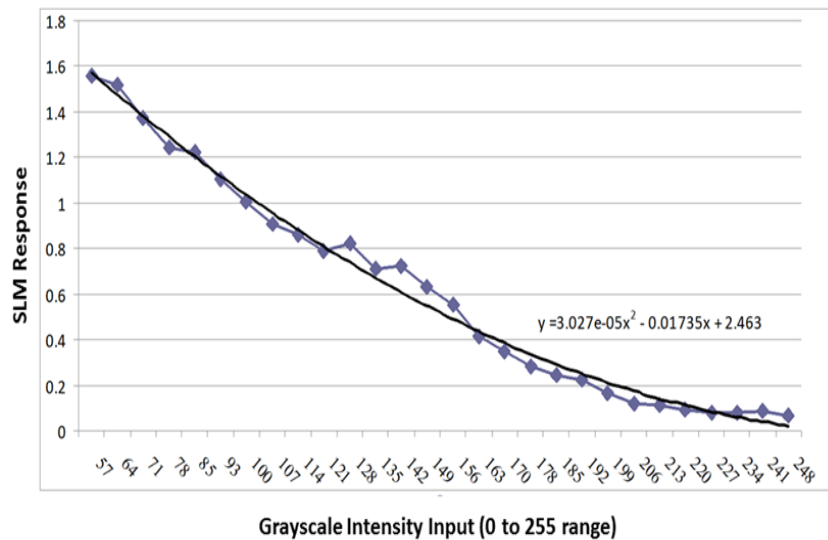


Figure 5. LC SLM amplitude response calibration

Figure 5 shows how the irradiance is changed as the contrast is varied. The grating being generated by the LC SLM is created by sending two values: 255 and the value on the x-axis of the plot. For the two values of 255 and 248 (which would be the top left sections in the two left images in Figure 4) a result in low contrast and low irradiance is

observed. For two values of 255 and 57 (which would be the bottom right sections in the two right images of Figure 4) a result in high contrast and high irradiance is observed.

Atmospheric simulations with the LC SLM

The first image in Figure 6 is the amplitude generated by a WaveProp simulation, the second image is what is sent to the BNS LC SLM, the third image is the measured pupil plane irradiance and the fourth image is the interferogram. Looking at first image and the third image in Figure 6 we can see that the LC SLM is not fully illuminated but the pupil amplitude calculated by WaveProp is being applied to the laser beam by the SLM. The interferogram on the right of Figure 6 is showing the measured phase the device applied to the beam.

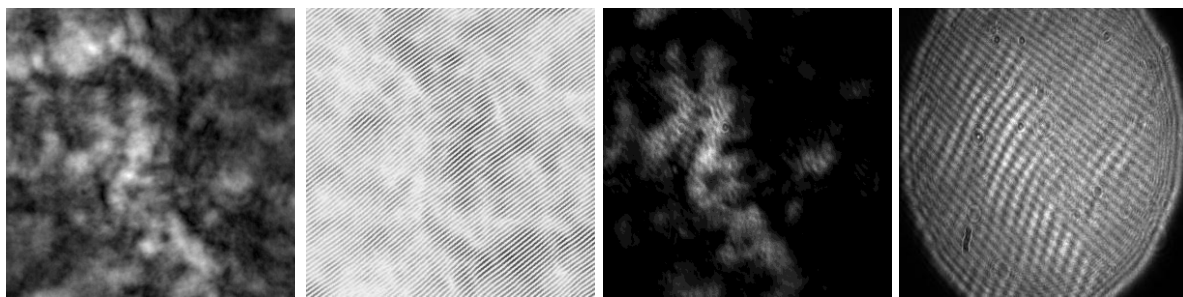


Figure 6. (Left) Amplitude from simulation, (center left) image sent to LC SLM, (center right) measured pupil plane irradiance, and (right) interferogram.

Future plans

This device has been integrated into an AO testbed at NPS and will be used to test AO performance for a variety of atmospheric conditions and path lengths⁹. Further characterization of the device is also planned. In addition to applying simulations onto the device in the laboratory, measurements of atmospheric turbulence in different scenarios are being obtained to also apply to the device in the laboratory for comparison and testing.

Conclusions

Initial results have been presented showing that an LC SLM can recreate the pupil plane amplitude and phase generated by WaveProp simulating a 4km range with 5 phase screens. This device is going to be used to generate atmospheric turbulence in the laboratory to test an AO system being developed at the NPS.

Acknowledgments

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