

## ACCURACY LIMITATIONS IN LONG-TRACE PROFILOMETRY\*

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# Accuracy Limitations in Long-Trace Profilometry

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**Abstract.** As requirements for surface slope error quality of grazing incidence optics approach the 100 nanoradian level, it is necessary to improve the performance of the measuring instruments to achieve accurate and repeatable results at this level. We have identified a number of internal error sources in the Long Trace Profiler (LTP) that affect measurement quality at this level. The LTP is sensitive to phase shifts produced within the millimeter diameter of the pencil beam probe by optical path irregularities with scale lengths of a fraction of a millimeter. We examine the effects of mirror surface "macroroughness" and internal glass homogeneity on the accuracy of the LTP through experiment and theoretical modeling. We will place limits on the allowable surface "macroroughness" and glass homogeneity required to achieve accurate measurements in the nanoradian range.

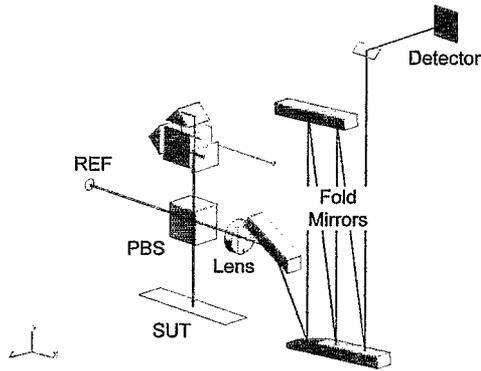
## INTRODUCTION

As manufacturers have improved the quality of optical surfaces used in grazing incidence x-ray reflector applications over the past 2 decades, it has become necessary to improve the performance of the metrology instrumentation used to measure these components. Large meter-long cylindrical aspheres are now routinely produced with 0.5  $\mu$ rad rms slope error specifications. X-ray microprobe beam lines and coherent imaging applications will require optical surfaces with slope errors in the 100 nrad range. It is a challenge to the metrologist to develop the instrumentation and techniques that will allow reliable and accurate measurements at this level.

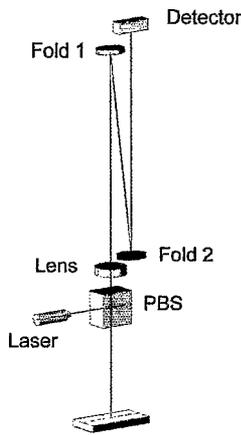
In making more demanding measurements with the LTP on high quality surfaces, one is confronted with the problem of repeatability and accuracy at the sub-microradian level. This has prompted us to investigate sources of systematic error that appear at this level of accuracy. We have identified two potential contributors to the error in the standard LTP II optical head configuration: macroroughness of the folding mirrors, and glass quality of the polarizing beam splitter (PBS).

## FOLDING MIRROR QUALITY

The Long Trace Profiler was developed at Brookhaven National Laboratory (BNL) specifically to meet the challenge of measuring long cylindrical aspheres that are frequently bent into toroidal and ellipsoidal shapes with axial curvatures in the range of several kilometers[1,2]. A sketch of the optical head of a commercial version of the LTP, the LTP II, is shown in Fig. 1. A surface with a significant curvature causes the reflected probe beam to travel transversely across the entrance aperture, through and over different parts of the glass and mirrors in the optical head. This is analogous to "retrace" error in conventional Fizeau-type interferometers. As the probe beam moves laterally over these surfaces, or inside the glass of the PBS or lens, it can pick up small differential phase shifts that distort the Gaussian beam and result in a shift of the peak position away from the nominal position. The LTP II is especially susceptible to this error owing to the large number of reflections in the folding mirror system between the lens and the detector.



**Figure 1:** Optical diagram of standard LTP II optical head. Probe beams reflect from the test surface, SUT, and reference mirror, REF, return through the polarizing beam splitter, PBS, and the Fourier transform lens, and are reflected 7 times off of 4 different folding mirrors.

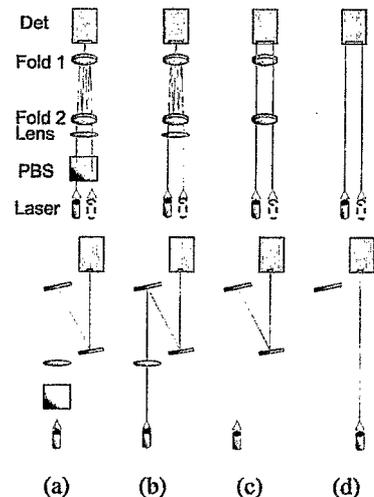


**Figure 2:** LTP III+ Test Bed optical head configuration with minimized folding mirror configuration.

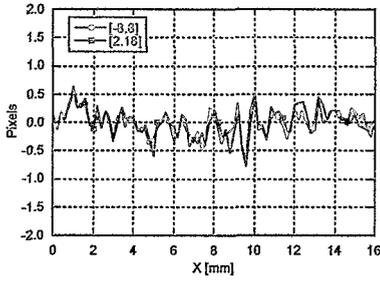
By removing different components from the optical system, various configurations of the test bed system can be created to isolate various error sources, as shown in Fig. 3. Figures 4, 5, and 6 show the results of such scans. The vertical scale is approximately the same in all 3 plots. Fig. 4 has the laser beam incident directly onto the detector. Fig. 5 adds a high-quality lens and commercial quality folding flats. The increase in the residual error due to the folding flats is significant. By changing the folding flats to super polished flats from Wave Precision (General Optics), the reduction in residual error is quite dramatic, as seen in Fig. 6. The rms slope error with the commercial flats is  $3.58 \mu\text{rad}$ , while with the Wave Precision flats is  $0.48 \mu\text{rad}$ . The order of magnitude difference between the standard quality and super polished surfaces is quite dramatic and confirms the fact that most of the observed error is a result of surface quality in the standard-polish mirrors. That the super polished mirrors produce such a small error signal also confirms that this lens does not contribute a significant amount to the observed slope error.

To investigate the effect of component quality on systematic error level, we modified the basic BNL LTP optical system design to simplify it and remove as many extraneous reflections as possible. The result is the LTP III+ Test Bed optical head shown in Fig. 2. Most significant is the reduction in the number and complexity of the folding mirrors. The lens can easily be changed and the spacing between the folding mirrors can be adjusted to provide the proper focal length. Also, the return beam from the SUT travels straight through the PBS, unlike in the LTP II system where the return beam reflects off of the internal surface in the PBS before it enters the lens. This extra reflection potentially adds an additional error source to the system, namely the quality of the interface coating in the PBS cube, which will be addressed in a later section. With this "open architecture" test bed system design, we can now begin to isolate error sources and look at the effect of component quality on the performance of the LTP.

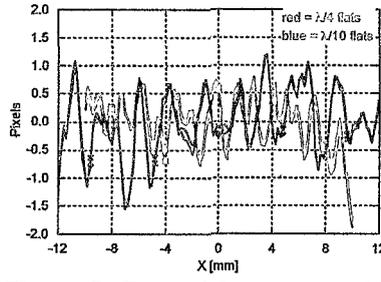
To investigate the quality of the optical system, it is necessary to use an external laser source that can be scanned across the entrance aperture of the optical head. We removed the internal laser source and set up an external source comprised of a HeNe laser coupled through a single mode fiber with an integral collimating lens producing a clean Gaussian beam with a diameter of about 1 mm. Instead of moving the laser source, the laser assembly remained stationary on the optical table and the optical head was scanned across the laser beam by use of the air bearing slide upon which the optical head is normally mounted. The motion of the air bearing is very smooth, especially over the short distances involved in the test bed scans, and the encoder positioning accuracy is specified to be about 1 micron.



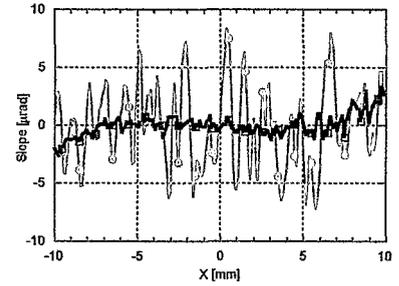
**Figure 3:** LTP III+ Test Bed configurations for external laser scans with various components selectively removed. Top row shows front view of laser beam path as it is scanned across the aperture; bottom row shows corresponding side view.



**Figure 4:** Direct beam onto the detector, average of two sets of scans with the laser shifted by 10 mm between sets. No systematic error from the air bearing is observed.



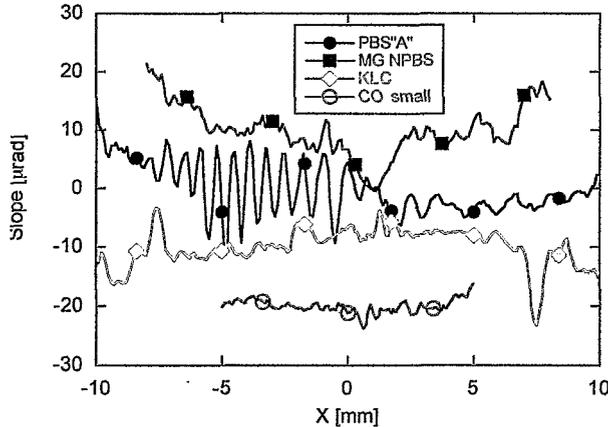
**Figure 5:** External laser scans with commercial quality  $\lambda/10$  flat mirrors used as folding mirrors. Fold 2 is rotated by  $90^\circ$  between scans.



**Figure 6:** External laser scans comparing two super polished fold flats (dark curve) with one standard flat and one super polished flat (lighter curve).

## POLARIZING BEAM SPLITTER CUBE QUALITY

The polarizing beam splitter is another potential error source in the LTP. The results of case "a" scans with 4 different cube beam splitters are shown in Fig. 7. All 4 scans were made with the super polished folding flats and the high quality 1250 mm lens. There is a considerable range in the quality of the beam splitters evident in the scans. Two are standard catalog items (MG NPBS and KLC) and two are custom made (PBS "A" and CO small).



**Figure 7:** External laser scans across 4 beam splitters. Curves are offset by  $10 \mu\text{rad}$  from each other.

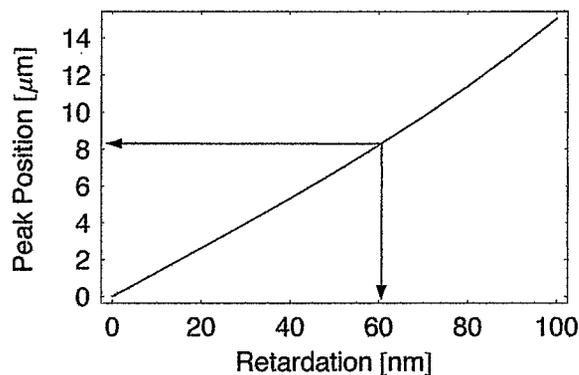
It is desirable to have a beam splitter with a flat slope profile around the central region of the aperture. All of these beam splitters have errors in the range of at least a few  $\mu\text{rad}$  around the central region. PBS "A" exhibits an unusual ripple pattern with an average rms of  $5.11 \mu\text{rad}$  or  $15 \mu\text{rad}$  peak-to-valley over an 8 mm extent. Most of the observed errors can probably be attributed to defects in the conventionally polished surfaces, although internal glass inhomogeneity cannot be ruled out. The peculiar periodicity in PBS "A" prompted measurements of the surface roughness of the two faces of the cube with a Micromap Promap 512 optical profiler. The results did not show any evidence for periodicity in the external surface. This prompted further investigations into the possible causes for the observed ripple in the transmitted beam.

## PHYSICAL OPTICS DISTORTION MODEL

The position of the focal spot in the image plane is linearly related to the angle of incidence of the probe beam onto the Fourier transform lens aperture, provided the spatial periods of surface irregularities in the SUT and on the internal optical head components are larger than the laser beam probe diameter. In the present case, the irregularities producing the beam deviation are comparable in size to the beam diameter. The period of the ripple in PBS "A" is seen to be 0.75 mm from the measured data; the Gaussian laser beam diameter is about 1 mm. In order to relate the LTP measurements to the physical irregularities of the glass medium and the surfaces, we developed a simple Fraunhofer diffraction integral model for Gaussian beam propagation through a medium with a periodic optical phase modulation.

The expression for the scalar electric field of a Gaussian laser beam in the focal plane of a lens with focal length  $F$ , subject to a sinusoidal phase shift irregularity, is given by:

$$E_n(x_2) \propto \int e^{-\left(\frac{x_s}{b}\right)^2} e^{-i\frac{kx_s x_2}{F\lambda}} e^{-i2\pi\frac{A}{\lambda} \cos\left[2\pi\left(\frac{x_s}{L} - \frac{x_n}{L}\right)\right]} dx_s \quad (1)$$



**Figure 8:** Maximum model distortion shift in image peak as a function of amplitude of phase shift error sinusoid. Arrows mark the 60 nm retardation that matches the observed 8.15  $\mu\text{m}$  shift in the PBS "A" measurements.

error function. In Fig. 8 we plot the maximum computed lateral shift as a function of phase irregularity amplitude. The amplitude of the error function that produces the 8.15  $\mu\text{m}$  lateral shift in the peak is seen to be about 60 nm, which corresponds to a wavefront quality of about  $\lambda/10$  in the optical components at millimeter spatial periods. A factor of 10 reduction in surface error would produce an rms error of about 0.5  $\mu\text{rad}$  and would require  $\lambda/100$  quality optics. Further reduction of systematic error effects to the 100 nrad level would require at least a  $\lambda/500$  wavefront error specifications. Since this wavefront error is a composite of each individual surface, the actual surface error tolerance required to give this wavefront quality is closer to  $\lambda/1000$  over millimeter spatial periods. This is not an impossible specification to meet, but it requires careful fabrication methods and special selection techniques, which are generally costly to implement. These improvements will need to be incorporated into future LTP developments if nanoradian accuracy is required in the measurement process.

where  $x_s$  is the aperture coordinate,  $b$  is the Gaussian laser beam width parameter,  $k$  is the wavenumber for the laser light,  $A$  is the amplitude of the phase irregularity sinusoid,  $L$  is the period of the ripple, and  $x_n$  is the distance that the sinusoid is shifted under the Gaussian beam to simulate translation of the optical head.

The root-mean-square average over the region of the ripple signal in PBS "A" is 5.11  $\mu\text{rad}$ . The corresponding sinusoid has an amplitude of  $A = 7.22 \mu\text{rad}$  or a peak-to-valley amplitude of about 15  $\mu\text{rad}$ . Using the angle-to-position scale factor for the 1.25 m lens focal length, we require that the phase shift error cause the intensity peak to move by  $\pm 8.15 \mu\text{m}$  on the detector. As the sinusoid is shifted across the Gaussian beam, the image in the focal plane becomes distorted, resulting in a lateral shift of the peak across the detector with the same period as the

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## ACKNOWLEDGMENT

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