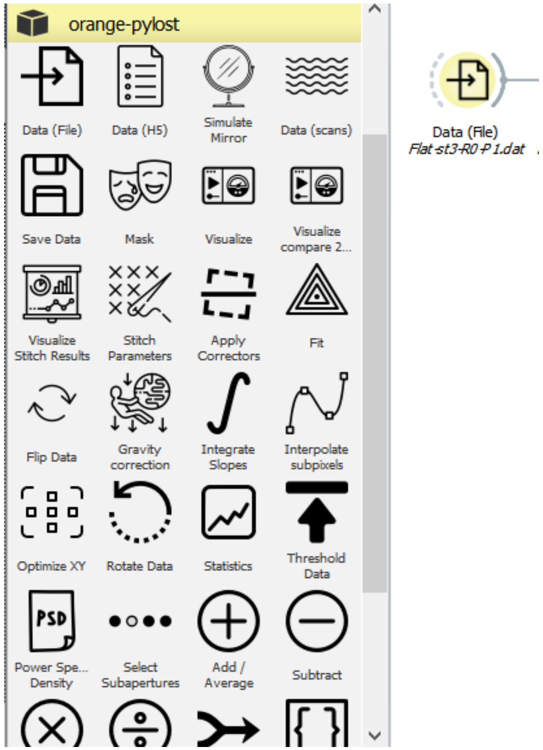

Subaperture stitching algorithms for X-ray mirror metrology

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OUTLINE

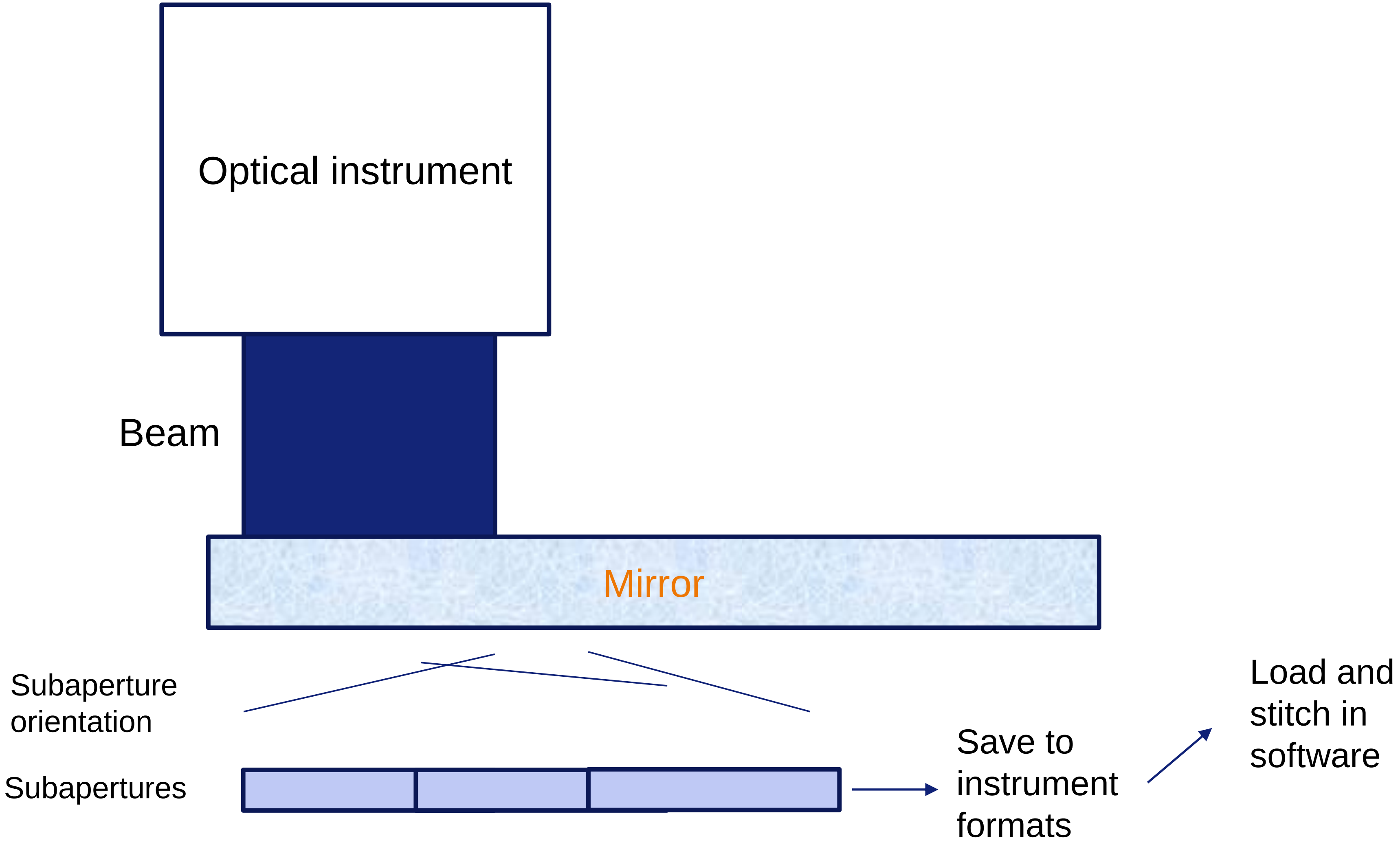
- Subaperture stitching algorithms
- Stitching software - PyLOSt
- Simulations studying software performance
- Comparisons with commercial stitching softwares
- Conclusions

STITCHING SOFTWARE - PYLOST

- **X-ray mirror apertures are typically larger than optical metrology instruments**
- **Subaperture stitching is frequently used for large optics**
  - E.g. Stitching Fizeau, micro-stitching interferometry (MSI), SHARPeR
- **Universal stitching software for synchrotron mirrors**
  - For an European collaboration project ‘Metrology on One-Nanometer-Precise Optics (MooNpics)’ as part of the CALIPSOplus European project
  - **Py**thon & PyQt based **L**arge **O**ptic **St**itching software (**PyLOSt**)
  - Continued within LEAPS-INNOV Superflat European project
- **Stitching data with different algorithms developed in PyLOSt**
  - Progressive Stitching
  - Matrix Overlap Error
  - Global Optimization

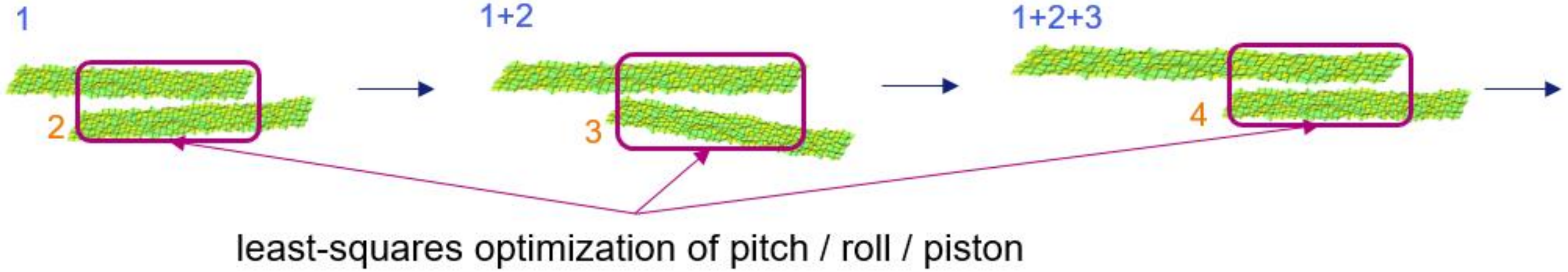
STITCHING SUBAPERTURE PROCEDURE

- **Stitching procedure with an optical instrument moving over a long mirror with overlapping sub-apertures**



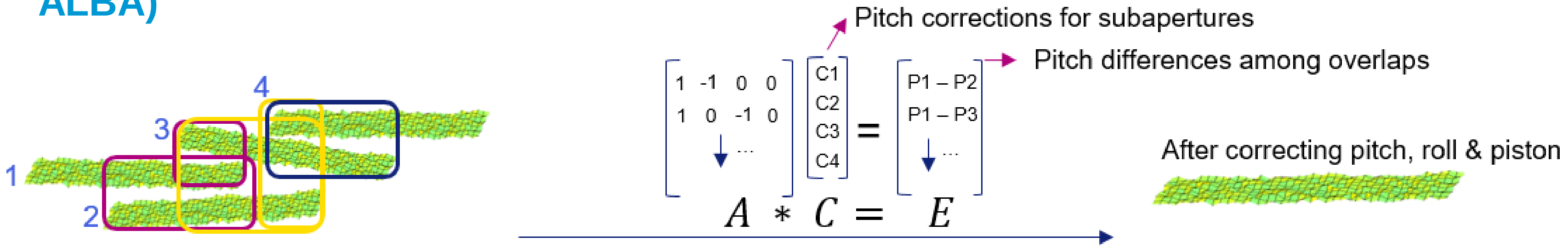
STITCHING ALGORITHMS

- **Progressive stitch (developed in discussions with Francois POLACK from SOLEIL)**
  - Sub-apertures are successively joined



least-squares optimization of pitch / roll / piston

- **Matrix overlap errors (based on algorithm provided by Josep NICOLAS from ALBA)**



Pitch corrections for subapertures

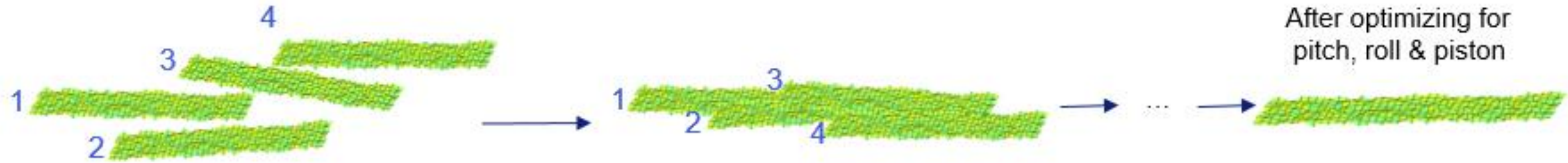
Pitch differences among overlaps

$$\begin{bmatrix} 1 & -1 & 0 & 0 \\ 1 & 0 & -1 & 0 \\ \downarrow & \cdots & & \end{bmatrix} \begin{bmatrix} C1 \\ C2 \\ C3 \\ C4 \end{bmatrix} = \begin{bmatrix} P1-P2 \\ P1-P3 \\ \downarrow \; \cdots \end{bmatrix}$$

$$A * C = E$$

After correcting pitch, roll & piston

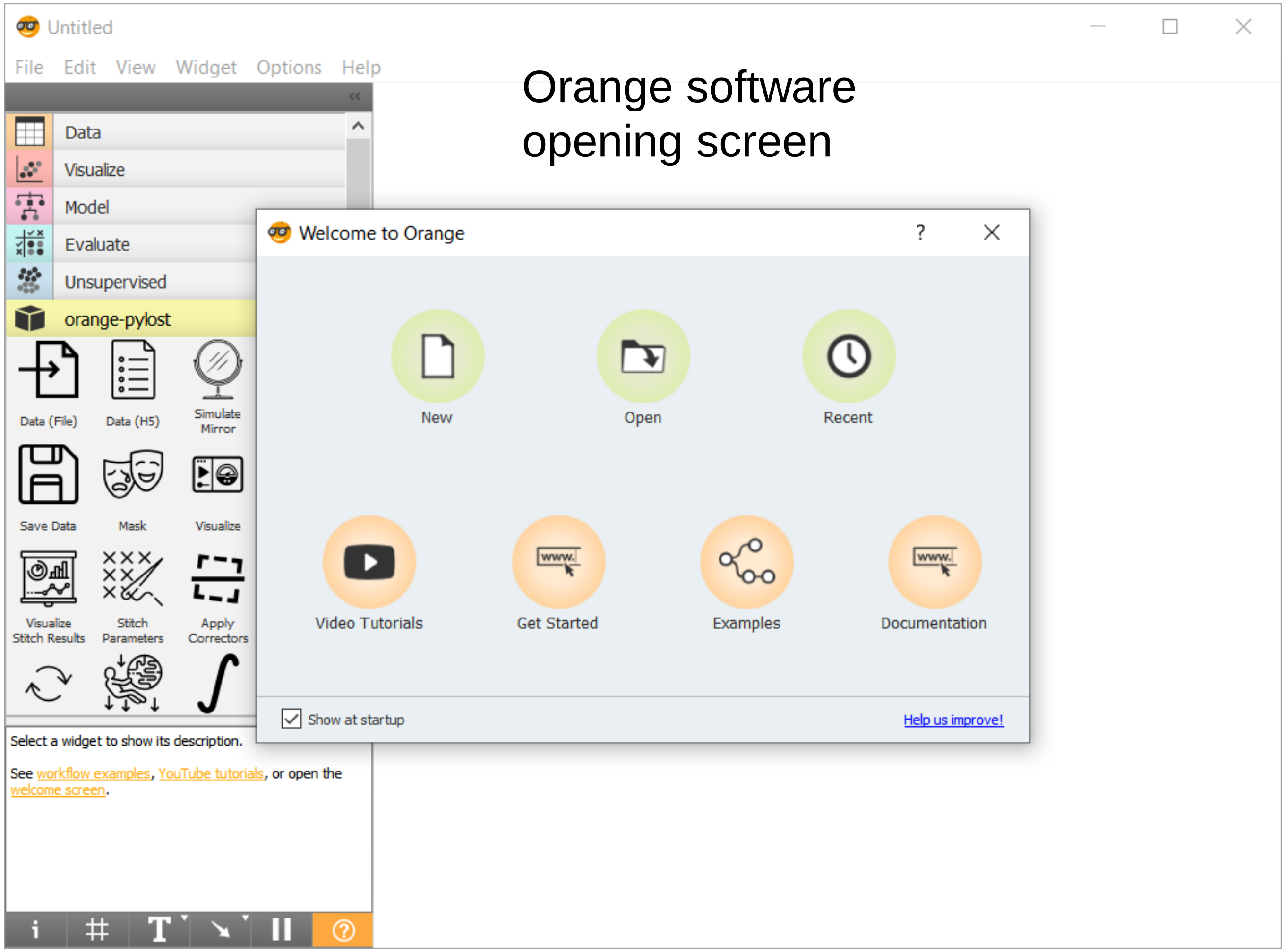
- **Global optimization**
  - Optimize global error function of overlap errors (for all pixels)
    (least-squares optimization of pitch / roll / piston)



After optimizing for pitch, roll & piston

STITCHING SOFTWARE – PYLOST

- **Implemented using Orange Data Mining software platform**
- **The stitching workflows are managed with various widgets connected on an orange canvas**

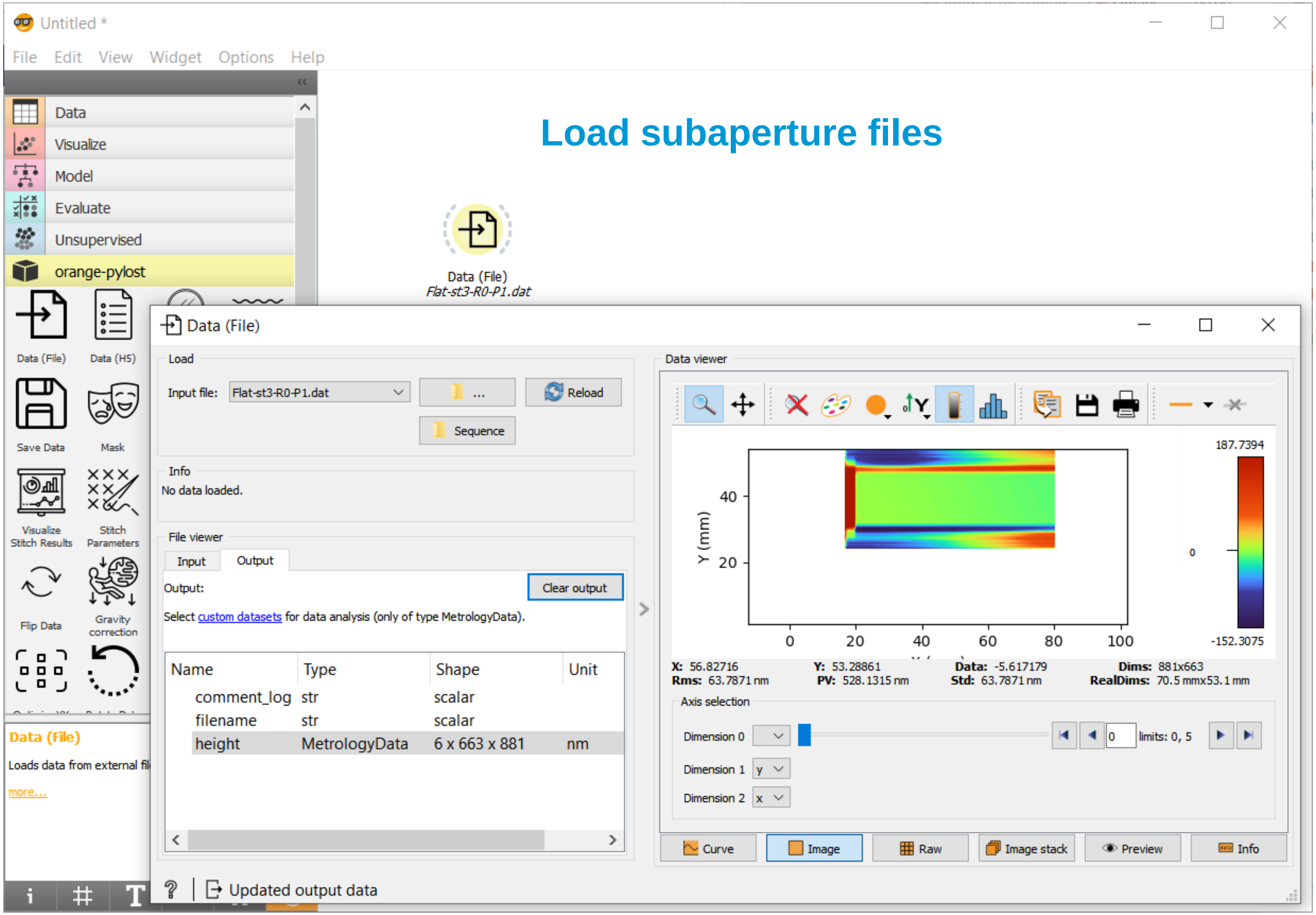


Select a widget to show its description.

See workflow examples, YouTube tutorials, or open the welcome screen.

Orange software opening screen

STITCHING SOFTWARE – PYLOST



Load subaperture files

Data (File)

Loads data from external fil

more...

Input file: Flat-st3-R0-P1.dat

No data loaded.

Output:

Select custom datasets for data analysis (only of type MetrologyData).

Name	Type	Shape	Unit
comment_log	str	scalar	
filename	str	scalar	
height	MetrologyData	6 x 663 x 881	nm

X: 56.82716 Y: 53.28861 Data: -5.617179 Dims: 881x663

Rms: 63.7871 nm PV: 528.1315 nm Std: 63.7871 nm RealDims: 70.5 mmx53.1 mm

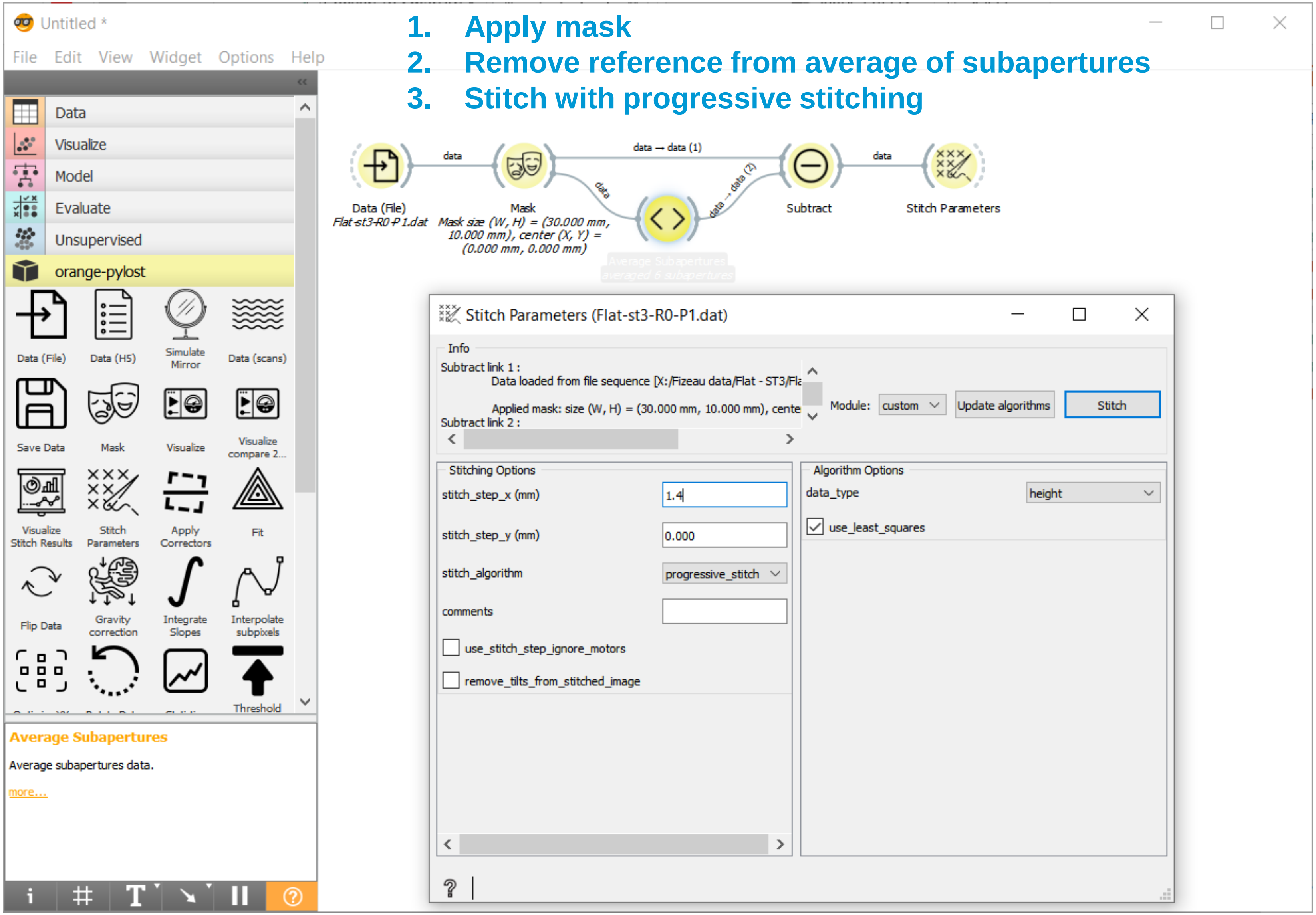
Dimension 0 ▾ 0 limits: 0, 5

Dimension 1 y ▾

Dimension 2 x ▾

STITCHING SOFTWARE – PYLOST

1. Apply mask
2. Remove reference from average of subapertures
3. Stitch with progressive stitching



Average Subapertures

Average subapertures data.

more...

Stitch Parameters (Flat-st3-R0-P1.dat)

Info

Subtract link 1 :
Data loaded from file sequence [X:/Fizeau data/Flat - ST3/Fla
Applied mask: size (W, H) = (30.000 mm, 10.000 mm), cente
Subtract link 2 :

Module: custom | Update algorithms | Stitch

Stitching Options

stitch_step_x (mm): 1.4
stitch_step_y (mm): 0.000
stitch_algorithm: progressive_stitch
comments:
□ use_stitch_step_ignore_motors
□ remove_tilts_from_stitched_image

Algorithm Options

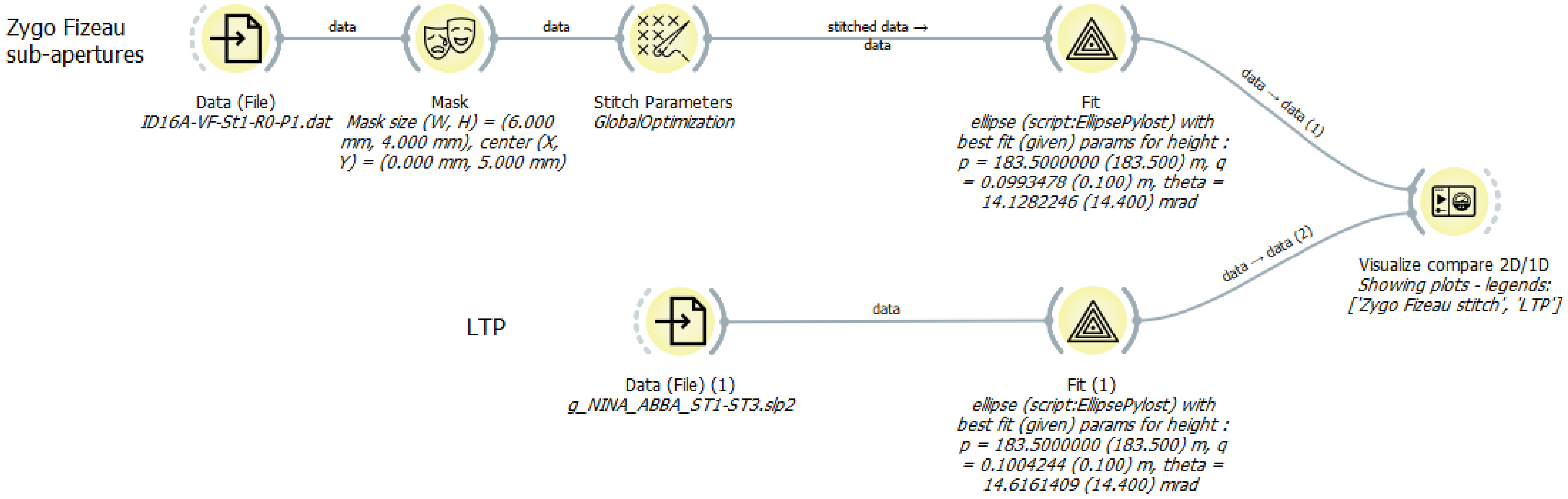
data_type: height
☑ use_least_squares

PYLOST SOFTWARE FEATURES

- **Stitching with different algorithms of 2D heights / slopes from various metrology instruments**
  - Easy to incorporate new stitching algorithms
- **Widgets for data masking, polynomial / ellipse fitting, visualization etc.**
- **MetrologyData ← astropy.Quantity ← numpy.ndarray**
  - Data: numpy array
  - Parameters: unit, detector dimensions, pixel size etc.
- **Various instrument file readers included, Zygo MetroPro dat/datx, Veeco OPD etc.**
  - Easier inclusion of new file readers
- **Ability to perform wide range of tasks in combination of widgets**
- **Saving data to hdf5 and python pickle formats, saving and sharing workflows**
- **Open source code distributed under MIT License.**

STITCHING AN ELLIPTICAL MIRROR

- **A 70 mm long elliptical mirror is measured by Zygo Fizeau interferometer in 72 sub-apertures with 0.789 mm step along tangential direction**
- **The mirror is also measured by ESRF LTP**
- **The Fizeau sub-apertures are stitched using PyLOSt global optimization**
- **A best fit ellipse is removed from the stitching as well as LTP as shown in the following workflow**
  - Specified ellipse parameters p = 183.5 m, q = 0.1 m, theta = 14.4 mrad



Data (File)
ID16A-VF-St1-R0-P1.dat

Mask
Mask size (W, H) = (6.000 mm, 4.000 mm), center (X, Y) = (0.000 mm, 5.000 mm)

Stitch Parameters
GlobalOptimization

Fit
ellipse (script:EllipsePylost) with best fit (given) params for height : p = 183.5000000 (183.500) m, q = 0.0993478 (0.100) m, theta = 14.1282246 (14.400) mrad

Visualize compare 2D/1D
Showing plots - legends: ['Zygo Fizeau stitch', 'LTP']

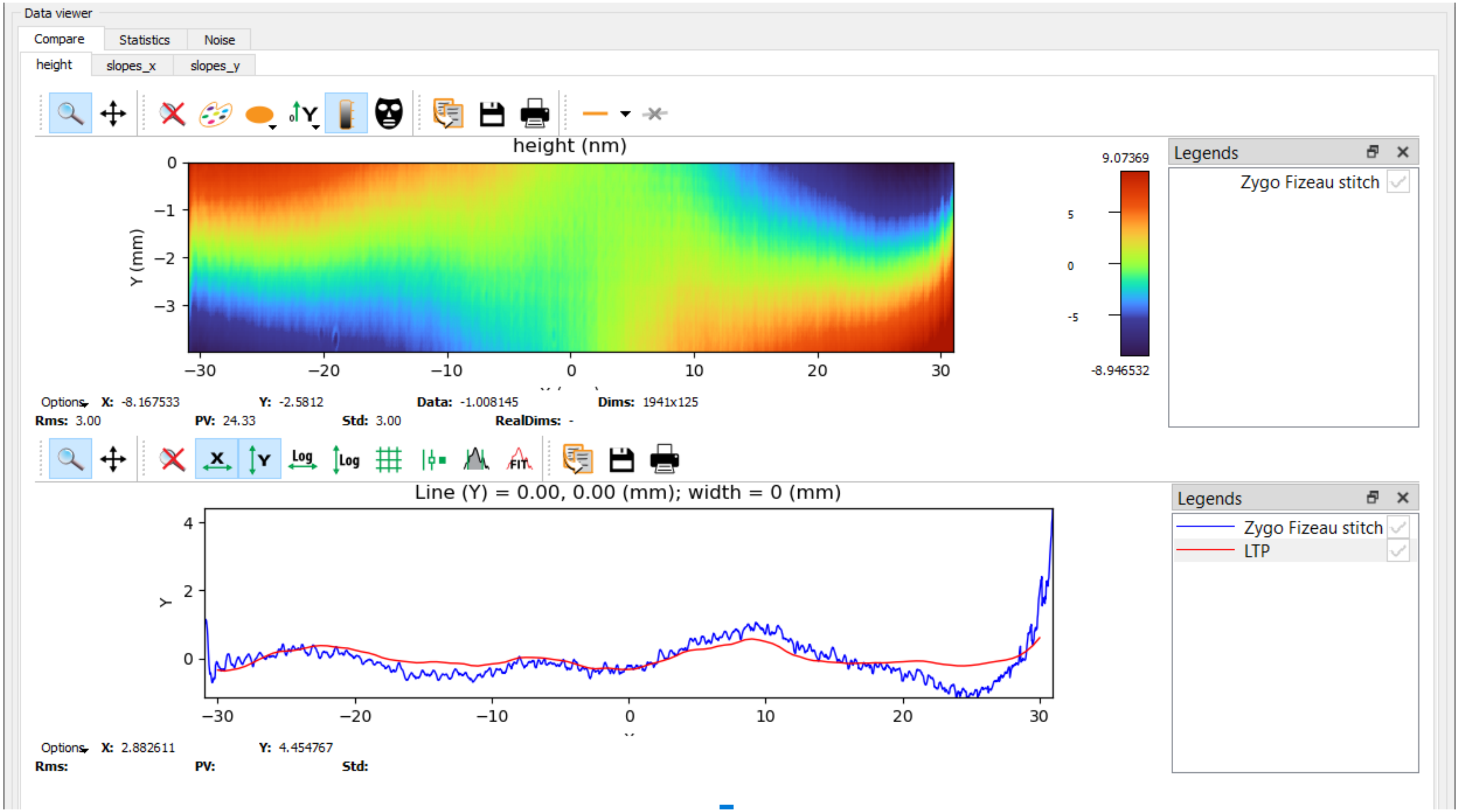
Data (File) (1)
g_NINA_ABBA_ST1-ST3.slp2

Fit (1)
ellipse (script:EllipsePylost) with best fit (given) params for height : p = 183.5000000 (183.500) m, q = 0.1004244 (0.100) m, theta = 14.6161409 (14.400) mrad

STITCHING AN ELLIPTICAL MIRROR

Stitching results

Rms: Fizeau (2D) = 3 nm, Fizeau (central line) = 0.57 nm, LTP (1D) = 0.23 nm
q: Fizeau = 0.0993 m, LTP = 1.004 m
Theta: Fizeau = 14.1282 mrad, LTP = 14.6161 mrad



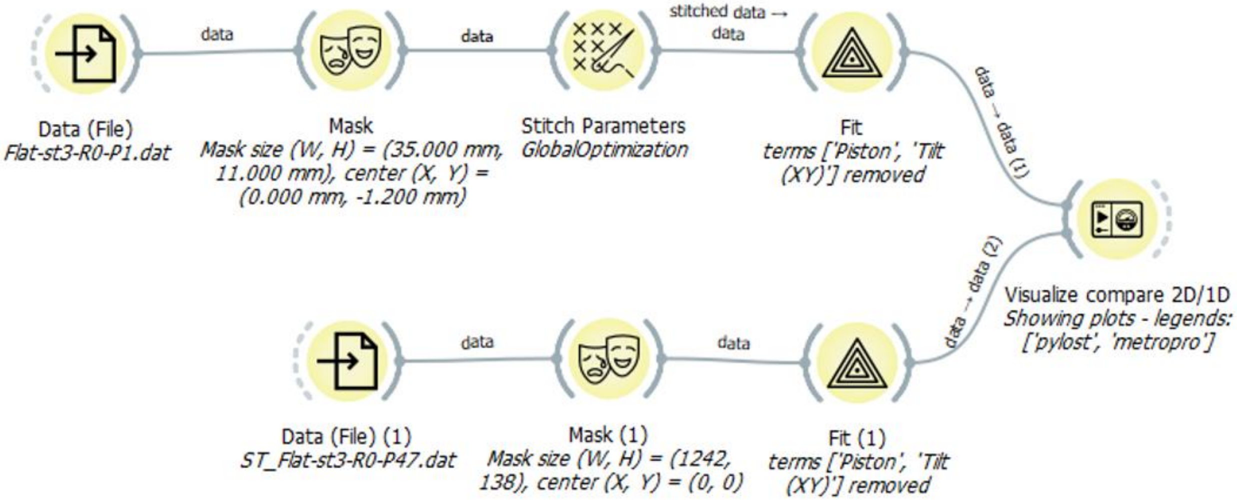
Options X: -8.167533 Y: -2.5812 Data: -1.008145 Dims: 1941x125
Rms: 3.00 PV: 24.33 Std: 3.00 RealDims: -

Options X: 2.882611 Y: 4.454767
Rms: PV: Std:

COMPARISON TO ZYGO METROPRO STITCHING

- **A 100mm long flat mirror is measured with Zygo Fizeau interferometer in 47 sub-apertures with step 1.4 mm along tangential direction**
- **The subapertures are stitched with Zygo MetroPro and PyLOSt global optimization and both the results are compared**

(a) Stitching workflow



Data (File)
Flat-st3-R0-P1.dat

Mask
Mask size (W, H) = (35.000 mm, 11.000 mm), center (X, Y) = (0.000 mm, -1.200 mm)

Stitch Parameters
GlobalOptimization

Fit
terms ['Piston', 'Tilt (XY)'] removed

Visualize compare 2D/1D
Showing plots - legends: ['pylost', 'metropro']

Data (File) (1)
ST_Flat-st3-R0-P47.dat

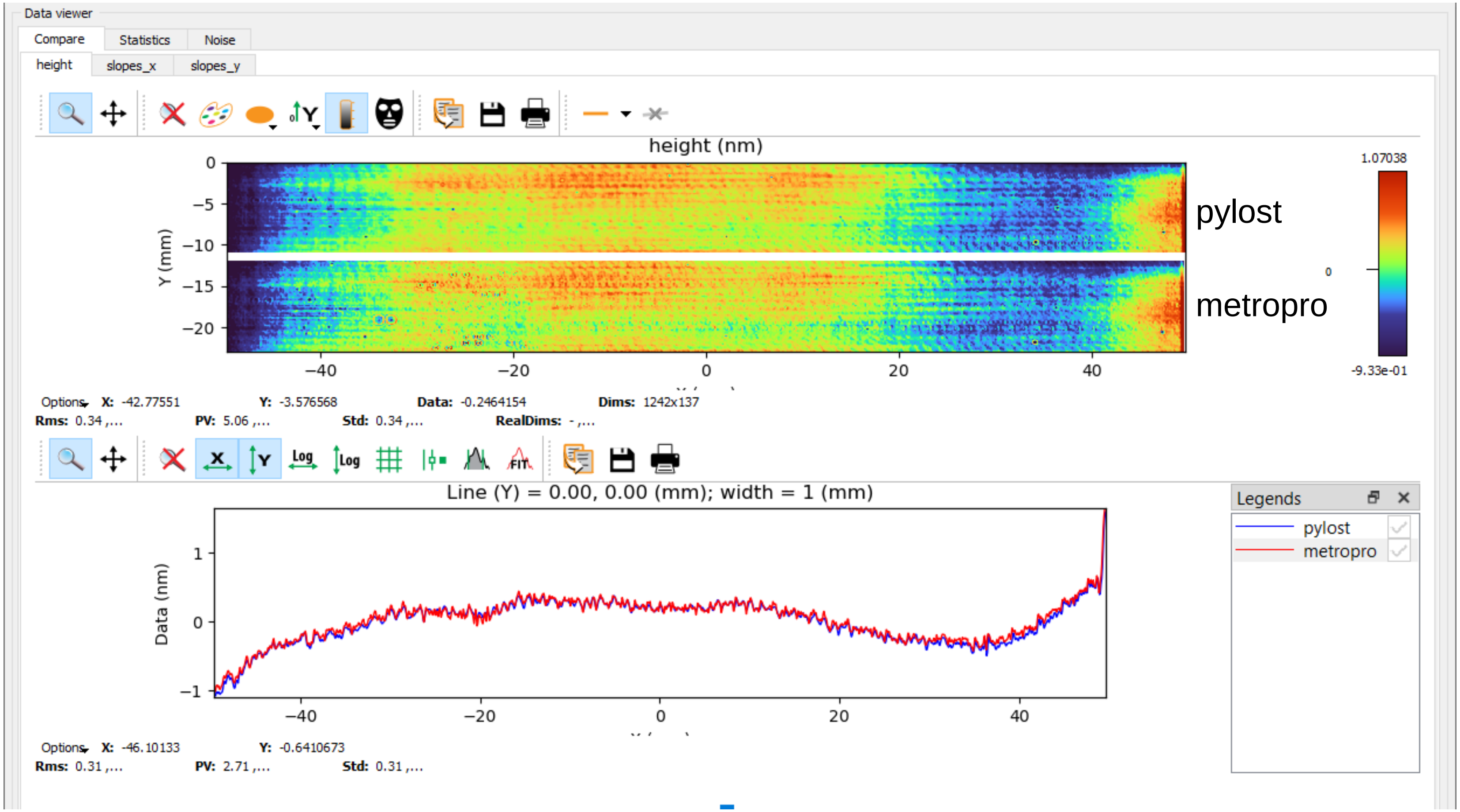
Mask (1)
Mask size (W, H) = (1242, 138), center (X, Y) = (0, 0)

Fit (1)
terms ['Piston', 'Tilt (XY)'] removed

COMPARISON TO ZYGO METROPRO STITCHING

Stitching results

Rms pylost = 0.34 nm, rms metropro = 0.33 nm
Rms difference = 0.095 nm

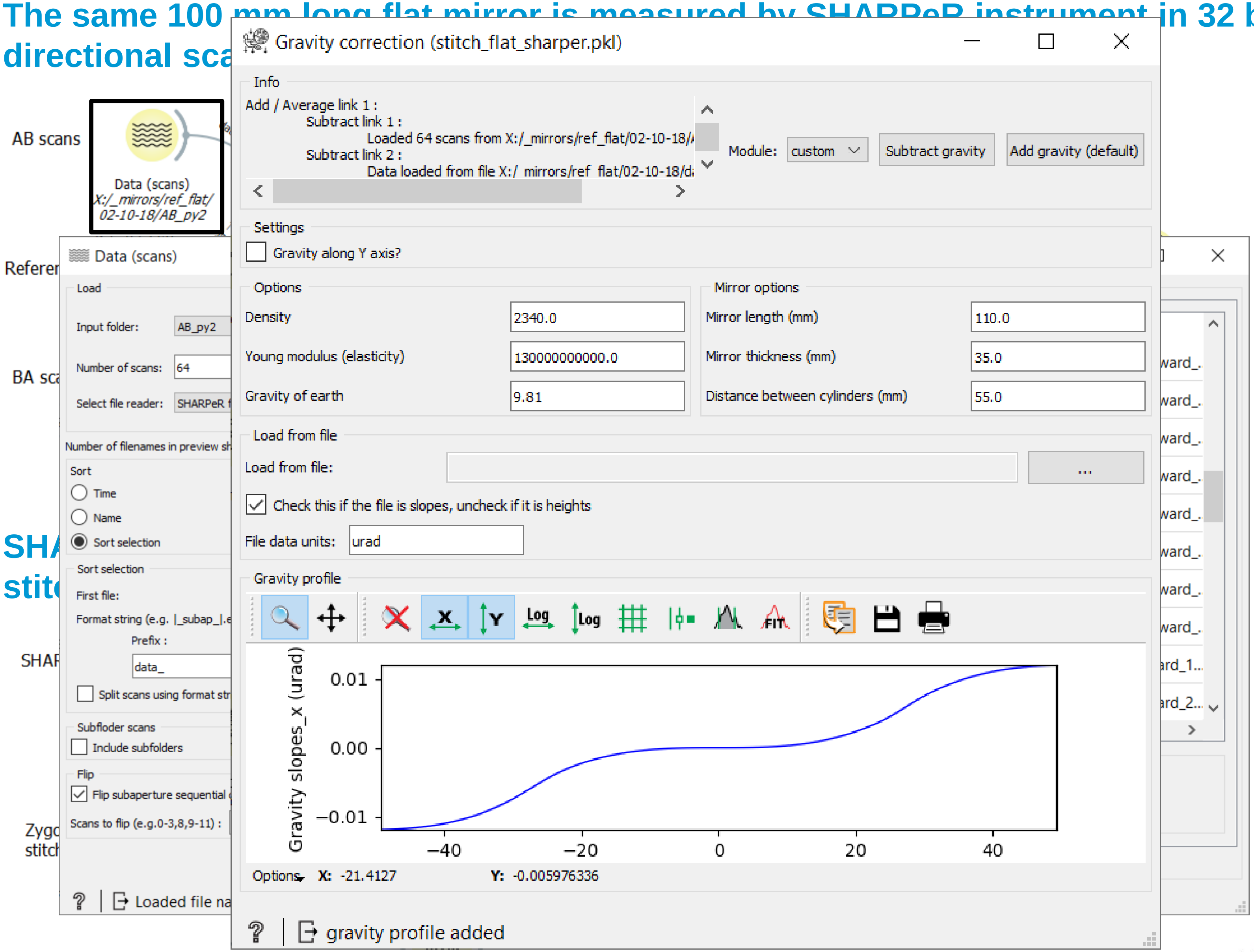


Options X: -42.77551 Y: -3.576568 Data: -0.2464154 Dims: 1242x137
Rms: 0.34 ,... PV: 5.06 ,... Std: 0.34 ,... RealDims: - ,...

Options X: -46.10133 Y: -0.6410673
Rms: 0.31 ,... PV: 2.71 ,... Std: 0.31 ,...

STITCHING EXAMPLE – SHARPER SLOPES (2D)

- The same 100 mm long flat mirror is measured by SHARPeR instrument in 32 bi-directional sca



Gravity correction (stitch_flat_sharper.pkl)

Info

```
Add / Average link 1 :
        Subtract link 1 :
                Loaded 64 scans from X:/_mirrors/ref_flat/02-10-18/A
        Subtract link 2 :
                Data loaded from file X:/_mirrors/ref_flat/02-10-18/da
```

Module: custom

Settings

☐ Gravity along Y axis?

Options

Density: 2340.0

Young modulus (elasticity): 130000000000.0

Gravity of earth: 9.81

Mirror options

Mirror length (mm): 110.0

Mirror thickness (mm): 35.0

Distance between cylinders (mm): 55.0

Load from file

Load from file:

☑ Check this if the file is slopes, uncheck if it is heights

File data units: urad

Gravity profile

Options X: -21.4127 Y: -0.005976336

gravity profile added

Data (scans)

Load

Input folder: AB_py2

Number of scans: 64

Select file reader: SHARPeR f

Number of filenames in preview sh

Sort

○ Time

○ Name

● Sort selection

Sort selection

First file:

Format string (e.g. |_subap_|.e

Prefix : data_

☐ Split scans using format str

Subfloder scans

☐ Include subfolders

Flip

☑ Flip subaperture sequential

Scans to flip (e.g.0-3,8,9-11) :

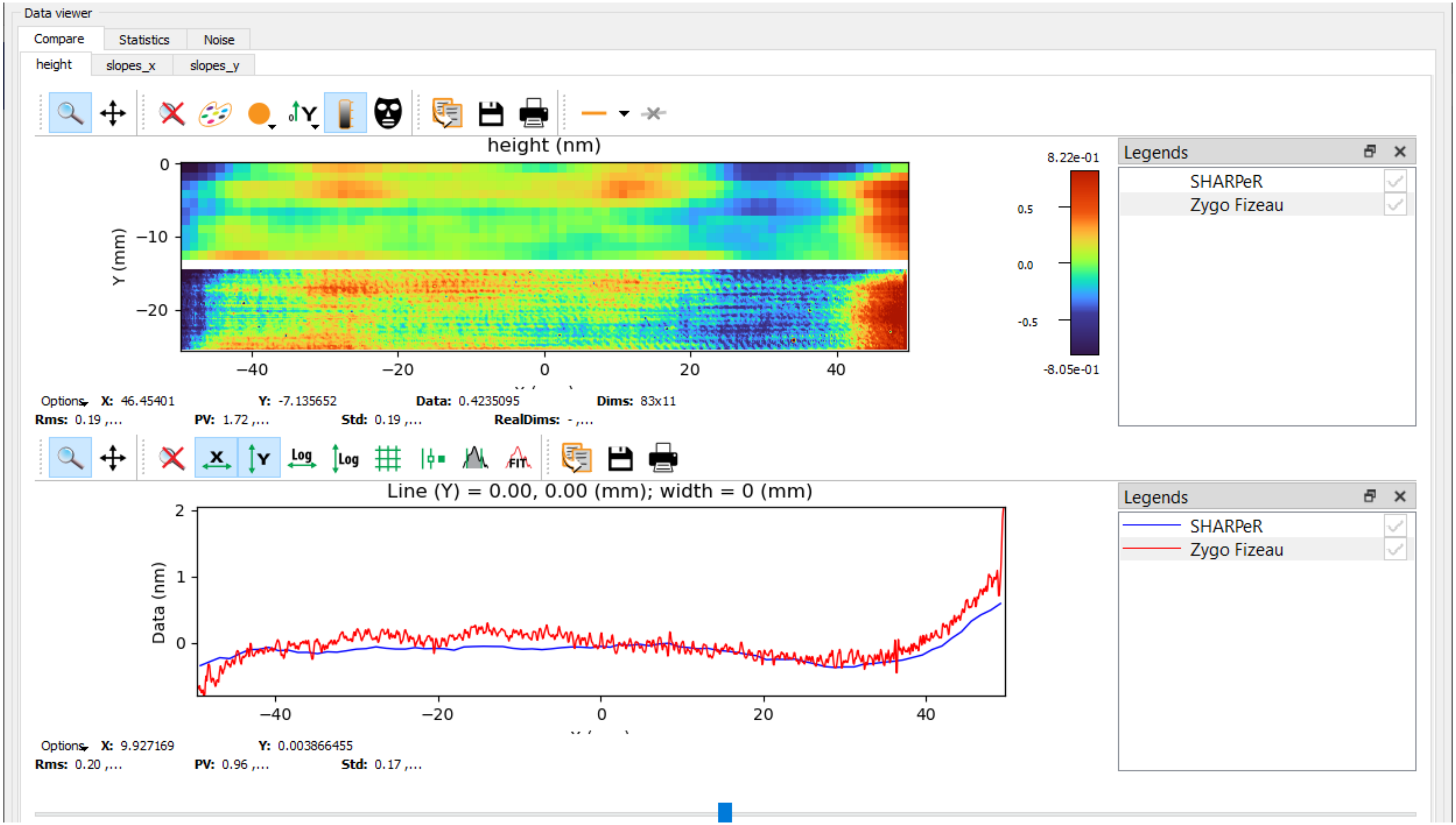
Loaded file na

- SHA
stit

STITCHING SHARPER DATA

Stitching results

Rms: sharper (2D) = 0.19 nm, Fizeau (2D) = 0.28 nm



Options X: 46.45401 Y: -7.135652 Data: 0.4235095 Dims: 83x11

Rms: 0.19 ,... PV: 1.72 ,... Std: 0.19 ,... RealDims: - ,...

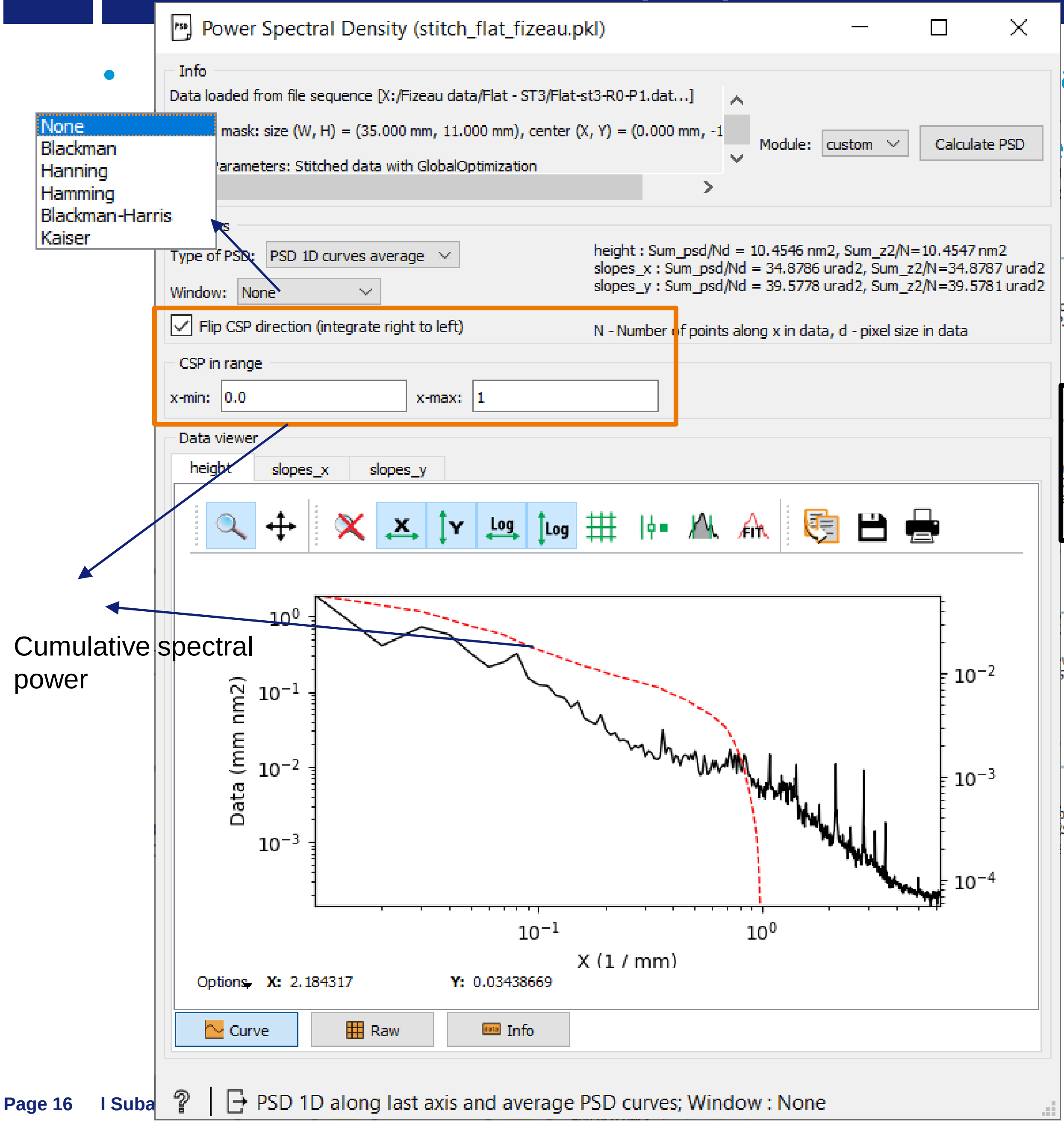
Options X: 9.927169 Y: 0.003866455

Rms: 0.20 ,... PV: 0.96 ,... Std: 0.17 ,...

POWER SPECTRAL DENSITY (PSD) WIDGET

- average (sagittal)

nts



Power Spectral Density (stitch_flat_fizeau.pkl)

Info

Data loaded from file sequence [X:/Fizeau data/Flat - ST3/Flat-st3-R0-P1.dat...]

mask: size (W, H) = (35.000 mm, 11.000 mm), center (X, Y) = (0.000 mm, -1

arameters: Stitched data with GlobalOptimization

Module: custom

Type of PSD: PSD 1D curves average

Window: None

height : Sum_psd/Nd = 10.4546 nm2, Sum_z2/N=10.4547 nm2
slopes_x : Sum_psd/Nd = 34.8786 urad2, Sum_z2/N=34.8787 urad2
slopes_y : Sum_psd/Nd = 39.5778 urad2, Sum_z2/N=39.5781 urad2

☑ Flip CSP direction (integrate right to left)

N - Number of points along x in data, d - pixel size in data

CSP in range

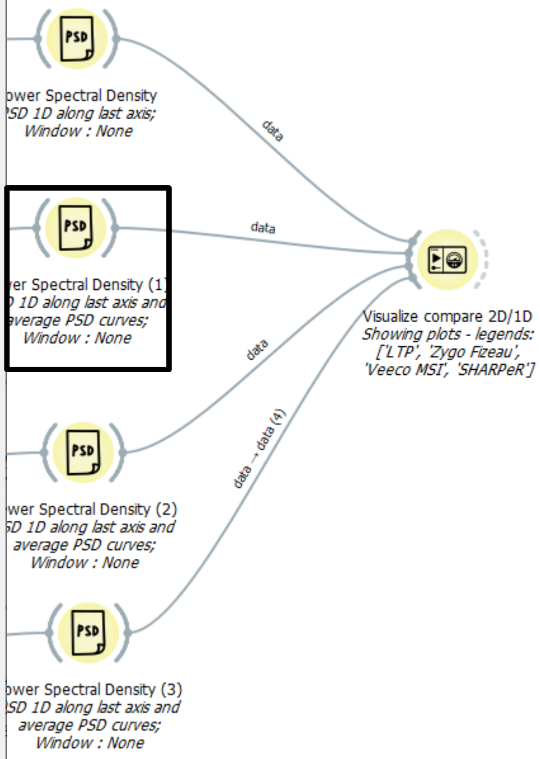
x-min: 0.0 x-max: 1

Data viewer

Options X: 2.184317 Y: 0.03438669

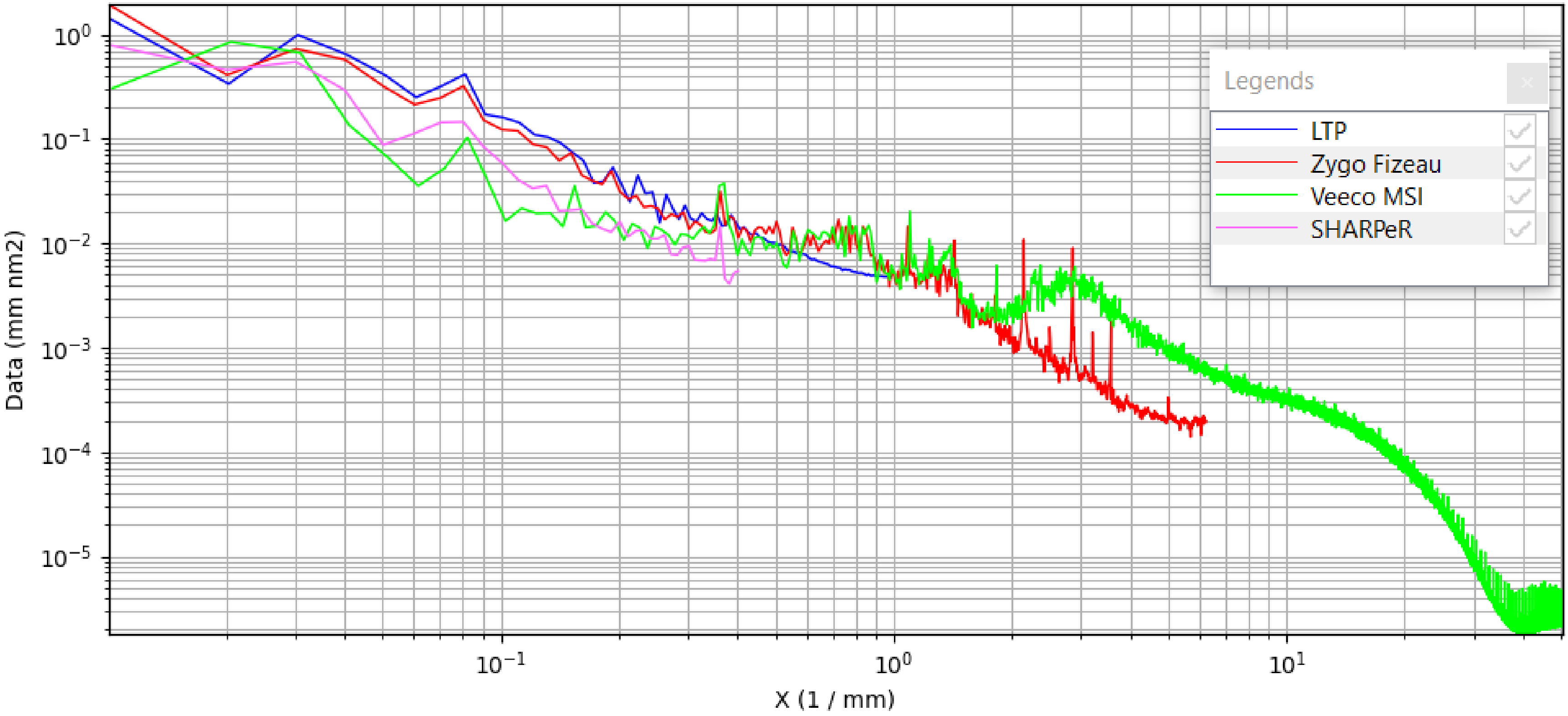
PSD 1D along last axis and average PSD curves; Window : None

Cumulative spectral power



PSD COMPARISON

PSD comparison for measurements on flat mirror, by LTP, Zygo Fizeau stitching, Veeco MSI stitching, SHARPeR stitching

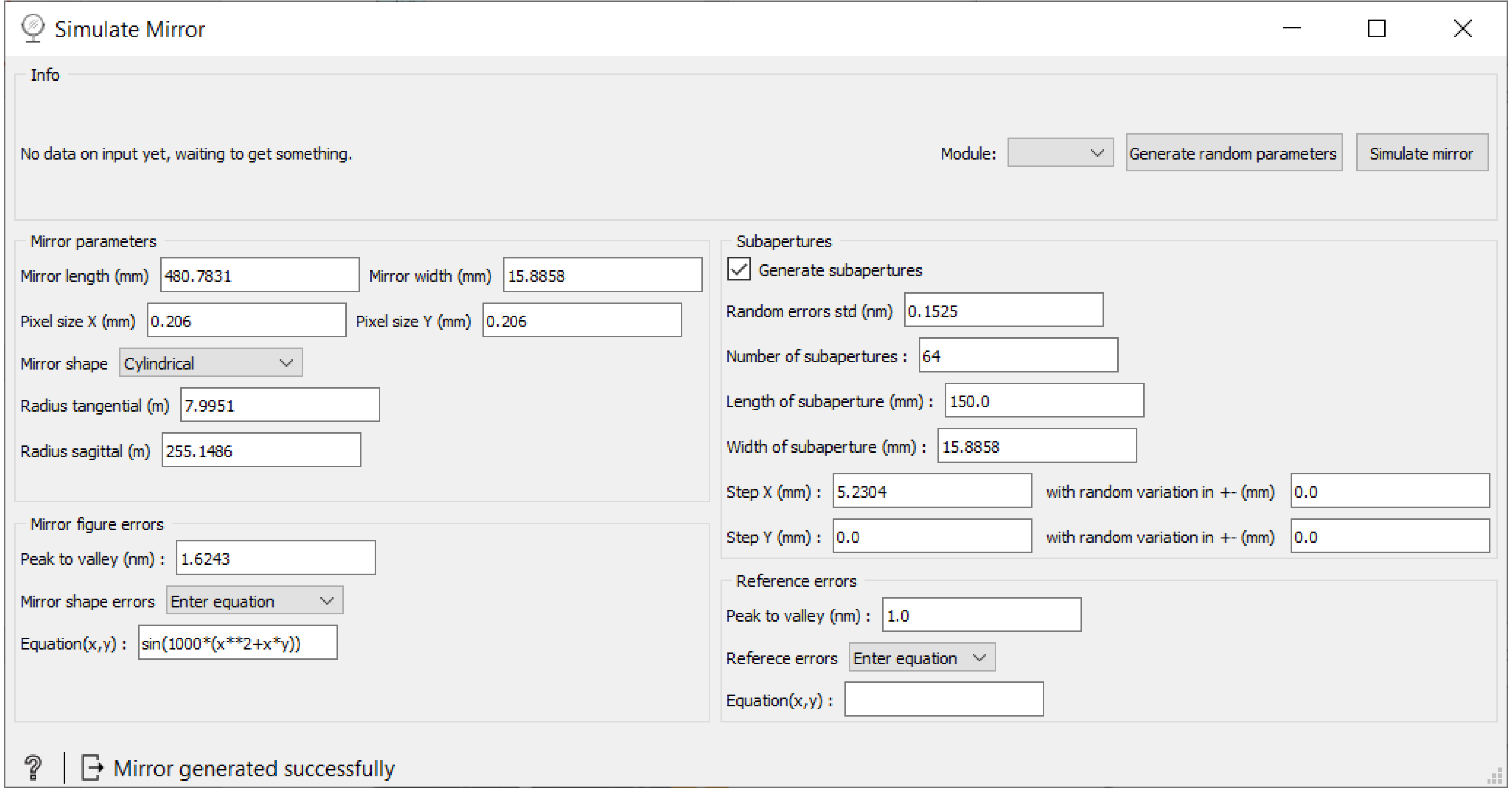


SIMULATIONS IN PYLOST

- **Simulation widget is used to generate different mirror subapertures**
  - Different shapes: flat, cylinder, sphere, ellipse etc
  - Shape or shape error by given equation, e.g. $height\ error = \sin(100 * y * x^2)$
  - Fixed / random motor step in x and y to generate subapertures
- **Simulate 2D mirror surface**
  → generate subapertures
  → stitch subapertures with different algorithms
  → compare mirror to stitch surface

SIMULATIONS IN PYLOST – CYLINDRICAL MIRROR

- Generate a cylindrical mirror with parameters shown in the figure



Simulate Mirror

Info

No data on input yet, waiting to get something.

Module: | Generate random parameters | Simulate mirror

Mirror parameters

Mirror length (mm) 480.7831
Mirror width (mm) 15.8858
Pixel size X (mm) 0.206
Pixel size Y (mm) 0.206
Mirror shape Cylindrical
Radius tangential (m) 7.9951
Radius sagittal (m) 255.1486

Mirror figure errors

Peak to valley (nm) : 1.6243
Mirror shape errors Enter equation
Equation(x,y) : sin(1000*(x**2+x*y))

Subapertures

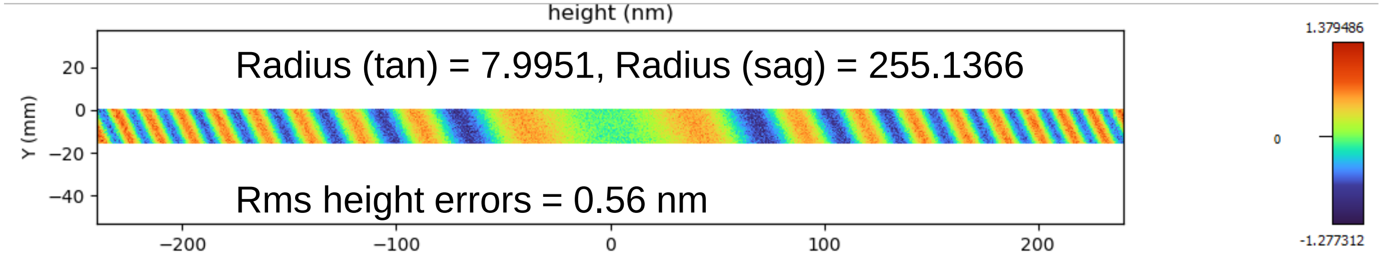
☑ Generate subapertures
Random errors std (nm) 0.1525
Number of subapertures : 64
Length of subaperture (mm) : 150.0
Width of subaperture (mm) : 15.8858
Step X (mm) : 5.2304 with random variation in +- (mm) 0.0
Step Y (mm) : 0.0 with random variation in +- (mm) 0.0

Reference errors

Peak to valley (nm) : 1.0
Referece errors Enter equation
Equation(x,y) :

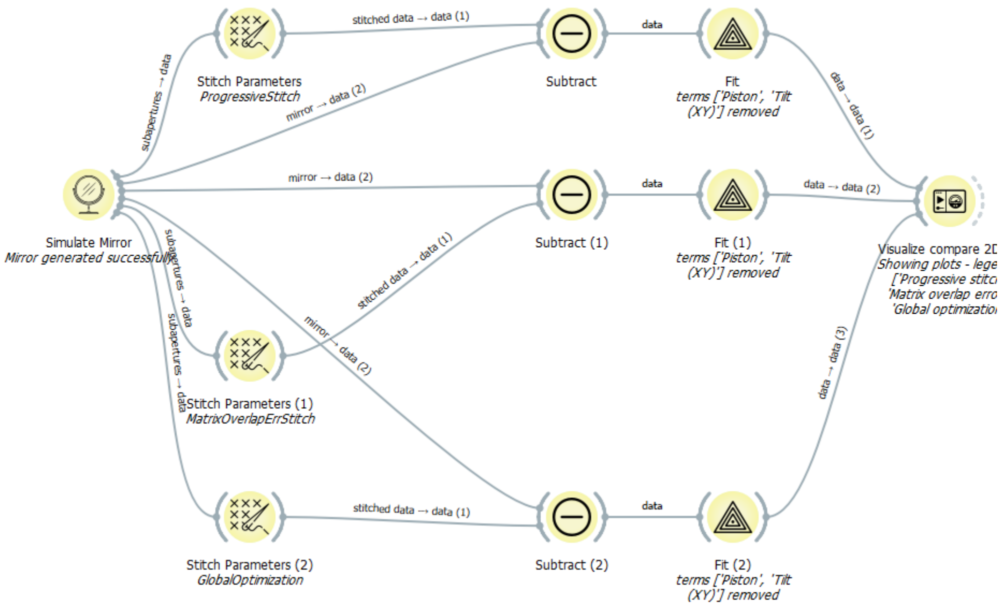
Mirror generated successfully

- Stitched height errors with Global optimization



SIMULATIONS IN PYLOST – CYLINDRICAL MIRROR

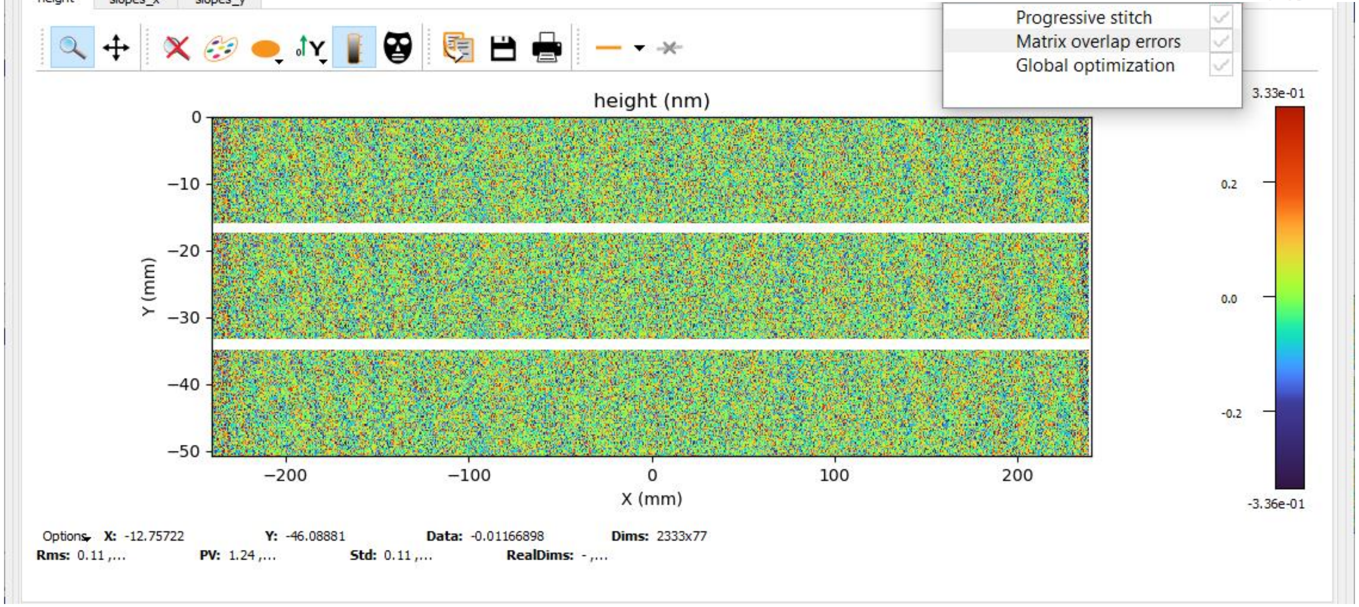
- Stitching with progressive, matrix overlap error and global optimization.
- Stitched surfaces subtracted from simulated mirror surface.
- The difference is 0.11 nm rms for all methods



Data viewer

Compare | Statistics | Noise

height | slopes_x | slopes_y



Options X: -12.75722 Y: -46.08881 Data: -0.01166898 Dims: 2333x77
Rms: 0.11 ,... PV: 1.24 ,... Std: 0.11 ,... RealDims: - ,...

RESOURCES

- **The source code is available at**
  - https://gitlab.esrf.fr/moonpics_stitching_2018/orange-pylost https://gitlab.esrf.fr/moonpics_stitching_2018/PyLOSt
  - Orange-pylost has all the widgets and PyLOSt has some core functions like stitching and fitting
  - Installation instructions are available in the gitlab page
- **Documentation is available in a help widget in the orange-pylost software**
- **Installation and documentation is also available at**
  - https://leaps-superflat.eu/pylost/

CONCLUSIONS

- New stitching software (PyLOSt) based on python is developed for X-ray mirror metrology
- Different stitching algorithms developed for height / slope data from different instruments
- Simulated mirror data is used to validate stitching algorithms
- PyLOSt stitching provided similar results on test data compared to commercial stitching softwares like Zygo MetroPro
- Easy installation of software using source code available on ESRF gitlab