Measurement of a 2-meter flat using a pentaprism scanning system

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ABSTRACT

A scanning pentaprism system may be used as an absolute test for an optical flat. Such a system was built and used to test a 2-meter flat mirror. This system uses light from an autocollimator that is reflected from 2 pentaprisms to project reference beams of light onto the flat mirror. The light reflected from the mirror back through the pentaprisms provides information on low order optical aberrations in the flat mirror. We report results of the test on a 2-meter flat.

Keywords: Pentaprism, flat mirror, optical testing

1. INTRODUCTION

A perfectly flat mirror reflects collimated light back as collimated light. Instead of using a large diameter collimated beam to test a large flat mirror, small sections of the flat mirror may be tested using a much smaller beam. Data obtained may then be stitched together to get complete information about the mirror surface. A suitable way to do this is to use a scanning pentaprism setup. The added advantage of using a pentaprism is that it deviates light by exactly 90^0 regardless of the angle of the incident beam. Thus, the resulting measurements are independent of prism alignment. The paper is organized into the following 6 sections: 1.1 Principles of Operation, 2 Integration, 3 Alignment, 4 Operation and Data Collection, 5 Results, 6 Error Analysis, 7 Conclusions and Future Work, Acknowledgements, and References.

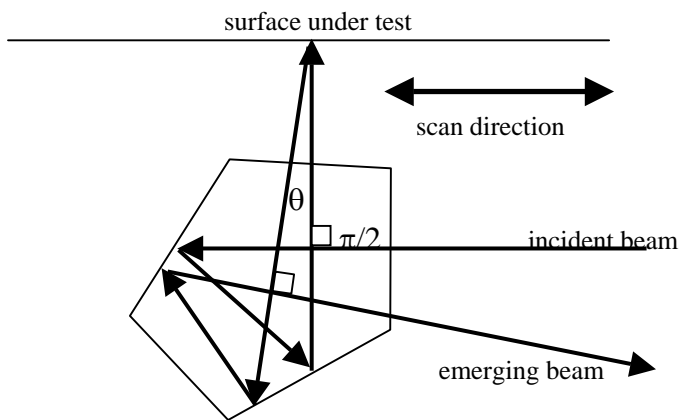### 1.1: Principles of Operation

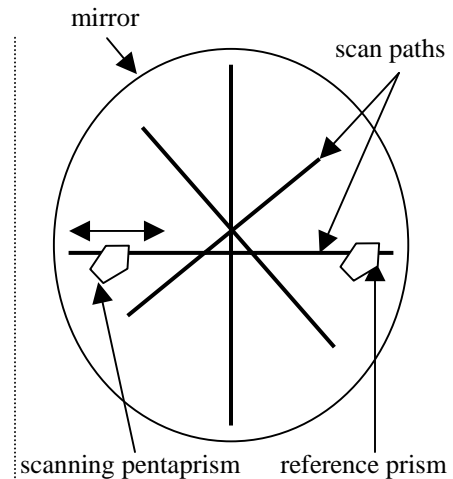Fig 1a: Deviation angle θ is due to the tilt in the surface under test.

Fig 1b: Multiple scans across surface

Figure 1 above shows a pentaprism measuring the tilt of the test surface at a particular location. It can be seen that the pentaprism intercepts only a subset of all parallel rays from the test surface. The pentaprism can now be scanned across the surface to determine the transverse ray aberration of the surface. The pentaprism assembly provides accurate measurements only along the scan direction. To obtain information of low order aberrations of the full test surface multiple radial scans need to be taken.
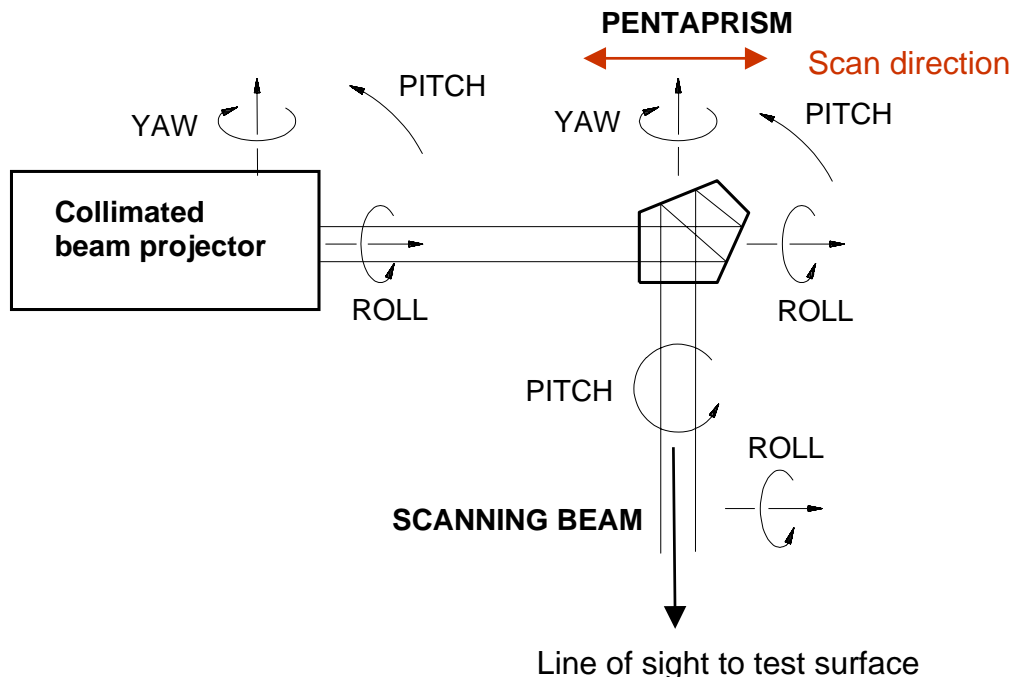
Fig 2: Definition of degrees of freedom for scanning pentaprism

Figure 2 above defines the degrees of freedom for the prism as roll, pitch and yaw. Even though the prism will suffer finite pitch rotation as it is scanned, the deviated beam will have no motion in the pitch direction. This is the magic of the pentaprism.

The system operation measures the angular displacement of the spot from the scanning prism relative to spots from a fixed, reference prism. This system of differential measurements is insensitive to vibrations, motion of the auto-collimator and other common path errors.

2. INTEGRATION

Fig 3a: Above is the test flat. The support structure and the reflection of the pentaprism system is visible
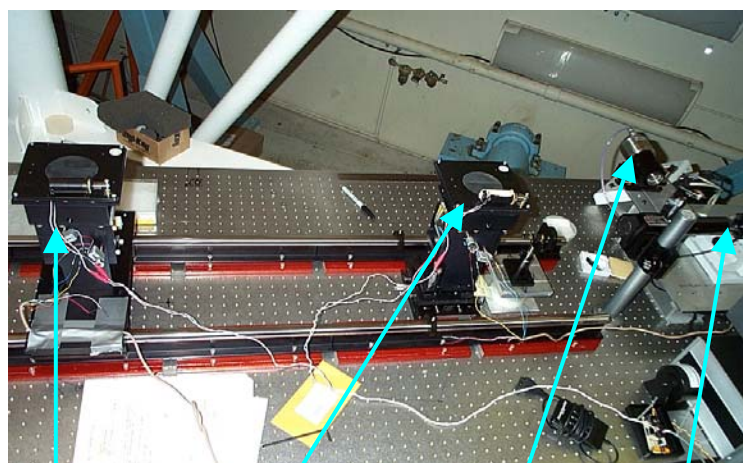
Scanning prism   Reference prism   Alignment autocollimator   Electronic autocollimator

Fig 3b: Above is the as-built system.

2.1 Hardware

The scanning plane must be parallel to the surface under test. The mirror under test was mounted in a test tower 20 meters above the scanning system. The mirror was already mounted many years ago with a tilt of 1.79^0 in the N-S direction. Furthermore, to obtain scans in multiple radial orientations, a rotating system was necessary. An optical table, on which the pentaprism system was built, was placed on a rotating bearing. This rotating bearing was tilted at an angle of 1.79^0. The scanning prism was mounted on a carriage spanning 2 parallel, precision-machined rails. The reference prism was placed between the two rails at the end nearest the autocollimator.

2.2 Electronics

Picomotors control the roll and yaw of each of the 2 prisms. To de-couple the roll and yaw motions of the scanning prism, a reference mirror is attached to the prism mount along the line of sight of an additional autocollimator. A shutter is placed above each prism, and these are connected through an electronically controlled circuit.

2.3 Software

The picomotors, shutters and the output of the autocollimators is controlled by a LabView program.

3. ALIGNMENT

The accuracy and sensitivity of the experiment depend crucially on the optical alignment of the system. To achieve repeatable and accurate alignment, the alignment procedure was divided into 2 steps: coarse alignment and fine alignment. The coarse alignment was accomplished by the use of a standard HeNe laser. The fine alignment step involved the co-alignment of the autocollimator with the HeNe laser, followed by minute adjustments to the autocollimator and prisms to ensure that the 2 return beams are coincident.
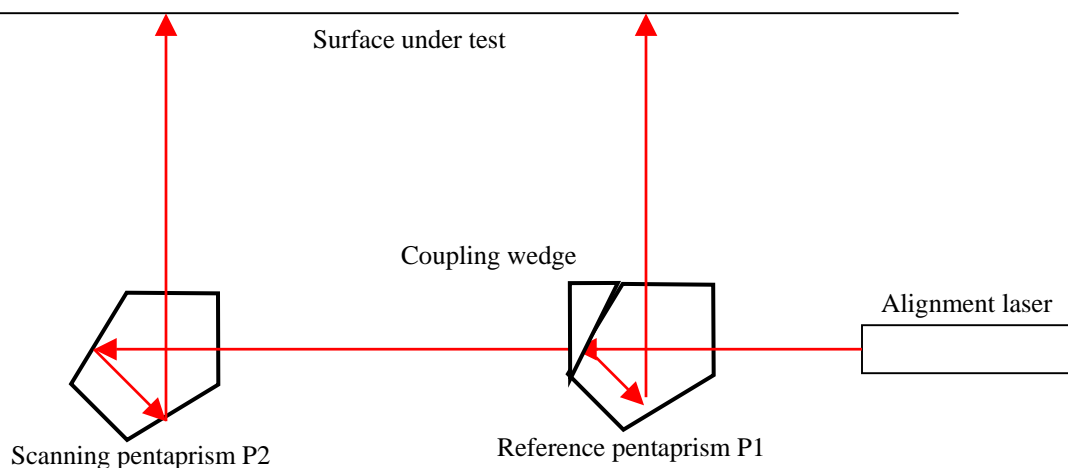
3.1 Coarse Alignment

Fig 4: Above is the schematic for the test alignment setup. The alignment laser (HeNe) is replaced by an electronic autocollimator for making measurements.

3.1.1 Aligning HeNe laser to slide rail and table

The beam height was established by centering the prisms and autocollimators to a common height. The height of the HeNe laser was adjusted to be parallel to the table. This was done by measuring the beam height at 2 different locations along the table and then by adjusting the tilt of the laser accordingly. The HeNe laser was adjusted so that the beam passed through the center of the front and top surfaces of the scanning prism (P2). Now P2 was moved back and forth along the slide rail and the way in which the spot produced by the HeNe laser moved on the front and top surfaces of P2 was observed. The HeNe laser was

translated perpendicular to the rails until spots on the front and top surfaces no longer moved as one translated P2 back and forth along the rail.

3.1.2 Aligning prisms to the test flat

The relative alignment between the 2 prisms was achieved by looking at back reflections from the prism surfaces. These reflections from both prism 1 (P1) and P2 were lined vertically back at the face of the HeNe laser. (There are 2 back reflections from P1 and the 3 others from P2). Adjusting only the yaw controls on the prisms did this. (The roll adjustment does not affect the back reflections).

Now only the roll control was adjusted on P1 and P2 to get the reflected beam from the flat back through the prisms and onto the front face of the HeNe laser. To accomplish this, the table was adjusted making it parallel to the test flat, raising one side at a time with the adjustable jack stands. The return spots from each prism were made to go back onto the front face of the HeNe laser. Further, as P2 was translated these spots were noted to be stationary.

3.1.3 Use of wedge window

The prisms were not fabricated to deviate light by perfectly 90^0. The deviation error in each prism was specified by the manufacturer to be +-5 arcmin. When the prisms were aligned the return spots did not go back through both prisms simultaneously. Hence, a wedge window was used to steer one of the beams back through the prism. The wedge window was placed into a holder on top of P1 and rotated to ensure that both return beams from the test flat went through the 2 prisms simultaneously. The wedge window was glued into this position.

3.1.4 Establishing P1 position

To sample as much of the test flat as possible, P1 was placed at the edge of the test flat. Its position on the table was established by looking at the HeNe laser spot going through P1 incident on the flat. The footprint of the mirror was an irregular hexagon, and the position of P1 had to be determined each time the table was rotated into position for the next scan.

3.2 Fine Alignment

The system was now roughly aligned. However, for fine alignment the procedure given below was used.
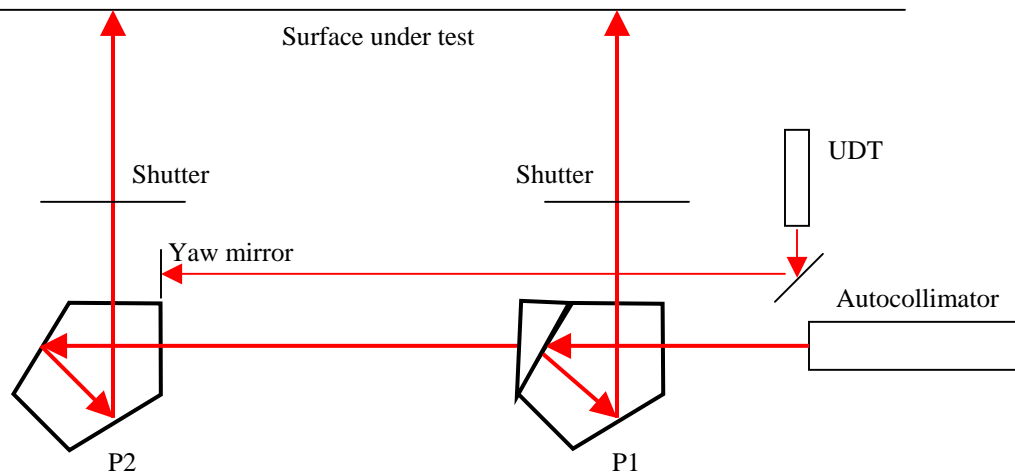

Fig 5: Above is shown the schematic of the full setup.

3.2.1 Aligning the electronic autocollimator

To transfer the HeNe laser alignment to the autocollimator (Elcomat HR, built by Möller-Wedel), a mirror was placed facing the HeNe laser between the HeNe laser and P1. The mirror was adjusted until the reflection was aligned perfectly with the emerging beam. The mirror was now aligned to the system. The HeNe laser was removed from the path of the Elcomat. The Elcomat was aligned to the fixed mirror. The mirror was removed from the path of the Elcomat and the return from each prism was tested separately. The Elcomat was adjusted by small amounts to center the signal in the middle of the instrument range. P1

or P2 roll was also adjusted to ensure that the 2 signals were as close to each other as possible. The Elcomat HR has a sensitivity of 0.01", with a full measurement range of 3000" of tilt.

3.2.2 Aligning the UDT
An additional autocollimator (UDT built by UDT Instruments) helps in the decomposition of the motion of P2 into purely yaw and roll components. The UDT alignment was accomplished by first aligning the HeNe to the reference mirror placed on the P2 mount. The HeNe laser was placed in the UDT mount, in place of the UDT. The tip/tilt of the mirror angled at 45^0 in front of the UDT mount was adjusted so that the HeNe beam was normally incident on the reference mirror on the P2 mount, and the beam reflected back to the face of the HeNe laser. The alignment was fine tuned to ensure that the reflected beam didn't walk off the face of the HeNe laseras P2 was translated along the rails. The HeNe laser was replaced with the UDT. The x, y signal coordinates from the UDT was adjusted to as close to (0,0) as possible by making small adjustments to the 45^0 mirror.

3.2.3 Decoupling yaw and roll with pitch
During scanning one would expect the return beam from the flat to move a little bit due to warping in the rails, slop in the carriage and mounts and due to the fact that the rails were not exactly parallel to the beam from the autocollimator. To recover proper alignment, the prisms are automatically repositioned in roll and yaw by the feedback provided by the 2 autocollimators. To ensure that a change in roll or yaw didn't change the pitch reading on the autocollimator, further adjustments to the prisms were made. The prisms were separately moved in roll and yaw, and the influence of these movements on the pitch reading was observed. The prisms were walked through a series of yaw-roll-yaw movements, until no change in the pitch reading was observed for a range of say, 20 arcseconds of motion in roll or yaw. This was the stage where the autocollimator axes, and the prism axes were coincident.

4. OPERATION AND DATA COLLECTION

4.1 LabView software initialization
The LabView software that operates in a feedback loop to maintain alignment of the prisms during the scanning operation was initialized. During this time the prism initial positions are stored as a file named SetPoints. Slope calculations are then performed, which involves calibrating the range of motion for each picomotor with the Elcomat and UDT readouts. This gives a calibration of the number of picomotor turns vs. arcseconds of beam displacement. This data is stored in another file named Slopes. The slope ranges were adjusted manually, and care was taken not to exceed the range of acquisition.

4.2 Hardware position initialization
Each scan commenced with P2 placed right next to P1. The minimum distance achievable between P1 and P2 was 6". This position established the first scan point. Data was taken every 2 inches from hereon until the opposite edge of the flat was encountered. Each scan crossed the center of the flat.

4.3 Closed loop operation
Starting from the first scan point the LabView software is put into closed loop operation through the Inscan task. The prism shutters open alternately and acquire data averaged over a specified time. We averaged each data point over at least 100sec and often more. The Inscan task was stopped before manually moving the P2 carriage to the next position.

4.4 Ensuring repeatability
Each complete scan comprised a forward scan and a backward scan to ensure that there was repeatability in our operation. The distance between 2 scan points on the forward scan was 4", while the backward scan points were staggered by 2" by taking data midway between these points every 4". In this way we were able to get data every 2".
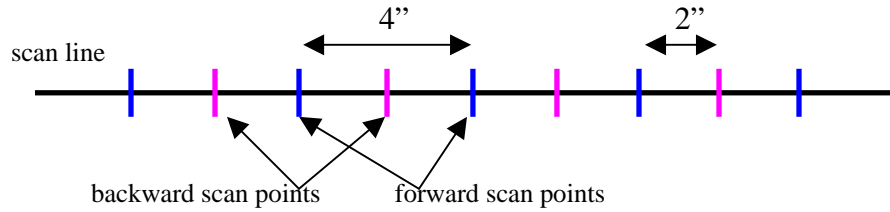
Fig 6: Forward and backward scan schematic.

4.5 Taking multiple scans

After one scan is completed, the table was rotated about the center of the flat on the 'lazy susan' to prepare for the next scan. Scans were taken every 30^0 or so, with 6 complete scans.

4.6 Tackling unsampled areas

Due to system constraints we were unable to sample the area between the position of P1 and the first position of P2 on the 2-meter flat in several places. Therefore, 2 scans out of the 6 were chosen and these scans were extended to the unsampled regions by rotating the table by 180^0 and retaking the scan data. In this way we obtained 8 complete scans, where 2 scans were largely overlaps of their counterparts rotated by 180^0.

4.7. Initial scan measurements

Below are shown the initial 6 repeatable scans. Each point shown is an average of over 4 data points, each recorded over a period of 40 seconds, making each data point an average over 160 seconds. The y-axis is the inscan tilt measurement in mrad. The x-axis is the position measurement in inches.
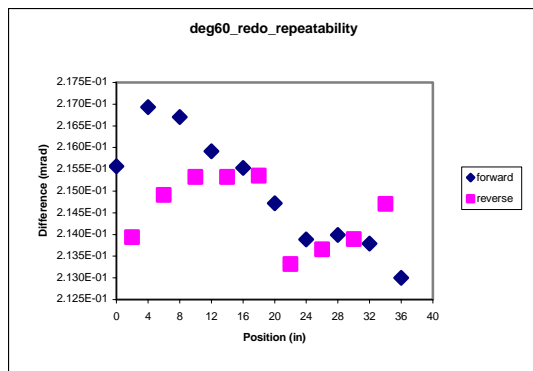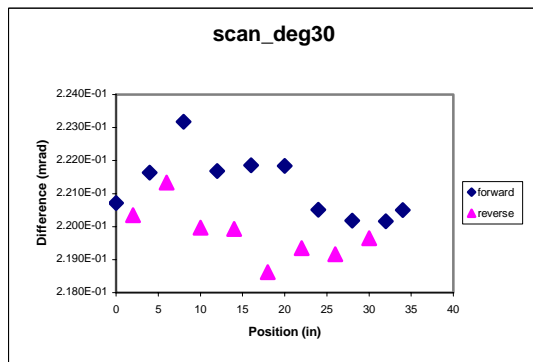

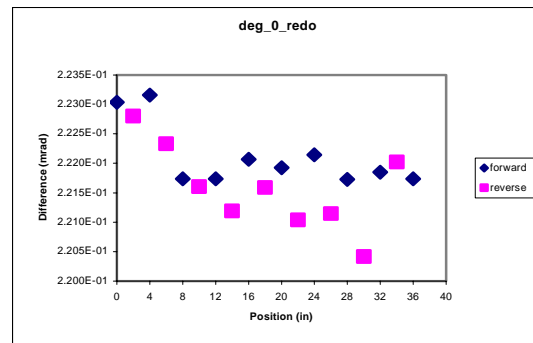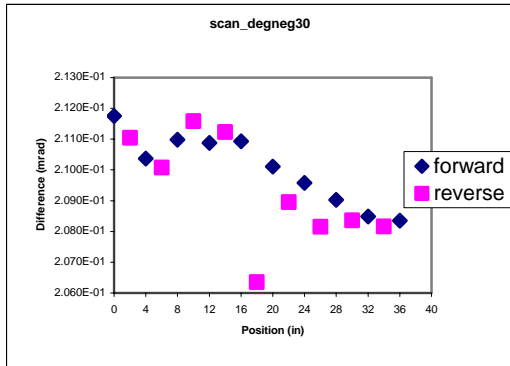Fig 7a: Scan 1
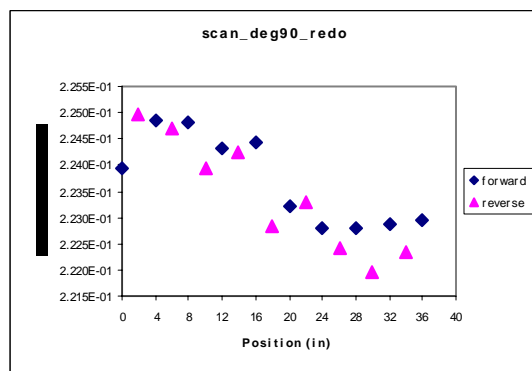
Fig 7b: Scan 2
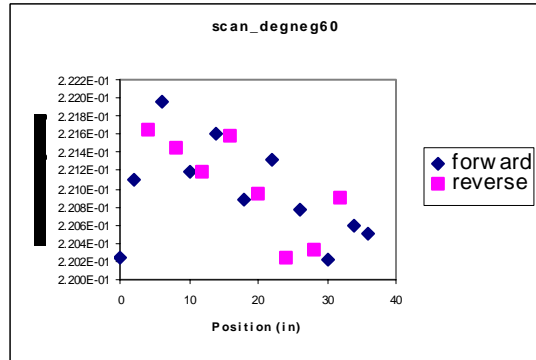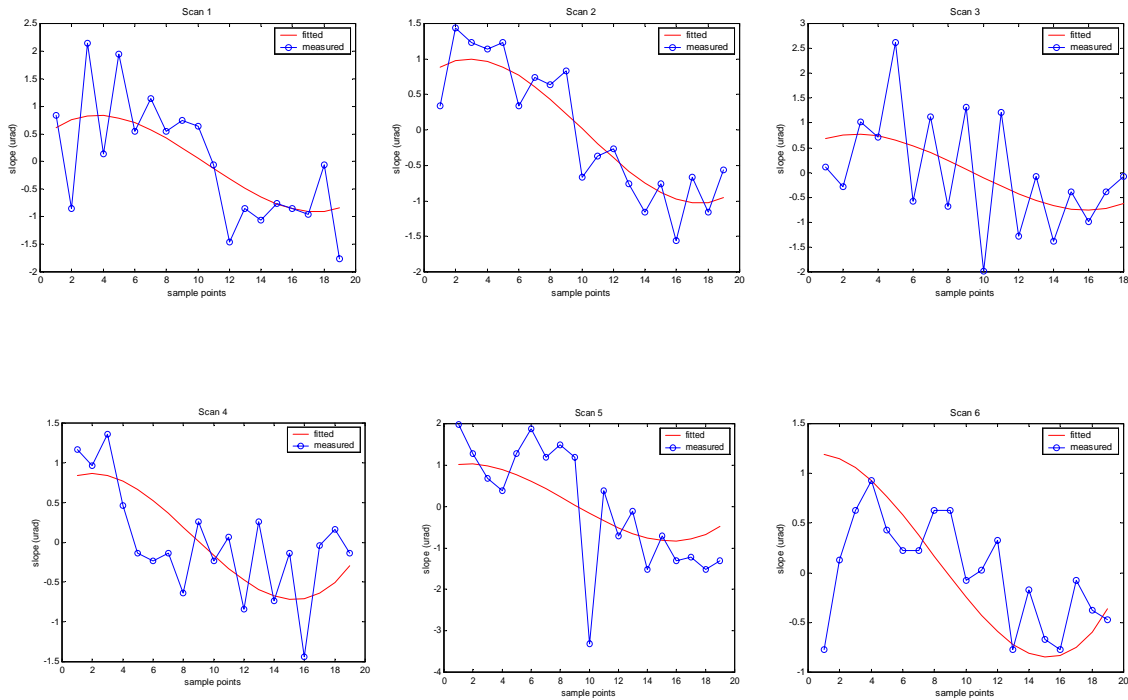

Fig 7c: Scan 3

Fig 7d: Scan 4

Fig 7e: Scan 5

Fig 7f: Scan 6

4.8 Fitted scan data

A Matlab code (written by Noah Siegel) generates the following fitted curves for each scan. The algorithm used is a least squares fit, fitted to as many Zernike modes as one may specify. The curves below are fitted to modes 4 through 11.

4.9 Extra scans

2 extra scans were taken to sample unsampled areas.
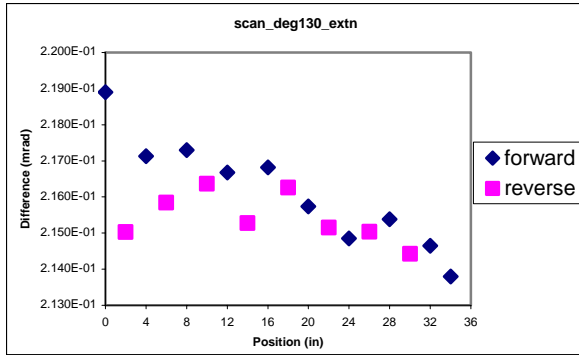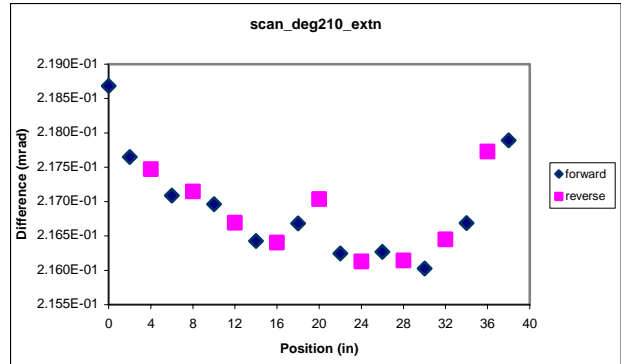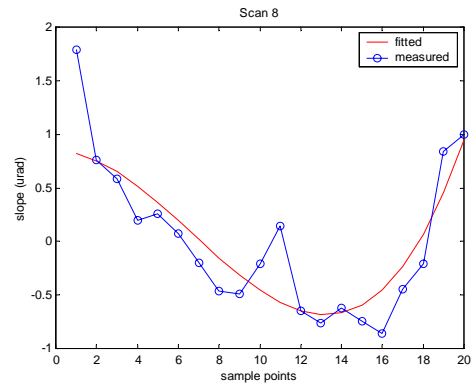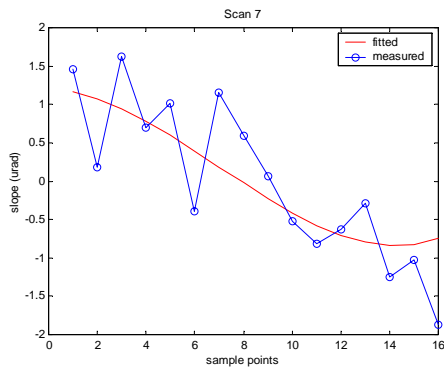The scans are shown below:

Fig 7g: Scan extension 1

Fig 7h: Scan extension 2

The corresponding fitted scans from Matlab are shown below:

5. RESULTS

The schematic below shows, to scale, the full 2.1-meter mirror, the mount structure and the dashed outline of the sampled area over which measurements were made.
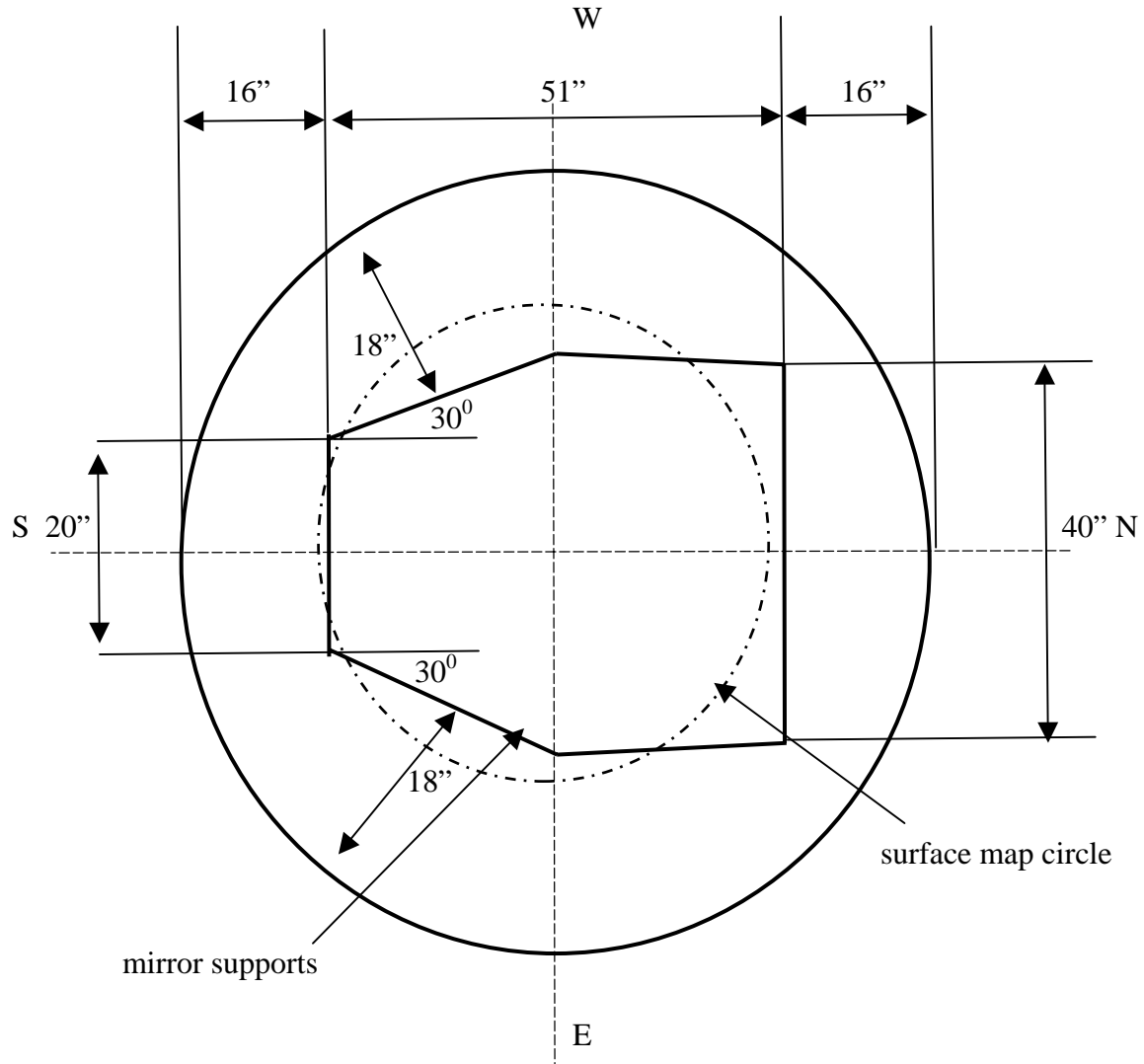

Fig 8: Above is the schematic of the test flat and the support structure.

The surface map circle is determined by taking the longest scan distance as the diameter. Taking any smaller a circle causes some information to be lost without causing the surface map to look any different. The 'x' mark along the scan line labels the location of a data point. There is an overall error in registration of about 1", which is not very significant.

The final output is a surface map of the 2-meter test flat, showing the values for Zernike coefficients 4 to 11.
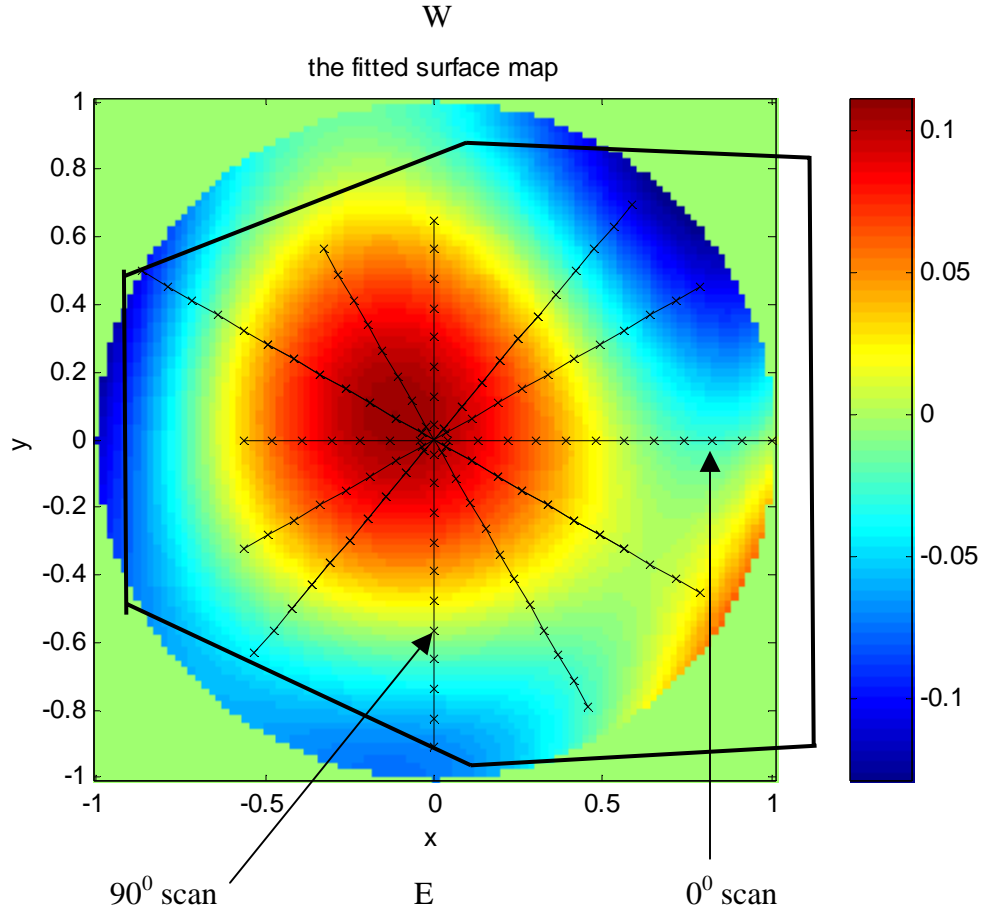
Fig 9: Surface map, showing 6 scan orientations, and sampled points for each scan. Also seen is the registration of the surface map with respect to the mirror mounts.

Power	Cos astig	Sin astig	Cos coma	Sin coma	Spherical	Cos Tref	Sin Tref
-0.091	0.0025	-0.0334	-0.0149	0.0252	0.0236	0.0298	-0.0175

Table 1: Surface error: Zernike aberration coefficients in microns.

6. ERROR ANALYSIS

The pentaprism system had some intrinsic noise associated with it. This noise had several sources, including air turbulence, building vibrations and optical tower flexure. The optical tower is exposed to the sun, and since it is mostly made of metal, it bends away from the sun as the sun moves across the sky. The air turbulence is mainly caused due to the fact the air at the top of the tower is much warmer than the air near the pentaprism setup. Air vents in the building cause some of this air to mix, adding to the turbulence. To characterize this noise the pentaprism setup was used in a staring mode, to look at a fixed position on the test flat over an extended period of time. The difference reading between the 2 prisms is plotted below.
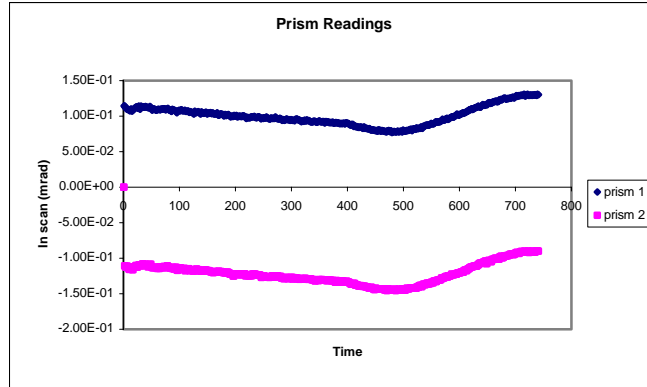
Fig 10: Prism readings in staring mode to characterize system noise.

The standard deviation of the difference between the 2 prism readings is the noise. This was found to be 923 nrad. A program was written to generate random noise and this was added to the data to observe the influence of the noise on the final results. A typical random noise distribution yields the following Zernike errors (in microns of surface error):

Power	Cos astig	Sin astig	Cos coma	Sin coma	Spherical	Cos Tref	Sin Tref
-0.0295	0.0018	-0.1694	-0.0010	0.0833	0.0150	0.0748	-0.0733

Table 2: Noise in surface error: Zernike aberration coefficient errors due to noise.
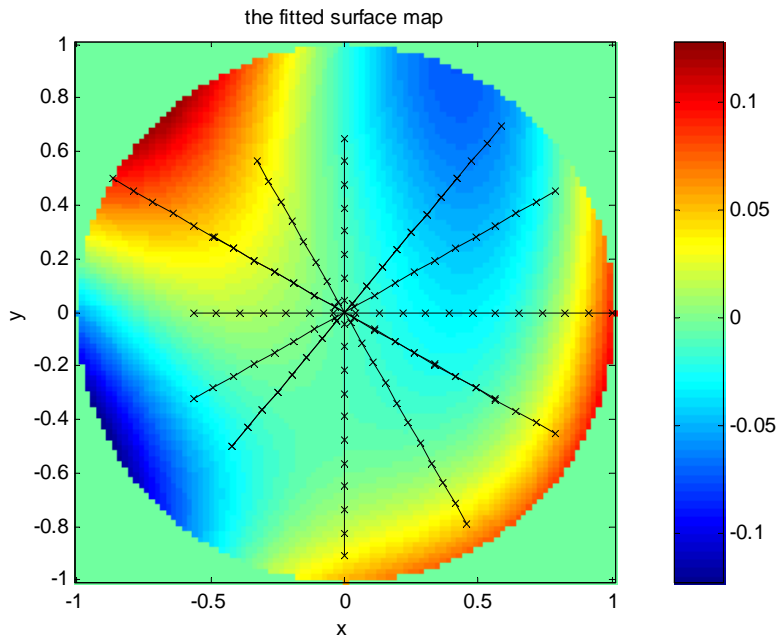

Fig 10: Above shows the noise surface map. This is the error expected in the surface map shown in fig 9.

7. CONCLUSIONS AND FUTURE WORK

The pentaprism test is a reliable absolute test for optical flats. It should also be noted that measurements an order of magnitude better can be made with the use of higher quality pentaprisms, in more controlled environments. Our future pentaprism testing systems plan to measure surface tilts of 50nrad or less. We plan on measuring surface flatness of liquid mirrors over long baselines using a similar setup as an absolute calibration test.

ACKNOWLEDGEMENTS

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