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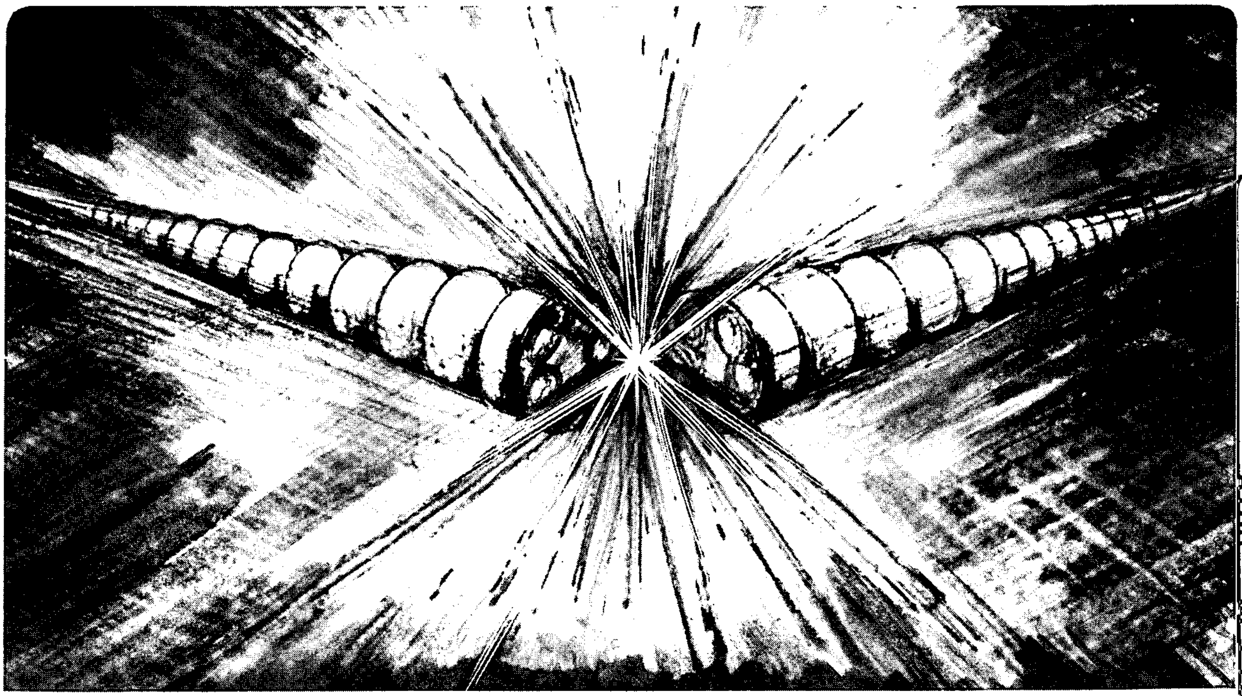

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Advancements in one-dimensional profiling with a long trace profiler

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ABSTRACT

Over the last several years the long trace profiler (LTP) has been evolving into a sophisticated machine capable of measuring surface profiles of very long dimensions. This report explains improvements, both hardware and software, that have helped to achieve accuracies and ranges in surface profiling that have been unobtainable until now. A comparison made by measuring standard optical surfaces on other instruments corroborates these accuracies.

1. INTRODUCTION

Optics for synchrotron beamlines are different from optical components made for infrared and visible light, because the shorter wavelengths of the ultraviolet and X-ray radiation require grazing incidence from most reflecting surfaces. Hence, the optics tend to be very long, even though the radiation beam is only a few mm diameter. The high brightness of today's 3rd generation synchrotrons puts a greater demand on the fabricator in terms of mechanical stability under varying heat loads[1], surface microroughness[1,2], and surface figure.

In 1982, von Bieren[3] built a pencil beam interferometer which was designed to measure large aspheres. This idea was used by Takacs[4] in 1988, but applied to a long, one-dimensional trace. The LTP Takacs built came from a need to measure the long, narrow mirrors that are used in synchrotron beamline optical systems. Now the Advanced Light Source at Lawrence Berkeley Laboratory requires optical surfaces with unprecedented figure accuracy. So the need for greater measurement accuracy has required improvements in the performance of the LTP.

2. IMPROVEMENTS OF THE 2ND GENERATION LTP

The LTP that Takacs built already incorporated many ideas that are necessary for accurate measurements, such as installing the system in a clean area, putting a shroud around the profiler table to reduce air currents, and setting the LTP on a vibration isolated table. We may take these items for granted now, but are important enough that they should be mentioned. Slope measurements made on the LTP at Lawrence Berkeley Laboratory show that the rms system noise can be reduced from over 3 μrad to under 1 μrad by establishing this proper environment.

The time that a measurement takes will also determine accuracy. It is desirable from a mechanical stability standpoint to keep the time for acquiring profile data to a minimum. Selection of a computer and writing of the program play an important role in how fast the required data is taken. Generally, the shorter a program is, the faster it will run. Also, other resident programs on the computer may slow down the system. It is then desirable to have no other unnecessary resident programs while acquiring data. Input/output operations for transferring data should be streamlined. In the case of writing data to a disk (or even a virtual disk), the disk should be uncluttered and free of unmarked bad sectors. In the case of transferring data between external devices and the computer, the fastest input/output scheme should be used.

Profiler data is meaningful only if it is interpreted and annotated properly. For this reason the software for the LTP stamps the data with a mnemonic each time the data is changed in any way. For example, when the surface profile data is "detrended" to calculate and remove curvature, the data is annotated accordingly. This aids the communication between the measurement operator and the person who is comparing specification to finished product. This detrend history record is also helpful when documents are retrieved from archives.

Choice of a proper algorithm[5] for converting interference patterns to slope values should be based on speed of the algorithm and how clean the interference pattern is (i.e., on how well the LTP optical system is aligned, absence of stray light, etc.). Although two algorithms have been described[5], the curve fit method used by Takacs will be used in this paper also; it is simpler and easier to explain.

3. OPERATIONAL THEORY OF THE LTP

Figure 1 shows a schematic of the LTP. An air bearing carriage, which holds the LTP optical system for gathering slope data, moves along a stiff ceramic beam. A brushless d.c. servo motor was chosen to propel the carriage because of its low heat dissipation and smooth rotational movement. While the carriage moves, "snapshots" of an interference pattern between two mutually coherent light beams are taken at regular intervals along the x axis and recorded in the computer. These interference patterns are then processed[5] in order to calculate the relative slope of the surface under test (SUT) as a function of x.

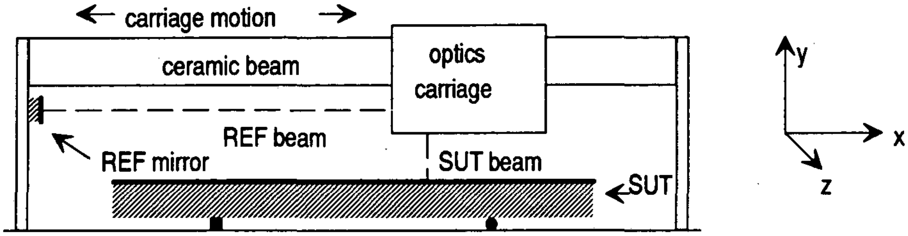

Figure 1. Schematic of the long trace profiler.

A schematic of the LTP optical system is shown in Figure 2. A pair of collimated, parallel beams is produced by the laser, collimator, BS1, and corner reflectors CR1 and CR2. After reflecting from the SUT, the beam pair is directed into the Fourier transform (FT) lens, which produces an interference pattern on the detector array. The detector array sends the interference pattern data to the computer.

Basically, the sinusoidal interference pattern consists of approximately one cycle of the sinusoid. Thus, it is easy to track the phase shift of the sinusoid from one interference pattern to another. If the position of the detector array at some point on the sinusoidal pattern (say, its minimum) is v_1 and the detector position of this same point on the next pattern is v_2, then the slope change from x1 to x2 is

$$m(x_2) - m(x_1) = K_1(v_2 - v_1), \tag{1}$$

where $K_1 = \dfrac{L}{2Nf}$ is a constant. L is the physical length of the photodetector array, N is the number of elements in the array, and f is the FT lens focal length.

Making use of the extra beam pair produced by BS2 has been described[6]. This beam pair is used as a reference (REF), reflecting from the REF mirror and going through the same optical system as the SUT beam. Any change in slope calculated for this beam will only be from curvature of the ceramic beam, pitching of the carriage during movement, and laser pointing instability. Subtracting the REF slope function from the SUT slope function is very effective in reducing the largest source of errors innate to the LTP.

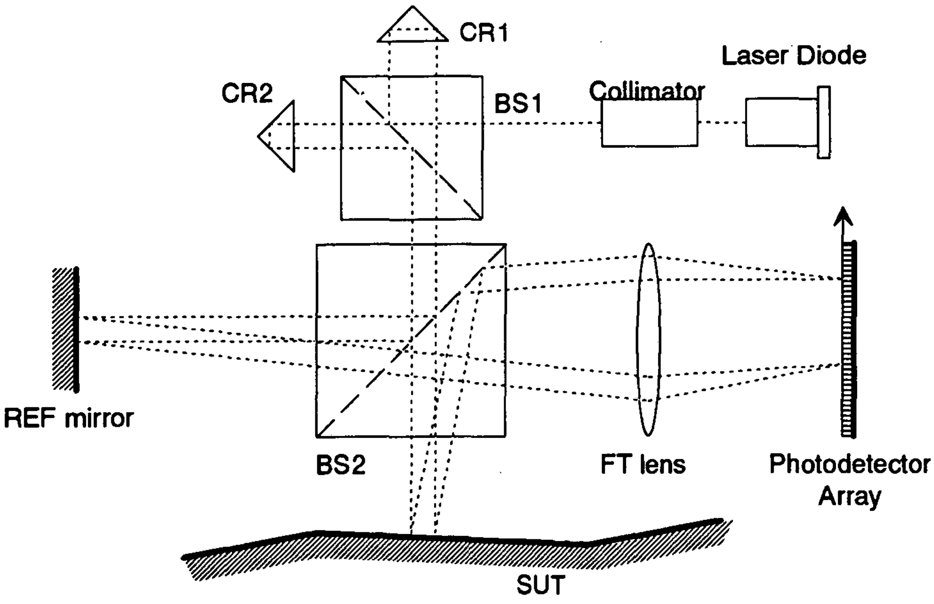

Figure 2. Schematic of the optical system.

The REF mirror was originally mounted on the pedestal of the LTP. However, it is necessary to mount the REF mirror as close as possible to the SUT in order to reduce errors from mechanical changes between the SUT mount and the REF mount. It is also desirable to have the SUT mounted on a stable stage. The stage should have enough degrees of adjustment for positioning the SUT so that the SUT is not touched just before it is scanned. (Touching may heat up one part of the SUT, creating thermal distortion.)

4. LENS DESIGN OF THE LTP OPTICAL SYSTEM

The lens in the optical system has been described as a Fourier transform lens. This follows because the image in the back focal plane of the lens is a Fourier transform of the object (beam pair) in the front focal plane. However, it is seen from the above discussion that a lens system is required that converts angle of an incoming beam pair into position on the detector array. This is an $f\theta$ lens system.

If the lens system has distortion, then the $f\theta$ mapping will not be consistent for rays entering different heights of the entrance pupil. See Figure 3. If the scanned length of the SUT is x_S and the minimum optical path from the REF mirror to the lens system is x_0, then (relative to the lenses) the REF beams could come from points along the optic axis between x_0 and $x_0 + x_S$. If the REF beam angle is between -10 µrad and +10 µrad (our current range), then the aperture required for the FT lens is

$$D_a = 2(x_0 + x_S)\tan(\phi). \quad (2)$$

For ϕ = 10 mrad, a maximum x_S of 1000 mm and an additional x_0 of 102 mm, the clear aperture of the FT lens should then be 22 mm. When designing an optical system for the LTP, distortion should be minimized for this $f\theta$ system.

For a fixed angle ϕ, distortion will be manifest as interference pattern position v being dependent on the REF mirror distance $x_0 + x_S$. In other words, the optical system will have different magnifications at different positions along x. If the REF interference pattern is set at one edge of the detector array, then maximum distortion will be experienced. In this situation, even if the carriage motion is perfectly straight, the REF interference pattern will wander slightly around that end of the detector array and the carriage motion will appear to be curved. The obvious solution is to keep the REF beam as close to the optic axis as possible. However, this is not feasible when SUTs with large curvatures are measured. The REF pattern must be moved to one edge of the detector array so that the SUT pattern may move over the rest of the array during the scan. Chopping the beams so that alternate REF and SUT patterns may be imaged is another solution, but requires more processing by the computer. Vibrations from mechanical choppers could be prohibitive.

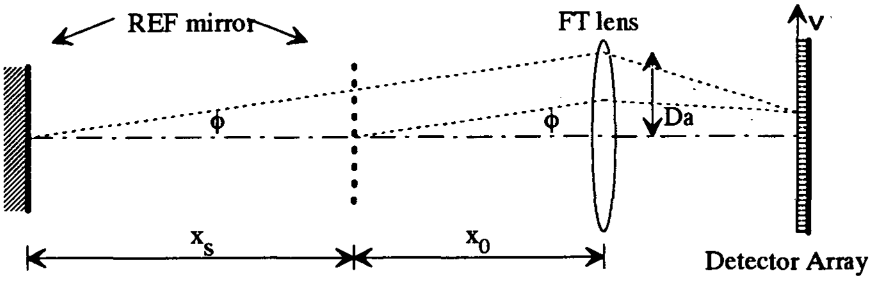

Figure 3. Aperture requirement for the lens design.

5. MEASUREMENT OF DISTORTION AND ABSOLUTE SLOPE

Here, "absolute slope" means the actual difference in any two slope values within the measurement range of the LTP. It is easy to get good precision in measurement for small differences in slope; precision of the LTP is on the order of 0.1 μrad. But distortion, other aberrations of the optical system, and systematic noise cause the measurement of larger slope differences to have significantly greater error. These errors can be measured by swinging a test mirror through a known angle. Figure 4 shows an experimental setup for doing this.

A piezoelectric transducer P is remotely controlled to move the mirror block M through a range of 5 mrad. This causes the REF beam to move through a range of +/-10 mrad. The monitoring mirror M2 moves through the same range of angles as REF mirror M1. The laser measurement system measures only linear displacement, so the precision optical system A is required to convert angular movement of M2 to displacement. The precision of this angular measurement system is 0.28 μrad, the range is +/-8.7 mrad (just over our requirement of +/-5 mrad), and the accuracy over this entire range is better than one part in 500 (according to the manufacturer).

The angle of M is set by applying the proper voltage to P. The drift and hysteresis of the piezoelectric device P gives some uncertainty in setting the angle of M exactly, but the laser angle measurement system gives feedback so that the angle is known precisely. The angle is easily set to within a fraction of 1 μrad. When a desired angle (or slope) is attained, a "snapshot" of the interference pattern is taken, and the slope is calculated. This is done for at least two slope values for each position x of the carriage, and for several positions x of the carriage. This way, the distortion of the optical system is mapped.

Although the original LTP optical system was designed as a FT system, it was not designed as an $f\theta$ system. Later, another lens was selected that had much better performance in terms of $f\theta$ mapping. After measuring a nickel plated Glidcop^{TM} flat (160 mm clear aperture length) with the original LTP optical system, the original optical system was measured using the setup in Figure 4. The results of those measurements are shown in Figure 5. Then the original FT lens was replaced with the new $f\theta$ lens. Again, after measuring the same nickel plated Glidcop^{TM} flat with the new optical system, the new LTP optical system was measured with the setup shown in Figure 4. The results of those measurements are shown in Figure 6.

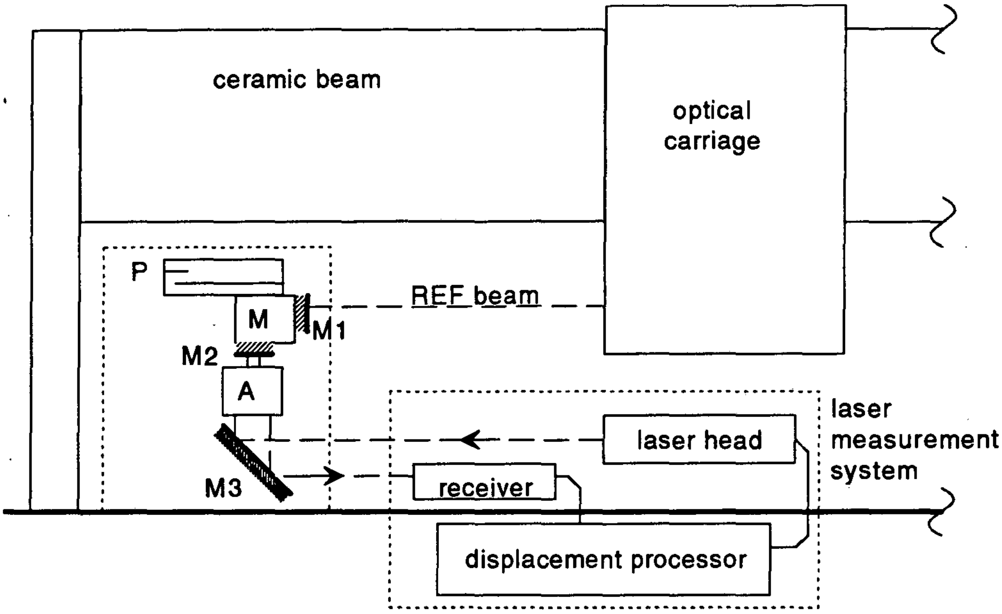

Figure 4. Measurement of absolute slope.

The important information in Figures 5 and 6 is the removed radius. The rms slope error is expected to be approximately the same after all the curvature is removed, since distortion in the lens system appears as curvature error. The measured distortion is the difference between measured slope value and actual angle set for ϕ = 4.0 mrad. The distortion in the original LTP optics adds a significant amount of curvature to the measurement. In Figure 5, this curvature is seen to give almost a full wave peak-to-valley of height. In Figure 6, the new optical system reduces this figure to approximately $\lambda/40$ (λ=633 nm) over the full aperture of the SUT. (The glitch in Figures 5 and 6 is real; there is a small dent at that location of the mirror.)

6. RADIUS MEASUREMENT OF CURVED OPTICS

A polished grating blank that was made for a synchrotron beamline was measured after calibrating the LTP for absolute slope with the setup shown in Figure 4. The specification for radius of curvature of this grating blank that was given to the polishing vendor was 55 m (concave); clear aperture length was 160 mm. After calculating the slope, the slope function was detrended by fitting a straight line to it. This line function was then subtracted from the slope function, resulting in residual slope error with the curvature removed. The curvature removed was 54.89 m. This same grating blank was later measured on a Shack interferometer radius bench, resulting in a radius of curvature of 55.14 m. The difference between these measurements is 0.45%.

7. CONCLUSIONS

Performance of the LTP has been characterized for several parameters. The LTP can routinely measure slope of

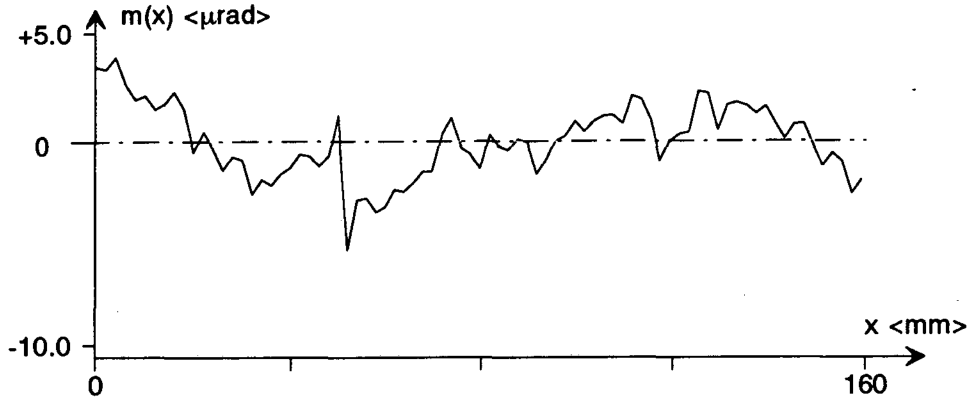

Figure 5. Measurement of flat with original LTP optical system.
Radius removed = 6608 m; rms slope variation = 1.62 μrad.
Measured distortion for scan range: +16.61 to -30.14 μrad at ϕ = -4.5 to +4.5 mrad.

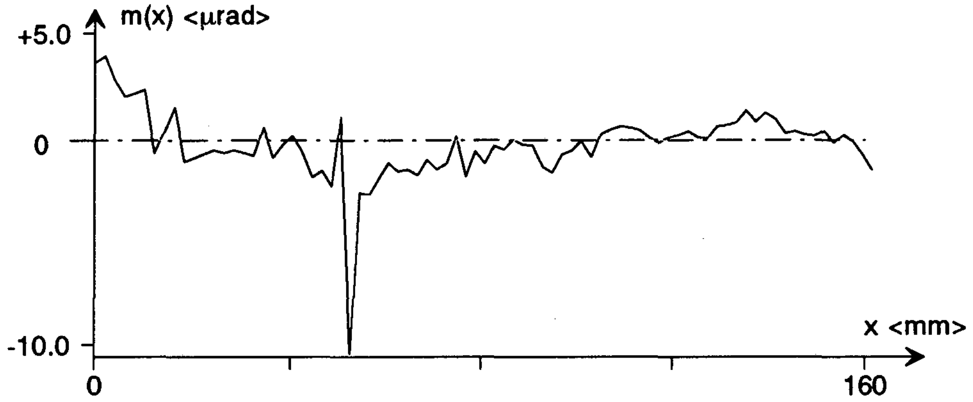

Figure 6. Measurement of flat with new LTP optical system.
Radius removed = 197910 m; rms slope variation = 1.70 μrad.
Measured distortion for scan range: -1.4 to +6.6 μrad at ϕ = -4.5 to +4.5 mrad.

long optical surfaces with system noise of less than 1 μrad rms over a scan length of 160 mm. Radii of curvature can be calculated with an accuracy of better than 1%. Measurements of several optics characterized by other methods indicate that the LTP can measure figure over a scan length of 160 mm to better than λ/10.

The distortion measurements presented here are preliminary and compare the original LTP optical system with one in which the FT lens was replaced with an off-the-shelf lens which was designed for conjugates better suited for the LTP application. We realize that there is room for improvement, and a much improved lens design is now in progress. In spite of the limitations pointed out in this paper, the LTP may be the only instrument that can measure optics with irregular figure (e.g., aspherical) that are one meter long (longer planned) with the order of precision and accuracy described here.

8. ACKNOWLEDGEMENTS

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