Two-Dimensional Differential Deposition: Figure Correction of Thin-Shell Mirror Substrates for X-ray Astronomy

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ABSTRACT

This paper describes a new variation of the differential deposition/differential erosion technique for mid-frequency surface-height error correction. In our approach, the technique is extended to two dimensions in order to correct surface-height errors in thin-shell cylindrical mirror segments with high throughput. We describe the new infrastructure currently being developed to realize this technique, including an LTP system for surface metrology of mid-frequency surface-height errors, a new UHV linear stage for precise substrate motion during deposition or erosion, and most crucially, the development of electronically-actuated aperture arrays that are mounted in front of a rectangular magnetron cathode, or a rectangular ion source, in order to modulate the deposition/erosion rate of material in two dimensions, in real-time.

Keywords: X-ray optics, segmented mirrors, differential deposition

1. INTRODUCTION

An effective approach to the development of grazing-incidence X-ray telescopes for astronomy having large collecting area and high resolution is the use of thin-shell cylindrical mirror segments that are nested as densely as possible. The most recent embodiment of this approach is the NuSTAR hard X-ray instrument:[1] each NuSTAR telescope contains 133 concentric mirror layers constructed from 0.21-mm-thick slumped glass segments (Fig. 1); the instrument achieves angular resolution of order 1 arcmin, and is sensitive to energies as high as 80 keV. The same general approach for telescope construction is planned for many future Explorer-class missions[2] targeting both the hard (e.g., HEX-P, BEST) and soft (e.g., AEGIS, AXSIO, WHIMEX) X-ray bands. The hard X-ray missions will use multilayer coatings, as in NuSTAR, while soft X-ray missions will likely use single-layer Ir coatings. But regardless of the choice of energy band-pass and mirror coating, the ability to achieve the science goals associated with these missions will depend in large part on the achievable angular resolution of the telescope mirrors. Furthermore, the X-ray Surveyor mission currently being formulated,[3] as well as future facility-class missions that use highly-nested X-ray telescopes will almost certainly require better telescope resolution than can be achieved at present.[4]

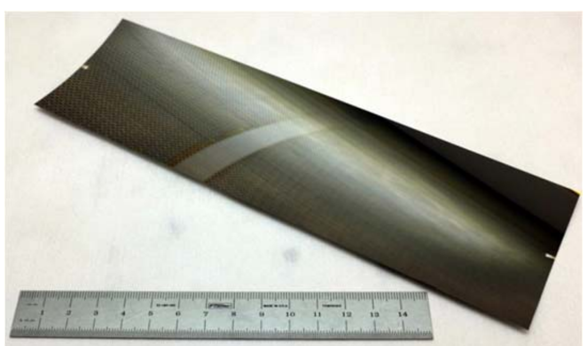


Figure 1. A coated NuSTAR shell, constructed from thermally-formed thin glass.

While there are many potential sources of figure error in thin-shell mirror substrate, the mid-spatial frequency (i.e., mm-range) axial surface-height errors in particular have now been identified as a limiting factor, at least in the case of the NASA/GSFC-produced segmented glass shells, to achieving resolution below about 6 arc-seconds.[5] Because these errors are generated by the slumping process itself, and not by the shell assembly/mounting processes, it will be necessary to implement post-slumping surface correction in order improve the performance of X-ray telescopes constructed from these shells to 1 arc-second or better.[6,7] To illustrate the problem, shown in Fig. 2 is a typical 1D axial surface profile of a ~6.5 arc-second HPD thin-glass shell from NASA/GSFC (provided courtesy of W. Zhang). The measurement shows peak-to-valley residual surface height variations of order ~60 nm, over spatial scales ranging from 1 to 20 mm, approximately. It will be necessary to reduce these errors by a factor of ~5–10 in order to achieve sub-arc-second resolution. (It will also be necessary to correct surface errors that occur over longer scales as well, a problem that can be addressed independently from the mid-frequency errors that we focus on here.)

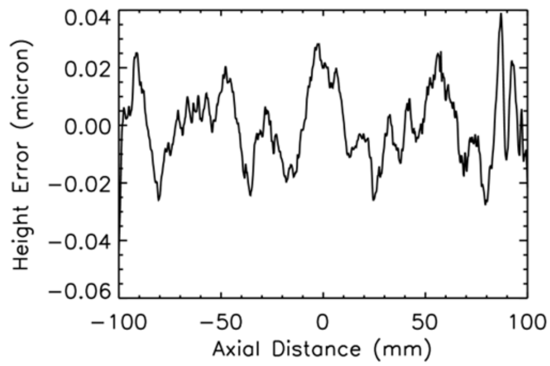


Figure 2. A typical 1D surface height profile of a ~6.5 arc-second HPD glass shell made by W. Zhang (NASA/GSFC.)

This paper describes the development of a new differential deposition/differential erosion technique for surface error correction in thin-shell cylindrical mirror segments. Differential deposition/erosion surface figuring techniques are already widely used for precision optics fabrication in other wavelength regimes, and in the X-ray band for ultra-precise synchrotron optics production;[8,9,10,11,12] differential deposition is already being pursued at NASA/MSFC in order to correct surface errors in thin-shell mirror substrates.[13,14,15] Our implementation of this technique uses a novel approach in order to extend the differential deposition/erosion concept to two dimensions. The ultimate goal is to develop a cost-effective method for high-throughput manufacturing of sub-arc-second mirror shells, as would be needed for the production of large-area telescopes for future astronomy missions containing thousands, or perhaps tens of thousands of individual mirrors.

In section 2 we explain the 2D differential deposition/erosion concept, and how it will be used for surface error correction in thin-shell cylindrical mirror substrates. In section 3 we describe the development of the new technology needed to implement our approach: the electronically-actuated aperture arrays (so-called “dynamic apertures”) that are used to control the spatial distribution in two dimensions of sputtered atoms from a rectangular magnetron cathode, or of ions emitted from a rectangular ion source; a new UHV linear stage for our existing magnetron sputtering system for precise control of substrate position and velocity during deposition or erosion; and a new long-trace profiler (LTP) system for high-precision, mid-frequency surface metrology of shin-shell mirror substrates. We conclude in section 4 with a summary of our progress thus far, and a discussion of future prospects, including some of the other applications that might benefit from the technology that we are now developing.

2. DIFFERENTIAL DEPOSITION/EROSION

Conventional Approach

In the conventional approach to differential deposition for surface error correction, a small, fixed-width aperture is placed in front of a source of deposited material, such as a planar magnetron cathode used for sputtering; the width of the aperture determines the spatial distribution in one dimension of deposited atoms on the coated surface. As illustrated in Fig. 3, the substrate moves past the fixed aperture (or alternatively, the substrate and source are fixed and the aperture is moved). In one mode, the substrate motion is continuous, and the substrate velocity, which is inversely proportional to the deposited film thickness, is modulated as the substrate moves past the aperture, in accord with the pre-measured surface-height profile, so as to deposit more material in the ‘valleys’, and less material on the ‘hills’. Alternatively, in ‘stepping mode’, the substrate is moved from one position to the next, and the substrate dwell time at each position is adjusted in accord with the required film thickness to be deposited at that position.

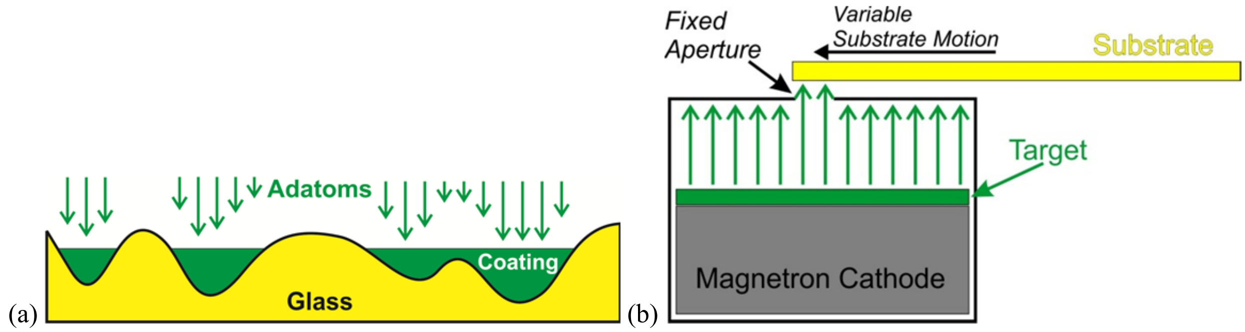


Figure 3. (a) Differential deposition is used to correct surface-height errors by depositing more material in the ‘valleys’, and less material on the ‘hills’. (b) A fixed-width aperture is placed over a sputtering source, such as a magnetron cathode, and the substrate moves past the aperture (from right to left in this diagram) following a prescribed velocity profile that is determined by the pre-measured axial surface-height errors.

The same techniques can be used for differential erosion, with the sputter source replaced by an ion source, as shown in Fig. 4. In this case the amount of material removed from the glass surface due to ion erosion is inversely proportional to the substrate velocity, or in ‘stepping mode’, proportional to the substrate dwell time. Furthermore, as shown in Fig. 5, with a sputter source and an ion source placed side by side in the same chamber, differential deposition and differential erosion techniques can be combined, e.g., in order to achieve a faster rate of surface correction, better surface finish, and/or reduced stress- or thermal-expansion-mismatch-induced distortions. In one mode, differential deposition is used only to deposit material in the valleys, while differential erosion is used only to reduce the heights of the hills. In another mode, the substrate surface is coated with a sacrificial layer of material of uniform thickness, and then differential erosion is used to correct the surface-height errors that are replicated in the deposited sacrificial layer; this latter approach might be preferable if the deposited film can be eroded more quickly than the underlying substrate material, for example, or if the surface finish of the eroded film is smoother than the surface finish of the eroded substrate.

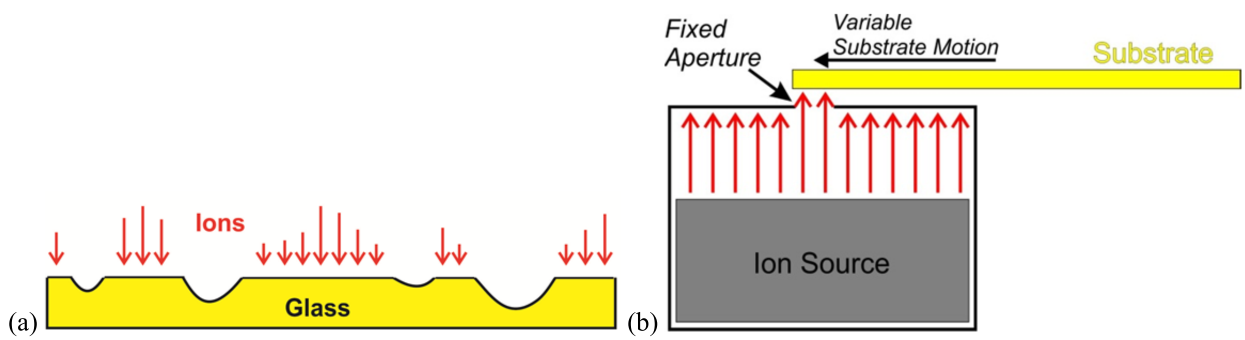


Figure 4. (a) Differential erosion is used to correct surface-height errors by eroding more material from the ‘hills’, and less material from the ‘valleys’. (b) As in differential deposition (Fig. 4), a fixed-width aperture is placed over an ion source, and the substrate moves past the aperture following a prescribed velocity profile that is determined by the pre-measured axial surface-height errors.

In any case, the conventional approach to differential deposition/erosion as just outlined only works efficiently in one dimension, i.e., the direction of substrate motion, which is ostensibly parallel to the axial direction of a cylindrical mirror shell. If a fixed-width aperture that spans the full width of the substrate is used, then the same amount of material will be added or removed in the azimuthal direction, perpendicular to the direction of substrate motion, everywhere on the substrate. Assuming that surface-height errors also vary azimuthally, which is generally true in the case of thermally-formed, thin-shell glass substrates, this approach would thus only correct axial surface-height errors along one stripe on the cylindrical substrate; surface-height errors would remain (or possibly worsen) everywhere else. If instead a ~square aperture is used, then material is deposited or eroded only along one narrow stripe in the axial direction that is roughly as wide as the aperture; to correct axial surface-height errors over the entire substrate surface, the substrate would need to follow a raster scan, as shown conceptually in Fig. 6, so as to correct surface errors over the whole surface one stripe at a time.

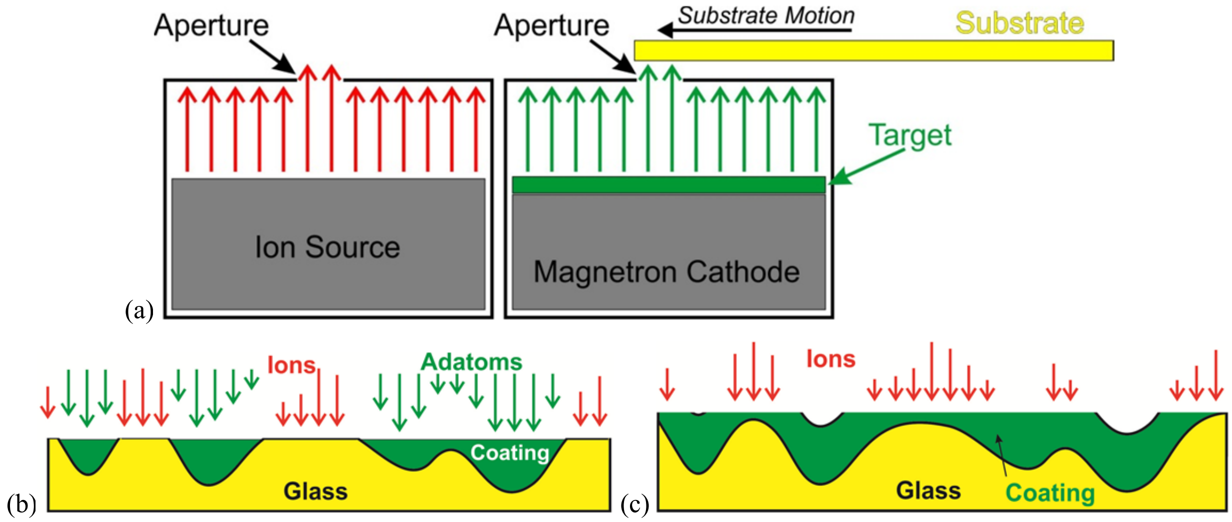


Figure 5. (a) Using both an ion source and a sputtering source placed side-by-side in the same chamber, differential deposition and differential erosion techniques can be combined. (b) In one mode, differential erosion is used to reduce the surface error high points, while differential deposition is used to fill in the low points. (c) In another mode, a sacrificial layer of uniform thickness is deposited on the surface to be corrected, and then differential erosion is used to correct the surface-height errors in the deposited film, rather than directly in the glass substrate.

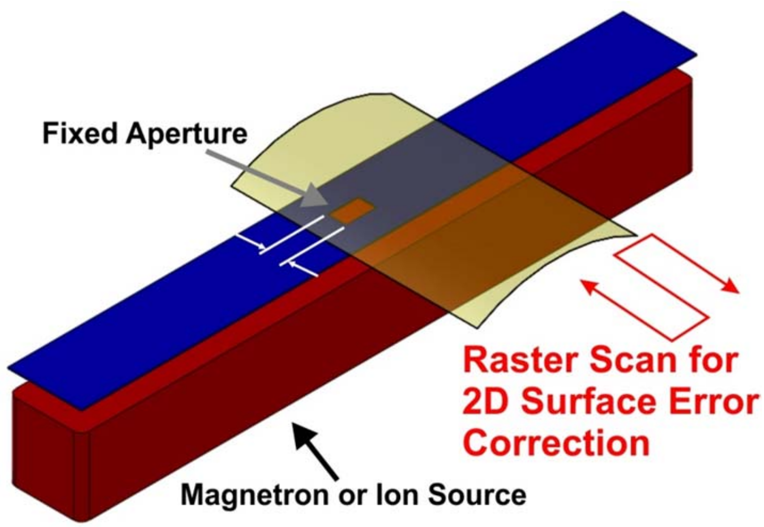


Figure 6. To extend the conventional differential deposition/erosion techniques explained above to two dimensions, a small, ~square aperture could be used, and the substrate raster-scanned, as illustrated.

Two-Dimensional Differential Deposition/Erosion

In the two-dimensional approach to differential deposition/erosion that we are developing, the fixed-width aperture described above is replaced with a so-called 'dynamic aperture', which is an electronically-actuated aperture whose width can be controlled in real-time, during deposition or erosion. In this case, the substrate motion is uniform, while the dynamic aperture width is adjusted during substrate motion in accord with the pre-measured surface-height error profile. Using an array of dynamic apertures placed along the length of the sputter or ion source, surface-height errors can be corrected simultaneously along adjacent stripes over the entire cylindrical mirror substrate. Indeed, as illustrated conceptually in Fig. 7, multiple shells can be corrected simultaneously, in principle; the number of shells that can be corrected at the same time is limited only by the (azimuthal) width of the shells and by the length of the sputter or ion source.

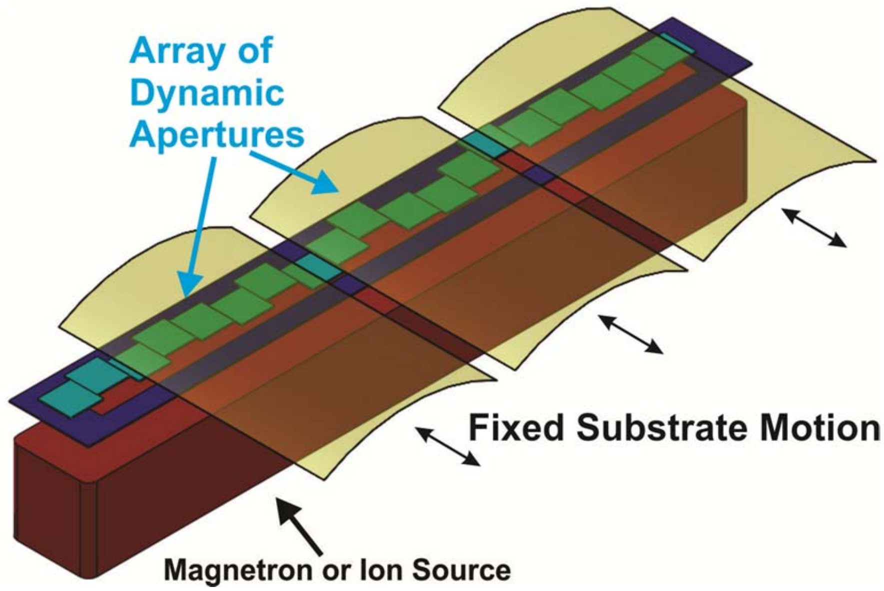


Figure 7. Using an array of dynamic apertures – apertures whose widths can be controlled in real-time during deposition or erosion – differential deposition/erosion techniques can be efficiently extended to two dimensions.

3. TECHNOLOGY DEVELOPMENT FOR 2D DIFFERENTIAL DEPOSITION/EROSION

Dynamic Apertures

Shaped apertures, or deposition masks, have a long history in thin film deposition for spatial control of film thickness. The dynamic aperture arrays that we are now developing were inspired by the adjustable aperture arrays shown in Fig. 8, which were designed to be used with our rectangular, planar magnetron sources (Fig. 8b). The position of each ‘finger’ in these aperture arrays is adjustable, but only prior to deposition, when they can be accessed while the coating chamber is at atmospheric pressure. These static, adjustable aperture arrays were used, for example, to deposit steep, laterally-graded multilayer coatings, such as those being developed for soft X-ray polarimetry applications,[16] following an iterative procedure in which the finger positions were fine-tuned, based on the uniformity achieved in previous coating runs, until acceptable coating uniformity was achieved.

We are now developing dynamic aperture arrays that will be similarly mounted in front of both rectangular, planar magnetron sources and rectangular ion sources, as illustrated in Fig. 9. The dynamic apertures must provide precise, independent motion of each finger during deposition or erosion, and must be sufficiently resilient to the harsh environments of magnetron sputtering and ion beam erosion. Thus, there must be a minimum of moving parts, all of which must be sufficiently shielded from sputtered atoms and ions. Furthermore, the individual fingers must be easily replaced for cleaning, in the case of differential deposition, and highly resilient to ion beam erosion, in the case of differential erosion. The width of the fingers in the direction perpendicular to the direction of substrate motion (i.e., the azimuthal direction with respect to the cylindrical substrate) must be small enough to allow for axial surface error corrections to be made along adjacent stripes on the substrate surface with sufficient azimuthal resolution (as determined by the actual azimuthal variation in axial figure errors on cylindrical mirror shells.) Finally, given that a large number of dynamic apertures will be used simultaneously during 2D surface error correction, the mechanisms must be highly reliable, and the number of wires needed to control each dynamic aperture must be minimized, so that the electrical vacuum feed-through requirements are manageable.

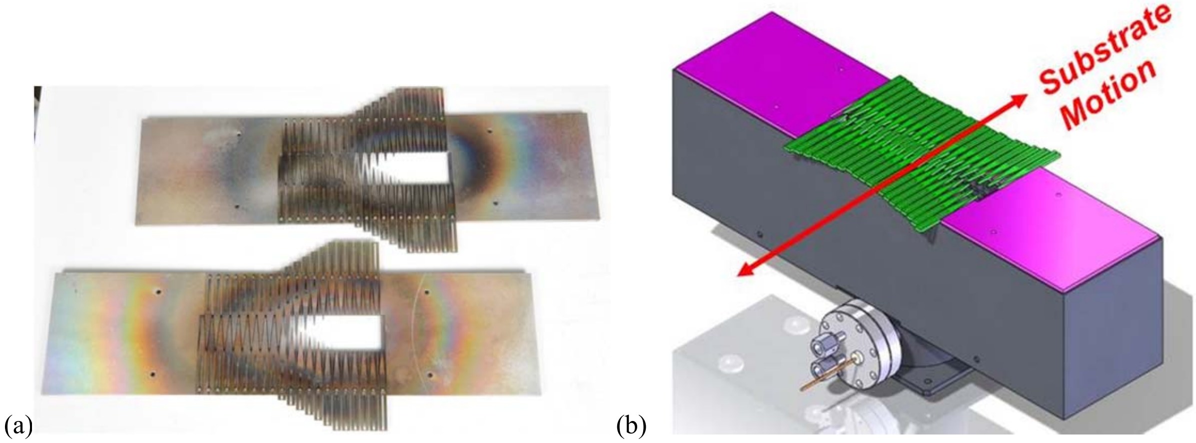


Figure 8. (a) Static, adjustable aperture arrays have been used to control the spatial uniformity of sputtered films. The aperture arrays shown here were used to deposit steep, laterally-graded multilayer coatings for soft X-ray polarimetry. (b) A CAD model of a static, adjustable aperture array mounted to a planar, rectangular magnetron cathode.

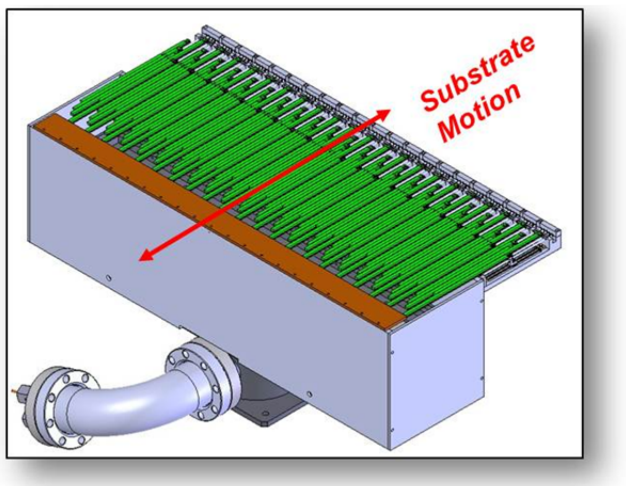
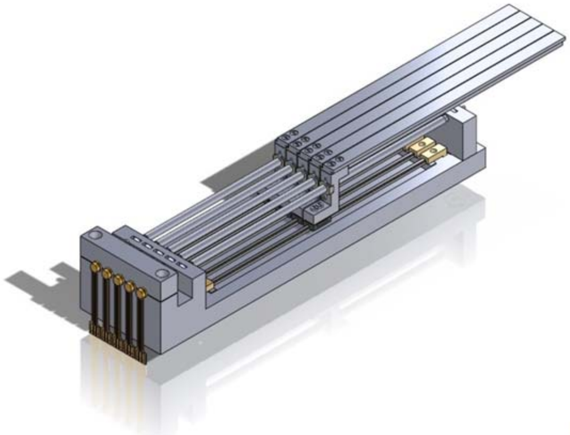
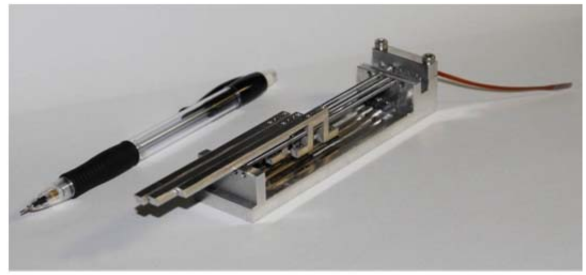


Figure 9. A CAD model of a planar, rectangular magnetron cathode populated with an array of dynamic aperture modules.

We are adopting a modular approach to the development of dynamic aperture arrays. Our first prototype, shown in Fig. 10, comprises an array of five individually-driven fingers, each controlled by its own custom-designed UHV micro-motor (developed by MicroMo). For this first prototype, the fingers are 5 mm wide. They are attached to small lead screws, and small linear ball bearing slides are used to constrain motion along one direction. To fully populate the 50-cm-long rectangular magnetron cathodes currently in use at RXO, for example, 20 such modules will be required per cathode (as shown in Fig. 9.)



(a)



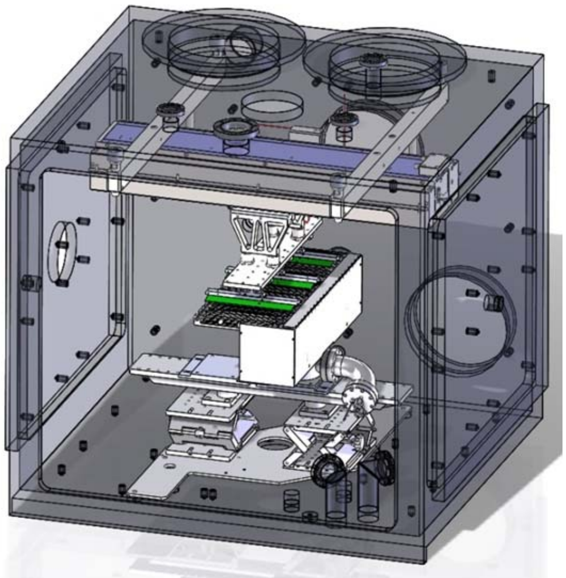
(b)

Figure 10. (a) CAD model, and (b) photo of the first prototype dynamic aperture module, which consists of 5 individually-activated fingers, each 5 mm wide.

UHV Linear Stage

The large coating chamber used for multilayer deposition at RXO can currently be configured in two different coating geometries: in the so-called circular geometry, which is optimized for coating normal-incidence EUV optics with multilayers, the magnetron cathodes are mounted along the diagonals of the base of the vacuum chamber and sputter up, while the substrate faces down and rotates along a circular path past each cathode.[17] In the cylindrical geometry,[18] which is optimized for depositing reflective Ir or multilayer coatings onto a large number of cylindrical shell substrates per run, the cathodes are oriented vertically, face-out, while the substrates are mounted face-in and also rotate along a circular path past each cathode. Neither of these coating geometries are well-suited to the differential deposition/erosion techniques described here. Consequently, we have developed a new UHV linear stage in order to realize a third, linear coating geometry in this chamber that is well-suited to differential deposition/erosion.

The new UHV linear stage (developed by Primatics), is designed to mount from the top of the square coating chamber, as shown in Fig. 11. Cylindrical mirror shells are mounted to the moving platen face-down, and the magnetron cathode(s) and/or rectangular ion source are mounted to the bottom of the chamber face up, as shown. The linear stage provides 650 mm of travel, with 50 μm accuracy. The sample platen is electrically isolated, so that a substrate bias voltage up to 300V can be applied during deposition. The stage was recently delivered to RXO and will be installed in the coating chamber later this year.


(a)

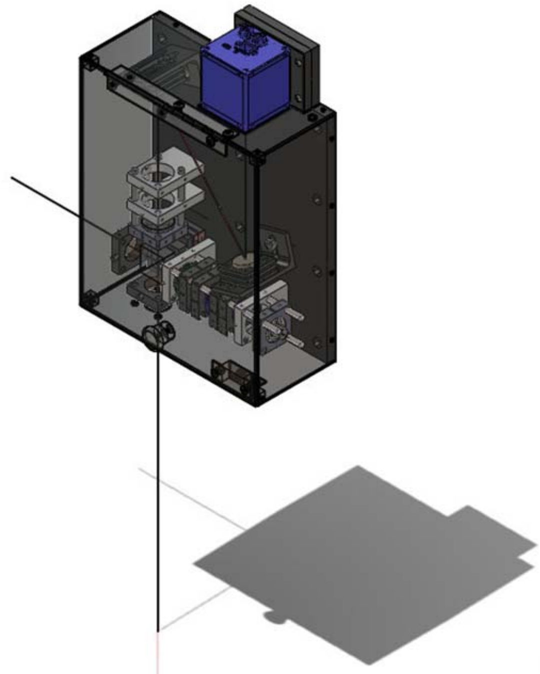
(b)

Figure 11. A CAD model of the new UHV linear stage for differential deposition/erosion is shown in (a), mounted to the top of RXO's large, square coating chamber. Rectangular magnetron cathodes and/or ion sources are mounted on the bottom of the chamber. (Only one magnetron cathode, fully populated with a dynamic aperture modules, is shown in this image.) The stage is shown in (b), where it is resting upside-down on a bench prior to installation in the chamber. Three cylindrical mirror shells are shown resting on the platen. (Mounting fixtures to hold the shells securely to the platen have not yet been fabricated.)

Long-Trace Profiler

In order to accurately correct mid-frequency surface-height errors, it is necessary to accurately measure these errors, both before and after correction. To this end, we are constructing a new long-trace profiler[19] (LTP) for surface metrology in the mid-spatial frequency range. The new LTP optical head, shown in Fig. 12, uses a custom F-Theta lens having a 500 mm focal length designed by P. Takacs (fabricated by Optimax), and a high-quality polarizing beam-splitter (fabricated by JML Optical). The position of the probe and reference beams are measured using a CCD imager having 5.5 μm pixels (Imperx). The system is sensitive to slope errors in the range ±20 mrad.

As shown in Fig. 13, the LTP optical head is mounted to a custom X-Y gantry (Newport Corp.) comprising an air-bearing linear stage with 300 mm of travel for motion in the "X" direction (i.e., the measurement direction), and two mechanical stages (recirculating ball bearing slides) with 400 mm of travel for motion in the "Y" direction. All stages are driven by linear motors. The new LTP system will be aligned, calibrated and tested later this year; performance results will be presented in the future.



(a)

(b)

Figure 12. (a) CAD model and (b) photo of RXO's new LTP optical head for mid-frequency surface metrology.

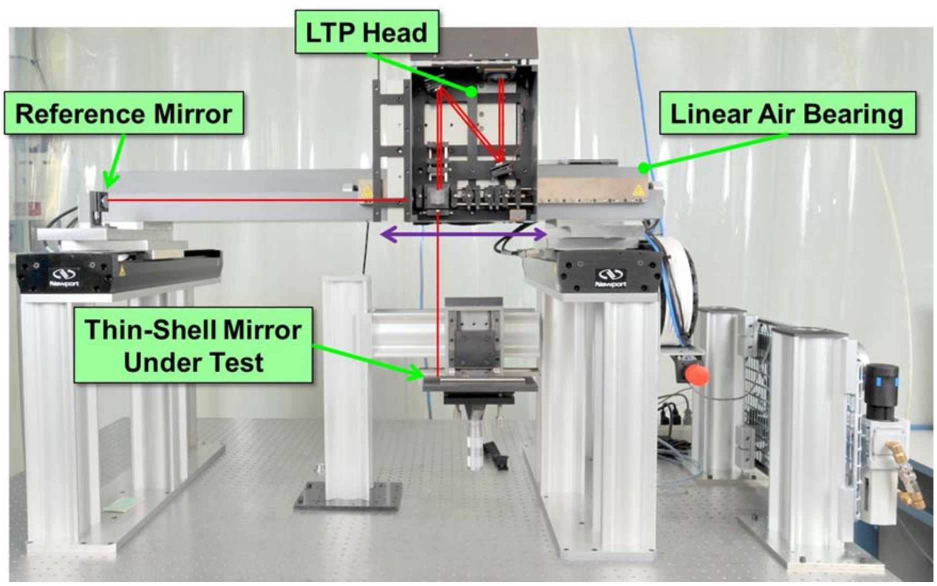


Figure 13. The LTP head mounted to an X-Y air-bearing gantry system.

4. SUMMARY AND CONCLUSIONS

We have described our concept for two-dimensional differential deposition/differential erosion, for high throughput correction of mid-frequency surface-height errors in thin-shell cylindrical mirror segments. The key technology on which our approach is based is the use of an array of electronically-actuated apertures, which is mounted in front of a rectangular magnetron cathode, or a rectangular ion source, in order to modulate the deposition/erosion rate of material in two dimensions, in real-time as the substrate moves past at a fixed velocity. We have realized a first prototype dynamic aperture module, and have also developed a new UHV linear stage for our existing sputtering system that will enable the precise, linear substrate motion that is required for this work. We have also constructed a new LTP for high-accuracy mid-frequency surface metrology of cylindrical shells. The new LTP will be operational later this year; we also plan to have the coating system operating in the linear geometry later this year as well, so that we can test the performance of prototype dynamic apertures. Once we have developed a robust dynamic aperture module, we will aim to demonstrate the ability to sufficiently correct surface-height errors over large areas by two-dimensional differential deposition and/or erosion.

Looking to the future, where high-throughput surface error correction techniques will be needed for the mass production of thin-shell mirror substrates, we envision a new, large deposition chamber, as shown conceptually in Fig. 14. The new chamber will accommodate both surface error correction by differential deposition/erosion, as well as in situ surface metrology (using an LTP, or perhaps some other metrology technique). The system would be equipped with a long-throw linear stage, and a load-lock, so as to avoid the long pump-down times that are typically required for thin film deposition. With additional magnetron cathodes, the system could also be used to deposit reflective Ir or multilayer coatings on the substrates after surface errors have been corrected, without breaking vacuum, further increasing production efficiency.

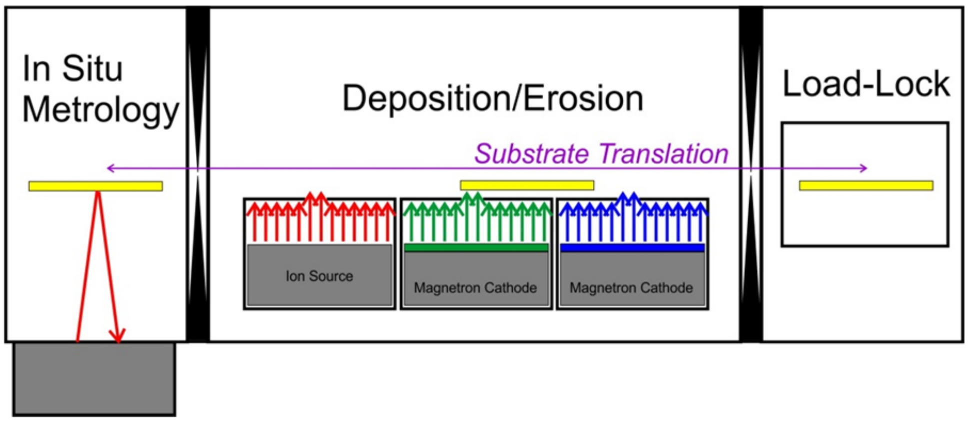


Figure 14. Schematic diagram of a new coating and metrology chamber for closed-loop surface-height error correction.

The new dynamic aperture modules that we are developing may also find wide application in other areas of thin-film deposition and ion beam erosion. For example, dynamic aperture arrays can be used for profile-coating to produce aspherical substrates,[20] and for the growth of multilayer coatings that are laterally-graded in two dimensions, for a variety of applications. Dynamic aperture arrays could also be used to greatly improve both the azimuthal and axial coating uniformity of reflective multilayer films deposited onto thin-shell mirror substrates. Yet another application is the two-dimensional control and elimination of stress-induced substrate distortions resulting from either single-layer Ir films or hard X-ray multilayer films deposited onto thin-shell mirrors. That is, coatings having precise uniformity control in two dimensions can be deposited on both the front- and back-sides of thin-shell mirror substrates, in order to balance the stresses in these films and thereby reduce stress-induced substrate distortions that would otherwise degrade angular resolution. Another idea is to use two-dimensional thickness control of the individual layers that comprise a (non-reflective) multilayer film that is deposited on the back-side of such substrates, in order to induce precisely-controlled, stress-driven distortions so as to correct intrinsic low-frequency surface errors. This approach would exploit the known variation in multilayer film stress with the relative layer thicknesses of the two materials that comprise the multilayer,[21] as shown, for example in Fig. 15 for the case of Mo/Si multilayers. As can be seen in this figure, the film stress can be adjusted from compressive to tensile by changing the relative thickness of the individual Mo and Si layers. Spatial control of the multilayer layer thickness ratio, with ~cm-scale resolution, would enable the ability to deposit back-side films with prescribed tensile or compressive stresses as a function of position, analogous to other techniques that are currently being pursued using Cr,[22] piezo[23] or magnetostrictive[24] films to correct figure errors.

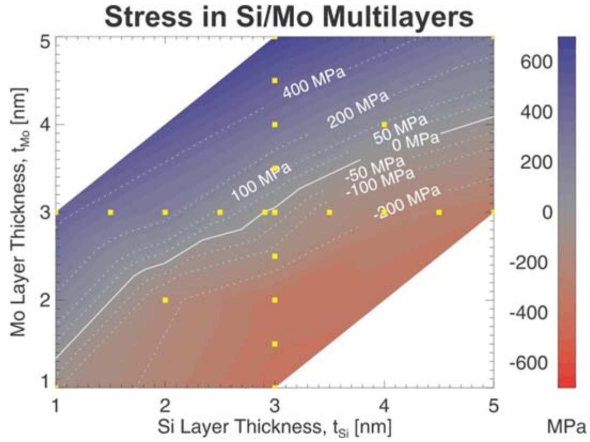


Figure 15. Variation in film stress in a multilayer depends sensitively on the layer thickness ratio of the two multilayer materials. In the case of Mo/Si multilayers, film stress can be adjusted from compressive to tensile by adjusting the Mo:Si layer thickness ratio.

5. ACKNOWLEDGEMENTS

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REFERENCES

[1] F. A. Harrison et al, ‘The Nuclear Spectroscopic Telescope Array (NuSTAR) high-energy X-ray mission’, Ap. J, 770, 103 (2013)

[2] “Workshop on X--ray Mission Architectural Concepts”, Maritime Institute, Linthicum, MD, 14-Dec-2011, http://pcos.gsfc.nasa.gov/studies/x-ray-mission.php

[3] A. Vikhlinin, M. Weisskopf, J. Gaskin, and H. Tananbaum, ‘X-ray Surveyor: Science drivers and strawman mission design’, http://pcos.gsfc.nasa.gov/physpag/large-missions/2015-06-X-ray-Surveyor-PhysPAG.pdf

[4] R. S. McClelland, C. Powell, T. T. Saha, W. W. Zhang, ‘Design and analysis of mirror modules for IXO and beyond’, Proc. SPIE Vol 8147, 81470O (2011)

[5] W. Zhang, private communication

[6] W. W. Zhang, M. P. Biskach, P. N. Blake, K.W. Chan, T.C. Evans, M. L. Hong, W. D. Jones, L.D. Kolos, J. M. Mazzarella, R. S. McClelland, S. L. O’Dell, T. T. Saha, and M. V. Sharpe, ‘Lightweight and high angular resolution X-ray optics for astronomical missions’, Proc. SPIE Vol. 8147, 81470K (2011)

[7] K.-W. Chan, M. Hong, T. Saha, W. Zhang, ‘Metrology of IXO mirror segments’, Proc. SPIE Vol. 8147, 814716 (2011)

[8] N.I.Chkhalo, E. B. Kluenkov, A. E. Pestov, V. N. Polkovnikov, D. G. Raskin, N. N. Salashchenko, L. A. Suslov, M. N. Toropov, ‘Manufacturing of XEUV mirrors with a sub-nanometer surface shape accuracy’, NIM-A, 603, 62, (2009)

[9] J.-P. Tock, J.-P. Collette, P. Gailly, D. Kampf, ‘Figuring sequences on a super-smooth sample using ion beam technique’, Proc. SPIE Vol. 3739, 124 (1999)

[10] T. Arnold, G. Böhm, R. Fechner, J. Meister, A. Nickel, F. Frost, T. Hänsel, A. Schindler, ‘Ultra-precision surface finishing by ion beam and plasma jet techniques – status and outlook’, NIM-A, 616, 147 (2010)

[11] L. Peverini, I. V. Kozhevnikov, A. Rommeveaux, P.V. Vaerenbergh, L. Claustre, S. Guillet, J.-Y. Massonnat, E. Ziegler, J. Susini, ‘Ion beam profiling of aspherical X-ray mirrors’, NIM-A, 616, 115, (2010)

[12] G. E. Ice, J. S. Chung, J. Z. Tischler, A. Lunt, L. Assoufid, “Elliptical X-ray microprobe mirrors by differential deposition’, Rev. Sci. Instrum., 71, 2635 (2000)

[13] M. K. Gubarev, K. Kilaru, B. D. Ramsey, ‘An investigation of differential deposition for figure corrections in full-shell grazing-incidence X-ray optics’, NIM-A, 616, 273 (2010)
[14] K. Kilaru, B. D. Ramsey, M. V. Gubarev, J. A. Gaskin, S. L. O’Dell, W. Zhang, ‘Differential deposition to correct surface figure deviations in astronomical grazing-incidence X-ray optics’, Proc. SPIE 8147, 81470X (2011)
[15] B. Ramsey, K. Kilaru, C. Atkins, M. V. Gubarev, J. A. Gaskin, S. O’Dell, M. Weisskopf, W. Zhang, S. Romaine, ‘Improving X-ray optics through differential deposition’, Workshop on X-ray Mission Architectural Concepts, Maritime Institute, Linthicum, MD, 14-Dec-2011, http://pcos.gsfc.nasa.gov/studies/x-ray-mission.php
[16] H. L. Marshall, N. S. Schulz, D. L. Windt, E. M. Gullikson, E. Blake, D. Getty, Z. McInturff, ‘The use of laterally-graded multilayer mirrors for soft X-ray polarimetry’, Proc. SPIE, 9144 (2014)
[17] D. L. Windt and W. K. Waskiewicz, ‘Multilayer facilities for EUV lithography’, J. Vac. Sci. Technol. B, 12, 3826-3832 (1994)
[18] D. L. Windt, ‘Advancements in hard X-ray multilayers for X-ray astronomy’, Proc. SPIE 9603-42 (2015) *these proceedings*
[19] P. Z. Takacs, ‘Precision Science and Technology for Perfect Surfaces’, JSPE Publication Series No.3, 301 (1999)
[20] B. Shi, J. Qian, and R. Conley, ‘Profile-coating of X-ray optics using the new magnetron sputtering deposition system’, Proc. SPIE 9588-9 (2015)
[21] D. L. Windt, ‘Stress, microstructure and stability of Mo/Si, W/Si, and Mo/C multilayer films’, J. Vac. Sci. Tech., A., 18, 980 – 991 (2000)
[22] Y. Yao, X. Wang, J. Cao, M. E. Graham, S. Vaynman, S. E. Grogans, Y. Cao and M. P. Ulmer, ‘Stress manipulated coating: a new surface correction method for light weight x-ray optics’, Proc. SPIE 9603-50 (2015) *these proceedings*
[23] P. B. Reid et al, ‘Development of adjustable X-ray optics with 0.5 arcsec resolution: a status update’, Proc. SPIE 9603-52 (2015) *these proceedings*
[24] X. Wang, Y. Yao, J. Cao, M. E. Graham, S. Vaynman, T. Liu, M. P. Ulmer, ‘Investigation of magnetically smart films applied to correct the surface profile of light weight X-ray optics in two directions’, Proc. SPIE 9603-55 (2015) *these proceedings*