Experimental Verification of Correlation-Based Wavefront Sensing

This project has explored the use of a correlation-based algorithm for wavefront sensing in a wide range of scenarios. Wavefront sensing is a technique by which the phase aberration (or, more typically, its gradient) is measured in an optical system. These measurements can be used in real time in an adaptive optics (AO) system to reduce the residual error and improve performance. In the case of an imaging system, the wavefront sensor (WFS) measurements can also be used in a postprocessing scheme.

In our first year, we showed the benefits of correlation in AO systems that used a point source that was either noisy or suffered from distortion. We also did initial experimental tests of correlation-based wavefront sensing in the remote-imaging scenario. In that case, no point source (such as a laser) is available for the WFS and instead the target itself is used. We established baseline requirements for SNRs and scene content. Such remote imaging is done in difficult conditions; the atmosphere along short horizontal or slant paths greatly reduces image quality. Scene-based wavefront sensing (so termed because of the use of the scene that is observed) could facilitate either real-time AO or improved image-processing techniques for surveillance applications.

Project Goals

In FY2005 our goal was to determine how a scene-based WFS can be used in a remote-imaging system to lead to improved imaging performance. We investigated the use of the scene-based WFS information in a range of established methods, including AO and the postprocessing techniques of speckle imaging and deconvolution.

Relevance to LLNL Mission

AO is an area of expertise at LLNL. This project will further extend LLNL capabilities in AO applications. Remote imaging is an important area for national security applications.

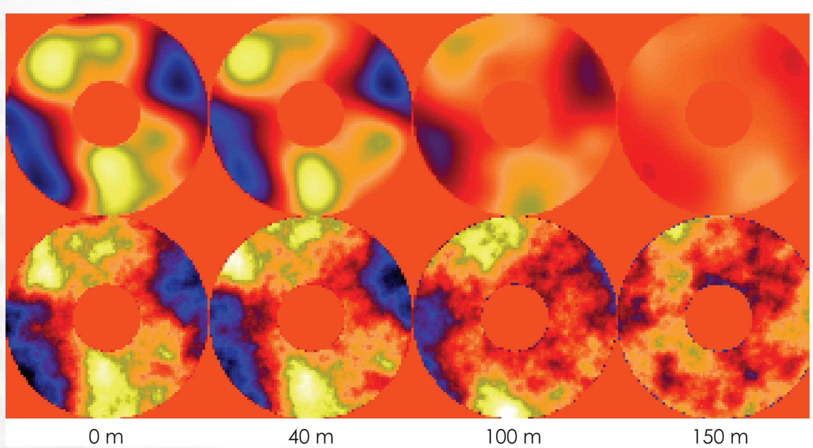
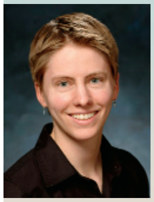


Figure 1. Reconstructed phases from scene-based WFS in wave-optics simulation along 200-m path. Top row: reconstruction. Bottom row: true phase. The turbulence is at the indicated distance from the telescope pupil.



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FY2005 Accomplishments and Results

It is necessary to verify that under distributed turbulence, the WFS measures the correct phase. Our wave-optics simulations have allowed us to determine that as the turbulence moves farther from the pupil, the aniso-planatism in the scene itself reduces both the resolution and the gain of the WFS measurement of the phase. Figure 1 shows phase reconstructions as the turbulence moves back from the pupil on a 200-m path.

Even with correct phase information, AO is limited, due to its use of phase conjugation. A single-mirror AO system will produce a small region of correction on-axis or a larger field with a low level of correction. A multi-mirror system has the potential to provide a wider field, but at significant complexity and cost. Instead, postprocessing techniques that provide much wider fields should be used.

As a baseline for postprocessing techniques, we consider the speckle-imaging technique, established for the remote-imaging scenario. This technique uses a series of short-exposure images for the average phase aberration. We augment this technique by using more detailed atmospheric information as obtained from the scene-based wavefront sensing. This extra information allows speckle to not depend on a model, and allows operation with fewer frames and in non-typical conditions.

The second technique for post-processing is deconvolution with WFS data. This is an established image-processing technique that undoes the convolution of the object with the optical transfer function, which blurs the image. Simulations show that even low-order WFS measurements can lead to good deconvolutions. Deconvolution performance is comparable to speckle performance when accurate information about the PSF across the field is used.

We tested this approach in our experimental telescope set-up and verified that a scene can provide accurate phase information and significantly improve image quality. We observed on a 75-m horizontal path over asphalt and took twelve 1-ms exposures. Figure 2 shows a portion of a WFS CCD image with the shamrock used as the scene. Figure 3 shows the shift-and-add image of the nearby resolution target and the restored image, after deconvolution with the WFS information.

Related References

1. Poyneer, L. A., D. W. Palmer, K. N. LaFortune, and B. Bauman, "Experimental Results for Correlation-Based Wavefront Sensing," Invited Paper, *Proc. SPIE 5894, Advanced Wavefront Control: Methods, Devices, and Applications III*, M. T. Gruneisen, J. D. Gonglewski, and M. K. Giles, Eds., pp. 58940N 2005.
2. Poyneer, L. A., "Scene-Based Shack-Hartmann Wavefront Sensing: Analysis and Simulation," *Appl. Op.*, **42**, pp. 5807-5815, 2003.
3. Poyneer, L. A., K. LaFortune, and C. Chan, "Scene-Based Wavefront Sensing for Remote Imaging," *Proc. SPIE 5162, Advanced Wavefront Control: Methods, Devices, and Applications*, J. D. Gonglewski, M. A. Vorontsov, and M. T. Gruneisen, Eds., pp. 91-102, 2003.

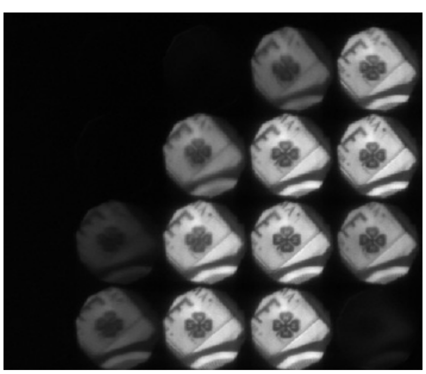

Figure 2. Portion of WFS CCD image from experiment. The shamrock is successfully used for scene-based wavefront sensing.

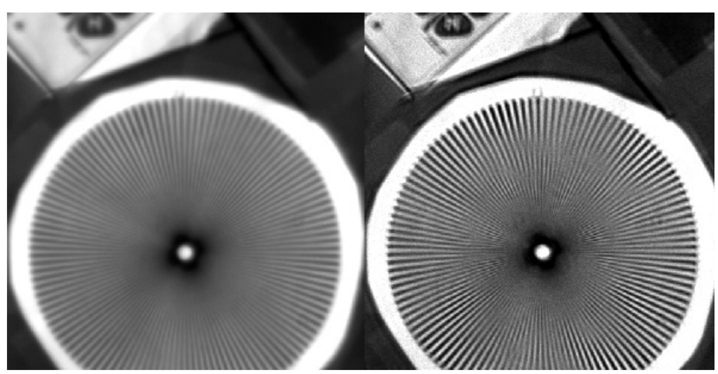

Figure 3. Left: shift-and-add image of resolution target near the shamrock. Right: image deconvolved with scene-based WFS data. This technique improves target contrast and resolution.