ACTIVE OPTICAL SYSTEMS

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Hartmann Wavefront Sensor Characterization

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Hartmann wavefront sensors (HWFS) measure the derivative of the spatial phase of a beam of light by segmenting the beam into an array of rays using an aperture array and measuring the displacement of the diffracted spots relative to a reference location. In the lab, optical engineers want a device that measures the spatial phase of a beam of light, not the derivative. Devices like interferometers that measure the spatial phase nearly directly are relatively easy to characterize. Since there are many different numerical methods that convert the measured derivative of the spatial phase to the spatial phase, it is difficult to devise a simple method of characterizing the ability of a HWFS to measure the spatial phase.

In this application note, we present here a method of characterizing the performance of a HWFS that is easily implemented in a moderately well equipped laboratory without any special equipment. Figure 1 shows the optical setup used when making this measurement. First laser light is expanded from in a two lens telescope, often with a pinhole at the focus of the first lens, so that the beam is much larger than the HWFS input aperture. Expanding the beam creates a fairly uniform intensity profile at the HWFS input aperture. The second lens in the telescope is placed on a translation stage so that the distance between the lens and the focus (or pinhole) can be varied. Varying this distance allow control over the wavefront curvature.

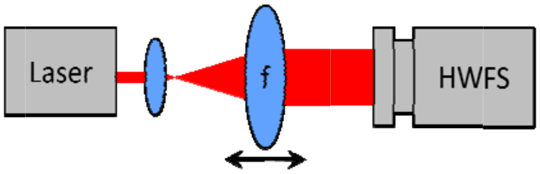

Figure 1 - Optical Setup for Hartmann wavefront sensor calibration

We employed this setup to make a series of measurements with a calibrated wavefront sensor with a 320 x 240 pixel grid of 14.5 µm pixels behind a Hartmann array with 83 µm apertures on a 332 µm grid with a separation between the aperture array and the camera of 6.5 mm. We used a 633 nm laser for this experiment. The first measurement was of the noise when measuring a nominally flat wavefront. The HWFS was illuminated with a collimated beam and a reference was created based on an intensity average using the same number of frames that we were using to take the data. We were subtracting the average slope, but not filtering the slopes based on the RMS. The relative threshold was 0% and the absolute threshold was 30 counts. The separation between the Hartmann array and the imager was 6527 microns. There was an array of 13x10 sub-apertures being illuminated.

A series of measurements were made with varying number of frames of intensity averaging. We reconstructed the wavefront using the Southwell reconstructor described in the AOS Wavefront Sensor Manual. To obtain an average performance of the wavefront sensor, we averaged data from 20 different individual experiments for each point.

Table 1 shows the results of these experiments. We found that in our lab setup the drift of experimental setup was limiting the potential for many frame averaging to be effective in consistently reducing the noise. Therefore, there was an optimum number of averages at 10 frames.

Table 1 - Flat Wavefront Noise Study

Axis	Intensity Averaging (frames)	RMS Slope (µrads)	RMS Wavefront (nm)
X	None	119	68.3
Y	None	78.6	-
X	10	66.8	33.5
Y	10	55.4	-
X	100	100	51.2
Y	100	77.2	-

We did one more experiment to evaluate the wavefront sensor sensitivity in which we evaluated the ability of the sensor to measure wavefront curvature by fitting the slopes for varying amounts of wavefront curvature. To accomplish this we moved the 500-mm focal length collimating lens in 0.1” steps over 1.0” range after creating an intensity averaged reference using 100 frames with the input wavefront 0.5” from the collimated position so that the output beam was diverging. This corresponded to the -0.5” position in the data. In the AOS software, diverging wavefronts are reported as positive curvature. At each of the lens displacements, we took 10 measurements of the wave curvature with no intensity frame averaging and then averaged the curvature in diopters (1/m) to create an average radius of curvature.

Table 2 and Figure 2 show the results of this experiment. We found that there were some measurements that were significantly off from where we expected them to be in the Y-axis, but the X-axis was significantly better. When the X and Y-axis radius of curvature values were averaged, the resulting average radius of curvature that was measured quite accurately matched the theoretical values, especially when the wavefront curvature was relatively large. According to theory, the peak-to-valley wavefront amplitude, given by $\phi_{PV} = r_{MAX}^2/(2R)$, where R is the radius of curvature and r_{MAX} is the maximum aperture radius considered (5.5 mm in this case) is only 376 nm for the largest wavefront curvature (9.8 m). This is only a factor of 10 from the RMS wavefront error demonstrated in the previous experiment for 10-frame averaging.

Table 2 - Fit Slopes Curvature vs Lens Displacement

Lens Displacement (inches)	X Radius of Curvature (m)	Y Radius of Curvature (m)	Average Radius of Curvature (m)	Theory Predicted Curvature (m)	Error in ROC (%)	Theory Sagittus (nm)
-0.5	-795.7	-252.4	-524.0	Infinite	-	0
-0.4	-350.6	-51.0	-200.8	-98.4	10.6	37.7
-0.3	-97.6	-26.1	-61.9	-49.2	19.5	75.3
-0.2	-37.5	-26.7	-32.1	-32.8	5.2	113
-0.1	-24.7	-58.2	-41.5	-24.6	29.1	151
0.0	-17.0	-17.5	-17.3	-19.7	14.0	188
0.1	-16.7	-13.4	-15.1	-16.4	10.12	226
0.2	-13.2	-19.0	-16.13	-14.1	9.9	264
0.3	-8.82	-13.0	-10.9	-12.3	17	301
0.4	-8.40	-12.5	-10.5	-10.9	8.6	339
0.5	-8.07	-11.5	-9.8	-9.8	3.6	376

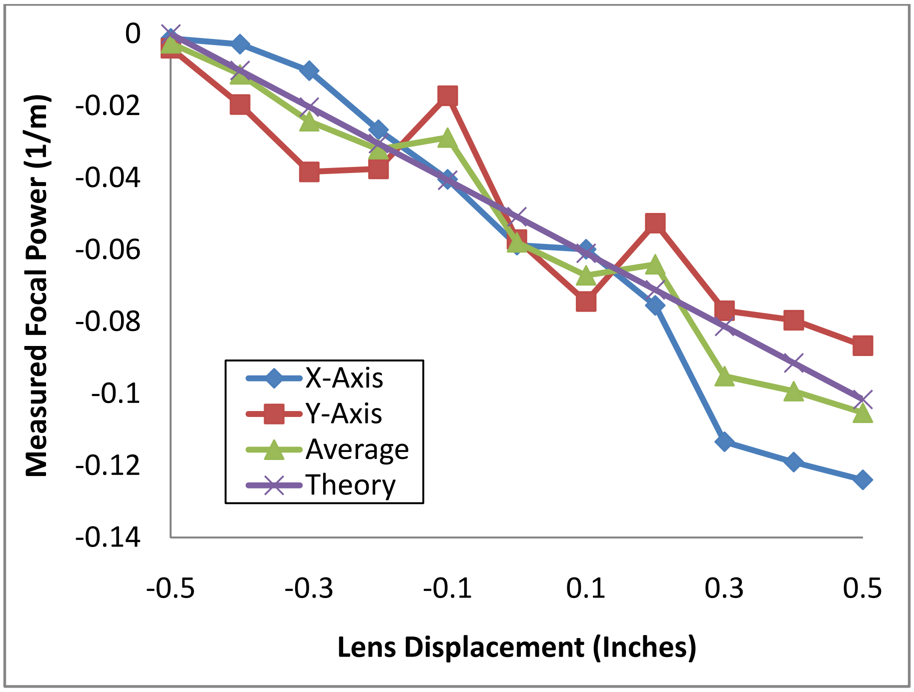

Figure 2 - Wavefront Curvature vs Lens Displacement