Metrology for High Performance X-ray Optics: stitching, beam spreading

Lahsen Assoufid

X-ray Science Division/Optics Fabrication and Metrology Group

Advanced Photon Source

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Outline

- State-of-the-art in hard x-ray mirrors
- Fabrication and metrology of diffraction-limited hard x-ray K-B mirrors—Experience of the x-ray Optics Fabrication and Metrology group at the APS
- Fabrication and metrology of coherence preserving mirrors
- Importance of at-wavelength mirror metrology

State-of-the-art in hard x-ray mirror quality as of April 2007

Large flat mirror > 0.5 m long

Slope error	Roughness
0.5 - 0.7 µrad, rms	1 - 1.3 Å, rms

Small mirrors <300 mm long

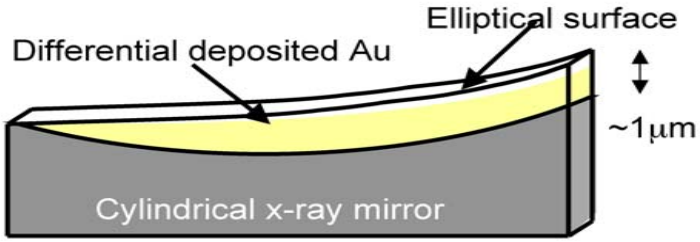
Slope error	Roughness
0.25-0.3 µrad, rms	<0.5 -1 Å, rms

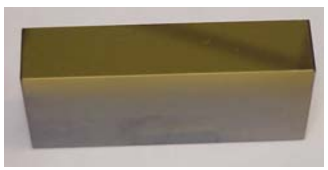
Better mirror quality may be required to preserve coherence properties of high performance sources such as NSLS-II, X-ray FELs, ERLs.

New approaches have to be considered for both fabrication and metrology of these mirrors.

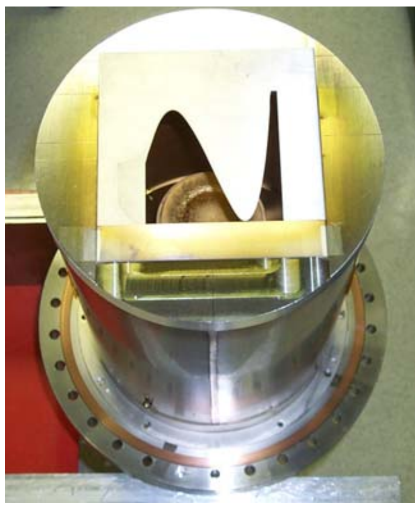
Fabrication and metrology of profile-coated hard x-ray nanofocusing K-B mirrors at APS

Cylindrical or spherical substrate

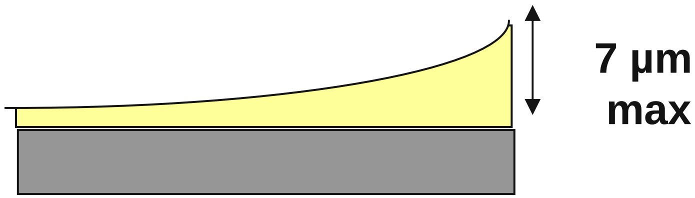


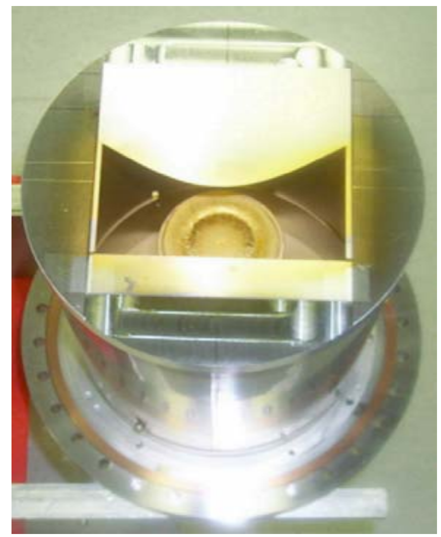


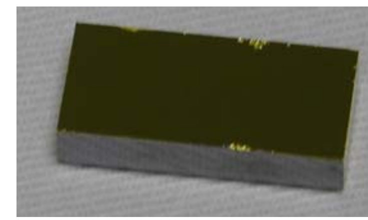
L= 90 mm



Flat substrate







L= 20 mm

<u>Differential Deposition:</u>
G. E. Ice, J.-S. Chung, J. Tischler, A. Lunt, L. Assoufid, *Rev. Sci. Instrum.* 71(7), 2635 (2000).
<u>Profile Coating:</u>
C. Liu, L. Assoufid, R. Conley, A. T. Macrander, G. E. Ice, and J. Z. Tischler, Opt. Eng. 42, 3622 (2003).

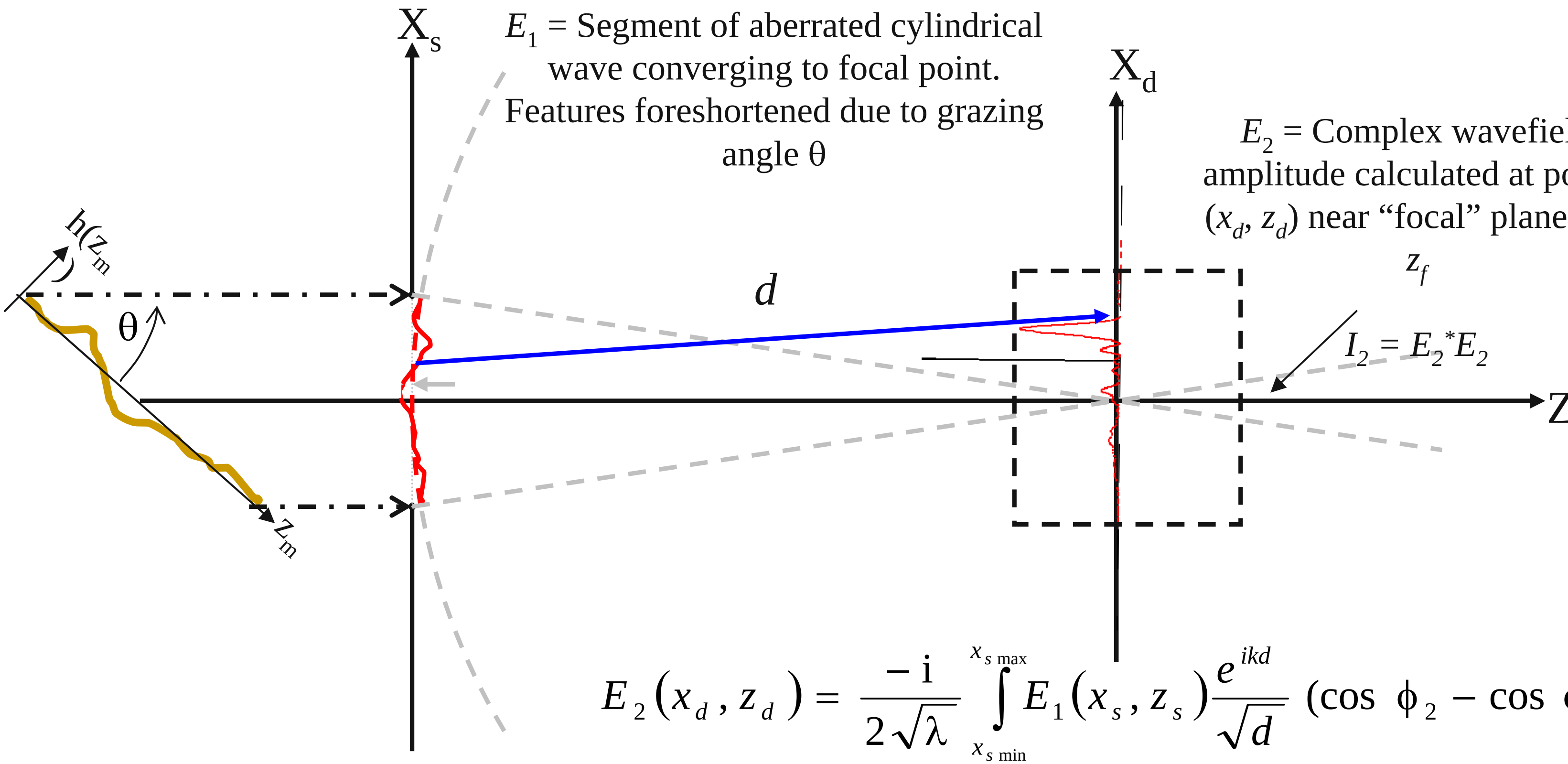
Metrology of high performance K-B mirrors: APS microinterferometer stitching system

- MicroXAM RTS microscope interferometer (KLA-Tencor Corp/ADE Division)
- Phase shifting monochromatic light interferometry at λ=550 nm (for supersmooth surfaces)
- 2-D area measurements
- Automated subaperture measurement and stitching capability
  - provide the large dynamic range and resolution needed for surface profile measurements of diffraction-limited K-B mirror
- Repeatability (R_q of difference map under identical conditions):
  - Single submap
    - *RMS < 0.038 nm* (2-D area measurements)*
  - Stitched data (56 mm long stitched maps):
    - *RMS<1nm, P-V <2.5 nm*

*Ref: ADE Phase Shift, Corp. specification data sheet.

Wave optics simulation of precisely figured X-ray K-B mirrors using metrology data

C.M. Kewish, L. Assoufid, A.T. Macrander, and J. Qian, *Appl. Opt.* 46, p.2010 (2007)

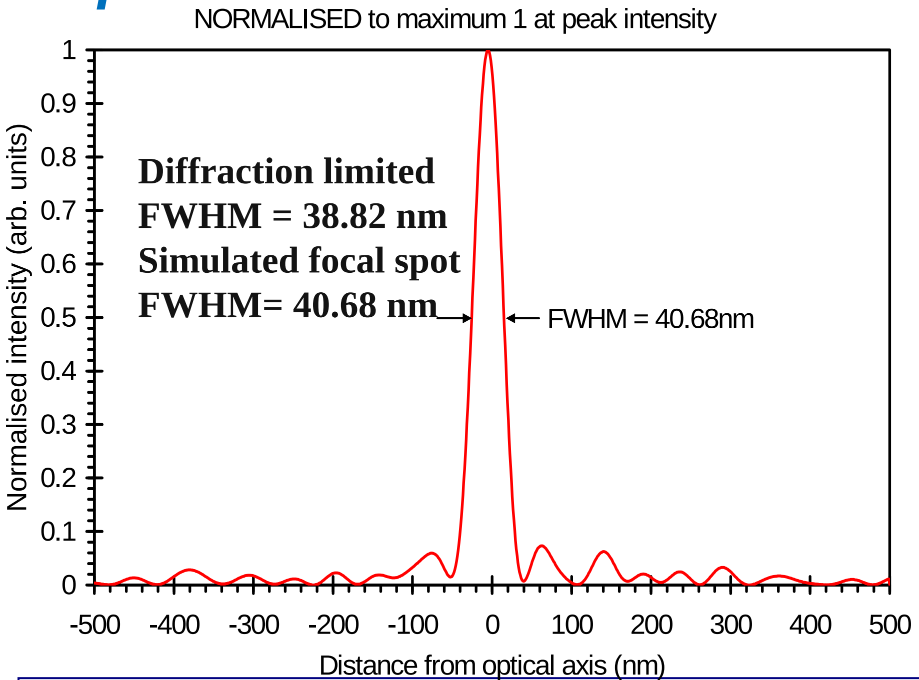


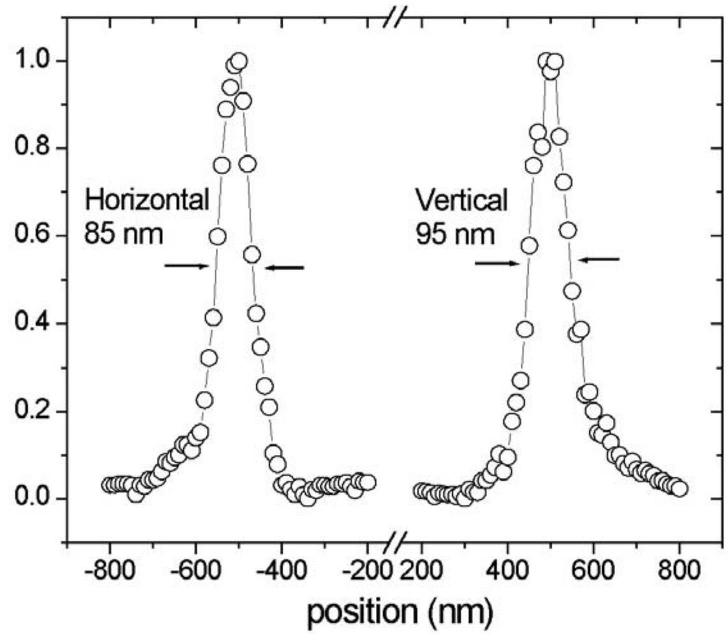
$$E_2(x_d, z_d) = \frac{-\mathrm{i}}{2\sqrt{\lambda}} \int_{x_{s\,\min}}^{x_{s\,\max}} E_1(x_s, z_s) \frac{e^{ikd}}{\sqrt{d}} (\cos\phi_2 - \cos\phi_1)\, \mathrm{d}x_s$$

Diagram not to scale

$$d = \sqrt{(x_d - x_s)^2 + (z_d - z_s)^2}$$

Au-coated K-B Mirror pair for the APS 34-ID Beamline: Simulated and measured normalized intensity and focal spot size





Vertical focusing mirror simulation results, using metrology data

C. M. Kewish, et al., *Appl. Opt.* **46**, p.2010 (2007).

Experiment results (@ APS 34-ID)

W. Liu, Gene E. Ice, J.Z. Tischler, A. Khounsary, C. Liu, L. Assoufid and A.T. Macrander, *Rev. Sci. Instrum.* **76**, p.113701 (2005).

Pt-profile-coated mirrors are being developed, and further beamline tests are being planned

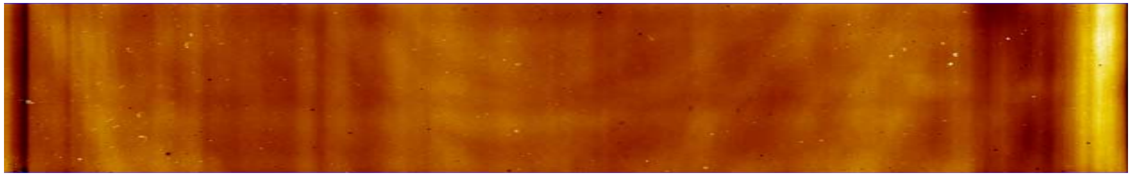
Fabrication and testing of a K-B mirror pair for the ESRF 13-ID beamline, in collaboration with the ESRF X-ray Optics Group

Design Parameters

Parameters	M1(VF)	M2(HF)
Size (mm)	40	25
Distance to source, s1 (m)	98	98
Distance to focus, s2 (mm)	77.5	7
Incidence angle (mrad)	3.9	3.7

The mirrors were fabricated at the APS by depositing an elliptical Au-profiled thin film on 50 mm flat Si substrates. They were cut to size (46 mm for the VF and 30 mm for the HF) after deposition.

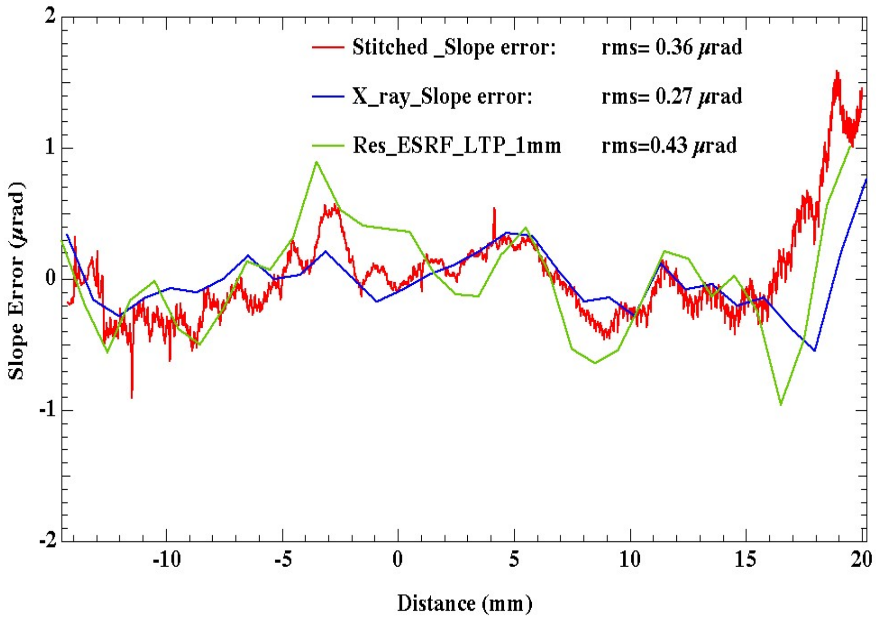
VF(M1) Mirror: Stitched map with the best fit polynomial shape removed

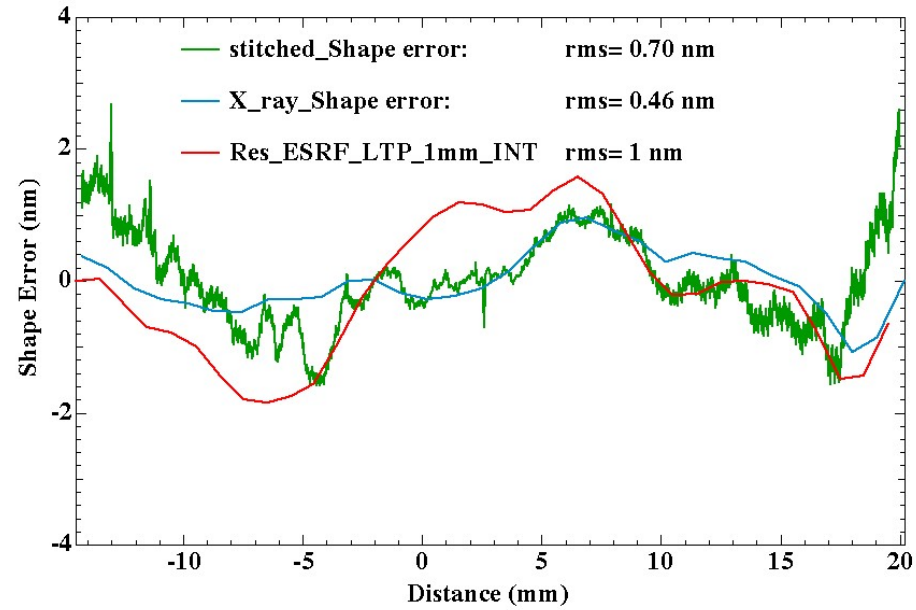


- Full aperture reconstruction required stitching of 2x12 submaps
- Each submap is 5mm x 5mm (2.5x objective lens)
- Overlap between adjacent submaps was 30%
- Size: ~7 mm x 43.5 mm (aperture length=40 mm)

Photos of HF mirror (top) and VF mirror (bottom)

Beamline testing at the ESRF ID-13 beamline––Comparison with stitching and LTP data of the vertical focusing mirror (M1)





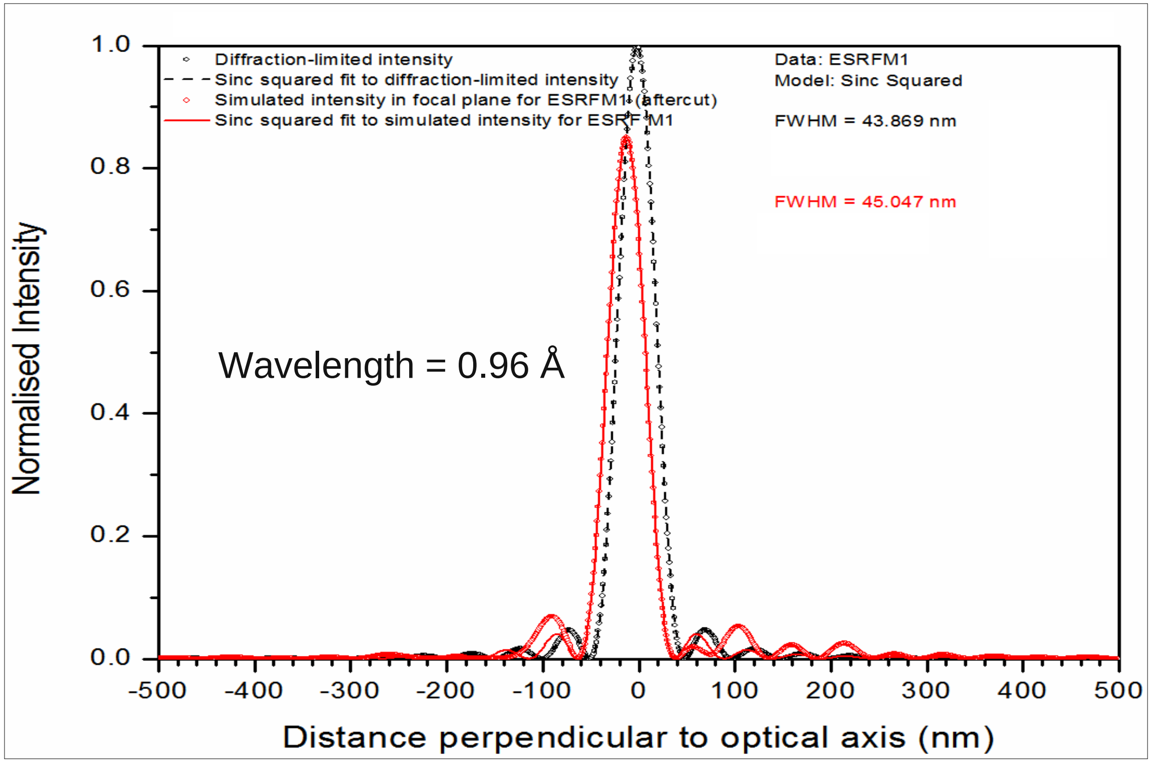
X-ray measurements done at ESRF ID-13 (98 m long) beamline (O. Hignette L. Assoufid, M. Burghammer)

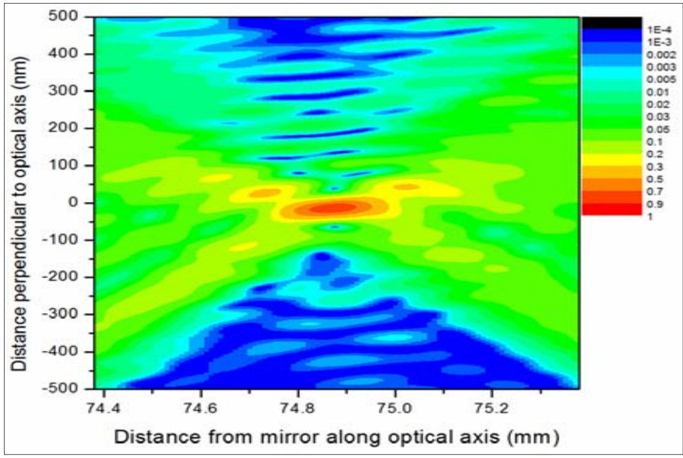
–Wavelength = 0.96 Å

ESRF LTP Data by A. Rommeveaux (ESRF x-ray optics group)

Parameter	Design Value	Metrology data fitting	
		LTP (ESRF)	Stitching (APS)
Distance to source, s1 (m)	98	98	98
Distance to focus, s2 (mm)	77.5	74.3	76.4
Incidence angle (mrad)	3.9	3.58	3.67

ESRF M1(VF) Mirror: performance prediction using wave optics simulation with microstitched data





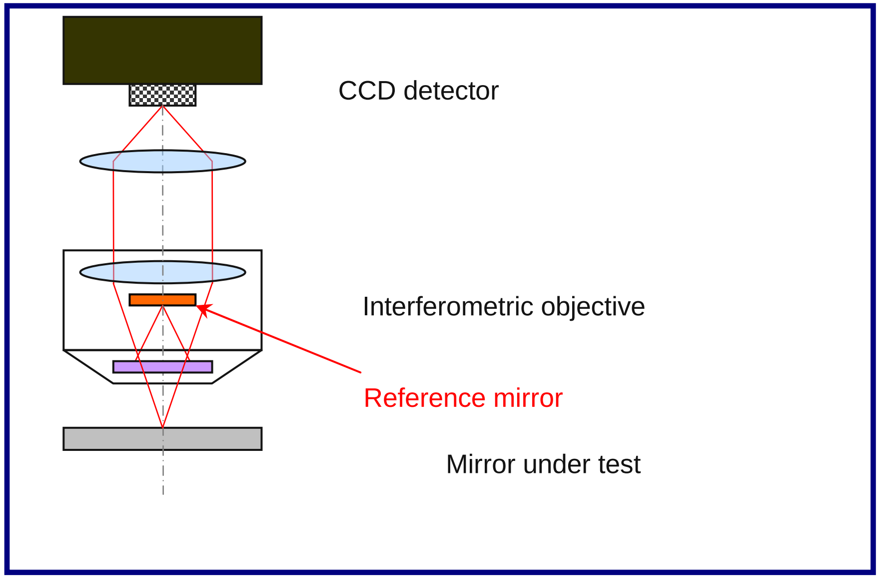
- Predicted FWHM = 45.05 nm. Diffraction limit: 43.86 nm.
- Measured spot size ~70-100 nm, which is larger thatnthe predicted spot size. This is believed to be largely due to structural vibrations of the setup.
- Further testing to be carried out at a later date, possibly on a Pt-coated K-B mirror pair.

Pt-profile-coated mirrors are being fabricated, and improvements to the beamline setup and testing procedure are underway at the ESRF.

Microinterferometer stitching system: Limitations and possible sources of errors

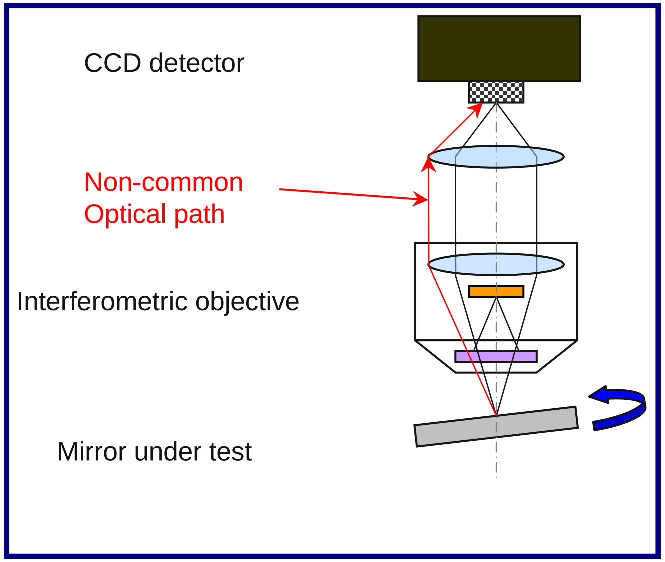
- Quality of the interferometer reference mirror
- Quality of calibration optic/reference map acquisition
- Modulation Transfer Function
- Focus errors (not so significant with 2.5x objective lens)
- Vibration (fringe printing): minimized by implementing phase correlated error correction
- Scanning stage errors (very small)
- Retrace errors

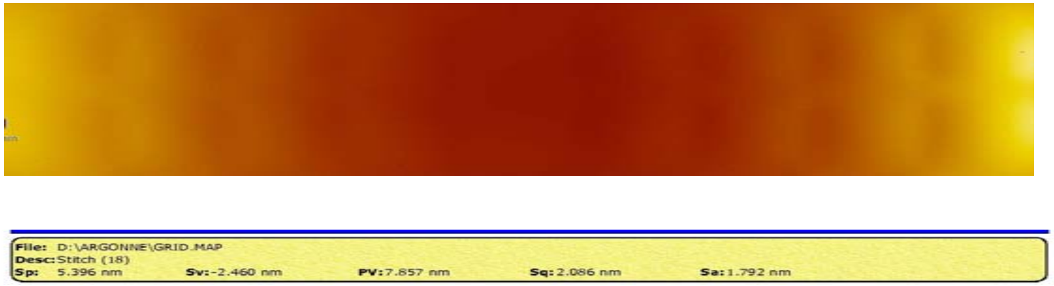
Mirau Objective



Effect of Retrace Errors and Their Correction

- Retrace errors originate from the test and reference wavefronts passing through the microscope's optical system along slightly different paths which then produces an optical path length variation. The spatial variation of optical path lengths is interpreted as a coma-type figure error with a magnitude that is proportional to the observed wavefront tilt.
- For elliptical mirrors, the tilt of each submap is changing as a function of position. This results in an overall curvature error if individual submaps are not corrected before stitching.

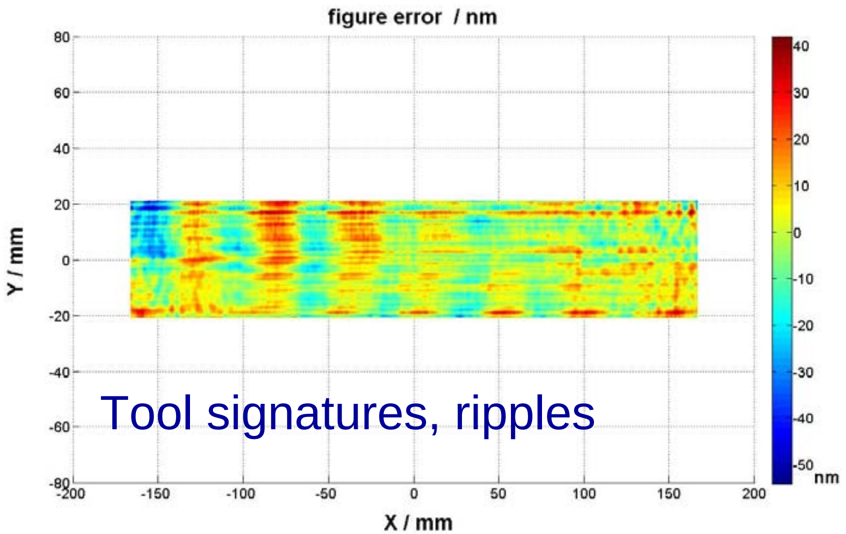


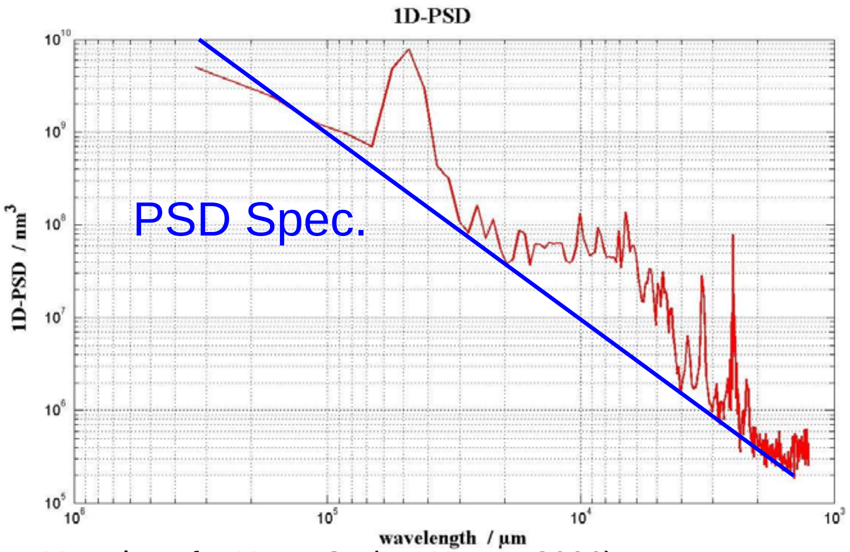


Difference between corrected and uncorrected maps shows that retrace error resulted in sag error of 7.85 nm.

Fabrication and metrology of coherence preserving mirrors

- Fabrication of coherence preserving mirrors will likely require deterministic/local polishing correction techniques



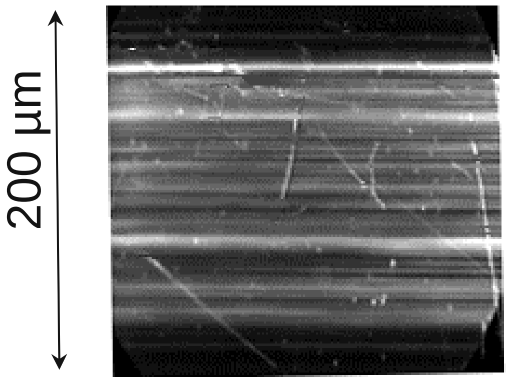


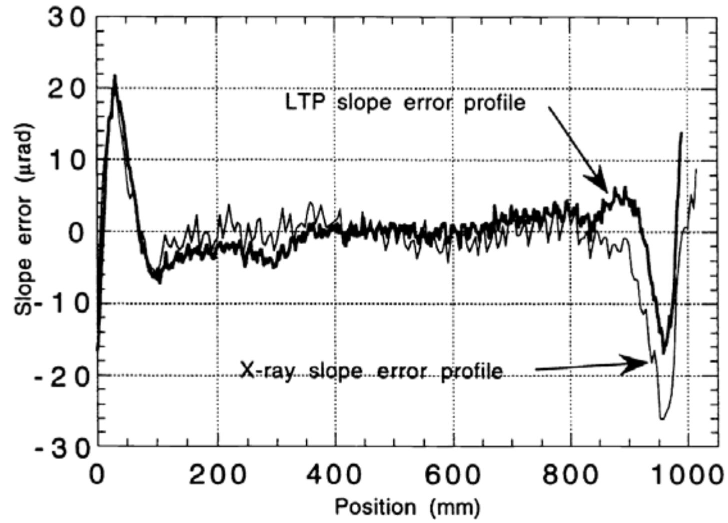
Courtesy A.Seifert, ZEISS (The 3rd International Workshop on Metrology for X-ray Optics, Korea, 2006)

- Local polishing tool produces medium- and short-length scale ripples
- Careful characterization of the optical surface at all spatial wavelength is essential (2D area metrology and stitching)
- Procedure for quality control of such mirrors has not been fully developed at a synchrotron radiation laboratory.

Importance of at-wavelength characterization of x-ray mirrors

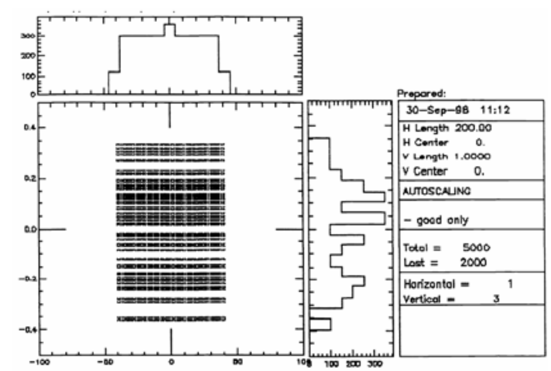
Although the mirror met the specs, x-ray CCD images of the mirror reflected beam revealed details not predictable by simply examining LTP data





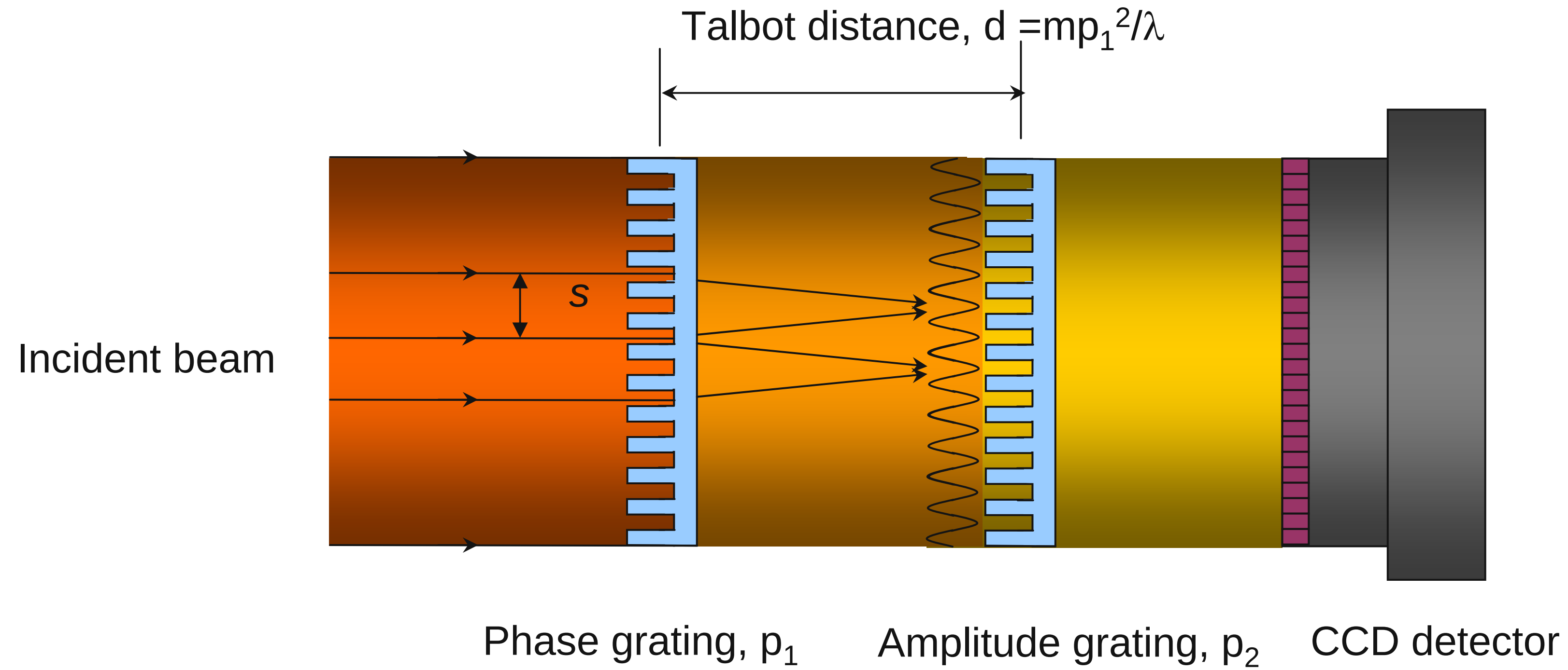
A CDD image of 10 keV x-ray beam reflected from the APS 1-BM VF mirror
(- Material: Zerodur coated
with Pt (750 Å)/Cr(50 Å)
- Length: 1.02 m
- Roughness: 3 Å rms
- Slope error: 4.9 µrad rms

L. Assoufid, J. Lang, J. Wang, G. Srajer, SPIE Vol. 3447 (1998), pp.106-116.



Shadow simulation using LTP data reveals a structured beam

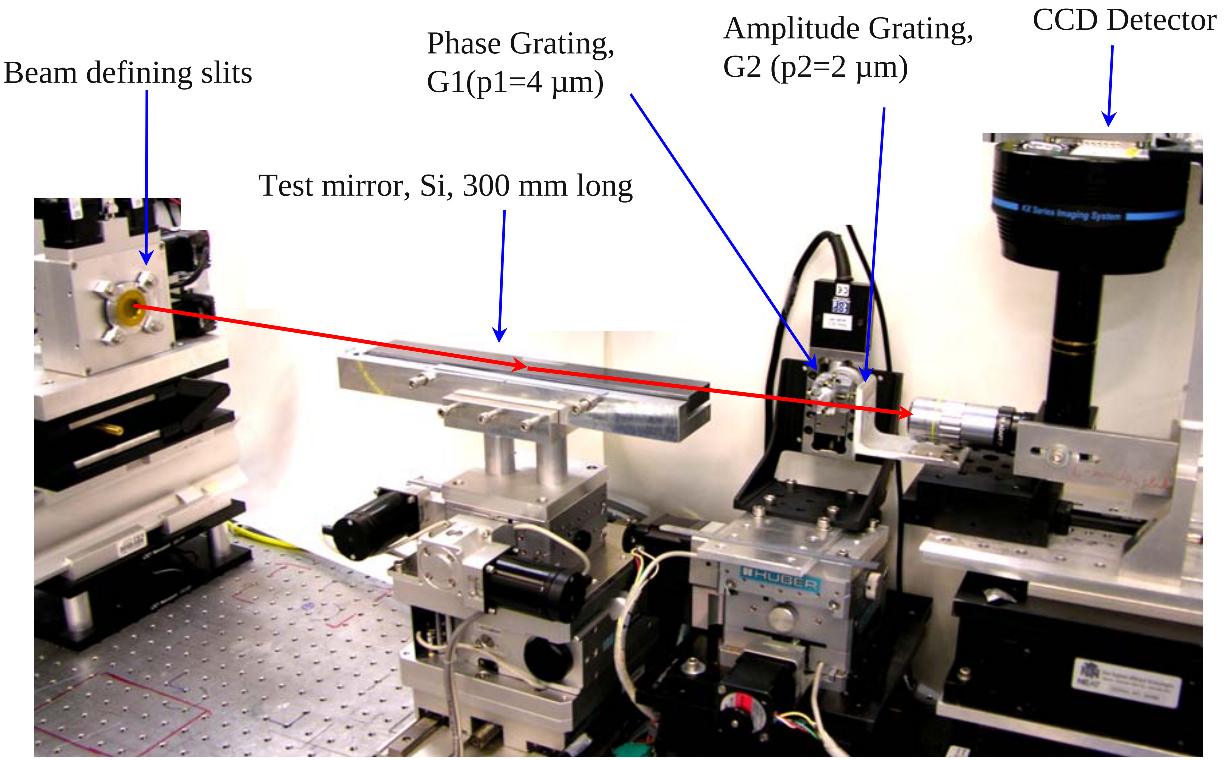
At-wavelength wavefront sensing and optics characterization: ***Use of an x-ray grating interferometer***



- Periodic **self-imaging** of diffraction grating
- Phase imaging: C. David et al. Appl. Phys. Lett., 81 (2002); Momose, Opt. Express 11 (2003).
- X-ray wavefront analysis and optics characterization: T. Weitkamp et al., Appl. Phys. Lett. 86, 054101 (2005).

Preliminary tests of an x-ray grating interferometer @ APS 8-ID beamline

(L. Assoufid, C. Rau, M. Sprung, A.Sandy)*



Unprocessed Moiré Fringe Pattern

The acquired Moiré fringe pattern was heavily affected by a contribution from the beamline Be windows. Further tests are to be carried out in the near future with an improved setup.

Summary

- Future sources such as NSLS-II, X-ray FELs, ERLs will provide beams with high spatial coherence. As as result, optical surfaces with much tighter tolerances will be required to fully preserve their beam characteristics.

- We are at a new transition in x-ray optics requirements: **New approaches have to be considered for both their fabrication and metrology.**

- Area metrology tools capable of characterizing an optical surface at all spatial frequencies with subnanometer accuracy are becoming essential.

- Metrology and quality control of coherence-preserving optics have yet to be developed. In this regard developing at-wavelength metrology techniques (x-ray interferometry, imaging, phase retrieval, etc.) may be essential. It is also key to validate new laboratory measurement tools as well as optics performance simulation codes. **Easy access to a suitable metrology beamline is highly desirable.**

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- Jun Qian (Metrology measurements)
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- Wenjun Liu (34-ID beamline)
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- Gene Ice (ORNL)
- John Tischler (XOR/UNICAT)
- C. Rau (now at Diamond-UK), M. Sprung, A. Sandy (8-ID beamline)

ESRF

- Olivier Hignette (X-ray Optics Group)
- Manfred Burghammer, Christian Riekel (ID-13 beamline)
- Amparo Rommeveaux (Metrology)

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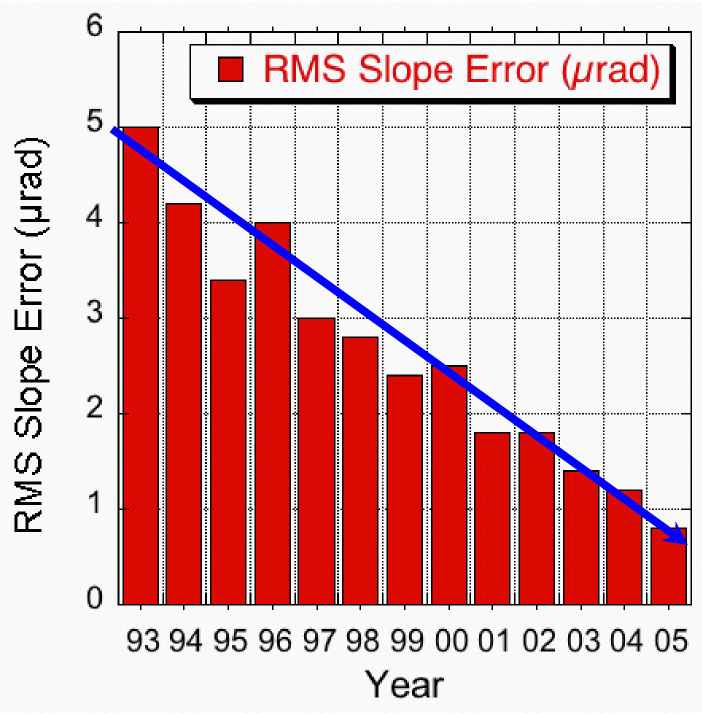
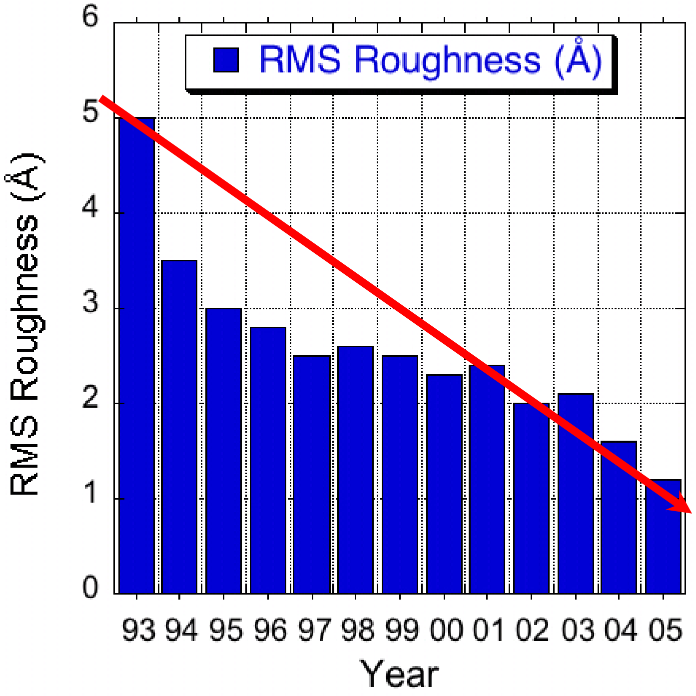
Evolution of surface quality of large hard x-ray mirrors during 1993-2005





- Compiled from APS, ESRF data (A. Rommeveaux) and SPring-8 (H. Ohashi)
- Mirror materials: Si, ULE Glass, Fused Silica, Zerodur (1 m or larger)
- Mirrors acquired from various vendors