Advanced Light Source Optical Metrology Laboratory (*brief overview*)

Valeriy V. Yashchuk

OPTICAL METROLOGY LABORATORY
EXPERIMENTAL SYSTEMS GROUP
ADVANCED LIGHT SOURCE
LAWRENCE BERKELEY NATIONAL LABORATORY

November 14, 2006

Outline

- *Introduction*
  - *'Who is who' at the ALS OML?*
  - *Mission of the OML and Overview of available instruments*
- *OML at the ALS: What can we do for our customers?*
  - *Answers via examples of real metrology with different instruments*
  - *Comparison with alternative metrology instruments*
  - *Some ways to improve ALS metrology and motivation for investments in ALS metrology*
- *Conclusions*

ALS OML Team and Collaborators

- **OML Team**

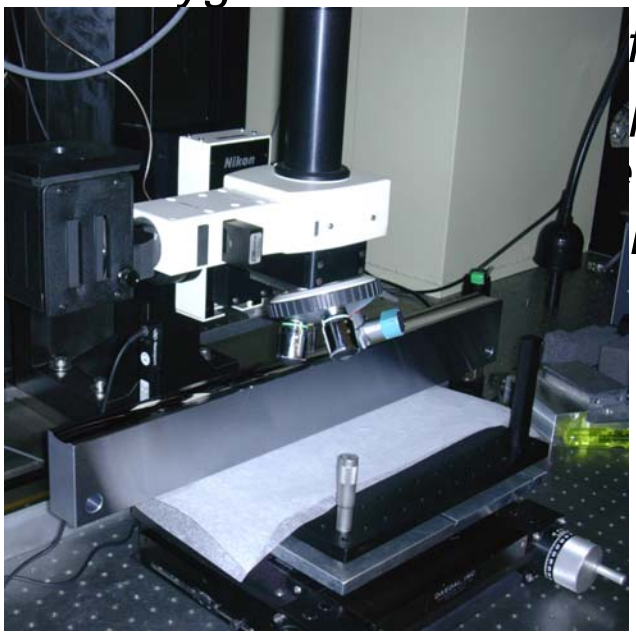
✓ Staff Scientists:	Valeriy Yashchuk	- leading the OML, method and instrumentation development
	Wayne McKinney	- analyzing software, scattering calculations
	Malcolm Howells	- theory
✓ Engineer:	Steve Irick	- routing metrology measurements
✓ Post Bachelor:	Jonathan Kirschman	- test measurements

- **OML collaborations**

✓ Eugene Church and Peter Takacs (BNL)	- metrology method and instrumentation development, scattering calculations, instrumentation test and calibration standards;
✓ Frank Siewert, Thomas Zeschke, and Tino Noll (BESSY)	- KB-mirror design, - Universal calibration mirror design, LTP development,
✓ Michael Schultz, Ralf Geckeler, Peter Thomsen-Schmidt, and Rolf Kruger-Sehm (PTB)	- LTP development, interferometric microscope test and calibration standard
✓ Daniele Cocco (ELETTRA)	- round robin LTP test
✓ ALS SSG and Tom Tonnessen (InSync)	- Mirror polishing and metrology, high quality test/calibration mirror
✓ World-wide	- establishing Virtual Optical Metrology Laboratory to unite efforts of metrologists of X-ray optics

ALS ESG Optical Metrology Laboratory: *Overview*

- ***Mission of the OML***
  - ✓ *Metrology of surface figure and finish of X-ray optics*
  - ✓ *Bending mirror adjustment, characterization, and calibration*
  - ✓ *Evaluation of beamline performance*
  - ✓ *General metrology and tests*
- ***Metrology instrumentation at the OML***
  - ✓ *Micromap™-570 interferometric microscope*
  - ✓ *Zygo™ GPI 6-in interferometer*



filer

pler Vibrometer

t-up

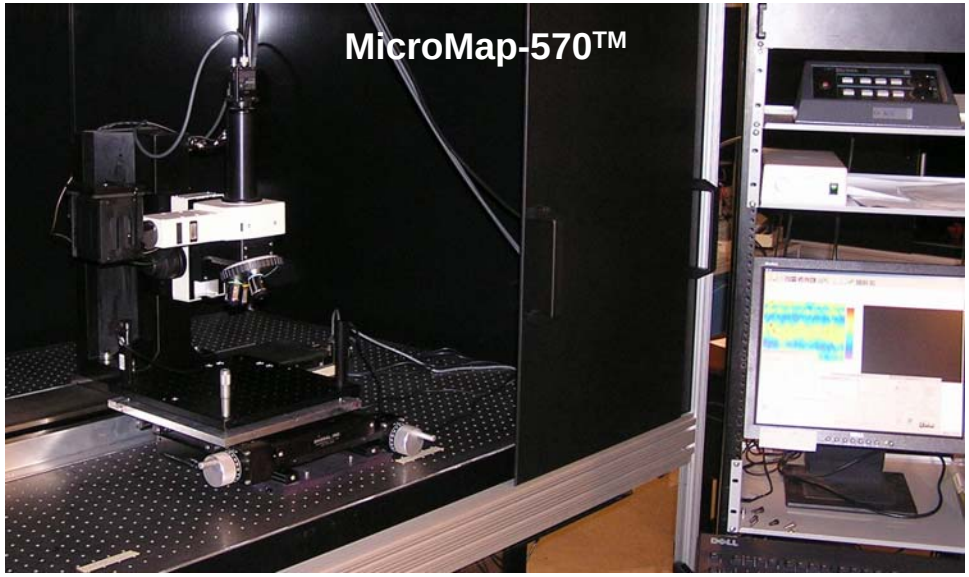
interferometers, c

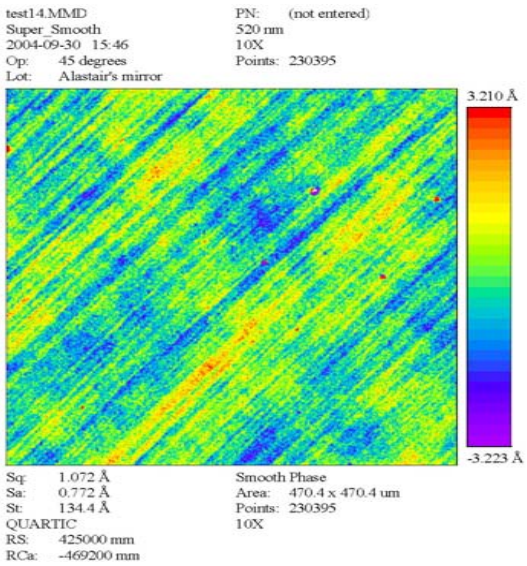
Outline

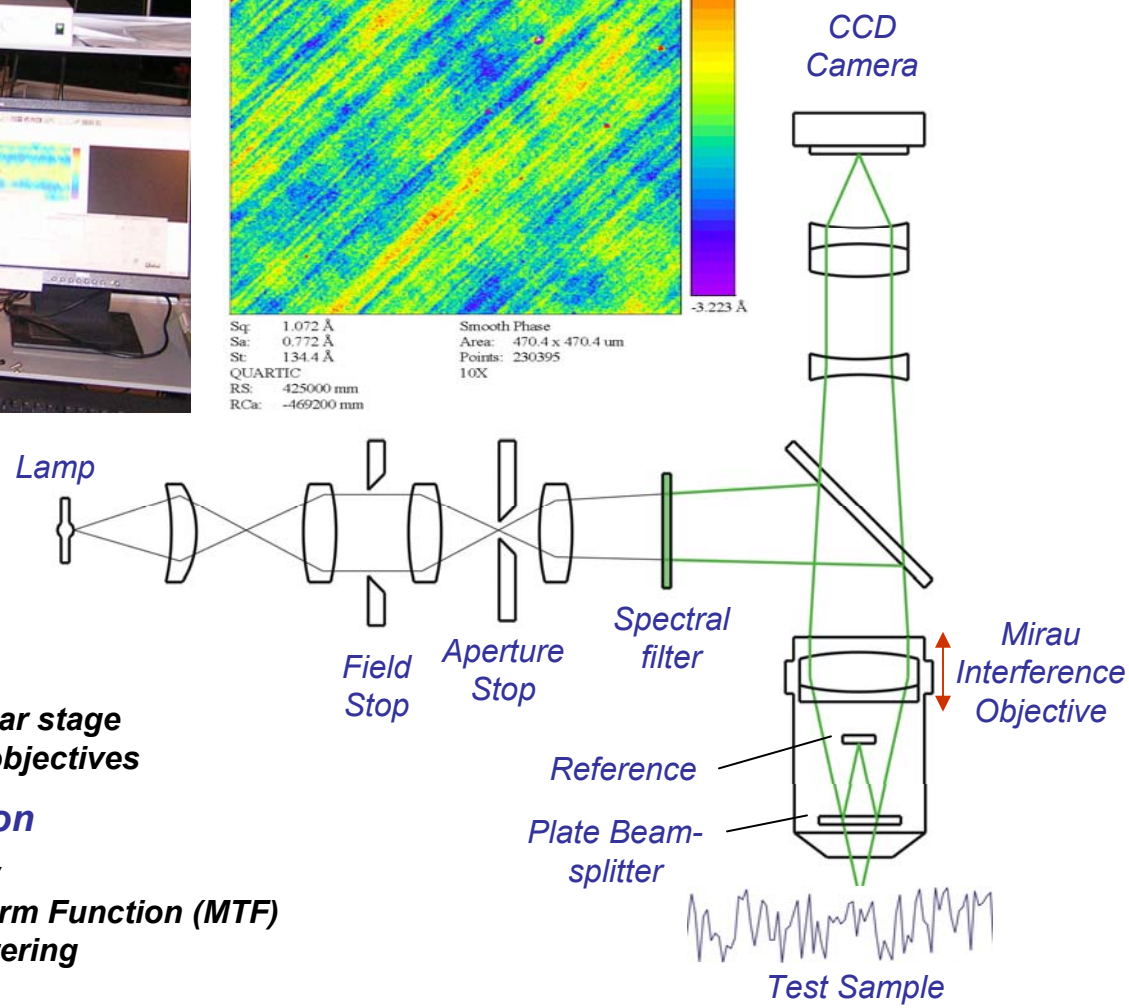
- *Introduction*
  - *'Who is who' at the ALS OML?*
  - *Mission of the OML and Overview of available instruments*
- *OML at the ALS:* ***What can we do for our customers****?*
  - *Answers via examples of real metrology with different instruments*
  - *Comparison with alternative metrology instruments*
  - *Some ways to improve ALS metrology and motivation for investments in ALS metrology*
- *Conclusions*

MicroMap-570™ interferometric microscope

Surface characterization at higher spatial frequency





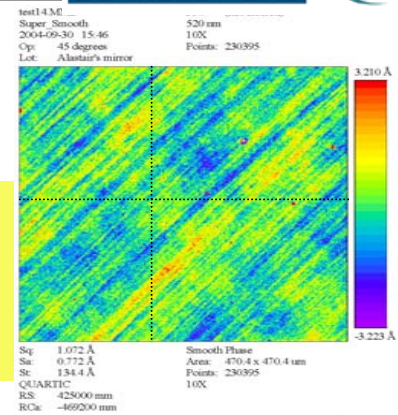


Developments:

- ***Improvement of environmental and operational conditions***
  - ✓ ***Vibration-isolated optical table***
  - ✓ ***Dust-protected, ventilated hutch***
  - ✓ ***Easy movable arrangement with a linear stage***
  - ✓ ***Cleaning and re-aligning 2.5x and 5x objectives***
- ***Power spectral density (PSD) evaluation***
  - ✓ ***Correction of the read-out asymmetry***
  - ✓ ***Accounting of the Modulation Transform Function (MTF)***
  - ✓ ***Cross-check with AFM and X-ray scattering***

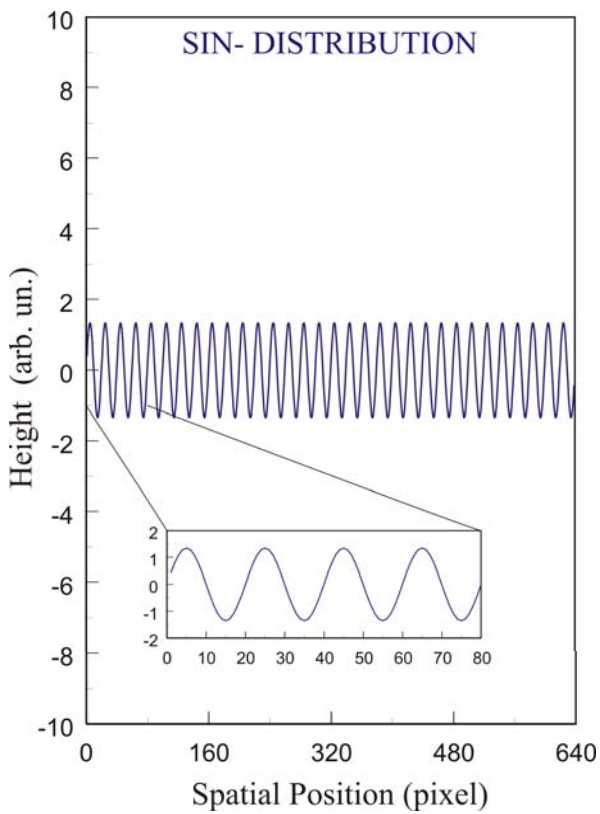
Limitations of "One number" Statistical X-ray optical metrology

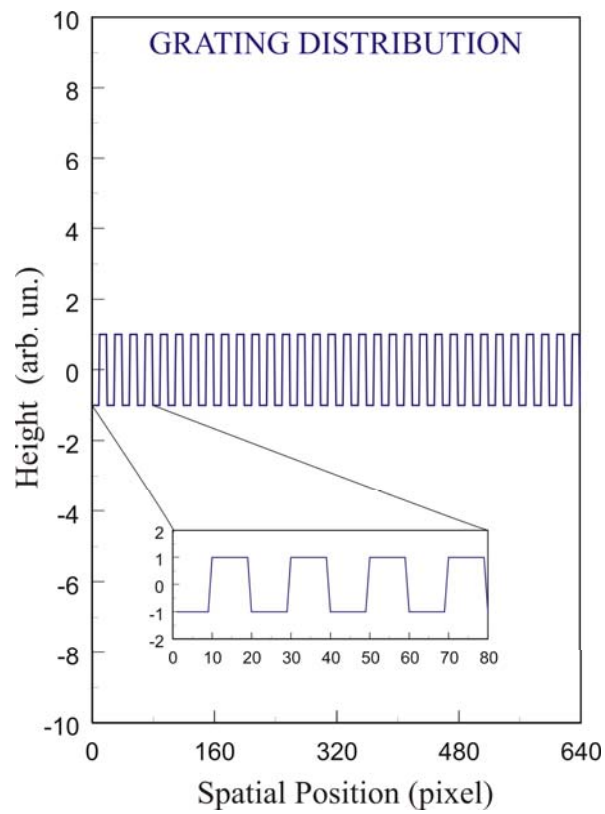
Roughness (rms): $$R_{RMS} \approx \left[\frac{1}{N} \sum_{n=1}^{N} (h_n - \hat{h})^2 \right]^{1/2}$$

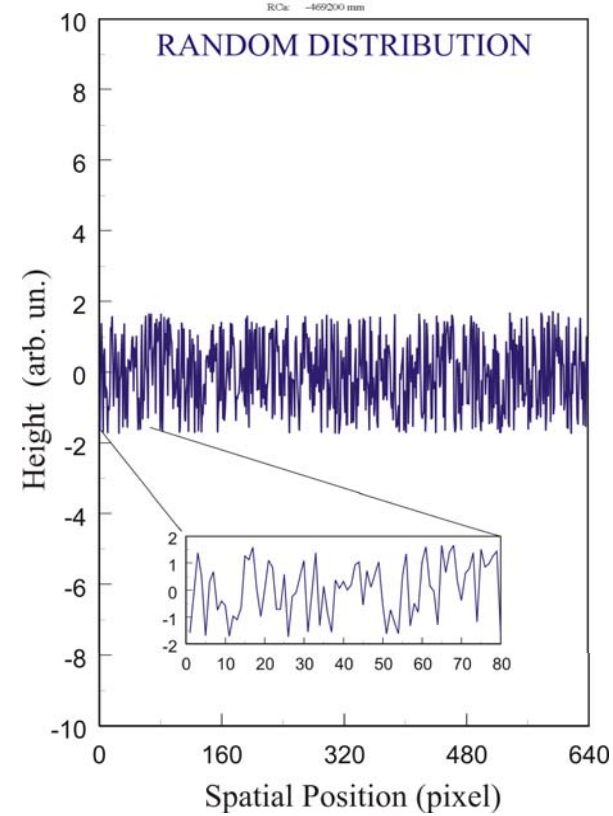


For all these cases the roughness value is the same!

The two-dimensional sketches show the need for at least two parameters. One is vertical (roughness) and one is horizontal (wavelength).

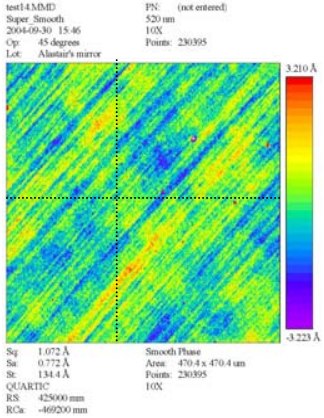






Two-dimensional Power Spectral Density (PSD)

The 2D PSD function may be viewed as a Fourier decomposition of the 2D surface height distribution into harmonic basis functions:



$$S_2(u,v) = \lim_{A\to\infty} \left\langle \frac{1}{A} \left| \int_{-L_y/2}^{L_y/2} dy \int_{-L_x/2}^{L_x/2} h(x,y)\, e^{-2\pi i(ux+vy)} dx \right|^2 \right\rangle$$

L_x and L_y are the tangential and sagittal dimensions of the measured surface region, A; u and v are the spatial frequency variables corresponding to the tangential, x, and sagittal, y, coordinates.

In the case of discrete measurements, 2D PSD distribution can be evaluated from

$$S_2(l,k) = M\ N\ \Delta x\, \Delta y \left| F_{l,k} \right|^2; \qquad F_{l,k} = \frac{1}{M} \sum_{m=0}^{M-1} \left[\exp\left(\frac{-2\pi i\, m l}{M} \right) \frac{1}{N} \sum_{n=0}^{N-1} h_{m,n} \exp\left(\frac{-2\pi i\, n k}{N} \right) \right]$$

M and N are the number of pixels and Δx and Δy are the pixel dimensions in the tangential and sagittal directions, respectively; $F_{l,k}$ are the elements of the Fourier transform matrix

One-sided (positive frequency only) 1D PSD distribution can be evaluated from the 2D PSD:

Tangential: $S_1(k) = 2\, g(k) \sum_l S_2(l,k)$

Sagittal: $S_1(l) = 2\, g(l) \sum_k S_2(l,k)$

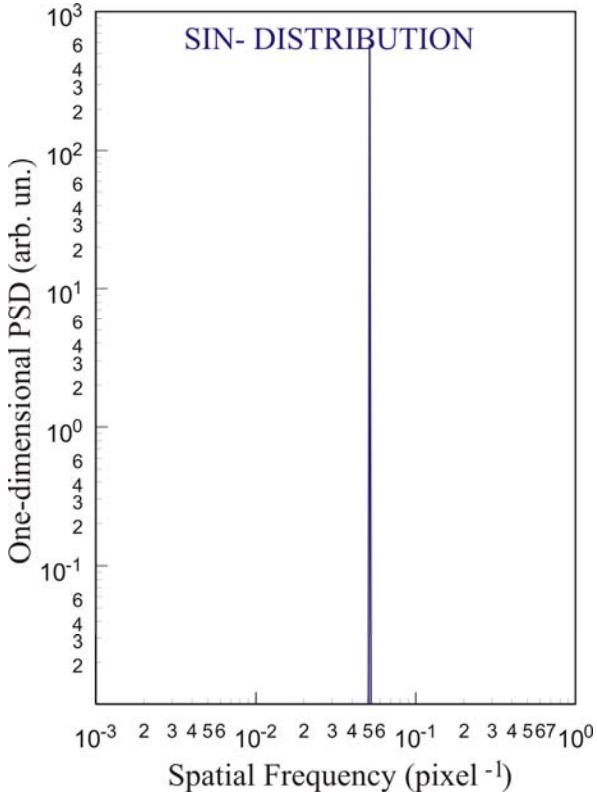
$$\begin{cases} 0 \le l \le M/2, \quad 0 \le k \le N/2, \\ g(l) = 1/2 \quad at \quad l = 0,\ M/2, \\ g(k) = 1/2 \quad at \quad k = 0,\ N/2, \quad and \\ g(l) = 1 \quad and \quad g(k) = 1 \quad otherwise \end{cases}$$

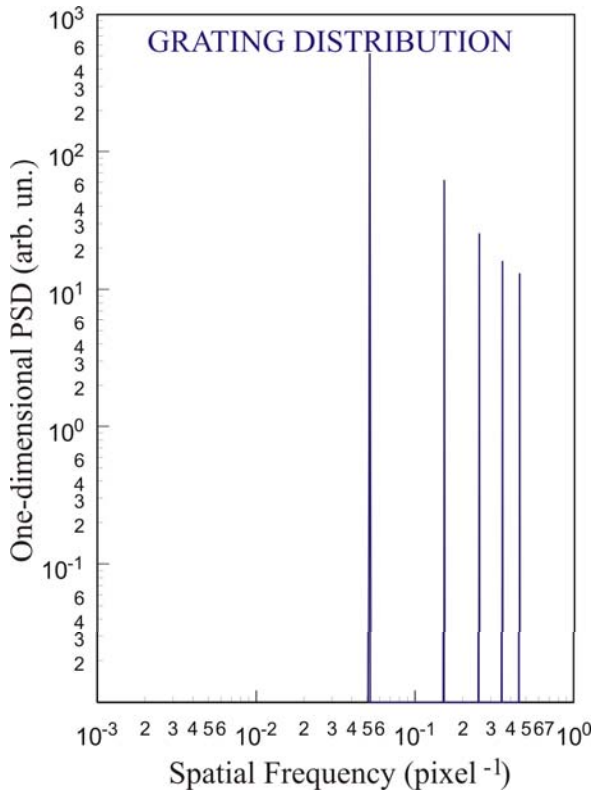
J.C. Stover, *Optical Scattering: Measurement and Analysis (second ed., Bellingham, 1995)*

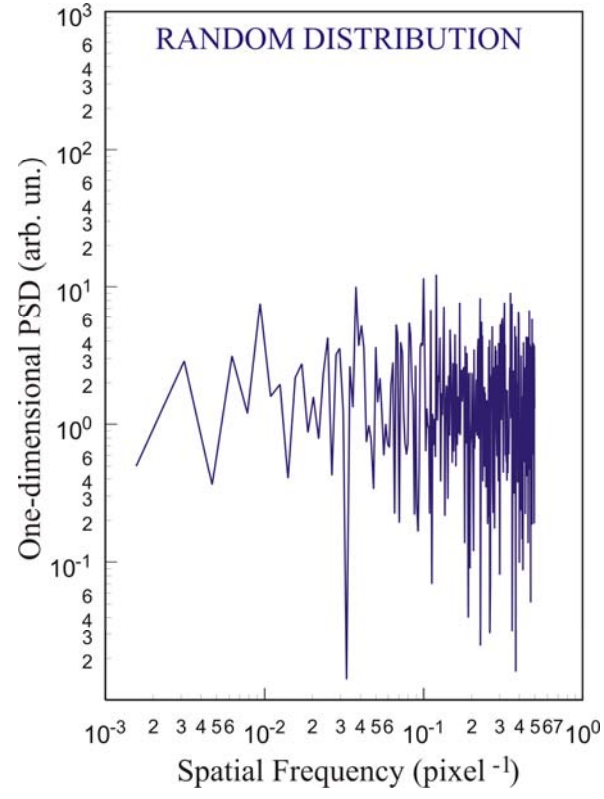
PSD-based X-ray optical metrology

Roughness (rms): $R_{RMS} \approx \left[\sum_{i=1}^{I} S_1(f_i)\Delta f_i \right]^{1/2}$

The roughness value is the same. But the PSD spectra are different!







PSD contains more essential information on surface properties

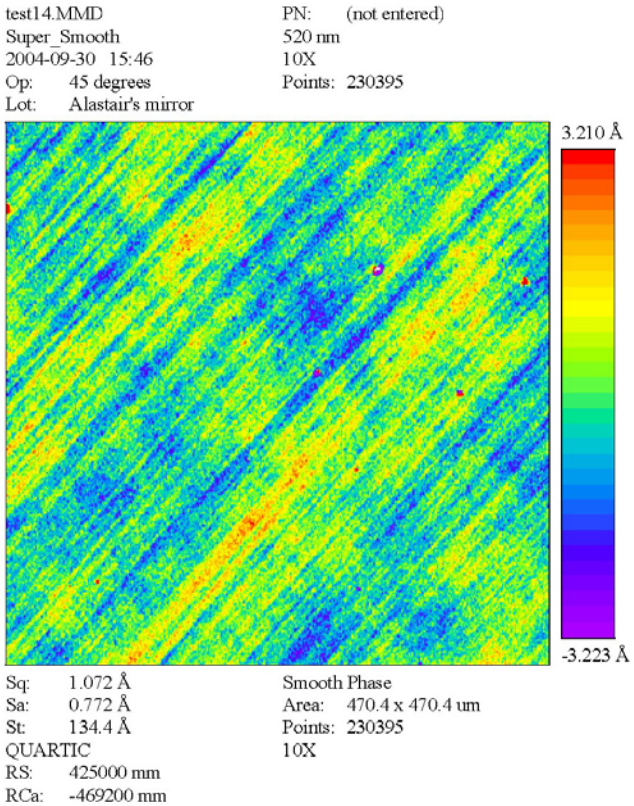
$$S_{MEASURED}(u,v) = S_{SURFACE}(u,v) \cdot MTF^2(u,v)$$

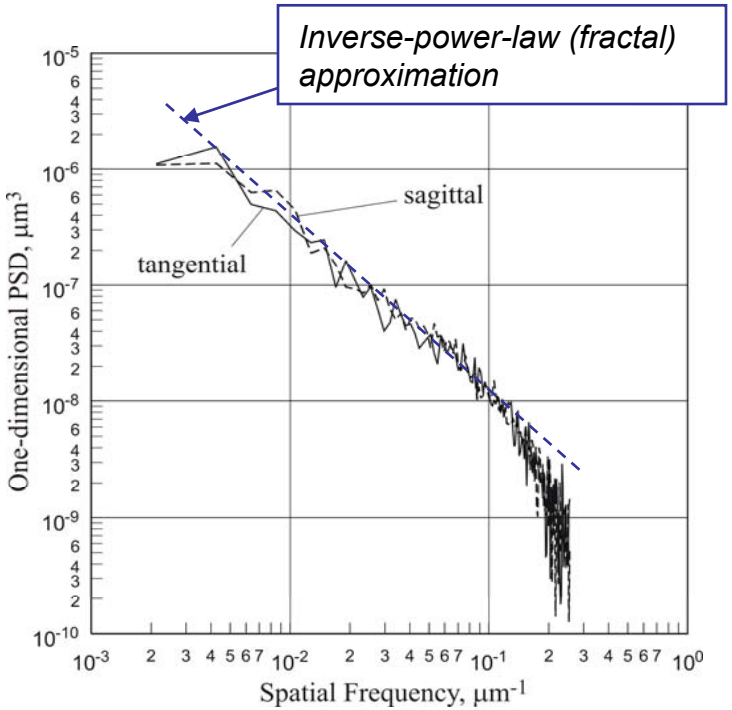
- possibility for calibration

1D and 2-D PSD measurements with a smooth surface

MicroMap measurement with a super-polished crystal silicon mirror

Super smooth mode





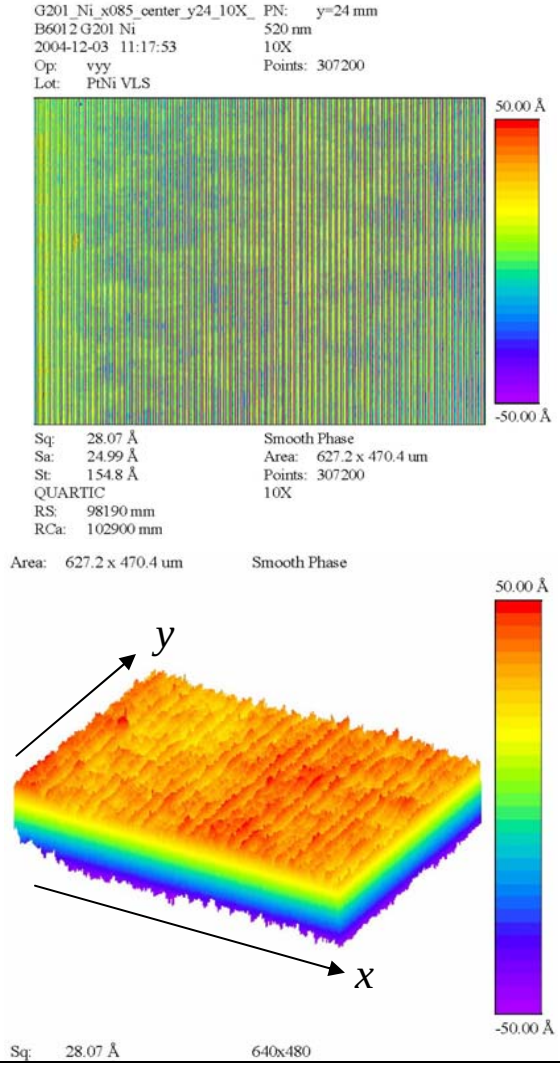
Reliable PSD measurement at higher spatial frequency ranges requires correction for the instrument Modulation Transfer Function (MTF). Standard test surfaces and MTF calibration and correction procedures have to be developed.

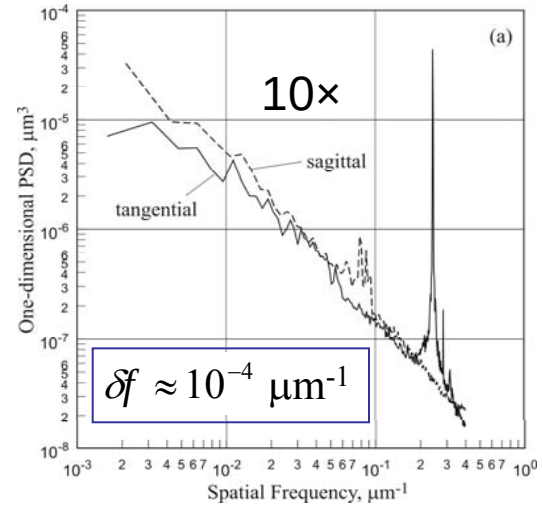
V. V. Yashchuk, A. D. Franck, S. C. Irick, M. R. Howells, A. A. MacDowell, W. R. McKinney, *Two dimensional power spectral density measurements of X-ray optics with the Micromap interferometric microscope,* SPIE Symposium on Optical Metrology 2005, part of LASER2005, World of Photonics , SPIE Proceedings 5858, pp. 58580A-1-12 (Munich, Germany, 12-17 June 2005).

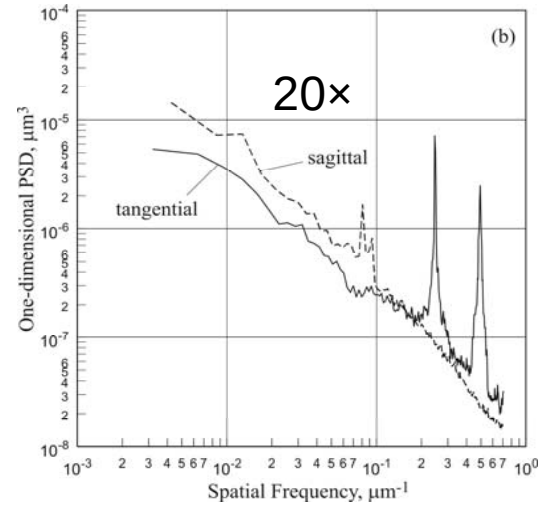
V. V. Yashchuk, E. M. Gullikson, M. R. Howells, S. C. Irick, A. A. MacDowell, W. R. McKinney, F. Salmassi, T. Warwick, J. P. Metz, and T. W. Tonnessen, *Surface Roughness of Stainless Steel Mirrors for Focusing Soft X-rays,* Applied Optics 45(20), OT-65462 (2006)

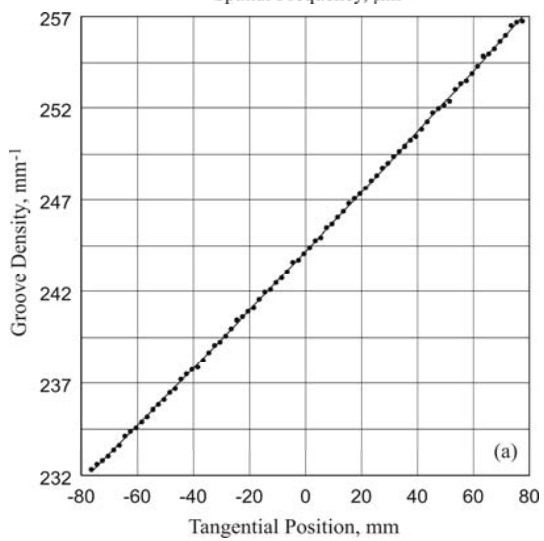
PSD measurements at higher spatial frequencies

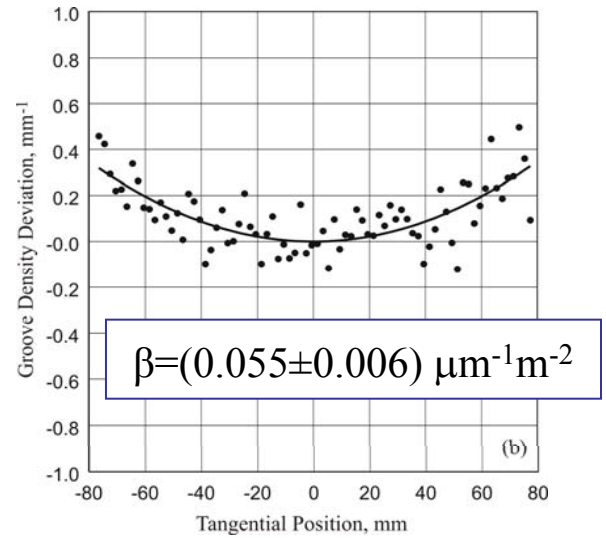
MicroMap™ measurements with X-ray grating with variable groove density







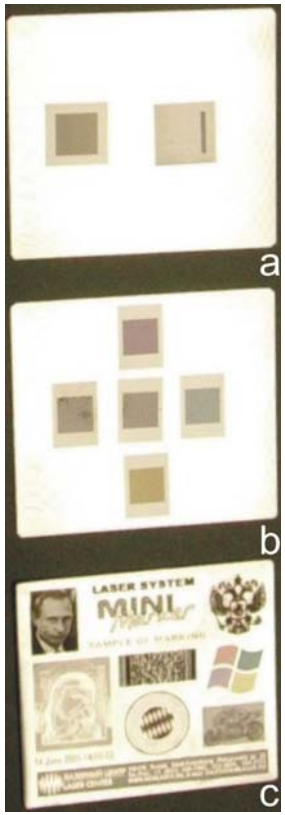




V. V. Yashchuk, A. D. Franck, S. C. Irick, M. R. Howells, A. A. MacDowell, W. R. McKinney, *Two dimensional power spectral density measurements of X-ray optics with the Micromap interferometric microscope,* SPIE Symposium on Optical Metrology 2005, part of LASER2005, World of Photonics , SPIE Proceedings 5858, pp. 58580A-1-12 (Munich, Germany, 12-17 June 2005).

MicroMap performances and limitations

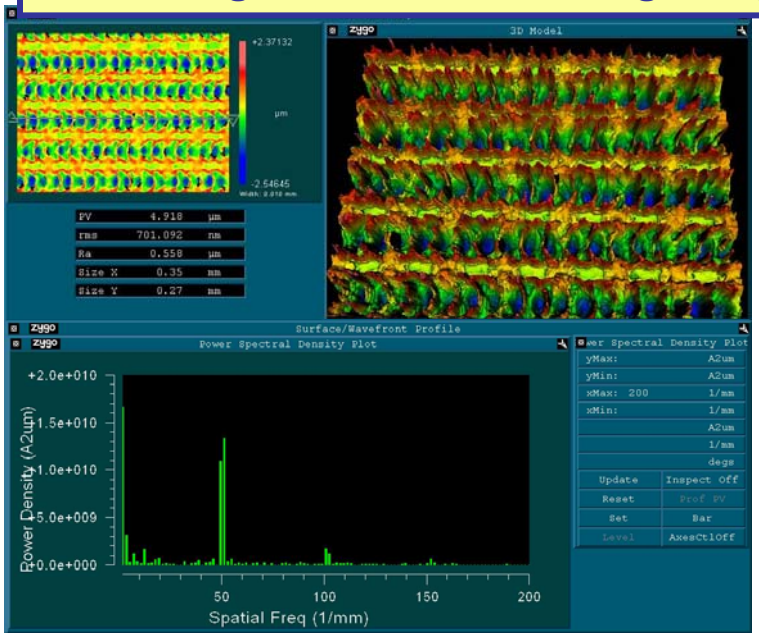
Laser-etched test patterns



a – Test pattern used for the cross-test of the instruments;
b – test plate with set of patterns different in spot and line separation;
c – demonstration patterns produced by the Laser Center Ltd (St. Petersburg, Russia).

ZYGO NV6 ... significantly rough ... mplitude

New interferometer for stitching…



Height variation (rms):

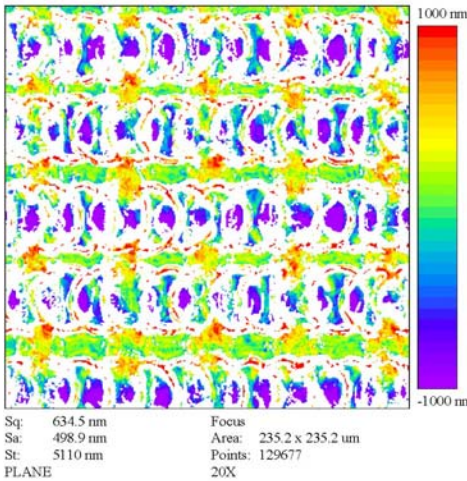
ZYGO: 0.70 µm
MMap: 0.63 µm

Peak-to-valley Height variation :

ZYGO: 4.9 µm
MMap: 5.1 µm

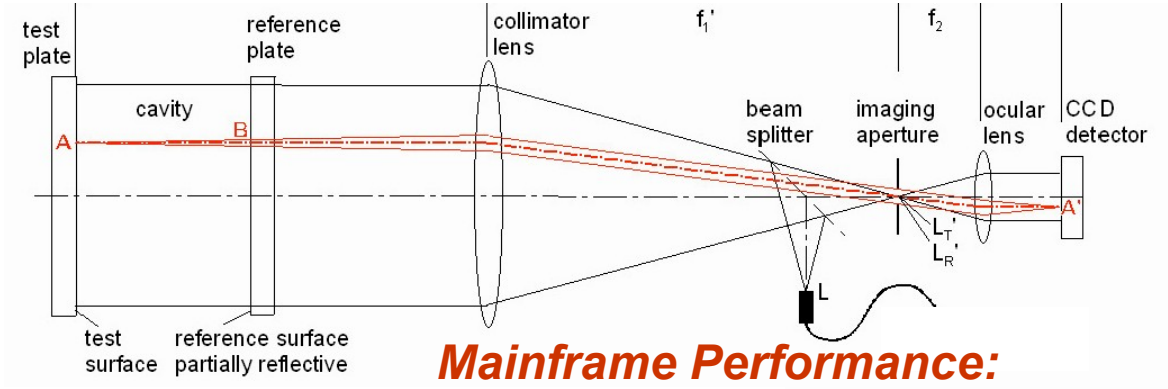
Specified height resolution:

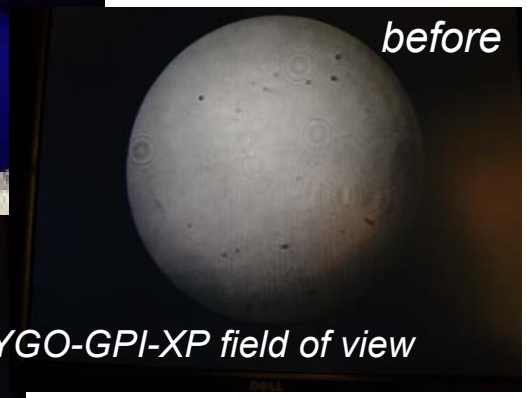
ZYGO: 0.5 Å
MMap: 0.5 Å



ZYGO-GPI™ interferometer

Surface characterization at lower spatial frequency





ZYGO-GPI-XP field of view

Mainframe Performance:

- ***Aperture:*** ***150 mm***
- ***Wavelength:*** ***543.5 nm (He-Ne)***
- ***Accuracy:*** ***λ/100 PV ≈ 5.4 nm***
- ***Repeatability of PV:*** ***λ/300 PV ≈ 1.8 nm***
- ***Spatial Sampling:*** ***640 x 480 pixels***
- ***Digitization:*** ***8 bits***

Improvements:

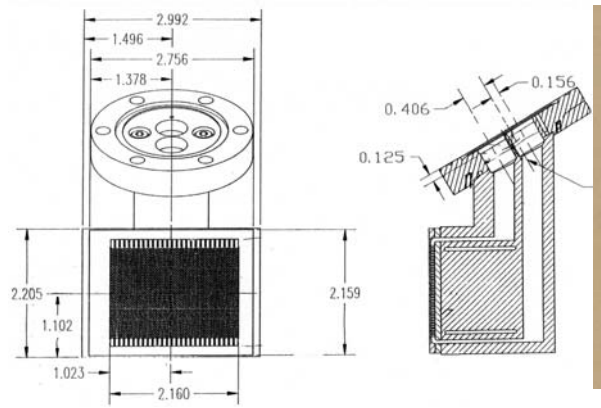
- ✓ ***Beam-splitter upgrade***
- ✓ ***Off-site service for cleaning and software updating***
- ✓ ***Laser replacement***

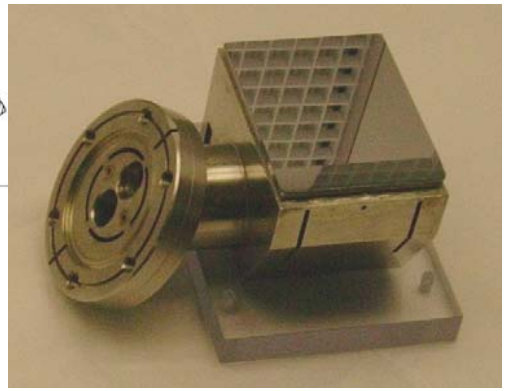
Limitations:

Air turbulence
Unfriendly Software!
Old computer (~ $12K to replace)

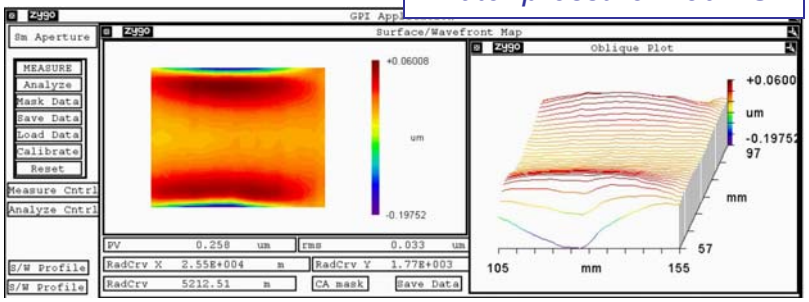
Water-pressure test with ZYGO-GPI™ interferometer

Prospective M1 mirror at BL 9.0.1 with a Silicon pin-post water cooling system

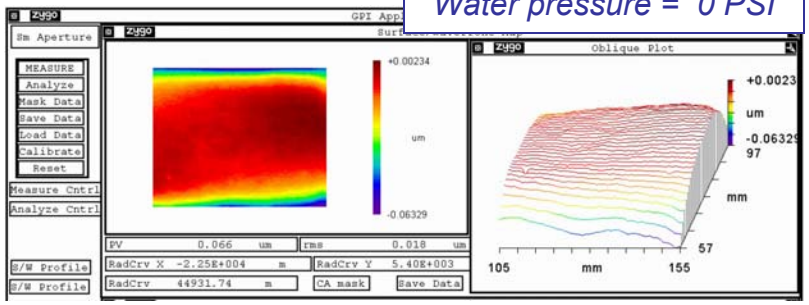


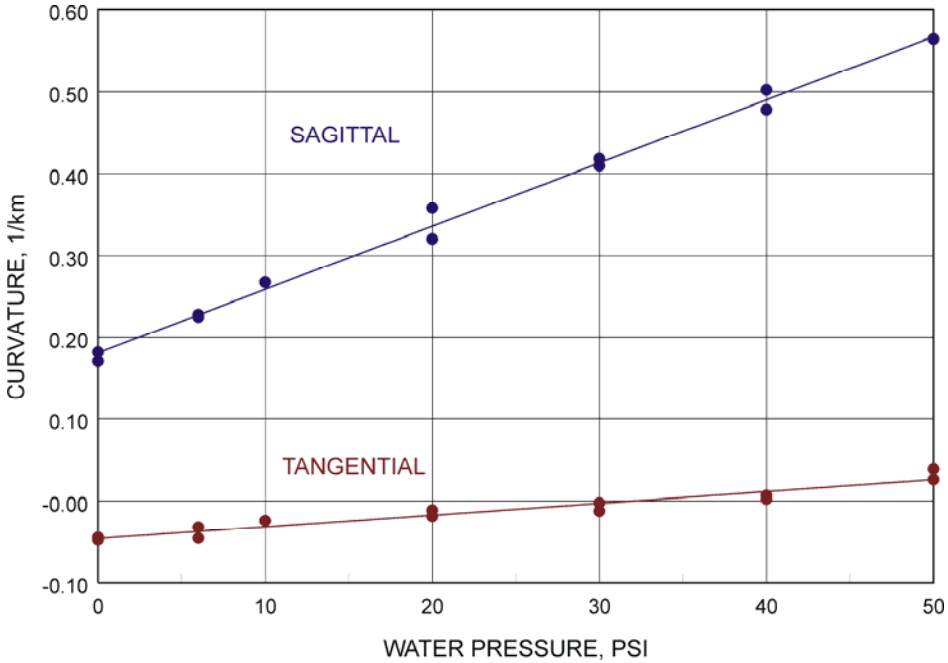


Water pressure = 50 PSI

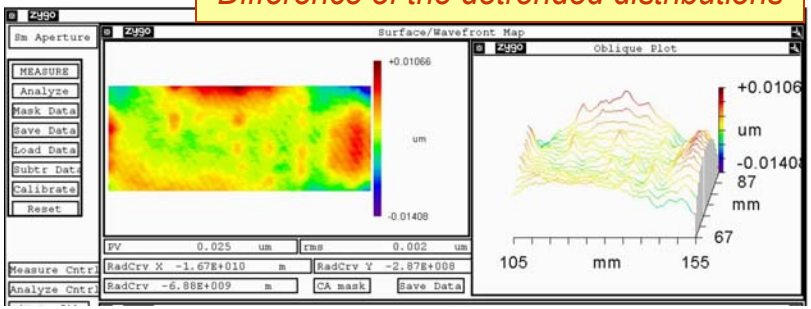


Water pressure = 0 PSI





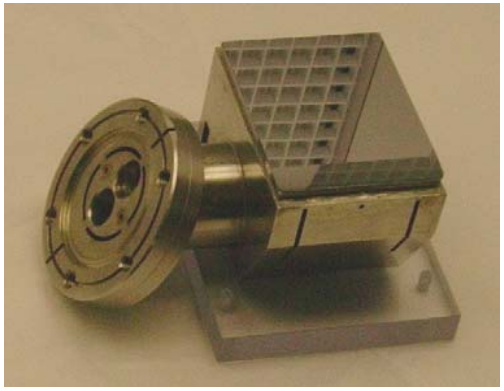
Difference of the detrended distributions

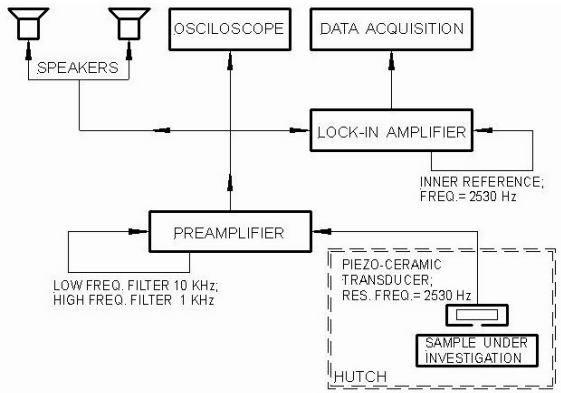


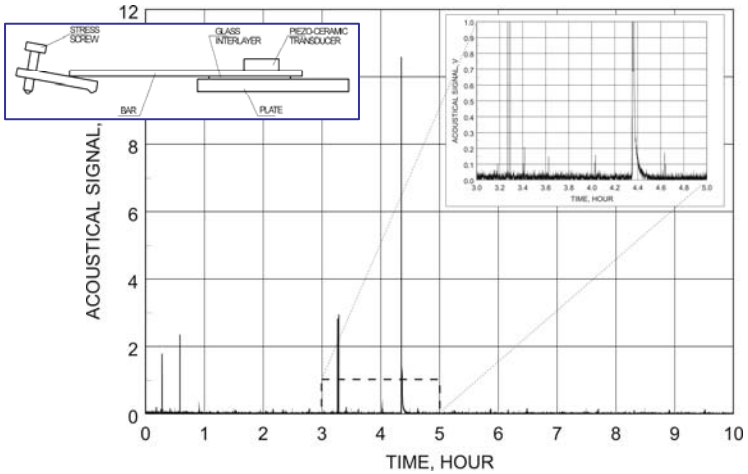
Water-pressure test

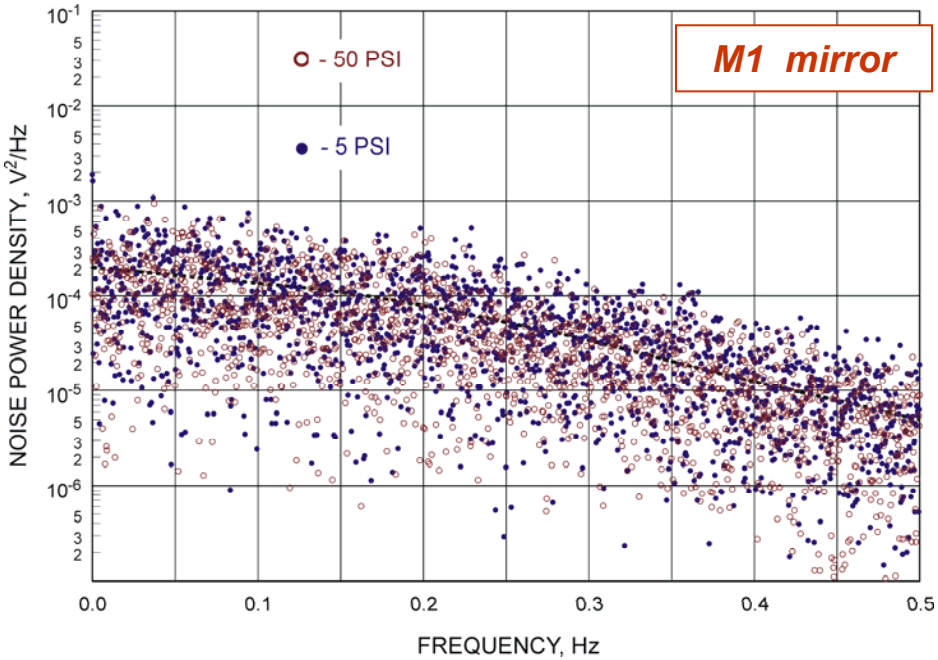
Acoustic noise measurements searching for cracks

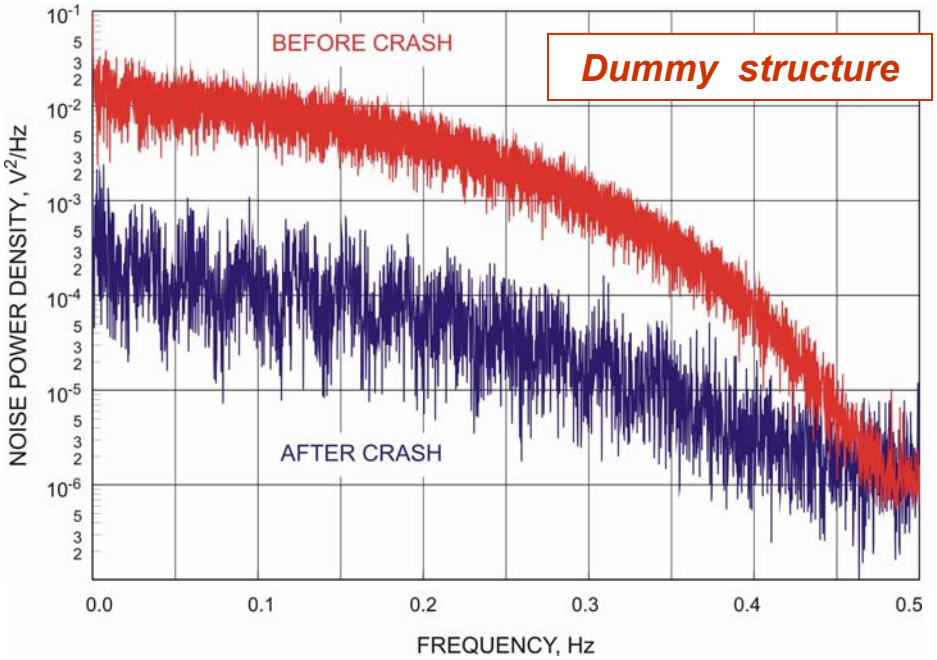
Prospective M1 mirror at BL 9.0.1 with a Silicon pin-post water cooling system





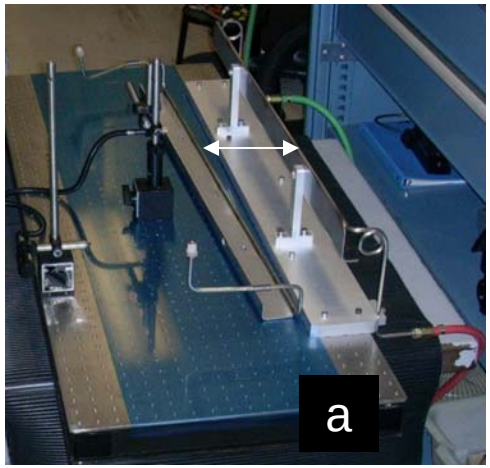


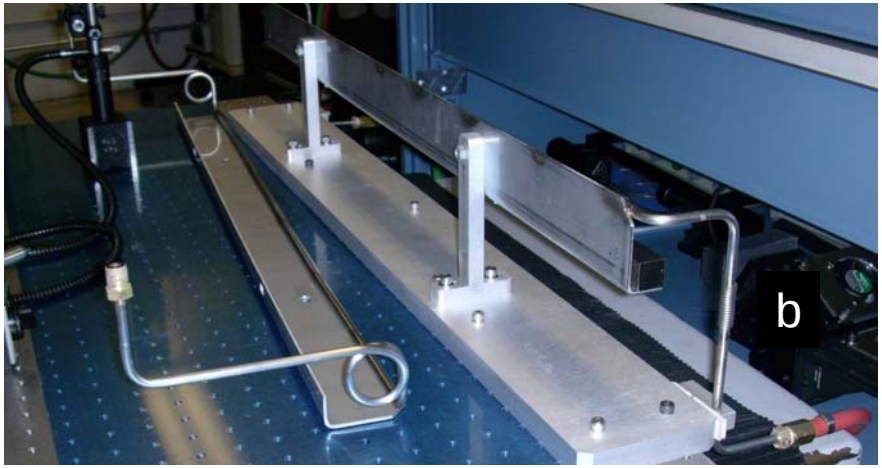


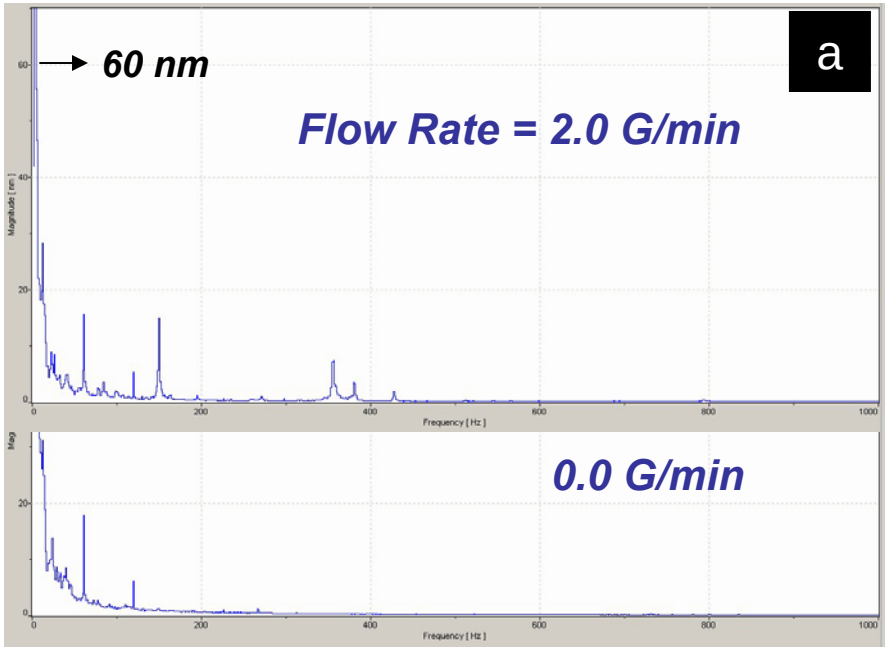


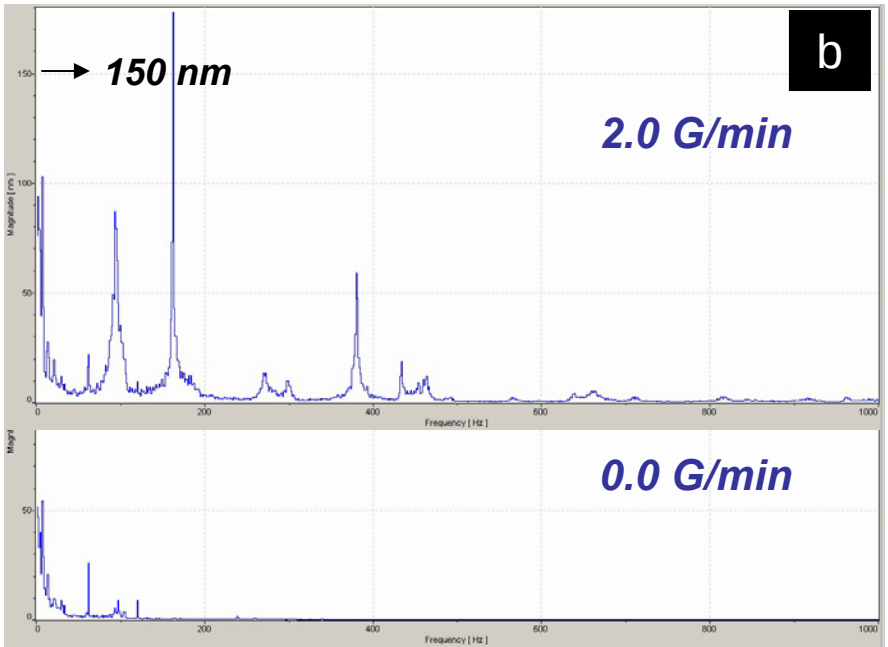
Measurement of vibrations with Polytec™ laser Doppler vibrometer

Vibrations of two mechanical structures equipped with a water cooling pipe







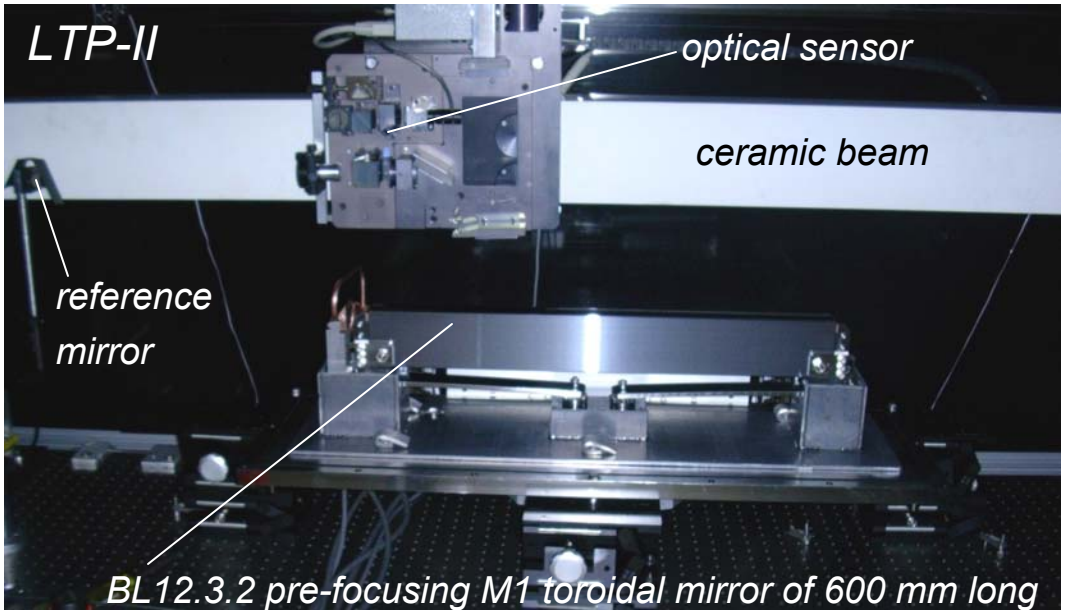


Long trace profiler LTP-II

Surface characterization at lower spatial frequency

Mainframe Performance:

- *1D slope-trace measuring instrument*
- *For mirrors as long as 1 m*
- *Accuracy: ~1 µrad*
- *Spatial Sampling: 1 mm*
- *Digitization: 16 bits*
- *Indispensable for bending mirror adjustment, characterization, and calibration*



Developments:

- ✓ *Improvement of elliptical shape calculation algorithm*
- ✓ *Ghost effect elimination procedure*[1]
- ✓ *Procedure for effective adjustment of bendable mirrors*[2]
- ✓ *Reference mirror (1-in diam) replaced with a super flat mirror (3-in diam.)*
- ✓ *Improvement of environmental and operational conditions*
  - ➢ ***Dust-protected, ventilated hutch***
  - ➢ ***Room temperature stabilization (~0.2ºC) with a conditioner***

---

[1] *V. V. Yashchuk,* S. C. Irick, A. A. MacDowell, *Elimination of 'ghost'-effect-related systematic errors in metrology of X-ray optics with a long trace profiler,* SPIE Symposium on Optical Metrology 2005, part of LASER2005, World of Photonics, SPIE Proceedings 5858, pp. 58580X-1-8 (Munich, Germany, 12-17 June 2005).

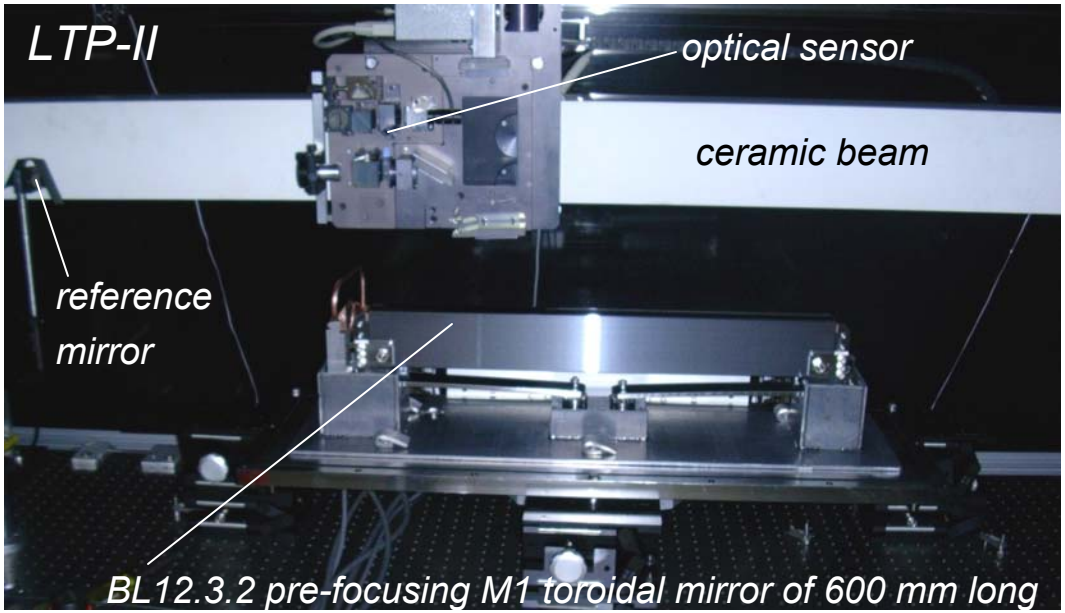
[2] W. R. McKinney, S. C. Irick, A. A. MacDowell, T. Warwick, and V. V. Yashchuk, *Optimal Use of LTP or Interferometer Data for the Adjustment of Bendable Mirrors,* AIP Conference on Synchrotron Radiation Instrumentation SRI-2006, III Workshop on Optical Metrology (Daegu, South Korea, May 27, 2006).

Long trace profiler LTP-II

Surface characterization at lower spatial frequency

Mainframe Performance:

- *1D slope-trace measuring instrument*
- *For mirrors as long as 1 m*
- *Accuracy: ~1 µrad*
- *Spatial Sampling: 1 mm*
- *Digitization: 16 bits*
- *Indispensable for bending mirror adjustment, characterization, and calibration*



Developments:

- ✓ *Improvement of elliptical shape calculation algorithm*
- ✓ *Ghost effect elimination procedure*[1]
- ✓ *Procedure for effective adjustment of bendable mirrors*[2]
- ✓ *Reference mirror (1-in diam) replaced with a super flat mirror (3-in diam.)*
- ✓ *Improvement of environmental and operational conditions*
  - ➢ ***Dust-protected, ventilated hutch***
  - ➢ ***Room temperature stabilization (~0.2ºC) with a conditioner***

---

[1] *V. V. Yashchuk,* S. C. Irick, A. A. MacDowell, *Elimination of 'ghost'-effect-related systematic errors in metrology of X-ray optics with a long trace profiler,* SPIE Symposium on Optical Metrology 2005, part of LASER2005, World of Photonics, SPIE Proceedings 5858, pp. 58580X-1-8 (Munich, Germany, 12-17 June 2005).

[2] W. R. McKinney, S. C. Irick, A. A. MacDowell, T. Warwick, and V. V. Yashchuk, *Optimal Use of LTP or Interferometer Data for the Adjustment of Bendable Mirrors,* AIP Conference on Synchrotron Radiation Instrumentation SRI-2006, III Workshop on Optical Metrology (Daegu, South Korea, May 27, 2006).

Bendable Optics at the ALS

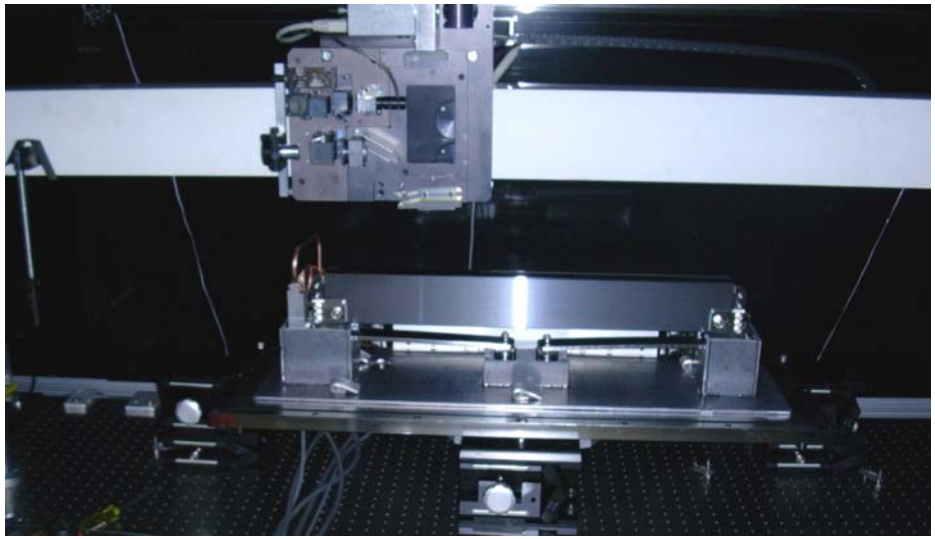
– *as a part of pre-focusing and end-station Kirkpatrick-Baez (KB) focusing systems*

– *based on controlled bending of a flat substrate with unequal end couples*

– *and controlled variation to the mirror width*

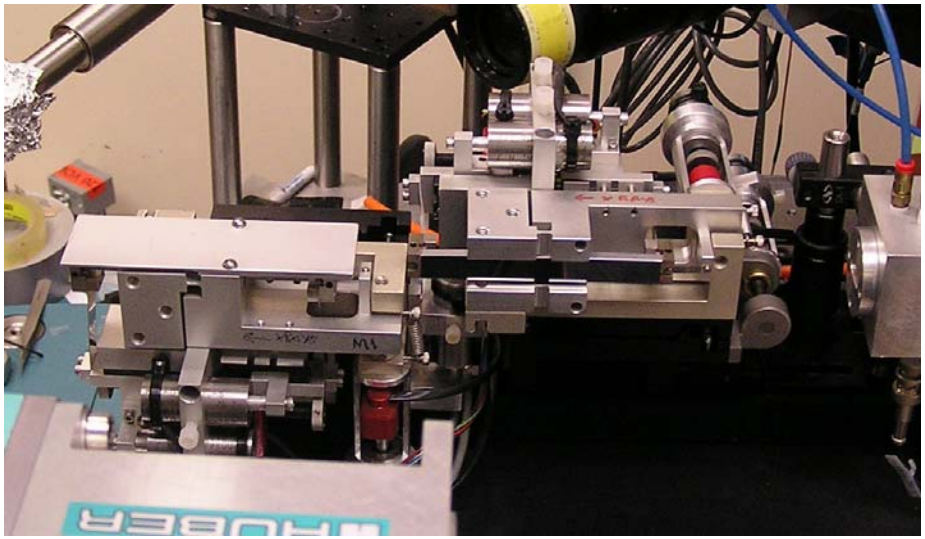
M.R.Howells, et al., *Theory and practice of elliptically bent x-ray mirrors,* Opt. Eng.39(10), 2748-61 (2000)

Back side-cantilever bending mechanism



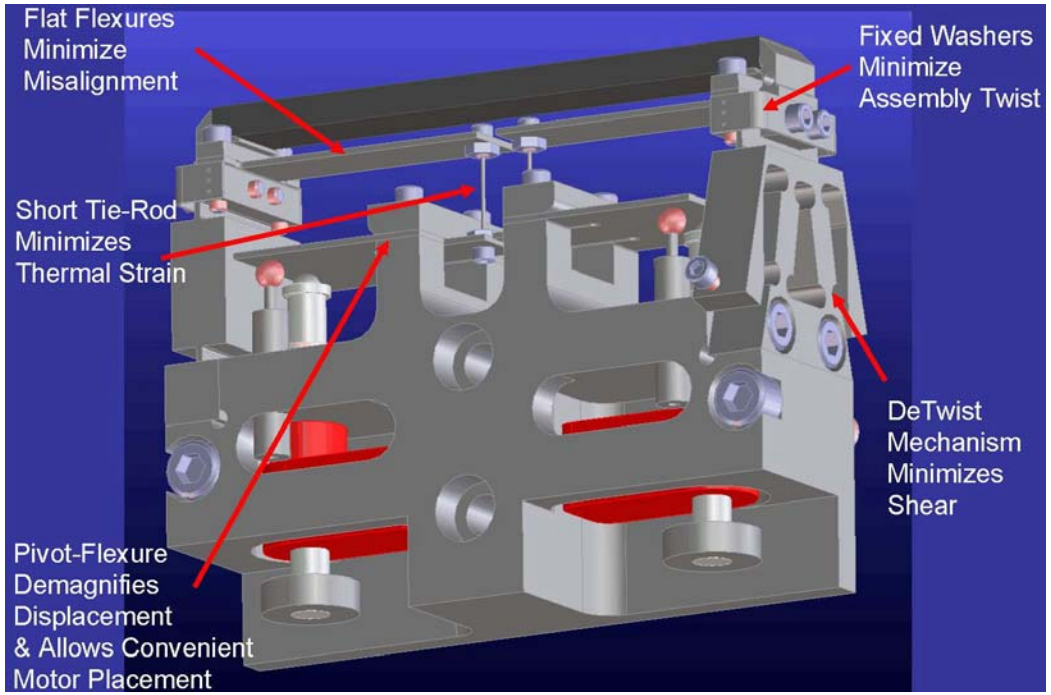
BL12.3.2 pre-focusing M1 toroidal mirror

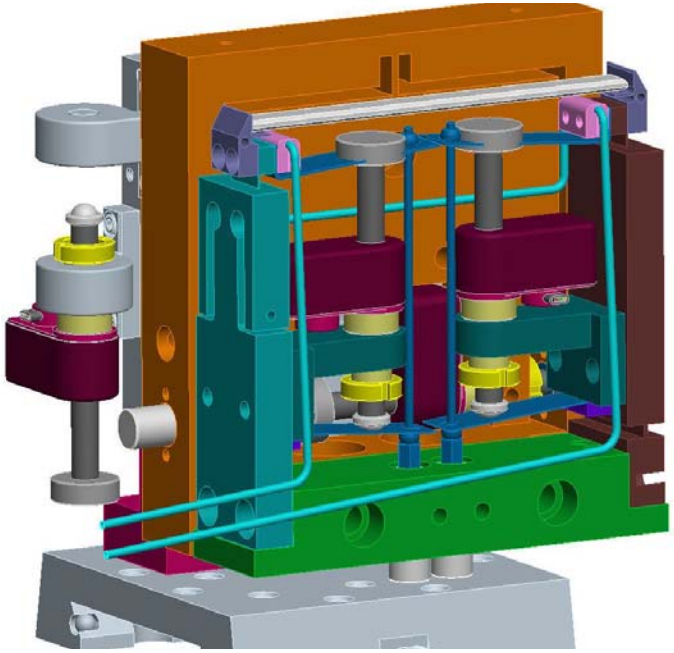
S-shaped-leaf-spring bending mechanism

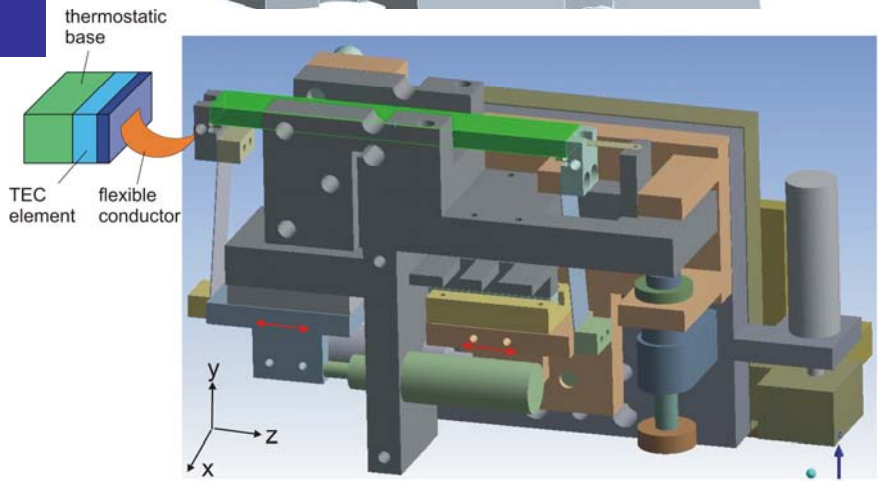


BL7.3.3 end station KB elliptical mirrors

Development of Bendable KB Mirrors at the ALS







Tino Noll and Valeriy V. Yashchuk,
Some Results of ALS-BESSY Collaboration Work on Development of KB-mirror Design,
ALS Light Source Note LSBL-771, January, 2006, Berkeley

Valeriy V. Yashchuk and Tino Noll,
KB Mirror End Piece Cooling via a Flexible Heat Conductor,
ALS Light Source Note LSBL-772, January, 2006, Berkeley

Bending mirror adjustment, characterization, and calibration with the LTP

Motivation:

Practical reasons:

to save the OML working time for adjusting

to save beamline scientist's time for fine tuning the optics

'Philosophical' reasons:

"Laziness is the mother of progress."

Kuzma Prutkov

to connect metrology and beamline performance

W. R. McKinney, S. C. Irick, A. A. MacDowell, T. Warwick, and V. V. Yashchuk, *Optimal Use of LTP or Interferometer Data for the Adjustment of Bendable Mirrors,* AIP Conference on Synchrotron Radiation Instrumentation SRI-2006, III Workshop on Optical Metrology (Daegu, South Korea, May 27, 2006).

Method: *problem to be solved*

100-mm-long elliptical mirror specified with:

***r* = 18.901 m**

***r′* = 0.120 m**

θ= 0.0031 rad

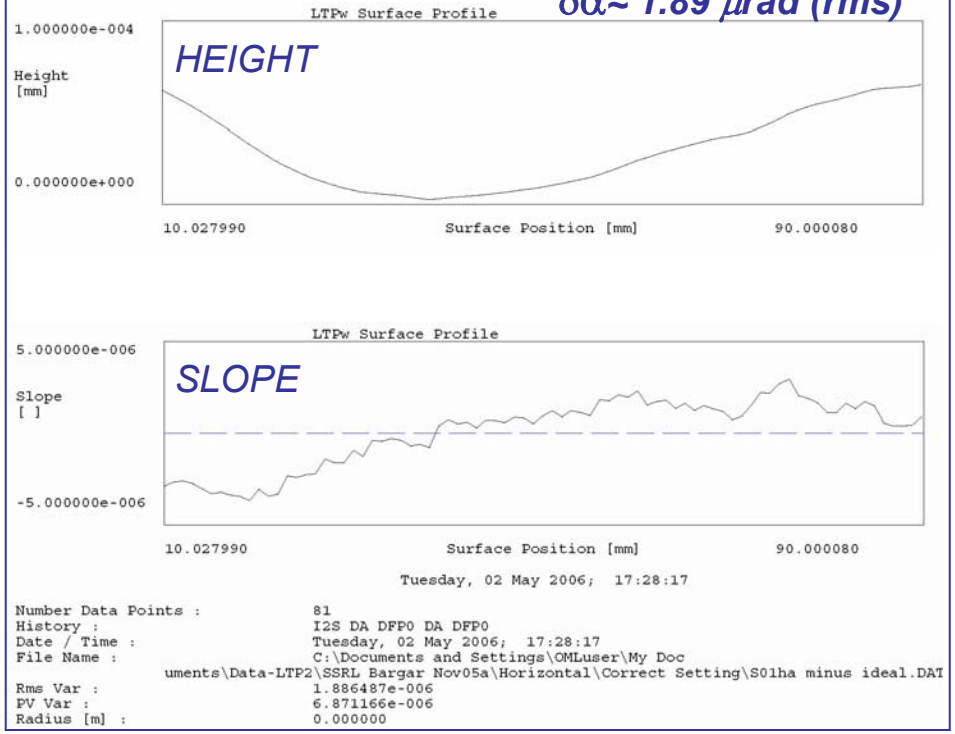
The problem:

How can the operator reliably chose the settings for the next iteration of bendable mirror adjustment ?

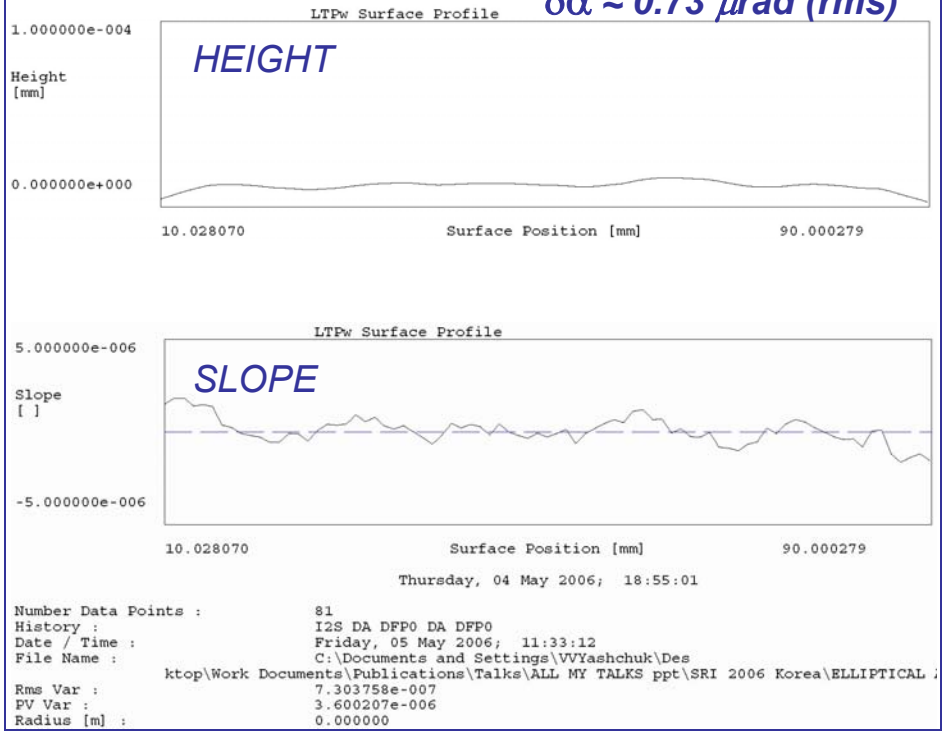
Figure-of-merit for adjustment:

δα ≤ 1 μrad (rms)

δα≈ 1.89 μrad (rms)



δα ≈ 0.73 μrad (rms)

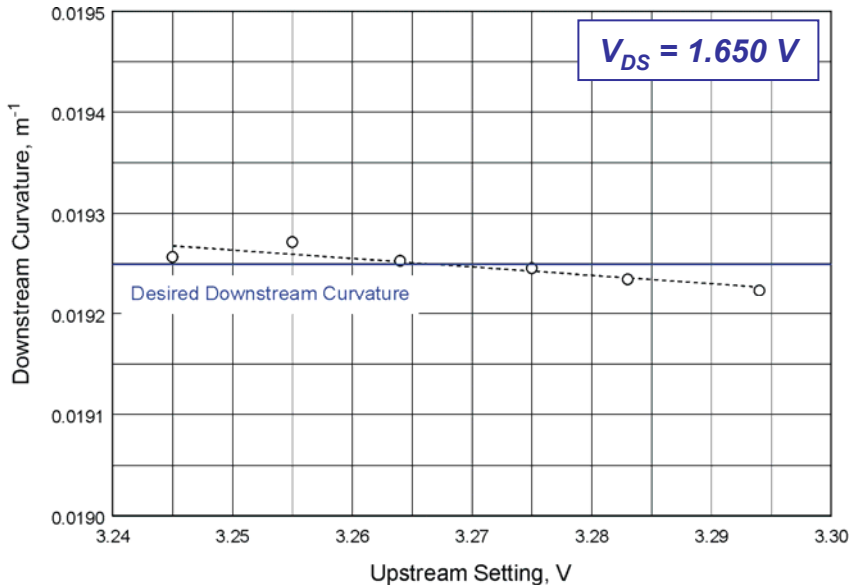


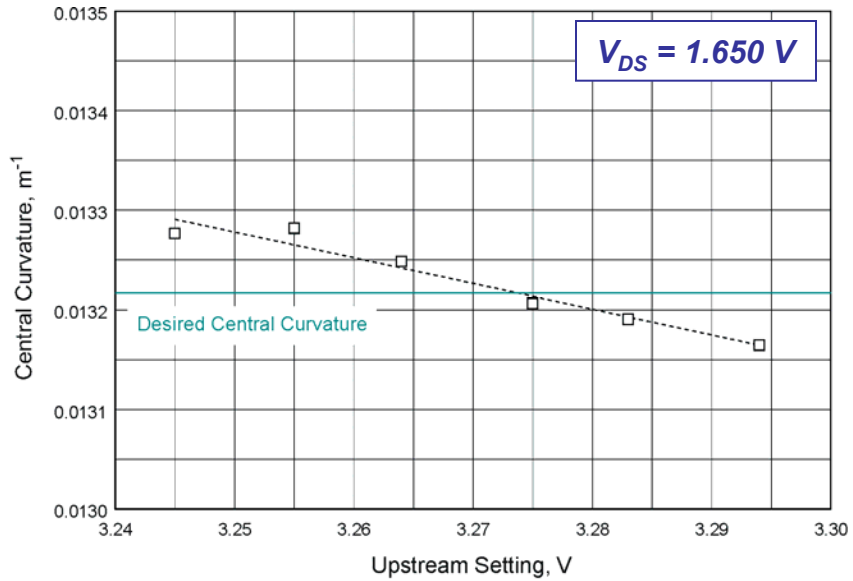
Settings: V_{US} = 3.250 V V_{DS} = 1.650 V

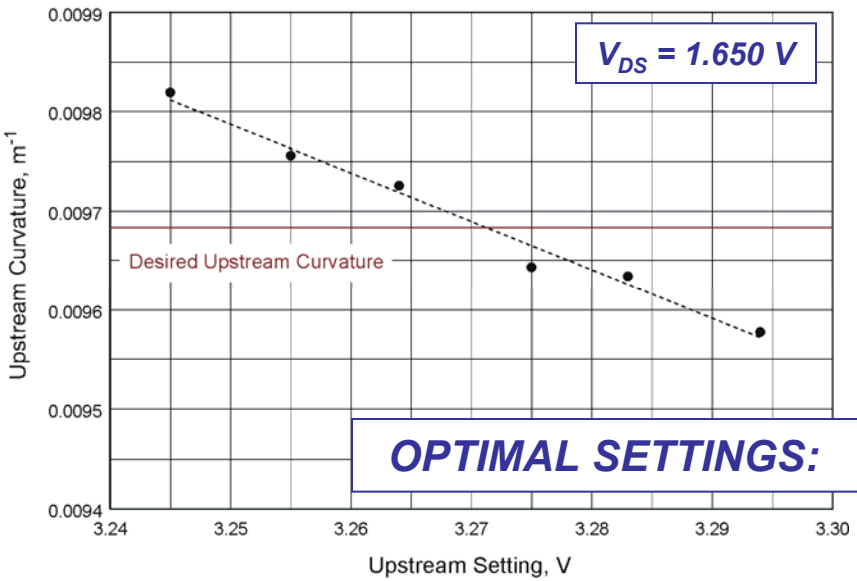
V_{US} = 3.275 V V_{DS} = 1.650 V

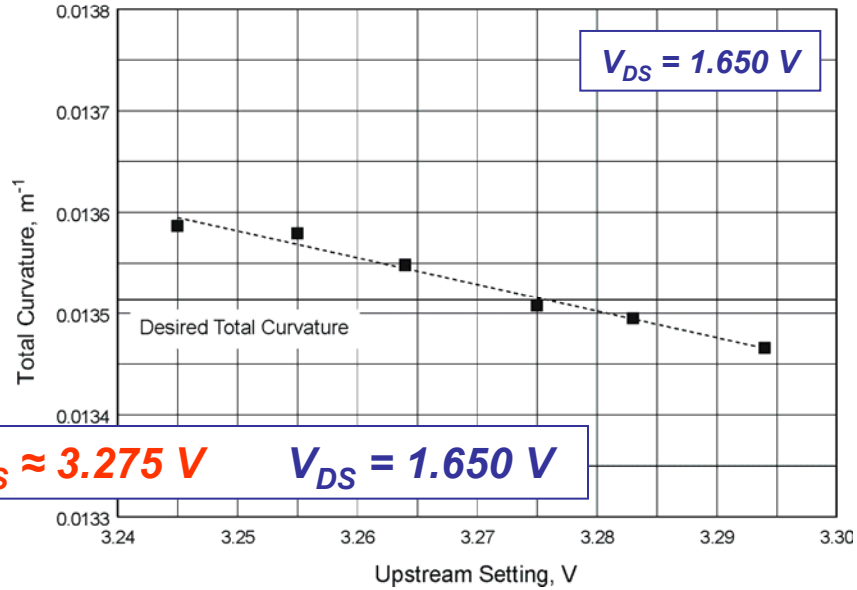
Linear dependence of Curvature on bender settings

(100-mm-long elliptical KB mirror)







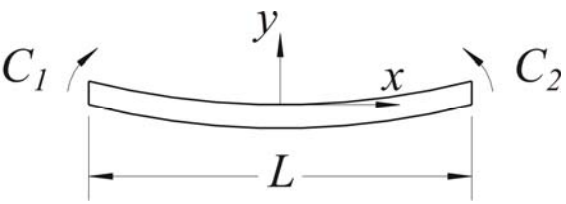


OPTIMAL SETTINGS: $V_{US} \approx 3.275$ V $V_{DS} = 1.650$ V

Surface slope error of a bendable mirror

Beam theory applied to a bent structure:

M. R. Howells, et al., *Theory and practice of elliptically bent x-ray mirrors,* Opt. Eng. 39(10), 2748-61 (2000)



$$EI(x)\frac{\partial^2 y}{\partial x^2} = \frac{C_1 + C_2}{2} - \frac{C_1 - C_2}{L}x$$

E is the mirror elastic modulus;
$I(x)$ is the mirror section moment;
C_1 and C_2 are the bending moments

After simple transformations:

$$EI(x)\frac{\partial^2 y}{\partial x^2} = C_1\left(\frac{1}{2} - \frac{1}{L}x\right) + C_2\left(\frac{1}{2} + \frac{1}{L}x\right)$$

$$\frac{\partial^2 y}{\partial x^2} = C_1\left(\frac{1}{2} - \frac{1}{L}x\right)\frac{1}{EI(x)} + C_2\left(\frac{1}{2} + \frac{1}{L}x\right)\frac{1}{EI(x)}$$

$$\frac{\partial^2 y}{\partial x^2} = C_1 g_1(x) + C_2 g_2(x)$$

where: $g_1(x) = \left(\frac{1}{2} - \frac{1}{L}x\right)\frac{1}{EI(x)}; \quad g_2(x) = \left(\frac{1}{2} + \frac{1}{L}x\right)\frac{1}{EI(x)}$

After integrations:

$$\alpha(x,C) = \frac{\partial y}{\partial x} = C_0 + C_1 f_1(x) + C_2 f_2(x)$$

where: $f_1(x) = \int g_1(x)\,dx; \quad f_2(x) = \int g_2(x)\,dx;$

For ideal elliptical surface:

$$\alpha^0(x,C) = C_0^0 + C_1^0 f_1(x) + C_2^0 f_2(x)$$

?Method to find the model functions?

The surface slope error is a linear combination of unknown functions:

$$\Delta\alpha(x,C) = \Delta C_0 + \Delta C_1 f_1(x) + \Delta C_2 f_2(x)$$

Application of regression analysis to on-beam KB mirror tuning

Observation: *surface slope error (deviation from ideal ellipse) measured with LTP*

$$\delta\alpha(x_i) = \eta(x_i, C) + \varepsilon_i;$$

where: ε_i is the error variable;
C are the bending parameters
x_i are the sampling points on the surface

The model is a *linear* combination of *unknown* functions:

$$\eta(x,\theta) = \Delta C_0 + \Delta C_1\ f_1(x) + \Delta C_2\ f_2(x)$$

Method to find the model functions:

$$-\quad \delta\alpha_{20}(x_i) = \Delta C_0 + \Delta C_1\ f_1(x_i) + \Delta C_2\ f_2(x_i) + \varepsilon_{oi}$$

$$+\quad \delta\alpha_{21}(x_i) = \Delta C_0 + (\Delta C_1 + \delta C_1)\ f_1(x_i) + \Delta C_2\ f_2(x_i) + \varepsilon_{1i}$$

$$\delta\alpha_{21}(x_i) - \delta\alpha_{20}(x_i) = \delta C_1\ f_1(x_i) + \varepsilon_{10i}$$

$$f_1^*(x_i) = \frac{\delta\alpha_{21}(x_i) - \delta\alpha_{20}(x_i)}{\delta C_1} \qquad f_2^*(x_i) = \frac{\delta\alpha_{22}(x_i) - \delta\alpha_{20}(x_i)}{\delta C_2}$$

$$-\quad \delta\beta_{20}(x_i) = \Delta C_0 + \Delta C_1\ f_1(x_i) + \Delta C_2\ f_2(x_i) + \varepsilon_{oi}$$

$$+\quad \delta\beta_{22}(x_i) = \Delta C_0 + \Delta C_1\ f_1(x_i) + (\Delta C_2 + \delta C_2)\ f_2(x_i) + \varepsilon_{2i};$$

$$\delta\alpha_{22}(x_i) - \delta\alpha_{20}(x_i) = \delta C_2\ f_2(x_i) + \varepsilon_{20i}$$

Regression matrix:

$$\hat{A} = \begin{bmatrix} 1 & f_1(x_1) & f_2(x_1) \\ 1 & f_1(x_2) & f_2(x_2) \\ \vdots & \vdots & \vdots \\ 1 & f_1(x_m) & f_2(x_m) \end{bmatrix}$$

$$\hat{A} \approx \begin{bmatrix} 1 & f_1^*(x_1) & f_2^*(x_1) \\ 1 & f_{1\ 1}^*(x_2) & f_2^*(x_2) \\ \vdots & \vdots & \vdots \\ 1 & f_1^*(x_m) & f_2^*(x_m) \end{bmatrix}$$

Solution:

$$\Delta\hat{C}^* = (\hat{A}'\hat{A})^{-1}\hat{A}'\delta\alpha_{20}$$

$$D(\Delta\hat{C}^*) = \sigma^2(\hat{A}'\hat{A})^{-1}$$

$$D\hat{y} = \sigma^2\hat{I}$$

$$\sigma^2 \approx \frac{\sum_i [\delta\alpha_{20} - \Delta C_1^*\ f_1^*(x_i) - \Delta C_2^*\ f_2^*(x_i)]^2}{m-p}$$

O. Hignette, A.Freund, and E. Chinchio,

Incoherent X-ray Mirror Surface Metrology,

Proceedings of SPIE 3152, 188-199 (2000)

Observation: ***surface slope error (deviation from ideal ellipse) measured in the CCD plane***

$$\delta y_2(x_i) = \eta(x_i, C) + \varepsilon_i;$$

where: ε_i *is the error variable;*
C *are the bending parameters*
x_i *are the sampling points on the surface*

The model is a linear combination of unknown functions:

$$\eta(x,\theta) = C_1\ f_1(x) + C_2\ f_2(x)$$

Method to find the model functions:

$$-\quad \delta y_{20}(x_i) = C_1\ f_1(x_i) + C_2\ f_2(x_i) + \varepsilon_{oi}$$

$$+\quad \delta y_{21}(x_i) = (C_1 + \delta C_1)\ f_1(x_i) + C_2\ f_2(x_i) + \varepsilon_{1i}$$

$$\delta y_{21}(x_i) - \delta y_{20}(x_i) = \delta C_1\ f_1(x_i) + \varepsilon_{10i}$$

$$f_1^*(x_i) = \frac{\delta y_{21}(x_i) - \delta y_{20}(x_i)}{\delta C_1} \qquad f_2^*(x_i) = \frac{\delta y_{22}(x_i) - \delta y_{20}(x_i)}{\delta C_2}$$

$$-\quad \delta y_{20}(x_i) = C_1\ f_1(x_i) + C_2\ f_2(x_i) + \varepsilon_{oi}$$

$$+\quad {}_{22}(x_i) = C_1\ f_1(x_i) + (C_2 + \delta C_2)\ f_2(x_i) + \varepsilon_{2i};$$

$$\delta y_{22}(x_i) - \delta y_{20}(x_i) = \delta C_2\ f_2(x_i) + \varepsilon_{20i}$$

Regression matrix:

$$\hat{A} = \begin{bmatrix} f_1(x_1) & f_2(x_1) \\ f_1(x_2) & f_2(x_2) \\ \vdots & \vdots \\ f_1(x_m) & f_2(x_m) \end{bmatrix}$$

$$\hat{A} = \begin{bmatrix} f_1^*(x_1) & f_2^*(x_1) \\ f_1^*(x_2) & f_2^*(x_2) \\ \vdots & \vdots \\ f_1^*(x_m) & f_2^*(x_m) \end{bmatrix}$$

Solution:

$$\hat{C}^* = (\hat{A}'\hat{A})^{-1}\ \hat{A}'\ \delta\hat{y}_{20}$$

$$D\hat{C}^* = \sigma^2\ (\hat{A}'\hat{A})^{-1}$$

$$D\hat{y} = \sigma^2\ \hat{I}$$

$$\sigma^2 \approx \frac{\sum_i [\delta y_{20} - C_1^*\ f_1^*(x_i) - C_2^*\ f_2^*(x_i)]^2}{m - p}$$

Method: *applied to a 100-mm-long elliptical mirror*

100-mm-long elliptical mirror specified with:

***r* = 18.901 m**

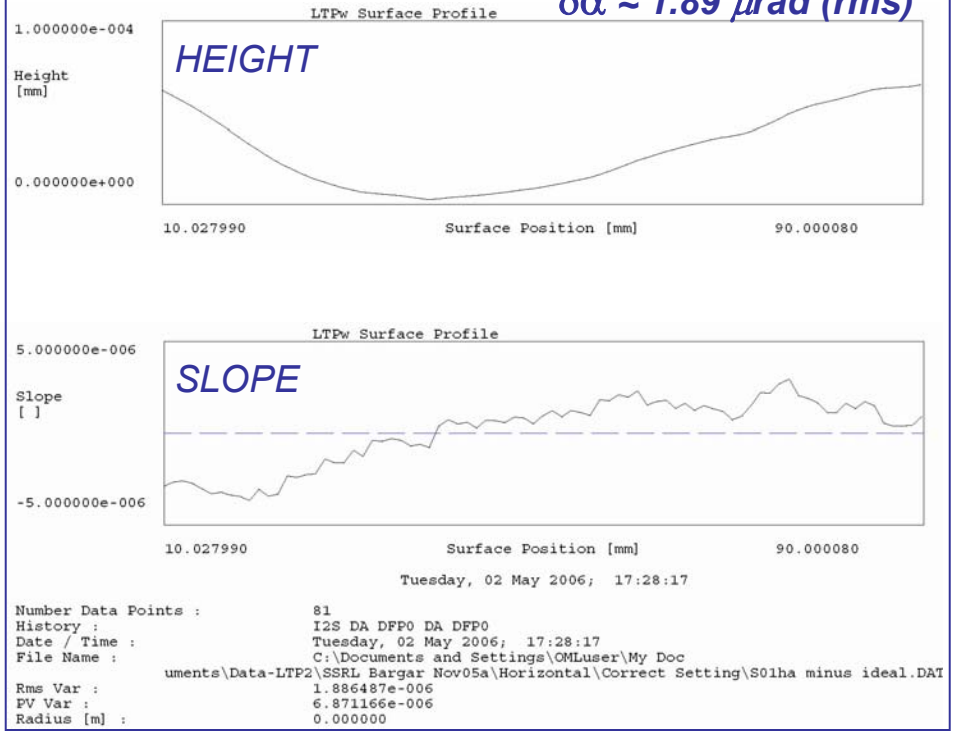
***r′* = 0.120 m**

θ = 0.0031 rad

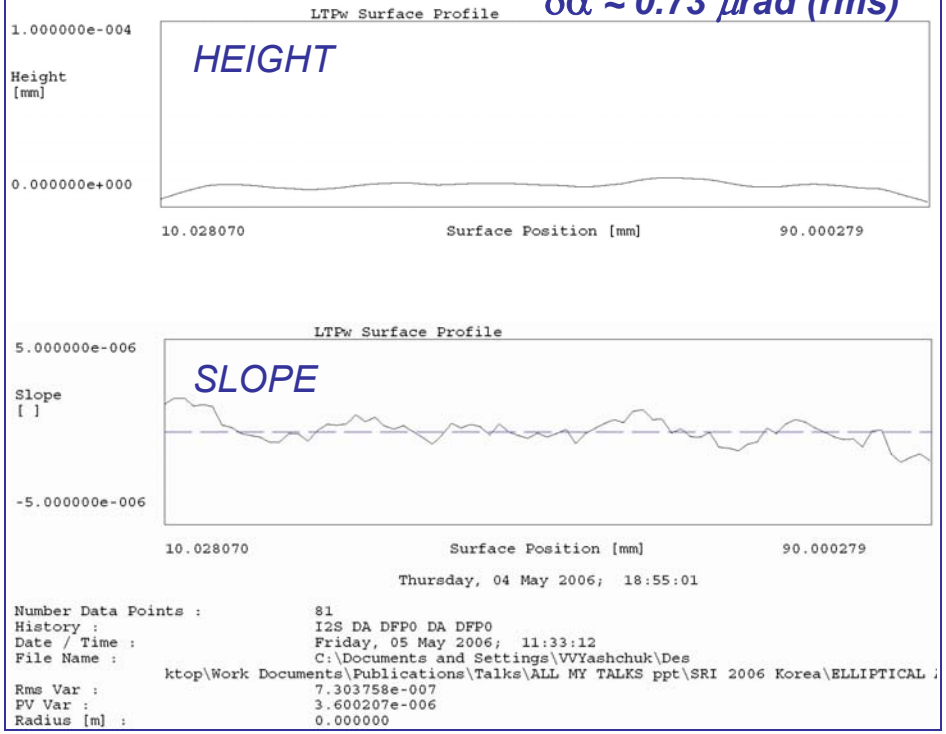
Figure-of-merit for adjustment

δα ≤ 1 μrad (rms)

δα ≈ 1.89 μrad (rms)



δα ≈ 0.73 μrad (rms)



Settings: V_{US} = 3.250 V V_{DS} = 1.650 V

V_{US} = 3.275 V V_{DS} = 1.650 V

$\delta\alpha$ (rms) as a figure-of-merit for adjustment ?

100-mm-long elliptical mirror specified with:

r = 18.901 m

r′ = 0.120 m

θ = 0.0031 rad

Figure-of-merit for adjustment

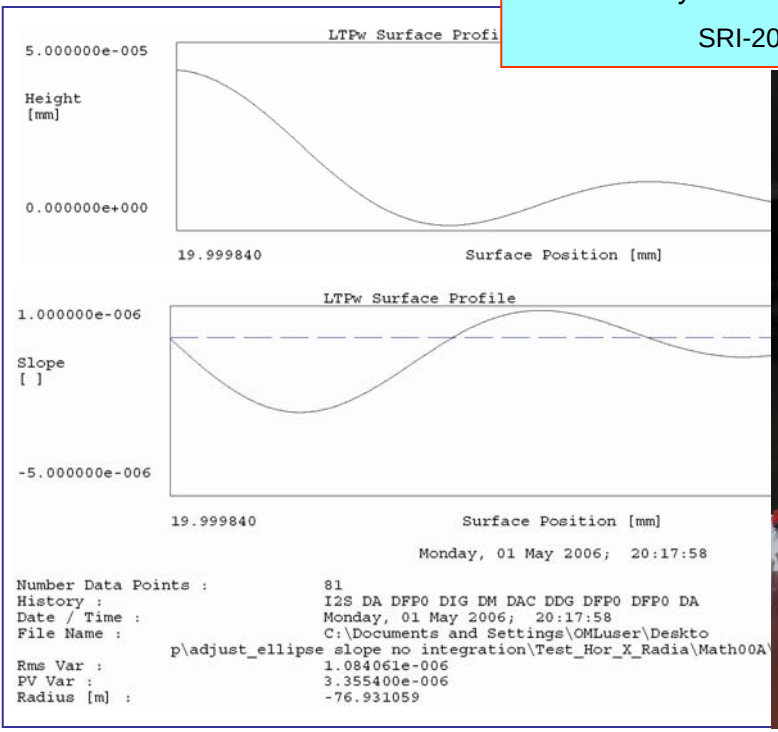
$\delta\alpha \leq 1\ \mu$rad (rms)

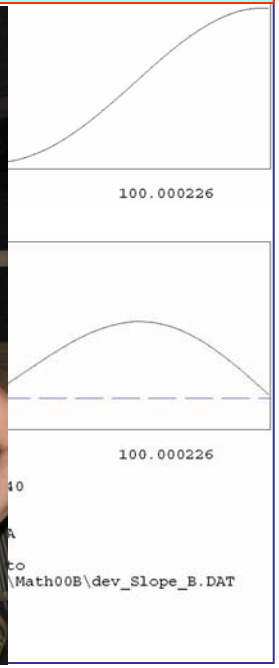
Deterministic character of the measurement requires
a deterministic evaluation of the mirror performance

V. V. Yashchuk, E. L. Church, M. R. Howells, W. R. McKinney, and P. Z. Takacs,

21-st Century Metrology for Synchrotron Radiation Optics - Understanding How to Specify and Characterize Optics,

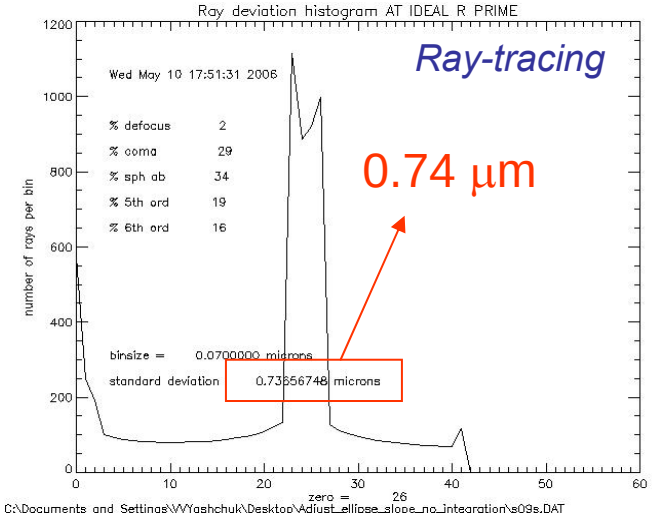
SRI-2006, III Workshop on Optical Optical Metrology, (Daegu, South Korea, May 27 - June 03, 2006).

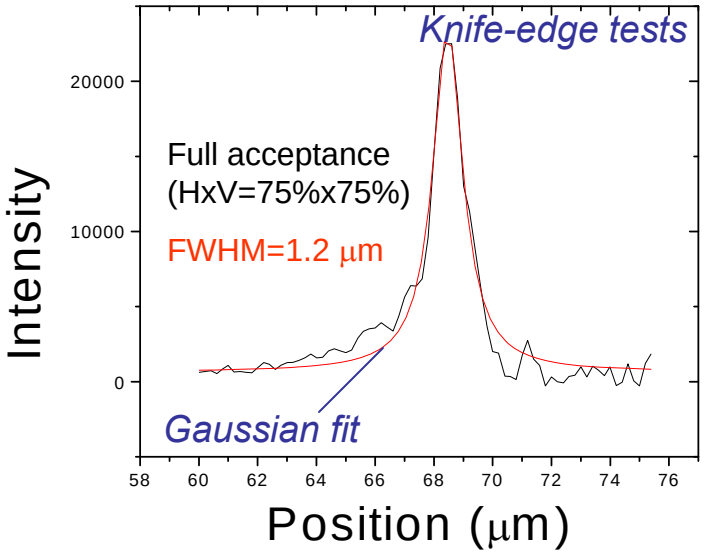




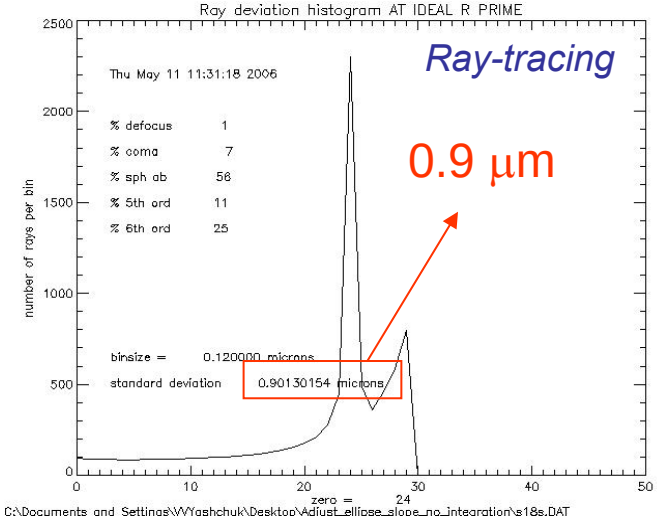
Ray-trace simulation and knife-edge tests of KB mirrors at the ALS BL7.3.3

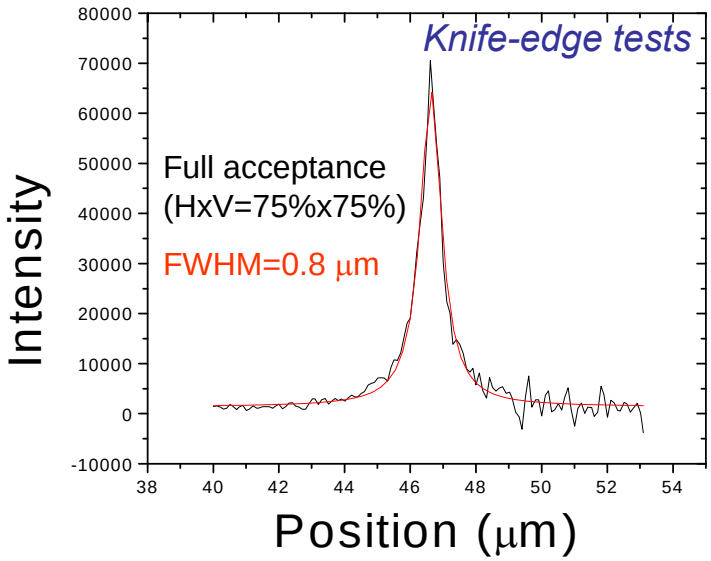
Horizontally focusing 100-mm-long elliptical mirror





Vertically focusing 100-mm-long elliptical mirror





Horizontal mirror parameters:

$r = 3.387$ m

$r' = 0.274$ m

$\theta = 0.004$ rad

Vertical mirror parameters:

$r = 3.528$ m

$r' = 0.133$ m

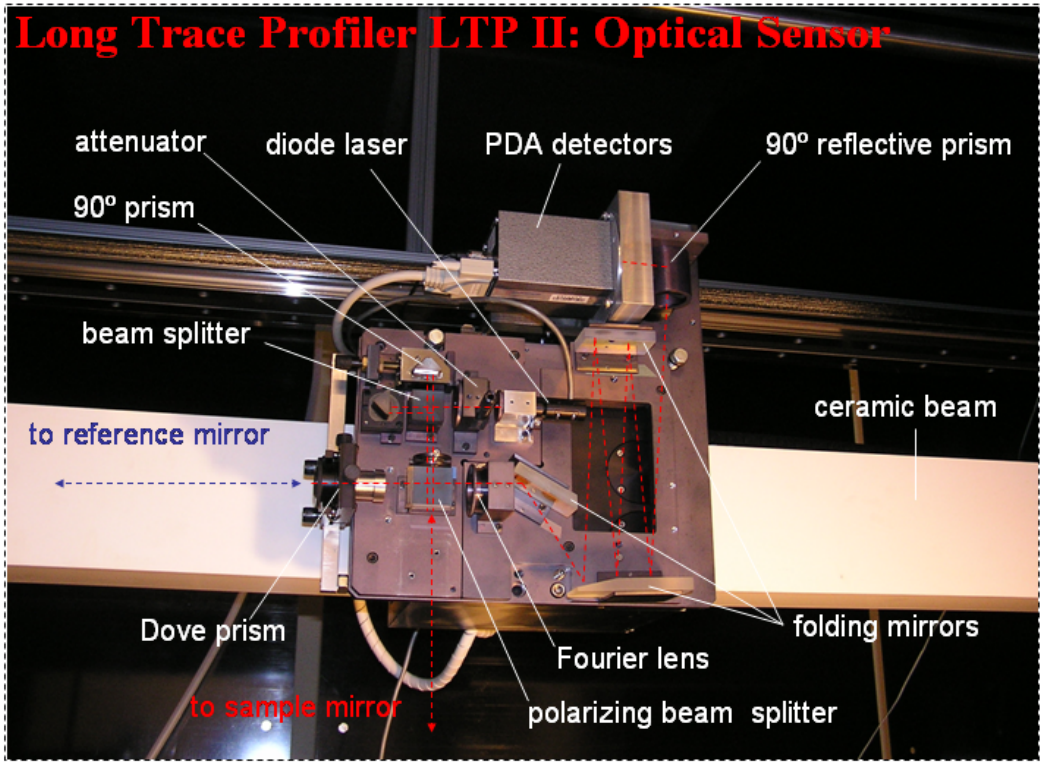
$\theta = 0.004$ rad

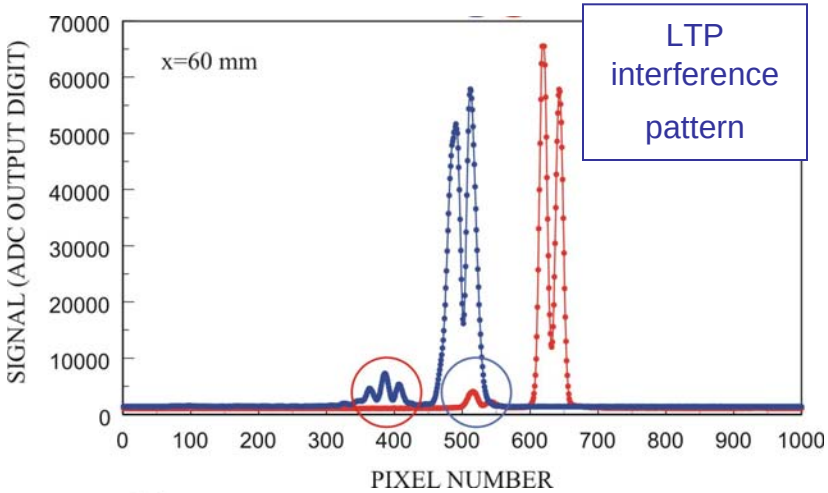
Ray-trace simulation does not account for:

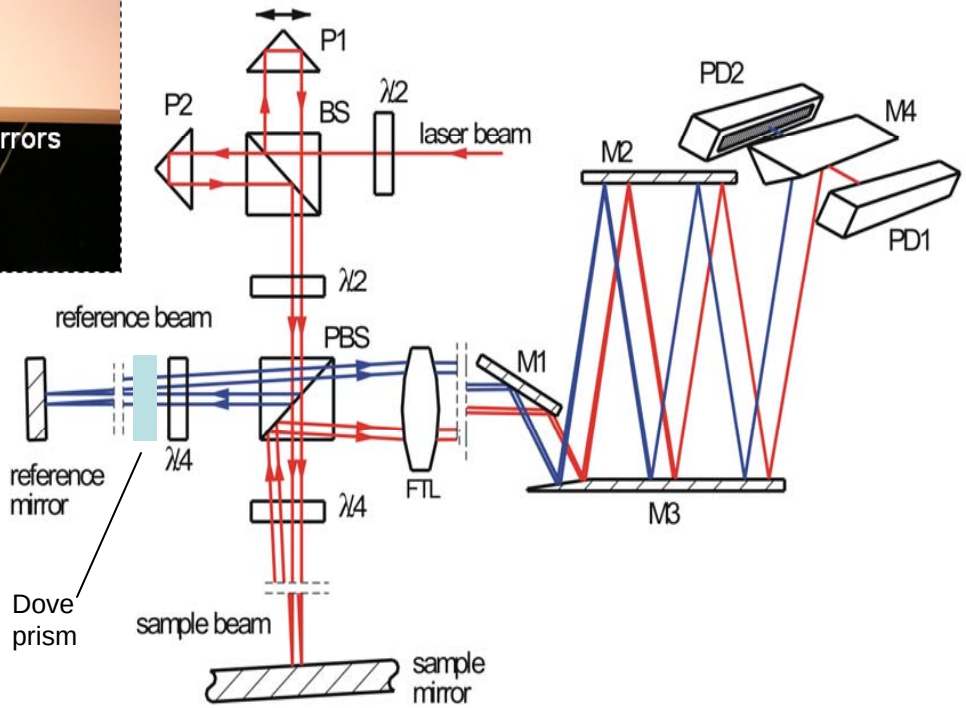
-surface roughness

-higher than 6-th order polynomial surface figure deviations

Foundations of Long trace profiler LTP-II:
Pencil-beam interferometer







P. Z. Takacs, S. K. Feng, E. L. Charch, S. Qian, and W. Liu, *Long trace profile measurement on cylindrical aspheres, in Advances in Fabrication and Metrology for Optics and Large Optics,* J. B. and R. A. Parks, eds., Proc. SPIE 966, 354 (1989).

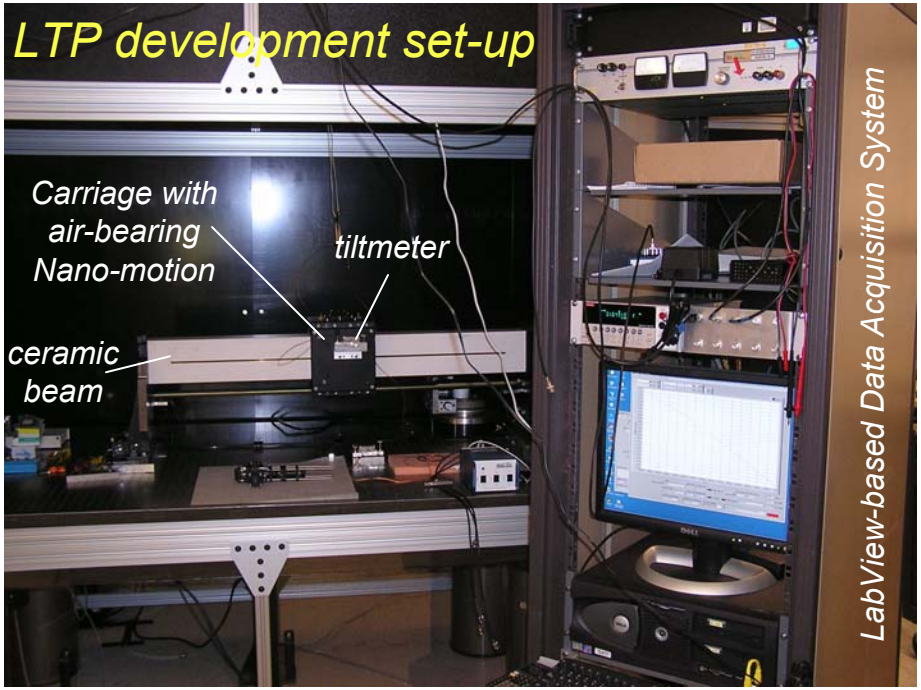
S. C. Irick, W.R. McKinney, D. L. T. Lunt, and P. Z. Takacs, *Using a straightness reference in obtaining more accurate surface profiles,* Rev. Sci. Instrum. 63, 1436 (1992).

How to improve

Surface characterization at lower spatial frequency?

LTP-II Mainframe Performance:

- 1D slope-trace measuring instrument
- For mirrors as long as 1 m
- Accuracy: ~1 µrad
- Spatial Sampling: 1 mm
- Digitization: 16 bits



Necessary Task:

- Accuracy: ~0.1 µrad

Upgrading the LTP-II:

- ✓ Keep the instrument operational
- ✓ Increase hardware reliability
- ✓ Increase reliability of data measured
- ✓ Investigate performance limitations

Developing a new LTP:

- ✓ Build LTP development set-up
- ✓ Test new hardware to be used with LTP-II
- ✓ Cross-check measurements
- ✓ Test new approaches and ideas

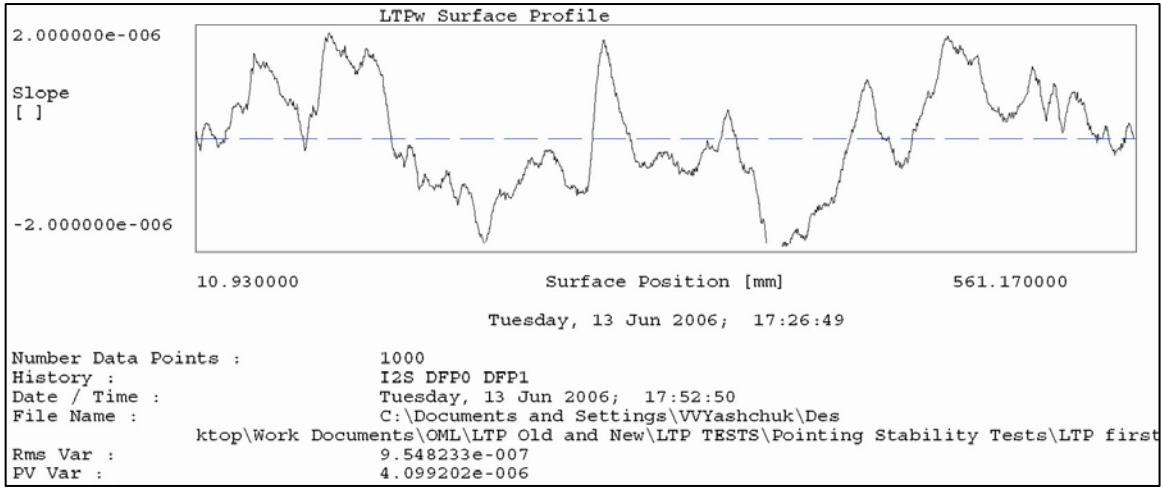
Environmental condition must be improved first!

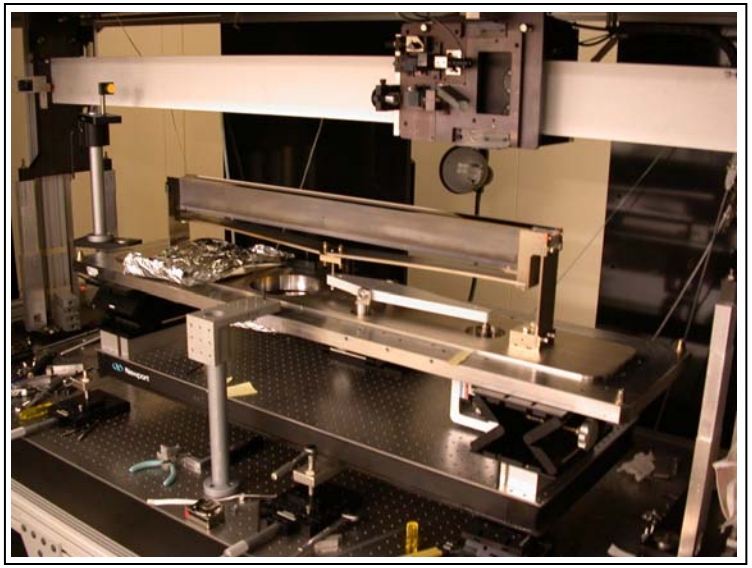
Air-convection noise in the LTP reference channel

Air-convection is due to temperature gradients inside the hutch (~20 mK);

Air-convection correlates with air-density fluctuation along optical paths

Air-density fluctuation causes pointing instability of the laser beam





Straightforward ways for improvement:

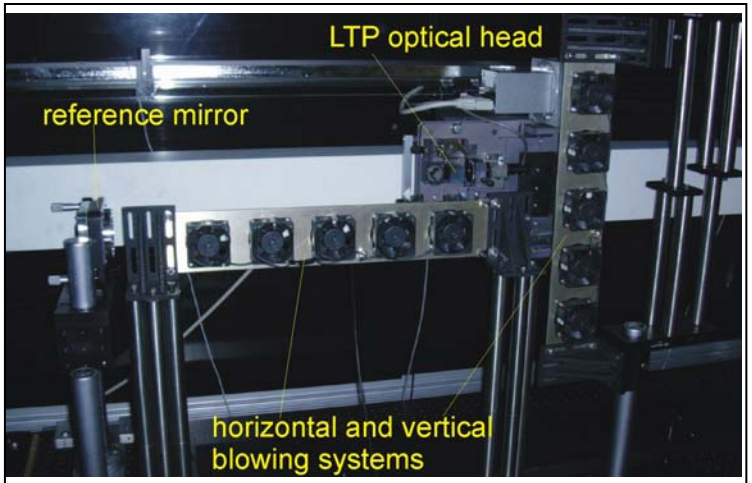
- *Carefully sealing the LTP-II hutch*
- *Temperature stabilization on the level of ~ 1 mK*

(similar to BESSY and PTB)

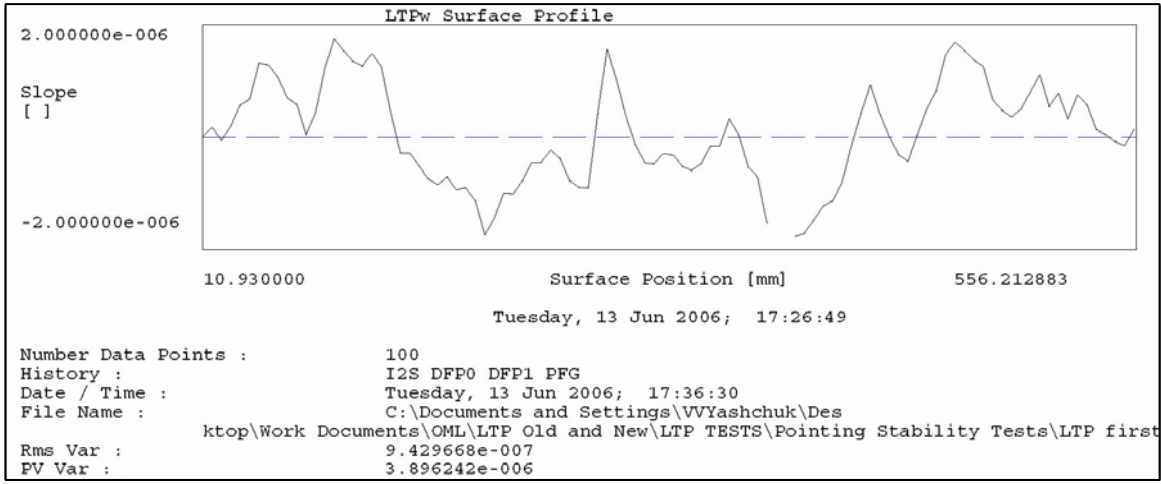
Air-blowing against air-convection noise in the LTP reference channel

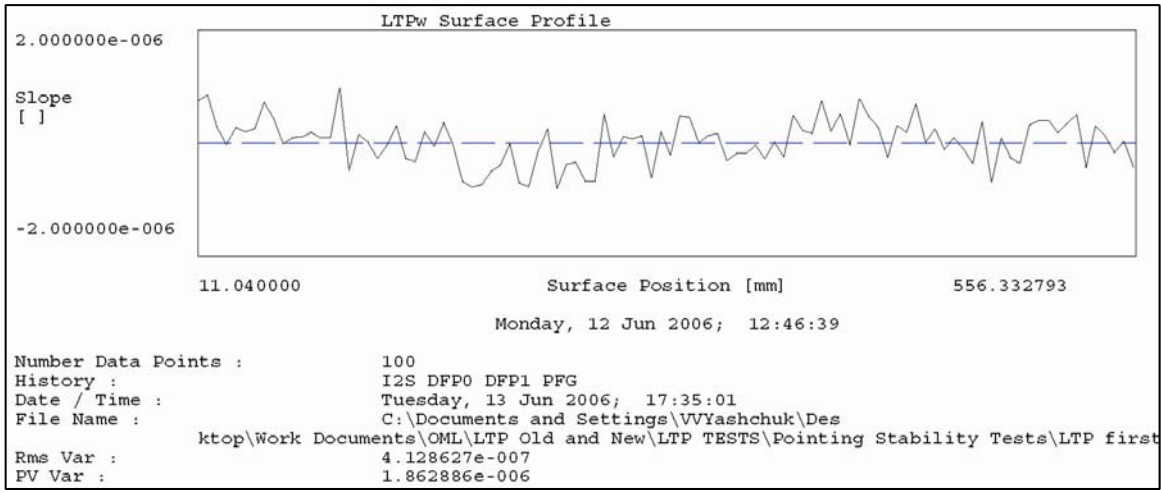
V. V. Yashchuk, S. C. Irick, A. A. MacDowell, W. R. McKinney, P. Z. Takacs,
Air convection noise of pencil-beam interferometer for long-trace profiler,
Proc. SPIE 6317-13, 2006

Air-blowing suppresses low-frequency air density fluctuations inside the hutch at the expense of high-frequency noise



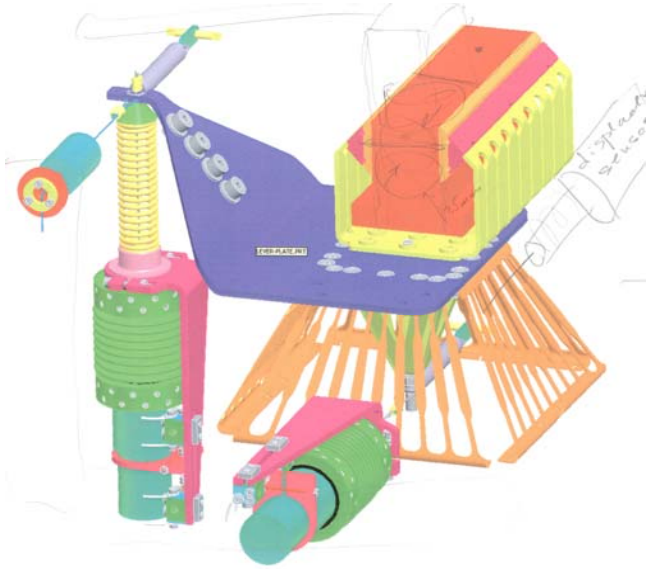
Set-up for measurement of air-convection noise in the LTP reference channel

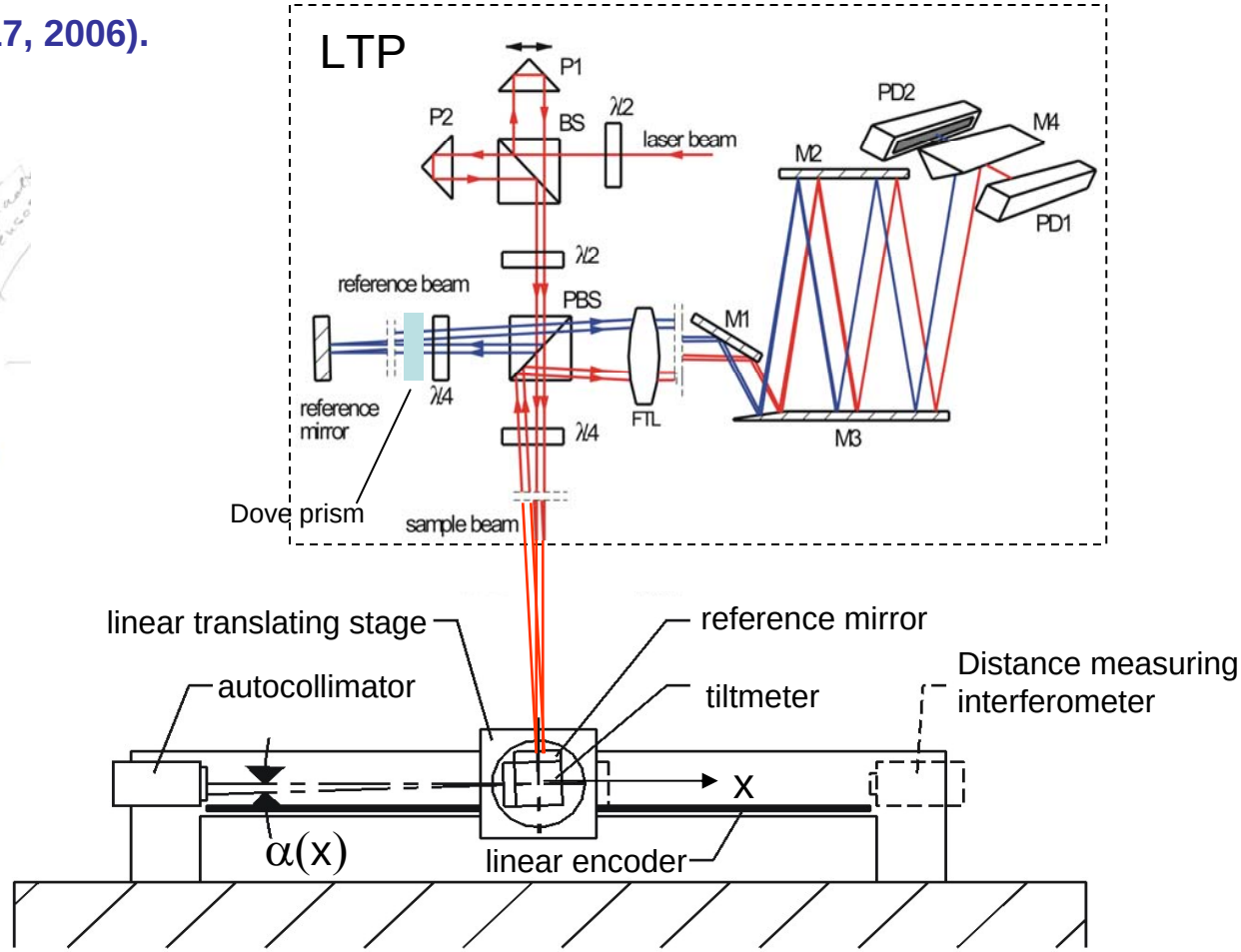




Calibration of the LTP with an Universal Test Mirror (UTM)

V. V. Yashchuk,
Universal Test Mirror for Calibration of Long Trace Profilers: Proposal,
Light Source Note LSBL-XXX
(ALS, LBNL, Berkeley, October 17, 2006).





Valeriy V. Yashchuk,
Wayne McKinney,
Tony Warwick,
Tino Noll,
Frank Siewert,
Thomas Zeschke,

Universal Test Mirror for Calibration of Long Trace Profilers: Design Consideration,
(in progress)

Metrology development at LBNL

base established; enhancement needed

Example projects in ALS Optical Metrology Lab

systematic investigation of LTP performance to reach 0.1 μrad measurements required by brightness preserving optics for ALS, LCLS, NSLS2…..

standards based on a Binary Pseudorandom Grating for precise calibration of interferometric microscopes

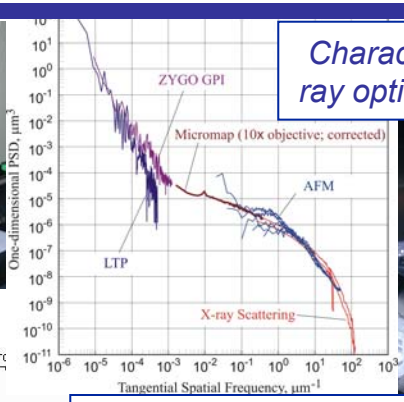
developed theory of X-ray scattering by rough surfaces for evaluation of the beam-line performance

developed power spectral density analysis of metrology data in order to analyze figure and finish simultaneously from advanced manufacturing

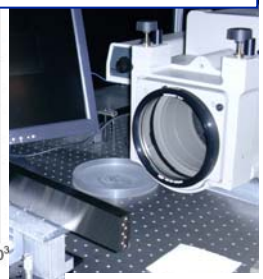
collaborating with vendors in order to advance US manufacturing technology, new materials, new bonding techniques

collaborating with metrology teams at BNL, BESSY, PTB, ESRF, ELETTRA and organizing the Virtual Optical Metrology Laboratory (VOML) to share the developed techniques, methods, designs, and results

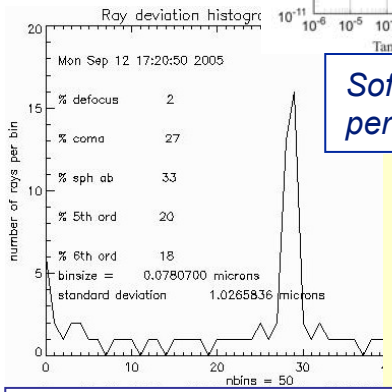
Micromap-570



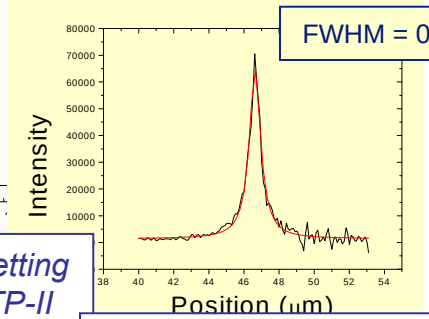
Characterization of X-ray optics with 2D PSD



ZYGO GPI

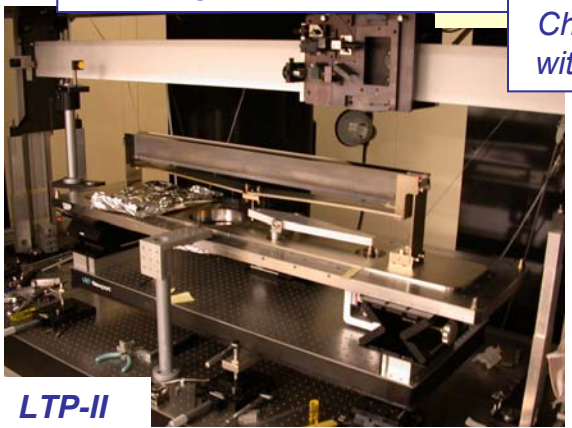


Software for beam-line performance evaluation



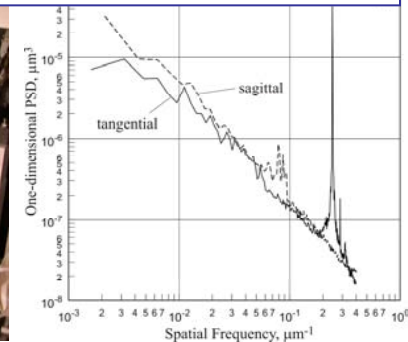
FWHM = 0.8 μm

Efficient procedure for setting bending mirrors with LTP-II



LTP-II

Characterization of gratings with variable groove density



Resources needed at LBNL to develop the DOE CENTER for X-RAY METROLOGY

DOE Center for X-ray Metrology capital expenses:

Improved environmental conditions in the OML	1,120K
Design and fabrication, remote Data Acquisition System	90K
Upgrade of the OML metrology instruments	952K
Upgrade of the existing LTP-II system	41K
Developmental Long Trace Profiler set-up	86K
Test of approaches to super accurate long trace profiling;	237K
Development of an Universal Calibration Mirror (UCM)	290K
Development of a roughness standard based on BPR grating	162K

TOTAL CAPITAL EXPENCES: 2,978K

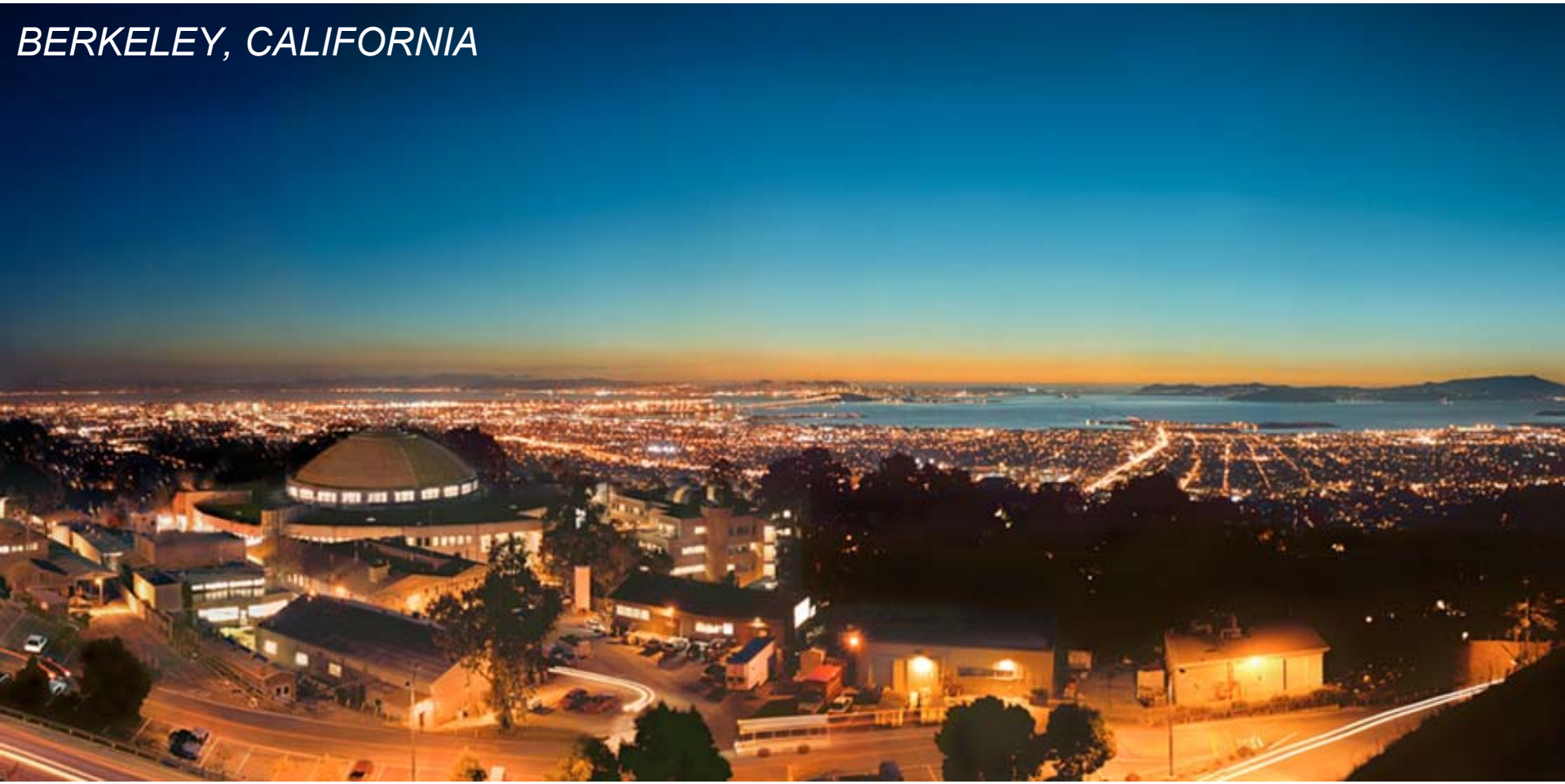
DOE Center for X-ray Metrology operating expenses:

OML operating expenses per year for equipment	150K
Manufacturing budget for co-development with industry	450K
OML operating expenses per year for personnel	1,870K

3 scientists, 2 science/engineering associates,
1 technician, 2 post-docs, 3 students

TOTAL OPERATING EXPENCES: 2,470K

THANKS!



Optical Metrology Laboratory
Experimental Systems Group
Advanced Light Source
Lawrence Berkeley National Laboratory

vvyashchuk@lbl.gov