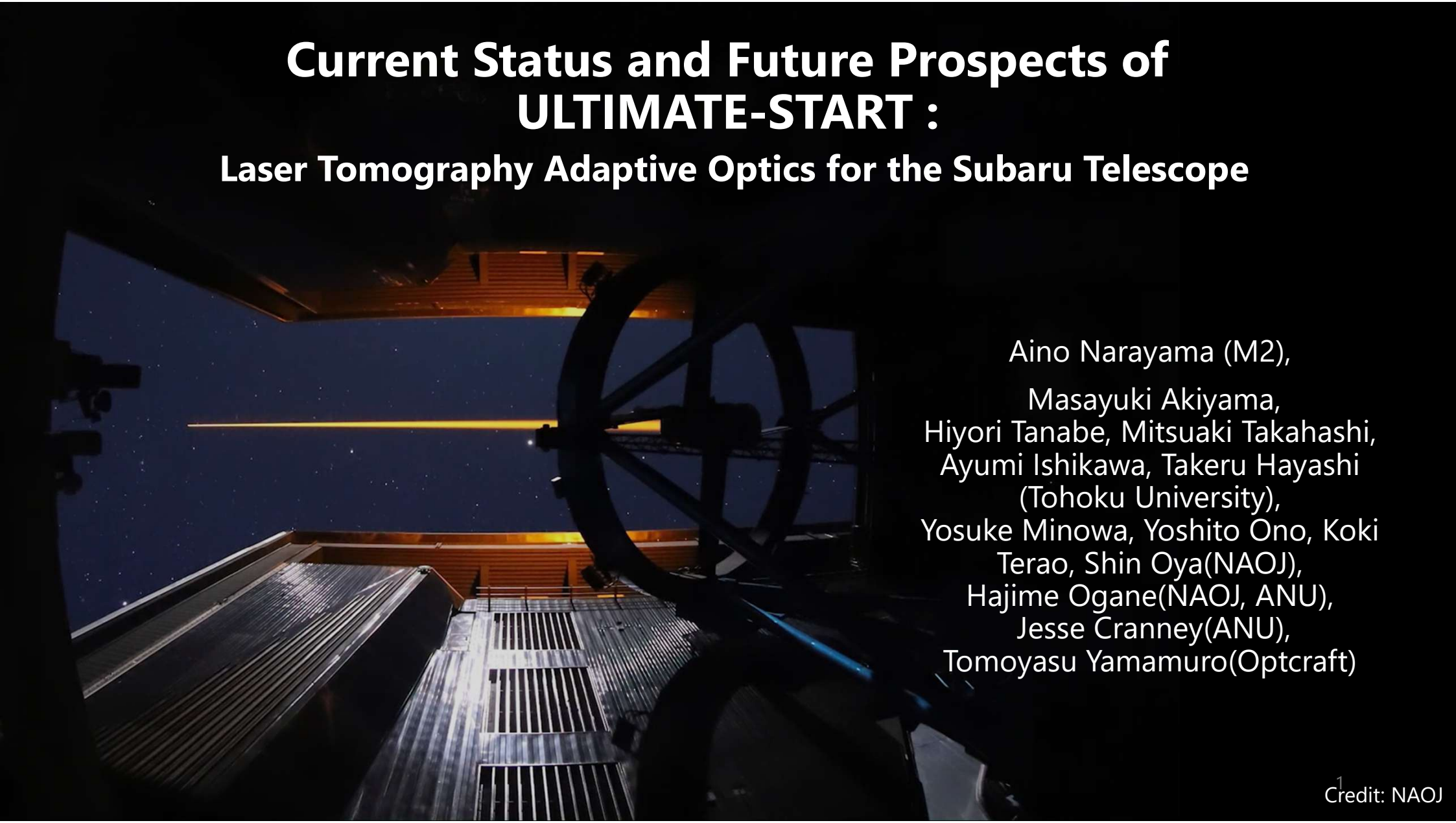
Current Status and Future Prospects of ULTIMATE-START :

Laser Tomography Adaptive Optics for the Subaru Telescope



Aino Narayama (M2),

Masayuki Akiyama,
Hiyori Tanabe, Mitsuaki Takahashi,
Ayumi Ishikawa, Takeru Hayashi
(Tohoku University),
Yosuke Minowa, Yoshito Ono, Koki
Terao, Shin Oya(NAOJ),
Hajime Ogane(NAOJ, ANU),
Jesse Cranney(ANU),
Tomoyasu Yamamuro(Optcraft)

Credit: NAOJ

What is ULTIMATE-START ?

ULTIMATE-START is prototype of ULTIMATE Subaru, providing a narrow-field LTAO mode in ULTIMATE

ULTIMATE-START: Subaru Tomographic Adaptive optics Research experimenT

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

Feature

① **Use 4 LGS & 4 WFS**

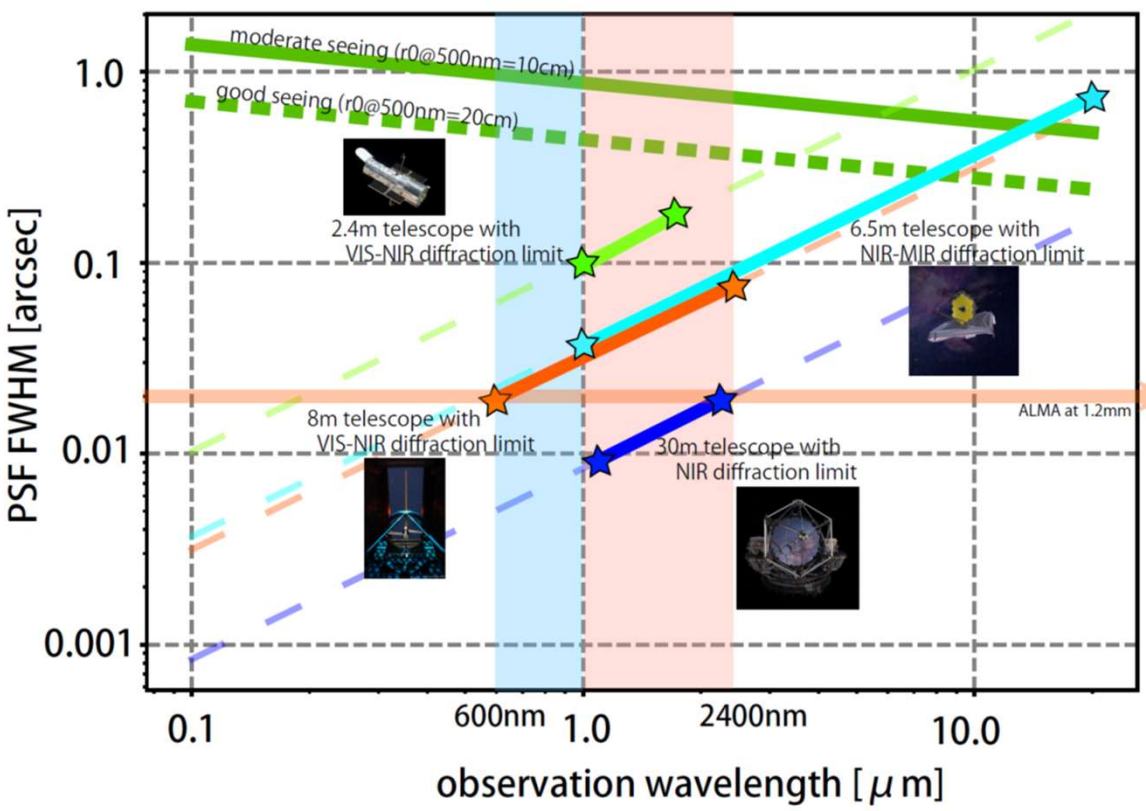
- Laser light source (589nm, TOPTICA) divided into **4 LGS**
- LGS asterism diameters are selectable from **10", 20", 30", 40"**

② **DM upgrade**

- 188DM → **ALPAO 64×64DM** : enable much finer wavefront corrections

©国立天文台

Goal of ULTIMATE-START



Simulated images of a galaxy 10 billion years ago

Goals：

- Achieve diffraction-limited performance in the **visible and near-infrared (NIR)** bands
- Attain a FWHM of **0.02 arcsec at 600 nm**

Science goals：

- Advance understanding of **galaxy formation and evolution**
  - Star formation
  - Galaxy mergers
  - The role of AGN feedback

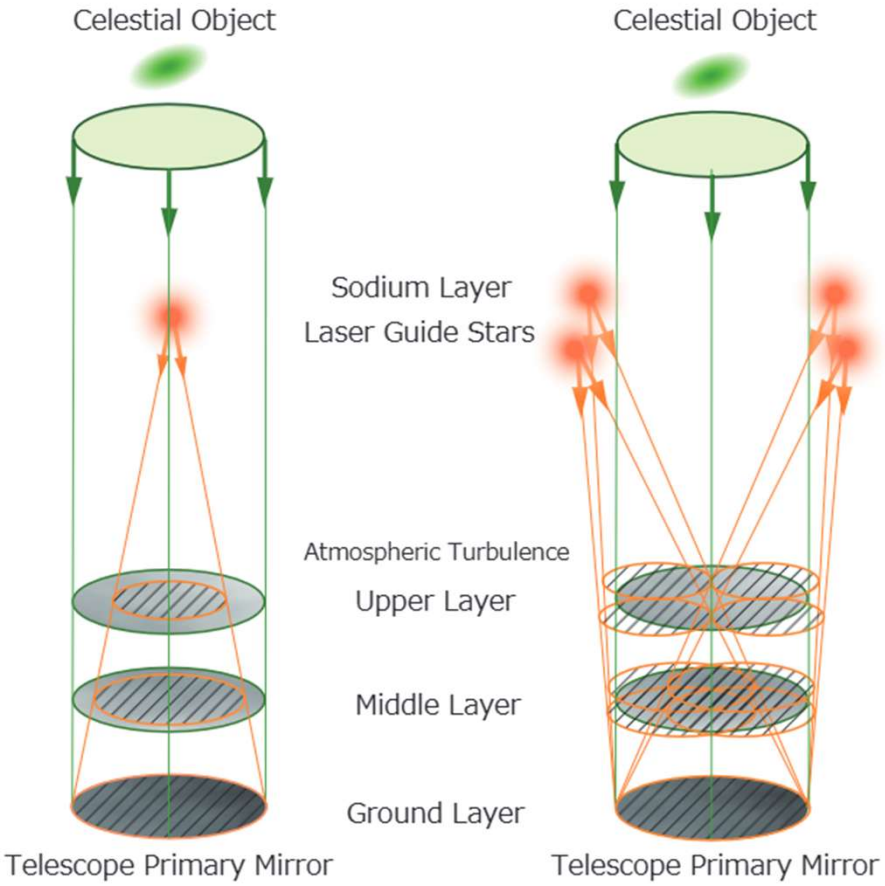
What is LTAO ?

Conventional Subaru AO system

SCAO

Single Conjugate Adaptive Optics

- **Only one laser guide star (LGS)** is used.
- There are areas where the wavefront cannot be measured, reducing the correction accuracy
  ➡ **Cone effect**



ULTIMATE-START

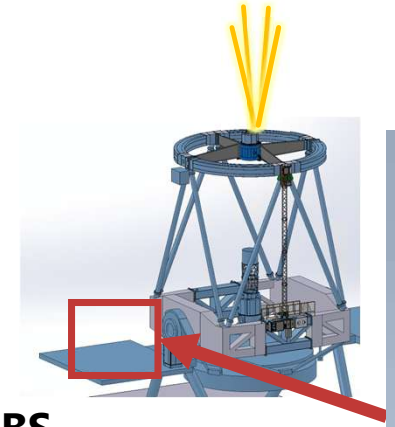
LTAO

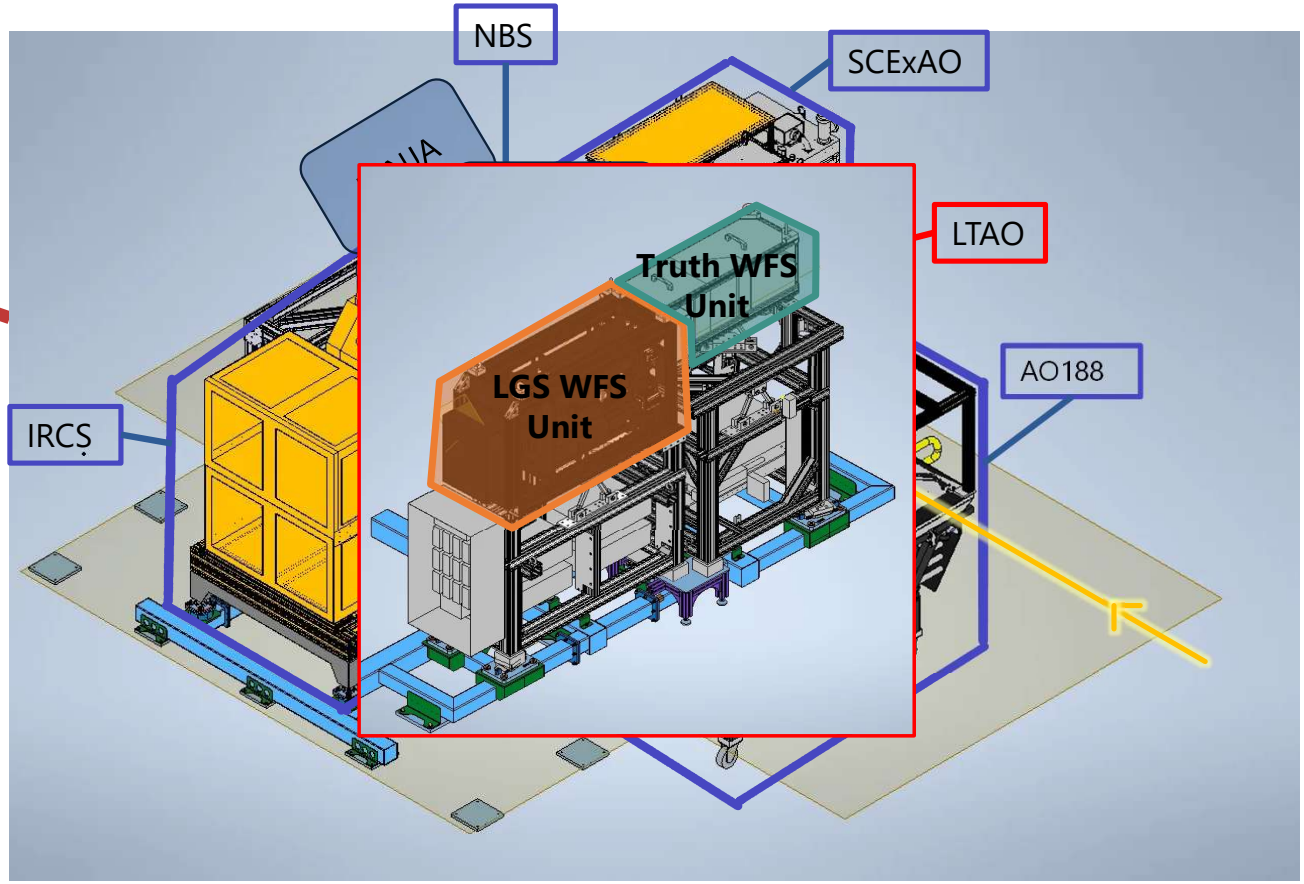
Laser Tomography Adaptive Optics

- Reduces the cone effect and improves AO correction performance
- Use multiple LGSs and estimate wavefront at each altitude

Overview of LTAO

- Light from the telescope passes through **AO188**, then through **LTAO**,
- And is subsequently directed to each instrument via the **NBS**



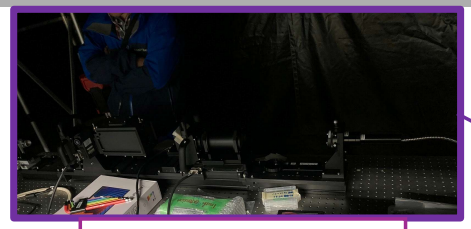


Instruments:

- **IRCS**（Infrared Camera and Spectrograph）
- **SCExAO**（Coronagraphic ExAO）
- **NINJA**（High-sensitivity, wide-band spectrograph）: currently being installed
- **3D Ⅱ**（Visible IFU）: planned for future installation

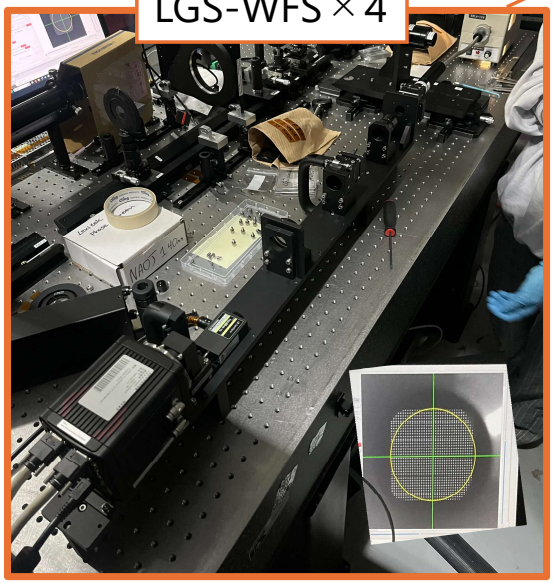
Installation : August 6–22, 2025

Alignment work on Obs floor

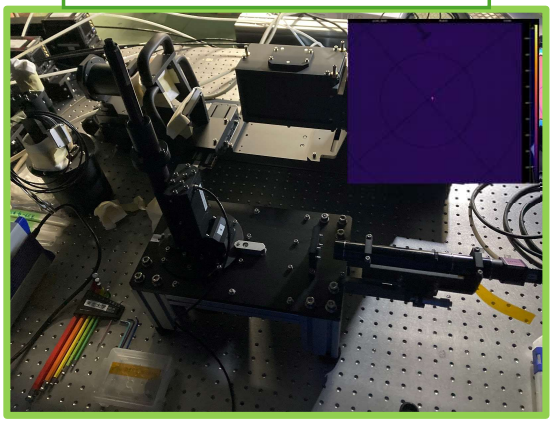


Pre-focal optics

LGS-WFS × 4



Offner relay optic × 4



Period：August 6-22, 2025

✓ **Alignment of individual optical systems under summit environmental conditions**

- Pre-focal optics
- Four LGS wavefront sensors (LGS-WFSs)
- Four Offner relay optics

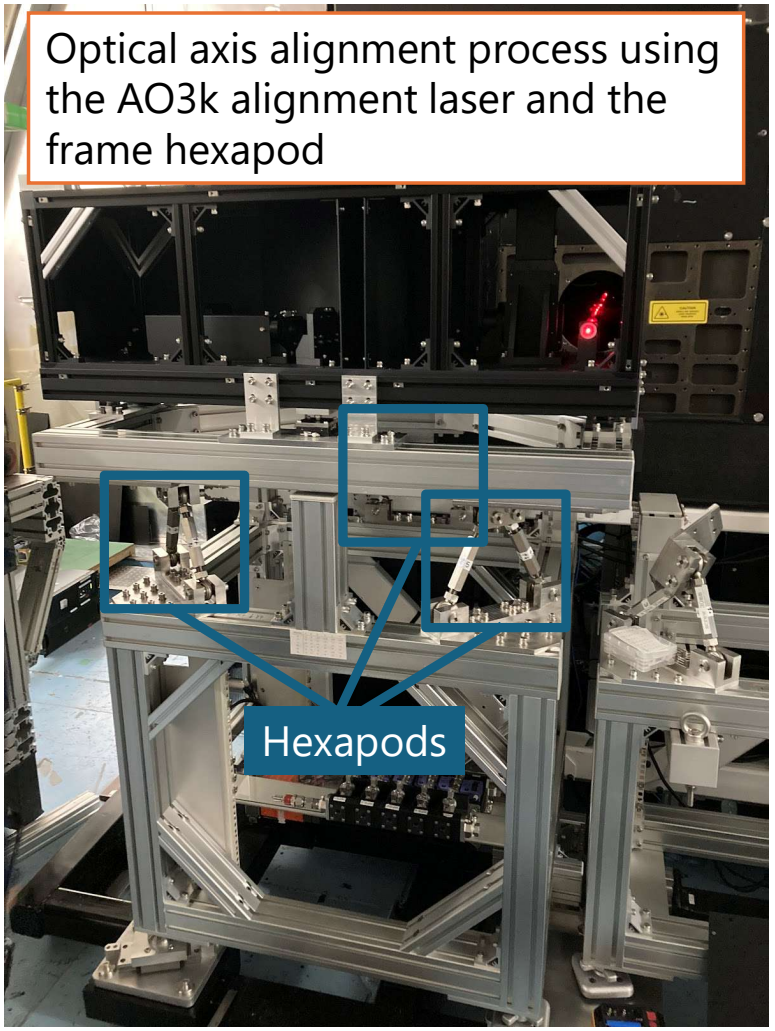
Installation : August 6–22, 2025

Installation work on NsIR

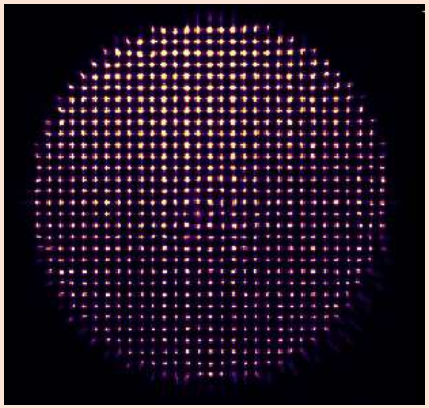
Period：August 6-22, 2025

- ✓ Alignment of individual optical systems
- ✓ **Installation and alignment on the common platform**
- ✓ **System testing and data acquisition**

Optical axis alignment process using the AO3k alignment laser and the frame hexapod



Final :
WFS Image Check
Confirmed proper light injection into each WFS.
Verified 32 × 32 sub-apertures on all sensors.

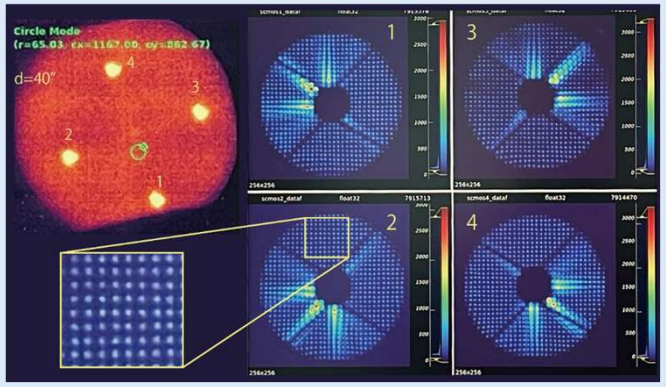


First onsky observation

Details on P06:Akiyama-san

Date : December 3, 8

- Truth WFS loop close with NGS
- Acquisition test of 4 laser guide stars



DM Loop close test	NGS	LGS
Truth WFS	○	
LGS WFS (one by one)	○	TBC
4LGS WFS		TBC

- Truth WFS Loop Close with NGS → Success !

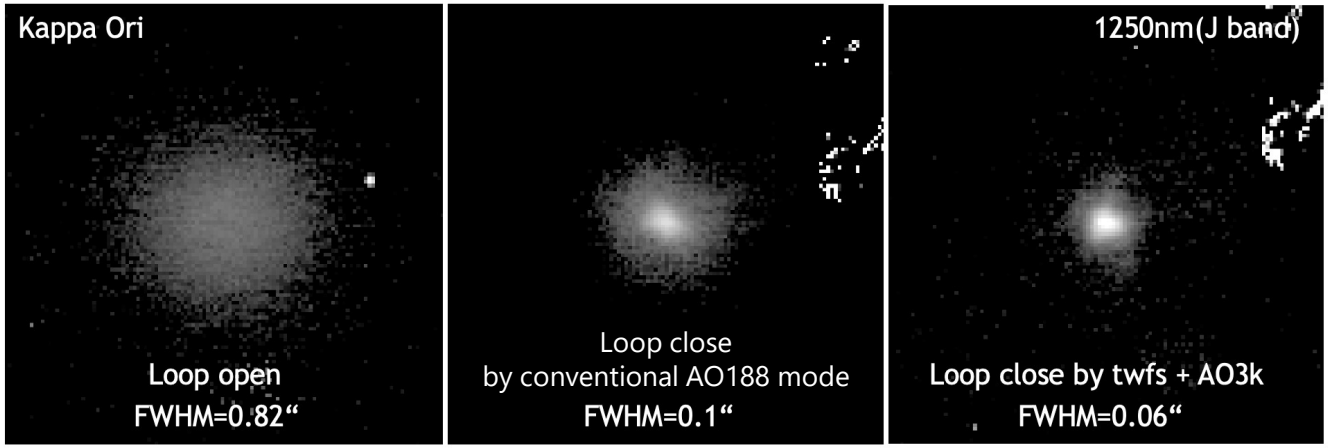


Fig 1 : Taken by IRCS

- LGS WFS Loop Close Test with NGS → Success !
- LGS Loop Close Test with 1LGS WFS → TBC
- Acquire 4LGS to 4LGS-WFS and close **LTAO loop**
  → TBC (4 LGS were acquired with offsets)

Tip-Tilt correction with machine learning approach

- Trying to apply **reinforcement learning to Tip-Tilt mirror for achieving 0.003” TT residual**

PID

Control value

$$u(t) = \underbrace{K_p e(t) + K_i \int_0^t e(t)d\tau + K_d \frac{de(t)}{dt}}_{\text{PID gain parameter}} \quad (e(t)\text{: error})$$

Provides reactive control based on current and historical error signals.
Controller performance depends on gain tuning.

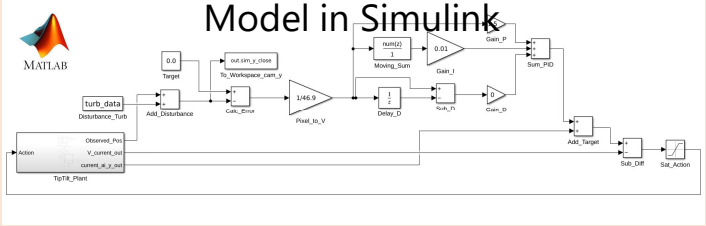
Reinforcement learning

$$V_\pi(s) = \mathbb{E}_\pi[\, R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \cdots \mid S_t = s \,]$$

Learns an optimal policy that maximizes the expected cumulative future reward $V_\pi(s)$.
Achieves advanced control strategies by leveraging historical turbulence measurements and delay information.

Environment

Model in Simulink



II

TipTiltEnv.py

State
= error from past 5 steps
+ previous action
Reward
= - error^2

Action
= TTM target voltage

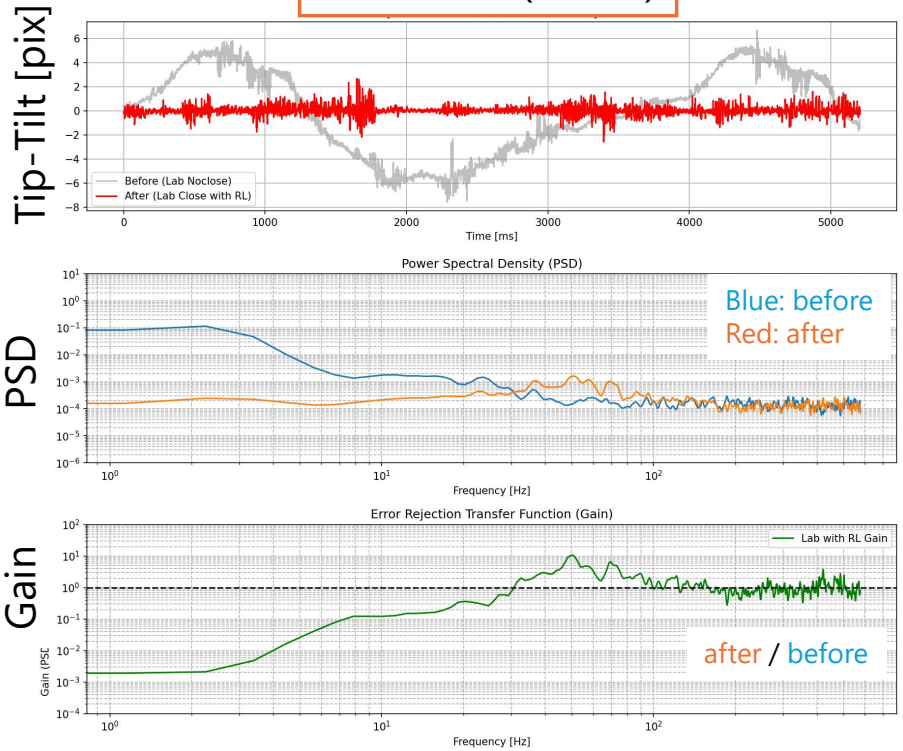
Agent 【Recurrent PPO with LSTM】

learns the optimal policy to maximize rewards.

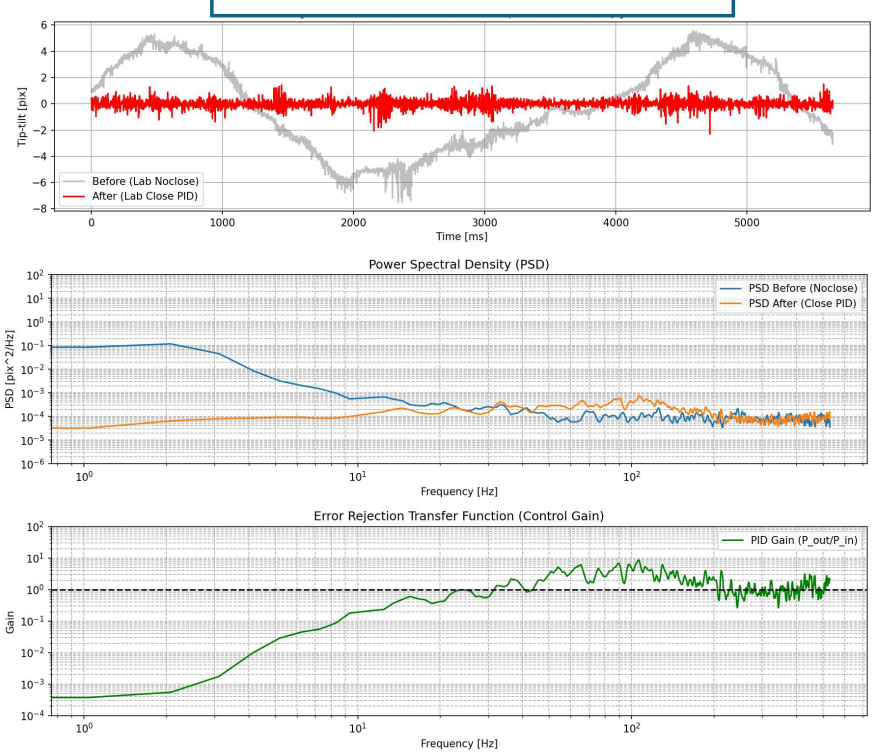
Learning curve
x : traning time
y : average reward

Tip-Tilt correction with machine learning approach

Results with RL
3.25→0.32 (9.85%)



Results with optimal PID
(KP=0.85, KI=0.008, KD=0.08)
3.34→0.28 (8.50%)



Under the current setup, reinforcement learning and PID control exhibit **comparable performance**.
Future work includes improving the reinforcement learning model and tuning hyperparameters.

Summary

Achievements in 2025

- **Installation & First Light:** Completed LTAO installation and achieved first light.
- **Demonstrated Performance:** Successfully acquired calibration data and demonstrated AO loop close using an NGS & the Truth WFS.

Next Steps (June 2026)

- **Full LTAO Loop Close:** Acquire 4 LGSs to 4 LGS-WFSs simultaneously and aim to achieve full LTAO loop close in the next engineering observation.

As an early career researcher

- Experiencing instrument integration and commissioning at the summit gave me insights that cannot be obtained through simulations alone.
- I learned the importance of flexibility and problem-solving in real operational environments.
- I also came to appreciate the collaborative effort required to support world-class astronomical observations.
- This experience has further motivated me as an instrument developer, and I am deeply grateful for the opportunity.