Figure correction of mirror substrates

OWG Figure correction subgroup
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Speaker: Brandon Chalifoux

Figure correction sub-group

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David Windt	Reflective X-Ray Optics, LLC. (RXO)

Purpose of figure correction

While it may be possible to:

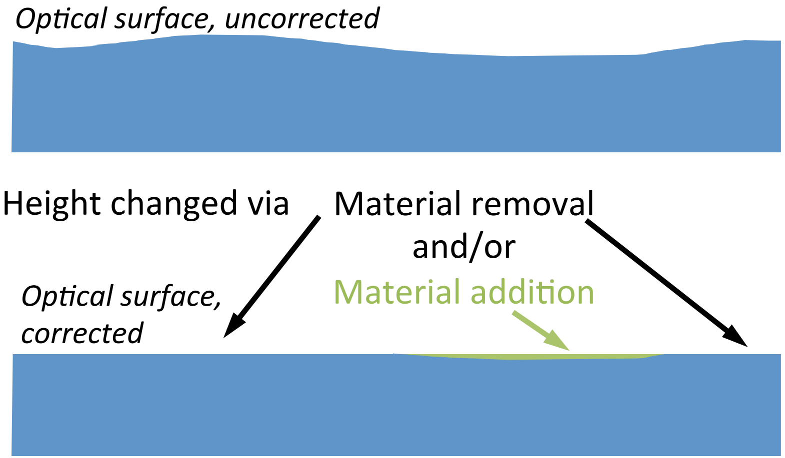
- Create a set of perfect mirrors,
- Coat them without distortion,
- Align and mount them without distortion, and
- Launch a telescope with no additional errors,

this is not guaranteed!

Mirror correction may be required to achieve the mission requirements. The corrections may be applied at various points in the optical assembly fabrication process to address different error sources.

Figure correction methods

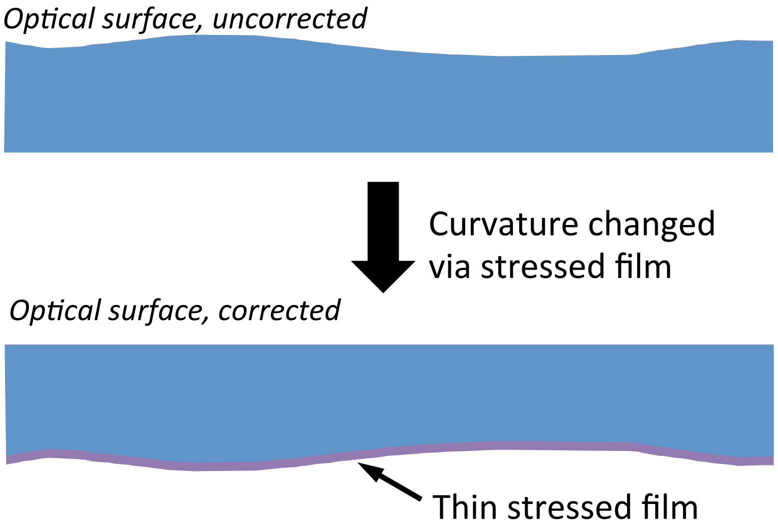
Height-based methods



$$\theta = \partial h/\partial z \rightarrow high\ pass\ filter$$

Height-based methods behave like a high-pass filter. Care must be taken to avoid introducing higher spatial frequency errors, but high-frequency errors may, in principle, be corrected.

Curvature-based methods



$$\theta = \int \kappa\, dz \rightarrow low\ pass\ filter$$

Curvature-based methods behaves like a low-pass filter. Higher spatial frequency errors are difficult to correct or unintentionally introduce.

List of approaches being studied

Method	Institution(s)	Method type
Differential deposition	Marshall Space Flight Center, Reflective X-ray Optics, LLC	Height
Ion beam figuring	INAF Osservatorio Astronomico di Brera	Height
Piezo-electric films	SAO, Penn State University	Curvature
Magneto-strictive films	Northwestern University	Curvature
Ion implantation stress	Massachusetts Institute of Technology	Curvature
Stress-controlled metal films	Northwestern University	Curvature

References for each approach will be given in corresponding slide

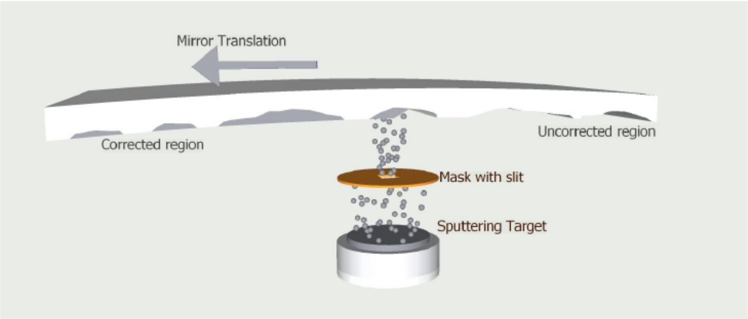
When to perform figure correction?

- Later correction may enable correction of more errors
- Earlier correction may be easier to perform metrology

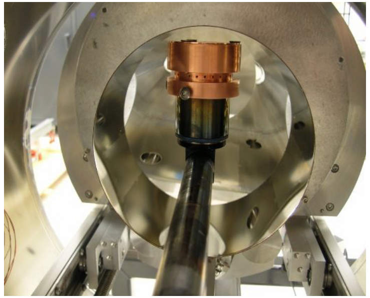
- Some methods (e.g., ion implantation) are probably not feasible once the mirrors are mounted.
- Other methods (e.g., PZT films) may allow corrections post-launch, but post-launch metrology is a challenge.

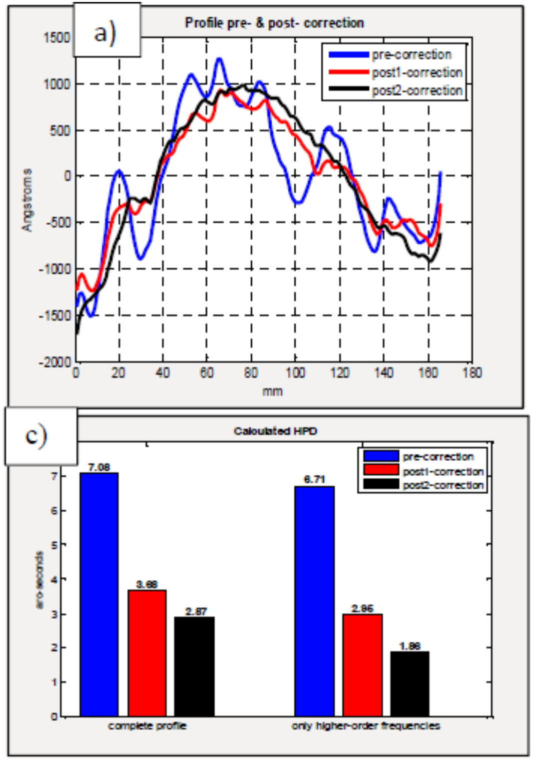
1D differential deposition

Mirror translation speed controls sputter deposition at each point on mirror



Sputtering head within full-shell mirror





Correction of mid-frequency errors in a single meridian shows ~2x improvement for a single correction stage.

Slope measurements taken with Long Trace Profiler, confirmed by x-ray testing.

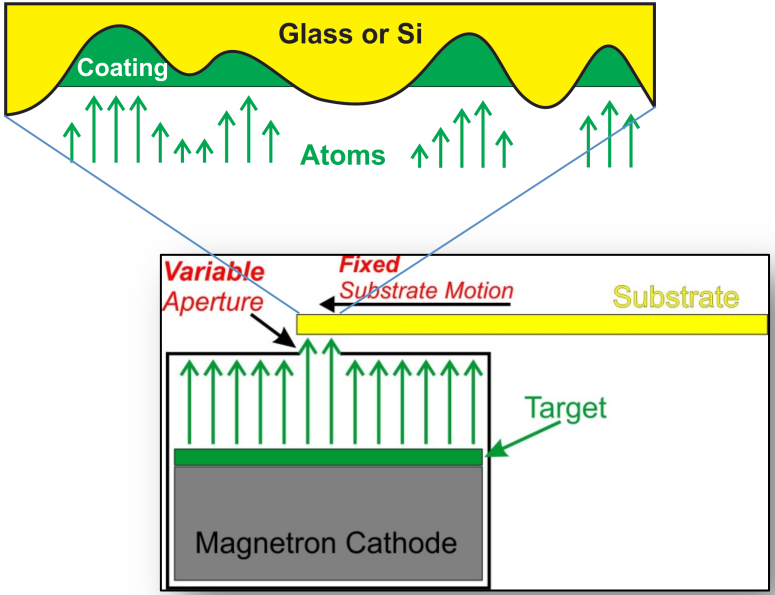
Recent publication and source of all images:
K. Kilaru, et al. *Progress in differential deposition for improving the figures of full-shell astronomical grazing-incidence X-ray optics.* Proc. SPIE 9603 (2015)

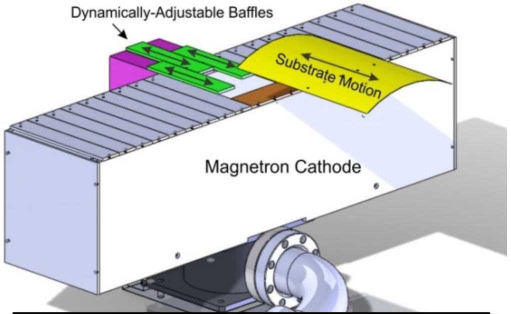
2D differential deposition

Local deposition rate controlled dynamically with variable apertures; substrate speed constant.

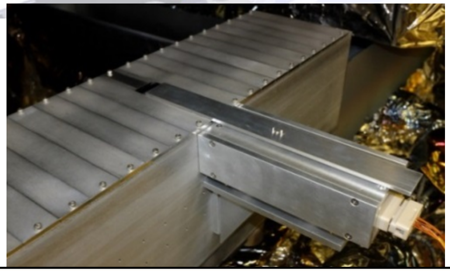
This enables multiple meridians to be coated in parallel, with a goal of increasing throughput.

Differential erosion may also be possible.





Dynamic Aperture concept.

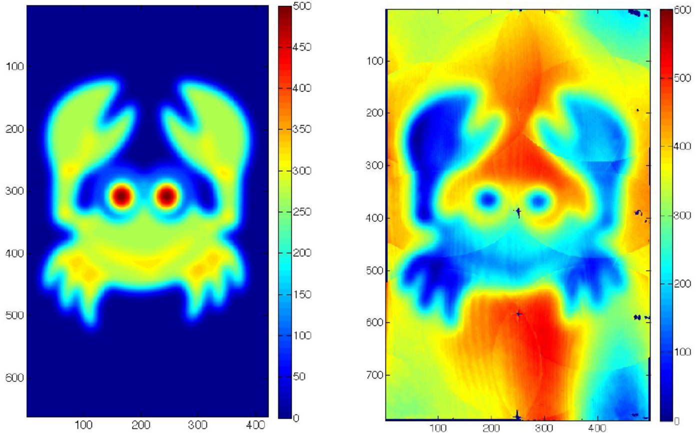


Prototype “1-finger” dynamic aperture.

Recent publication:
D.L. Windt and R. Conley, *Two-dimensional differential deposition: figure correction of thin-shell mirror substrates for X-ray astronomy.* Proc. SPIE 9603 96031H (2015).

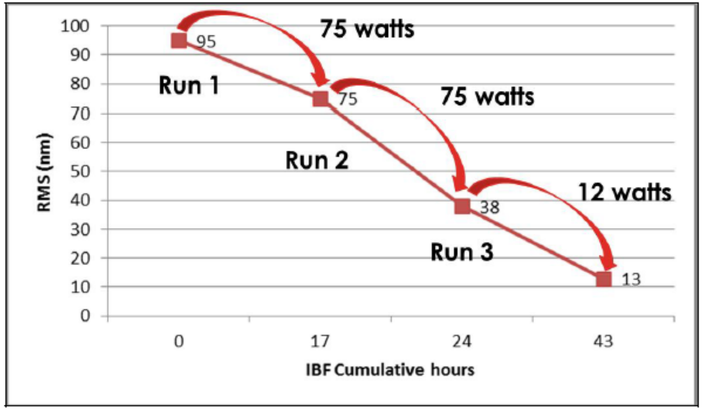
Ion beam figuring

Material is removed by sputtering atoms from mirror surface, using an ion gun.
Material removal at each point is controlled by changing dwell time.



IBF-induced change in thickness of a D-263 glass sheet. *Image: Civitani, et al. (2016).*

Thin mirrors with internal stress will also deform due to surface erosion. This effect was observed in response to the above IBF.



IBF residual error on a ~1m diameter [thick] mirror, after 3 runs. *Image: Ghigo, et al. (2014).*

Recent publications:

M. Ghigo, et al. *Ion figuring of large prototype mirror segments for the E-ELT.* Proc. SPIE 9151 (2014).

M. Civitani, et al. *Ion beam figuring thin glass plates: achievements and perspectives.* Proc. SPIE 9905 (2016).

Curvature-based methods

In a curved substrate, change in curvature is roughly related to integrated stress.

Determining integrated stress profile to provide correction is typically done by calculating or measuring "influence functions" of various actuators, and inverting

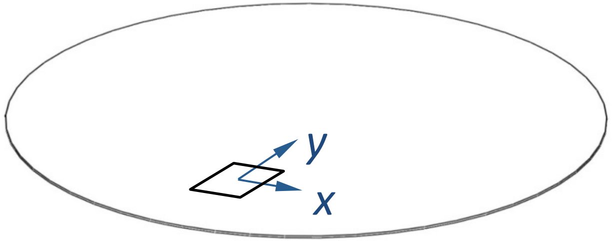
Stoney's equation

$$S_e = \frac{E h_s^2}{6(1-\nu)} \Delta\kappa_e$$

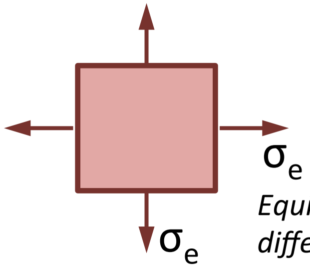
Integrated stress — Substrate properties — Measured curvature

E	Elastic modulus
ν	Poisson's ratio
h_s	Substrate thickness
$\Delta\kappa_e$	Equibiaxial change in curvature
S_e	Equibiaxial Integrated stress

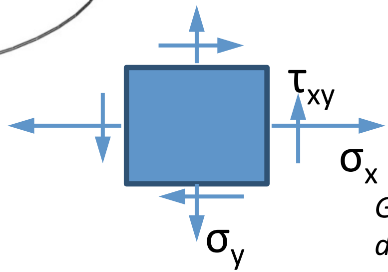
Stress states on a surface



Substrate with a differential surface element outlined



Equibiaxial stress state in a differential surface element.



General stress state in a differential surface element.

Equibiaxial stress:

- More methods to apply
- Film stress effectively becomes a scalar
- Relies on over-constrained mounting
- Correcting film stress errors could always be accomplished with equibiaxial stress.

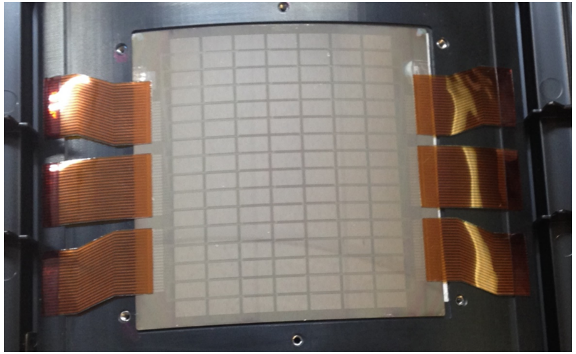
General stress:

- Fewer methods to apply
- Three components of stress that need to be controlled
- Correction does not require over-constrained mounting scheme

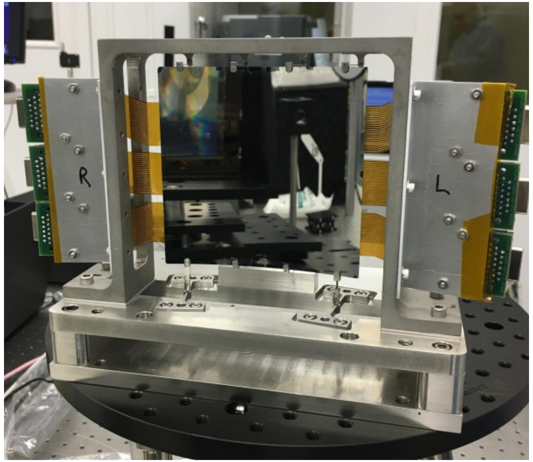
Piezo-electric films

Lead Zirconium Titanate (PZT) films undergo strain proportional to an applied electric field.

Stress type	Equibiaxial only
Max. integrated stress	~150 N/m (tensile)
Substrate compatibility	Silicon, glass



Fabricated (Left) and Mounted (Right) Adjustable Optic.



High Fidelity Deterministic Figure Control Unit, Rev. 3

Current issues under study:

- Film stack stress control
- PZT long-term stability
- Methods of on-orbit strain and temperature monitoring
- Electronic control strategies

Recent publication:

R. Allured, et al. *Laboratory demonstration of the piezoelectric figure control of a cylindrical slumped glass optic.* Proc. SPIE 9905 (2016).

Magneto-strictive films

Magneto-strictive films (e.g., Terfanol-D) undergo strain proportional to an applied magnetic field. A magnetically-hard material would be needed to retain the field in the magneto-strictive material.

Stress type	Non-equibiaxial
Max. integrated stress	~+10..-50 N/m (direction-dependent)
Substrate compatibility	Magnetic materials, silicon and glass under investigation

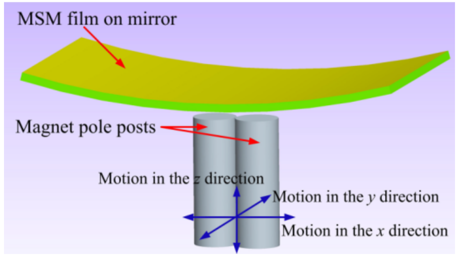
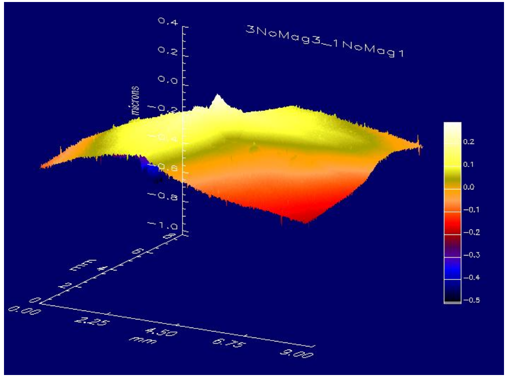


Image from
X. Wang, et al. 2016.



~0.2 microns/~3mm
retained after field removal

Potential issues under study:

- Stress (or strain) profile
- Long-term stability
- Viability of magnetically-hard films
- Stress control of film stack
- On orbit corrections [tricky]

Recent publication:
X. Wang, et al. *Deformation of rectangular thin glass plate coated with magnetostrictive material.* Smart Materials and Structures, **25** (8), 2016.

Ion implantation stress

Energetic ions implanted into a substrate cause morphological changes and stress relaxation.

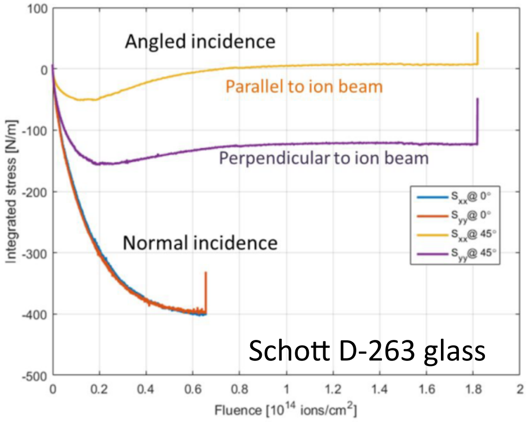


Image from Chalifoux, et al. 2016.

Stress type	Silicon, SiO_2: Equibiaxial Eagle XG, D-263 glass: gen.
Integrated stress range	Silicon: -100 N/m (comp.) SiO_2: -300 N/m (comp.) to +1200 N/m (tens.)
Substrate compatibility	Silicon, glass

Current issues under study:

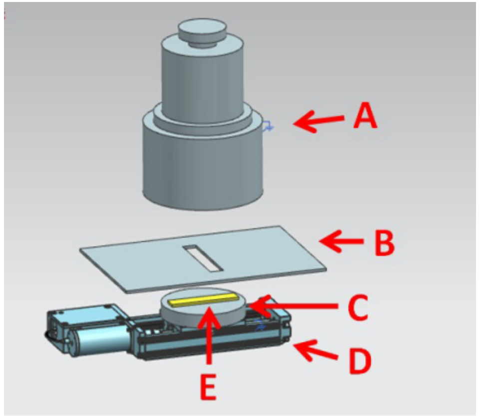
- Stress-dose profile for different materials
- Short-term stress relaxation and long-term stability in different materials
- Surface roughening

Recent publication:

B. Chalifoux, et al. *Gas bearing slumping and figure correction of X-ray telescope mirror substrates.* Proc. SPIE 9905 (2016).

Stress-controlled metal films

Stress in metal films during magnetron sputtering may be controlled by adjusting substrate bias to change the energy of impacting ions.



Other groups also investigating using film stress to correct figure:

- NASA MSFC
- NASA GSFC
- RXO

Stress type	Equibiaxial
Integrated stress range	-250…+250 N/m
Substrate compatibility	Silicon, glass

Current issues under study:

- Stress resolution and accuracy
- Spatial resolution and accuracy

Recent publication:

Y. Yao, et al. *Stress manipulated coating for figure reshape of light weight X-ray telescope mirrors.* Proc. SPIE 9603 (2015).

Conclusions

- Two types of approaches are under development:
  - Height-based methods may be most effective for correcting mid-frequency errors
  - Curvature-based methods may be most effective for correcting low-frequency errors
- The effectiveness of curvature-based methods may be linked to the mounting scheme, if only equibiaxial stress may be applied.
- Any method under development would need to be industrialized to be viable for the Lynx mission.