SBIR – Phase I project NNX15CM48P:

BeatMark^{TM} –a software tool based on InTILF method for analysis, modeling, and simulation of surface metrology data

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Valeriy Yashchuk (LBNL), Yury Tyurin (Second Star)

Mirror Tech Days
11-11-2015

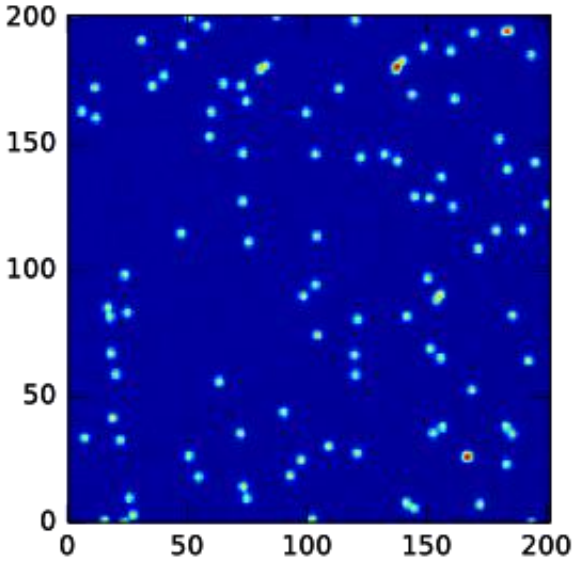
Second Star Algonumerics, LLC

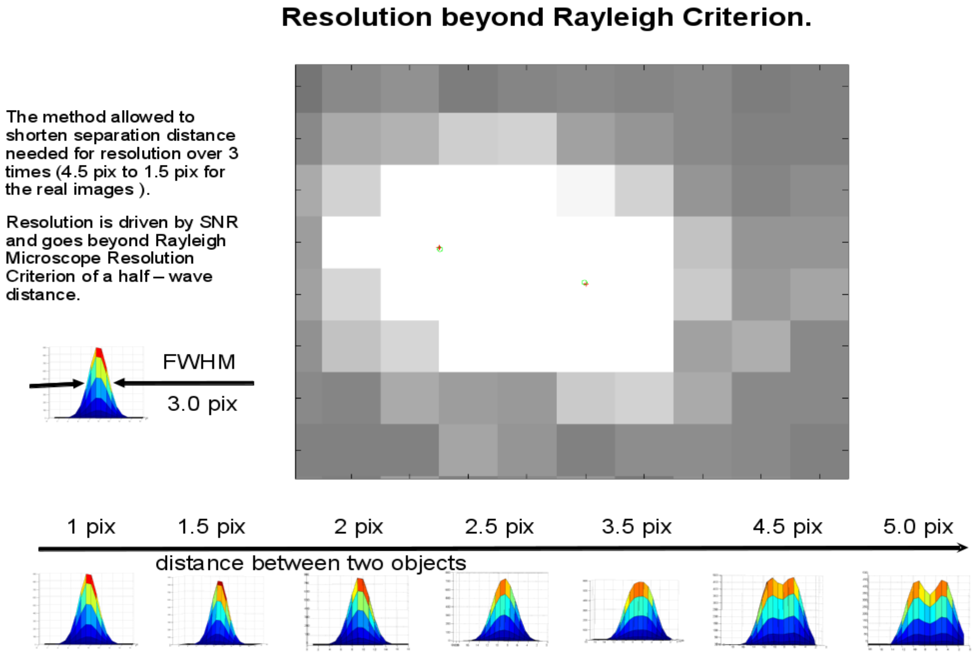
Second star to the right, and straight on till morning

Second Star Algonumerix LLC works in R&D, based in Boston MA

- Statistical Signal and Image Analysis and Pattern detection

One of our patented products is an image processing software specialized in detection of point sources with super-resolution accuracy beyond Raleigh Criterion.





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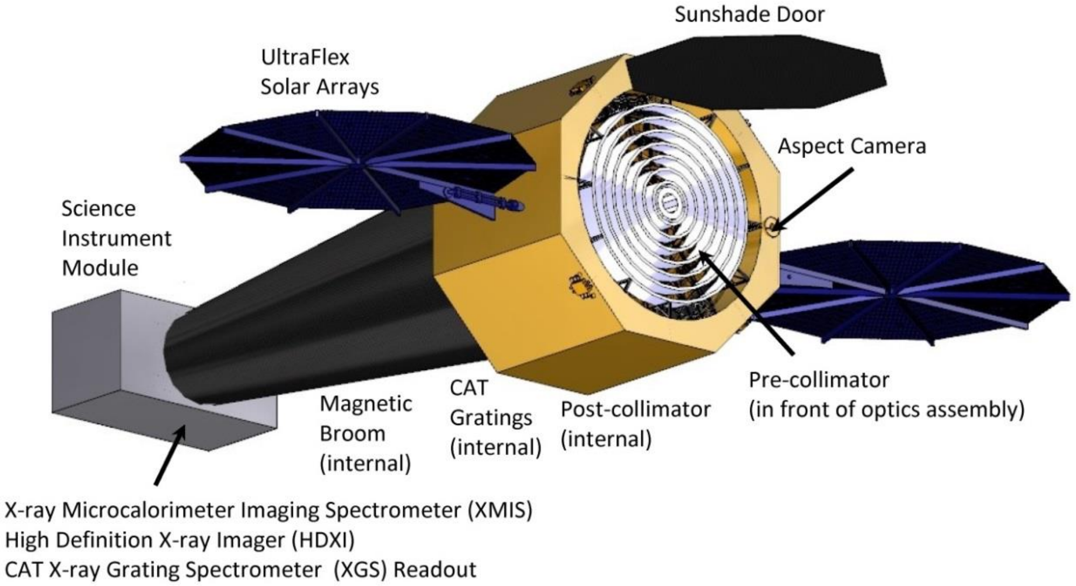
Objective of the project: To reduce fabrication cost of x-ray mirrors

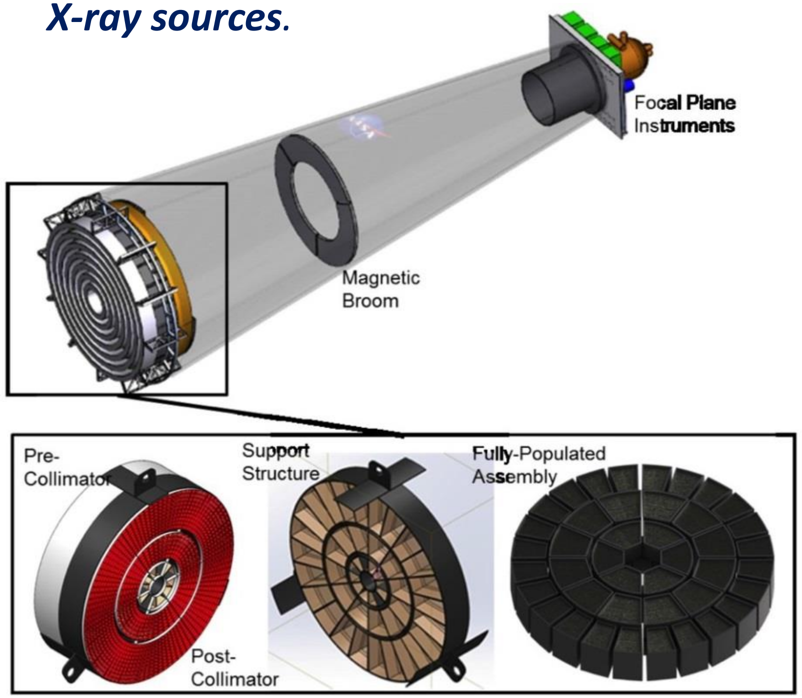
X-ray Surveyor Mission Concept*



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

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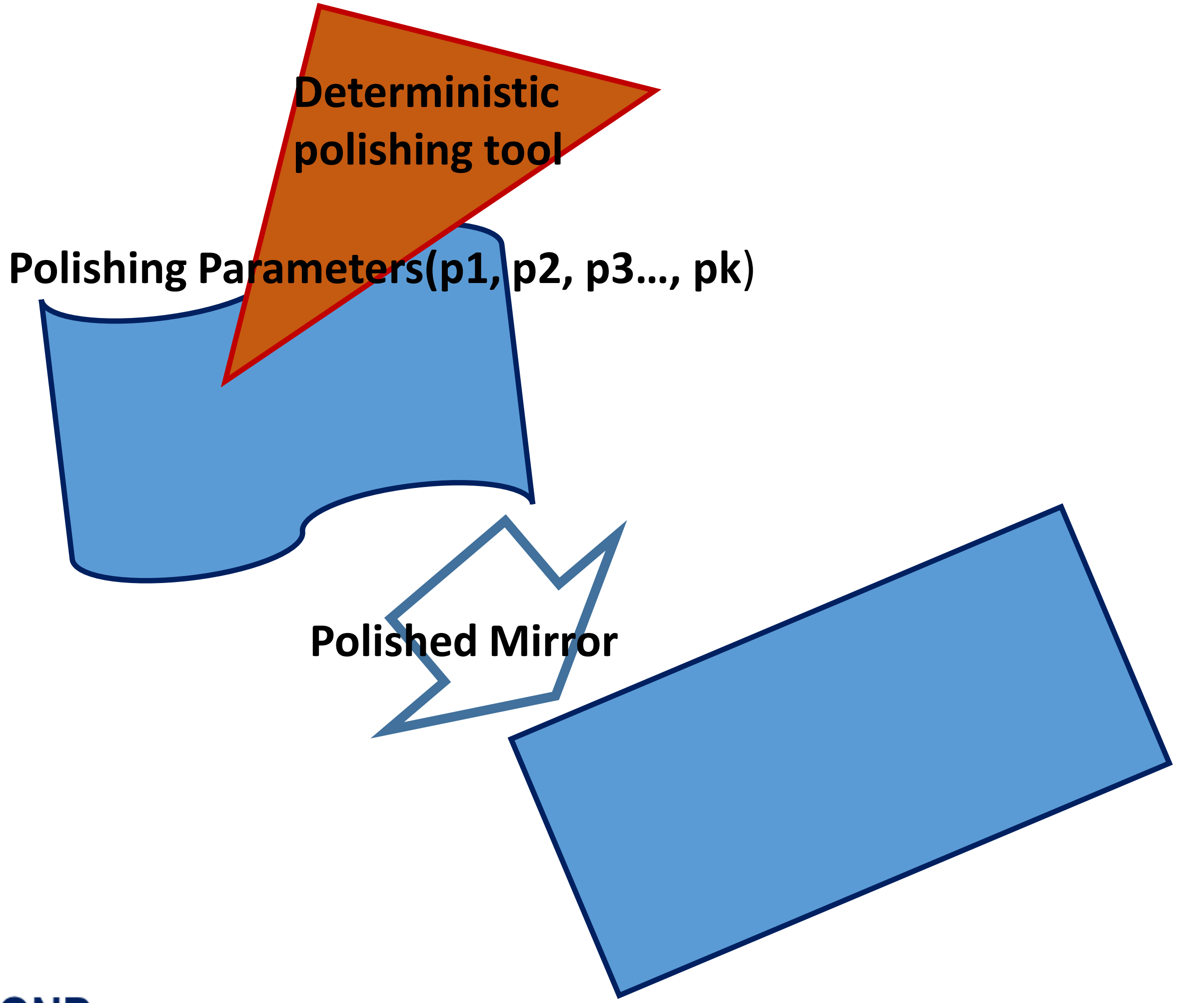
* J. A. Gaskin, M. C. Weisskopf, A. Vikhlinin, et. al., "The X-ray Surveyor Mission: A Concept Study," Proc. SPIE 9601, UV, X-Ray, and Gamma-Ray Space Instrumentation for Astronomy XIX, 96010J (August 24, 2015); doi:10.1117/12.2190837

Production of an x-ray mirror



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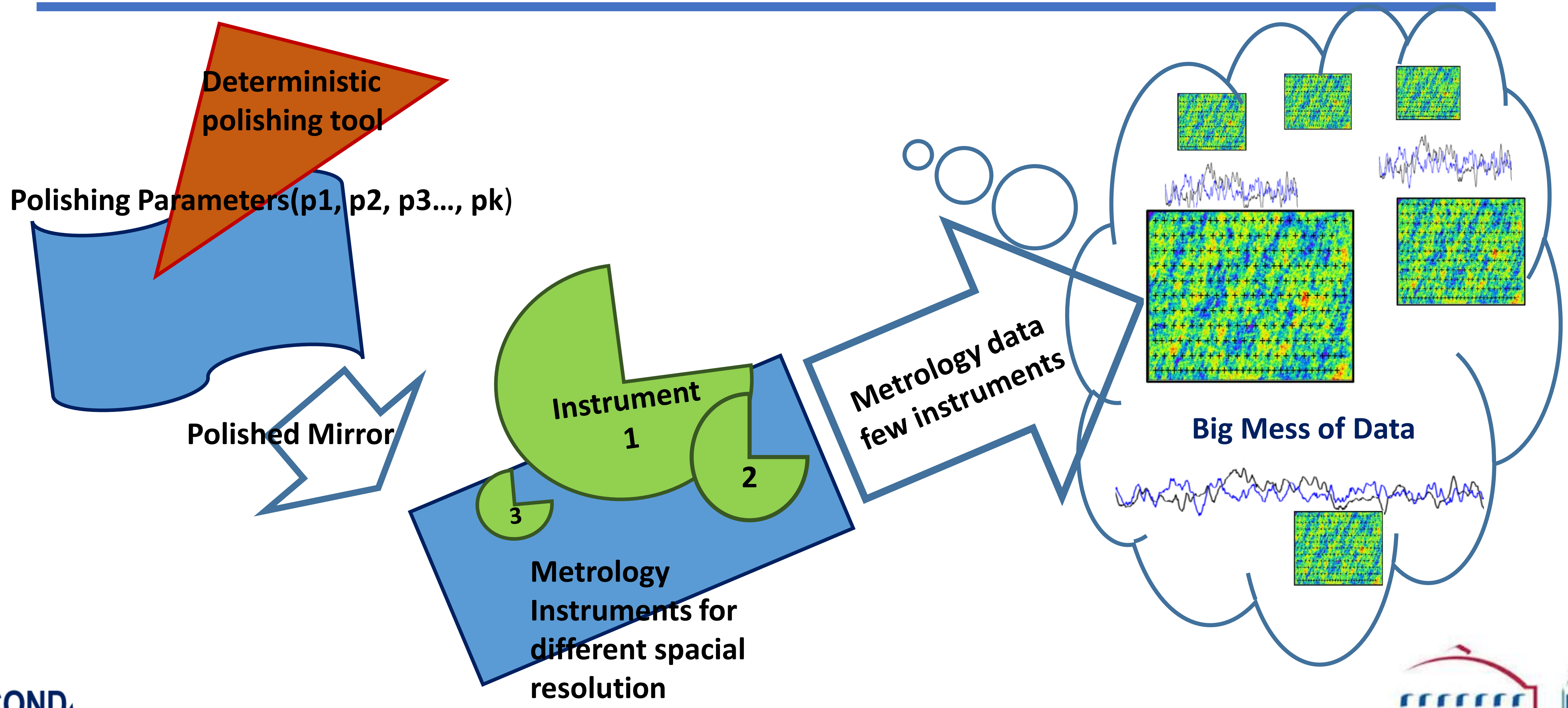
Current State of the art



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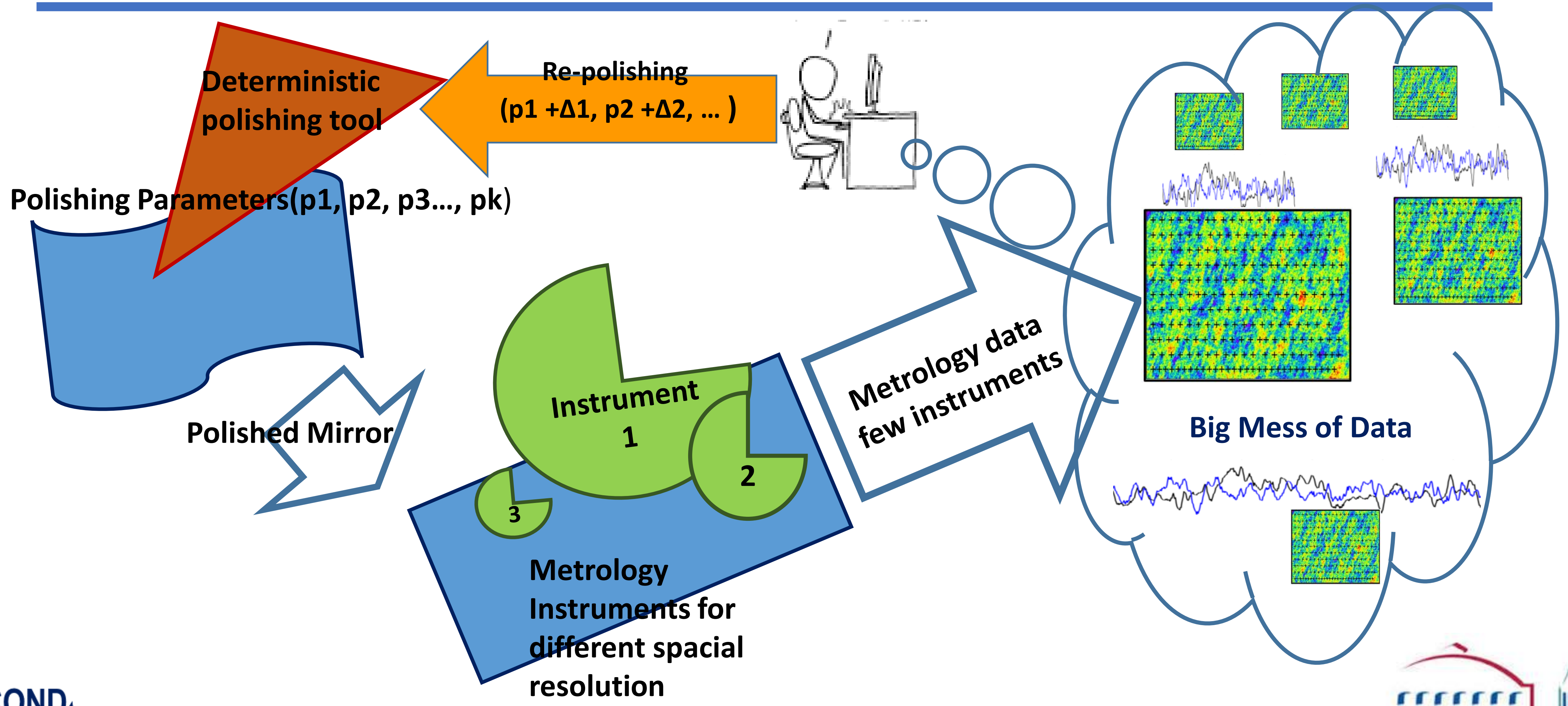
Current State of the art



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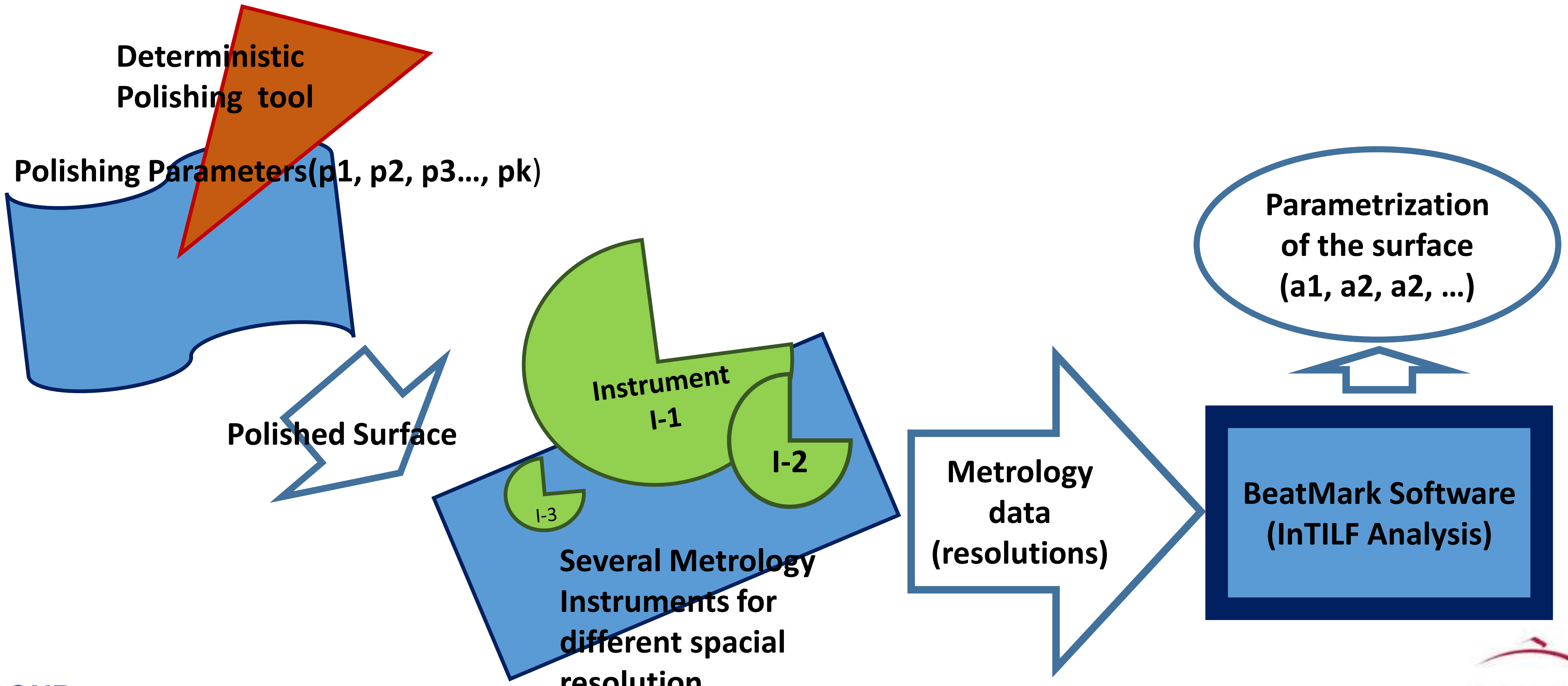
Parametrization of the mirror surface



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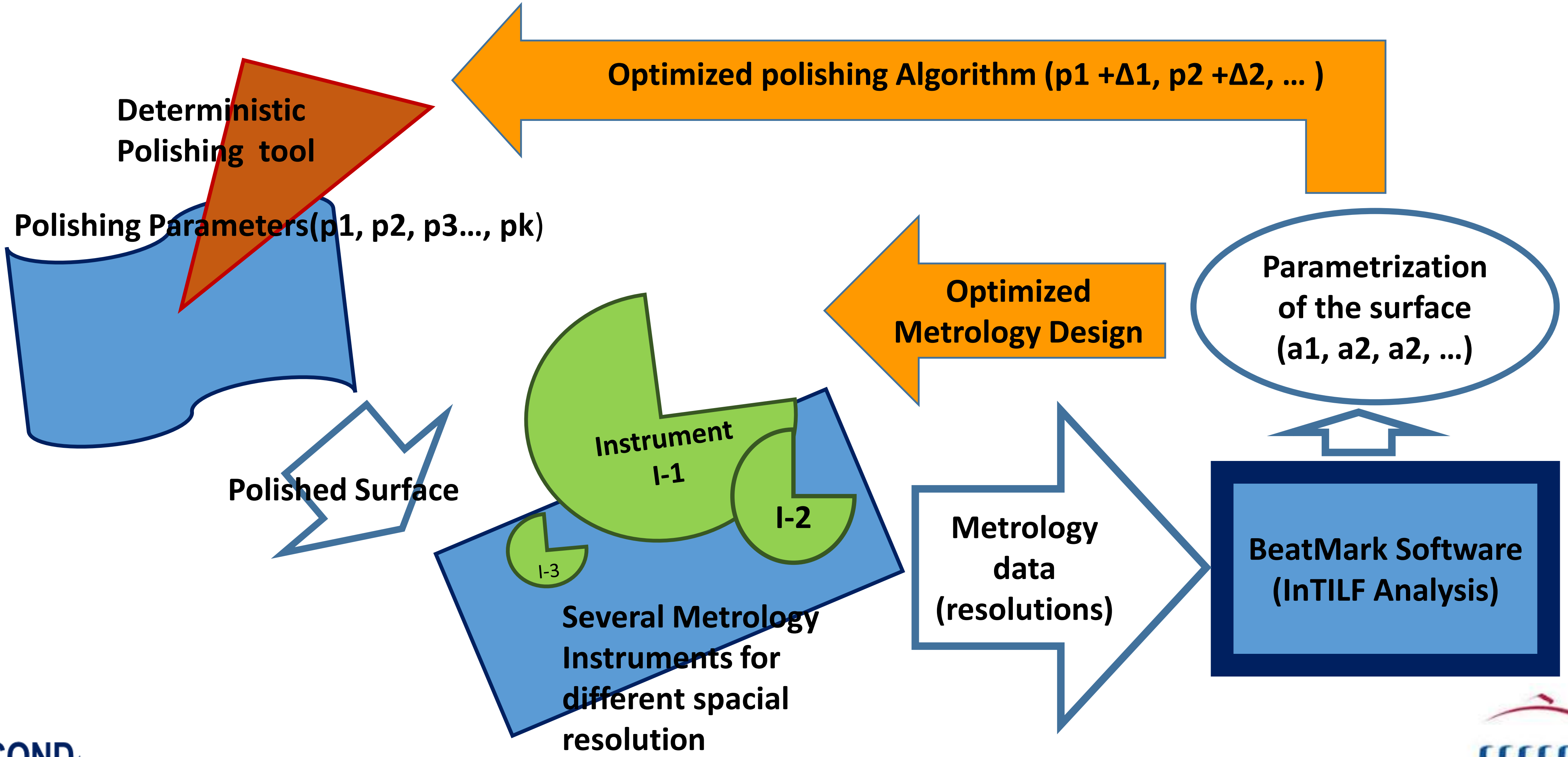
Parametrization of the mirror surface to optimize metrology and polishing



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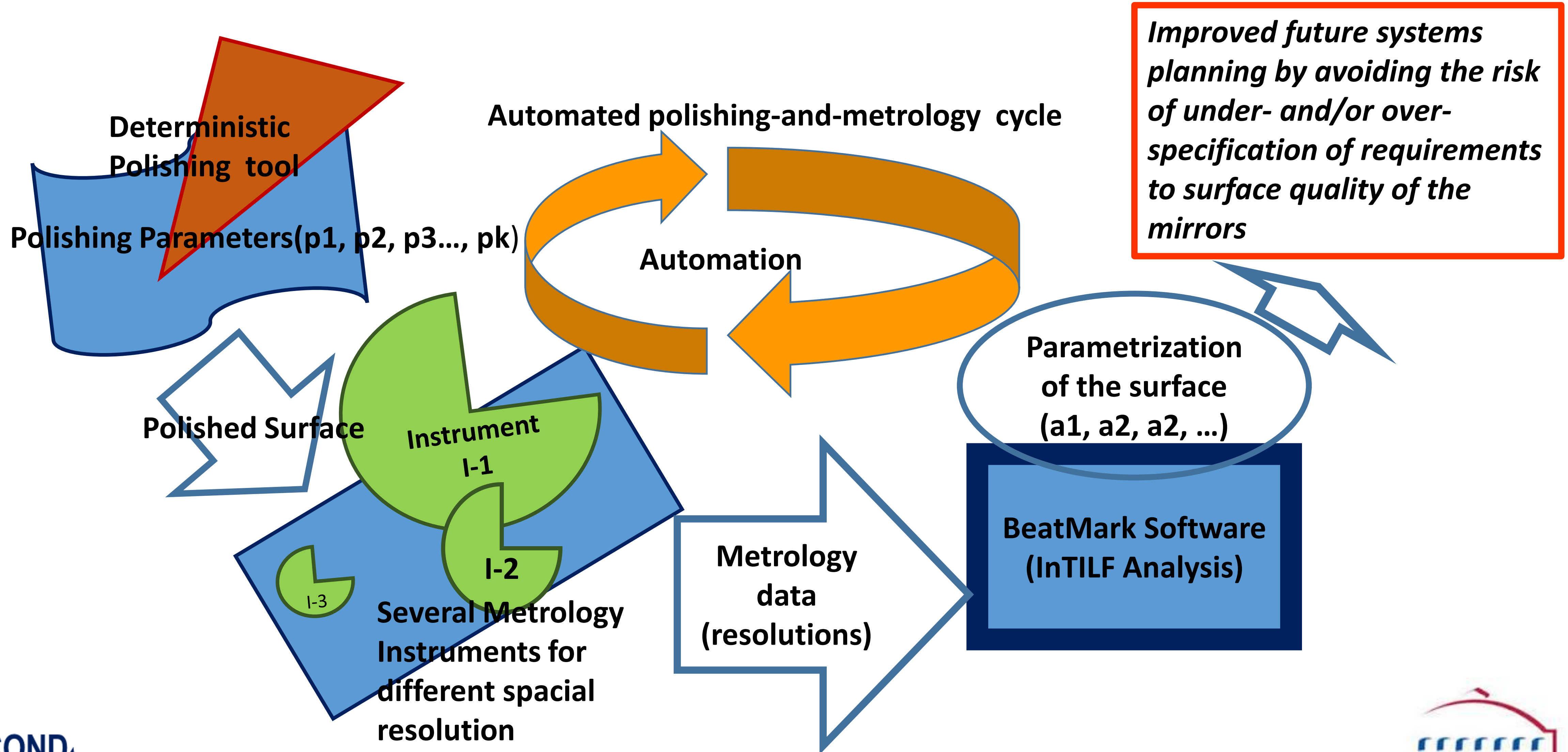
Parametrization of the surface to optimize metrology, polishing and planning



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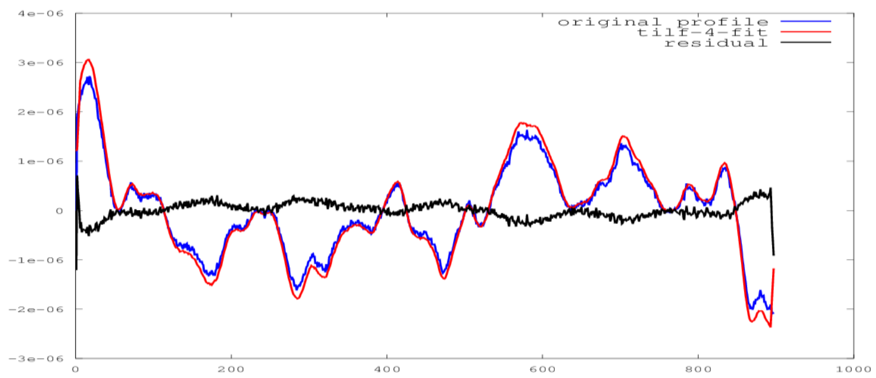
Objective of the project: ***To reduce fabrication cost of x-ray mirrors***

- ***Optimize the volume of metrology measurement required for evaluation of mirror surface quality***
  - *by creating a parametrization through a general statistical model to describe the data obtained with different metrology instrumentation having a broad range of spatial frequency bandwidths;*
- ***Increasing the efficiency and quality of deterministic polishing – metrology cycle***
  - *by optimizing the volume and the cost of metrology for fabrication*
  - *by providing an efficient feedback for improvement of polishing processes*
  - *by preparing the polishing – metrology cycle for automation*
- ***Resulting in a more attractive and competitive x-ray optical fabrication market***
- ***Avoiding the risk of under- and/or over-specification of requirements to surface quality of the mirrors***
  - *by providing (forecasting) highly reliable metrology data for numerical evaluation of performance of telescopes using mirrors from different vendors (technologies) before optical fabrication;*

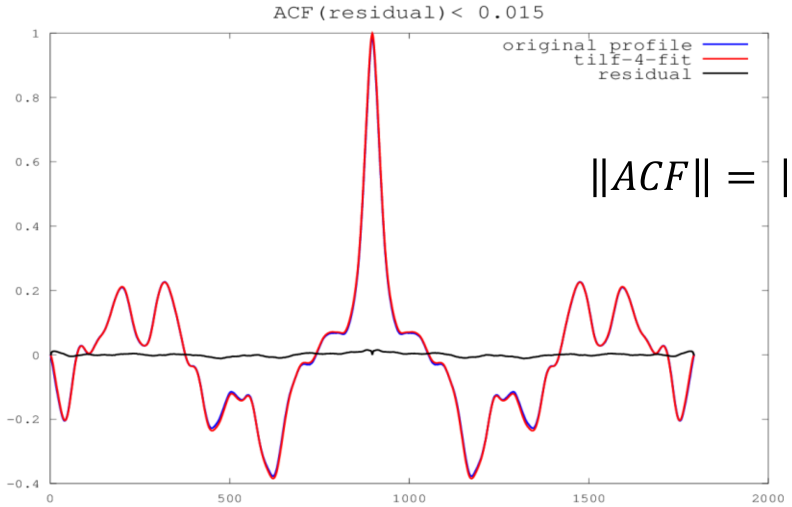
Method: Detection of patterns left on the surface by the polishing tool

In Phase I we concentrated on 1-d profile data and built a prototype software tool based on the method

Data *X(t)- profile of a real X-Ray mirror*
***Model Y(t):* (I-A)*Y(t) = C*W(t)**
W(t) white noise ; A and C linear operators



Auto Covariance Function *ACF*



$$\|ACF\| = \|PSD\|$$

If ACF of two stochastic functions X and Y are close then their PSD are close also:

$$\|ACF(X) - ACF(Y)\| = \|PSD(X) - PSD(Y)\|$$

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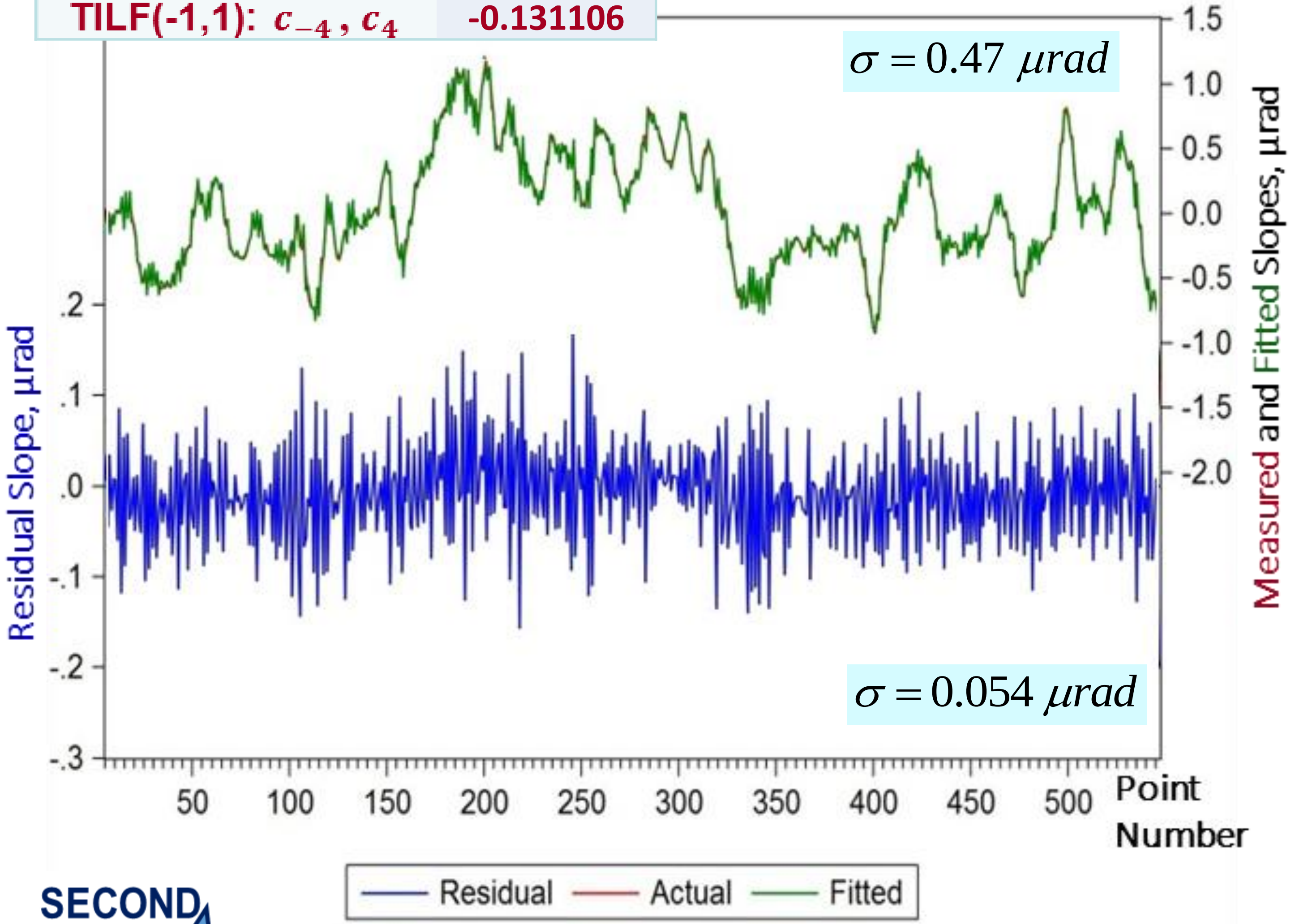
Key technology: Parametrization of (x-ray) mirrors surface topography*

Model Parameter	Coefficient
TILF(-1,1): c_{-1}, c_1	1.098397
TILF(-1,1): c_{-4}, c_4	-0.131106



Statistical modeling (fitting):

Surface topography is a result of a *stationary* time invariant stochastic process:

$$\alpha[n] = \sum_{l=-p}^{p} c_l\, \alpha[n-l] + \sum_{l=-q}^{q} b_l\, v[n-l]$$

$\alpha[n]$ **is a discrete surface slope distribution, measured over** $x_n = n \cdot \Delta x$ **,** $n = 1, \ldots, N$ **and** $(N-1)\Delta x$ **is the trace length,**

$v[n]$ **is zero mean unit variance white Gaussian noise.**

and p **are the orders of the autoregressive (AR) and** q **moving average (MA) processes, respectively.**

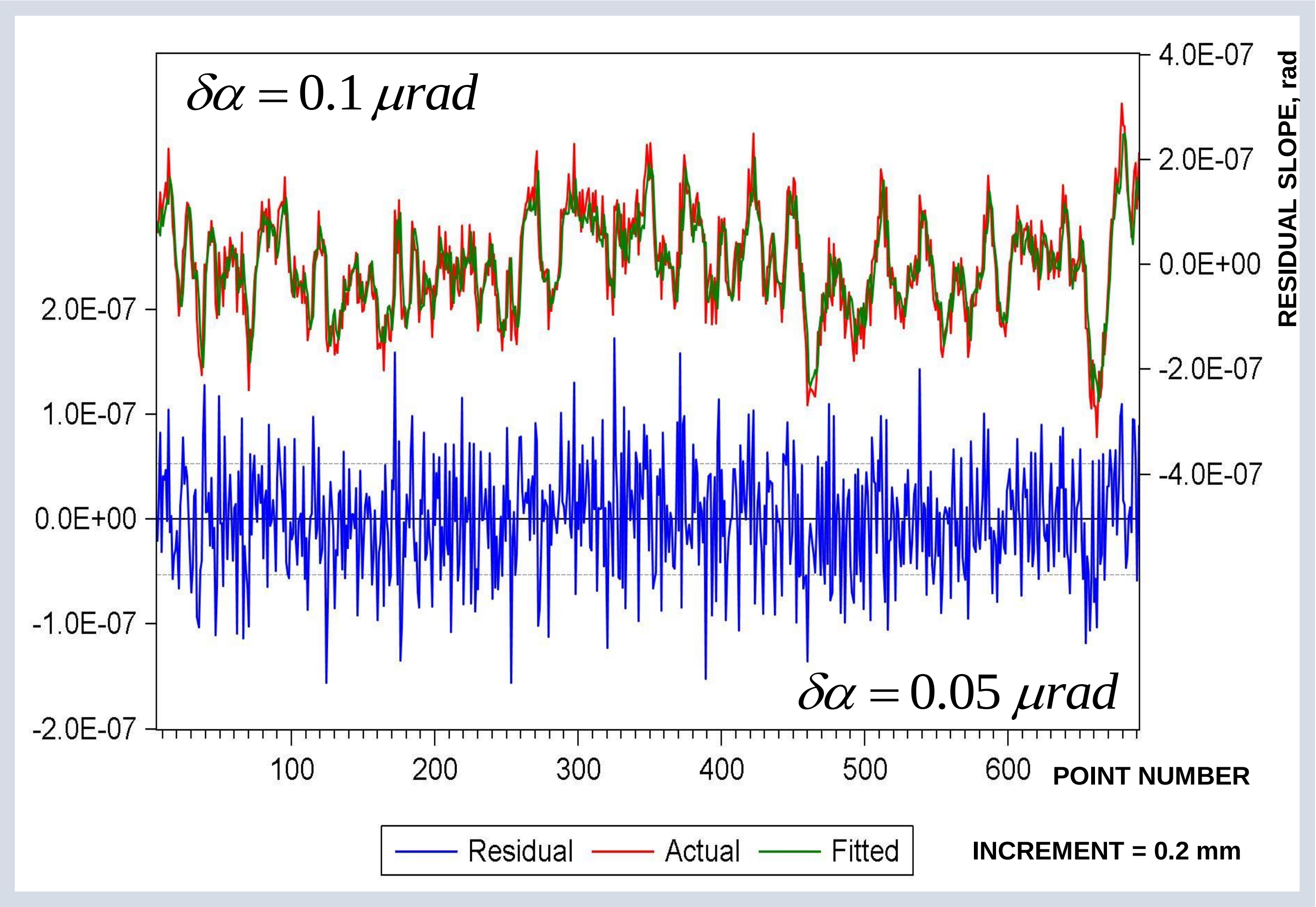
* Y. V. Yashchuk and V. V. Yashchuk, "Reliable before-fabrication forecasting of expected surface slope distributions for x-ray optics," Proc. SPIE 8141, 81410N-1-15 (2011); Opt. Eng. 51(4), 046501-1-15 (2012).

* V. V. Yashchuk, Y. N. Tyurin, and A. Y. Tyurina, "Application of the time-invariant linear filter approximation to parametrization of surface metrology with high-quality x-ray optics," Opt. Eng. 53(8), 084102 (2014).

* V. V. Yashchuk, Y. N. Tyurin, and A. Y. Tyurina, "Modeling of surface metrology of state-of-the-art x-ray mirrors as a result of stochastic polishing process,"SPIE Proc. (2015, in press).

Key technology: Parametrization of (x-ray) mirrors surface topography*

Stochastic modeling of Surface Slope Metrology with LCLS Splitting Mirror with L=150 mm*



Brendan Murphy, "X-ray split and delay mirrors specifications,"

LCLS, 02/16/11: Drawings PF-391-946-11 and SA-391-946-13.

Stochastic process:

$$\alpha[n] = \sum_{l=1}^{p} a_l\, \alpha[n-l] + \sum_{l=0}^{q} b_l\, \nu[n-l]$$

with the parameters:

Variable		Coefficient
AR(1)	a_1	0.636773
AR(2)	a_2	0.351020
AR(5)	a_5	-0.147487
MA(2)	b_2	- 0.065918

* Y. V. Yashchuk and V. V. Yashchuk, "Reliable before-fabrication forecasting of expected surface slope distributions for x-ray optics," Proc. SPIE 8141, 81410N-1-15 (2011); Opt. Eng. 51(4), 046501-1-15 (2012).

* V. V. Yashchuk, Y. N. Tyurin, and A. Y. Tyurina, "Application of the time-invariant linear filter approximation to parametrization of surface metrology with high-quality x-ray optics," Opt. Eng. 53(8), 084102 (2014).

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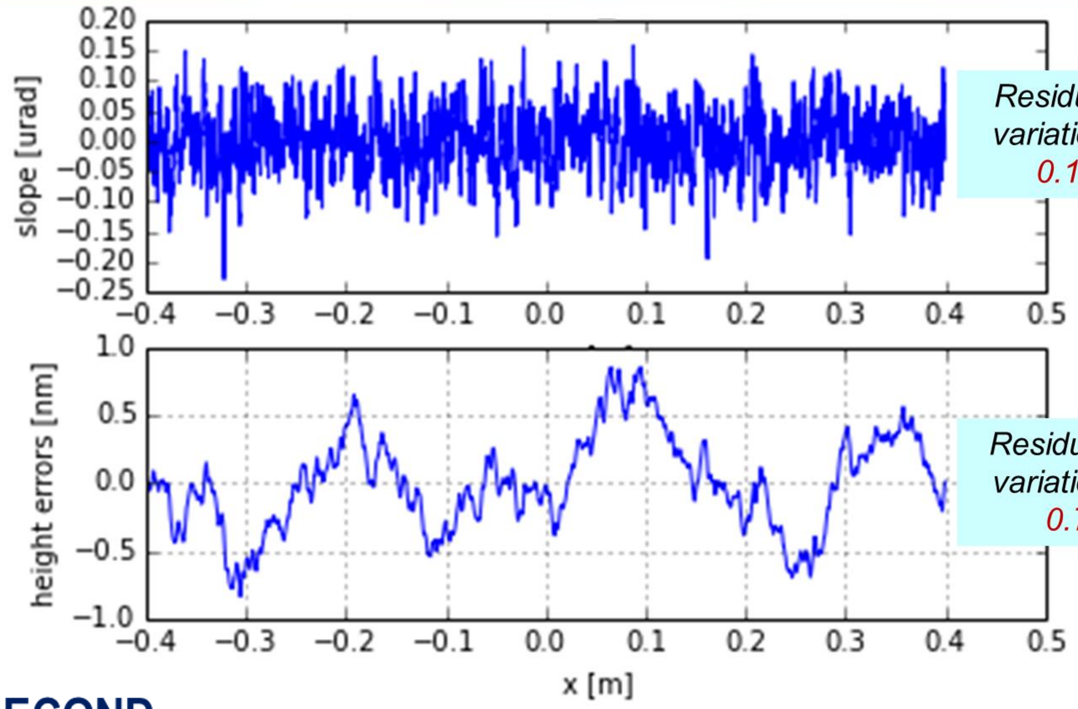
Objective of the project: To decrease fabrication cost of x-ray mirrors

- ***Avoiding the risk of under- and/or over-specification of requirements to surface quality of the mirrors***
    - *by providing (by forecasting) highly reliable metrology data for numerical evaluation of performance of telescopes using mirrors from different vendors (technologies) before optical fabrication.*

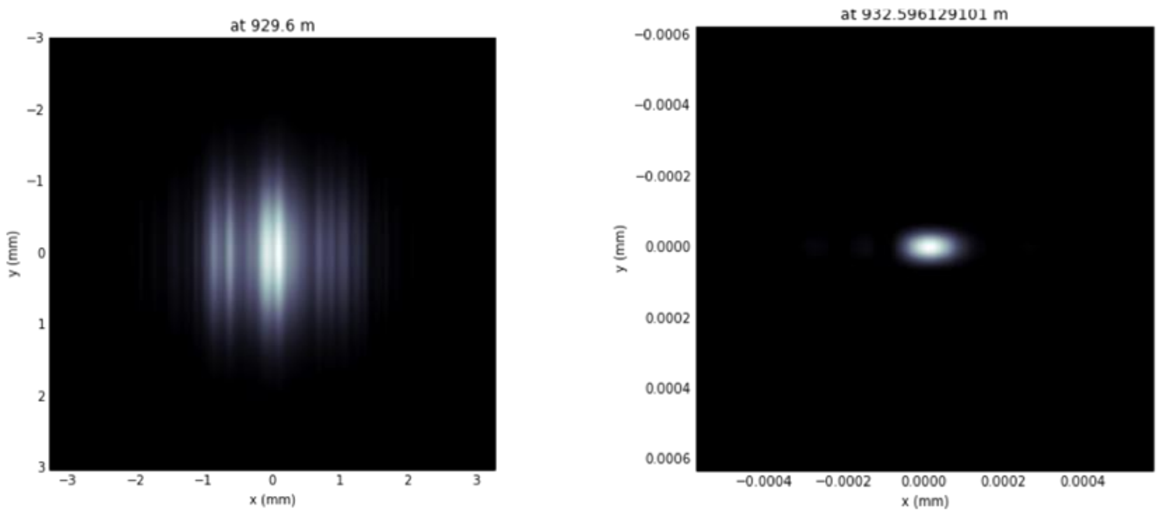
E.g.: Forecasting of slope and height topography of 800 mm mirror for European XFEL SASE1 beamline*



Residual slope variation (rms) *0.1 µrad*

Residual height variation (rms) *0.7 nm*

680 m from offset mirror **in-focus**



**The profile was generated with ARMA model of the LCLS Splitting mirror with L=150 mm;*

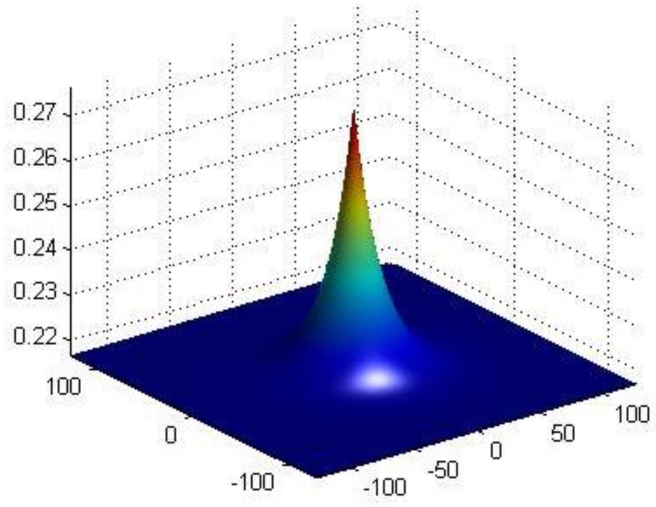
*** V. V. Yashchuk, L. Samoylova, and I. V. Kozhevnikov, "*Specification of x-ray mirrors in terms of system performance: new twist to an old plot,*" Opt. Eng., 54(2), 025108 (2015).**

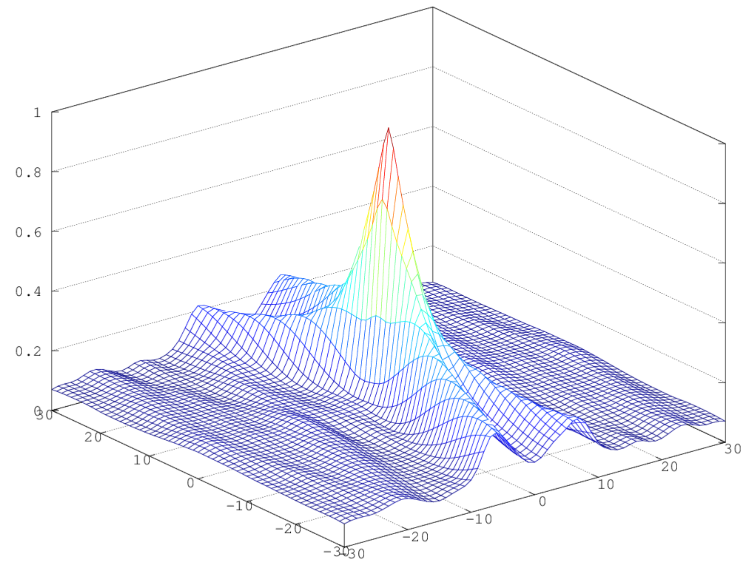
Achieved In Phase I

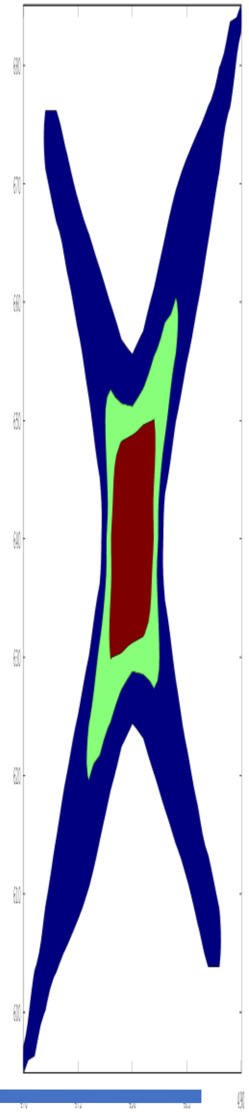
- We developed a 1D InTILF parametrization tool and tested its performance on several data set from different real x-ray mirrors (different vendors). We learned: Takes 2-5 parameters to capture-90-95% of the signal (residual error of 4-10% depending on the mirror).
- We developed an 1D InTILF tool for generation of profiles from this parametrization. The profiles are statistically equivalent to the parametrized profile. We proved high spectral fidelity of the procedure. The tool can be used for future optical system planning.
- We developed a theoretical foundation for 2D – analysis - we plan to make it to industrial software in Phase II. We learned that the 2D algorithm may require some computational sophistication, but we have a plan.

The importance of 2D analysis

Compare the delta-like ACF of white noise (left) to a real x-ray mirror example (right)







Level sets of the ACF

Analitical Derivation of 2D InTILF models is completed.

2D Software development is planned for Phase II

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Propose Phase II technical Objectives

1. **Industrial Software Tool BeatMark™**

   parametrization (analysis and generation) of 2-D data

   - intuitive user interface
   - analysis of the data from existing x-ray mirror producers

2. **Recommendations for re-polishing** based on analysis results
3. **Stitching of the metrology data of different spacial resolution**

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X-ray mirror metrology issues

- *Huge cost of x-ray mirrors*
- *Large amount of data to measure*
- *No 2D analysis method available*
- *No compact parametrization*
- *No method for combining the data from different instruments*
- *No method for estimation of mirror behavior in an optical system*
- *No generation of statistically equivalent data for simulation*
- *No available Polishing feedback*

BeatMark^{TM} effects

- *Decreased cost of fabrication of x-ray mirrors*
- *Optimization in metrology processing time and cost*
- *Increasing the efficiency of deterministic polishing*
- *Enable comprehensive analysis of the data taken at multiple resolution*
- *Preparing the entire polishing-metrology cycle for automation*
- *Resulting in a more attractive and competitive x-ray optical fabrication market by lowering the entry barrier to x-ray market for optics manufacturers*
- *Avoiding the risk of under- and/or over-specification of requirements to surface quality of the mirrors*

Acknowledgement

The authors are expressing their gratitude to

NASA for its SBIR-I **NNX15CM48P** funding.

To Chris Ilsley, Michael McComas and Peter Panov (of Second Star) for help and useful discussions.

To Daniel J. Merthe, Nikolay A. Artemiev, and Daniele Cocco for help with high accuracy surface slope measurements of the LCLS beam split and delay mirror, and to Gary Centers and Wayne McKinney for very useful discussions. This work was supported in part by NASA Small Business Innovation Research SBIR grant to Second Star Algonumerix **I NNX15CM48P**, LBNL 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.

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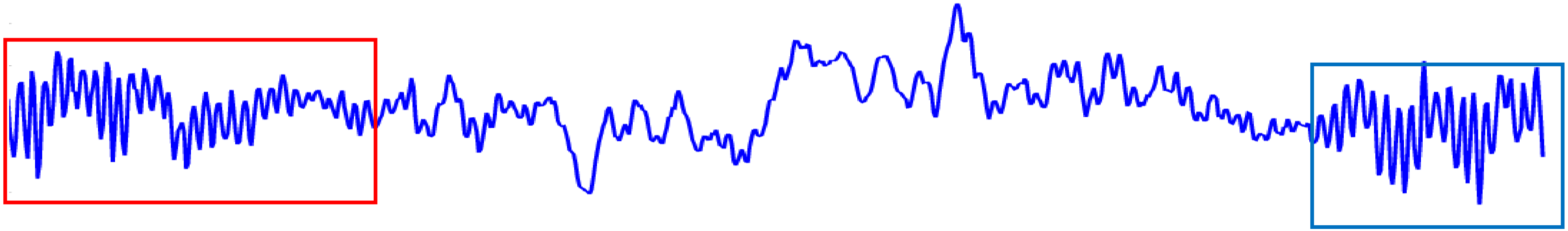
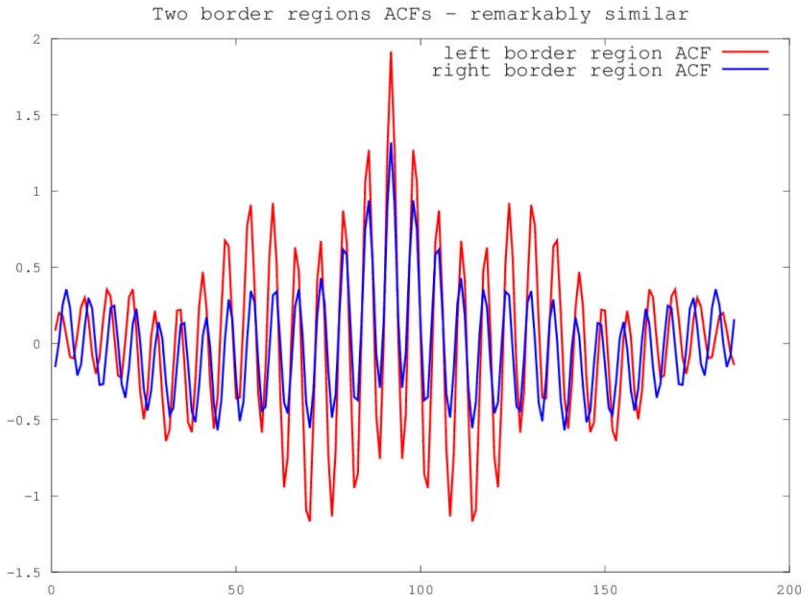
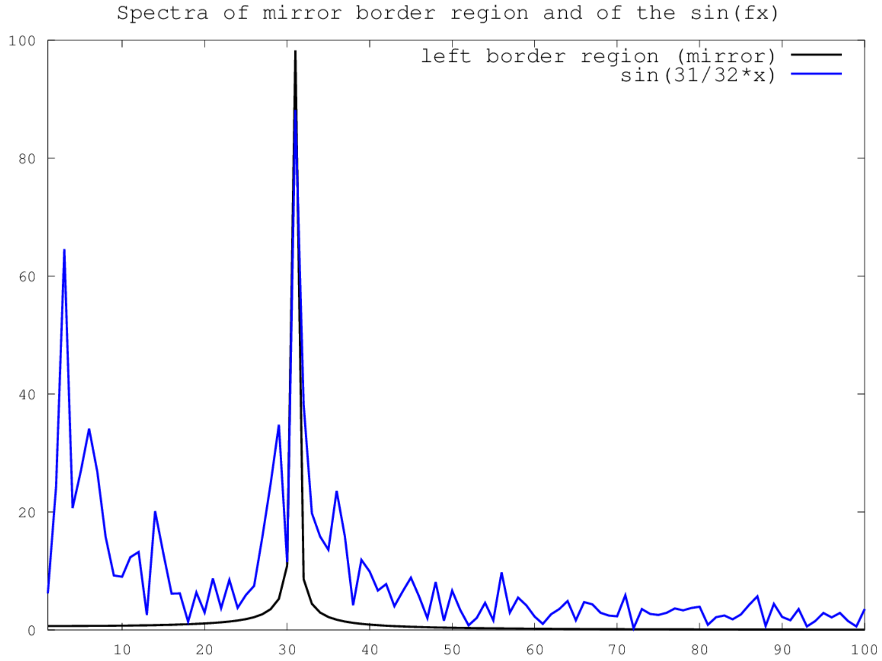
InTILF software analysis application example 4
spasial resolution (step) ~1.5 mm







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