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Binary pseudo-random grating as a standard test surface for measurement of modulation transfer functions of interferometric microscopes

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Outline

- *Motivation:*

  Power spectral density (PSD) from surface roughness data
  Reliable 2D PSD measurements require correction for instrumental MTF
  Step-height standard and its disadvantages

- *Binary Pseudo-random (BPR) Grating for MTF measurements*

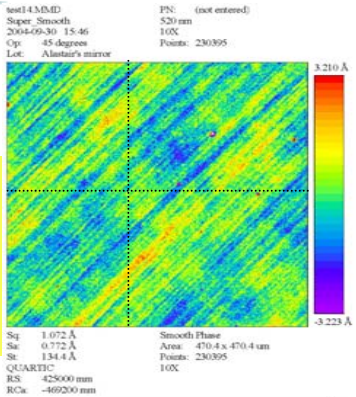
  Theoretical introduction: What is a BPR sequence?
  What are the BPR sequences good for?
  BPR grating as a standard test surface
  Application of a BPR grating to measure MTF of the Micromap™-570

- *Conclusions*

"One number" statistical surface metrology

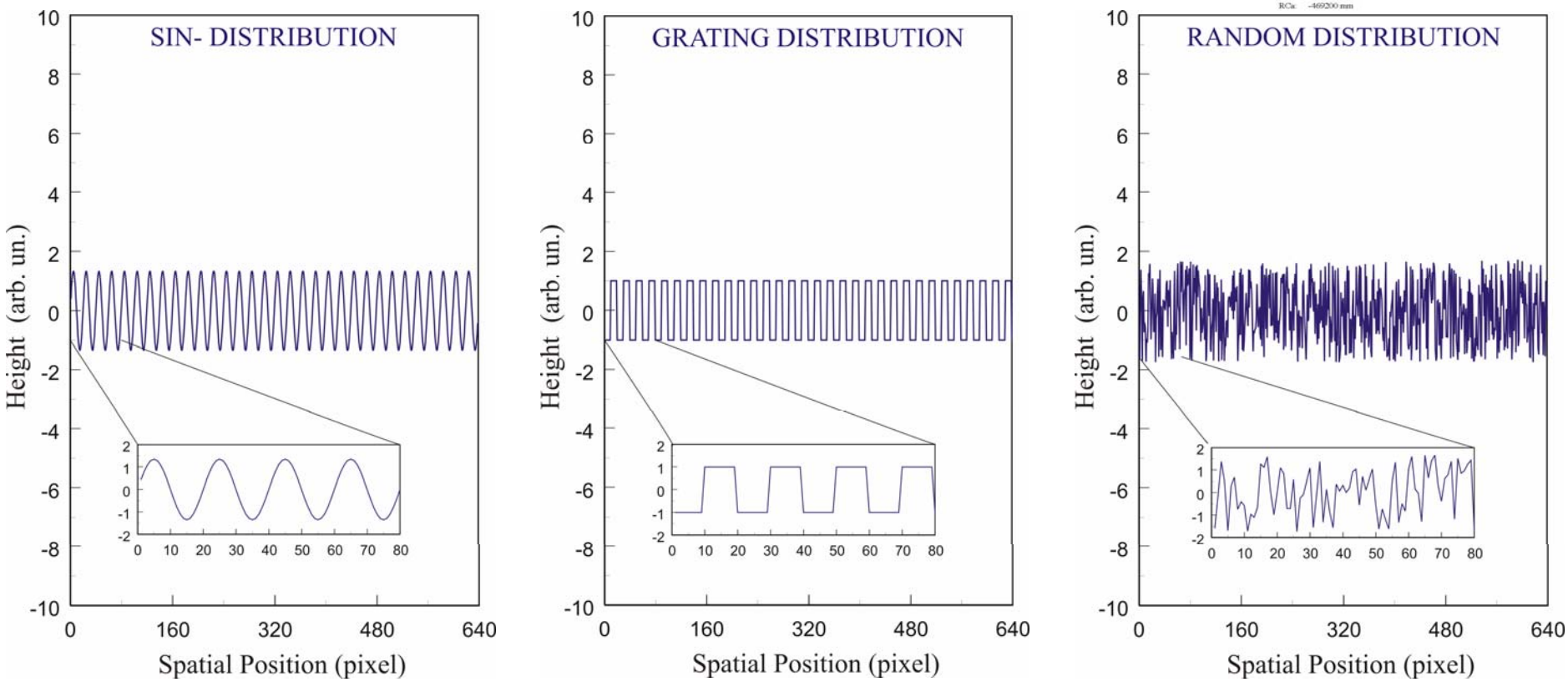
Roughness (rms):

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



For all these cases the roughness value is the same!

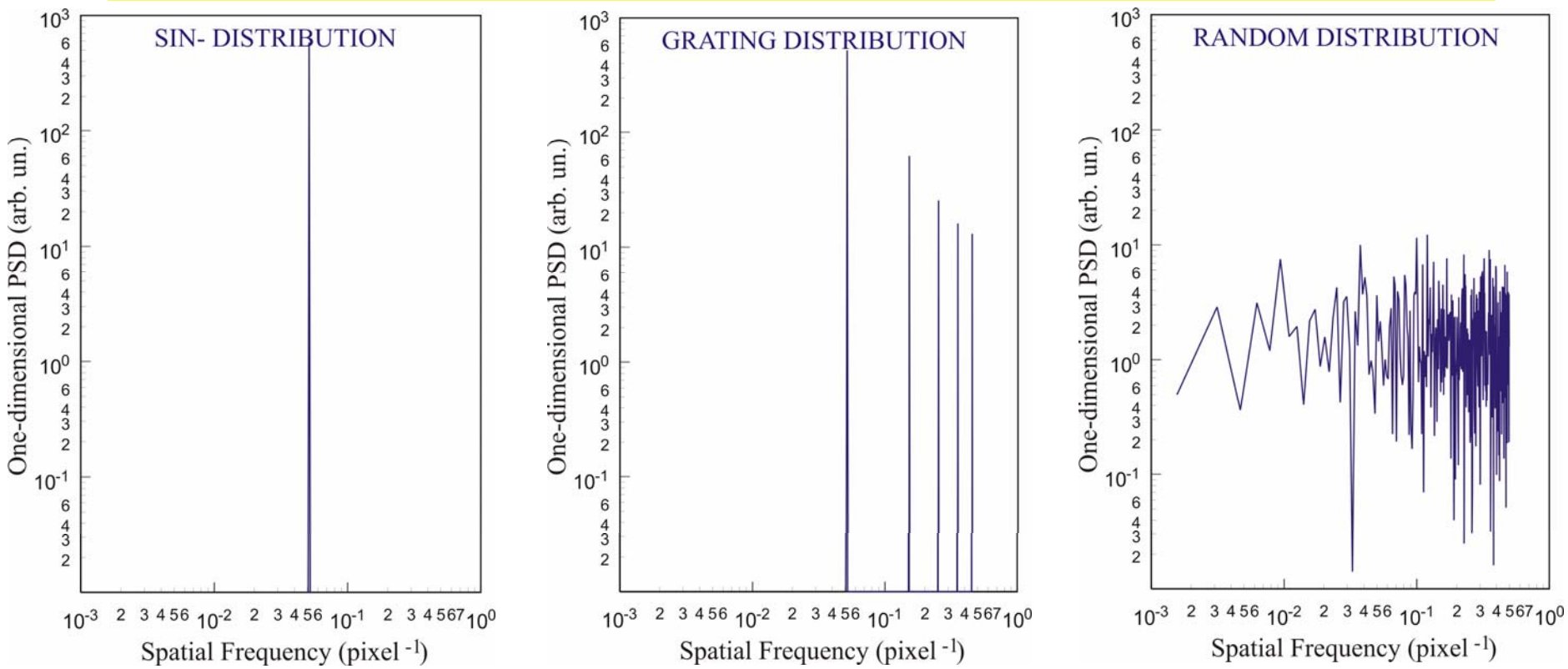
The two-dimensional sketches show the need for at least two parameters. One is vertical (roughness) and one is horizontal (wavelength).



Power Spectral Density (PSD) based surface 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!

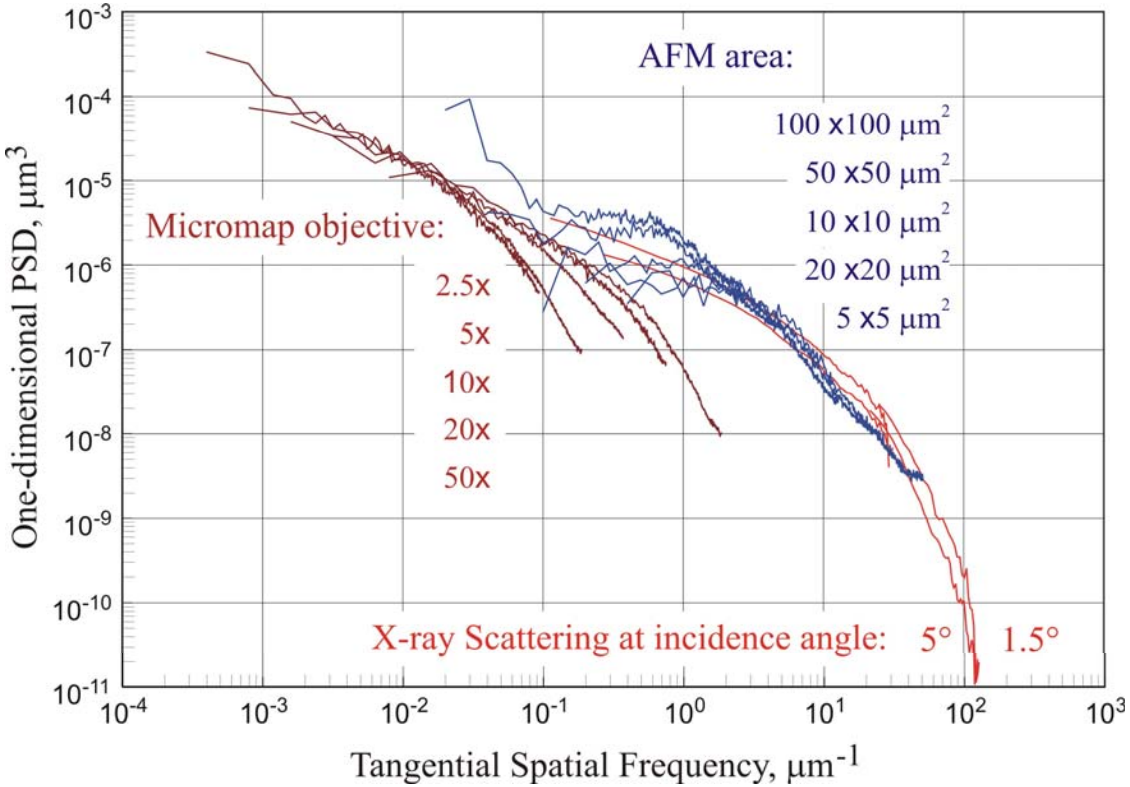


PSD based metrology permits measurement of instrumental modulation transfer function (MTF)

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

PSD measurements with 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).

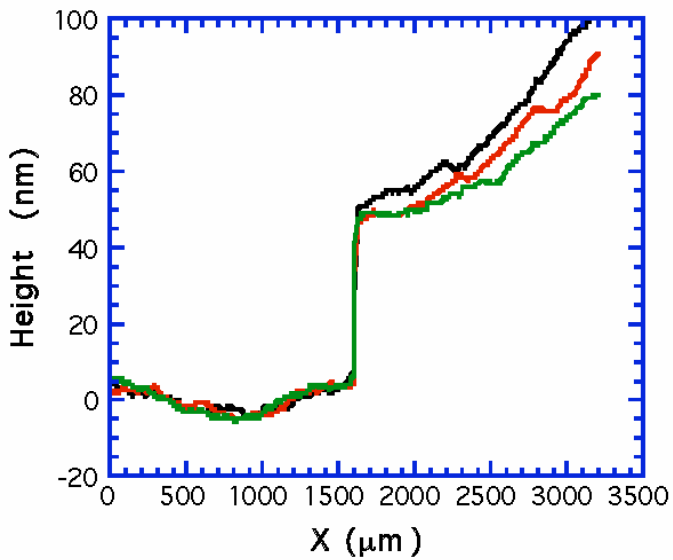


Fig. 1 Scans across the edge on a commercially available step height standard. The variability in the edge height and the surface irregularity are typical of the quality of this type of standard.

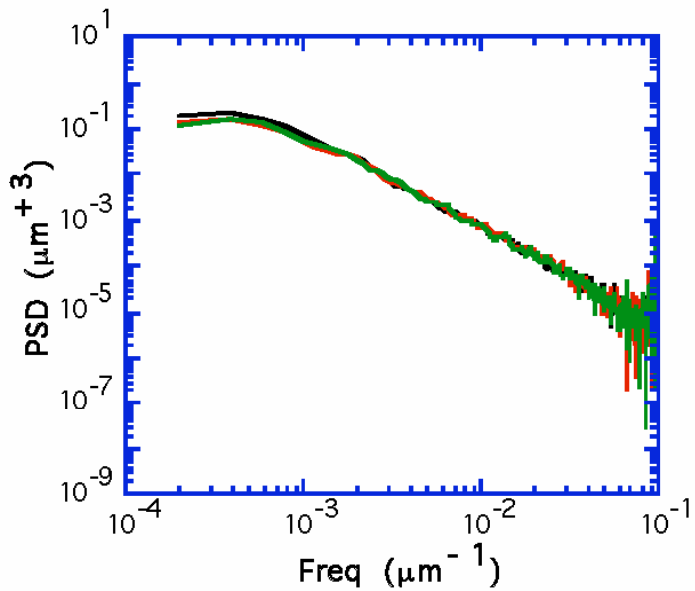


Fig. 2 PSD curves for the profiles in Fig. 1. Intrinsic surface roughness contributes to the noise in the high frequency region. A Blackman filter has been used to pre-process the raw data and the restoration filter appropriate for this profiler has been applied to spectra.

Disadvantages:

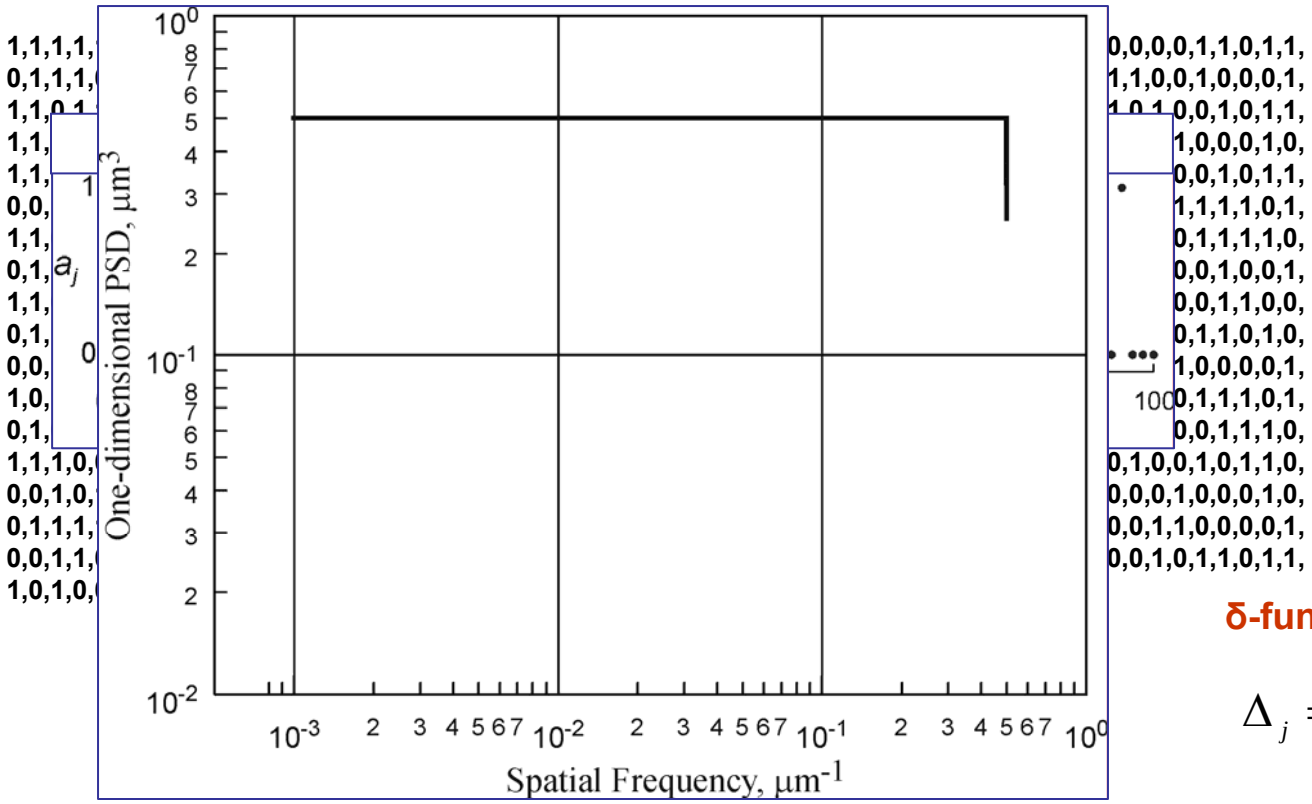
- $\propto 1/f^2$ ***intrinsic PSD spectrum and, therefore, low sensitivity to the higher spatial frequency distortion;***
- ***necessity to preprocess data to filter out PSD variations at higher spatial frequencies;***
- ***strong dependence of calibration on position of the step in the instrumental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

Introduction to

Binary Pseudo-random (BPR) sequences

BPR sequence with 1023 elements

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



sequence correlation function:

$$A_j = \sum_{i=0}^{N-1} a_i a_{i+j}$$

'deconvolution' sequence:

$$b_k = \frac{2a_k - 1}{2^{n-1}}$$

δ-function-like correlation function:

$$\Delta_j = \sum_{i=0}^{N-1} a_i b_{i+j} = \frac{1}{2^{n-2}} \sum_{i=0}^{N-1} a_i a_{i+j} - 1$$

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

[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).**

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

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

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

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

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

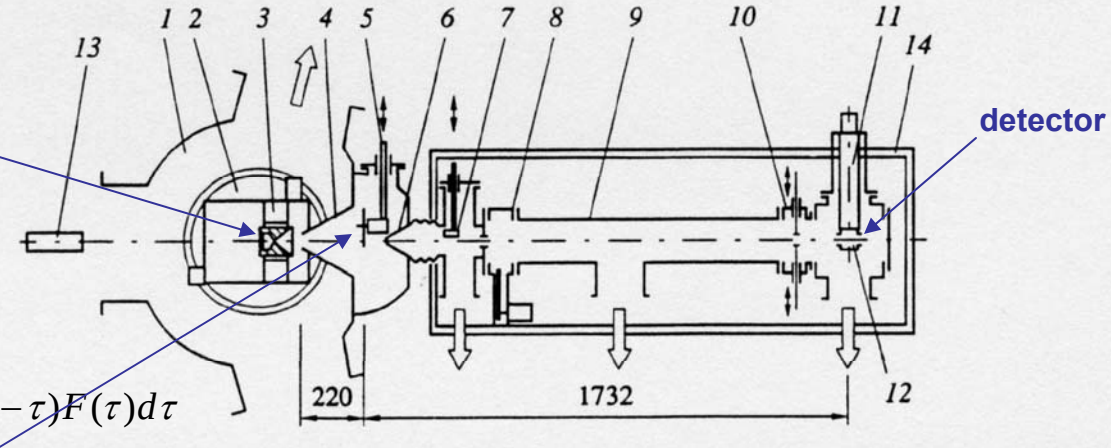


Fig. 1. Diagram of the cross-correlation TOF spectrometer of molecular beams: (*1*) source chamber; (*2*) alignment stage; (*3*) supersonic nozzle; (*4* and *6*) skimmers; (*5*) chopper; (*7*) calibration effusive source; (*8*) vacuum seal; (*9*) transit chamber; (*10*) diaphragm unit; (*11*) MX-7304A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

pseudo-random chopping in order to increase duty cycle

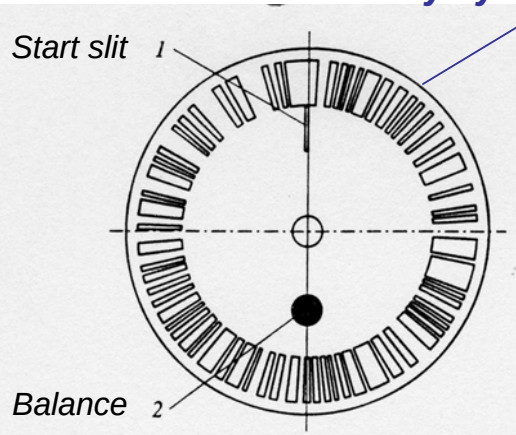


Fig. 2. Chopper disk: (*1*) starting slit and (*2*) balancing load.

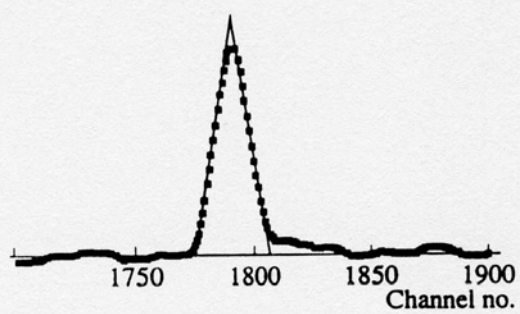


Fig. 5. Autocorrelation functions of the TOF spectrometer obtained by the convolution of the sequence of light-beam choppings with an ideal inverse sequence $\{B_j\}$ (curve) and with a reconstructed inverse sequence $\{B_j^*\}$ (straight line).

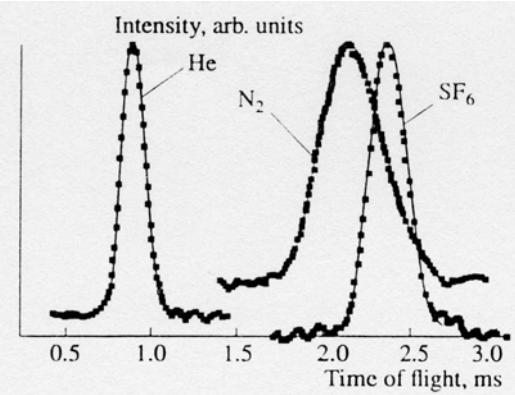
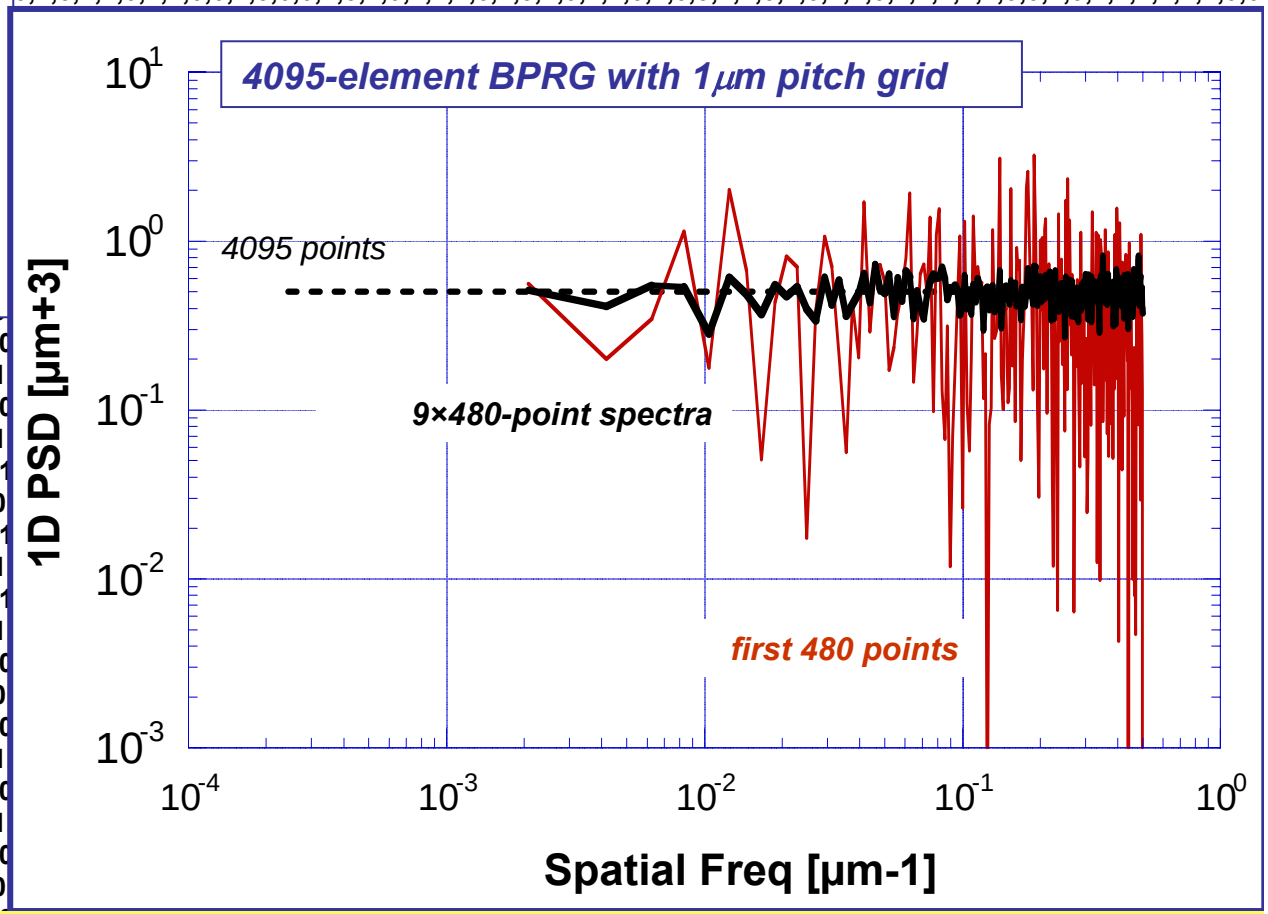


Fig. 6. TOF Spectra of He, N_2, and SF_6 beams. Solid lines are the results of the total fitting with parameters given in the table.

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*



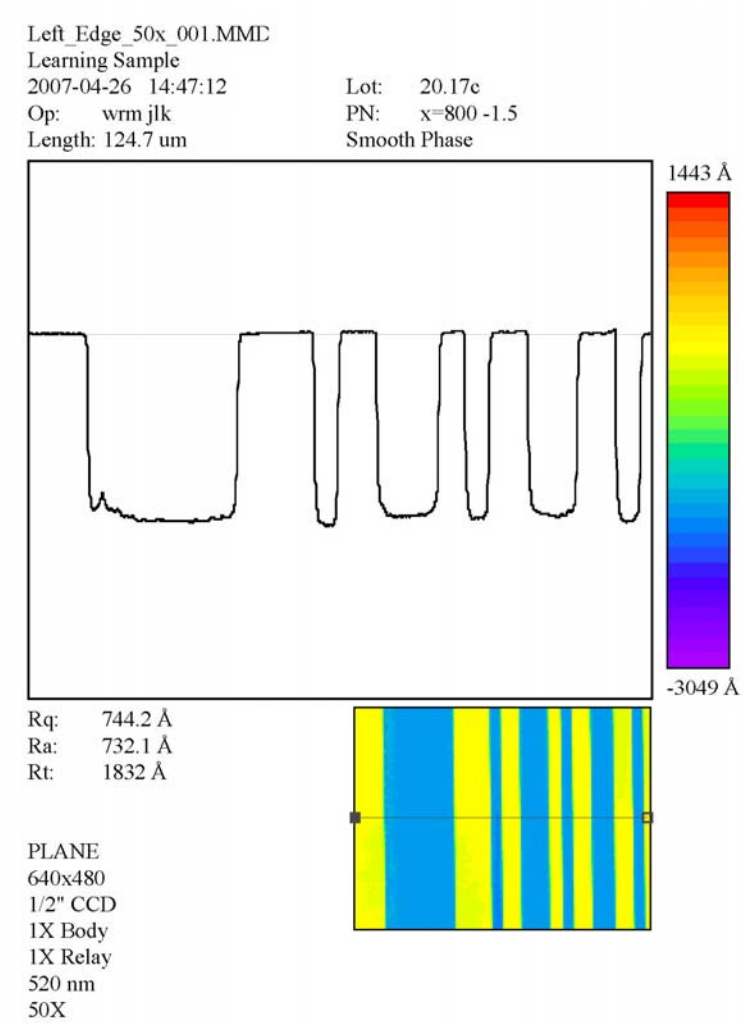
The PSD spectrum of the BPRG is mathematically strongly *deterministic*!

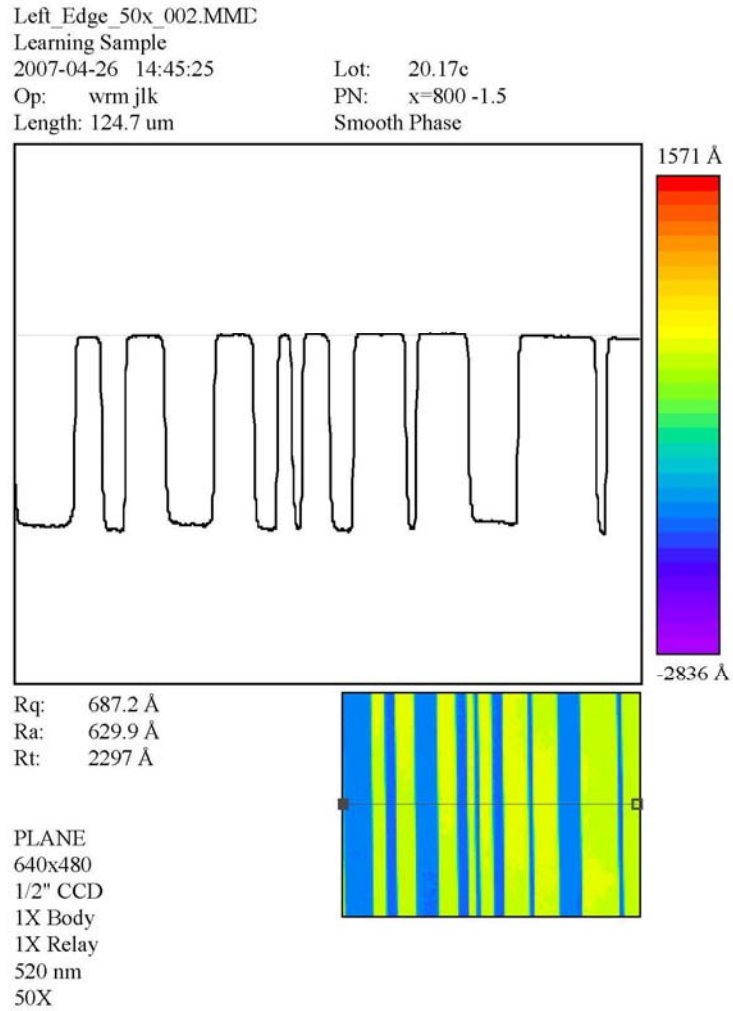
Micromap-570 measurement with

BPRG test surface (2.5 µm pitch)

50x objective

(0.26 µm pixel size)



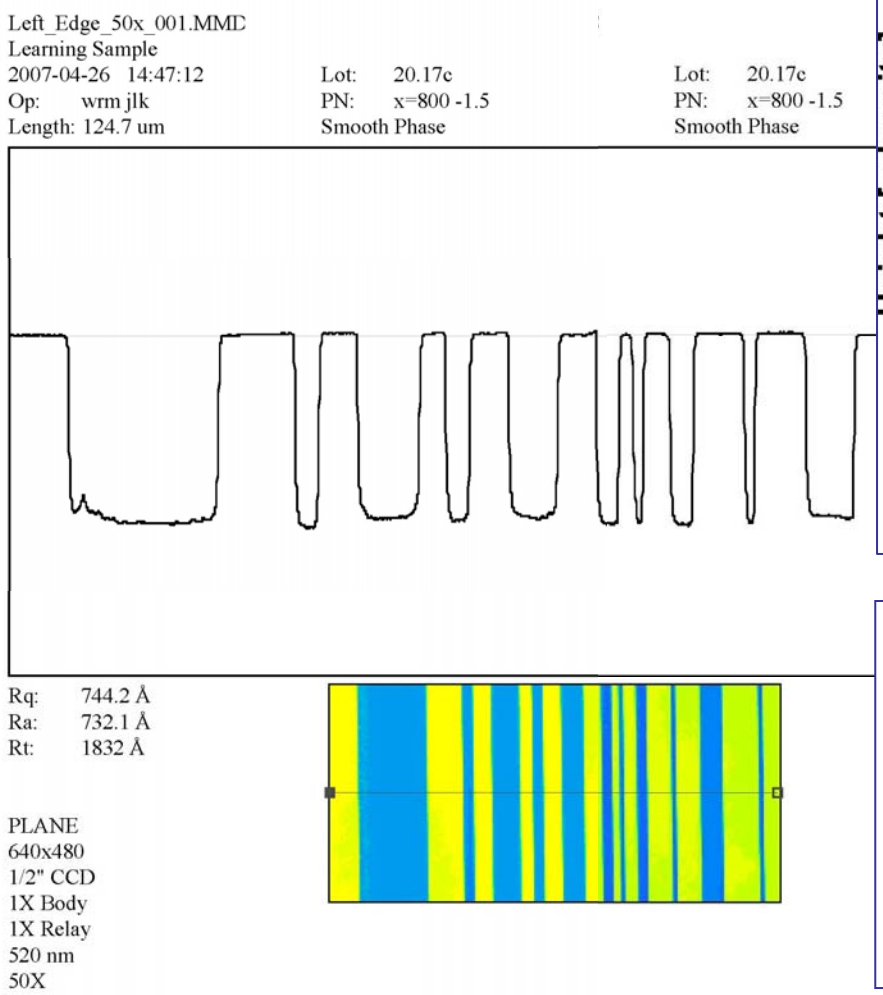


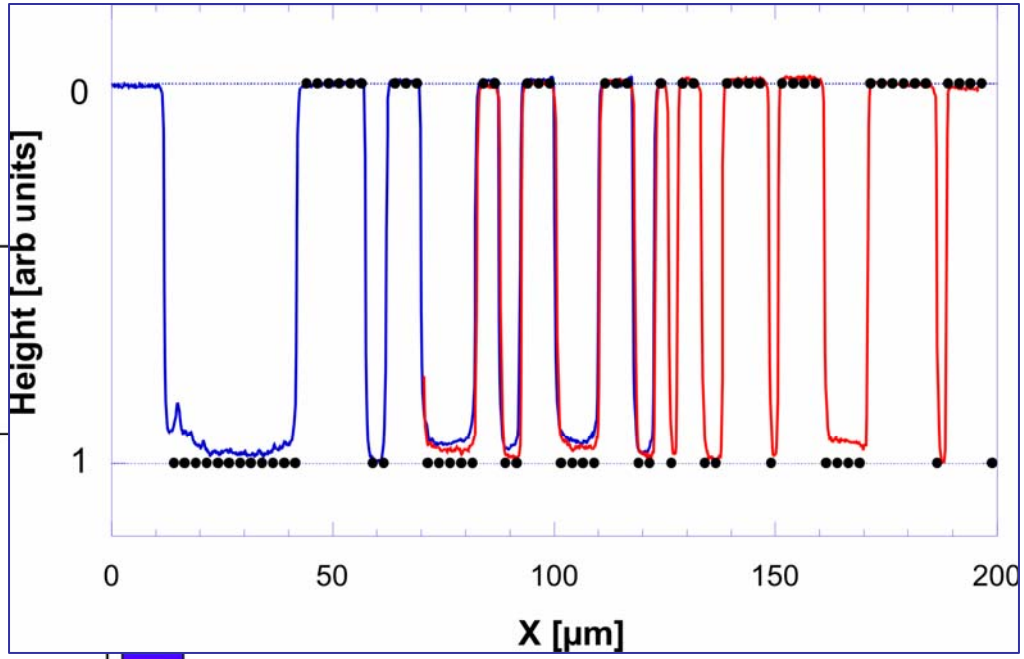
Micromap-570 measurement with

BPRG test surface (2.5 µm pitch)

50x objective

(0.26 µm pixel size)





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

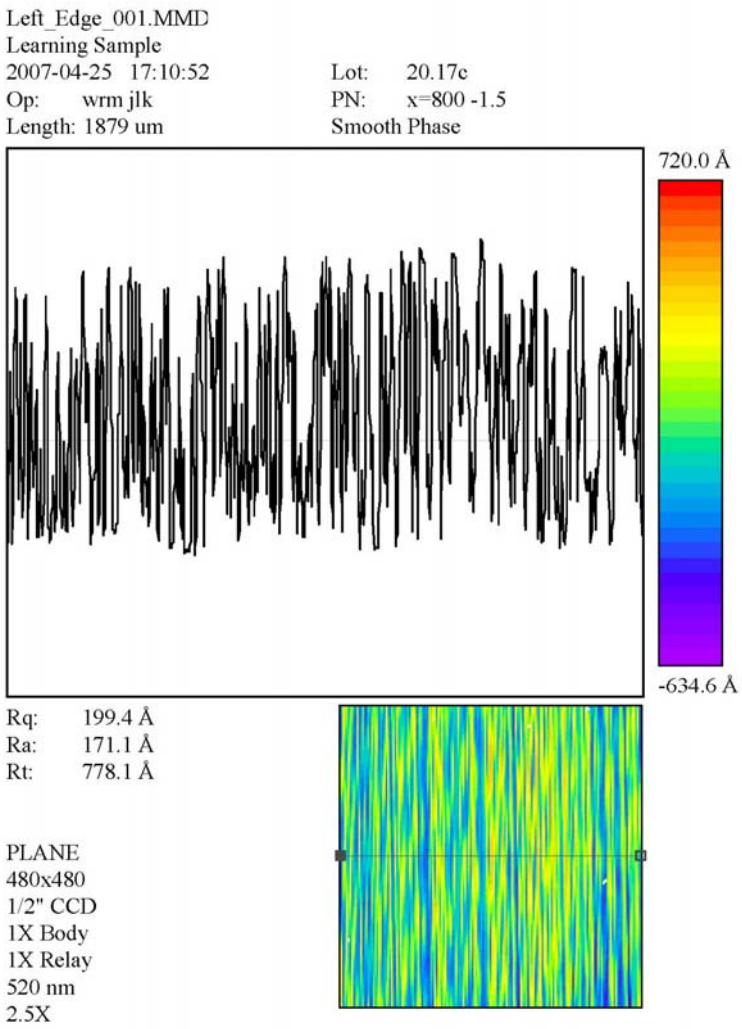
The discrepancy (λ=520 nm) is due to the uncertainty of the phase-retrieval algorithm of micro-roughness instruments.

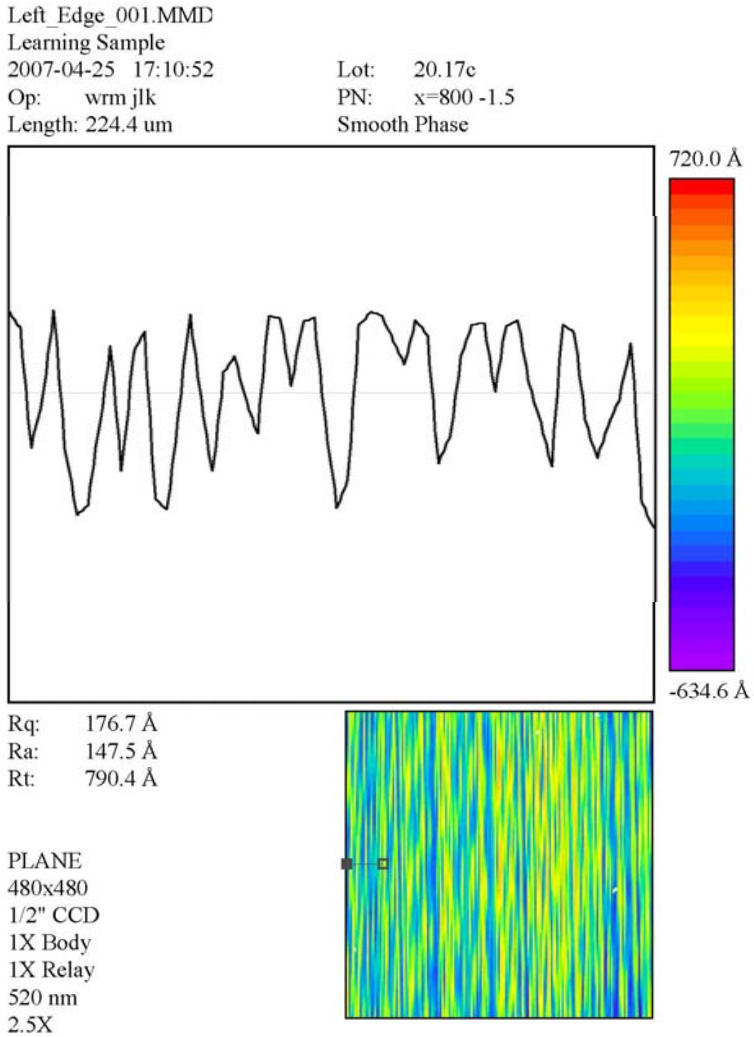
Micromap-570 measurement with

BPRG test surface (2.5 µm pitch)

2.5x objective

(3.9 µm pixel size)

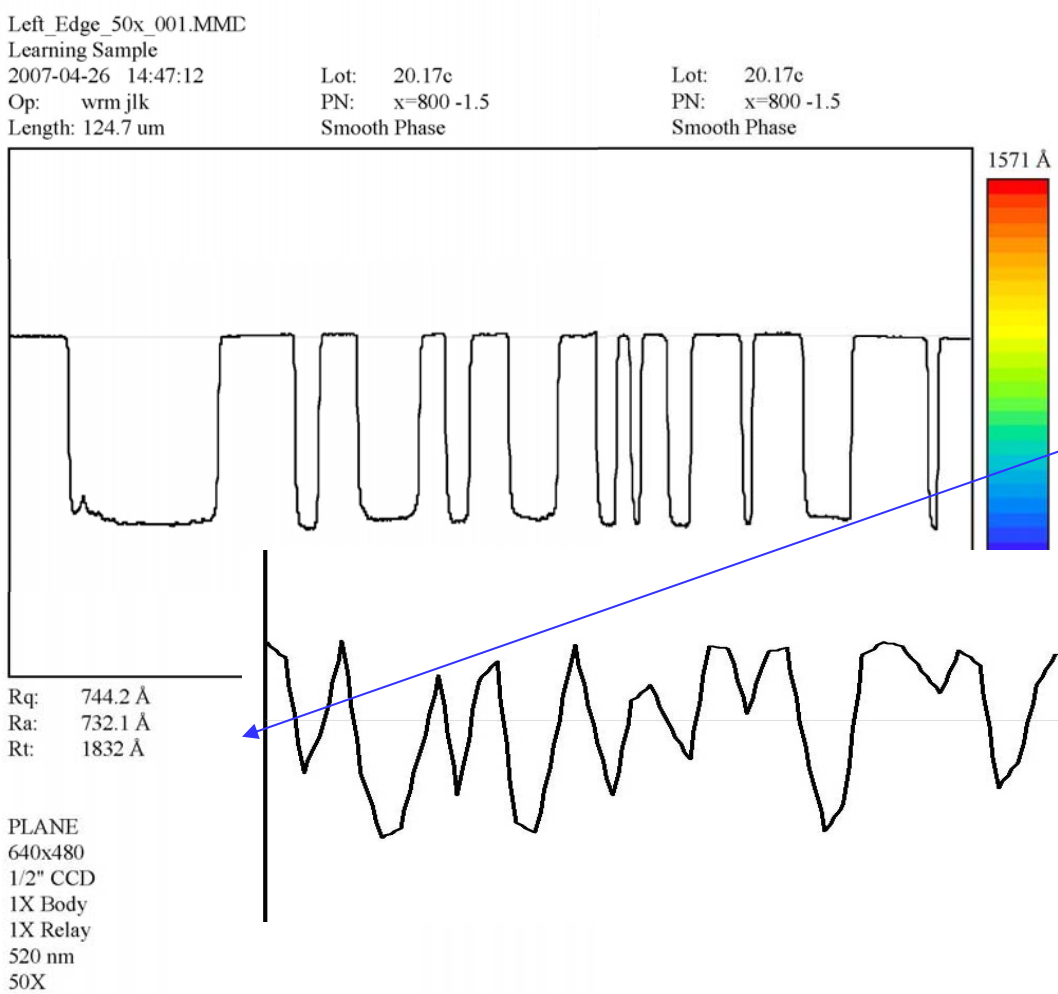




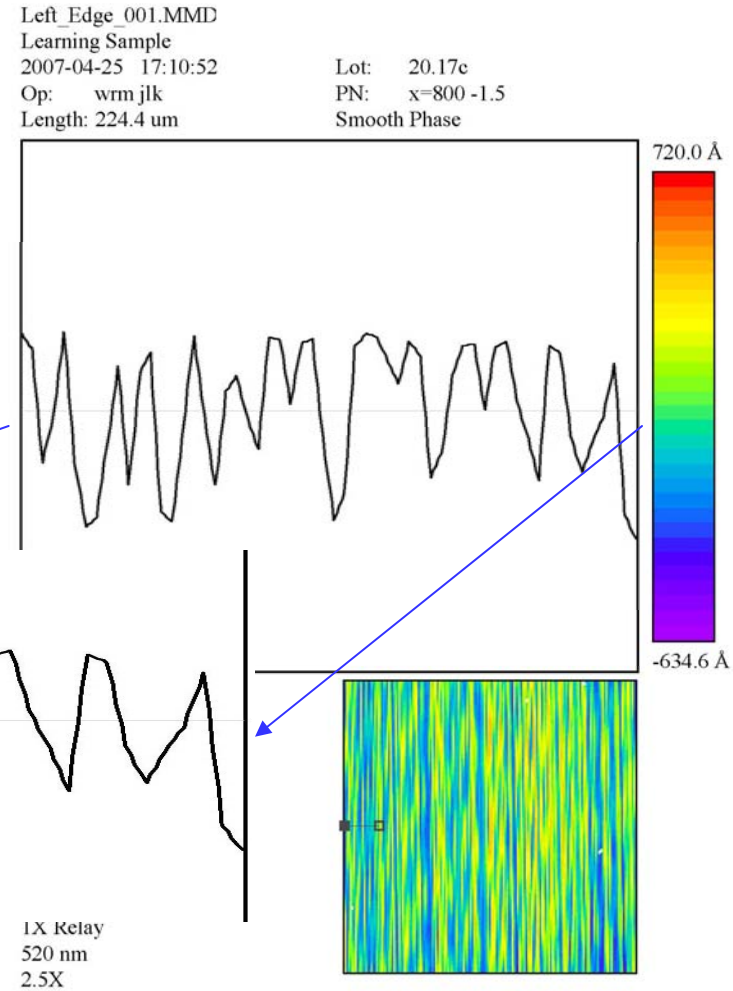
Micromap™-570 measurement with

BPRG test surface (2.5 µm pitch)

50x objective
(0.26 µm pixel size)

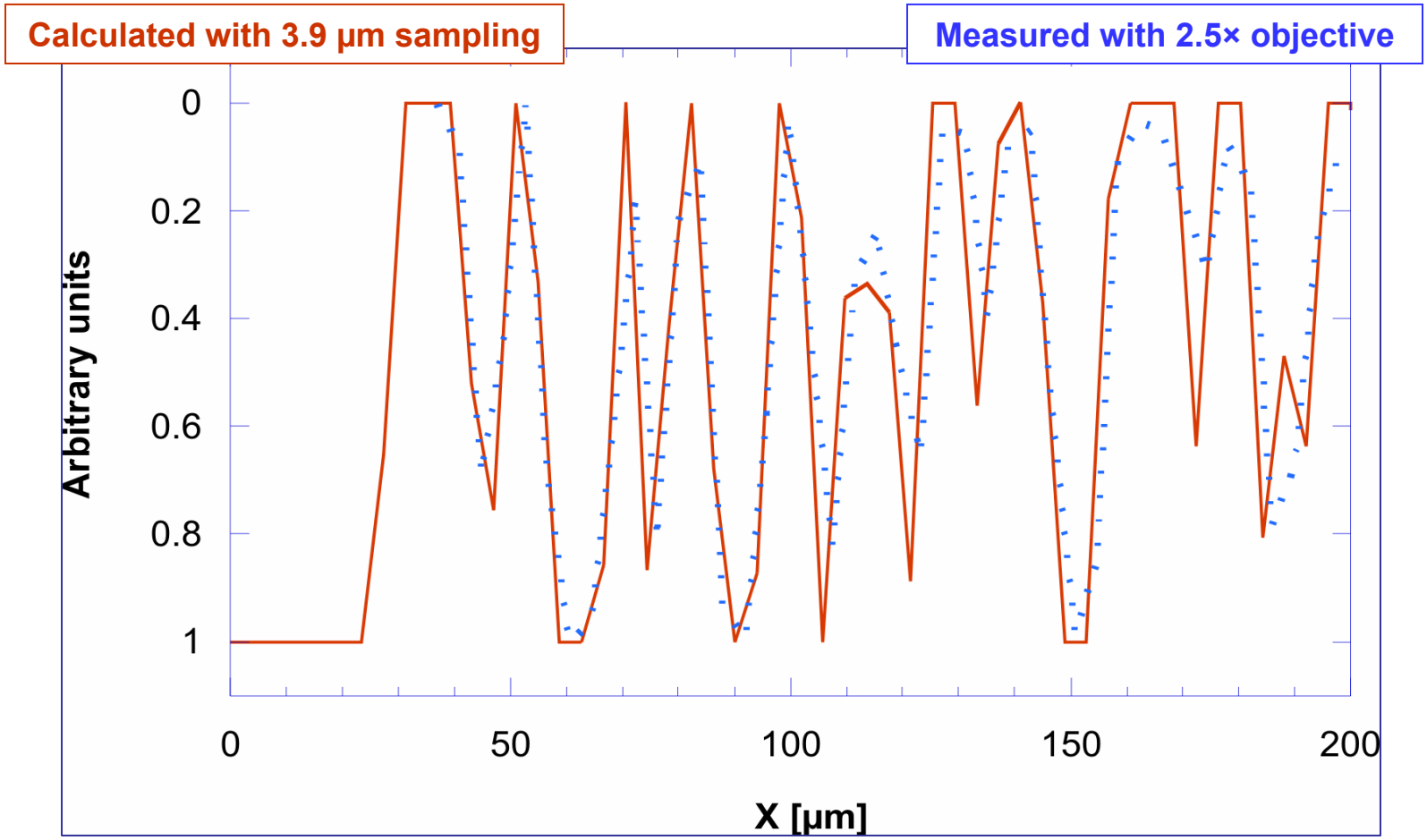


2.5x objective
(3.9 µm pixel size)



Micromap™-570 measurement with

BPRG test surface (2.5 µm pitch)

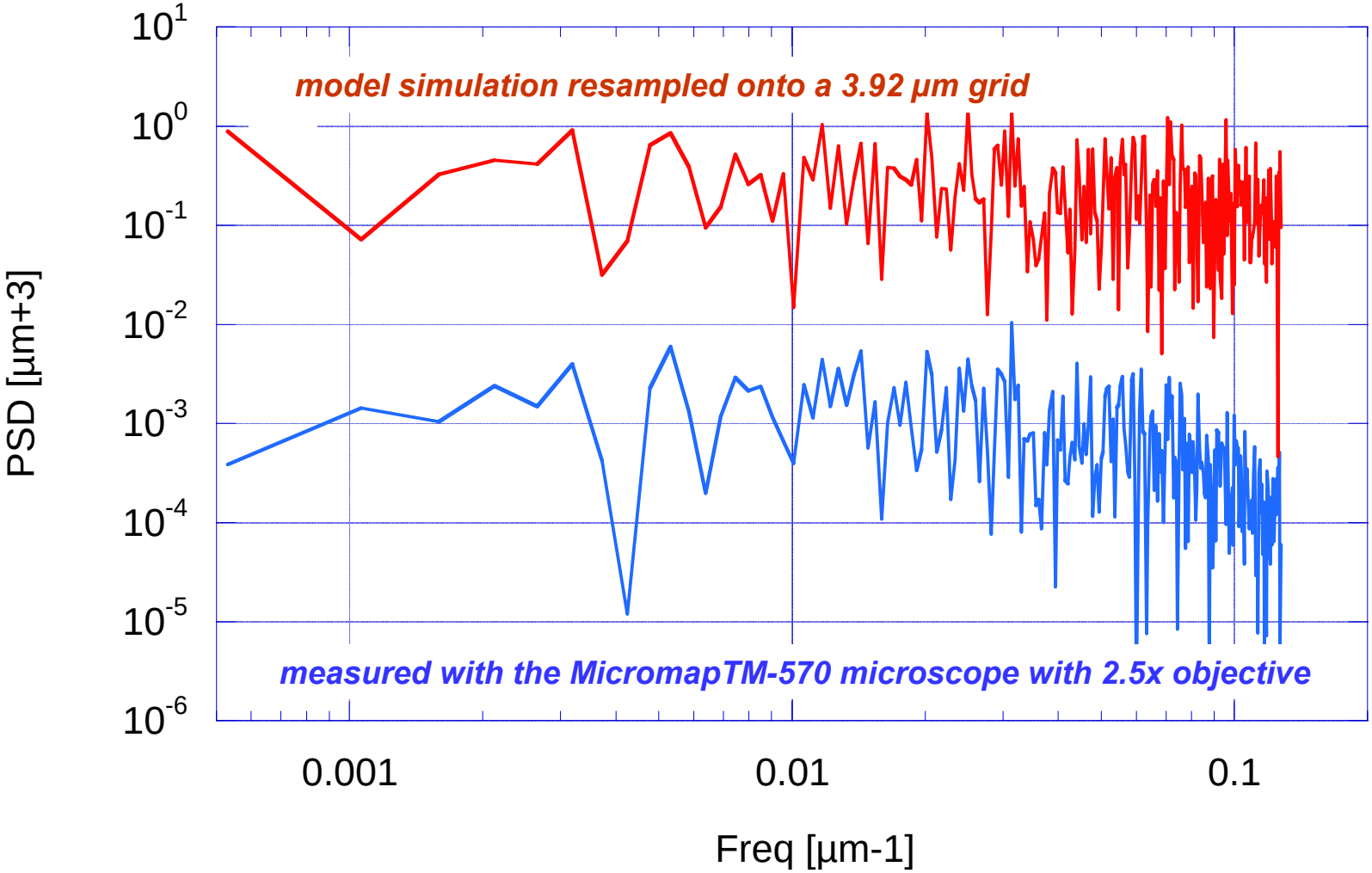


The difference in PSD presentation is to be described with the MTF

PSD spectrum of BPRG test surface

of 4095 elements with 2.5-μm pitch

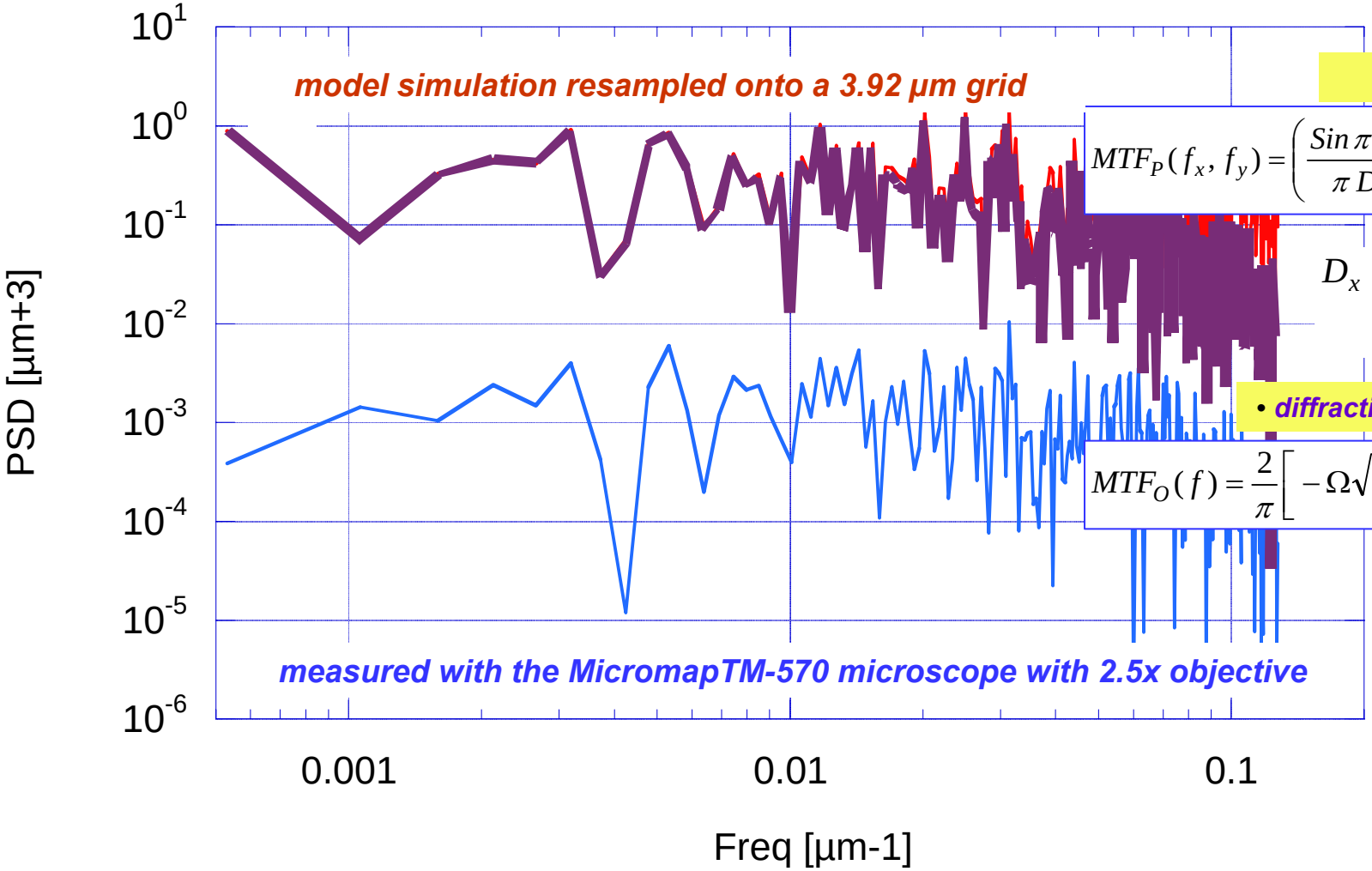
The difference of the PSD spectra is due to the instrumental MTF



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.

MTF correction with BPRG test surface of 4095 elements with 2.5-μm pitch

The theoretical PSD spectrum is corrected to account for the instrumental MTF due to:*)



• effective pixel size

$$MTF_P(f_x, f_y) = \left(\frac{Sin\,\pi D_x f_x}{\pi D_x f_x}\right)\left(\frac{Sin\,\pi D_y f_y}{\pi D_y f_y}\right)$$

$$D_x = D_y = 1.35 \cdot d_{pixel}$$

$$\approx 5.3\,\mu m$$

• diffraction limited objective

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

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

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

$$NA = 0.075$$

$$\lambda = 520nm$$

*) 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

BERKELEY LAB

BROOKHAVEN NATIONAL LABORATORY

Developed in collaboration with Thomas Zeschke (BESSY, Germany)

PSD application - Version 0.1 - 04/13/2007

Miscellaneous

Essential	Optional	Show
Select working directory		
Open files		->
	Surface statistics	
Detrend	Skip detrending	->
	Print detrended data	
	Clip heights 100 [micron] 0.0561399	->
2D PSD IC parameter 1.35		->
	Noise subtraction	->
	2D PSD -> sigma	
1D PSDs		->
	2D PSD Fractal Numerator 2.88E-004 Exponent 6.21E-001	->
MTF correction RollOffConst. 2.73473 Amplitude 5.0E-3		->
MTF to 1D PSD		->

Results : --> Postscript --> EXCEL

History

```
1D MTF n
Finished

Started
Finished

Started
data sig
dc term
mtf  sig
dc term
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
```

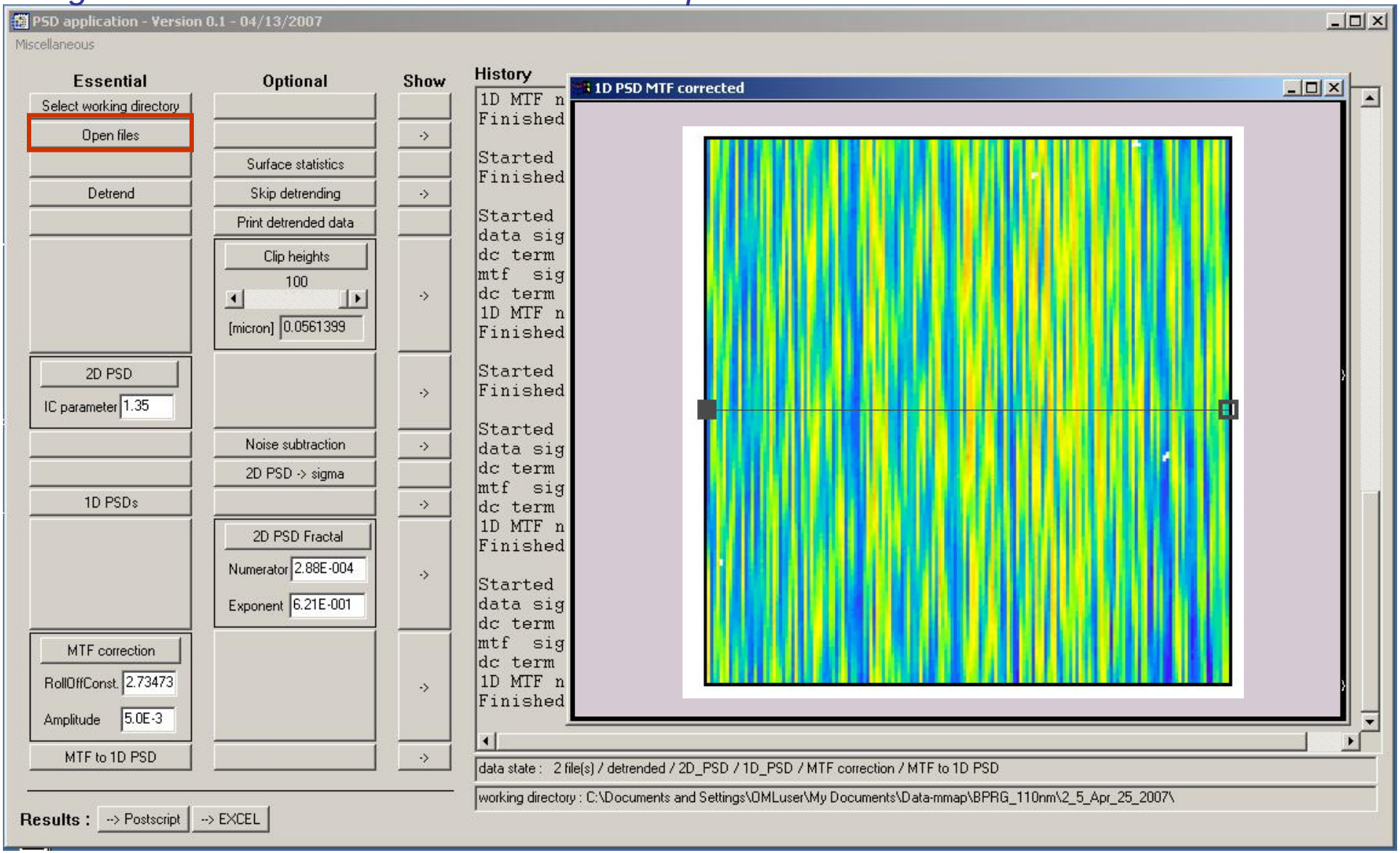
1D PSD MTF corrected

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\

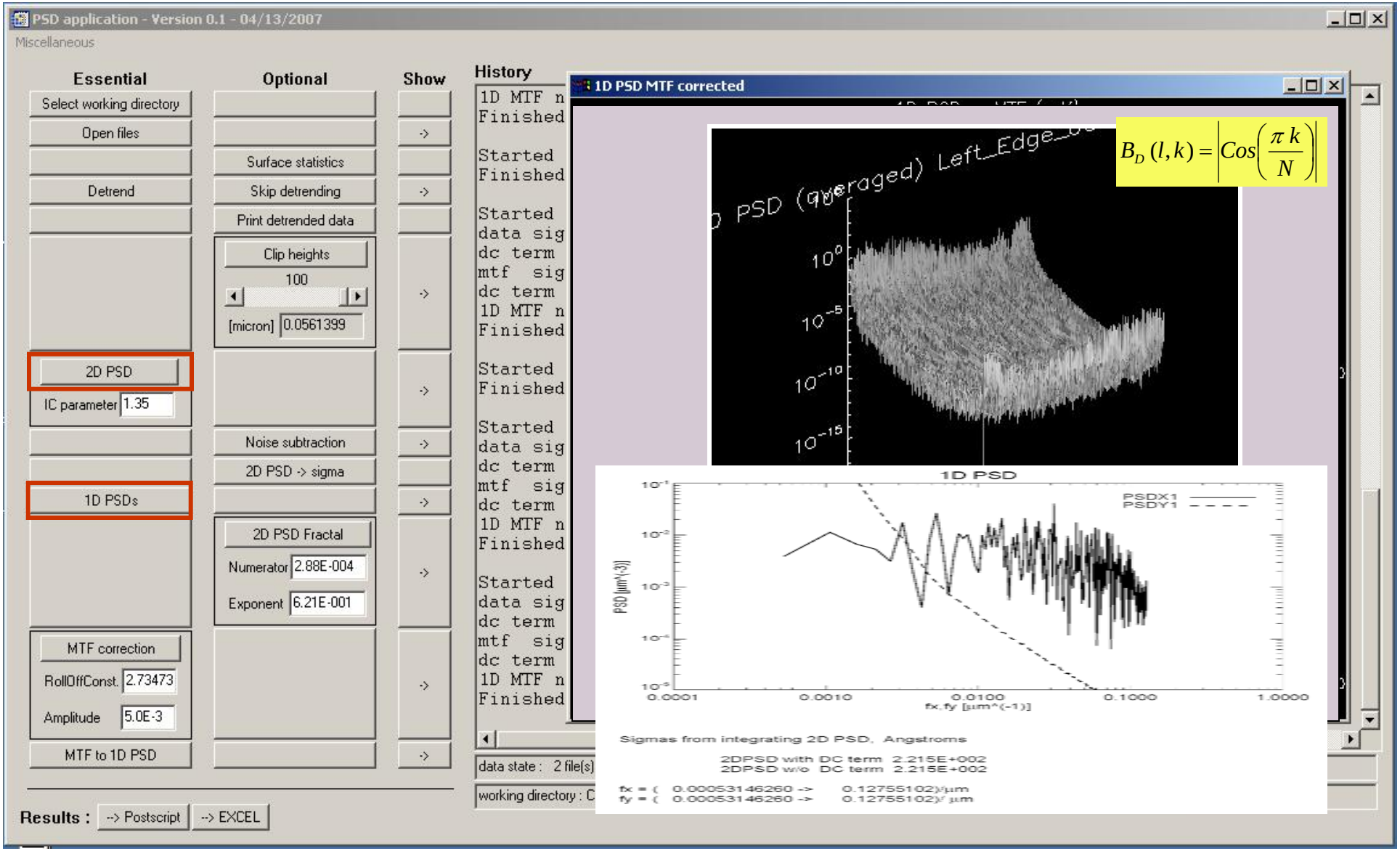
ALS OML PSD Software for Micromap™-570

Height distribution measured with Macromap-570



ALS OML PSD Software for Micromap™-570

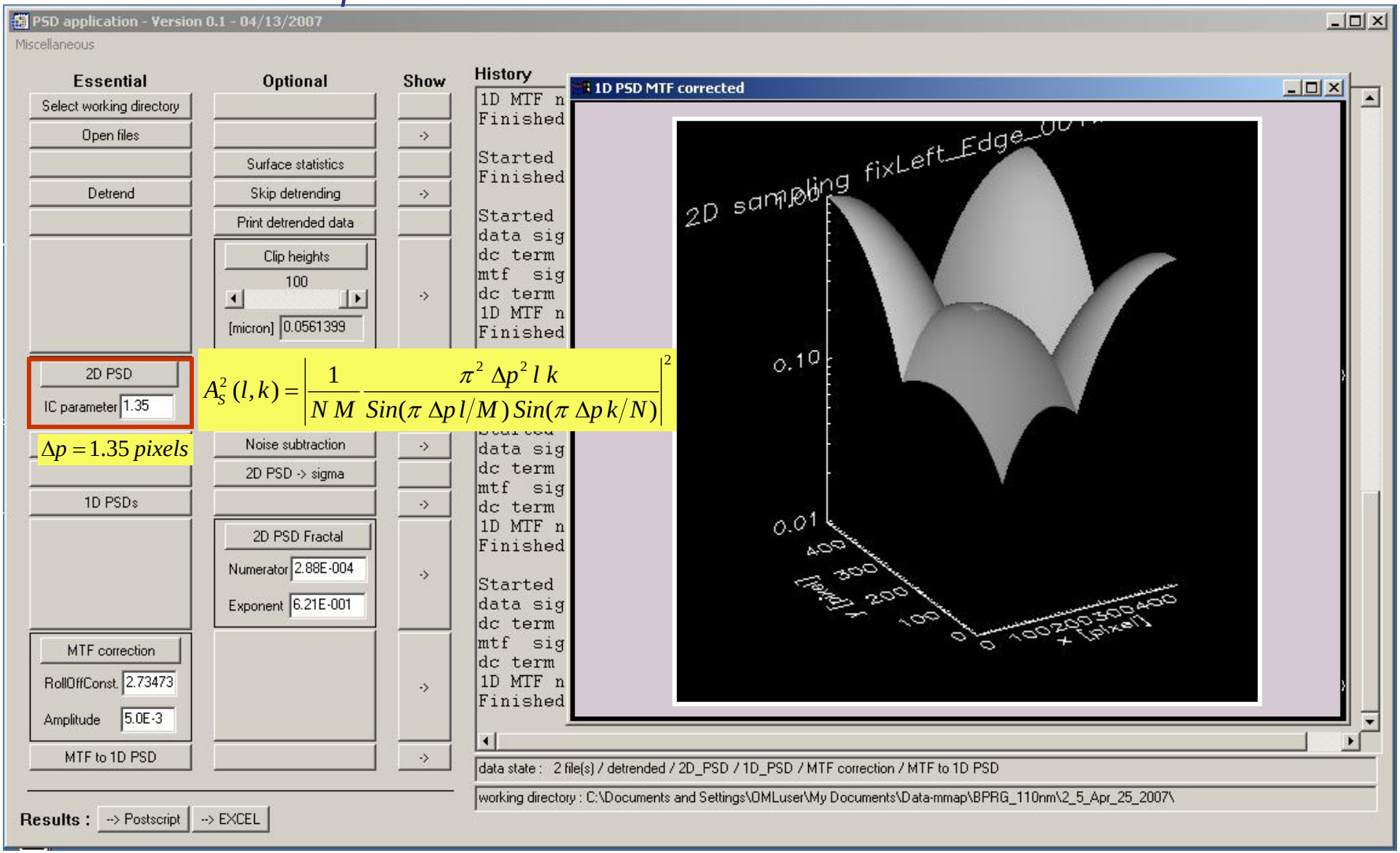
Correction of CCD read-out asymmetry



$$B_D(l,k) = \left| Cos\left(\frac{\pi k}{N}\right) \right|$$

ALS OML PSD Software

Correction of finite pixel size

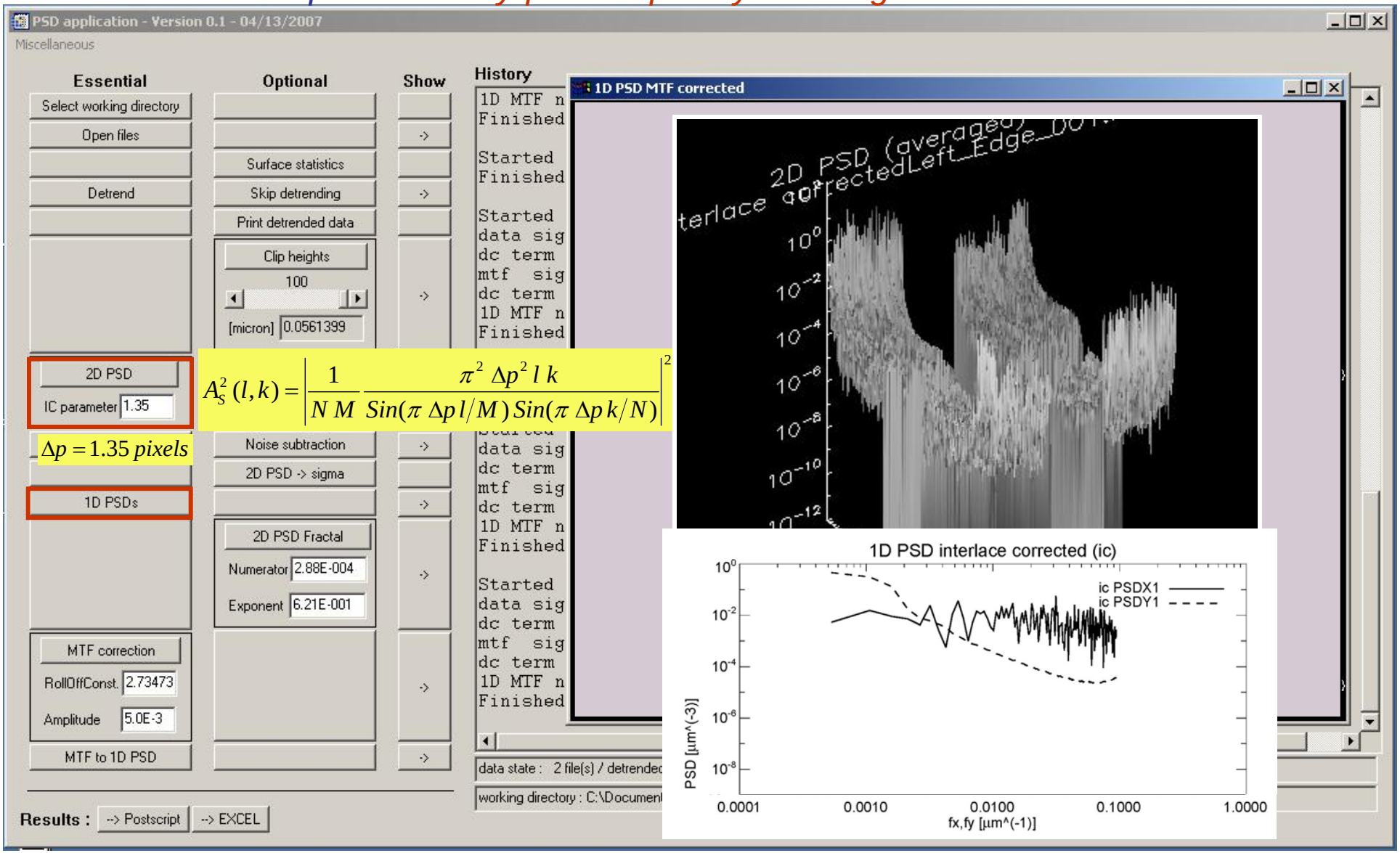


$$A_S^2(l,k) = \left| \frac{1}{N\,M} \frac{\pi^2\,\Delta p^2\,l\,k}{Sin(\pi\,\Delta p\,l/M)\,Sin(\pi\,\Delta p\,k/N)} \right|^2$$

$$\Delta p = 1.35\ pixels$$

ALS OML PSD Software for Micromap™-570

Correction of finite pixel size: Nyquist frequency is changed

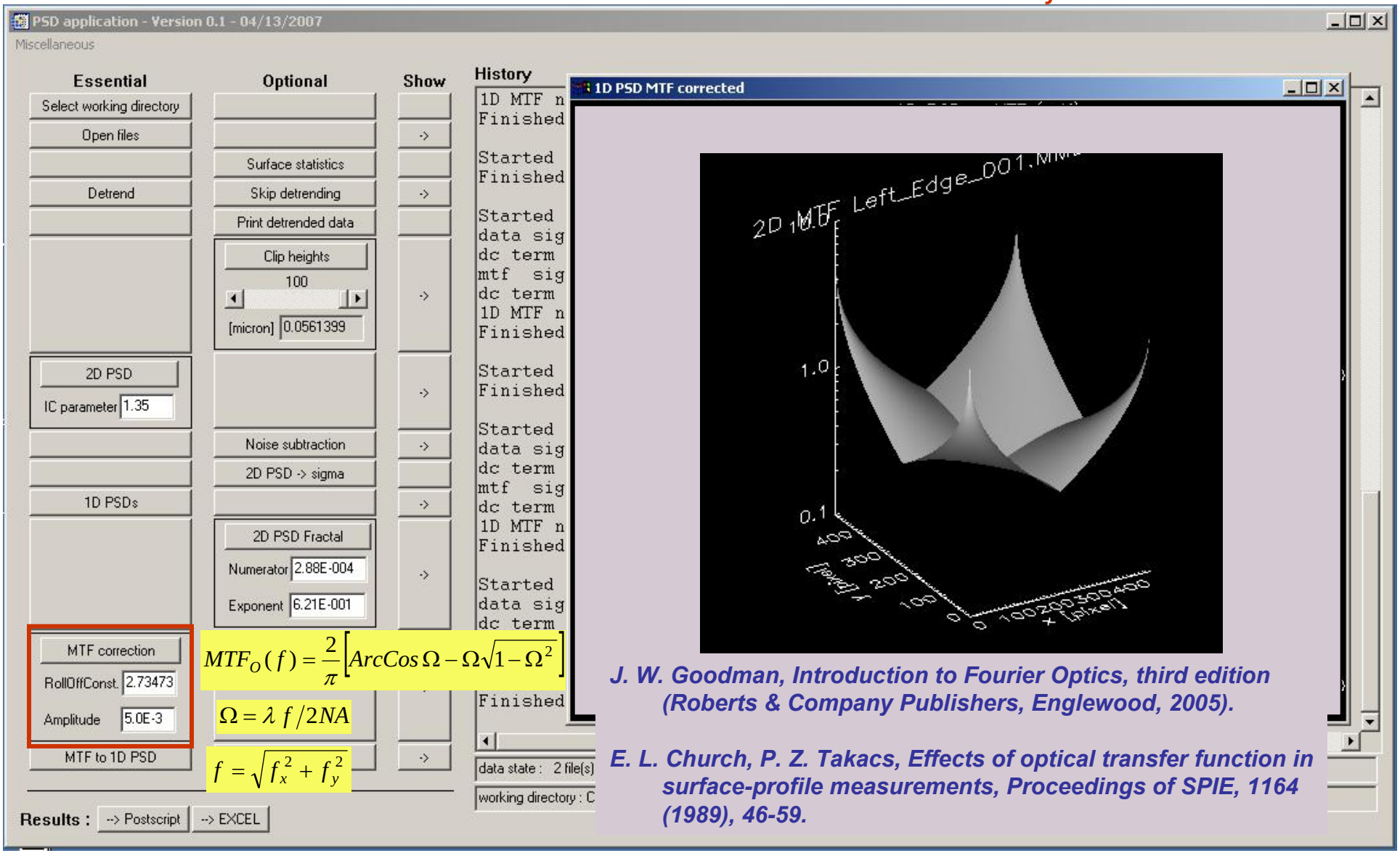


$$A_S^2(l,k) = \left| \frac{1}{N\,M} \frac{\pi^2\,\Delta p^2\,l\,k}{Sin(\pi\,\Delta p\,l/M)\,Sin(\pi\,\Delta p\,k/N)} \right|^2$$

$$\Delta p = 1.35\ pixels$$

ALS OML PSD Software for Micromap™-570

Correction of incoherent transfer function of a diffraction-limited objective



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

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

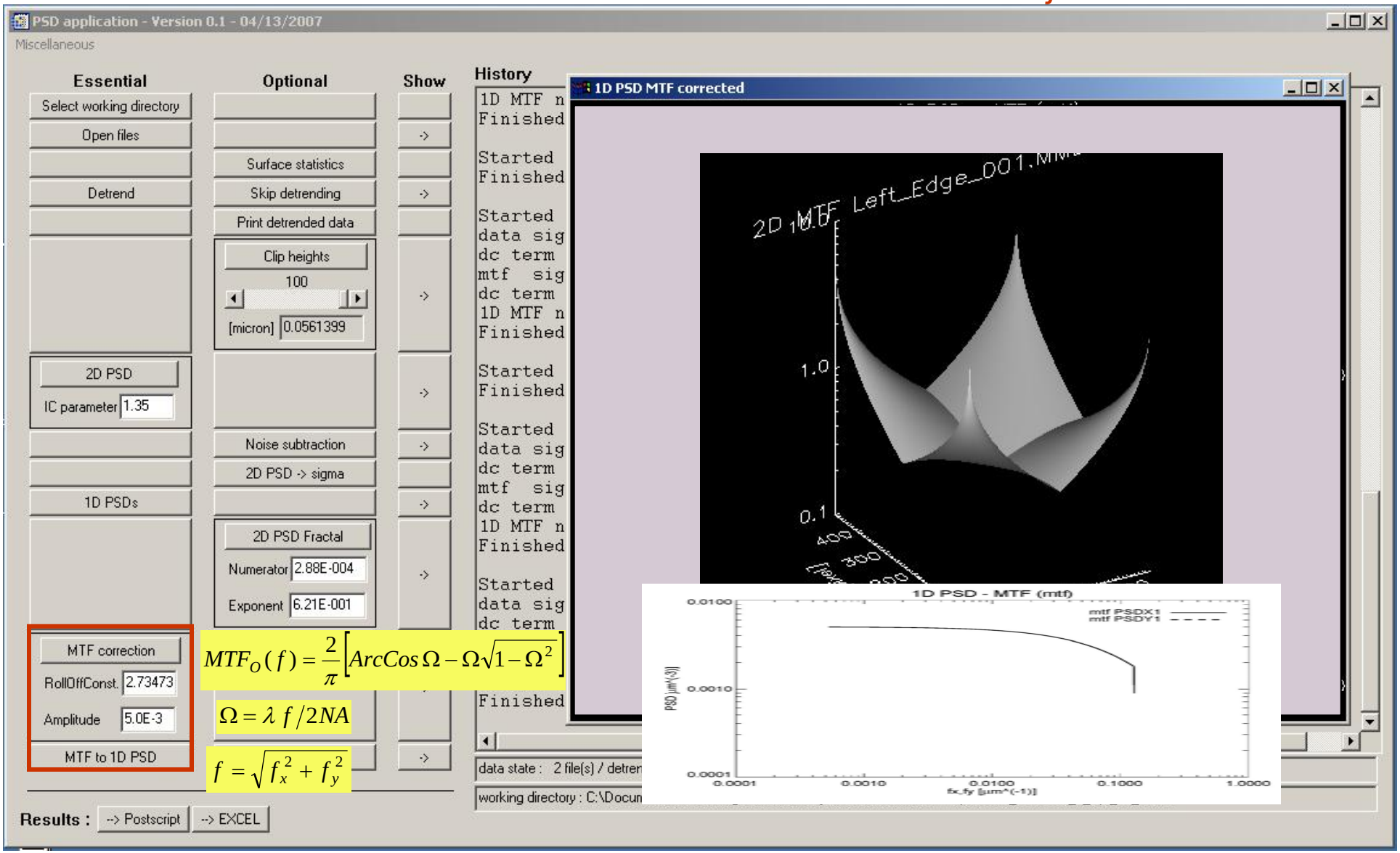
$$f = \sqrt{f_x^2 + f_y^2}$$

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



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

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

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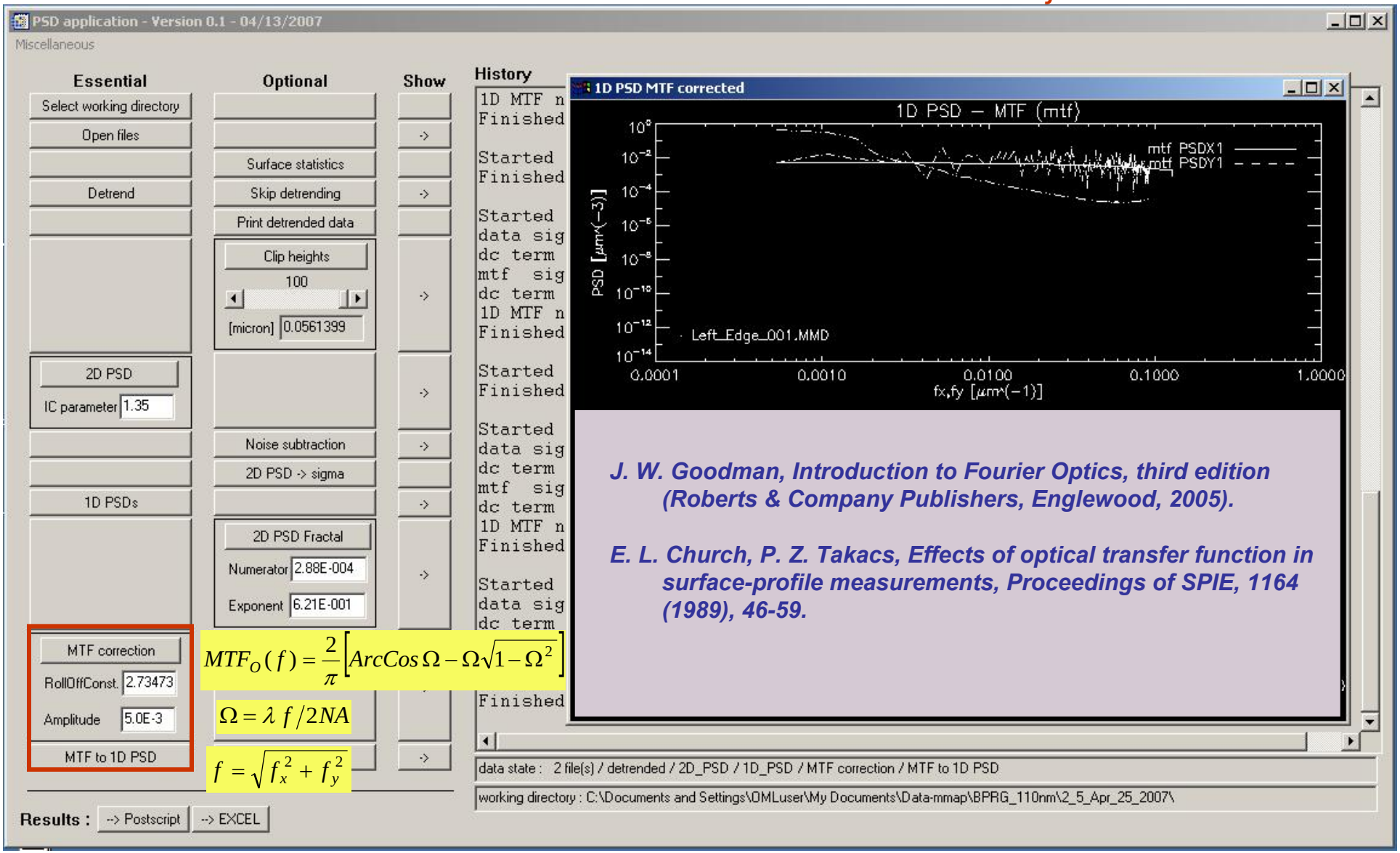
ALS OML PSD Software for Micromap™-570

Correction of incoherent transfer function of a diffraction-limited objective



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

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

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

Conclusions

✓ *Efficiency of Binary Pseudorandom Grating (BPRG) based method for MTF measurements has been demonstrated.*

✓ *Consistence of the BPRG calibration and semi-empirical calibration based on extrapolation of measurements with different objectives has be shown.*

✓*The developed PSD algorithm allows for correction of the CCD read-out asymmetry and accounting for the MTF due to finite pixel size and diffraction-limited objective.*

✓*PSD analysis was successfully applied to the MicroMap-570 interferometric microscope measurements of surface roughness.*

✓ ***Next:*** *MTF correction based on PSD measurements with 2D binary pseudorandom test surface;*

Binary pseudorandom test surface based standard

Acknowledgements

The authors are grateful to

John Warren,

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at Brookhaven National Lab for fabrication of the BPRG test surface, and

Farhad Salmassi

at the Lawrence Berkeley Lab for measurements with an atomic force microscope.

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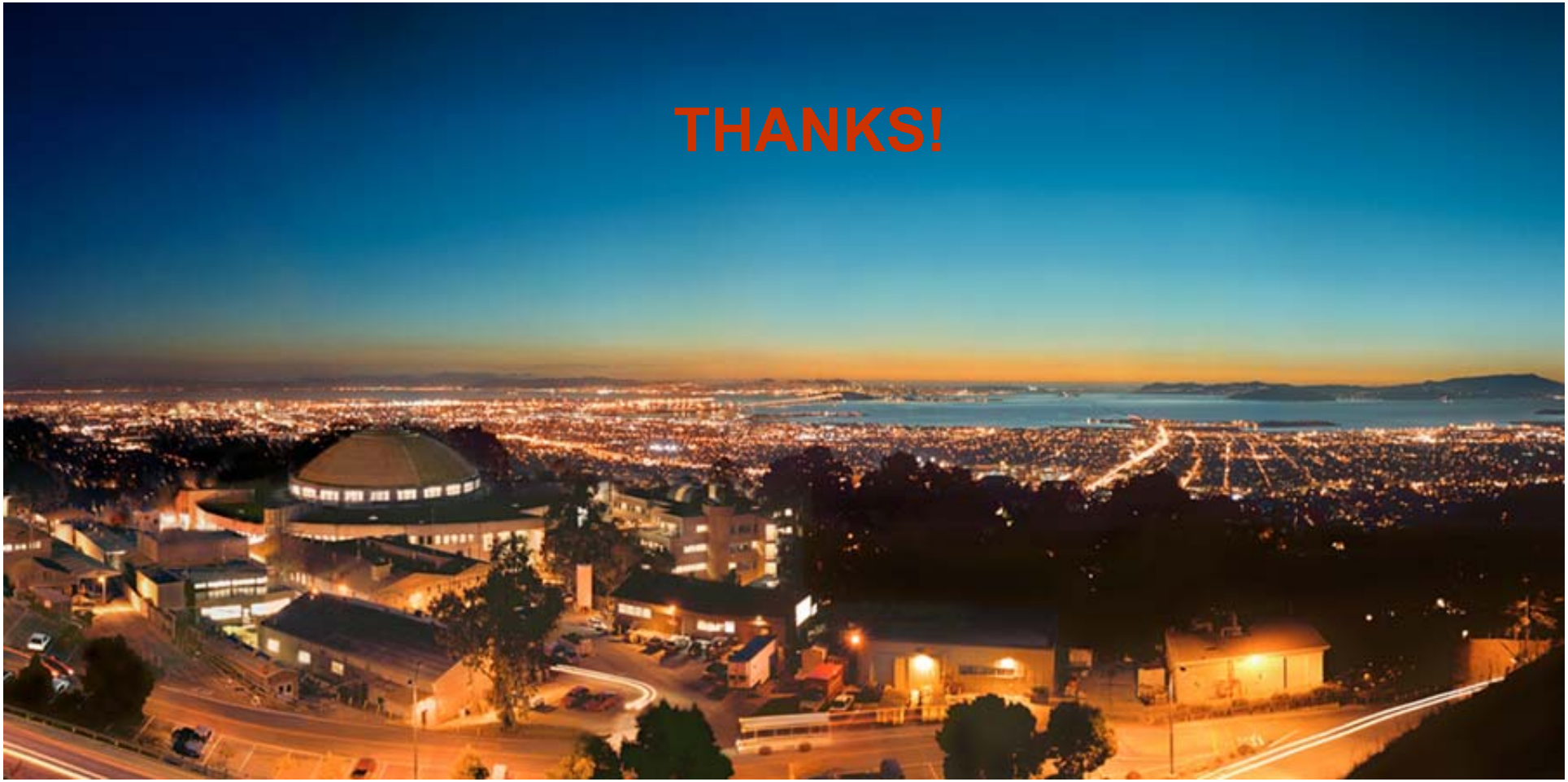

OPTICAL METROLOGY LABORATORY
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