You're Invited to the
ESG/SSG Monthly Seminar Series Meeting
October 2007

"Optical Metrology: Why it Matters to You"

Presented By:

Valeriy Yashchuk

Lawrence Berkeley National Laboratory

Tuesday, October 9th Bldg. 2-100B 9:00 a.m.

10/2/2007

Optical Metrology:

Why it Matters to You!

Valeriy V. Yashchuk

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

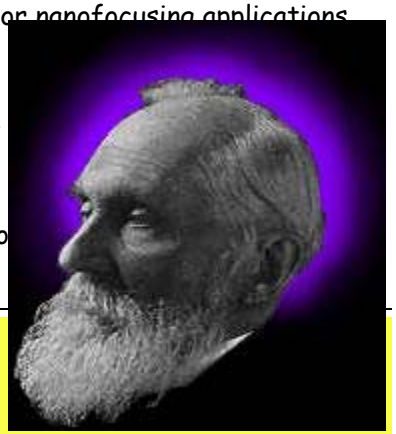
October 09, 2007

Workshop: Advanced X-Ray Optics Metrology for Nanofocusing and Coherence Preservation

time	Session I	Speaker	Talk Title (title placeholder)
1:00	US Overview	Howard Padmore, LBNL	Synchrotron Optics: A historical perspective and new challenges
1:20	Japan Overview	Kazuto Yamauchi, Osaka University	Recent achievements and next strategies in hard-x-ray nano-focusing
1:40	Europe Overview	Frank Siewert, BESSY	0.05 μrad accuracy metrology for a new generation of reflective SR-optics
2:00	SOLIEL	François Polack, SOLEIL	X-ray optics development and metrology at SOLEIL

Pressing need for optics with 0.1 nm and 0.1 μrad (rms)

	Session II		
3:00	Spring-8	Tetsuya Ishikawa, Spring-8	Optics for coherent x-rays from SR and XFEL
3:15	Optics for FEL / ELETTRA	Daniele Cocco, ELETTRA	The photon beam transport system of the Fermi@elettra FEL project
3:30	BNL (NSLS I/II)	Peter Takacs, BNL	Mirror fabrication and metrology issues for nanofocusing applications
3:45	APS	Ali Khounsary, APS	Nano-focusing research the APS
4:00	LCLS	John Arthur, SLAC	LCLS X-ray Source Properties and Optics
4:15	ALS	Yi-De Chuang, LBNL	Optics for MERLIN
4:30	LCLS	Regina Soufli, LLNL	X-ray optics development for the Linac Co
	Session III		



"If you can not measure it, you can not improve it."

Sir William Thomson (Lord Kelvin)

Friday, October 5, 2007, 1:00 — 5:30 Speakers and Discussion
Organized by Valeriy Yashchuk and Ken Goldberg

http://goldberg.lbl.gov/MetrologyWorkshop07/

Outline

- ***Introduction***
  - *What is Metrology of X-ray optics?*
  - *Overview of available instruments*
- ***OML at the ALS: What can we do for you?***
  - *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*
- ***Summaries***
  - *Missions and missionaries of the OML*
- ***Conclusions***

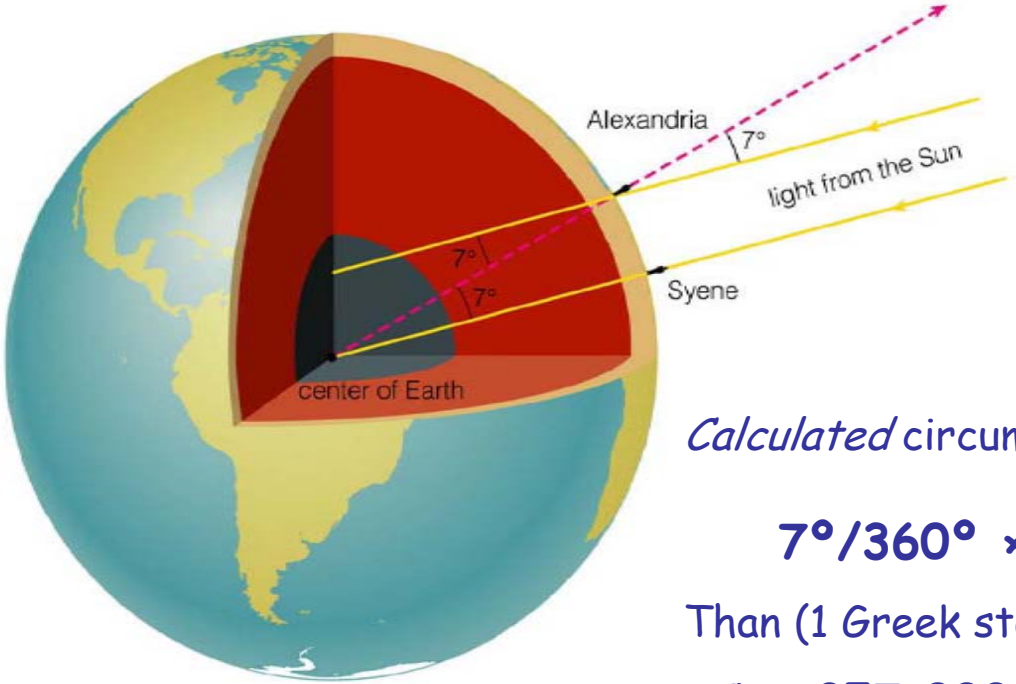
What is Metrology?

Historical roots

Etymology of the word 'Metrology':

*from Greek 'metron' =measure, and 'logy' = the study of_*

Measurement of circumference of the Earth using optical metrology



Measured Syene to Alexandria distance

L ≈ 5000 stadia;

and angle

φ ≈ 7°

Calculated circumference of Earth, ***C***:

7°/360° × C ≈ 5000 stadia

Than (1 Greek stadion ≈ 148.5 m)

C ≈ 257,000 stadia ≈ 38,200 km

Compare to modern value (around the poles)

C ≈ 40,008 km

Eratosthenes
(276 BC-194 BC)

calibration problem!

The exact size of the stadion used by Eratosthenes is no longer known. The common Attic stadion was about 185 m.

What is Metrology of x-ray optics?

Super-modern definition

"Metrology is the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology."

Bureau International des Poids et Mesures (BIPM)
[Eng.: International Bureau of Weights and Measures]
http://www.bipm.org/en/convention/wmd/2004/

"Metrology of x-ray optics is the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in the field of x-ray science and technology."

ALS OPTICAL METROLOGY LABORATORY)
[developed especially for the presentation]

All uncertainty of the determinations is due to either

random errors, systematic errors, or mistakes.

The undying objective of METROLOGY is to avoid or at least to minimize random errors, systematic errors, and mistakes.

How to minimize experimental systematic error?

At the OML we apply:

✓ ***The observation of a known process, i.e. through calibration with a standard***

Used to calibrate the MTF of the MicroMap™-570 interferometric microscope

V. V. Yashchuk, W. R. McKinney, P. Z. Takacs, *"Binary Pseudo-random Grating as a standard test surface for measurement of modulation transfer functions of interferometric microscopes,"* SPIE Proc. 6704-07 (2007)

✓ ***Identification and elimination (i.e. by averaging) of sources for systematic errors***

Used to upgrade the LTP-II to precision of ~0.3 μrad (rms)

J. L. Kirschman, E. E. Domning, K. D. Franck, S. C. Irick, A. A. McDowell, W. R. McKinney, G. Y. Morrison, B. V. Smith, T. Warwick, V. V. Yashchuk, *"Flat-field calibration of CCD detector for Long Trace Profiler,"* SPIE Proc. 6704-18 (2007)

✓ ***A subsequent measurement with more sophisticated experimental equipment***

UTM technique suggested to measure the LTP systematic error

V. V. Yashchuk, *W. R.McKinney, T. Warwick, T. Noll, F. Siewert, T. Zeschke, R. D. Geckeler, "Proposal for a Universal Test Mirror for Characterization of Slope Measuring Instruments,"* SPIE Proc. 6704-09 (2007)

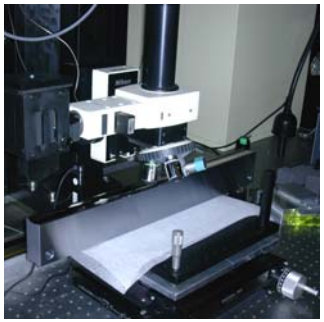
ALS Optical Metrology Laboratory

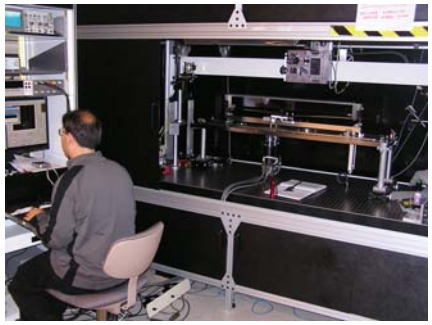
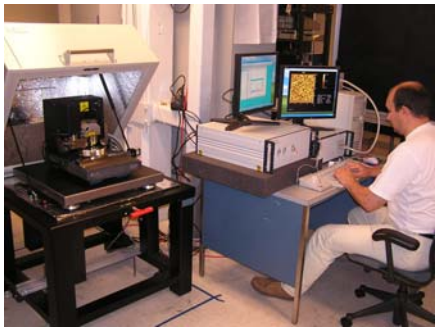
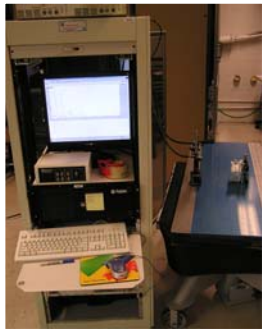
Overview

"To measure is to know."

Sir William Thomson (Lord Kelvin)

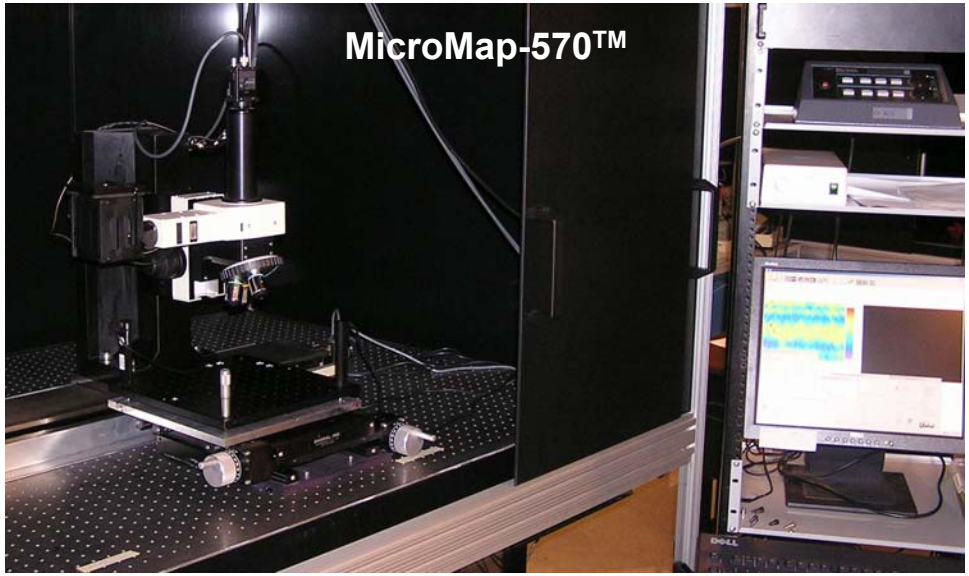
- ***Metrology instrumentation at the OML***
  - ✓ *Micromap™-570 interferometric microscope*
  - ✓ *Zygo™ GPI 6-in interferometer*
  - ✓ *Upgraded LTP II long trace profiler*
  - ✓ *Veeco™ Dimension-3000 SPM*
  - ✓ *Polytec™ Laser Doppler Vibrometer*
  - ✓ *LTP development set-up*
  - ✓ *Distance measuring interferometers, diode lasers, laser beam profiler…*



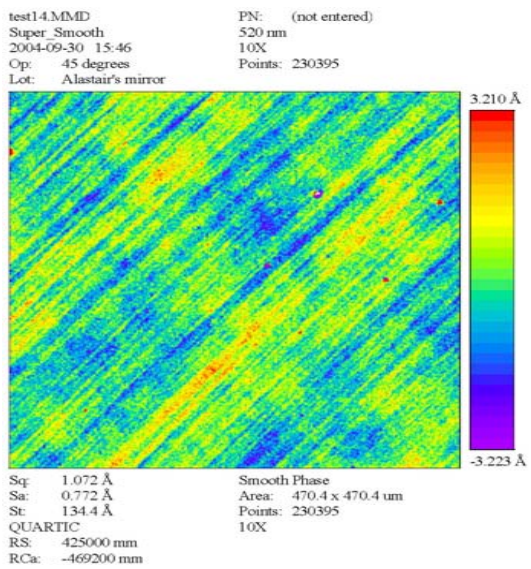
MicroMap-570™ interferometric microscope

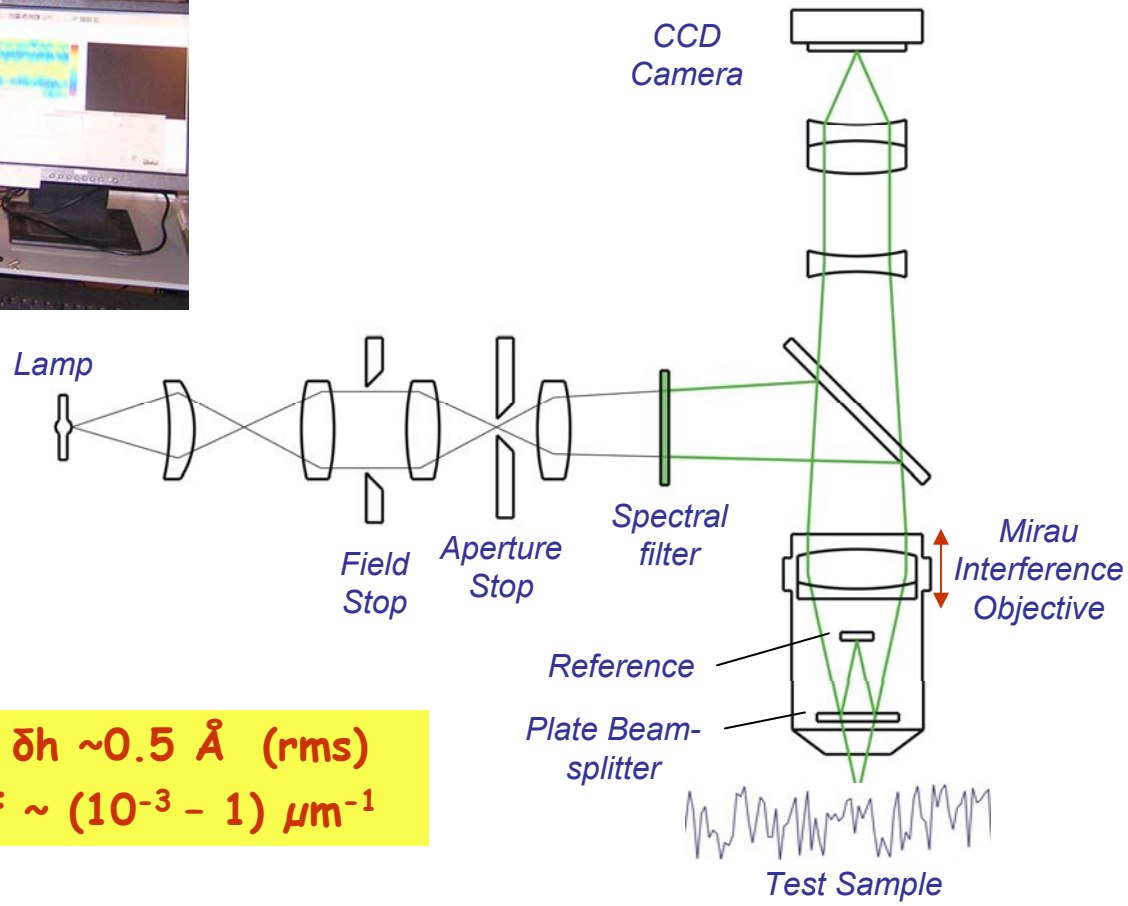
Surface characterization at higher spatial frequencies



Provides:

- ✓ ***2D surface height distributions*** $h(x,y)$
- ✓ ***Power spectral density (PSD) evaluation***





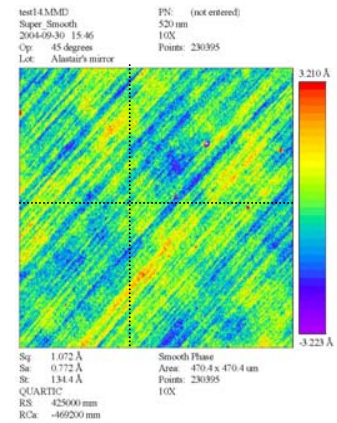
δh ~0.5 Å (rms)

f ~ (10^{-3} – 1) μm^{-1}

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

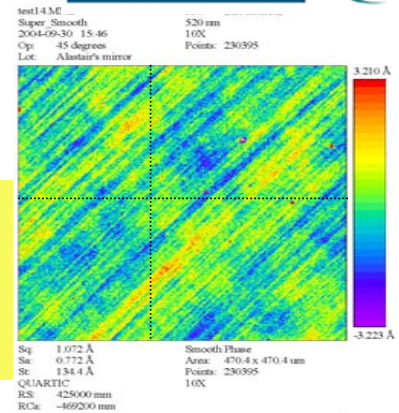
$$\begin{cases} 0 \le l \le M/2, \quad 0 \le k \le N/2, \\ g(l) = 1/2 \quad at \quad l = 0,\ M/2, \\ g(k) = 1/2 \quad at \quad k = 0,\ N/2, \quad and \\ g(l) = 1 \quad and \quad g(k) = 1 \quad otherwise \end{cases}$$

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

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

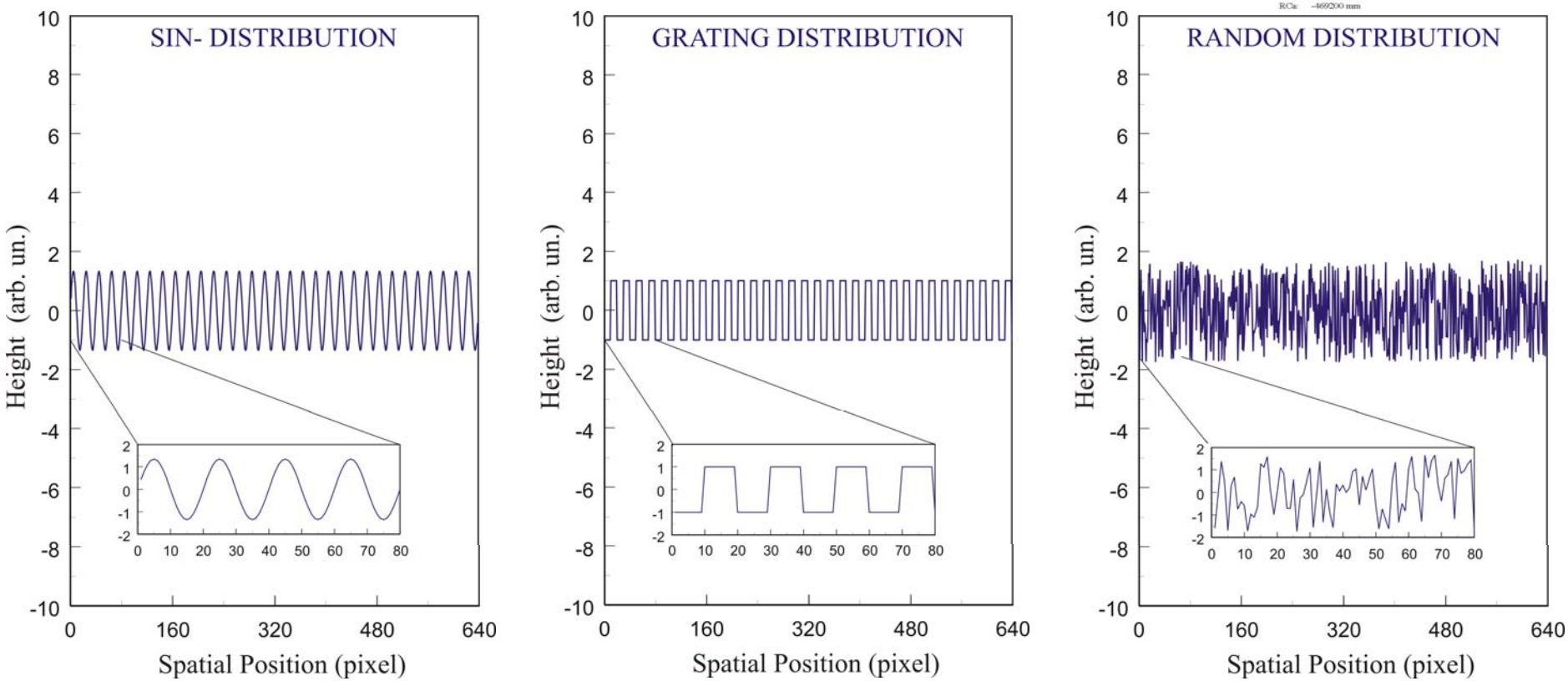
Roughness (rms):

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



For all these cases the roughness value is the same!

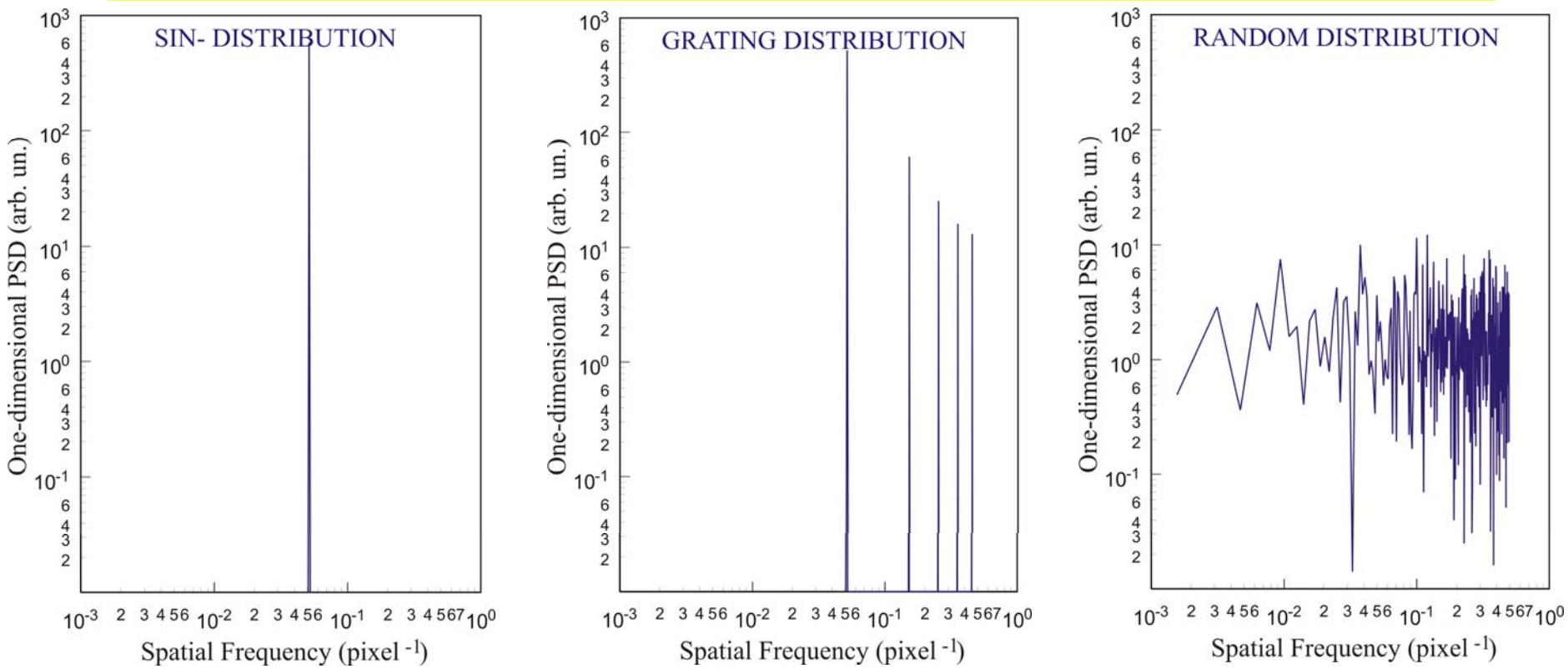
The two-dimensional sketches show the need for at least two parameters. One is vertical (roughness) and one is horizontal (wavelength).



Surface metrology based on Power Spectral Density (PSD)

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

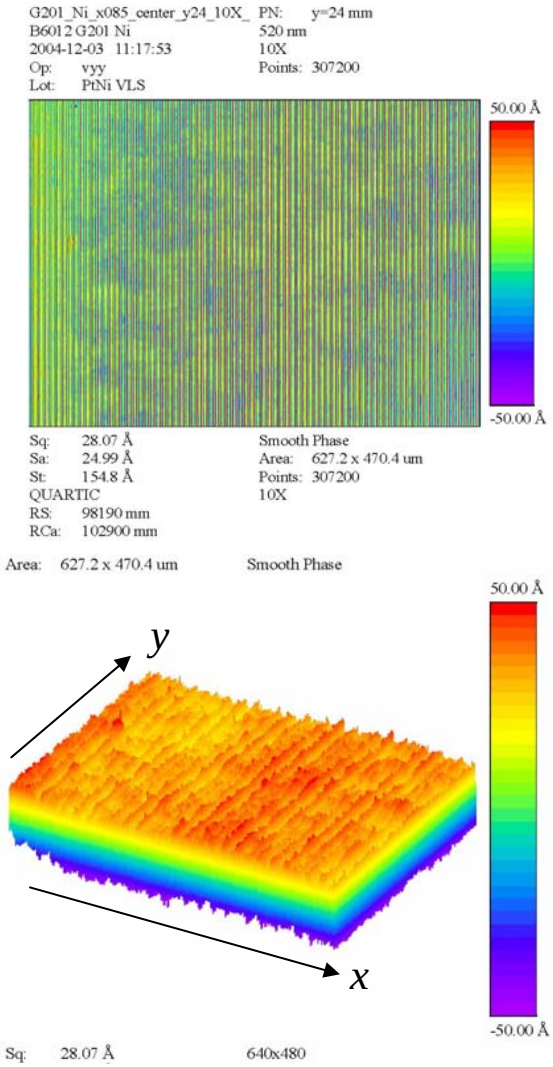
The roughness value is the same. But the PSD spectra are different!

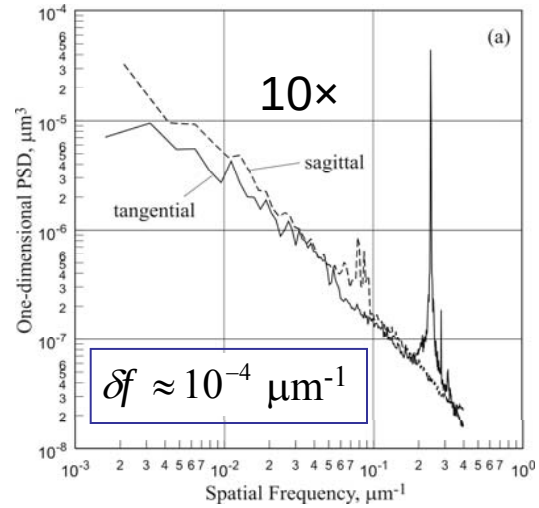


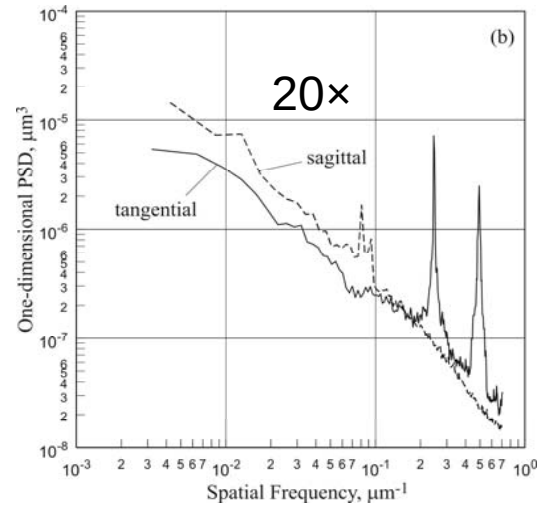
PSD based metrology permits measurement of instrumental modulation transfer function (MTF)

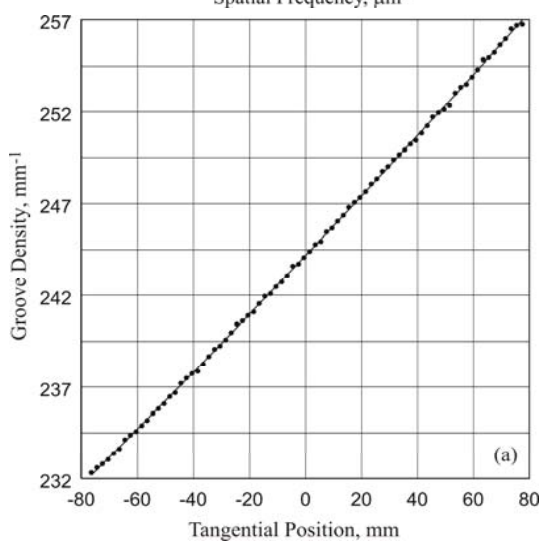
$$S_{MEASURED}(u,v) = S_{SURFACE}(u,v) \cdot MTF^2(u,v)$$

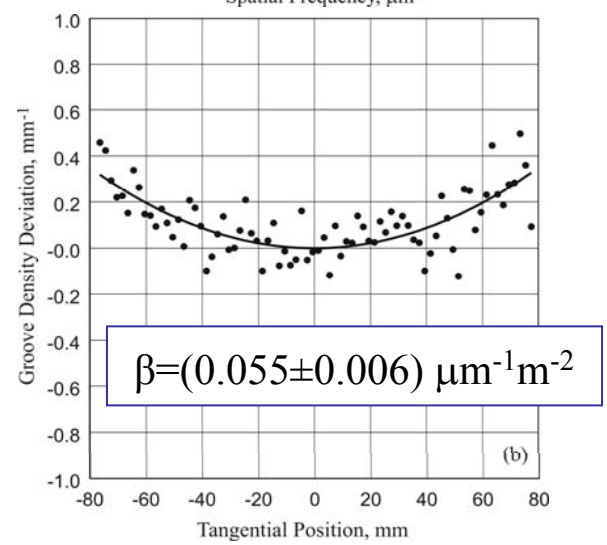
PSD measurements with
X-ray grating with variable groove density











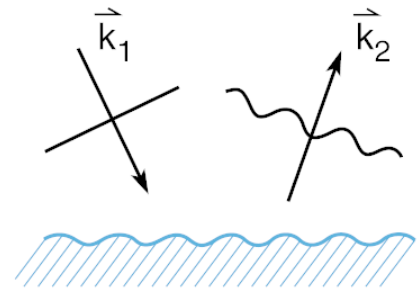
V. V. Yashchuk, A. D. Franck, S. C. Irick, M. R. Howells, A. A. MacDowell, W. R. McKinney, *Two dimensional power spectral density measurements of X-ray optics with the Micromap interferometric microscope,* SPIE Symposium on Optical Metrology 2005, part of LASER2005, World of Photonics , SPIE Proceedings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

Scattered intensity is proportional to the PSD in the smooth surface limit

Surface roughness is *imprinted* in the phase of the scattered wave.

$$F(\vec{x}) = e^{i\phi(\vec{x})} - 1 \approx i\phi(\vec{x}) = iq_z h(\vec{x}) \quad \text{if} \quad \phi(\vec{x}) << 1$$

$$\phi(\vec{x}) = q_z h(\vec{x})$$



$$\vec{q} = \vec{k}_2 - \vec{k}_1$$

$$2\pi\vec{f} = \vec{q}_{\parallel} = q_x\hat{x} + q_y\hat{y}$$

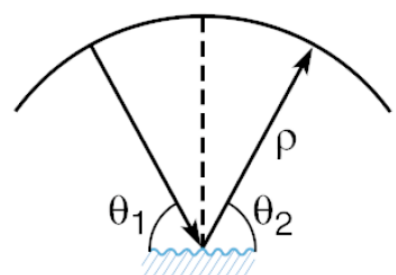
- The scattered wave in the far field may be calculated by the diffraction integral

$$S(\vec{f}) = \frac{2\pi \sin\theta_1}{\lambda^2} \int_A F(\vec{x}) e^{-i2\pi\vec{f}\cdot\vec{x}} d\vec{x} \approx i\frac{2\pi \sin\theta_1}{\lambda^2} q_z H(\vec{f})$$

- The scattered intensity,

$$I_{sca} = |u|^2 = \frac{|S|^2}{k^2\rho^2} RI_0 \approx \frac{RI_0}{\rho^2}\frac{\sin^2\theta_1}{\lambda^2} q_z^2 \left|H(\vec{f})\right|^2$$

$$u = S\frac{e^{-ik\rho + i\omega t}}{ik\rho} ru_0$$



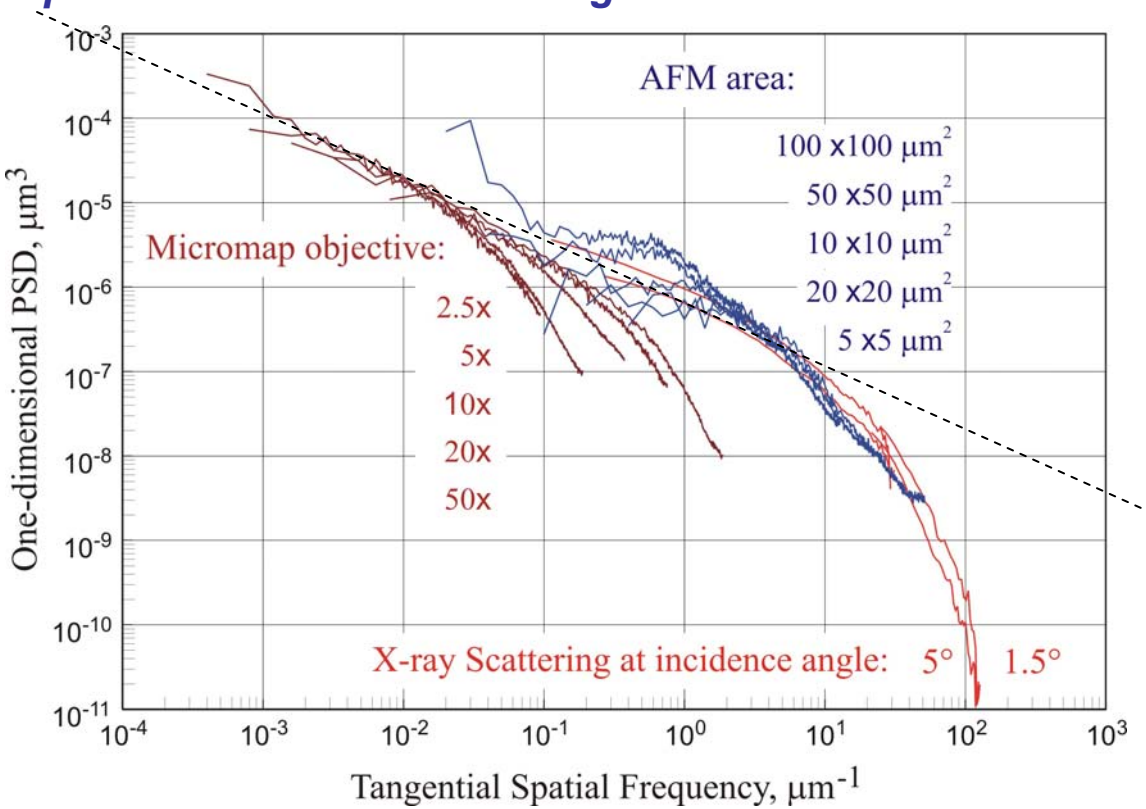
- Angular scattering distribution:

$$\frac{1}{P_0}\frac{dP}{d\Omega} = \frac{1}{I_0 A \sin\theta_1}\rho^2 \langle I_{sc} \rangle = \frac{16\pi^2}{\lambda^4}\sin^3\theta \cdot R \cdot \mathrm{PSD}(\vec{f})$$

courtesy of Eric Gullikson

PSD measurements with the real instruments

MicroMap-570 measurement with a gold coated stainless steel mirror [1,2]



Reliable PSD measurement requires correction for the instrument MTF.

Standard test surfaces and MTF calibration procedures must be developed.

[1] 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).

[2] 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).

Step-height standard

P. Z. Takacs, M. X. Li, K. Furenlid, E. L. Church,
Step-height standard for surface-profiler calibration, SPIE Proceedings 1995, 235-44 (1993).

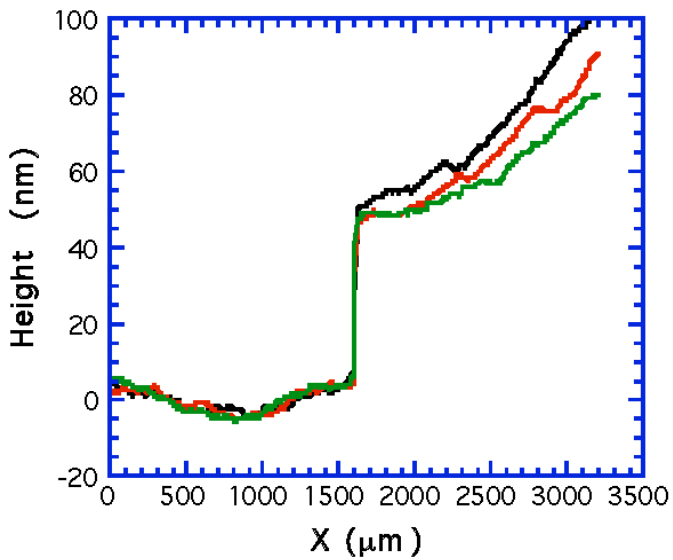


Fig. 1 Scans across the edge on a commercially available step height standard. The variability in the edge height and the surface irregularity are typical of the quality of this type of standard.

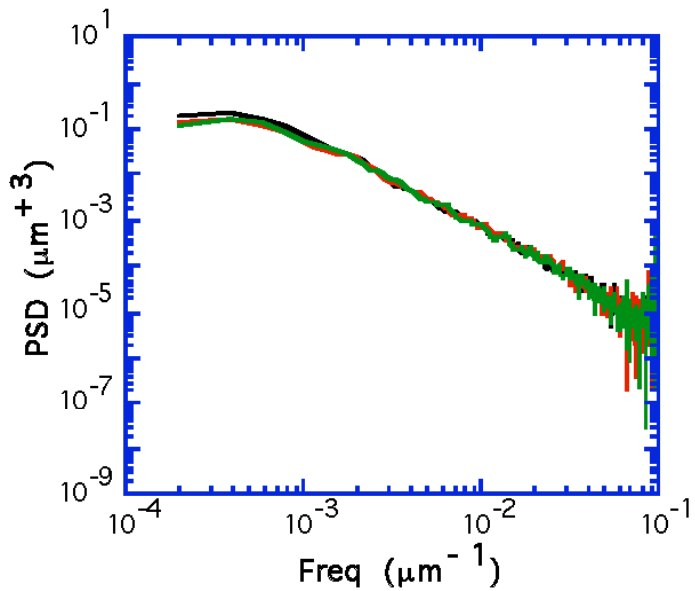


Fig. 2 PSD curves for the profiles in Fig. 1. Intrinsic surface roughness contributes to the noise in the high frequency region. A Blackman filter has been used to pre-process the raw data and the restoration filter appropriate for this profiler has been applied to spectra.

Disadvantages:

- $\propto 1/f^2$ ***intrinsic PSD spectrum and, therefore, low sensitivity to the higher spatial frequency distortion;***
- ***necessity to preprocess data to filter out PSD variations at higher spatial frequencies;***
- ***strong dependence of calibration on position of the step in the instrumental field of view.***

Introduction to

Binary Pseudo-random (BPR) sequences

BPR sequence with 1023 elements

for n=10 with recursion coefficient M=45 [a)]

1,1,1,1,1,1,1,1,1,1,0,0,0,0,0,1,1,0,1,1,1,1,1,1,0,1,0,1,0,1,0,0,1,0,0,0,1,1,0,0,1,1,0,1,0,0,0,0,1,1,0,0,0,0,1,1,0,1,1,
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0,1,1,1,1,1,0,1,1,1,1,1,0,1,1,0,1,1,0,1,0,0,0,0,0,1,0,0,0,1,1,0,1,1,1,0,1,1,0,1,1,1,1,0,0,0,1,0,0,1,0,0,1,1,0,0,0,0,1,
0,0,1,1,0,0,1,0,1,0,0,0,1,1,1,1,0,1,0,0,1,0,0,0,0,1,0,0,1,0,0,0,1,0,0,0,1,1,1,1,1,1,0,0,1,1,0,1,1,1,0,0,1,0,1,1,0,1,1,
1,0,1,0,0,1,1,1,0,0,1,1,1,0,0,1,0,1,0,0

[a)] D. D. Koleske, and S. J. Sibener, *Generation of pseudorandom sequence for use in cross-correlation modulation,* Rev. Sci. Instrum. 63(8), 3852-3855 (1992).

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Introduction to

Binary Pseudo-random (BPR) sequences

BPR sequence with 1023 elements

for n=10 with recursion coefficient M=45 [a)]

1,1,1,1,1,1,1,1,1,1,0,0,0,0,0,1,1,0,1,1,1,1,1,1,0,1,0,1,0,1,0,0,1,0,0,0,1,1,0,0,1,1,0,1,0,0,0,0,1,1,0,0,0,0,1,1,0,1,1,
0,1,1,1,0,0,0,0,1,1,0,0,1,0,1,1,0,0,1,1,0,1,1,0,0,0,1,0,0,1,1,0,1,1,0,1,0,1,0,0,0,1,1,0,1,0,1,0,1,1,1,1,0,0,1,0,0,0,1,
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1,1,0,0,0,1,0,1,1,0,0,1,1,0,0,1,0,0,0,0,0,1,0,1,0,1,1,0,0,1,0,1,1,1,0,1,1,0,0,1,1,1,0,1,0,0,1,0,1,0,0,1,0,1,1,
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0,0,1,0,1,1,1,0,1,0,0,0,1,1,0,0,0,1,0,1,0,1,0,1,0,1,0,0,0,0,0,0,1,0,0,1,0,1,0,1,0,0,1,1,0,0,1,1,1,0,0,0,0,1,0,0,0,1,0,
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0,0,1,1,0,0,1,0,1,0,0,0,1,1,1,1,0,1,0,0,1,0,0,0,0,1,0,0,1,0,0,0,1,0,0,0,1,1,1,1,1,1,0,0,1,1,0,1,1,1,0,0,1,0,1,1,0,1,1,
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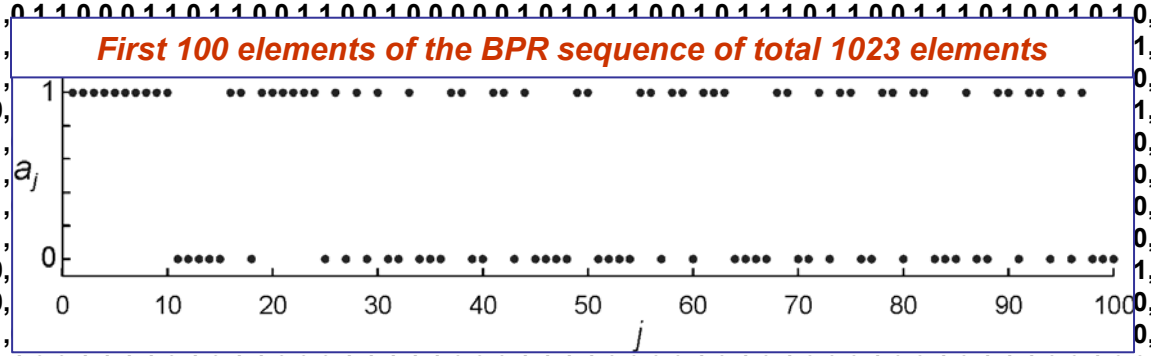

[a)] D. D. Koleske, and S. J. Sibener, *Generation of pseudorandom sequence for use in cross-correlation modulation,* Rev. Sci. Instrum. 63(8), 3852-3855 (1992).

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V. V. Yashchuk, W. R. McKinney, P. Z. Takacs, *"Binary Pseudo-random Grating as a standard test surface for measurement of modulation transfer functions of interferometric microscopes,"* SPIE Proc. 6704-07 (2007)

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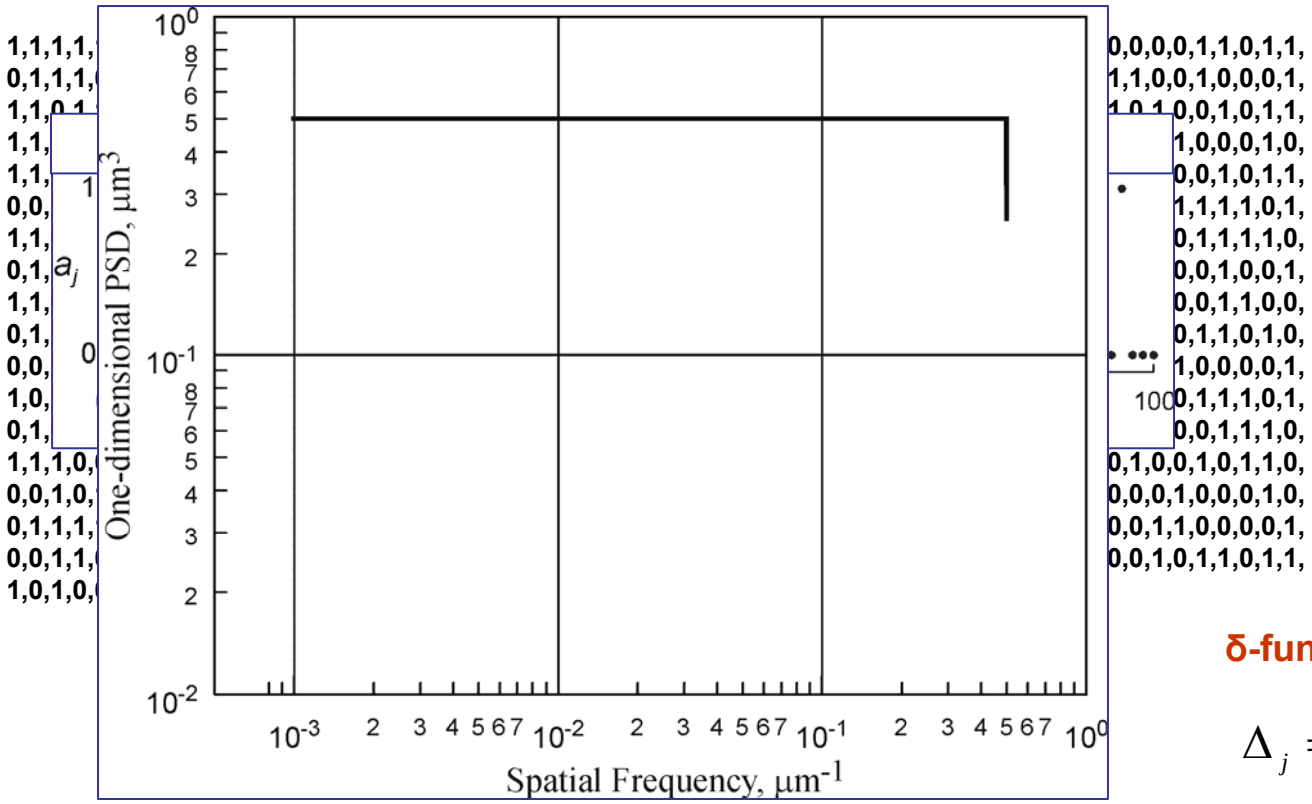

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The best *random* sequences are mathematically strongly *deterministic*!

V. V. Yashchuk, W. R. McKinney, P. Z. Takacs, *"Binary Pseudo-random Grating as a standard test surface for measurement of modulation transfer functions of interferometric microscopes,"* SPIE Proc. 6704-07 (2007)

Binary Pseudo-random Chopping in a Time-of-flight Spectrometer

$$f(v)dv = \frac{l}{t^2} f\left(\frac{l}{t}\right) dt = F(t)dt.$$

$$F(t) = \int_{-\infty}^{\infty} \delta(t-\tau) F(\tau) d\tau$$

$$F(t) = \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\infty} A(t-\tau) F(\tau) d\tau \right] B(t-\mu) d\mu =$$

$$\int_{-\infty}^{\infty} \left[\int_{-\infty}^{\infty} A(t-\tau) B(t-\tau-\mu) d\mu \right] F(\tau) d\mu = \int_{-\infty}^{\infty} \delta(t-\tau) F(\tau) d\tau$$

pseudo-random chopping in order to increase duty cycle

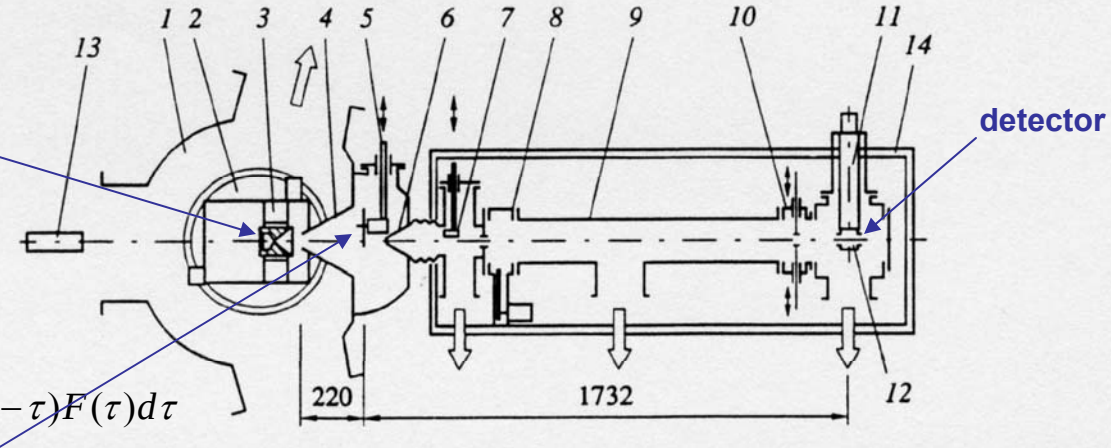

Fig. 1. Diagram of the cross-correlation TOF spectrometer of molecular beams: (*1*) source chamber; (*2*) alignment stage; (*3*) supersonic nozzle; (*4* and *6*) skimmers; (*5*) chopper; (*7*) calibration effusive source; (*8*) vacuum seal; (*9*) transit chamber; (*10*) diaphragm unit; (*11*) MX-7304A mass spectrometer; (*12*) ionizer; (*13*) laser; and (*14*) alignment platform.

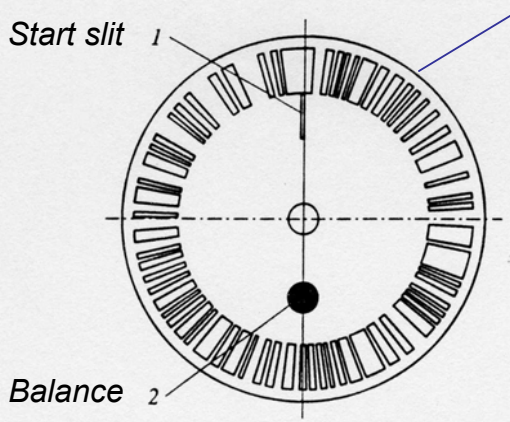

Fig. 2. Chopper disk: (*1*) starting slit and (*2*) balancing load.

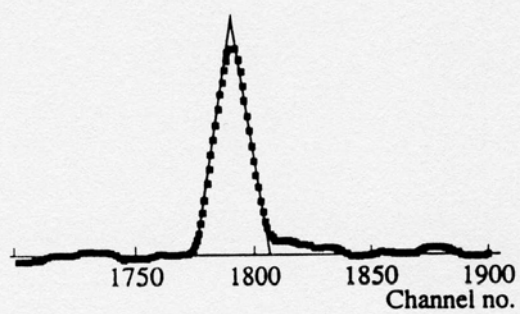

Fig. 5. Autocorrelation functions of the TOF spectrometer obtained by the convolution of the sequence of light-beam choppings with an ideal inverse sequence $\{B_j\}$ (curve) and with a reconstructed inverse sequence $\{B_j^*\}$ (straight line).

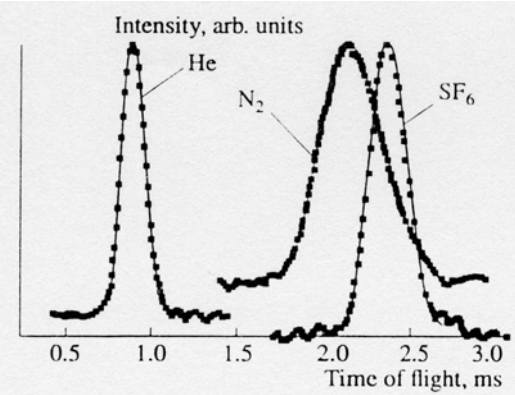

Fig. 6. TOF Spectra of He, N_2, and SF_6 beams. Solid lines are the results of the total fitting with parameters given in the table.

V. V. Yashchuk, B. N. Ashkinadzi, M. N. Groshev, V. F. Ezhov, T. A. Isaev, V. A. Knyazkov, G. B. Krygin, V. L. Ryabov, *Cross-Correlation Time-of-Flight Spectrometer of Gas-Dynamic Molecular Beams,* Instruments and Experimental Techniques, 40(4), 501 (1997).

Binary Pseudo-random Grating as a Standard Test Surface for MTF measurement

- ✓ *A prototype BPR grating test surface was etched into a silicon substrate using a conventional lithographical process.*
- ✓ *The grating consists of*
  - *4095 elements;*
  - *2.5 μm groove width;*
  - *174 nm effective depth*
- ✓ *It is good for 2.5× objective with pixel size of 3.9 μm*

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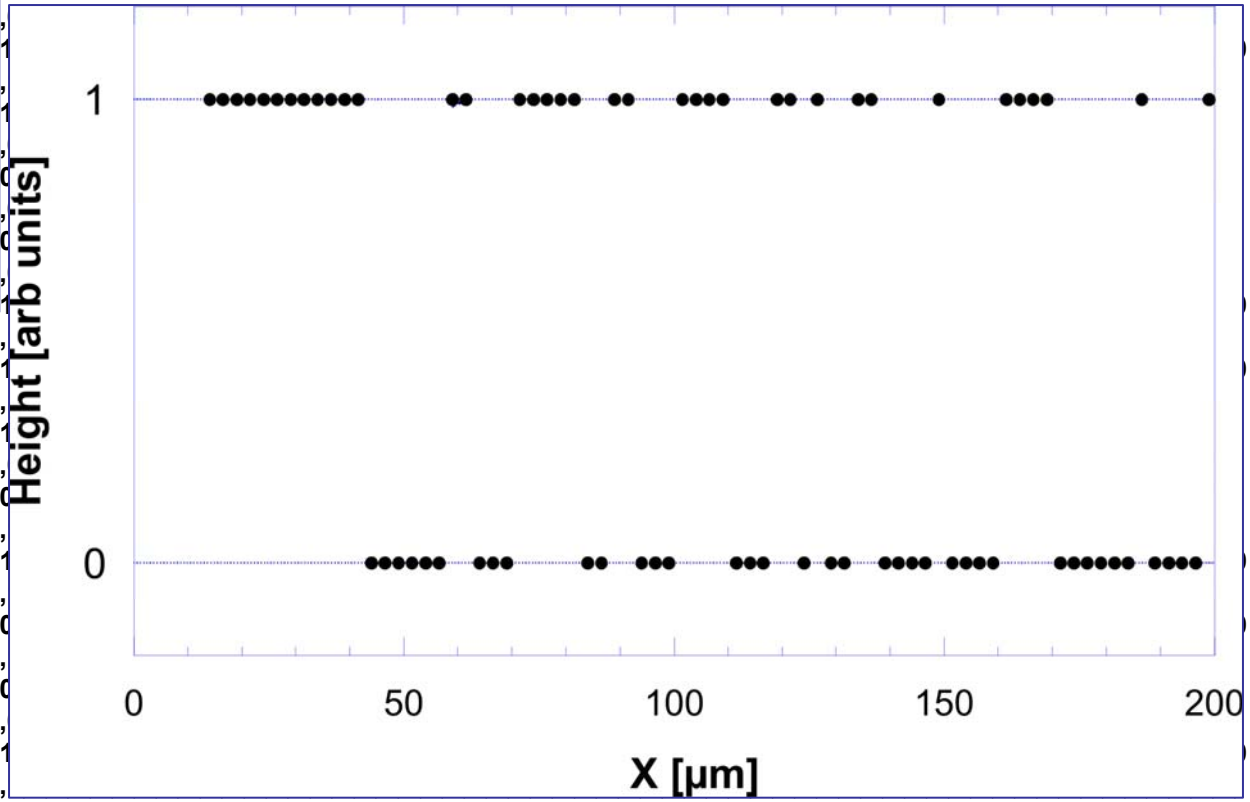

First 200 elements of the BPR sequence of total 4095 elements

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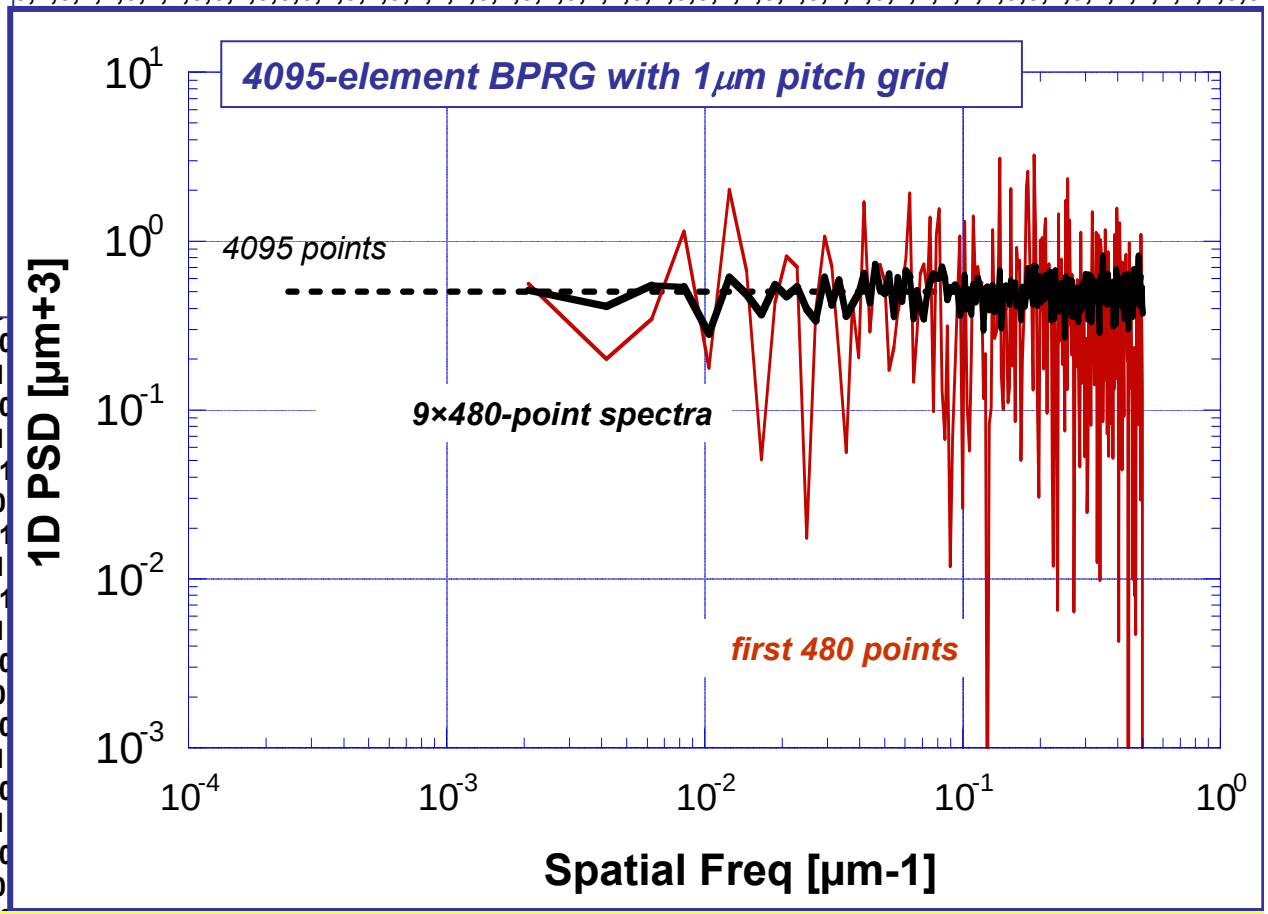


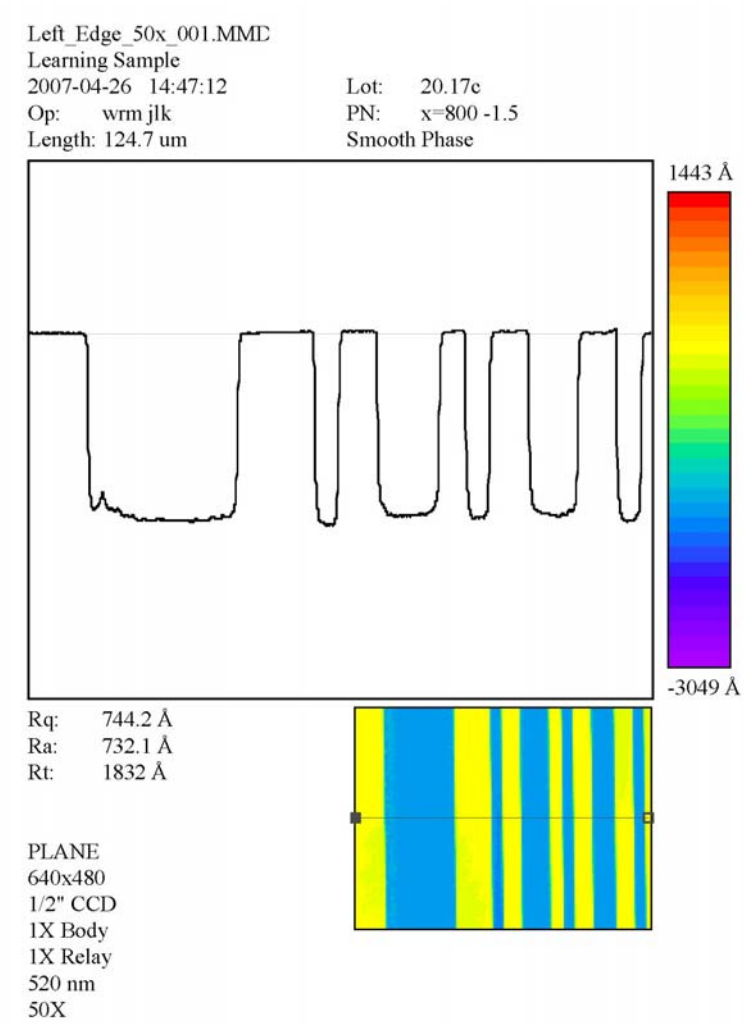
The PSD spectrum of the BPRG is mathematically strongly *deterministic*!

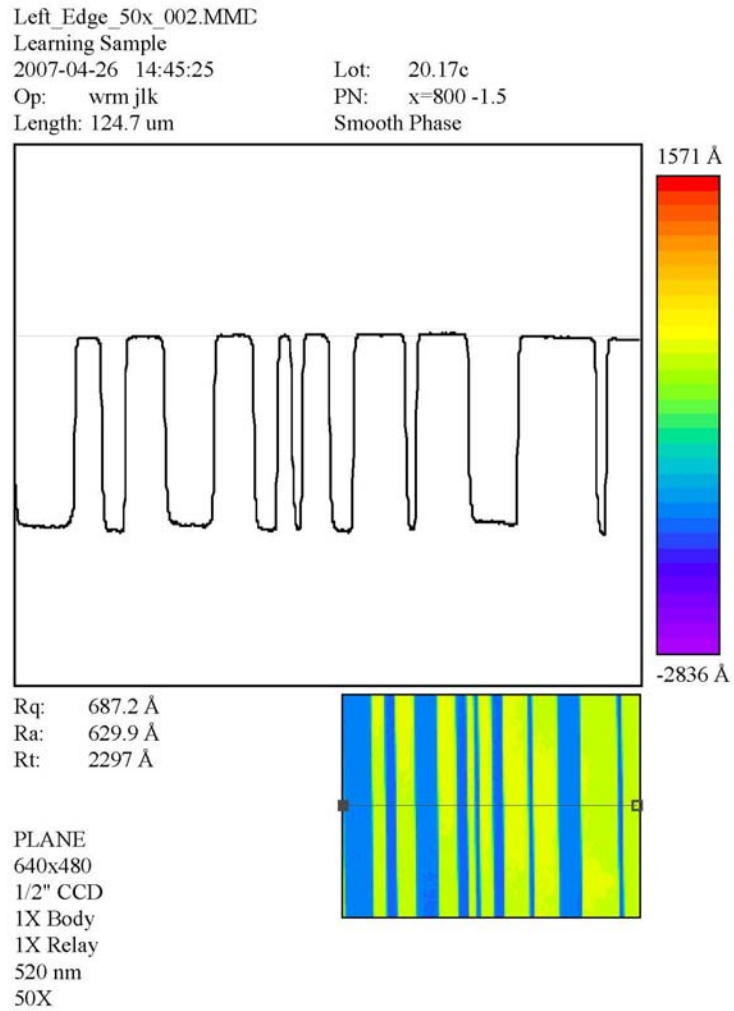
Micromap-570 measurement with

BPRG test surface (2.5 μm pitch)

50x objective

(0.26 μm pixel size)





Micromap-570 measurement with

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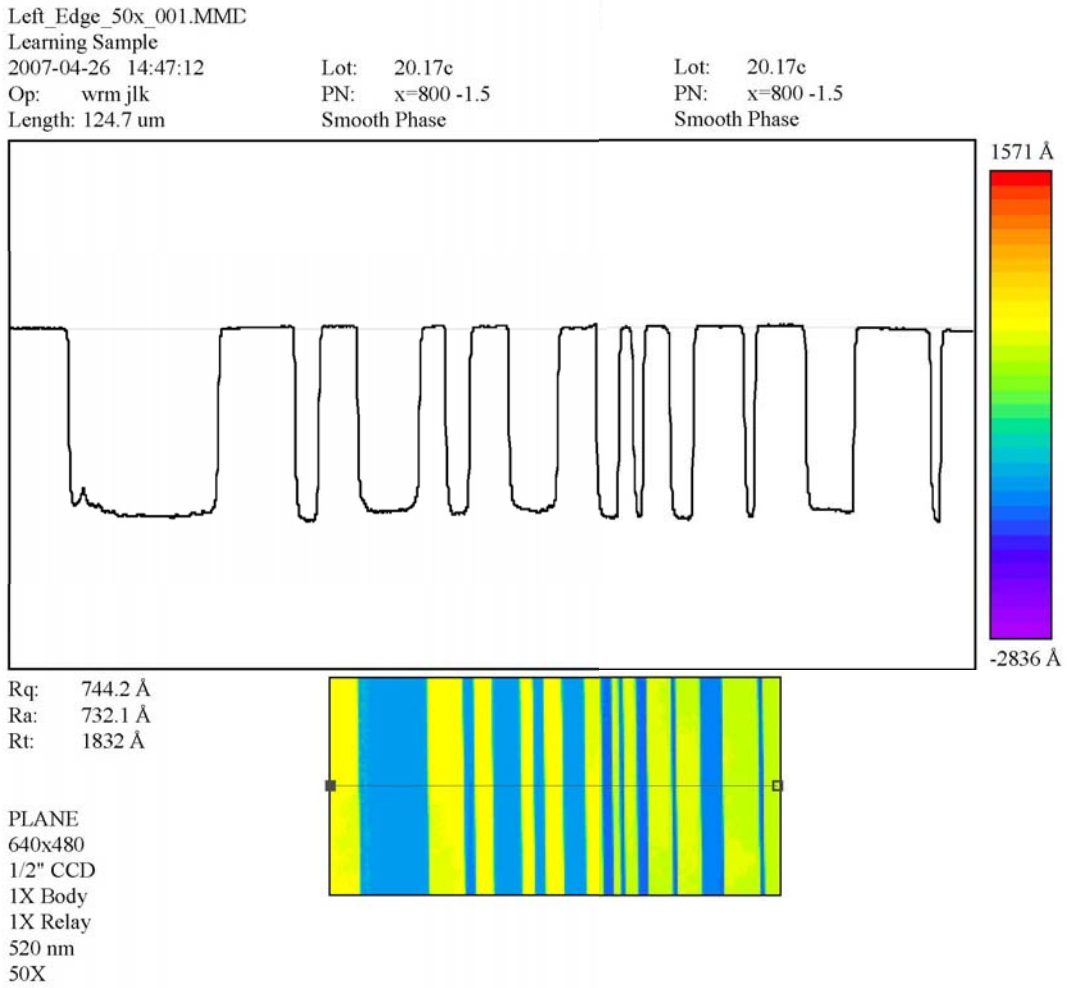
50x objective

(0.26 μm pixel size)



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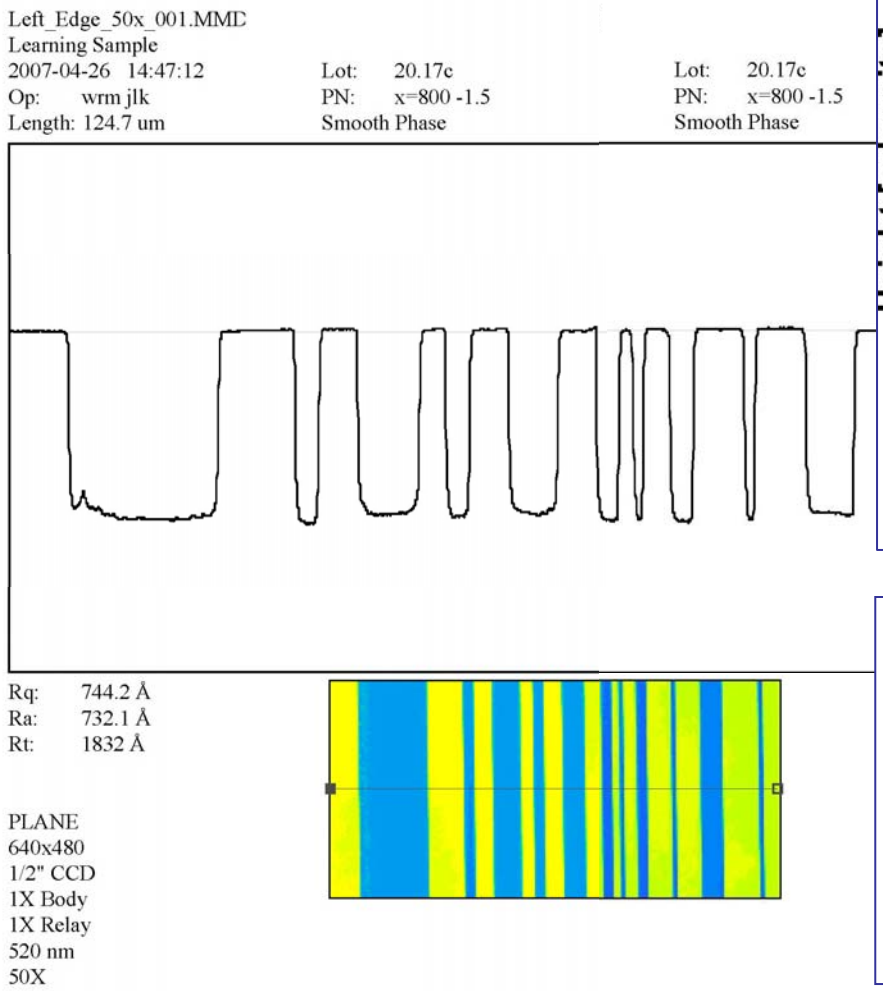
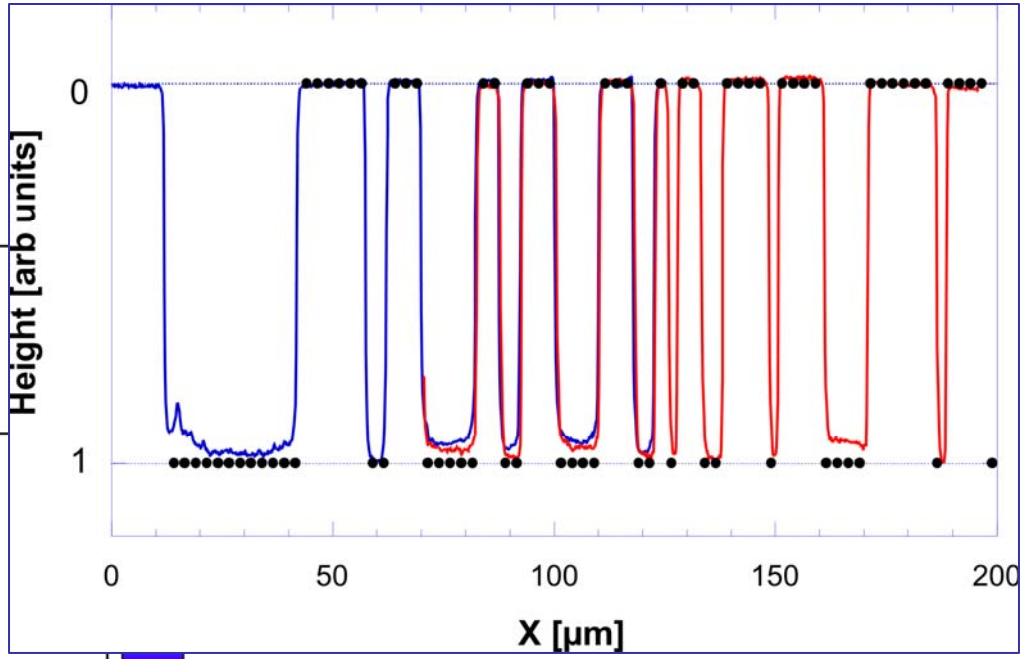




The etch depth was measured to be ~700 nm with an AFM and 174 nm with the Micromap™-570.

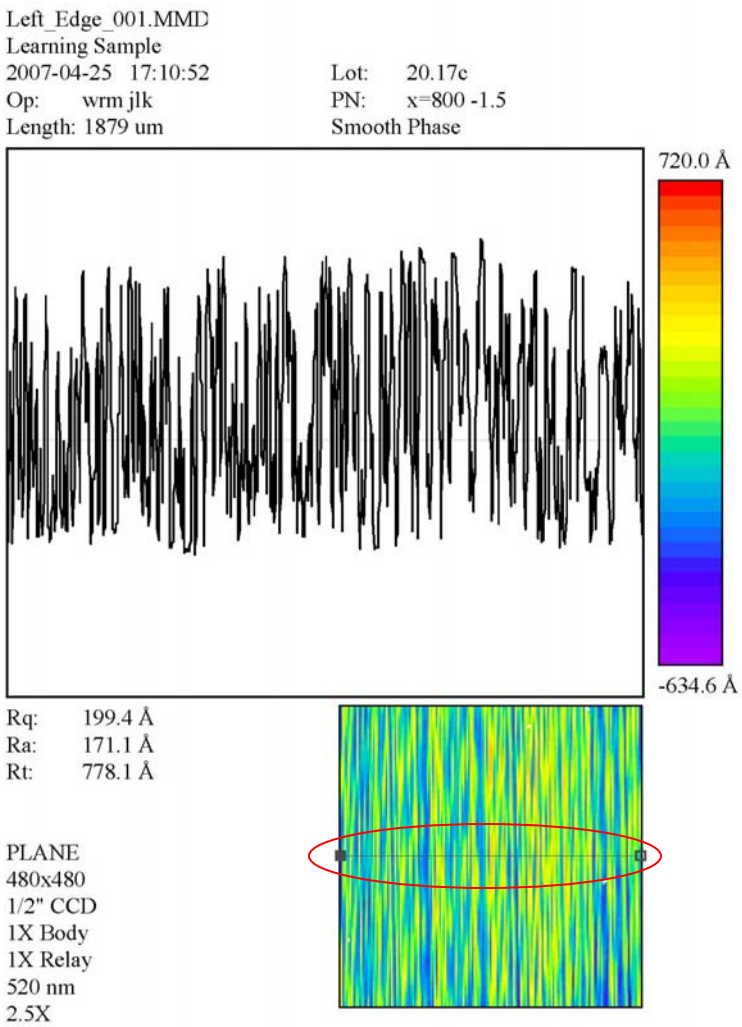
The discrepancy (λ=520 nm) is due to the uncertainty of the phase-retrieval algorithm of micro-roughness instruments.

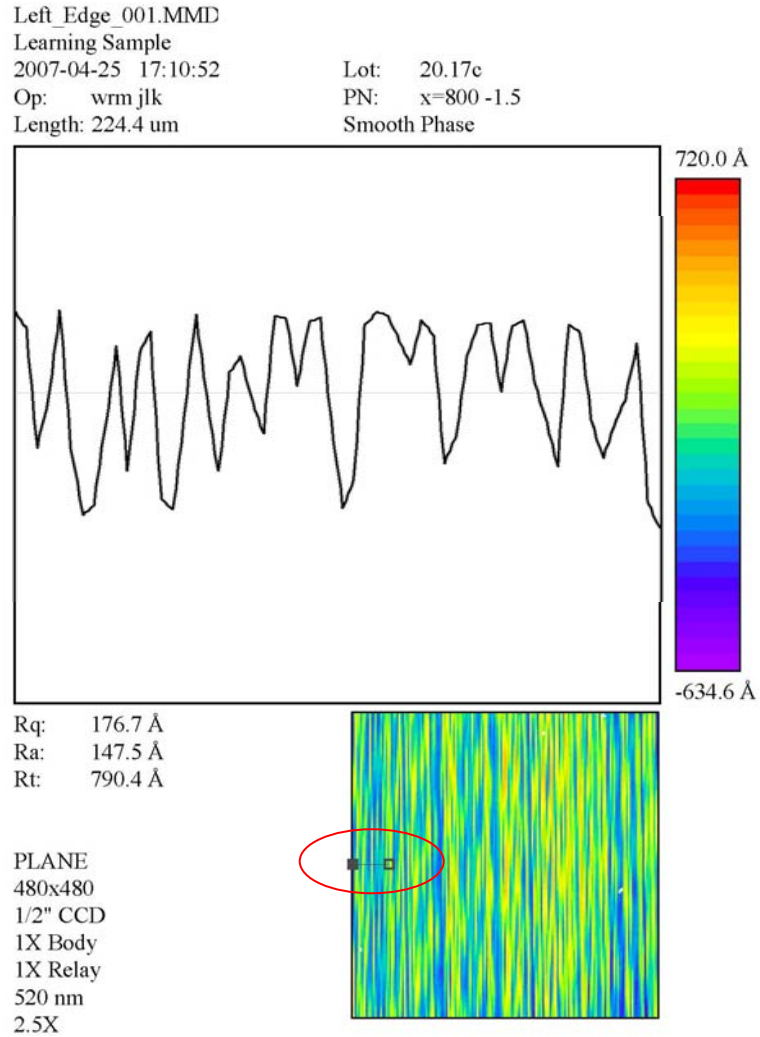
Micromap-570 measurement with

BPRG test surface (2.5 μm pitch)

2.5x objective

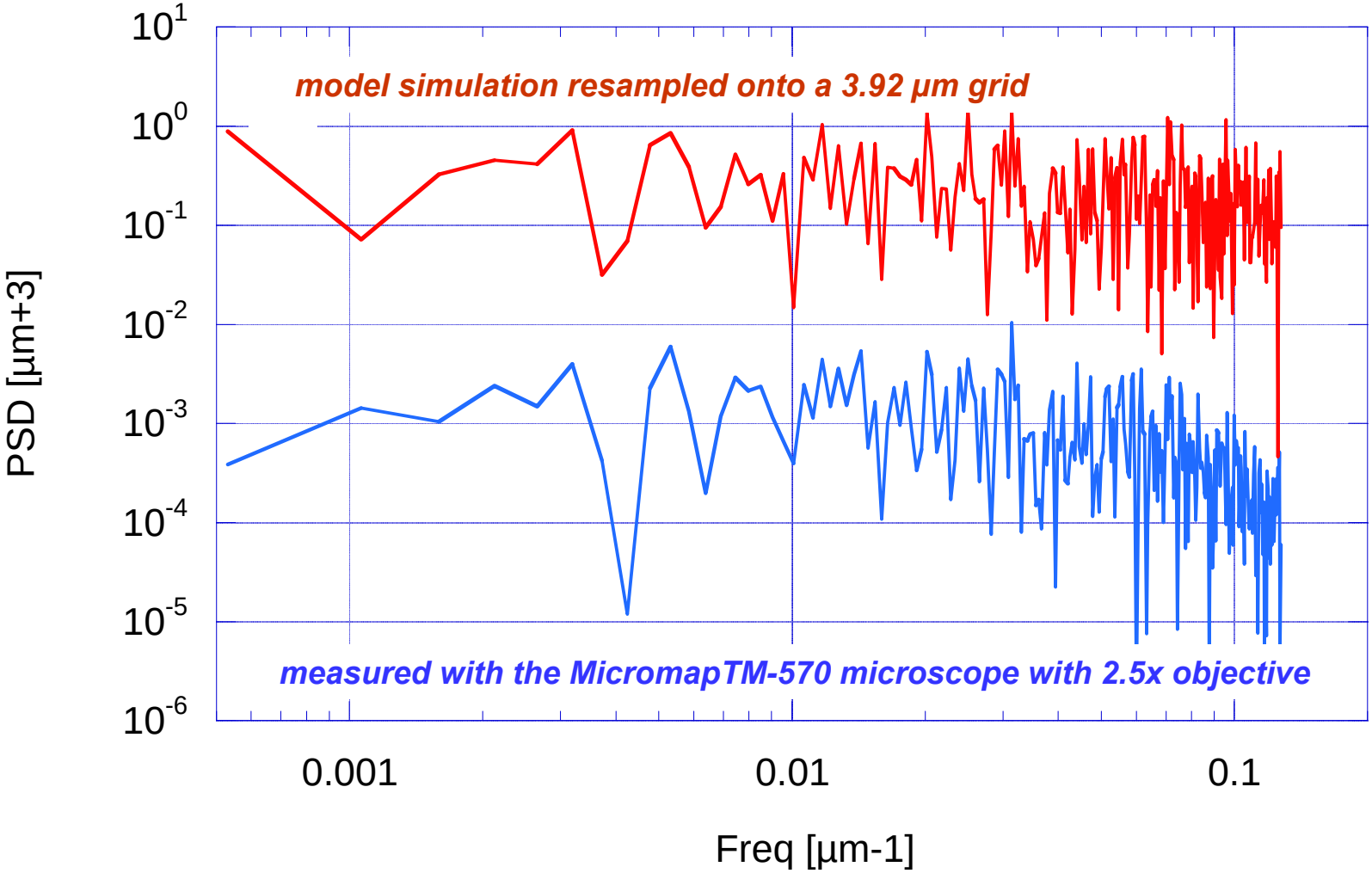
(3.9 μm pixel size)





PSD spectrum of BPRG test surface of 4095 elements with 2.5-μm pitch

The difference of the PSD spectra is due to the instrumental MTF

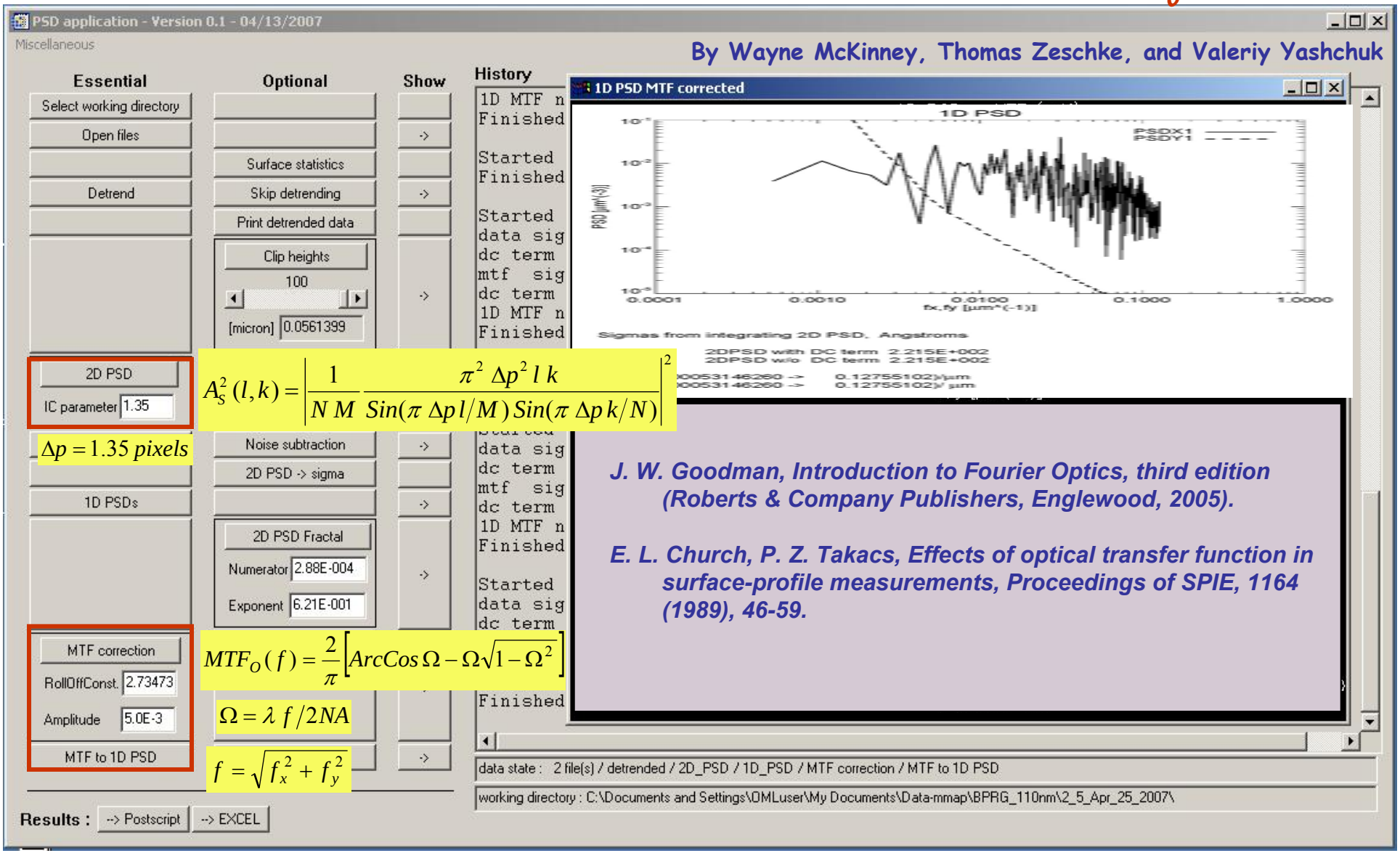


The simulation and measurement fields of view correspond to the 480 pixel row length in the Micromap. Vertical offset of the lower spectrum is made for clarity.

ALS OML PSD Software for Micromap™-570

Correction of incoherent transfer function of a diffraction-limited objective

By Wayne McKinney, Thomas Zeschke, and Valeriy Yashchuk



$$A_S^2(l,k) = \left| \frac{1}{N\,M} \frac{\pi^2\,\Delta p^2\,l\,k}{Sin(\pi\,\Delta p\,l/M)\,Sin(\pi\,\Delta p\,k/N)} \right|^2$$

$$\Delta p = 1.35\ pixels$$

$$MTF_O(f) = \frac{2}{\pi}\left[ArcCos\,\Omega - \Omega\sqrt{1-\Omega^2} \right]$$

$$\Omega = \lambda\, f / 2NA$$

$$f = \sqrt{f_x^2 + f_y^2}$$

J. W. Goodman, Introduction to Fourier Optics, third edition (Roberts & Company Publishers, Englewood, 2005).

E. L. Church, P. Z. Takacs, Effects of optical transfer function in surface-profile measurements, Proceedings of SPIE, 1164 (1989), 46-59.

ALS OML PSD Software for Micromap™-570

Correction of incoherent transfer function of a diffraction-limited objective

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PSD application - Version 0.1 - 04/13/2007

Miscellaneous

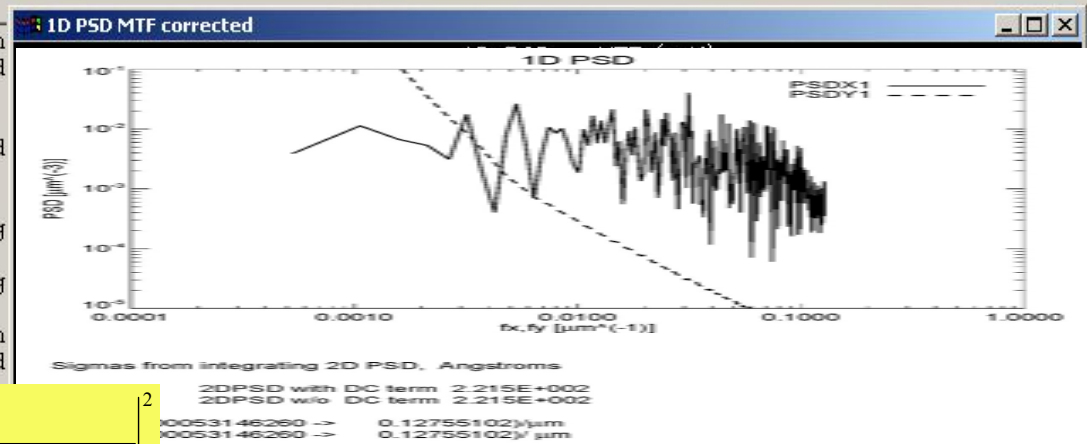
Essential: Select working directory; Open files; Detrend; 2D PSD; IC parameter 1.35; 1D PSDs; MTF correction; RollOffConst. 2.73473; Amplitude 5.0E-3; MTF to 1D PSD

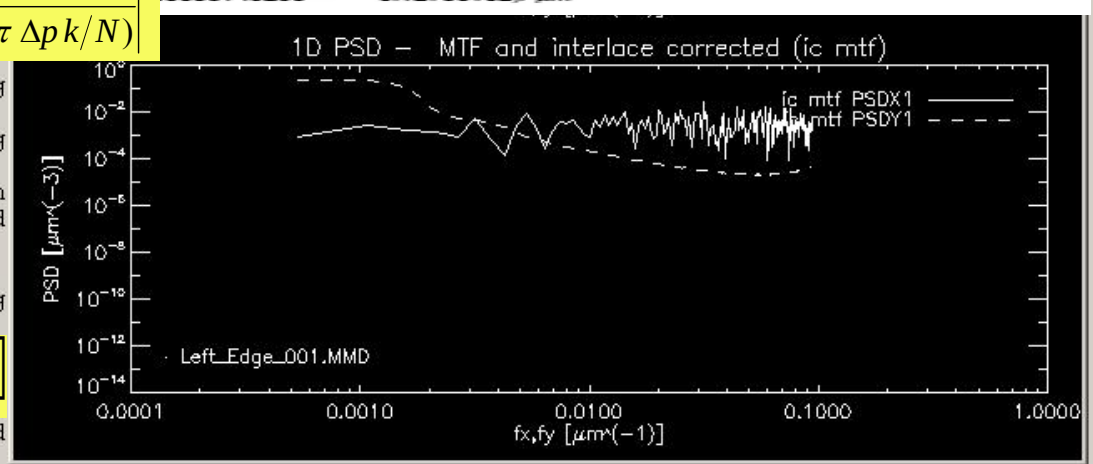
Optional: Surface statistics; Skip detrending; Print detrended data; Clip heights 100 [micron] 0.0561399; Noise subtraction; 2D PSD -> sigma; 2D PSD Fractal; Numerator 2.88E-004; Exponent 6.21E-001

Show: ->

History:
```
1D MTF n
Finished

Started
Finished

Started
data sig
dc term
mtf  sig
dc term
1D MTF n
Finished

Started
data sig
dc term
mtf  sig
dc term
1D MTF n
Finished

Started
data sig
dc term

Finished
```

Results : --> Postscript --> EXCEL





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data state : 2 file(s) / detrended / 2D_PSD / 1D_PSD / MTF correction / MTF to 1D PSD

working directory : C:\Documents and Settings\OMLuser\My Documents\Data-mmap\BPRG_110nm\2_5_Apr_25_2007\

NEXT

MTF correction based on PSD measurements with 2D Binary Pseudo-random test surface

This Uniformly Redundant Array was generated with a code provided by Stefano Marchesini

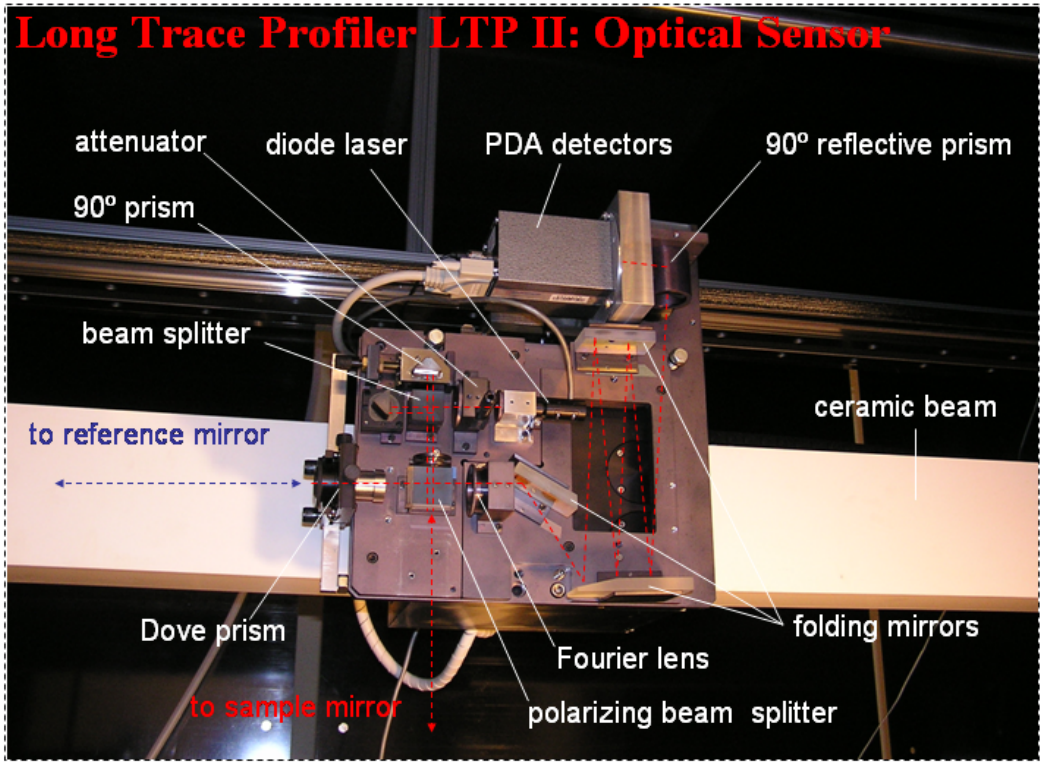
Rossana Combie (ED) works on fabrication

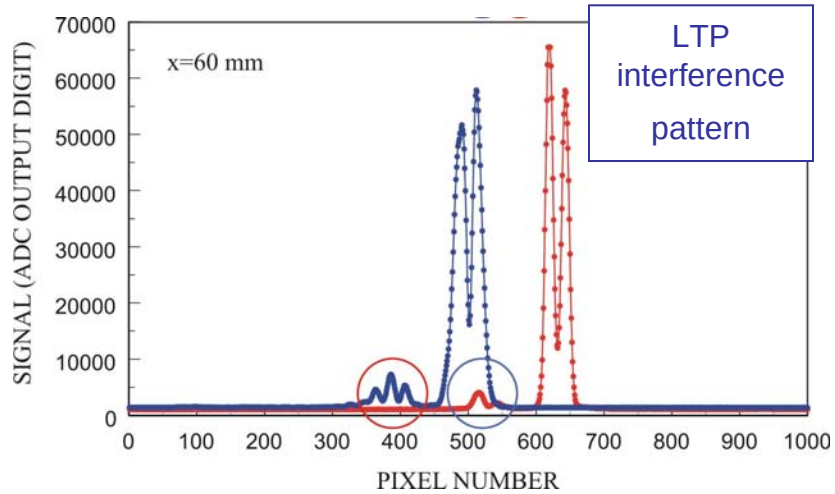
International standard (ISO) based on Binary Pseudo-random test surface

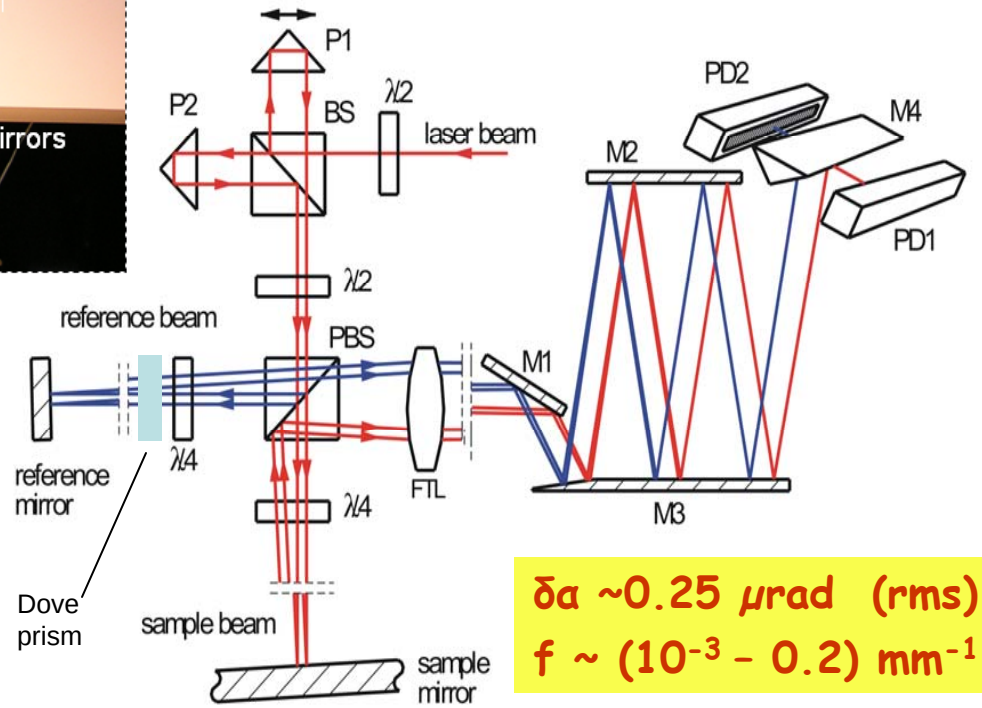
Optics and Electro-Optics Standards Council

Long trace profiler LTP-II:

Surface characterization at lower spatial frequencies







$\delta\alpha$ ~0.25 μrad (rms)

$f \sim (10^{-3} - 0.2)\ mm^{-1}$

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).

History of the Long Trace Profiler at the ALS

5-10 μrad

LTP-II system purchased from Continental Optics with old wheel-based drive system

~1 μrad

Reference arm and dual array detector, drive belt to replace wheel

~0.7 μrad

Enclosures designed to reduce air convection and stabilize temperature added

~0.25 μrad

2D CCD detector and original method to reduce systematic errors developed

0.1 μrad

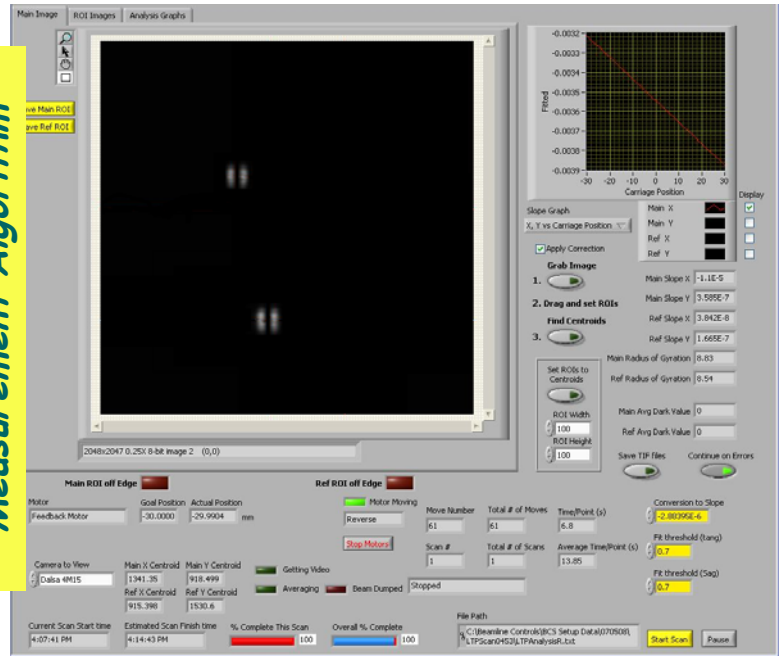
Precise Calibration with Universal Test Mirror is under development

2D Slope Measuring Profiler *a la* BESSY NOM

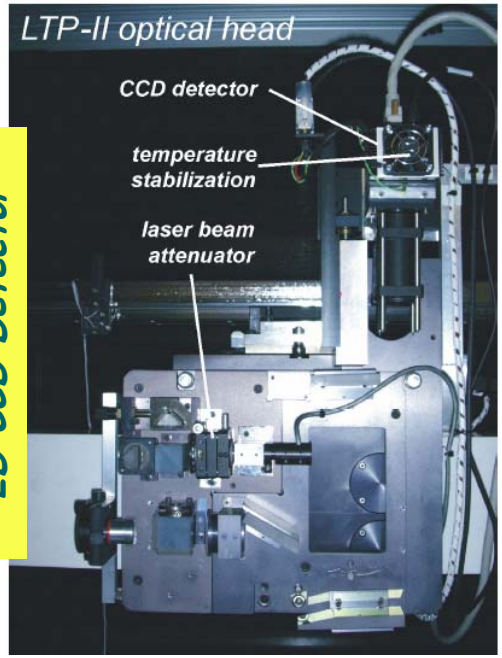
1990 — 1994-1995 — 2004 — 2007 — 20($$)$^{-1}$

Data Acquisition

Measurement Algorithm



2D CCD Detector



Bendable mirror tuning with the LTP:

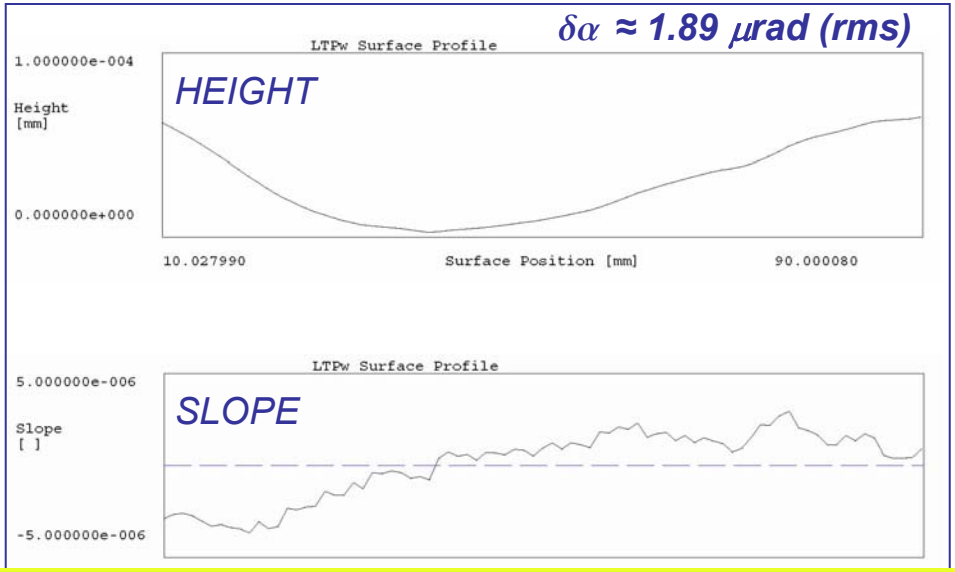
Problem to be solved

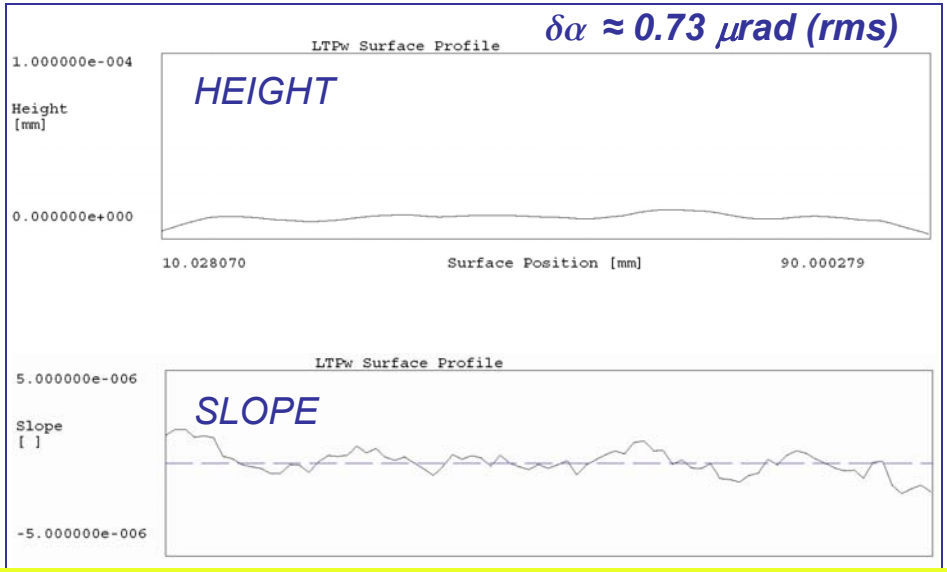
100-mm-long elliptical mirror specified with:

***r* = 18.901 m, *r′* = 0.120 m, *θ* = 0.0031 rad**

Figure-of-merit for adjustment:

***δα* ≤ 1 *μ*rad (rms)**





The problem:

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

Settings: V_{US} = 3.250 V V_{DS} = 1.650 V	V_{US} = 3.275 V V_{DS} = 1.650 V

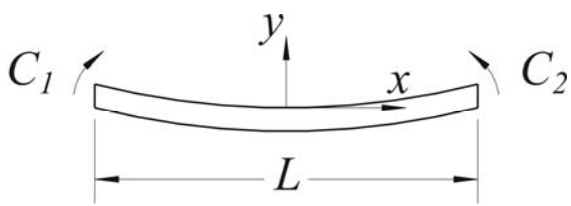
W. R. McKinney, S. C. Irick, J. L. Kirschman, A. A. MacDowell, A. Warwick, V. V. Yashchuk, "New Procedure for the Adjustment of Elliptically Bent Mirrors with the Long Trace profiler," SPIE Proc. 6704-15 (2007)

Bendable mirror tuning with the LTP:

Theory

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:

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

Bendable mirror tuning with the LTP:

Application of regression analysis

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:

$$\eta(x_i, C) = \Delta C_0 + \Delta C_1\ f_1(x_i) + \Delta C_2\ f_2(x_i)$$

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:

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

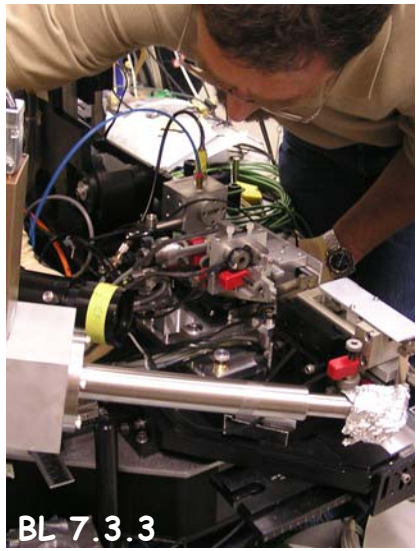
$$D(\Delta\hat{C}^*) = \sigma^2(\hat{A}'\hat{A})^{-1}$$

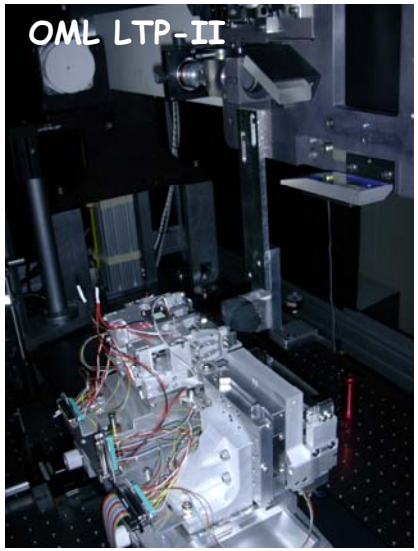
$$D\hat{y} = \sigma^2\hat{I}$$

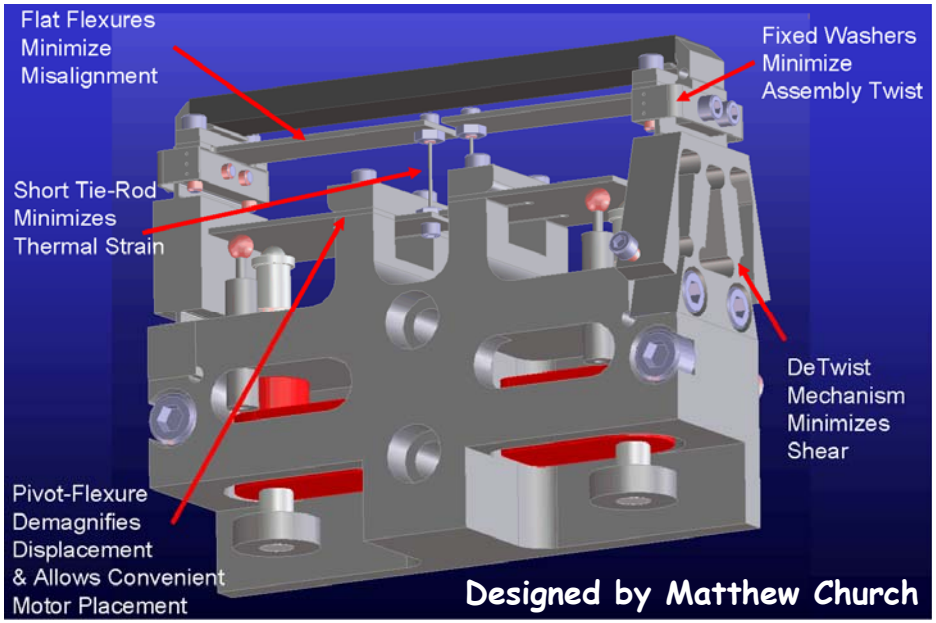
$$\sigma^2 \approx \frac{\sum_i [\delta\alpha_{20} - \Delta C_1^*\ f_1^*(x_i) - \Delta C_2^*\ f_2^*(x_i)]^2}{m - p}$$

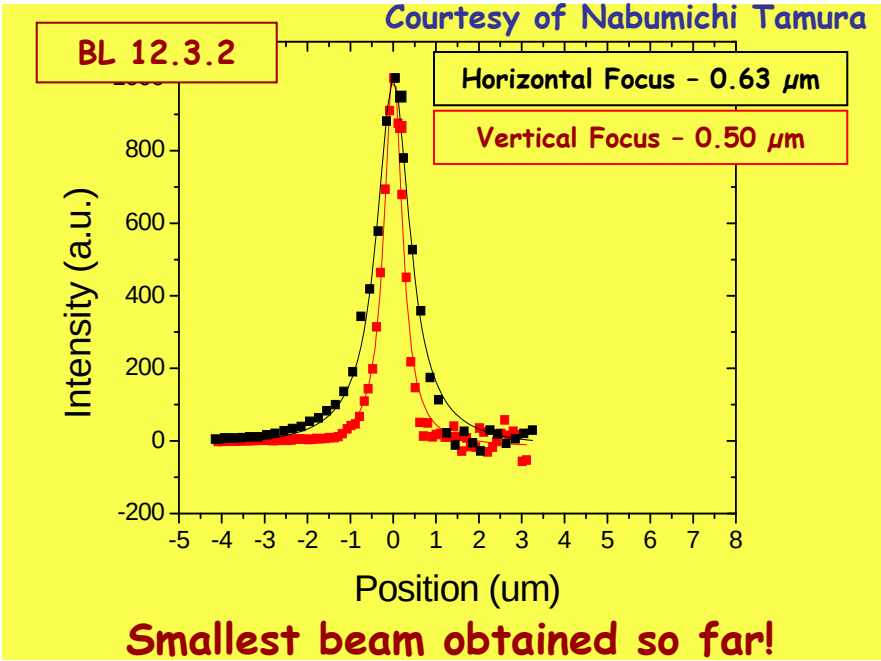
Bendable mirror tuning with the LTP:

Application to BL7.3.3 and BL12.3.2 KB mirrors

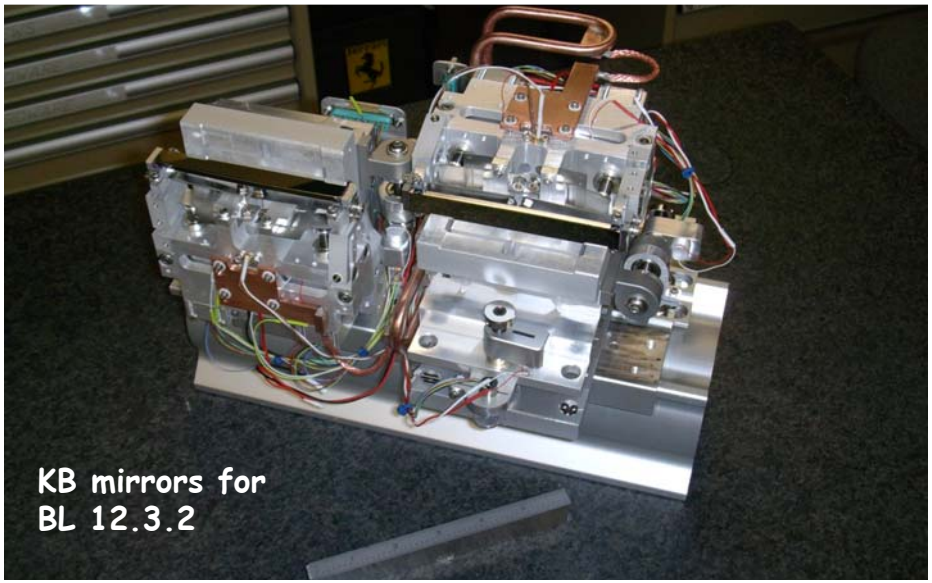








Smallest beam obtained so far!

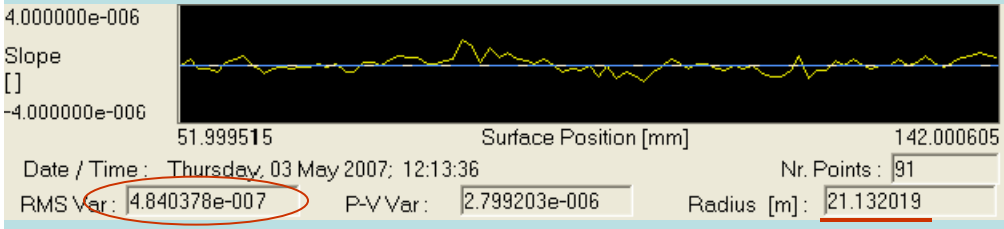


LTP-II systematic errors and requirements for precise calibration

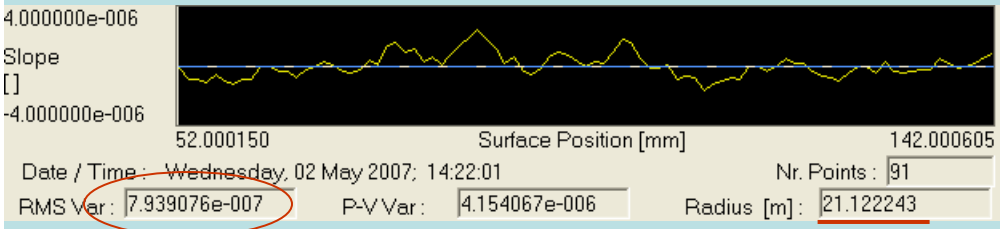
1. High performance calibration must account for peculiarities of optics under test and an experimental arrangement.

2. Calibration method must be universal, applicable to variety of optics and experimental arrangements

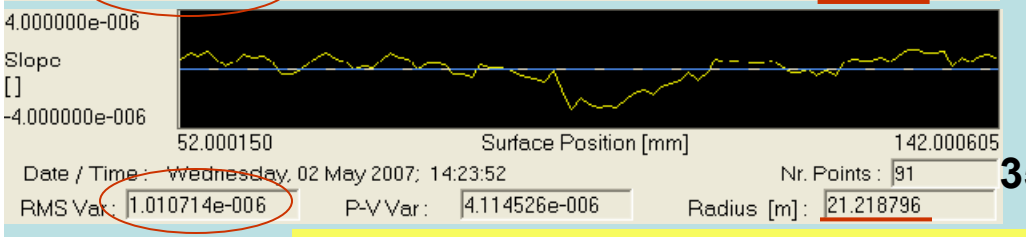
*Grating blank measured with upgraded ALS LTP-II *)*



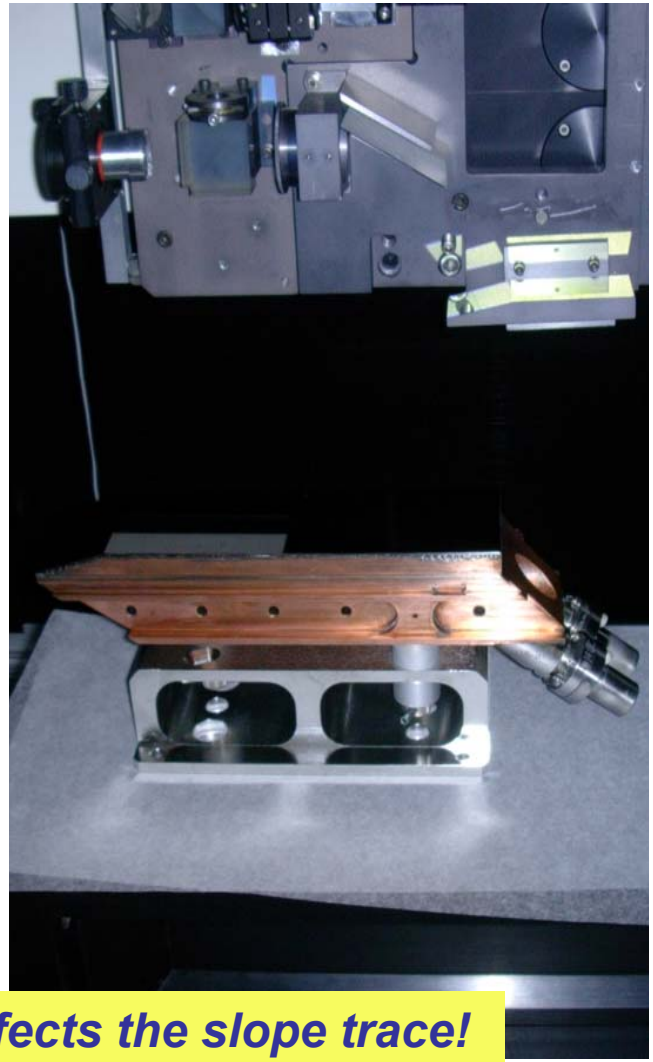
50mm



150mm



350mm

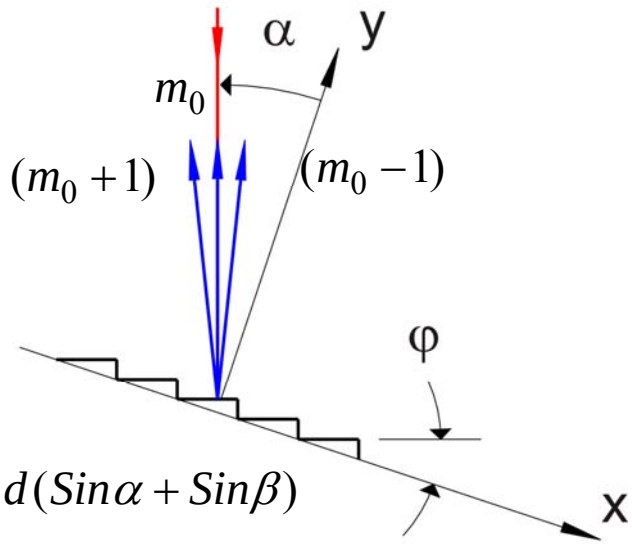


The distance to the surface under test affects the slope trace!

) J. L. Kirschman, E. E. Domning, K. D. Franck, S. C. Irick, A. A. McDowell, W. R. McKinney, G. Y. Morrison, B. V. Smith, T. Warwick, V. V. Yashchuk, "Flat-field calibration of CCD detector for Long Trace Profiler," SPIE Proc.* ***6704**-18 (2007)*

Limitations of the existing calibration methods

Calibration with a diffraction grating [1)]



$$m\lambda = d(Sin\alpha + Sin\beta)$$

Littrow configuration: $\alpha = \beta = \varphi$

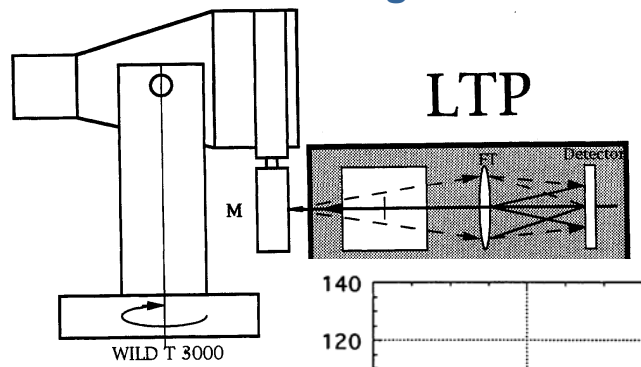
$$m_0 = {2d}/{\lambda}\, Sin\varphi$$

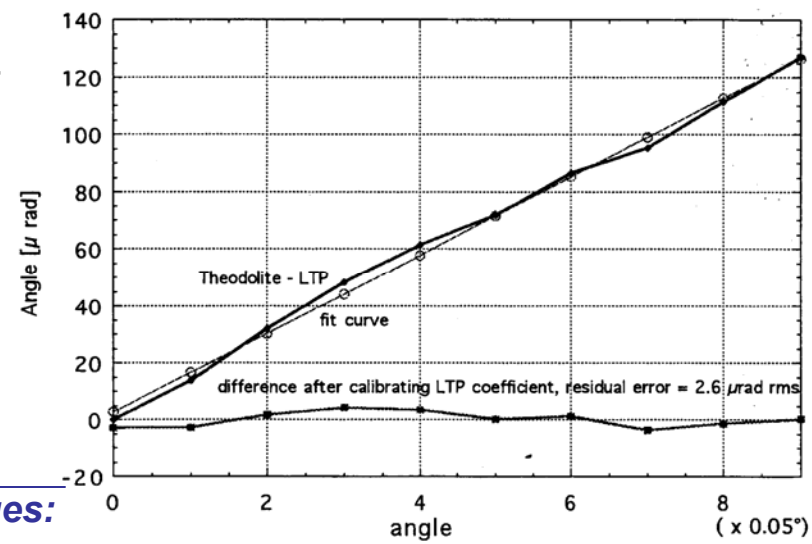
Disadvantages:

- ***provides linear approximation of the calibration***
- ***limited number of calibration points***
- ***depends on fabrication accuracy of the grating***
- ***requires calibration of the laser wavelength***

[1)] S. C. Irick, *Angle calibration of the long trace profiler using a diffraction grating,* Light Source Note LSBL-160 (Berkeley, 1992).

Calibration with a high resolution (0.03”) theodolite [2)]





Disadvantages:

- ***provides linear approximation of the calibration***
- ***depends on position of the reference mirror***
- ***manual operation, therefore limited number of calibration points***
- ***requires precise calibration of the theodolite***

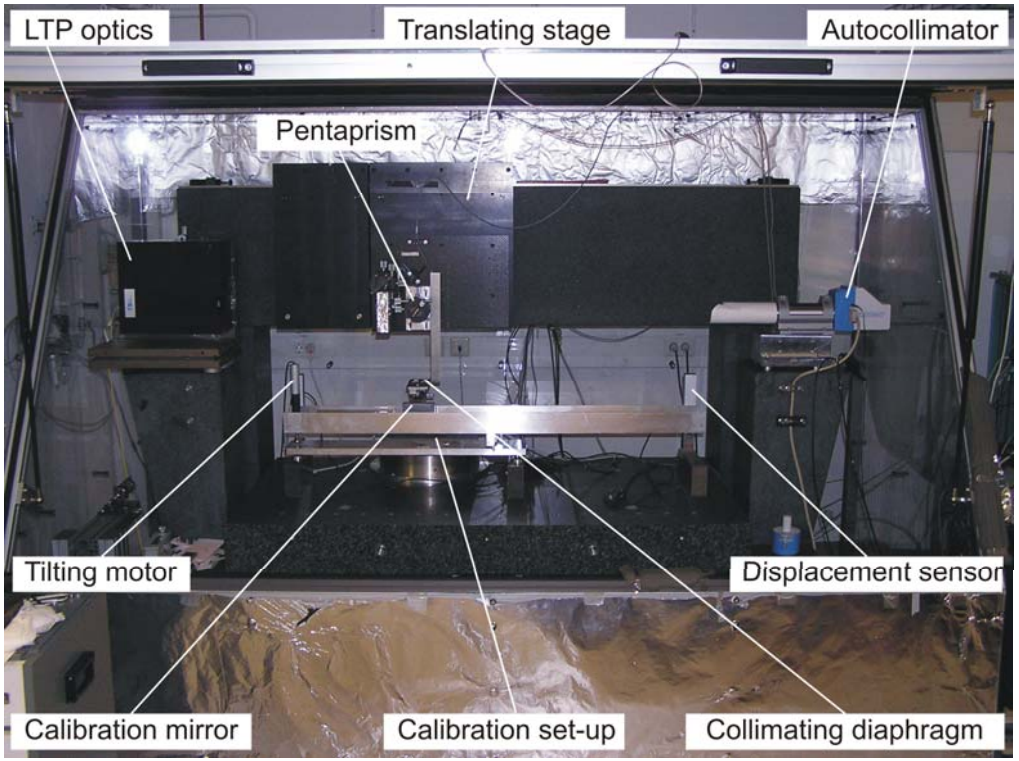
[2)] Shinan Qian, G. Sostero, P.T. Takacs, *Precision calibration and systematic error reduction in the long Trace profiler, Opt. Engineering 39(1), 304-10 (1999).*

High performance of the NOM is due to very careful calibration!

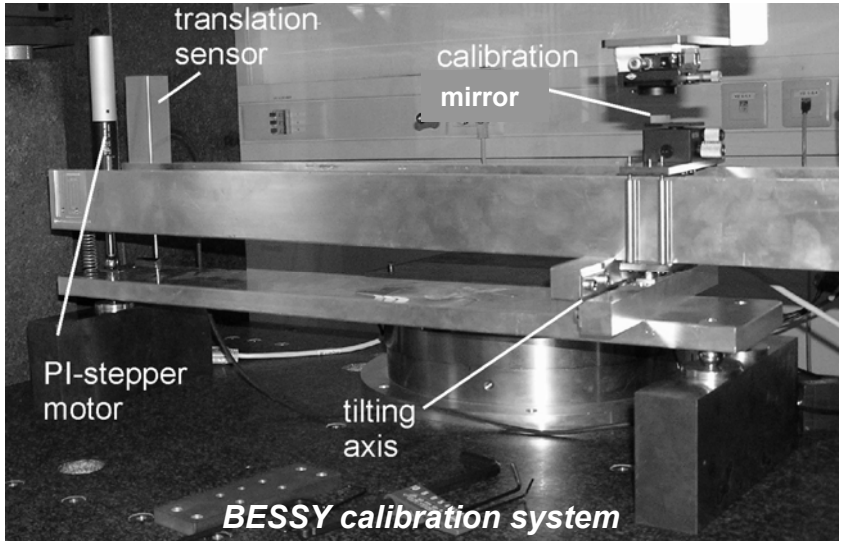
The BESSY NOM provides the world-best sensitivity to surface slope measurements:

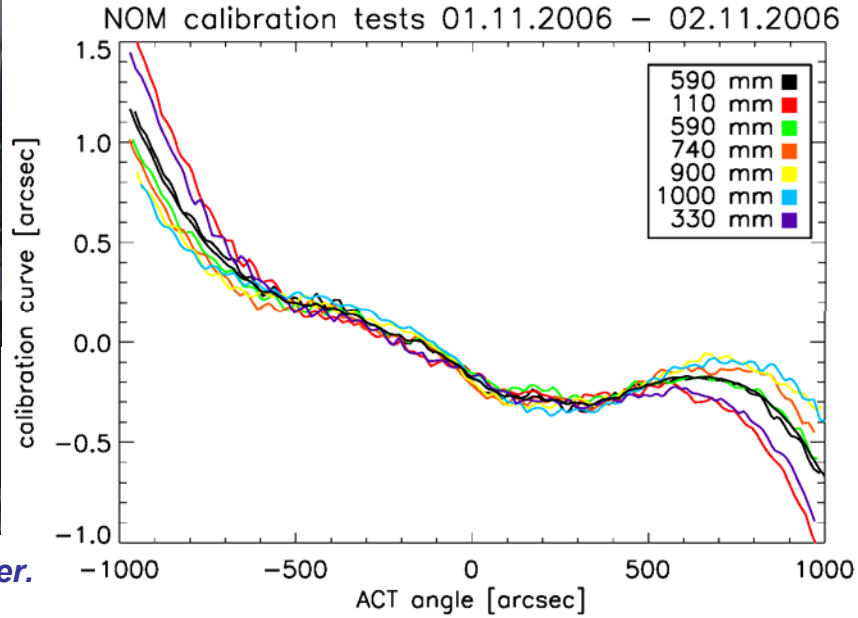
~0.25 μrad (rms) for a significantly curved mirror and

~0.05 μrad (rms) for a flat mirror.

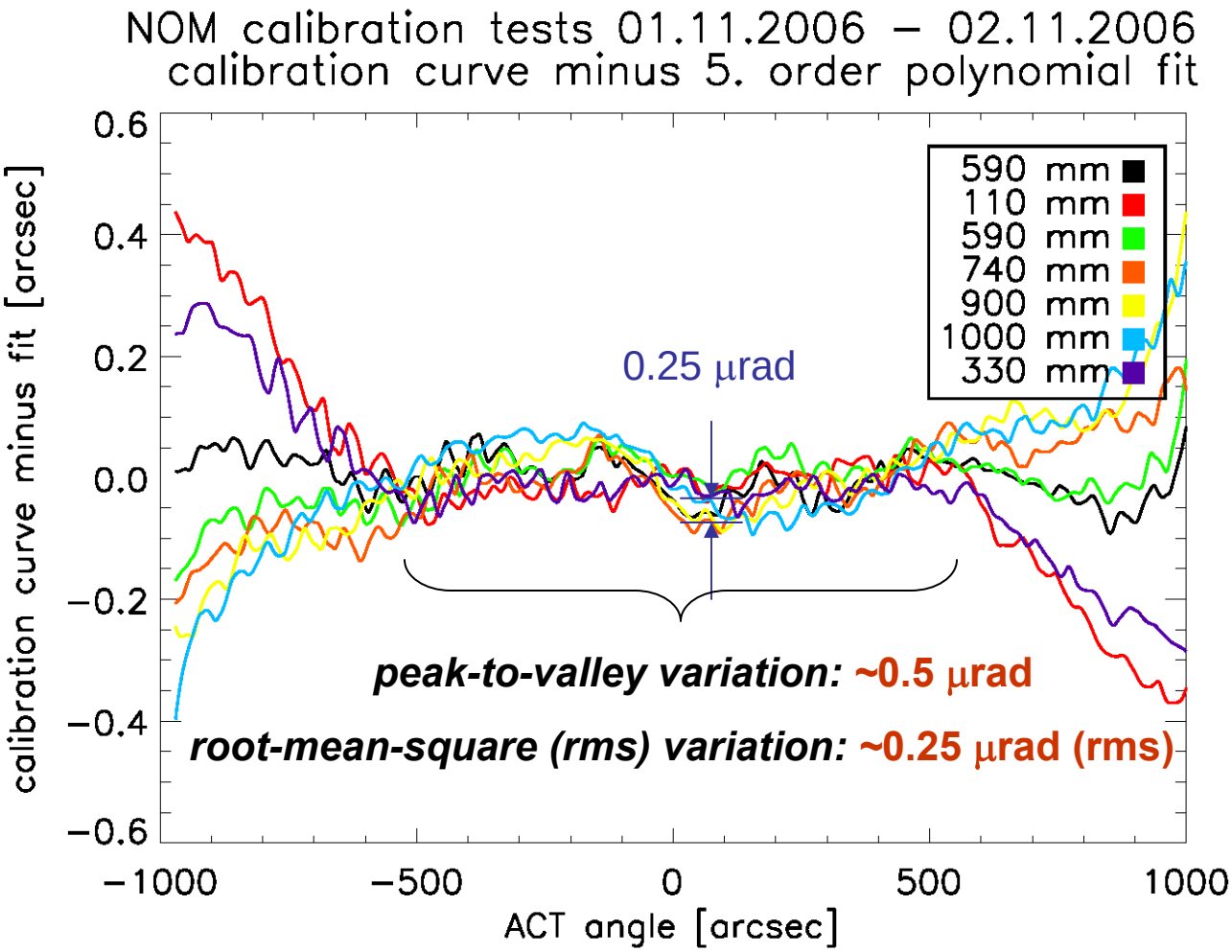


BESSY calibration set-up installed for calibration of the NOM profiler.





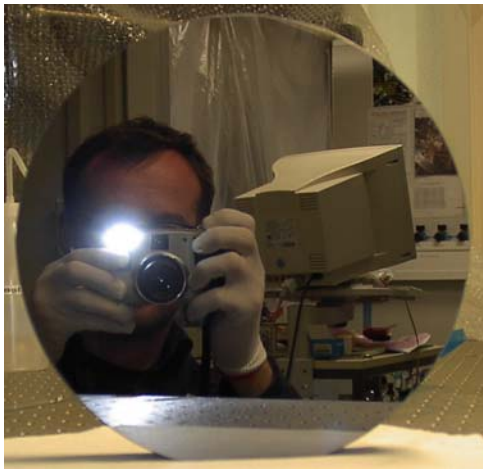
Importance of calibration with high spatial frequency

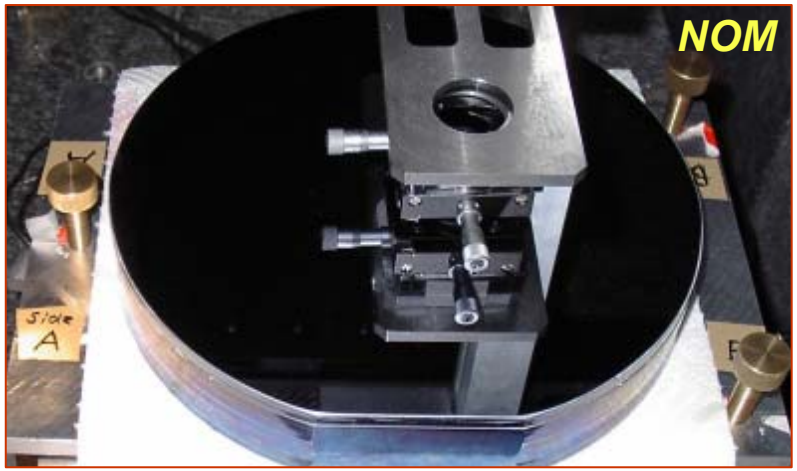


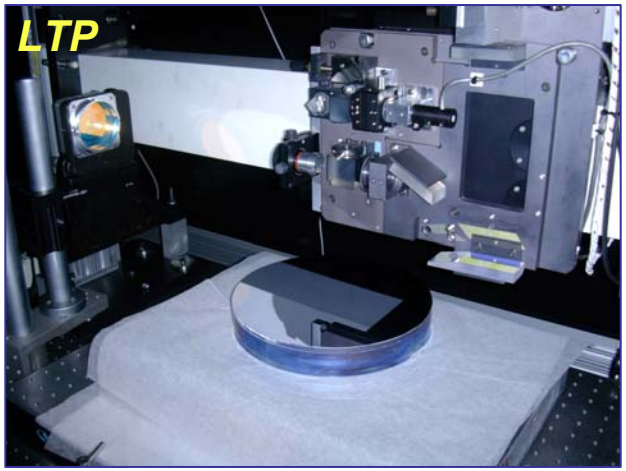
Calibration curves of the NOM autocollimator arm obtained at different positions of the calibration mirror.
Firth-order polynomial is subtracted.

Cross-comparison of BESSY NOM and ALS LTP

metrology of 15-m spherical substrate for MERLIN project

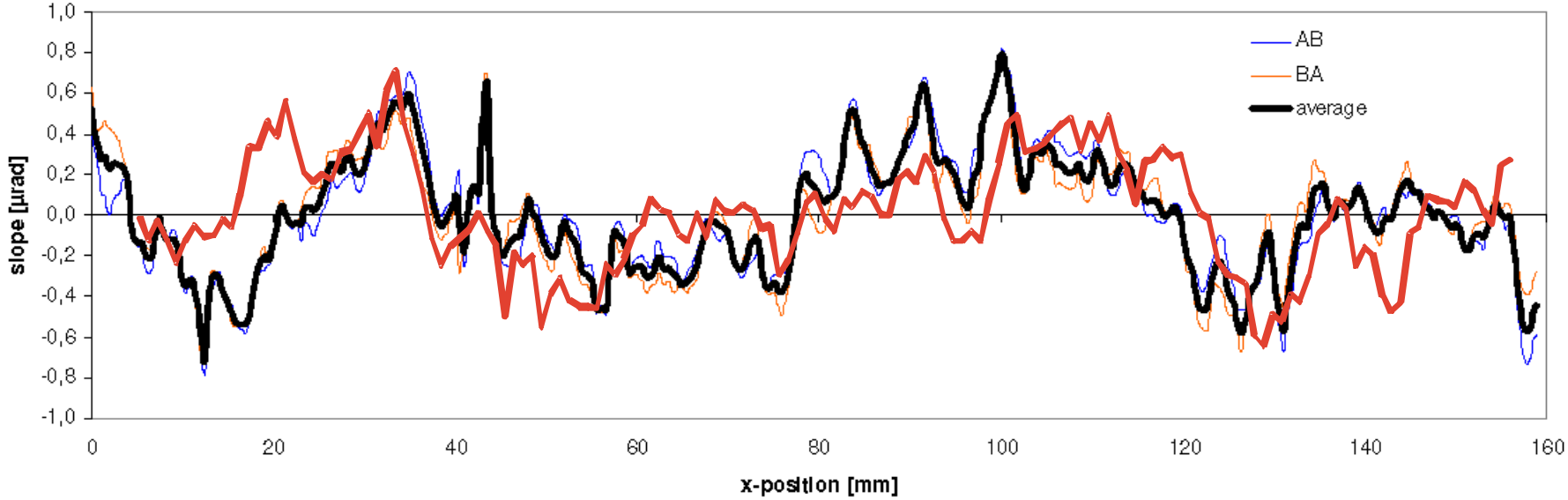






Best fit radius: 14.9620 m
Slope Variation:1.44 µrad (pv) and 0.278 µrad (rms)

Best fit radius: 15.065 m
Slope Variation:1.44 µrad (pv) and 0.293 µrad (rms)



Concept of
Universal Test/calibration Mirror (UTM)

Requirements:

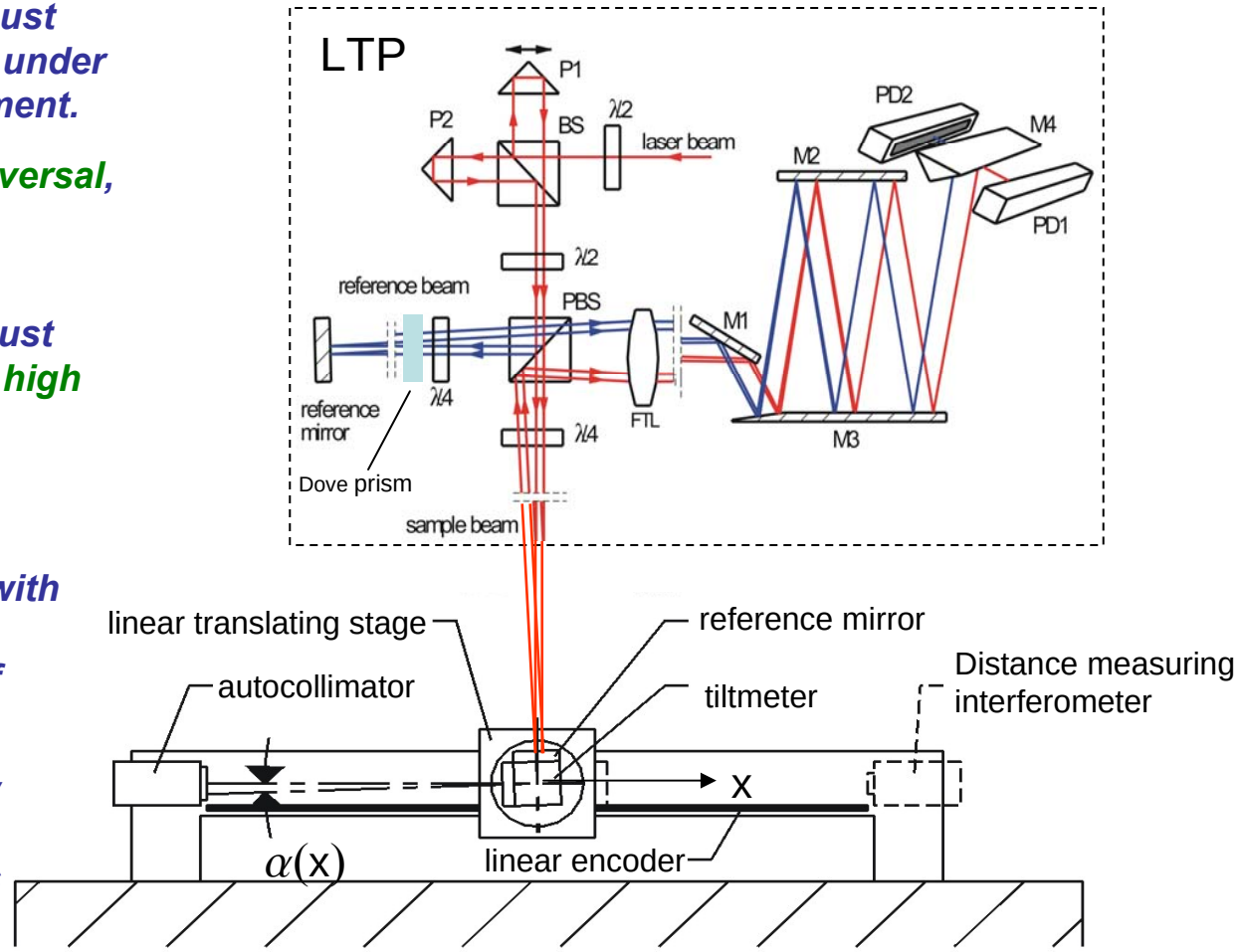
1. High performance calibration must account for peculiarities of optics under test and an experimental arrangement.

2. Calibration method must be universal, applicable to variety of optics and experimental arrangements.

3. Dedicated calibration system must provide nonlinear calibration with high special frequency resolution.

Idea:

- *Generate a specific test surface with an 'ideal' quality and with a shape absolutely identical to the shape of the surface under test (SUT).*
- *Can be accomplished with a very high quality mirror and extremely precise translation and tilt controls*



An extremely precise tilting stage (accuracy <0.05 μrad) is the cornerstone of a UTM system

Developing the UTM

PTB

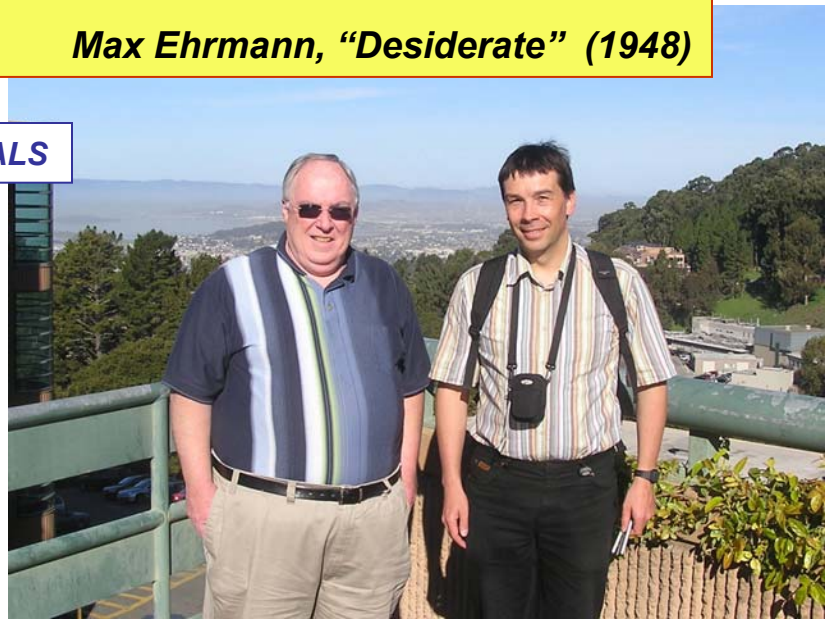
"Enjoy your achievements as well as your plans"

Max Ehrmann, "Desiderate" (1948)

BESSY

…discussing UTM…

ALS



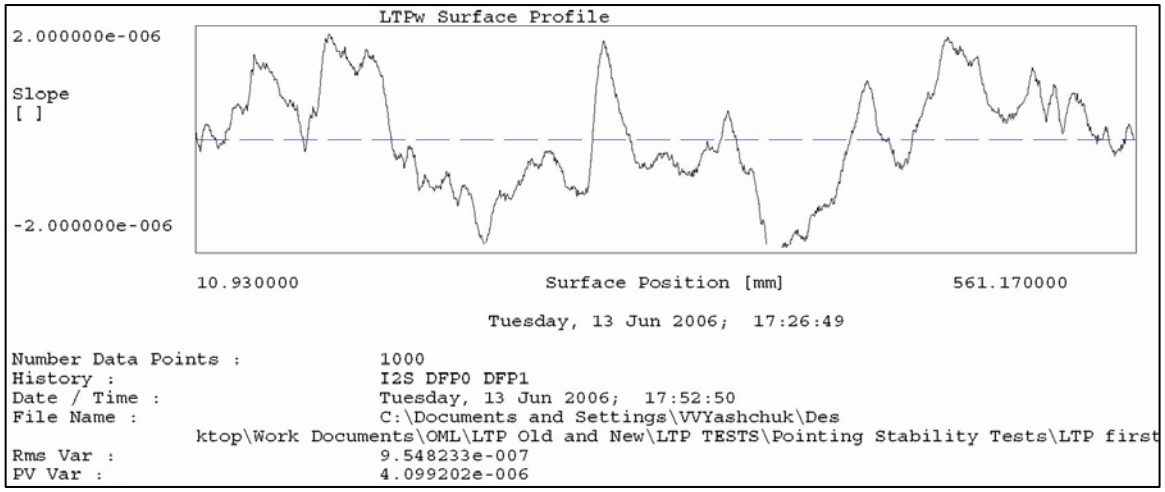
Environmental conditions must be improved first!

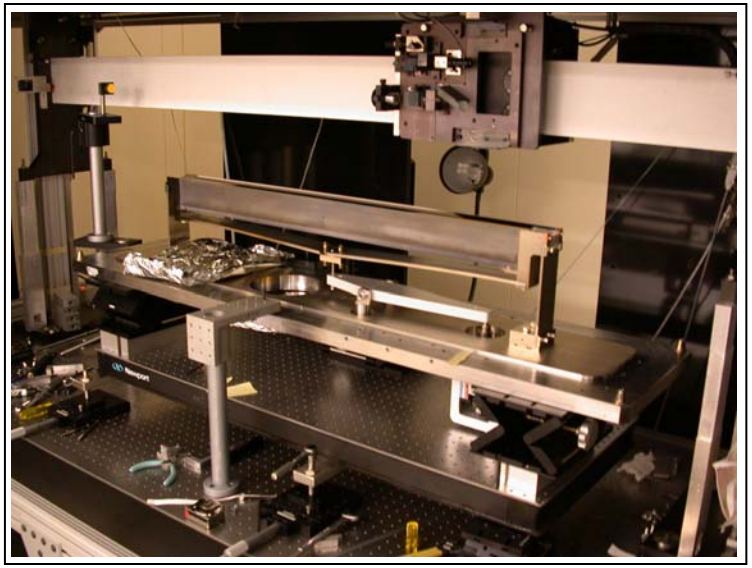
Air-convection noise in the LTP reference channel

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*

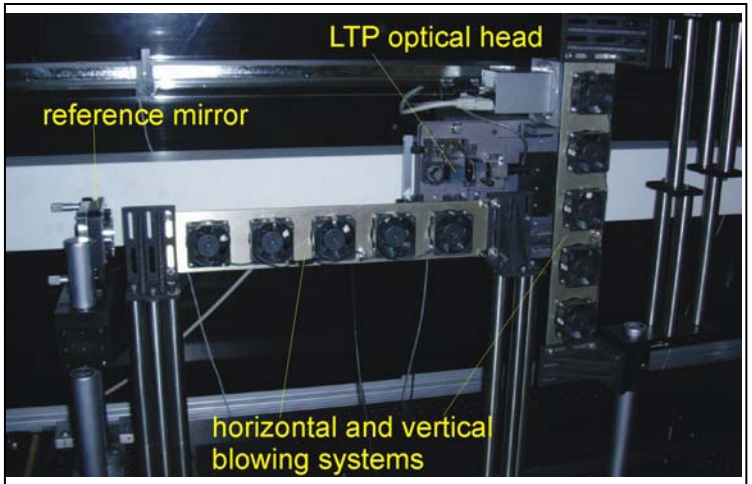
(similar to BESSY and PTB)

Air-blowing against air-convection noise

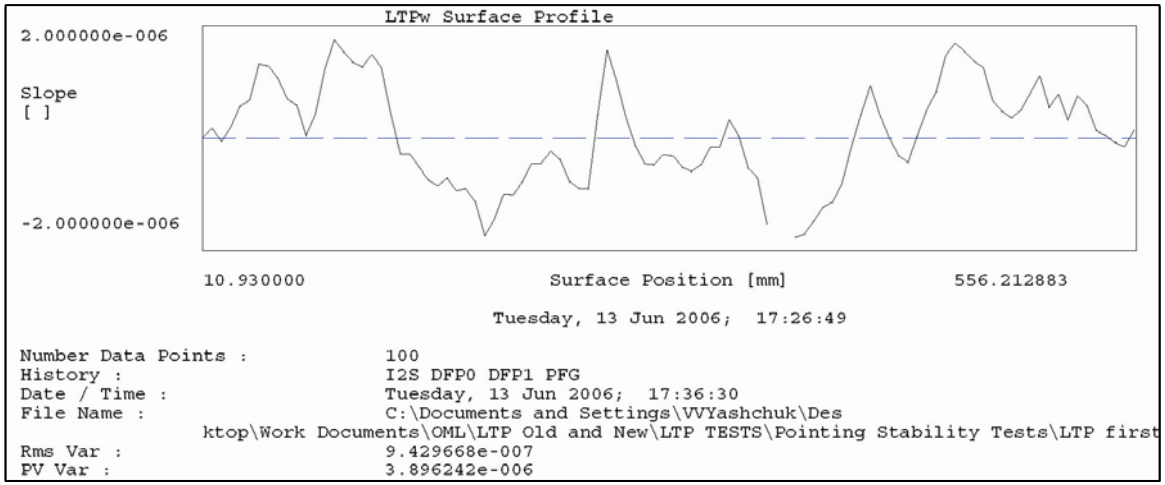
in the LTP reference channel

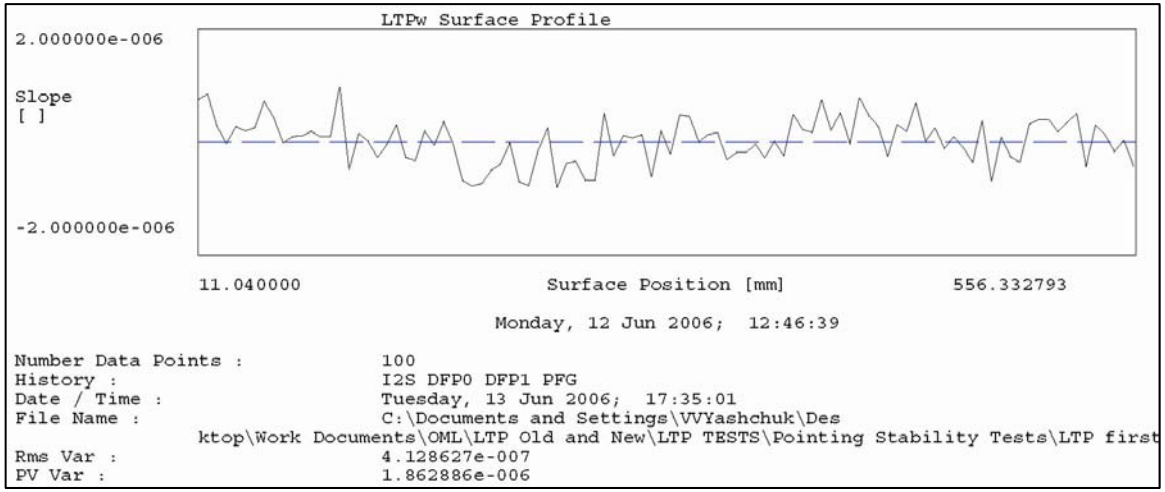
V. V. Yashchuk, S. C. Irick, A. A. MacDowell, W. R. McKinney, P. Z. Takacs,
Air convection noise of pencil-beam interferometer for long-trace profiler,
Proc. SPIE 6317-13, 2006

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





Air-blowing against air-convection noise

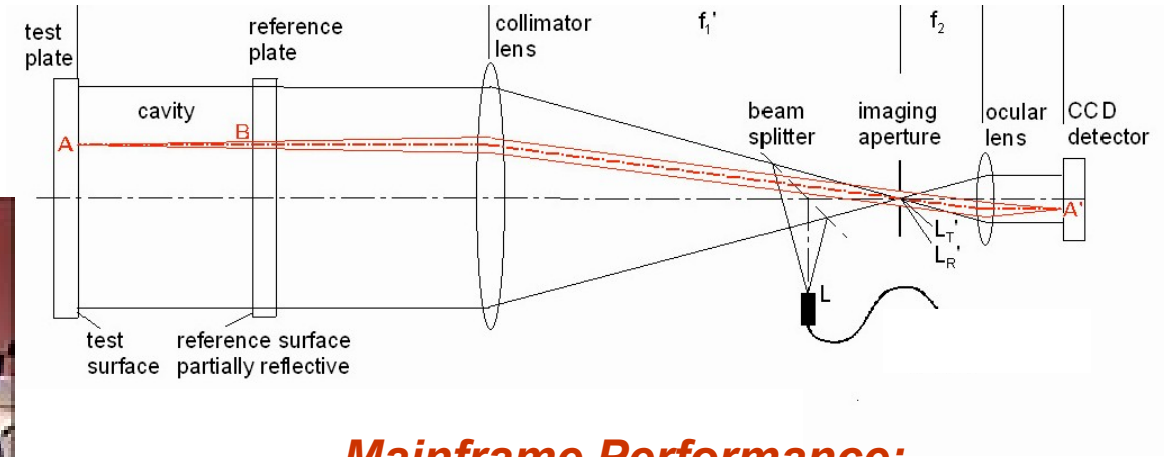
used at the IOM (Leipzig, Germany) by Dr. Thomas Hänsel

Leibniz Institute for Surface Modification (IOM - Institut für Oberflächenmodifizierung),

Leipzig, Germany, November 13, 2006

ZYGO-GPI™ interferometer

Surface characterization at lower spatial frequencies



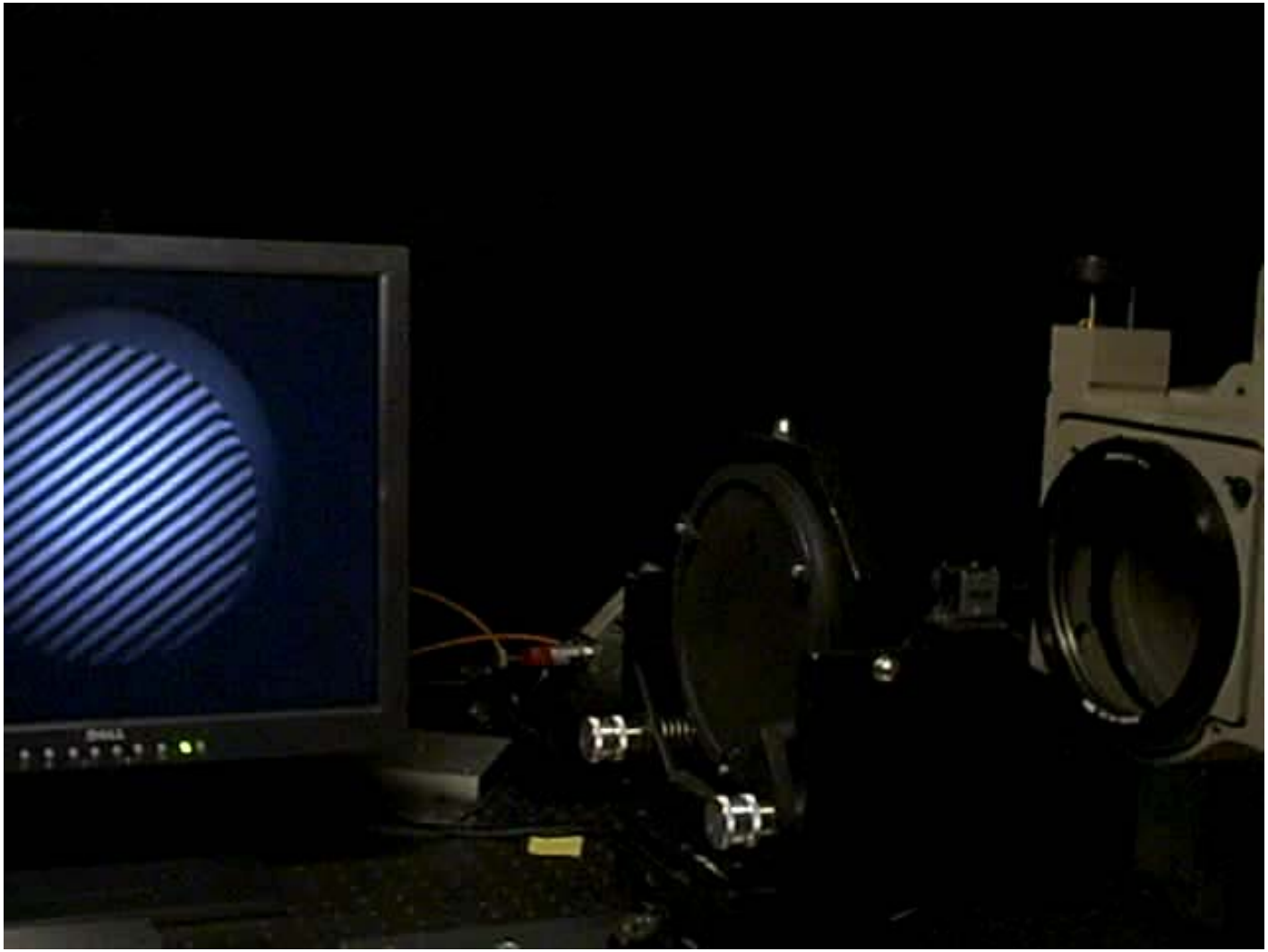
Mainframe Performance:

- *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*

Limitations:

Air turbulence
Unfriendly Software!
Old computer (~ $22K to replace)

Lab environmental conditions and metrology performance

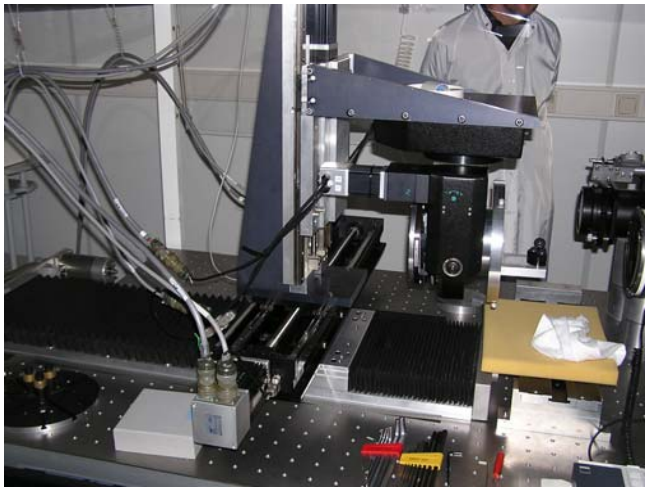


$\Delta T \approx 10\,K \leftrightarrow \Delta l \approx 1\,\mu m$

$0.1\,nm \leftrightarrow 1\,mK$

Optical Metrology Laboratory at the IOM

(Leipzig, Germany)



4-axis positioning system (Aerotech Inc.)

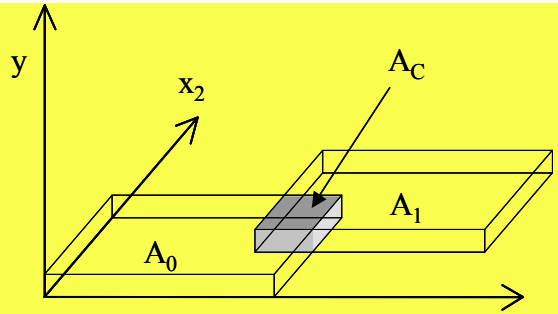
X/Y- linear ball screw stages:

- *travel ranges: 750/500 mm*
- *accuracy: 1µm/25mm*
- *repeatability: 1µm*

U/Z- Tilt: Gimbal Mount

- *repeatability: 0.75arcsec (~3.6 µrad)*
- *resolution: 0.009 arcsec (~43 nrad)*

Dr. Thomas Hänsel in the IOM optical metrology laboratory



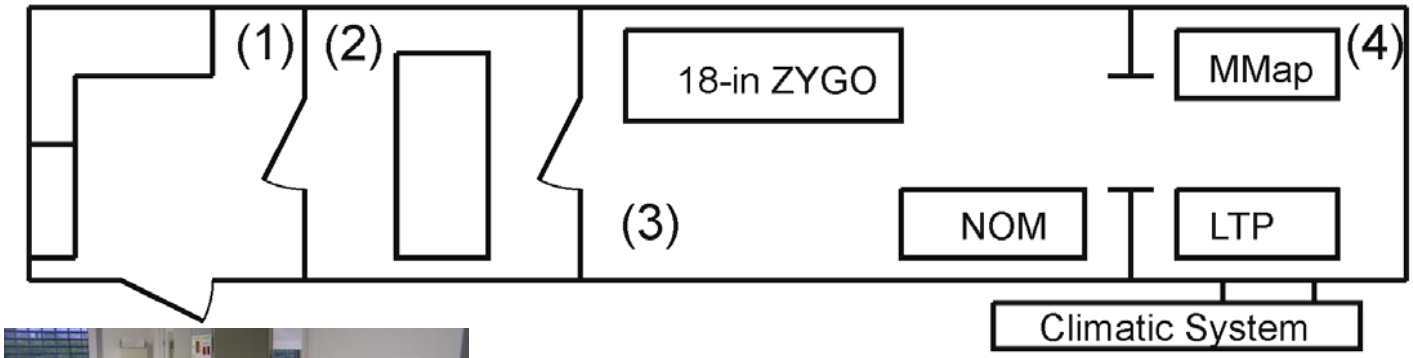
Sub-aperture Stitching Interferometry based on DIRECT100 (Carl Zeiss Oberkochen)

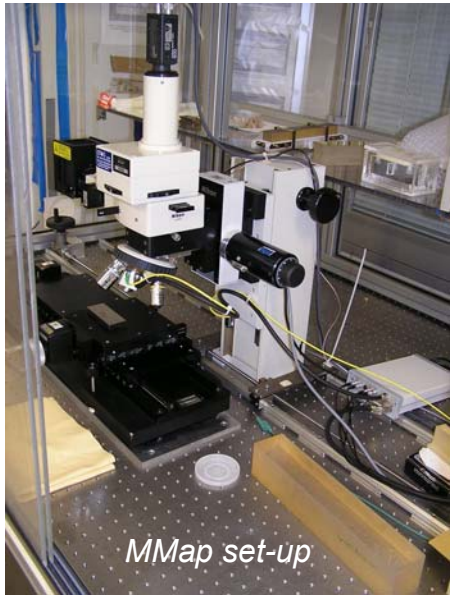
- *mode: Direct Measuring Interferometry (DMI)*
- *reproducibility: < 0.0005λ rms*
- *accuracy: < 0.002 λ rms*

ZYGO GPI™:
Phase Shifting
< 0.003λ rms
< 0.01 λ rms

BESSY optical metrology laboratory

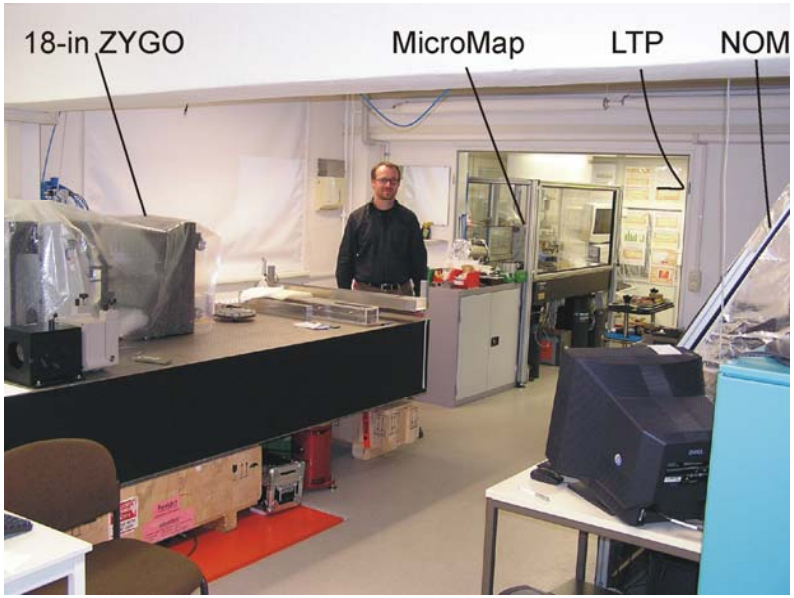
Schematic plan of BESSY OML



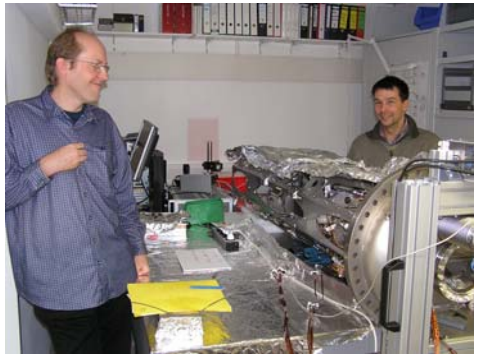


(1): Technological room

Lab climatic system and NOM two-layer hutch provide temperature stability of ~1 mK/hour



(3) and (4): OML with major optical metrology instruments

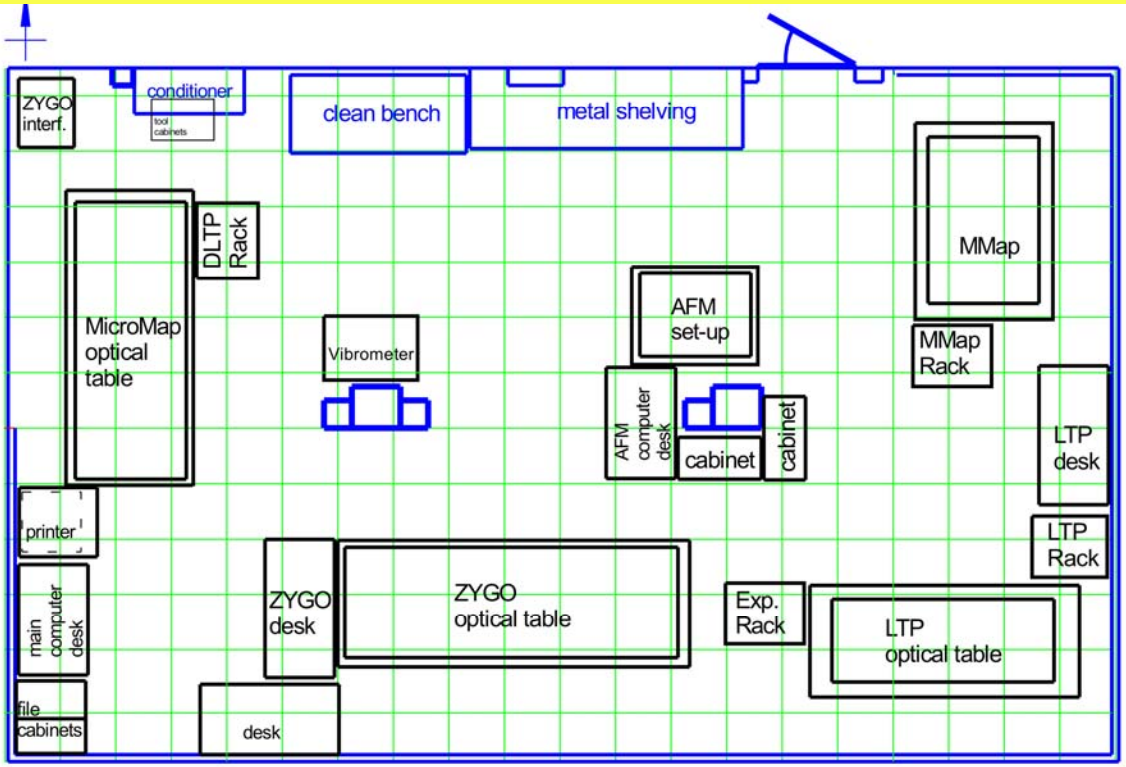


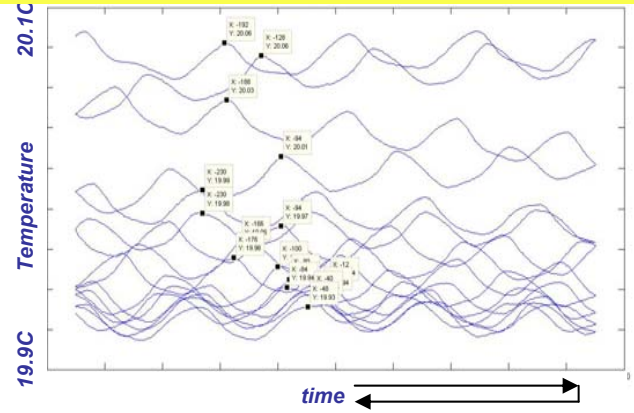
(2): Assembly room

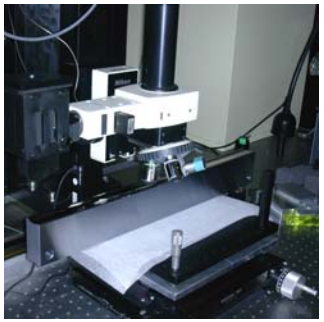
Climatic system

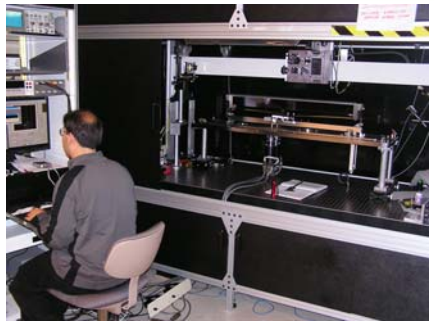
ALS Optical Metrology Laboratory

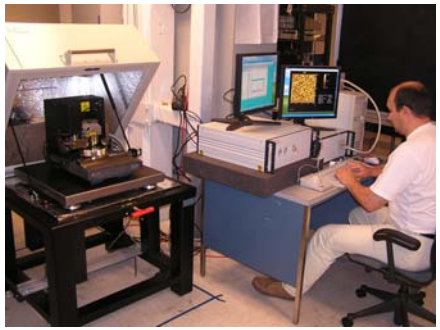
Strong need for clean room and stable environmental conditions!











Summarizing: *Missions and missionaries of the OML*

BERKELEY LAB

• *OML Team*

Strong need for increase of manpower in ALS metrology!

- ✓ *Staff Scientists:* *Valeriy Yashchuk* - *leading the OML, method and instrumentation* development
  - Wayne *McKinney* - *analyzing software, scattering calculations (retire in ~ 3 years)*
  - *Malcolm Howells* - *scattering theory (one day a week)*
- ✓ *Engineers:* *Steve Irick* - *routing metrology measurements (on sick leave for ~ a year)*
  - *Jonathan Kirschman* - *routing metrology and test measurements (till June 2008)*

• *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; autocollimator-based slope measuring instrumentation*
- ✓ *Daniele Cocco (ELETTRA)* - *round robin LTP test*
- ✓ *Jim Metz and Tom Tonnessen (InSync)* - *Mirror polishing and metrology, InSync LTP upgrade; high quality test/calibration mirrors*
- ✓ *World-wide* - *establishing international standard for MTF calibration of microscopes*
  - *establishing Virtual Optical Metrology Laboratory to unite efforts of metrologists of X-ray optics*

Conclusions

Right now, the quality of optical components limits the potential performance of a synchrotron radiation beam line;

Right now, on-site vendor independent metrology is essential for a critical inspection of delivered and mounted optical elements; setting bendable optics, providing reliable metrology data and evaluation of on-beam performances;

New optical components beyond the limits of 0.3 μrad (rms) and 2 nm (rms) require metrology tools of 3-5 times superior accuracy;

"Don't specify what you cannot measure!"

by Frank Siewert, BESSY

Improvement of mirror technology would be impossible without improvement of metrology;

"At Carl Zeiss Laser Optics GmbH, contribution of optical metrology into a mirror price is up to 30%,"

by Andreas Seifert

Improvement of metrology would be impossible without improvement of laboratory environmental conditions, all state-of-the-art optical components, and test/calibration technologies.

Answering to

Why does Metrology Matter to You?

"Measurement science is no, however, purely the preserve of scientists. It is something of vital importance to us all. The intricate but invisible network of services, suppliers and communications upon which we are all dependent rely on metrology for their efficient and reliable operation."

Bureau International des Poids et Mesures (BIPM)

[Eng.: International Bureau of Weights and Measures]

http://www.bipm.org/en/convention/wmd/2004/

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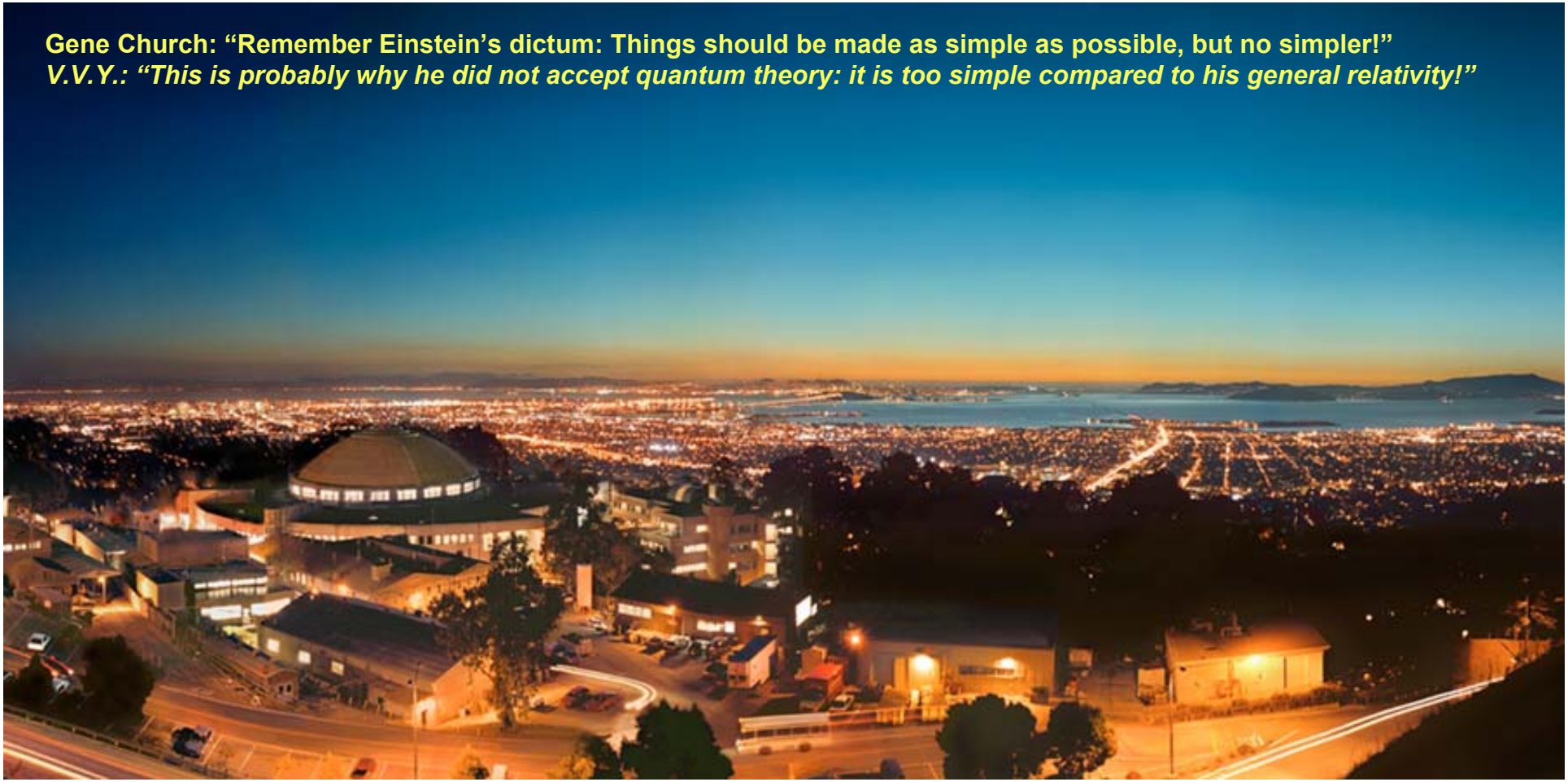
THANKS!



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