

Status of multi-beam long trace-profiler development

Mikhail V. Gubarev^{1*}, Daniel J. Merthe², Kiranmayee Kilaru¹, Thomas Kester¹, Brian Ramsey¹,
Wayne R. McKinney², Peter Z. Takacs³, A. Dahir⁴ and Valeriy V. Yashchuk²

¹NASA Marshall Space Flight Center, Huntsville, AL 35812, USA

²Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

³Brookhaven National Laboratory, Upton, NY, 11973, USA

⁴Texas A&M University-Commerce, Commerce, TX 75428, USA

ABSTRACT

The multi-beam long trace profiler (MB-LTP) is under development at NASA's Marshall Space Flight Center. The traditional LTPs scans the surface under the test by a single laser beam directly measuring the surface figure slope errors. While capable of exceptional surface slope accuracy, the LTP single beam scanning has slow measuring speed. Metrology efficiency can be increased by replacing the single laser beam with multiple beams that can scan a section of the test surface at a single instance. The increase in speed with such a system would be almost proportional to the number of laser beams. The progress for a multi-beam long trace profiler development is presented.

Keywords: Long trace profiler, optical metrology, x-ray optics metrology, multi-beam profiler, surface profile measurement, Grazing incidence X-ray optics, X-ray mandrel metrology

1. INTRODUCTION

Future x-ray astrophysical missions would require sub-arc-second x-ray optics with few meters effective area, which translates into the need for metrology instrument capable of measuring the optical figure of large area surface for fabrication and optical performance prediction purposes. That necessitates the development of the figure metrology instrument with sub-micro-radian accuracy and short data acquisition time. The long trace profiler (LTP) is a slope-measuring instrument widely used for figure metrology of grazing incidence X-ray optics and it fulfills the metrology accuracy requirement. However, the LTP is scanning instrument that measures the slope change between the measuring points on the surface under the test, so it is relatively slow. Moreover, because the point-by-point scanning approach the LTP is sensitive to the environmental instabilities, so averaging over multiple scans is necessary in order to achieve high accuracy of the surface slope measurements. That increases the data acquisition time even further.

MSFC uses a vertical LTP^{[1],[2],[3]} to measure the profiles of outer surface figure of cylindrical mandrels, and the inner surface of the replicated full-shell and segmented X-ray mirrors. In this the surface under the test is placed vertically in order to minimize the contribution of the gravitational sag to the figure profile of the surface under the test. The MSFC's vertical LTP uses He-Ne laser as the source of light.

*Mikhail.V.Gubarev@nasa.gov; Phone: 1 256 544-7816; FAX 1 256 544-2659

The LTP is the pencil beam interferometer. The schematic of the LTP is shown in Figure 1. The LTP uses a single laser beam to scan along the test surface. The polarized laser beam is split into two beams by a beam splitter. One of the beams gets reflected off the reference mirror while the other reflects off a test surface. The purpose of the reference beam is to correct the errors due to the motion of the optical components. The reflected beams focused on the detector by a Fourier Transform (FT) lens. The position of this beam on the detector with respect to the reference beam position gives the change in mirror surface slope at each scan point compared to the previous scan point. The position of the beam is calculated using a centroid algorithm. The slope profile measured can be then integrated to obtain the height profile of the surface under the test. The slope resolution possible with this system is $<1 \mu\text{rad}$, which is adequate for fabrication of 1-2 arc second class optics. The data acquisition rate is roughly 1 point per second for single scan.

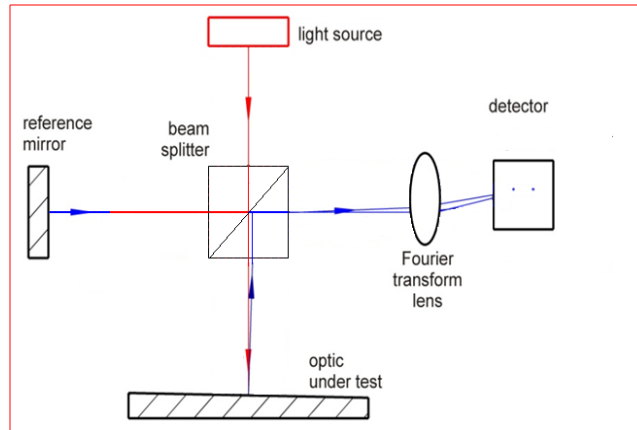


Figure 1. The schematic of the traditional LTP. Polarization preserving wave plates are not shown

The data acquisition rate could be improved if the LTP would simultaneously collect the slope data from multiple points on the surface under the test. In the multi-beam LTP (MBLTP) approach, the single laser beam is replaced with multiple beams which simultaneously measure a section of test surface in a single instance^{[4], [5]}. Therefore, the time of measurement can be reduced at a rate proportional to the number of laser beams. Figure 2 shows the basic optical layout of the MBLTP approach, in which a laser beam exiting the source is split into multiple equal intensity beams of defined spatial and angular separation. A polarizing beamsplitter then splits the beams into reference and test paths as discussed before. The FT lens then focuses the beams exiting the interferometer onto a 2D detector.

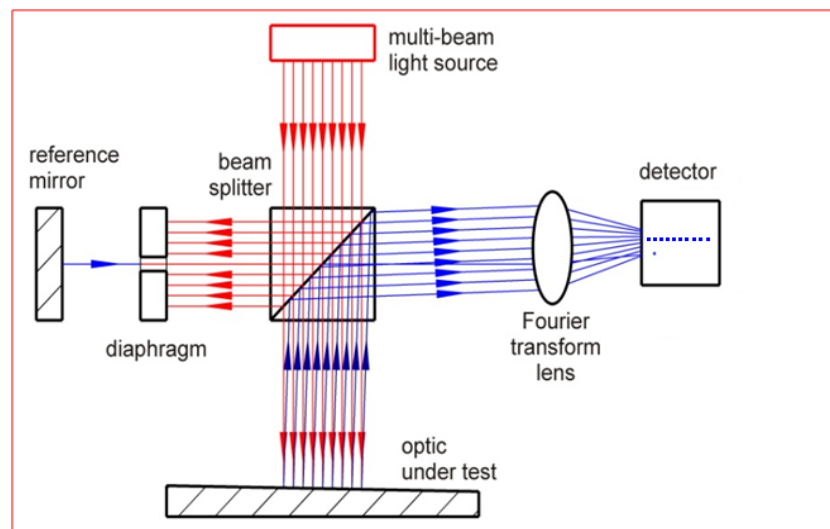


Figure 2. The schematic of the multi-beam LTP. Polarization preserving wave plates are not shown

A collaborative effort has been made to develop a new LTP in which the single laser scanning beam of classical LTP is replaced with multiple beams ^{[4], [5]}. In order to utilize multiple beams the LTP optical elements had to be redesigned and the MBLTP optical board breadboard was assembled for the proof-of-concept study. We are reporting the further progress in the MBLTP development.

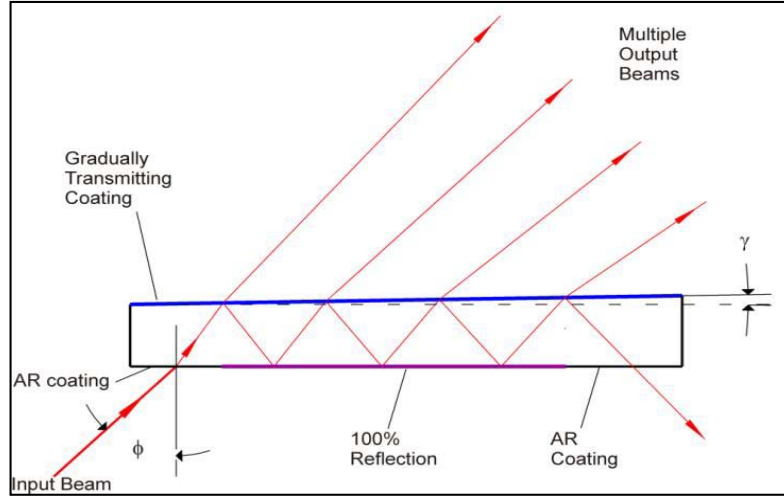


Figure 3. Geometrical layout of multiple-beam generating etalon. One side of the etalon has a customized gradually transmitting coating while the central region of other side has 100% reflective coating.

2. Multi-beam LTP

Obtaining multiple equal-intensity beams of desired spatial and angular separation is a technical challenge and the wedged etalon beam splitter has been designed and fabricated for the task. Such beam splitters have been used for wafer curvature measurements ^[6], for strain monitoring in thin films ^[7], as well as to produce multiple, equal-intensity beams for two-dimensional beam steering ^[8] and for a galvanometric scanner of a confocal scanning microscope ^[9]. The schematic of the beamsplitter is shown in figure. The etalon has a 50 mm x 50 mm dimension with a thickness of 3 mm and a wedge angle (γ) of 60 μ radian. The etalon beamsplitter is designed to produce ten beams with angular separation of 250 microradians. The spatial separation of the beams is defined by the thickness of the etalon while the angular beam separation is defined by the wedge angle. The angular beam separation sets the initial positions of the beams on the LTP detector. The change in the slope of the surface under the test between the scan points would result in the change in position of a beam. The etalon has a gradually transmitting silver coating on one of the surfaces to obtain almost equal intensity off the outgoing beams. The central region of the other surface of the etalon has a silver coating with zero transmission and the outer region have an antireflection coating, enabling 100% beam input into the etalon. The etalon is designed to split the laser beam that is incident at an angle of 49.5° into 10 equal intensity beams. One of the etalons fabricated for the multi-beam LTP is shown in figure 4.

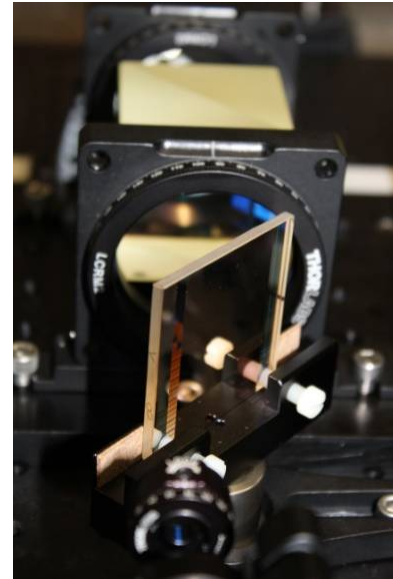


Figure 4. Etalon beamsplitter installed at the multi-beam LTP breadboard.

The FT lens of 500 mm focal length was custom designed. The design is challenging given to the requirements of low wave front distortion in order to minimize the effect of the lens on systematic errors and wide lateral range required to accommodate multiple beams and the large angular range of the surface slope that is desired to be measured. The final design is an air-spaced doublet and this lens was fabricated by Optimax Systems Inc. ^[10].

The 500 mm focal distance was decided in order to avoid the use of folding mirrors, which are necessary for larger focal distance of the lens, but can cause systematic errors. In order to preserve the resolution of the LTP the detector with pixel size smaller than 25 microns, the pixel size of existing MSFC's LTP detector. JAI AM 1600 GE camera manufactured by 1st Vision Inc^[11] is used for the multi-beam LTP, it has 7.4 μm pixel size with 36.1 mm x 24 mm of active area.

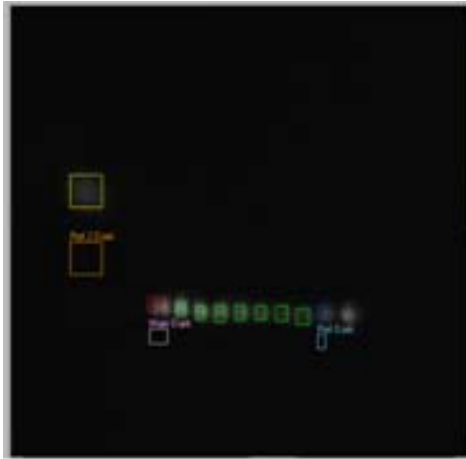


Figure 5. Ten signal and one reference beams on the detector



Figure 6. Redesigned optical board of the MBLTP. The view is from behind of the detector.

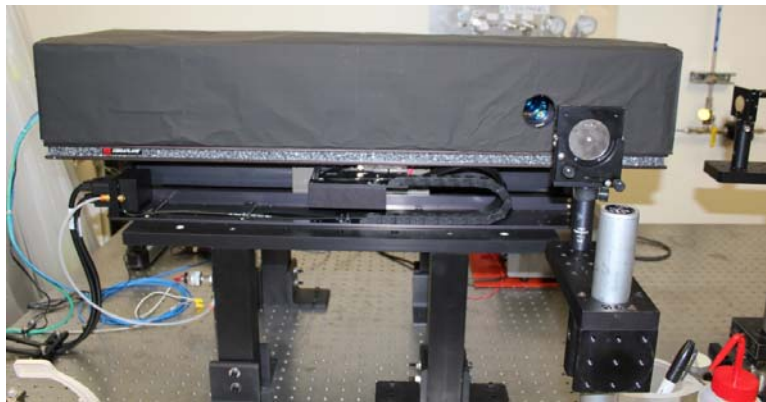


Figure 7. The MBLTP during slope measurements of 50 mm diameter mirror. The reference mirror is shown on right

A breadboard of the multi-beam LTP optical board was assembled. The initial tests were carried out with the optical board assembled on a manual mechanical stage. The reference mirror was installed outside of the breadboard. The LabViewTM based LTP control software provided by Lawrence Berkeley National Laboratories was modified at MSFC for the detector. The software was also modified to track eleven laser beams representing the slope of the surface under the test at ten positions and the one position at the static reference mirror. In order to speed up the data collection with the MBLTP a partial frame readout of 4872x800 pixels was used. This translates in a readout speed

of 1.5 fps. The distance between the detector and the FT lens was optimized by minimizing the beam sizes at the detector. An example of the beam pattern at the detector is shown in figure 5.

A curved mirror was used to calibrate the multi-beam LTP. The mirror profile was measured using the MBLTP breadboard installed on the manual mechanical stage. The data collected for each beam were stitched together and compared to the slope profile of the curved mirror measured using the ZYGO interferometer. The calibration factor converting the pixel size into the surface slope was varied to achieve the best fit between the data collected by the MBLTP breadboard and the interferometer. The best fit was obtained at 7.47 micro-radians per pixel.

After completion of the calibration tests the breadboard was redesigned to fit smaller footprint and installed on an Aerotech ABL1500 linear air-bearing stage with 400 mm travel. The picture of redesigned optical board is shown in figure 6. The LabView software was modified to control the stage. The stage was placed on the raisers so the measurement of inner surface of cylindrical mirror shells with up to 500 mm diameter be possible. The MBLTP optical board positioned on the air-bearing stage is shown in figure 7.

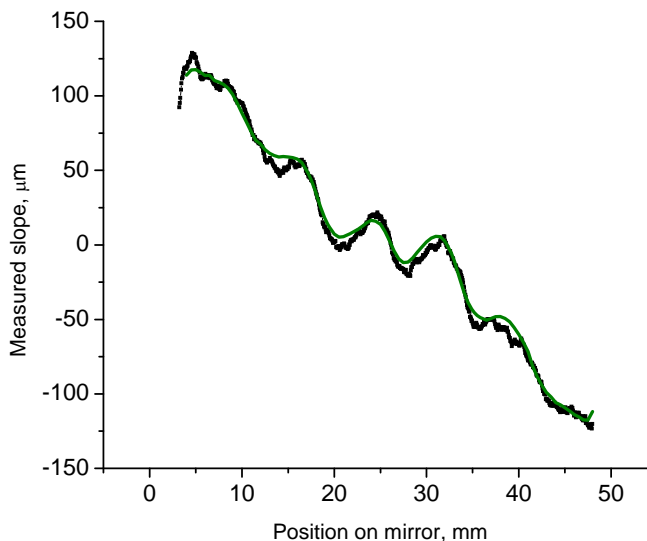


Figure 8. The slope profile of a curved mirror measured with the MBLTP (green line) compared to the slope profile measured with the ZYGO interferometer (black line).

For the proof-of-concept demonstration a central strip of a curved 50 mm diameter sample has been measured. The optical board was moved in 1 mm steps during the measurements and the software tracked and recorded the positions of each beam on the detector during the scan. The scan was completed in 25 seconds, compared to the acquisition time of the traditional LTP for the same sample to be about 1 minute. The data collected for each beam were stitched together in accordance with the angular and spatial beam separation and compared to the slope profile of the curved mirror measured using the ZYGO interferometer. The slope profiles of the flat mirror measured with the LTP and the interferometer are shown in figure 8. Note, most of the slope profile of the flat mirror measured with the LTP represents an average of ten scans by individual beams.

We are planning to continue the multi-beam LTP calibration experiments. The results of the systematic error analysis for the instrument will be presented in near future.

3. CONCLUSIONS

A multi-beam LTP is under development at MSFC in collaboration with Lawrence Berkeley National laboratory and Brookhaven National Laboratory. This instrument uses multiple beams to make simultaneous measurements in a single instance axis of scan of the test surface. This leads to a significant increase in the rate at which surface profile metrology of grazing incidence optics can be done.

Proof-of-concept tests have demonstrated viability of the multi-beam LTP approach. Incorporation of an air-bearing stage with the multi-beam LTP optical board a. Experiments to estimate the accuracy of the slope measurements by the MBLTP and the possible measurement rate will be performed after that.

This proof of concept study forms the groundwork for a future modular metrology approach where-in an entire length of a test surface can be measured in a single instance using multiple optical beams and also multiple frequencies can also simultaneously be measured.

4. ACKNOWLEDGEMENTS

We would like to acknowledge the partial funding available for this work from MSFC's technology investment program and Technical Excellence Program. Also, our acknowledgements to Lawrence Berkeley National Laboratory for providing the LTP control software code in order to speed up the development process. This manuscript has been authored, in part, by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy. The Advanced Light Source is supported by the Director, Office of Science, Office of Basic Energy Sciences, Material Science Division, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231 at Lawrence Berkeley National Laboratory.

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or The Regents of the University of California.

5. REFERENCES

- [1] Li, H., Li, X., Gringel, M.W., and Takacs, P.Z., "Measurement of X-ray Telescope Mirrors Using A Vertical Long Trace Profiler", *Optical Engineering*. 35(2), P. 330-338, (1996).
- [2] Li,H., Takacs, P.Z., and Overslizen, T., "Vertical scanning long trace profiler: a tool for metrology of X-ray mirrors", in *Materials, Manufacturing, & Measurement for Synchrotron Radiation Mirrors*, Proc. SPIE, 3152, 180-187, (1997).
- [3] Mikhail Gubarev, Thomas Kester, Peter Takacs, "Calibration of vertical-scan long trace profilometer at MSFC", *Optical manufacturing and testing IV*, Proceedings of SPIE, 4451, 333 (2001).
- [4] K. Kilaru, D. J. Merthe, M. V. Gubarev, T. Kester, C. M. Benson, W. R. McKinney, P. Z. Takacs, V. V. Yashchuk, "Development of a multi-beam long trace profiler" *Proc. SPIE* 8147, 814719 (2011)
- [5] M. V. Gubarev, D. J. Merthe, K. Kilaru, , T. Kester, R. Eng, W. R. McKinney, P. Z. Takacs, V. V. Yashchuk, "Progress of multi-beam long trace-profiler development" *Proc. SPIE* 8501, 85010B (2012)
- [6] M.M. Rajadhyaksha, R. H. Webb, "Plate Beamsplitter to Produce Multiple Equal-Intensity Beams," *Appl. Opt.* 34(34), 8066-8066 (1995).
- [7] D. Litvinov, R. Clarke, C. A. Taylor II, D. Barlett, Real-time strain monitoring in thin film growth: cubic boron nitride on Si (100), *Mater. Sci. and Eng. B66*, 79-82 (1999).
- [8] M. Toyoshima, F. Fidler, M. Pfennigbauer, and W. R. Leeb, "Two-dimensional optical beam deflector operated by wavelength tuning", *Opt. Exp.* 14(9), 4092-100 (2006).

[9] http://refractiveindex.info/?group=GLASSES&material=F_SILICA

[10] <http://www.optimaxsi.com/>

[11] <http://www.lstvision.com/>