3DCNNを用いた Phase Diversity 波面収差測定法の開発

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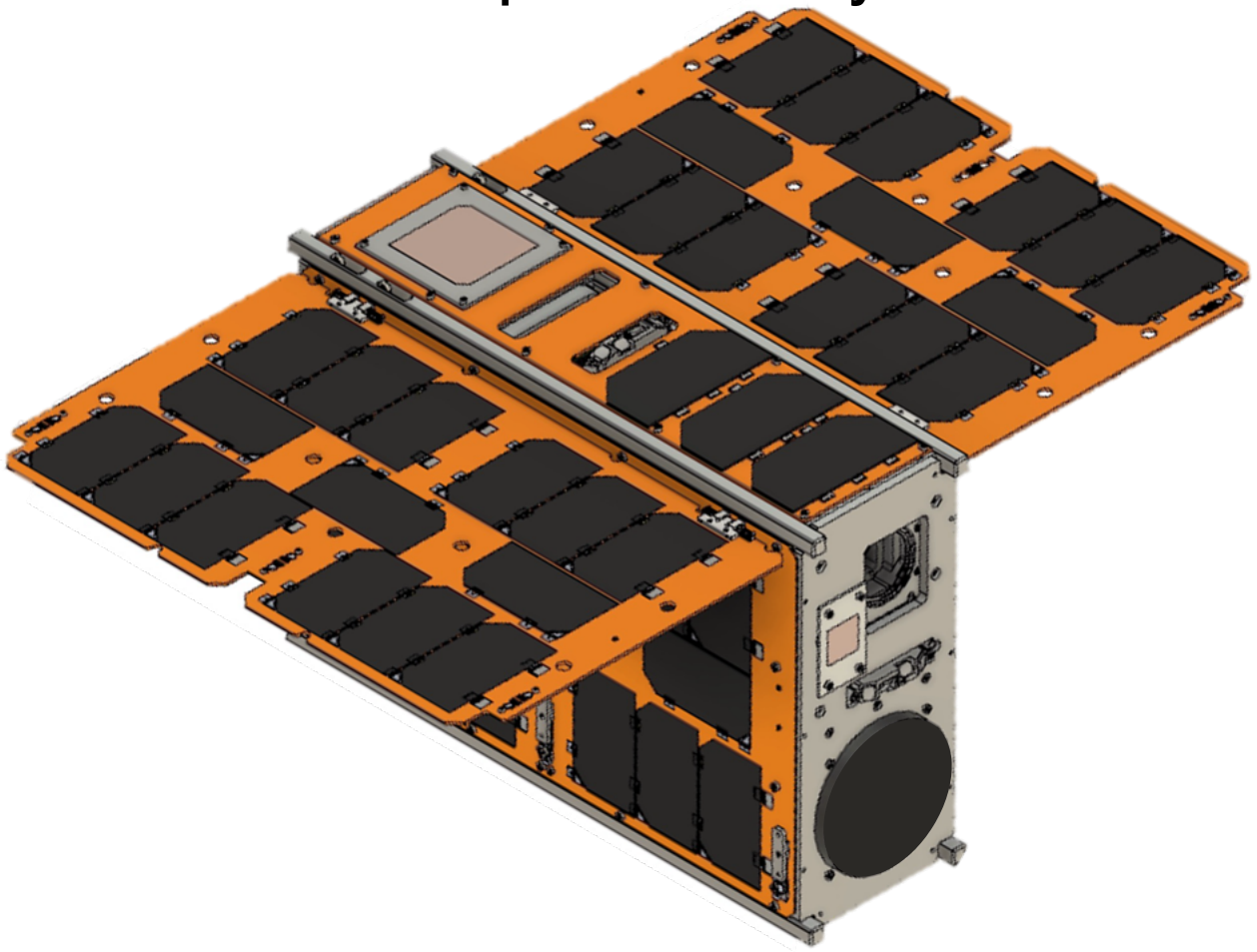
1. Overview of VERTECS
2. Issues in Telescope Wavefront Measurement
3. Phase Diversity Wavefront Measurement Using 3D-CNN

1. VERTECS

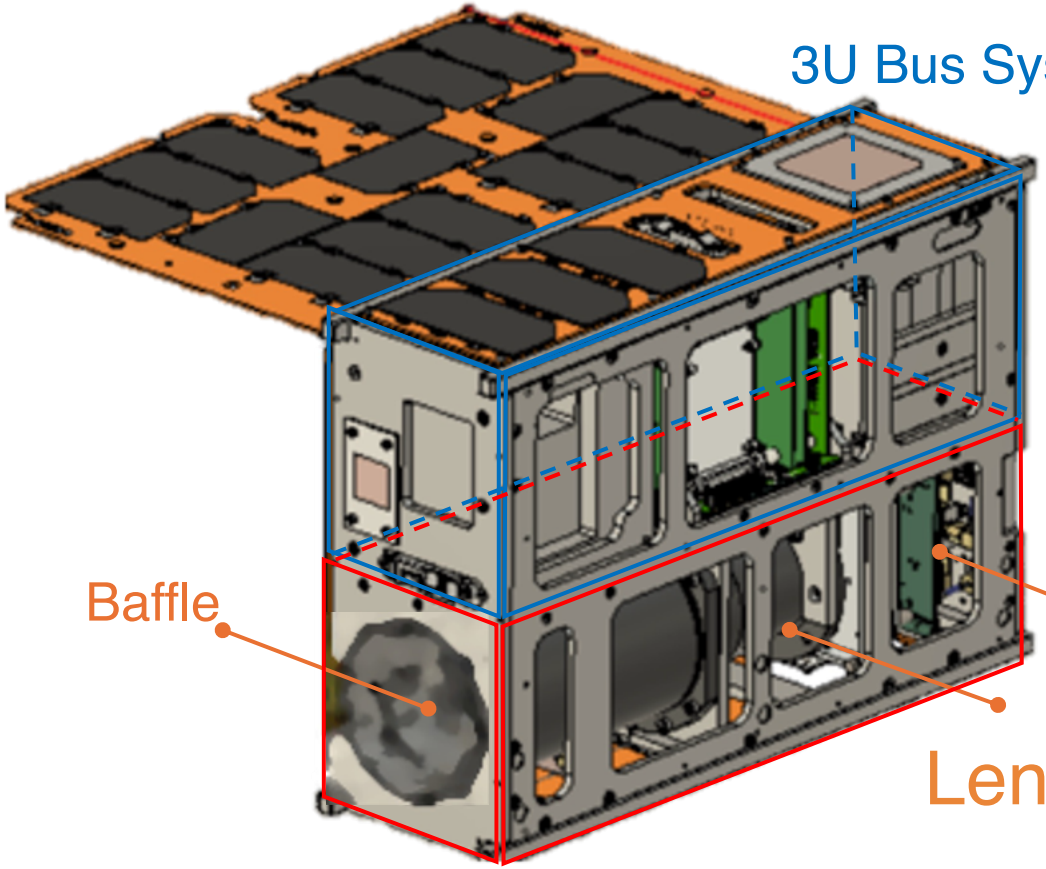
Visible Extragalactic background RadiaTion Exploration by CubeSat

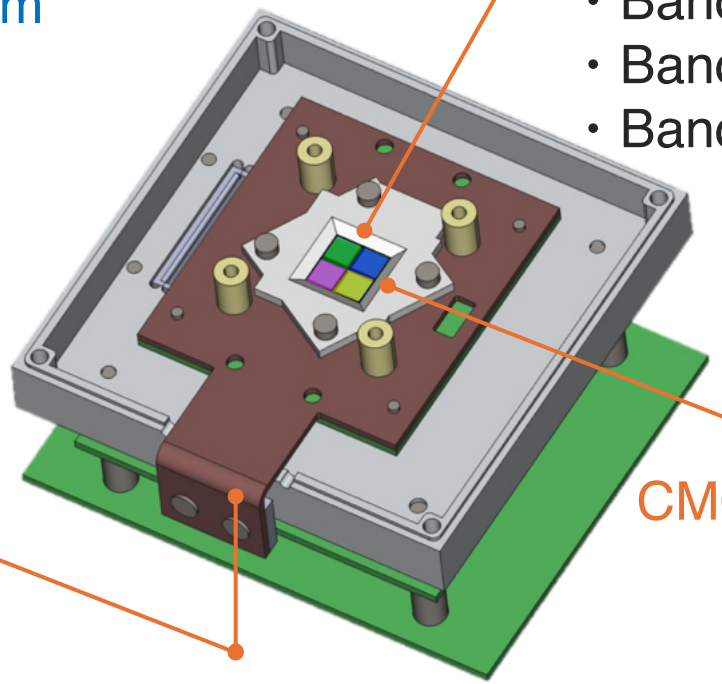


- 10 cm × 20 cm × 30 cm
- Development started in 2022
- Flight model in development

1. VERTECS

Telescope: 10 cm × 10 cm × 30 cm





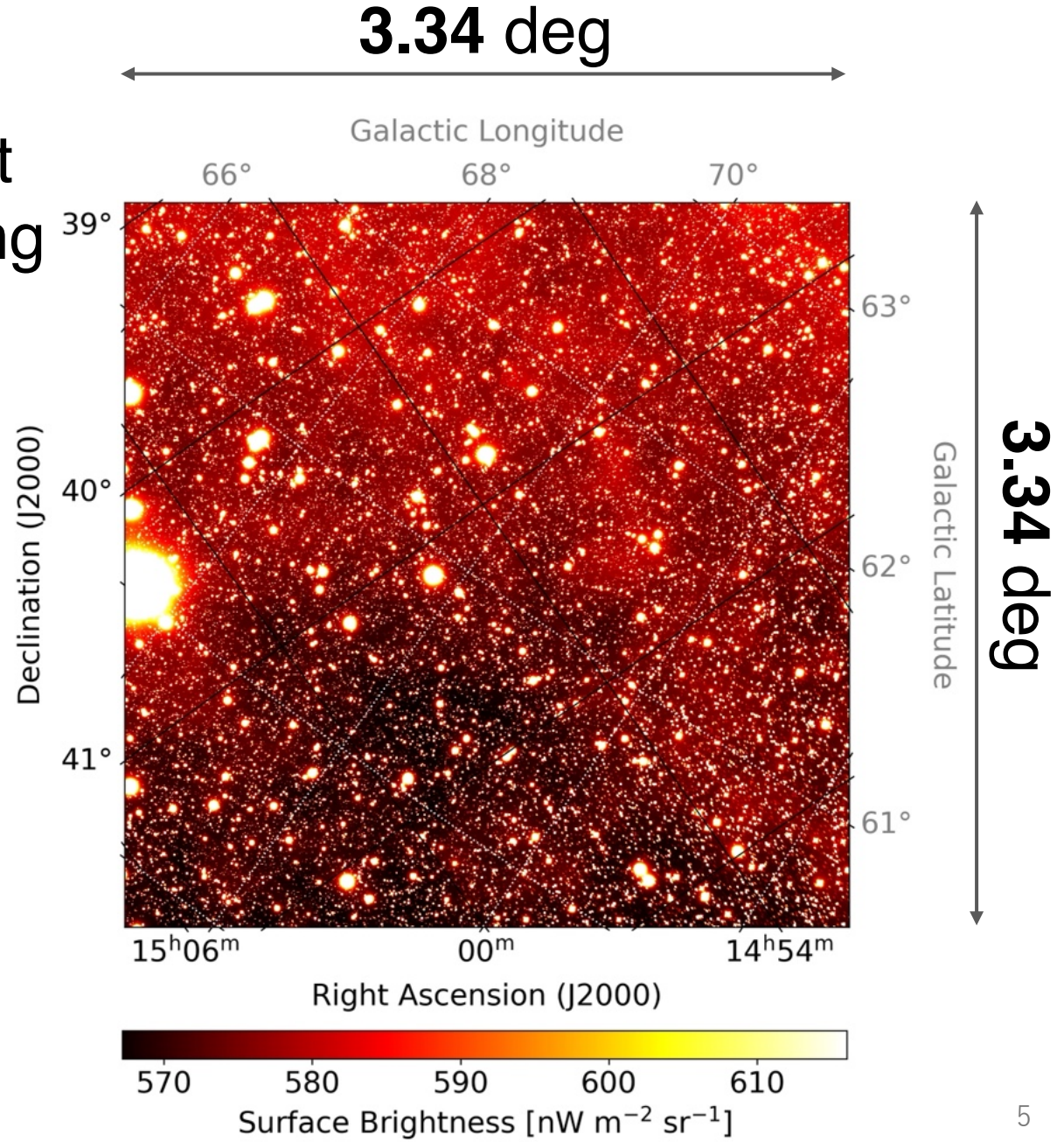
- Band-1: 0.4 - 0.5 μm
- Band-2: 0.5 - 0.6 μm
- Band-3: 0.6 - 0.7 μm
- Band-4: 0.7 - 0.8 μm

- Pupil diameter: 35 mm
- Focal length: 70 mm, F/2

1. VERTECS

Extragalactic Background Light Requires Accurate Star Masking

- Stars are masked.
- Foreground light is modeled and subtracted.
- PSF wings extending outside the mask negatively affect the foreground modeling.
- A PSF model is created to remove the PSF wings as well.



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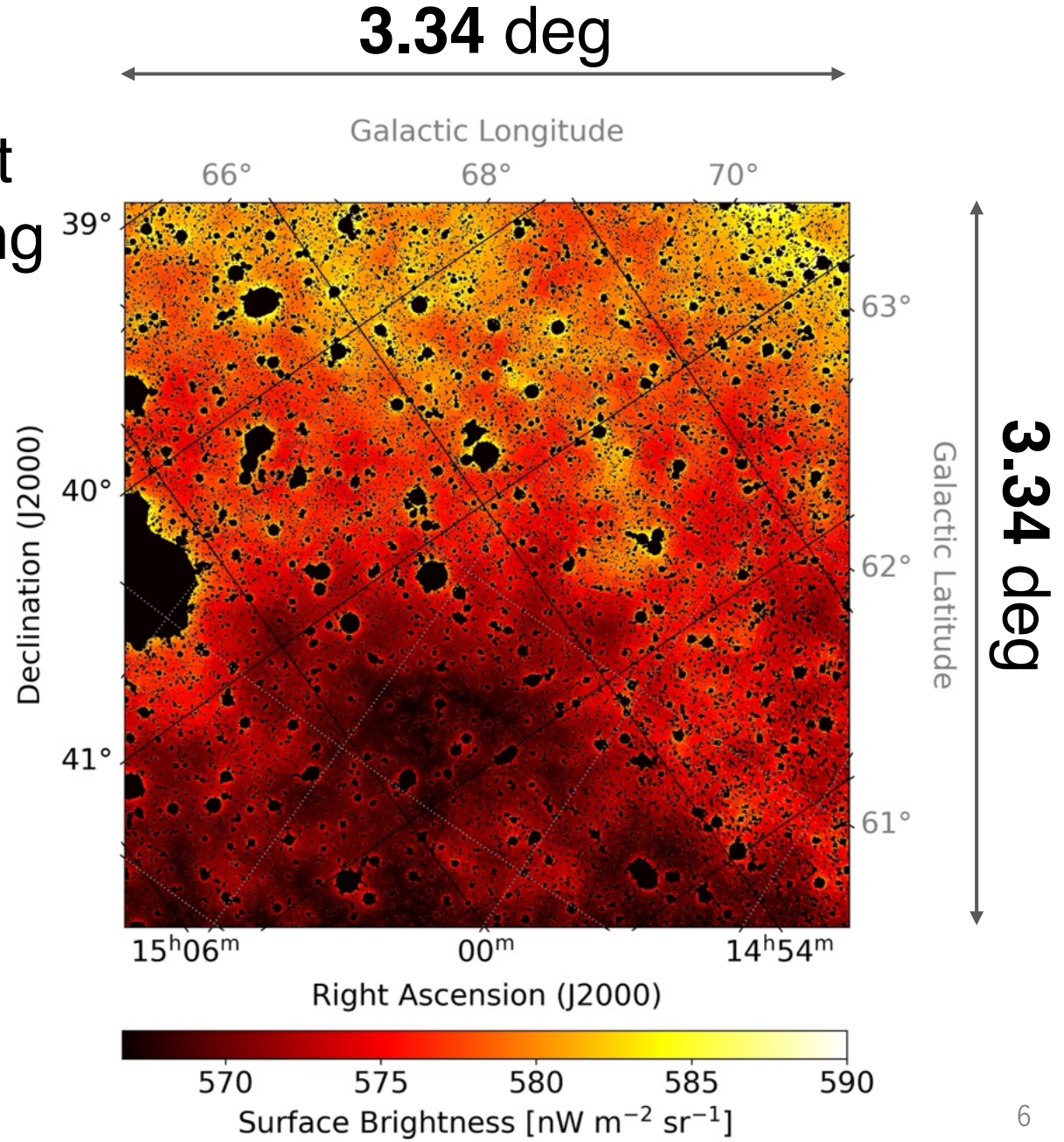

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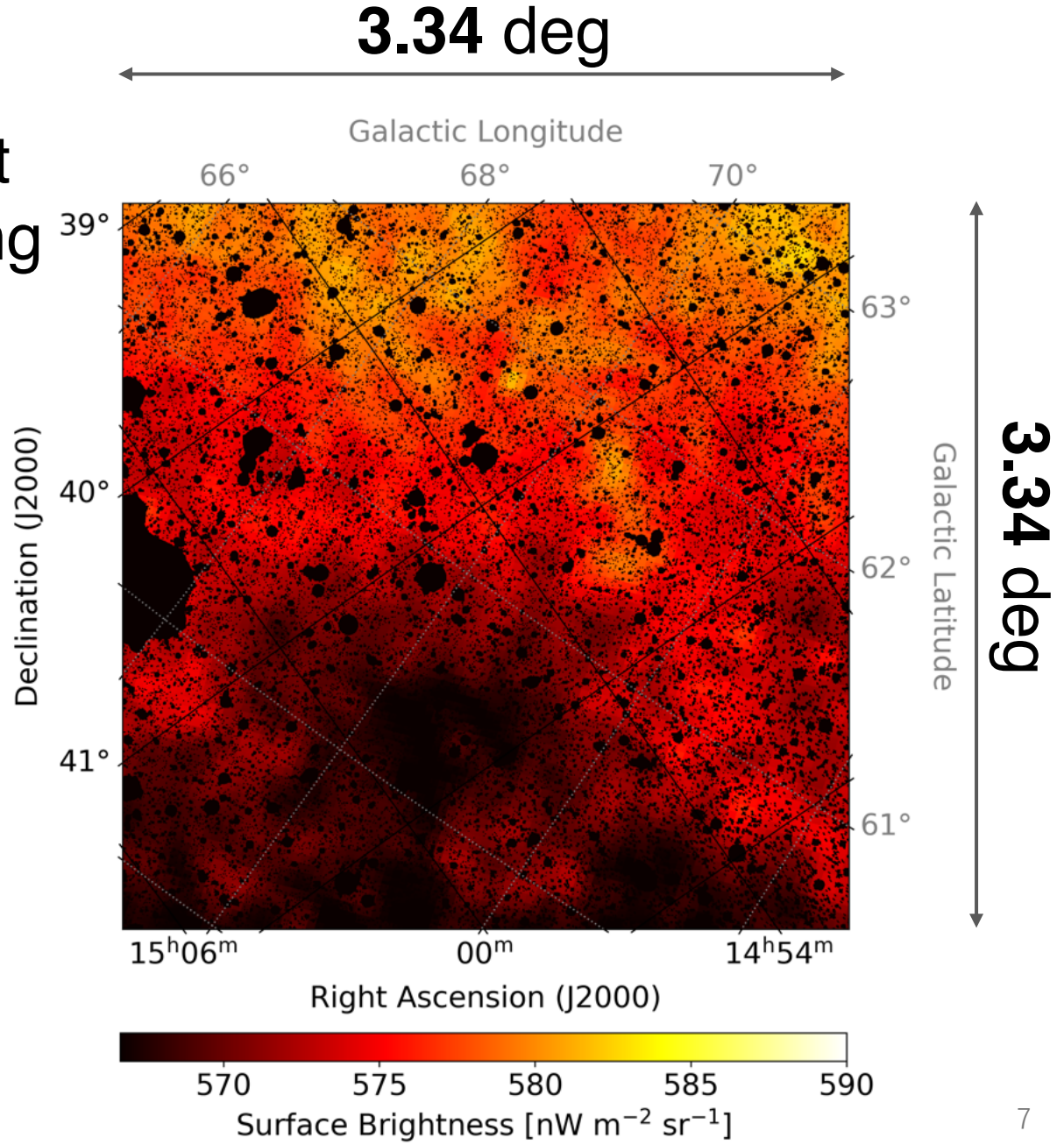


1. Overview of VERTECS
2. **Issues in Telescope Wavefront Measurement**
3. Phase Diversity Wavefront Measurement Using 3D-CNN

2. Telescope Wavefront Measurement

VERTECS lens: f = 70 mm, F/2

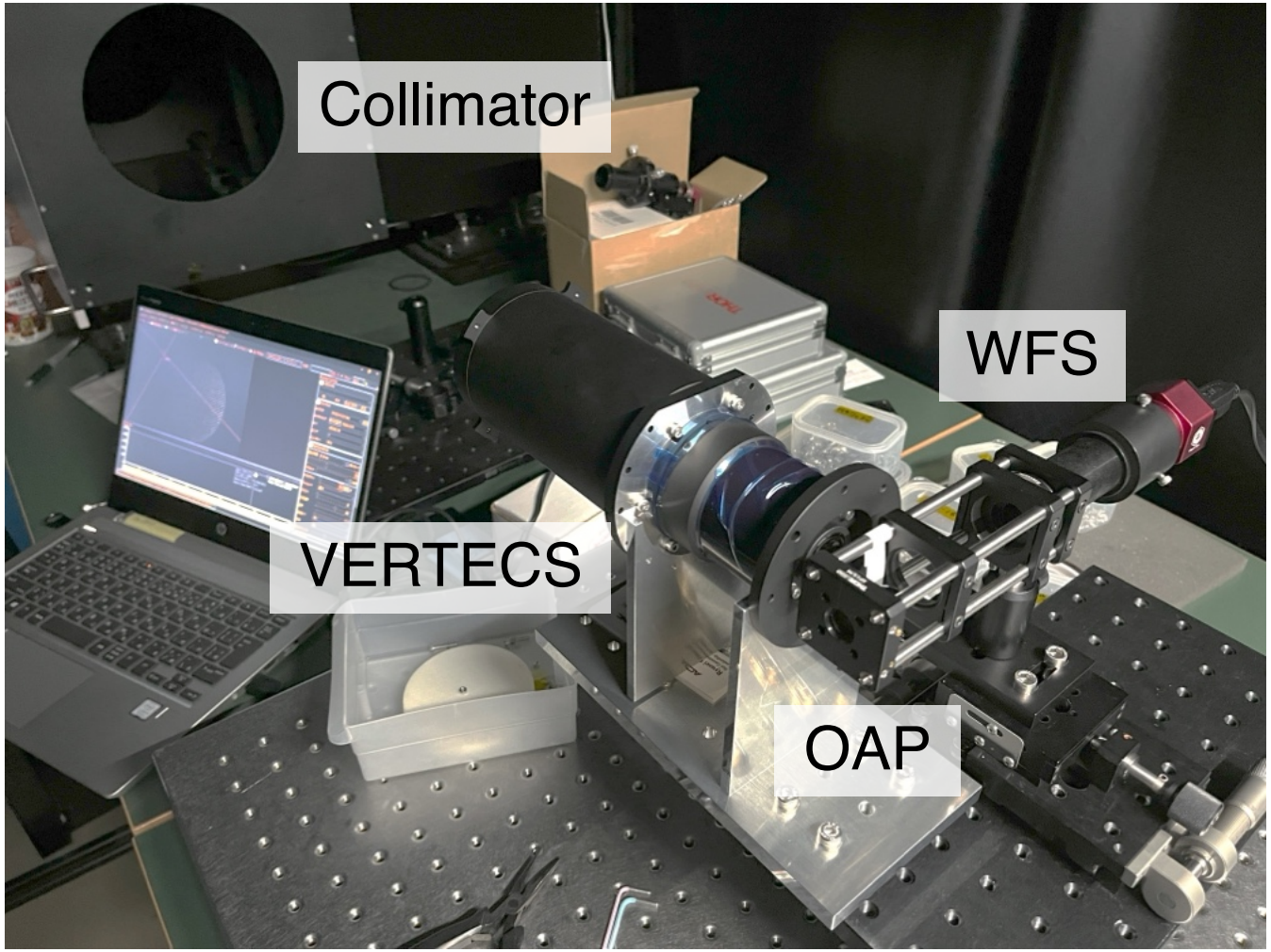
a. Wavefront Measurement with a Shack-Hartmann Sensor

b. (Conventional) Phase Diversity Wavefront Measurement

c. 3D-CNN-Based Phase Diversity Wavefront Measurement

2. Telescope Wavefront Measurement

a. Wavefront Measurement with a Shack-Hartmann Sensor

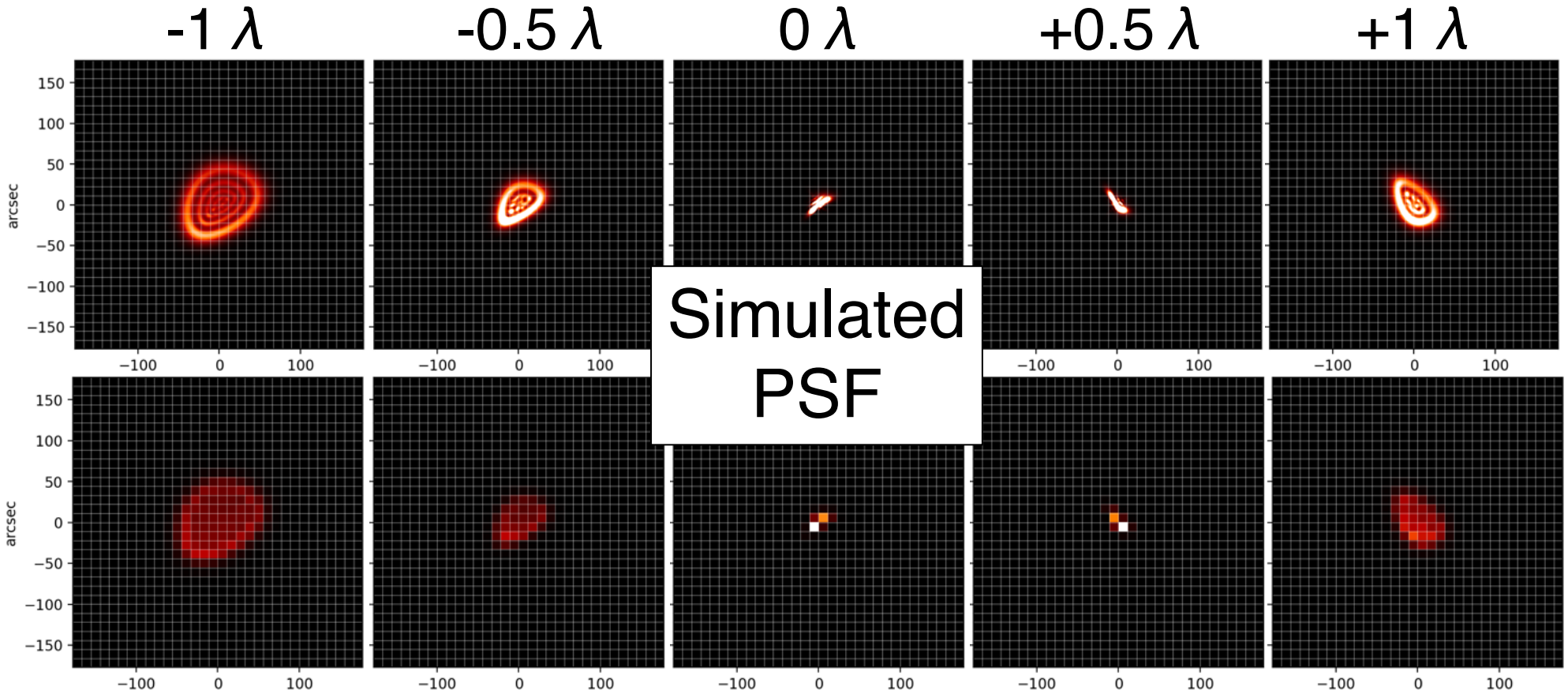


- Under oblique incidence, even a slight alignment error introduced coma aberration.
- Limited scanning accuracy on the image plane made it hard to separate from real field curvature.
- Since white light was used, chromatic aberration across the VERTECS observation bands could not be reproduced.
- Test time was limited due to the satellite’s test schedule.

2. Telescope Wavefront Measurement

b. (Conventional) Phase Diversity Wavefront Measurement

Input: Through-Focus Data



▶ Results were highly dependent on the initial values.

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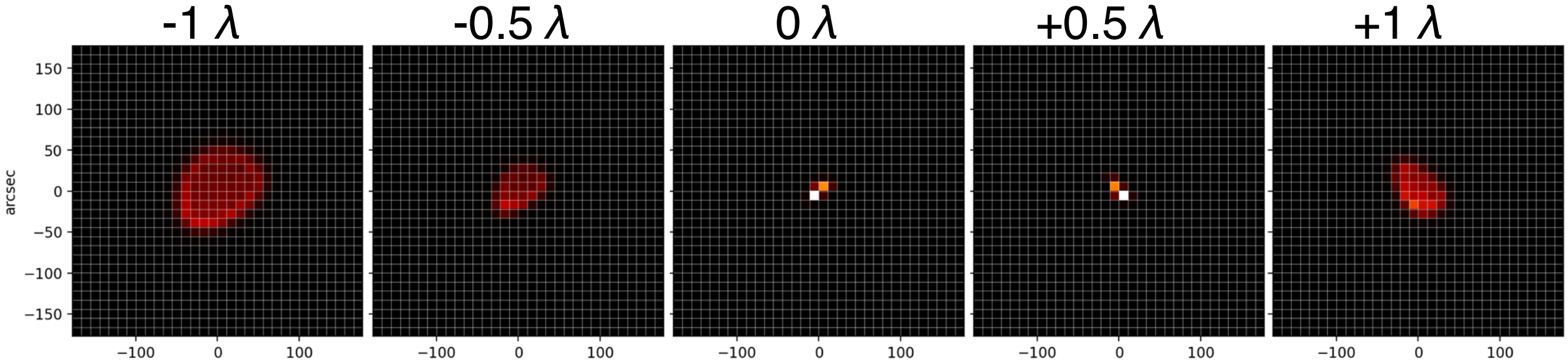
3. 3D-CNN-Based Phase Diversity

Why Conventional Phase Diversity Failed

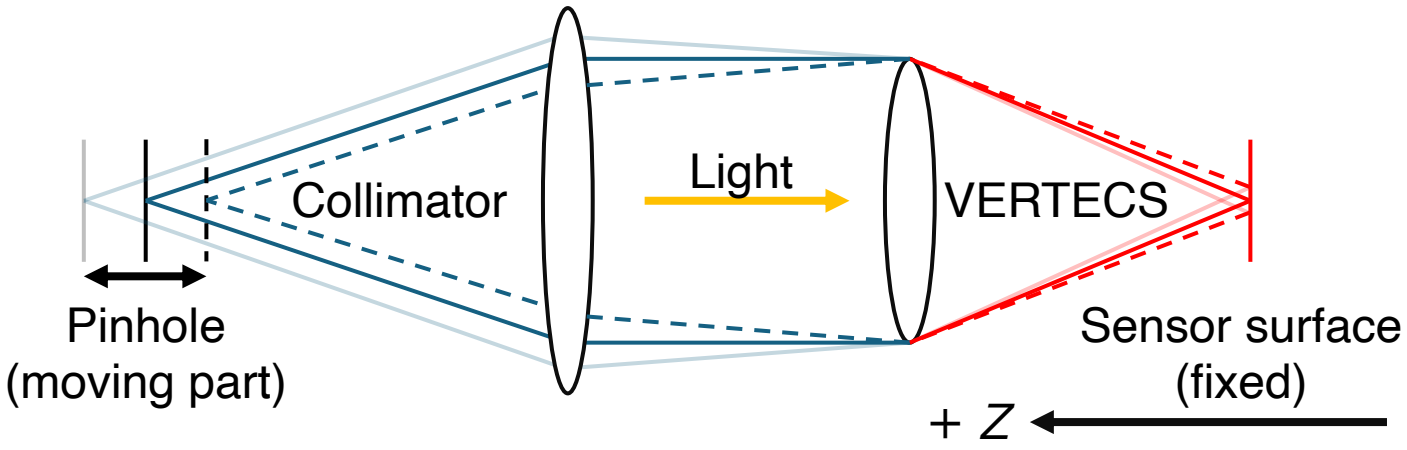


VERTECS PSF, 11.08 “/pixel

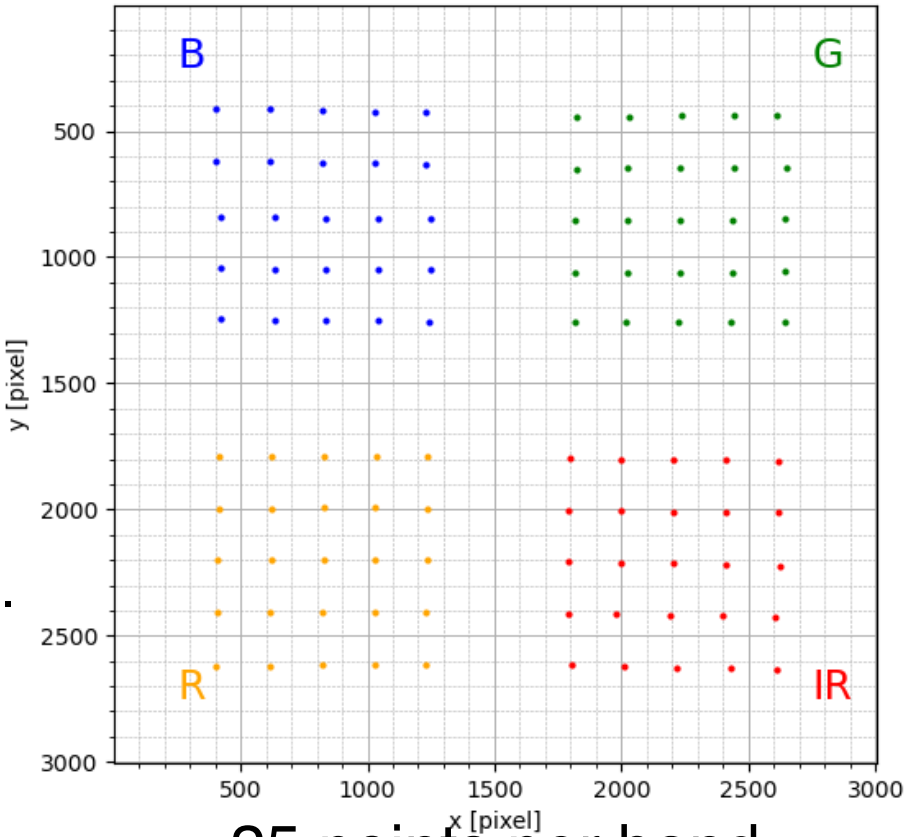
Limited ability to extract fine features (large pixel scale)

3. 3D-CNN-Based Phase Diversity

Through-Focus Test Setup



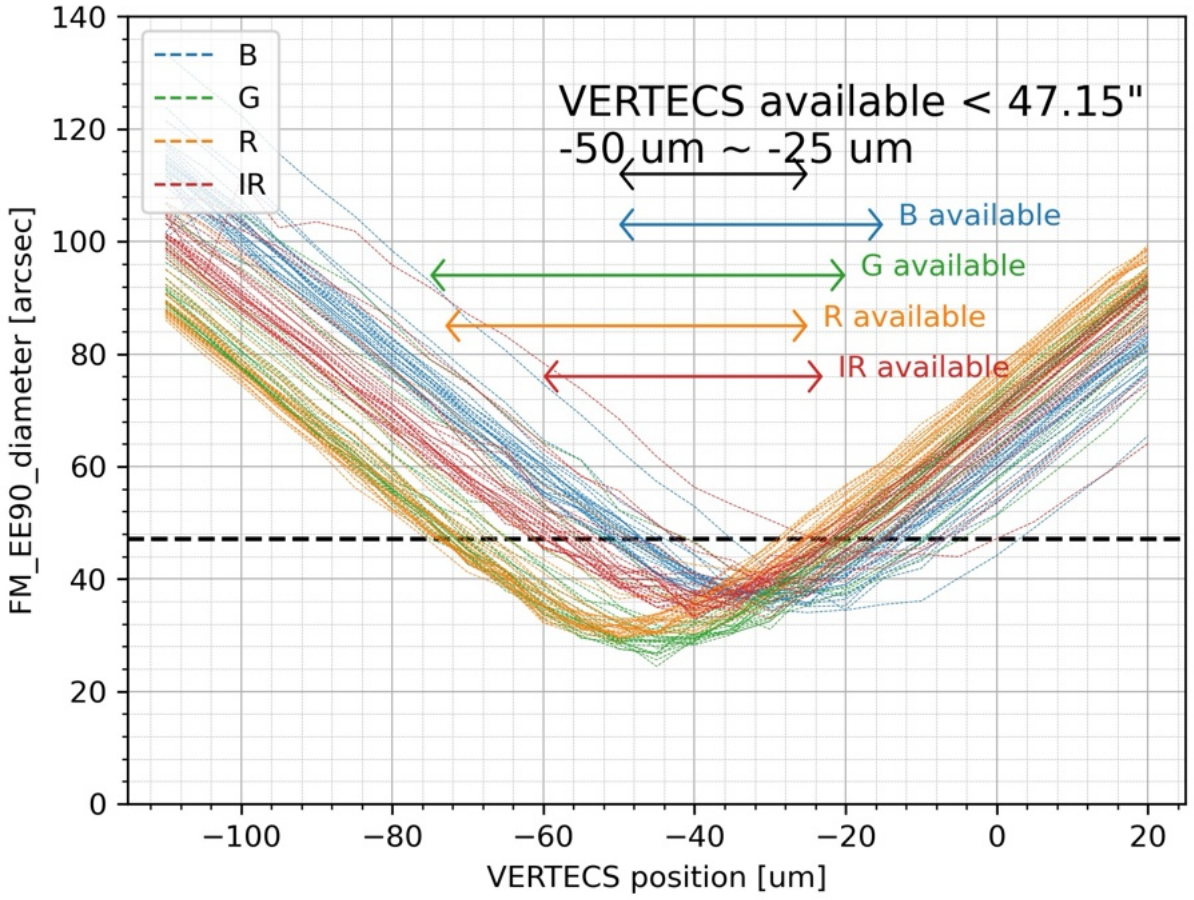
- VERTECS has no movable mechanism for focusing.
- Through-focus test conducted by shifting the collimator pinhole position.
- Telescope mounted on a two-axis stage to change the incident angle.



25 points per band
(100 points total for 4 bands)

3. 3D-CNN-Based Phase Diversity

Through-Focus Test Results



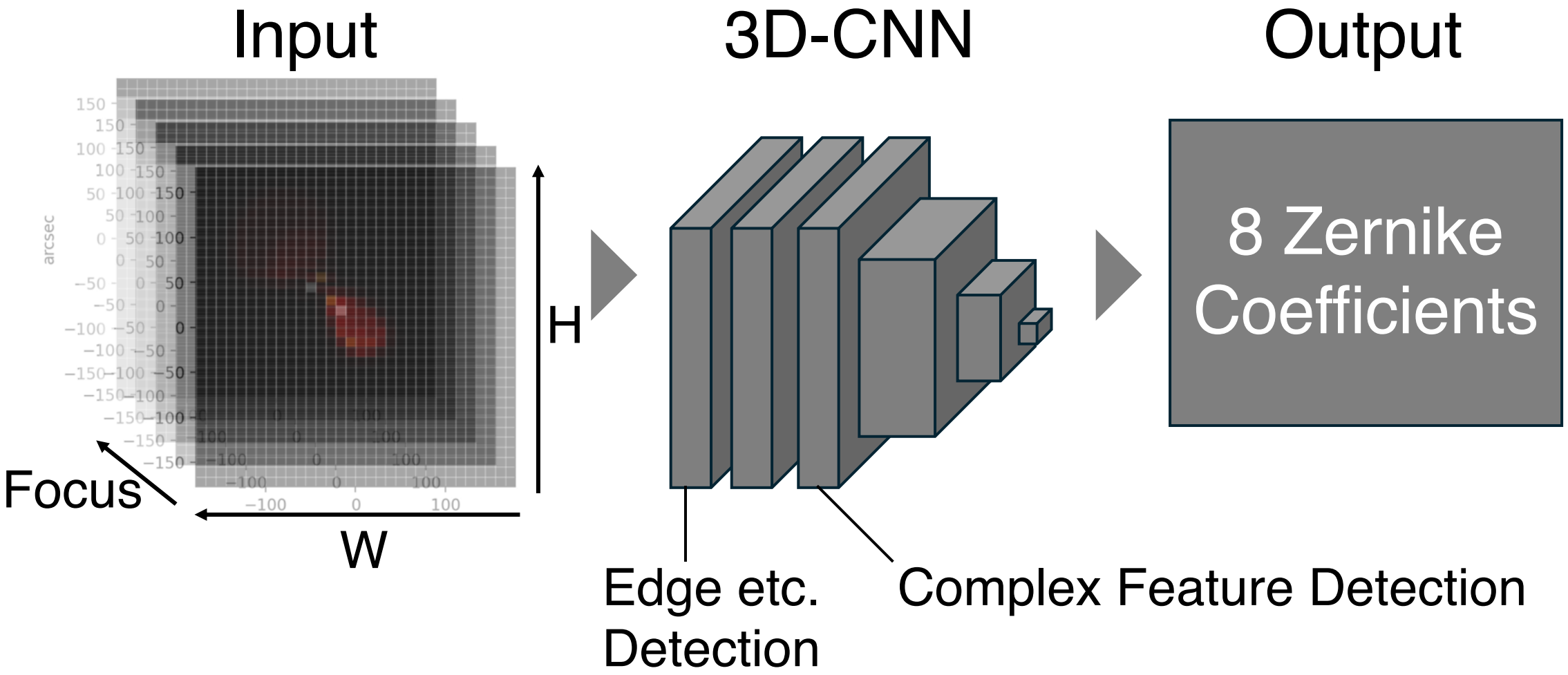
- 1pixel: 11.08 arcsec
- Required imaging performance: **EE90 diameter < 47 arcsec**

	B	G	R	IR
PSF size [arcsec]	**38.9** ± 1.2	**31.5** ± 2.4	**34.2** ± 2.4	**38.6** ± 1.2
Focal length [μm]	-30 ± 6	-43 ± 6	-47 ± 4	-36 ± 9

- Confirmed PSF **sharper than the requirement**
- Depth of focus (with chromatic aberration): **25 μm**

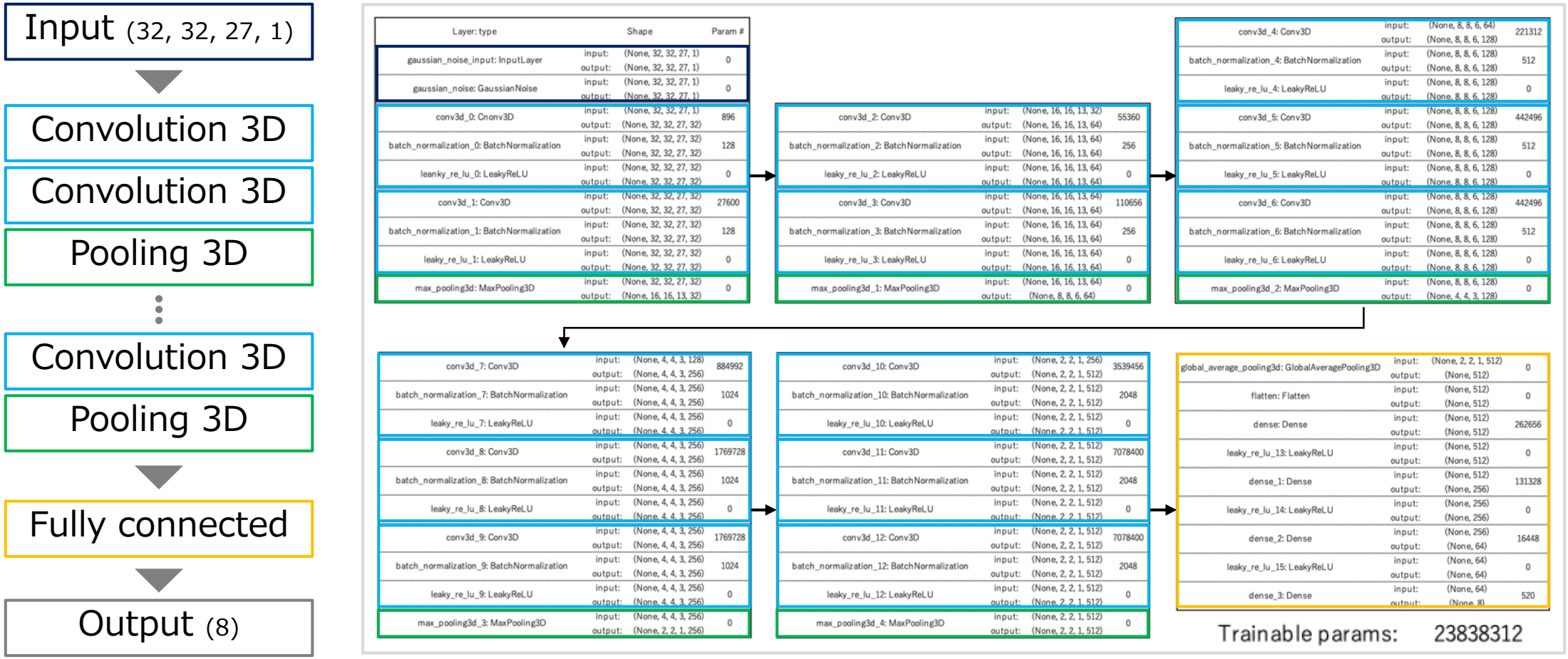
3. 3D-CNN-Based Phase Diversity

CNN: Convolutional Neural Network



3. 3D-CNN-Based Phase Diversity

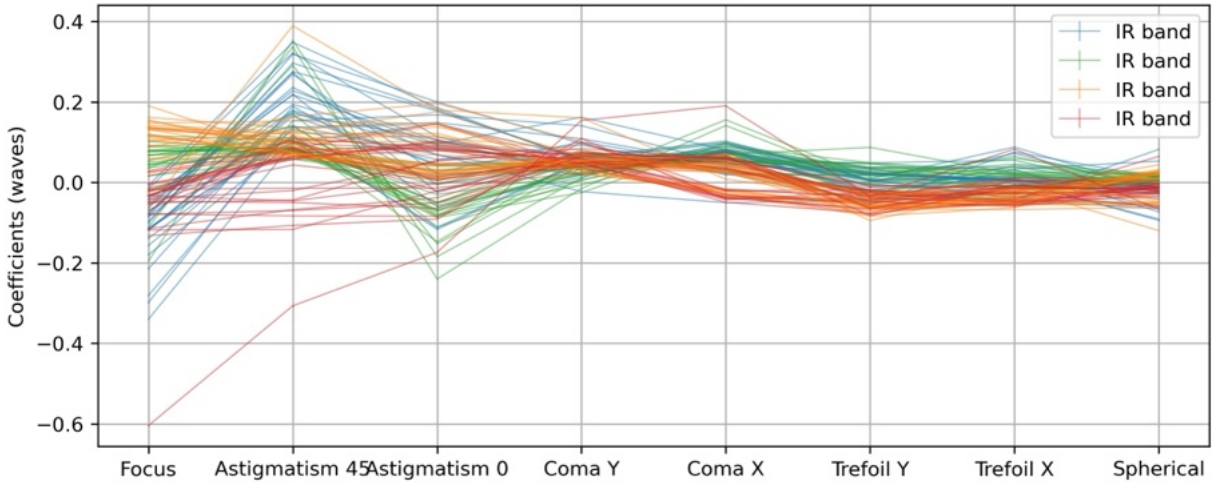
3D-CNN Model Architecture



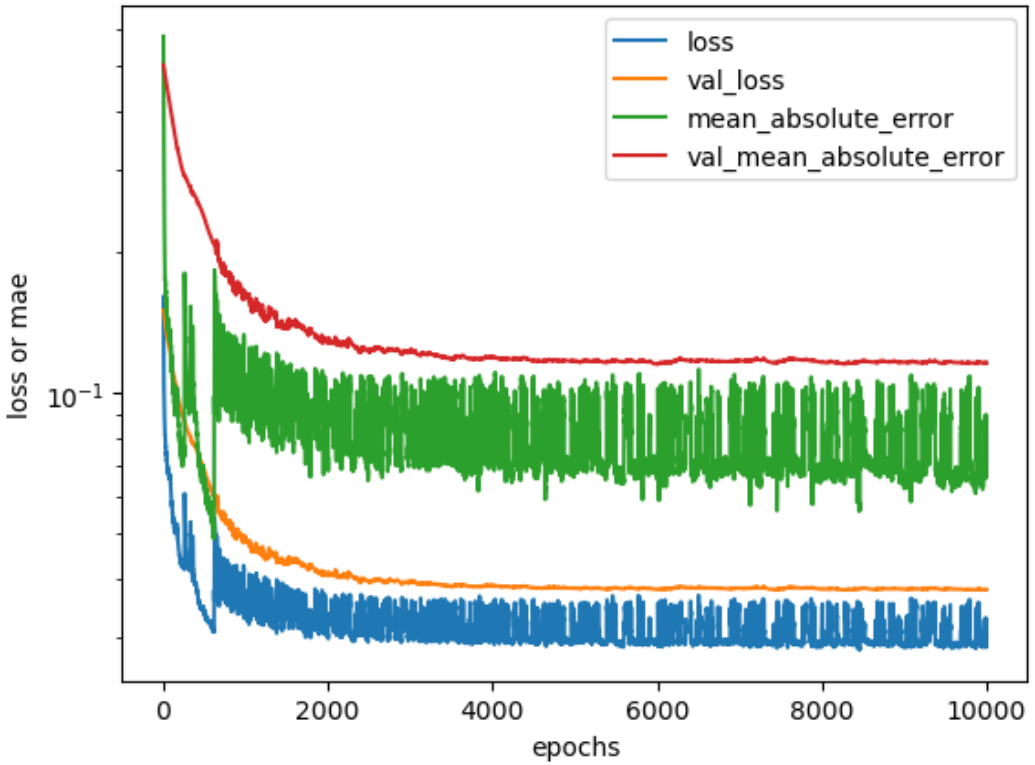
3. 3D-CNN-Based Phase Diversity

Results of Training 3D-CNN Model

- Trained for ~2-3 hours on GPU (RTX 4060, 8GB VRAM)



Zernike mode (noll index)



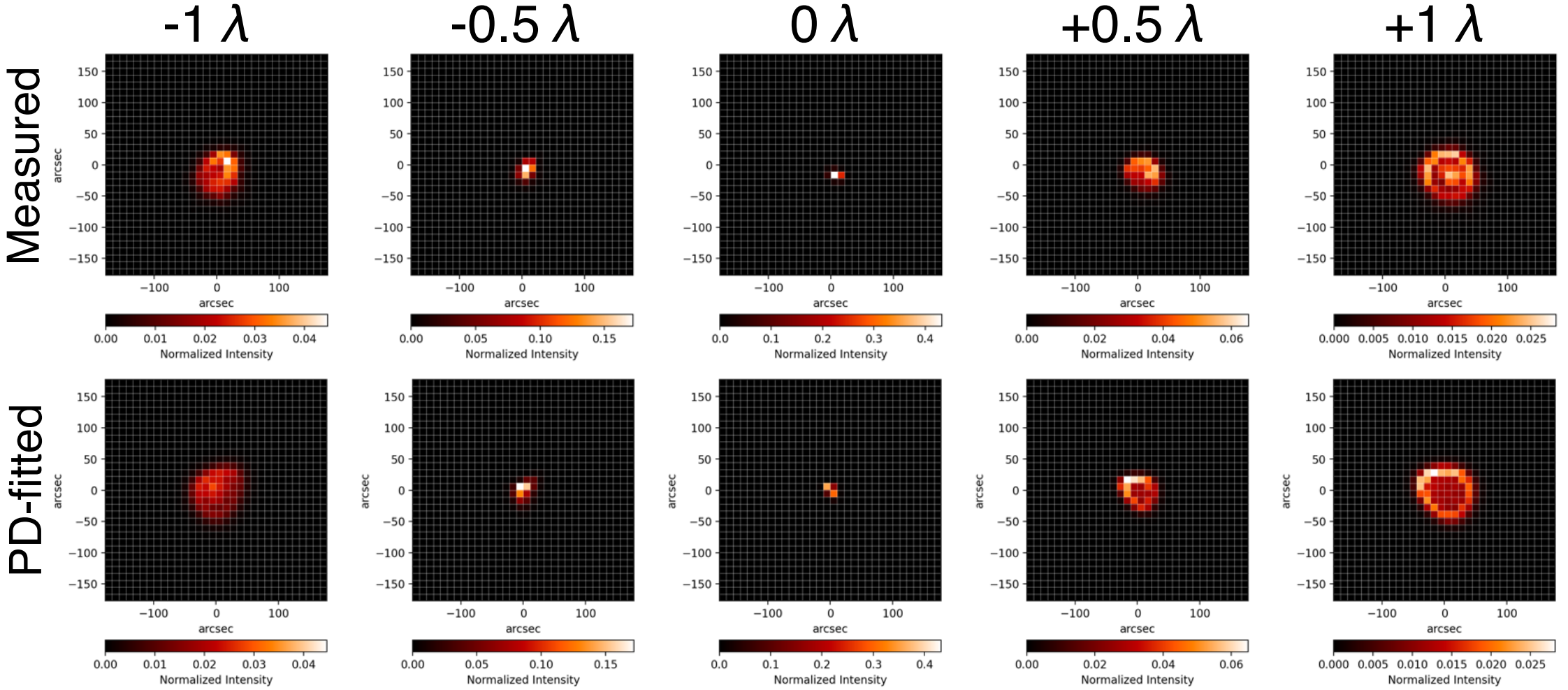
Learning curve

▶ Accuracy of each Zernike coefficient **better than ~0.1 wave**

3. 3D-CNN-Based Phase Diversity

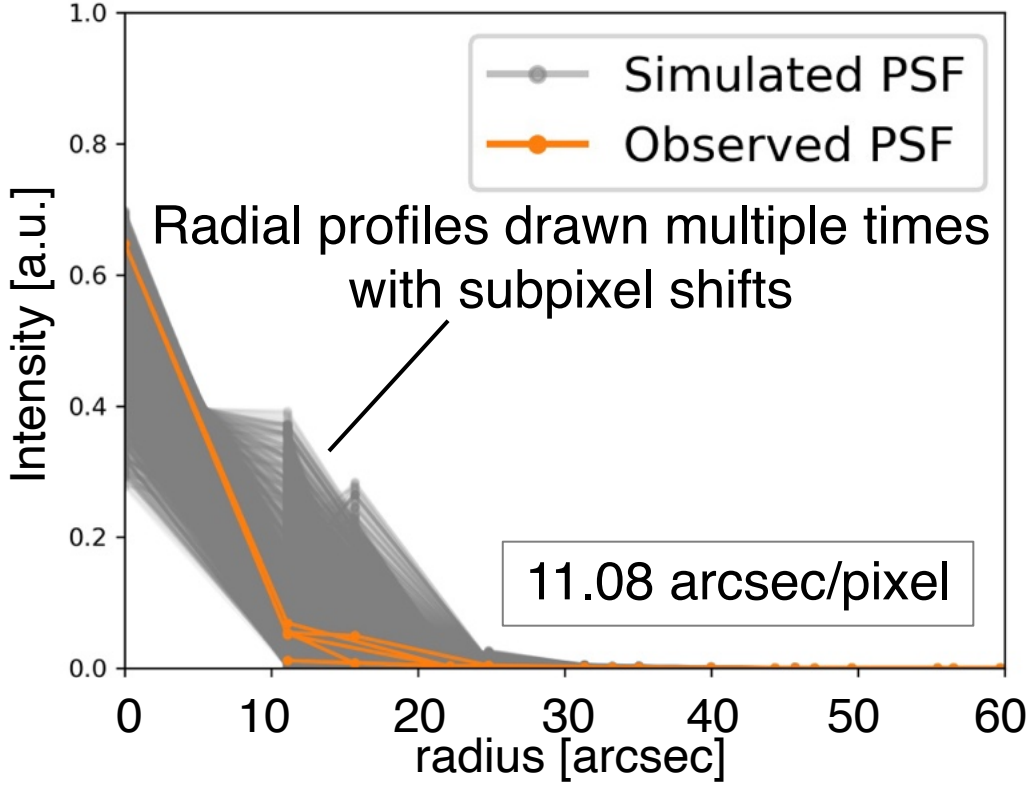
PSF Verification

VERTECS PSF, 11.08 “/pixel



3. 3D-CNN-Based Phase Diversity

PSF Radial Profile Check



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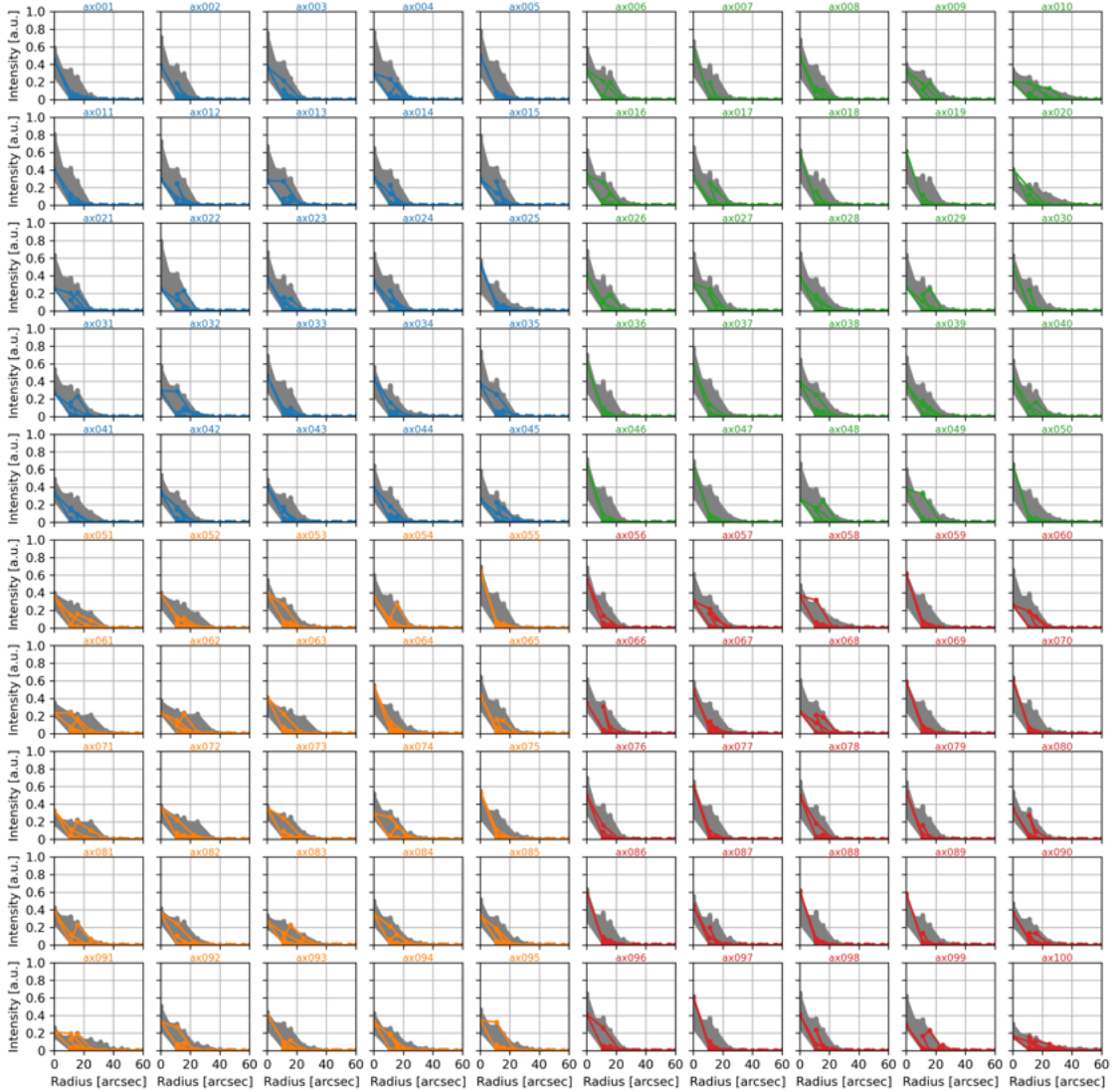


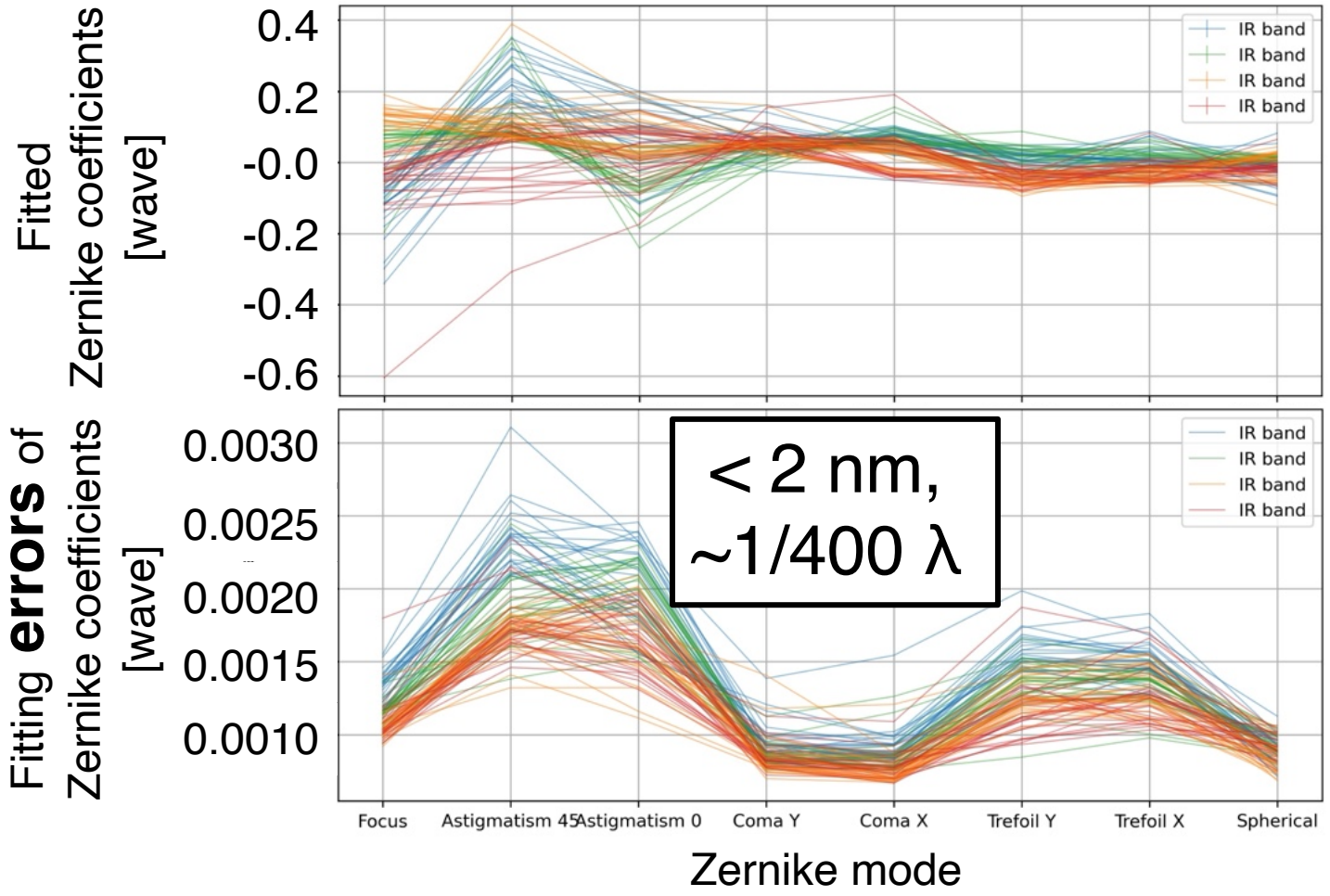
3. 3D-CNN-Based Phase Diversity

Results of Phase Diversity Fitting

- Initial estimates:
  < **0.1 λ** accuracy
  (by 3D-CNN)

- Zernike coefficients:
  < **1/400 λ** precision
  (by PD Fitting)

Detailed accuracy
to be confirmed with
other telescopes
(higher sampling)



3. 3D-CNN-Based Phase Diversity

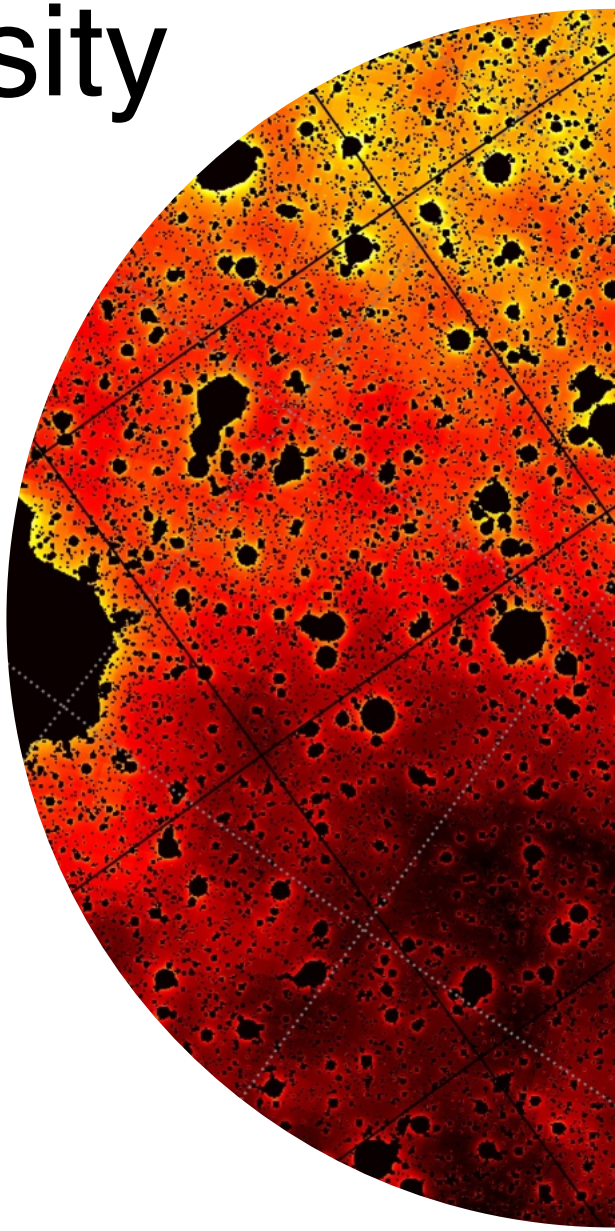
Use of the Obtained PSF Model

Current Work:

- Simulated observation images generated using the PSF model
- Applied to foreground light modeling and observation planning of the cosmic optical background light

Future Work:

- Evaluated the effect of PSF wings on foreground light modeling
- Develop an algorithm to estimate attitude stability and focus variation from observation images



Summary

1. A Phase Diversity technique based on machine learning (3D-CNN) was developed for wavefront aberration measurement of the VERTECS satellite.
2. The 3D-CNN accurately estimates the initial values for Phase Diversity optimization, effectively avoiding local minima.
3. The resulting PSF model is utilized for foreground light modeling and analysis of the cosmic optical background radiation.

ありがとうございました。