

可視赤外線観測装置技術ワークショップ2025  
2025/11/10 - 2025/11/11

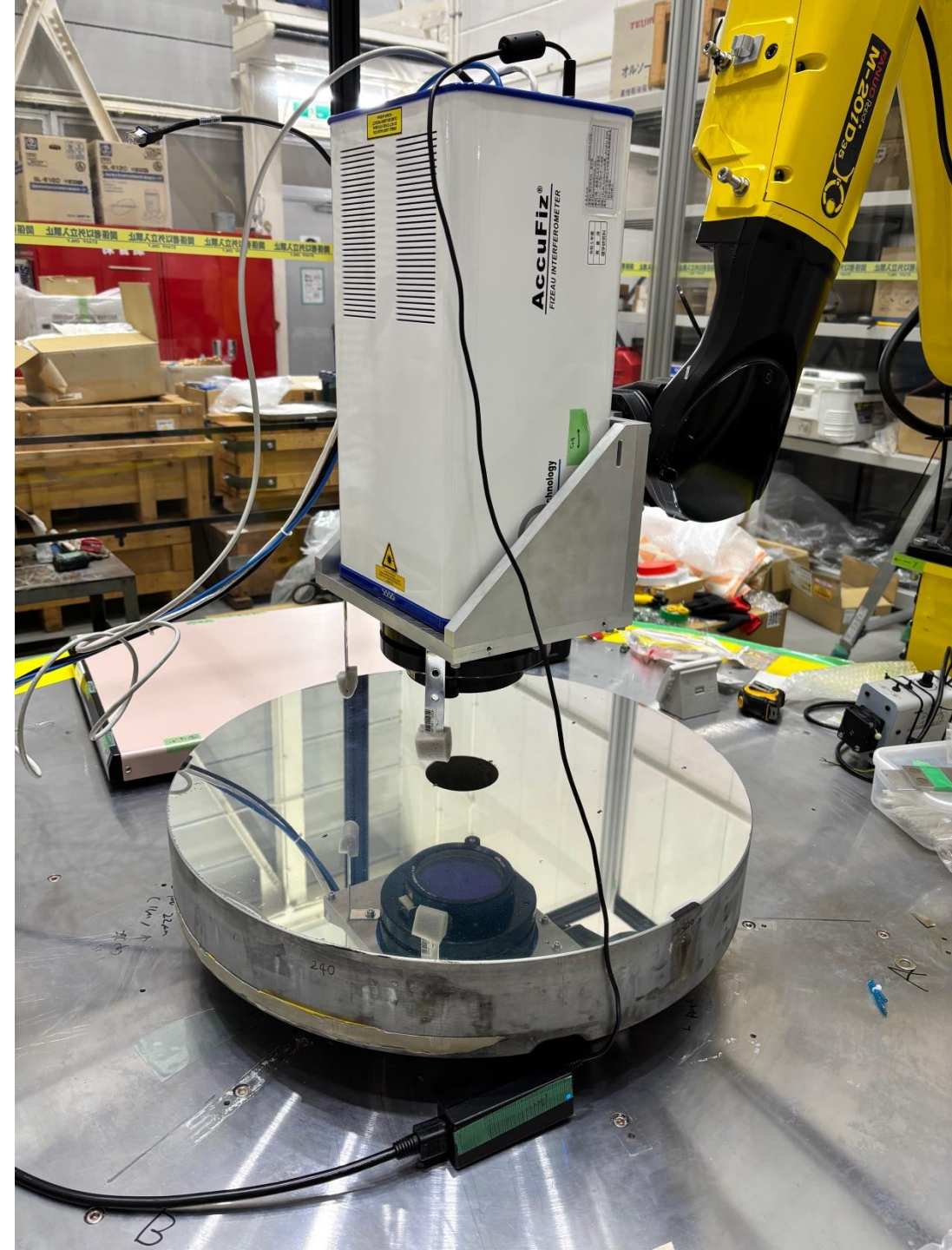
# Sub-Aperture Interferometry and Data-stitching based on elasticity

Astrophysics, Graduate School of Science, Kyoto University

**Chihiro Fukunaga**<sup>1</sup>

Mikio Kurita,<sup>1</sup> Ryo Tsukui<sup>2</sup>

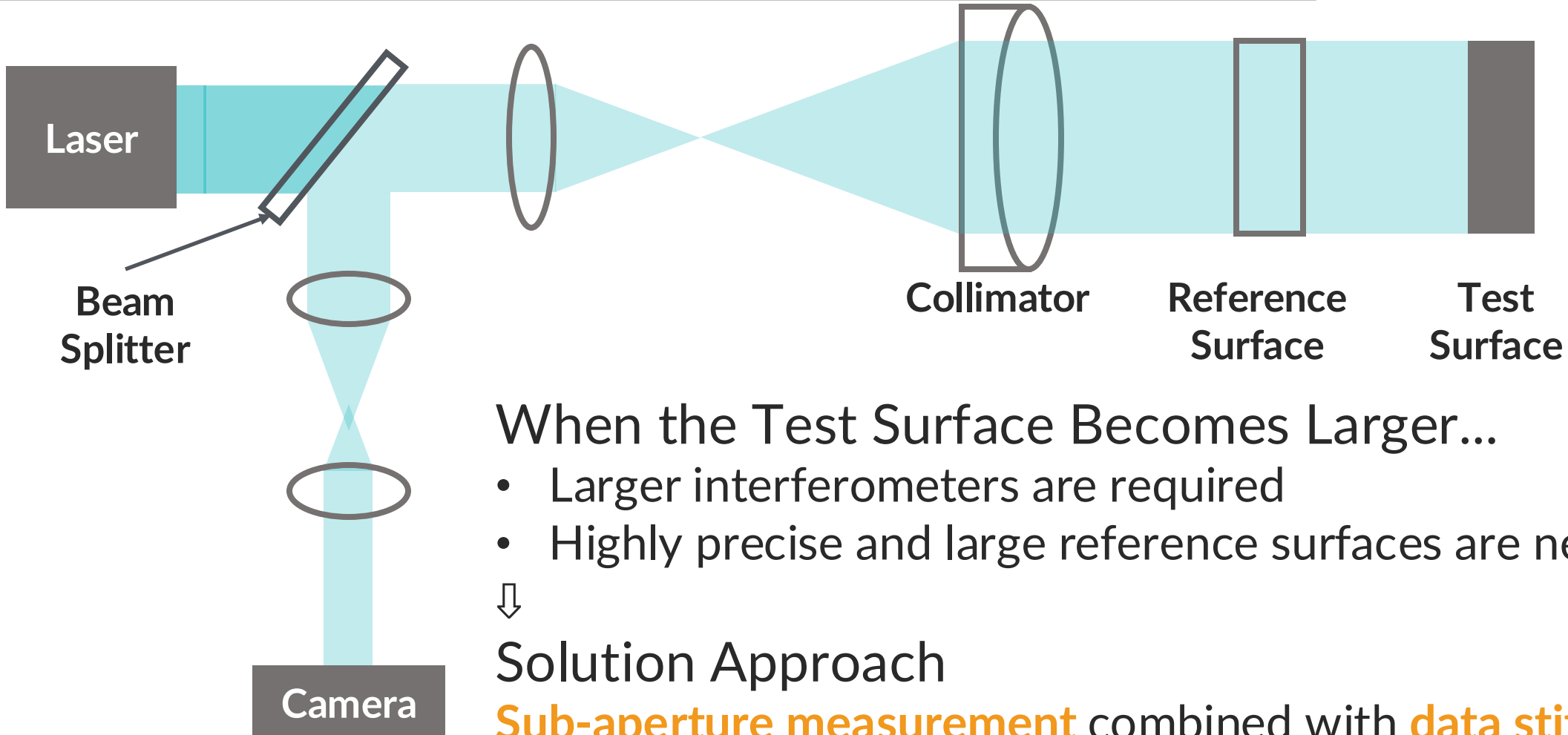
(1) Kyoto University, (2)LogistLab



# Challenges in Large Mirror Measurement

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## Interferometer Layout for Flat Surface Measurement



When the Test Surface Becomes Larger...

- Larger interferometers are required
- Highly precise and large reference surfaces are needed



Solution Approach

**Sub-aperture measurement** combined with **data stitching**

→ Enables **a flexible and widely applicable** measurement method



SAI setup

## SAI = robotic arm + interferometry

- Interferometer: AccuFiz E100 (4D Technology)
- Robotic Arm: M-20iD/35 (FANUC)

## Vibration Environment

- Use of carrier fringe mode of the interferometer
  - Verification of vibration condition
- Repeatability test (p.5)

## Stitching of Sub-Aperture Data

→Elastic Data Stitching (p.7)

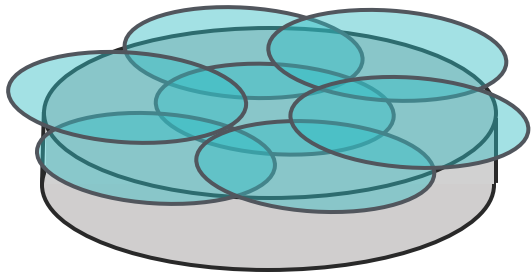


image of SA

# Robotic-Arm-Based Interferometric Measurement

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## Repeatability test of interferometric measurement

Measurement of a  $\Phi 100$  mm flat mirror (P-V  $\lambda/20$ ) ; repeatability and results compared

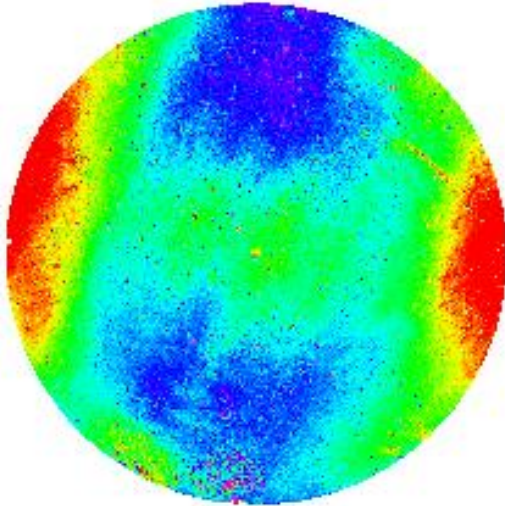
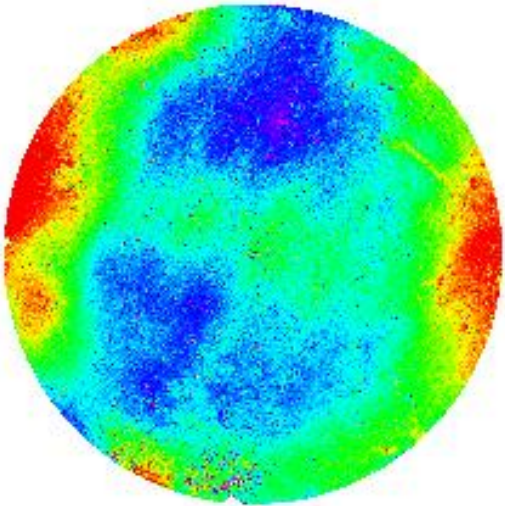
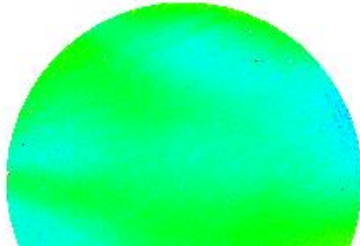
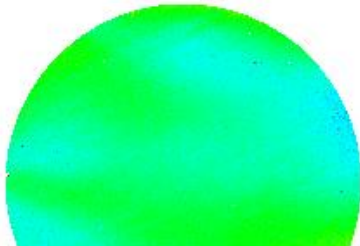
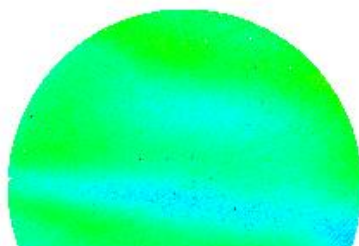
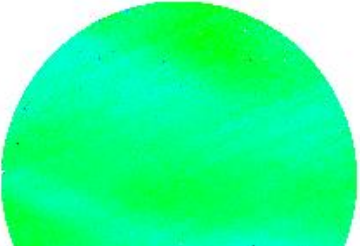
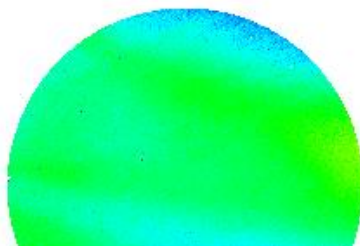


V.S.



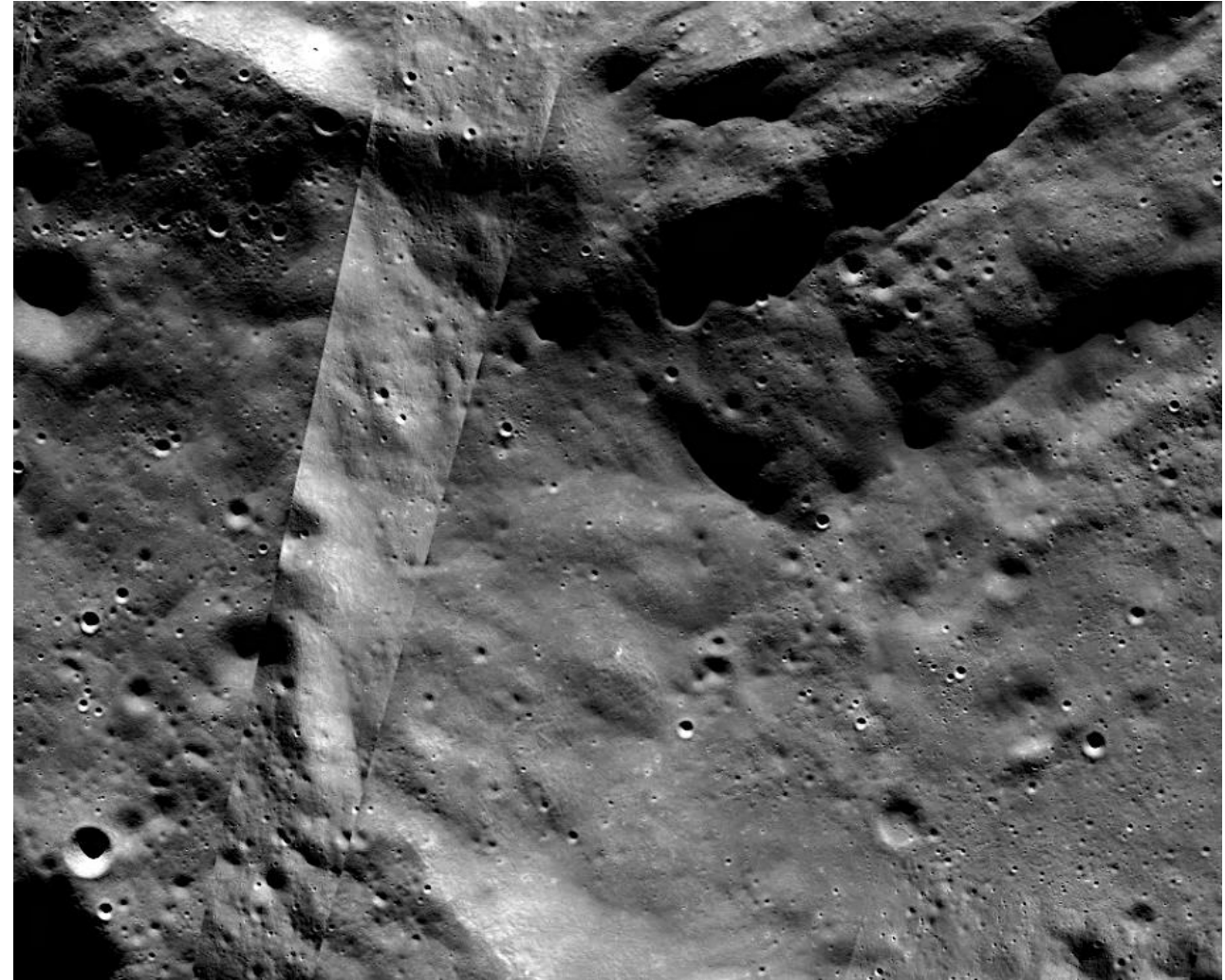
## Repeatability test of interferometric measurement

Comparison of result in surface figure(-10 ~ 10 nm) ※1 shot = average of 10 measurement (exposure time 2.31ms)

Vibration-isolated 5-shot average	on the robotic arm			
	5-shot average	Difference from the average of five measurements		
				
		PVr 10.99 nm RMS 1.35 nm	PVr 11.0 nm RMS 1.35 nm	PVr 7.12 nm RMS 1.20 nm
PVr 28.3 nm RMS 5.07 nm Repeatability 2.08 nm	PVr 25.5 nm RMS 4.56 nm Repeatability 1.25 nm			
		PVr 5.56 nm RMS 0.868 nm	PVr 10.1 nm RMS 1.47 nm	

✓ Repeatability comparable to that in the stable environment

How can we achieve stitching without **discontinuities**?



the surface of the Moon by LRO[1]

# Elastic Data Stitching

[2]Otsubo (1994)

[3]Kurita & Ishii (2022)

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Ex : 1-D data stitching

Conventional (LSM)<sup>[2]</sup>

Elastic Data Stitching<sup>[3]</sup>

Data Modeling

Rigid body

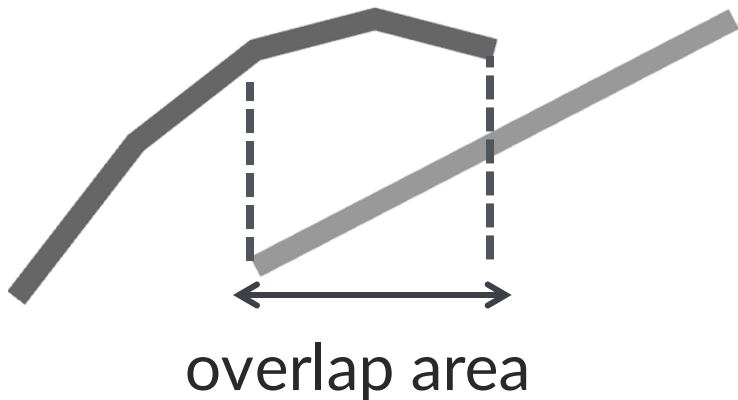
Elastic body

Stitching Method

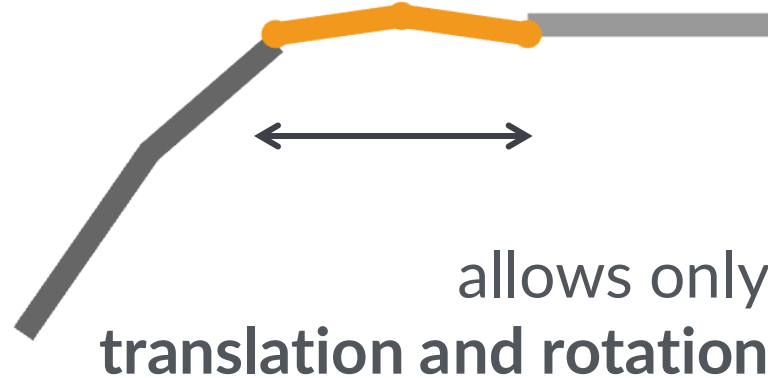
Least-squares method

minimize Elastic energy

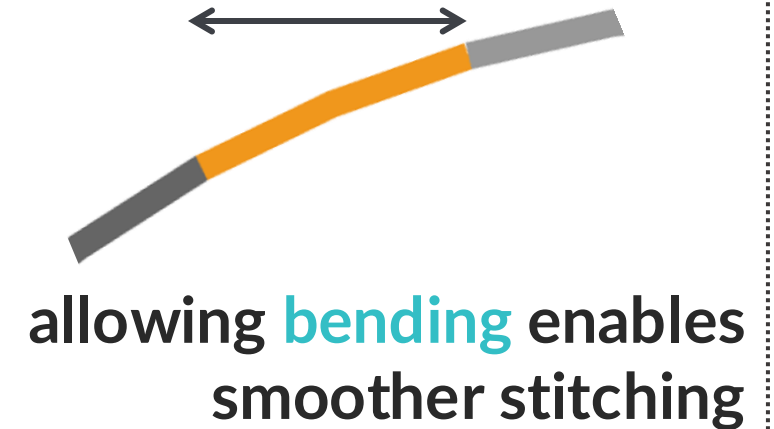
In Sub-Aperture measurements,  
measurement errors occur in  
overlapping area



step discontinuous  
at boundaries

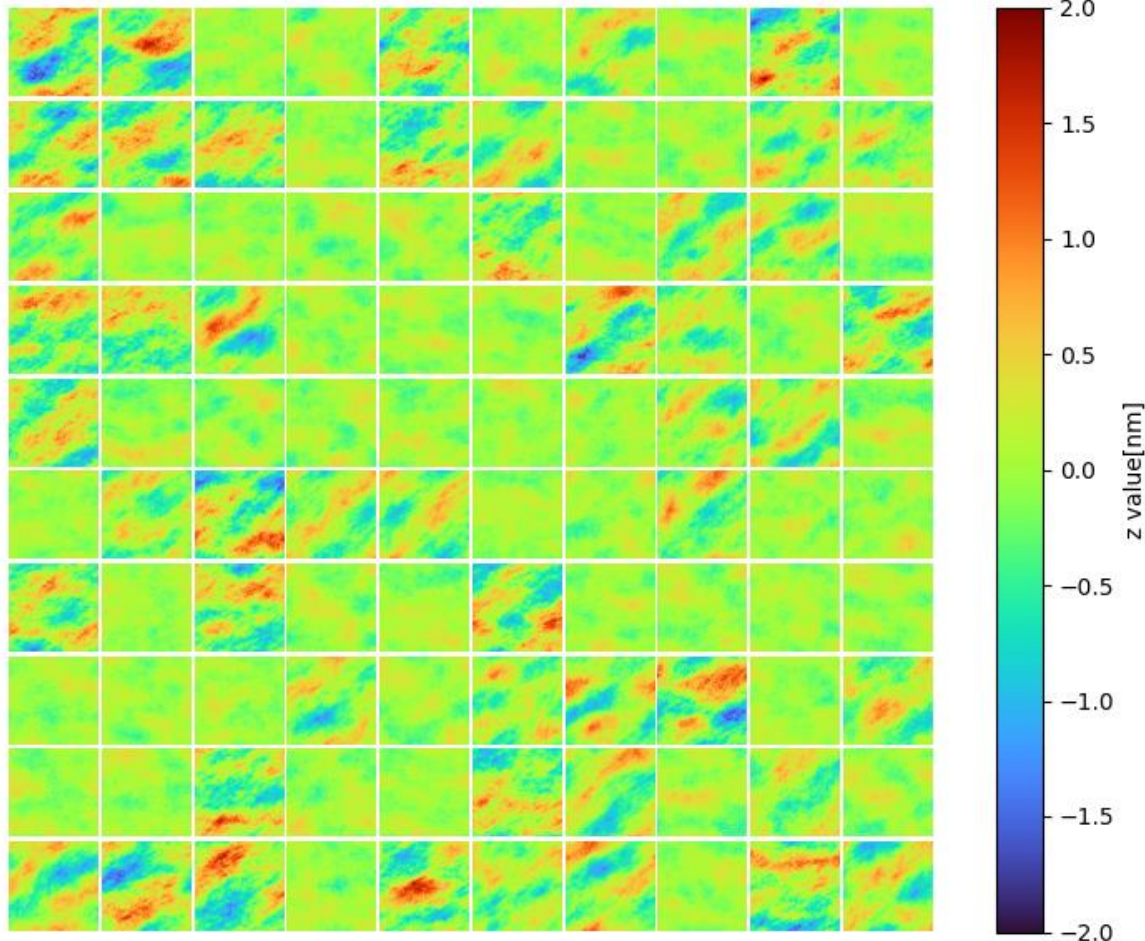


continuous boundaries



⇒ Extend Elastic Data Stitching to 2-D and apply to interferometry data

Comparison Stitching result: Our method vs. Conventional method(LSM)



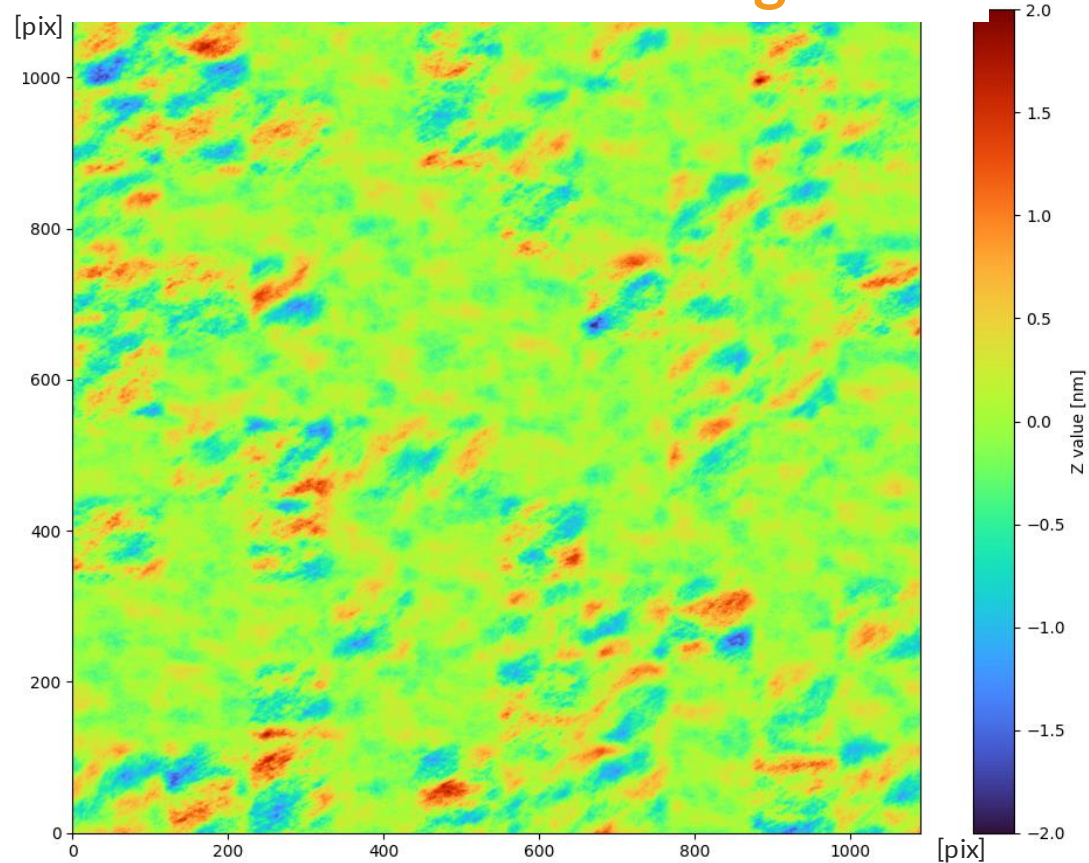
Data Used for Stitching

## Comparison Method

1. Get actual measurement error from the interferometric measurement
2. Generate 100 simulated datasets (120 pix  $\times$  120 pix ) based on the error data
3. Stitch with an overlap width of 10 pix

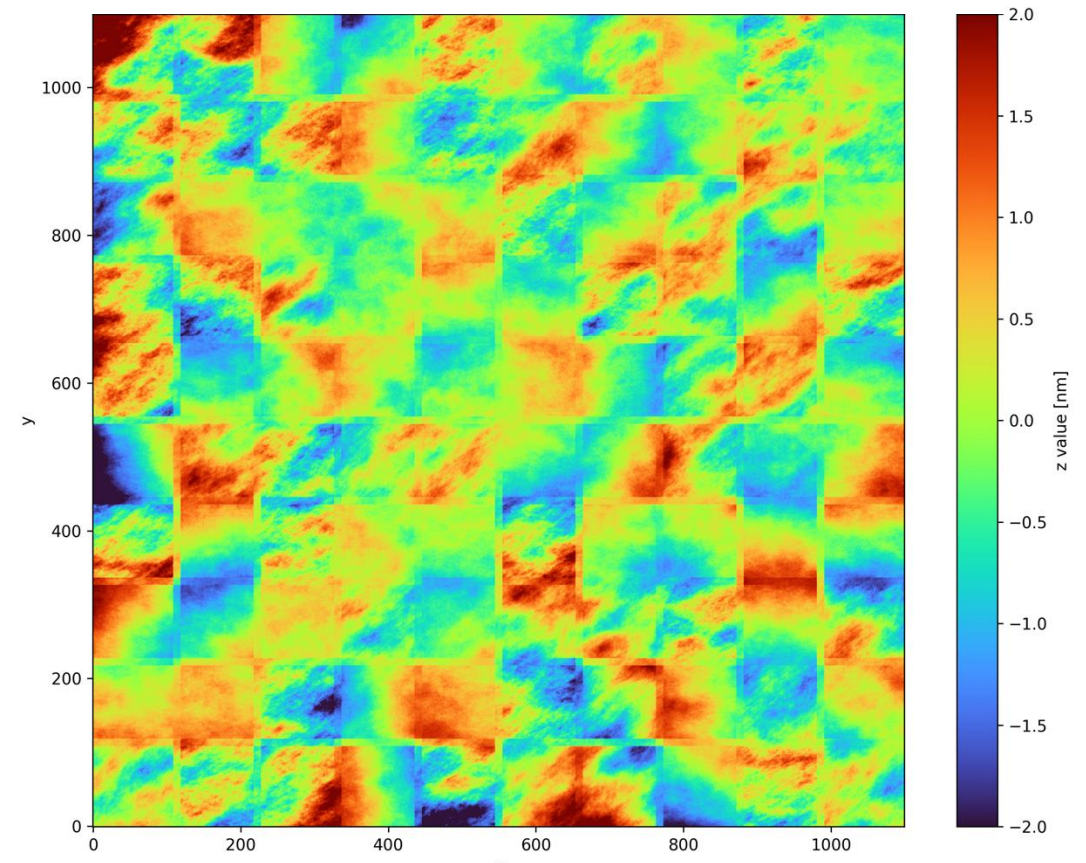
Comparison Stitching result: Our method vs. Conventional method(LSM)

## Elastic Data Stitching



Stitching time 420 sec, PV 4.24 nm, RMS 0.340 nm

## LSM<sup>[2]</sup>

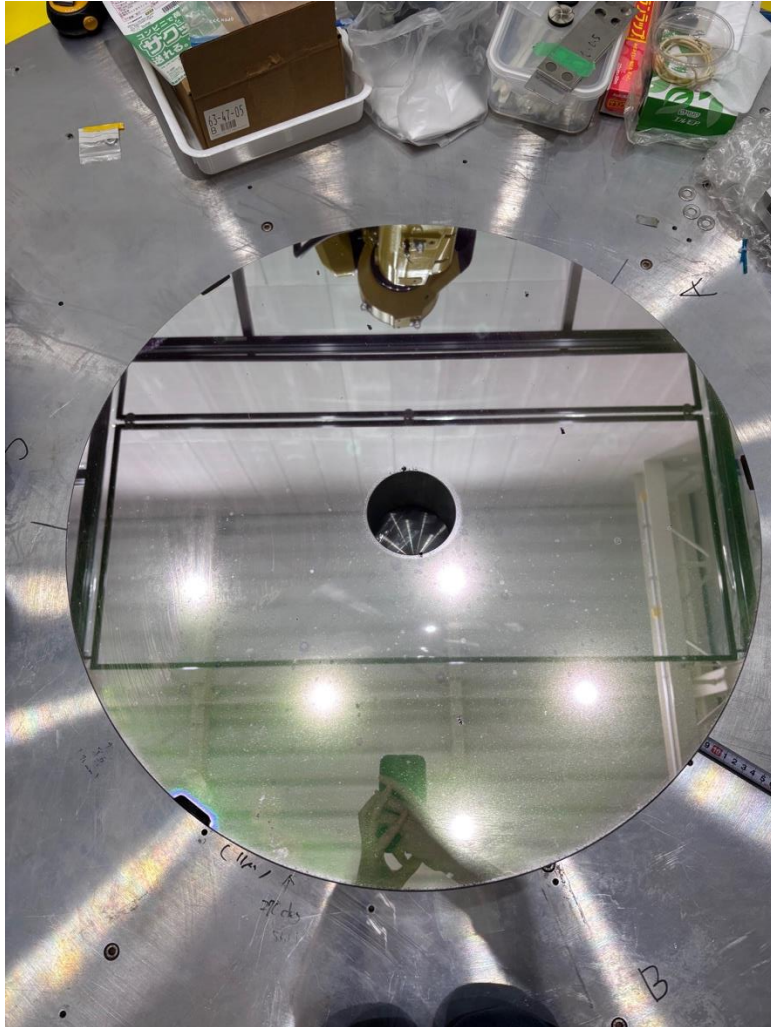


Stitching time 12 sec, PV 6.13 nm, RMS 0.69 nm

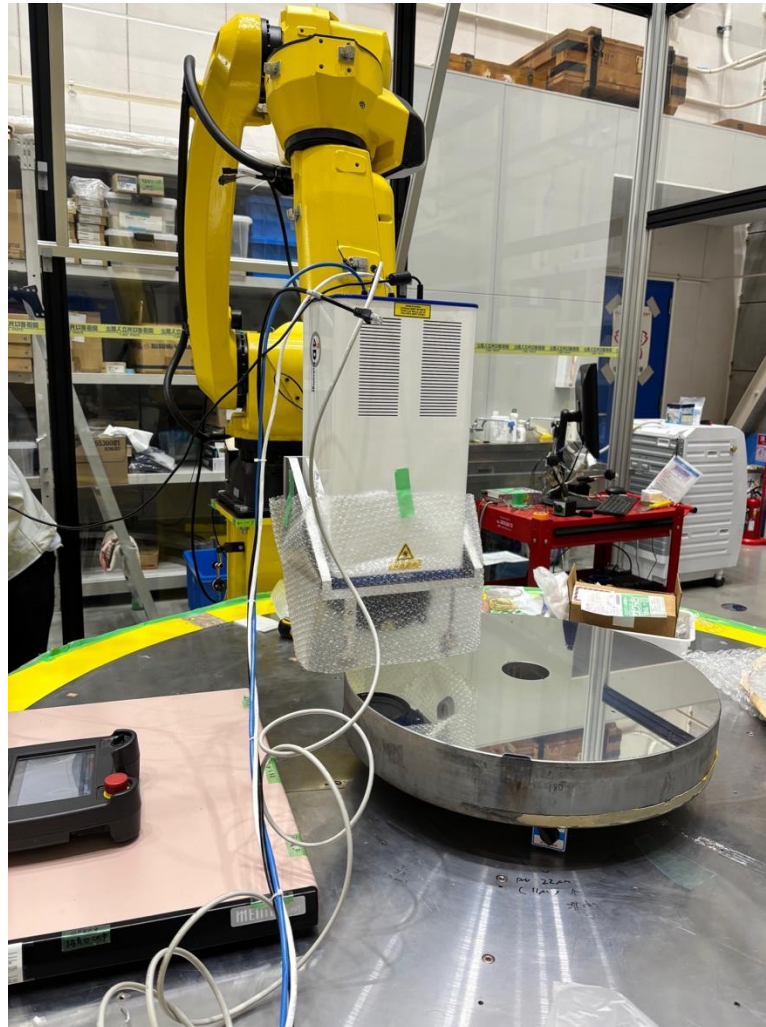
**Elastic data stitching achieves continuous boundaries** (Future work: reducing computation time)

# SAI experiment and current situation

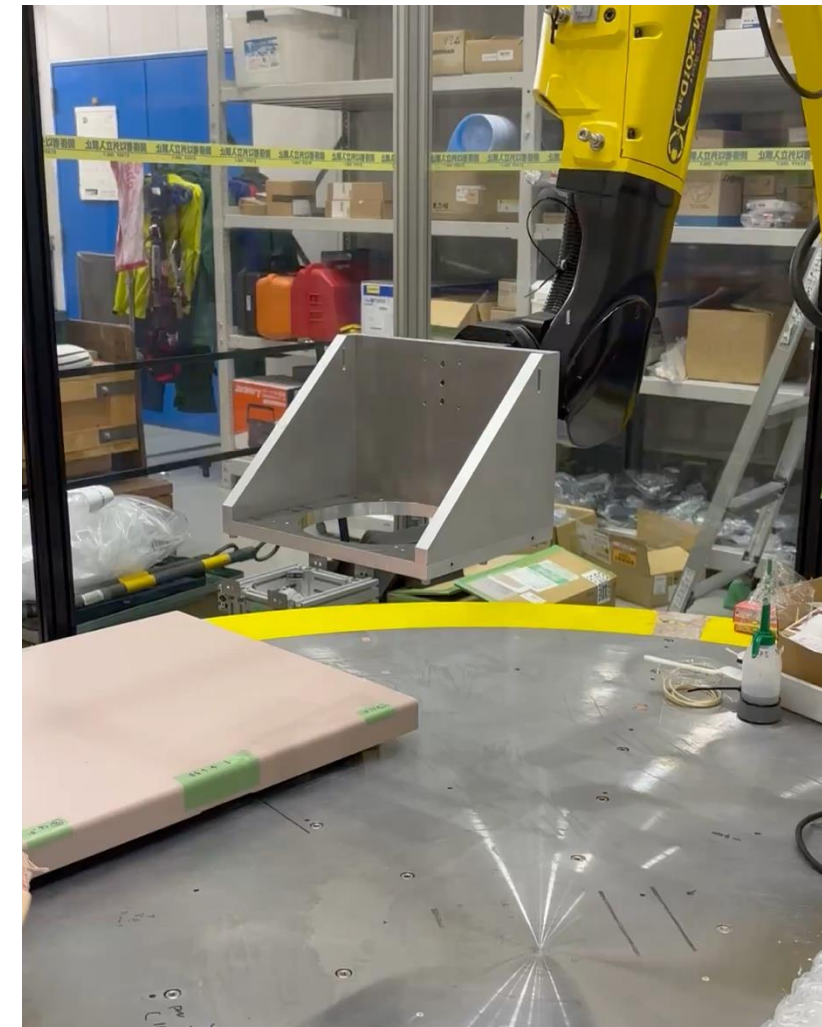
Goal: Measure a large mirror using SAI and complete the stitching



Test mirror( $\Phi 630$ , flat)



SAI setup



Test of the robotic arm

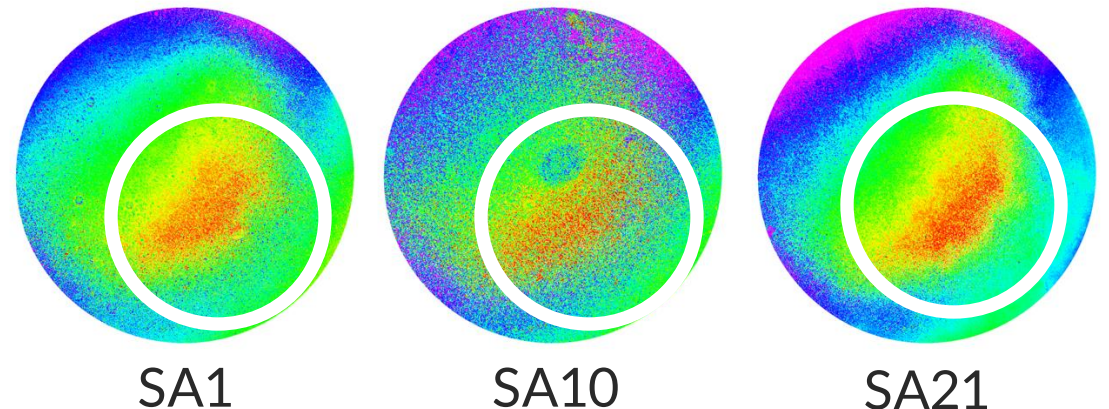
## Current Situation

Common structure was observed in the result of SAI measurement of the mirror

Possible causes

1. **True shape of the  $\Phi 630$  mirror**  
→ considered unlikely based on comparison with large-aperture interferometer result
2. **retrace error**  
→ the structure remained even after subtraction of the error
3. **Reflectivity mismatch between the reference flat and the  $\Phi 630$  mirror**  
→ see next page

Representative SAI result (3 examples)  $\Rightarrow$   
(Piston/Tip/Tilt was subtracted)  
○ : Observed common structure

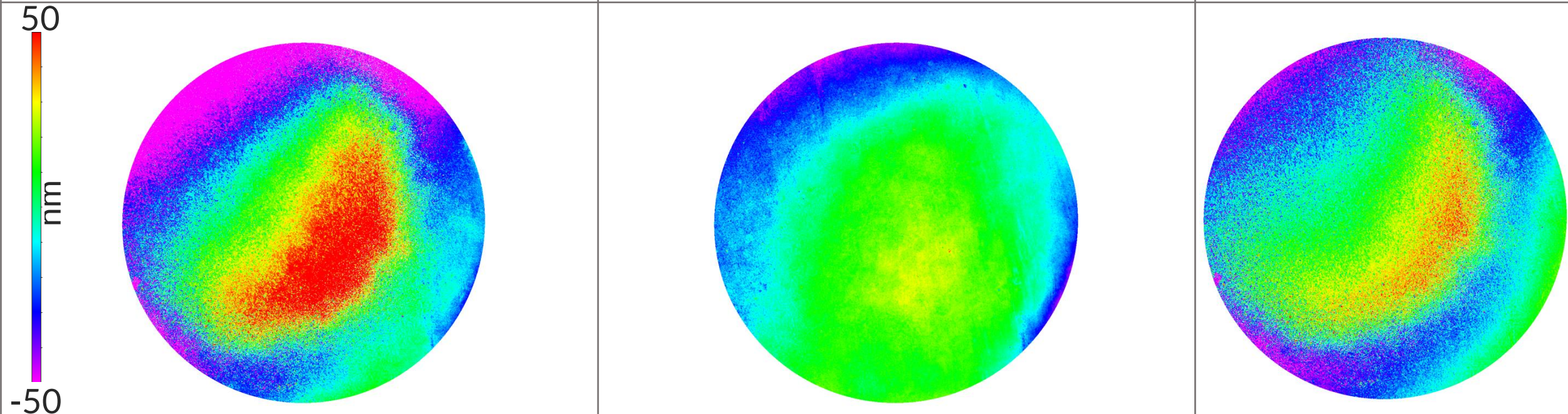


## Current Situation: Results with 2 different reference flats

**A. Measure result with reference flat for **uncoated mirror****  
surface accuracy P-V 11 nm, RMS 2 nm

**B. Measure result with reference flat for coated mirror**  
surface accuracy P-V~30 nm, RMS~5 nm

**A-B**  
P-V 330 nm, **RMS 23.5 nm**



The RMS difference of A and B: **Larger than the RMS difference of the reference flat (~5.39 nm)**  
Because **coated surface has higher reflectivity**, the increased intensity of the test beam may have caused **multiple reflections** in interferometer, leading to fringe distortion.

<b>Goal</b>	<b>Development More flexible measurement method for large mirror: SAI based on robotic arm + Elastic data stitching</b>
<b>Current Situation</b>	<ul style="list-style-type: none"><li><input checked="" type="checkbox"/> <b>Evaluation of reproductivity</b> by measuring <math>\Phi 100</math> flat mirror → Achieved repeatability equivalent to the stable environment</li><li><input checked="" type="checkbox"/> <b>Simulation of Elastic data stitching</b> → Successfully achieved seamless stitching without discontinuous</li><li><input checked="" type="checkbox"/> <b>SAI experiment</b> → Possible fringe distortion due to high reflectivity of the coating</li></ul>
<b>Next Step</b>	<ol style="list-style-type: none"><li>1. Conduct SAI using a mirror <b>with lower reflectivity (uncoated)</b></li><li>2. Stitching the data</li><li>3. <b>Compare and evaluate accuracy against full-aperture measurement</b></li></ol>

[1] NASA, GSFC, Arizona State University. "Northern Polar Mosaic". LROC.  
<https://www.lroc.asu.edu/posts/gigapan>,

[2] Otsubo, M., Okada, K., & Tsujiuchi, J. (1994).  
Measurement of large plane surface shapes by connecting small-aperture interferograms.  
Optical Engineering, 33(2), 608-613.

[3] Kurita, M. & Ishii, A. (2022).  
Data-stitching algorithm based on elasticity  
Appl. Opt. 61, 8333-8340

[4] Somatsu, M. (2024) Master thesis

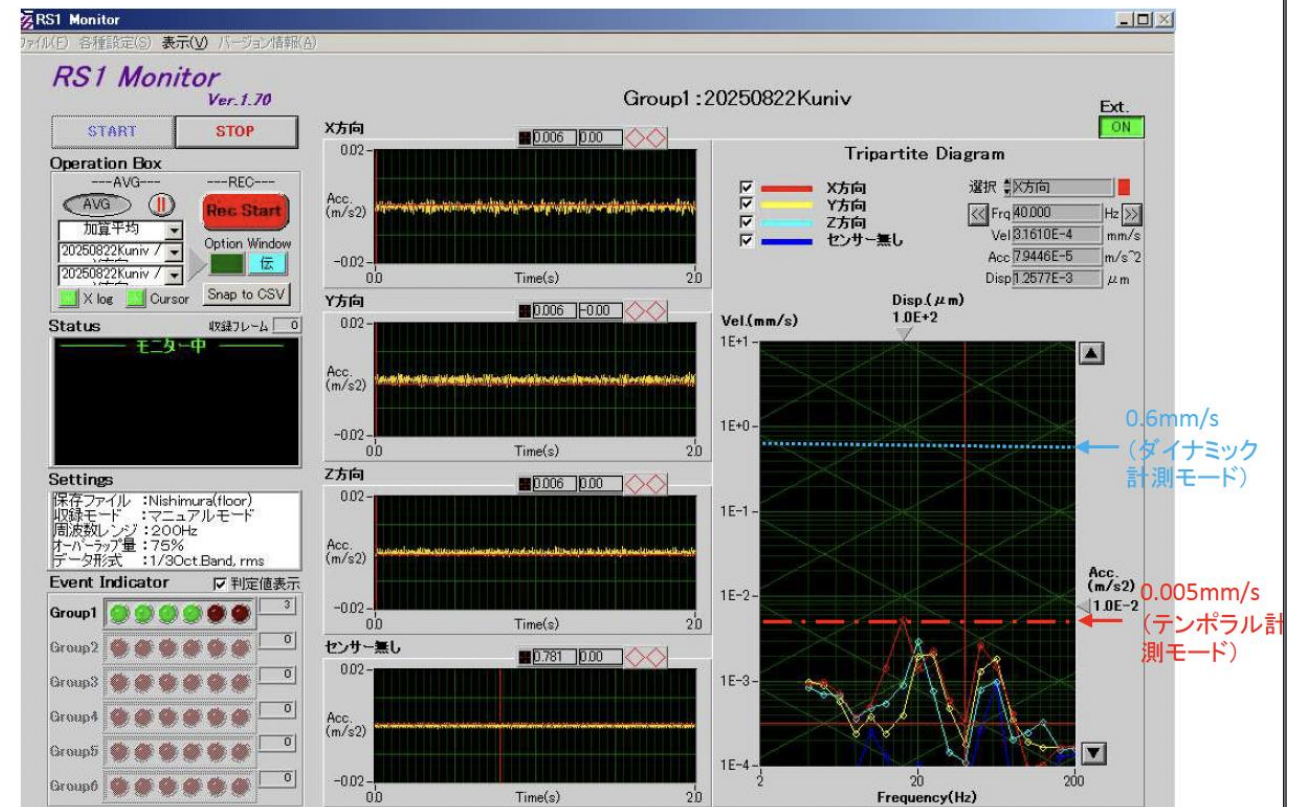
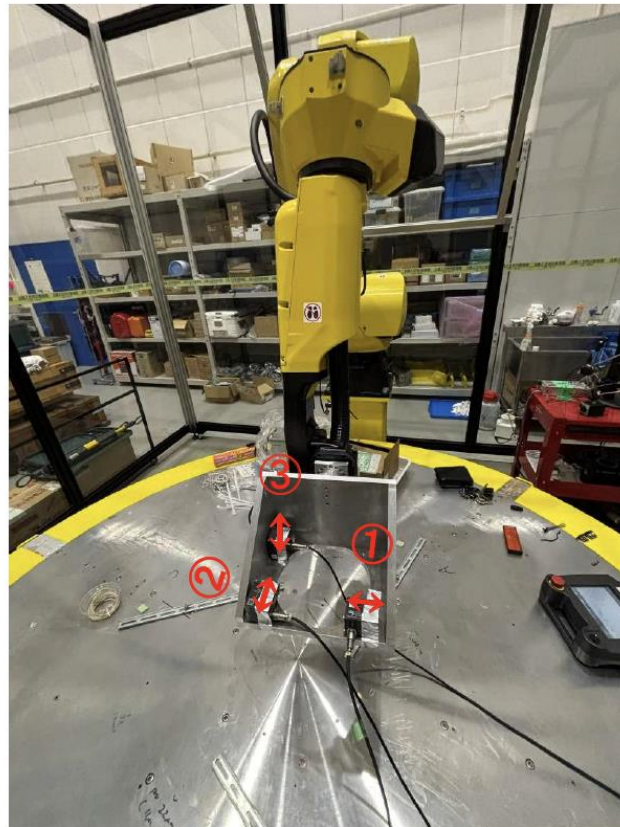
# Appendix

## 西村製作所振動計測



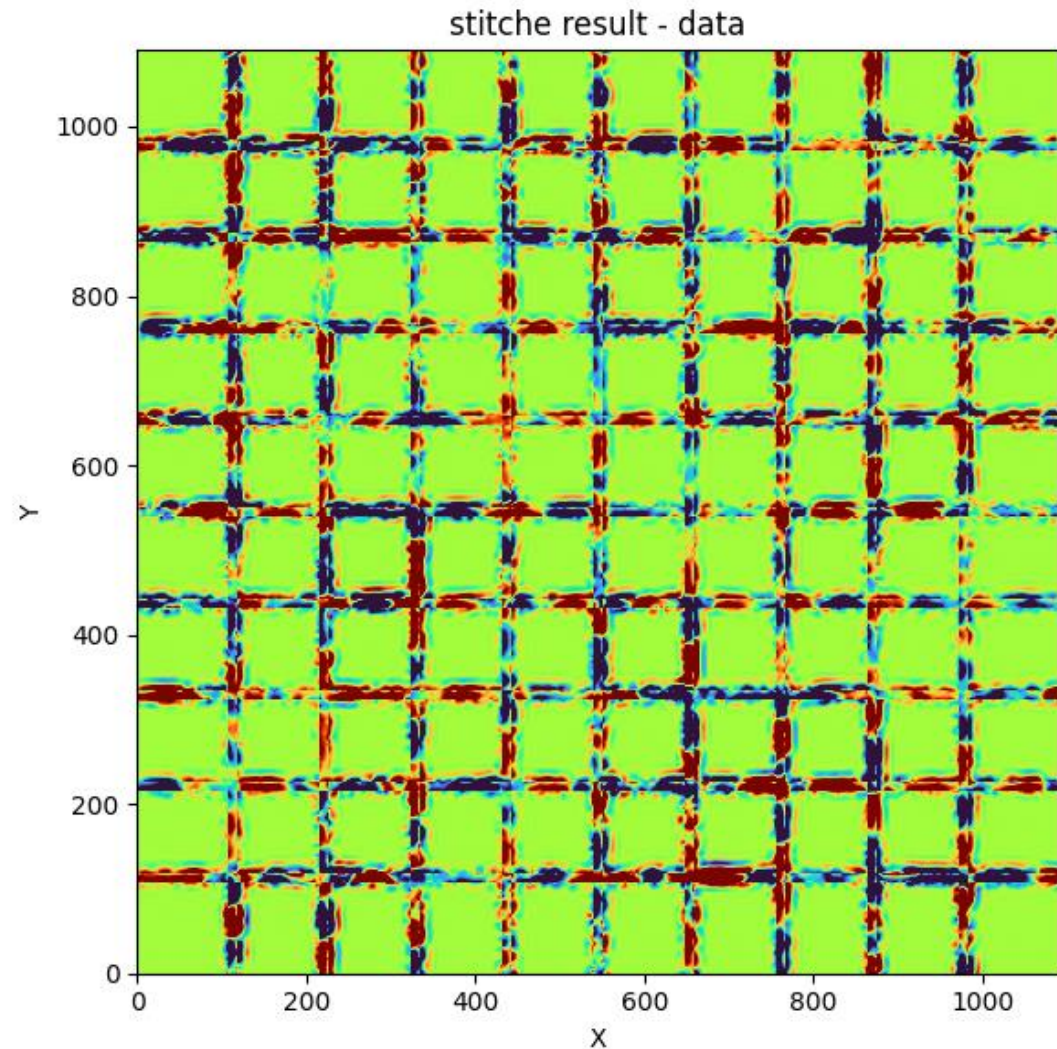
測定位置: ロボットアーム

※写真中のGroup名は実際の計測位置とは異なります。

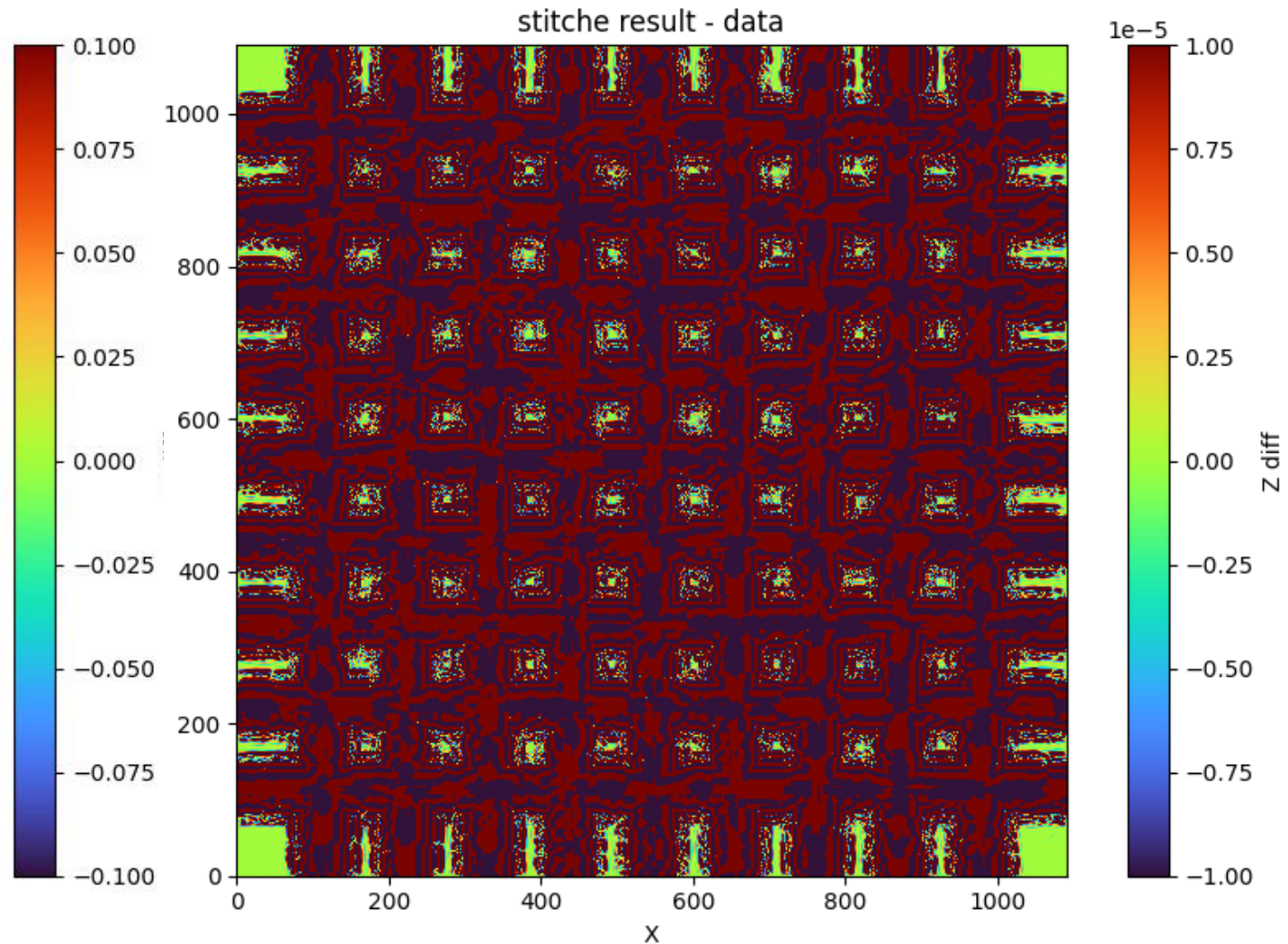


# p.9 補足 弾性体ステッチ 結果とデータの差分

ステッチ結果からステッチ前のデータ(重複領域は平均)を差し引く



差分(P-V 0.2 nm)



差分(P-V 0.0002 nm)  
※ステッチ結果は7桁

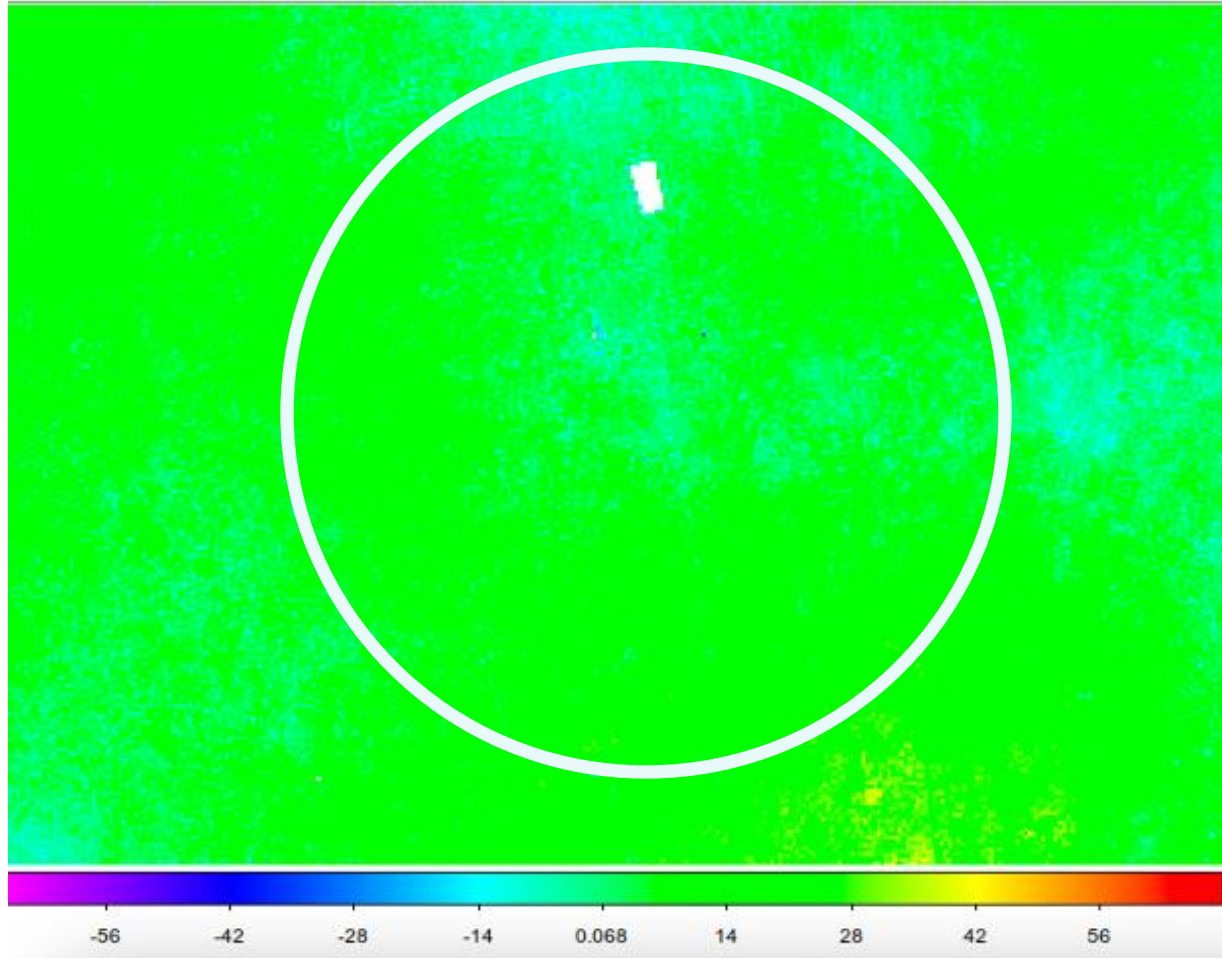
## p.11 の構造の解明 補足

1. 真の形状かどうか
2. リトレースエラーかどうか

# Φ500計測結果と比較

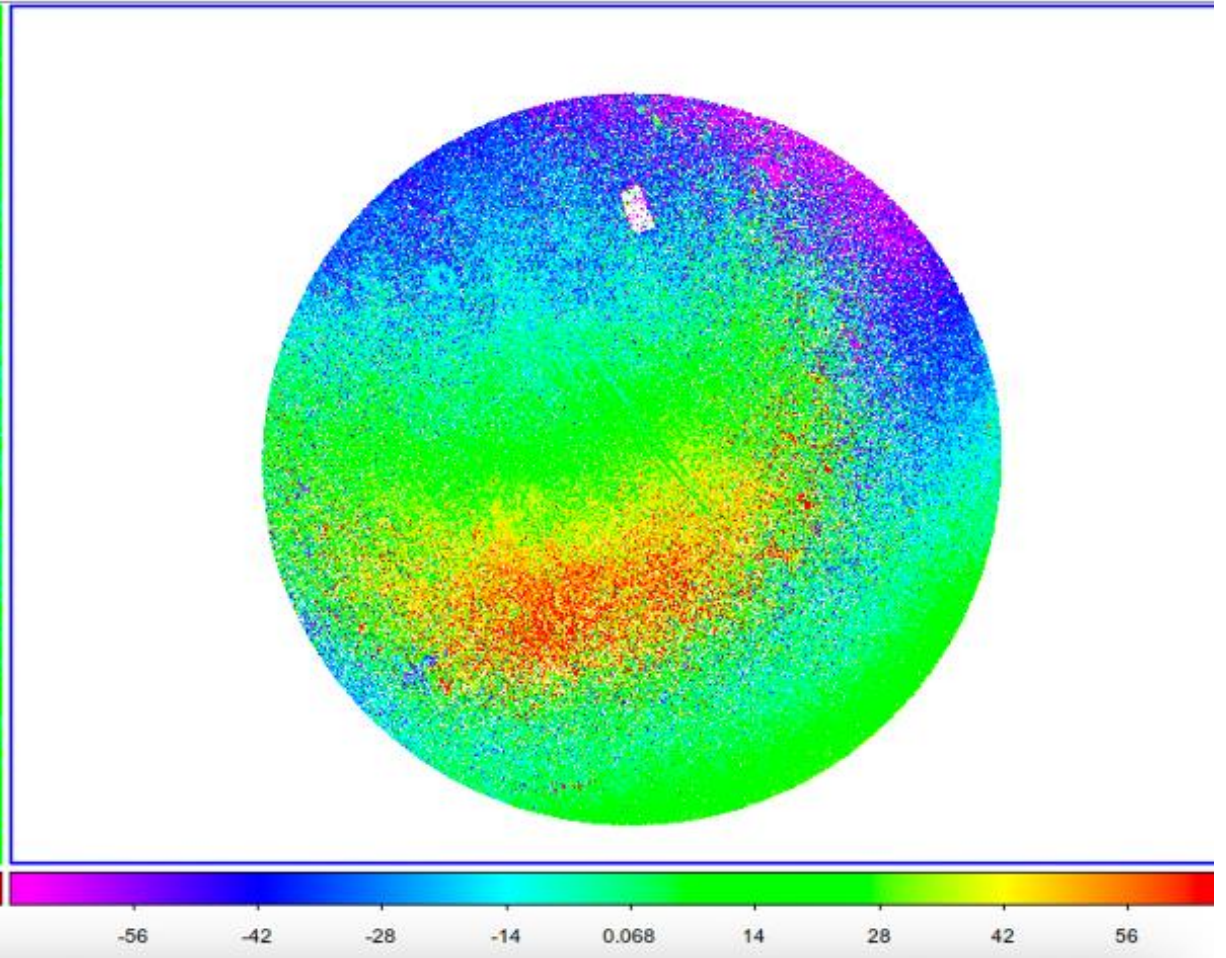
Φ500結果

円：おおよそのSA16の位置



SAI SA16の計測値

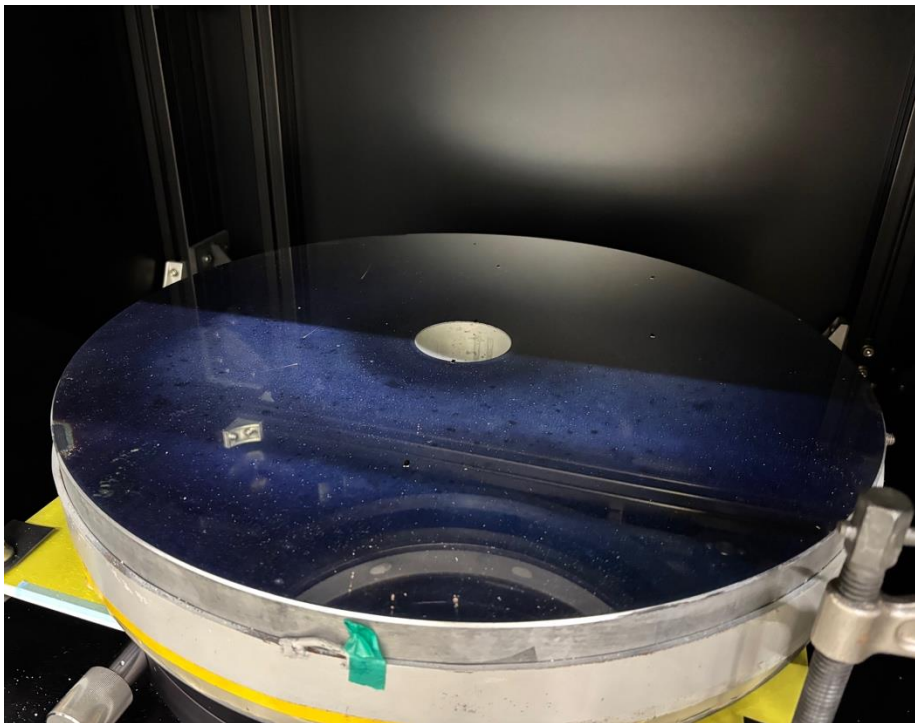
(リトレースエラー較正済み)



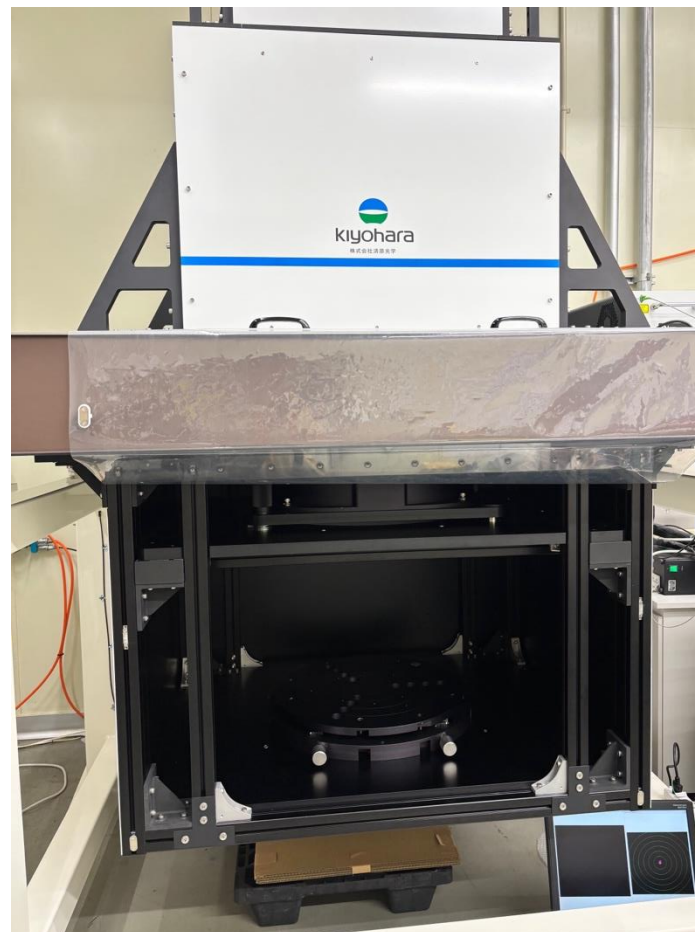
カラーバーは-70~70 nm

SAIの結果に見られるような構造は、Φ500計測結果に見られなかった⇒**真の形状でない可能性が高い**

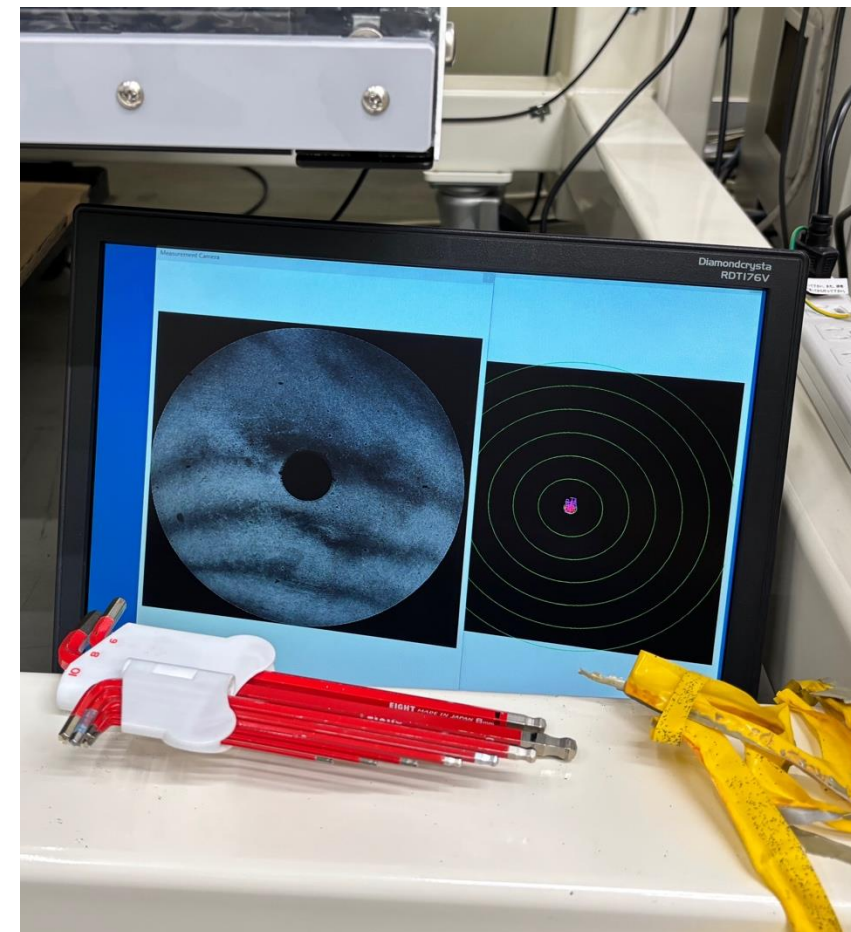
# Φ500mm 干渉計測の結果について



計測対象のΦ630 平面鏡

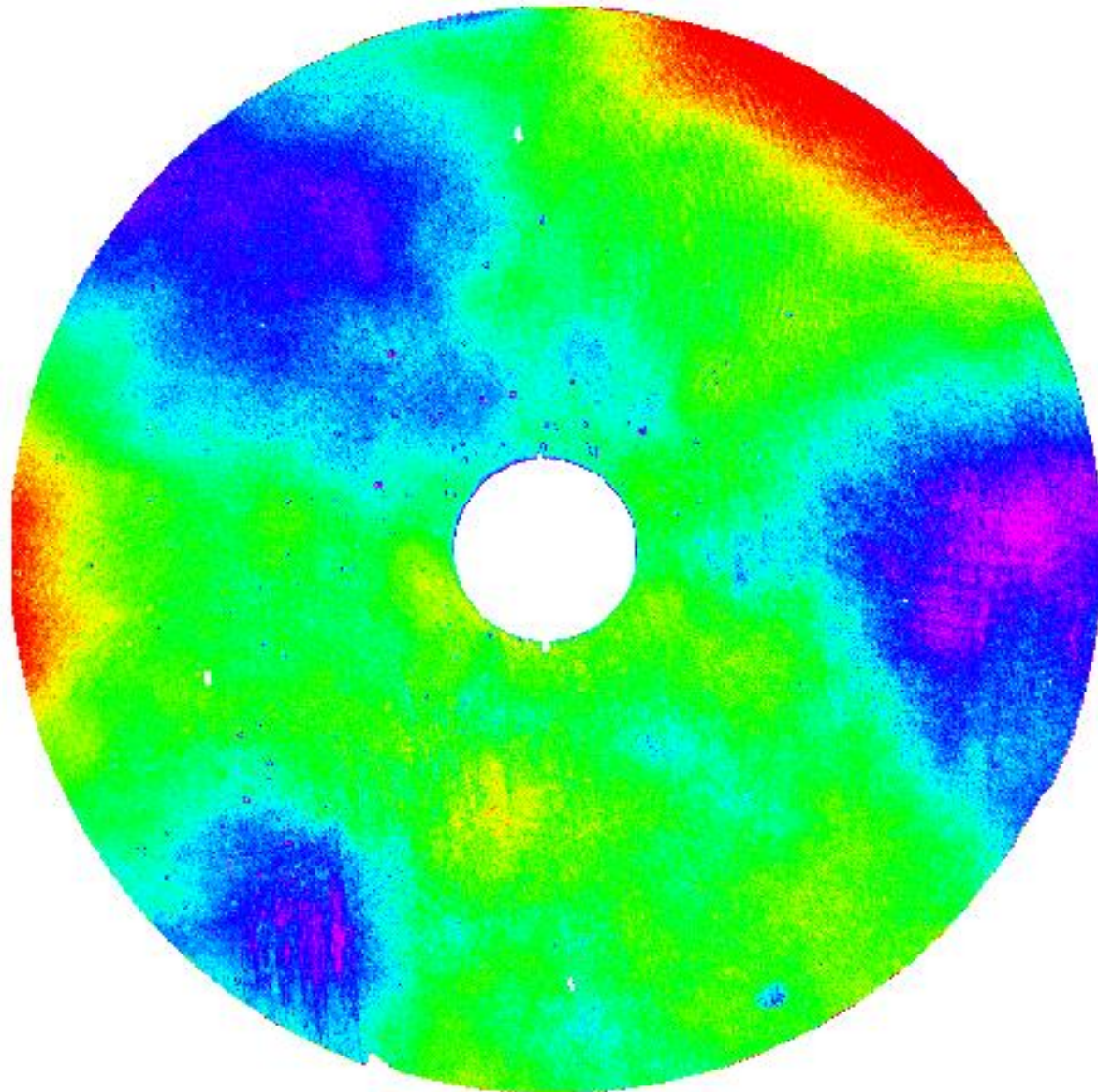


Φ500mm 干渉計を用いて計測  
今後行うSAIの計測結果と比較予定



計測の様子

10回計測平均(再現性 9.733 nm )



PV [nm] : 277.641002  
RMS [nm] : 20.226813(~1/30λ)  
PV\_Z36 [nm] : 112.551539  
RMS\_Z36res [nm] : 7.482840  
PVr [nm] : 135.000059  
RMSi [nm] : 18.240981

