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Sub-microradian surface slope metrology with the ALS Developmental Long Trace Profiler

Valeriy V. Yashchuk [a,*], Samuel Barber [a], Edward E. Domning [a], Jonathan L. Kirschman [a], Gregory Y. Morrison [a], Brian V. Smith [a], Frank Siewert [b], Thomas Zeschke [b], Ralf Geckeler [c], Andreas Just [c]

[a] *Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA*
[b] *Helmholtz Zentrum Berlin für Materialien und Energie, Elektronenspeicherring BESSY-II, Albert-Einstein-Strasse 15, 12489 Berlin, Germany*
[c] *Physikalische-Technische Bundesanstalt Braunschweig (PTB), Bundesallee 100, 38116 Braunschweig, Germany*

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ABSTRACT

A new low-budget slope measuring instrument, the Developmental Long Trace Profiler (DLTP), was recently brought to operation at the ALS Optical Metrology Laboratory. The design, instrumental control and data acquisition system, initial alignment and calibration procedures, as well as the developed experimental precautions and procedures are also described in detail. The capability of the DLTP to achieve sub-microradian surface slope metrology is verified via cross-comparison measurements with other high-performance slope measuring instruments when measuring the same high-quality test optics. The directions of future work to develop a surface slope measuring profiler with nano-radian performance are also discussed.

1. Introduction

Development of X-ray optics for third and fourth generation X-ray light sources with a level of surface slope precision of 0.1–0.2 μrad requires the development of adequate fabrication technologies and dedicated metrology instrumentation and methods [1,2].

The best performing slope measuring profilers, such as the Nanometer Optical Component Measuring Machine (NOM) at Helmholtz Zentrum Berlin (HZB)/BESSY-II (Germany) [3–6] and the Extended Shear Angle Difference (ESAD) instrument at the PTB (Germany) [7–9], come close to the required precision. These instruments utilize a schematic (Fig. 1) with a movable pentaprism [10–14] and an electronic autocollimator (AC) as a contactless optical slope sensor [3,15]. The high performance of the instruments is based on the precision calibration of the ACs for the specific application with small apertures of 2.5–5 mm in diameter [16,17].

The Developmental Long Trace Profiler (DLTP) is a slope measuring instrument recently brought into operation at the Advanced Light Source (ALS) Optical Metrology Laboratory (OML). Similar to the NOM and ESAD, the DLTP is based on a movable pentaprism and a precisely calibrated autocollimator. In contrast to the NOM, this is a reasonably low-budget instrument used at the ALS OML for the development and testing of new measuring techniques and methods. Some of the methods developed with the DLTP [18–21] have been already implemented into the ALS LTP-II slope measuring long trace profiler [22]. In the course of the developmental work, the ALS LTP-II was upgraded and has demonstrated a capability for <0.25 μrad surface metrology with significantly curved optics and about 0.1 μrad accuracy with close to flat optics [23].

Besides the application as a test facility at the OML, the DLTP is developed as a slope measuring instrument, supplementary to the existing LTP-II. There are a number of arguments for the development. First, the systematic errors of an autocollimator-based instrument should be significantly different [24] from that of the LTP [18,23]. In the LTP, the optical reference arm was added [22] to monitor the carriage wiggling and laser pointing instability. Unfortunately, currently, the performance of the reference arm is one of the most important factors limiting the accuracy of LTP measurements [23]. The use of a movable pentaprism in the DLTP makes the slope measurement insensitive, in first approximation, to carriage wiggling [25], allowing for a schematic free of an optical reference arm. Second, the use of an autocollimator precisely calibrated with a high-performance stationary calibration system, as the one at the PTB [16,17], allows transfer of calibration accuracy to the DLTP measurement. Third, the closed and self-sufficient design and high stability of the DLTP autocollimator [26] provides an opportunity for a deep automation of the measurement process that can require very long time for efficient suppression of the errors due to instrumental drifts and systematic effects.

In the present work, we describe the DLTP design and its major components (Section 2), the methods used to precisely align the

* Corresponding author. Tel.: +1 510 495 2592; fax: +1 510 486 7696.
E-mail address: vvyashchuk@lbl.gov (V.V. Yashchuk).

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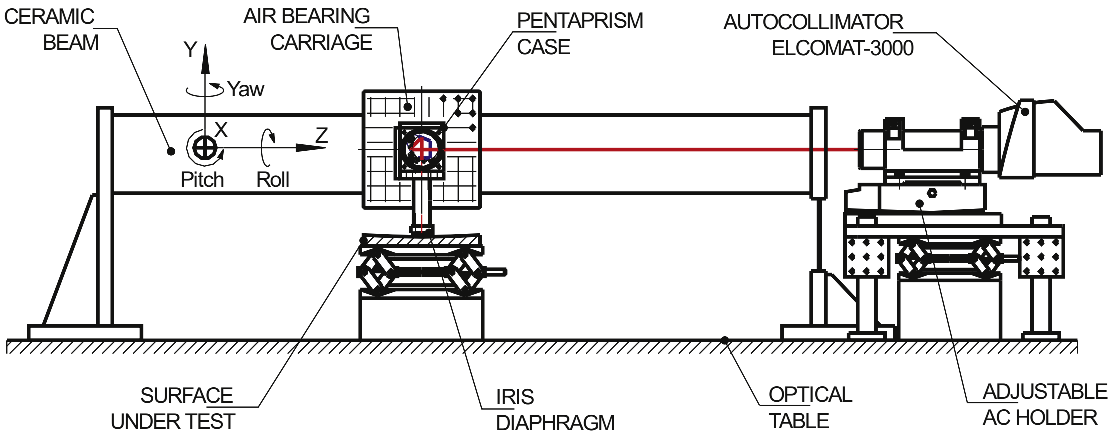

Fig. 1. Simplified model of an autocollimator-based profiler.

components (Section 3) and the measurement procedures developed to decrease errors of the DLTP measurements (Section 4). In Section 5, the performance of the DLTP is verified via a number of measurements with high-quality mirrors. A comparison with the corresponding results obtained with the world's best slope measuring instrument, the HZB/BESSY-II NOM, and also with the upgraded ALS LTP-II, proves the accuracy of the DLTP measurements on the level of 0.1–0.4 μrad, depending on the curvature of a surface under test (SUT). The directions of future work to develop a surface slope measuring profiler with a reliable accuracy of <0.1 μrad are discussed in Section 6.

2. DLTP experimental setup

Fig. 1 shows a simplified model of an autocollimator-based profiler. To a large extent, the model depicts the arrangement and essential components of the ALS DLTP.

The DLTP components are mounted on a Newport optical table with inactivated pneumatic isolation. The complete setup is enclosed within a hutch to enable more stable (than that in the laboratory) environmental conditions during the measurement. The DLTP uses an electronic autocollimator "ELCOMAT 3000 special" [26] as a slope measuring optical sensor. The autocollimator is mounted on a kinematic stage that allows precise alignment of the autocollimator's optical axis and the direction of the carriage translation. For diverting the autocollimator's light beam by 90° towards the surface under test (SUT) and also the reflected beam back to the autocollimator, a bulk pentaprism is mounted on a Thorlabs kinematic cage cube platform and placed in a cube case attached to an air-bearing carriage. The carriage is translated along a ceramic beam with a Nanomotion™ motor to trace the surface under test (SUT) oriented face up. Below we describe each DLTP component in detail.

2.1. Autocollimator calibrated at the PTB

The autocollimator ELCOMAT 3000 [26] used in the DLTP is a model originally customized to work with a small aperture in the HZB/BESSY-II NOM [4]. At the specified accuracy of ± 0.25 arcsec (for an aperture of ≥ 5 mm), the specified instrument reproducibility is 0.05 arcsec (0.24 μrad) over the total slope range ± 4.8 mrad. The high reproducibility allows to increase the accuracy by applying a precise calibration and, therefore, to use the autocollimator as a sensor of a surface slope profiler for sub-μrad metrology.

The autocollimator was calibrated at the PTB by a direct comparison of the device with a high-precision Heidenhain WMT 220 angle comparator [27] as a reference standard [16,17]. The fundamental principle of the used comparator is the subdivision of the circle, representing an error-free natural standard: 2π rad = 360°. In order to ensure the performance of the comparator, different cross- and self-calibration methods have been applied [28–32]. The comparator is located in a clean-room laboratory. The lab is kept at a highly stable ambient temperature ($\Delta T < 0.05$ K), a constant laminar air flow ($v = 20$ cm/s) and very small floor vibrations. Finally for the comparator, a standard uncertainty [33] of $u = 0.001$ arcsec (5 nrad) is assigned.

In the course of calibration, the autocollimator measures the angle of a plane mirror attached to the comparator's rotor unit. The autocollimator is rotated by 90° to align its main measuring axis for the DLTP application (Y-axis) with the comparator's horizontal plane of rotation.

The calibration data β_{cal} are defined as the angle measurements α_{AC} by the autocollimator minus the angles α_{WMT220} provided by the primary standard. Therefore, to get a corrected value of the SUT slope α_{AC}^{corr}, the calibration value β_{cal} has to be subtracted from the raw angle reading α_{AC} of the autocollimator.

Two different sets of calibrations were performed.

The parameters for the first calibration set were optimized for the application of the autocollimator in the DLTP. The calibrations cover an angle range ± 1000 arcsec (± 4.85 mrad) with sampling steps 10 arcsec (49 μrad). The reflecting surface under test, a temperature-stable ceramic mirror, coated for high reflectivity, was placed 330 and 550 mm from the autocollimator. A circular aperture with a diameter of 2.5 mm was placed directly in front of the reflecting mirror and, by means of an auxiliary laser pointing device, centered on the optical axis of the autocollimator. This location of the aperture is strongly recommended for deflectometric applications. A standard measurement uncertainty of $u = 0.015$ arcsec (0.073 μrad) is stated [expanded measurement uncertainty $U = 0.03$ arcsec (0.146 μrad) with a coverage factor $k = 2$]. Measurement uncertainties are calculated according to Refs. [33,34]. The standard measurement uncertainty corresponds to the 68% level of confidence in the case of a normal distribution; whereas, the expanded uncertainty with coverage factor $k = 2$ corresponds to the 95% level of confidence [35].

Fig. 2 shows two selected calibrations (of the Y-axis used for the tangential slope measurement) from this data set.

The deviations on large angular scales in Fig. 2 are caused by aberrations of the optical components of the autocollimator and errors in their alignment. The saw-tooth-like oscillating pattern on smaller angular scales (Fig. 3) is caused by aliasing as