Automated suppression of errors in LTP-II slope measurements of x-ray optics.
Part 2: Specification for automated rotating/flipping/aligning system

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1. Introduction

In a previous report [1], we summarized the major sources of the random, systematic, and drift errors in surface slope measurements with a long trace profiler. We also discussed the methods developed and actively used at the ALS OML to minimize the contribution of the errors to high precision measurements with the upgraded ALS LTP-II [2]. We have shown that a further improvement of the measurement accuracy and efficiency (including time consumed) would be achieved with a mechanical system that provides automatic rotation, flipping, and alignment of a surface under test (SUT) (see a brief summary in the next section).

The goal of the present report is to outline a general specification for an automated rotating, flipping, and aligning (ARFA) system that would be integrated with the ALS LTP-II and a new state-of-the-art optical slope measuring system (OSMS) as one proposed in Ref. [3]. As a part of a slope measuring instrument, the ARFA system must support the required accuracy of surface slope metrology with absolute error below 0.1 µrad.

2. Brief overview of experimental approaches to minimize errors of slope measurements

Random error is the inconsistent variation in measurements of exactly the same experimental arrangement. These errors are caused by unpredictable and unrepeatable fluctuations in the readings of the measurement instrument due to the limited precision of the instrument or due to the random character of spurious effects. The contribution of random errors in the same experimental conditions can, in principle, be made as small as required simply by averaging multiple sequential scans.

Systematic error is the error that is systematically reproduced at the same configuration of an experimental system. The major sources of systematic error for the current version of the upgraded LTP-II are the imperfections of the optics and optical materials used in the LTP optical sensor: the beam splitters, reference and folding mirrors, wave-plates, Fourier transform lens, and Dove prism. The method actively used at the OML in order to suppress systematic error consists in averaging over multiple measurements with different alignments of SUT tilt in the tangential and sagittal directions, shift in the tangential direction, and flipping of SUT orientation by 180^o. Because of difference of the optical paths of the LTP beam through the LTP sensor optics, systematic perturbations in these measurements will appear at different places of the slope trace and, therefore, will be effectively averaged out. Unfortunately, such suppression is currently rather inefficient due to a significant increase of overall measurement time due to multiple manual readjustments of the SUT.

The drift error problem in the upgraded ALS LTP-II can be partially overcome by using an original method of drift error suppression as suggested in Ref. [4]. The method is based on averaging over multiple measurements in conjunction with a combination of reversing the scan direction and flipping the orientation of the SUT. The upgraded ALS LTP has the capability to automatically reverse the direction of scanning allowing for a significant suppression of drift errors. With automatically flipping of the SUT orientation with an integrated SUT rotating/flipping stage, the contribution of the errors associated with the instrumental and set-up drifts can be completely zeroed. The total number of scans that should be performed according to the prescribed optimal scanning strategies depends upon the degree of polynomial describing the temporal dependence of the drift. In practice, in order to make a contribution of the drift error in the measured slope trace negligible, a measurement run should consist of 8 or 16 sequential scans.

In summary, by integrating an automated rotating, flipping, and aligning system, designed to provide fully controlled flipping, tilting, and shifting of a SUT, as the next step of the ALS LTP-II upgrade, we would significantly improve the accuracy and efficiency of the high precision measurements with the upgraded ALS LTP-II. A capability for rotation and shifting of a SUT would support 2D surface slope mapping measurements, analogous to an approach used with the HBZ/BESSY-II NOM instrument [5].

3. Requirements to the accuracy of SUT flipping

In this section, we estimate the accuracy of flipping an SUT required in two practical cases. First, we consider slope measurements with a sagittal cylindrical substrate that is designed for use with a bendable toroidal x-ray mirror; second, we analyze a case of a tangentially curved cylindrical mirror. The geometrical parameters of the optics are chosen based on ALS-related applications. Because we suppose that the overall absolute error of the measurements must be less than 100 nrad, the absolute error related to the SUT mis-alignment due to flipping of its orientation should not surpass 10 nrad.

3.1. Flipping of a sagittal cylindrical substrate for a bendable toroidal mirror

Figure 1 illustrates the first case. A 1-meter long sagittal cylinder with radius of curvature of $R = 50\,\text{cm}$ is measured along the cylinder's generating line (shown in Fig. 1 with a dot-dashed line) in order to characterize the surface figure of the optic. A misalignment $\delta\alpha$ between the measured trace (a dashed line) and the generating line would lead to a spurious variation of the surface slope along the measured trace.

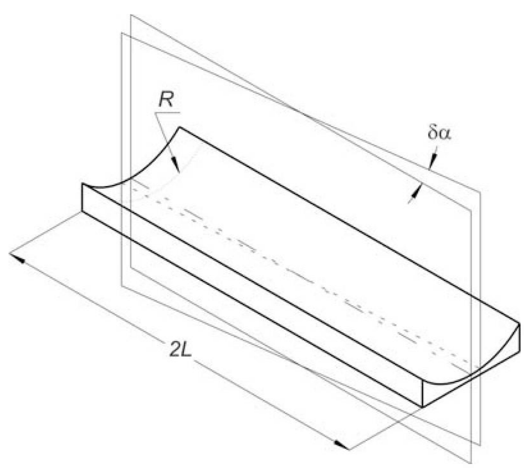

Figure 1: Sketch of a surface slope measurement with a sagittal cylinder with the radius of curvature of R and the length of $2L$. A misalignment between the measured trace (a dashed line) and the cylinder's generating line (shown with a dot-dashed line) is denoted by $\delta\alpha$. The misalignment leads to a spurious variation of the surface slope along the measured trace.

The spurious surface figure is described with a sector of an ellipse:

$$y(x) = \pm\frac{b}{a}\sqrt{a^2 - x^2} \tag{1}$$

with the semi-major axis a and the semi-minor axis b given, respectively, by

$$\begin{aligned} a &= R/Sin\delta\alpha\,, \\ b &= R. \end{aligned} \tag{2}$$

The maximum slope error $\delta\beta$ would be at the mirror edges, $x = \pm L$:

$$\delta\beta \approx y'(x) = Sin^2\delta\alpha \cdot L \cdot (R^2 - L^2 Sin^2\delta\alpha)^{-1/2}. \tag{3}$$

In order to estimate the required accuracy $\delta\alpha$ for the SUT flipping at the given maximum slope error $\delta\beta$, one can solve Eq. (3) with respect to $Sin^2\delta\alpha$. A physically meaningful solution is:

$$2Sin^2\delta\alpha = \delta\beta^2\left(\sqrt{1+4R^2/L^2\delta\beta^2} - 1\right). \tag{4}$$

So far as the maximum allowed systematic error due to the misalignment is $\delta\beta = 10^{-8}\,rad$, the second term in the radicand in Eq. (4) is much larger than 1. Therefore, an approximation valid for a practical use is:

$$\delta\alpha \le \delta\beta^{1/2}\frac{R}{L} \approx 30\ \mu\text{rad}. \tag{5}$$

Note that the limitation given by Eq. (5) is applicable to the accuracy of measurements of the tangential slope. The corresponding spurious sagittal slope, $\delta\gamma$, is significantly larger:

$$\delta\gamma \approx \delta\alpha \cdot L/R \approx \delta\beta^{1/2} \approx 100\ \mu\text{rad}. \tag{6}$$

This circumstance provides a very sensitive method for initial alignment of a sagittally curved SUT by minimizing the spurious slope variation in the sagittal direction.

The limitation established by Eq. (5) can also be used to estimate the allowed wobbling of the SUT rotation (perpendicularity) and sagittal translation (directionality). However, in Tables 1 and 2 below, we put a more restrictive specification in order to limit a possible spurious slope in the sagittal direction to the level of about 10 μrad.

3.2. Flipping of a tangential cylindrical mirror

Figure 2 sketches the appearance of a spurious slope variation due to a misalignment in measurements with of a tangential cylindrical mirror. Let us assume that the radius of curvature of the mirror is $R = 15$ m; and its total length is $2L = 100$ cm. This is an extreme case because the total variation of the tangential slope is about ±30 mrad that significantly (by a factor of more than 3) exceeds an angular range covered with a modern slope profiler.

In this case, the measured figure is also described with a sector of an ellipse. However now, the semi-major axis a and the semi-minor axis b are, respectively,

$$\begin{aligned} a &= R/Cos\delta\alpha\,, \\ b &= R. \end{aligned} \tag{7}$$

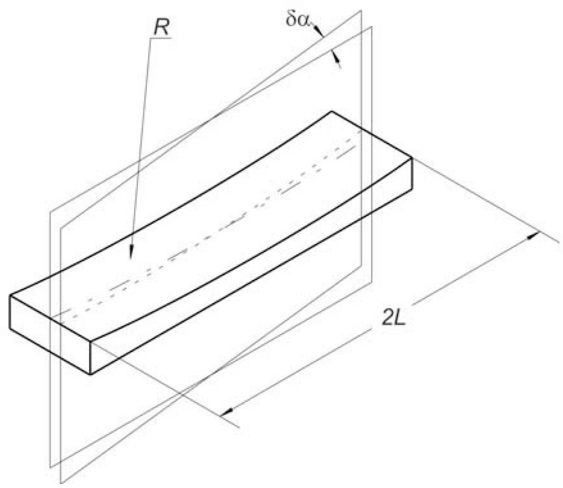

Figure 2: Sketch of a surface slope measurement with a tangential cylinder with the radius of curvature R and the length of $2L$. A misalignment between the measured trace (a dashed line) and the cylinder's section line (shown with a dot-dashed line) is denoted by $\delta\alpha$. The misalignment leads to a spurious systematic decrease of the surface slope along the measured trace compared to the measurement along the section line.

The corresponding slope error $\delta\beta$ can be estimated as a difference between the correct slope trace of the cylinder and the measured slope:

$$\begin{aligned} \delta\beta &\approx y'(x,\delta\alpha=0)-y'(x,\delta\alpha\neq 0) \\ &= x\cdot(R^2-x^2)^{-1/2} - x\cdot Cos^2\delta\alpha\cdot(R^2-x^2Cos^2\delta\alpha)^{-1/2}. \end{aligned} \tag{8}$$

Taking into account that the slope error $\delta\beta$ in Eq. (8) reached its maximum at the mirror edges, $x=\pm L$ and assuming that $R^2 >> L^2$ (the typical case of x-ray optics), one can get the same expression for the misalignment error (with a requirement that $\delta\beta = 10^{-8} rad$) as for the case considered in Sec. 3.1:

$$\delta\alpha \le \delta\beta^{1/2}\frac{R}{L} \approx 0.5\,\text{mrad}. \tag{9}$$

Note that in the case considered here, the requirement for the accuracy of flipping is significantly weaker than that of the case of a sagittal cylinder (Sec. 3.1). For completeness, the details of the derivation of Eq. (8) are given in the Appendix.

4. General specification for an ARFA system

An ARFA system is designed to be integrated into a state-of-the-art optical surface slope measuring system such as an LTP, NOM, OSMS, etc., and must provide:

- a yaw rotation and 180^o orientation flipping of a SUT with the length up to 1 m and the weight up to 30 kg;
- precision manual alignment of SUT roll and pitch angles in the range of ±5 degrees;
- automatic change of roll angle and y-translation (in the sagittal direction) of ±3-inch displacement.

Figure 3 shows a conceptual design of a desired ARFA system.

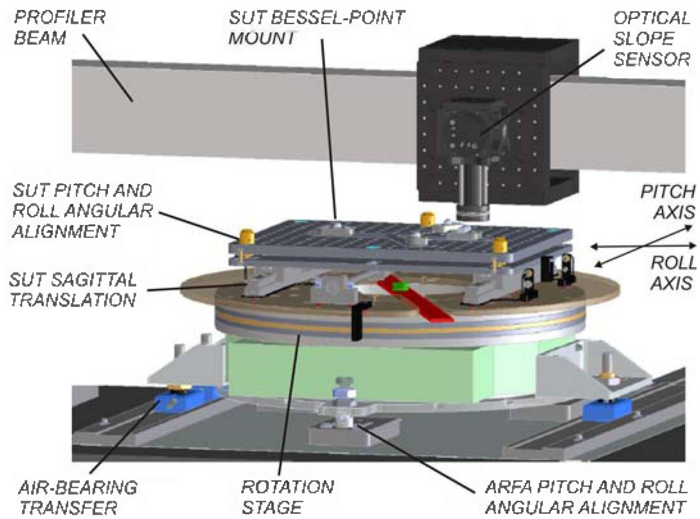

Figure 3: Conceptual design of an automated rotating, flipping, and aligning (ARFA) system for use with a slope profiler. A tool for a precision positioning of the ARFA system with respect to the profiler's vertical optical axis is depicted with a bar in red below the SUT alignment stage.

The design in Fig. 3 allows for convenient and quick assembly/dis-assembly (transfer) and alignment of the system with respect to the optical axis of the slope profiler. Two separate kinematic adjustments provide independent angular positioning of a SUT and alignment of the system's rotation axis with respect to the direction of the sample light beam of the profiler.

Detailed specifications for the major parameters of an ARFA system are collected in Tables 1 and 2. Note that in comparison to the corresponding specifications in [3], the parameters in the tables are less restrictive. This becomes possible due to the additional analysis of the required system performance discussed above.

Table 1: Major parameters of an ARFA rotation system.

Specified Parameter	**Values**	**Units**
Rotation range	±180	degree
Rotation resolution	≤5	µrad
Minimum rotation speed	≤0.01	Degrees/sec
Maximum rotation speed	≥1	Degree/sec
Rotation repeatability (full range)	≤5	µrad@1σ
Reversal error (360°)	≤5	µrad
Rotation accuracy (full range)	≤10	µrad
Integrated angular encoder - accuracy - repeatability	 ≤2 ≤2	 µrad@1σ µrad@1σ
Setting time for move-stop-wait-measure (MSWM) mode	≤0.3	sec
Rotation stage perpendicularity (wobble)	≤5	µrad
Rotation stage eccentricity	≤5	µrad
Thermal stability of the rotation stage roll, pitch, and yaw angles (for each)	≤2	µrad/K
Manual alignment of perpendicularity of rotation axis to the sensor light beam direction - range - resolution	 ±10 ≤10	 mrad µrad
Rotation stage lowest eigenfrequency, with load	≥40	Hz
Rotation stage load capacity (including alignment stage and SUT)	≥50	Kg
Heat loading from motors and sensors	≤2	W

Table 2: Major parameters of an SUT alignment kinematic stage for an ARFA system.

Specified Parameter	**Values**	**Units**
Tilting range for roll and pitch angles	±5	degrees
Tilting resolution for roll and pitch angles	≤5	μrad
Alignment stability for roll and pitch angles	≤3	μrad/K
Minimum tilting speed	≤3	μrad/sec
Maximum tilting speed	≥20	μrad/sec
Tilting repeatability (full range)	≤10	μrad@1σ
Tilting accuracy(full range)	≤10	μrad@1σ
Integrated tilt (roll and pitch) sensors -accuracy -repeatability	 ≤2 ≤2	 μrad@1σ μrad@1σ
Setting time for each angle	≤1	sec
Sagittal translation -range -resolution -accuracy -repeatability	 ±75 ≤2 ≤5 ≤5	 mm μm μm μm
Integrated sagittal position sensor -accuracy -repeatability	 ≤1 ≤1	 μm@1σ μm@1σ
Sagittal translation directionality (wobble)	≤10	μrad
Alignment stage lowest eignfrequency	≥40	Hz
Alignment stage load capacity	≥30	Kg
Heat loading from motors and sensors	≤1	W

5. CONCLUSIONS

We have discussed general specification for an automated rotating, flipping, and aligning system that would be integrated into the ALS LTP-II and a new optical slope measuring system (OSMS) proposed in Ref. [3] and under development at the ALS OML. As a part of the instrument, the ARFA system must support absolute accuracy of surface slope measurement below 0.1 μrad, vital for metrology with ALS state-of-the-art x-ray optics and future optics for the Next Generation Light Source (NSLS). Corresponding requirements to the ARFA design and performance specifications have also been analyzed.

The upgrade of the ALS LTP-II with a suitable ARFA system will lead to significant suppression of systematic and drift errors of slope measurements. At the same time, an integrated ARFA system would allow for more efficient measurements without unnecessary time for multiple re-alignments of an SUT. Two dimensional surface slope mapping would also be possible.

In the next notes, we will discuss a design of an ARFA system based on a high precision Huber 1-Circle Goniometer-440XE rotation stage [6] and the optimal scanning strategies for high precision measurements with the system.

APPENDIX

Let us start from Eq. (8) that describes the slope error $\delta\beta$ as a difference between the slope trace inherent for a tangential cylinder and the slope distribution measured along a scanning line misaligned by an angle $\delta\alpha$:

$$\delta\beta \cong y'(x,\delta\alpha=0) - y'(x,\delta\alpha\neq 0)$$
$$= \sqrt{\xi}\cdot(1-\xi)^{-1/2} - \sqrt{\xi}\cdot Cos^2\delta\alpha\cdot(1-\xi Cos^2\delta\alpha)^{-1/2}, \qquad \text{(A1)}$$

where $\xi = x^2/R^2 << 1$. Considering only the liner terms of the Taylor series of $(1-\xi)^{-1/2}$ and $(1-\xi Cos^2\delta\alpha)^{-1/2}$:

$$(1-\xi)^{-1/2} \approx 1+\xi/2 \quad \text{and}$$
$$(1-\xi\cdot Cos^2\delta\alpha)^{-1/2} \approx 1 + Cos^2\delta\alpha\cdot\xi/2, \qquad \text{(A2)}$$

one gets from (A1)

$$\delta\beta \cong \sqrt{\xi}\cdot(1+\xi/2) - \sqrt{\xi}\cdot Cos^2\delta\alpha\cdot(1+Cos^2\delta\alpha\cdot\xi/2)$$
$$= \sqrt{\xi}\cdot\left[1+\xi/2 - Cos^2\delta\alpha - Cos^4\delta\alpha\cdot\xi/2)\right]. \qquad \text{(A3)}$$

Assuming $\delta\alpha$ <<1,

$$Cos^2\delta\alpha \approx 1-\delta\alpha^2 \quad \text{and}$$
$$Cos^4\delta\alpha \approx (1-\delta\alpha^2)^2 \approx 1-2\delta\alpha^2. \qquad \text{(A4)}$$

Inserting (A4) into (A3), one gets

$$\delta\beta \approx \xi\left[1+\frac{1}{2}\xi^2 - 1 + \delta\alpha^2 - \frac{1}{2}\xi^2(1-2\delta\alpha^2)\right]$$
$$= \xi\cdot(\delta\alpha^2 + \xi^2\cdot\delta\alpha^2) \approx \xi\cdot\delta\alpha^2. \qquad \text{(A5)}$$

Finally from (A5), we get [compare with Eq. (9)]:

$$\delta\alpha \approx \delta\beta^{1/2}\frac{R}{x}. \qquad \text{(A6)}$$

REFERENCES

1. Z. Ali and V. V. Yashchuk, "Automated suppression of errors in LTP-II slope measurements with x-ray optics. Part 1: Review of LTP errors and methods for the error reduction," LSBL Note (Berkeley, May 11, 2010).

2. 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).

3. V. V. Yashchuk, P. Z. Takacs, W.R. McKinney, L. Assoufid, F. Siewert, T. Zeschke, "Development of a new generation of optical slope measuring profiler," *Nucl. Instr. and Meth.* **A** (in press: doi:10.1016/j.nima.2010.10.063).

4. V. V. Yashchuk, "Optimal measurement strategies for effective suppression of drift errors," *Rev. Sci. Instrum.* **80**, 115101-10 (2009).

5. F. Siewert, J. Buchheim, T. Zeschke, G. Brenner, S. Kapitzki, K. Tiedtke, "Sub-nm accuracy metrology for ultra-precise reflective X-ray optics," *Nucl. Inst. and Meth.* **A 635**(1- S1), S52-S57 (2010).

6. *Huber 1-Circle Goniometer-440XE rotation stage* (http://www.xhuber.de/en/Products/Positioning_Devices/Circle_Positioning/1_Circle_Goniometer/440/440.rsys)

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