Calibration of the GroundBIRD Telescope Current Status and Future Prospects

Miku Tsujii on behalf of the GroundBIRD collaboration

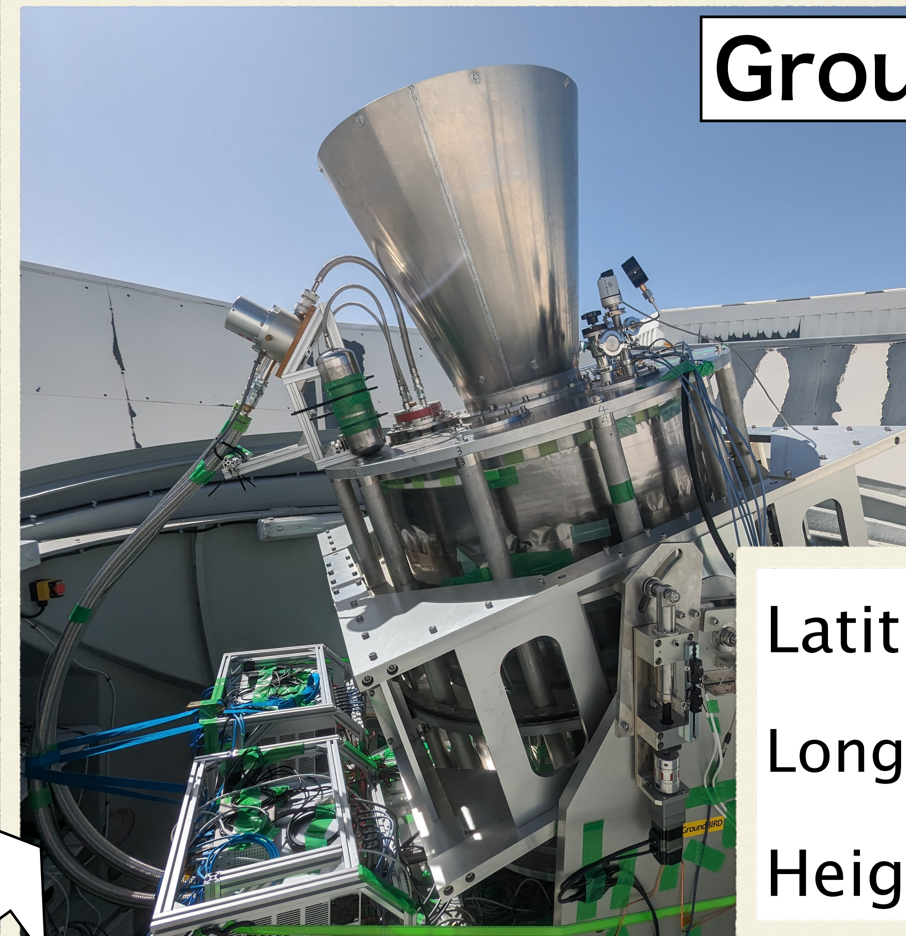
Outline

- **GroundBIRD experiment**
- **Status report of the on-site calibration**
  - Performance verification of detectors at a laboratory
  - Pointing calibration using Moon observation data
  - NEP and beam pattern
  - Polarization angle calibration
- **Summary**

Location of GroundBIRD

Ground-based CMB polarization observation experiment

International collaboration with Japan, Spain, Korea, the Netherlands, and the UK



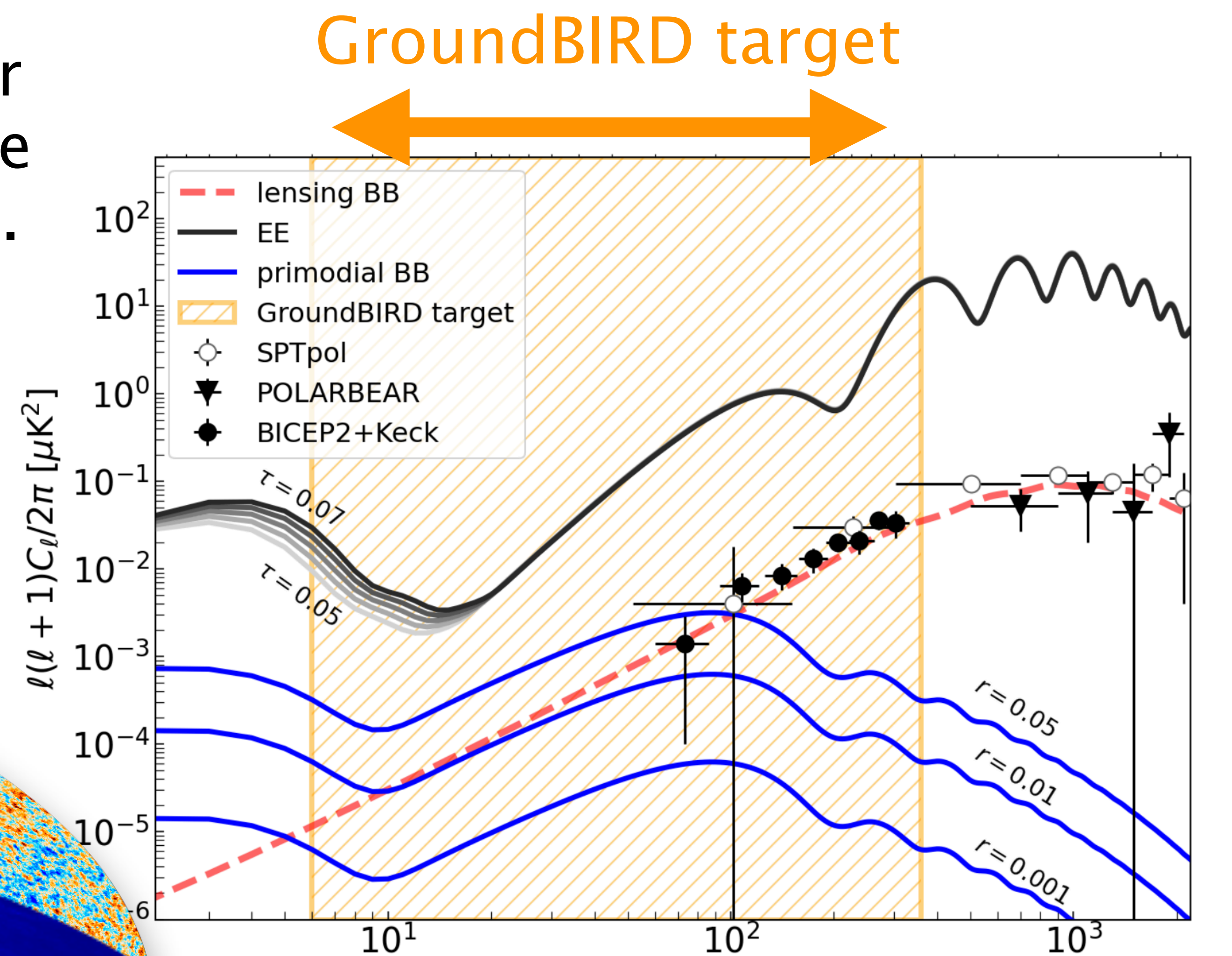
Latitude : 28°18′ N

Longitude : 16°30′ W

Height : 2400 m

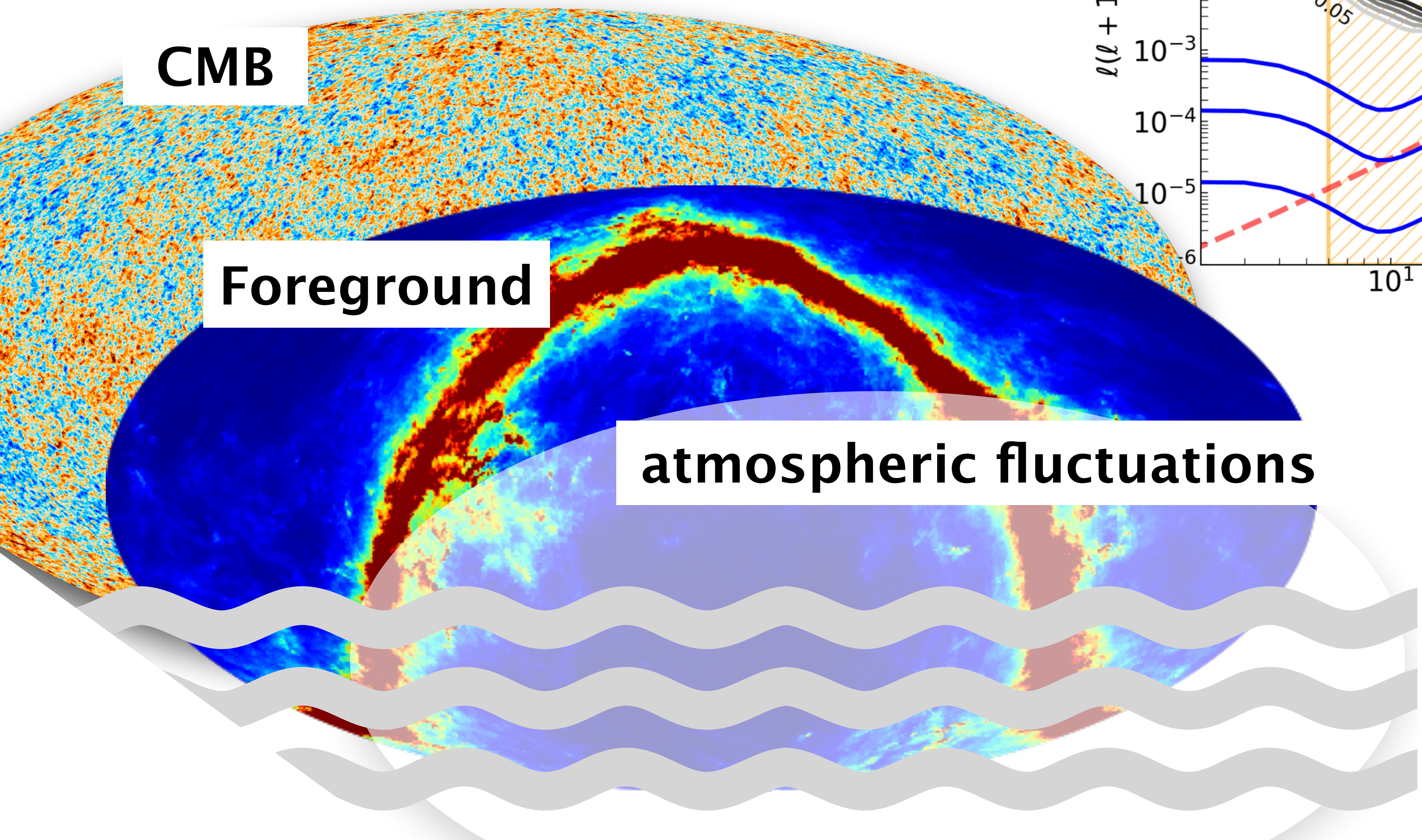
Scientific objective of GroundBIRD

GroundBIRD is a ground-based polarimeter for CMB observations targetting to measure from reionization to recombination bumps.



Credit: S.Honda

The atmospheric fluctuations must be mitigated to measure the reionization bump from the ground.



GroundBIRD telescope

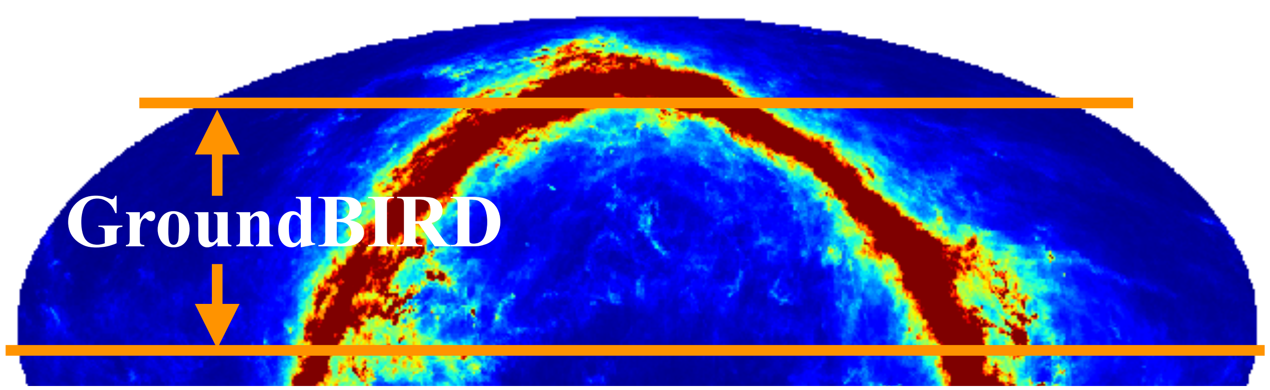
Strategy against atmospheric fluctuations

high-speed rotation scans :
20RPM(120°/sec)

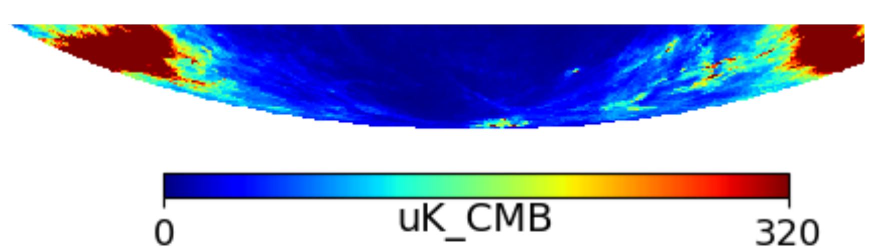
+

detector with fast enough response :
MKIDs

→mitigating 1/f atmospheric fluctuation

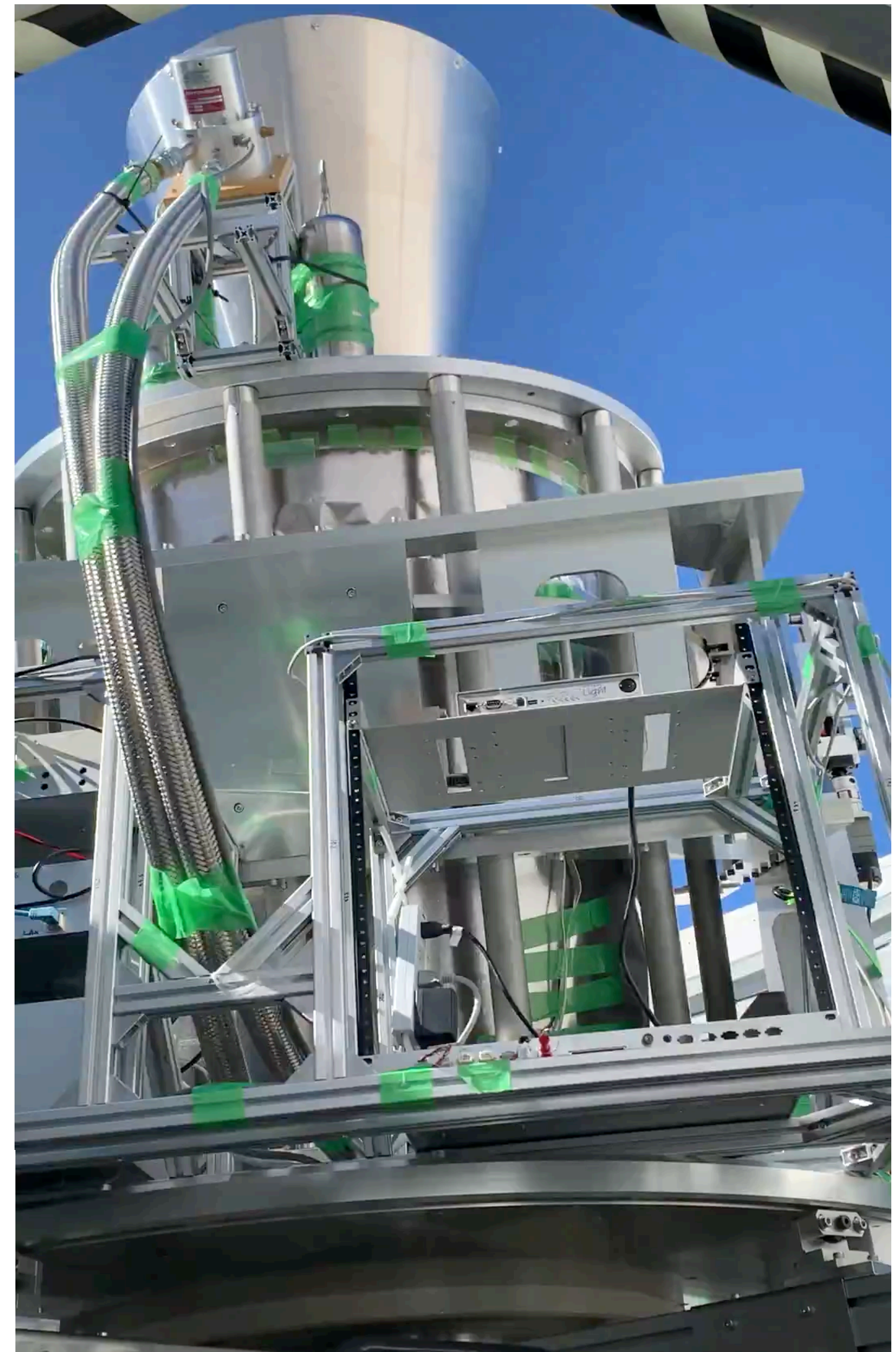


40% of full-sky observations!



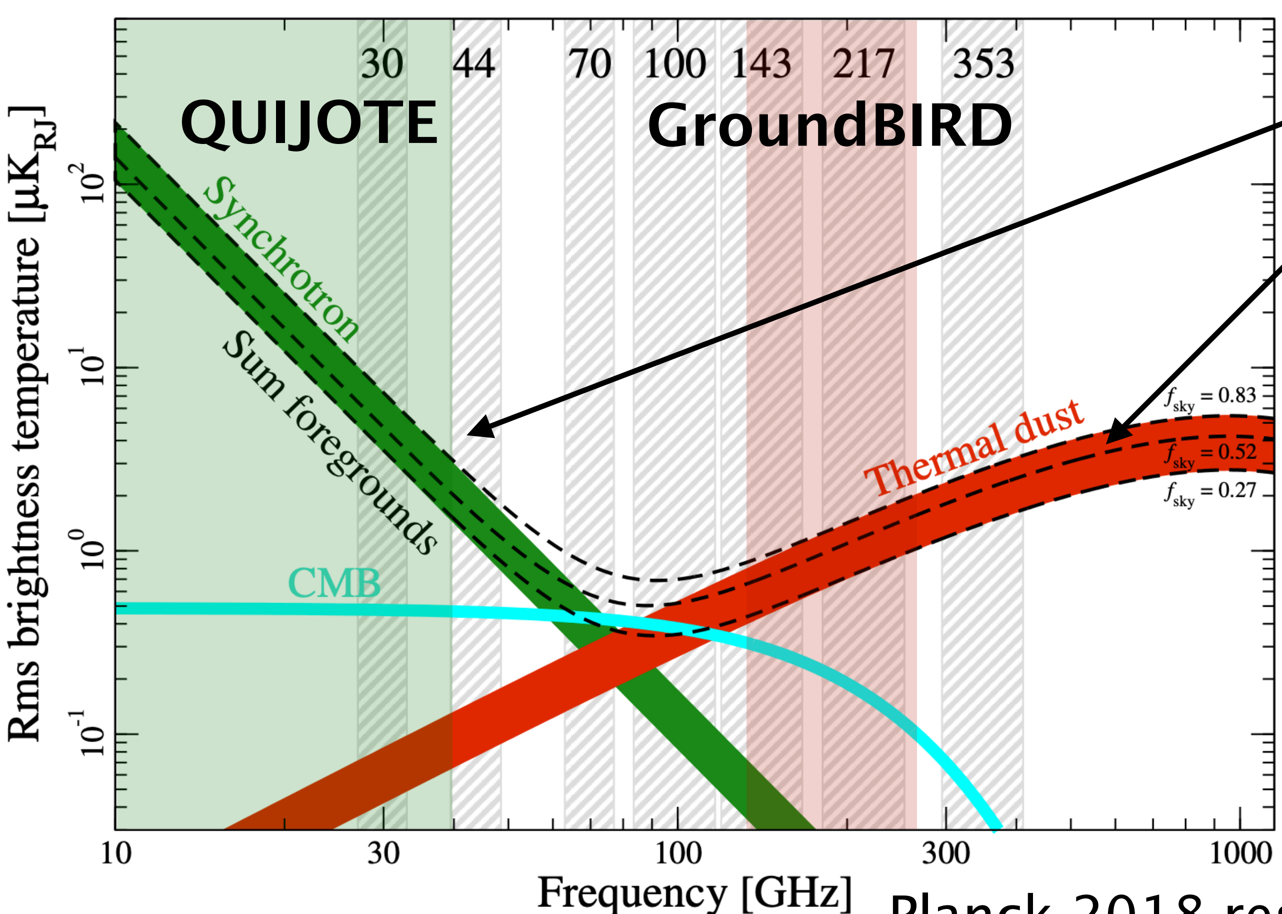
FOV: ~ 16°
FWHM: ~ 0.6° @ 145G
~ 0.4° @ 220G

GroundBIRD



GroundBIRD and QUIJOTE alliance

- GroundBIRD's observation frequencies: 145GHz and 220GHz
- We plan to combine data from the QUIJOTE telescope to achieve accurate foreground removal.



Planck 2018 results. IV

Galactic foreground signals

The GroundBIRD forecast paper

K. Lee, et al., (2021) ApJ 915 88

Data accumulation for 3 years

leads sensitivity of $\sigma(\tau) \sim 0.01$

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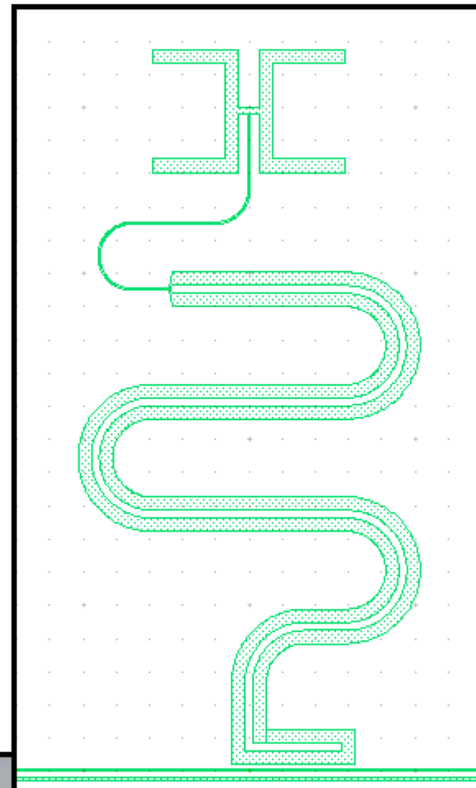
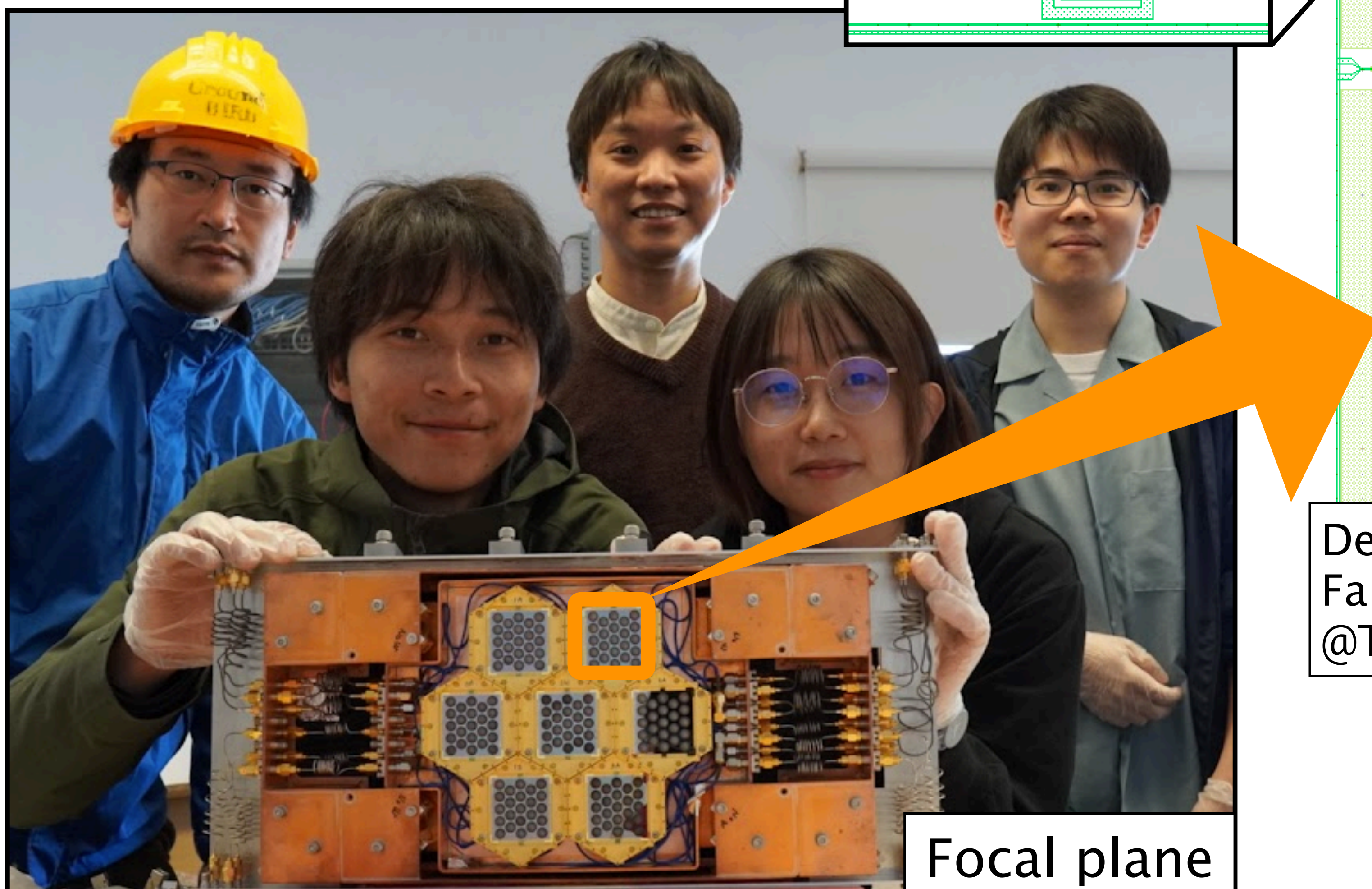
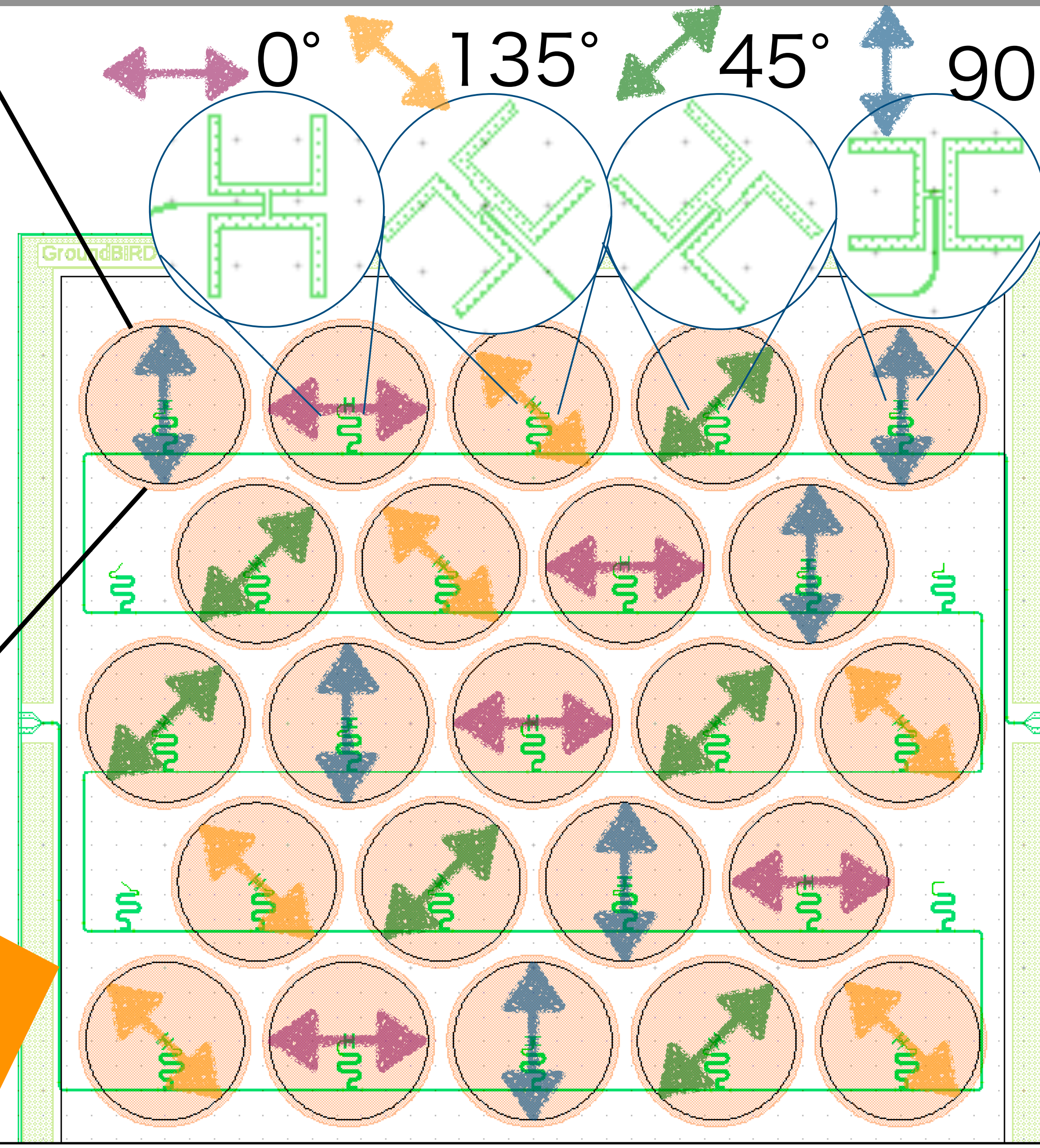
We installed the full set of detectors in 2023!

To achieve rapid rotation scanning performance compatible with diffraction-limited, we employ Microwave Kinetic Inductance Detectors(MKIDs) with time constants on the order of 10 μs.





Focal plane

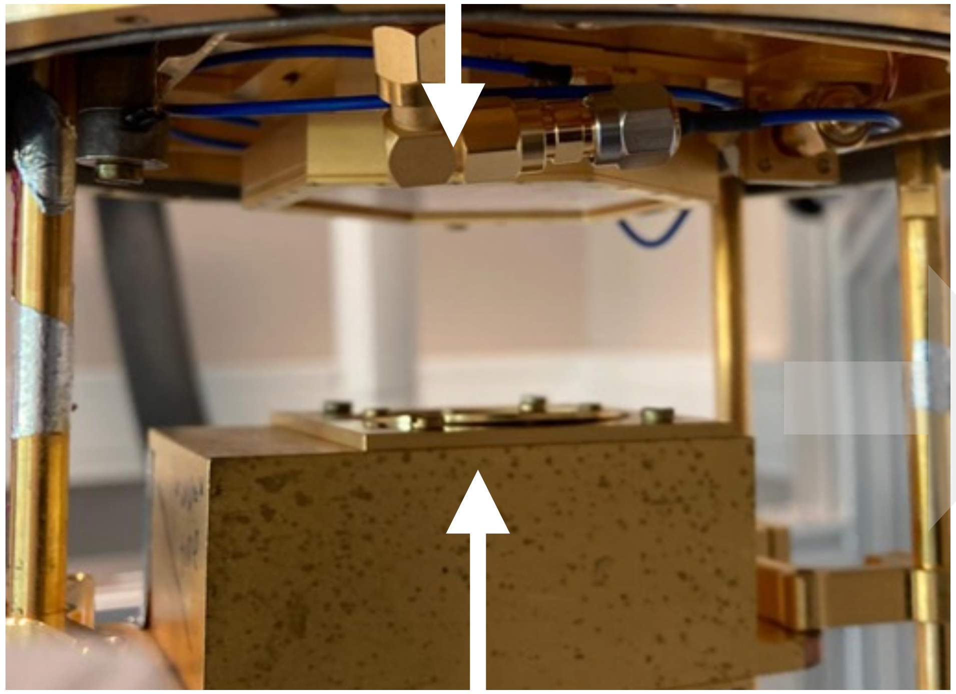


Designed @Tohoku(Tanaka)
Fabricated and evaluated performance
@TU Delft and SRON (Karatsu, Tanaka, Baselmans)

145 GHz 6 array × 23 kids
220 GHz 1 array × 23 kids

MKIDs performance at lab measurement

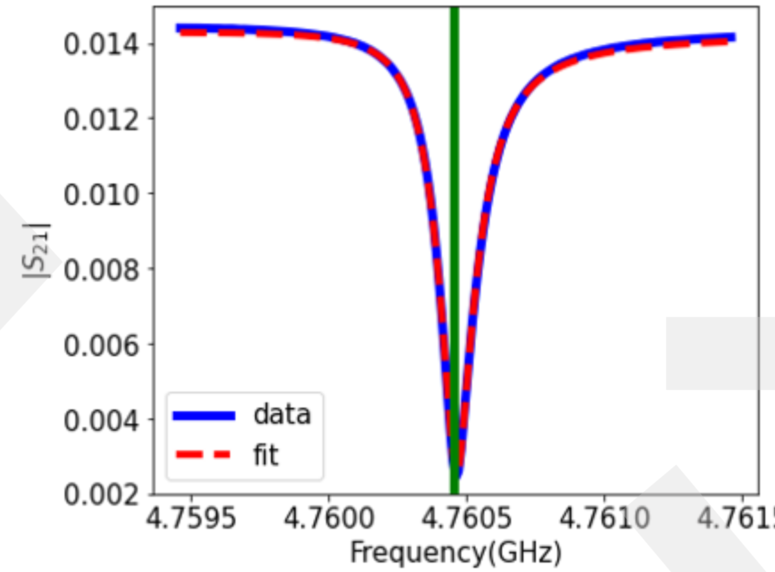
MKID array 230mk



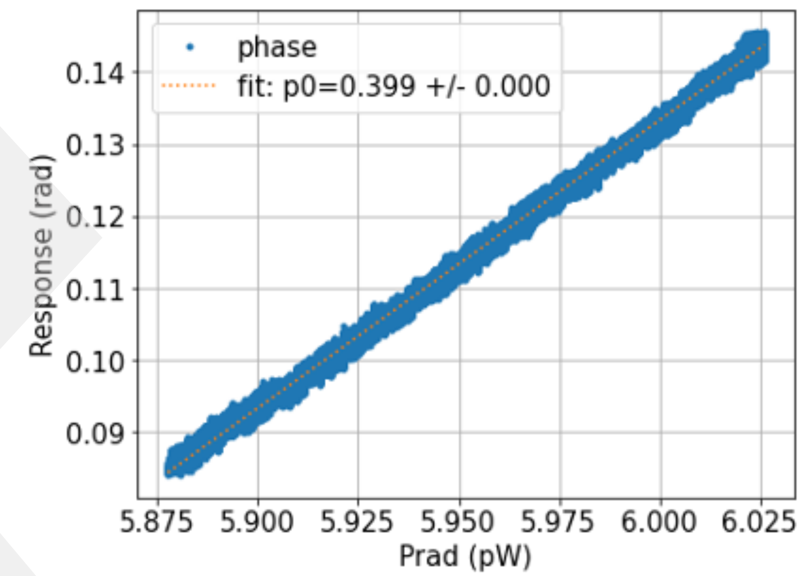
Blackbody source 30K

Lab measurements were done @TU Delft and SRON

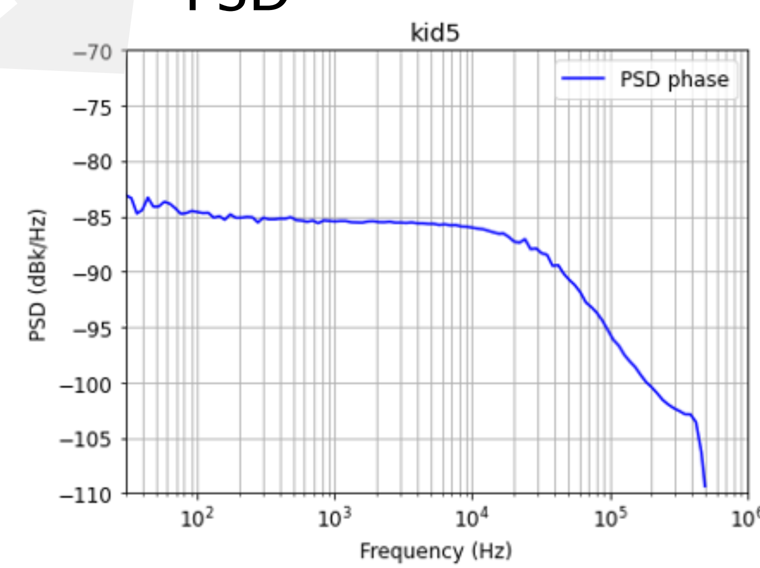
Sweep and fitting



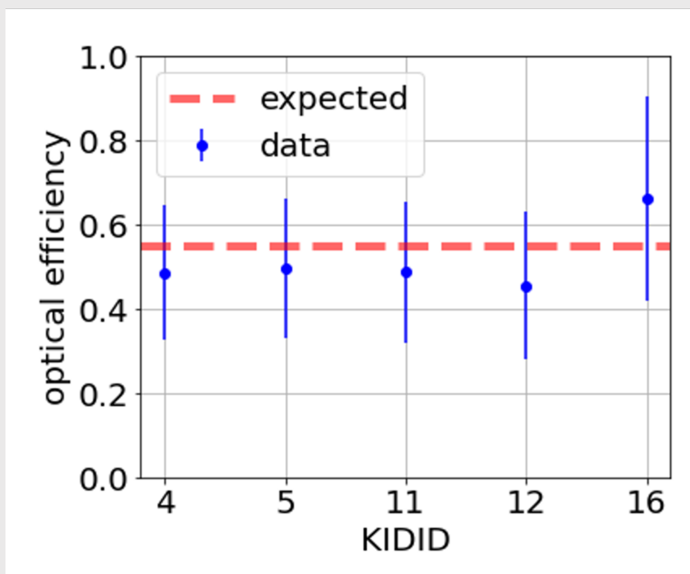
TOD with an MKID:
blackbody temperature is changed



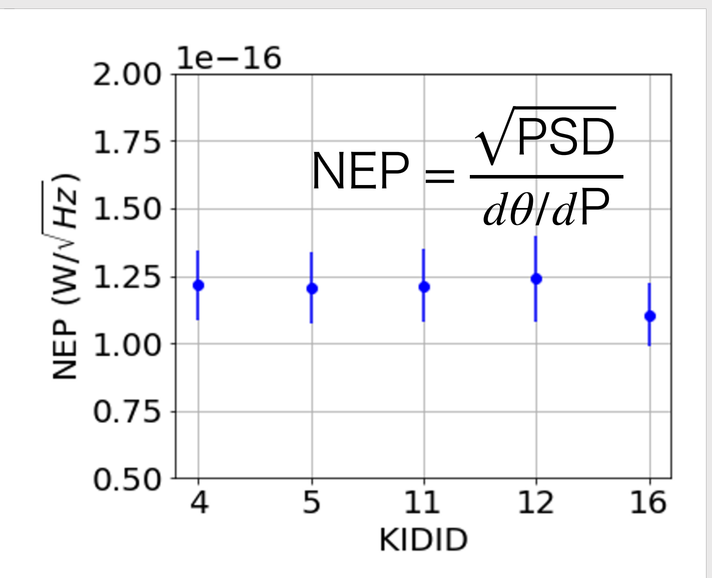
PSD



Optical efficiency



Noise equivalent power

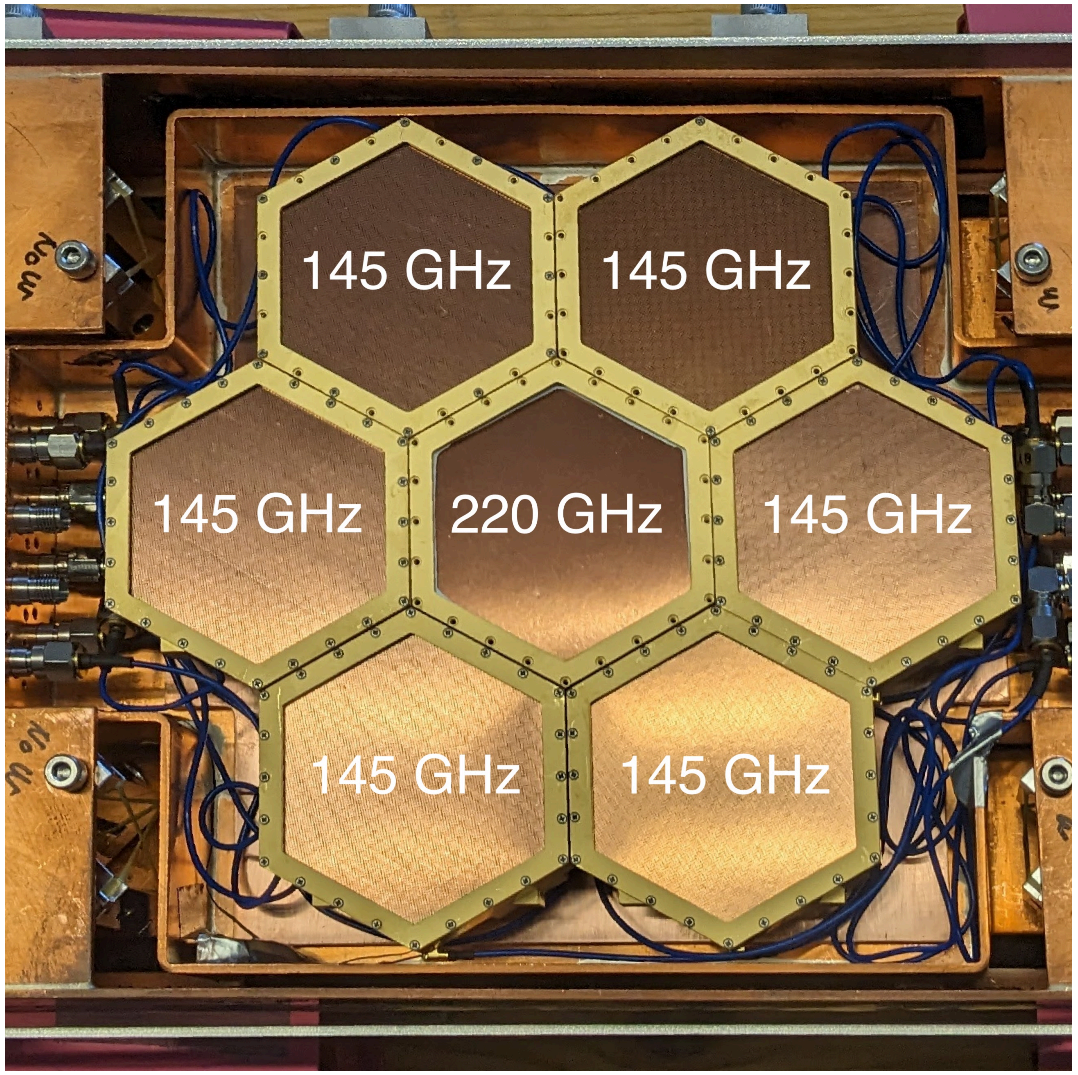


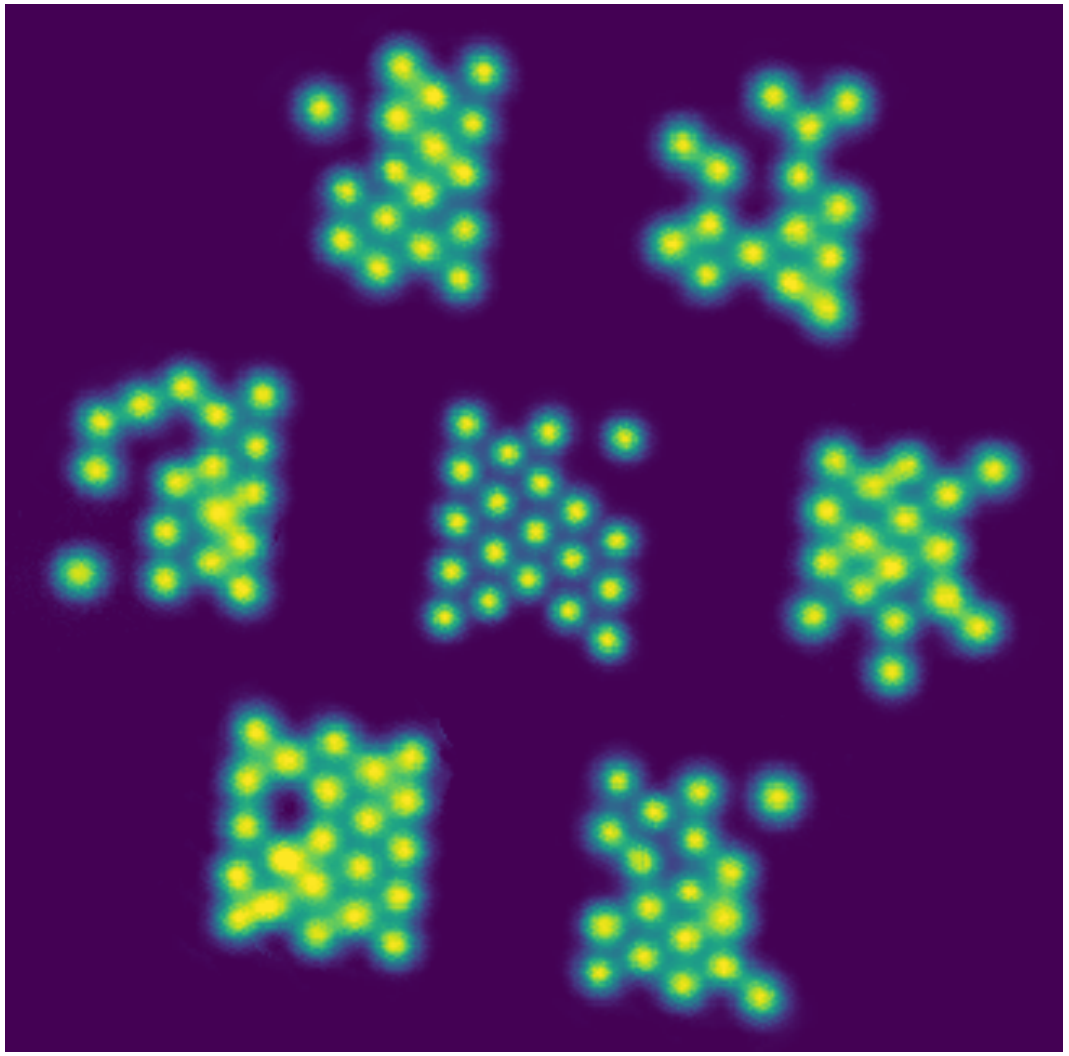
$$NEP = \sqrt{\frac{2h\nu P_{\rm rad}(1+\eta_{\rm opt}n) + 4\Delta P_{\rm rad}/\eta_{\rm pb}}{\eta_{\rm opt}}}$$

Credit: T.Tanaka

Pointing calibration using the Moon

Beam centered map from the Moon observation





Each detector's response has been normalized.

The Moon is an extended source for GroundBIRD.
GroundBIRD beam width (=36′) ~ the Moon's visible size.

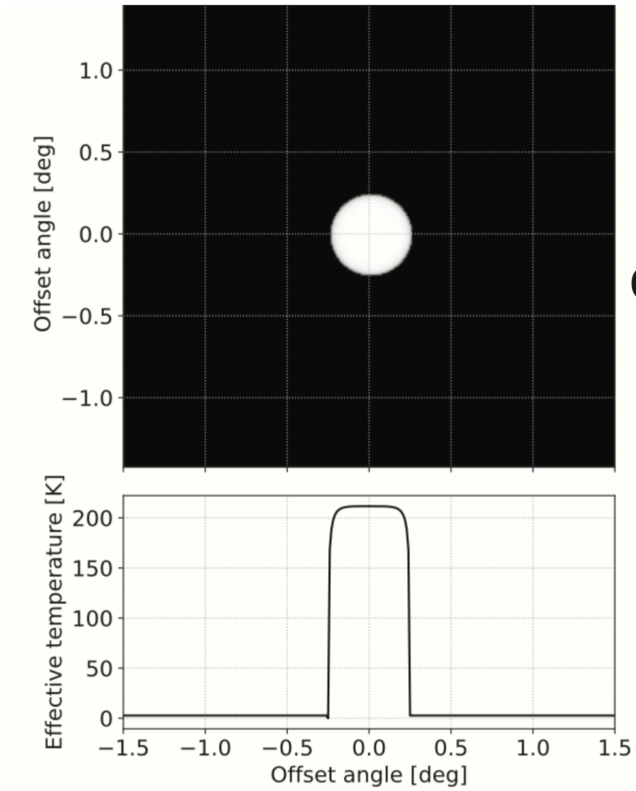
Detail: Y. Sueno, et al., (2024) PTEP

We established a new pointing calibration method using the Moon, applicable to small aperture telescopes.

Pointing calibration using Moon

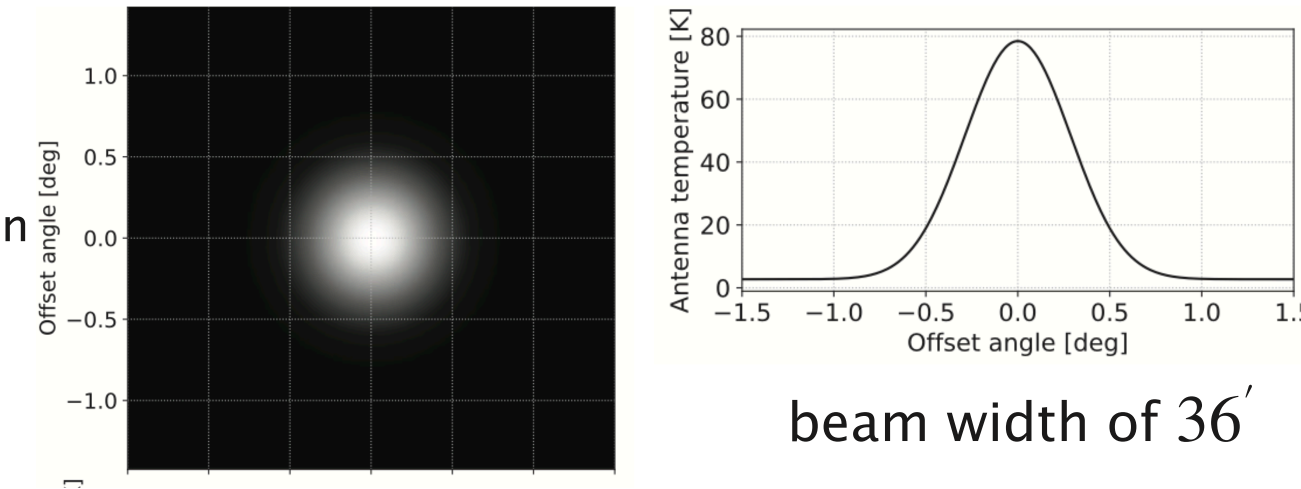
(Fig6, 9, and 14 Y. Sueno, et al., (2024) PTEP)

The Moon's brightness temperature from the Earth



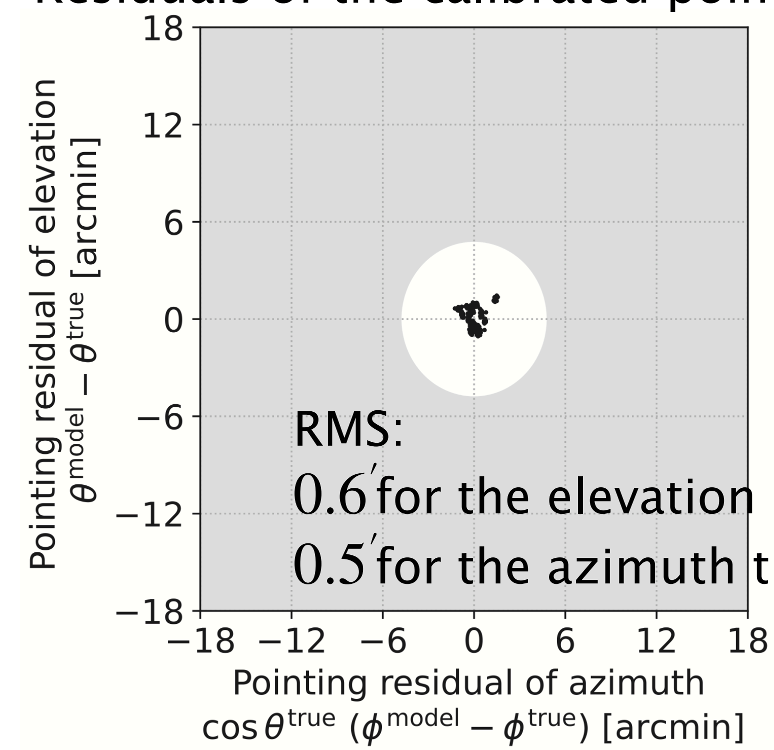
Convolved brightness distribution
with the beam modeled
using the simple 2D Gaussian

Example of the Moon observation model



beam width of $36'$

Residuals of the calibrated pointing



RMS:
$0.6'$ for the elevation
$0.5'$ for the azimuth times cosθ

Observation data were fitted with the observation model

- Two months of observation data
- Scan at 10RPM
- Elevation at 70 degrees

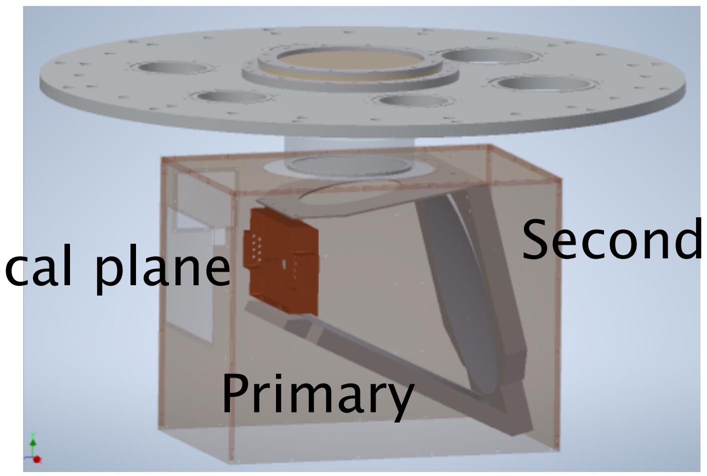
→ **Extracted Moon positions for each detector**

Successfully achieved an uncertainty of $3.3'$ including all systematic uncertainties.

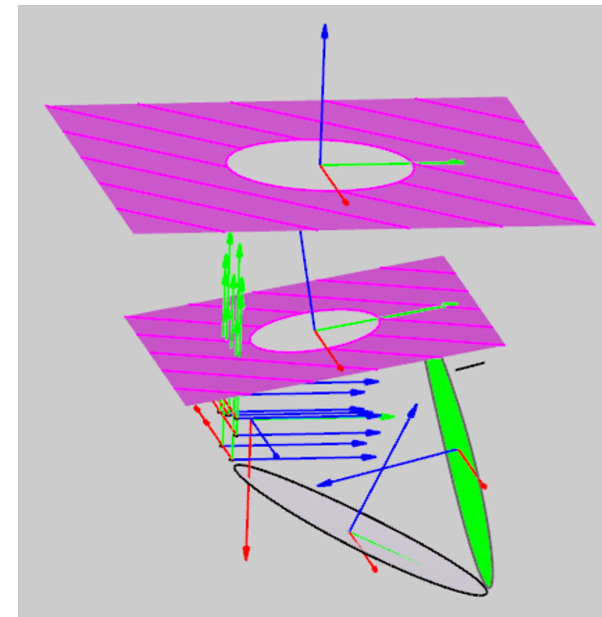
We are continuing the Moon observation for pointing calibration with the new detector setup!

BEAM pattern modeling by GRASP simulation

GRASP: General Reflector Antenna Solware Package

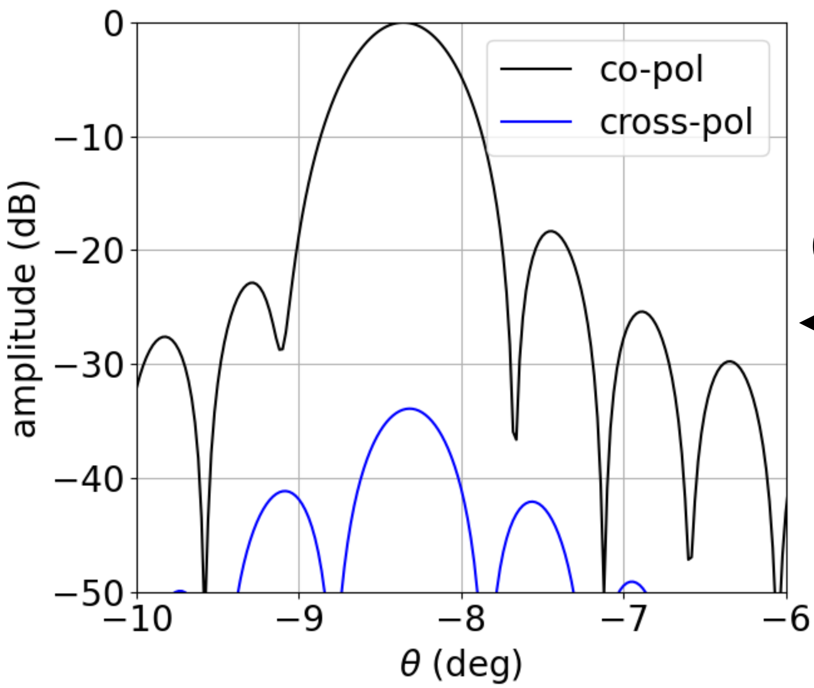


Simulation



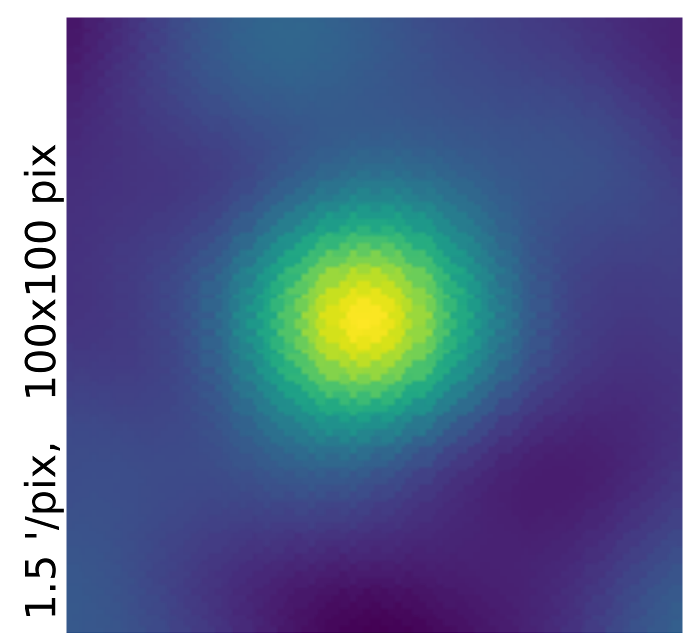
Beam pattern and NEP analyses using Jupiter observation are ongoing!

Simulated beam pattern



Compare

An image of Jupiter captured map

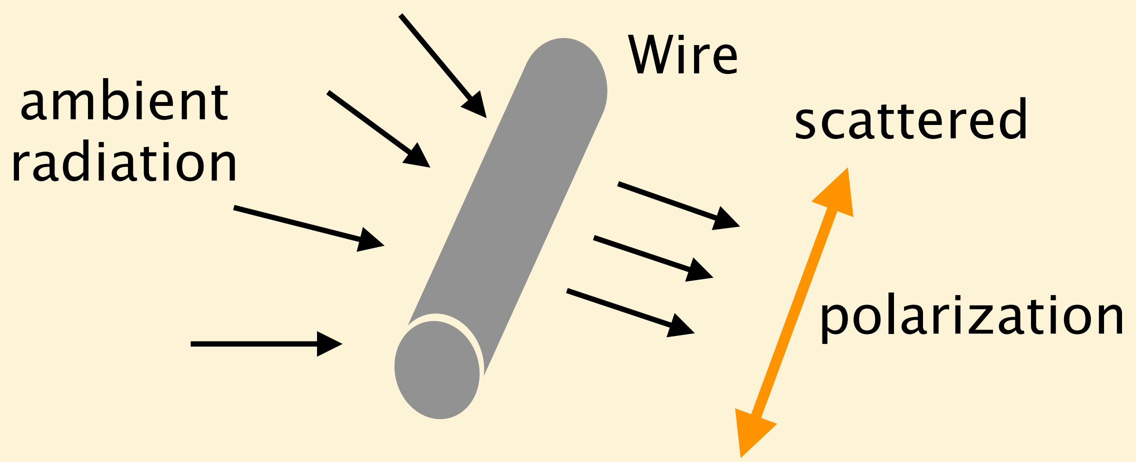


145 GHz MKID smoothed with a FWHM of ~0.6°

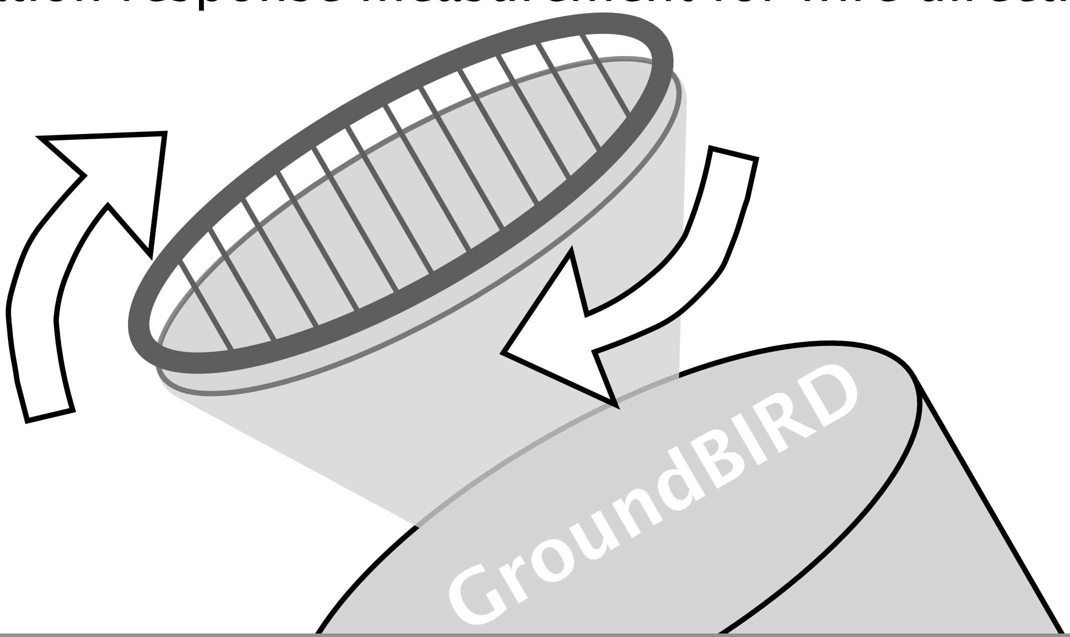
Polarization Calibration using Sparse Wire grid

- Challenge: Using celestial objects as polarization calibrators is hard for a small aperture telescope.
- Solution: Sparse wire grid
- Advantage: Calibration is possible anytime

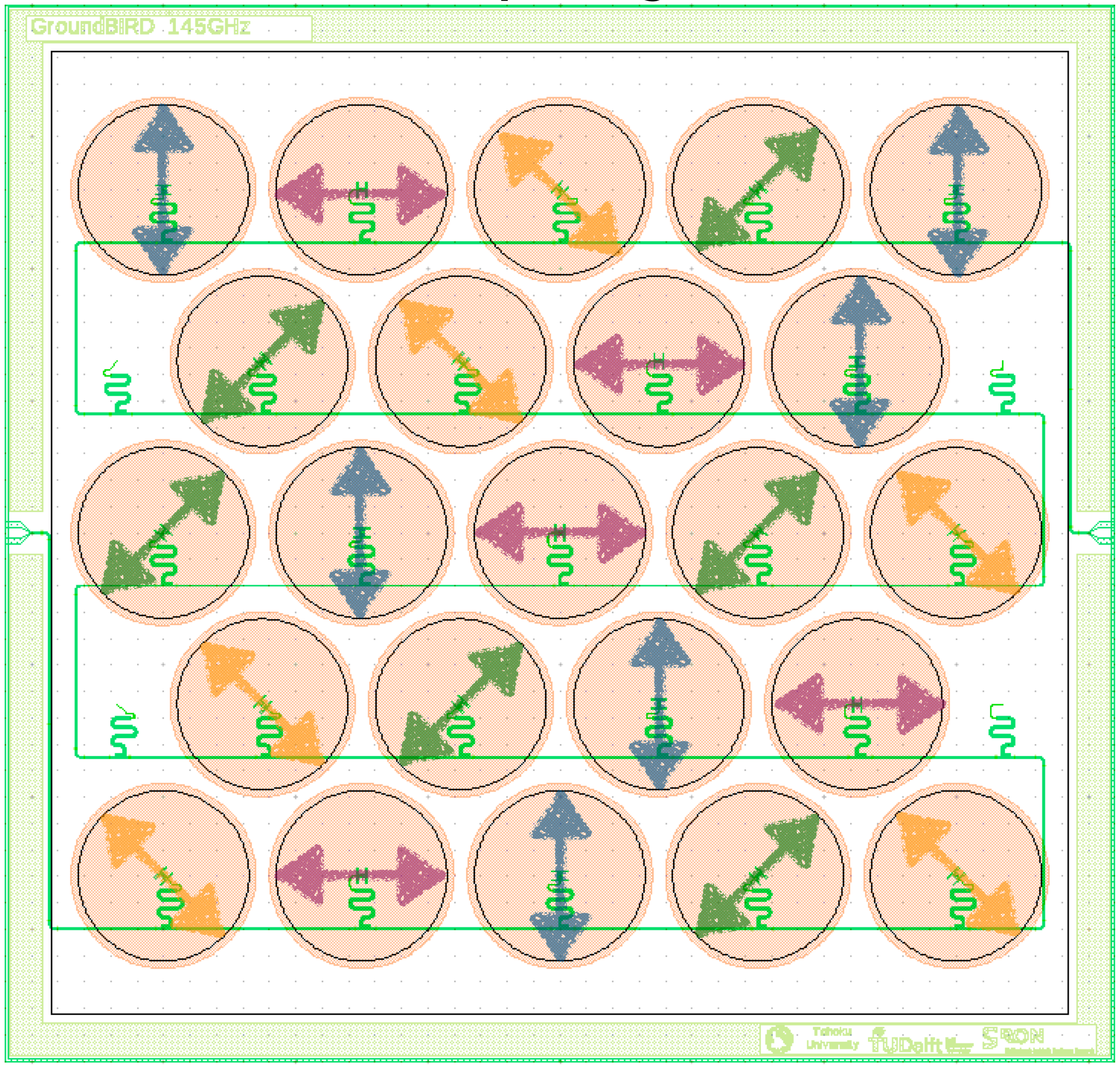
Created polarization along the direction of the wire



Polarization response measurement for wire direction



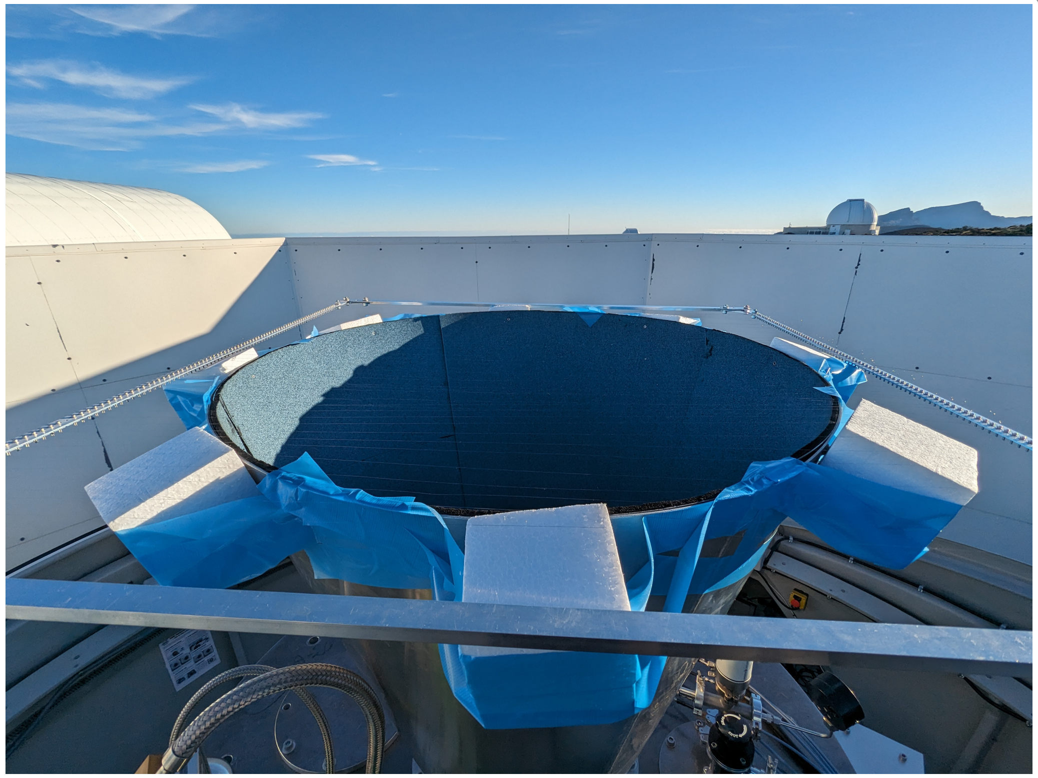
Chip design



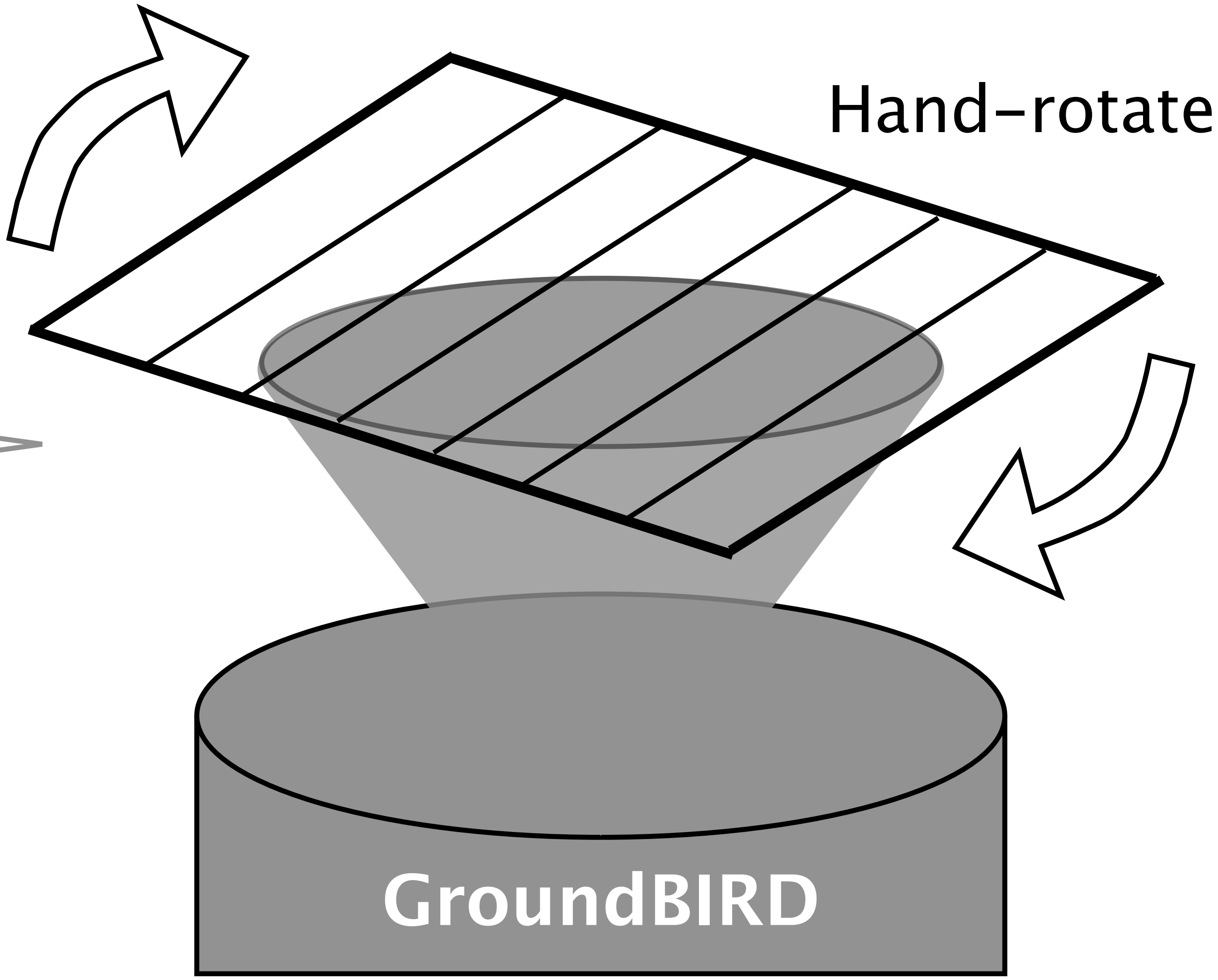
- Single polarized double-slot antenna
- To measure Stokes parameters Q and U, the antenna is oriented in 4 directions

Polarization Calibration using Sparse Wire grid

Before constructing the instrument, we conducted a verification test using a simplified setup to confirm if polarization signals can be measured as expected.



Location: on the baffle
Diameter: 0.1mm
Material: Wolfram
No. of wires: 50
Intervals: 16 mm
2 seconds integration

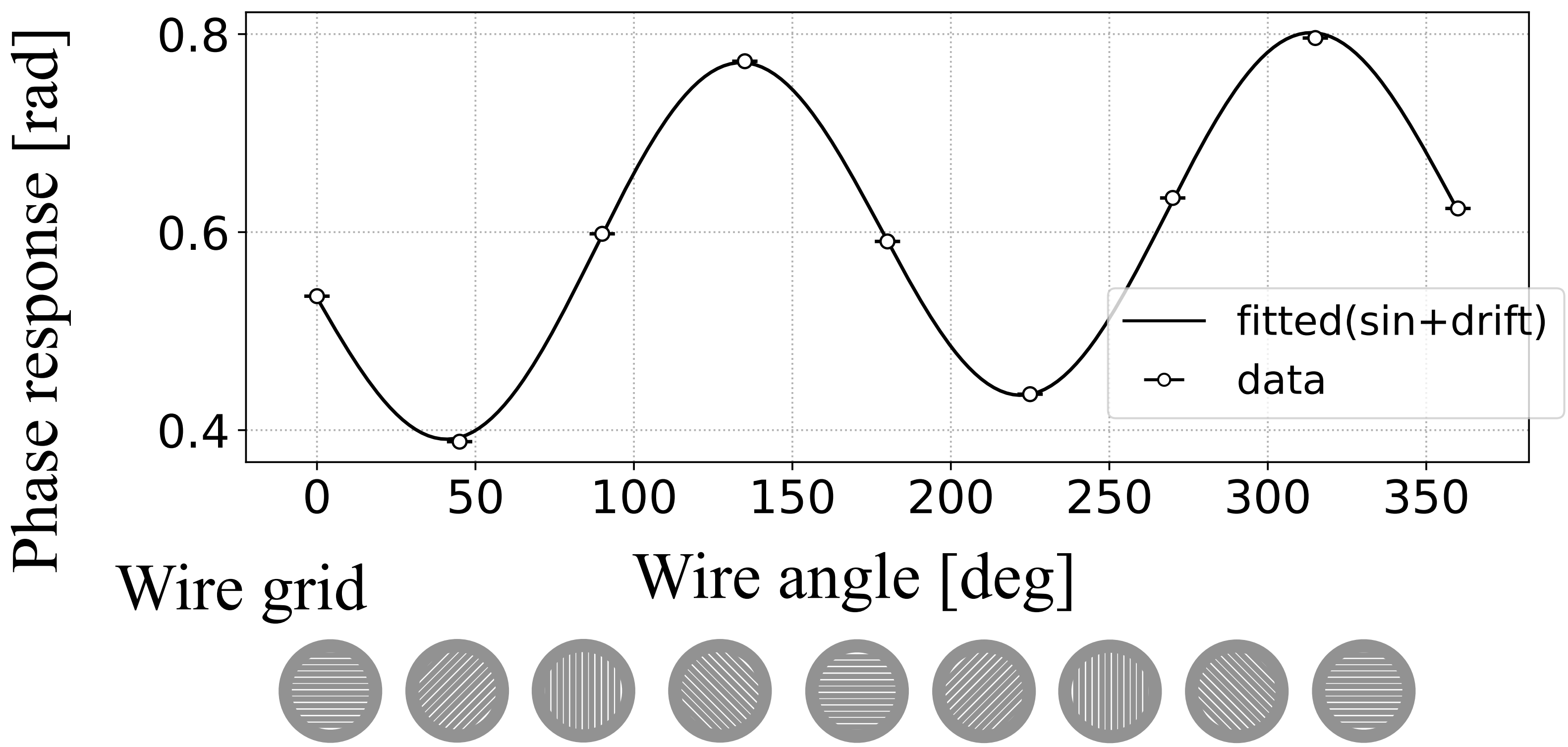


The frame was rotated by 45 degrees each time during data acquisition, with the time recorded.

This is a test to ensure that the signal is visible. The accuracy is about ±4°.

Fitting with trigonometric and cubic functions

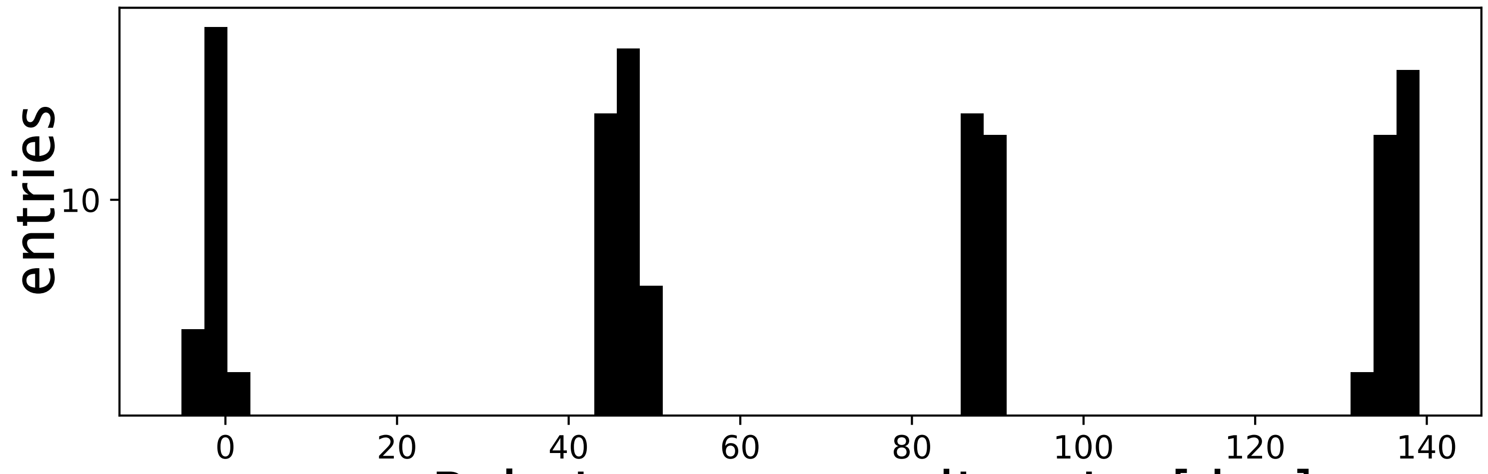
example



Modulated signals by wires were observed.

Confirmed the antenna directions were almost consistent with the design.

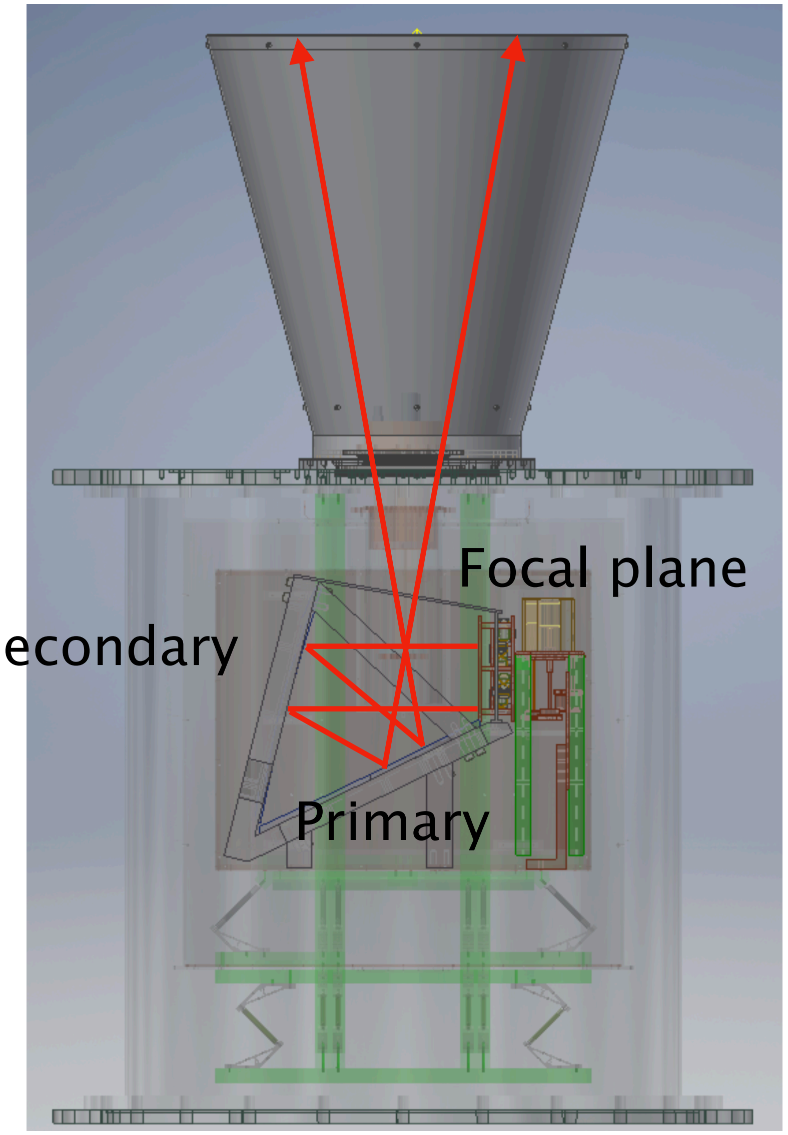
Distribution of measured antenna direction



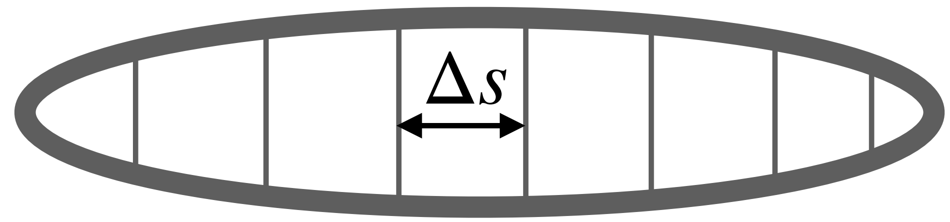
Based on these results,
we are currently developing a high-precision polarization angle calibration device!

Where should we install the wire grid?

3D model of the GroundBIRD telescope



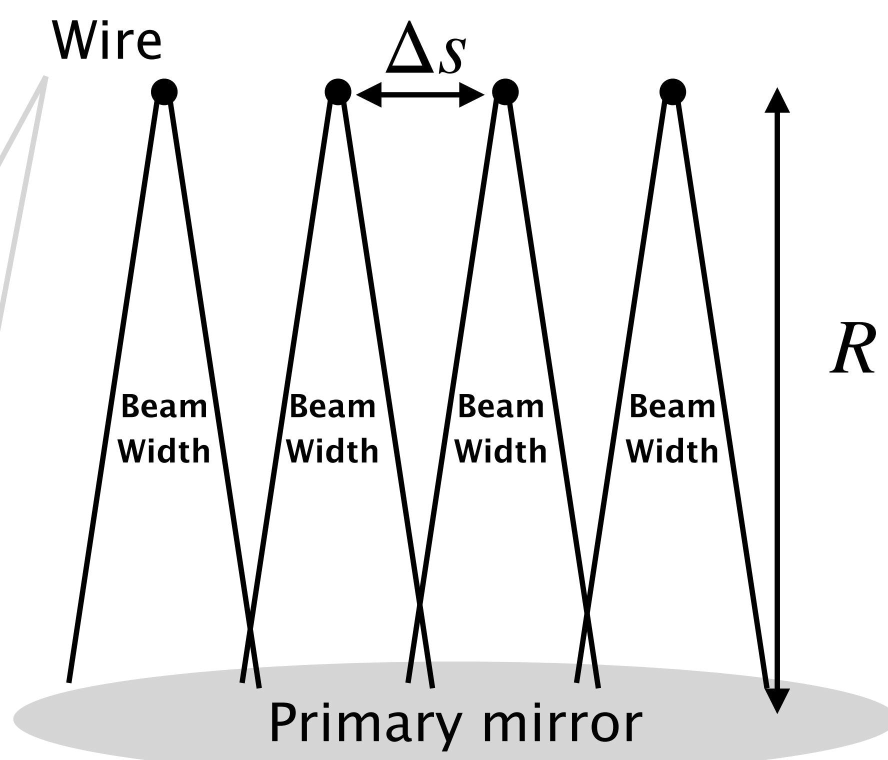
Sparse Wire Grid: A device with metal wires stretched at intervals larger than the wavelength.



$\Delta s > \lambda$

Aim: calibrate the polarization angle using the same light path as the observation.
→ Focus on a mirror utilization rate.

Polarized signals come from the wires in all 360 degrees.
However, only the light spread to about the beam width can be detected.



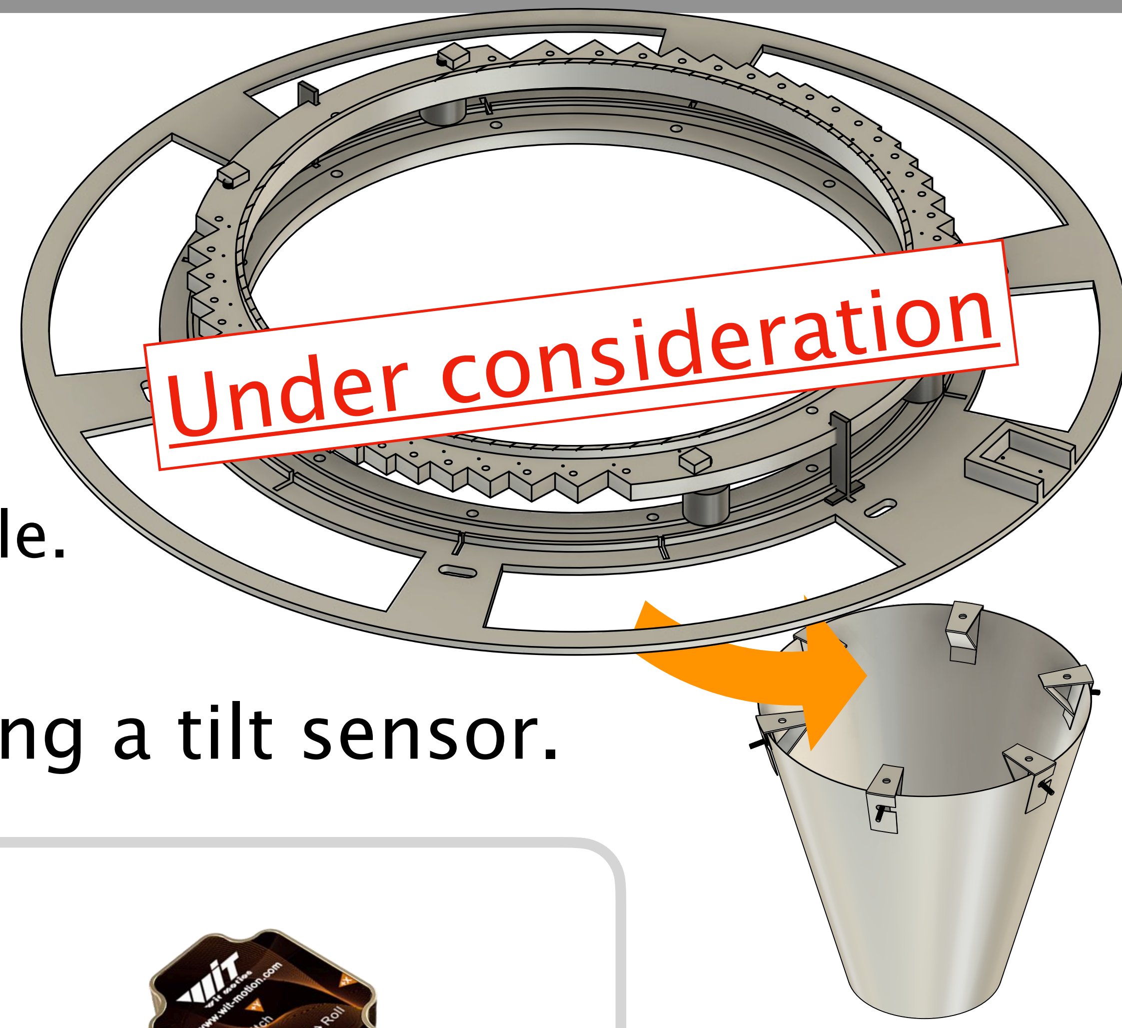
Conditions for using the entire surface of a mirror

$$R > \frac{\Delta s}{\text{Beam width}}$$

(Very rough calculation)

→ Must be placed as far away as possible. But still near the field.

The new wire grid calibrator(Under consideration)



Requirement

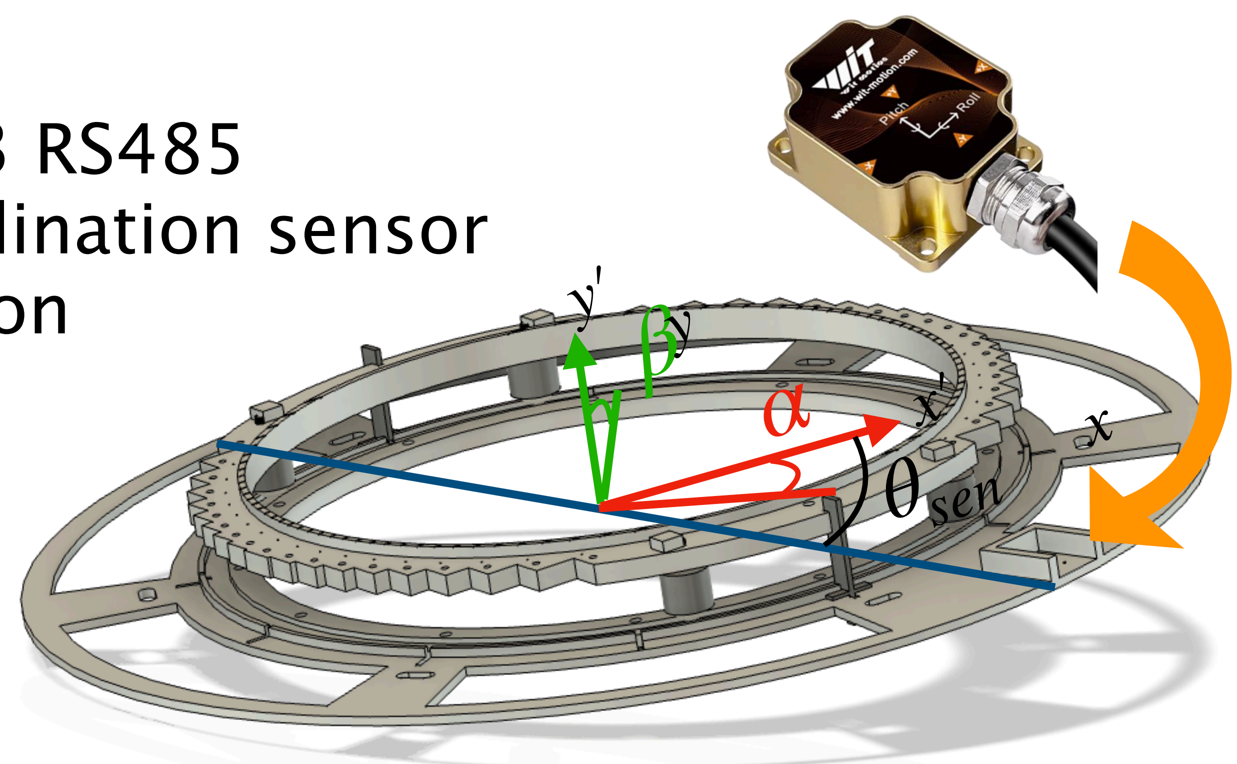
- Accuracy of 0.5 degrees or better
- Wire spacing of 15mm
- Must be compatible
  with the current GroundBIRD system
- Install as far away from the mirror as possible.

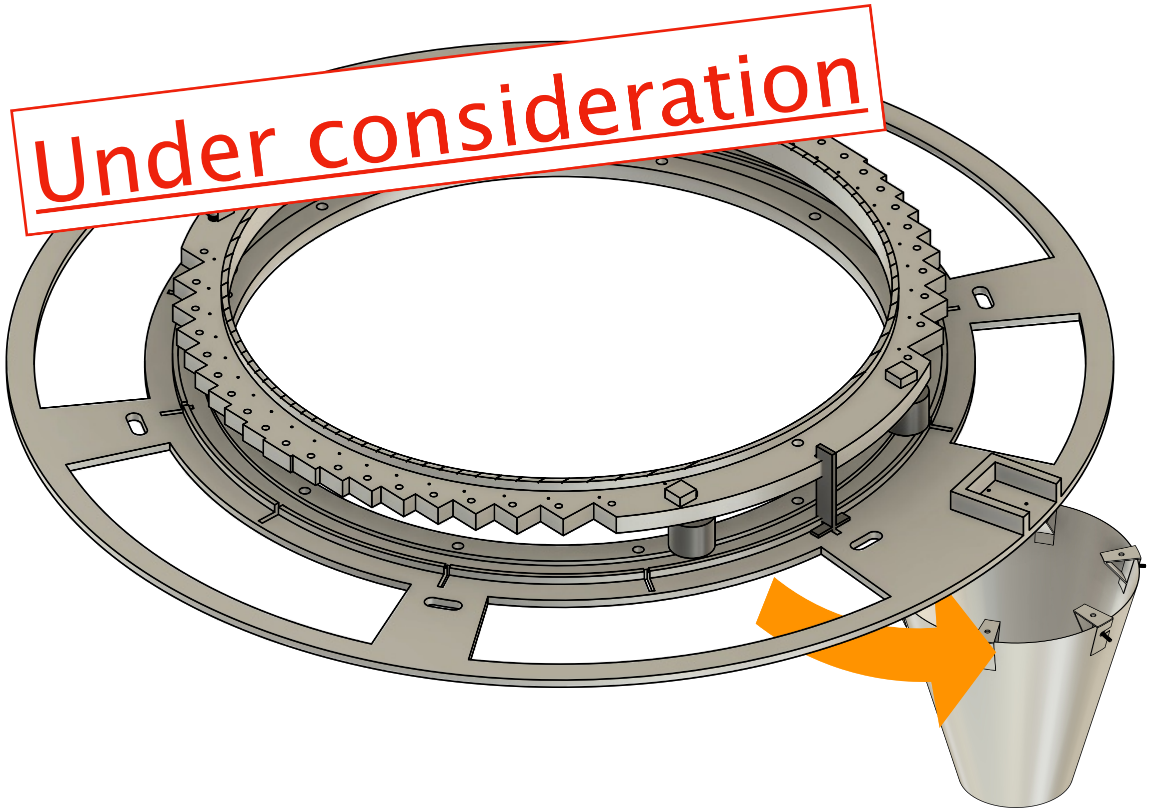
The absolute angle will be measured using a tilt sensor.

Tilt sensor

- WitMotion HWT9073 RS485
- Azimuth, 2-axis inclination sensor
- Wire heading dilection

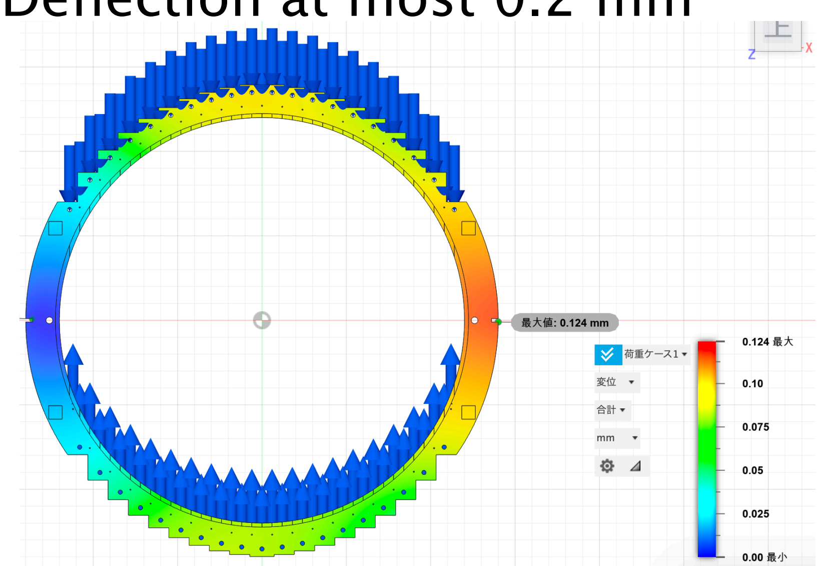
$$\theta_{sen} = \arctan \frac{\sin \alpha}{\sin \beta}$$





Frame deflection

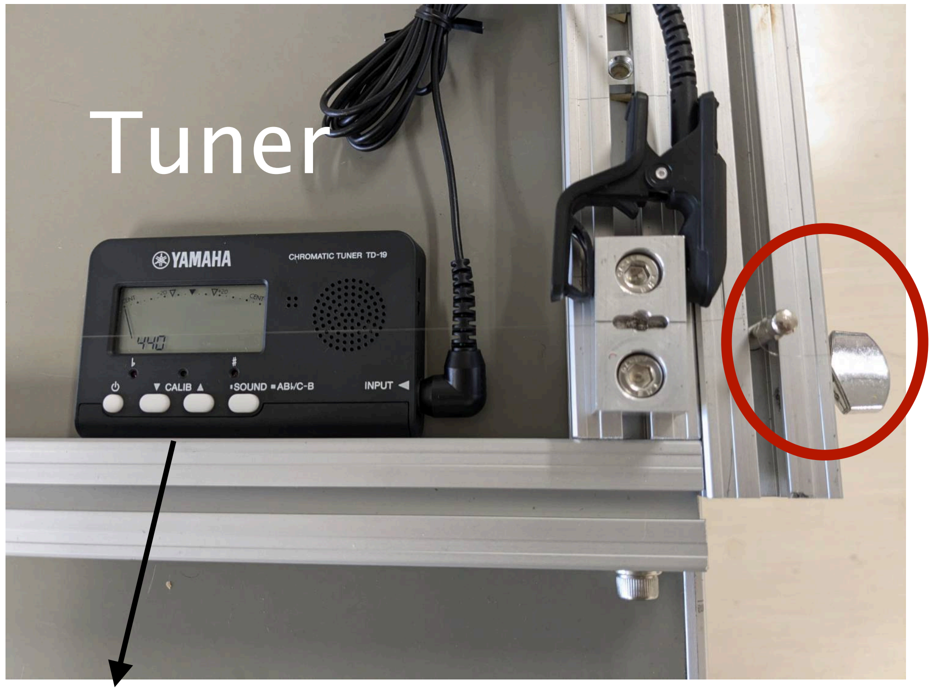
- Simulated with Fusion360
- Each wire tension:10 N
- Deflection at most 0.2 mm



Fixing method and wire tension

Simple installation method is needed for efficient work at the observatory
-> Adopted guitar-like mechanism
: guitar pegs and tuner
Benefit: Ease of setup and adjustment

Guitar pegs



Relationship between wire tension and frequency.

$$T = 4\rho L^2 f^2$$

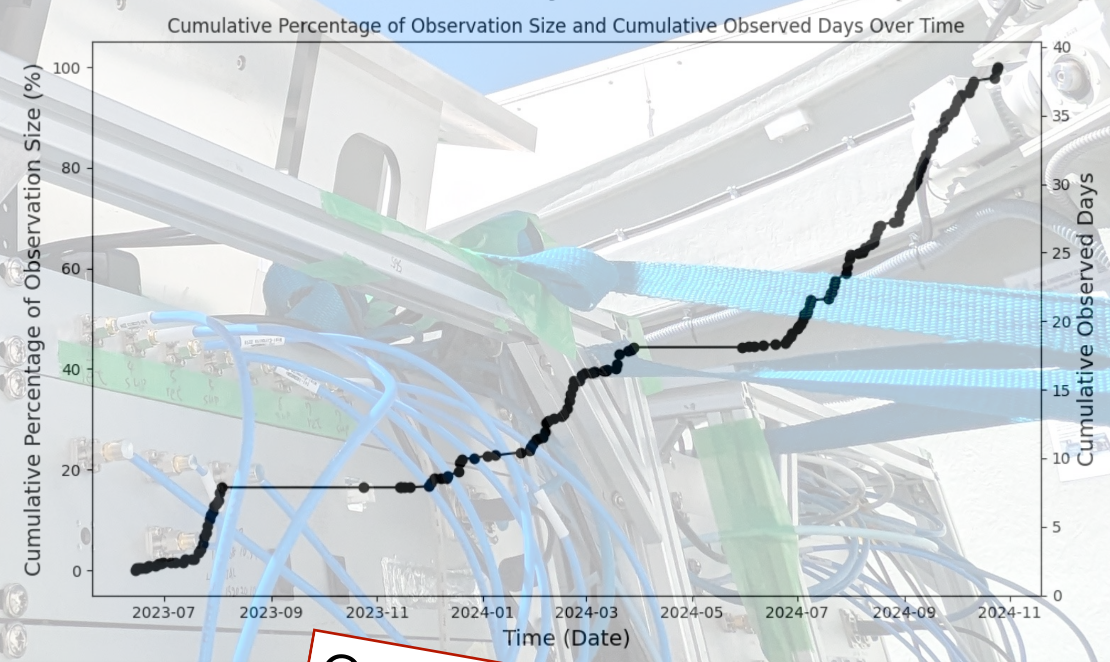
T : Wire tension ρ : The line density

f : frequency L : The length of the string

- **GroundBIRD is a ground-based CMB experiment specifically designed to measure at large angular scales.**
- **The full set of MKID arrays was successfully installed in May 2023.**
- **Telescope calibration in progress**
  - ⋆ **NEP @lab measurement: done and got the same result as expected.**
  - ⋆ **Pointing calibration using the Moon with uncertainty of $3.3'$**
  - ⋆ **Polarization calibration with sparse wire grid**
    - Tests with a simplified setup were successful.
    - The final version of the wire grid is under construction.
    - Plan to perform far-field polarization angle calibration using an artificial source launched by the drone with Milano- Bicocca team!
- **Long-term observations initiated**

GroundBIRD observations

The observed time so far ~35 days from new detectors (~June 2023)



Future prospects

Calibration (On going) → **Three years observation** (On going) → **Final result**