Deep-Turbulence Simulation in a Scaled-Laboratory Environment Using Five Phase-Only Spatial Light Modulators

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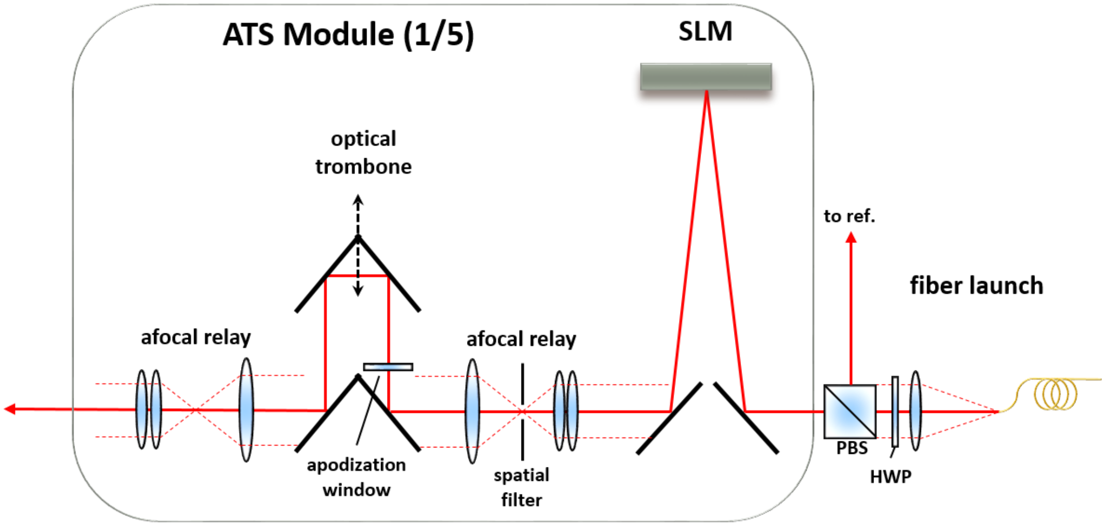
Abstract: The presence of distributed-volume or "deep" turbulence presents unique challenges for beam-control applications which look to sense and correct for disturbances found along the laser-propagation path. This study uses five spatially distributed phase-only reflective spatial light modulators (SLMs) to accurately model deep-turbulence effects. In practice, we can match the Fresnel numbers for tactical engagement scenarios using optical trombones and relays placed in between the SLMs. Similar to computational wave-optic simulations, we can also command repeatable high-spatial-resolution phase screens to the SLMs with the proper statistics (i.e., Kolmogorov, von Karman, etc.).

Keywords: Deep turbulence, Wavefront sensing, Digital holography, Pupil-plane recording geometry, Branch points and cuts, Atmospheric turbulence characterization, and Spatial heterodyne interferometry

1. Introduction

Coherent-light propagation through deep turbulence causes scintillation, which manifests as non-uniform, time-varying irradiance coupling between the object and receiver planes. The Rytov number (also referred to as the log-amplitude variance) gives a measure for the strength of scintillation experienced. As the scintillation becomes severe (i.e., for Rytov numbers greater than ~0.25), this coupling gives rise to branch points in both the coherent light transmitted to the object as well as the coherent light received from the object. These branch points add a rotational component to the phase function that traditional-least-squares reconstruction algorithms cannot account for. As such, the rotational component is often referred to as the hidden phase (thanks to the foundational work of Fried [1]). The existence of branch points leads to unavoidable 2π phase discontinuities in the phase function. Because of inter-actuator coupling, continuous-face sheet deformable mirrors (DMs) are unable to fully compensate for the branch cuts. Thus, in the presence of moderately deep turbulence (i.e., for Rytov numbers greater than ~0.5), the corresponding branch-point problem tends to be the "Achilles' heel" to current beam-control solutions [2].

To accurately simulate deep-turbulence conditions in a scaled-laboratory environment, AFRL/RD teamed with Guidestar Optical Systems, Inc. to develop an atmospheric turbulence simulator (ATS). As shown in Fig. 1, the developed ATS uses five spatially distributed phase-only reflective spatial light modulators (SLMs). In practice, we can match the Fresnel numbers for tactical engagement scenarios using optical trombones and relays placed in between the SLMs. Similar to computational wave-optic simulations [3, Chapter 9], we can also command repeatable high-spatial-resolution phase screens to the SLMs with the proper statistics (i.e., Kolmogorov, von Karman, etc.). Because the framerates for commercial-off-the-shelf (COTS) SLMs are on the order of 150 Hz for visible light, this laboratory setup is appropriate for scaled-time demonstrations, where we develop the reconstruction algorithms in software, and demonstrate closed-loop performance at approximately 1-10 Hz with affordable COTS hardware for the wavefront sensor (WFS) and DM. Since deep turbulence conditions can provide Greenwood frequencies on the order of 1 kHz, this scaled-time laboratory setup does not allow for real-time demonstrations; however, it does provide a flexible test bed in which to test novel beam-control solutions.



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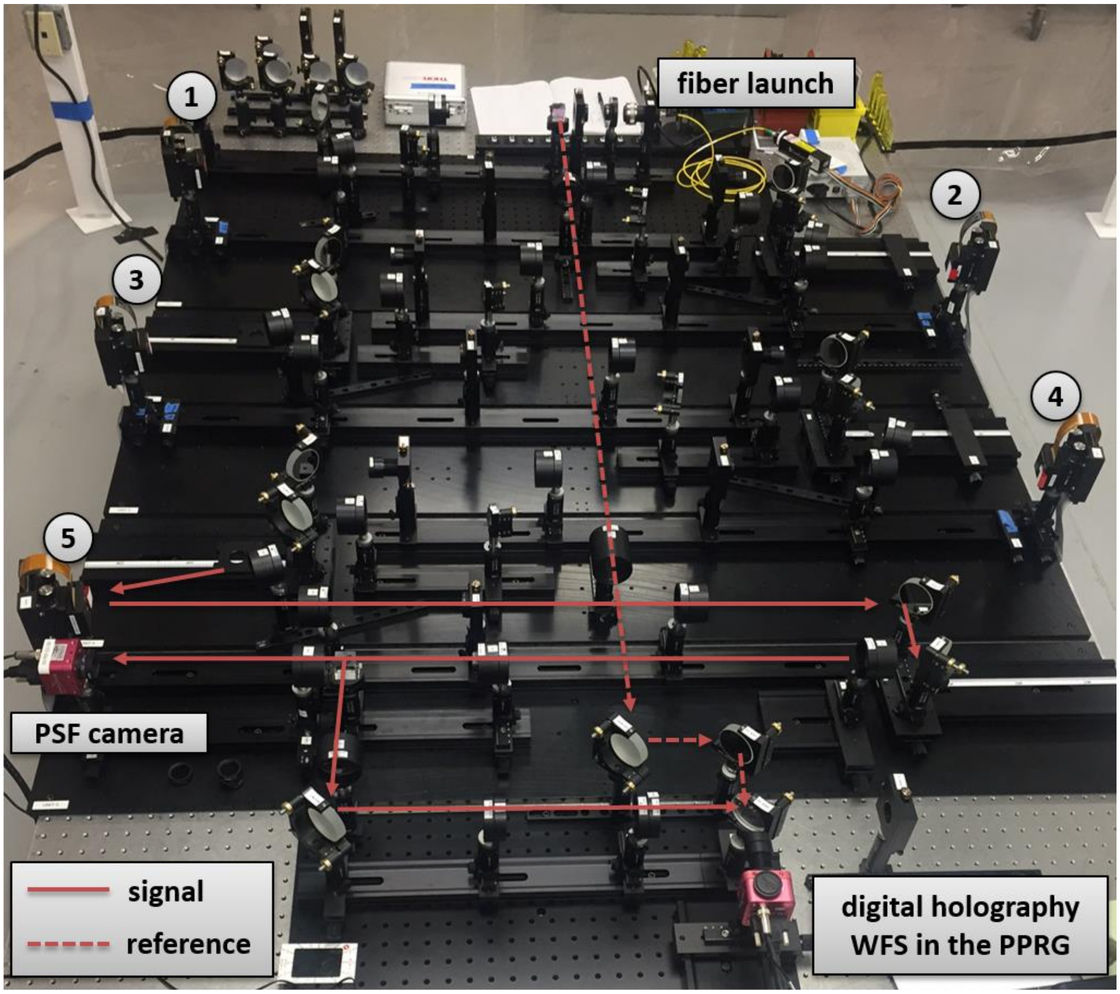

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Figure 1. The atmospheric turbulence simulator (ATS) within the Phasor Laboratory at AFRL/RDL uses five modules in series with spatial light modulators (SLMs) to simulate deep-turbulence effects.

2. Demonstration

Included with the ATS is a digital holography (DH) WFS in the pupil-plane recording geometry (PPRG). This instrument allows for the characterization of the simulated deep-turbulence effects and the demonstration of various beam-control concepts. For example, Fig. 2 shows snapshots of the developed ATS GUI for simulated turbulence conditions where $D/r_0 = 4$. Note that we can command repeatable high-spatial-resolution phase screens to the SLMs contained within the ATS and can also calculate the least-squares (LS) estimated phase from the DH WFS in the PPRG. Specifically, in Fig. 2a, the 5th SLM is commanded to flat so that the DH WFS is operating in an open-loop configuration, whereas in Fig. 2b, the 5th SLM is commanded to a phase correction based on a leaky integrator control law. In the latter configuration, the residual wavefront error is nearly nulled. This result is indicative of an adaptive-optics system operating in null-seeking control loop or a closed-loop configuration.

In this particular demonstration [cf. Fig. 2], we positioned the optical trombones of the ATS, so that all of the SLMs were conjugate to each other and the pupil of the DH WFS. In practice, we can use the ATS GUI to calculate the appropriate positions of the optical trombones, so that we can distribute the SLMs all along the propagation path of the collimated single-mode fiber launch. This key feature is what allows us to match the Fresnel numbers for tactical engagement scenarios in a scaled-laboratory environment.

3. Future work

For all intents and purposes, the leading WFS architectures for beam-control applications include the Shack-Hartmann (SH) WFS, the self-referencing interferometer (SRI) WFS, and the DH WFS. This is because they each offer an appropriate amount of functionality within the engineering trade space. With respect to the SH WFS, direct detection through a lenslet array offers both light efficiency and an estimate of the phase function through slope measurements. Traditional-least-squares reconstruction algorithms is what provides this estimate; however, in the presence of branch points and the associated branch cuts, these algorithms fall short. Branch-point-tolerant reconstruction algorithms for the SH WFS do exist [4], but these algorithms need to be tested in hardware to fully quantify performance. On the other hand, interferometric WFSs, such as the SRI WFS and the DH WFS, provide access to an estimate of the amplitude and the wrapped phase (i.e., the complex optical field). This wrapped-phase estimate directly contains information about the branch points and the associated branch cuts; however, in commanding a DM through traditional-least-squares reconstruction algorithms, one does not exploit this information. Branch-point-tolerant reconstruction algorithms do exist which exploit the wrapped-phase estimate [5], but once again, these algorithms need to be tested in hardware to fully quantify performance. Furthermore, the SNR gains in using coherent detection with DH versus direct detection with the less-light-efficient (compared to the SH WFS) SRI also needs to be quantified in hardware.

Future work will take on all of these hardware demonstrations using the flexible laboratory test bed described above. Such a head-to-head comparison of existing beam-control technology will not only inform future applications of interim capabilities (with respect to the deep-turbulence problem defined above), but it will also lead to real-time hardware demonstrations.

4. References

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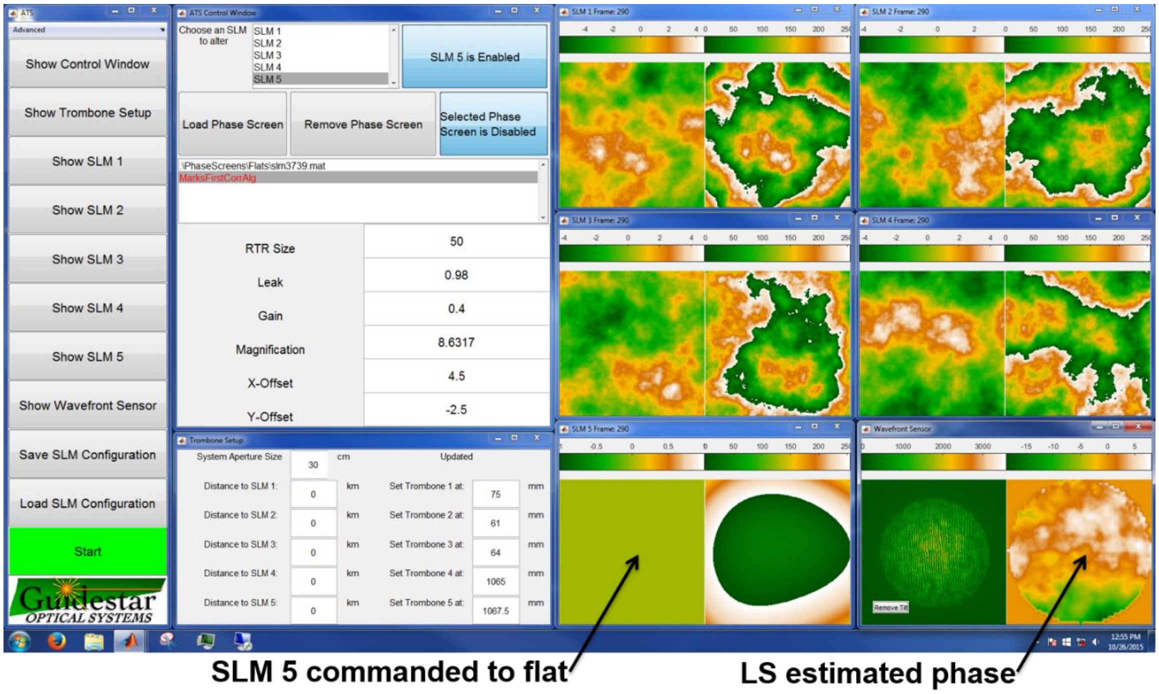

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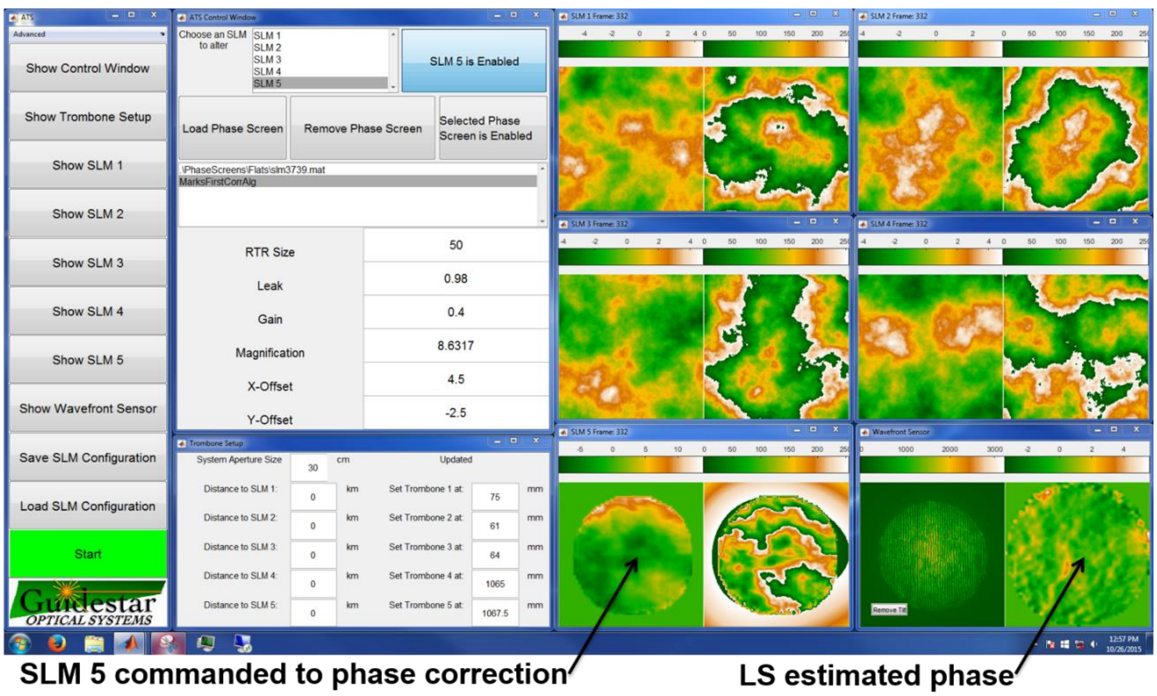

(b)

Figure 2. Open- and closed-loop demonstrations using the atmospheric turbulence simulator (ATS) GUI.

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