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Angular calibration of surface slope measuring profilers with a bendable mirror

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ABSTRACT

Performance of state-of-the-art surface slope measuring profilers, such as the Advanced Light Source's (ALS) long trace profiler (LTP-II) and developmental LTP (DLTP) is limited by the instrument's systematic error. The systematic error is specific for a particular measurement arrangement and, in general, depends on both the measured surface slope value and the position along a surface under test. Here we present an original method to characterize or measure the instrument's systematic error using a bendable X-ray mirror as a test surface. The idea of the method consists of extracting the systematic error from multiple measurements performed at different mirror bendings. An optimal measurement strategy for the optic, under different settings of the benders, and the method of accurate fitting of the measured slope variations with characteristic functions are discussed. We describe the procedure of separation of the systematic error of an actual profiler from surface slope variation inherent to the optic. The obtained systematic error, expressed as a function of the angle of measurement, is useful as a calibration of the instrument arranged to measure an optic with a close curvature and length. We show that accounting for the systematic error enables the optimal setting of bendable optics to the desired ideal shape with accuracy limited only by the experimental noise. Application of the method in the everyday metrology practice increases the accuracy of the measurements and allows measurements of highly curved optics with accuracy similar to those achieved with flat optics. This work was supported by the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Keywords: Systematic error, long trace profiler, metrology of X-ray optics, bendable mirrors, characteristic function, regression analysis, synchrotron radiation.

1. INTRODUCTION

Performance of state-of-the-art surface slope measuring profilers, such as the Advanced Light Source's (ALS) long trace profiler LTP-II[1,2] and developmental LTP (DLTP)[3] is limited by the instrument's systematic error. In general, the systematic error depends on both the measured surface slope value $\alpha(x_i)$ and the position x_i along a surface under test (SUT), and can then be expressed as $S(\alpha(x_i), x_i)$.[4,5]

In order to totally account for the systematic error of slope profilers, a sophisticated calibration method based on a Universal Test Mirror (UTM) is under development by a collaboration of the optical metrology groups at the ALS, HZB/BESSY-II and the PTB.[6]

A partial suppression of the LTP systematic error associated with optical inhomogeneity of materials and surface quality of the LTP optical elements (beam splitters, Dove prism, quarter wave plate, Fourier transform lens, folding mirrors) is also possible without a precision calibration.[1,3,7] For this, one can, for example, average multiple measurements with different angular alignments (pitch and roll angles), longitudinal positions, and orientations of the SUT with respect to the LTP.[7] Because of differences in the optical paths of the LTP sample beam through the LTP sensor optics, systematic perturbations in these measurements appear at different places of the slope trace and, therefore, are effectively averaged out. Practically, in this way, the high special frequency systematic error of the LTP-II can be suppressed to the level of 0.1 to 0.4 μrad, depending on the curvature of the SUT.

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Here we report on development of an original method for accounting for the instrument's systematic error in measurements with bendable X-ray mirrors. A proof of principle experimental work on angular calibration of a long trace profiler was performed with the DLTP.[3] Measurement of the DLTP's systematic error and the consequent calibration is done with the help of a second Kirkpatrick-Baez bendable mirror M214[8] of the ALS beamline 7.0.2 MAESTRO[9]. We show that the most accurate measurements can be performed with a slope measuring profiler calibrated for each particular arrangement of measurements, such as bending (determining slope variation of an SUT), as well as its position with respect to the translation system of the profiler and the distance between the SUT and the profiler's optical sensor. The measurements were performed in two steps. First, an intrinsic shape of the SUT was measured over M214 nearly flat substrate with the DLTP set in the side-facing arrangement.[10,11] Second, the mirror was measured under different bending settings. The systematic error was extracted from these measurements as a difference between residual slope traces measured over the flat and bent mirror. A closed-loop procedure for in situ angular calibration of a slope measuring profiler with a bendable optic is described.

In section 2 we present a theoretical consideration of the idea of the method and the methodology for extracting a systematic error from multiple measurements with bendable optics. In section 3 we describe measurement of an intrinsic shape of M214 mirror substrate performed over unbent nearly flat substrate. Section 4 is dedicated to measurements with the bent mirror and consequent processing of the results. Section 5 presents a procedure for determining the instrumental systematic error from multiple measurements with flat and bent mirror and calibration of the DLTP, discussion of possible sources of systematic error, and applicability of instrumental calibrations to various experimental conditions. Finally, section 6 gives a proposal for universal calibration tool based on dedicated bendable mirror.

2. IDEA OF THE METHOD

Generally speaking, the idea of the method consists in extraction of the systematic error from multiple measurements performed at different mirror bendings. The method includes the following steps.

Step 1. With a totally unbent, close to plane shape of the mirror, a high precision measurement of the surface slope trace inherent to the mirror substrate $\alpha_0\left(x_i\right)$ is performed over tangential positions uniformly distributed along the mirror surface with an increment Δx .

In the course of the measurement with the unbent mirror, the optical path of an LTP probe beam is almost unchanged. Therefore, random noise, error due to the instrumental drift, and the systematic error due to the optical imperfections can be easily suppressed by averaging over slope trace recorded with different angular alignments.[1,3,7] Currently, the new ALS X-Ray Optics Laboratory (XROL) is capable of an accuracy of slope measurements with close-to-plane substrates on the level better than 30 nrad (rms).[11,12] The measurement presented in this work were performed in the old laboratory space with environment condition limiting the accuracy to ≤ 60 nrad (rms).[13,14]

Step 2. Characteristic functions $f_A(x_i)$ and $f_B(x_i)$ of the slope change along the optical surface effected by two mirror benders A and B are measured with high precision.[15,16] In order to find the characteristic functions we perform three measurements at three different combinations of the bender settings C_A and C_B :[15-17]

$$\begin{aligned}
&\alpha_1(x_i;C_A,C_B) && \text{at the settings} \quad \left\{C_A,C_B\right\}, \\
&\alpha_2(x_i;C_A+\delta C_A,C_B) && \text{at the settings} \quad \left\{C_A+\delta C_A,C_B\right\}, \\
&\alpha_3(x_i;C_A,C_B+\delta C_B) && \text{at the settings} \quad \left\{C_A,C_B+\delta C_B\right\}.
\end{aligned} \tag{1}$$

The corresponding characteristic functions are:

$$\begin{aligned}
f_A(x_i) &= \frac{\alpha_1(x_i;C_A,C_B)-\alpha_2(x_i;C_A+\delta C_A,C_B)}{-\delta C_A} \quad \text{and} \\
f_B(x_i) &= \frac{\alpha_3(x_i;C_A+\delta C_A,C_B+\delta C_B)-\alpha_2(x_i;C_A+\delta C_A,C_B)}{\delta C_B}.
\end{aligned} \tag{2}$$

Note that the characteristic functions found in such way are basically free of the major systematic errors because the measurements are genuinely differential.

Step 3. A measurement is carried out with the mirror bent to a shape providing slope variation that covers the LTP angular range of interest,

$$\alpha_4(x_i;C_A^*,C_B^*) \quad \text{at the settings} \quad \left\{C_A^*,C_B^*\right\}. \tag{3}$$

The trace $\alpha_4(x_i;C_A^*,C_B^*)$ should be measured with all experimental precautions necessary to suppress, to the required level of accuracy, the errors due to random noise and temporal instrumental drifts. Practically, by using the experimental methods developed at the ALS XROL,[18] it is possible to suppress the random and drift errors to the level below 30 nrad.[11,12] Therefore, omitting residual random and drift errors, the measured trace $\alpha_4(x_i;C_A^*,C_B^*)$ can be presented as a sum of the surface figure $\alpha_4^*(x_i;C_A^*,C_B^*)$ due to the applied bending couplings C_A^* and C_B^*, the slope trace inherent to the mirror substrate $\alpha_0\left(x_i\right)$, and the systematic error trace $Syst(x_i)$ sought:

$$\alpha_4(x_i;C_A^*,C_B^*) = \alpha_4^*(x_i;C_A^*,C_B^*) + \alpha_0\left(x_i\right) + Syst(x_i). \tag{4}$$

Step 4. The surface figure $\alpha_4^*(x_i;C_A^*,C_B^*)$ can be reliably estimated by fitting the measured slope trace $\alpha_4(x_i;C_A^*,C_B^*)$ with the found characteristic functions of the mirror benders $f_A(x_i)$ and $f_B(x_i)$ [see Eq. (2)]:

$$\alpha_4^*(x_i;C_A^*,C_B^*) \cong C_A^* \cdot f_A(x_i) + C_B^* \cdot f_B(x_i). \tag{5}$$

The high reliability of the fitting is due to the differential nature of the measurements (see discussion in Step. 2), the characteristic functions of the mirror, $f_A(x_i)$ and $f_B(x_i)$, correlate neither with $\alpha_0\left(x_i\right)$ nor with $Syst(x_i)$. However, the fitting removes a low spatial frequency systematic error that is accidentally proportional to the characteristic functions.

Note also that if $\alpha_0\left(x_i\right)$ in Eq. (4) was measured at a slight bending with the couplings $\left\{C_A^0,C_B^0\right\}$, the bending shape is also removed by the fit. In order to account for this possibility, we designate the residual (after removing the best-fit shape) part of the inherent unbent slope trace of the mirror substrate as $\delta\alpha_0\left(x_i\right)$:

$$\delta\alpha_0\left(x_i\right) \cong \alpha_0\left(x_i\right) - C_A^0 \cdot f_A(x_i) + C_B^0 \cdot f_B(x_i). \tag{6}$$

Step 5. Combining Eqs. (4-6), we get an estimation of the measurement systematic error:

$$Syst(x_i) \cong \Delta\alpha\left(x_i\right) - \delta\alpha_0\left(x_i\right), \tag{7}$$

where

$$\Delta\alpha\left(x_i\right) = \alpha_4(x_i;C_A^*,C_B^*) - C_A^* \cdot f_A(x_i) - C_B^* \cdot f_B(x_i). \tag{8}$$

In Eqs. (7,8), we assume that the distributions of the measured positions on the surface are the same for the bent and unbent substrate. That is true with a good approximation for the case of grazing incidence X-ray mirrors under consideration. In this case, the slope variation at the maximum bending is within ± 5 mrad that is approximately equal to the dynamic range of the ALS LTP and DLTP instruments. The corresponding error of a measurement step (assuming an unchanged uniform sampling by translating the instrument's optical sensor) is $\sim \Delta x \cdot (0.005)^2 \approx 25$ nm for a typical 1-mm increment. In spite of the existence of a cumulative effect for the edge points, the positioning difference is still very small (<1 µm) compared to the spatial resolution of the instruments that is >1 mm.

Step 6. Repeating the Steps 3-5 with the mirror bent to different shapes, a set of estimations of the systematic errors, $Syst_k(x_i)$, $k = 1,2,...,K$ (K is a total number of estimations) is obtained.

Step 7. In this step we convert the systematic error traces $Syst_k(x_{k,i})$ derived as functions of the tangential positions to dependences $Syst_k(\alpha_{k,i})$ on inherent surface slope angles $\{\alpha_{k,i}\}$.

Indeed, a useful calibration should provide a relation between the inherent (real) surface slope angles and the measured angles which include instrumental systematic error.

However, even the same set of the measured positions $\{x_i\}$ of different $Syst_k(x_i)$ does not correspond to the same set of the surface slope angles. This is because the measurements of $Syst_k(x_i)$ are made with different shapes, and, possibly, over different areas of the mirror.

In order to convert $Syst_k(x_{k,i})$ to the dependences $Syst_k(\alpha_{k,i})$ on inherent surface slopes under measurements $\alpha_{k,i}$, we use the bent shape of the mirror $\alpha_k^*(x_{k,i};C_{A,k}^*,C_{B,k}^*)$ [compare with Eq. (4)] and the mirror residual inherent slope trace $\delta\alpha_0\left(x_{k,i}\right)$ [given by Eq. (6)]:

$$\alpha_{k,i} = \alpha_k^*(x_{k,i};C_{A,k}^*,C_{B,k}^*) + \delta\alpha_0\left(x_{k,i}\right) = C_{A,k}^* \cdot f_A(x_{k,i}) + C_{B,k}^* \cdot f_B(x_{k,i}) . \tag{9}$$

With additional index k in Eq. (9), we account a possibility for repeated slope measurements over different sets of positions and/or couplings.

Finally using Eq. (9), the angular dependence of the instrumental systematic error is constructed from $Syst_k(x_{k,i})$ by putting in accordance the found set of angles $\{\alpha_{k,i}\}$ and the measured positions $\{x_{k,i}\}$:

$$Syst_k(\alpha_{k,i}) = Syst_k[x_{k,i}(\alpha_{k,i})] . \tag{10}$$

Step 8. The final three steps are directed to get a more reliable instrumental slope calibration by averaging over multiple measurements of the systematic error $Syst_k(\alpha_{k,i})$.

First, the found $Syst_k(\alpha_{k,i})$ are interpolated to a new set of slope angles $\{\alpha_j\}$ uniformly distributed with a desired increment $\Delta\alpha$ over the instrumental dynamic range of interest, $[\alpha_{\min},\alpha_{\max}]$. A result of the interpolation is a set of interpolated traces of the instrumental systematic error

$$Syst_k(\alpha_j), \quad j = 1,2,...,(J+1), \quad J = (\alpha_{\max} - \alpha_{\min})/\Delta\alpha . \tag{11}$$

Step 9. An averaged systematic error trace is calculated by averaging over the interpolated traces $Syst_k(\alpha_j)$:

$$Syst_{avr}(\alpha_j) = \frac{1}{K}\sum_{k=1}^{K} Syst_k(\alpha_j) . \tag{12}$$

Step 10. An instrumental calibration file is generated as a set of pairs of the inherent surface angles and the corresponding measured angles:

$$Calibration = \{\alpha_{mes,j},\alpha_{real,j}\}, \quad \alpha_{real,j} = \alpha_j, \quad \alpha_{mes,j} = \alpha_j + Syst_{avr}(\alpha_j) . \tag{13}$$

The calibration method described in the previous section provides two sets of data on the instrumental systematic error.

First, Eq. (7) gives an estimation of the measurement systematic error for a particular slope measurement $Syst(x_i)$ that can be directly applied to correct the measurement:

$$\alpha_{4,corr}(x_i) \cong \alpha_4(x_i) - Syst(x_i) . \tag{14}$$

Second, in the form of Eq. (13), the determined averaged calibration can be used to correct the measurement performed with other optics but measured with the same experimental arrangement, including position and alignment of the optic, and a close surface curvature.

In this case, the corrected slope trace is found by interpolating the calibration dependence $\alpha_{real,j}(\alpha_{mes,j})$ to the new set of the measured angles $\{\alpha_{mes,n}\}$ as a measured trace $\alpha_{mes}(x_n)$. The procedure is in some extend analogous to the one used in Step 7; and it is the same as the calibration procedure currently applied to DLTP measurements.[3]

3. DLTP MEASUREMENT OF SUBSTRATE'S INTRINSIC SHAPE

M214[19,20] mirror blank is a single-crystal silicon substrate with the overall dimensions 450 mm × 25 mm × 30 mm (length × width × height). The clear aperture is 300 mm × 15 mm. This is a horizontally focusing mirror with source-to-mirror distance 3.8 m and two working focal distances 1.5 m and 4.0 m, and grazing incidence angle 1.5 deg. Total slope variations are 3.6 mrad and 2.0 mrad with average radii of curvature 82 m (strong curvature) and 149 m (moderate curvature), respectively.

The substrate is sagittally profiled to be optimally bent to an elliptical cylinder[21] corresponding to the short focal shape. Sagittal width of the substrate as a function of the tangential direction is calculated by applying beam bending calculations on a constant-thickness beam, and then confirmed by finite element analysis (FEA) of the mirror substrate idealized with pure end moments.[22] Comprehensive characterization of the substrate as well as the performance measurement of the entire mirror assembly is presented in Ref.[8]

Slope measurements performed over an almost flat SUT with the slope variation on the level of microradians are almost free of an instrumental systematic error. Transversal variation of the probe beam position across the instrumental optic is on the level of microns, which is orders of magnitude smaller than the beam's cross section. The optical path of the reflected probe beam and, consequently, the systematic error, which the beam experiences on its way through the instrumental optic are essentially the same through the entire slope variation of the flat SUT.

To distinguish between the systematic instrumental error and the shape inherent to the SUT, slope measurements were performed with the unbent nearly flat substrate. To achieve the highest attainable accuracy[13,14] multiple measurements were performed in according with the optimal strategy.[18] Detailed description of the measurement procedure can be found in Refs.[7,23,24] Accuracy of the DLTP probe beams positioning with respect to the measured trace is estimated to be on the level of 0.1 mm in the tangential direction. Results of slope measurements of the unbent mirror taken with the DLTP are presented in Fig. 1.

The substrate's intrinsic shape was measured over the unbent mirror as follows. The benders were set in their neutral positions to apply minimal (ideally zero) end moments (torques) to the substrate's ends. Characteristic functions of the mirror were measured with the benders' puller rods in steps of 1 mm in according with the procedure discussed in the second section of this work [see Eqs. (1), (2)] and presented in details in Refs.[15,16] The total slope variations of the substrate over its clear aperture, which correspond to the three steps of the characteristic functions measurements, were approximately 5 μrad, 150 μrad, and 300 μrad. To obtain the substrate's intrinsic shape each of the three mirror shapes were fitted with a characteristic function fit[15,16] and corresponding residuals were averaged.

The black solid curve in Fig. 1 shows the averaged residual slope trace of the mirror substrate with variation $\sigma = 0.23\mu rad$ (rms) [see Eq. (5)]. In order to account for possible shifts between the traces in the tangential direction measured over the flat and curved substrate, we performed one hundredth sub-pixels re-sampling and used consecutive correlation analysis of corresponding residual slope traces to align datasets for averaging. This procedure was applied to each slope trace presented in this work. Half of the difference between residual slope traces measured over the SUT bent to the maximal (300 μrad) and minimal (5 μrad) (bleu dashed curve) indicates the level of possible systematic error presented in the measurement. In the case of slope measurements with the almost flat mirror, the difference between slope traces show practically no systematic error. Assuming, that the noise is not correlated in the measurements, the variation of the residual slope trace difference multiplied by square root of two indicates that the value of the experimental noise of a single measurement is on the level of $\sigma = 0.10\mu rad$ (rms).

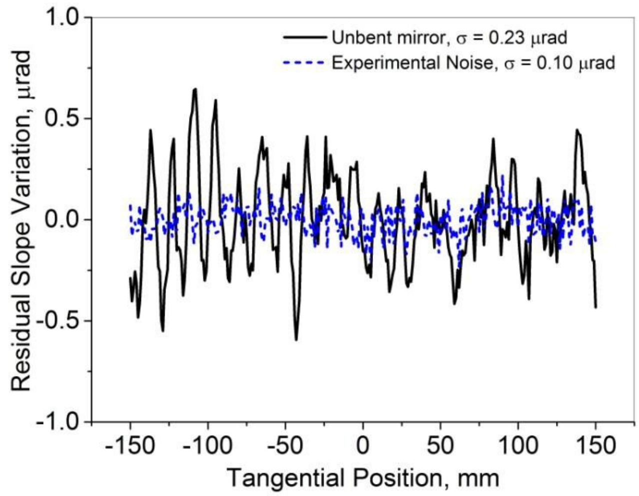

Figure 1: Average residual slope trace (black solid curve) and the half difference between two residual slope traces (blue dashed curve) measured with the DLTP over the unbent, nearly flat mirror with slightly different benders' settings. The variation of the residual slope trace averaged over all measurements performed over the almost flat mirror is 0.23 μrad (rms). The contribution of the experimental noise in a single slope trace measurement calculated as the RMS of the half of difference of the residual SUT's slope variations multiplied by the factor of square root of two is 0.10 μrad (rms).

4. MEASUREMENTS WITH BENT MIRROR

An experimental arrangement with the M214 mirror assembly installed on the DLTP set for side-facing measurements[10,11] is shown in Fig. 2.

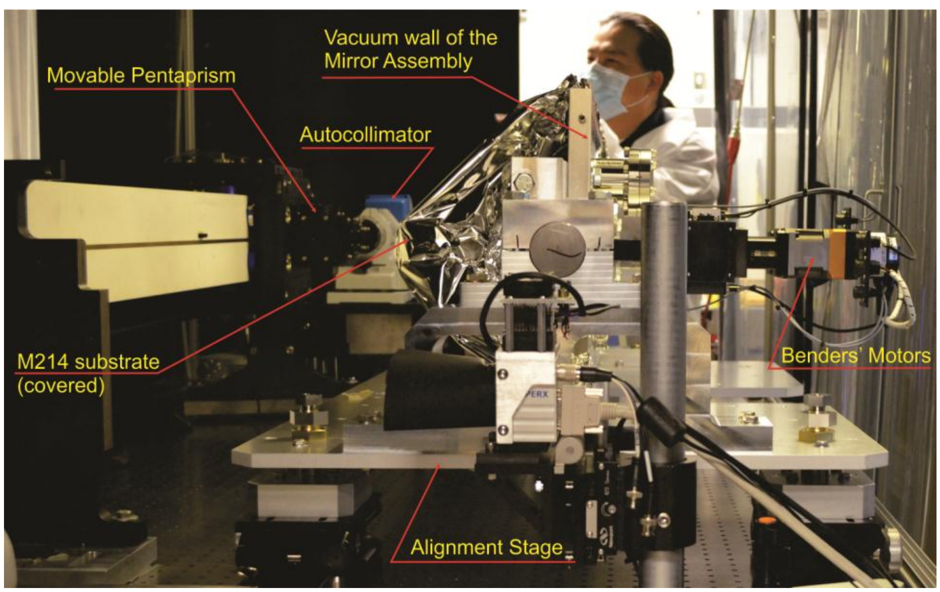

Figure 2: Experimental arrangement with the M214 mirror assembly installed on the DLTP set for side-facing measurements[10,11] (The in-vacuum parts of the mirror assembly are covered with Al foil).

The DLTP side-facing arrangement allows for slope metrology with optics with shape, to first order, not affected by gravity. Before measurements the DLTP was carefully aligned in according with the procedure described in Refs.[25,26]

4.1 Measurement of characteristic functions for short and long focusing shapes

In the measurement of the instrumental systematic error we make use of the fact that characteristic functions of benders do not contain intrinsic substrate's shape and do not contain instrumental systematic due to their differential character.[15,16]

Characteristic functions were measured for both mirror shapes corresponding to the two focal distances with strong (short focus) and moderate (long focus) curvatures.[8] To obtain characteristic functions for each mirror shape we performed three measurements over the same SUT's trace bent to slightly different shapes corresponding to different settings of the benders [see Eqs. (1), (2)].[14,15] Note that relatively small variation of the substrate's shape by relatively small change of the benders' settings does not lead to a noticeable change of the instrumental systematic error experienced by the reflected probe beam.

The measured characteristic functions are depicted in Fig. 3a. Figure 3b shows the differences between the characteristic functions of the upstream and the downstream benders (solid black and dashed blue curves respectively) measured at strong and moderate curvatures of the mirror.

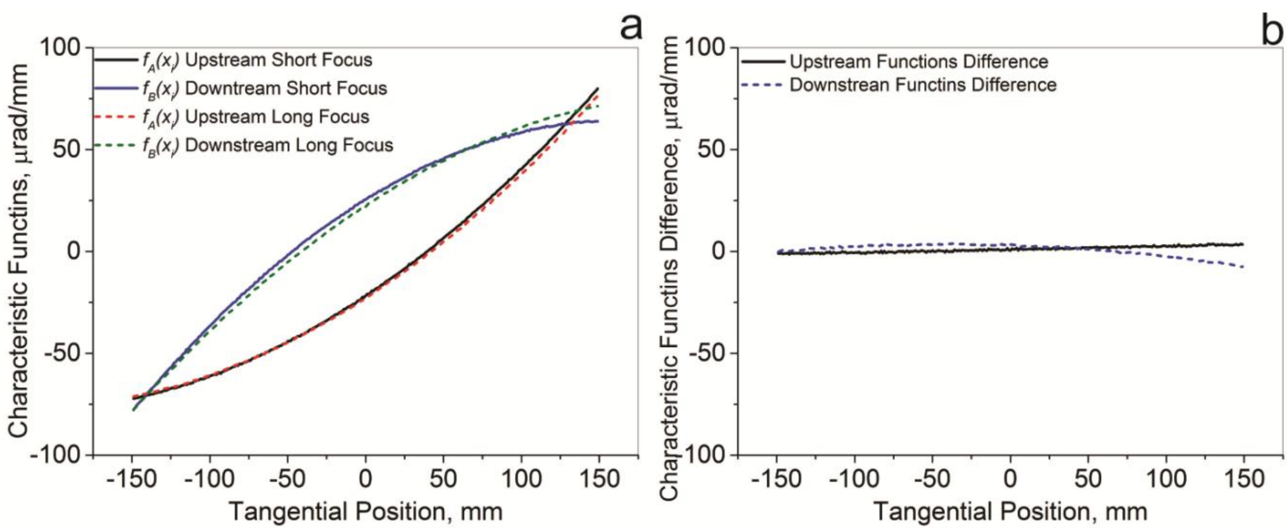

Figure 3: a) characteristic functions measured with the mirror bent to the short focal distance (strong curvature, lower black and upper blue curves) and to the long focal distance (moderate curvature, lower red and upper green curves); b) Difference of the characteristic functions (upstream solid black and downstream dashed blue curves).

The measured characteristic functions look very similar. However, contrary to M213 mirror assembly,[8] the largest difference between the characteristic functions is observed for the downstream part of the substrate [see Fig. (3b)]. The difference between corresponding characteristic functions indicates the level of non-linear mechanical response of the mirror shape on a change of the benders' settings. This is probably related to sagittal shaping of the substrate[19,21] which is not symmetrical in the tangential direction. To precisely set the mirror to the short or long focal distance shapes we used corresponding set of the characteristic functions.

4.2 Comparison of residual slope traces measured over bent and flat mirror

The substrate was shaped sagittally to be optimally bent to the short focusing shape. Its experimentally measured slope trace is accurately approximated with the help of corresponding characteristic functions and the ideal calculated shape.[17]

The residual, after subtraction of the best characteristic functions' fit, slope trace of the substrate $\Delta\alpha\left(x_i\right)$ Eq. (8) bent to the short and long focusing shape (strong and moderate curvatures, respectively), and the flat substrate's residual slope trace $\delta\alpha_0\left(x_i\right)$ Eq. (6) are shown on Fig. 4a and 4b (black solid and blue dashed curves, respectively).

In the case of bending the substrate to the long focusing shape (moderate curvature), a significant third order polynomial shape remains after subtraction of the best characteristic functions fit. This is because the sagittal shape of the substrate is not optimized for the long focus shape. In order to compare the residual slope traces of the bent mirror with the one measured over the flat mirror the best 3rd order polynomial fit was additionally subtracted from the residual slope trace of the bent mirror. The total slope variation of the subtracted third polynomial fit is on the level of 3 μrad (PV) and cannot considerably influence on the instrumental systematic error.

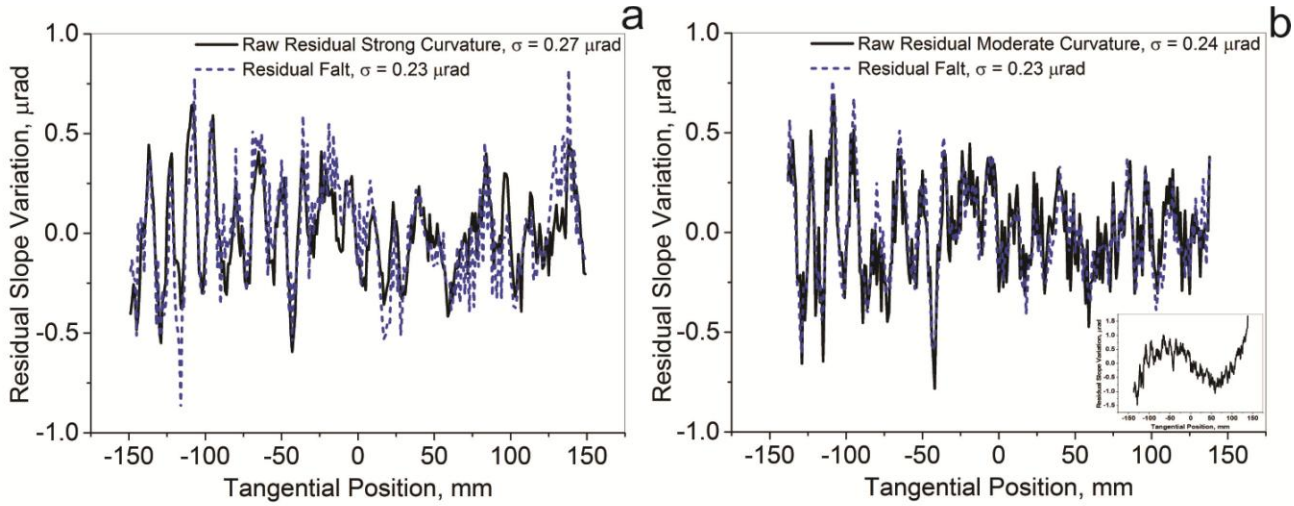

Figure 4: Dashed blue curves show residual slope traces measured over the mirror bent to the strong (a) and moderate (b) curvatures. Solid black curves on both plots show the substrate's intrinsic shape. The inset in the right plot presents residual slope trace of the mirror bent to moderate curvature after subtraction the best characteristic functions fit only.

In both cases variations of the residual slope traces measured over the bent substrate [0.27 μrad (rms) and 0.24 μrad (rms) for strong and moderate curvatures, respectively] are larger than the variation of the residual slope trace measured over the almost flat mirror [0.23 μrad (rms)]. This suggests that the instrumental systematic error strongly depends on curvature of the SUT.

5. ANGULAR CALIBRATION OF THE DLTP

Differences between the residual slope traces measured over bent and flat mirror plotted as functions of tangential position of the DLTP movable pentaprism (see Fig. 4) give angular deviation of the probe beam due to local slope variations of the instrumental optics $Syst(x_i)$ as a function of the linear coordinate along the SUT [see Eq. (7)]. In order to present the systematic as a function of the SUT's slope variation $Syst(\alpha_i)$, we plot the probe beam's angular deviation with respect to the measurement angle [see Eq. (10)].

To build the measurement angle α_i [Eq. (9)] we need to establish the relation between the tangential coordinate of the DLTP's movable pentaprism and corresponding slope of the SUT. The measurement angle must be free of the instrumental systematic error and the intrinsic SUT's shape. For this we make use of the characteristic functions' fit, represented by Eq. 9.

Differences between residual slope traces measured over bent and free standing flat substrate, representing angular perturbations of the reflected probe beam due to instrumental systematic error $Syst(\alpha_j)$ are shown in Fig. 5a. The curves were smoothed by 15 points adjacent - averaging method because subtraction of two data sets measured in similar conditions results in unjustified increase of noise very similar to that appearing during differentiation of experimental data.

In according with the procedure described in step 7 we build DLTP calibration curves, which provide relations between the actual slope trace of the SUT and measured angle which includes instrumental systematic error. The resulted DLTP calibration curves are shown in Fig. 5b [see Eq. (13)].

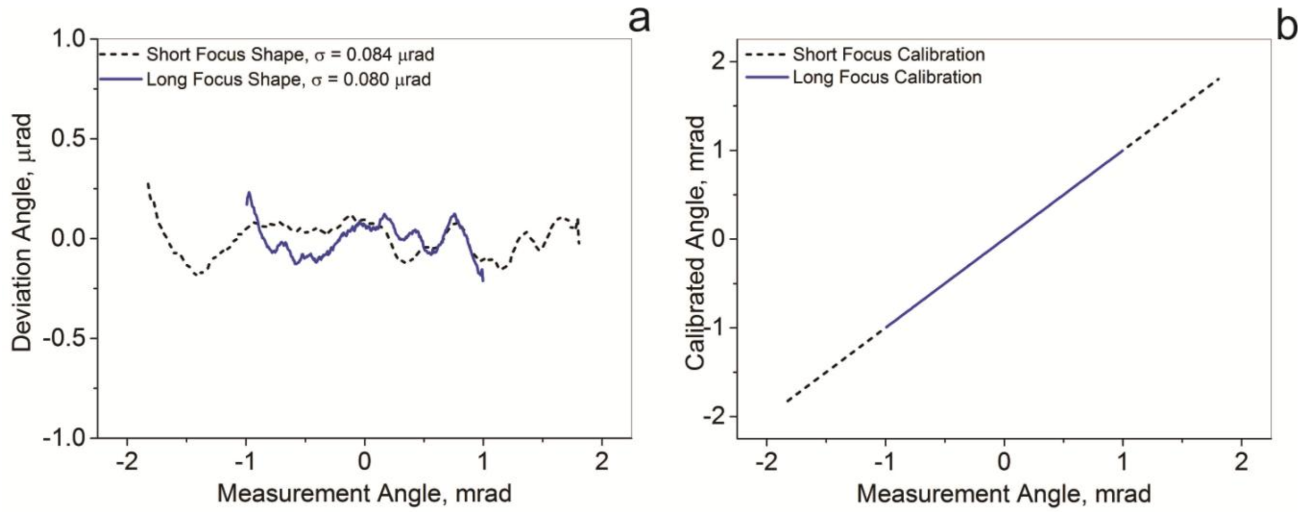

Figure 5: a) DLTP systematic errors as angular deviations of the DLTP probe beam plotted with respect to the measurement angle; b) DLTP calibration curves measured over the mirror bent to short (strong curvature) and long (moderate curvature) focus distance shapes (dashed black and solid blue curves on both plots, respectively).

In order to verify applicability of the obtained calibration curves we use different sets of slope measurements performed with M214 bendable mirror. Figure 6 presents residual slope trace measured over the nearly flat mirror (black solid curves) and residuals of calibrated data sets measured over strongly bent(Fig. 9a) and moderately bent(Fig. 9b) mirror (blue dashed curves), as well as their difference (red dotted curves).

Square root of the difference between variances of unbent and calibrated residual slope traces measured over strongly bent (0.10 μrad) and moderately bent (0.12 μrad) mirror are very close to the RMS value of the experimental noise, on the level of 0.1 μrad (rms). This indicates that there is a very week (ideally zero) correlation between the measured slope trace and the extracted systematic error of the instrument. It shows that the described method of extracting systematic error from multiple measurements performed over a curved mirror bent to different shapes (curvatures) gives very good and reliable calibration of a slope measuring profiler.

The DLTP systematic errors measured over the strongly bent and moderately bent SUT, which correspond to ~3.6 mrad and ~2 mrad total slope variation, exhibit reasonable correlation,[27] but nevertheless cannot be thought as parts of the same curve to be averaged. This means that we cannot build one universal calibration curve readily applicable for all possible experimental arrangements.

To obtain an ultimately precise calibration of a slope measuring profiler the instrument must be calibrated respecting actual experimental arrangement for each particular SUT. This includes an actual SUT's length including its total slope variation, distance between the DLTP pentaprism (or more generally profiler's optical sensor) and the SUT, variation of the distance between the DLTP pentaprism and the autocollimator during a scan, and finally, overall inclination of the SUT with respect to the profiler's optical axis.

Major sources of dependence of the instrumental systematic error on actual parameters of the SUT and its arrangement with respect to the DLTP are schematically shown in Fig. 7.

In Fig. 7 we show that one SUT bent to different curvatures (or shapes) has points of the same slope with respect to the profiler's optical axis located at different positions with respect to the profiler's translation system. The probe beam reflected from these points under the same angle with respect to the profiler's optical axis goes along different optical paths (beams 1 and 2) through the profiler's optical sensor (autocollimator in the case of the DLTP). Moreover, the same SUT positioned tangentially (or laterally) at the same place with respect to the profiler's translation system but with different distance from the pentaprism sends the reflected probe beam along different optical paths through the pentaprism as well as through the autocollimator's optics (beams 1 and 3). An absolute value of an overall inclination of the SUT with respect to the profiler's optical axis influences the angle between the incident and reflected probe beams and, this way, sends the reflected beam over different regions of the pentaprism and the autocollimator (or more generally through the profilers optics). Consequently, the profiler's systematic error is a combination of the pentaprism's mirrors slope variations and systematic error intrinsic to the autocollimator, which is unique for each particular experimental arrangement. It leads to the fact that the profiler's systematic error strongly depends on geometrical parameters of the experiment and measurement data taken over the same SUT with the same shape and curvature measured under different experimental configuration contain different systematic error.

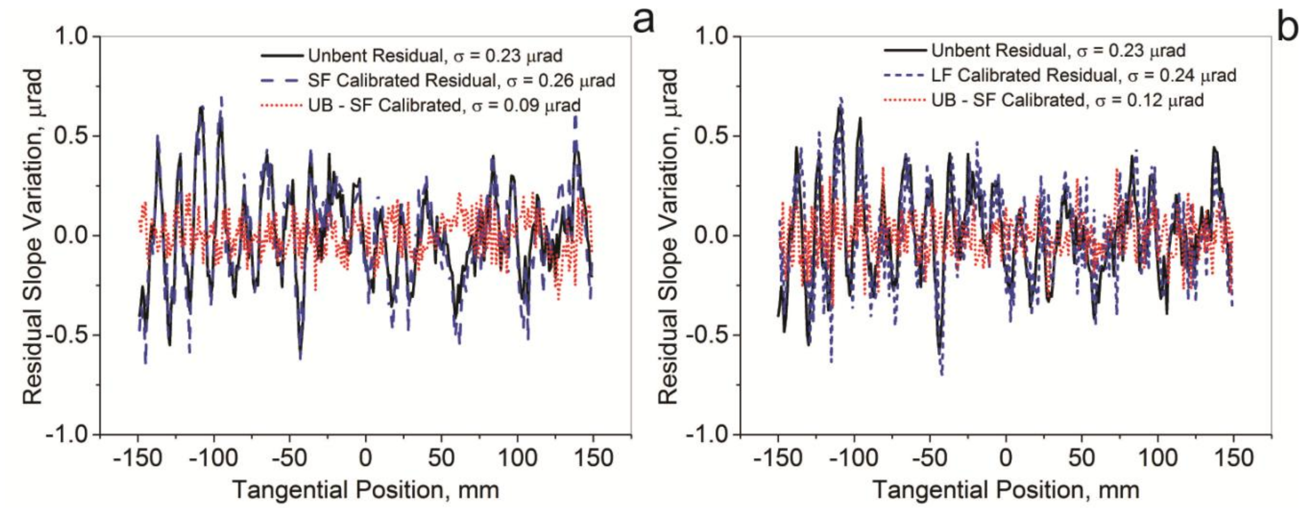

Figure 6: Residual slope trace of the mirror measured over nearly flat mirror (solid black); calibrated residual slope traces measured over the strongly bent (a) and moderately bent (b) mirror (dashed blue); differences between these residual slope traces (dotted red).

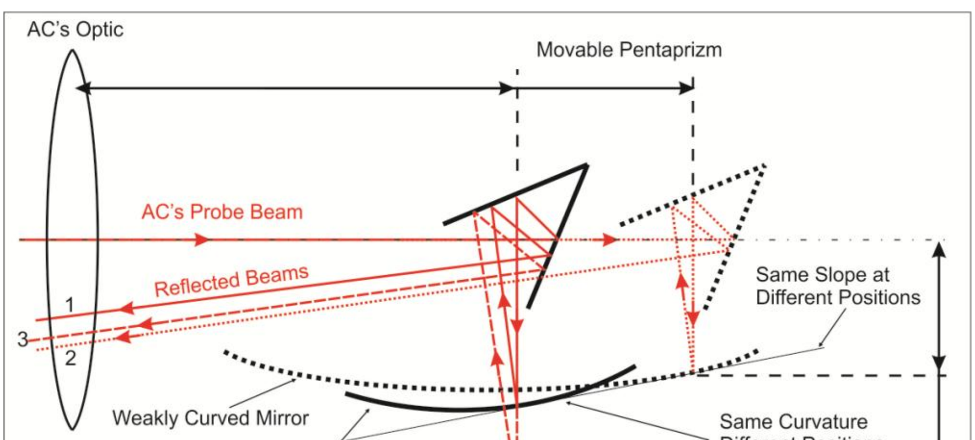

Figure 7: Various sources of the systematic error of a long trace profiler when measuring optics with different curvatures and with different arrangements.

As the first step on calibration of a long trace profiler, a precise calibration of its optical sensor is usually performed. A detailed description of the DLTP's autocollimator calibration measurements is described in Ref.[28] In these measurements the distance between the angle comparator and the autocollimator was fixed. Such calibration appears to be mostly applicable to measurements performed with short and strongly curved optic, when the overall change of the distance between the SUT and the profiler's optical sensor is small comparing with the total length of the reflected probe beam optical path from the SUT to the detector.[11]

Figure 8 shows systematic errors plotted as deviation angles with respect to the measurement angle. The red dotted curve presents the systematic error of the autocollimator measured for a fixed distance between an angle comparator[28] and the autocollimator of 550 mm. The black dashed and blue solid curves show the systematic error of the DLTP measured with strongly and moderately curved mirror with similar average distance between the SUT and the autocollimator, respectively.

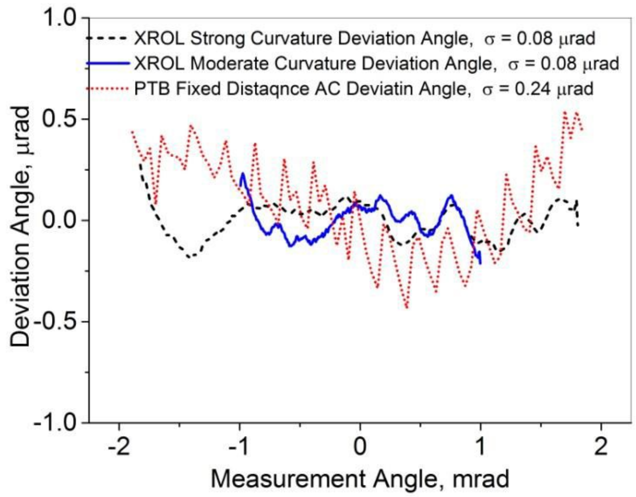

Figure 8: XROL DLTP (dashed black and solid blue curves) and PTB autocollimator (dotted red curve) systematic errors plotted as the deviation angles with respect of the measurement angle. The DLTP systematic errors were measured with the bendable M214 mirror bent to strong (dashed black curve) and to moderate (solid blue curve) curvatures. Autocollimator calibration was measured with the fixed distance between the angular comparator and the autocollimator 550 mm.

In the case of measurements of rather long optics, described in this article, when the change of the optical path of the reflected probe beam during scans is similar to the overall distance between the SUT and the profiler's optical sensor, the dependence of the deviation angle on the measurement angle has practically no relation to the systematic error intrinsic to the autocollimator itself. In this case the profiler's systematic error is a function of the measurement angle and the position of the profiler's translation system with respect of its optical sensor.

6. PROPOSAL FOR UNIVERSAL CALIBRATION MIRROR

We have described a procedure for angular calibration of a slope measuring profiler with a bendable mirror which is the subject for current measurements. However, whenever calibration of a profiler with a bendable mirror, which is actually to be measured, is to be performed, this appears to be excessively long and rather complicated procedure. In order to reliably extract the profiler's systematic error from such measurements one needs to repeat each time the entire cycle of measurements described in this report.

In order to perform angular calibration of a profiler in a faster, simpler, and more reliable way, we propose to develop a dedicated bendable mirror as universal calibration tool for slope measuring profilers. This tool will make this method applicable, in particular, for precise slope metrology of optics with fixed shapes. Such a dedicated, bendable mirror must have a long and relatively thin substrate, able to be bent to virtually any curvature used in synchrotron radiation and free electron X-ray laser applications.

A required flexibility of the mutual arrangement of the universal calibration mirror and the profiler must allow replication of any experimental configuration of an SUT with respect to the profiler, for which the profiler is to be calibrated. The calibration mirror must be bent to the shape and the overall curvature similar to the SUT actually to be measured in order to produce an accurate calibration curve to subtract from raw measurements.

Characteristics, such as intrinsic slope variation of the bendable substrate and characteristic functions of the benders of such a universal calibration mirror must be thoroughly measured once. Based on these measurements it would be possible to rapidly, and at the same time reliably, set the tool to a shape close to a desired shape of an SUT to be measured, in order to measure the profiler's systematic error for particular experimental conditions.

This method of calibration with proof of principle shown in this work on the example of the DLTP is easily applicable to any slope measuring profiler such at the Long Trace Profilers[1,2,29-31] or NOM-like[32-36] systems.

7. DISCUSSION AND CONCLUSION

A closed loop metrology procedure of calibration of a slope measuring profiler with the help of a bendable optic has been presented.

The method of extraction of a systematic error of a long trace slope profiler from measurements performed with an optic bent to different curvatures has been described. We have indicated various sources of systematic error of a slope profiler and demonstrated that, in the case of ultra-precise metrology with a long curved optics, the long trace profiler must be calibrated each time for the actual experimental arrangement.

Regarding the example of the M214 mirror assembly manufactured for the ALS beamline 7.0.2 MAESTRO we have measured systematic error of the DLTP for 3.6 mrad and 2 mrad ranges of measurement angle and showed that this method allows slope metrology with a long and highly curved optic with accuracy limited mostly by experimental noise.

We have demonstrated that a simple angular calibration of an optical sensor of a long trace profiler is definitely not enough for the use in ultra-precise slope metrology with extremely well profiled modern X-ray optics manufactured for synchrotron radiation and free electron lasers applications.

The measurements described were performed in the old lab space with rather poor environment conditions, where we had to turn off the temperature stabilization which was able to keep the temperature on level of 0.25 K (peak-to-valley) with the periodic of oscillation with a period of ~15 min. This led to a constant increase of the temperature by a few degrees Celsius with noticeable night and day temperature variation. Moreover, the mirror assembly was too large to be placed completely inside the DLTP hutch and a part of the bending mechanisms rested outside the hutch's walls. The opened hutch's doors brought higher air turbulence which considerably increased the experimental noise and the temperature variations resulted in not very high stability of measurements due to sensitivity of the mirror shape to the temperature variations.

This year the XROL has been moved to a new, dedicated clean-room facility that provides improved environmental and instrumental conditions vitally required for high accuracy metrology with state-of-the-art X-ray optics.[12] This provides 60 mK (peak-to-valley) temperature variations of the ambient air (less than 2 mK within the instrumental hutches) with a much lower level of air turbulence, which has increased the level of stability of the slope metrology up to three times[11] compared to that reported in this article.

Another method of angular calibration with highly curved optics of fixed curvature is presented in Ref.,[11] where authors report same day measurements with accuracy on the level of 80 nanoradians and repeatability of 40 nanoradians.

Here, we propose a universal calibration tool and the method for calibration of long trace profilers based on a dedicated bendable mirror which allows fast and reliable measurement of a profiler's systematic error for any experimental arrangement and shape and curvature of an SUT.

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