Metrology of a mirror at the Advanced Photon Source: comparison between optical and x-ray measurements

Lahsen Assoufid, Jonathan Lang, Jin Wang, and George Srajer
Advanced Photon Source, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439 USA

Introduction

The performance of grazing-incidence mirrors used on beamlines at third-generation synchrotron radiation sources is highly dependent on both the magnitude of large-scale irregularities (figure error) and the smoothness (microroughness or finish) of their reflecting surfaces. Typically, surfaces with slope errors and roughnesses better than 3 µrad and 3 Å rms, respectively, are required in order to preserve the brilliance of these sources. Considering the high cost of mirrors and their long delivery times, it is important to evaluate their optical quality upon the delivery from the manufacturer as part of the acceptance criteria. At the Advanced Photon Source (APS), this is routinely done using optical interferometers available at the metrology laboratory. The state-of-the-art optical instruments available in this laboratory [1] have adequate sensitivity and cover a wide range of spatial frequencies to provide the user with useful information necessary to predict the performance of optics. However, the ultimate tests are those performed at, or near, wavelengths at which the optic is intended to operate.

The present paper describes the metrology of a vertically focusing mirror on the SRI-CAT 1-BM beamline [2] at the Advanced Photon Source (APS), using both an optical long trace profiler (LTP) [3] and x-rays. During the x-ray tests various aspects of the mirror, in addtion to surface profile were investigated. These include reflectivity, focusing properties, and surface topography. This paper focuses on the mirror surface profile and topography.

Methods and Materials

The evaluated mirror is a permanent component of the 1-BM beamline [2] and is located 45.5 m from the source, after a collimating mirror and a double-crystal monochromator. The substrate is made from a flat bendable Zerodur that is 1020 mm long, 65 mm wide, and 60 mm high. The reflecting surface is coated with a 750 Å-thick layer of palladium (with a ~50 Å chromium buffer layer) and was specified to have a 3 Å rms roughness and ≤5 µrad rms slope error. The bender mechanism has a four-point scheme and is actuated with a stepper-motor-driven lead screw. The mirror radius can be adjusted from infinity (flat shape) to about 3 km (a cylinder).

The optical measurements were carried out using the LTP at the metrology laboratory of the APS [4], while the x-ray measurements were performed on 1-BM. The LTP scans were taken along the mirror centerline with the mirror facing up and simply supported at the bottom face near the ends. The x-ray profile measurement method consisted of scanning the mirror surface with a fine, well-collimated, monochromatic pencil beam at grazing-incidence angle. The experimental setup consisted of a system of vertical and horizontal slits, a collimating mirror, a double-crystal monochromator, a set of narrow vertical slits (beam defining slits), the test mirror (which is used for vertical focusing), and finally a CCD camera for recording the intensity profile of the reflected x-ray beam. The source size (FWHM) is 0.3 mm x 0.3 mm. The maximum accepted horizontal and vertical angular openings are limited to 3.7 and 0.17 mrad, respectively. The first set of slits limits the beam size to 3 mm horizontally and 2 mm vertically. The beam reflected from the collimating mirror is monochromatized to 10 keV (1.239 Å wavelength) by the double-crystal silicon (Si) (111) monochromator. The narrow vertical slits located 37.8 m downstream from the monochromator limit the beam height to 200 µm at the CCD camera position. Because of the use of a monochromatic beam, the size of these vertical slits was chosen to be much larger than the transverse coherence length of the bending magnet source at 1.239 Å wavelength, so that the measurements are based on pure ray tracing. The transverse coherence length can be expressed as $l_t=\lambda D/2\sigma$, where σ is the source size, λ is the radiation wave length, and D the distance from source to slits. With the described setup, the effective value of D through the collimating mirror is 25.5 m; thus, the transverse coherence length is about 53 µm.

In order to measure the slope error profile, the mirror surface is scanned by vertically translating the mirror, and the intensity and position of the specularly reflected pencil beam is recorded at the CCD camera (located 10 m from the mirror) vs. the mirror position. The relative location of the centroid of each recorded intensity profile gives a measure of the local slope error and is displayed vs. position on the mirror surface. In this fashion, the beam, which was incident on the mirror, hits the same spot on the optics that preceded it, thus keeping the same beam characteristics during the entire scanning operation. The mirror table is actuated by three precision translation stages with a minimum vertical step size of 0.635 µm. The translation stage induces an angular error of +/- 0.43 µrad over the 1.020 m mirror length. However, this value is comparable to the LTP repeatability.

Results

Table 1 compares the corresponding statistical data over the total mirror length. Figure 1 compares the measured x-ray slope error profile with the LTP measurements over the central 820 mm trace length. The total measured trace length for the x-ray profile contains 292 points with a 4.71 mm increment along the mirror length, while that of the LTP has 545 points with a 2 mm sampling rate. The x-ray measurements were carried out with the unfocused mirror (i.e., no bending moment was applied to the mirror). The LTP residual slope error profile was obtained by subtracting the tilt and the best-fit cylinder from the raw profile.

Table 1: Comparison of the statistical data from the LTP and the x-ray profile measurements over the total mirror length.

Measurement	Root-mean square (µrad)	Peak-to-valley (µrad)
LTP	4.9	38.5
x-rays	6.3	46.6

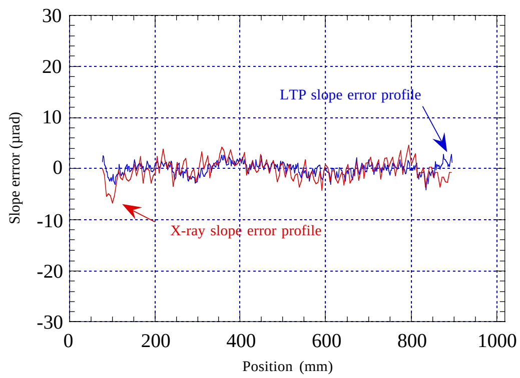

Figure 1: Comparison between the LTP profile and the x-ray measurements over the central 820 mm trace length of the mirror surface.

Discussion

As one can see from Figure 1, the two residual slope error profiles correlated identical features. The statistical values, calculated for the profiles measured over the entire mirror length (not shown here), agreed within 17 – 22%. The difference at the edges is believed to be due to the mirror mounting. During the LTP measurements, the mirror was unmounted and was simply supported at the bottom face (mirror facing upward) near the ends, while during the x-ray measurements, the mirror was attached to the bender, which is expected to affect the shape of the mirror ends. The measured x-ray profile shows, indeed, that the mirror is slightly constrained by the bending mechanism.

The difference in the finer details was expected because the x-ray profile was obtained with a much lower resolution than was the LTP measurement. The x-ray beam footprint on the mirror surface was about 35 mm. Therefore, the local slope error measurement had an effective resolution of about 35 mm. However, to obtain a well-defined slope error profile, data were taken by oversampling at 4.71 mm increments. Although the resolution was much larger than the step size, we can see finer features on a length scale much smaller than the resolution value at each step. Moreover, the close agreement between the two profiles shows that the error introduced by the vertical translation stage of the mirror was not significant enough to be detected. Therefore, optical long-trace profilometry measurements can be used as first step to predict performance of beamline mirrors and in many cases can avoid time-consuming beamline tests. However, a comprehensive understanding of a mirror's performance requires a full evaluation of its reflective surface. One way do this is by entirely illuminating the surface by an incident monochromatic beam and recording its surface topography on a CCD camera. Figure 2 shows a topography of the mirror surface recorded at λ= 0.917 Å (E = 13.5 keV). The image of the reflected beam exhibits a series of parallel stripes along with some randomly oriented intense lines. The randomly oriented intense lines are due to defects on the CCD camera scintillator, but the series of parallel stripes was found to arise almost entirely from the surface structure of the vertically focusing mirror. (Small contributions were expected from the collimating mirror and the double-crystal monochromator.) To make sure the observed stripes were not a contribution from other optical elements, images were recorded at various wavelengths and mirror bending radii. The spacing between the stripes remained constant as the radiation wavelength changed, and it shrank or expanded correspondingly as the mirror radius was varied. These measurements revealed that even optical surfaces with slope errors as small as 5 µrad rms can affect the spatial profile of the x-ray beam. Fortunately, the magnitude of the observed features was not significant enough to affect use for typical experiments conducted on the1-BM beamline.

We should emphasize the purpose of this experiment was merely a qualitative comparison between LTP measurements and mirror performance in the actual operating environment. A more comprehensive experimental study is needed. For example, a more accurate x-ray profilometry can be done by performing high-resolution measurements using a pink or white beam (a broader bandwidth) rather than monochromatic radiation, which allows one to use a much narrower pencil beam [5, 6] and to measure surface slope errors with a much higher lateral resolution.

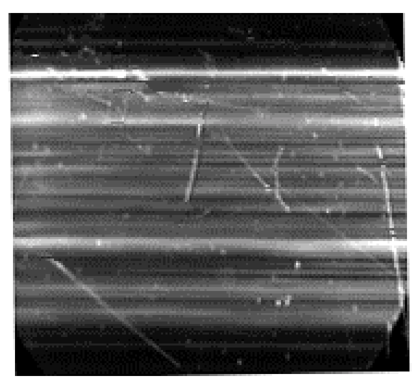

Figure 2: CCD image of the incident monochromatic x-ray beam collected 10 m from the tested mirror set at 2.8 mrad angle and at λ = 0.917 Å (13.35 keV).

Acknowledgments

Use of the Advanced Photon Source was supported by the U.S. Department of Energy, Basic Energy Sciences, Office of Science, under Contract No. W-31-109-Eng-38.

References

[1] C. Bresloff and D. Mills, *Rev. Sci. Instrum.* **67**(9), (1996) CD ROM.

[2] J.C. Lang, G. Srajer, J. Wang, and P. Lee, *Rev. Sci. Instrum.* **70**(1), 4457 – 4462 (1999).

[3] P. Z. Takacs, S.-N. Qian, and J. Colbert, *Proc. SPIE* **749**, 59 – 64 (1987).

[4] P. Takacs, E.L. Church, C. Bresloff, and L. Assoufid, *Appl. Opt.*, **38(1)**, 5468 – 5479 (1999).

[5] P. Gondoin, A. Freund, S. Gougeon, D. de Chambure, K. van Katwijk, D. Labergerie, U. Lienert, and N. Schulz, *Proc. SPIE* **2515**, 70 – 83 (1987).

[6] Olivier Hignette, Andreas Freund, and Elia Chinchio, *Proc. SPIE* **3152**, 188-199 (1997).