

AOS Hartmann Wavefront Code Verification

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After creating the first version of the wavefront sensor software, we evaluated its performance in the laboratory using lenses to vary the input wavefront curvature. When this was working well, we sought to evaluate the software functionality on higher-order aberrations. Since we could not easily create the required aberrations in the laboratory using conventional optics, we decided to create simulated Hartmann sensor images.

We used Matlab to generate the simulated images. The image generation script generates an arbitrary aberration, averages the wavefront derivative over the Hartmann sensor sub-apertures, and then generates a simulated image using Gaussian focal spots. These images were generated for a set of the lowest-order Zernike polynomials in a variety of different amplitudes. We decided to limit our output to a circle that just fit onto the Hartmann sensor since Zernike polynomials are only orthogonal over the unit circle. The parameters of the Hartmann sensor we simulated are summarized in Table 1. These images are available for others to evaluate on the AOS web site.

Table 1 - WFS Parameters Used for Simulated Hartmann Sensor Images

| Parameter | Value |
|-----------------------------|---------------------------|
| Screen to Camera Separation | 7 mm |
| Pixel Sizes | 14.5 μm square |
| Pixel Resolution | 320 x 240 |
| Pixels per Sub-Aperture | 20 pixels square |
| Zernike Radius | 1.74 mm |

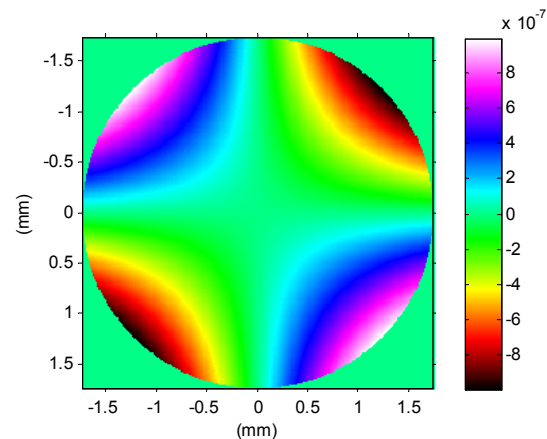
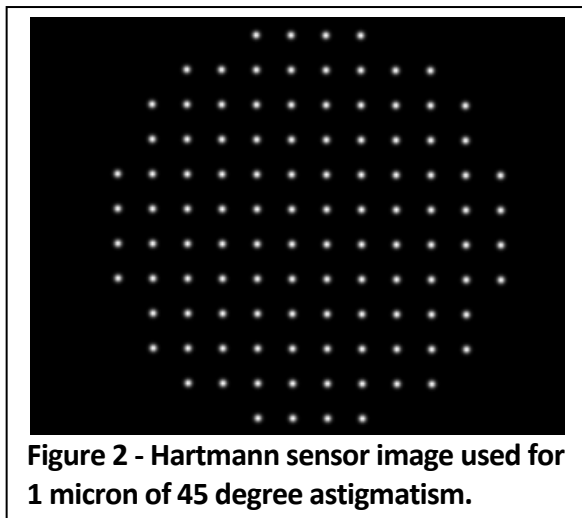


Figure 1 - High resolution false-color plot of the phase of 1 micron of 45-degree astigmatism

After generating the simulated images, we wrote Matlab code with the exact same algorithms we implemented in the AOS wavefront sensor code and then analyzed all the images. Figure 1 shows the high resolution phase profile we use for 1 micron



of 45 degree astigmatism (Zernike #5 where piston is 0). Figure 2 shows the raw wavefront sensor image data that was generated based on this aberration.

Figure 3 shows the wavefront that was reconstructed by analyzing the image in Figure 2 relative to a nominal flat reference. Although low resolution, this reconstructed wavefront is clearly 45-degree astigmatism. Figure 4 shows the Zernike decompositions of

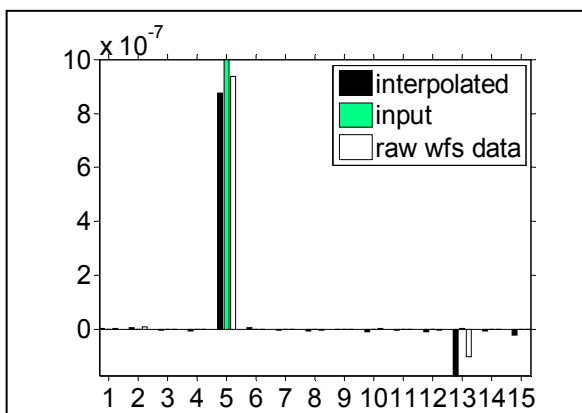
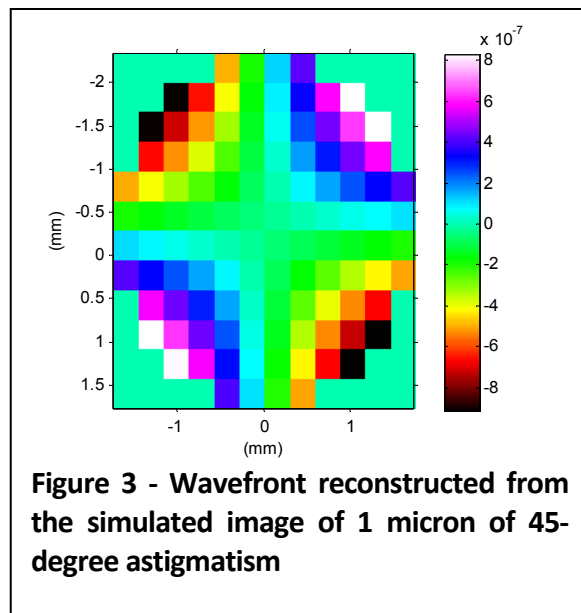
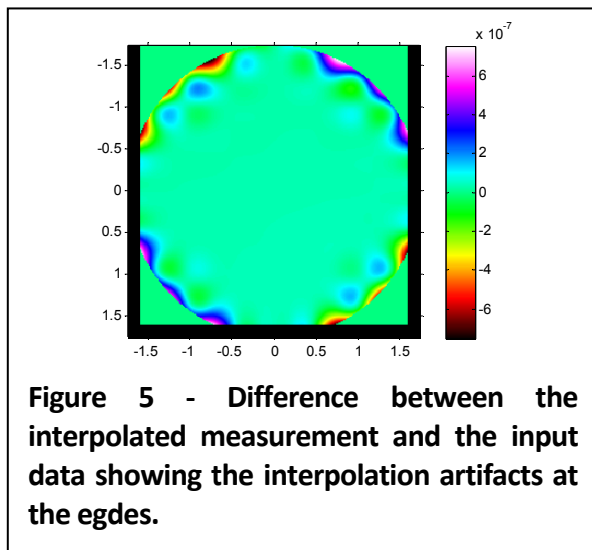


Figure 4 - Zernike decomposition of the input high-resolution wavefront (input), the raw low-resolution measured wavefront data (raw wfs data), and the measured wavefront interpolated onto a higher resolution grid (interpolated).



the high resolution (240x240, 14.5µm pixel grid) input aberration (input), the low-resolution raw wavefront sensor data (raw wfs data), and the raw wavefront sensor data interpolated onto the same grid as the high-resolution data.

One of the most interesting things about the Zernike decompositions is that the interpolated data always had worse matching to the input aberration than the raw wavefront sensor data. This is primarily due

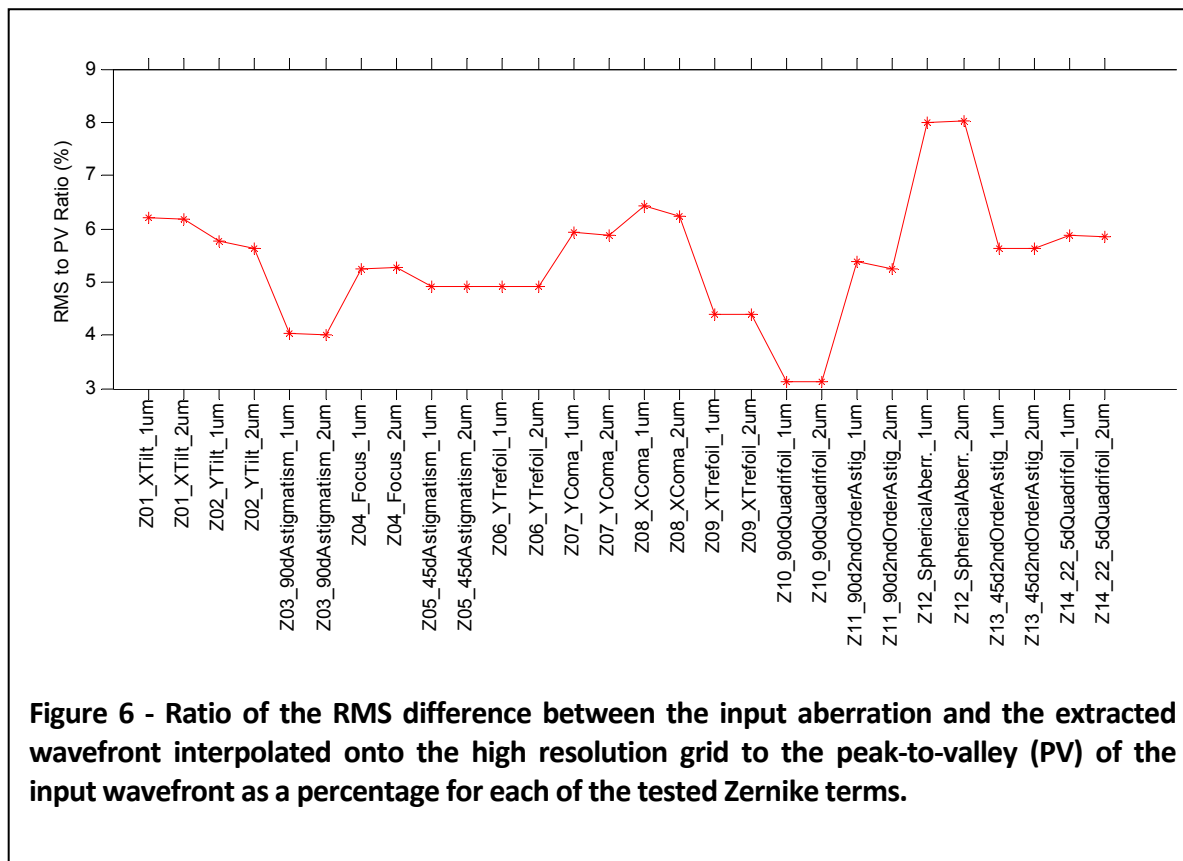


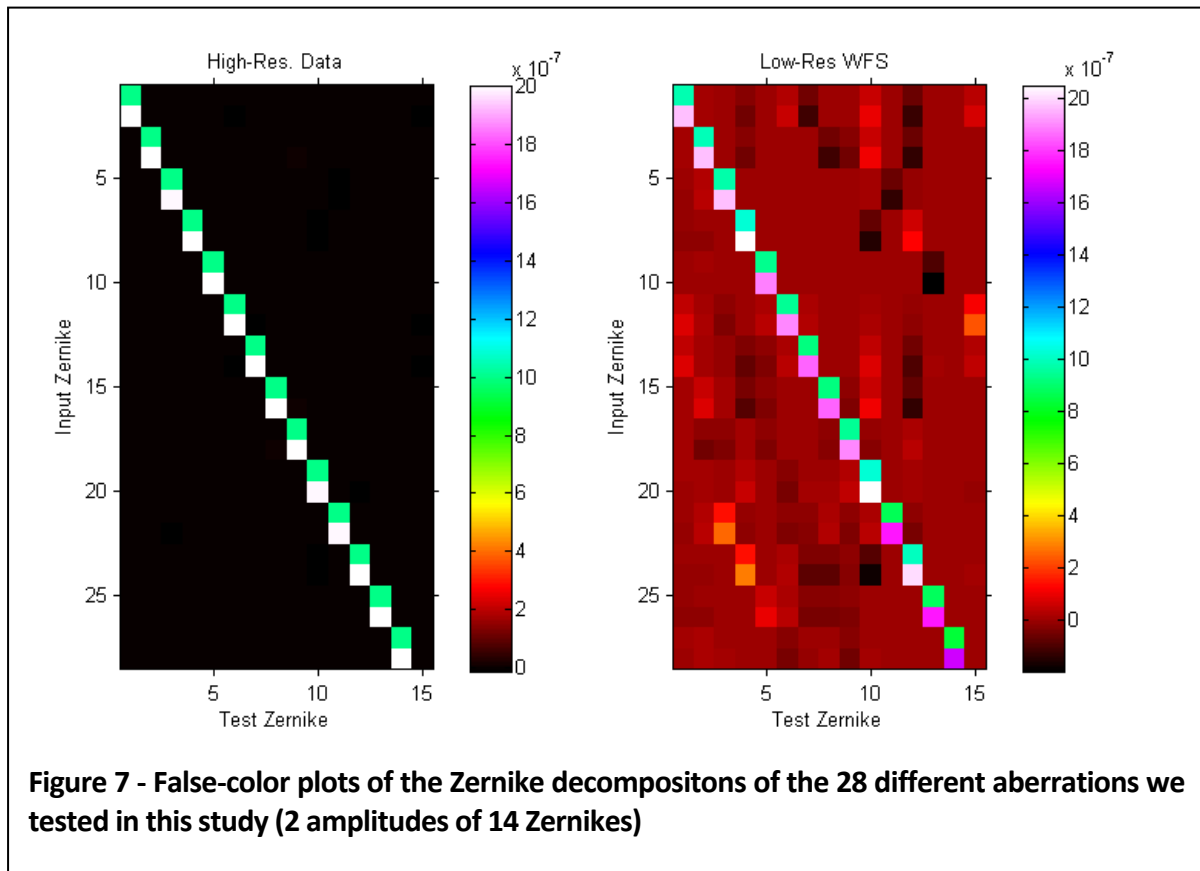
to the edges of the interpolated data being a poor representation of the data, as is shown in Figure 5. We tried every standard interpolation technique available in Matlab, but all of them were similar in behavior. There may be a better way to interpolate the edges to achieve better matching, but we decided to use the raw data for the Zernike decomposition instead of investigating new interpolation techniques.

We repeated this analysis for Zernikes 1 to 14 (Zernike 0 was piston) using a N then L ordering of the Zernikes. We calculated the RMS difference between the high resolution input wavefront and the reconstructed wavefront interpolated onto the high-resolution grid. Figure 6 shows an analysis of all the aberrations we studied for both 1 and 2

μm amplitudes. Clearly some of the aberrations were better measured on the wavefront sensor sub-aperture grid, but in no case did the RMS to PV ratio exceed 9% and on average was 5.4%. Since the differences were largest at the edges due to the interpolation artifacts, we also did this analysis looking only at the RMS over a radius equal to 85% of the Zernike radius and found that the mean was only 1.6%.

We also decomposed all the measured wavefronts into Zernike terms, again using an overlap integral technique on the reconstructed wavefront. Figure 7 shows false-color plots of the decomposition of the input aberration, which is nearly diagonal, and the reconstructed low-resolution wavefront, which has small non-zero off-axis terms. The





non-zero off-axis terms are primarily due to the resolution of the wavefront sensor being quite low (112 sub-apertures).

Conclusions

In this application note, we showed that the techniques we are using for reconstructing the data and doing Zernike decomposition are valid and producing expected results. As part of this analysis, we generated a set of simulated wavefront sensor images that can be used for verification of other wavefront sensors in the future. We hope to continue this line of analysis in the future with more rigorous error analysis.