

SYSTEMATIC ERROR REDUCTION:
NON-TILTED REFERENCE BEAM METHOD FOR LONG TRACE PROFILER*

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August, 2007

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Systematic error reduction: non-tilted reference beam method for Long Trace Profiler

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Abstract

Systematic error in the Long Trace Profiler (LTP) has become the major error source as measurement accuracy enters the nanoradian and nanometer regime. Great efforts have been made to reduce the systematic error at a number of synchrotron radiation laboratories around the world. Generally, the LTP reference beam has to be tilted away from the optical axis in order to avoid fringe overlap between the sample and reference beams. However, a tilted reference beam will result in considerable systematic error due to optical system imperfections, which is difficult to correct. Six methods of implementing a non-tilted reference beam in the LTP are introduced: 1) application of an external precision angle device to measure and remove slide pitch error without a reference beam, 2) independent slide pitch test by use of not tilted reference beam, 3) non-tilted reference test combined with tilted sample, 4) penta-prism scanning mode without a reference beam correction, 5) non-tilted reference using a second optical head, and 6) alternate switching of data acquisition between the sample and reference beams. With a non-tilted reference method, the measurement accuracy can be improved significantly. Some measurement results are presented. Systematic error in the sample beam arm is not addressed in this paper and should be treated separately.

Introduction

The Long Trace Profiler (LTP) [1-3] has undergone significant improvement over the 20 years since its original development in 1987. Great efforts have made in improving LTP accuracy including slide pitch error elimination by use of a reference beam [4], equal optical path difference beam splitter development [5-8], precise temperature control, curve fitting improvement, different kinds of LTP innovation and so on [9-17]. The LTP accuracy has been improved from ten micro-radians to one micro-radian and is proceeding into the nanometer and nano-radian range. The greatest challenge now is the metrology requirements for optical components for fourth-generation synchrotron radiation sources, where 1-nm focusing of x-ray beams will be required. However, the negligible error factors of the LTP in previous time are emerging to impact the nanometer measurement accuracy. Systematic error of the LTP has become the major error source for nanometer measurement. Several synchrotron radiation laboratories around the world are dedicating to it. [18-26].

One of systematic errors is caused by the imperfection of optical components quality in the LTP combined with the scanning beam sweeping over different regions of the optics, so that it picks up optical components error as systematic error. There are two methods to reduce this kind of error: improving optics quality and restricting beam sweeping. This paper will only describe the effort to reduce the reference beam sweeping during the measurement.

For a scanning optical head LTP, a fixed reference mirror must be used for subtracting the slide pitch error from the test data [4]. In order to avoid overlapping of sample and reference fringes, the reference mirror R (Figure 1) must be tilted by some angle in horizontal direction (for linear detector) or/and in vertical direction (for dual array and area detectors) in order to shift the reference fringe toward the edge of the detector. The farther the optical head moves away from the reference mirror, the farther the reference beam moves away from the optical axis as a result of the tilt angle. So the reference beam will sweep over a region (shadow area on Figure 1) and will pick up a significant amount of systematic error from all of the optical components in the beam paths, especially from the PBS and the FT lens.

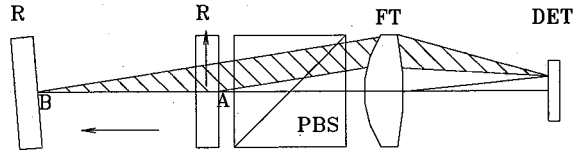


Figure 1 Reference beam sweeping during the scanning

How large is the error? Figure 2 shows slope errors of 2 sets of cube beam splitters (CBS) tested in 0, 90 and 180 degrees positions with the LTP. The residual slope error after detrending polynomial "1" is about $5 \mu\text{rad}$ P-V and $1.5 \mu\text{rad}$ rms in 10 mm scanning range, which is related to height error of tens nanometers.

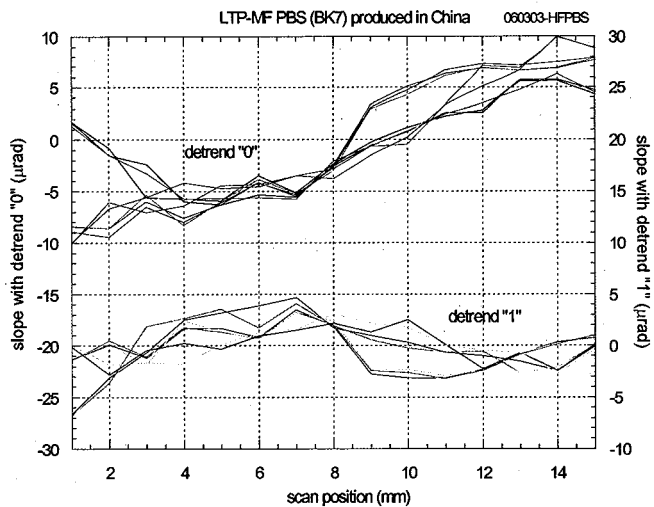


Figure 2 Slope error produce by cube beam splitter

An effective way to eliminate reference arm systematic error is to use non-tilted reference beam.

Approaches to eliminate reference arm systematic error

Six methods of non-tilted reference beam can eliminate reference beam systematic error:

- Application of separated precision angle test device to measure and remove slide pitch error without using reference beam (Figure 3 a)). This method had been used in the LTP I of BNL, the first LTP, with an autocollimator.
- Recently Yashchuk at Berkeley and Cocco at Trieste suggested applying tiltmeter to replace reference beam [27].
- Independent sequence non-tilted reference tested separately (Figure 3 b) at different time to avoid beam

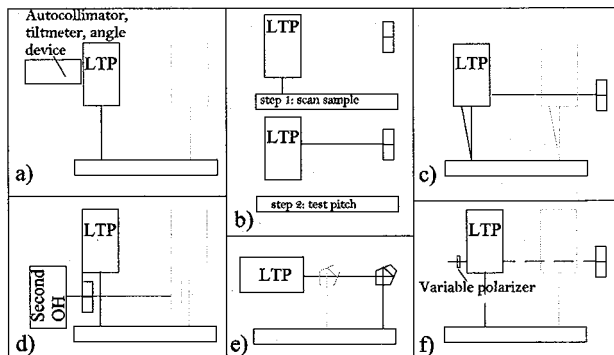


Figure 3 Six methods of using non-tilting reference beam

- non-reference beam by use of extra angle devices
- independent sequence non-tilting reference tested separately
- non-tilting reference with tilting sample beam for plane mirror test
- non-tilting reference by use of a second optical head
- non-reference beam by use of penta-prism scan
- non-tilting reference by use of alternating sample and reference beam

overlapping.

- c) Non-tilted reference beam combined with tilted sample beam in scanning optical head mode (Figure 3 c)). This method is suitable for testing plane or near-plane mirror, because in this condition optical path of tilted sample beam will not sweep laterally
- d) Non-tilted reference beam method by use of a second optical head to avoid overlapping (Figure 3 d)).
- e) Penta-prism scanning mode with non-reference beam correction (Figure 3 e)). As described in a previous paper, penta-prism LTP doesn't require reference beam to correct slide pitch error.
- f) Alternate data acquisition of sample and reference beams. This can be achieved by use of mechanical or electronic switches to alternately switch the sample beam and reference beam to the CCD. Figure 3 f) shows an electrically controlled polarizer/wave-plate used to rotate beam polarization direction to 0 or 90 degrees alternately, so that only the sample beam or reference beam can reach CCD at any given instant without overlapping.

Methods a) and e) eliminate the reference beam completely so that a tilted reference no longer exists; methods b) and f) use time-sharing to avoid overlapping the sample beam and reference beam. For those methods that use both beams simultaneously, a non-tilted reference method can improve measurement accuracy significantly. However, this method only eliminates systematic error in the reference beam arm. The systematic error in the sample beam arm should be treated separately.

Independent sequential slide pitch measurement by use of non-tilted reference beam

In this measurement method, the slide pitch error is measured with a non-tilted reference beam independent from the sample beam with the same LTP.

1) Applicability

This method can be applied only if all sequential pitch measurements are identical and stable. The following experimental results illustrate its applicability and limitations. Figure 4 a) shows 5 sequential pitch angle measurements with the LTP-MF at NSRL, China. The difference between the average of the 5 scans and each individual scan is $0.58 \mu\text{rad}$ rms (Figure 4 b)). Figure 5 a) shows 4 pitch scans with the LTP-MF at BNL. Its slide pitch repeatability is about $0.39 \mu\text{rad}$ rms

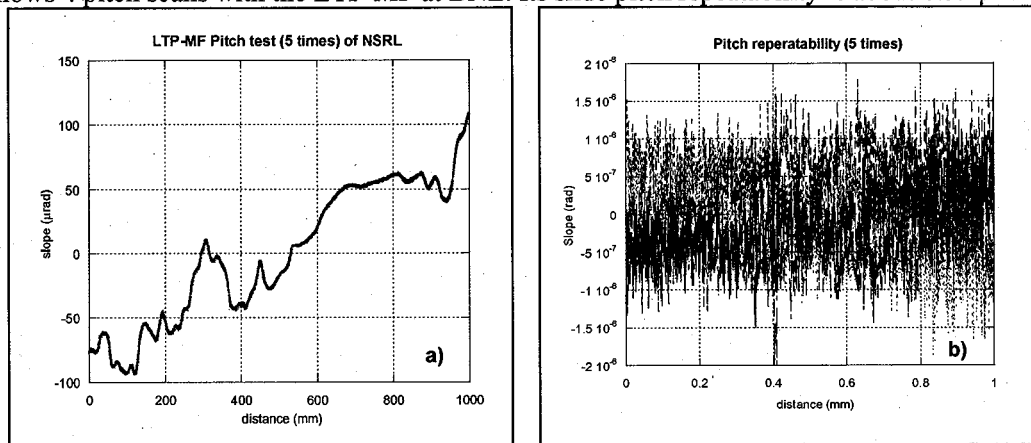


Figure 4 Five sequence slide pitch repeatability tests of NSRL LTP-MF in one meter: about $0.58 \mu\text{rad}$.
a) slope b) slope difference from mean

(Figure 5 b)). In both cases the non-tilted reference slide pitch tests are stable, so this reference

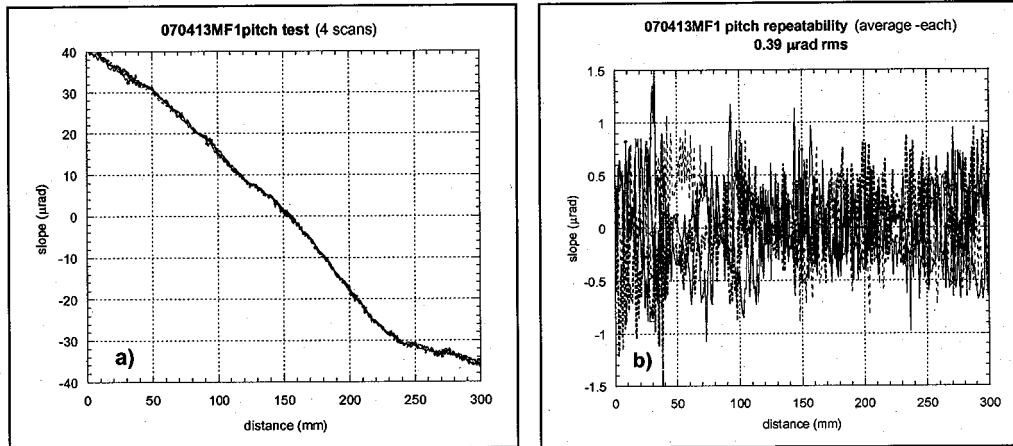


Figure 5 Four sequence slide pitch repeatability tests of BNL LTP-MF in 300 mm meter: about 0.39 μrad
 a) slope b) slope difference from mean

correction method is applicable in this situation. Figure 6 shows unstable reference pitch data from an LTP II with large cable forces acting on the air bearing carriage (Figure 6 (1) to (4)). In this condition it is not possible to use the independent non-tilted reference method. But after final careful adjustment of the cable force (Figure 6 (a) and (b)), it became stable. This example indicates that the slide pitch repeatability must be checked before using this method. Any change in mechanical conditions could impact the reference beam data stability.

- 2) Comparison measurements between tilted reference beam and non-tilted reference beam measured separately. Firstly, the non-tilted sample beam and tilted reference are tested at the same time; secondly, sequentially separated measurements with a non-tilted reference beam are made. The non-tilted reference beam is adjusted to be near the CCD center at pixel number 1024. The tilted reference beam was adjusted to be centered at pixels 1150, 750 and 500 which correspond to tilt angles of -4.5, 9.6 and 18 mrad. Using the same set of the non-tilted sample beam measurements to subtract tilted reference and sequence non-tilted reference data, two sets of residual heights can be obtained. In Figure 7a) and b) solid line curves are non-tilted sample beam and non-tilted reference beam scans measured separately on a plane mirror. The dashed lines in figure 7 a) are measurements with a tilted reference beam that illustrate the larger error.

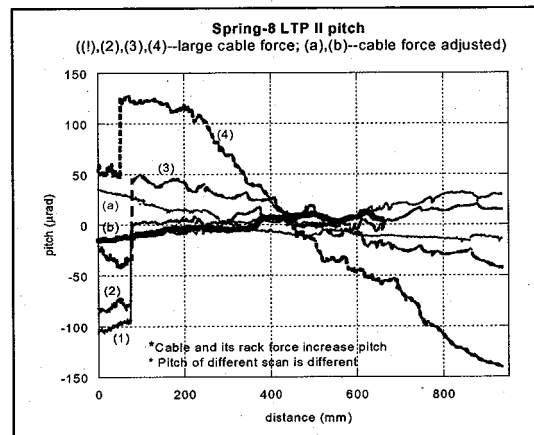


Figure 6 - Unstable reference pitch data from an LTP II with large cable forces.

Non-tilted reference combining with tilted sample test

In scanning optical head mode, if a plane (or near-plane) mirror is under test, during the scan the tilted sample beam returns through the optical system along the same path without sweeping, because the distance between LTP optical head and plane mirror does not change. The reference beam is set at the center of the CCD at pixel 1024 without tilting. Figure 7 (b) shows the

comparison when the sample beam is tilted to pixels 500, 1200, and 1500 related to tilt angles of 18, -6 and -16.7 mrad. The measurement result is nearly the same as the non-tilted sample and

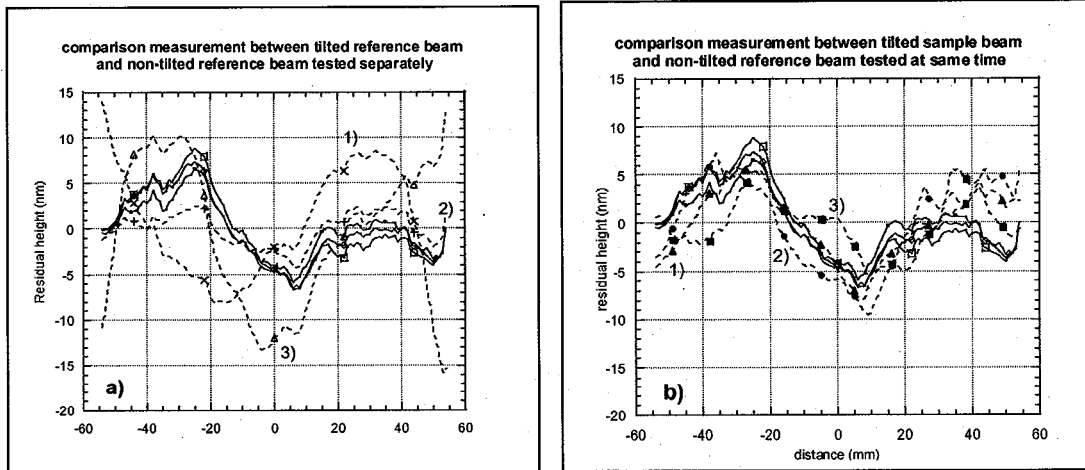


Figure 7 Plane mirror comparison measurements: solid lines use method of non-tilted sample beam and non-tilted reference beam measured separately

- a) Dashed lines use tilted reference and non-tilted sample beams measured at the same time, (1) reference tilt angle 18 mrad, (2) reference tilt angle 9.6 mrad, (3) reference tilt angle -4.5 mrad
- b) Dashed lines use non-tilted reference and tilted sample beams measured at the same time, (1) sample beam tilt angle 18 mrad, (2) sample beam tilt angle -6.2 mrad, (3) sample beam tilt angle -16.7 mrad

sequential non-tilted reference method. This method is good for a plane mirror test.

Non-tilted reference beam method by use of a second optical head (OH)

The Multiple Function LTP (LTP-MF) (Figure 8 and Figure 9) has two OHs, which can operate in scanning OH mode, penta-prism scan mode and independent in-situ LTP test mode. If two OHs are combined together for measurement, the LTP-MF can perform non-tilted reference beam measurements to eliminate the reference beam systematic error. One OH is installed on air bearing only to measure the sample beam, and the second OH is installed on granite table as a reference beam to measure the slide pitch error with a reference mirror set on the air bearing carriage. In this case, the first and second LTP-MF beams are incident on different CCDs of the two OHs, and there is no longer a fringe-overlap problem. Thus, the reference beam can be

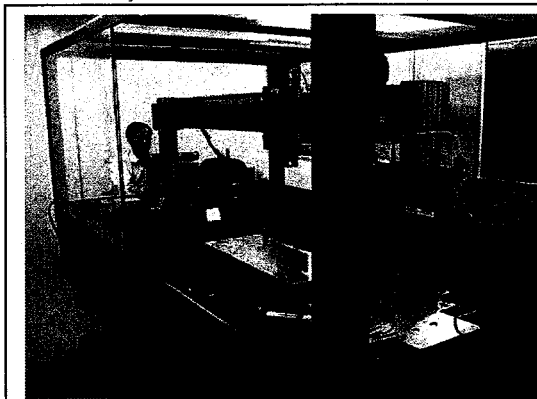


Figure 8 LTP-MF at NSRL, China is testing a plane mirror with two optical heads

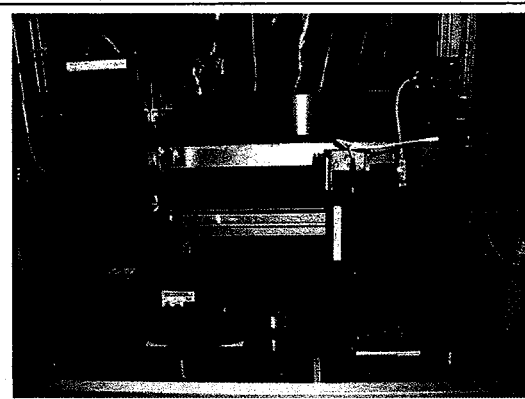


Figure 9 New setup of LTP-MF at BNL is testing a plane mirror with two optical heads

adjusted to the CCD center precisely. The only sub-requirement for 2 OHs test is to synchronize two OHs data acquisitions. The second LTP OH is in response to a trigger from the first LTP for starting data acquisition. The OOI software is modified.

Before measurement, it is important to align 2 OHs precisely in order to obtain identical pitch test results from 2 OHs with one scan.

Figure 10 is the comparison of residual height errors (after best sphere subtraction) on a plane ZERODUR mirror with 4 methods: sequence non-tilted reference (Figure 10 a)), 2 OHs non-tilted reference (Figure 10 b)), penta-prism LTP (Figure 10 d)), and tilted reference (Figure 10 c)). In all cases the sample beam is not tilted.

However, the radius of curvature of the subtracted sphere are slightly different. This introduces a nanometer-level absolute height error and it needs to improvement.

Conclusion

Experimental results indicate that a tilted reference will produce larger systematic errors resulting from optical component imperfection. Six non-tilted reference beam methods can be effectively used to improve measurement accuracy. The independent sequential non-tilted reference method, the penta-prism non-reference scan method and the non-tilted reference beam plus tilted sample beam methods are convenient for use with older LTPs. New non-tilted reference methods, including application of different precision angle measurement devices, non-tilted reference by use of a second optical head, and alternate data acquisition of sample and reference beams, require new hardware and software updates, and are suitable for new LTP development. More work has to do to reach absolute nanometer accuracy.

Acknowledgments

The authors would like to thank Ohashi of Spring 8 for helpful discussion and to thank Y. Kan and other members of NSRL for their help. This manuscript has been authored by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy. The United States Government retains, and the publisher, by accepting the article for publication, acknowledges, a world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for the United States Government purposes. This research was sponsored in part by the U. S. Department of Energy and the National Synchrotron Radiation Laboratory, University of Science and Technology of China.

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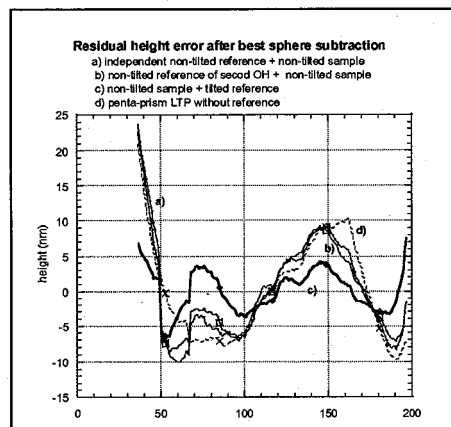


Figure 10 Comparison tests of 3 non-tilted reference methods and one tilted reference.

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