

Nov. 12, 2025

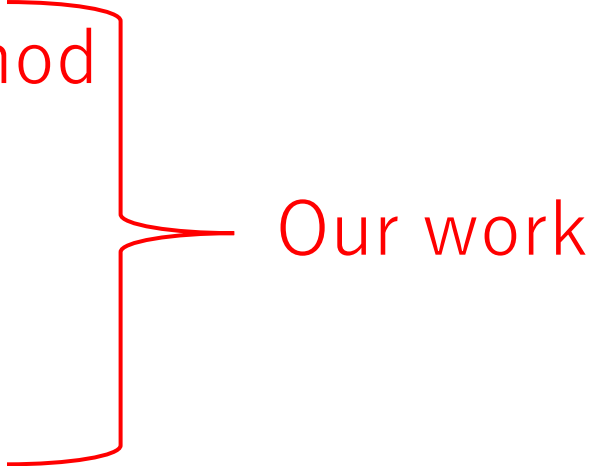
The Optical & Infrared Astronomical Instrumentation Workshop 2025 @ Kyoto Sangyo University

Figure Reconstruction from Interferometric Measurements under Vibrational Conditions

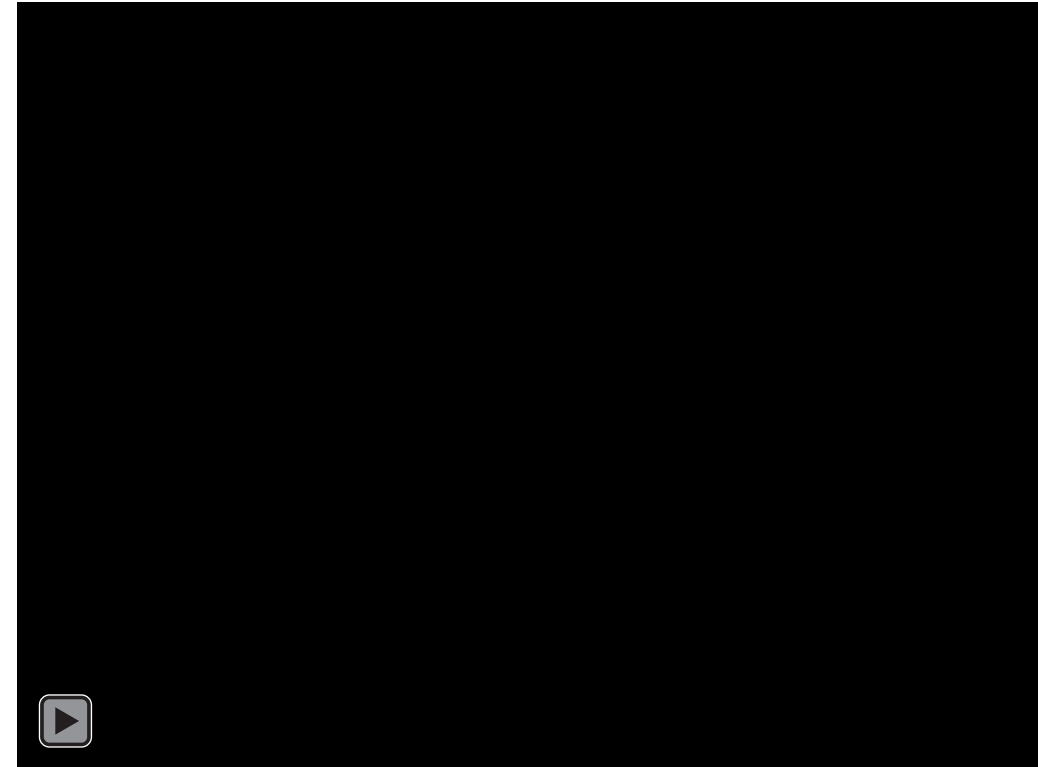
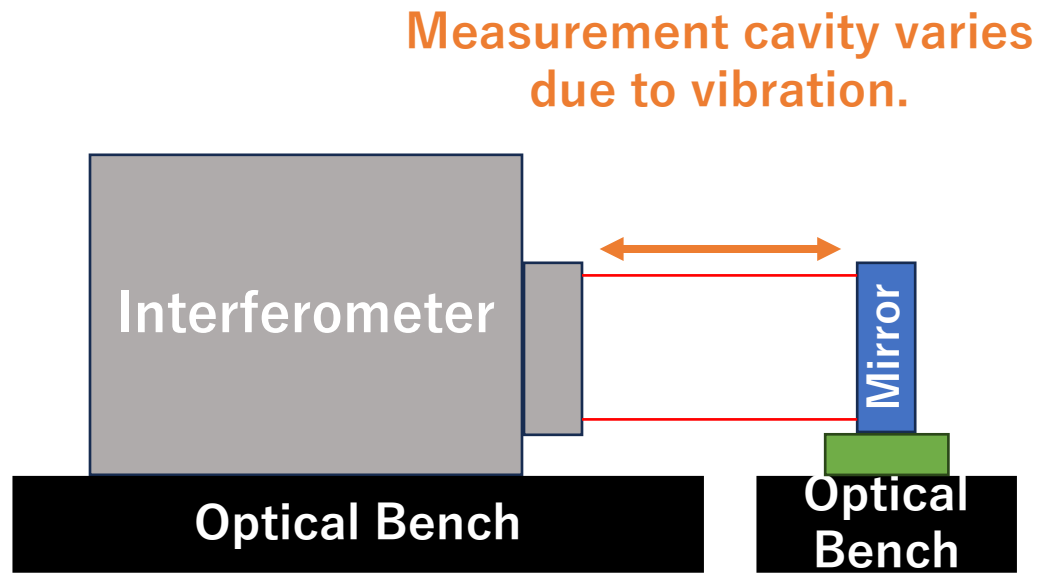
Taiki Bessho(1,2)*, Makoto Komaki(2), Yuji Ikeda(1,2),
Masahito Uchiyama(1,2)

(1) Photocross Co., Ltd., (2) Kyoto Sangyo University

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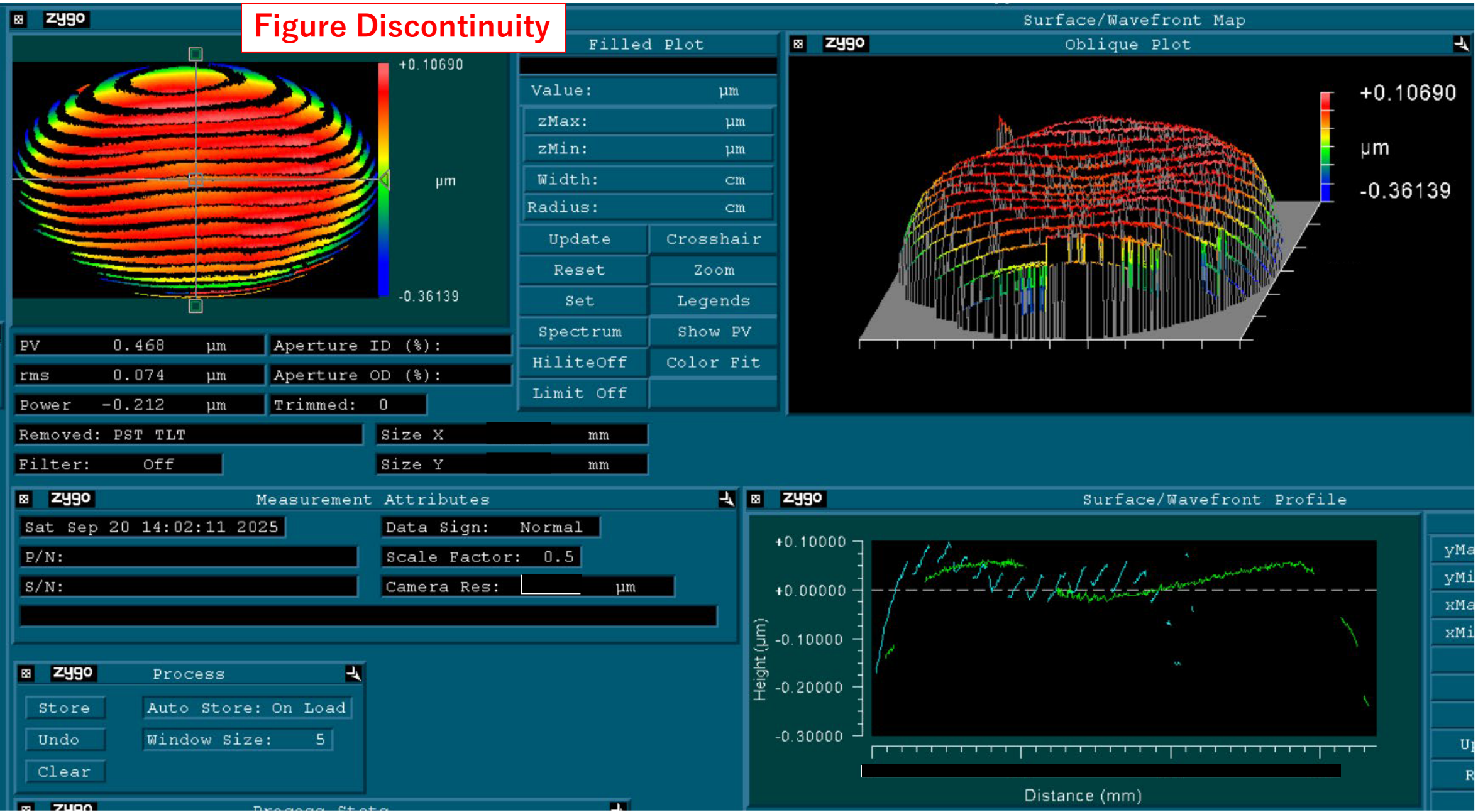
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 3. Temporal Phase-Shifting Method
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Interferometric Measurement under Vibrational Conditions

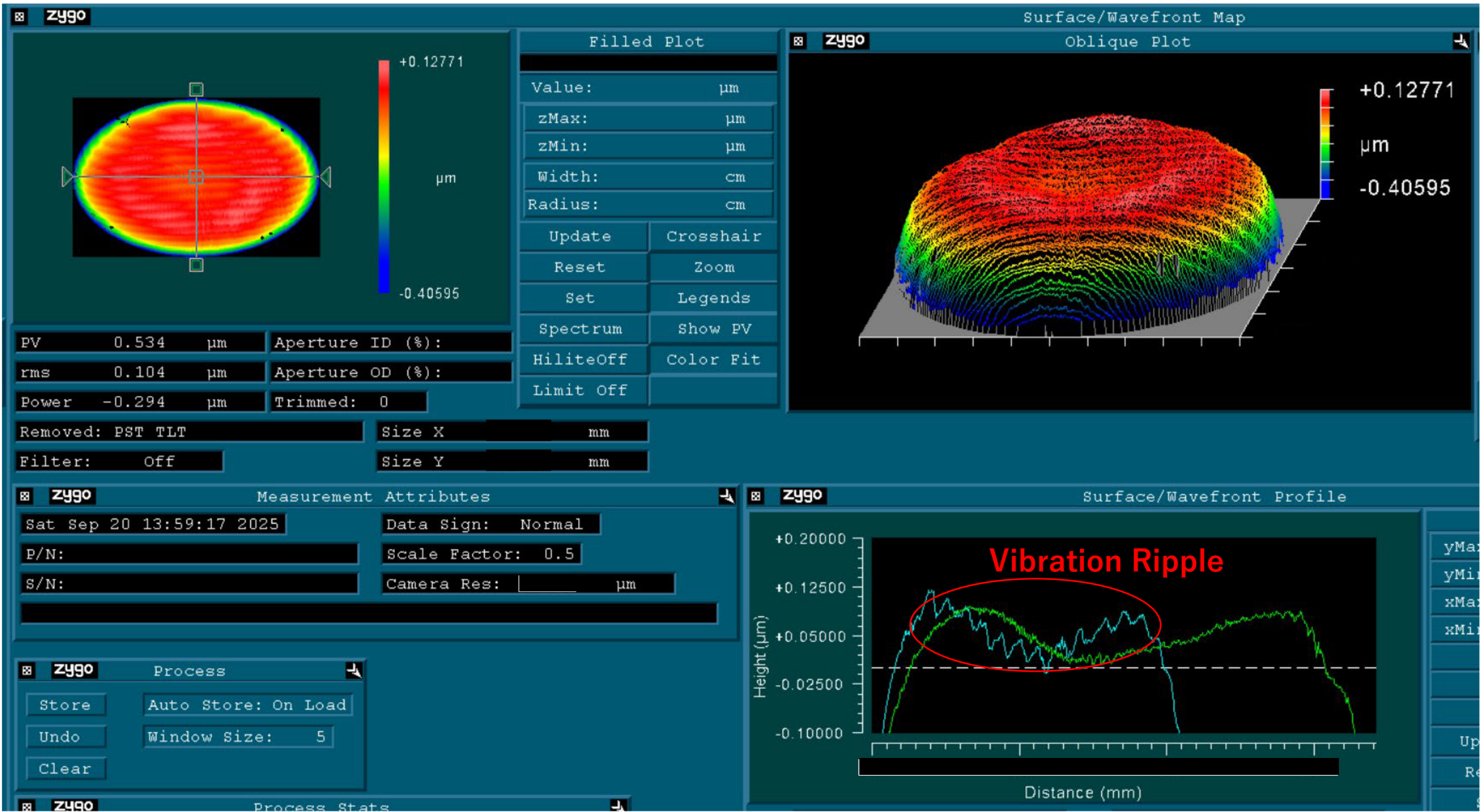


Measurement Error Example 1

Figure Discontinuity

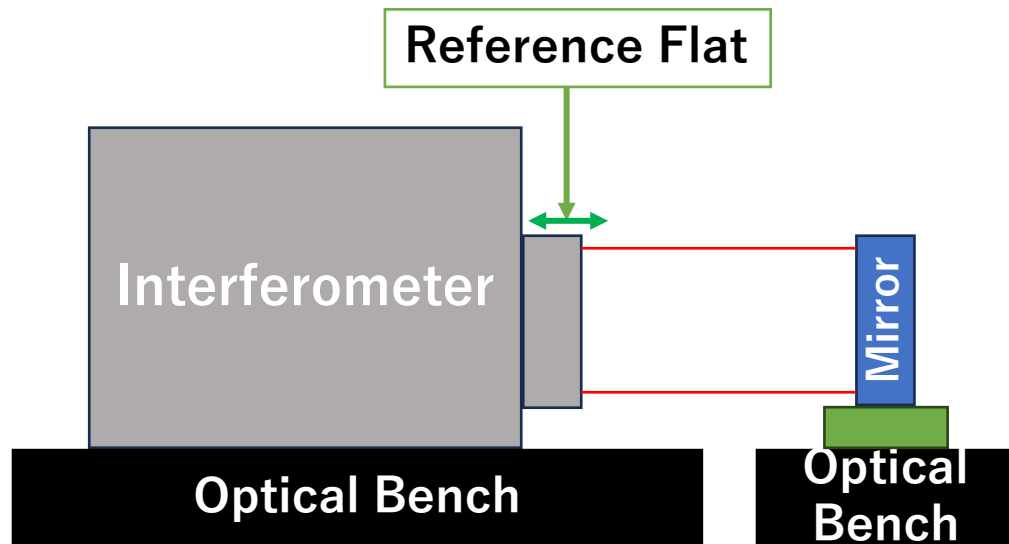


Measurement Error Example 2

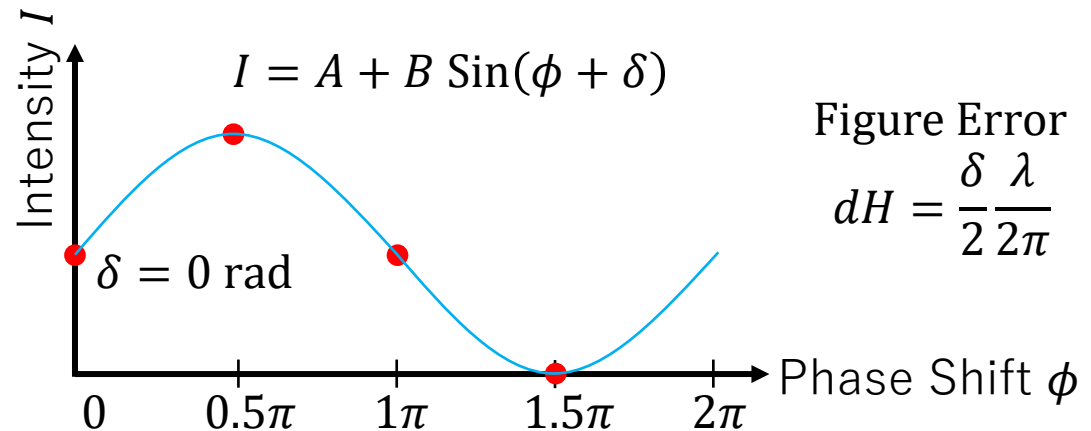
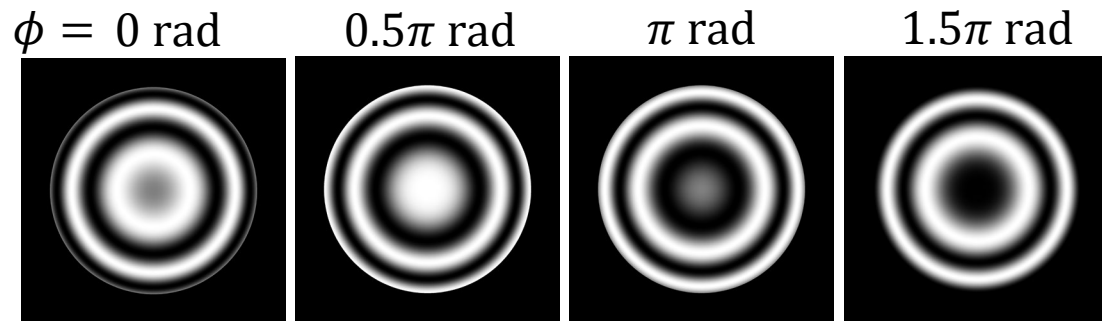


Why Does Vibration Corrupt the Measurements?

Temporal Phase Shift Method



- Many interferometers use “**Temporal Phase Shift**” method.
- Acquire a series of interferogram images while **translating the reference flat** (= Phase Shift ϕ) to accurate positions.
- The mirror figure error is determined, in wavelength units, by fitting the intensity variation at each point to the corresponding phase shift ϕ .



Why does vibration corrupt the measurements?

Temporal Phase Shift Method
under vibration condition

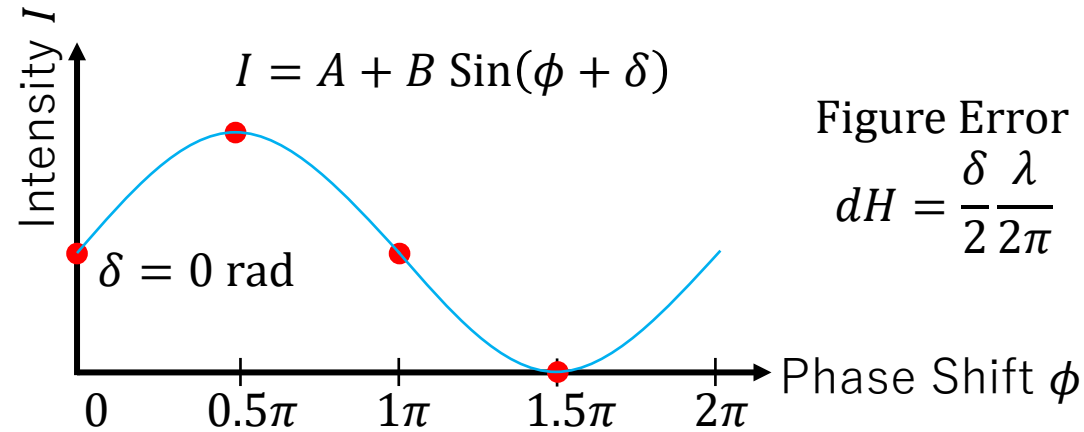
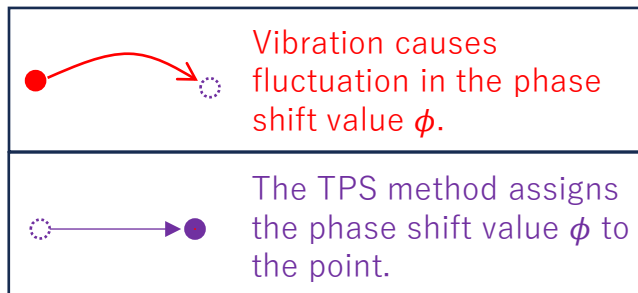
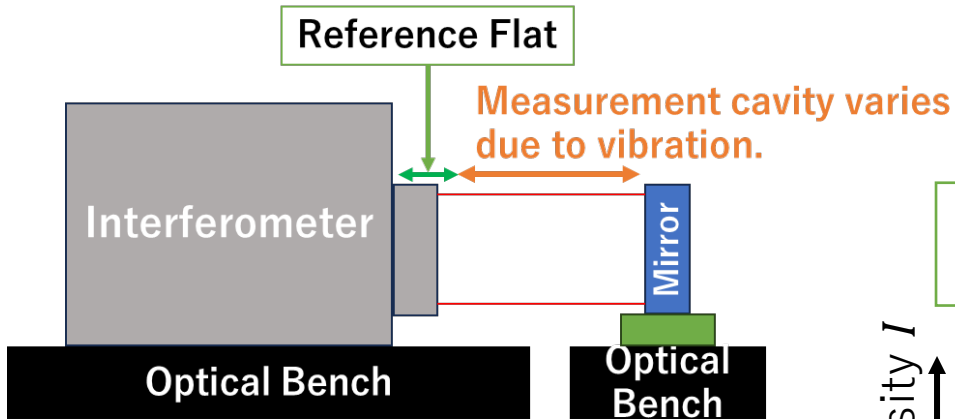
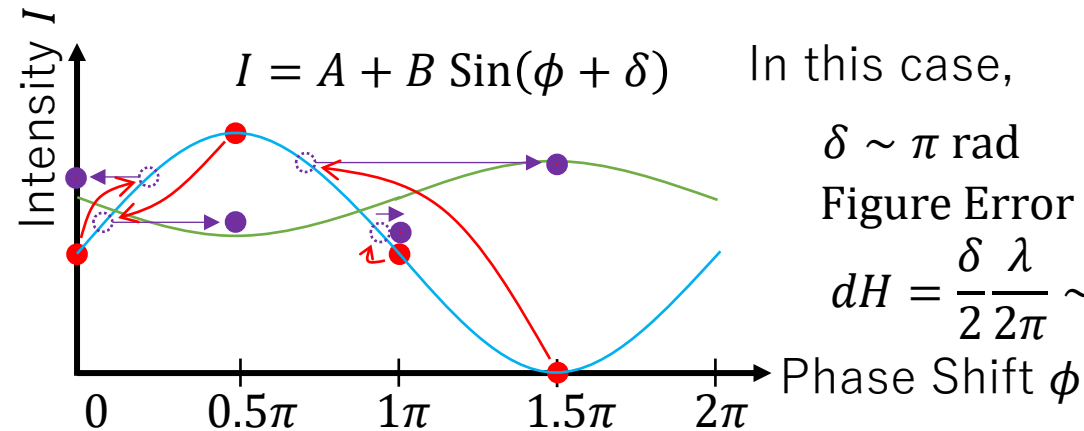


Figure Error

$$dH = \frac{\delta \lambda}{2 \cdot 2\pi}$$



The fit is no longer meaningful because each intensity does not correspond to the phase shift introduced by the reference flat movement.



In this case,

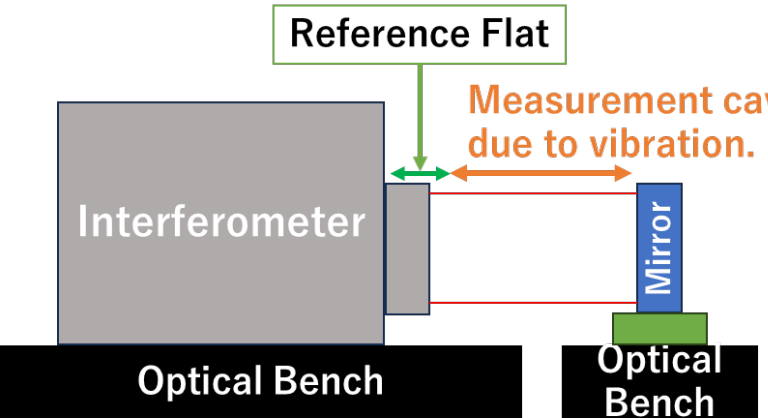
$$\delta \sim \pi \text{ rad}$$

Figure Error

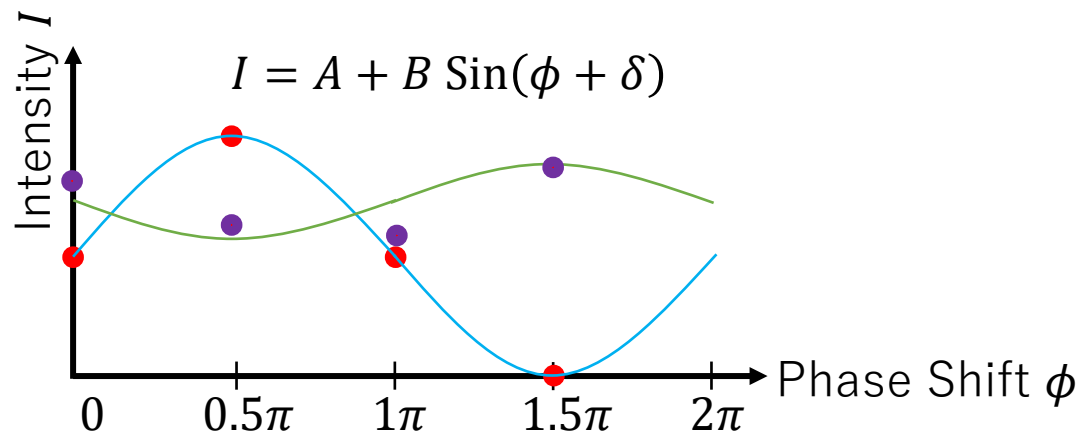
$$dH = \frac{\delta \lambda}{2 \cdot 2\pi} \sim 0.25\lambda = 158 \text{ nm}$$

How to recover the measurement?

Temporal Phase Shift Method under vibration condition

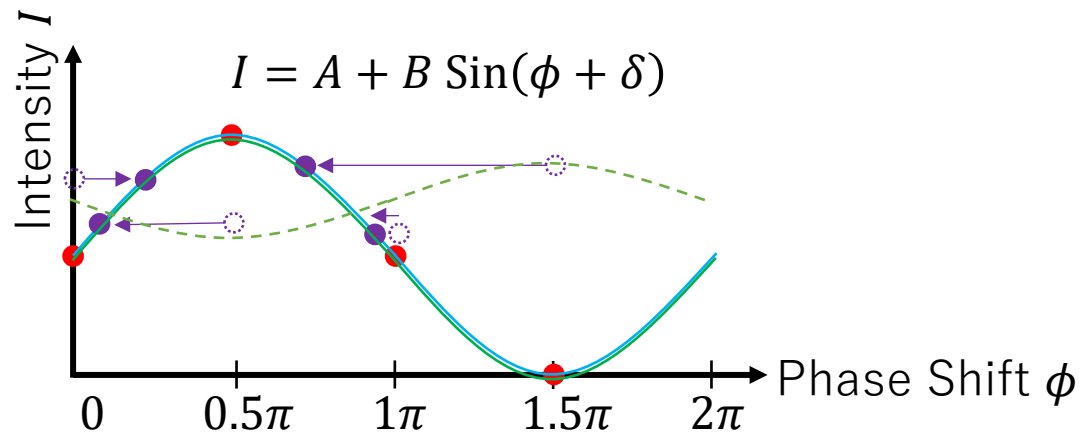


● ← ○ Estimate the true phase shift value ϕ including vibrational effect.



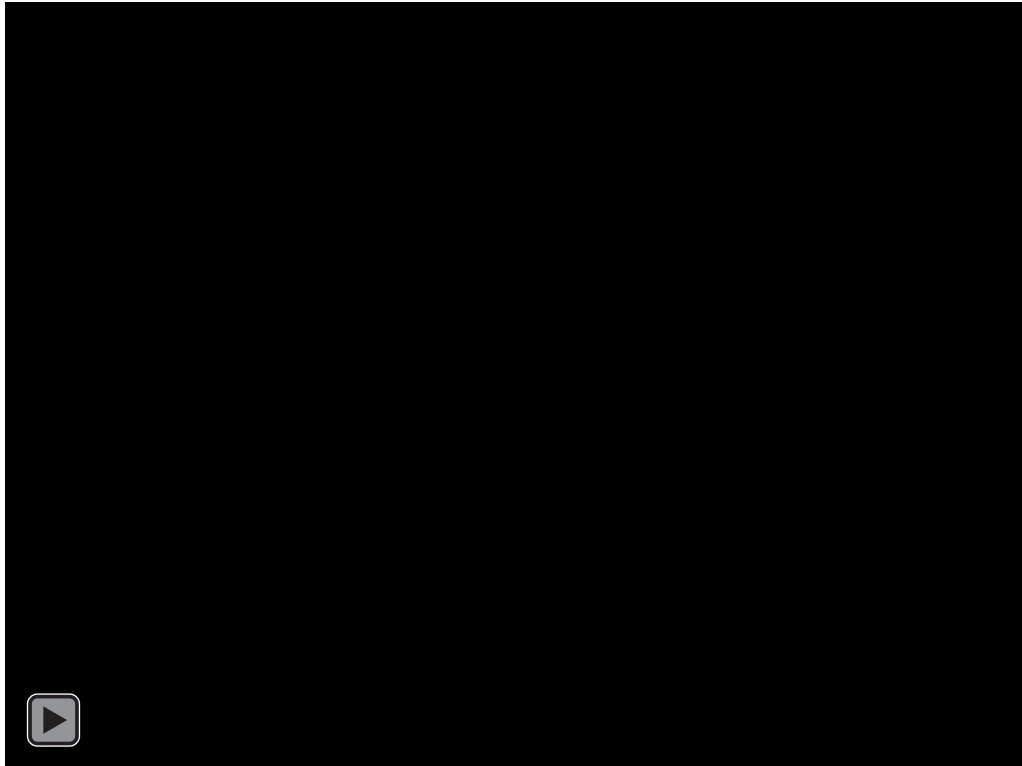
If we can estimate the phase shift for each interferogram image.

The true value of δ can be retrieved.



But how can we possibly do that?

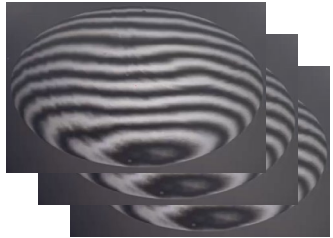
Use special information



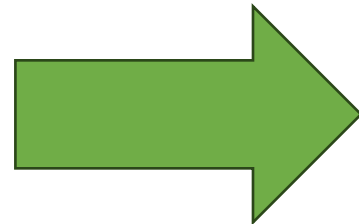
- A trained human observer can roughly infer the mirror figure simply by watching the vibrating interference fringes, even without explicit phase-shift information.
- Such observers implicitly use the *shape and relative movement* of the fringes.
- For instance, when the measurement cavity length changes due to vibration, *tilt-type* fringes move in parallel.
- A computer can also exploit this kind of structural information.

Random Phase Shift Method

Interferogram
Fringe Images
($N = 132$ frames)

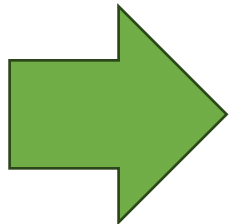


Discrete
Fourier
Transformation

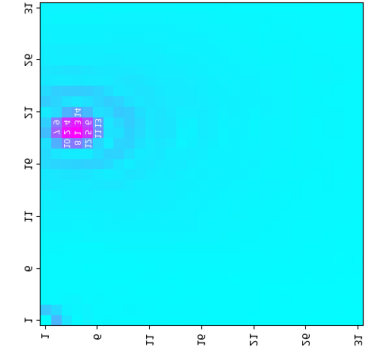


Complex
Arrays

Abs
Average



$$\frac{1}{N} \sum_{i=1}^N \left| \text{Complex Arrays} \right| =$$



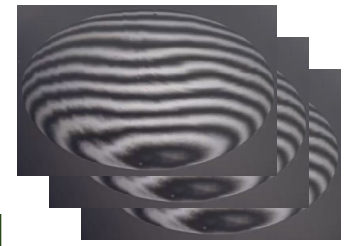
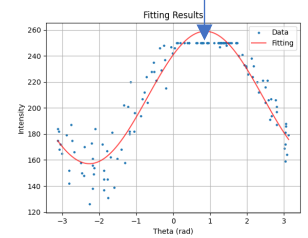
Determine
spatial frequency
to focus on

Complex
Arrays

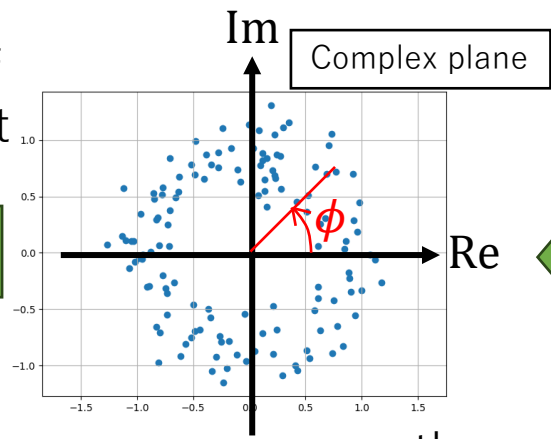
Sum

the complex values
for each array and more ...

Mistake in the measurement.
Laser intensity was too high, causing camera saturation.

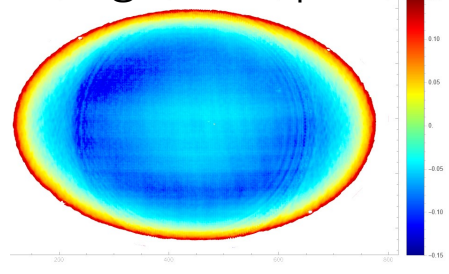


Calculate
Angle ϕ
of each point



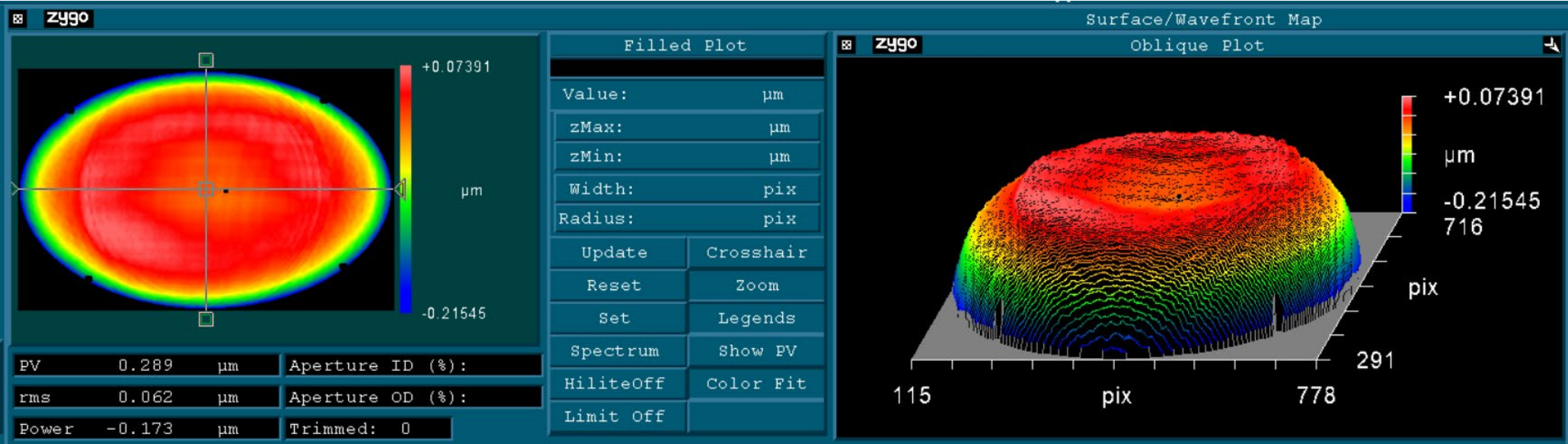
Estimated Phase Shift
 $\phi = \phi_1, \phi_2, \dots, \phi_N$

Figure Map

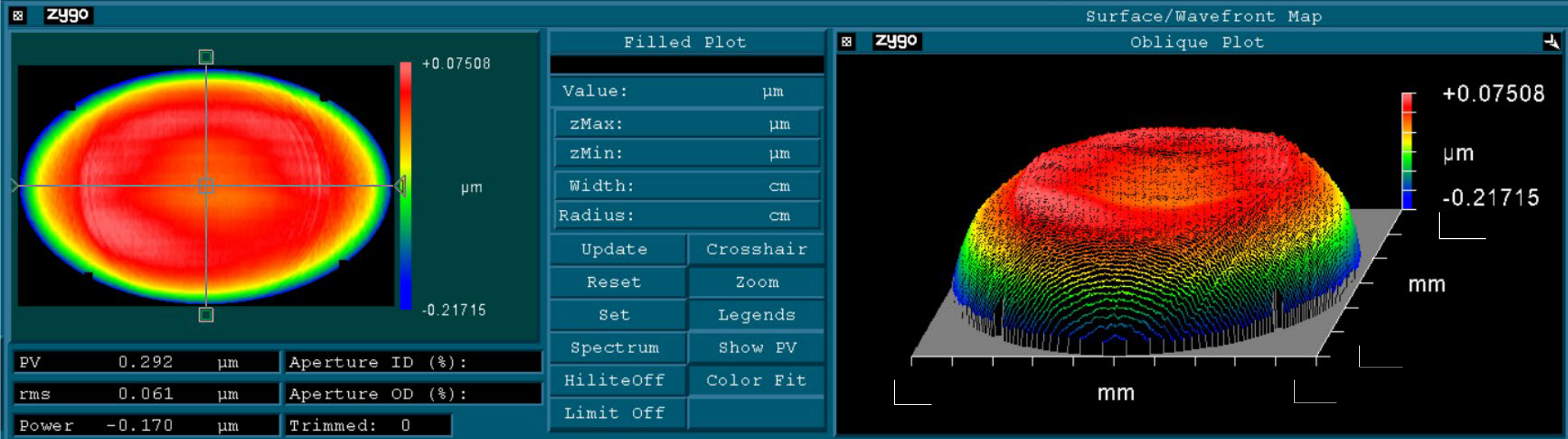


Measurement Accuracy

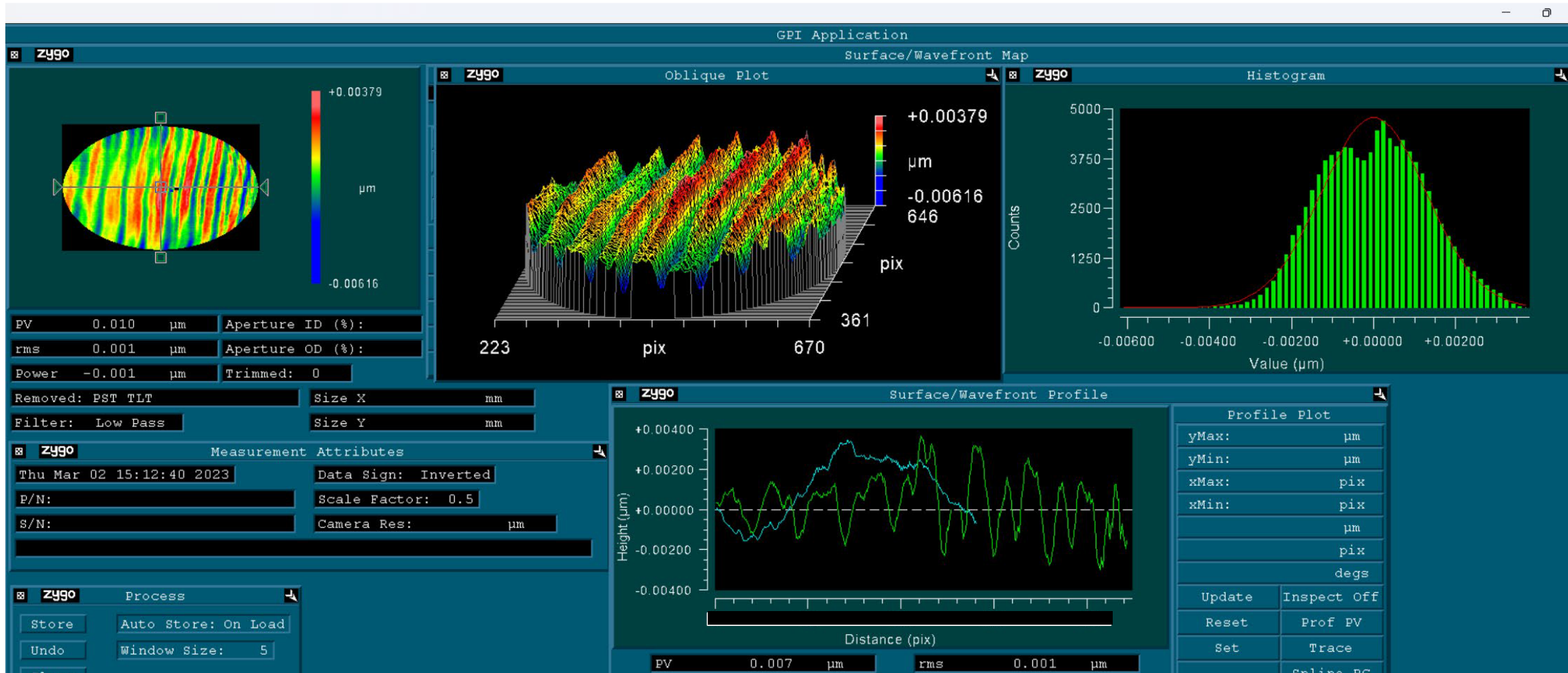
RPS



Zygo

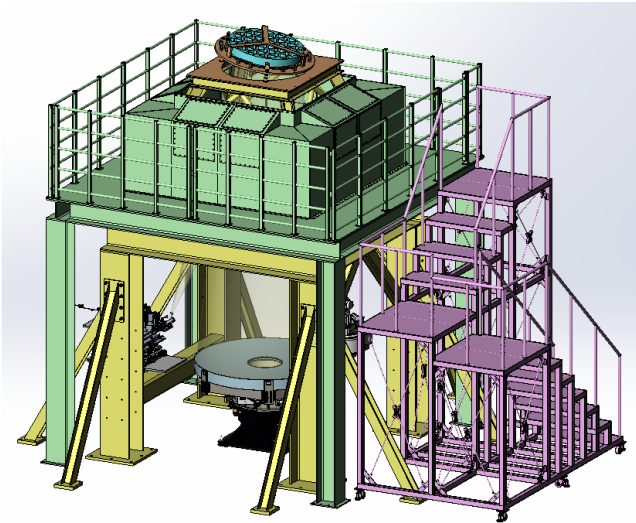
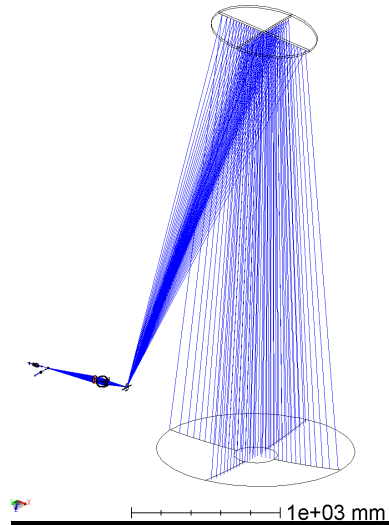


Measurement Accuracy

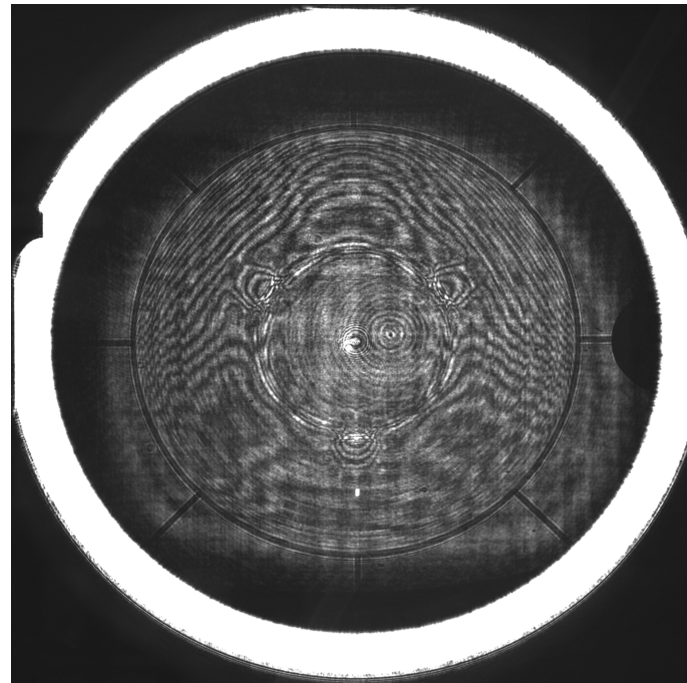


Measurement discrepancy ≤ 10 nm

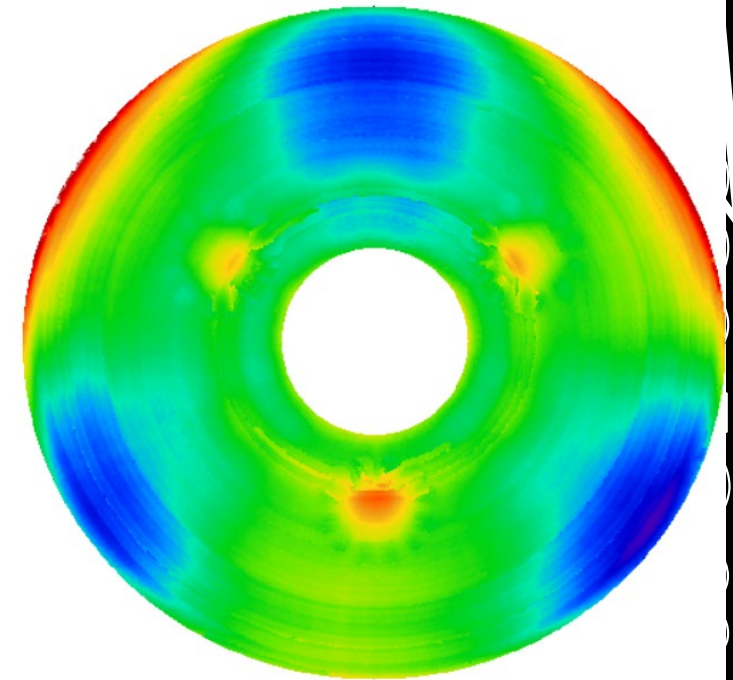
Field Test Large Aperture Aspheric Mirror ϕ 1.3 m



Interferogram Fringe Image



RPS Figure Reconstruction



RPS can reconstruct the mirror figure even without known phase-shift information.



Summary & Application

Random Phase Shift Method

Advantages (PROS):

- Enables accurate figure measurement even when temporal phase-shifting fails under vibration.
- No piezo phase shifter required.
- No time synchronization needed between phase shifter and detector.
- Can utilize vibration itself as a non-ideal phase shifter.

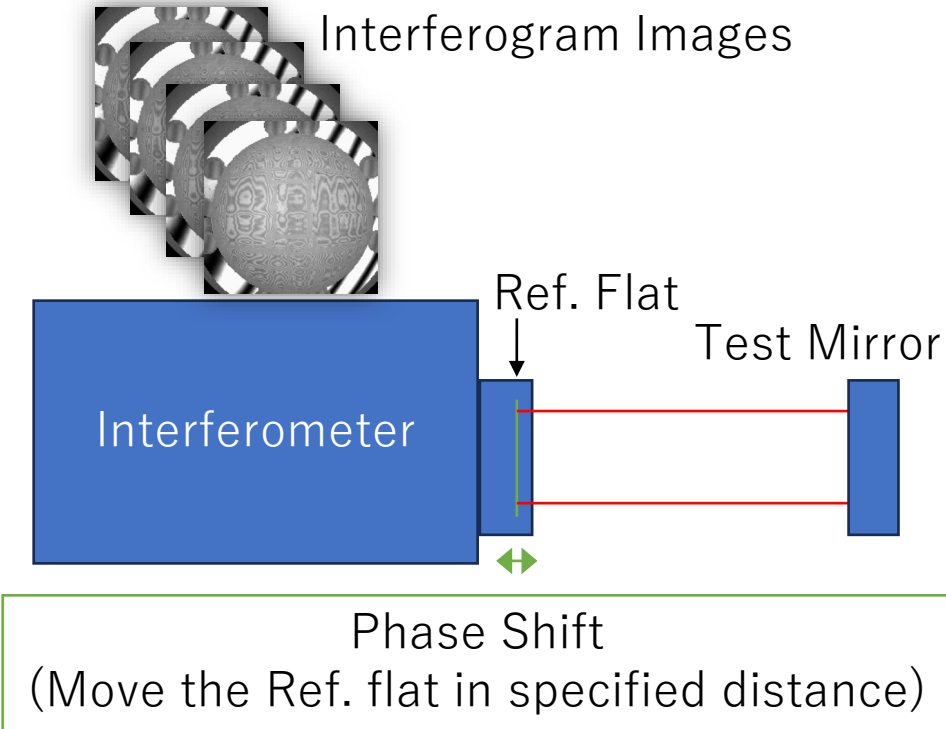
Limitations (CONS):

- If each interferogram has a different tilt, phase-shift estimation becomes difficult.
- Consequently, reconstruction errors may appear in the RPS figure.

Appendix

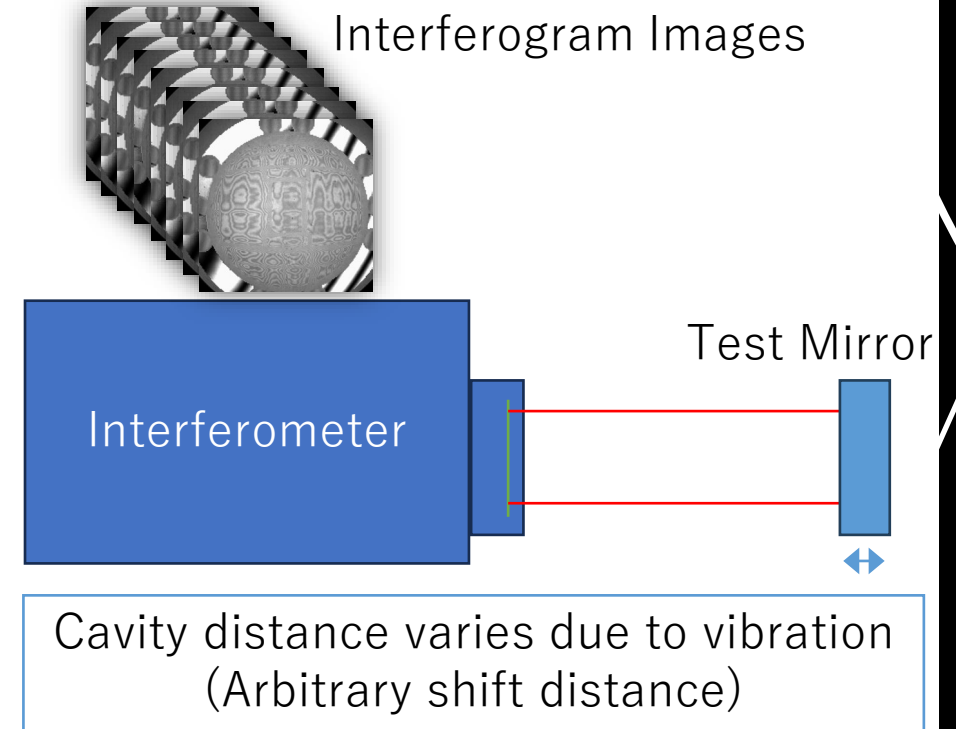
Comparison of the two methods

Temporal Phase Shift



- “Interferogram images + phase shift value” determine the mirror figure.
- Figure measurements are very difficult if vibration affects phase shift.
- Very accurate figure measurements if phase shift is accurate.

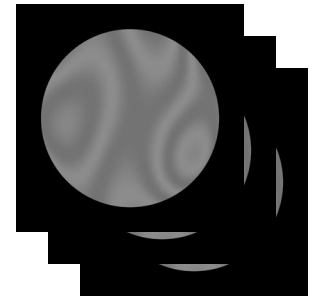
Random Phase Shift



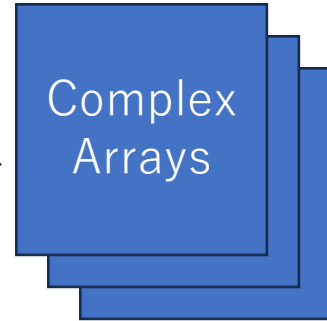
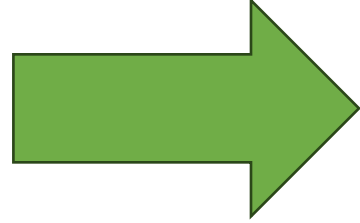
- “Interferogram images” determine the mirror figure. No phase shift value is required.
- hundreds of interferogram images are required.
- Exploit vibration as non-accurate phase shifter.
- If the tilt mode in the vibration is large ($> 2\lambda$ P.V. WFE), RPS gets difficult.

Simulation Case

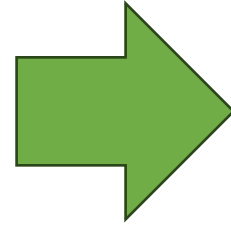
Interferogram
Fringe Images
($N = 200$ frames)



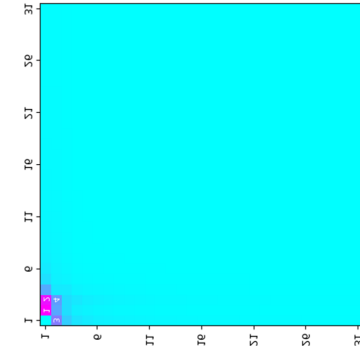
Discrete
Fourier
Transformation



Abs
Average



$$\frac{1}{N} \sum_{i=1}^N \left| \text{Complex Arrays} \right| =$$



Fitting residuals are very small.
→ Accurate phase determination

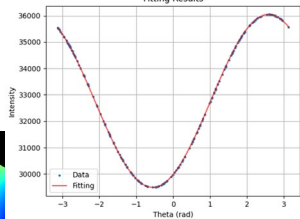
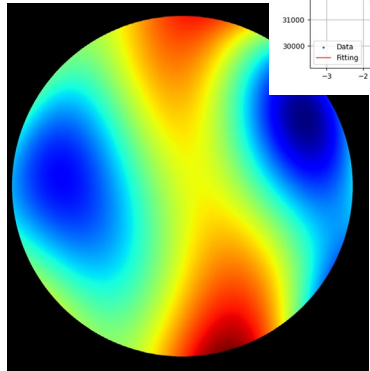
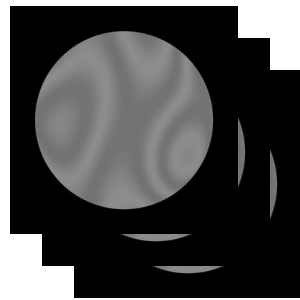


Figure Map



RPS Error < 0.01 nm

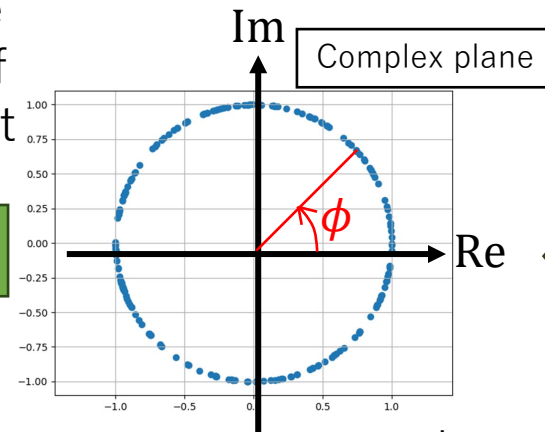
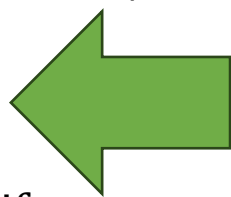


&

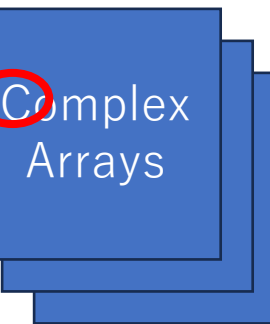
Estimated Phase Shift

$$\phi = \phi_1, \phi_2, \dots, \phi_N$$

Calculate
Angle ϕ
of
each point



Determine
spatial frequency
to focus on



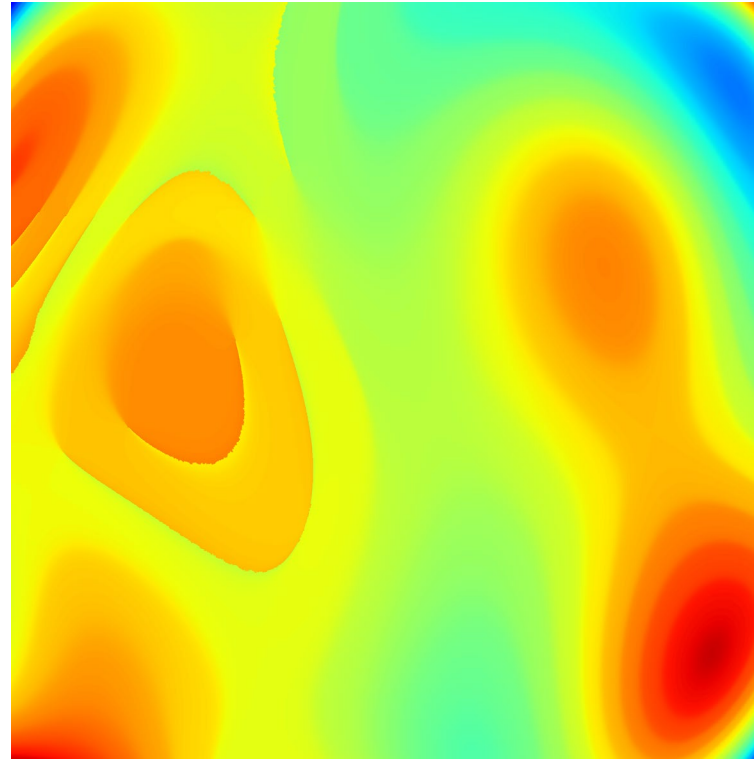
Sum

the complex values
for each array and more ...

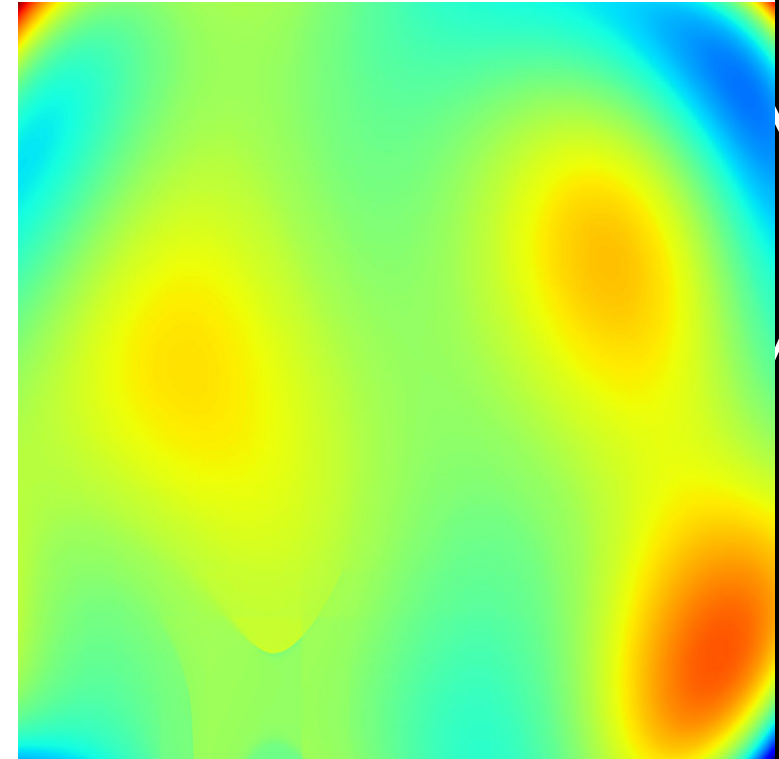
If tilt mode exists

Interferogram Images
Tilt = 1.6λ (PV)

No Sectioning



5x5 Sectioning



In the presence of moderate tilt vibration, the standard RPS method may perform poorly, potentially introducing large piston gaps or figure errors (see "No Sectioning" figure).

The *Sectioned RPS method*—which divides the interferogram into multiple overlapping sub-apertures and applies RPS locally—can significantly reduce such errors. The stitched figure map (see "5x5 Sectioning" figure) shows improved accuracy.