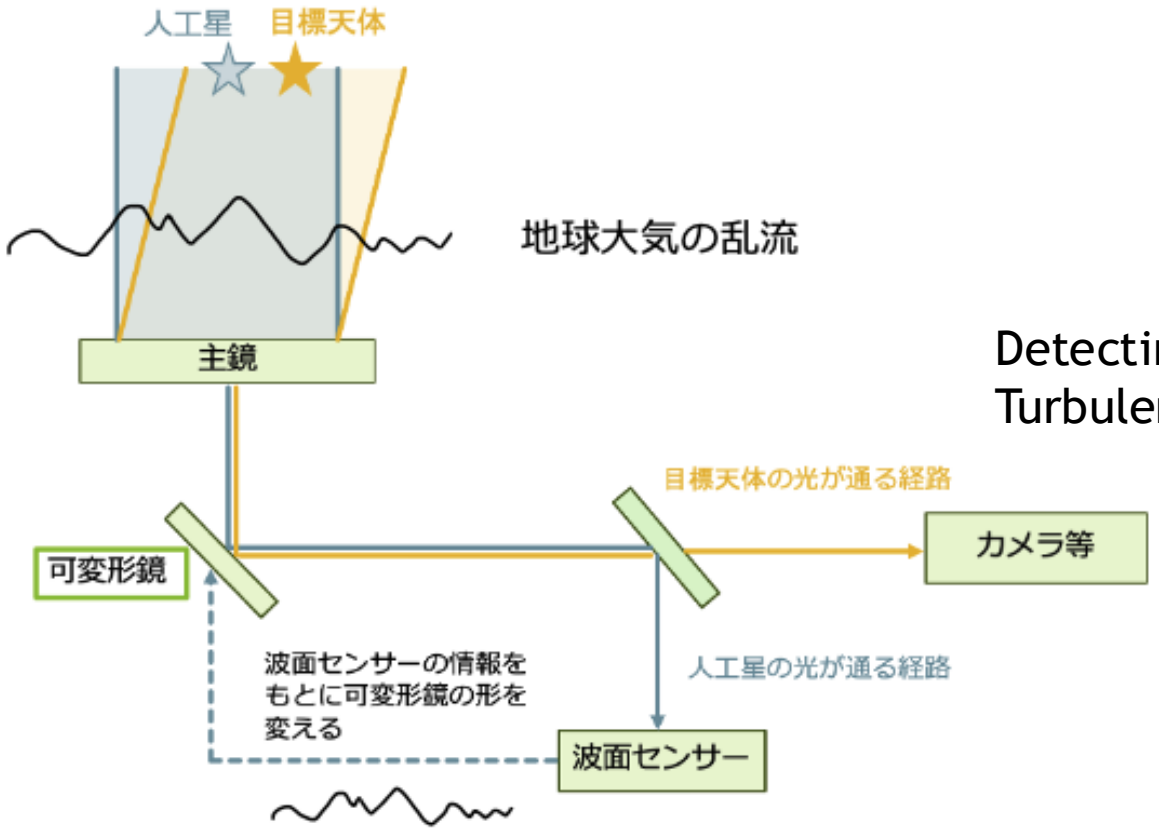
ULTIMATE-START:
Subaru Tomography Adaptive optics
Research experimenT

ULTIMATE-START： Optimization of Tomographic Wavefront Estimation for the Subaru Telescope Laser Tomography Adaptive Optics System

Hiyori Tanabe,Masayuki Akiyama,Mitsuaki Takahashi,Aino Narayama
(University of Tohoku)、
Yosuke Minowa、Yoshito Ono、Koki Terao、Shin Oya(NAOJ)、
Hajime Ogane(Australian National University)

1. Background



What is Adaptive Optics?

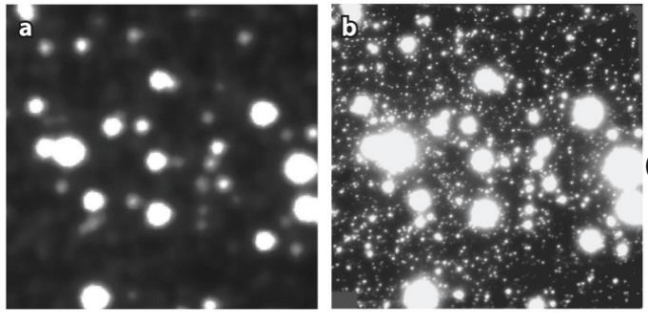
An optical technology that eliminates optical aberrations caused by atmospheric turbulence to improve observational accuracy

Adjustment Process

Detecting atmospheric Turbulence with wavefront sensors

Deform the DM based on wavefront sensor information

Can observe light that has been corrected in real time



Ex)

FWHM improved from 0.85 to 0.092

Francois Rigaut and Benoit Neichel(2018)'Multiconjugate Adaptive Optics for Astronomy', Annual Review of Astronomy and Astrophysics,281

What is ULTIMATE-START?

→ Subaru Tomography Adaptive optics Research experimenT

Project to implement Laser Tomography Adaptive Optics (LTAO) on the Subaru Telescope

(Akiyama+20, SPIE)

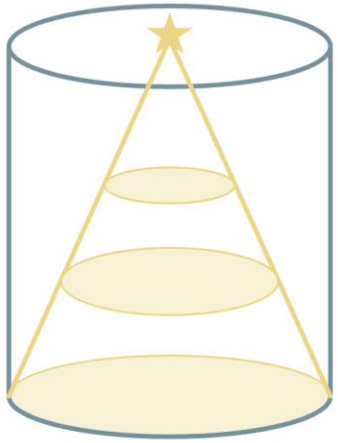
Feature

- Using four laser guide stars (LGS) and four wavefront sensors
  - Split the laser light source (589 nm, TOPTICA) into four LGS beams
    The diameter of the LGS asterism can be selected from 10“, 20”, 30“, or 40”.
- Upgrade of AO188
  - ALPAO DM with 3228 actuators

The wavefront sensor was installed on the Subaru Telescope in August 2025

→ Achieves high spatial resolution in the visible light region (>600 nm)

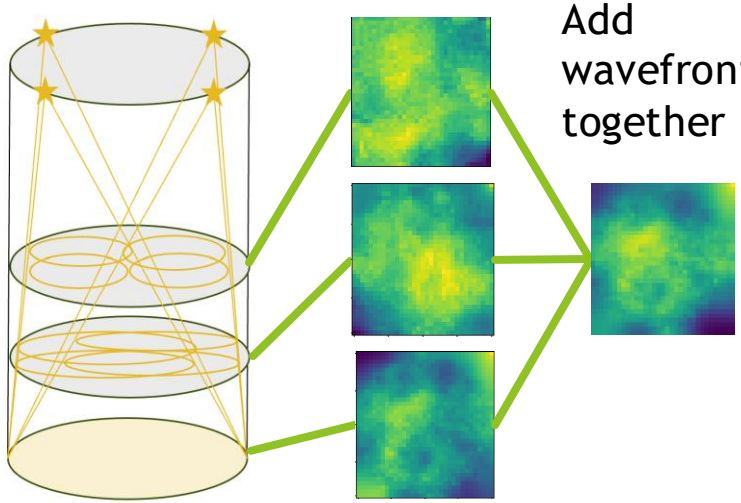
Feature of LTAO



SCAO

Using a single LGS results in reduced accuracy due to the presence of unmeasurable regions.

➡ Corn effect

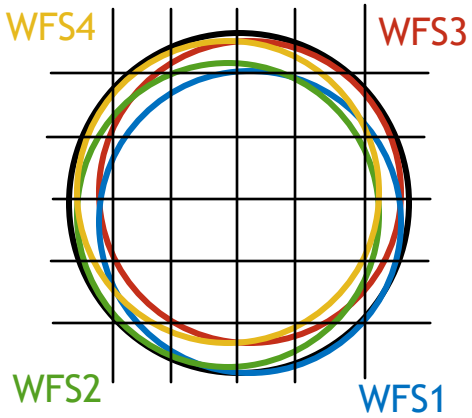


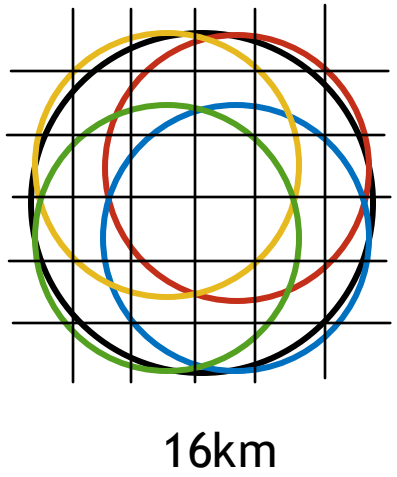
Reconfigure at each height

LTAO

Perform wavefront estimation by decomposing in the height direction using multiple LGSs

➡ Can Improve accuracy





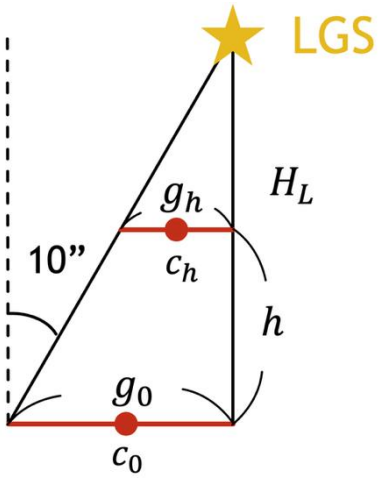
Since the overlapping regions change at each height, phase points must be reconstructed from the four WFSs while accounting for data point shifts

The objective is to create an appropriate reconstruction matrix and verify that the wavefront sensor under development achieves the required accuracy

2. Method

Compare the results of the three methods and determine the optimal wavefront reconstruction matrix creation method.

a. Geometric arrangement



The width g_h of a phase point at a height h is

$$g_h = \frac{H_L - h}{H_L} g_0$$

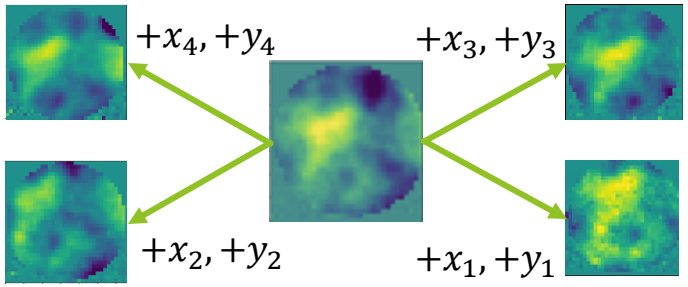
The LGS asterism is 10 arcseconds,

$$c_h = c_0 + h\left(\frac{10[“]}{3600} \times \frac{\pi}{180}\right)$$

The coordinates of wavefront w at a given height h

$$w_{ij}\left(\frac{H_L - h}{H_L} x_{i0} + h\left(\frac{10[“]}{3600} \times \frac{\pi}{180}\right)\cos(a), \frac{H_L - h}{H_L} y_{i0} + h\left(\frac{10[“]}{3600} \times \frac{\pi}{180}\right)\sin(a), h\right)$$

b. Correlation arrangement

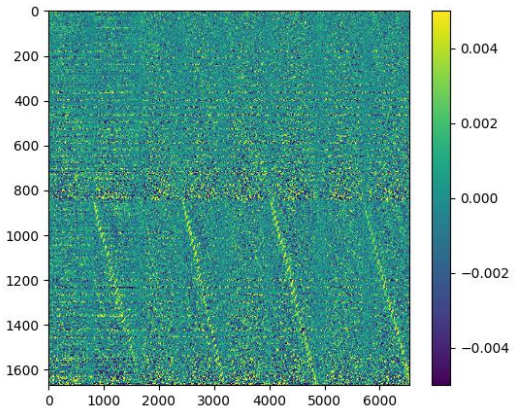


Calculate the correlation value when the wavefronts of each WFS are shifted and superimposed with the TWFS wavefront

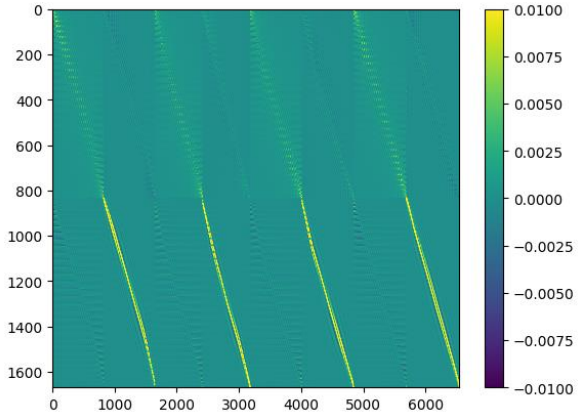
➡ Create the complement matrix at the aperture position where the correlation is highest

c. Arrangement using Learn & Apply method

Measurement value



Model

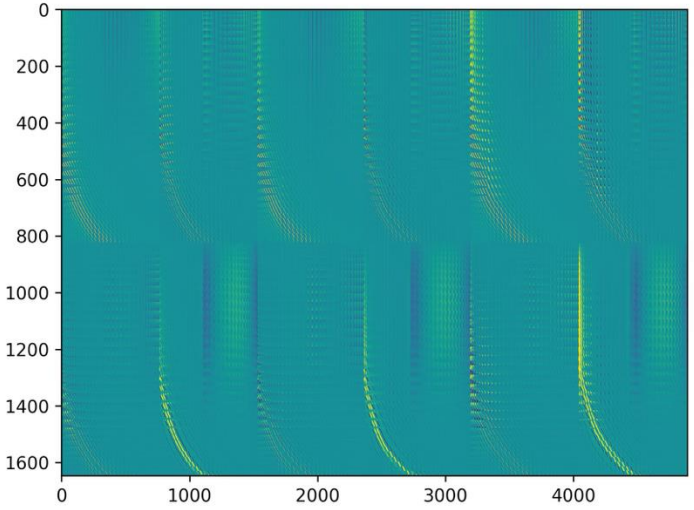


<u>What is Learn & apply method?</u>

A method for performing wavefront correction directly from the measured values of each WFS and TWFS

$$s_{TWFS} = A \begin{pmatrix} s_{WFS1} \\ s_{WFS2} \\ s_{WFS3} \\ s_{WFS4} \end{pmatrix}$$

$s_{TWFS}, s_{WFS1}, s_{WFS2}, s_{WFS3}, s_{WFS4}$: Measurement value of each WFS



By comparing the correspondence matrix A of the model derived from the measured values and geometric configuration, reconstruction aligned with the measurement results can be performed.

WFS1	WFS1	WFS2	WFS2	WFS3	WFS3	WFS4	WFS4
x	y	x	y	x	y	x	y

Slope of TWFS's x

Slope of TWFS's y

Reconstruct Matrix

Estimate the wavefront in the height direction using data measured by four WFSs

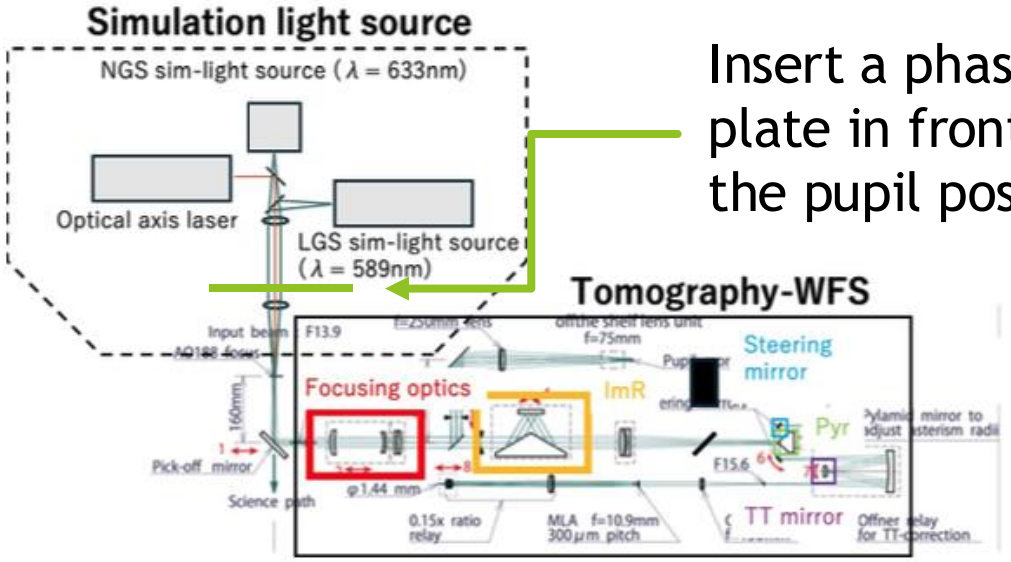
Determining wavefronts using Fried geometry

$$\begin{pmatrix} s^{[1]} \\ s^{[2]} \\ s^{[3]} \\ s^{[4]} \end{pmatrix} = \begin{pmatrix} G_{[1]}w^{[1]} \\ G_{[2]}w^{[2]} \\ G_{[3]}w^{[3]} \\ G_{[4]}w^{[4]} \end{pmatrix} \qquad (s:, the\ slope\ of\ each\ WFS, G: Fried-Geometry, w: reconstruct\ wavefront)$$

Using the reconstructed wavefront, the phase point values at each altitude are interpolated

$$\begin{pmatrix} s^{[1]} \\ s^{[2]} \\ s^{[3]} \\ s^{[4]} \end{pmatrix} = \begin{pmatrix} G_{[1]}A_{[1]}^{[1]} & G_{[1]}A_{[1]}^{[2]} & G_{[1]}A_{[1]}^{[3]} \\ G_{[2]}A_{[2]}^{[1]} & G_{[2]}A_{[2]}^{[2]} & G_{[2]}A_{[2]}^{[3]} \\ G_{[3]}A_{[3]}^{[1]} & G_{[3]}A_{[3]}^{[2]} & G_{[3]}A_{[3]}^{[3]} \\ G_{[4]}A_{[4]}^{[1]} & G_{[4]}A_{[4]}^{[2]} & G_{[4]}A_{[4]}^{[3]} \end{pmatrix} \begin{pmatrix} \phi^{[1]} \\ \phi^{[2]} \\ \phi^{[3]} \end{pmatrix} \qquad (A: Matrix\ for\ interpolating\ data\ points)$$

Data acquisition



Insert a phase plate in front of the pupil position

Data used

Observation Date	2024年7月7日~9日
Observation site	Laboratory of Hawaii Observatory
Observation target	Simulated light source
Number of lenslets	32×32
Phase plate to be used	$r_0 = 0.46$
Altitude of LGS	90km

Position for inserting the phase plate

Position of Phase plate	0	1	2	3	4	5
Altitude[km]	3.57	6.66	9.76	12.9	15.9	19.0

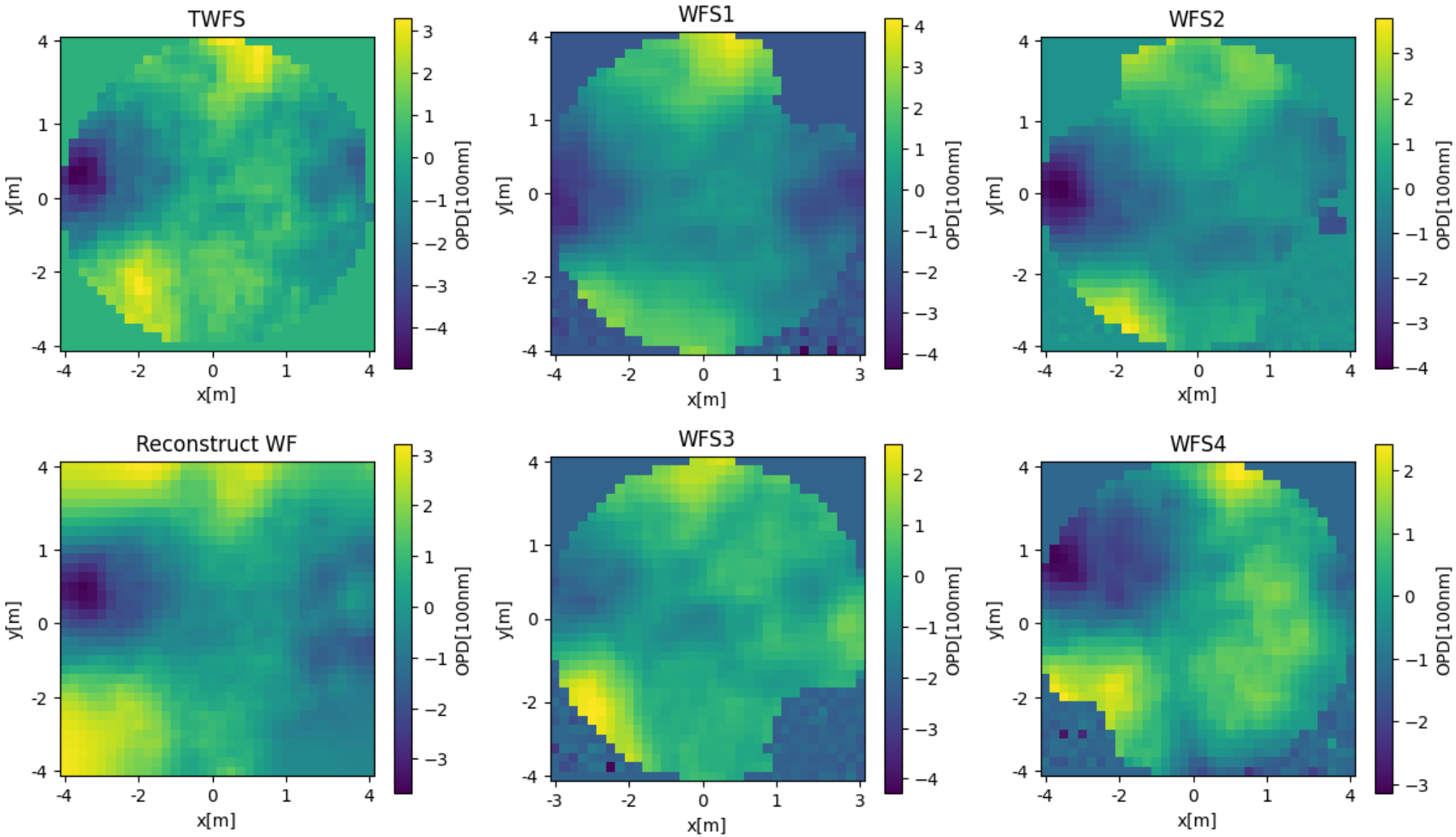
Reconstructing wavefronts using four WFS → Calculate the difference between the reconstructed wavefront using Truth-WFS for performance evaluation and the original wavefront

3.Result

Reconstruct Wavefront

Geometric arrangement

Each WFS and reconstructed wavefront at 19.4 km



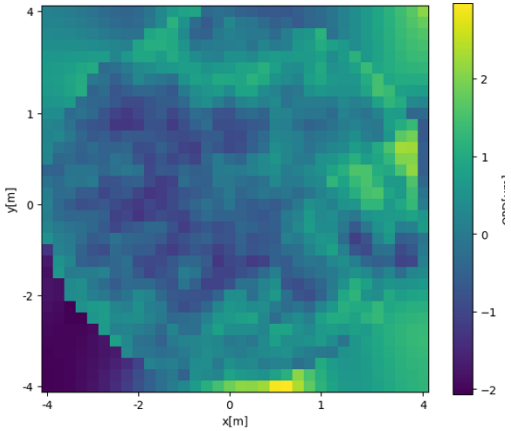
The residual wavefront error RMS was calculated for the reconstructed wavefronts at each height (in units of μm)

	TWFS	Geometric arrangement	Correlation arrangement	Learn & Apply
3.57km	1.49	0.388	0.385	1.81
6.66km	1.43	0.400	0.457	1.66
9.76km	1.19	0.463	0.586	2.18
12.9km	0.853	0.559	0.623	1.92
15.9km	1.11	0.641	0.834	2.60
19.0km	1.44	0.674	0.830	1.37

In any case, performance below 100 nm has not been achieved

When applying the Learn & Apply method for reconstruction using only observed quantities, the residual wavefront error RMS is 0.098 μm (98 nm). Therefore, with an optimal setup, performance below 100 nm should be achievable

4. Discussion



Residuals of the reconstruct WF and TWFS

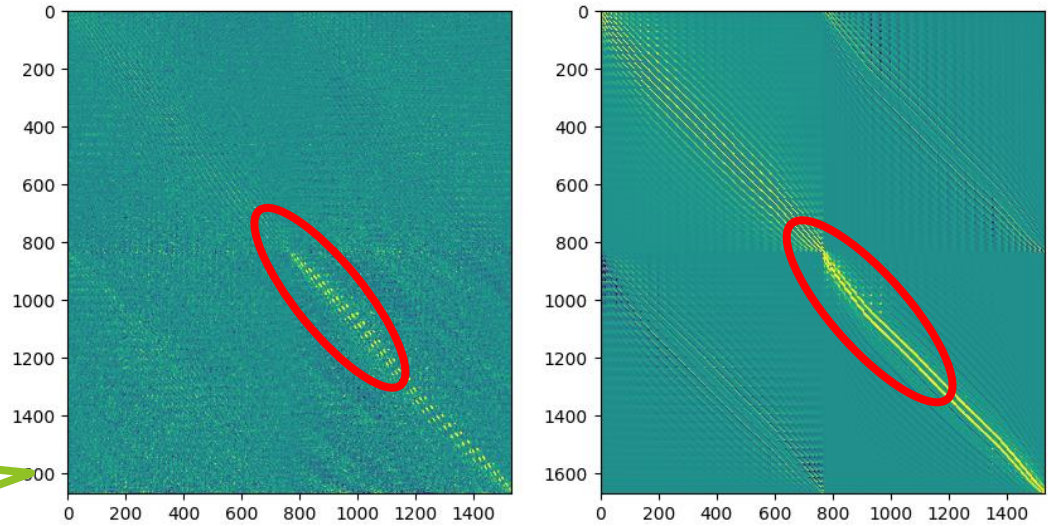
・When comparing geometric placement and correlated placement, geometric placement yields higher accuracy

Each sub-aperture covers only a 0.25m × 0.25m area, and positioning with finer precision than this is not possible

On the other hand, even with geometric arrangements, wavefront patterns remain in the residuals, making an optimal model that accounts for errors and other factors essential

・When focusing on the straight lines of the response matrix during the Learn & Apply method, you can observe that the degree of curvature differs at the edges

By refining the linear fitting method, we can find a more appropriate straight line



Focusing on the ○ section, the correspondence matrix derived from the measured values exhibits an upward curvature, whereas the correspondence matrix from the geometric configuration exhibits a downward curvature.

5. Conclusion

・ The residual wavefront error RMS when reconstruction was performed using a geometric arrangement was 0.521 μm

➡ Performance has not yet reached the target of below 100nm

The geometric arrangement does not accurately reproduce the actual setup

・ The residual wavefront error RMS when reconstruction was performed using correlation mapping was 0.619 μm

➡ It is difficult to find the optimal setup because alignment cannot be achieved at scales smaller than 0.25m, which is the size of the 1sub-aperture

・ The residual wavefront error RMS when reconstruction was performed using the Lean & Apply method is 1.92 μm

➡ There is point for improvement in the straight-line fitting method

・ Using the Lean & Apply method, there is potential to improve the residual wavefront error to 0.098 μm with the current setup