Anchal Agarwal grew up in Kolkata, India, where she completed high school. She is currently pursuing a major in Electrical Engineering at the University of Michigan, Ann Arbor with a specialty in Microfabrication and Circuits. She has been on the Dean's list in every semester and is an active member of the Eta Kappa Nu Honor Society. During the summer of 2011, she was awarded the Lee Teng Fellowship to work at the Advanced Photon Source at Argonne National Laboratory. In her spare time, Anchal enjoys painting, singing and swimming. After graduation, she plans to pursue a PhD, possibly in Optoelectronics.

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DEVELOPMENT OF A NANORADIAN RESOLUTION SLOPE MEASURING SENSOR FOR X-RAY OPTICS

ANCHAL AGARWAL AND LAHSEN ASSOUFID

ABSTRACT

The Advanced Photon Source (APS) is building a new generation long trace profiler (LTP) that will be capable of measuring mirrors slope profile with 50 nanoradian resolution. This new profiler is designed to accommodate multiple high resolution slope sensors with different dynamical ranges. The goal of the work was to participate in building a test bench to characterize a nanoradian resolution slope sensor. For this, it was critical that a code be developed that can determine the location of the centroid of a laser spot with subpixel accuracy. A Matlab code based on Fourier transform method was used to enable high precision and verified using an autocollimator. The code was further verified by testing it on an existing optical slope sensor board. The test bench for an improved experiment was installed. This paper describes the Fourier transform algorithm used to locate the centroid of the beam spot, the code, the results of testing and the rationale behind the prototype of the improved experiment.

INTRODUCTION

The Advanced Photon Source is preparing for a major upgrade in its beamlines and experiment stations. It is an ongoing process and will take a few years to be completed. The upgraded beamlines will require mirrors and optics of unprecedented quality. X-Ray mirrors need to be evaluated for smoothness before it can be used as a high degree of smoothness is required to preserve source properties. A slope irregularity of more than a few microradians and a height roughness exceeding a few angstroms will cause the beam to scatter and the brilliance of the beam source to be diminished. A special instrument called the Long Trace Profiler (LTP) is used to measure the mirror slope profile (See fig. 1, fig. 2). The LTP that is currently in use at APS gives an accuracy of ≥ about 300nrad [5]. The upgrade requires that the LTP gives a much better accuracy for the slope profile. To enable this, a new generation Long Trace Profiler is being developed.

This new system is set to be operational in 2012. It will hold multiple sensors. The body for the LTP was bought recently, and the development of the new sensors is under progress. My task was to characterize a possible nanoradian resolution slope sensor. The development of this new multisensory Long Trace Profiler will be done in two phases. In the initial phase, the current linear low resolution camera system will be replaced with a commercial autocollimator. Fig.1 shows the principle of an autocollimator. The target resolution for Phase I is ~100nrad. Later, an improved sensor with 50nrad resolution will be installed. Thus, there will be an improvement of ten times. A key point in achieving high resolution profilometry is to develop a code that can accurately calculate the shift in the centroid location of the reflected beam. This shift can conveniently be translated into the change in slope of the mirror surface using the following relation:

$\tan \alpha = \frac{d}{L}$ where d is the shift, and L is the distance between the reflecting surface and the CCD camera. For a system with no lens or optics, this can be approximated to: $\alpha \approx \frac{d}{L}$ because $\alpha <<<1$, and is equal to the slope of the mirror. Thus, a plot of α vs. the position on the test surface gives the slope profile for the surface.

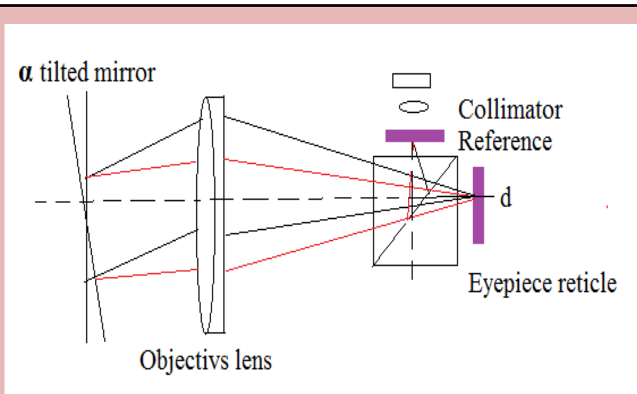

Fig. 1: Working principle of an autocollimator

Fig. 2 is an image of the existing Long Trace Profiler at the APS. It can measure mirrors up to 1.5 meters in length [5].

Fig. 2: Image of the old version of the Long Trace Profiler

Fig.3 is a simplified diagram of the LTP installed with an autocollimator-based sensor. The slope error on the mirror surface will cause deviation in the reflected beam and thus enable the autocollimator to estimate the slope.

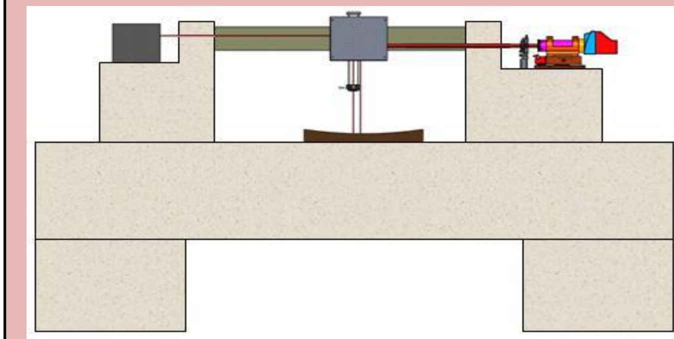

Fig. 3: Highly simplified schematic of the new Long Trace Profiler that uses the commercial autocollimator

Traditional Methods of Determining the Focal Point

The simplest known method of determining the focal point of a beam spot is the center of mass process. The term "center of mass" has been borrowed from physics. A body in a power field behaves as if its entire mass was concentrated at one point. The focus, therefore, represents the position of the body. A major drawback of this method is the strong weighing of the boundaries. There is notably more noise at the boundaries, and this leads to large distortions. A more traditional method, the Gaussian fit, would come into question, and it is a very accurate method if the profile as the approximate shape of a Gaussian. But in practice, beam spots are not totally symmetric. Apart from this problem, there are other drawbacks: the algorithm is numerically intensive and it can be highly inaccurate if there is a significant amount of noise.

The Fourier Transform Method

This method avoids the disadvantages described above. The basic idea of this method is to measure the symmetric and asymmetric proportion of the profile with respect to the coordinate axis. If we are dealing with a symmetrical profile, whose symmetry axis is not the origin, the fourier expansion is asymmetric [4].We position the profile (usually asymmetric) at a place where the asymmetric share is minimal. The shift in the position is described by Δ x, and gives us the centroid of the beam spot. This method has a further advantage in that higher frequency components can be filtered out. This is because disorders of a profile are usually high frequency in nature.

Description of the algorithm:

A (real) profile f(x) can be defined on 2N discrete points. Then this profile can be represented as a Fourier series:

$$f(x) = \sum_{k=-N}^{N} C_k e^{2\pi ikx/N} \qquad (1)$$

Where $C_k=a_k+ib_k$ are the fourier coefficients. The condition $C_k=C^*_{-k}$ results from the Fourier transformation of the measured distribution. If the function f(x) is symmetric about the origin x=0, the imaginary components of C vanish. The term

$$A = \sum_{k=-N}^{N} (IM[C_k])^2 \qquad (2)$$

is a measure of the asymmetry of the function f(x) with respect to the origin. If one shifts by the distance Δ x, is can be represented as a new function f(x- Δ x). Thus, A can be written as:

$$A(\Delta x) = \sum_{k>0}^{N} (IM[C_k e^{-2\pi ik\Delta x/N}])^2 \quad (3)$$

In ideal undisturbed symmetric profiles such as Gaussian or bell-box, all asymmetric Fourier components disappear. The result is a Fourier development with only the corresponding symmetric oscillations around the origin. In these cases, the maximum of the fundamental frequency is the symmetry axis of the profile. All higher components are symmetrical relative to this axis. There is no perfect technique to determine the focal spot in these measurement profiles because of the superimposed noise and other errors. Such disturbances cause an error in the calculation of the symmetry axis position.

In many cases, the phase of the fundamental frequency is largely stable. If this holds, only the positions of the first order Fourier coefficients need to be determined. Thus we assume the axial symmetry of an unperturbed profile, and limit ourselves to the fundamental frequency, k = 1.

It then follows from (3):

$$IM[C_1 e^{-2\pi\Delta x/N}] = a_1 \sin(2\pi\Delta x/N) - b_1 \cos(2\pi\Delta x/N) = 0 \quad (4)$$

And Δ x can be determined as:

$$\Delta x = \frac{N}{2\pi}\left(\arctan\left(\frac{b_1}{a_1}\right) + \Phi\right) \quad (5)$$

Matlab Script:

This subroutine accepts a single image as the parameter and returns the x and y co-ordinates of the centroid position:

```
function [y, x} = FindCentroid (image)

matrix = double(image);
[rlength, clength] = size(image);

i = [1:rlength];
SIN_A = sin((i - 1) * 2 * pi / (rlength - 1));
COS_A = cos((i - 1) * 2 * pi / (clength - 1));

j = [1:clength]';
SIN_B = sin((j - 1) * 2 * pi / (clength - 1));
COS_B = cos((j - 1) * 2 * pi / (clength - 1));

a = sum(COS_A * matrix);
b = sum(SIN_A * matrix);
c = sum(matrix * COS_B);
d = sum(matrix * SIN_B);

if (a > 0)
    if (b > 0)

        radjust = 0;
    else
        radjust = 2 * pi;
    end
else
    radjust = pi;
end
if (c > 0)
    if (d > 0)
        cadjust = 0;
    else
        cadjust = 2 * pi;
    end
else
    cadjust = pi;
end

y = (atan(b / a) + radjust) * (rlength - 1) / 2 / pi
+ 1;
x = (atan(d / c) + cadjust) * (clength - 1) / 2
/ pi + 1;
```

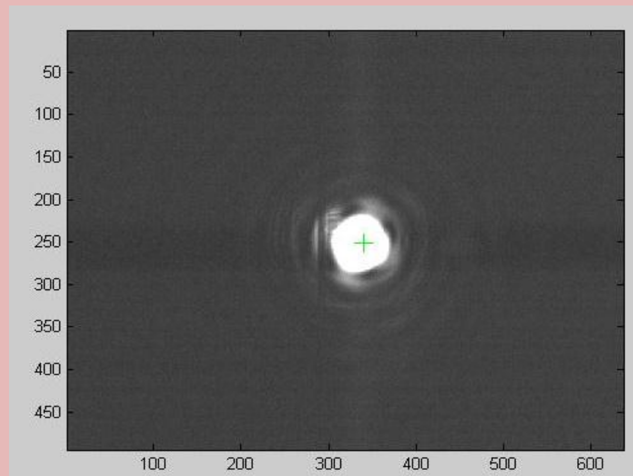

Fig. 4: the green hair cross is on the centroid of a beam spot that was calculated using the written code

The second subroutine calls the previous routines and plots the slope profile of the mirror being inspected as a function of distance from the reference point:

```
function []=
slopeProfile(imcell,pixelsize,stepsize,kx,ky)
%creating a cell of images size N

N=length(imcell);

distx=zeros(N,1);
disty=zeros(N,1);
slopex=zeros(N,1);
slopey=zeros(N,1);

refim=imcell{1};

for i=1:N;
    im=imcell{i};
    [x y ax ay]=slope(refim,im,pixelsize,kx,ky);
    distx(i)=(i-1)*stepsize;
    disty(i)=(i-1)*stepsize;
    slopex(i)=ax;
    slopey(i)=ay;
end

subplot(2,1,1)
plot(distx,slopex,'k:+');
title('slope profle horizontal');
xlabel('distance from reference point');
ylabel('slope (radians)');
hold on;


subplot(2,1,2)
plot(disty,slopey,'m:+');
title('slope profile vertical');
xlabel('distance from reference point');
ylabel('slope (radians)');
hold on;
```

The following code generates the best fit line and the scatter plot for the validation experiment:

```
function []= auto(imcell,pixelsize,stepsize,k)

au=[0 0.0002 0.00034 0.0008 0.0012 0.0016 0.00199
0.0024 0.00443 0.00478 0.00518 0.00558 0.00671
0.01041 0.01081 0.01126 0.01161 0.01202 0.01242
0.01281 0.01322];
 % autocollimator sample data

au=au.*pi*10^6/180;
N=length(imcell);
distx=zeros(N,1);
disty=zeros(N,1);
slopex=zeros(N,1);
slopey=zeros(N,1);

refim=imcell{1};

for i=1:N;
    im=imcell{i};
[distx1
disty1]=FindCentroidLaserSpotUsingFourier(refim);
[distx2
disty2]=FindCentroidLaserSpotUsingFourier(im);
dx=(distx2-distx1)*pixelsize;
dy=(disty2-disty1)*pixelsize;

distx(i)=(i-1)*stepsize;
disty(i)=(i-1)*stepsize;
slopex(i)=dx*k*10^6;
slopey(i)=dy*k*10^6;

end

p1 = polyfit(distx,slopex,1);   % p returns 2
coefficients fitting r = a_1 * x + a_2
r1 = p1(1) .* distx + p1(2); % compute a new vector
r that has matching datapoints in x

% now plot both the points in y and the curve fit in
r
plot(distx, -slopex, 'rx');
hold on;
plot(distx, -r1, 'r-');
hold on;

p2 = polyfit(disty,au',1);   % p returns 2
coefficients fitting r = a_1 * x + a_2
r2 = p2(1) .* disty + p2(2); % compute a new vector
r that has matching datapoints in x

% now plot both the points in y and the curve fit in
r
plot(disty, au', 'kx');
hold on;
plot(disty, r2, 'k-');
hold on;

title('NON-AVERAGED DATA PLOT FOR THE CALIBRATION
EXPERIMENT');
    xlabel('change in angle of the mirror
(microradians) controlled by the PI Stage');
    ylabel('slope (microradians)');

    legend('black line: Autocollimator');
        legend('red line: CCD Camera data');
hold on;
```

The following function generates the surface profile of a test mirror:

```
function []= av(imcell,pixelsize,stepsize,k)
%creating a cell of images size N
N=length(imcell);
distx=zeros(N,1);
disty=zeros(N,1);
slopex=zeros(N,1);
slopey=zeros(N,1);
rms=0;
refim=imcell{1};

for i=1:N;
    im=imcell{i};
[distx1
disty1]=FindCentroidLaserSpotUsingFourier(refim);
[distx2
disty2]=FindCentroidLaserSpotUsingFourier(im);
dx=(distx2-distx1)*pixelsize;
dy=(disty2-disty1)*pixelsize;

distx(i)=(i-1)*stepsize;
disty(i)=(i-1)*stepsize;
slopex(i)=dx*k*10^6;
slopey(i)=dy*k*10^6;

end
p1 = polyfit(distx,slopex,1);   % p returns 2
coefficients fitting r = a_1 * x + a_2
r1 = p1(1) .* distx + p1(2); % compute a new vector
r that has matching datapoints in x
for i=1:N
    slopex(i)=slopex(i)-p1(1)*distx(i)-p1(2);
    rms=rms+(slopex(i)^2);
end

rms=sqrt(rms/N)
% now plot both the points in y and the curve fit in
r
distx
slopex

plot(distx, slopex, 'r');
axis([0 220, -30 30]);
title('NON-AVERAGED PLOT');
legend('SLOPE PROFILE OF THE TEST SURFACE');
    xlabel('Horizontal Distance (mm)');
    ylabel('slope (microradians) (Deviation from the
line of best fit)');

hold on;
```

VALIDATION OF THE MATLAB CODE

The written code was verified and validated using an industrial autocollimator. The following diagram shows a rough schematic of the experiment that was done for this validation. A PZT stage (from PI-USA Inc.) was used to change the inclination of the mirror. This PI stage was controlled by a software called Nanocapture. This software allowed six degrees of freedom: x-axis, y-axis, z-axis, x-rotation, y-rotation, and z-rotation. For this experiment, only the x-rotation was used.

The class II laser and the CCD camera were set at 90 degrees to each other and the mirror mounted on the PI stage made an angle of roughly 45 degrees with both (fig. 5, 6). This position was set as the initial position on the Nano capture software. The autocollimator was positioned perpendicular to the mirror such that the initial reflected beam from the mirror to the autocollimator was as close to the origin as possible. In other words, the incident and reflected beams on the mirror from the autocollimator were made to coincide. The reading for this position was taken along with the image of the beam spot on the CCD camera. The software that controls the CCD camera was provided by its manufacturer, Prosilica.

Then, the controller for the PI stage was programmed to turn 200 μrad in steps of 10μrad. The readings for each position and its corresponding images were taken manually. This data was processed on Matlab and the plots for the autocollimator and the CCD Camera were generated on the same graph for comparison. Thus, we had 2 references to calibrate the code with. The best fit line on both the plots displayed high correlation (fig.7).

Despite the linearity of the best fit line, this data was not sufficient to draw any conclusions. There was a considerable amount of fluctuation in the readings due to thermal instability and noise.

The next step was to average many images for each position to get a more accurate position for the centroids. A similar process was followed for this. It was the best averaged estimate for the position of the beam.

Once the data was collected, one single mean image of the 10 images for every position. These images were processed in Matlab along with the data from the autocollimator to create a plot similar to the previous one (fig.8).

The data was almost linear for both, the autocollimator and the CCD Camera and indicated a very high correlation (almost parallel). But, there was a difference in the angle displayed on the PI stage software and the measured angle. No enclosure was used so there may have been a significant amount of thermal fluctuations over a period of time. A more accurate data can be obtained by careful calibration work.

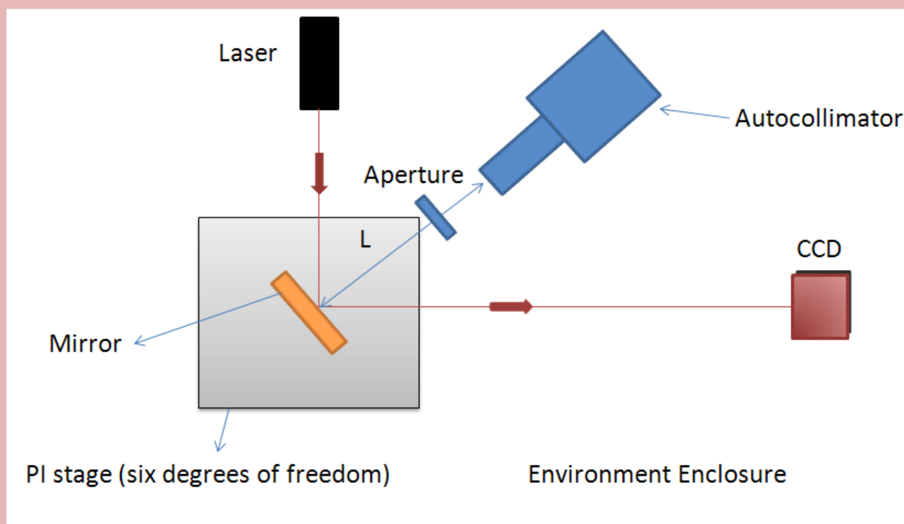

Fig. 6: Schematic of the experiment used for calibrating the Code with an autocollimator

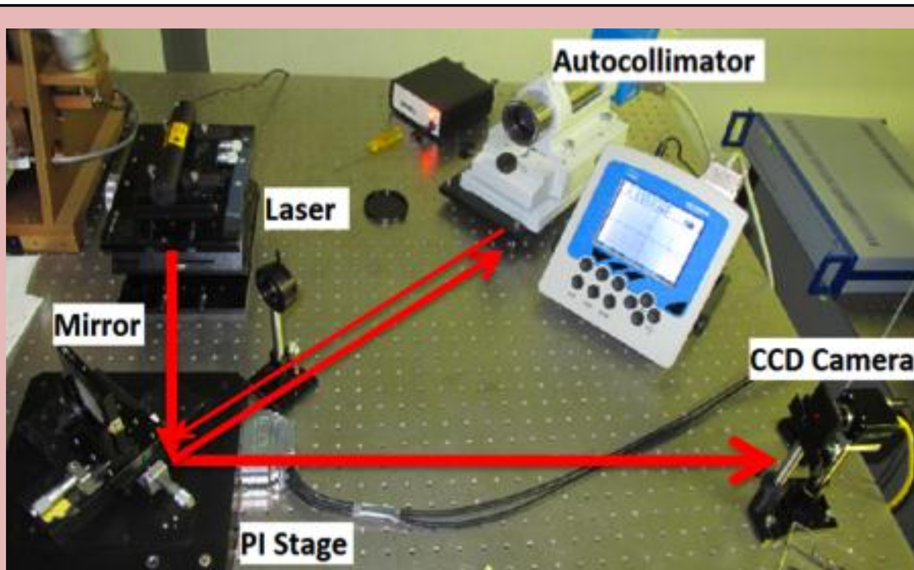

Fig. 5: Actual setup of the experiment used for calibrating the Code with an autocollimator

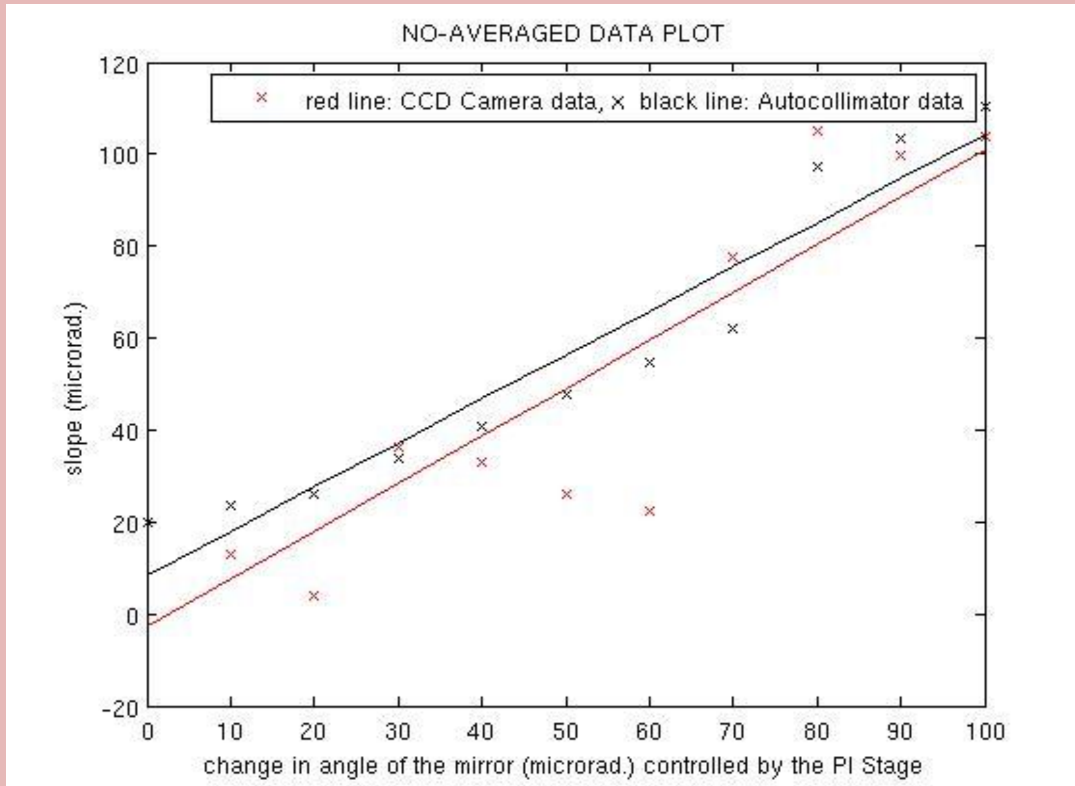

Fig. 7: Non-Averaged, sample plots of the data for the calibration experiment shows a large standard deviation and high correlation

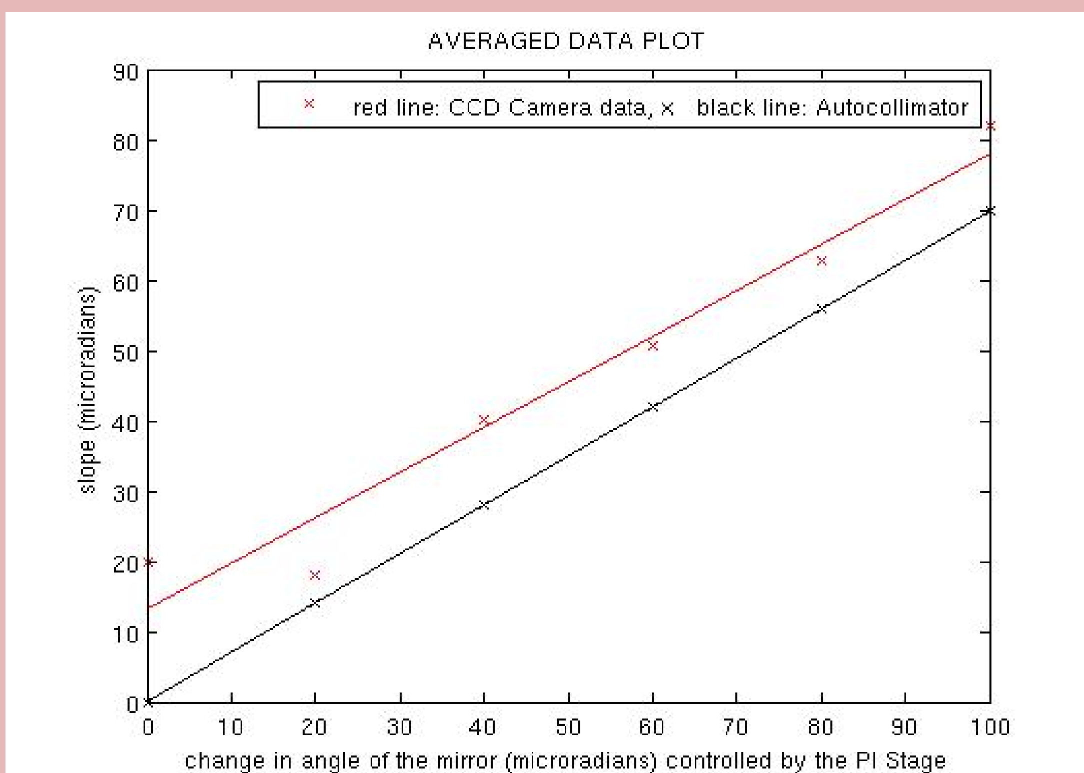

Fig. 8: Averaged plots of the data for the calibration experiment show a small standard deviation and high linearity and correlation

TESTING THE CODE USING THE LTP OPTICS BOARD

The LTP uses a double array detector to monitor the probe and the reference beams, respectively (see Fig. 9 and 10). The reference beam measures the optics board motion errors through a stationary mirror during scanning while the probe beam monitors the mirror surface. The motion error profile is subtracted from the measured mirror profile to yield the surface slope of the mirror. The first task was to mount the CCD camera in the place of the existing linear array detector. The laser beam position was tuned such that it falls roughly in the center of the camera. The schematic of the existing optics board is displayed in fig.9 and a photograph of the LTP optics board is shown in fig.10. The length of the X-Ray mirror used for testing was 240mm. But the scanning was done only for the mid 220mm section. The rate of scan was 1mm per ½ second. This rate was entirely controlled by the software.

As the optics board translated linearly across the mirror, images were taken at a distance of ~ 1mm manually. Seven sets of reading were taken with this arrangement. Later 3 sets were discarded due to possible errors in them. The images for each data set were indivually processed and the devation of the slope from the best fit line was plotted as a function of the position on the mirror (fig. 11, 12, 13).

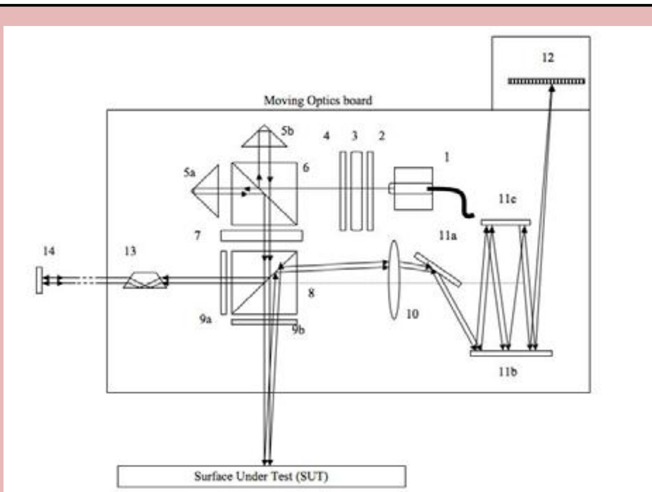

Fig. 9: Schematic of the Optics Board where 1 = laser fiber mount, 2 = fixed polarizer, 3 = rotating polarizer, 4 = fixed polarizer, 5a&b = porro prisms, 6 = beam splitter, 7 = rotating half-wave plate, 8 = polarizing beam splitter, 9a&b = quarter-wave plates, 10 = fourier transform lens, 11a-c = folding mirrors, 12 = 5mp CCD camera, 13 = dove prism, 14 = stationary reference mirror. [5]

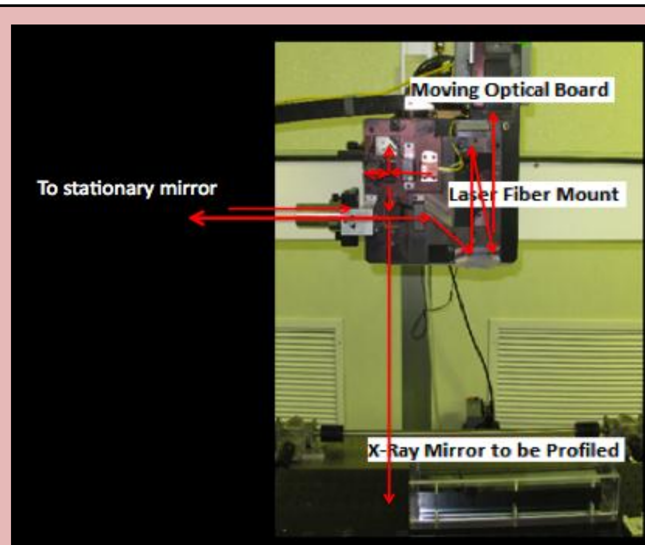

Fig. 10: Image of the existing sensor system

The RMS Values for the deviation of the slope from the best fit line were as follows: 3.1299 µrad, 3.04740 µrad, 2.5317 µrad and 2.6210 µrad. To get a more accurate slope profile, an average image of the 4 images at each location from the 4 data sets were created (thus a set of 220 images was created) and built into a new image cell. This cell was treated like the previous cells and the slope profile of this data set was generated (fig. 14). The RMS value for this data set was ~2 µrad, which was reasonable.

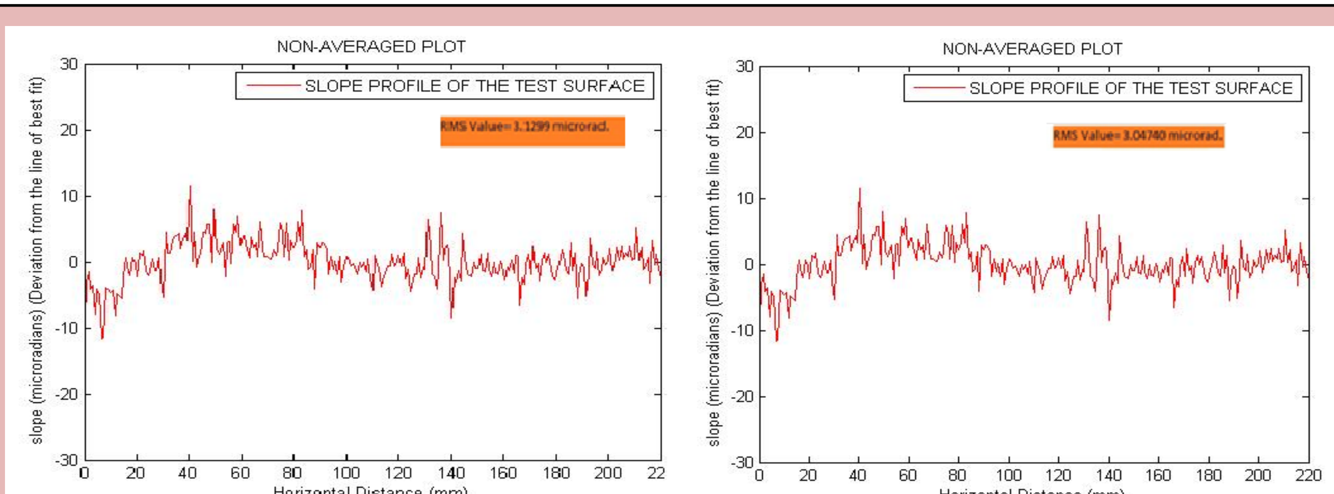

Fig. 11: Non- averaged profiling results

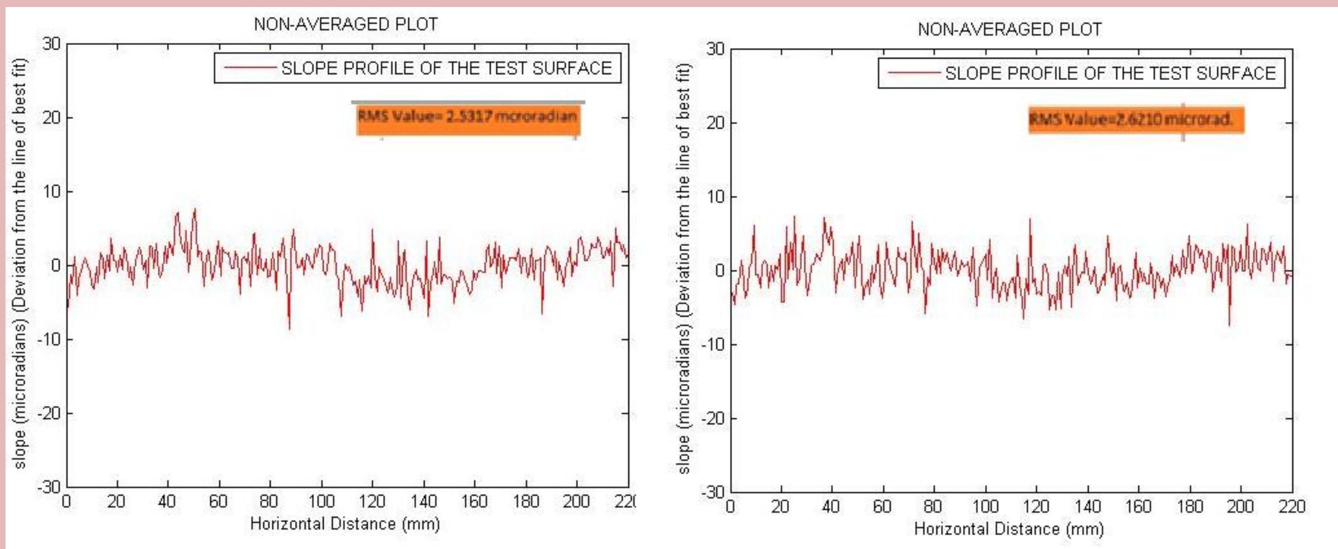

Fig. 12: Non- averaged profiling results

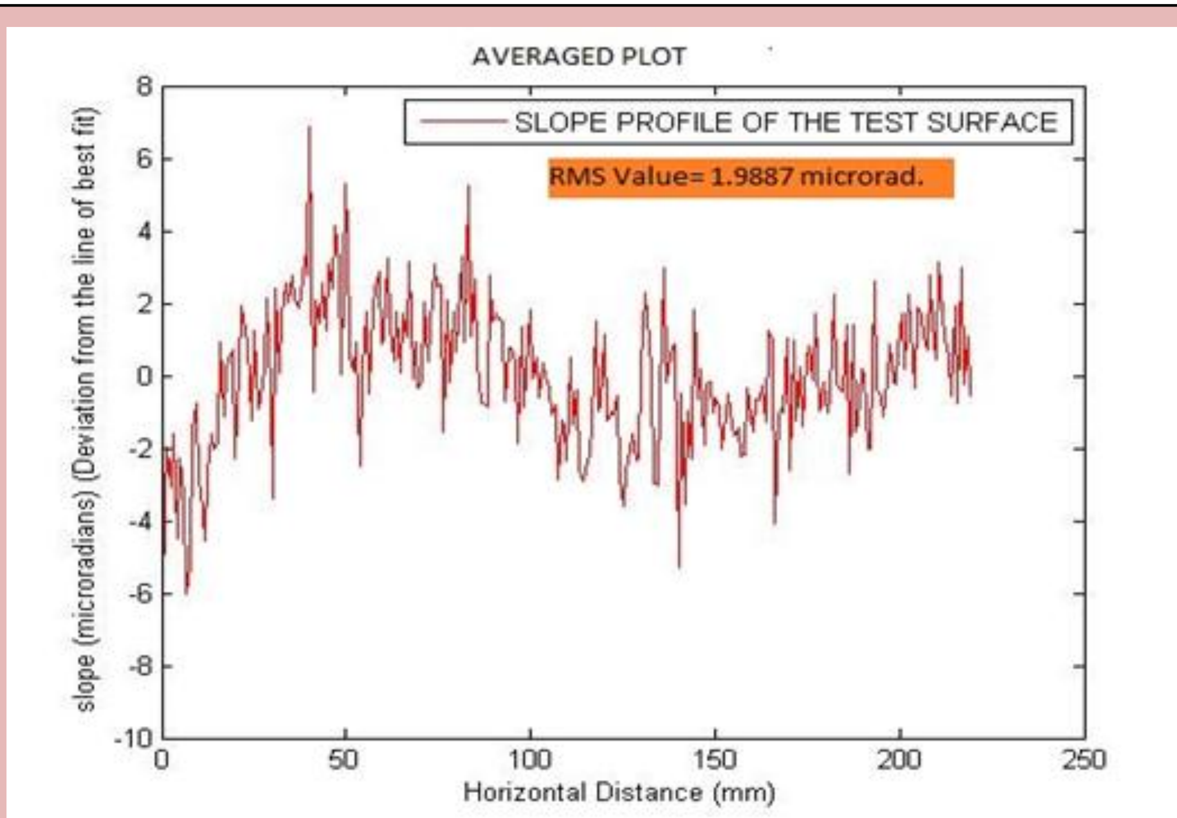

Fig. 13: Averaged profiling results for four data sets

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Test bench for the Prototype of a Compact Autocollimator Sensor

The next part of the project consists of setting up an experiment of the prototype of a compact autocollimator sensor which is based on the work published in reference [3]. This would also enable us to verify the written code.

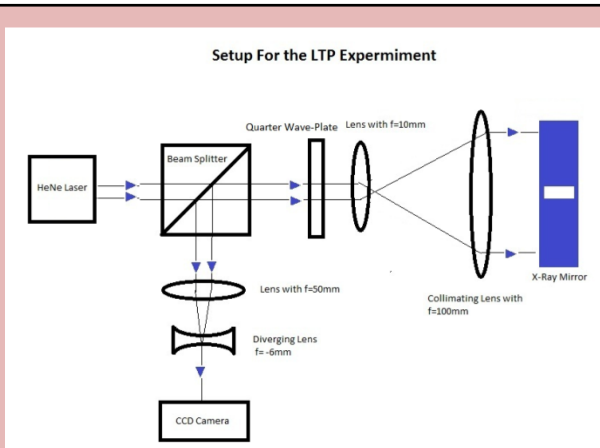

Fig. 14: Schematic of the Test Bench for the experiment

Fig.14 gives a schematic diagram of the test bench of the prototype. A beam emitted by the laser source becomes linearly polarized after passing through a polarization beamsplitter. If the angle between the fast axis of the ¼ wave plate and the direction of laser polarization is set to be 45 degrees, then the light emerging from the ½ wave plate becomes circularly polarized. After passing through the collimating lens pair the divergence angle of the laser beam and angular drifts will be suppressed, hence providing a highly stable beam. The angle of the reflected light from the test mirror becomes double of the rotational angle of the mirror itself. The resolution is defined by the ratio of the collimating lens (f_2 = 100 mm) to that (f_1 = 10 mm) of the upstream focusing lens which in our case is f_2/f_1= 10. Thus, the measured angle is amplified 10 times.

Circularly polarized light becomes linearly polarized light after passing through the quarter-wave plate again, but the direction of polarization shifts by 90 degrees. Therefore, the laser can be reflected only via the polarization beamsplitter. The laser beam then passes through the concave and convex lens combination and is captured by the CCD camera. This data can then be processed to calculate the shift in the position with respect to changing angles of the test mirror.

This experiment serves a number of purposes. Firstly, it allows us to verify the code with better accuracy, as the collimating lens pair enhances the measured slope by 10 times. This experiment also serves as a test bench for the prototype of a possible sensor to be integrated into the Long Trace Profiler.

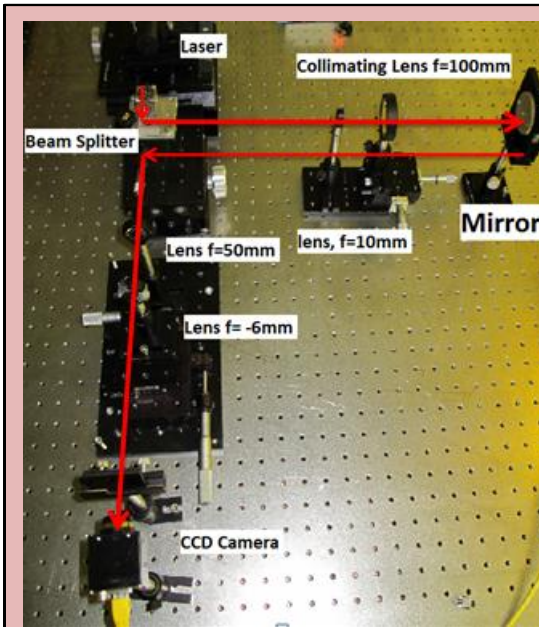

Fig. 15: Setup for the experiment

Sources of Error

The results obtained are greatly affected by a number of factors. The primary sources of error are the thermal fluctuations in the environment. These fluctuations cause the beam to be deflected and appear as mirror surface slope. The second problem is the fluctuations in the intensity of the beam spot. Other sources include instrumentation error.

Conclusion and Future Work

The most significant part of this study was to be able to successfully write and run the routines to locate the centroid of a laser spot, to calculate slope and to generate the slope profile. The verification of the code using the autocollimator experiment produced agreeable results. Time averaged graph from the CCD Detector displayed high linearity and strong correlation with the autocollimator graph. I was also able to perform metrology on a test surface and generate an averaged surface profile. Further work is needed to validate to concept.

Acknowledgement

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