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SHARPEST: atmospheric turbulence characterization for future AO systems at the Subaru Telescope

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Introduction

Future AO systems and atmospheric turbulence profile

Laser Tomography Adaptive Optics (LTAO)

ULTIMATE-START: Subaru Tomography Adaptive optics Research experimenT

- Multiple LGS + tomography for precise wavefront sensing
- Nearly diffraction limit for NIR+OPT wavelength range
- **Coarse (a few layers) turbulence profile (<20km) is important for tomography**

Ground Layer Adaptive Optics (GLAO)

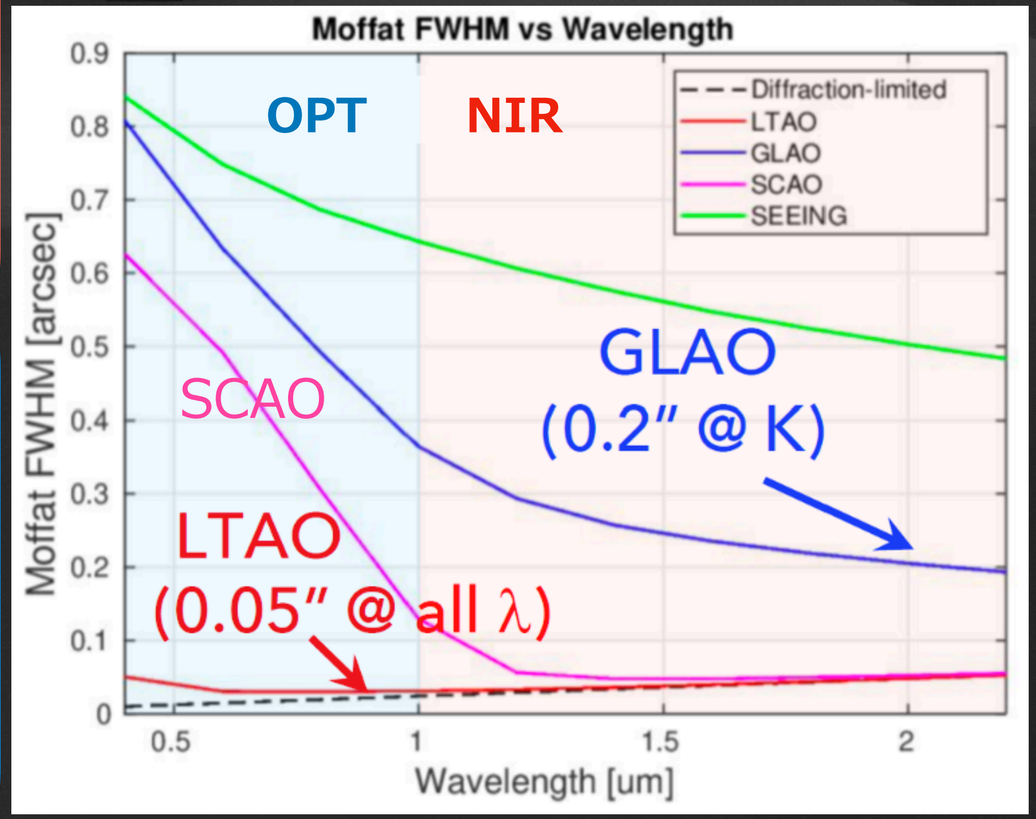
ULTIMATE Subaru

- Correct only ground layer turbulence
- 14x14 arcmin FoV (<1x1 arcmin in SCAO/LTAO)
- **Turbulence at the ground and/or inside the dome is important to predict performance and understand system**

Typical wavefront error (RMS)

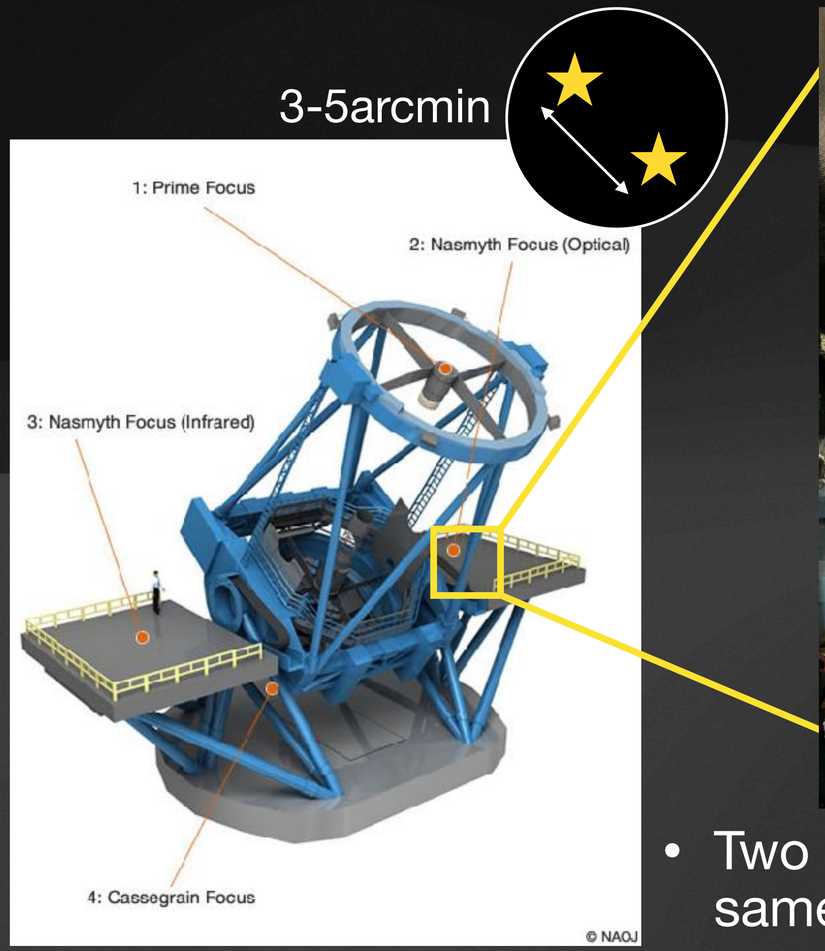
$\sigma_{\mathrm{LTAO}} \sim 100$ [nm]

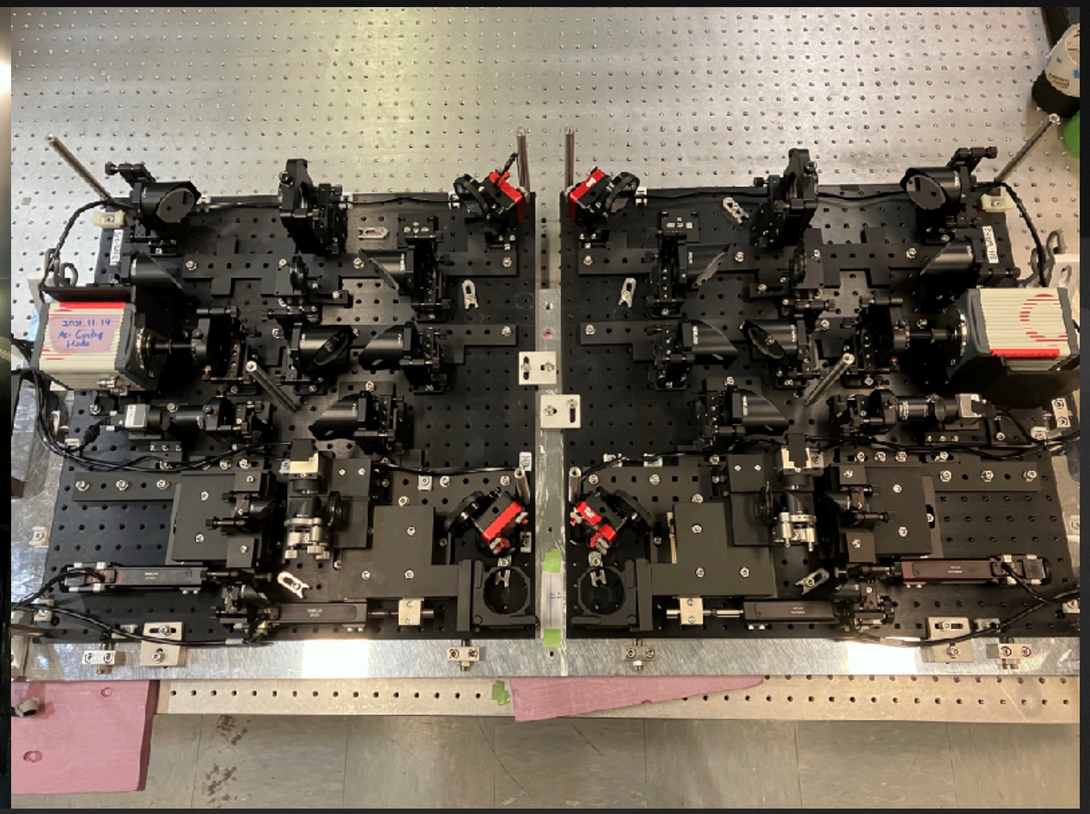
$\sigma_{\mathrm{GLAO}} \sim 500$ [nm]



SHARPEST project

Shack-Hartmann Atmospheric tuRbulence Profiling Experiment at the Subaru Telescope



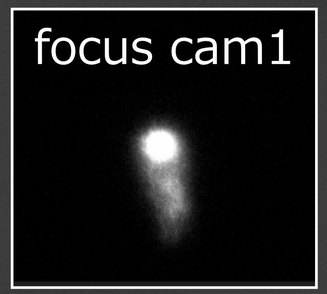


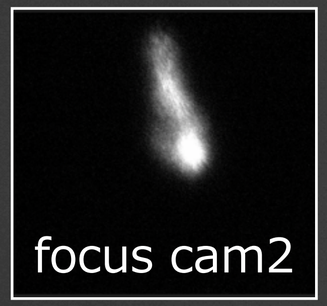
- Two SH sensors installed directly at Subaru to measure turbulence in the same line of sight with science instruments
- Coarse (a few km) turbulence sensing of entire altitude (<20km) and fine (~20m) sensing of ground altitude (<1km) at the same time

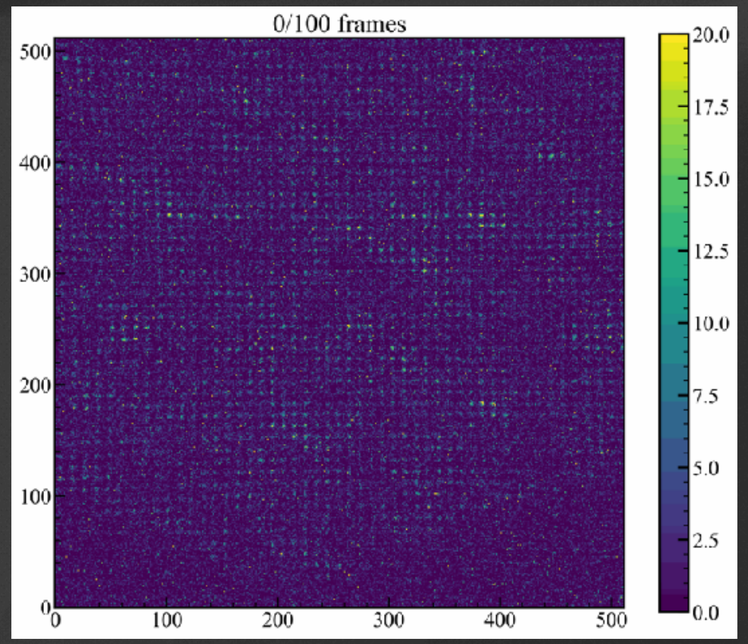
Observation and Data

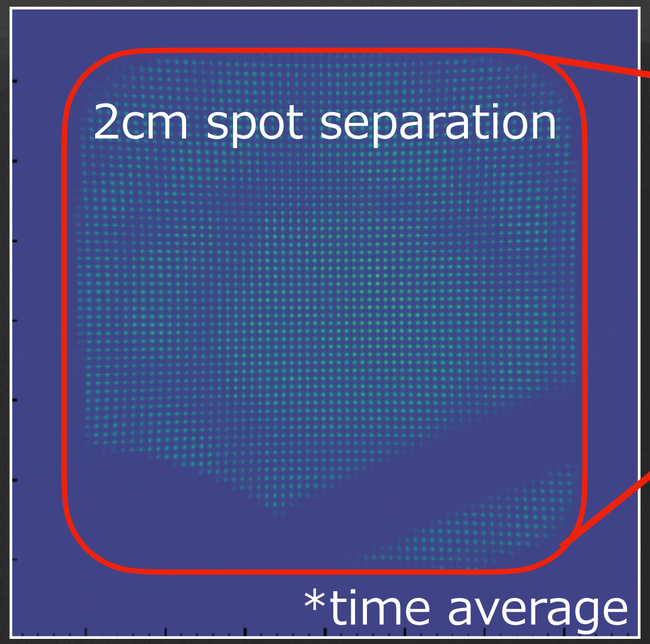
Three past engineering observations with Subaru Telescope

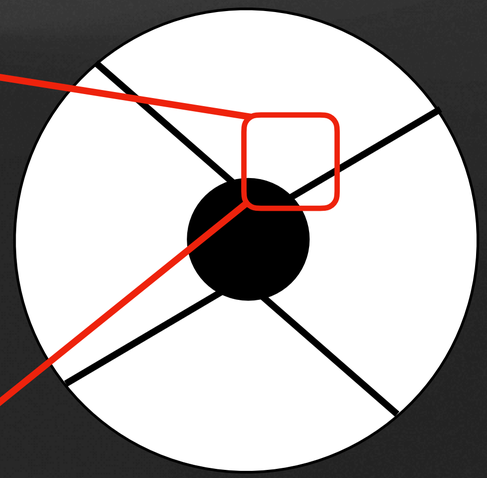
Date	Nov.12 2022, first half	Mar.14 2023, second half	May.05 2023, second half
Weather	clear	partly cloudy	partly cloudy
Target	m_V=5.9, m_R=5.0	m_V=0.0, m_R=2.6, m_R=4.8	m_V=0.0, m_V=4.7, m_V=5.2
Test item	acquisition, SH measurement	pixel scale check, SH measurement	SH measurement
Exposure	2.9, 4.3, 13 ms	1.4, 2.9, 4.3, 13 ms	1.4, 2.9, 4.3, 6.0, 8.0, 10, 13 ms











Shade by M2 central cone and M2/M3 spider

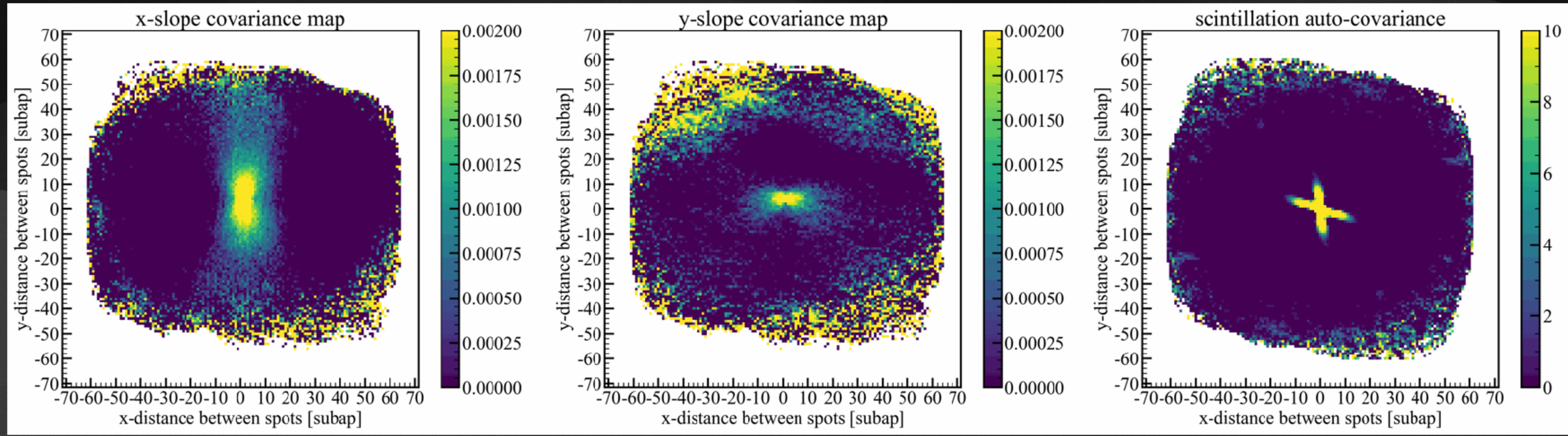
First step of analysis

Spatial correlation maps of Wavefront/Scintillation

correlation map of wavefront (x-slope)

correlation map of wavefront (y-slope)

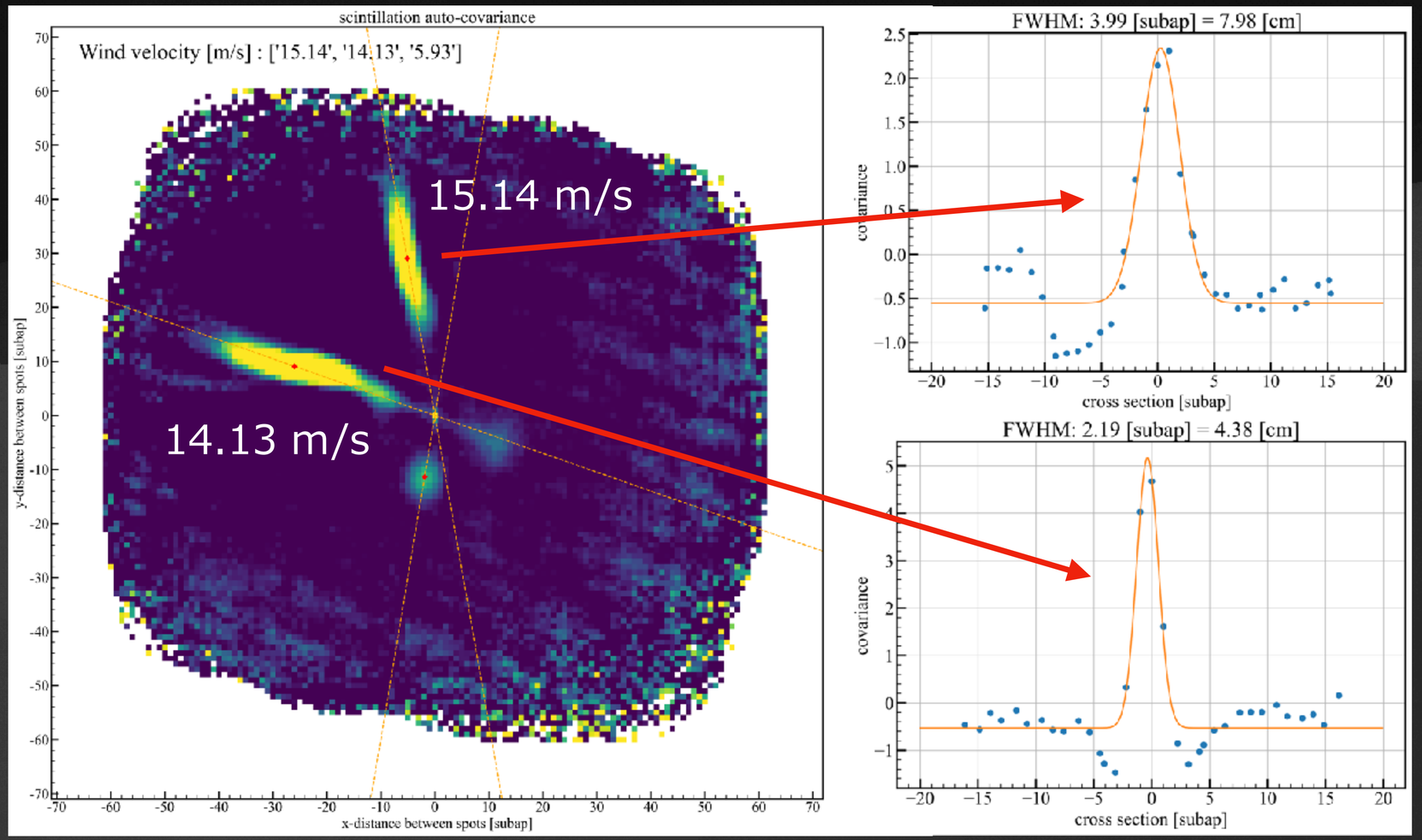
correlation map of scintillation



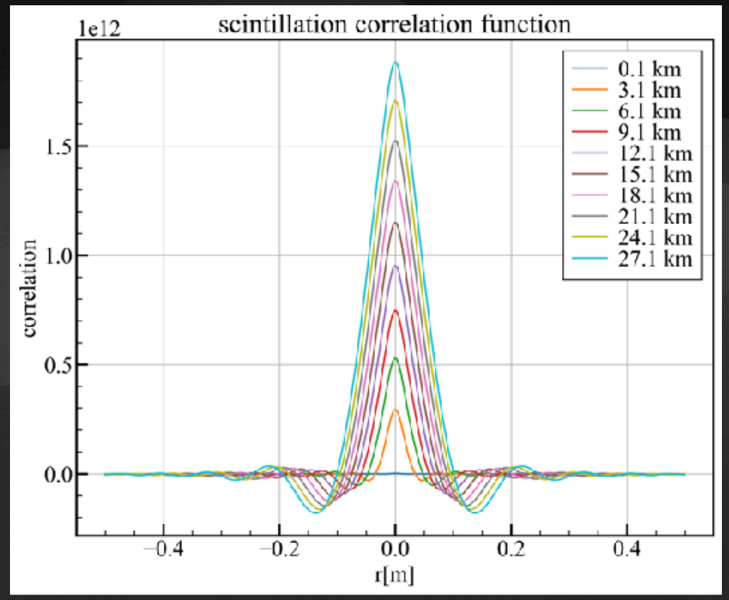
- Equivalent with spatial power spectrum, comparable with theory (e.g. Kolmogorov model)
- Spatial correlation map with changing time lag gives us information on wind.

Analysis 1/3

Temporal correlation analysis of scintillation



FWHM $= 0.78\sqrt{\lambda h}$ (Kolmogorov)



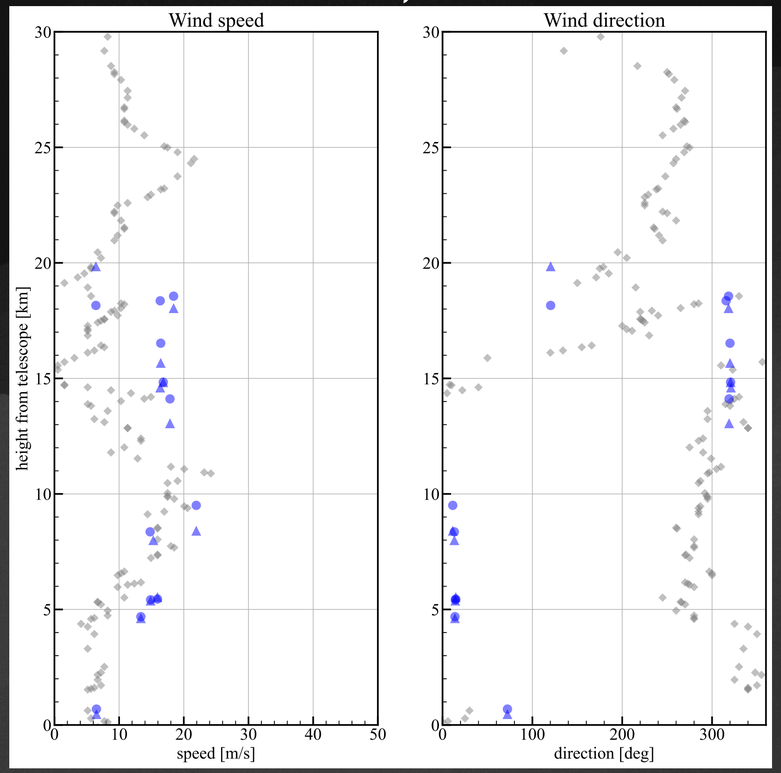
- Wind speed/direction from signal movement
- Wind height from signal width

Result 1/3

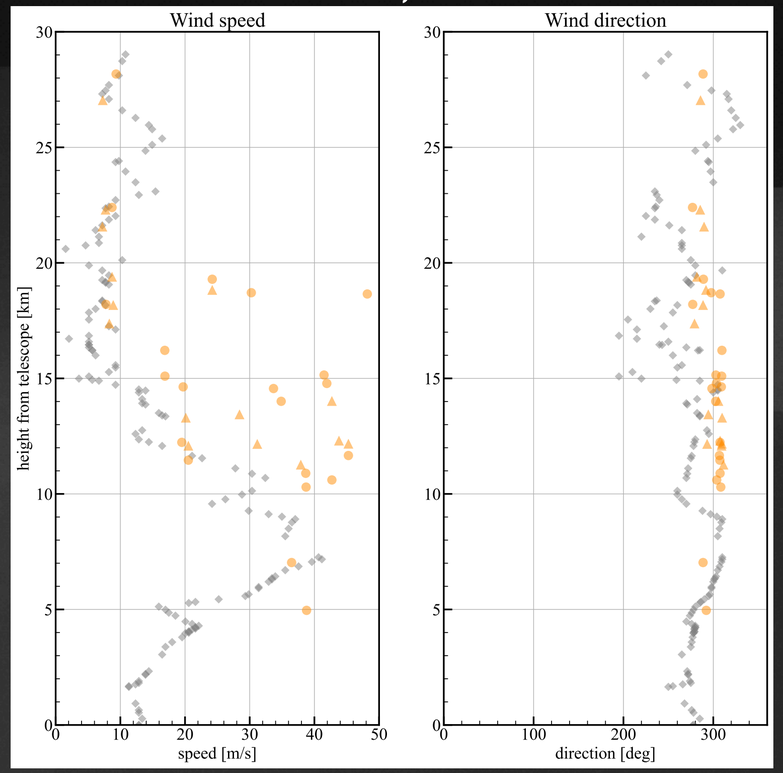
Wind speed/direction profile

rawinsonde

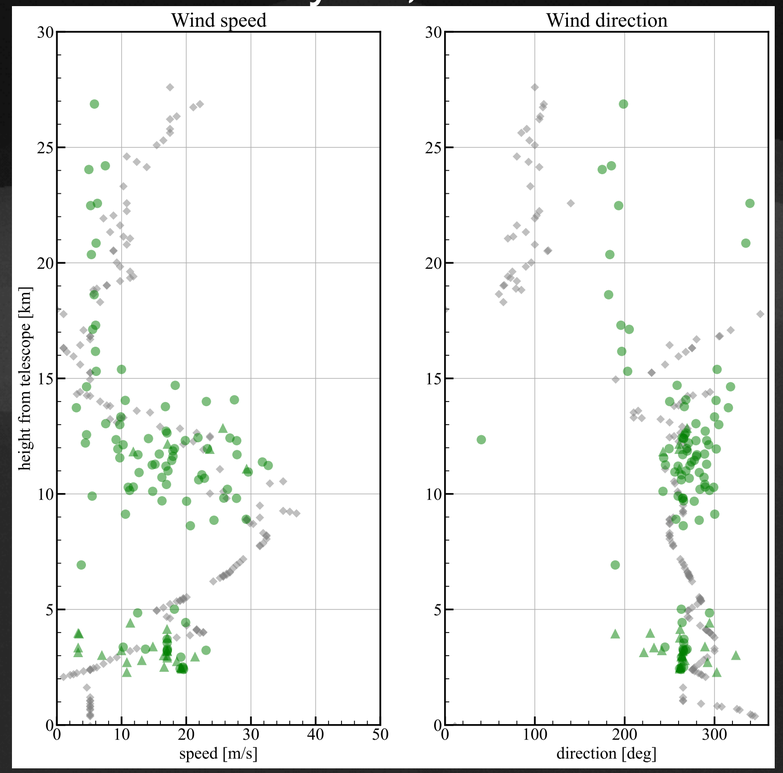
Nov.12, 2022



Mar.14, 2023



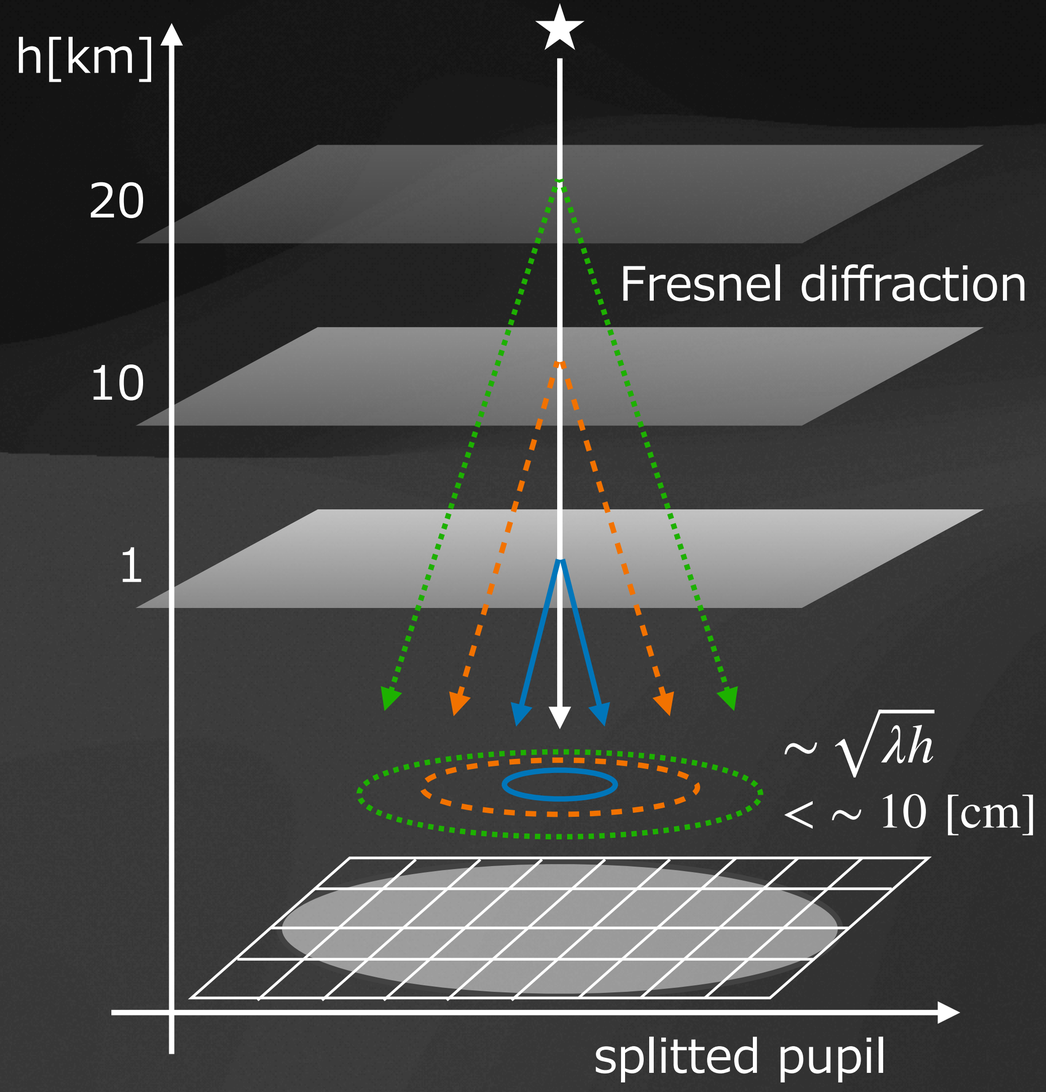
May.05, 2023



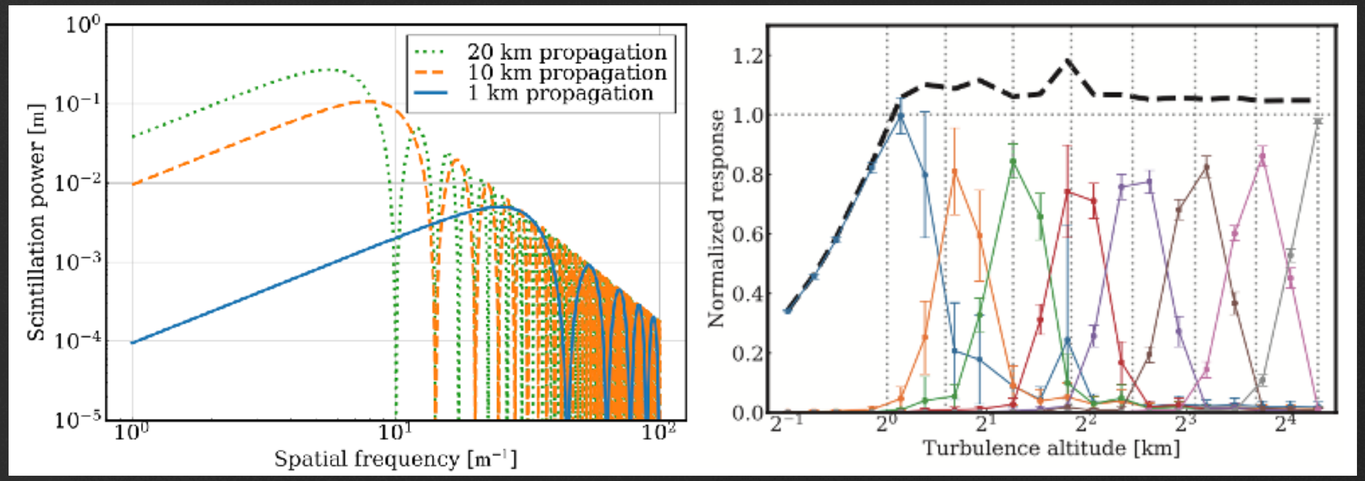
- Compared with rawinsonde measurement at Hilo airport (~50km / a few hours apart)
- Good match with each other. Largest uncertainty is wind altitude (a few km)

Analysis 2/3

Spatial correlation analysis of scintillation

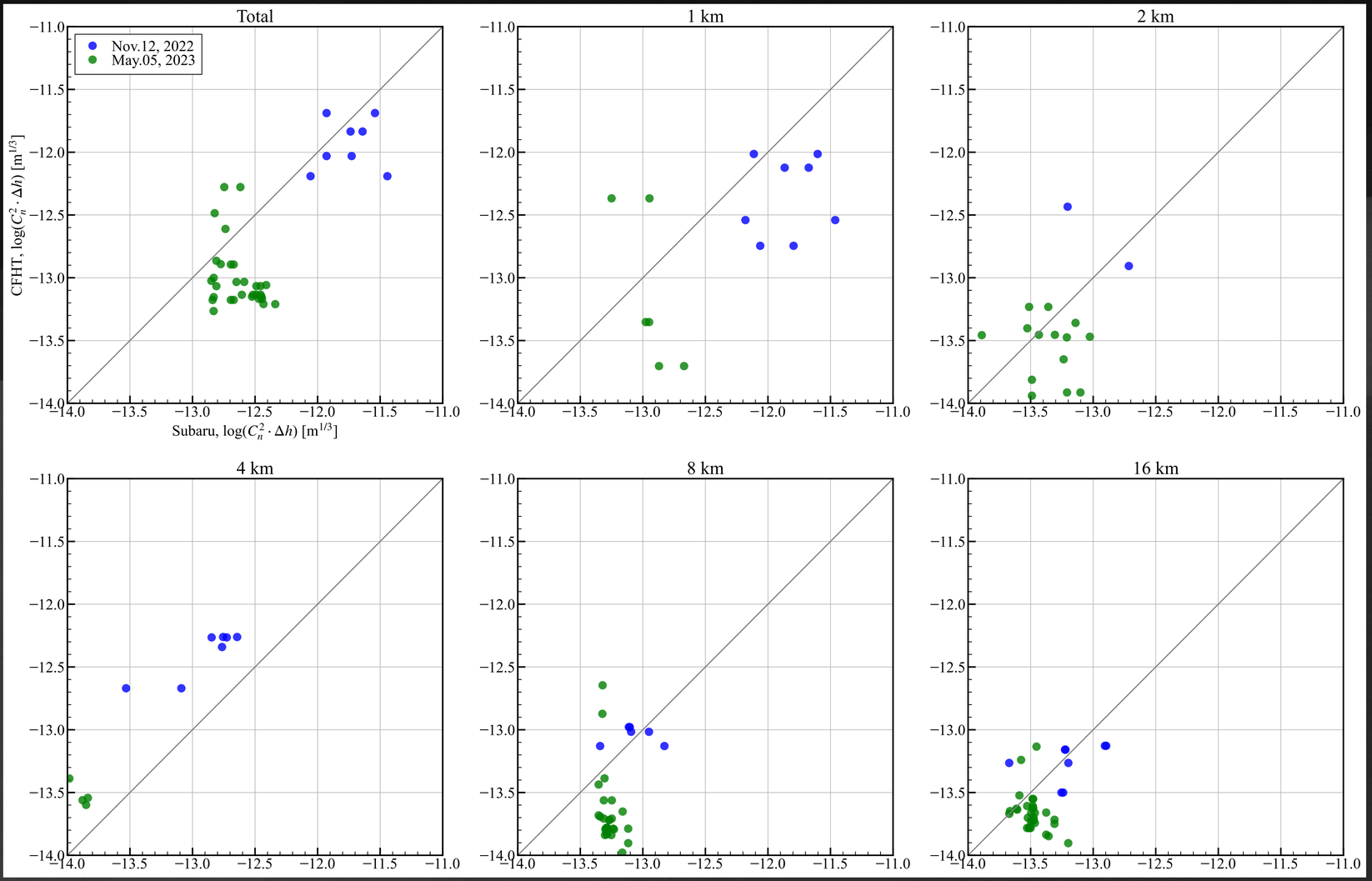


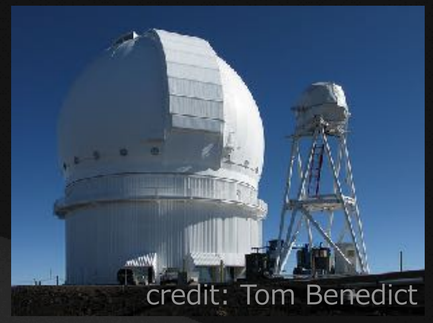
- Shack-Hartmann Multi Aperture Scintillation Sensor
- Correlation of scintillation with multiple spatial scale
  - Altitude resolution : a few km
  - Altitude range : >1km (with 2cm subaperture)
- Need fine pupil sampling (cm scale)



Result 2/3

Free atmospheric turbulence profile

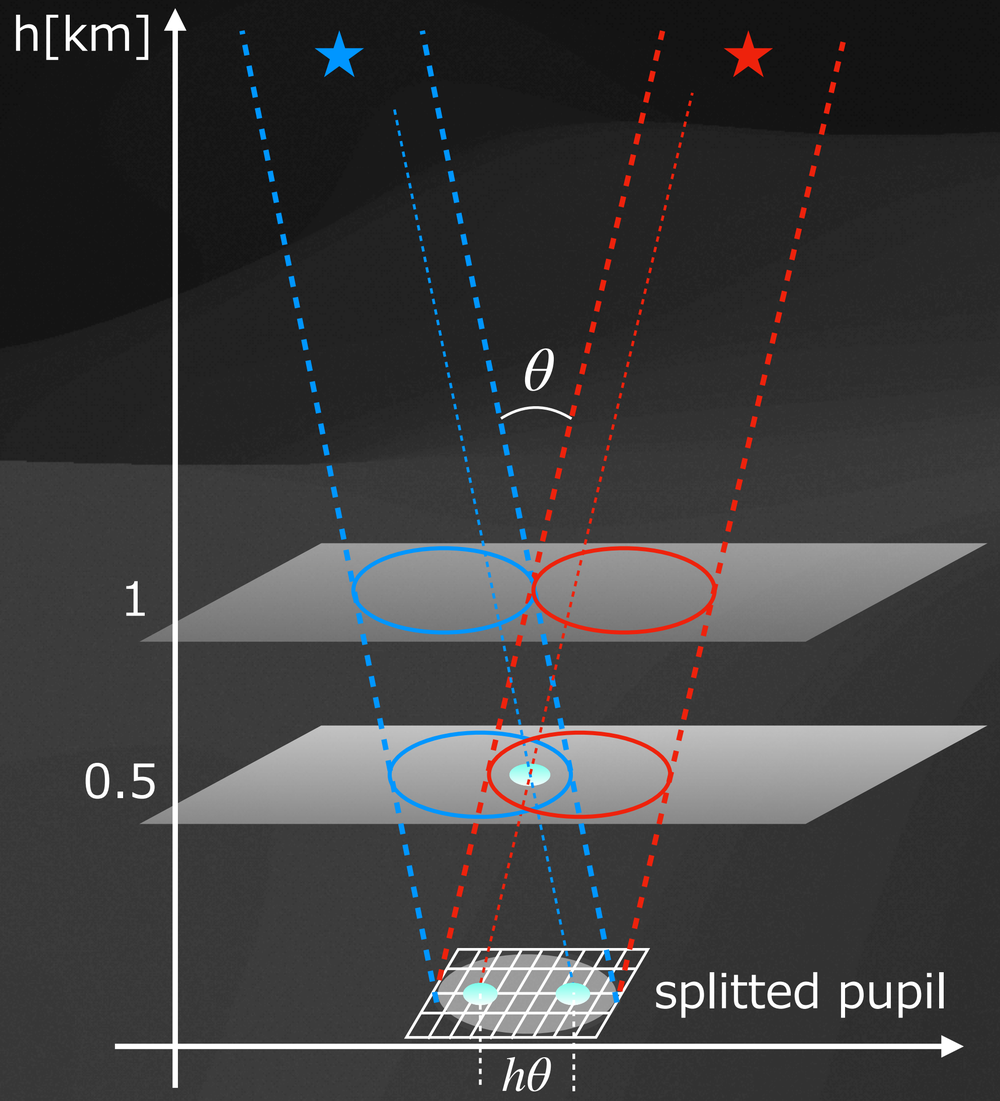




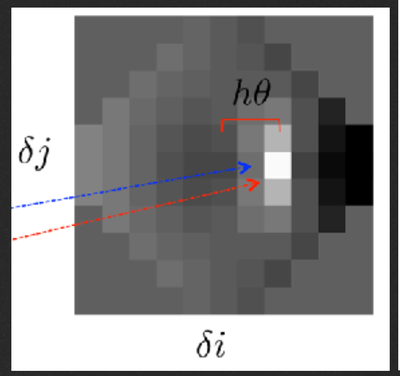
- Compared with MASS-DIMM measurement at CFHT telescope
- Overall trend is consistent with each other. Typical scatter is ~0.5dex.
- Technical demonstration of SH-MASS is achieved.
- We can theoretically reconstruct higher resolution (8-10 layers).

Analysis 3/3

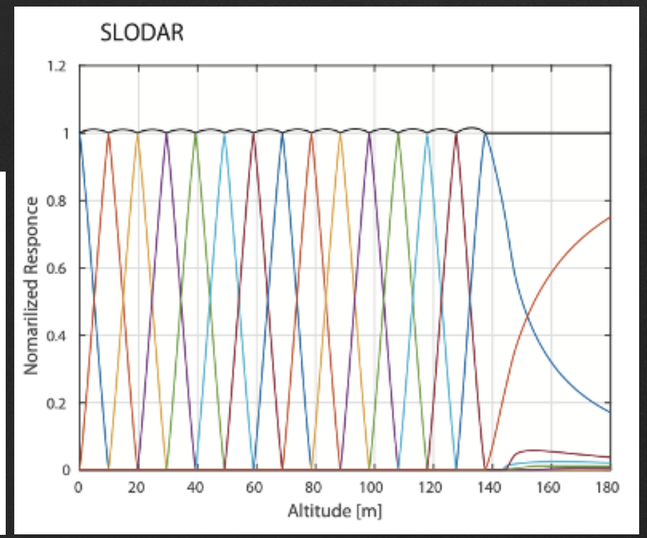
Angular correlation analysis of wavefront



- SLope Detection And Ranging (Wilson+2002)
- Measure wavefront of star pair with separation of θ
  - Altitude resolution : d/θ (d : subaperture size)
  - Altitude range : $<D/\theta$ (D : telescope size)
- In case of $\theta = 3 - 5$ arcmin, $d = 2$ cm, $D = 1.4$ m,
  - Altitude resolution : ~20m
  - Altitude range : <400m

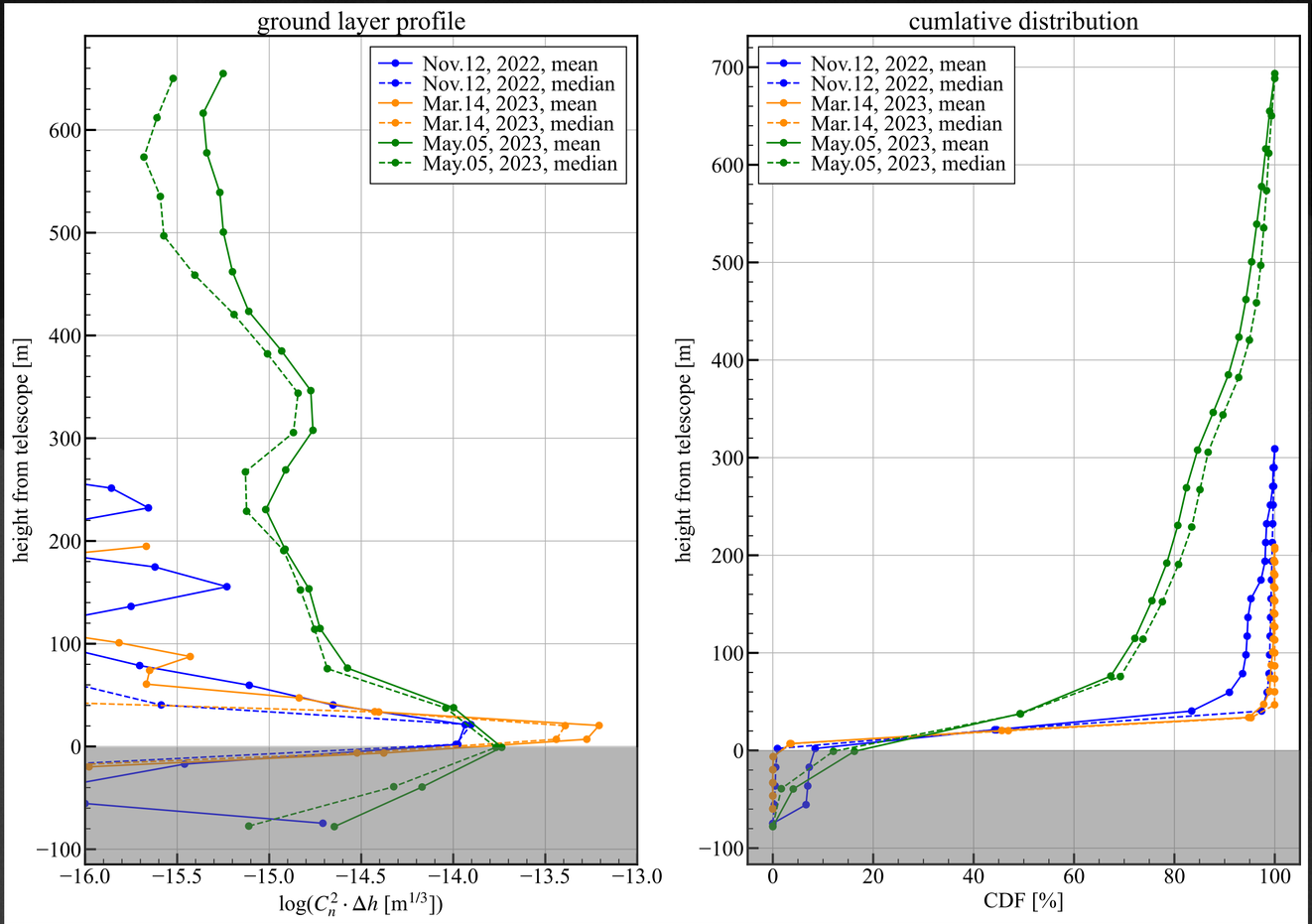


Wavefront correlation map (Ono+2016)

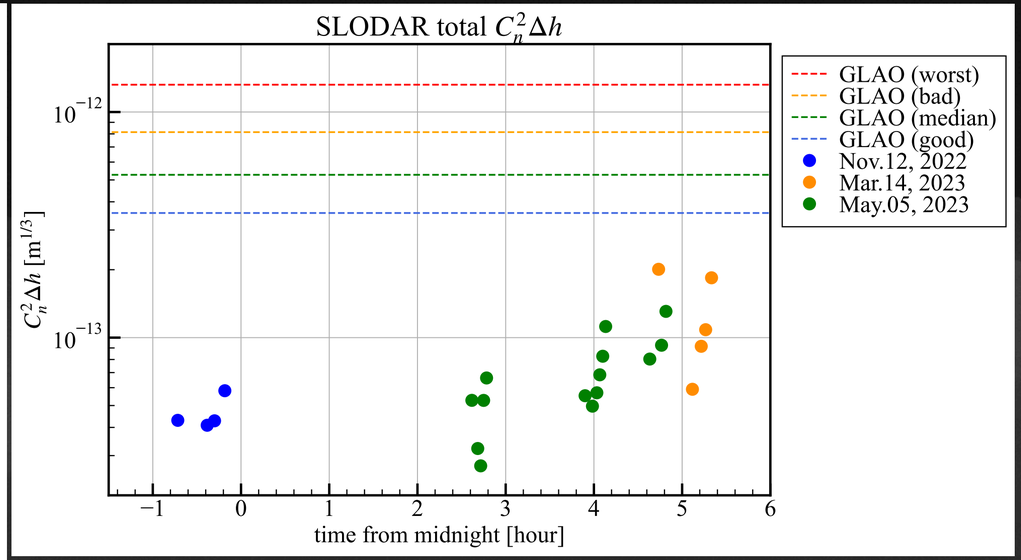


Result 3/3

Ground layer turbulence profile



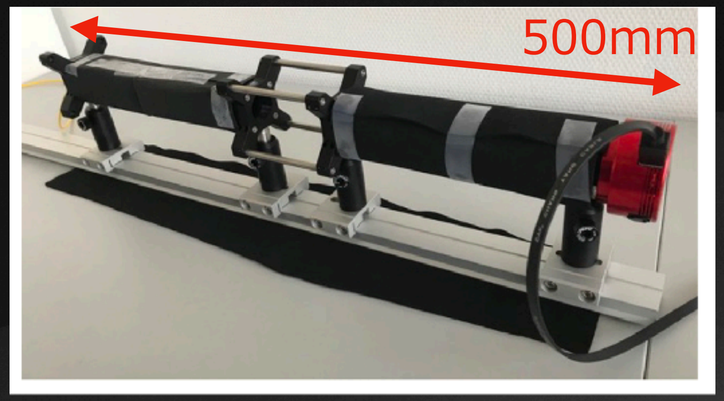
Gray-hatched area (negative altitude) means between primary mirror and secondary mirror.

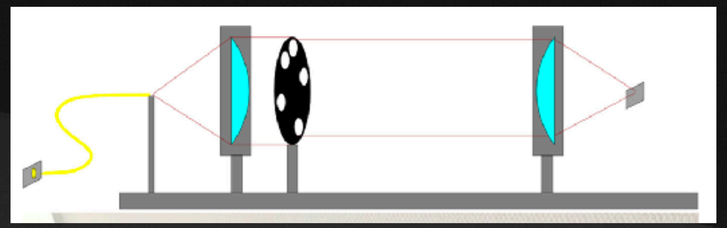


- >50% of total turbulence is at less than 30m above.
- Total amount of turbulence is smaller than that assumed in GLAO simulation.
- Discrepancy from Kolmogorov? Calibration is necessary.

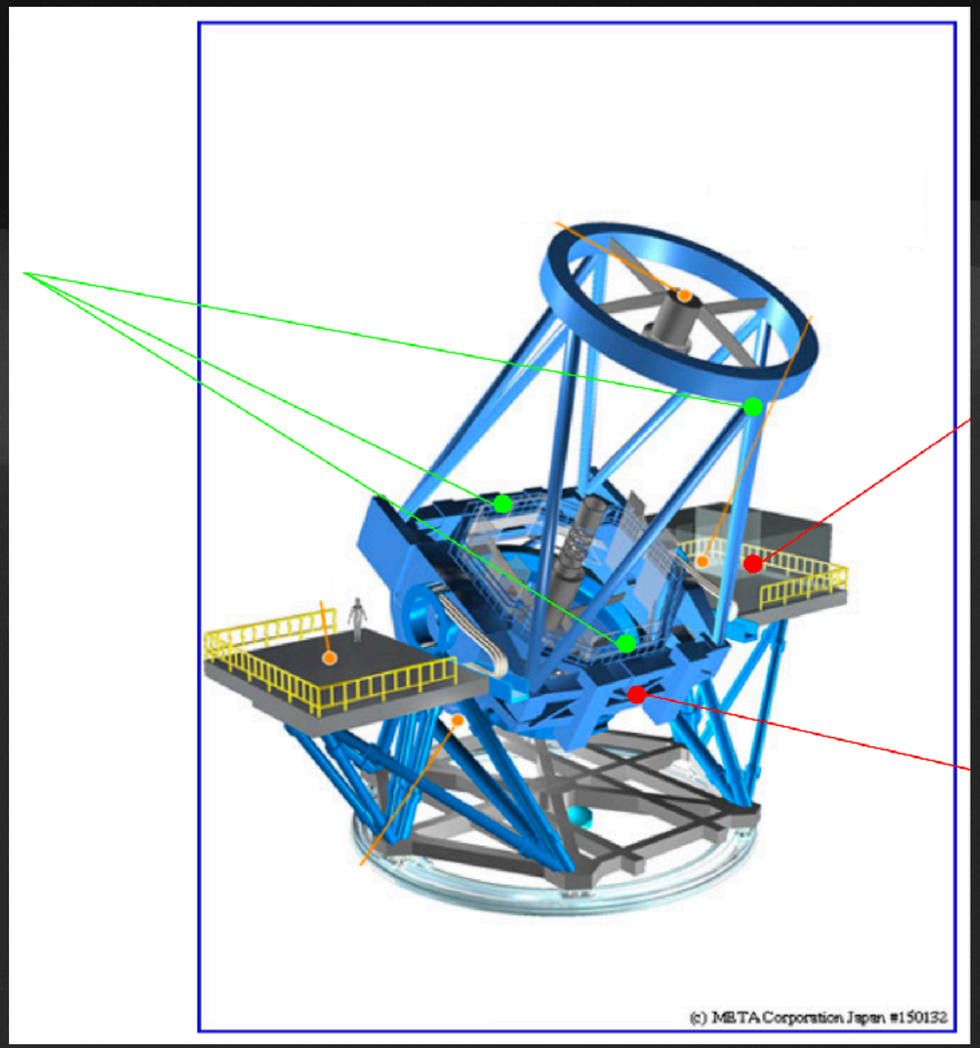
Future prospects

Calibration of GL turbulence with AIR-FLOW





Lai et al. 2019



- AIR-FLOW (Lai et al. 2019)
  - Localized optical turbulence sensor
  - Compute phase structure function from wavefront measurement of internal laser
- Possibility of simultaneous measurement
  - Several AIR-FLOW at different positions of telescope
  - Calibration of dome seeing at different height, direction

Summary

- Atmospheric turbulence characterization for future LTAO/GLAO systems at Subaru Telescope.
- Demonstration of several analysis based on wavefront/scintillation measurements with Shack-Hartmann sensor.
- Wind profile and free atmospheric turbulence profile shows good agreement with independent measurements.
- Ground layer profile shows that large amount of turbulence concentrates in <30m above telescope, suggesting dome(-related) seeing is important, though quantitative calibration is necessary as a next step.