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NANOMETER PRECISION IN LARGE SURFACE PROFILOMETRY*

Peter Z. Takacs
Brookhaven National Laboratory
Upton, NY 11973-5000

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Peter Z. Takacs
Instrumentation Division 535B, Brookhaven National Laboratory
Upton, NY 11973 USA

Abstract

The Long Trace Profiler (LTP) is in use at many synchrotron radiation (SR) laboratories throughout the world and by a number of manufacturers who specialize in fabricating grazing incidence mirrors for SR and x-ray telescope applications. Recent improvements in the design and operation of the LTP system have reduced the statistical error in slope profile measurement to the 1 standard deviation level of 0.3 microradian for 0.5 meter long mirrors. This corresponds to a height error on the order of 10-20 nanometers. This level of performance allows one to measure with confidence the absolute shape of large cylindrical aspheres and spheres that have kilometer radii of curvature in the axial direction. The LTP is versatile enough to make measurements of a mirror in the face up, sideways, and face down configurations. We will illustrate the versatility of the current version of the instrument, the LTP II, and present results from two new versions of the instrument: the *in situ* LTP (ISLTP) and the Vertical Scan LTP (VSLTP). Both of them are based on the penta prism LTP (ppLTP) principle that utilizes a stationary optical head and moving penta prism. The ISLTP is designed to measure the distortion of high heat load mirrors during actual operation in SR beam lines. The VSLTP is designed to measure the complete 3-dimensional shape of x-ray telescope cylinder mirrors and mandrels in a vertical configuration. Scans are done both in the axial direction and in the azimuthal direction.

Keywords: Metrology; Profilometry; Figure measurement; X-ray mirrors; Aspherics

1. Introduction

The Long Trace Profiler (LTP) is a non-contact optical profiling instrument used for measuring the surface slope and figure errors on large cylindrical mirrors, such as those used in x-ray beam lines at synchrotron radiation (SR) light sources [1, 2]. Surface slope errors with a magnitude of a few microradians on grazing-incidence mirrors seriously compromise the beam quality of 3rd generation SR sources. Knowledge of the precise surface curvature of meter-long cylindrical and toroidal mirror segments is essential for the proper assembly and alignment of SR beam lines. The much-improved commercial version of the LTP (LTP II) is optimized for measuring the absolute surface figure of the large, long-radius mirrors used in these beam lines [3].

Recent improvements and modifications to the LTP II system have significantly improved the repeatability and accuracy of the measurement and extended its measurement applicability to other types of optical components. These improvements and modifications include the addition of a Dove prism to the standard LTP II optical configuration [4, 5] and implementation of the penta prism LTP (ppLTP) technique [6] in two versions: the *In Situ* LTP (ISLTP) [7, 8] and the Vertical Scan LTP (VSLTP) [9-12]. The ISLTP has been successful in measuring mirror heat load distortion at ELETTRA in Italy and at the Advanced Photon Source (APS) at Argonne National Laboratory. The VSLTP was developed for NASA Marshall Space Flight Center by Continental Optical Corporation in collaboration with BNL through a NASA SBIR grant

2. LTP II Operating Principle

Based on the principle of the pencil-beam interferometer developed by von Bieren [13, 14], the LTP is optimized for measuring large flats and spheres and especially aspheric surfaces with extremely long radii of curvature in the tangential direction, such as grazing incidence toroids and cylinders. The standard LTP II configuration has a nominal scan length of 1 meter and is designed to measure concave and convex surfaces that have at most a total slope change of 10 mrad. The shortest radius of curvature, R_{min}, that can be measured over a given scan length, L, must satisfy the following inequality:

$$\frac{L}{|R_{\min}|} \le 10\ mrad. \qquad (1)$$

The length of the scan is limited only by the length of the air bearing translation stage used to move the optical head. The largest scan length systems currently are 2 meters at ESRF in Grenoble[15]and at the APS [16].

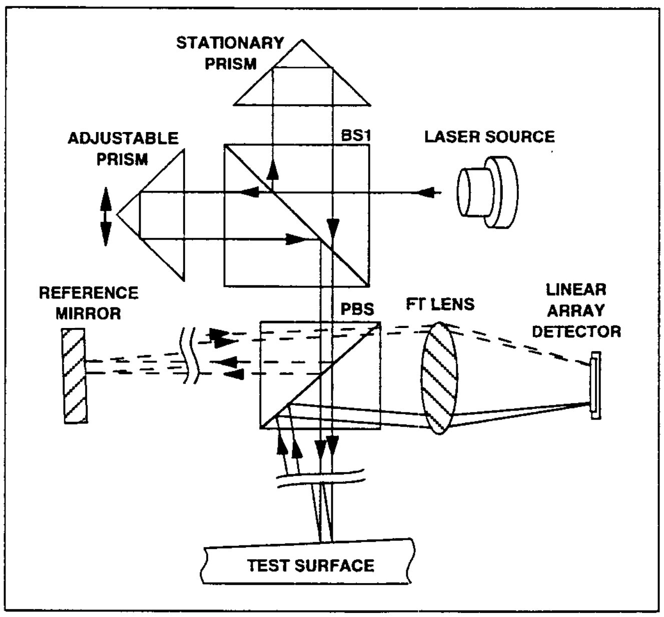

Fig. 1 Schematic diagram of the standard LTP II optical system.

The LTP measures the local slope profile of a surface by measuring the angle at which a laser probe beam is reflected as it is translated across the surface by a linear translation stage [1, 13, 14]. A simplified schematic of the LTP optical system is shown in Fig. 1. A beam splitting arrangement separates a laser beam into a pair of collinear beams, separated by a distance of about one millimeter. The beam pair is split again into two sets of probe pairs by a polarizing beamsplitter (PBS), and each set is separately directed into the reference arm or the test surface arm of the system. Upon reflection from the test and reference surfaces, both sets of beams are directed back into the optical head, where they pass through a Fourier transform lens, and are brought to a focus on a linear array detector. Each set of beam pairs produces its own interference fringe pattern on the detector, and the location of the minimum in each fringe pattern is a direct measure of the local slope of the surface.

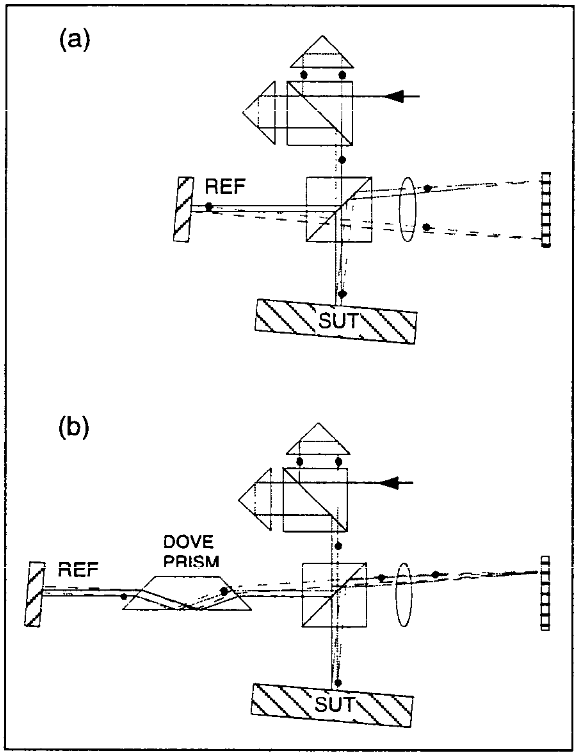

Fig. 2 Phase relationship between thermal and mechanical errors in the test and reference beams (a) without, and (b) with the Dove prism installed in the LTP II optical head. The pitch angle error is shown highly exaggerated.

3. Error Reduction Methods

As the optical head of the standard LTP II is driven along the translation stage, the major source of measurement error is caused by pitch angle error in the direction of travel. Pitch angle error causes the test and reference beams to move in <u>opposite</u> direction on the detector (Fig. 2a).The magnitude of the carriage pitch error can be on the order of tens of microradians. Changes in temperature and temperature gradients in the optical and mechanical components produce angular errors that cause the fringes to move in the <u>same</u> direction on the detector. The reference arm was mainly designed to correct for mechanical pitch error by adding the reference signal to the test signal, since the magnitude of the pitch error is usually much greater than the thermal drift error. Unfortunately, correcting both errors at the same time in the standard LTP II is not possible [4-6, 17]. The residual error left in the processed data is a significant limitation in achieving high accuracy with the standard LTP II.

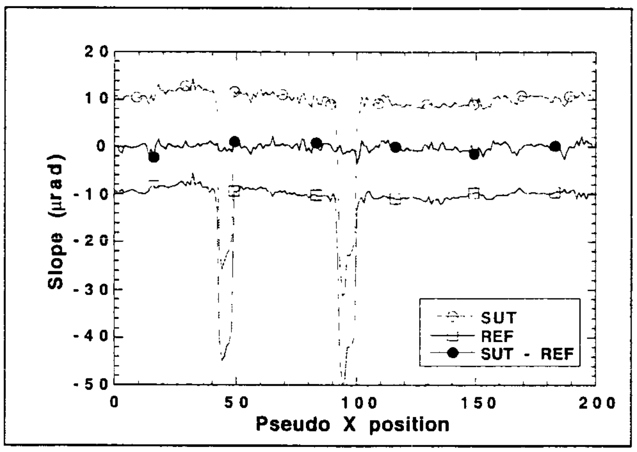

Fig. 3 Error correction with Dove prism. External force applied to the optical head causes large error signals in test and ref beams that are completely corrected. RMS of residual is 0.86 μrad.

Various methods have been devised for dealing with these error sources[3, 17-20]. We have chosen to implement two other methods for pitch error correction: the Dove prism method for the LTP II, and the penta prism LTP method.

The sense of the pitch error

term alone can be changed by inserting a Dove prism into the reference arm on the LTP II optical head [4, 5]. This enables simultaneous correction of thermal and mechanical errors by a simple subtraction of the test and reference signals. By tracing the path of the reference beam through the system in Fig. 2b, we can see that pitch error causes the beams in both the test and reference arms to move in the same direction. The thermal drift error phase is unchanged. Subtraction of the test and reference signals in Fig. 2b now cancels both thermal and mechanical errors completely. Fig. 3 illustrates the completeness of the correction for mechanical error. As the scan was recorded, force was applied to the optical head to produce a large pitch error. The reference subtraction completely removes both errors, leaving a 0.86 μrad residual, which is essentially system noise.

The other pitch error reduction method is to use a scanning penta prism and a stationary optical head. This scanning method is identified as the penta prism LTP (ppLTP) [6]. The penta prism is driven by a translation stage containing mechanical pitch errors. However, the nature of the penta prism is such that the probe beam is always deviated by a 90° angle, independent of errors in the orientation of the penta prism. So with this scanning penta prism configuration, we need not make any corrections for mechanical pitch error. In the ppLTP the reference signal is used to correct only for the thermal drift errors.

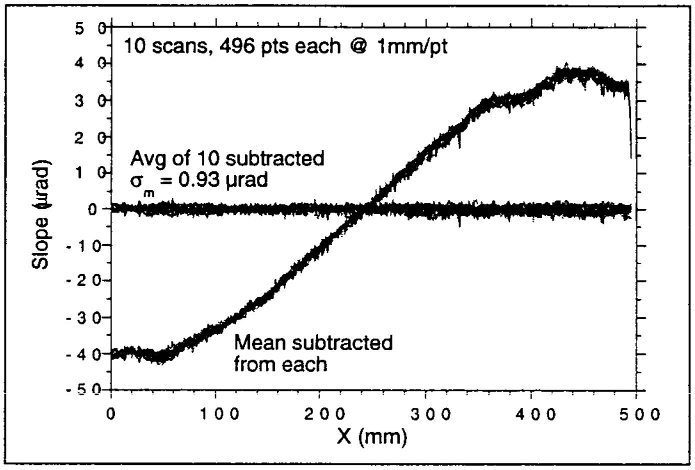

Fig. 4 Overlay of 10 scans on a 500 mm long mirror. Curves about zero are residuals after subtrating the average from each.. The 1 σ error bar for the average slope profile is 0.29 μrad.

4. Repeatability

Fig. 4 shows ten scans made with the Dove prism LTP II on a 500 mm long test mirror that are overlaid on each other to illustrate the repeatability in the measurement. Subtracting the average from each, we can overlay the residuals and view the slope error noise in each scan, shown as the curves about the horizontal center line. The standard deviation in the residuals is 0.93 μrad rms, while for the average of the ten the noise is less by a factor of

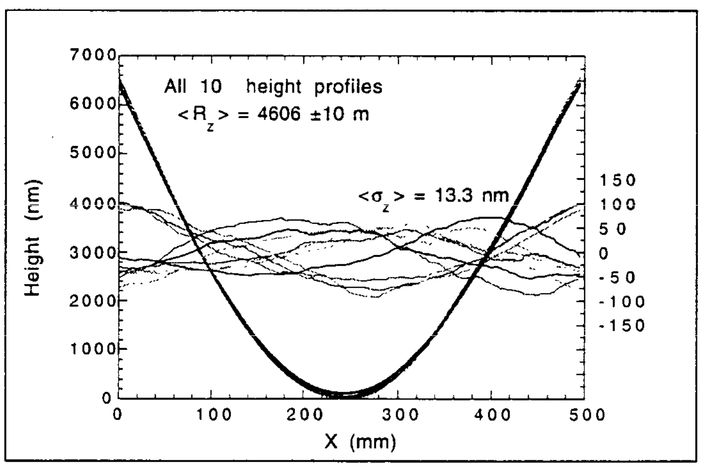

Fig. 5 Height profiles and residuals computed from the 10 slope profiles. in Fig. 4.

$\sqrt{10}$, which gives the standard deviation in the mean as 0.29 μrad rms for this data set. The corresponding rms error bars for the height residuals in Fig. 5 are 42 nm rms for a single scan and 13.3 nm rms for the average. The mean radius of the average height is 4606 meters with a standard deviation in the mean of 27 meters. The 0.6% relative error in the average is an excellent repeatability result for a long radius mirror measurement.

Tests to show the insensitivity of the ppLTP to errors in the mechanical stage are shown in Fig. 6. Curve (a) is the result of testing a mirror with the penta prism mounted on a mechanical slide that has a 25 μrad pitch error, and curve (b) is the result with a penta prism mounted on a high accuracy air bearing slide. Though the two slide accuracies are very different, the maximum difference between the measured profiles is only on the order of 10 nm. By eliminating pitch error effects in this way, the ppLTP operating routinely at ELETTRA is extremely stable and capable of highly accurate measurements [21]. Based on the success of the ppLTP method, two versions of the LTP II have been developed for different applications: the ISLTP and the VSLTP.

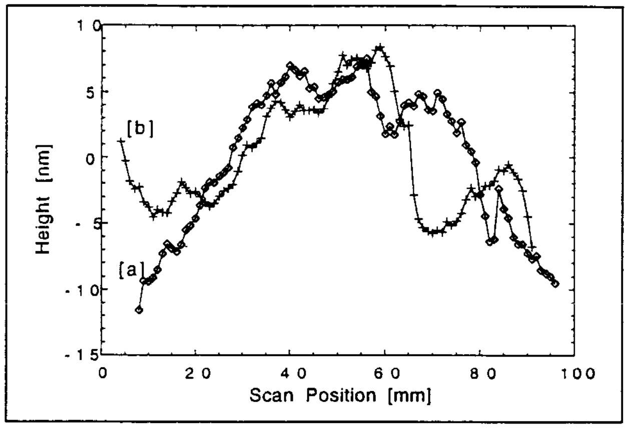

Figure 6. Measurements made with the ppLTP with the penta prism mounted on two slides of very different quality: (a) penta prism on a mechanical slide; (b) penta prism on an air bearing slide. Large pitch angle errors in the mechanical slide do not affect the accuracy of the measurement.

5. *In Situ* LTP (ISLTP) for High Heat Load Optics

In order to test mirror distortion under actual high heat load operating conditions from third-generation synchrotron light sources, the *in situ* LTP (ISLTP) was developed initially at ELETTRA [7, 21] and then through a collaboration between BNL, APS, and Continental Optical Corporation [22]. There are two basic configurations for *in situ* ppLTP distortion tests on SR beam lines. In both cases, the LTP optical head is always operated outside the vacuum chamber, while the test and the reference pencil beams pass from the laboratory environment into the (normally ultra-high) vacuum chamber. Depending on the specific problems and the mirror conditions, the two configurations for scanning the penta prism over the mirror surface are illustrated in Figure 7.

5.1 Configuration (a)

The penta prism and translation stage are mounted outside the vacuum chamber (Fig. 7a). In this case the sampling beam must pass through a large vacuum-isolation window which usually limits the length of the scan to be significantly less than the length of the mirror. Reference reflection and adjustment units are also located outside the window. In this case the entire profiler is operated under atmospheric pressure with the convenience of not having to deal with UHV components. For this

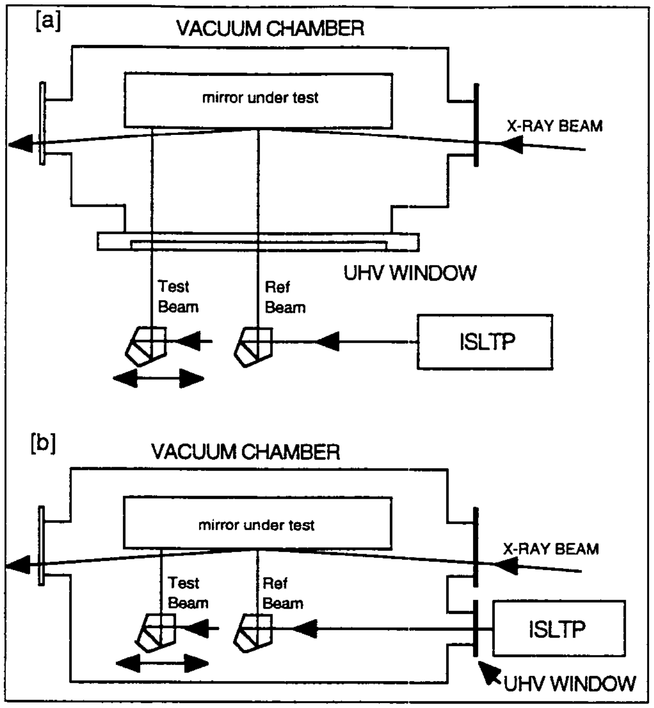

Fig. 7. Two alternatives for the in situ LTP distortion profile test by use of a penta prism LTP: [a] -- Penta prism scans outside the vacuum chamber with the beams through a large window. [b] -- Penta prism scans inside the vacuum chamber with the beams through a small window. The reference beam remains stationary in each configuration, reflecting from a fixed point on the surface.

reason this configuration was used for the *in situ* distortion profile tests at ELETTRA and at the APS [21, 22].

5.2 Configuration (b)

The penta prism is scanned inside the vacuum chamber (Fig. 7b). This configuration requires only a relatively small window to pass both the test and reference beams through the wall of the vacuum chamber. However, it does require more complicated ultra-high vacuum-compatible linear translation stage components and requires that the translation mechanism leaves no contamination on the mirror surface. In the case of a long mirror, this solution may be favorable even though it may require significant design work to implement.

6. APS Mirror Distortion

Recent measurements made at the Advanced Photon Source at Argonne National Laboratory have confirmed that distortion of mirrors subjected to the intense beams in 3rd generation synchrotron source beam lines is a serious problem [22]. Results from a set of measurements made on a 200 mm long Si mirror exposed to x-rays from the 2-ID-A 2.4 meter, 5.5 cm period undulator are shown in Fig. 8. These measurements were made with a beam current of 100 ma. The estimated total absorbed power in the mirror is 100 Watts. The scans were made using configuration (a) through a 90 mm diameter window. Each scan takes about 2 minutes to complete, and the scanning started immediately after the front end shutter was opened. A baseline profile is subtracted from each scan to remove the intrinsic surface radius of 1 km and the distortion effects of the UHV window.

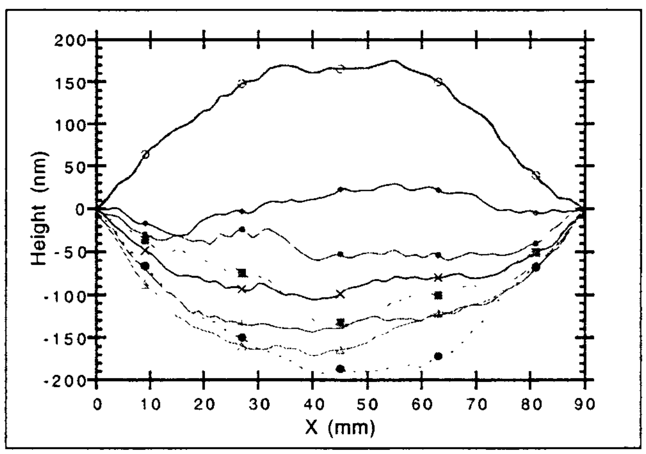

Fig. 8 - ISLTP scans of distortion on the M2C side-cooled Si mirror in the 2-ID-A beam line at the APS. Initial convex distortion turns into a steady-state concave surface after about 15 minutes of exposure.

The height profiles in Fig. 8 indicate that the initial transient distortion in the mirror is convex, as expected as the surface begins to heat up and expand. After a few minutes the surface returns to its original shape and then becomes more concave. After about 15 minutes a steady-state is reached with the surface in a more concave configuration, corresponding to a 20% change in the initial 1 km radius of curvature. When the shutter is closed and the heat load is removed, the surface becomes even more concave before it returns to its original baseline shape. The change in the steady-state curvature of the surface when it is exposed to the x-ray beam heat load is significantly larger than predicted by finite element calculations. The cause of this discrepancy is currently under investigation.

7. Vertical Scan LTP for X-Ray Telescope Optics

A critical problem in the fabrication of mirrors used in x-ray telescope systems is the lack of adequate metrology techniques to characterize the surface figure errors in the cylindrical aspheres used in these systems. Based on the requirements of a NASA SBIR program, and utilizing the ppLTP principle described previously, a Vertical Scan Long Trace Profiler (VSLTP) was developed to enable fast and accurate measurement of Wolter telescope mirrors and mandrels [9, 10]. The instrument is capable of scanning the inside or outside surfaces of mirror shells or mandrels in a vertical configuration. This configuration is necessary to minimize measurement artifacts in the thin-walled cylinders introduced by gravity sag. The present system is capable of measuring inside diameters as small as 100 mm with a vertical travel distance of 700 mm.

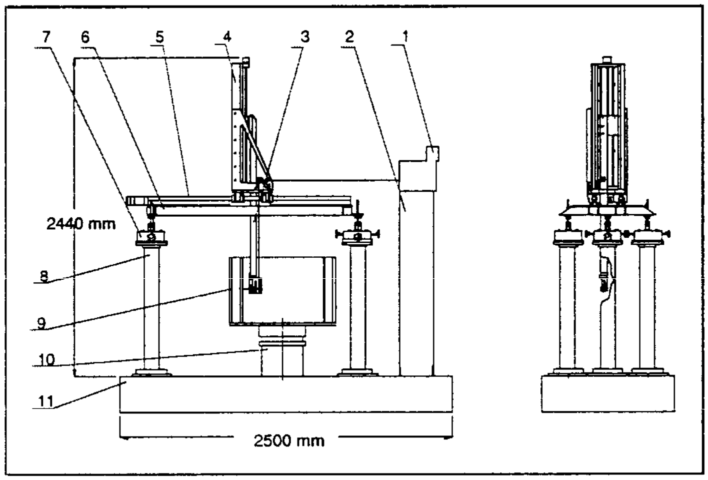

Fig. 9 Major components of the Vertical Scan LTP (VSLTP): 1. Optical head; 2. Support pier; 3. Beam director; 4. Vertical slide; 5. Horizontal slide; 6. Frame; 7. Kinematic mounts; 8. Legs; 9. Nested shell mirrors under test; 10. Rotary table; 11. Optical bench.

The X-ray telescope mirrors to be tested by the VSLTP are thin cylindrical shells, each consisting of a paraboloidal segment and an hyperboloidal segment, each with a long axial radius of curvature (typically hundreds of meters) and a short sagittal radius (usually between 10 and 100 cm), They are nearly impossible to test by conventional interferometric techniques. In addition, the thin shells are very susceptible to self-weight deflection caused by gravity and should be tested in a vertical configuration. To fully characterize the surface slope and height topography, the VSLTP needs to scan each segment in both the axial direction and the azimuthal direction This requires the ability to scan in two orthogonal scan directions, one purely translational, the other purely rotational. The two components of the test beam must, however, always be aligned parallel to the scan direction. The azimuthal scans require that the test beam pair be rotated by 90°. A Dove prism inserted into the test beam arm produces the desired beam rotation when it is rotated by 45° about its optical center line. It should be noted that the azimuthal scan measures departures of the surface from some nominal circular radius. At present the system is not configured to measure the absolute azimuthal radius.

Fig. 9 shows a sketch of the major parts of the VSLTP prototype instrument. They include the optical head and its support pillar, the horizontal ball bearing slide with a travel distance of 900 mm, the vertical ball bearing slide with a travel distance of 750 mm which is mounted on the horizontal slide, an air bearing rotary table capable of rotating 360 degrees, with a tilt/centering table mounted on the rotary table used to align the mirrors and mandrels under test. The overall dimensions of the instrument are about 2.5m x 2.5m x 1m.

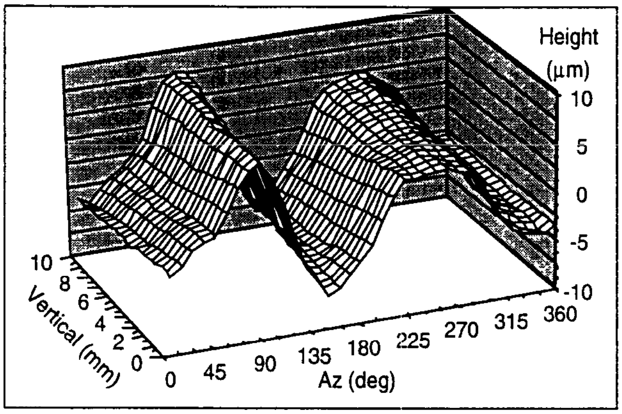

Fig. 10 Combined 10 mm long vertical and 360° azimuthal scans by the VSLTP made on the inside of a Wolter I telescope shell. The theoretical paraboloidal surface has been subtracted, as have rigid body alignment errors. The residual surface error is predominantly several microns of eccentricity between two orthogonal directions.

Measurements were made with the VSLTP on the inside of an electroless nickel Wolter I telescope shell which was replicated from a polished stainless steel mandrel. The diameter of the shell was only 11 cm. and represents the smallest inside diameter that can be measured with the present configuration. Vertical (axial) scans 10 mm long were made at intervals of 5 degrees over one complete revolution of the cylinder. Three complete 360° azimuthal scans were made at vertical height positions of 0, 5, and 10 mm. The combined axial and azimuthal scans are unfolded in azimuth and plotted in Fig. 10 to show the complete surface topography of this segment of the telescope. The ideal theoretical paraboloidal surface has been subtracted from this data, in addition to the effects of imperfect alignment of the cylinder with respect to the rotation axis of the rotary stage. The residual surface error map in Fig. 10 shows that the predominant error in the shell appears to be several microns of eccentricity between two orthogonal directions. The mandrel surface, from which this replica was made over ten years ago, is of much higher quality than the replica. Preliminary tests during the commissioning of the VSLTP indicate that the instrument is capable of microradian slope measurement repeatability and sub-micron height repeatability over its large scan range.

8. Summary

The LTP has been under development and in routine operation at BNL for the past 12 years. The LTP II is considered the instrument of choice by most SR laboratories and mirror manufacturers for measuring x-ray mirror surface slope and figure errors.

Owing to recent significant performance improvements, the LTP's repeatability and accuracy has been increased by an order of magnitude, with slope error bars for typical measurement parameters now in the range of 0.3 μrad rms and with height error bars in the 10 to 20 nm range. Several special versions of the LTP have been developed recently, including the ISLTP and the VSLTP. The LTP has the potential for wider applications in the fields of high power laser optics, FEL optics, adaptive optics, and X-ray or large aperture telescope optics, wherever large aspheric mirrors are used, or wherever absolute measurement of long-radius curvature or surface flatness is required.

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