ACTIVE OPTICAL SYSTEMS

AN025

On the Accuracy of Beam Position, Tilt, and Size Measured with a Shack-Hartman Wavefront Sensor

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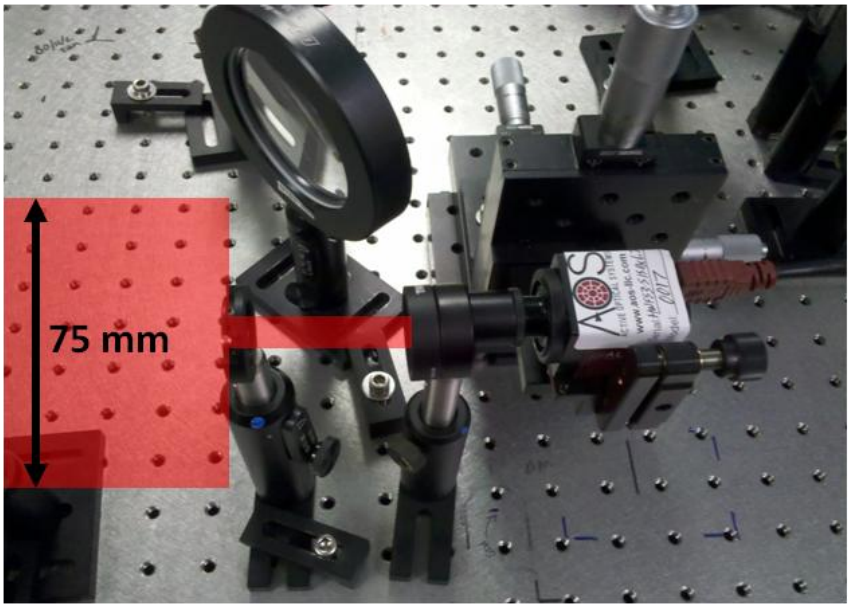
Abstract

Shack-Hartmann wavefront sensors (SHWFSs) are typically used to measure higher order aberrations of a beam, but they are very effective at measuring basic beam properties like size, position, and tilt. In this application note we are publishing results of measurements we made with two AOS wavefront sensors that show the accuracy of these Hartmann sensors.

Experimental Setup

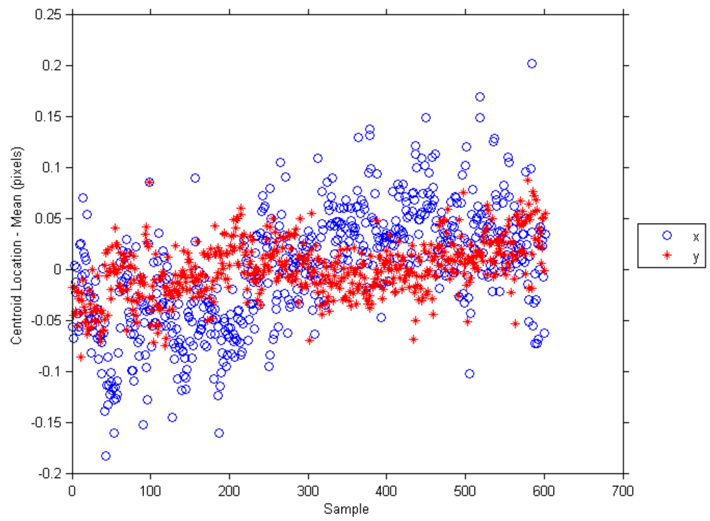
In each of these experiments we illuminated the wavefront sensor with a 633 nm HeNe laser that was expanded to 75-mm diameter to provide a relatively uniform irradiance. The wavefront sensor was mounted on a translation stage to enable sensor motion. An absorptive neutral density filter was used to reduce the laser power to keep the sensor out of saturation. A half-inch diameter iris was centered on the camera field to limit the beam size illuminating the aperture in some of the experiments. In this setup we tested two different wavefront sensors. The first was manufactured with a 500-micron pitch 13.8 mm focal length lens array and a Stingray F-033B camera with 9.9 micron pixel size. The second was manufactured with a 150-micron pitch 6.7 mm focal length lens array and a Guppy F-036B camera with 6.0 micron pixel size. The photograph below shows the experimental setup with the Guppy wavefront sensor.

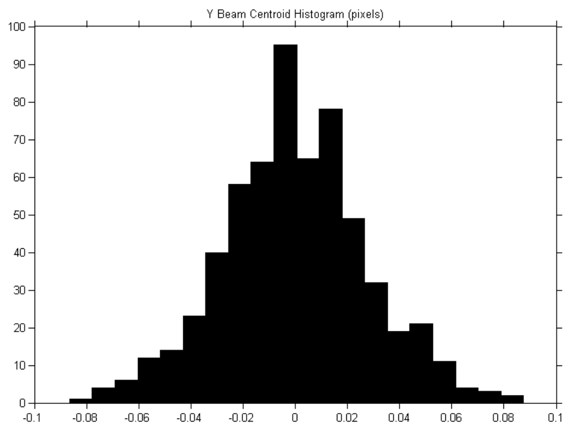


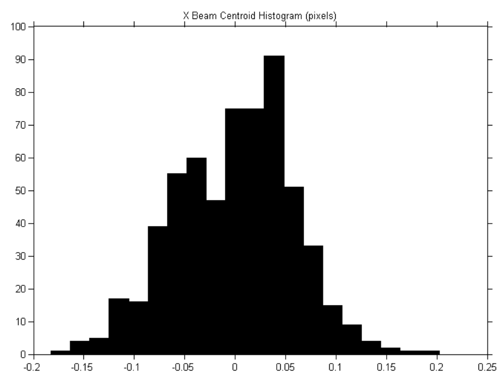
Each wavefront sensor was setup such that the intensity was >90% of the total intensity dynamic range by keeping the black level at 16 and the gain at its lowest setting and adjusting the exposure length. We consistently used a 10% threshold on centroiding for spot location determination. We also always acquired a full frame (typically 640 x 480 pixels) at the highest frame rate (typically 60Hz).

Full-Aperture Measurements

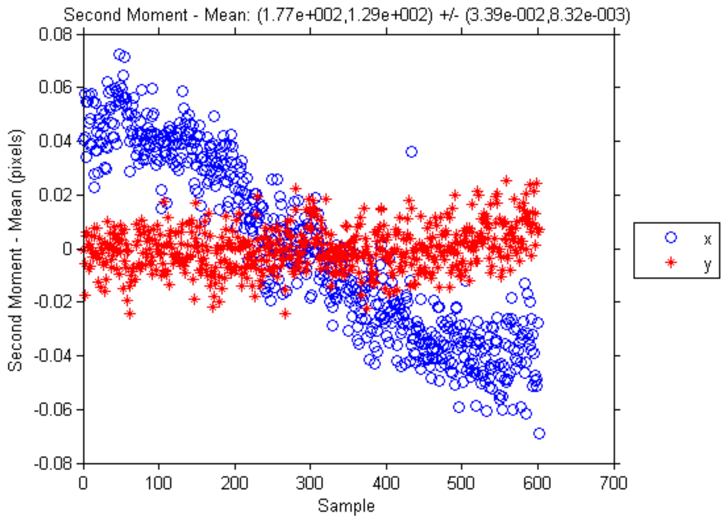
We began each experiment by illuminating the full sensor aperture and creating a reference. Then we made a series of measurements with no intensity frame averaging, 10 frame averaging, and 50 frame averaging. For the Guppy wavefront sensor, we acquired approximately 600 frames of data with no averaging. The figures below show the measured overall beam centroid location minus the average location and the histogram of the resulting measurement noise in the two axes. The noise was fairly Gaussian with a standard deviation in position of 0.06 and 0.03 pixels in the two axes.


Centroid Location - Mean (pixels)
Sample
x
y

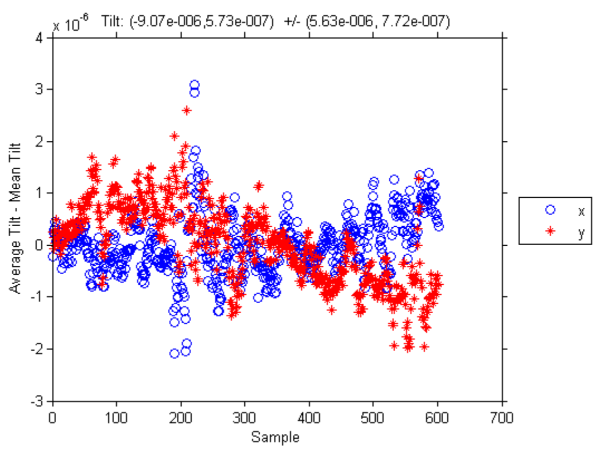

Y Beam Centroid Histogram (pixels)

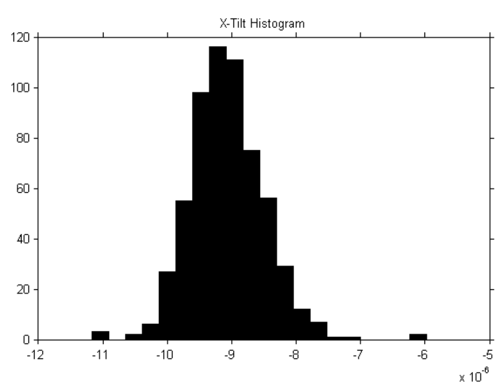

X Beam Centroid Histogram (pixels)

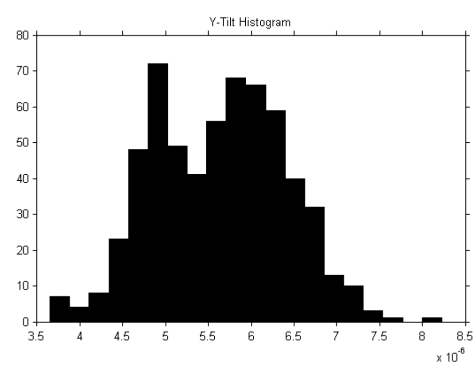
The second moment of the overall beam was calculated for each of the frames as well. There appeared to be an overall trend to the x second moment data despite our attempt to minimize any change in the experimental setup during these runs. The standard deviation of the second moment measurements was 0.034 and 0.0083 in the x and y axes respectively. The y-axis second moment variation was fairly Gaussian, but the x-axis data was affected by the trend.



Finally, we measured the overall beam tilt at each of these measurements. The variation in the tilt again showed a slight pattern to the data, which was reflected more clearly in the x-axis data than the y-axis. The measured tilt standard deviation was 5.6 and 0.77 µrads in the x and y axes respectively.







This entire experiment was repeated using 10 frames and 50 frames of intensity averaging. The table below summarizes the results for these measurements. The additional averages did not significantly change the performance, and, in many cases, actually degraded the performance.

Parameter	**Standard Deviation for Varying Number of Frame Averages**		
# of Averages	1	10	50
X Centroid (pixels)	0.0587	0.0657	0.0798
Y Centroid (pixels)	0.0279	0.023	0.0878
X Second Moment (pixels)	0.0339	0.0277	0.0988
Y Second Moment (pixels)	0.0083	0.0099	0.0122
X Tilt (radians)	5.73E-07	2.04E-06	3.77E-06
Y Tilt (radians)	7.72E-07	1.46E-06	3.27E-06

Stingray Wavefront Sensor with Full Aperture Illumination

We repeated the experiment with the Stingray wavefront sensor and achieved the results in the following table. This sensor had very comparable performance to the Guppy wavefront sensor, but showed a clear reduction in first and second moment noise with frame averaging. We did not see that reduction in noise in beam tilt with averaging. The standard deviation in the centroid position determination with no averaging was about 0.1 pixels in the two axes. The standard deviation of the second moment was about 0.04 pixels. The standard deviation of the beam tilt measurement was about 0.9 µradians.

Parameter	Standard Deviation for Varying Number of Frame Averages		
# of Averages	1	10	50
X Centroid (pixels)	0.1056	0.0337	0.0258
Y Centroid (pixels)	0.067	0.0271	0.0171
X Second Moment (pixels)	0.0408	0.0141	0.0056
Y Second Moment (pixels)	0.0304	0.0109	0.0054
X Tilt (radians)	8.89E-07	7.54E-07	7.11E-07
Y Tilt (radians)	9.87E-07	8.69E-07	1.81E-06

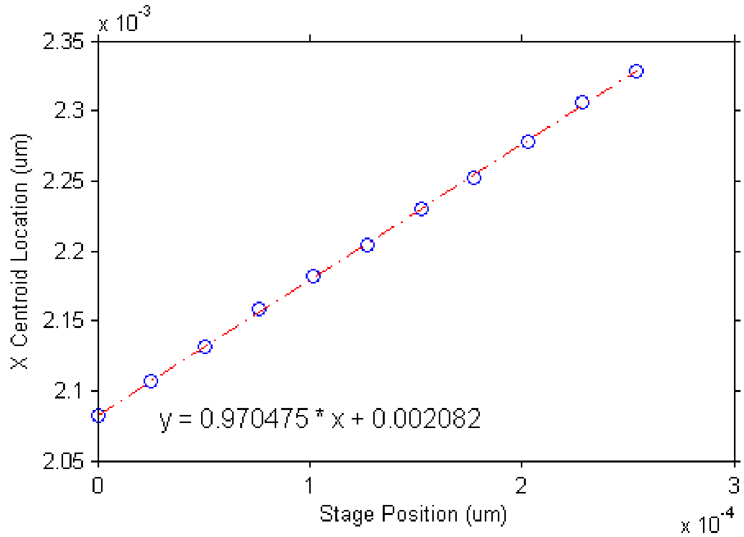
Small-Aperture Measurements with Translation

We were interested in the effect of a reduced aperture and the effect of moving the beam to different parts of the wavefront sensor. After establishing a reference with a fully-illuminated aperture, we limited aperture with an iris so that a circular beam aperture fit the sensor aperture. We then took a set of data at eleven different positions separated in the horizontal axis by 1 mil (25 microns) each. We then did average and standard deviation analysis on the first and second moment and the beam tilt. There is a table of results in the appendix. The following table shows the standard deviation averaged over all the positions to show the average effect of the sensor translation. Despite the smaller beam we were seeing very comparable performance to the full aperture results.

Parameter	Value
X Centroid Standard Deviation (pixels)	0.039449
Y Centroid Standard Deviation (pixels)	0.031017
X Second Moment Standard Deviation (pixels)	0.013122
Y Second Moment Standard Deviation (pixels)	0.010336

X Tilt Standard Deviation (radians)	1.65E-06
Y Tilt Standard Deviation (radians)	1.4E-06

We also fit the relationship between the measured x-centroid and the translation introduced by the actuator. The figure below shows this result for this analysis. We found that the slope was 0.97 instead of the predicted 1.0, but this can be explained by imprecision in the actuator.

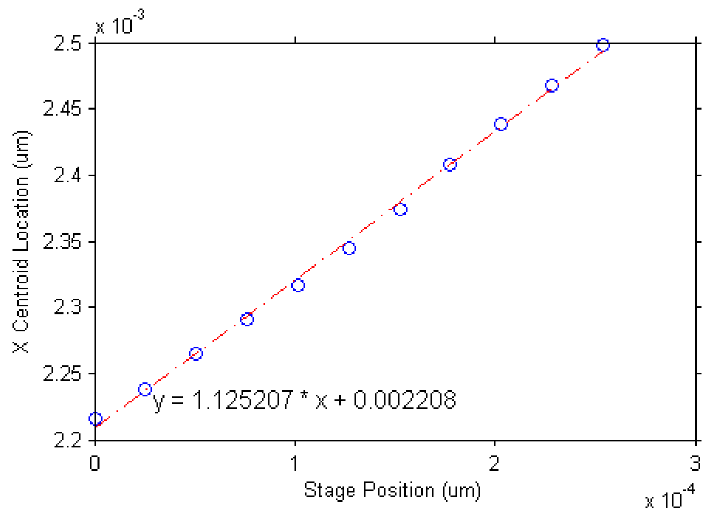


Stingray Wavefront Sensor

We repeated the small-aperture translation experiment with the Stingray wavefront sensor. The complete results for the test are in the appendix, but the table below summarizes the average noise performance. These were also fairly consistent with the full aperture results.

Parameter	Value
X Centroid Standard Deviation (pixels)	0.082098947
Y Centroid Standard Deviation (pixels)	0.081067901
X Second Moment Standard Deviation (pixels)	0.040887942
Y Second Moment Standard Deviation (pixels)	0.04113154
X Tilt Standard Deviation (radians)	1.17413E-06
Y Tilt Standard Deviation (radians)	1.28553E-06

We also fit the relationship between the measured x-centroid and the translation introduced by the actuator. The figure below shows this result for this analysis. We found that the slope was 1.12 instead of the predicted 1.0, but this again can be explained by imprecision in the actuator.



Conclusions

In this note, we presented data on the analysis of position, size, and tilt of an incident beam on two different wavefront sensors. In a variety of different conditions, we were able to show that both the Guppy and the Stingray wavefront sensors had standard deviations for first moment of approximately 0.1 pixels (1 micron). The second moment standard deviation was approximately 0.05 pixels (0.5 microns). The beam tilt standard deviation was approximately 1.5 microradians.

Parameter	**Approximate Standard Deviation**
Centroid	0.1 pixels (1 micron)
Second Moment	0.05 pixels (0.5 micron)
Beam Tilt	1.5 microradians

Appendix

Table of Results from Small-Aperture Translation Testing using a Guppy Wavefront Sensor

Stage Position (mil)	0	1	2	3	4	5	6	7	8	9	10	Average
Average X Centroid (pixels)	346.9717	351.0991	355.1943	359.6574	363.7257	367.4162	371.5707	375.434	379.6908	384.4186	388.1222	-
Average Y Centroid (pixels)	230.8871	231.1101	231.4045	231.601	231.6388	231.8253	231.9973	232.2431	232.5349	232.5409	232.6627	231.8587
X Centroid Standard Deviation (pixels)	0.042232	0.039855	0.031199	0.147971	0.028458	0.018002	0.029011	0.023858	0.019464	0.031276	0.022613	0.039449
Y Centroid Standard Deviation (pixels)	0.035456	0.030805	0.028645	0.095445	0.023477	0.024233	0.020795	0.021869	0.019447	0.020487	0.020525	0.031017
Average X Second Moment (pixels)	103.9639	103.8776	103.8901	103.8294	103.8213	103.6714	103.6951	103.6728	103.6524	103.7029	103.6198	103.7633
Average Y Second Moment (pixels)	108.2175	108.3407	108.3385	108.2191	108.2478	108.2754	108.2365	108.3294	108.3149	108.1954	108.1974	108.2648
X Second Moment Standard Deviation (pixels)	0.010428	0.011456	0.013292	0.039214	0.008364	0.011483	0.00901	0.007401	0.013515	0.010183	0.009999	0.013122
Y Second Moment Standard Deviation (pixels)	0.011414	0.010014	0.010708	0.011178	0.011922	0.009442	0.009586	0.008951	0.009958	0.010492	0.010032	0.010336
Average X Tilt (radians)	2.54E-06	1.12E-05	6.28E-06	-3.8E-06	-1.3E-05	-9.2E-06	2.44E-06	2.35E-06	-2.5E-06	-2.3E-05	-1.6E-05	-3.9E-06
Average Y Tilt (radians)	5.54E-06	-4.7E-06	-1E-05	-5.2E-06	-4.4E-06	-6.8E-06	-7.5E-06	-1.8E-05	-2.1E-05	-9.8E-06	-1.4E-05	-8.7E-06
X Tilt Standard Deviation (radians)	1.5E-06	1.66E-06	1.72E-06	6.39E-06	1.54E-06	9.38E-07	6.64E-07	7.89E-07	1.1E-06	9.67E-07	8.94E-07	1.65E-06
Y Tilt Standard Deviation (radians)	2.06E-06	1.93E-06	1.8E-06	3.78E-06	8.55E-07	9.8E-07	8.64E-07	1.02E-06	7.44E-07	7.49E-07	5.98E-07	1.4E-06

Table of Results from Small-Aperture Translation Testing using a Stingray Wavefront Sensor

Stage Position (mil)	0	1	2	3	4	5	6	7	8	9	10	Average
Average X Centroid (pixels)	223.8034	226.0901	228.8021	231.4392	233.9888	236.8049	239.8389	243.2242	246.3585	249.3096	252.3217	237.4529
Average Y Centroid (pixels)	228.789	228.959	229.0495	229.1867	229.4258	229.5278	229.4407	229.2661	229.1278	228.8349	228.5853	229.1084
X Centroid Standard Deviation (pixels)	0.082944	0.085708	0.092651	0.072777	0.086861	0.084477	0.088596	0.073632	0.083593	0.079252	0.072598	0.082099
Y Centroid Standard Deviation (pixels)	0.083778	0.076352	0.079634	0.081613	0.088687	0.084128	0.079054	0.081735	0.076436	0.082745	0.077586	0.081068
Average X Second Moment (pixels)	96.4467	97.25435	98.02682	98.53753	98.91677	99.23093	99.42056	99.48172	99.41631	99.15526	98.69164	98.59805
Average Y Second Moment (pixels)	98.28382	97.92674	97.57309	97.25605	97.01708	96.84832	96.80318	96.8426	96.99715	97.22847	97.50032	97.29789
X Second Moment Standard Deviation (pixels)	0.035505	0.044095	0.039919	0.042676	0.041435	0.041218	0.039911	0.041357	0.038872	0.041295	0.043485	0.040888
Y Second Moment Standard Deviation (pixels)	0.042055	0.036982	0.042989	0.043007	0.040247	0.041701	0.045067	0.040579	0.036041	0.040215	0.043563	0.041132
Average X Tilt (radians)	-2.9E-05	-2.9E-05	-3E-05	-2.9E-05	-3.2E-05	-3.8E-05	-4.8E-05	-6.1E-05	-6.3E-05	-6.5E-05	-6.5E-05	-4.4E-05
Average Y Tilt (radians)	1.72E-05	1.74E-05	1.97E-05	1.93E-05	1.99E-05	1.7E-05	1.88E-05	1.72E-05	1.87E-05	1.8E-05	1.72E-05	1.82E-05
X Tilt Standard Deviation (radians)	1.77E-06	1.5E-06	1.37E-06	1.71E-06	1.23E-06	7.07E-07	1.27E-06	8.36E-07	8.86E-07	8.98E-07	7.46E-07	1.17E-06
Y Tilt Standard Deviation (radians)	2.43E-06	1.05E-06	1.56E-06	1.44E-06	1.1E-06	9.18E-07	1.07E-06	1.61E-06	1.1E-06	9.98E-07	8.74E-07	1.29E-06

Example Analysis Script

```
setup;
ppt=0;

c=1;
fn{c}='Guppy_1avg_FullAp2.txt';c=c+1;
fn{c}='Guppy_10avg_FullAp.txt';c=c+1;
fn{c}='Guppy_50avg_FullAp.txt';c=c+1;

winVec = [ 717   288   624   400];

for jj=1:length(fn);
    c=c+1;
    clear d;
    d=importdata(fn{jj});

    if (length(d.textdata)==1)
        offset=0;
    else
        offset=1;
    end;
    if (ppt)
        TitleSlidePowerPoint(fn{jj});
    end;

    [n,s]=parse(char(d.textdata{1}),',');
    for ii=1:length(s);
        if (strfind(s{ii},'BEAM_XC'))
            ixc = ii-offset;
        end;
        if (strfind(s{ii},'BEAM_YC'))
            iyc = ii-offset;
        end;
        if (strfind(s{ii},'BEAM_X2'))
            ix2 = ii-offset;
        end;
        if (strfind(s{ii},'BEAM_Y2'))
            iy2 = ii-offset;
        end;
        if (strfind(s{ii},'BEAM_XTILT'))
            ixtilt = ii-offset;
        end;
        if (strfind(s{ii},'BEAM_YTILT'))
            iytilt = ii-offset;
        end;
    end;

    nf(winVec);
    clear dt;
    if (length(d.textdata)==1)
        for ii=1:length(d.data);
            dt(ii) = (d.data(ii,1));
        end;
    else
```

```
        for ii=2:length(d.textdata);
            dt(ii-1) = datenum(d.textdata(ii));
        end;
    end
    plot(dt);
    xlabel('index');
    ylabel('time');
    if (ppt)
        ToPPT('Time Stamps');
    end;

    nf(winVec);
    plot(d.data(:,ixc)-mean(d.data(:,ixc)),'bo');
    hold on;
    plot(d.data(:,iyc)-mean(d.data(:,iyc)),'r*');
    legend('x','y','Location','EastOutside');
    xlabel('Sample');
    ylabel('Centroid Location - Mean (pixels)');
    xcavg = mean(d.data(:,ixc))
    ycavg = mean(d.data(:,iyc))
    xcstd = std(d.data(:,ixc))
    ycstd = std(d.data(:,iyc))
    title(sprintf('Centroid: (%.2e,%.2e)+/-(%.2e,%.2e)',xcavg,ycavg,xcstd,ycstd));
    if (ppt)
        ToPPT(sprintf('Centroid Location - %s',fn{jj}));
    end;

    nf(winVec);
    hist(d.data(:,ixc)-mean(d.data(:,ixc)),20);
    title('X Beam Centroid Histogram (pixels)');
    if (ppt) ToPPT(); end;

    nf(winVec);
    hist(d.data(:,iyc)-mean(d.data(:,iyc)),20);
    title('Y Beam Centroid Histogram (pixels)');
    if (ppt) ToPPT(); end;

    nf(winVec);
    plot(d.data(:,ix2)-mean(d.data(:,ix2)),'bo');
    hold on;
    plot(d.data(:,iy2)-mean(d.data(:,iy2)),'r*');
    legend('x','y','Location','EastOutside');
    x2avg = mean(d.data(:,ix2))
    y2avg = mean(d.data(:,iy2))
    x2std = std(d.data(:,ix2))
    y2std = std(d.data(:,iy2))
    title(sprintf('Second Moment - Mean: (%.2e,%.2e) +/-
(%.2e,%.2e)',x2avg,y2avg,x2std,y2std));
    xlabel('Sample');
    ylabel('Second Moment - Mean (pixels)');
    if (ppt)
        ToPPT(sprintf('Second Moment - %s',fn{jj}));
    end;

    nf(winVec);
    hist(d.data(:,ix2)-mean(d.data(:,ix2)),20);
    title('X Beam 2nd Moment Histogram (pixels)');
    if (ppt) ToPPT(); end;
```

```
    nf(winVec);
    hist(d.data(:,iy2)-mean(d.data(:,iy2)),20);
    title('Y Beam 2nd Moment Histogram (pixels)');
    if (ppt) ToPPT(); end;

    nf(winVec);
    plot(d.data(:,ixtilt)-mean(d.data(:,ixtilt)),'bo');
    hold on;
    plot(d.data(:,iytilt)-mean(d.data(:,iytilt)),'r*');
    legend('x','y','Location','EastOutside');
    xlabel('Sample');
    ylabel('Average Tilt - Mean Tilt');
    dxavg = mean(d.data(:,ixtilt))
    dxstd = std(d.data(:,ixtilt))
    dyavg = mean(d.data(:,iytilt))
    dystd = std(d.data(:,iytilt))
    title(sprintf('Tilt: (%.2e,%.2e)  +/- (%.2e, %.2e)',dxavg,dxstd,dyavg,dystd));
    if (ppt)
        ToPPT(sprintf('Average Tilt - %s',fn{jj}));
    end;

    nf(winVec);
    hist(d.data(:,ixtilt),20);
    title('X-Tilt Histogram');
    if (ppt) ToPPT(); end;

    nf(winVec);
    hist(d.data(:,iytilt),20);
    title('Y-Tilt Histogram');
    if (ppt) ToPPT(); end;

    close all;
end;
```