Title

High precision tilt stage as a key element to a universal test mirror for characterization and calibration of slope measuring instruments

Journal
Review of Scientific Instruments, 87(5)

ISSN
0034-6748

Authors
Yashchuk, Valeriy V
Artemiev, Nikolay A
Centers, Gary
et al.

Publication Date
2016-05-01

DOI
10.1063/1.4950729

Peer reviewed

High precision tilt stage as a key element to a universal test mirror for characterization and calibration of slope measuring instruments

Valeriy V. Yashchuk,[1,a] Nikolay A. Artemiev,[2,b] Gary Centers,[1] Arthur Chaubard,[3] Ralf D. Geckeler,[4] Ian Lacey,[1] Harry Marth,[5] Wayne R. McKinney,[6,c] Tino Noll,[7,8] Frank Siewert,[7] Mathias Winter,[5] Thomas Zeschke[7]

[1]*Lawerence Berkeley National Laboratory, Advanced Light Source, One Cyclotron Road, Berkeley, CA 94720, USA*

[2]*KLA-Tencor Corp., 1 Technology Drive,Milpitas, CA 95035, USA*

[3]*The École nationale supérieure d'ingénieurs de Caen & Centre de Recherche, 6 Boulevard Maréchal Juin, 14000 Caen, France*

[4]*Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany*

[5]*Physik Instrumente (PI) GmbH& Co.KG, Auf der Roemerstrasse 1, 76228 Karlsruhe, Germany*

[6]*Diablo Valley College, 321 Golf Club Rd, Pleasant Hill, CA 94523, USA*

[7]*Helmholtz Zentrum Berlin, BESSY-II, Institute for Nanometre Optics and Technology, Albert-Einstein-Str. 15, 12489 Berlin, Germany*

[8]*Institute of Optics and Atomic Physics, Technical University of Berlin, Strasse des 17 Juni 135, 10623 Berlin, Germany*

The ultimate performance of surface slope metrology instrumentation, such as long trace profilers and auto-collimator based deflectometers, is limited by systematic errors that are increased when the entire angular range is used for metrology of significantly curved optics. At the ALS X-Ray Optics Laboratory, in collaboration with the HZB/BESSY-II and PTB (Germany) metrology teams, we are working on a calibration method for deflectometers, based on a concept of a universal test mirror (UTM) [Proc. SPIE 6704, 67040A (2007)]. Potentially, the UTM method provides high performance calibration, and accounts for peculiarities of the optics under test (e.g., slope distribution) and the experimental arrangement (e.g., the distance between the sensor and the optic under test). At the same time, the UTM calibration method is inherently universal, applicable to a variety of optics and experimental arrangements. In this work we present the results of tests with a key component of the UTM system, a custom high precision tilt stage, which has been recently developed in collaboration with Physik Instrumente,

[a] Author to whom correspondence should be addressed. Electronic mail: VVYashchuk@lbl.gov.

[b] This research was performed while N. A. Artemiev was at Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA.

[c] This research was performed while W. R. McKinney was at Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA.

GmbH. The tests have demonstrated high performance of the stage and its capability (after additional calibration) to provide angular calibration of surface slope measuring profilers over the entire instrumental dynamic range with absolute accuracy better than 30 nrad. The details of the stage design and tests are presented. We also discuss the foundation of the UTM method and calibration algorithm, as well as the possible design of a full scale UTM system.

I. INTRODUCTION

The development of high performance x-ray sources of the so-called 'fourth generation' family, the diffraction limited storage rings (DLSRs) and Free Electron Laser (FEL) facilities, brought to a focus the need for near-perfect x-ray optics capable of delivering light to experiments without significant degradation of brightness and coherence under the high power operating conditions experienced in beamlines.[1-6] The desired optics must have unprecedented tolerances for surface quality with the residual (after subtraction of an ideal shape) surface slope and height errors of $\sigma_s < 30-50$ nrad (root-mean-square, rms) and $\sigma_h < 0.5-1$ nm (rms), respectively.[5-9]

The key to achieving the high quality of these x-ray optics is metrology, used for both optical fabrication at the vendor's facilities and for performance optimization of the optics and optical systems at the light sources.[10-13] With that, the accuracy of the metrology has to be a few times better than the required optical quality.

However, the current performance of optical metrology instruments for x-ray optics generally falls short of these requirements (for review see, for example, Ref.[13] and references therein). The major limiting factors are the systematic errors inherent in the metrology instruments. In the case of surface slope measuring profilers, such as long trace profilers (LTP) based on a pencil-beam interferometer[14-16] and autocollimator-based deflectometers,[17-19] the systematic errors can be divided into two groups, distinguished by the spatial frequency range at which they perturb.

One group relates to the quality of the instrument's optical elements contributing to the error at relatively higher spatial frequencies. The systematic errors that originate from the following: optical homogeneity of materials used in the beam splitters, Fourier transform lens, and Dove prism, to the quality of the reflecting surfaces of the mirrors and mirror prisms, as well as components of the detector system[20] (such as a CCD), can all be attributed to this group. In a measured surface slope trace, these systematic errors appear as local (high spatial frequency) perturbations with amplitude up to 1 μrad and even larger (see, for example, Refs.[21-24] and references therein). Besides simply improving quality of the optical elements, there are experimental methods to decrease the contribution due to the high spatial frequency systematic errors. Namely, one should perform multiple measurements with the same surface under test (SUT), but with different alignments (tilt and position) and orientations with respect to the instrument's optics and detector.[25,26] For an optimally arranged set of measurements, the systematic perturbation would appear at different locations along the slope traces and could be reduced by averaging over the measurements. Practically, the high frequency systematic errors in measurements with strongly curved x-ray optics can be suppressed to a level below 0.25 μrad (rms).[27,28]

The other group of systematic errors relates to the uncertainty of the instrumental calibration, corresponding to relatively lower spatial frequencies. In an LTP, such an error appears as unaccounted nonlinearity of the position-to-slope conversion factor, e.g., due to aberration of the Fourier transform lens or slight out-of-focus position of the CCD detector. In state-of-the-art surface slope profilers, angular dynamic range runs almost over six orders of magnitude, from a few hundredths of a microradian to ten milliradians. The overall (over the entire instrument bandwidth) calibration of a profiler is extremely difficult and requires sophisticated methods and dedicated equipment to be developed. A simple calibration with a diffraction grating[29] only pertains to a particular and very limited part of the dynamic range. A general calibration of ACs at a limited set of positions also does not solve the problem. First, the calibration of an AC strongly depends on the distance between the AC and the SUT.[30] Moreover, the peculiarities of the measurement set-up, such as lateral position of the beam-limiting aperture, its size and shape, as well as the SUT's reflectivity, also strongly affect the calibration.[31]

In order to account for the peculiarities of the Nanometer Optic component measuring Machine (NOM),[17,23] a calibration method has been developed at Helmholtz Zentrum Berlin (HZB)/BESSY-II.[31] The method is based on use of a test flat mirror mounted on a precise vertical angle comparator. In the course of NOM calibration, the tilt of the mirror is controlled with two high precision displacement sensors (Heidenhain™ Certo CP 60 K) placed at the opposite ends of the stage at the base distance of about 1247 mm. With a resolution of approximately 10 nrad, the accuracy of tilting is estimated to be around 50 nrad (rms).[32] The advantage of the method is the possibility to use the SUT as a reference in the course of calibration of the NOM, before characterization of the SUT itself. The major drawback is that it only partially accounts the non-linearity of the calibration. The account is partial because it is performed at one certain position, or at a limited number of distances between the SUT and the NOM AC. For the same reason, the calibration does not solve the problem of high frequency systematic errors.

At the Advanced Light Source (ALS) X-Ray Optics Laboratory (XROL), in collaboration with HZB/BESSY-II and Physikalisch-Technische Bundesanstalt (PTB), Germany, metrology teams, we are working on a calibration method based on the concept of a universal test mirror (UTM).[33] Potentially, the UTM method provides high performance calibration, accounting for peculiarities of optics under test (e.g., slope distribution) and/or the experimental arrangement (e.g., distance between the sensor and the optic under test). At the same time, the UTM calibration method is inherently universal, applicable to a variety of optics and experimental arrangements (see also Sec. II below).

In this work we present the results of tests with a key component of the UTM system, a custom made high precision tilt stage, which has been recently developed in collaboration with Physik Instrumente (PI), GmbH & Co.KG. Specification compliance tests were carried out at the vendor's facility using a ZYGO™ laser interferometer ZMI-4000. The tests at the ALS XROL were based on a comparison of the calibration of the autocollimator (AC) obtained with the UTM tilt stage to that of PTB's measured using their high precision angular comparator.[34,35] The tests have demonstrated high performance of the stage and its capability (after additional precision calibration) to provide angular calibration of surface slope measuring profilers over the entire instrumental dynamic range with absolute accuracy better than 30 nrad. The details of the stage design and tests are presented. We also discuss the foundation of the UTM method and calibration algorithm, as well as the possible design of a full scale UTM system.

This paper is organized as follows: First, we briefly review the mathematical fundamentals of the UTM calibration method and formulate the major requirements of the dedicated calibration system (Sec. II). In Sec. III we describe, in detail, the design of the PI tilt stage made especially for application in the UTM system, along with the specification compliance tests performed at PI. The measurement procedure, data processing, and the results of characterization of the tilt stage with a calibrated AC are discussed in Sec. IV. We show that beyond providing a direct measurement of the stage stability and repeatability, the tests with the AC highlight the problems (discussed above) with usage of the calibrated AC as an angular standard traceable to the PTB angular comparator. In Sec. V we present the initial calibration of the ALS upgraded LTP-II[36] with the tilt stage. The investigations confirm the high performance of the stage and its capacity as a key element of the future UTM system under development.

II. FOUNDATIONS OF METHOD FOR CALIBRATION OF SLOPE PROFILERS WITH UNIVERSAL TEST MIRROR

A straightforward solution to comprehensive calibration of a profiler is to calibrate it for all possible arrangements and over the entire angular bandwidth. Such an ideal calibration will be described with a multi-dimensional calibration matrix, where each dimension corresponds to all possible realizations of any one of the important experimental parameters. For example, in the case of a NOM-like profiler the calibration matrix has to be at least three-dimensional, $\left[a_{i,j,k}\right]$, where the index i runs over all possible distances between the NOM AC and SUT; the index j accounts possible position of the NOM aperture; and the index k covers the AC angular range, about ±4.5 mrad, with an increment, corresponding to the NOM angular resolution of 10-20 nrad. Because of the huge number of the matrix elements to be precisely measured and long-term temporal instability of the measurement set-up, such a calibration is generally unpractical.

The method for calibration of slope profilers with Universal Test Mirror, first suggested in Ref.,[33] realizes the ideal calibration but with a set of parameters reduced to one determined by the arrangement of a particular measurement with a SUT. A proper UTM system has to be able to exactly reproduce the SUT slope distribution measured with the profiler. Additional measurements with such an ideal test mirror, reproducing the corresponding slope profile measurement of the SUT, separates the systematic error providing the desired (reduced to the number of points in the slope trace measured with the SUT) calibration valid for the particular arrangement of the SUT.

An algorithm of measuring a SUT using the UTM system is detailed in Ref.[33] In short, it consists of precision measurement of the SUT surface slope distribution $\alpha_{MES}(x)$ (note that this is the only measurement with the SUT which we need; all other measurements are performed with the UTM) and application of the distribution as a "defined figure" (DF) $\alpha_{DF}(x)$ for scanning the UTM when measuring with the profiler the UTM generated slope trace $\alpha_{DF\,MES}(x)$. The contribution of the systematic error is extracted in an iterative procedure of re-measuring UTM generated slope traces updated with $\alpha_{DF\,MES}(x) \to \alpha_{DF}(x)$ and comparing the result with $\alpha_{MES}(x)$.

The convergence of the procedure can be confirmed via the following consideration. Let us present the measurements with the SUT as a sum:

$$\alpha_{MES}(x) = \alpha_{SUT}(x) + \alpha_{SYS}^{M}(x)\,, \tag{1}$$

where $\alpha_{SUT}(x)$ is the slope trace of the surface under test (SUT) that would be measured with an ideal profiler, free of any systematic errors, and $\alpha_{SYS}^{M}(x)$ is the systematic error of the measurement. On the first iteration step, a slope trace $\alpha_{MES}(x)$ is used as a DF for UTM scanning:

$$\alpha_{DF1}(x) = \alpha_{MES}(x)\,. \tag{2}$$

The result of the profiler measurement with the UTM, when controlled according to the defined figure $\alpha_{DF1}(x)$, is a trace $\alpha_{DF1MES1}(x)$ that is

$$\alpha_{DF1MES1}(x) = \alpha_{DF1}(x) + \alpha_{DF1\,SYS1}(x)\,. \tag{3}$$

where $\alpha_{DF1\,SYS1}(x)$ is a trace of systematic distortions, corresponding to the first iteration.

Substituting (1) and (2) to (3), one can get:

$$\alpha_{DF1MES1}(x) = [\alpha_{SUT}(x) + \alpha_{SYS}^{M}(x)] + \alpha_{SYS}^{M}(x) + \delta\alpha_{DF1\,SYS1}(x)\,, \tag{4}$$

where the term $\delta\alpha_{DF1\,SYS1}(x)$ is an additional perturbation to the systematic error $\alpha_{SYS}^{M}(x)$, appearing due to the deviation of the used DF1 from the SUT figure. As to the value of $\delta\alpha_{DF1\,SYS1}(x)$, one should expect that for the angular wavelengths larger than the peak-to-value variation of $\alpha_{SYS}^{M}(x)$,

$$\alpha_{SYS}^{M}(x) >> \delta\alpha_{DF1\,SYS1}(x)\,. \tag{5}$$

The systematic errors of a modern slope profiler are less (or, at least, on the order of) 1 μrad, even for the most important case of a significantly curved SUT. Therefore, for the angular wavelengths larger than a few microradians, the difference between the single SUT measurement and the UTM one provides a good estimation of the systematic error:

$$\tilde{\alpha}_{SYS1}^{M}(x) \approx \alpha_{DF1MES1}(x) - \alpha_{MES}(x)\,, \tag{6}$$

Therefore, the UTM method provides the measurement specific calibration over almost the entire angular bandwidth of the measurements.

With additional iterations when using a difference between the slope trace measured with the UTM and the systematic error, estimated in the previous iteration, as the UTM defined figure:

$$\alpha_{DFN\,MESN}(x) = \alpha_{MES}(x) - \tilde{\alpha}_{SYS(N-1)}^{M}(x)\,, \tag{7}$$

one can improve the estimation of the systematic error, extending the angular wavelength range below the limit, discussed above, given by the peak-to-value variation of the systematic error itself.

Figure 1 schematically illustrates the UTM-based calibration method.

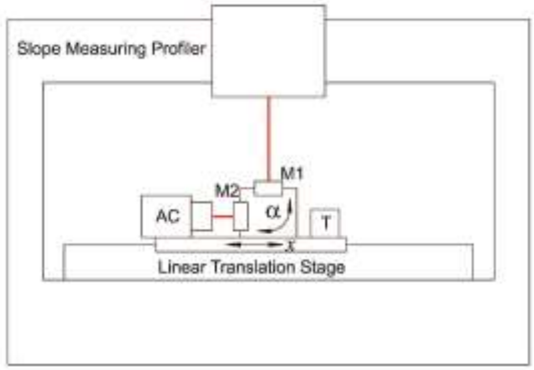


FIG. 1. Schematic illustration of the UTM-based calibration method. The UTM system includes a precision tilt stage with two reference mirrors, M1 and M2, and an autocollimator AC, all placed on a linear translation stage with a tilt sensor, T.

The major element of the UTM system is a precision tilt stage with two high quality reference mirrors, M1 and M2. M1 mirror reflects the sensor beam of the slope measuring profiler. An autocollimator, AC, is destined for calibration and control of the tilt stage by recording the tilt angle of the second reference mirror M2, synchronously tilted with M1. (Note that the distance between the AC and M2 is fixed that provides an opportunity for consistent traceability of the AC calibration; see also discussion in Secs. IV and V.) The repeatability and resolution of the stage have to be commensurate to that of the profiler. The tilt stage with the AC and two reference mirrors are mounted on a precision linear translation stage that is another significant part of the UTM system. The translation stage has to be capable of accurate (with minimal parasitic tilt/wobbling of the tilt stage) positioning of the tilt stage according to the spatial distribution of points in the slope trace measured with the SUT. A tilt sensor T serves to monitor and compensate the wobbling possible during the course of translation. The automated control for translation and tilt of the mirror allows simulation of a reflecting surface with any possible figure.

III. DESIGN AND COMPLIANCE TESTS OF A TILT STAGE FOR A UTM SYSTEM

In order to realize the potential advantages of the proposed method for calibration of state-of-the-art surface profilometers, a UTM tilt stage has to satisfy rather tight specifications dictated by the inherent temporal stability, repeatability, and accuracy of the profilometer's optical sensor.

The current accuracy limit of surface slope metrology demonstrated in measurements with flat or slightly curved x-ray mirrors is about 30-50 nrad (rms). [12,27,37-41] This can be thought of as a repeatability (reproducibility) limit of the profilometers. The slope sensor's systematic errors, illuminated in measurements with significantly curved optics, are typically about 1-2 μrad (rms).[33,36,42-44] With some experimental finesse, [25,26,42] the errors can be reduced to 0.25-0.4 μrad (rms). In order to totally realize the high repeatability of the slope sensors in measurements with significantly curved optics, an adequate calibration system should be capable of scanning the tilt angle of a reference mirror with resolution on the level of ~10 nrad and precision below 30 nrad (rms) over an angular range larger than the typical dynamic range of the profilers of about ±5 mrad. A larger tilting range of the stage is desired, in particular, in order to allow application of systematic error reduction techniques[25,26] when calibrating the stage (see also Sec. IV).

Below we describe a custom-made tilt stage Model N-310K021 designed and manufactured at Physik Instrumente GmbH & Co.KG especially for the application in a UTM system with the basic specification discussed above.

A. Design of the Physik Instrumente N-310K021 tilt stage

The PI model N-310K021 single-axis tilt stage, shown in Fig. 2, is designed to precisely tilt two reference mirrors in the range of ±10 mrad with angular resolution down to 4 nrad and repeatability of about 25 nrad.

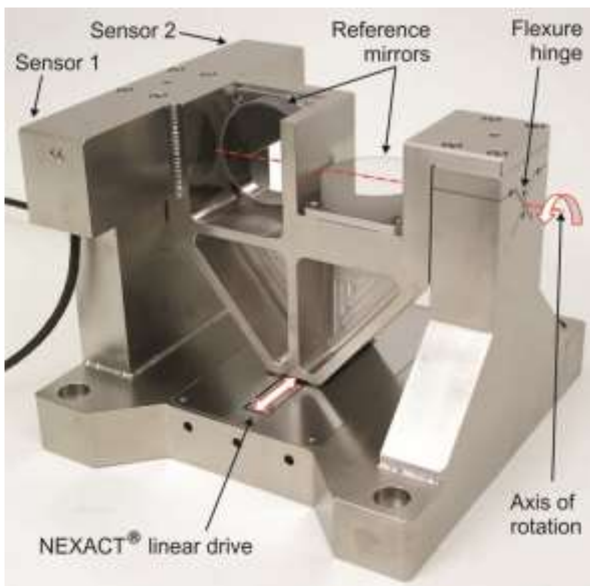


FIG. 2. The Physik Instrumente N-310K021 tilt stage custom-made for the application in a UTM system.

Benefiting from the relatively small tilting range, two very precise wire-cut EDM (electrical discharge machining) flexure hinges are used to provide friction, hysteresis and backlash free rotation around the axis located on the reflecting surfaces of the reference mirrors. The base of the stage holds a NEXACT® PiezoWalk® linear drive (Fig. 2) connected to the moved platform by a leaf spring which decouples the linear motion of ±1 mm from the rotation of the stage. Two SONY LASERSCALE® linear incremental encoders with resolution of about 60 pm serve as sensors of the opposite edge positions of the tilting cross-beam (Fig. 2). The sensors work in a differential mode to ensure only angular motion is detected and linear errors caused, for example, by tiny parasitic motion of the pivot point or by temperature variation, are canceled out. Moreover, for improved temperature stability, the body of the stage was made of Invar.

The reference mirrors with 2-in diameter and 0.5-in thickness were selected to be the best among a set of 10 reasonably inexpensive, flat, gold coated mirrors specified for surface flatness of λ/10 (Thorlabs, Inc). The flatness of the selected mirrors measured over the central area of approximately 0.5 in diameter is better that λ /100. The surface roughness is about 2A as measured with an interferometric microscope MicroMap-570 equipped with 2.5× objective (the corresponding field-of-view is 2.5 mm × 1.9 mm). The mirrors are mounted on detachable flanges using a silicone rubber adhesive, RTV, according to the technique developed for mirror assembly in a high-finesse power buildup cavity.[45]

The overall size of the stage is 200 mm (width) × 158 mm (height) × 200 mm (depth). The horizontal rotation axis of the stage is elevated by 130 mm perfectly matching the height of the ELCOMAT-3000 autocollimator optical axis when the AC is assembled on a two-axis adjustable mounting support (MÖLLER-WEDEL OPTICAL GmbH ident no.: 223 024). The AC in this arrangement was used for characterization of the stage at the ALS XROL (see Secs. IV and V). The compact design and relatively low mass (17 kg) are well suited for combining the tilt stage with a linear translation stage to realize the UTM method.

The N-310K021 tilt stage is operated in closed-loop mode via the E-712K102 digital controller using the difference of the signals from two linear sensors as a feedback. To ensure the flexures of the stage are not damaged, the moving range is limited by hard stops and additionally limited by parameter settings in the controller to ± 11,000 μrad.

B. Characterization of the tilt stage with a displacement measuring interferometer

For the specification compliance tests at PI GmbH, the stage performance was characterized with a ZYGO ZMI™ 4000 displacement measuring interferometer, arranged for differential measurement of distances with two laterally shifted beams.

The noise floor (stability level) of the set-up measured while operating the tilt stage with servo control loop switched OFF and ON is the same with the standard deviation $\sigma = 4\,\text{nrad}$ – Fig. 3a.

The tilting resolution and setting response time was verified by applying a small motion, induced by a square wave with 1 Hz frequency and 30-nrad peak-to-value amplitude, to the stage operating with closed-loop control. The result is presented in Fig. 3b. A tilt of 30 nrad is well resolved, having the same level of noise as in the stability test. Therefore, the tilting resolution, estimated as the full-width-half-maximum (FWHM) of a random Gaussian distribution of noise with $\sigma = 4$ nrad is $2.35\sigma \approx 10$ nrad. The positioning response time of this small tilting is less than 0.2 sec which is perfectly adequate for the UTM application.

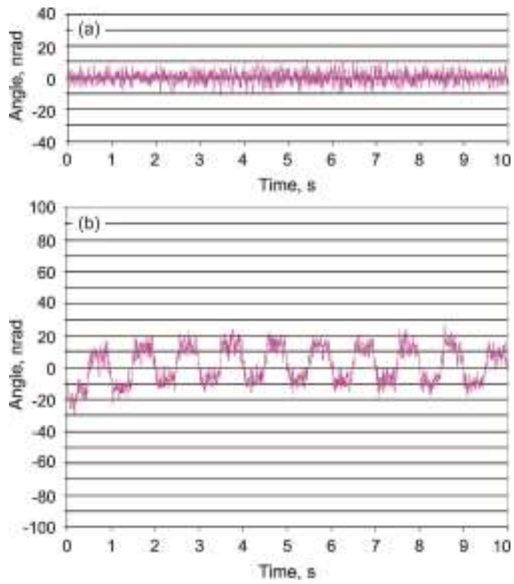


FIG. 3. (a) Stability test while operating the tilt stage with servo control loop switched ON. The corresponding standard deviation is $\sigma = 4$ nrad. (b) Tilting resolution and setting response test when applying to the stage a small motion, induced by a square wave with 1 Hz frequency and 30-nrad peak-to-value amplitude. The tilting resolution, estimated from the response trace is about 10 nrad.

The tilting bidirectional repeatability test was performed in 200 repeatable deflections of the stage by ± 1 mrad and returning to the central position with zero setting. A delay time of 2 seconds was applied before recording the central position. The measured distribution of the central positions is shown in Fig. 4. The bidirectional repeatability of the stage determined as the standard deviation of the best fit Gaussian distribution, shown in Fig. 4 with the solid line, is approximately 25 nrad. A similar level of repeatability was observed in the measurements with the XROL autocollimator, described in Sec IV.

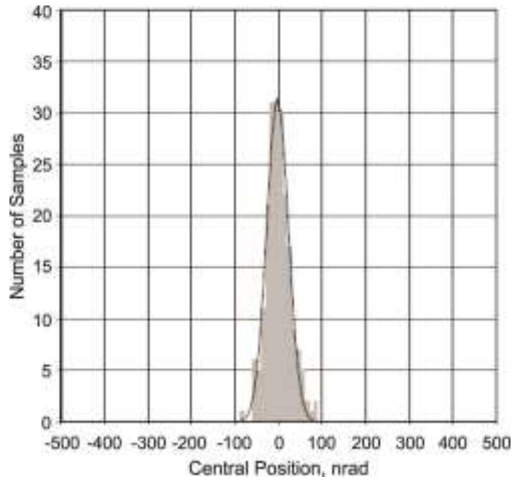


FIG. 4. Histogram of angular positions recorded after 200 repeatable deflections by ± 1 mrad and returning to the central position at the zero setting. The solid line depicts a Gaussian fit with standard deviation of ~ 25 nrad.

IV. UTM TILT STAGE CHARACTERIZATION WITH AN AUTOCOLLIMATOR

The metrology provided by the vendor and discussed in the previous section displays the high performance of the stage and its capacity to meet the requirements for application in a UTM system designed for calibration of state-of-the-art surface slope profilometers. However, for the UTM application the stage itself has to be calibrated over the entire dynamic range, with accuracy and angular resolution (tilting increment) both adequate to meet the level of metrological requirements for 4th generation light source optics. In this section, we described the results of calibration and performance characterization of the N-310K021 tilt stage with an autocollimator in the experimental arrangement corresponding to the UTM schematic in Fig. 1.

For the stage characterization, we used an ELCOMAT-3000/10 autocollimator, available at the ALS XROL. Autocollimators of this type are the most used slope sensors for angular deflectometric measurements of x-ray optics.[17-19,24,37,39,40,43] The autocollimators are initially calibrated at the PTB using their Heidenhain™ WMT 220 angle comparator.[34,35] The angle comparator utilizes subdivision of a full circle enclosure, which removes the need for an outside angular reference, to establish an angular standard. The ultimate standard measurement uncertainty of the WMT 220 is about 5 nrad.[46,47] With a highly stable autocollimator, calibration with standard uncertainty down to about 15 nrad is possible.[24,30,35,48] Figure 5 reproduces the PTB calibration of Y (the vertical) angle channel of the ALS ELCOMAT-3000/10. The calibration was performed in 2012 with a beam limiting aperture of 2.5-mm diameter and a flat reference mirror placed at a distance of 300 mm from the autocollimator. The distance between the aperture and the reference mirror was about 5 mm.

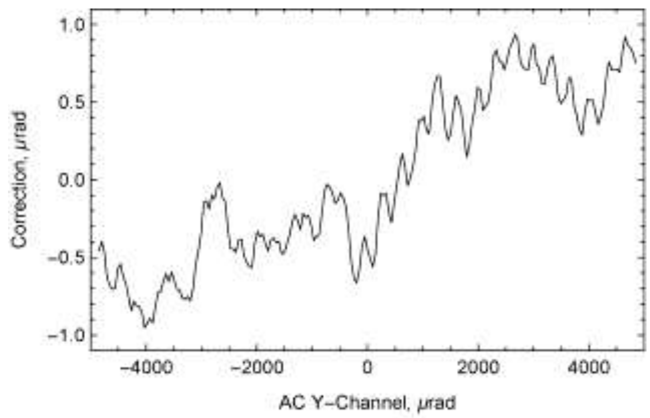


Figure 5: Calibration of Y-angle channel of the ALS autocollimator, ELCOMAT-3000/10, made in 2012 with the PTB WMT 220 angle comparator. A 2.5-mm circular aperture and a flat reference mirror, placed at the distance of 300 mm from the autocollimator, were used during the calibration.

In spite of the high precision of the calibration in Fig. 5, maintaining the traceability of the autocollimator to the PTB standard when used in an experimental arrangement and conditions like those at the ALS XROL, different from those during the PTB calibration, is an ongoing pursuit. Distance between the autocollimator and the SUT, size and shape of the beam limiting aperture, lateral aperture placement with respect to the autocollimator's optical axis, as well as temperature in the lab are among the factors that dramatically affect the calibration.[30,31] The exact reproduction of the PTB calibration set-up, other than at the PTB lab, is challenging if not impossible. Nevertheless, we have developed an experimental method presented below which, we believe, allows the tilting stage to be traceable back to the PTB angle comparator.

A. Experimental arrangement

Figure 6 shows the experimental arrangement used at the XROL for characterization and calibration of the N-310K021 tilting stage with the ALS ELCOMAT-3000/10, preliminarily calibrated at the PTB. The stage and autocollimator are mounted on an optical breadboard on a distance of 300 mm between the vertical reference mirror and the AC's input aperture. In order to suppress air convection noise,[49] the optical path is surrounded by a shielding tube attached to the AC. An iris diaphragm that serves as a beam limiting aperture is mounted on a two-dimensional translation stage attached to the free end of the shielding tube. The translation stage allows precise alignment of the aperture to the AC optical axis using the procedure described in Ref.[31] The distance between the aperture and the reference mirror is approximately 5 mm. During alignment, the AC light beam is additionally apertured with a large-aperture iris diaphragm mounted in the front of the AC inside the shielding tube.

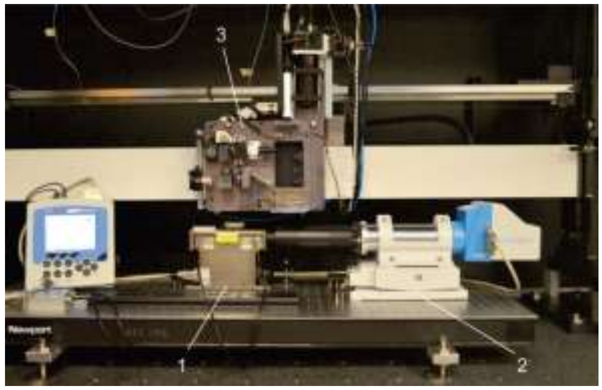


Figure 6: Experimental arrangement used at the XROL for characterization and calibration of the N-310K021 tilting stage (1) with the ALS ELCOMAT-3000/10 autocollimator (2), initially calibrated at the PTB. The set-up is placed on the ALS LTP-II granite table. The optical head of the LTP (3) is located to see the stage horizontal reference mirror. In this configuration the stage was used for calibration of the LTP (see Sec. VB).

With the desire to have the tilting stage traceable back to the PTB angle comparator, we arranged the autocollimator and tilt stage in an attempt to reproduce the PTB calibration set-up. Nevertheless, exact reproduction is hardly possible and many factors could be different. Besides the potential differences of the distance between the autocollimator and the reference mirror, size and shape of the beam limiting aperture, lateral aperture placement with respect to the autocollimator's optical axis, and temperature in the lab, we also could not place the iris diaphragm directly on the tilting stage. As a result, the aperture is not rotating with the tilting stage as it is in the PTB calibration set-up, where the beam limiting aperture and the reference mirror are both mounted to the WMT 220 rotor. Moreover, the thickness of our iris diaphragm is significantly smaller than that of the PTB aperture, a hole through a 3-mm thick plate, and the iris diaphragm has a hexagon-like shape rather than a circular one.[31] We also cannot expect that the autocollimator's calibration stays completely unchanged during the 3 years since the PTB calibration. In Sec. IVB we describe an experimental technique that still allows us to reliably use the PTB calibration of the AC for accurate characterization of the N-310K021 tilting stage.

B. Correlation analysis in the tilt stage calibration with the autocollimator

Expecting some deviation of the current AC effective calibration from that of PTB in Fig. 5, we treat the PTB calibration during measurements with the tilting stage as an initial characterization of the AC's systematic error and apply a recently developed technique[26] for suppression of instrumental systematic errors in surface slope measurements with high quality x-ray optics. The technique[26] uses correlation analysis of a measured surface profile to figure out a sequence of optimal repeatable measurements that upon averaging will lead to suppression of the instrumental systematic error.

In the case of measurements with our AC, the power spectral density (PSD) of the calibration trace (Fig. 5), shown in Fig. 7 with the solid line, suggests strong quasi-periodicity in the angular domain of the AC systematic error at periods of about 350 μrad, 1000 μrad, 1700 μrad, and 3000 μrad. Through averaging of a pair of measurements performed with two AC tilts different by half of a certain angular period (in correlation analysis, shifted by the corresponding anticorrelation length), this quasi-periodic systematic error will be suppressed.

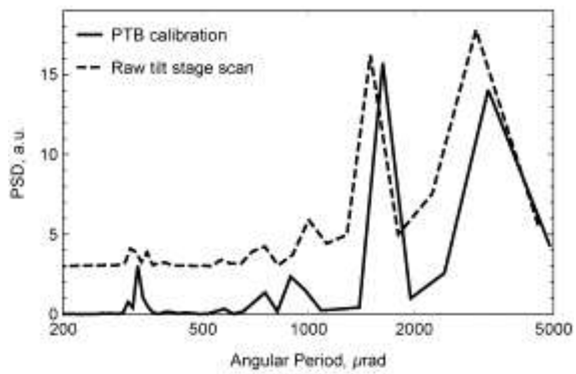


Figure 7: (solid line) PSD of the linearly detrended AC Y-angle calibration (shown in Fig. 5) measured with the PTB WMT 220 angle comparator and the (dashed line) PSD of the second-order detrended raw measurement of the stage tilting angle with the AC seen in plot (c) of Fig. 8. The raw tilt stage measurement PSD is vertically offset for clarity.

The calibration quasi-periodicity, depicted in Fig. 7 with the solid line, is clearly seen within the non-calibrated AC measurement of the stage tilt angle, in Fig. 8 (c) below, with the corresponding PSD distribution shown in Fig 7 with the dashed line. The measurement presented in Fig. 8, as well as all other measurements, is each a result of 4 sequential scans with 10 μrad increment performed in accordance with the optimal scanning strategies[50] designed to suppress the set-up temporal drift up to second order polynomial. An 8 scan sequence can suppress temporal drift up to the third order polynomial, but it was determined to be unnecessary during preliminary measurements.

In spite of the strong similarity of the quasi periodic oscillation and their PSD spectra, they are not exactly the same. This is why correction of the raw AC data with the PTB calibration does not remove the periodic variation characteristic for the AC systematic error – compare plots (c) and (d) in Fig. 8, where (c) the raw data from a measurement of the stage tilt angle with the AC without calibration and (d) with implementation of the PTB calibration, both presented after subtraction of the best fit quadratic polynomial to better observe the high angular frequency oscillations.

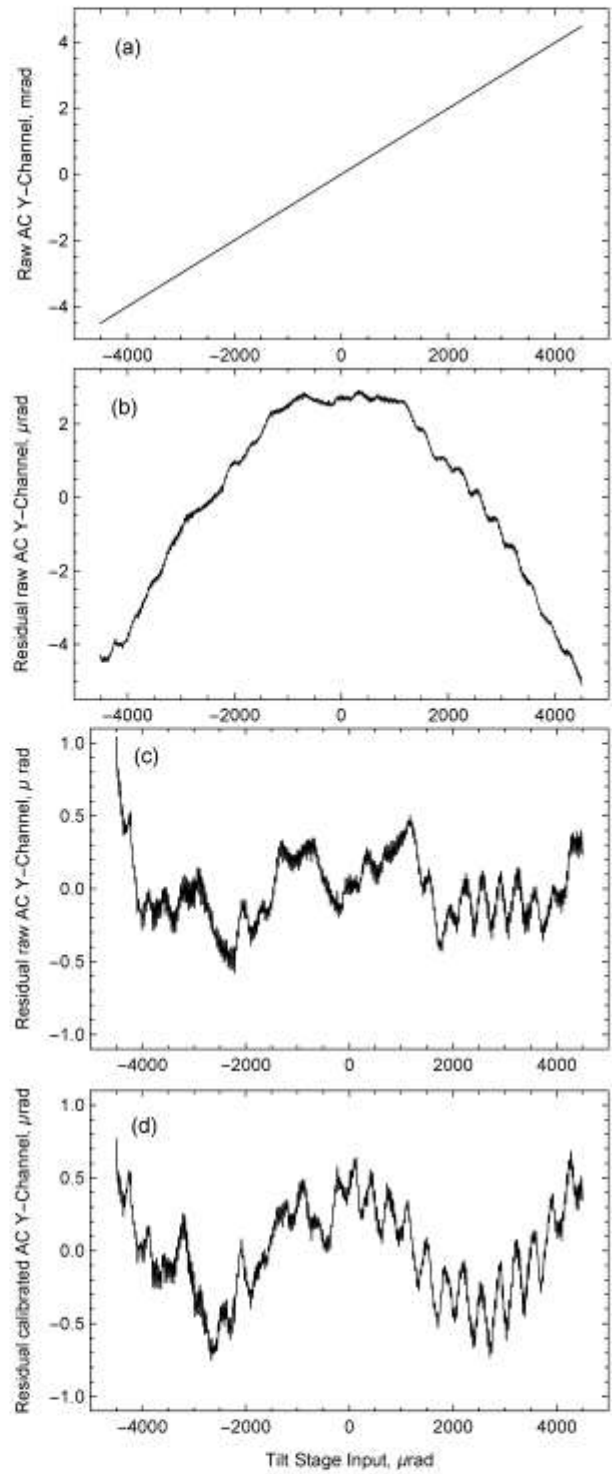


Figure 8: (a) Raw data of a measurement with the AC (without implementing the PTB calibration) of the stage tilt angle over ±4.5 mrad scanning range. The same data as in (a) but after subtraction of the best fit (b) linear and (c) quadratic polynomial. (d) The same measurement of the stage tilt angle but with the AC readings corrected according to the PTB calibration in Fig. 5. The measurement is a result of 4 sequential scans with 10 μrad increment, performed in accordance with the optimal scanning strategies,[50] designed to suppress the set-up temporal drift up to second order polynomial.

The observed high degree of repeatability of the measurements on the level of 25 nrad (rms), as the one shown in Fig. 8, suggests that the residual quasi-periodic and quadratic variation in the measured dependence of the raw AC Y-angle output signal of the stage tilt angle setting is due to a combination of systematic errors from the stage and the AC. In order to separate and suppress the AC systematic error, a set of repeatable measurements performed at different vertical angle alignments (tilts) of the autocollimator have been performed, thus translating the systematic error in the angular domain while keeping any contributions from the tilting stage stationary. With optimally chosen angular shifts one can anti-correlate the high frequency oscillations originating from the AC and average them out over the measurements.[26]

The optimal angles to tilt the AC are found using an autocorrelation of the trace in Fig. 8 and choosing the angular positions of the anti-correlated minima (as well as looking at the half periods of the corresponding PSD peaks in Fig. 7, the dashed line). Thus, one tilt angle for the AC was chosen of 170 µrad, found using ½ the lowest angular period peak of the measurement PSD which corresponds to suppression of the highest frequency variation. This suppression is illustrated between the raw measurement and trace 1 in Fig. 9 which is the average of two measurements, (each of 4 identical scans; one of the runs is shown in Fig. 9 with the solid line) only different by the relative tilt of the AC by 170 µrad.

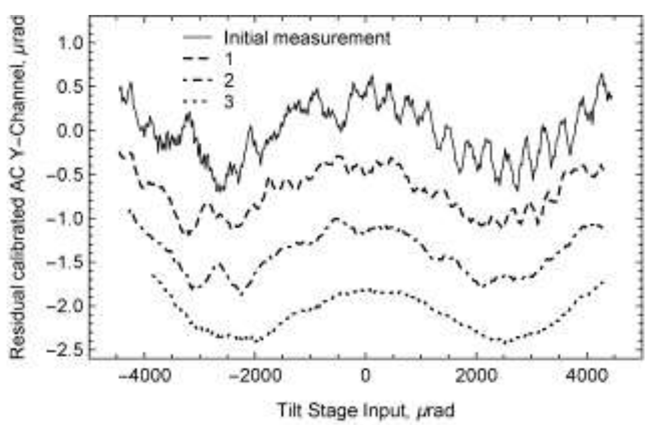


Figure 9: The solid line is the same run presented in Fig. 8 (d) after PTB calibration with nearly zero AC tilt. 1 – The average of two identical measurement runs (one of which is shown with the solid line) differing only by the relative tilt of the AC of 170 µrad. 2 – The average of two pairs of measurements, each pair recorded with 170 µrad relative tilt of the AC (similar to the trace 1), with relative tilt angle between the two pairs of 430 µrad. 3 – The average of two sets of 4 measurements arranged similar to trace 2, but with the relative AC tilt angle between the sets of 870 µrad. The traces are vertically offset for clarity.

The traces 2 and 3 in Fig. 9 demonstrate the suppression effect due to the additional tilts of the AC by 430 µrad and 870 µrad, respectively. Here, trace 2 is an average of two pairs of runs with a relative tilt angle between pairs of

430 μrad, while the runs in each pair were recorded with a 170 μrad relative tilt of the AC (similar to the trace 1). In turn, trace 3 is an average of 8 runs grouped to two sets of 4 runs, each set arranged similar to that of trace 2, but with a relative AC tilt angle between the sets of 870 μrad. The values of 430 μrad and 870 μrad for the additional tilts were found using an autocorrelation of the resultant trace 1 and trace 2, respectively.

The efficient suppression of the quasi-periodic variations in the tilt stage angle measurements with the AC, corresponding to the AC tilts applied to measurements in Fig. 9, proves that the variations are due to the AC systematic error, rather than to an imperfection of the tilting stage. This conclusion can be verified by application of the same error suppression procedure directly to the PTB calibration in Fig. 5. Figure 10 depicts the effect of the suppression when using the same tilt angles of 170 μrad, 430 μrad, and 870 μrad to sequentially shift and average the PTB calibration trace.

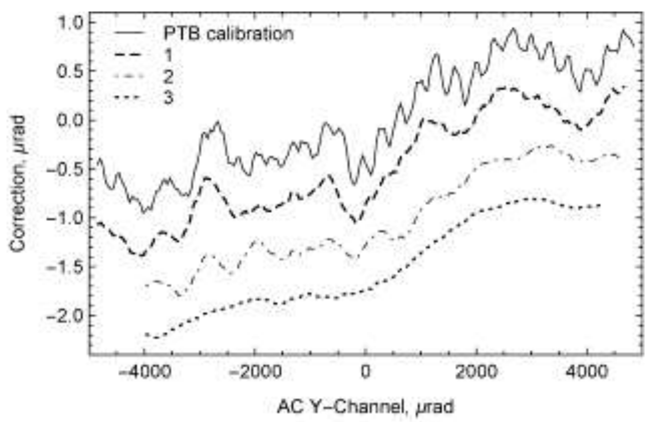


Figure 10: Illustration of the AC systematic error suppression by using 3 sequential shifts of the PTB calibration trace (the solid line) with the shift angles, 170 μrad, 430 μrad, and 870 μrad, the same as in the measurements in Fig. 9. 1 – The average of two PTB calibrations relative shifted by 170 μrad. 2 – The average of two pairs of the traces like trace 1, with the relative shift between the pairs of 430 μrad. 3 – The average of two pairs of 4 PTB calibration traces grouped as trace 2, but with the relative shift between the pairs of 870 μrad. The traces are vertically offset for clarity.

Figure 11 illustrates the AC systematic error suppression in the PSD domain. Here, PSDs of the traces (trace 3 in Fig. 9 and trace 3 in Fig. 10) resulting after application of the systematic error suppression procedure,[26] discussed above, are shown.

Comparing the PSD distribution in Figs. 7 and 11 one can see the complete removal of all but one of the peaks corresponding to the lowest angular frequency variation and a strong reduction of the integral error power (that is the squared rms variation of the corresponding averaged traces).

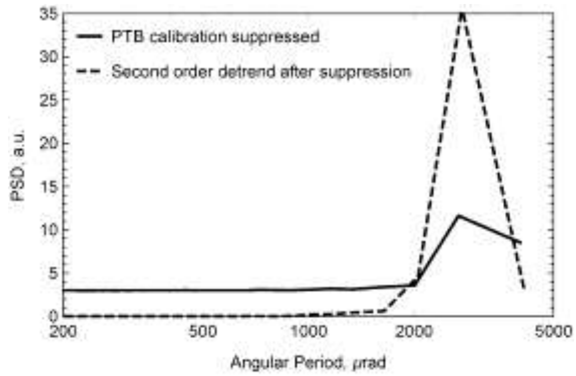


Figure 11: Illustration of the AC systematic error suppression in the PSD domain: (the solid line, offset for clarity) the PSD of the linearly detrended trace 3 in Fig. 10 that is the AC Y-angle calibration (shown in Fig. 5) averaged after the sequential angular shifts as discussed in the text; (the dashed line) the PSD of the trace 3 in Fig. 9 that is the result of averaging 8 measurement runs of the stage tilt angle with the calibrated AC optimally tilted between the runs. The increased power of the low angular frequencies (high period) spike is due to the residual 4^{th} order polynomial seen between Fig. 8 (c) and (d), an artifact of removing the best fit quadratic after applying AC calibration.

Note that each shift removes a corresponding amount from the edges of the signal. Because of this, we cannot remove the large low frequency variation, a shift of nearly 4000 μrad, as it would remove half of our valid calibration range. Moreover, when doing sequential shifts within the actual experimental arrangement, 2^n measurements for n translations is required. Development of an algorithm for finding an optimal (minimum) set of tilts that more rigorously accounts the peculiarity of the instrumental systematic error is a challenging problem, with which work on is currently in progress at the XROL in collaboration with Second Star Algonumerix, LLC.[51]

V. FIRST APPLICATIONS OF THE CALIBRATED UTM TILT STAGE

Further improvement of the tilt stage calibration is possible with a specially arranged re-calibration of the AC, used here, at PTB with the precision angular comparator. For this re-calibration, the autocollimator should be equipped with exactly the same opto-mechanical assembly, including the iris diaphragms, shielding tube, and alignment stage as shown in Fig. 6. Moreover, right before calibration, the ALS alignment procedure has to be applied for precision alignment of the beam limiting iris diaphragm.[31]

Before such a refined AC calibration we can use as a tilt stage calibration the residual tilt angle variation, shown in Fig. 12, obtained after removal of the best linear fit of the resulting (after averaging of 8 measurement runs arranged for suppression of the AC systematic error as described above) dependence of the stage tilt angle measured with the PTB calibrated AC. The calibrated tilt stage angles are obtained after an overall adjustment of the tilt stage input by a scale factor of 0.99703, found from the linear fit, and an additional nonlinear correction, shown in Fig. 12, which is added to the input values.

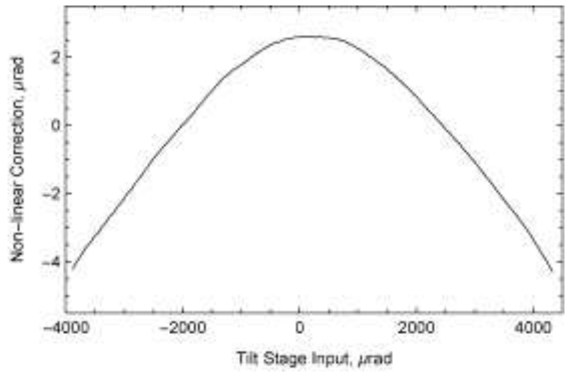


Figure 12: Nonlinear correction to the tilt stage calibration after determined linear function with the coefficient of 0.99703.

Below we describe the first applications of the calibrated tilting stage to characterize slope measurement instruments at the fixed distance between the instrument's sensor and the stage reference mirror.

A. Calibration of the AC with the N-310K021 tilting stage

As the first application of the calibrated UTM tilt stage, we compare the PTB calibration of the AC and our measured AC calibration using the calibrated tilt stage. Although the PTB calibration was used during the course of calibrating the tilt stage, it was suppressed using the methods discussed in Sec. IV to the curve 3 in Fig. 10.

In this case, the calibrated UTM tilt stage is used as an angle standard in the measurements of the raw AC Y-angle signal as a function of the corrected tilt angle of the vertical reference mirror rotated by the tilt stage. The same data as the ones depicted in Fig. 9 were used to generate a new AC calibration curve. Figure 13 compares the PTB calibration of the AC with the one obtained with the UTM tilt stage in the ALS XROL. In order to make better comparison, the XROL calibration trace was additionally filtered to correspond to the angular resolution of the PTB trace.

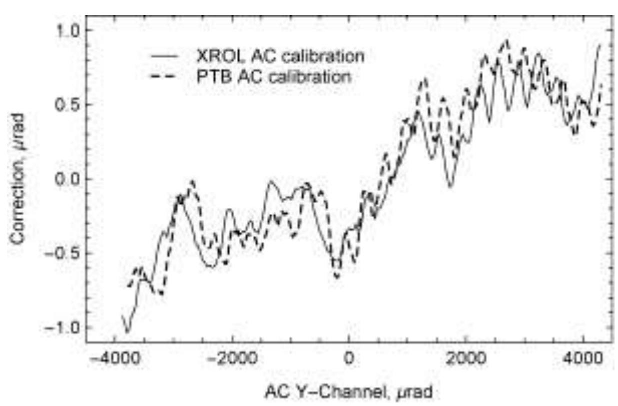


Figure 13: Comparison of the AC calibration traces measured at the ALS XROL (the solid line) and at the PTB (the dashed line).

In spite of the significant difference of the calibrations, one can see a strong similarity of the high angular frequency variation of the AC systematic error measured at the PTB and three year later at the XROL. If the overall translation, which can be thought of as a phase difference, between the calibrations is removed, the similarity will be seen even more clearly. In any case, additional calibration of the AC at the PTB with the XROL arrangement is suitable to discover the origin of the differences.

B. Calibration of the ALS LTP-II with the N-310K021 tilting stage

The ALS updated LTP-II[36] long trace profiler provides 1D surface slope profiling with the proven accuracy of tangential slope measurements with flat optics of < 80 nrad rms and with significantly curved optics (with radius of curvature ≥ 15 m) of < 250 nrad. Recently, the LTP CCD camera was replaced with one of a field of view 36 mm x 24 mm; correspondingly, the profiler's angular range was increased from ±2.5 mrad to approximately ±5 mrad.

The high performance of the ALS LTP-II becomes possible with use of experimental methods,[25,26,42] developed at the XROL for suppression of the measurement errors and utilized here for the measurements discussed in Sec. IV. These methods rely on a redundant set of multiple 1D traces, measured at different experimental conditions, such as different SUT positions, orientations, and tangential and sagittal tilts with respect to the LTP. The need for these redundant measurements can be avoided with precision calibration of the profiler.

In the course of measurement with the LTP, the optical head is translated along a SUT at approximately the same vertical distance. Unlike the sample channel, the optical path length in the reference channel is a subject of significant variation due to the longitudinal translation. Nevertheless, the range of angles monitored with the reference channel is rather small, about 10 μrad. Correspondingly, the change of the optical path across the LTP optical elements is also very small. This allows one to limit the LTP calibration to a calibration of the sample channel performed at a fixed longitudinal (scanning) position. In spite of the fact that it is not absolute, such a calibration still allows correction of a major part of the instrumental systematic errors which appear when measuring a significantly curved SUT. In order to correctly apply the calibration the distance to the reference mirror, fixed in the calibration measurements, as well as the zero angular position on the LTP CCD detector have to be carefully reproduced in measurements with other SUTs.

The experimental arrangement used for calibration of the ALS LTP-II[36] with the N-310K021 tilt stage is depicted in Fig. 6. Figure 14 shows the systematic error correction trace measured with the calibrated tilt stage. The correction trace is the difference between the reference mirror tilt angles measured with the LTP and the actual tilt angle set with the calibrated tilt stage. Note that the LTP calibration was performed only over the available angular range of the tilt stage calibration (Fig. 8).

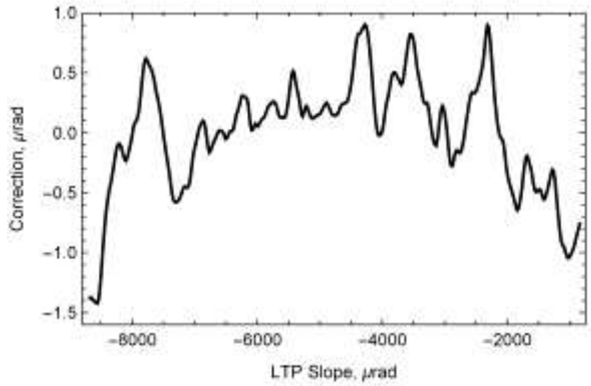


Figure 14: Calibration of tangential angle channel of the optical sensor of the ALS LTP-II, performed with the N-310K021 tilting stage calibrated at the XROL.

In the course of the calibration, we also calibrated the pixel-to-slope conversion factor for the new CCD camera that is now -2.86457 μrad/pixel and should be compared with the value of -2.88395 μrad/pixel used with the old camera. The difference can be due to a sub millimeter difference of the camera axial positions in the LTP sensor.

The performed calibration has also depicted a significant increase of the LTP systematic error with increase of its angular range. This is probably due to the increased imperfections at large angles of the LTP optical elements: polarizing beam splitter, Fourier transform lens, and folding mirrors.

VI. CONCLUSIONS

In this work we have reported the recent developments of the project for creation of an absolute calibration system for surface slope measuring profilers. The calibration system under development is based on the concept of a universal test mirror first suggested and discussed in Ref.[33]

Here, we have described a key component of the UTM system, a custom made high precision tilt stage. The stage has been recently developed in collaboration with Physik Instrumente (PI), GmbH & Co.KG. The high performance of the stage has been confirmed in the tests performed at the vendor’s facility using a ZYGO™ laser interferometer ZMI-4000, and at the ALS XROL with an electronic autocollimator ELCOMAT-3000/10 calibrated at the PTB using their high precision angular comparator. The tests have demonstrated that the precision (better than 25 nrad rms) and the stability (on the level of 4 nrad rms) of the stage are adequate to provide angular calibration of surface slope measuring profilers over the entire instrumental dynamic range with absolute accuracy better than 30 nrad.

In order to realize the stage's potential for calibration of profilometers, a high accuracy angular calibration of the stage is required. We have described an experimental method that allows us to have the tilting stage traceable back to the PTB high performance angle comparator WMT 220[34,35] via application of the AC calibrated at the PTB. Unfortunately, the AC calibration obtained at the PTB appears to not be directly applicable to the measurements with the tilting stage at the XROL. This is because of the extreme difficulty in exact reproduction of the same experimental arrangement at the XROL. The conclusion has been experimentally confirmed via comparison of the calibrations of the AC performed at the PTB and in the present investigation. While not an exact representation of the systematic error in our current arrangement, the PTB calibration still represents the general characteristics of the expected systematic error. This is justified by the nearly identical power spectral densities of the calibrations. The similarity of correlation properties of the calibrations has allowed us to successfully apply the method[26] for suppression of the deflectometer's systematic error and effectively use the PTB calibration after almost complete reduction of the higher angular frequency quasi-periodic systematic errors of the AC. We think that this approach is rather general and can find application in a broad class of experimental tasks.

As a first application of the fabricated and calibrated UTM tilt stage we have presented the results of calibrating the ALS LTP-II.

In conclusion, the performed investigations have confirmed total adequacy of the stage to the requirements for the UTM system under development. Usage of the stage for calibration of the LTP and NOM-like surface slope profilers can provide an improvement of slope metrology with significantly curved x-ray mirrors by a factor of up to 10, bringing them to a level crucial for state-of-the-art optics for x-ray beamlines at diffraction limited storage ring and free electron laser sources.

ACKNOWLEDGMENTS

The authors are grateful to D.E. Echizenya, Rob Duarte, Steve Irick, Nicholas Kelez, Jonathan Kirschman, Alastair MacDowell, Howard Padmore, and Tony Warwick for useful discussions. 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.

Part of this research was undertaken within the European Metrology Research Project EMRP-JRP SIB 58 Angle Metrology jointly funded by the EMRP participating countries within the EURAMET program of the European Union.

DISCLAIMER

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 favor 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.

REFERENCES

[1]M. Eriksson and J. F. van der Veen, Eds., Special issue on Diffraction-Limited Storage Rings and New Science Opportunities, J. Synchrotron Rad. 21(5), 837-1216 (2014) <http://journals.iucr.org/s/issues/2014/05/00/issconts.html>.

[2]R. Hettel and M. Borland "Perspectives and Challenges for Diffraction Limited Storage Ring Light Sources," Proceedings of PAC2013, MOYAB1, 19-23 (Pasadena, CA, USA, 2013) [ISBN 978-3-95450-138-0] <http://accelconf.web.cern.ch/accelconf/pac2013/papers/moyab1.pdf>.

[3]"Grand Challenge Science on Diffraction-Limited Storage Rings," A consensus report on future opportunities from scientists at ALS, LBNL; APS, ANL; NSLS-II, BNL; SSRL, SLAC together with a broad community of scientists at laboratories and universities (BESAC Subcommittee on Future Light Sources: July 10-12, 2013) <http://www.aps.anl.gov/Upgrade/Documents/DLSR_report_for_BESAC.pdf>.

[4]The Advanced Light Source Strategic Plan 2014–18, < http://www-als.lbl.gov/index.php/about-the-als/strategic-plan.html>.

[5]R. Barrett, “Precision and Stability Issues for X-ray Optics Systems,” presentation at the 4th DLSR Workshop (APS, Argonne, November 19-21, 2014). <http://www.aps.anl.gov/Upgrade/Workshops/2014/uploads/conf/Presentations/Misc-Presentations/BarrettPrecision_Stability.pdf >.

[6]D. Cocco, “Recent Developments in UV Optics for Ultra-Short, Ultra-Intense Coherent Light Sources,” Photonics 2015, 2(1), 40-49 (2015).

[7]L. Samoylova, H. Sinn, F. Siewert, H. Mimura, K. Yamauchi, and T. Tschentscher, “Requirements on Hard X-ray Grazing Incidence Optics for European XFEL: Analysis and Simulation of Wavefront Transformations,” Proc. SPIE 7360, 73600E/1-9 (2009).

[8]V. V. Yashchuk, L. Samoylova, and I. V. Kozhevnikov, “Specification of x-ray mirrors in terms of system performance: A new twist to an old plot,” Proc. SPIE 9209, 92090F/1-19 (2014).

[9]V. V. Yashchuk, L. Samoylova, and I. V. Kozhevnikov, “Specification of x-ray mirrors in terms of system performance: A new twist to an old plot,” Opt. Eng. 54(2), 025108/1-13 (2015).

[10]M. Idir and V. V. Yashchuk, Co-Chairs, “Optical and X-ray metrology,” in: X-ray Optics for BES Light Source Facilities, Report of the Basic Energy Sciences Workshop on X-ray Optics for BES Light Source Facilities, D. Mills and H. Padmore, Co-Chairs, pp. 44-55, U.S. Department of Energy, Office of Science, Potomac, MD (March 27-29, 2013); <http://science.energy.gov/~/media/bes/pdf/reports/files/BES_XRay_Optics_rpt.pdf>.

[11] L. Assoufid and T. Rabedeau, Co-Chairs, “X-ray Mirrors,” in: X-ray Optics for BES Light Source Facilities, Report of the Basic Energy Sciences Workshop on X-ray Optics for BES Light Source Facilities, D. Mills and H. Padmore, Co-Chairs, pp. 118-129, U.S. Department of Energy, Office of Science, Potomac, MD (March 27-29, 2013); <http://science.energy.gov/~/media/bes/pdf/reports/files/BES_XRay_Optics_rpt.pdf>.

[12]F. Siewert, J. Buchheim, T. Zeschke, M. Störmer, G. Falkenberg, and R. Sankari, “On the characterization of ultra-precise X-ray optical components: advances and challenges in ex situ metrology,” J. Synchrotron Rad. **21**, 968-975 (2014).

[13]P. Z. Takacs, "X-ray optics metrology," in: Handbook of Optics, 3rd ed., Vol. V, M. Bass, Ed., Chapter 46, McGraw-Hill, New York (2009).

[14]E. L. Church, P. Z. Takacs, "Use of an optical profiling instrument for the measurement of the figure and finish of optical quality surfaces," Wear **109,** 241-57 (1986).

[15]P. Z. Takacs, Shinan Qian, J. Colbert, "Design of a long trace surface profiler," SPIE Proc. 749 (1987), 59-64.

[16]S. C. Irick, W. R. McKinney, D. L. Lunt, P. Z. Takacs, "Using a straightness reference in obtaining more accurate surface profiles from a long trace profiler (for synchrotron optics)," Rev. Sci. Instrum. **63**(1), 1436-8 (1992).

[17]F. Siewert, T. Noll, T. Schlegel, T. Zeschke, and H. Lammert, "The Nanometre Optical Component Measuring Machine: a new Sub-nm Topography Measuring Device for X-ray Optics at BESSY," AIP Conference Proceedings **705**, 847-850 (2004).

[18]R. G. Geckeler, "ESAD shearing deflectometry: potentials for synchrotron beamline metrology," SPIE Proc. **6317**, 63171H/1-13 (2006).

[19]M. Schulz, G. Ehret, and A. Fitzenreiter, "Scanning deflectometric form measurement avoiding path-dependent angle measurement errors," J. Eur. Opt. Soc. Rapid Publications **5**, 10026/1-4 (2010).

[20]V. V. Yashchuk, "Positioning errors of pencil-beam interferometers for long-trace profilers," Proc. SPIE 6317, 6317 0A/1-12 (2006).

[21]P. Z. Takacs, "X-ray optics metrology," in: [Handbook of Optics], 3rd ed., Vol. V, M. Bass, Ed., Chapter 46, McGraw-Hill, New York, (2009).

[22]A. Rommeveaux, M. Thomasset, and D. Cocco, "The Long Trace Profilers," in: [Modern Developments in X-ray and Neutron Optics], A. Erko, M. Idir, T. Krist, A. G. Michette, Eds., Chapter 10, Springer-Verlag, Berlin/Heidelberg (2008).

[23]F. Siewert, H. Lammert, and T. Zeschke, "The nanometer optical component measuring machine," in: [Modern Developments in X-Ray and Neutron Optics], A. Erko, M. Idir, T. Krist, A. G. Michette, Eds., Chapter 11, Springer-Verlag, Berlin/Heidelberg (2008).

[24]R. Geckeler, A. Just, M. Krause, V. V. Yashchuk, Autocollimators for Deflectometry: Current Status and Future Progress, Nucl. Instr. and Meth. **A 616**, 140-146 (2010).

[25]Ali, Z., Artemiev, N. A., Cummings, C. L., Domning, E. E., Kelez, N., McKinney, W. R., Merthe, D. J., Morrison, G. Y., Smith, B. V. and Yashchuk, V. V., “Automated suppression of errors in LTP-II slope measurements with x-ray optics,” Proc. SPIE 8141, 81410O-1-15 (2011).

[26]V. V. Yashchuk, N. A. Artemiev, I. Lacey, and D. J. Merthe, “Correlation analysis of surface slope metrology measurements of high quality x-ray optics,” Proc. SPIE **8848**, 88480I/1-15 (2013).

[27]V. V. Yashchuk, N. A. Artemiev, I. Lacey, W. R. McKinney, and H. A. Padmore, “Advanced environmental control as a key component in the development of ultra-high accuracy ex situ metrology for x-ray optics,” Opt. Eng. 54(10), 104104/1-14 (2015).

[28] F. Polack, M. Thomasset, S. Brochet, A. Rommeveaux, “An LTP stitching procedure with compensation of instrument errors: Comparison of SOLEIL and ESRF results on strongly curved mirrors,” Nucl. Instrum and Methods A 616(2-3), 207-211 (2010).

[29]S. C. Irick, “Angle Calibration of the Long Trace Profiler Using a Diffraction Grating,” Light Source Beam Line Report LSBL-160 (Advanced Light Source, Berkeley, 1992).

[30]R. D. Geckeler and A. Just, “Distance dependent influences on angle metrology with autocollimators in deflectometry,” Proc. SPIE **7077**, 70770B/1-12 (2008).

[31]R. D. Geckeler, N. A. Artemiev, S. K. Barber, A. Just, O. Kranz, I. Lacey, F. Siewert, B. V. Smith, and V. V. Yashchuk, “Aperture use and alignment in autocollimator-based deflectometric profilometers,” Abstract to The International Workshop on Metrology for X-ray Optics, Mirror Design, and Fabrication, Satellite Workshop at the 12th International Conference on Synchrotron Radiation Instrumentation, SRI 2015 (Berkeley, USA, July 13-16, 2015); the corresponding paper has been submitted to Rev. Sci. Instrum.

[32]F. Siewert, J. Buchheim, and T. Zeschke, “Characterization and calibration of 2nd generation slope measuring profiler,” Nucl. Instrum. and Methods **A 616**(2-3), 119-127 (2010).

[33]V. V. Yashchuk, V. V., W. R. McKinney, T. Warwick, T. Noll, F. Siewert, T. Zeschke, and R. D. Geckeler, “Proposal for a Universal Test Mirror for Characterization of Slope Measuring Instruments,” Proc. SPIE **6704**, 67040A/1-12 (2007).

[34]R. Probst, R. Wittekopf, M. Krause, H. Dangschat, and A. Ernst, “The new PTB angle comparator,” Meas. Sci. Technol. **9**, 1059 – 1066 (1998).

[35]R. D. Geckeler and A. Just, “Optimized use and calibration of autocollimators in deflectometry,” Proc. SPIE 6704, 670407/1-12 (2007).

[36]J. L. Kirschman, E. E. Domning, W. R. McKinney, G. Y. Morrison, B. V. Smith, and V. V. Yashchuk, Performance of the upgraded LTP-II at the ALS Optical Metrology Laboratory, Proc. SPIE 7077, 70770A/1-12 (2008).

[37]S.G. Alcock, K.J.S. Sawhney, S. Scott, U. Pedersen, R. Walton, F. Siewert, T. Zeschke, F. Senf, T. Noll and H. Lammert, “The Diamond-NOM: A non-contact profiler capable of characterizing optical figure error with sub-nanometre repeatability,” Nucl. Instr. Meth. **A 616**(2-3), 224-228 (2010).

[38]Y. Senba, H. Kishimoto, H. Ohashi, H. Yumoto, T. Zeschke, F. Siewert, S. Goto, and T. Ishikawa, “Upgrade of long trace profiler for characterization of high-precision X-ray mirrors at SPring-8,” Nucl. Instr. and Meth. **A 616**(2-3), 237-240 (2010).

[39]J. Nicolas and J. C. Martınez, “Characterization of the error budget of Alba-NOM,” Nucl. Instr. and Meth. **A 710**, 24-30 (2013).

[40]S. Qian, R. D. Geckeler, A. Just, M. Idir, and X. Wu, “Approaching sub-50 nanoradian measurements by reducing the saw-tooth deviation of the autocollimator in the Nano-Optic-Measuring Machine,” Nucl. Instr. and Meth. **A 785**, 206-212 (2015).

[41]F. Siewert, J. Buchheim, S. Boutet, G. J. Williams, P. A. Montanez, J. Krzywinski, and R. Signorato, “Ultra-precise characterization of LCLS hard X-ray focusing mirrors by high resolution slope measuring deflectometry,” Optics Express **20**(4), 4525-4536 (2012).

[42]F. Polack, M. Thomasset, S. Brochet, and A. Rommeveaux, “An LTP stitching procedure with compensation of instrument errors: Comparison of SOLEIL and ESRF results on strongly curved mirrors,” Nucl. Instr. and Met. **A 616**(2-3), 207-211 (2010).

[43]V. V. Yashchuk, S. Barber, E. E. Domning, J. L. Kirschman, G. Y. Morrison, B. V. Smith, F. Siewert, T. Zeschke, R. Geckeler, and A. Just, “Sub-microradian surface slope metrology with the ALS Developmental Long Trace Profiler,” Nucl. Instr. and Meth. A 616(2-3), 212-223 (2010).

[44]S. K. Barber, G. Y. Morrison, V. V. Yashchuk, M. V. Gubarev, R. D. Geckeler, J. Buchheim, F. Siewert, and T. Zeschke, “Developmental long trace profiler using optimally aligned mirror based pentaprism,” Opt. Eng. 50(5), 053601-1-10 (2011).

[45]C. S. Wood, S. C. Bennett, J. L. Roberts, D. Cho, and C. E. Wieman, “Precision measurement of parity nonconsevation in cesium,” Can. J. Phys. 77, 7–77 (1999).

[46]A. Just, M. Krause, R. Probst, H. Bosse, H. Haunerdinger, C. Spaeth, G. Metz, andW. Israel, “Comparison of angle standards with the aid of a high-resolution angle encoder,” Precis. Eng. **33**(4), 530-3 (2009).

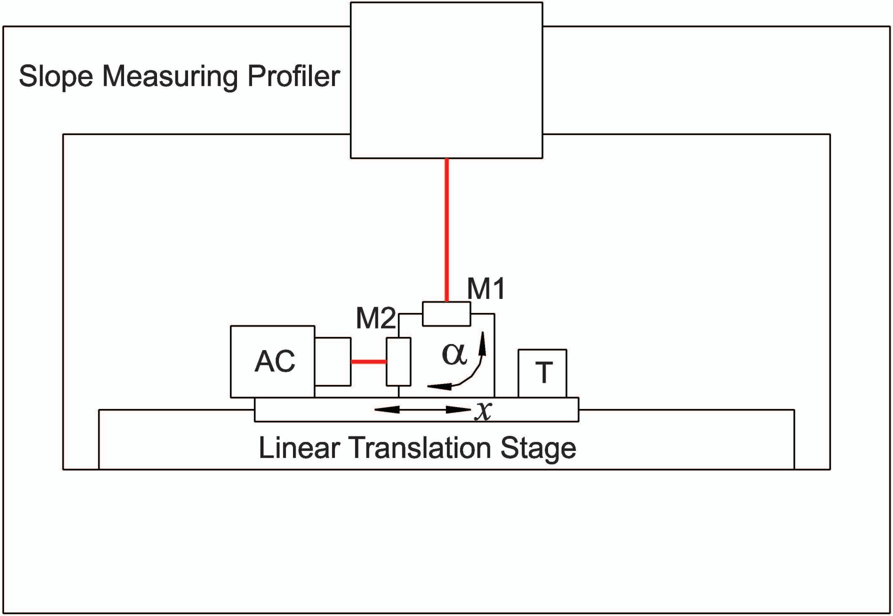
[47]R. D. Geckeler, A. Link, M. Krause, and C. Elster, “Capabilities and limitations of the self-calibration of angle encoders,” Meas. Sci. Technol. **25**, 055003/1-10 (2014).

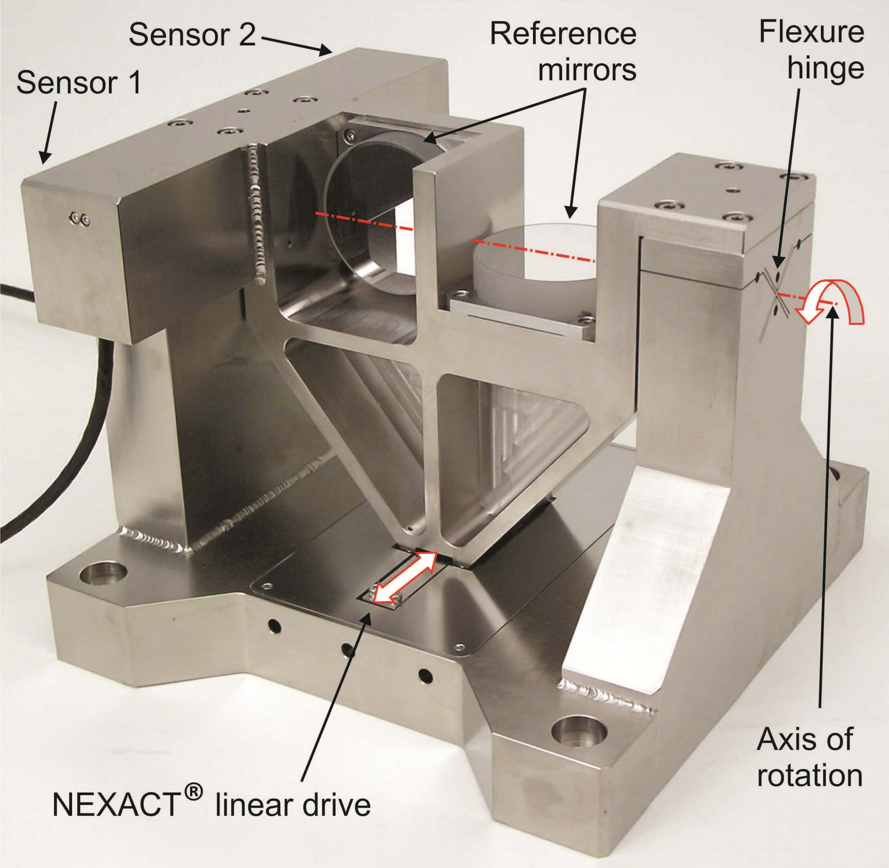
[48]A. Just, M. Krause, R. Probst, and R. Wittekopf, “Calibration of high-resolution electronic autocollimators against an angle comparator,” Metrologia **40**, 288-294 (2003).

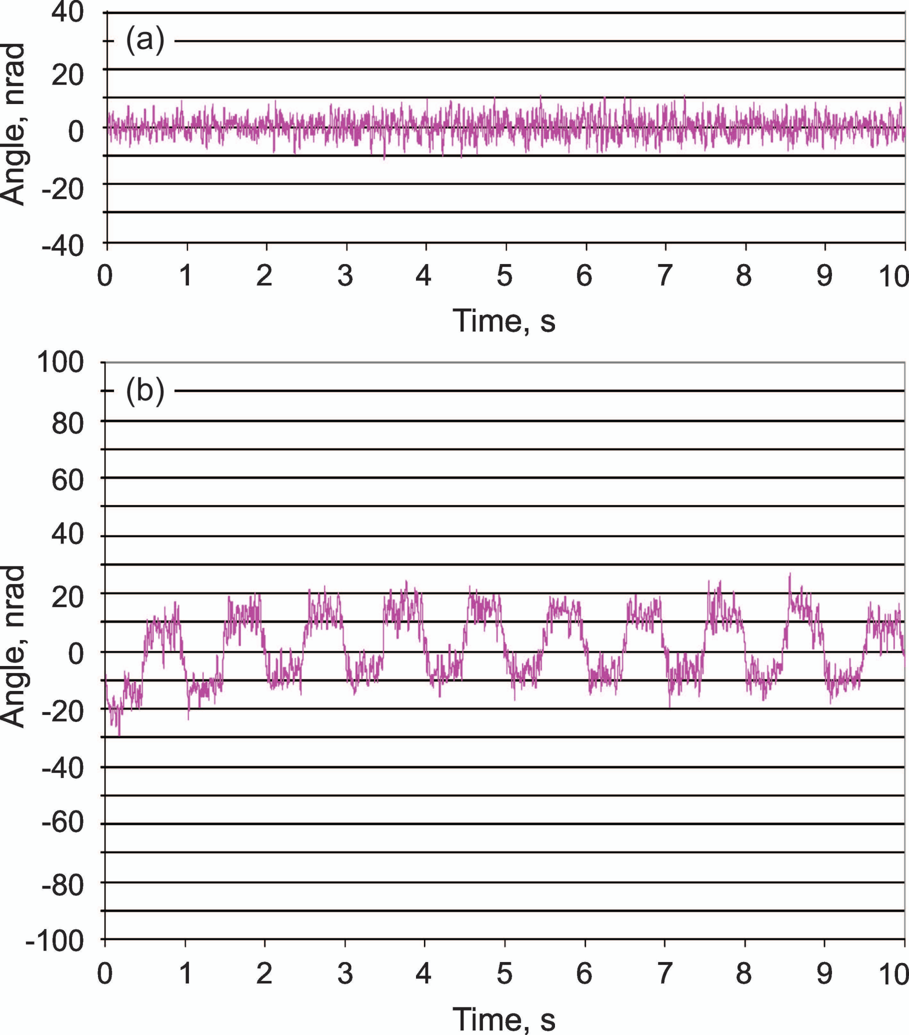
[49]V. V. Yashchuk, S. C. Irick, A. A. MacDowell, W. R. McKinney, P. Z. Takacs, “Air convection noise of pencil-beam interferometer for long-trace profiler,” Proc. SPIE **6317**, 63170D/1-12 (2006).

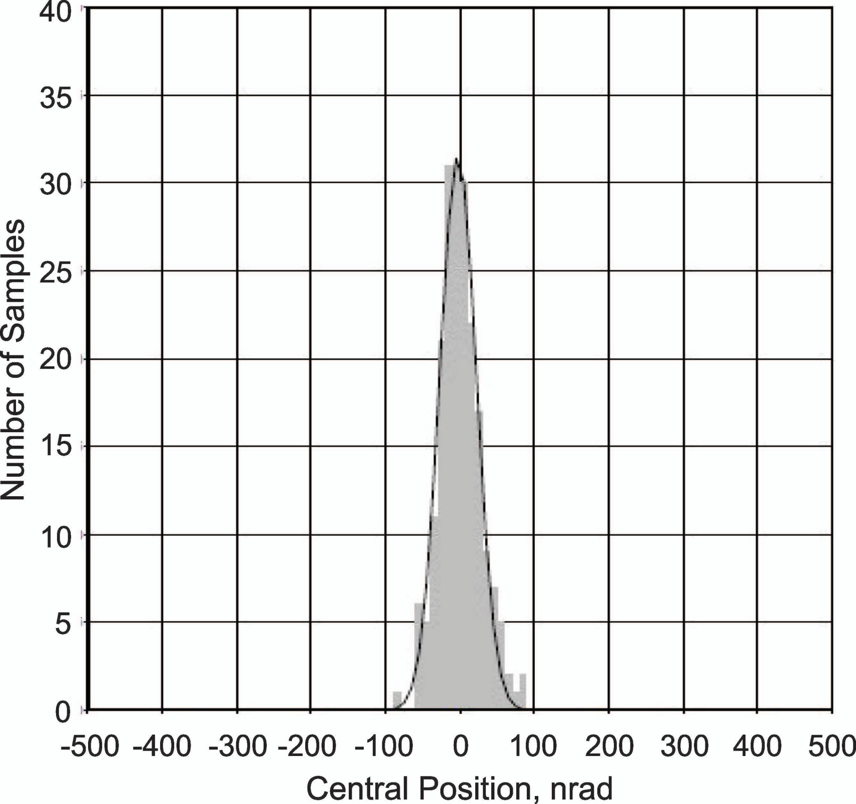
[50]V. V. Yashchuk, “Optimal Measurement Strategies for Effective Suppression of Drift Errors,” Rev. Sci. Instrum. 80, 115101-1-10 (2009).

[51]V. V. Yashchuk, Yu. N. Tyurin, and A. Yu. Tyurina, “Modeling of surface metrology of state-of-the-art x-ray mirrors as a result of stochastic polishing process,” Proc. SPIE **9809**, 98090M/1-16 (2015).

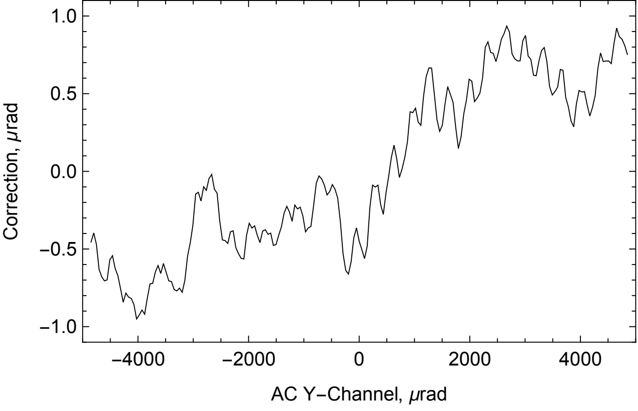

Slope Measuring Profiler
M1
M2
AC
α
T
x
Linear Translation Stage


Sensor 2
Sensor 1
Reference mirrors
Flexure hinge
Axis of rotation
NEXACT® linear drive

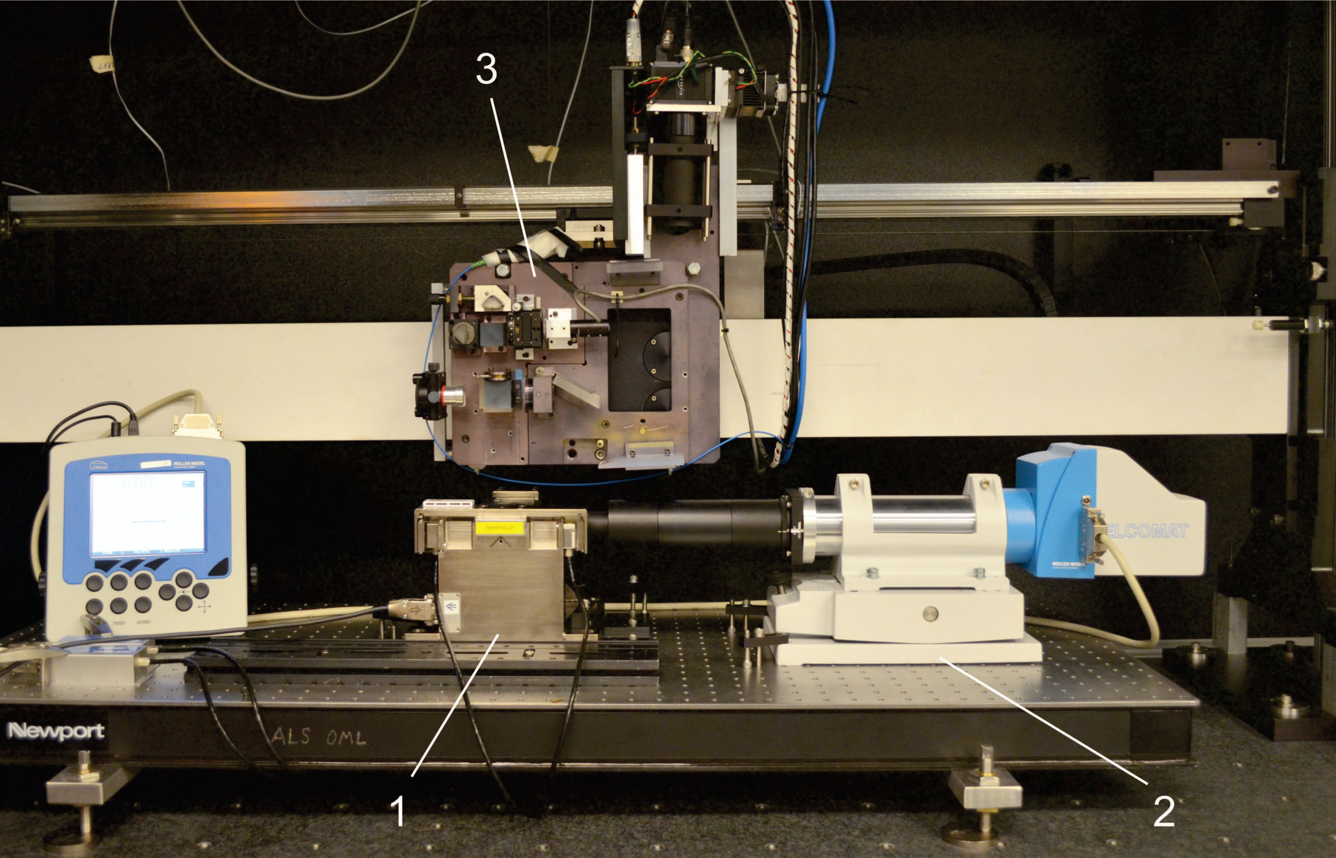

(a)
Angle, nrad
40
20
0
-20
-40
0 1 2 3 4 5 6 7 8 9 10
Time, s
(b)
Angle, nrad
100
80
60
40
20
0
-20
-40
-60
-80
-100
0 1 2 3 4 5 6 7 8 9 10
Time, s

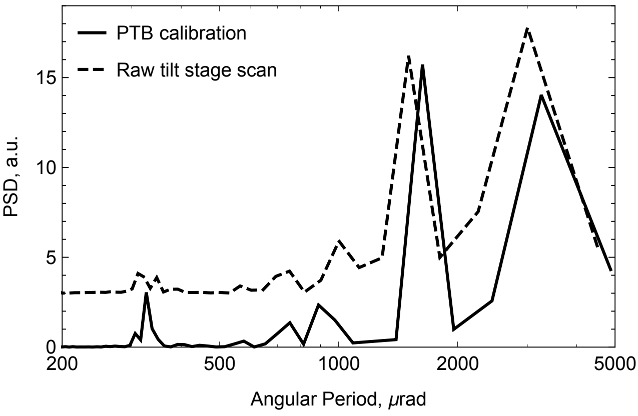


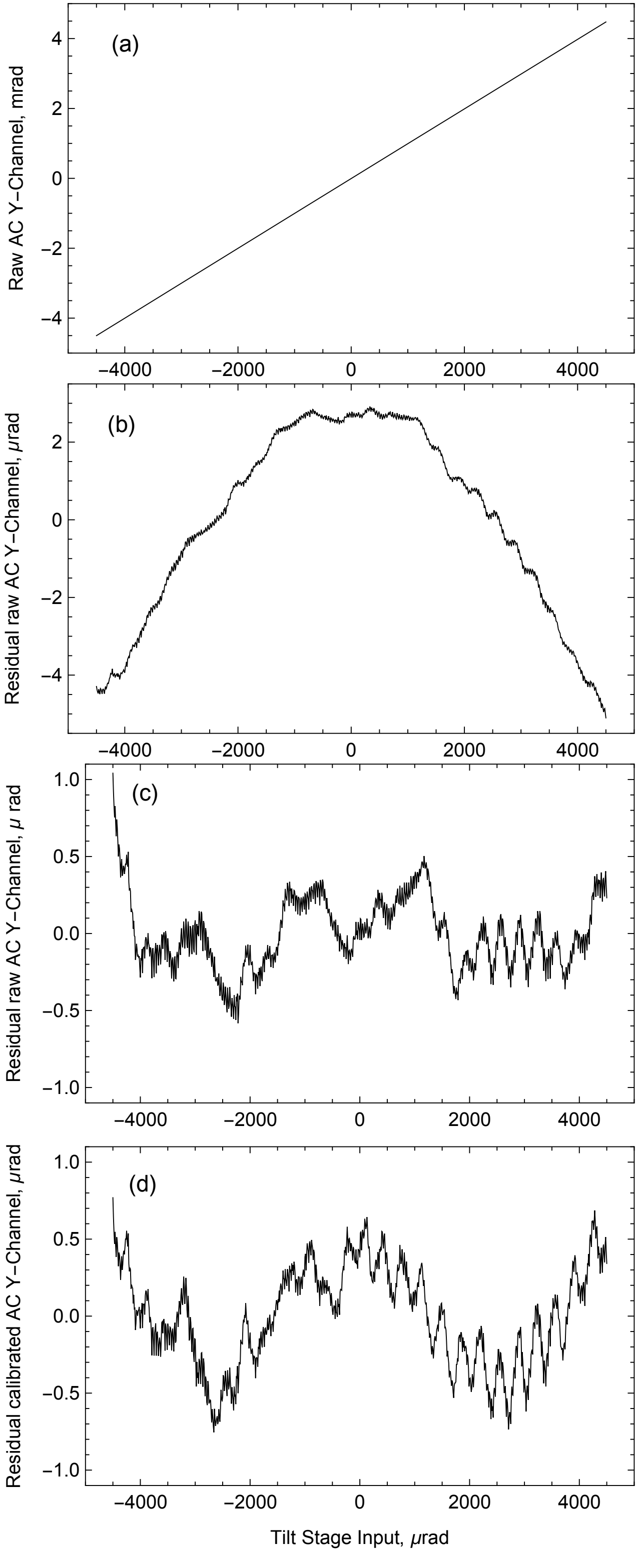
Number of Samples
40
35
30
25
20
15
10
5
0
-500
-400
-300
-200
-100
0
100
200
300
400
500
Central Position, nrad



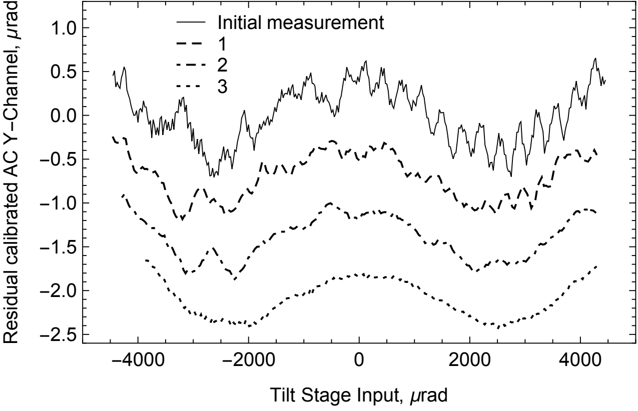
1.0
0.5
0.0
−0.5
−1.0
Correction, μrad
−4000
−2000
0
2000
4000
AC Y−Channel, μrad

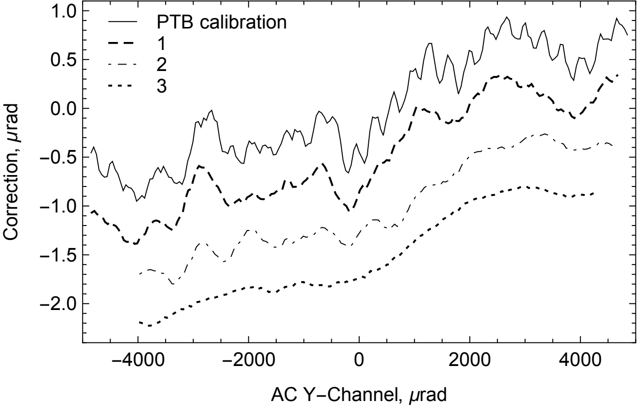

3
1
2
help
enter
Newport
ALS OML

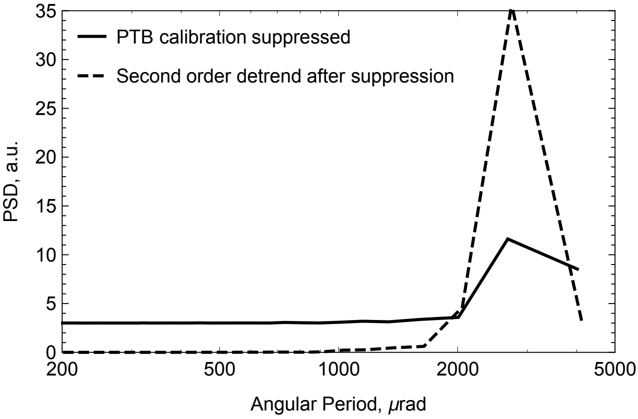

PTB calibration
Raw tilt stage scan
PSD, a.u.
0
5
10
15
200
500
1000
2000
5000
Angular Period, μrad



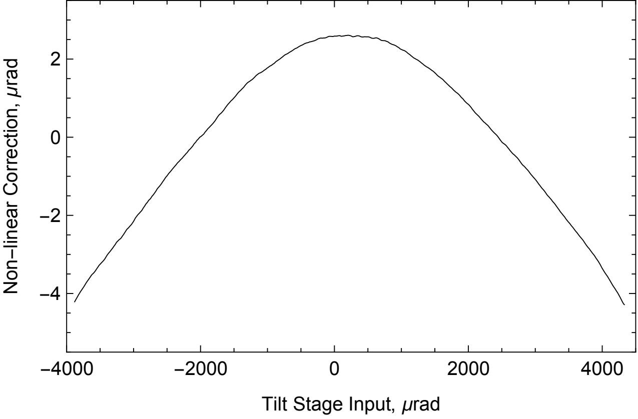
(a)
Raw AC Y−Channel, mrad
(b)
Residual raw AC Y−Channel, μrad
(c)
Residual raw AC Y−Channel, μ rad
(d)
Residual calibrated AC Y−Channel, μrad
Tilt Stage Input, μrad


Initial measurement
1
2
3
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
Residual calibrated AC Y−Channel, μrad
−4000
−2000
0
2000
4000
Tilt Stage Input, μrad

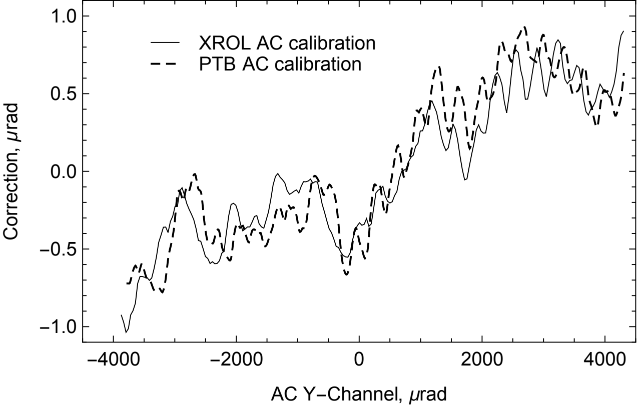

PTB calibration
1
2
3
Correction, μrad
AC Y−Channel, μrad
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−4000
−2000
0
2000
4000



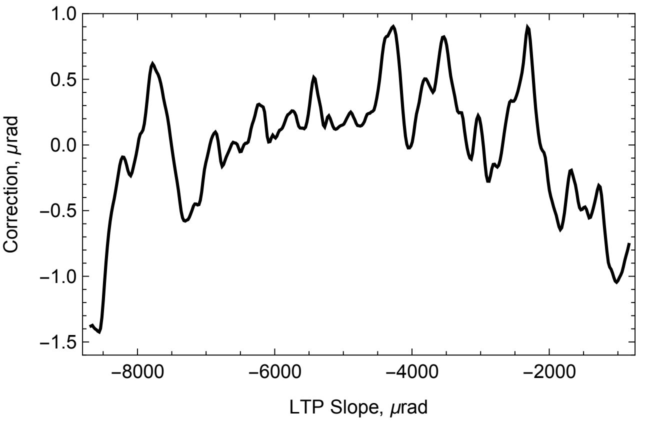
PTB calibration suppressed
Second order detrend after suppression
PSD, a.u.
0
5
10
15
20
25
30
35
200
500
1000
2000
5000
Angular Period, μrad



Non-linear Correction, μrad
Tilt Stage Input, μrad
2
0
−2
−4
−4000
−2000
0
2000
4000



XROL AC calibration
PTB AC calibration
1.0
0.5
0.0
−0.5
−1.0
Correction, μrad
−4000
−2000
0
2000
4000
AC Y−Channel, μrad



1.0
0.5
0.0
−0.5
−1.0
−1.5
Correction, μrad
−8000
−6000
−4000
−2000
LTP Slope, μrad