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Authors
Irick, S.C.
McKinney, W.R.
Lunt, D.L.J.
et al.

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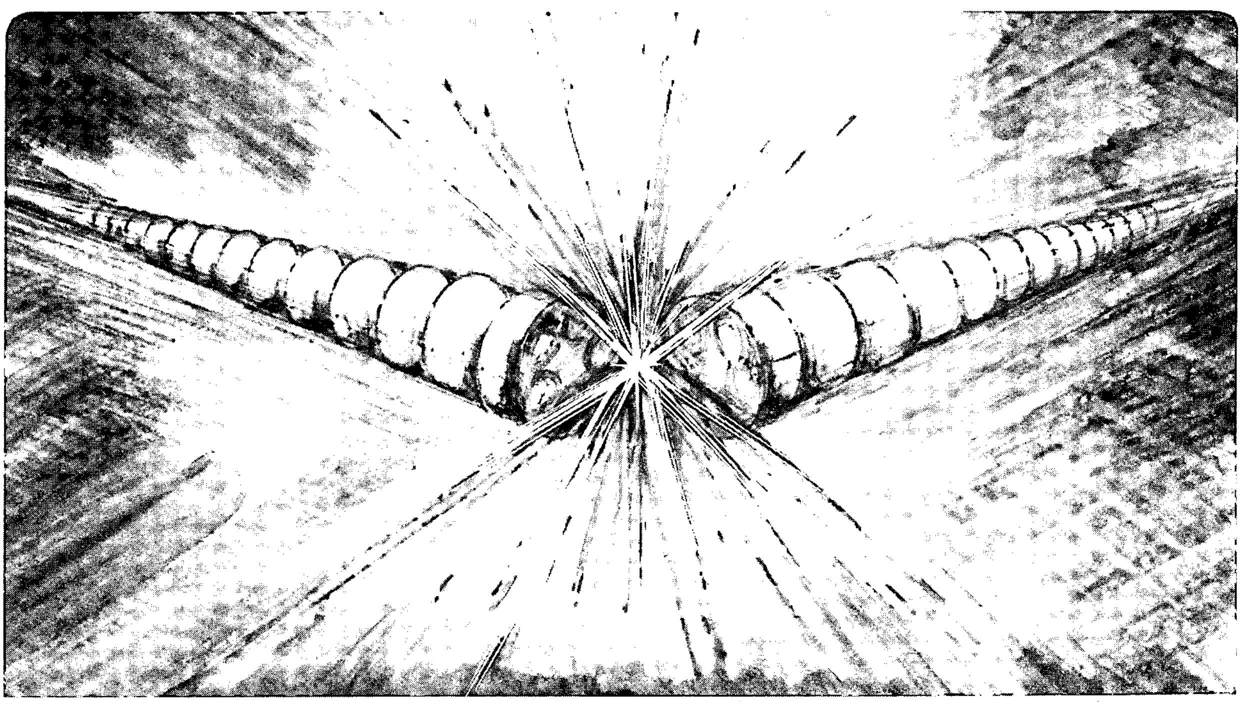

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S.C. Irick and W.R. McKinney

Advanced Light Source
Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

D.L.J. Lunt

Tuscon Optical Research Corporation
Tuscon, AZ 85719

P.Z. Takacs

Brookhaven National Laboratory
Instrumentation Division
Upton, NY 11973

July 15, 1991

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S. C. Irick and W. R. McKinney
Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720 USA

D. L. J. Lunt
Tucson Optical Research Corporation
Tucson, AZ 85719

P. Z. Takacs
Brookhaven National Laboratory
Instrumentation Division
Upton, NY 11973

Abstract

The Long Trace Profiler (Takacs et al.) has found significant applications in measuring the surfaces of synchrotron optics. However, requirements of small slope errors at all spatial wavelengths of the synchrotron optics mandate more accurate slope measurements. A straightness reference for the Long Trace Profiler greatly increases the accuracy of the instrument. Methods of using the straightness reference by interpreting the sequential interference patterns are discussed and results of measurements are presented.

Introduction

Optics for synchrotrons form a distinct class of optics because of the interaction of very intense short wavelength radiation with the optical material. Ordinary surfaces are effective at reflecting the radiation only at grazing incidence. For this reason the optic must be fairly long even if the radiation beam is only a few mm in diameter. Typical focusing mirrors in synchrotron beamlines may be up to one meter long. Focusing in the tangential meridian is then accomplished with radii of curvature that are typically meters to kilometers.

Important characteristics of these surfaces to be measured are scattering by the surface roughness and imaging aberrations caused by deviations from the ideal surface figure. Of course, scattering and imaging at the soft X-ray wavelengths is what matters. Determining surface finish (roughness) and figure, however, may be done with visible light methods, which are easier to work with. The effects of these on the shorter wavelengths may be determined later[1].

Several instruments are commercially available that can measure surface finish (surface sampling interval < 1 mm)[2]. However, most commercially available non-contacting instruments are limited in either the range of surface figure they can measure (short radii or infinite radii of curvature, but not a radius of, say, tens of meters) or the size of aperture they can measure. The Long Trace Profiler (LTP), developed by Takacs et al. [3,4], was designed to fill this need: to measure the surface figure (spatial periods from 1 mm to 1 m) of such optics. The LTP actually measures the slope of a surface at many places on the surface; from the slope function of the surface the height profile may be obtained. Earlier, K. von Bieren used a similar technique to measure rotationally symmetric aspheres with a pencil-beam interferometer[5].

Operation of the Long Trace Profiler

Figure 1 shows the main components that make up the system of the LTP. The most complex component is the optical carriage, which contains a motor for propelling the carriage along the ceramic beam, air-vacuum bearing pads, a readout head for precisely determining position of the carriage with respect to the ceramic beam, a photodetector array for sending interference pattern information to the computer, and an optical system for providing beams of light to surfaces whose slopes are to be measured.

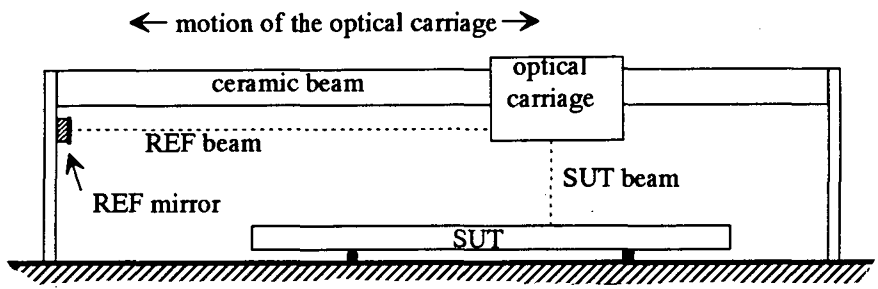

Figure 1. Schematic of the Long Trace Profiler.

A schematic of the optical system is shown in Figure 2. Light from the laser diode is collimated and sent to a beamsplitter BS1 and corner reflectors CR1 and CR2 so that two parallel, collimated, coherent beams emerge downward toward the surface under test (SUT). The beams reflect from the SUT back into the optical system, and beamsplitter BS2 directs the returning beams into the Fourier transform (FT) lens, which produces an interference pattern at the detector array. The interference pattern is produced very much as in Young's double slit experiment[6]. The interference pattern contains a sinusoidal component whose phase (position along the v axis) depends on the angle of the beam pair with respect to the optic axis, or on the phase difference in the light between the two beams. In either case, the position of the sinusoidal component will depend on the slope of the surface under test (SUT) with respect to the x axis.

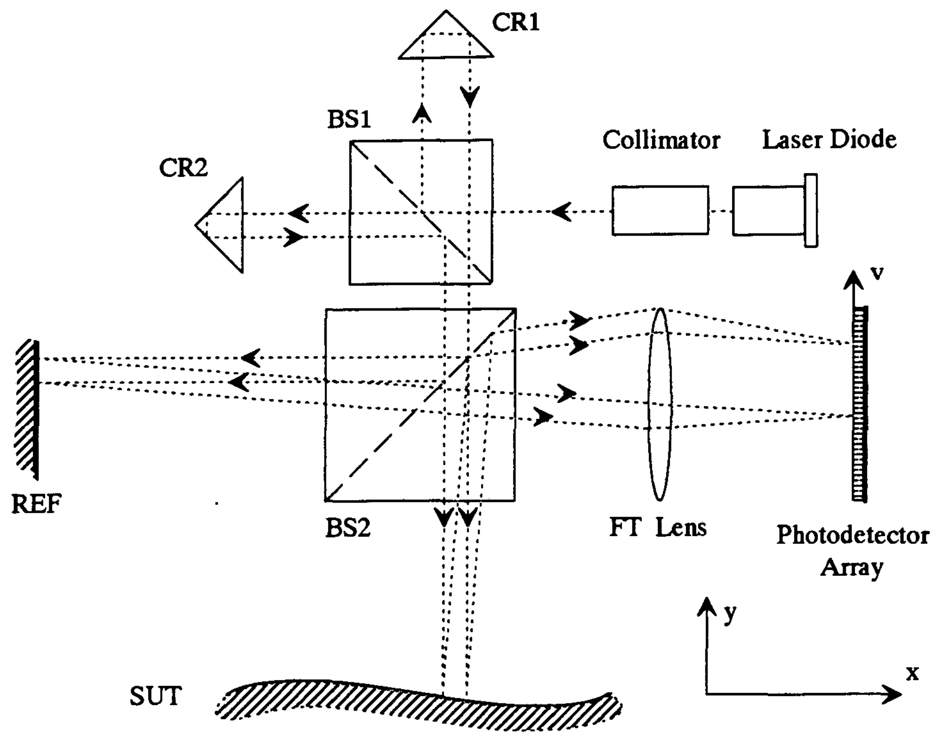

Figure 2. Schematic of the optical system.

The optical carriage moves along the ceramic beam from one end of the SUT to the other end. As it does so, at regular intervals along the SUT the light beam pair from the SUT is reflected back into the optical system and the interference pattern produced by the beam pair is sensed by the detector array. The slope of the SUT is determined by analyzing the interference pattern at each interval on the SUT.

Ideally, the position of the sinusoidal component of the interference pattern (and hence the slope calculated from this) will depend only on the slope of the SUT. In reality, the position will depend on a number of additional factors:

1. Beam pointing instability in the laser. As the beam propagation direction at the laser changes, the angle of the beam with respect to the optic axis also changes. This adds to the measured slope of the SUT.

2. Ceramic beam sag and other variations from a flat surface. As the optical carriage moves along the SUT, the carriage follows the "flat" top surface of the beam. Air bearing pads allow the ceramic surface to be followed within several microinches. However, any variations of this surface from perfectly flat, including sag of the beam in gravity, will cause the carriage to pitch back and forth as the carriage moves. This results in a change in incident angle of the beam pair at the SUT, which changes the apparent slope of the SUT.

3. Refractive index changes in the air where the beams propagate. Two sources of this are air turbulence and sound. Air turbulence can come from room air currents or from items in the vicinity of the LTP that have a different temperature. Sound vibrations are generally of a high enough frequency to not significantly affect LTP measurements, but they may induce mechanical vibrations in the measurement system.

4. Dimensional changes in the mounting between the SUT and the optical carriage. This can be caused by two phenomena: 1) Thermal stress relief from different parts of the LTP system having different temperatures; 2) mechanical stress relief from unstable mounting or elasticity in components.

Using a Straightness Reference

The above factors (1) and (2) (beam pointing instability and ceramic beam sag) may be compensated for by using the extra light beam pair produced by beamsplitter BS2 as a straightness reference. The extra beam pair reflects from a reference mirror (REF in Figure 2), enters BS2, and is focused by the FT lens to form another interference pattern at the detector array. The REF mirror is fixed with respect to the SUT mounting. Any slopes that are added to the SUT slope because of beam pointing changes or optical carriage pitches will show up separately as a slope represented by the REF interference pattern. Thus, the actual slope of the SUT can be determined by subtracting the measured REF slope from the measured SUT slope. This assumes that the above factors (3) and (4) are insignificant.

To test performance of the LTP, measurement of slope can be made on any known SUT. However, the only test surface whose slopes are well known by an independent measurement is a flat. Therefore, a flat was chosen as the SUT for evaluating the LTP's performance. The flat is a piece of Zerodur™ 175 mm long $\times$ 50 mm wide $\times$ 38 mm thick, specified to be flat within $\lambda/35$ ($\lambda = 633$ nm) over an aperture of 100 mm.

Figure 3 shows both slope functions for the REF and SUT. The average slope value for each is given at the vertical midpoint, and maximum slope deviation from the midpoint is labelled. Similarities in both slope functions are apparent. When the REF is subtracted from the SUT, a slope function for the SUT results whose rms fluctuation is a factor of more than 2 smaller than that for the uncompensated SUT measurement. The compensated SUT slope measurement is shown in Figure 4.

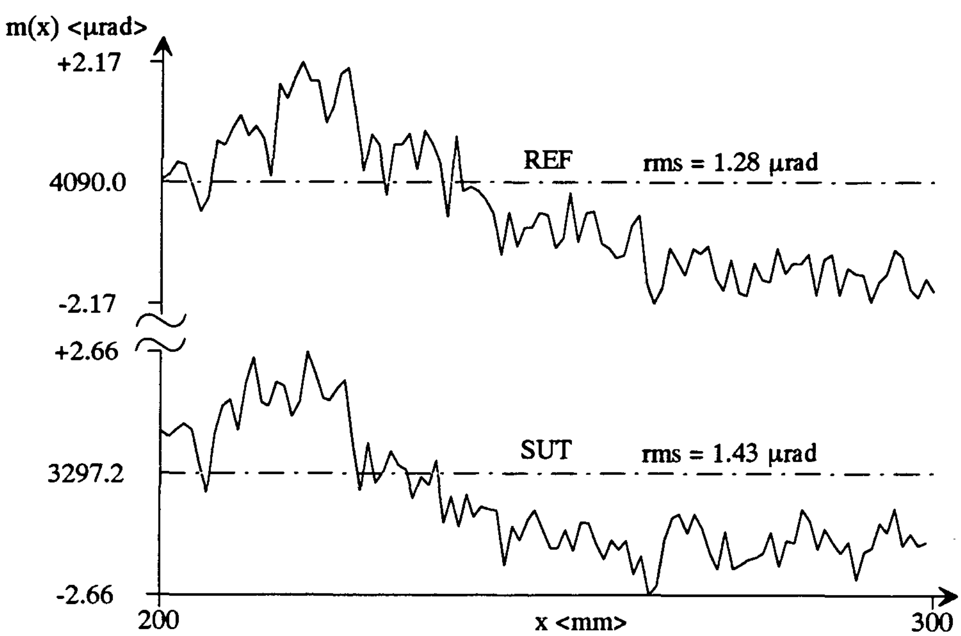

Figure 3. Measurement of REF slopes and SUT slopes.

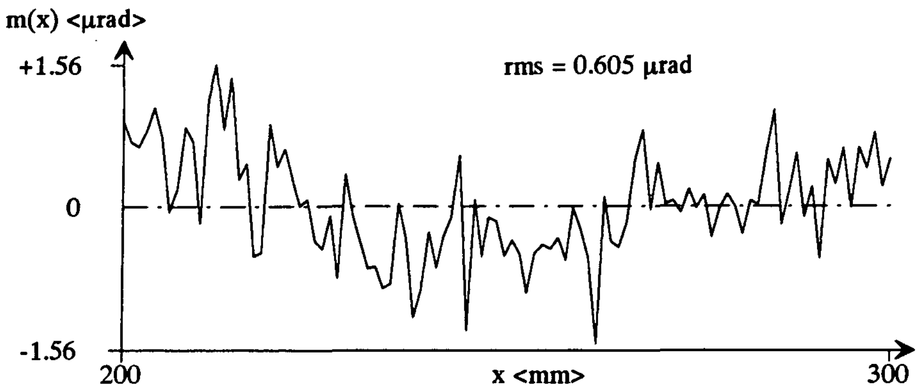

Figure 4. After subtracting REF slope from SUT slope.

The average slope was then set to zero. This has the same effect as removing tilt from the surface height profile.

The slope is converted to height by numerical integration over the measured 100 mm length. The height of the compensated SUT measurement is displayed as the solid line in Figure 5. Peak to valley variations of the compensated SUT measurement are equivalent to the surface being flat to with $\lambda/39$. This is within the specification for the flat. But then there is uncertainty as to how much of the structure in Figure 4 is due to the factors of air turbulence and dimensional changes.

A more important reason for compensating the SUT measurement can be seen after the slope is converted to height. Although a reduction in rms slope variation by a factor of 2 may appear small, a downward or upward trend in the slope function has much influence on the height profile. If the slope function is rapidly fluctuating about some average value, then integration tends to filter out the high frequency fluctuations, and the height profile will be fairly flat. On the other hand, if there is, for example, a downward trend in the slope function (indicating a gradually decreasing slope), then the height profile will have a significant amount of curvature. A dramatic difference in height profile is seen in Figure 5 between the compensated and uncompensated (broken line) SUT measurements. Much curvature is in the uncompensated measurement, giving a height profile that is about 4 times greater than that of the compensated measurement.

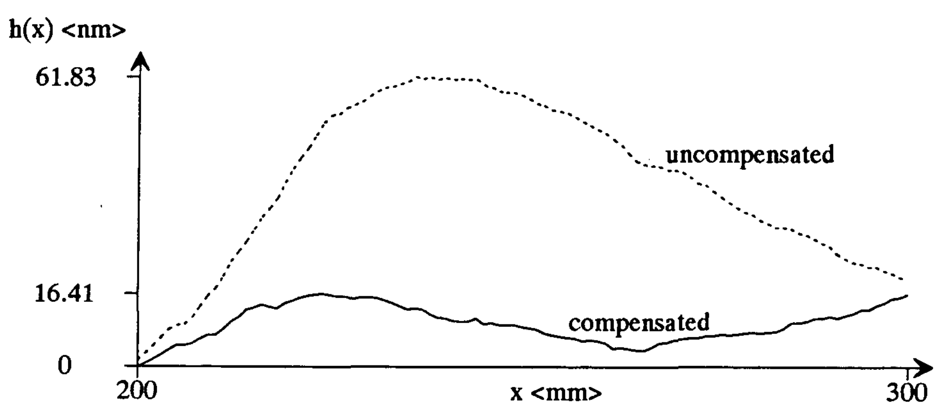

Figure 5. Resulting height profile of the SUT.

The fine structure in Figure 5 is repeatable. The larger S-shaped curve, however, changes somewhat with time and stabilizes to a minimum value of about 15 nm peak-to-valley after the optic and mounting are untouched for an hour. Further measurements have shown that the closer the REF mirror is in mounting to the SUT, the flatter the S-shaped curve becomes. The S-shape in the height function may also result from distortion in or poor alignment of the F. T. lens.

Conclusions

A method of removing errors in slope measurement of an optical surface has been described. These errors are from characteristics of the profiling instrument, and may be minimized by using a straightness reference. Other sources of slope measurement error are air turbulence and mounting dimension changes. These may be minimized by proper environment control and design of mounting.

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
INFORMATION RESOURCES DEPARTMENT
BERKELEY, CALIFORNIA 94720