BeatMark Software to reduce the cost of x-ray mirrors (Stochastic Analysis of Surface Metrology data)

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Overview

1. Our team and collaborators
2. Challenges in X-Ray mirror fabrication for Lynx X-Ray surveyor
3. What does the method solve?
4. Patterns and stochastic processes
5. 1D InTILF analysis method
6. BeatMark software
7. 2D analysis method
8. Planned Polishing Optimization
9. Conclusions

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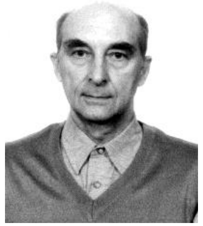
Our Team has over 160 years combined experience in developing new mathematical methods into software

Research and Math



Anastasia Tyurina
CEO and CTO

Prof. Yury Tyurin
head of math development

Software team

Dr. Sergey Panov (Lead/physics)

Doug Paris (GUI)

Peter Panov (GUI/IT/ Platforms)

Business Development

Michael McComas
(Proposals)

Chris Ilsley
(Strategy)

IP and licensing

Michelle Freno
(licensing) (IP)

Anna Ganelina

Interns

Jonathan Borowsky (WASHU)

Daniella Ganelin (MIT)

Jacob Panov (NHS)

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Second Star SBIR-II NNX16CM09C

Second Star works with amazing collaborators

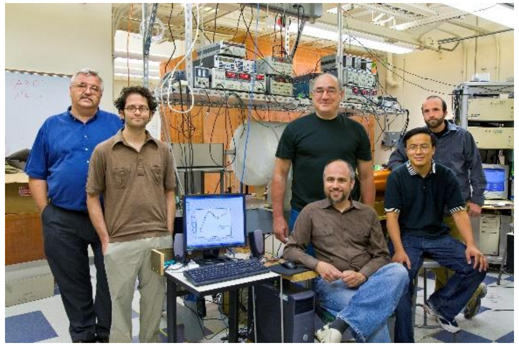
Polishing and metrology tools manufacturer

Dave Mohring (SBIR) Mike Bechtold (CEO)

Ed Fess (R&D head)

The best Metrology Lab in US

Dr Valeriy Yashchuk



Our collaborators think that if our technology works it will bring a revolution in polishing

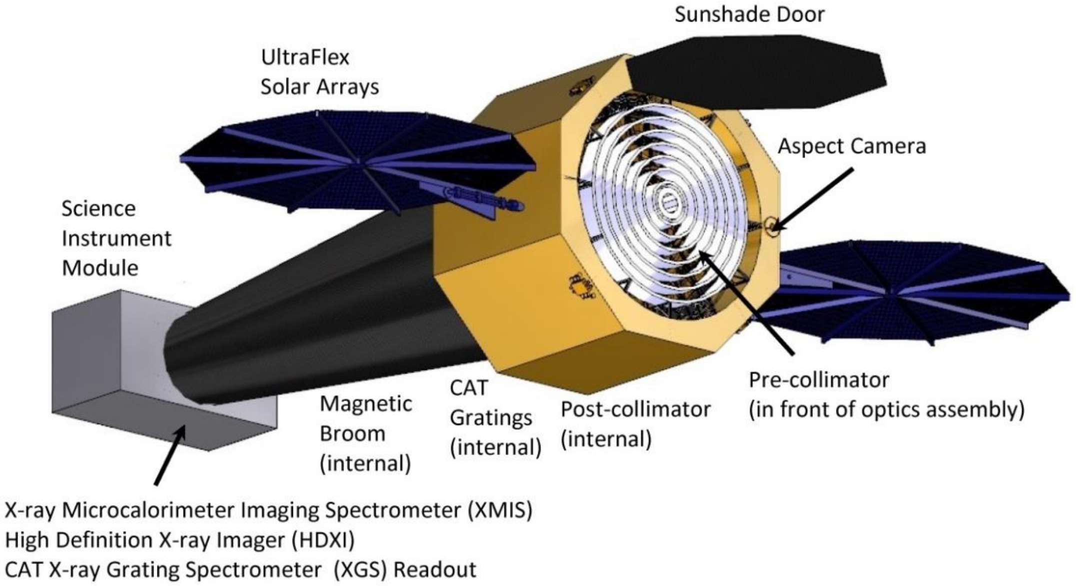
Misha Gubarev.

The project would not be where it is now without his expertize and support

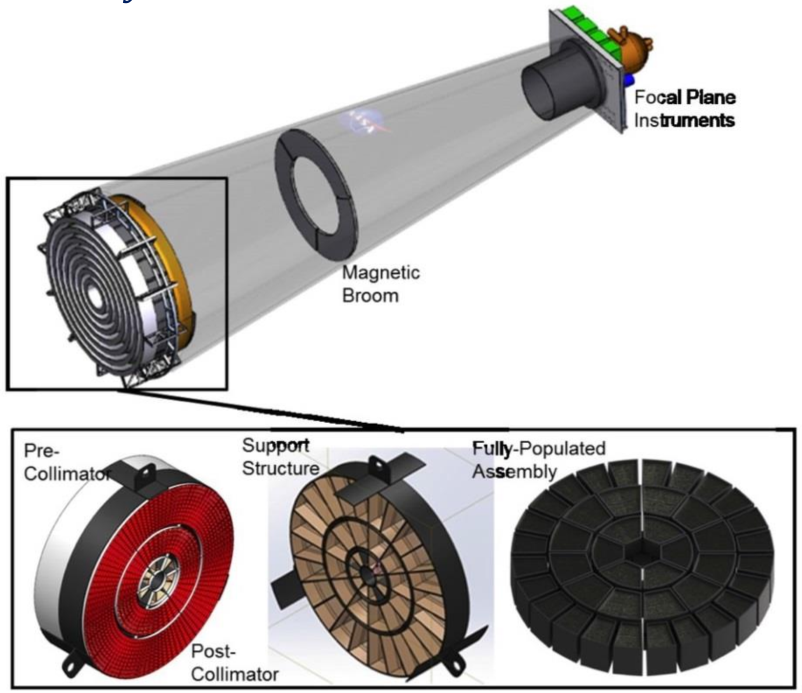
https://www.gofundme.com/mikhail-v-gubarevs-memorial

Objective of the project: To reduce fabrication cost of x-ray mirrors

X-ray Surveyor Mission Concept*



The X-ray Surveyor requires X-ray mirrors to achieve large throughput with high angular resolution (0.5 arcsec) in order to avoid X-ray source confusion and background contamination.
High angular resolution is critical for providing unique identifications of faint X-ray sources.



- *292-segmented shells nested into 42 individual mirror modules with overall size of 3 m outer diam.;*
- *~ 0.2 arcsec root-mean-square (rms) slope error;*
- *$2,952M estimated total cost of the mission.*

X-ray Surveyor Telescope

* J. A. Gaskin, M. C. Weisskopf, A. Vikhlinin, et. al., "The X-ray Surveyor Mission: A Concept Study," Proc. SPIE 9601, UV, X-Ray, and Gamma-Ray Space Instrumentation for Astronomy XIX, 96010J (August 24, 2015); doi:10.1117/12.2190837

What can our InTILF method do for X-ray mirror fabrication?

Yashchuk, V. V., Tyurin, Y. N., and Tyurina, A. Y., "Application of time-invariant linear filter approximation to parameterization of one- and two-dimensional surface metrology with high quality x-ray optics," Proc. SPIE 8848, 88480H-1-13 (2013).

Decrease Fabrication Cost

- Faster and easier fabrication through simplified and standardized quality control
- Polishing optimization
- Enable medium size mirror manufacturers to join the X-ray mirror market

Increase Fabrication Speed

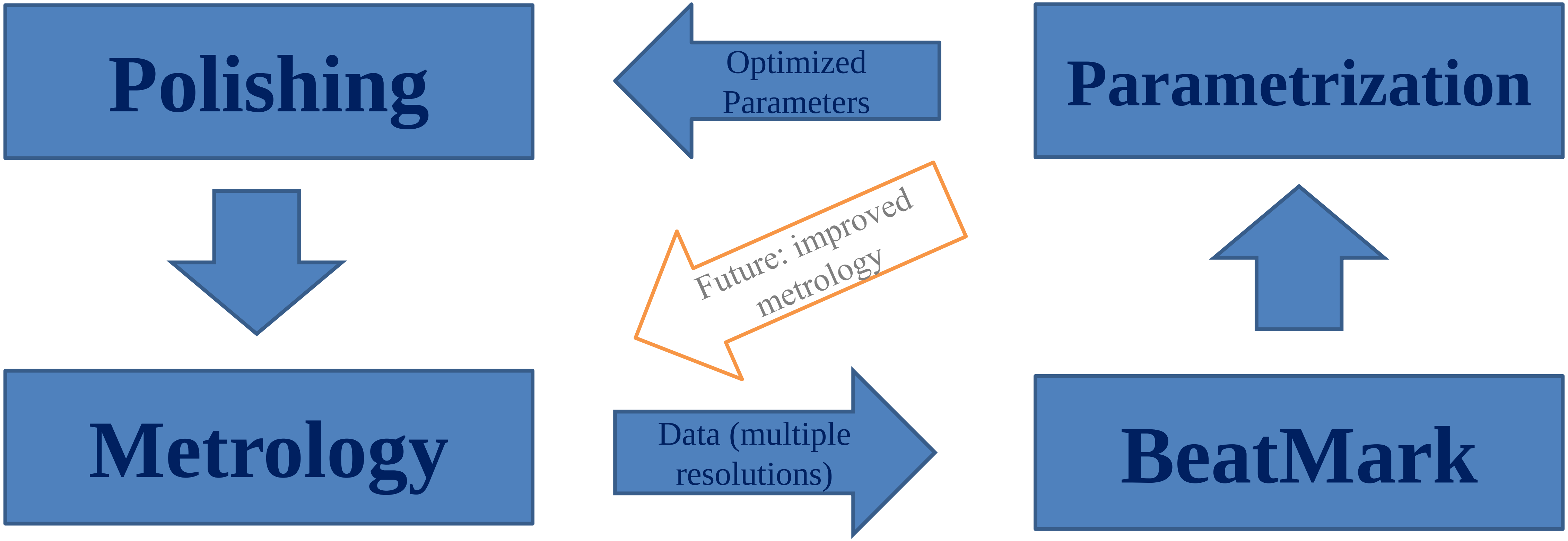
- Less metrology
- Less re-polishing

Increase Fabrication Predictability

- Metrics of quality and comparison of mirrors
- Generation of statistically equivalent metrology data
- Simulation of the X-ray mirror behavior within an X-ray optical system

see Opt Eng 54(2) 025108, Specification of x-ray mirrors in terms of system performance (Yashchuk, Samoylova, Kozhevnikov)

BeatMark software package is developed to improve the iterative polishing and metrology process



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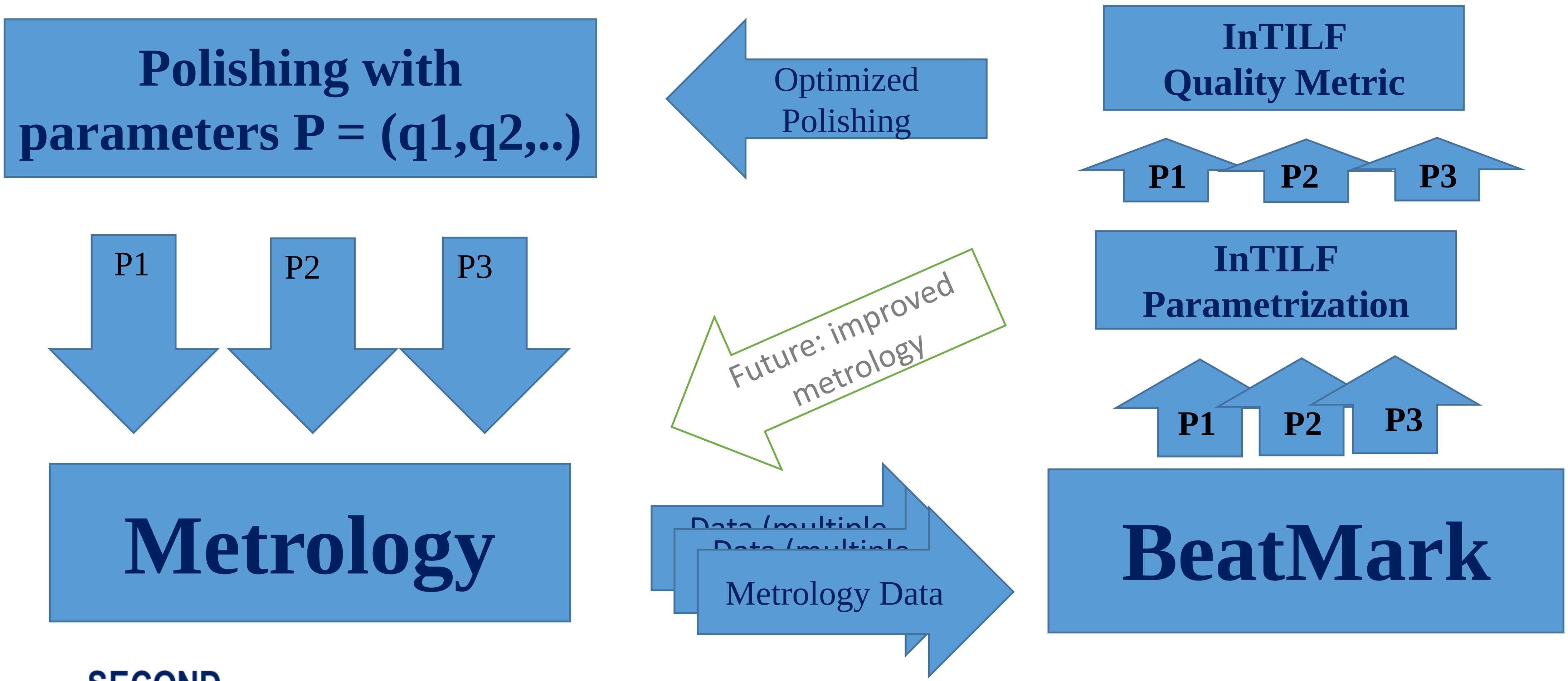
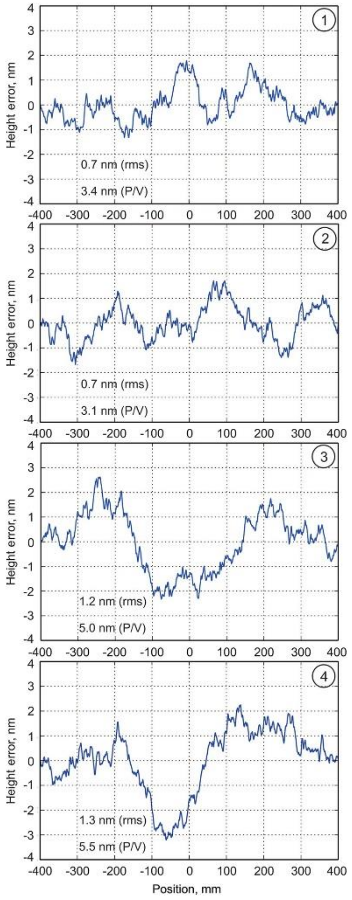
BeatMark concept step 2:
Optimization of polishing and metrology process



Patterns left on the mirror by polishing process are bad for imaging

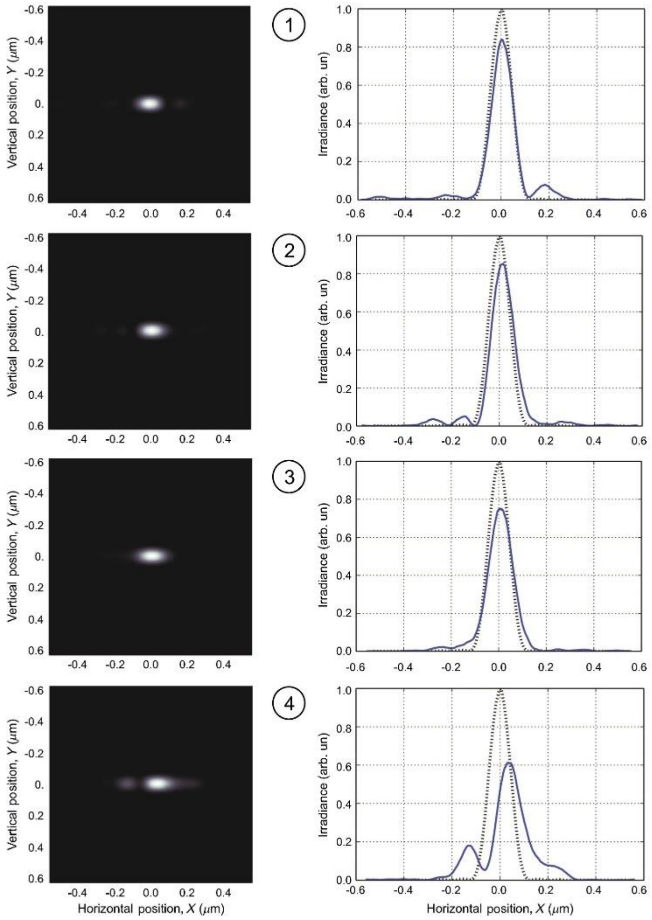
Yashchuk, Samoylova, and Kozhevnikov: Specification of x-ray mirrors in terms of system performance (0pt Eng. 54-2-025108-2015)

Simulated x-ray mirror profiles of the same surface height error rms



X-ray Mirror performance simulation

Simulated x-ray mirror imaging of a single point source (left) and its cross sections (right)



It is not just rms!

Polishing optimization idea

- Ideal mirror surface deviates from its form very slightly and in an absolutely random manner – white noise random
- White noise is an absolutely random process completely devoid of pattern
- A polishing tool might leave a pattern (correlations) on a mirror. If it is detected and characterized, the mirror can be improved by optimizing polishing parameters.
- Our task is to detect and characterize the pattern

We are in search of a pattern

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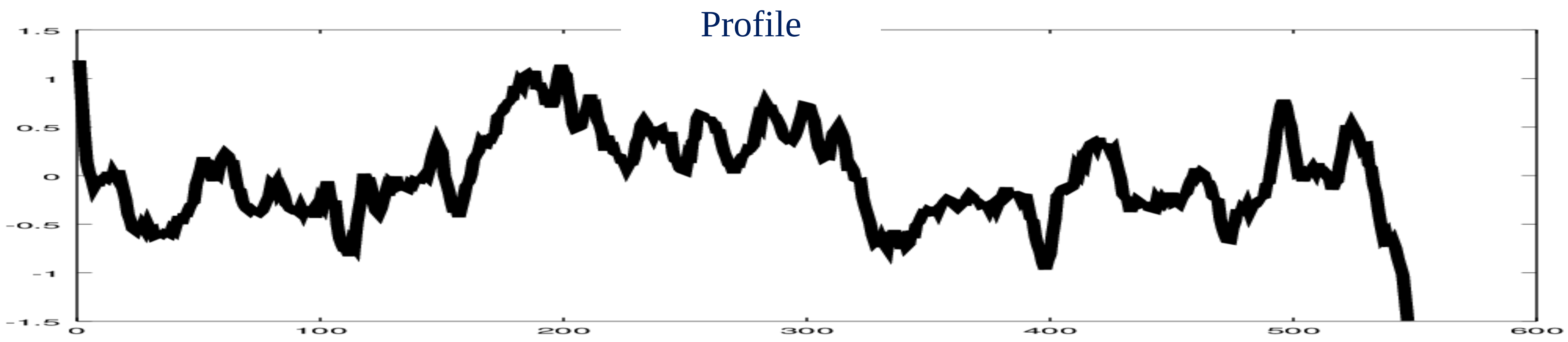
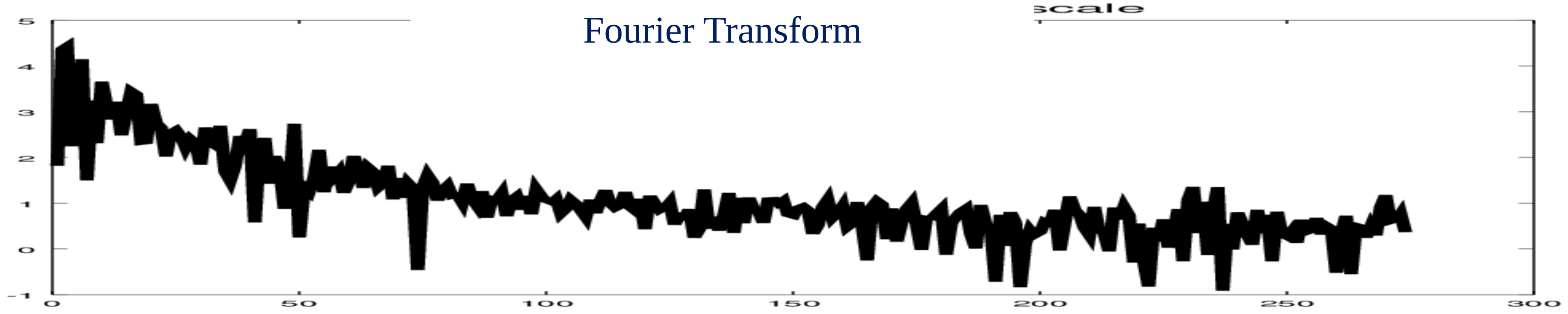
InTILF method looks for patterns not seen by Fourier Transform in stochastic signal





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Logic of the project

- Periodic process – spectral characteristics are surmised by Fourier transform
- Stochastic process – spectral characteristics are surmised with statistical tools
- We think we can optimize the polishing and metrology process because we learned to characterize stochastic surface data with

  Invertible Time Invariant Linear Filters (InTILF)

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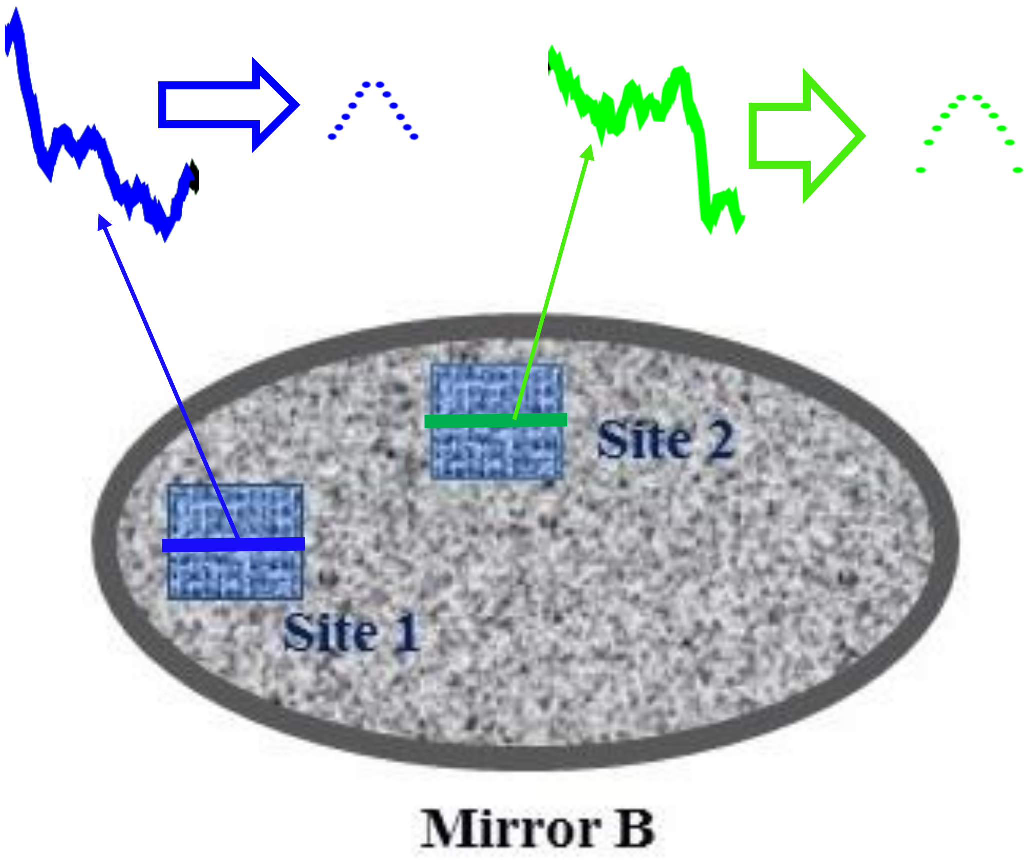
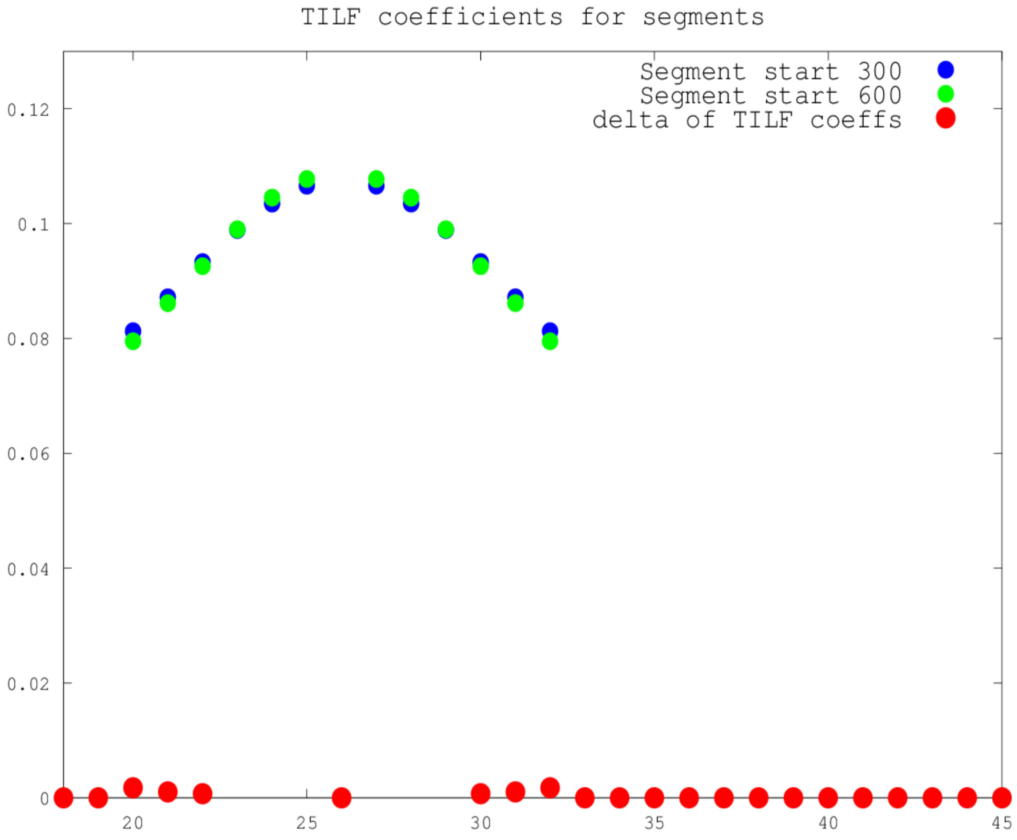
BeatMark method provides characterization of the surface based on small metrology samples

Segments length = 300

Segments length = 300





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Projects status

1) Software development
- 1D application – commercial prototype is ready
- 2D application developed for finding InTILF models

2) InDevelopment
- 2D surfaces generation
- Format readers

3) Application to polishing
- OptiPro completed its first polishing experiment (planned for year II of the project)
- LBNL received the samples and is re-measuring them
- Second Star is analyzing the data
- The team is preparing the second data collect

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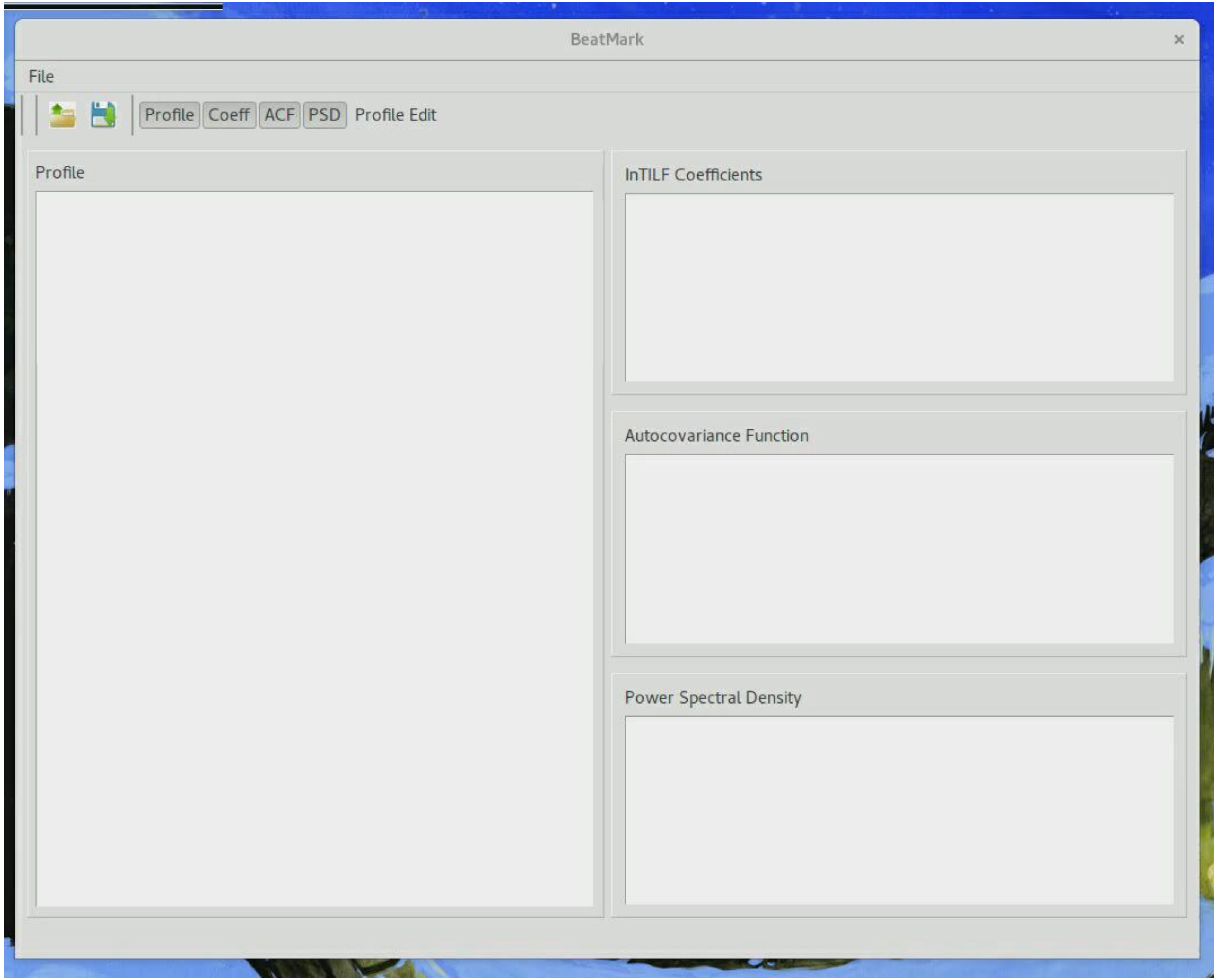
BeatMark prototype demo



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BeatMark provide first available statistical analysis of 2D metrology profiles (surface)

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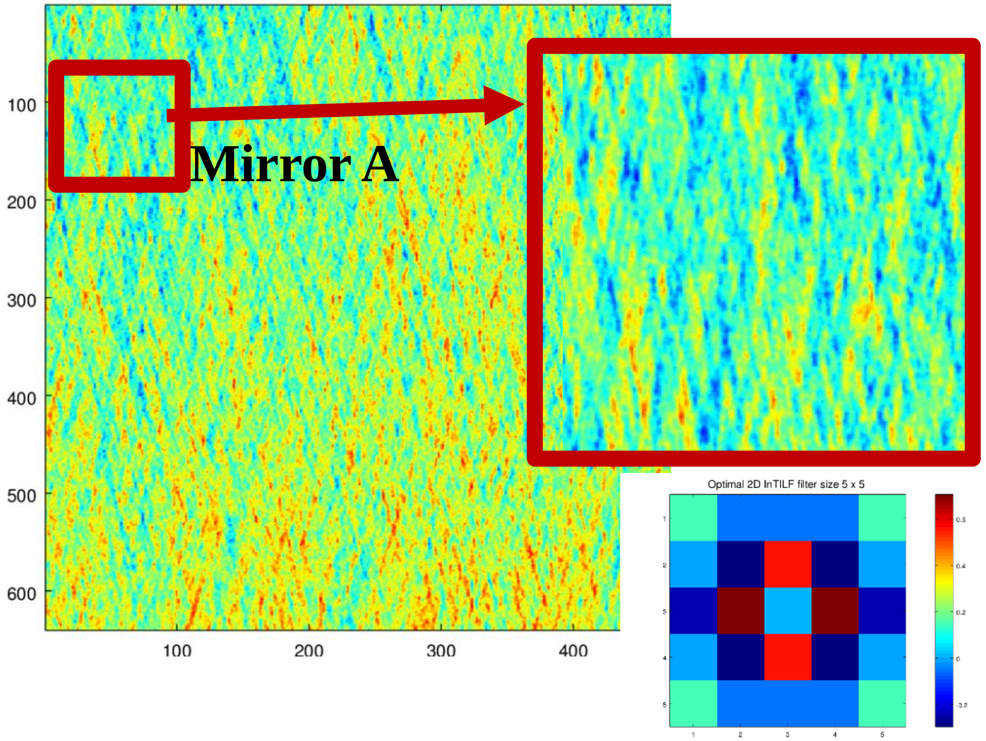
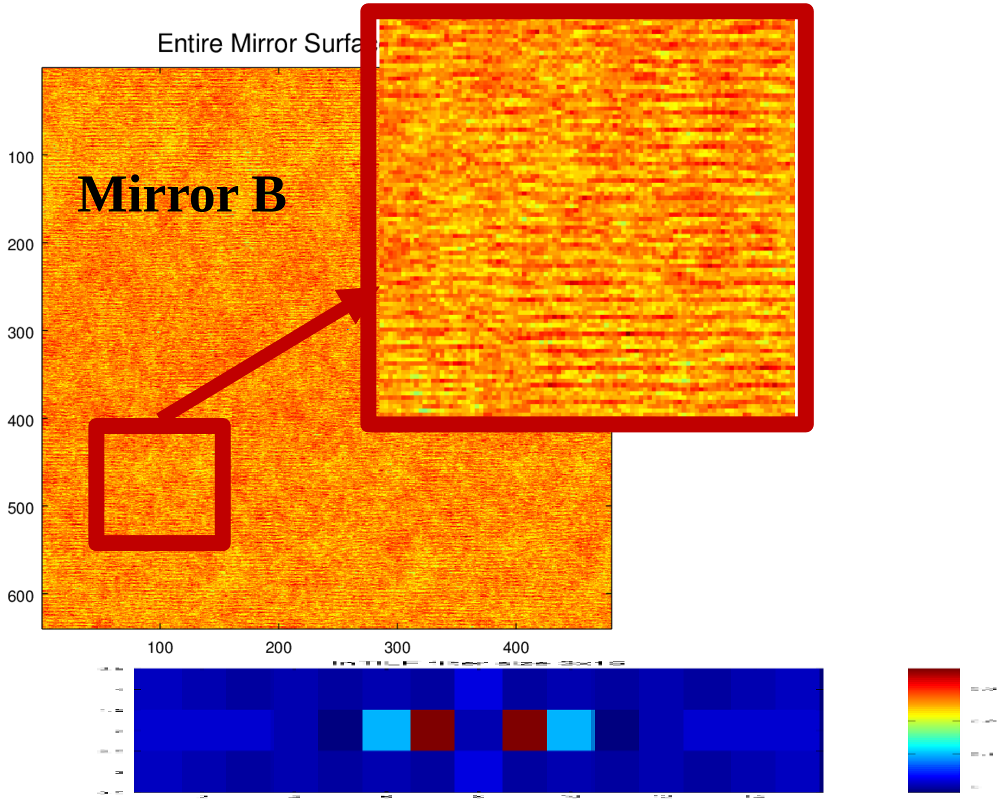
BeatMark-2D assessment of two mirrors





BeatMark assessment of Mirror A:
InTILF 5x5 matrix
Residual < 1 %

BeatMark assessment of Mirror B:
InTILF = 3 x15 matrix
Residual = 23%

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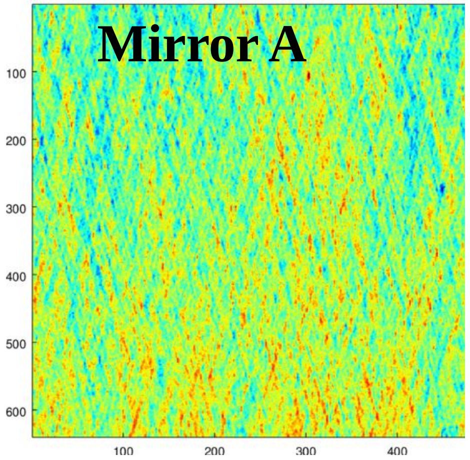
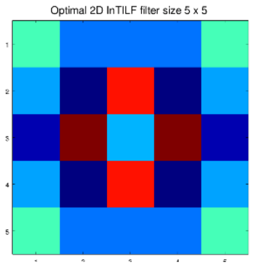
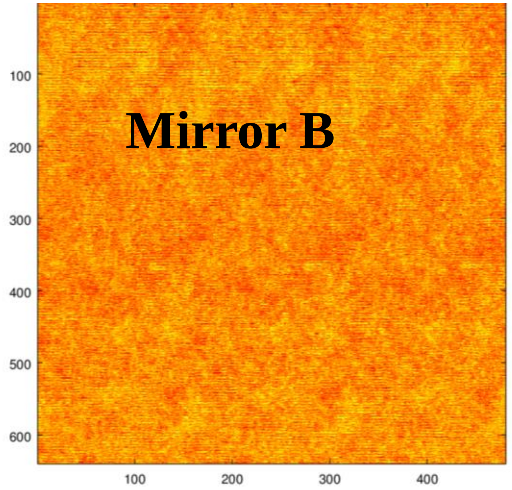
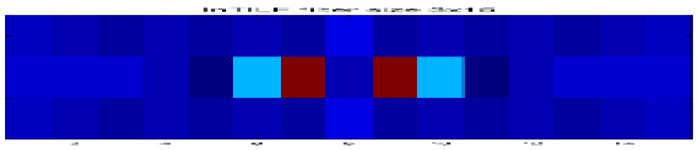
BeatMark-2D assessment of two mirrors









BeatMark assessment of Mirror A:
InTILF 5x5 matrix
Residual < 1 %

BeatMark assessment of Mirror B:
InTILF = 3 x15 matrix
Residual = 23%

How many parameters do fully describe a mirror?

A: 25 B: 45

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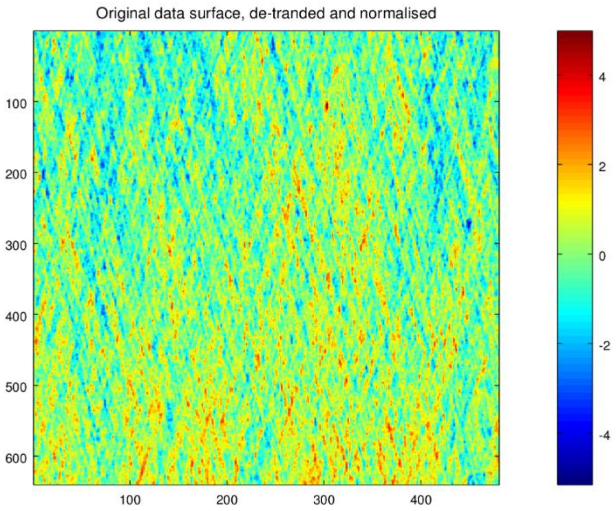
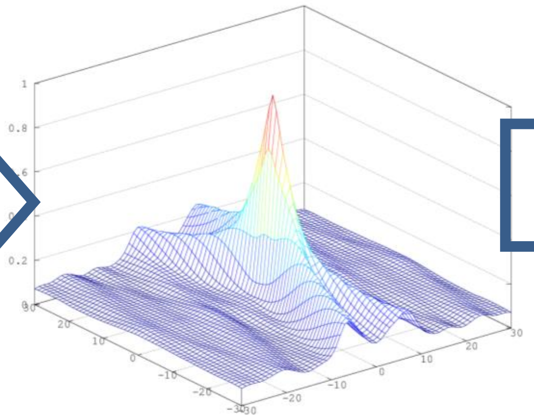
Construction of 2D InTILF model, mirror A

1. Start with 2D data



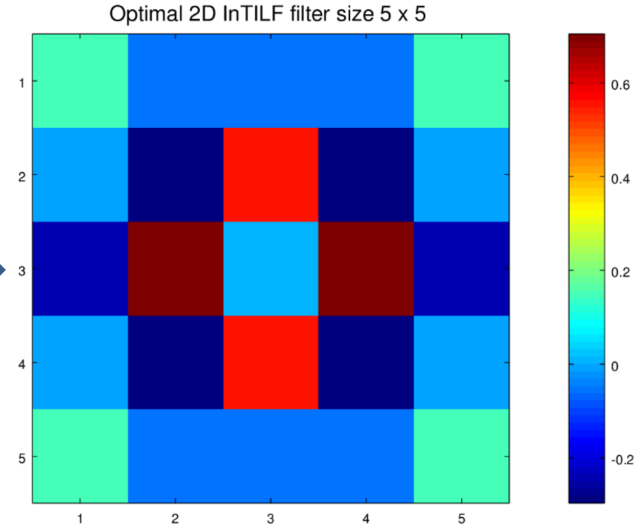
ACF

2. Compute
Auto Covariance Function



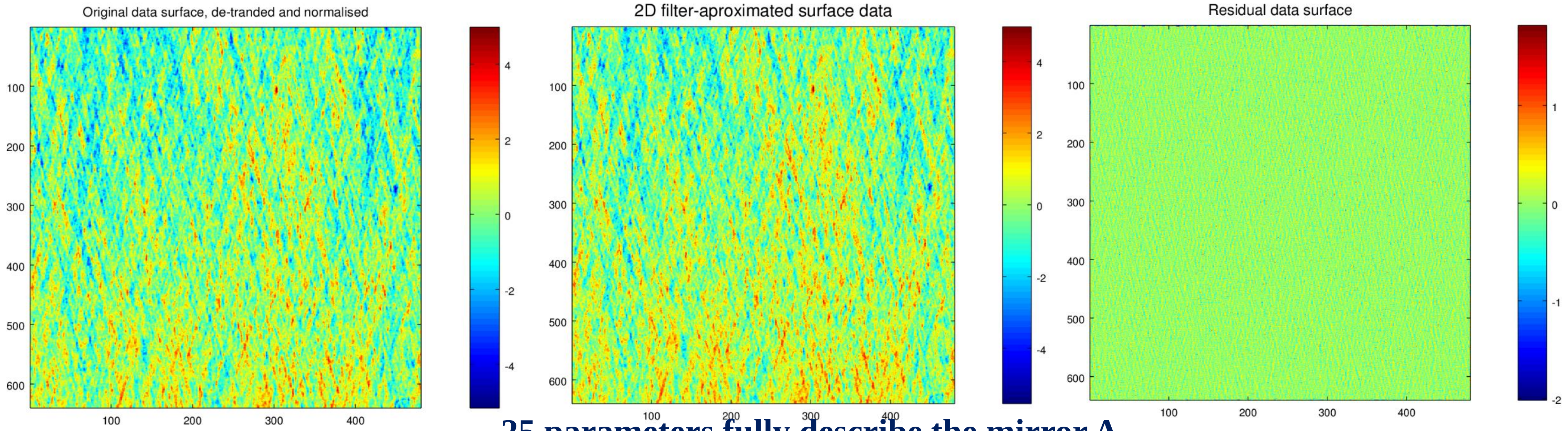
InTILF

3. Compute
InTILF (2D matrix)



2D InTILF analysis of Mirror A

Mirror A data: height distribution measured with an interferometric microscope ZYGO NewView^{TM}-7300 equipped with 2.5× objective with ×2.0 zoom. The Microscope is available at the ALS XROL.[18,19] The left-hand plot in Fig. 1 shows the rectangular surface area of 1.06 mm × 1.41 mm measured with the effective pixel size of 2.2 µm (the data set consists of 640 × 480 pixels^2). The measured surface topography has a characteristic ‘diamond’ like pattern with rms variation of the surface height of 6.75Å.

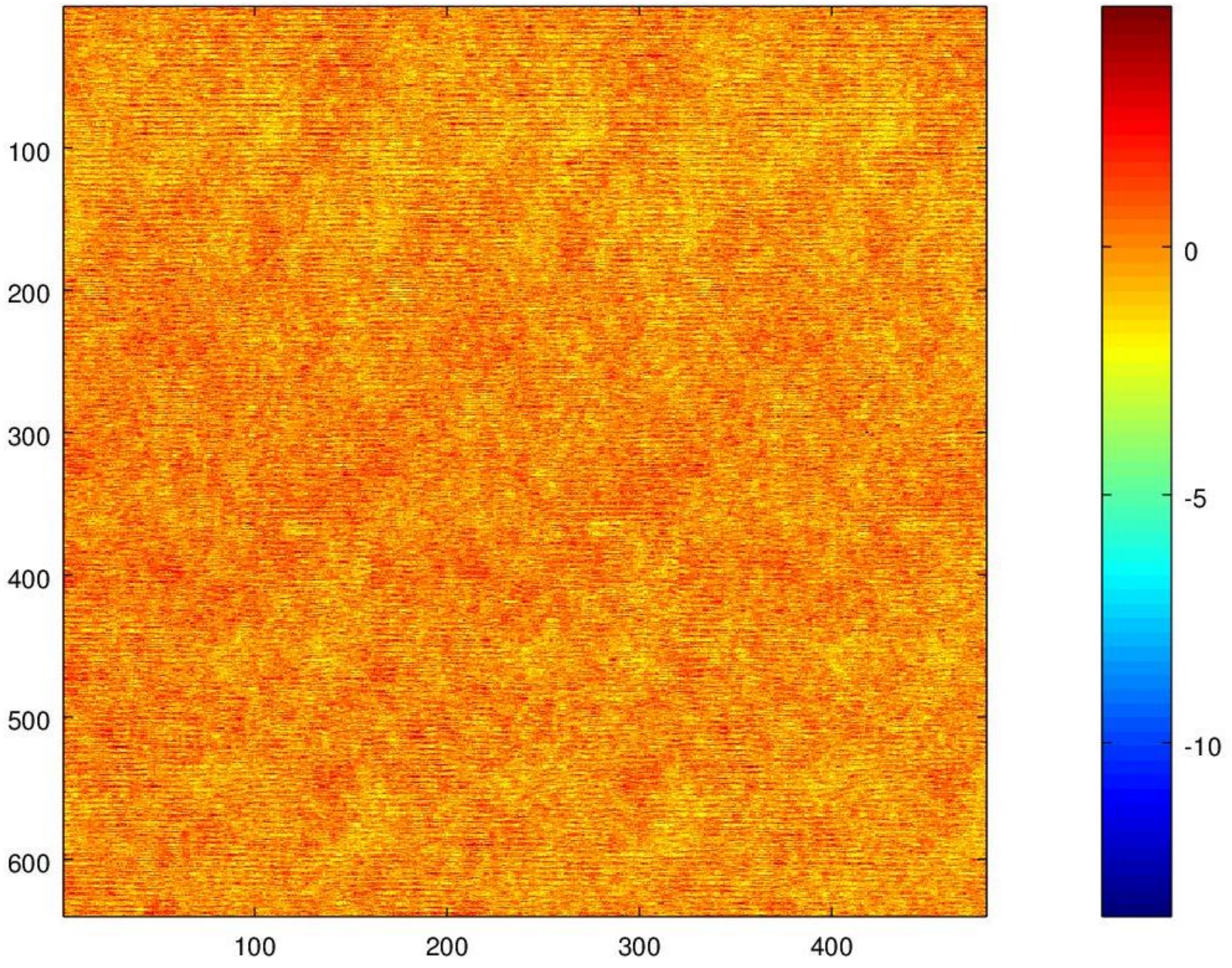


25 parameters fully describe the mirror A

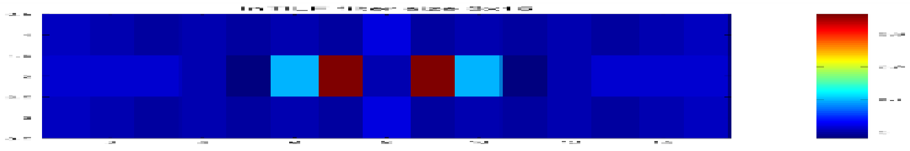
2D InTILF model accuracy: residual rms ~1%

InTILF analysis of mirror B

Height distribution of the mirror B
measured with the ALS XROL interferometric microscope
ZYGO NewView^{TM}-7300 equipped with 2.5× objective
with ×2.0 zoom
surface area 1.06 mm × 1.41 mm
effective pixel size of 2.2 µm (640 pixels × 480 pixels)
Measured surface topography has a structure of horizontal ‘strips’ with rms variation of the surface height of 1.74 Å.

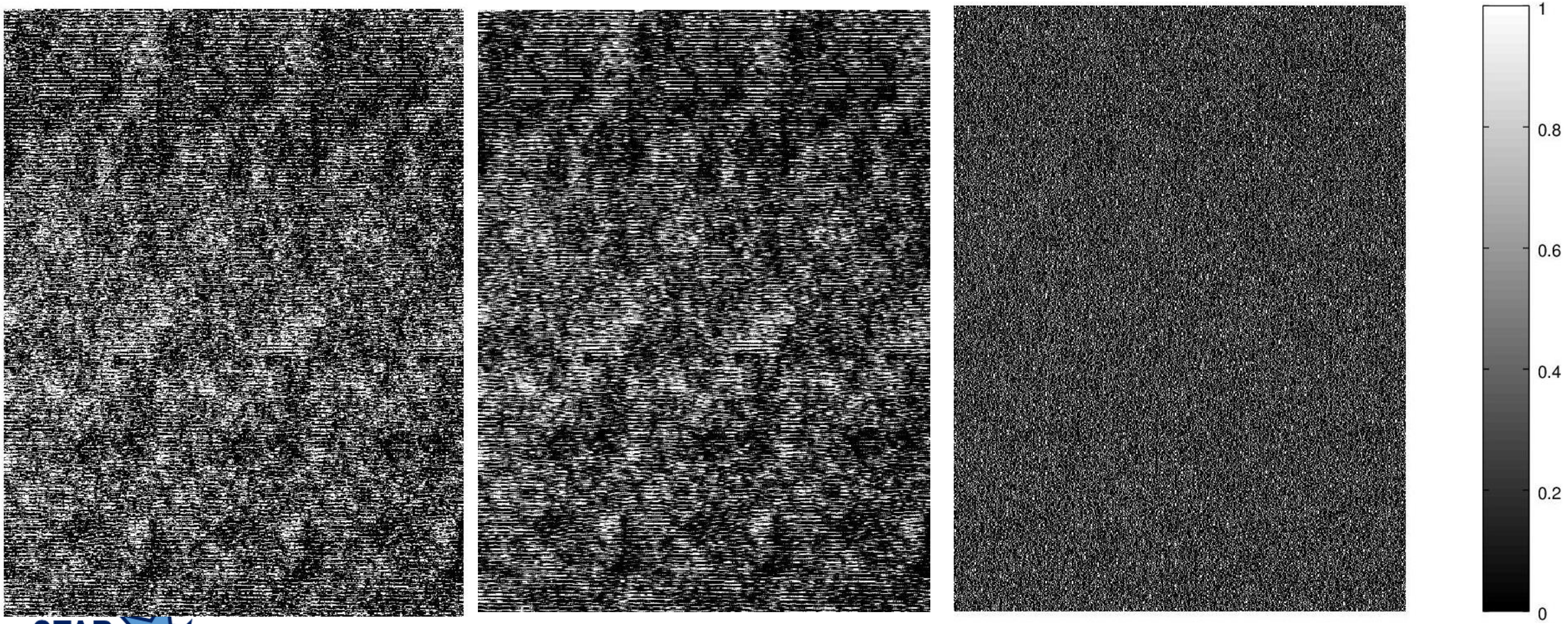


InTILF matrix 3 x 15



2D InTILF analysis of Mirror B

Original data (mirror B) | Filtered data = InTILF Model | Residual



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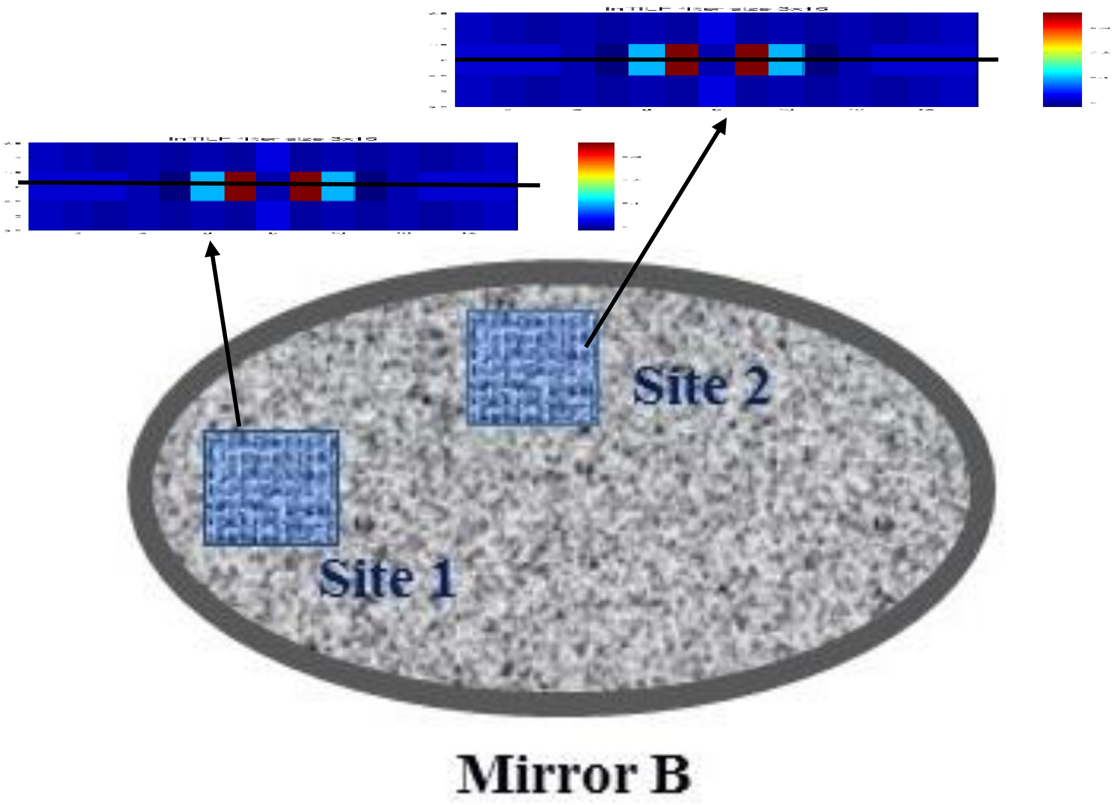
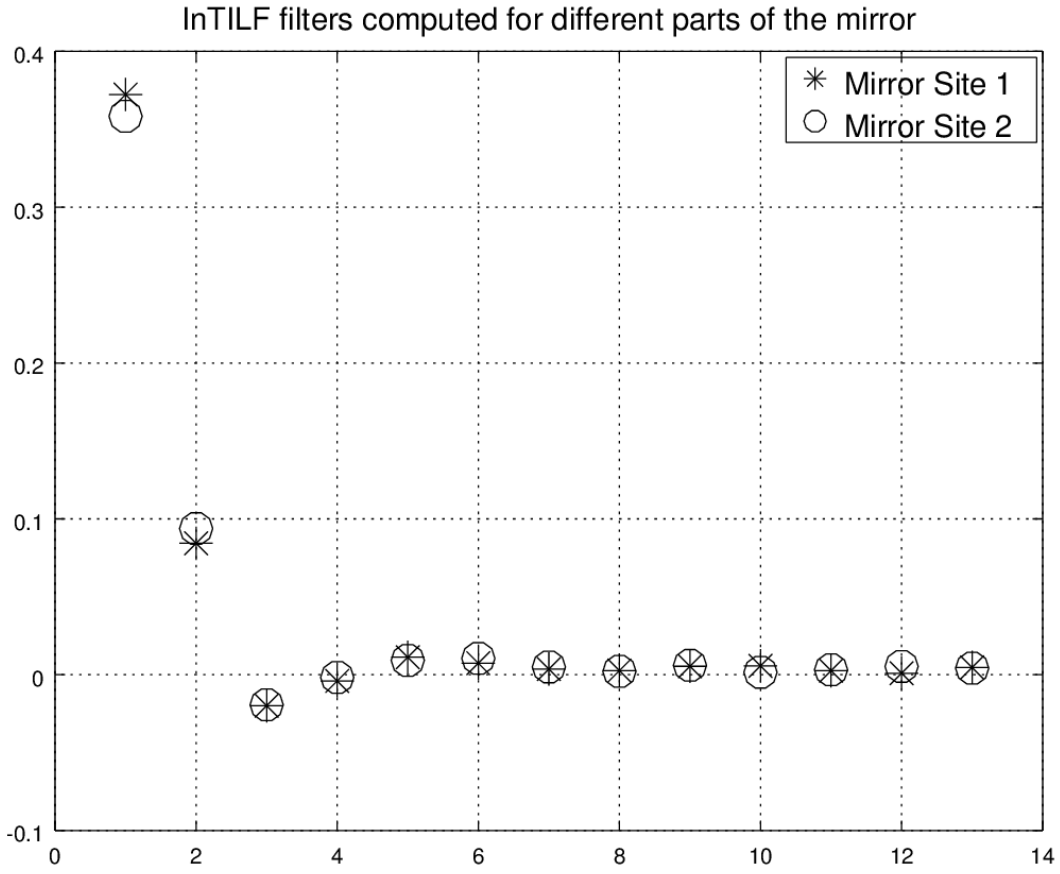
2D InTILF analysis is stable along the mirror





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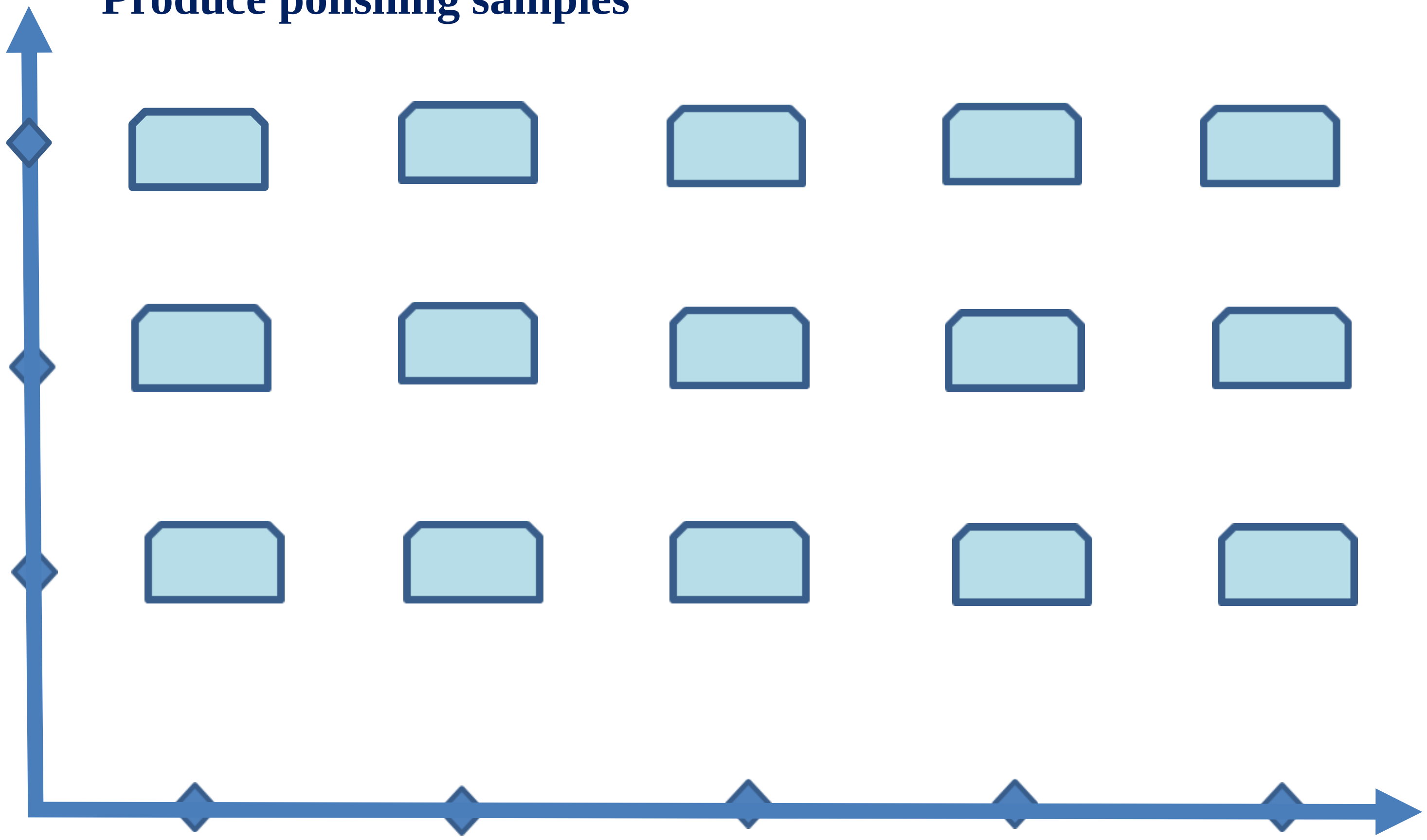
Good agreement of InTILF coefficients along the mid-row of InTILF matrices computed for metrology data from Site 1 and Site 2. The difference is < 3.5% value

Planned Polishing Optimization with BeatMark

Polishing space P – space of all different polishing parameters P = (q1, q2, …, qn)
Take sets of parameters on 'the grid'
Produce polishing samples



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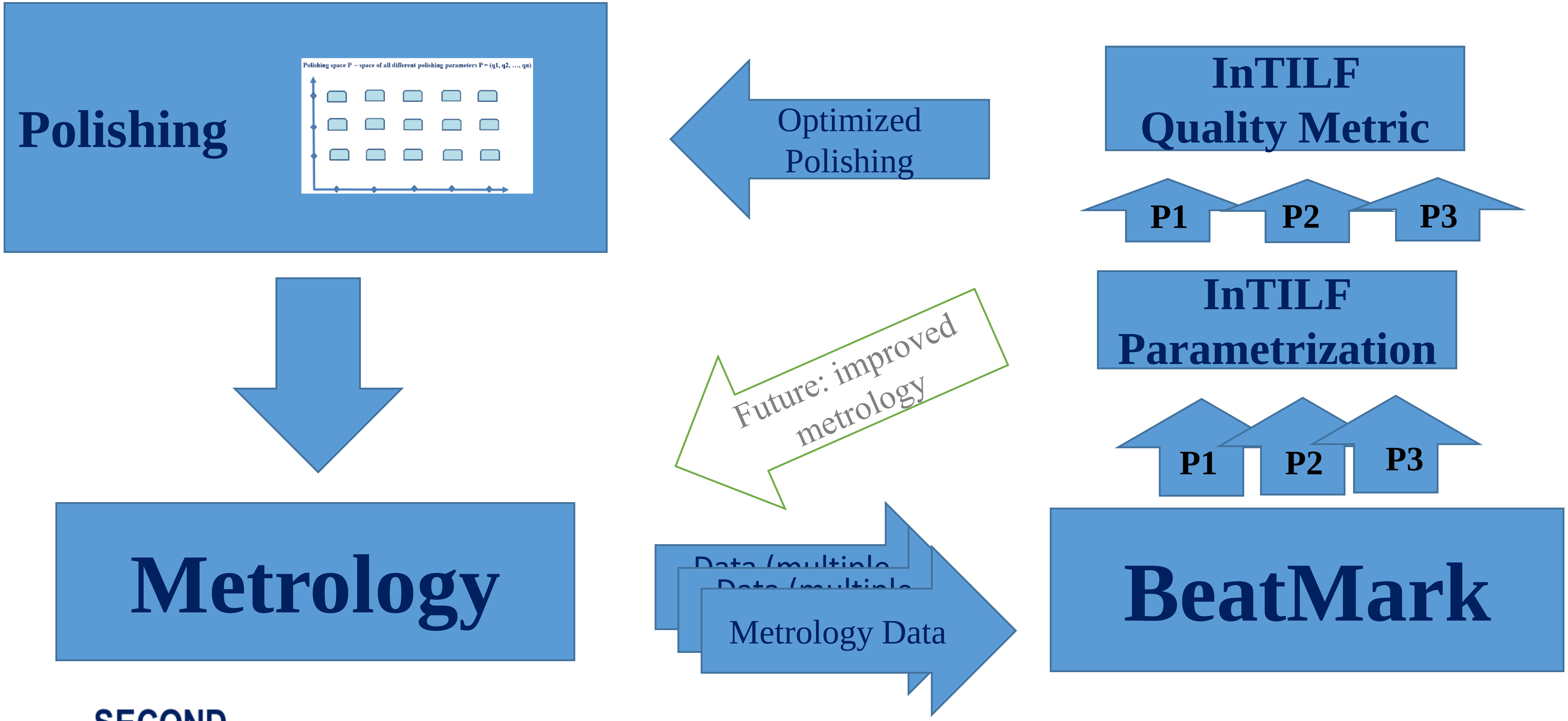
BeatMark concept step 2: Optimization of polishing and metrology process



Conclusions:

BeatMark software package:

- characterizes mirror surfaces with a **small number of parameters**
- needs only **modest amount of metrology data** to characterize **the entire surface**
- generates **simulated 'metrology' profiles** statistically equivalent to the original profile
- will provide the surface quality assessment through a **quality metric**
- will ultimately lead to **significant improvements in polishing**

Possible development of InTILF method may lead to comprehensive analysis of metrology data taken by instruments with different Modulation Transfer Function.

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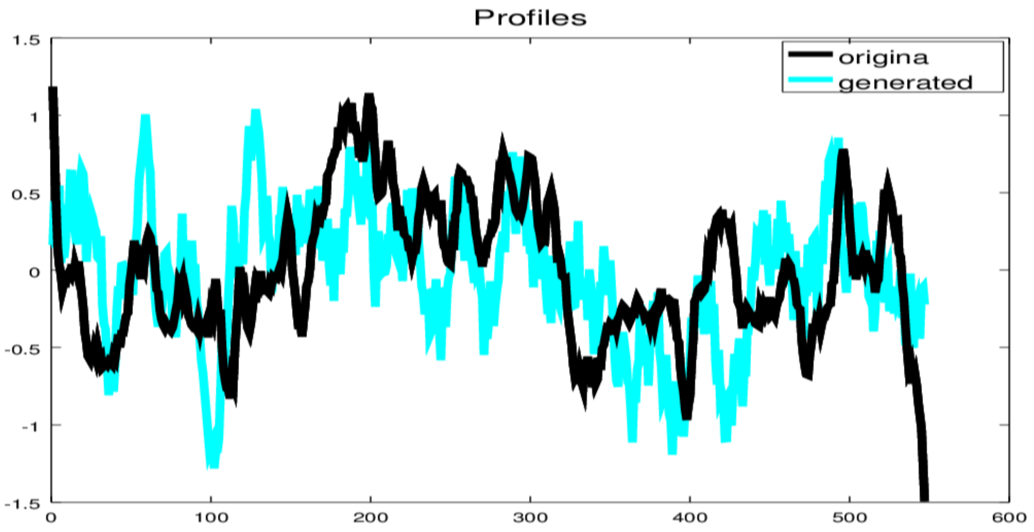
Acknowledgments

This work was supported in part by NASA Small Business Innovation Research SBIR grant to Second Star Algonumerix, project No. 15-1 S2.04-9193. The Advanced Light Source is supported by the Director, Office of Science, Office of Basic Energy Sciences, Material Science Division, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231 at Lawrence Berkeley National Laboratory.

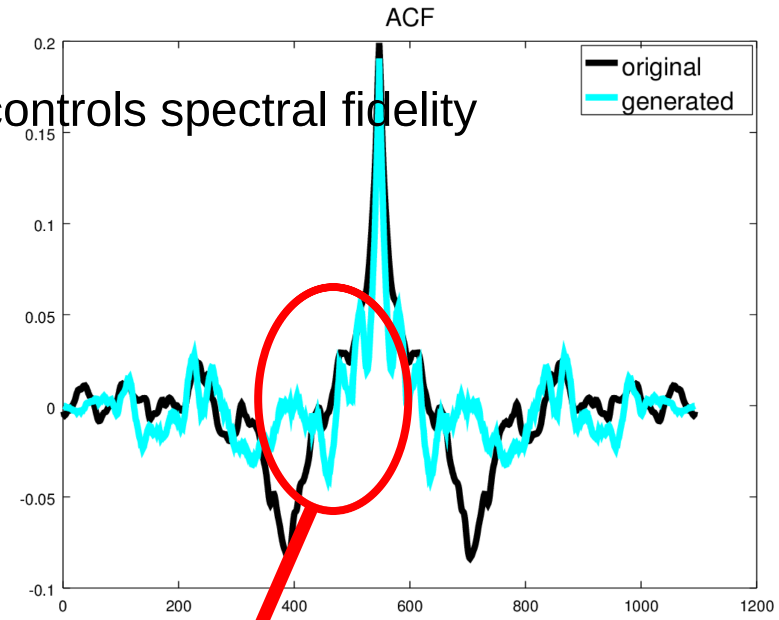
Thank you for your attention!

Appendix

UseCase2 – generation of 1D profiles statistically equivalent to the original using InTILF analysis



ACF controls spectral fidelity

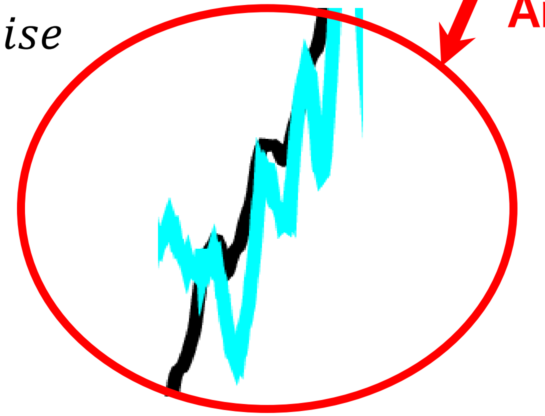


Generated profile Y(t):

$$Y(t) = \sum_l b(l) W(t-l), \text{where } W \text{ is White Noise}$$

$$b(l) \text{ are the } MA - InTILF \text{ coefficients}$$

An issue!



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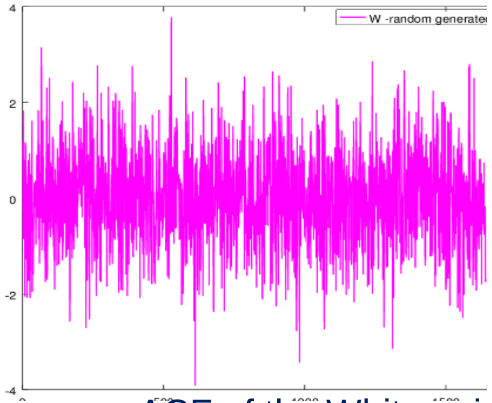
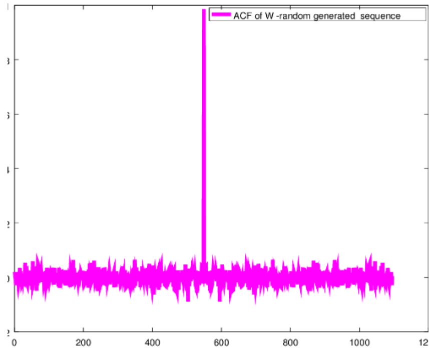
UseCase2: profile simulation required high quality random number generator

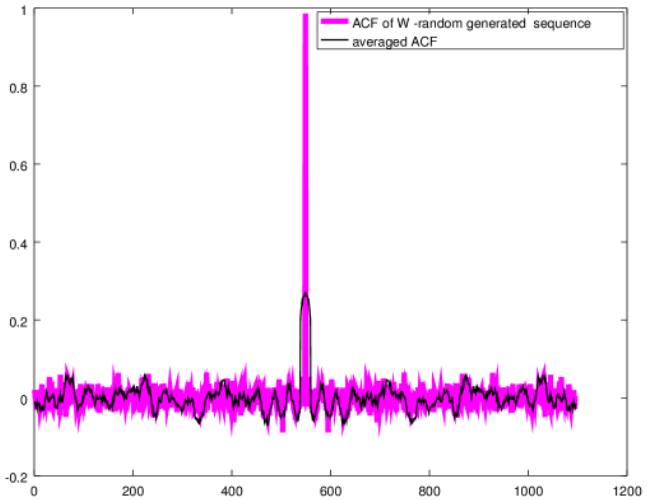
Random White noise profile

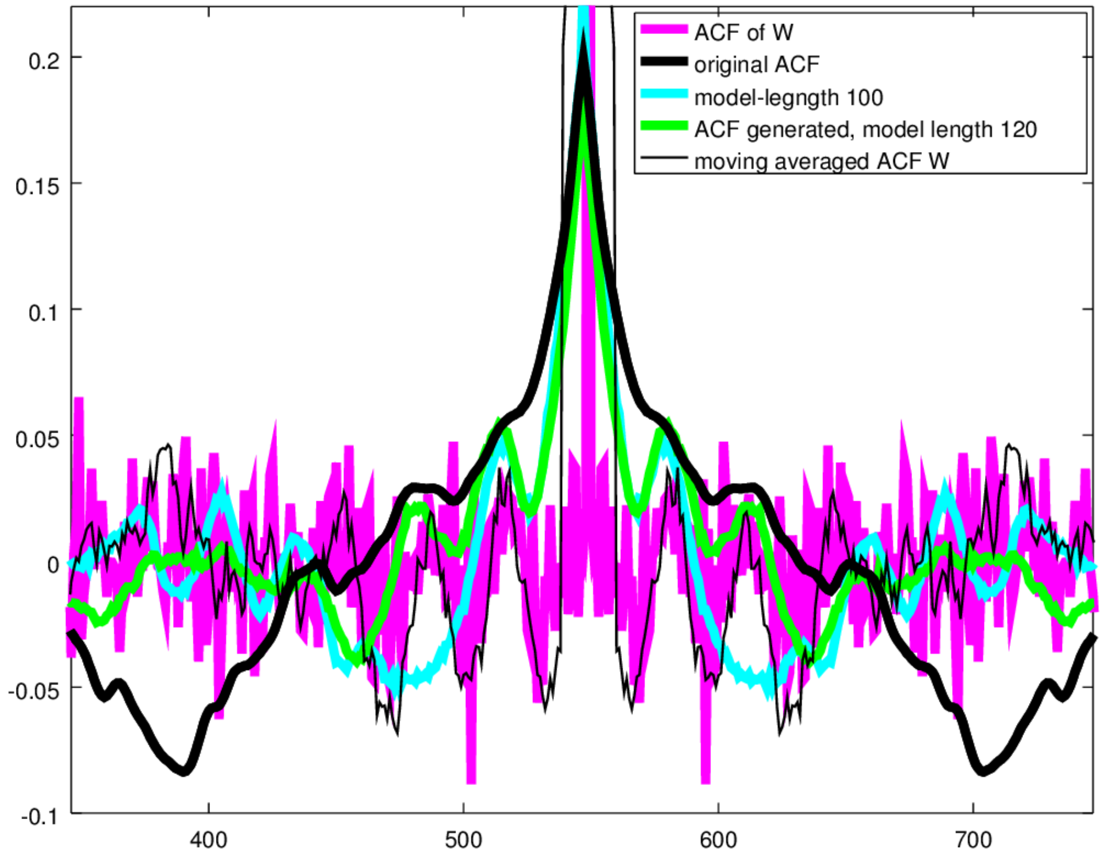


ACF of the White noise profile

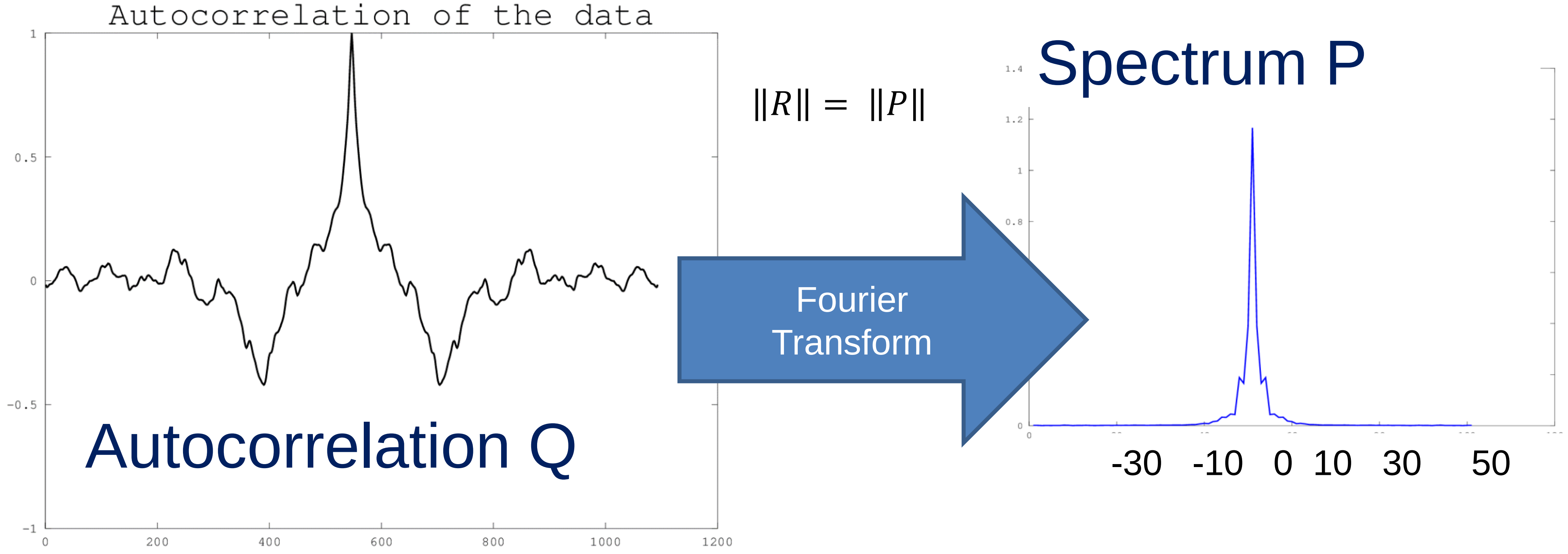


ACF of the White noise profile and its moving average





Autocorrelation Q - to - spectral density P



$$\|R\| = \|P\|$$

$$X(t) = \int_{-\pi}^{\pi} e^{itu}\Omega(du) = \sum_{k=1}^{k=L} e^{itu(k)} N(0, p(u(k))|\Delta|\,)$$

Stationary Random Process (SRP) and its Auto-covariance function (ACF) in 2D

Natural extension to 2D:

SPR: $\boldsymbol{x(t_1, t_2)}: \boldsymbol{Z^2 \rightarrow R^2}$ **& $\boldsymbol{E(X(t_1+h_1, t_2+h_2) * X(t_1, t_2)) = E(x(h_1, h_2)X(0)), \ \forall h=}$**
$\boldsymbol{(h_1, h_2)}$ => introduce ACF $\boldsymbol{Q_x(h) = Q_x(h_1, h_2) = E\{x(t_1+h_1, t_2+h_2)x(t_1, t_2)\}}$.

In 2D b) means that for any natural number m, any m integers $h_{1,} \dots, h_m$ and any real numbers $z_{1,\dots,} z_m$

$$\sum_{i,j=1}^{m} q(h_i - h_j) z_i z_j \geqslant 0$$

ACF $Q(.,.)$ of a stationary random process on a lattice $\mathbb{Z}^2$ can be represented as:

$$q(h_{1,} h_2) = \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} e^{ih_1x_1 + ih_2x_2} \mu(dx_1, dx_2), (h_{1,} h_2) \in \mathbb{Z}^2$$

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