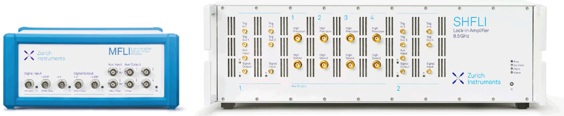
AIP Conference Proceedings

RESEARCH ARTICLE | JANUARY 15 2019

In-situ metrology for adaptive x-ray optics with an array of interferometric absolute distance measuring sensors FREE

Vivek G. Badami; Ernesto Abruña ✉; Lei Huang; Mourad Idir

AIP Conf. Proc. 2054, 060027 (2019)
https://doi.org/10.1063/1.5084658



AIP Publishing

In-Situ Metrology for Adaptive X-Ray Optics with an Array of Interferometric Absolute Distance Measuring Sensors

Vivek G. Badami[1], Ernesto Abruña[1, a)], Lei Huang[2] and Mourad Idir[2]

[1]*Zygo Corporation, Middlefield, CT 06455, USA.*
[2] *Brookhaven National Laboratory - NSLS II, Upton, NY 11973, USA*

[a)]Corresponding author: ernesto.abruna@ametek.com

Abstract. Adaptive x-ray mirrors are viewed as the main path to meeting the science and usability needs of the next generation of x-ray light sources. Currently these mirrors operate open loop with intermittent feedback from invasive sensors that measure the beam quality. We outline a novel design for *in situ* metrology of the shape of these mirrors using an array of interferometric sensors. We describe a proof-of-principle demonstration showing sub-nm agreement between shape changes measured by this technique to simultaneous measurements by a large-aperture 18” Fizeau interferometer.

INTRODUCTION

Evolving science and user needs are driving requirements for more control over the x-ray beam for the next generation of x-ray sources. These needs range from focal spot sizes <20 nm [1] for higher resolution imaging to dynamic adjustment of numerical aperture and spot size to enable multi-scale investigations [2]. Turnkey beam configuration is also becoming more important to allow multi-disciplinary users to spend more time on the fundamental focus of their experiments.

Adaptive optics capable of fine mirror shape control over a range of spatial wavelengths (e.g., piezo bimorphs) in conjunction with better control of the position and orientation of the beamline optics are one way forward to meeting these requirements. Adaptive optics have already been used to demonstrate so called “zoom” functionality, enabling continuously variable spot sizes ranging from 1 μm to 10s of nm [3]. Mimura *et al* have demonstrated the value of *in situ* mirror shape feedback in producing sub-10 nm focused line widths [4]. Today, beam diagnostics at the focal spot are commonly used to optimize the beam. However, these tools do not provide sufficient information for continuous optimization of the spot. Furthermore, these beam diagnostics can be invasive as they typically take the place of the sample being studied; time consumed for beam characterization is invariably time lost to the experimenter. Non-invasive systems exist but divert a part of the photon flux, making it unavailable for science use. For these reasons, real time *in situ* metrology of the mirror shape, position and orientation is advantageous for providing feedback to maintain a desired beam characteristic in the face of various perturbations to the mirror shape. It also provides a means of rapidly changing the spot size in dynamic applications as well as rapid reconfiguration of the beamline to adapt to changing experimental demands. All of this in turn translates to greater beam line time for science.

We propose such an *in situ* metrology system that is designed to directly monitor the reflecting surface of the mirror and demonstrate the performance of this technique as embodied in a proof-of-principle setup by comparison to a Fizeau interferometer.

MEASUREMENT PRINCIPLE

The basic principle of this measurement is based on the “bed-of-nails” type approach for the measurement of the shape of a deformable optic, a technique used for both optical fabrication metrology [5] as well as for *in situ* shape control for deformable astronomical optics [6]. Application of this technique to x-ray deformable optics has been demonstrated albeit in a limited fashion [7].

Proceedings of the 13th International Conference on Synchrotron Radiation Instrumentation – SRI2018
AIP Conf. Proc. 2054, 060027-1–060027-6; https://doi.org/10.1063/1.5084658
Published by AIP Publishing. 978-0-7354-1782-3/$30.00

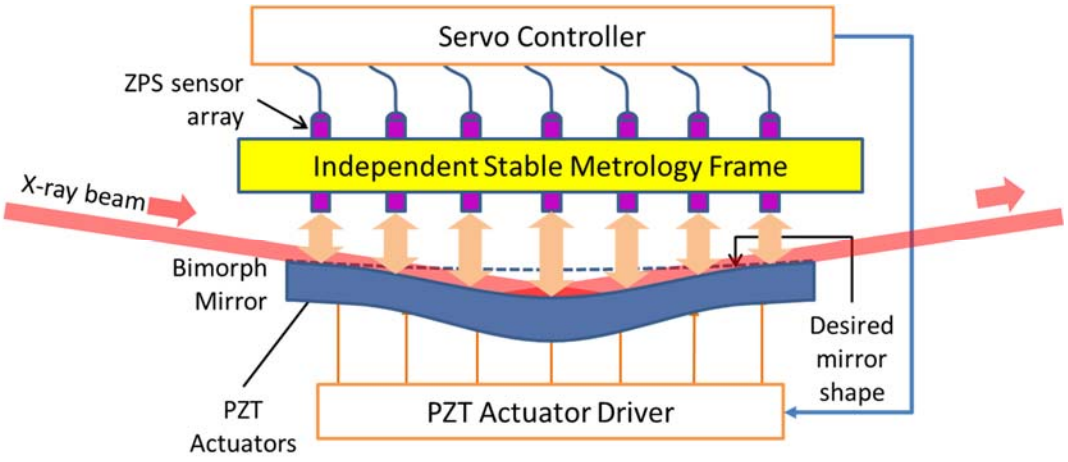


FIGURE 1. Overall measurement principle

Figure 1 depicts the overall concept wherein an array of sensors mounted in an independent stable metrology frame interrogates the reflecting surface of the mirror, in contrast to previous approaches which monitor the rear (non-reflecting) surface. Thermal and temporal stability of the metrology frame are key to the measurement, as is the mounting method of the metrology frame that ensures that mirror actuator motions do not produce deformations in the metrology frame. The signals from the array provide feedback for closed loop control of the mirror shape. This enables maintenance of mirror shape by correcting any perturbations from temperature and pressure changes, actuator creep, heat bumps, etc.

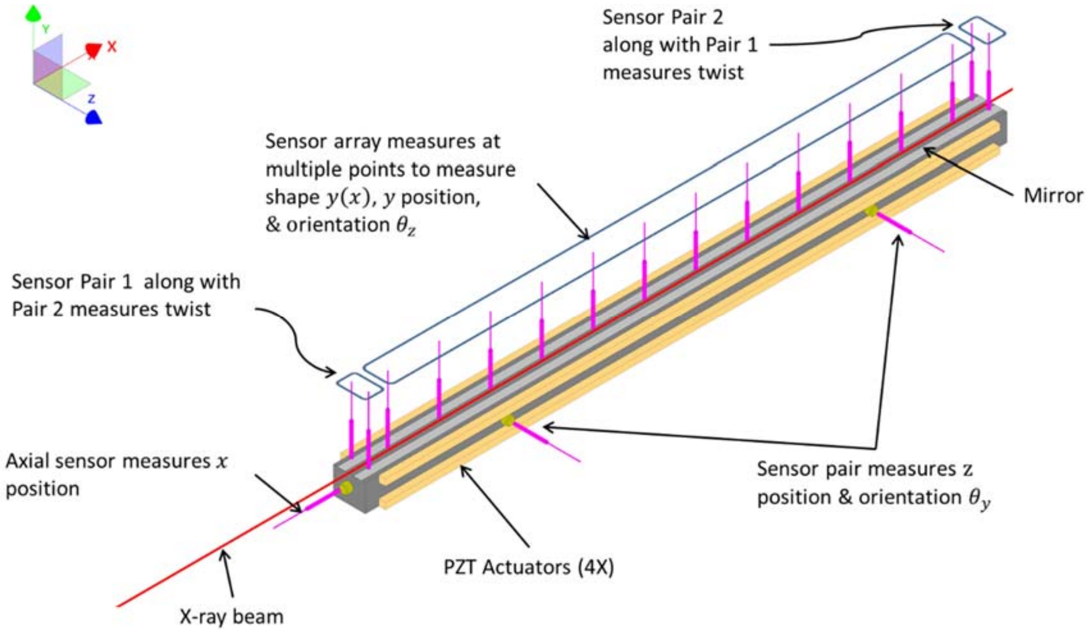
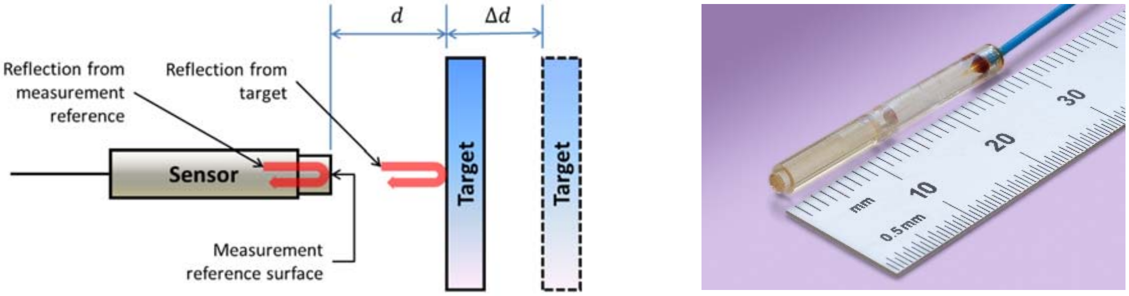


FIGURE 2. Measurement of shape and rigid-body motions. Mirror frame and metrology frame hidden for clarity.

Extension of this concept permits measurement of other non-rigid body motions such as twist and the rigid-body position and orientation of the mirror relative to the metrology frame as shown in Fig 2. The absolute nature of the sensors also enable the measurement of the absolute position and orientation of the mirror (x, y, z, θ_x, θ_y and θ_z) in addition to measurements of absolute shape and shape changes. The sub-nm repeatability of the absolute position measurement makes possible the reestablishment of a previously optimized mirror shape and position after events such as a stripe or mirror swap, or an actuator power down. While absolute measurement of mirror shape is possible, in this first demonstration we focus on only measuring *changes* in mirror shape.

SENSOR TECHNOLOGY

The sensor used to implement this measurement is a fiber-based absolute position interferometric sensor, specifically, the ZPS™ Sensor System produced by Zygo Corporation, which is designed specifically for applications requiring tens of measurement channels (up to 64) [8-10]. The sensor functions in a Fizeau configuration as shown in Fig. 3(a) where interference between the measurement reference surface and the target reflections generate the measurement signal. Most fiber position sensors can only measure the *displacement* Δd and have no knowledge of the starting position of the target; the ZPS sensor, in contrast, measures the *actual starting distance* d from the sensor reference surface to the target, and incremental changes Δd therefrom. This confers upon this sensor unique capabilities which are advantageous to the metrology of x-ray mirrors as described in the following sections. The sensor itself, shown in Fig. 3(b), is extremely compact (∅3 mm x 27 mm) which allows for the construction of an array of closely spaced sensors with a minimum spacing of 5-8 mm. The standard sensor design features a working distance of 3.5 mm and an angular acceptance range of ±1 mrad. Custom sensors for denser spacings or wider acceptance angles are also possible. Noise performance of these sensors is 0.02 nm $\text{Hz}^{-1/2}$(3σ).



(a) (b)

FIGURE 3. (a) Operating principle of the ZPS sensor (b) ZPS sensor

COMPARISON MEASUREMENT SETUP

We describe a proof-of-principle setup that demonstrates the performance of mirror shape change measurement by the ZPS sensor array in comparison to a large-aperture Zygo 18" Fizeau interferometer. Figure 4 shows the disposition of the metrology frame relative to the mirror similar to an actual in-service configuration in a beam line. The metrology frame is held in a fixed relationship to the mirror surface at a distance roughly equal to the sensor working distance, allowing the x-ray beam to graze the mirror surface just below the face of the metrology frame.

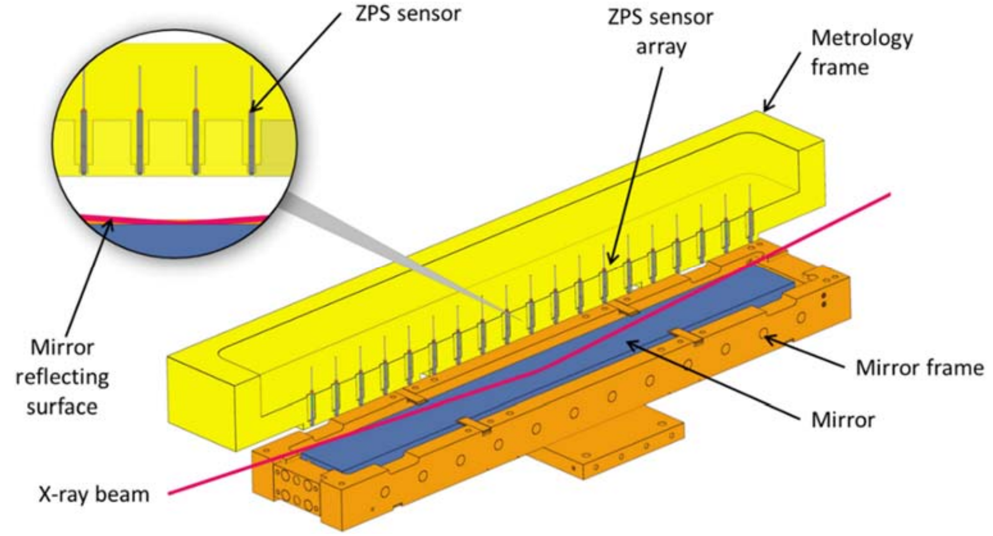


FIGURE 4. Disposition of metrology frame relative to the deformable mirrors. Metrology frame shown sectioned to reveal one of two linear arrays. Beamline implementation requires only one array for pure shape measurement.

Figure 5 provides a simplified representation of the full setup. The setup is comprised of a common baseplate to which mount both the deformable mirror and the metrology frame. The metrology frame attaches kinematically to the baseplate through a set of three bipods, the design of which minimizes the deformations of the metrology frame due to differential expansion between the baseplate and the metrology frame.

The mirror is a piezo actuated bimorph with 12 actuators distributed evenly along the ~450 mm length of the mirror. The mirror is comprised of piezo actuators sandwiched by two Zerodur® face sheets. The mirror mounts to an aluminum frame and bolts to a three degree-of-freedom (DOF) adjustment which sets the relative angle between the mirror and the metrology frame as well as the spacing between them. This adjustment (not shown) is a classic three ball/three vee mount designed for the nm level stability required for this measurement.

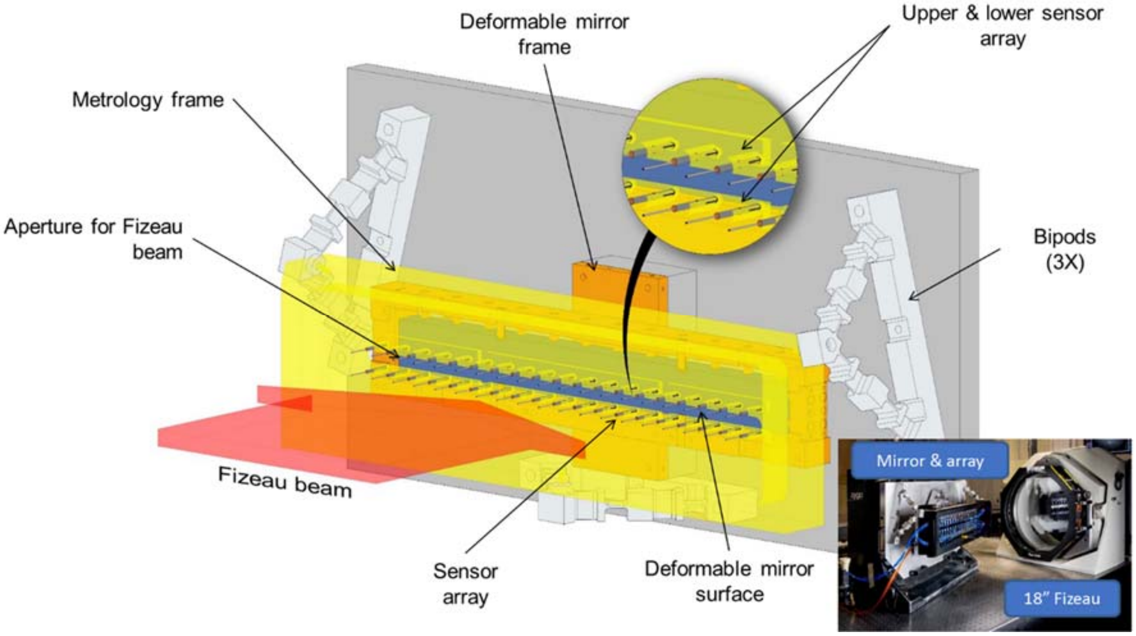


FIGURE 5. Overview of the measurement setup. Inset photograph shows the setup in front of an 18” Fizeau interferometer. Setup is rotated in the photograph to reveal details of the metrology frame.

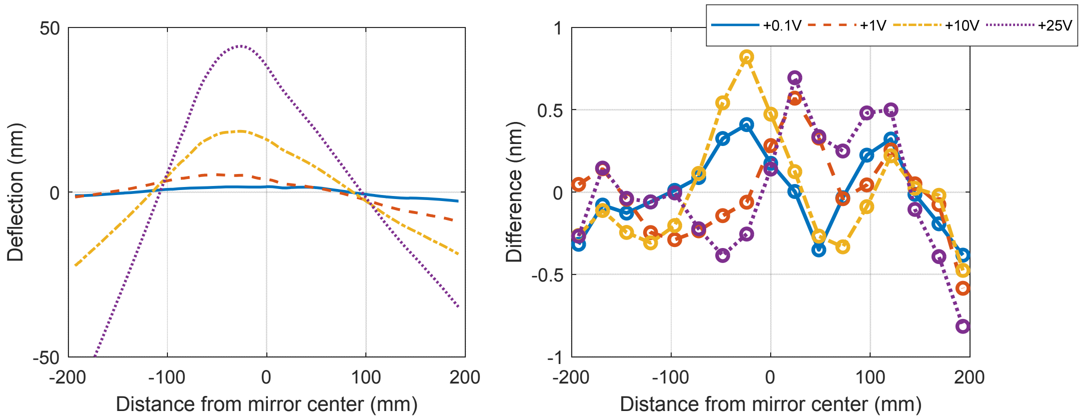
The metrology frame is the key part of the setup and holds the two linear sensor arrays of 17 sensors each. The sensors are spaced ~24 mm apart, which provides adequate sampling of the mirror surface for the measurement of low-order terms. An aperture which provides access to the mirror surface for the simultaneous Fizeau measurement in compliance with the Abbe principle separates the two linear arrays [11]. Construction of the metrology frame from high thermal diffusivity Aluminum 6061 minimizes frame deformation due to thermal gradients. Stability measurements of the mounted metrology frame and sensor mounts show a shape stability of 1 nm RMS over a period of several hours and temperature changes of 20 mK, while the sensor itself is stable to <1.0 nm/day [9].

RESULTS OF COMPARISON

The ZPS sensor array and Fizeau interferometer are compared by simultaneously measuring changes in the shape of the bimorph mirror. In each case, the Fizeau and sensor array measure the initial and final shapes of the mirror and the shape change is the difference between the initial and final shapes. The difference between the two measurements of shape change quantifies the agreement between the two methods.

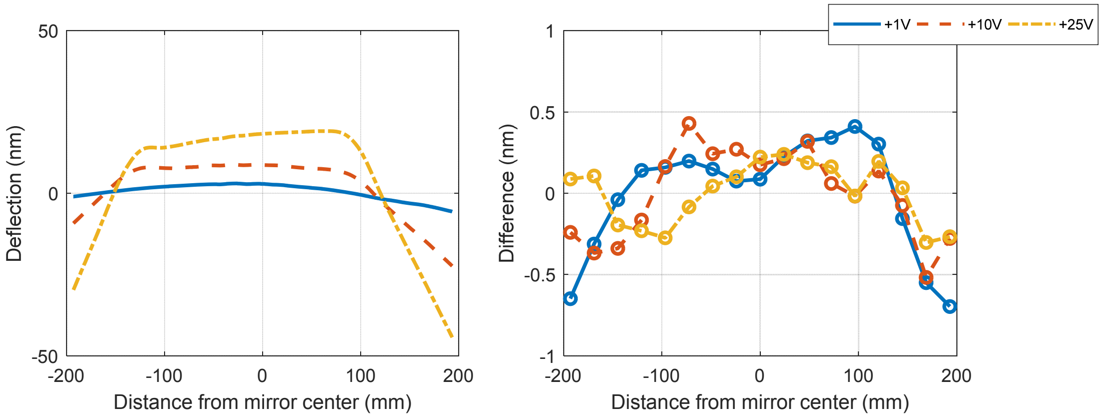
The initial shape of the mirror is taken to be its natural shape, i.e., shape with all actuators set to 0V. A 24 Hz cutoff filter on each of the array sensor channels minimizes the effect of ambient noise while providing adequate bandwidth for the quasi-static mirror deformations. A dedicated refractometer that is part of the sensor array system corrects the array measurement for the effects of slow changes to temperature and pressure on the refractive index of air. Each sensor data point is an average of 10k points at a 2 kHz sampling rate. A pairwise average of the two arrays produces an effective measurement at the same location as the center line of the Fizeau measurement. The data acquisition times of both the ZPS sensor and Fizeau interferometer are approximately equal (~5 sec).

Figures 6-8 show the mirror deflection and the difference data for a range of shapes and deflections. Fizeau measurements show the commanded shape with each measurement being the average of 32 phase measurements. Table 1 shows the RMS differences for the various cases. The short-term repeatability of the difference over the time period of a typical measurement on a pointwise basis is < 0.4 nm



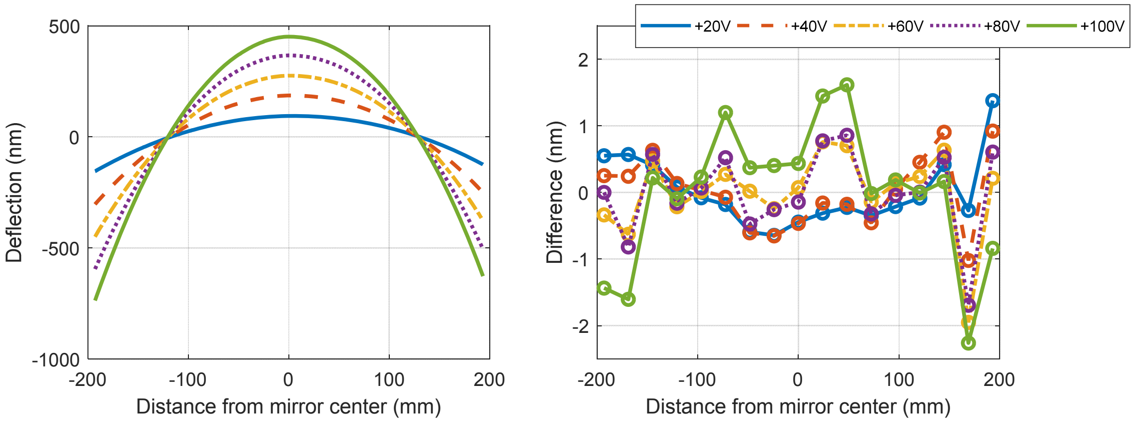
(a) (b)

FIGURE 6. (a) Deflection and (b) difference with actuators 5 & 6 activated



(a) (b)

FIGURE 7. (a) Deflection and (b) difference with actuators 3 & 9 activated



(a) (b)

FIGURE 8. (a) Deflection (b) difference with all actuators activated

Table 1. Summary of difference between Fizeau and sensor array mirror deflection measurements

Piezos Actuated	Applied Voltage (V)	Difference (nm RMS)
5 & 6	+0.1	0.23
	+1	0.26
	+10	0.34
	+25	0.37
3 & 9	+1	0.34
	+10	0.27
	+25	0.18
All	+20	0.52
	+40	0.55
	+60	0.59
	+80	0.61
	+100	0.92

SUMMARY & CONCLUSION

A proof-of-principle setup establishing the feasibility of sub-nm *in situ* mirror shape metrology has been demonstrated through a series of comparisons between the measurements of shape changes of a bimorph mirror by an array of ZPS™ sensors and a Fizeau interferometer. The comparisons show sub-nm agreement between the two measurement systems over a range of mirror shapes. The dominant contributor to the repeatability is the effect of air-turbulence in the Fizeau measurement due to the length of the cavity (~300 mm). The data also show low-order terms at the ~2-3 nm level which may be due to flexion of the metrology frame, Fizeau errors resulting from uncertainty in focusing and errors due to the high fringe densities. The overall measurement uncertainty for the point-wise difference varies with sensor position and mirror deflection and is estimated to be 1.5 nm (k=2) for the data shown.

Fabricating the metrology frame using low thermal expansion material or operating in a typical beamline vacuum environment will further reduce the uncertainty. Further testing of the applicability of this technique over a larger range of curvatures is ongoing. X-ray exposure testing of the sensors to determine radiation hardness is also ongoing.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the extensive help and support provided by Rich Boland, Dave Schenarts, Lars Selberg, Mike Holmes, Ned Bennett and Bruce Elder.

REFERENCES

1. Advanced Photon Source Upgrade Project: Preliminary Design Report, Document Number: APSU-2.01-RPT-002, pg. 6-117. (Sept 2017)
2. Ibid, pp. 6-6 - 6-20
3. T. Kimura, S. Matsuyama, K. Yamauchi, and Y. Nishino, "Coherent x-ray zoom condenser lens for diffractive and scanning microscopy," *Optics Express* **21**, 9267-9276 (2013).
4. H. Mimura et al, "Breaking the 10nm barrier in hard X-ray focusing," *Nature Physics* **10**, pp. 122-125 (2010).
5. R. J. Boland, "Using linear variable differential transformers and ultrasonic transducers to measure flatness and parallelism for NIF optics," Proc. SPIE 3782, Optical Manufacturing and Testing III, (11 Nov 1999).
6. R. Biasi, D. Gallieni, P. Salinari, A. Riccardi, and P. Mantegazza, "Contactless thin adaptive mirror technology: past, present, and future," Proc. SPIE 7736, 77362B (2010).
7. M. Vannoni, I. F. Martín, V. Music, and H. Sinn, "Calibration and optimization of an x-ray bendable mirror using displacement-measuring sensors," *Optics Express* **24**, 17292-17302 (2016).
8. L. L. Deck, "High-performance multi-channel fiber-based absolute distance measuring interferometer system", Proc. SPIE 7405, Instrumentation, Metrology, and Standards for Nanomanufacturing III, 74050E (21 Aug 2009).
9. V. G. Badami and E. Abruña, "Absolutely: Small Sensor, Big Performance," *Mikroniek*, Nr. 1, pp. 5-9 (2018).
10. http://www.zygo.com/zps/
11. E. Abbe, "Messapparate fur Physiker," *Zeitschrift für Instrumentenkunde* **10**, 446–448 (1890).