Antenna pattern measurements of millimeter-wave telescopes for LiteBIRD

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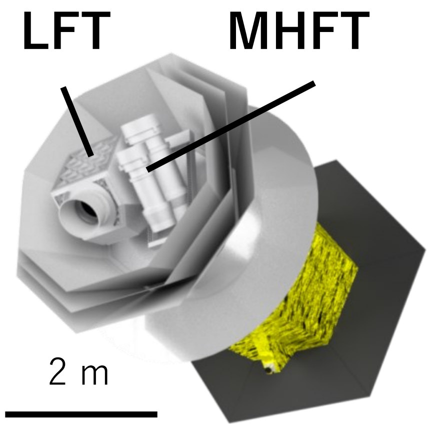
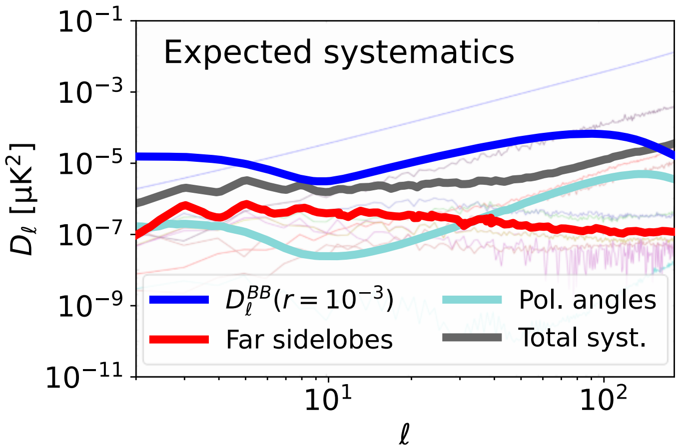
LiteBIRD and its telescopes

- JAXA's mission for all-sky survey of the large-angular-scale CMB polarization
- Frequency coverage of 34–448 GHz with three telescopes LiteBIRD Collab, PTEP 2023
- Far-sidelobe requirement: −56 dB knowledge (for the LFT) Y. Sekimoto+, SPIE 2020



	LFT	MFT / HFT
Frequency	34 – 161 GHz	89 – 224 / 168 – 448 GHz
Optics	Reflective	Refractive
Field of view	18° × 9°	Ø28°
Detectors	1080 TESs	2074 / 1354 TESs
Aperture dia.	400 mm	300 / 200 mm
Operation temp.	5 K	5 K



LiteBIRD Collab, PTEP 2023

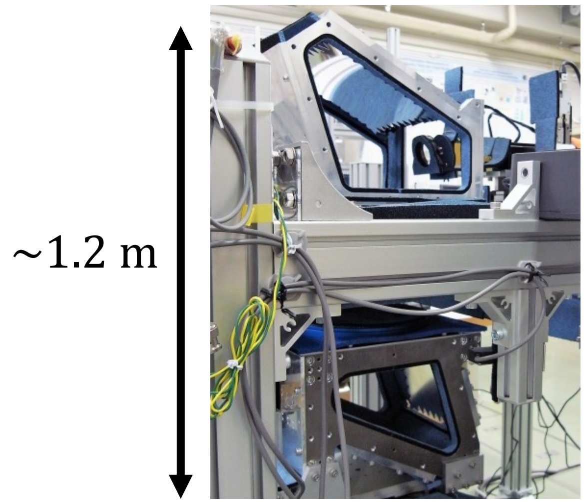
Aims of this study
- Verification of the wide-field antenna design by optical measurements
- Development of a measurement method feasible for future ground calibration

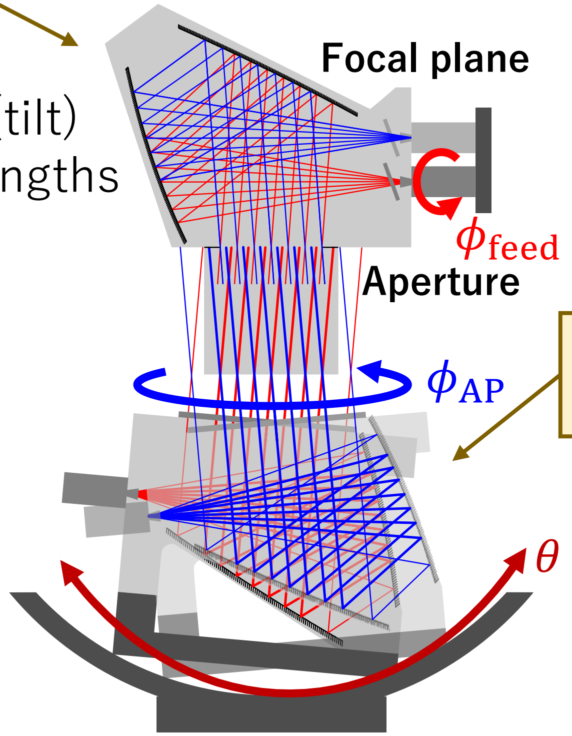
Laboratory measurement setup: CATR

- Directly measure the coupling to plane waves using collimating optics
- Conventional compact antenna test range (CATR) requires a large facility
  → a small dedicated setup for the beam center & pol. angle measurements

1/4-scaled LFT

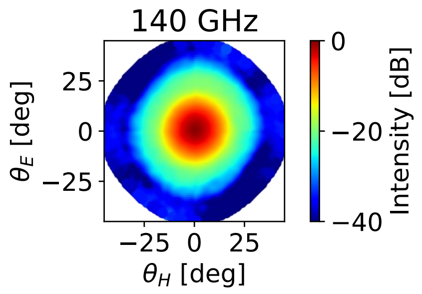
- Optics: scaled to 1/4 size
  Alignment: 30 μm (shift), 10″ (tilt)
- Measured at ¼-scaled wavelengths

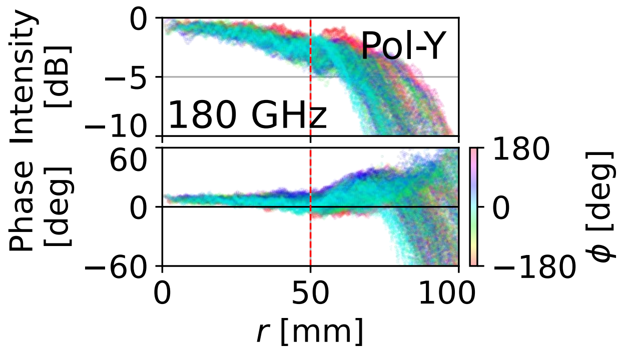




Focal-plane array: replaced with a dedicated corrugated horn + stages

Collimated-wave source



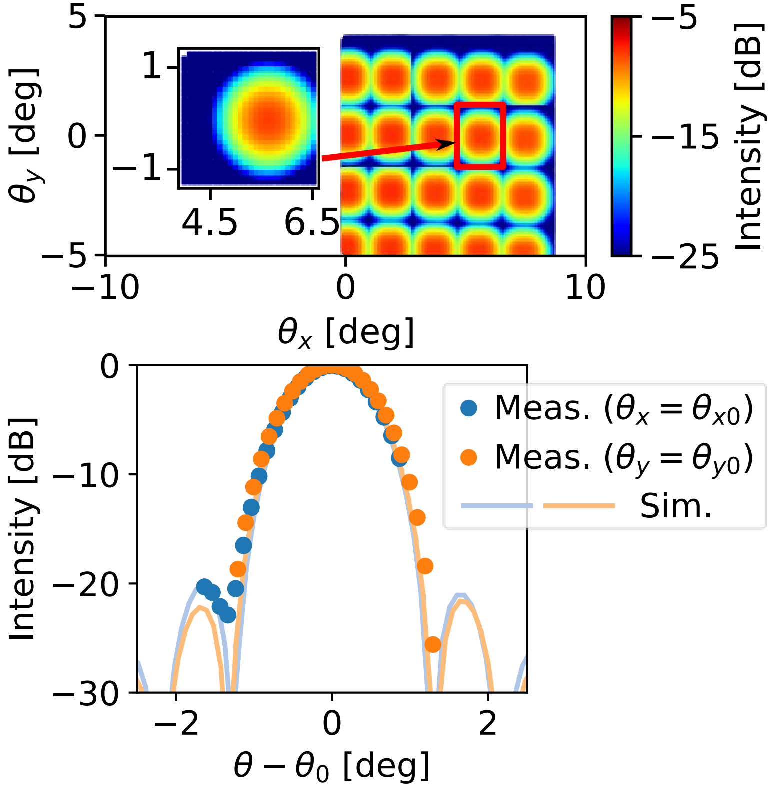


H. Takakura+, JATIS 2023

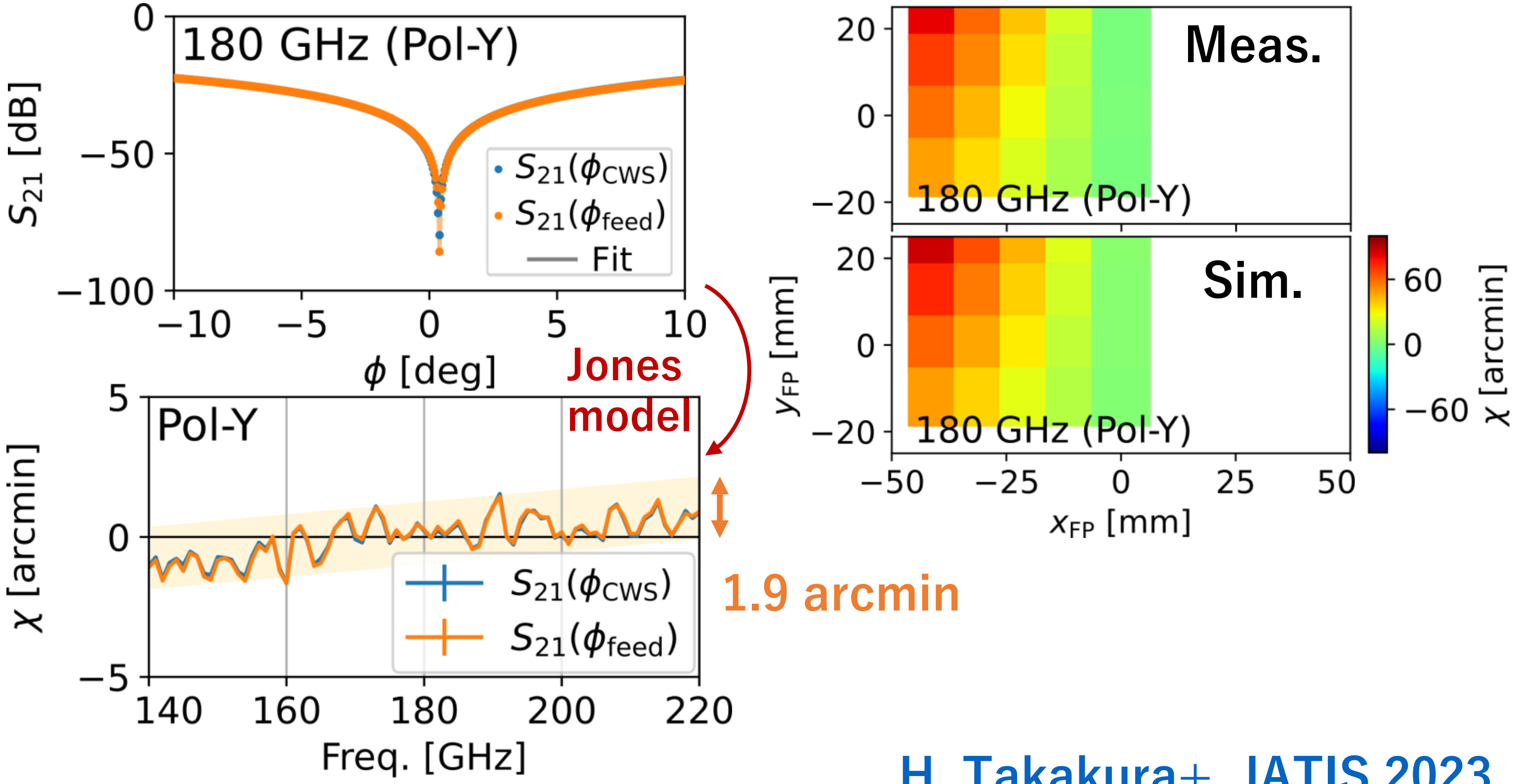
Antenna patterns & polarization angles

- Antenna patterns: determined the beam center at a $0.1'$ resolution
- Polarization angles: determined at a $1.9'$ resolution; consistent with simulation

Antenna patterns



Polarization angles



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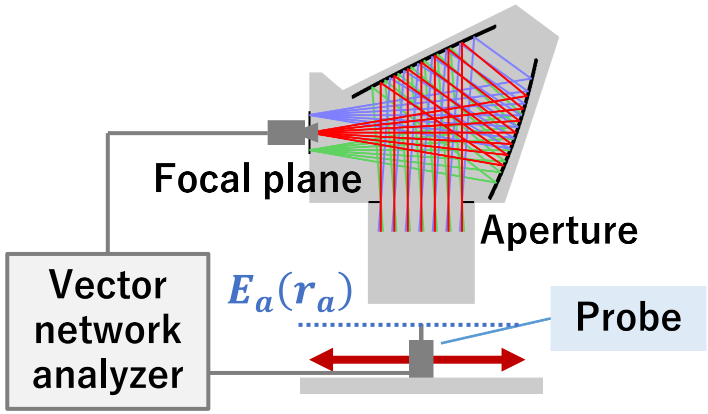
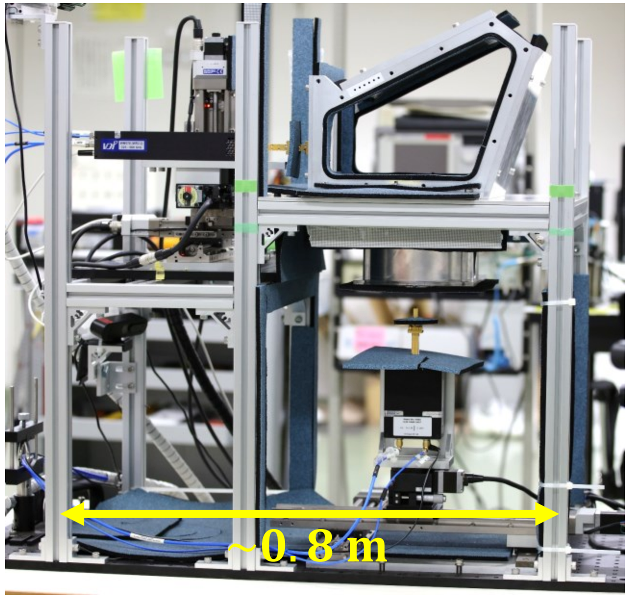
Laboratory measurement setup: near field

- Scan the aperture fields → decompose into plane waves by Fourier transform
- Smaller setup than CATR → far-sidelobe characterization & cryogenic meas.
- Require both amplitude & phase information → phase retrieval (next talk)

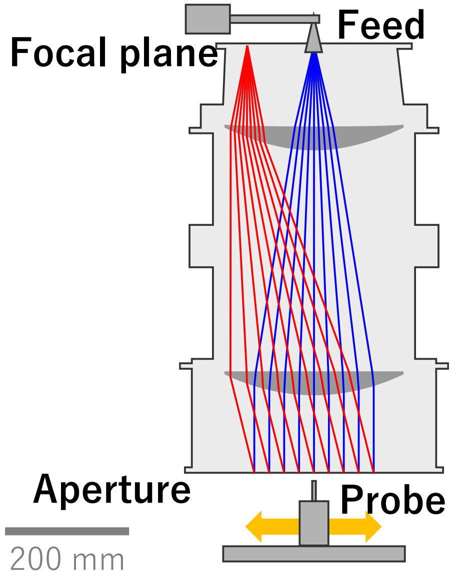
Setup for the ¼-scaled LFT (reflective)

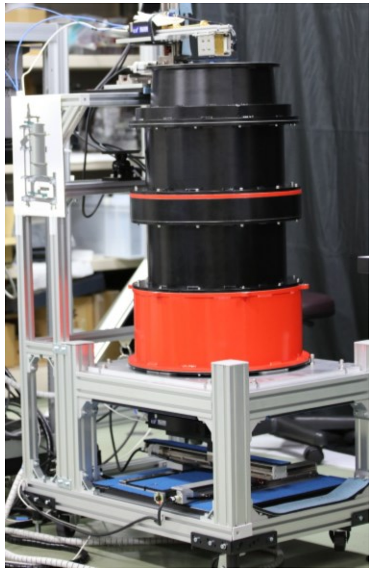


$$\hat{E}(\boldsymbol{k}) \propto \iint E_a(\boldsymbol{r}_a) e^{-i\boldsymbol{k}\cdot\boldsymbol{r}_a} d\boldsymbol{r}_a$$



Setup for the HFT (refractive)





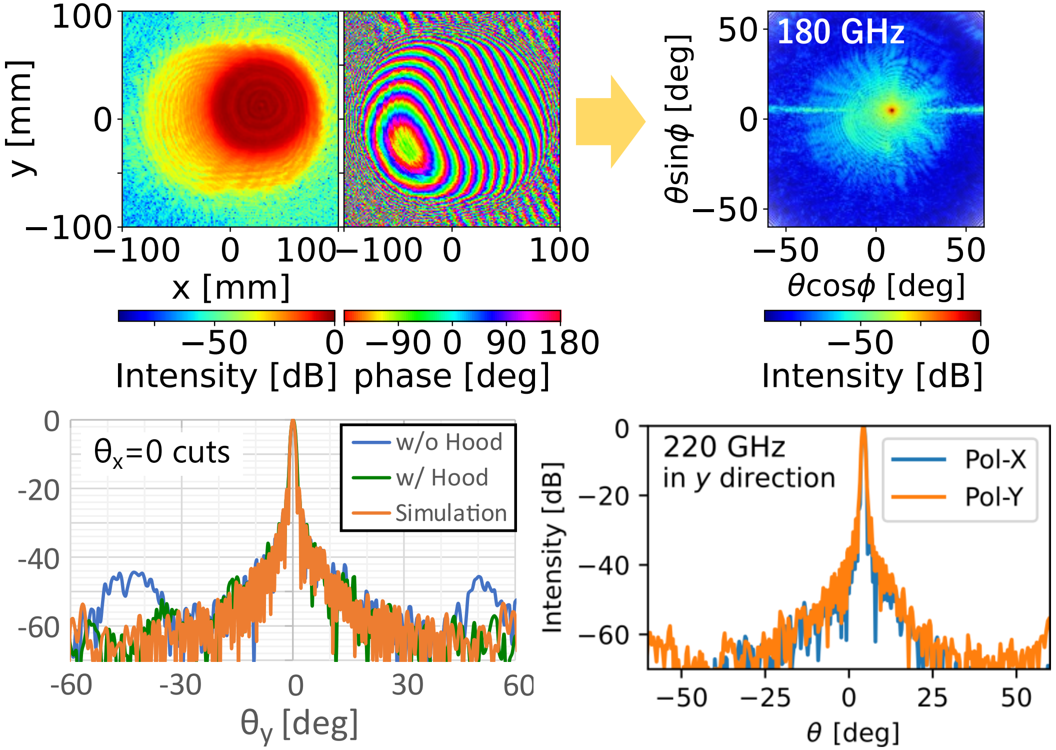
[H. Takakura+, IEEE TST 2019]

[E. Carinos, HT+, SPIE 2024]

Antenna patterns of the LFT & HFT

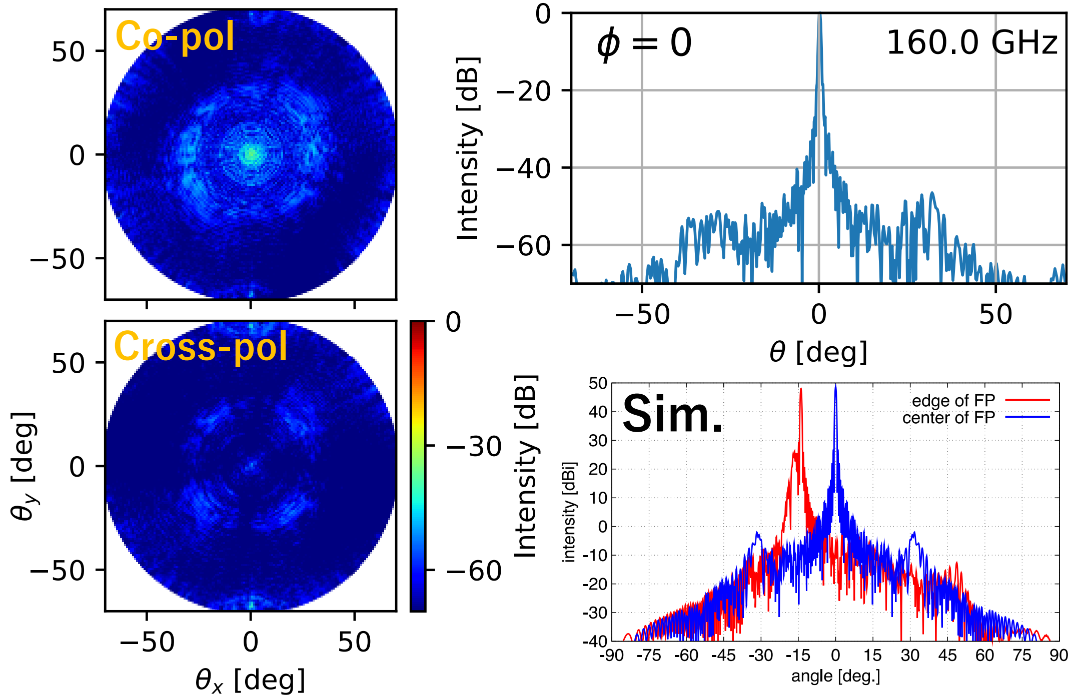
- Characterized far sidelobes down to the −70 dB level (both on- and off-axes)
- Consistent far-sidelobe features with simulations

Aperture fields & antenna patterns (LFT)



[H. Takakura+, IEEE TST 2019]

Antenna patterns (HFT)



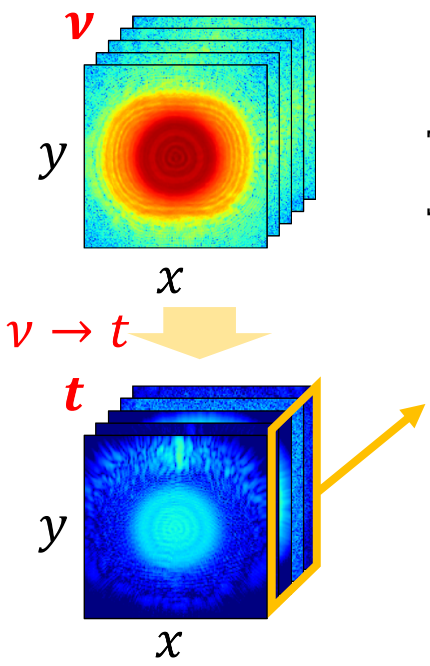
[E. Carinos, HT+, SPIE 2024]

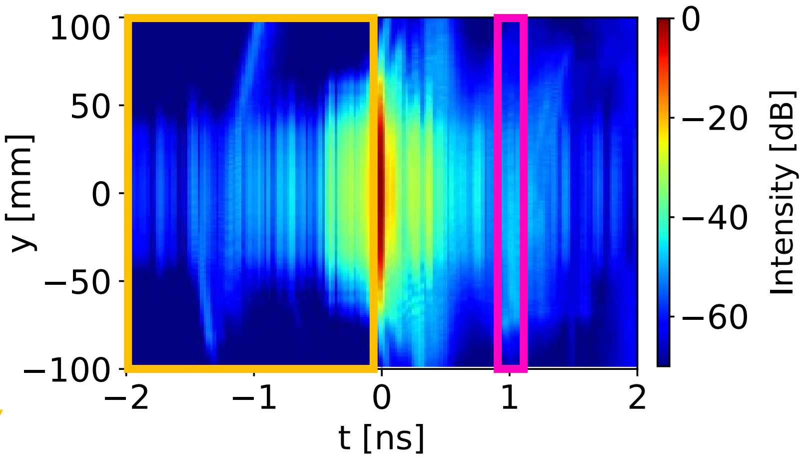
Stray light characterization by time gating

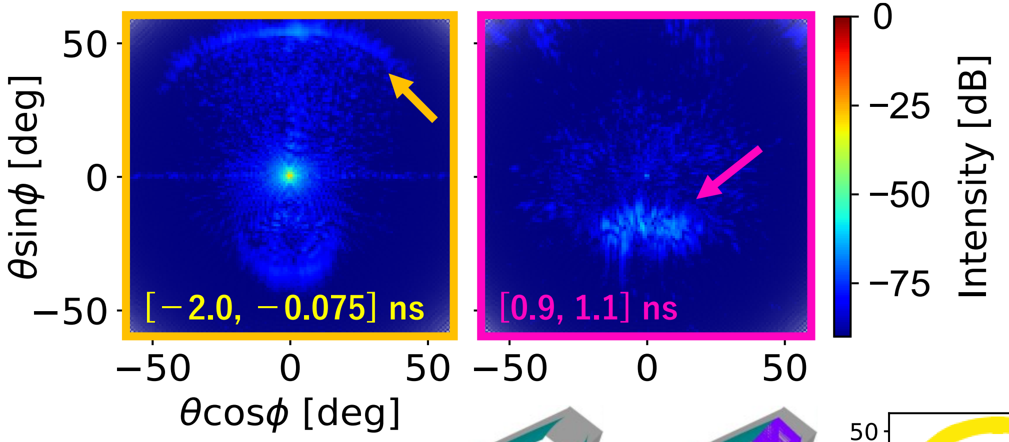
- Separated the aperture field with different arrival time (freq. meas. → time)
- ~0.1 ns resolution (path-length difference of 30 mm)
- Consistent arrival time and angle with simulation

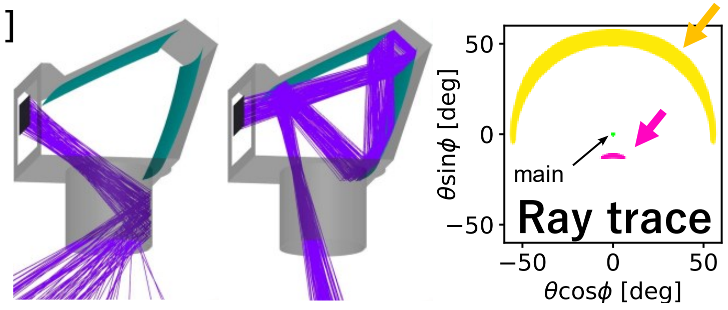
H. Takakura+, SPIE 2022

Aperture field | **Time profile** | **Time-gated antenna patterns**



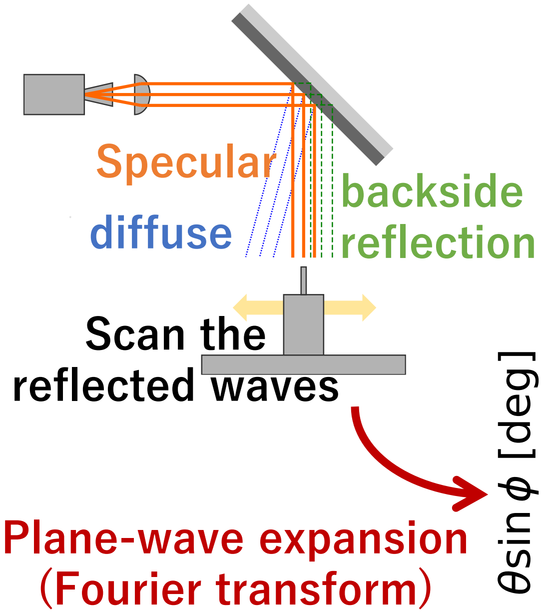




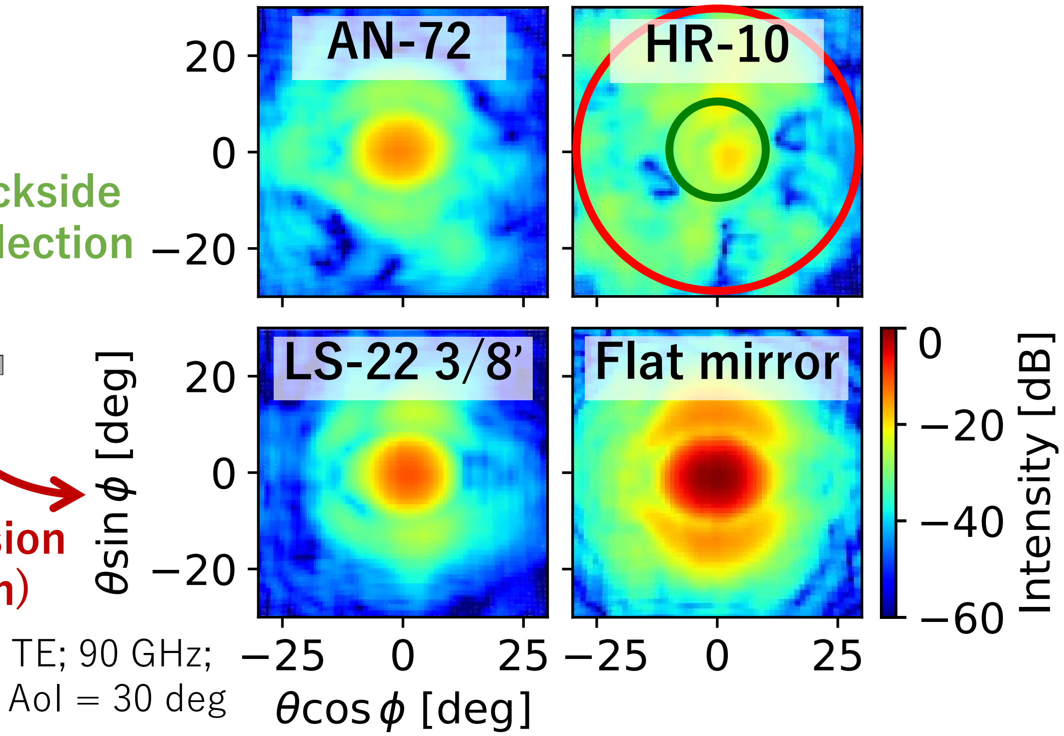


Millimeter-wave absorber characterization

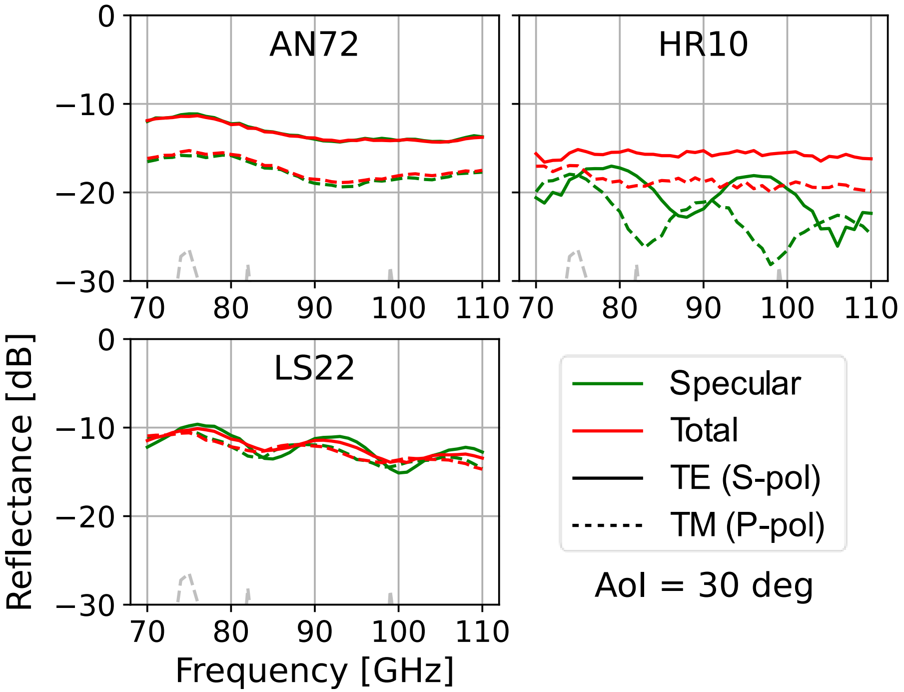
- Applied near-field measurement techniques to absorber characterization
- Enabled measurements of 2D diffuse reflection, in addition to specular one
- Less affected by standing waves and by uncertainty of reflection points



Angular profiles of reflected waves



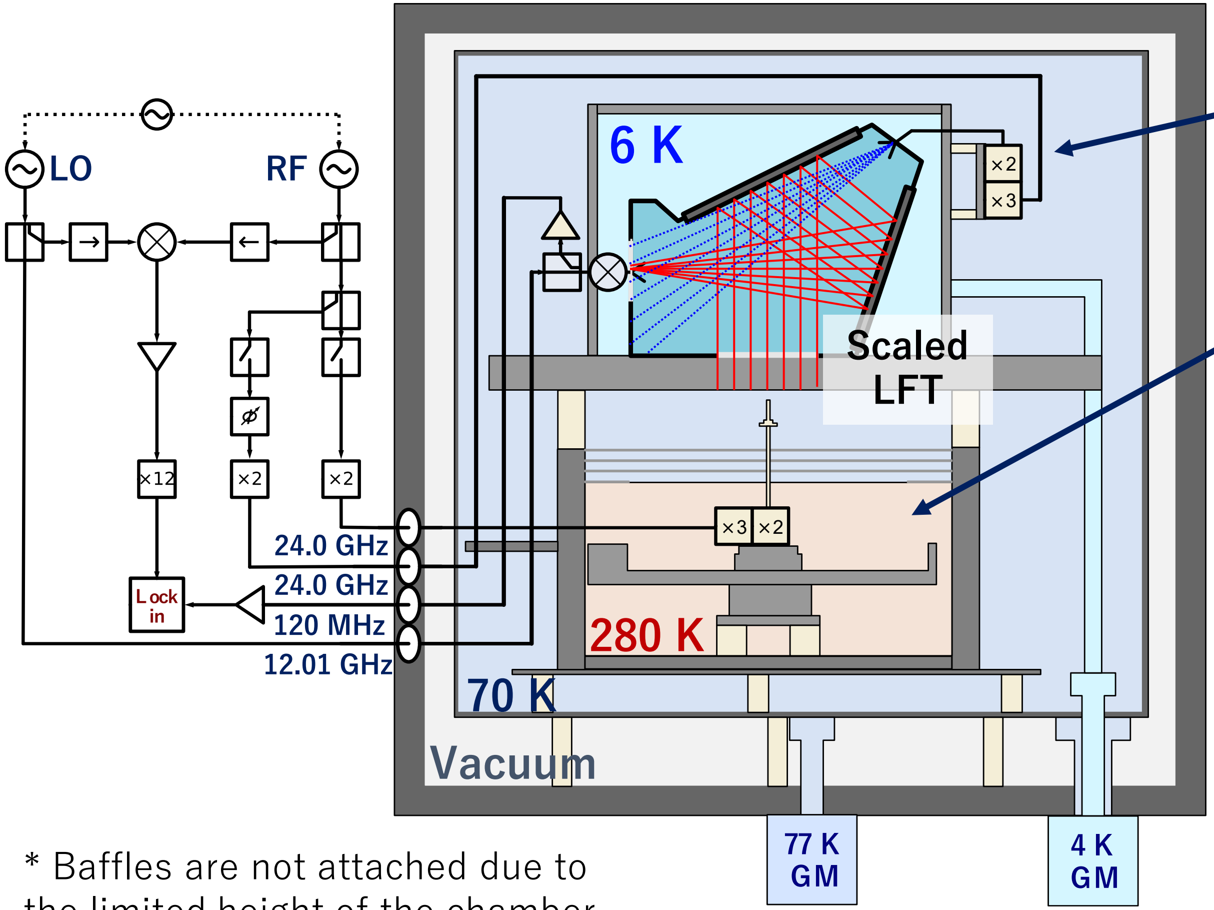
Specular & total reflectance



F. Miura, HT+, Appl Opt 2024

Cryogenic phase-retrieval measurements

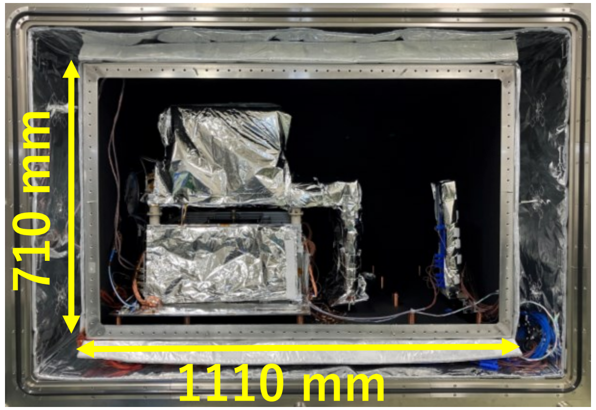
- Feasibility study for future cryogenic measurements with TES detectors
- Fully enclosed in the chamber; not truncated & diffracted by vacuum windows

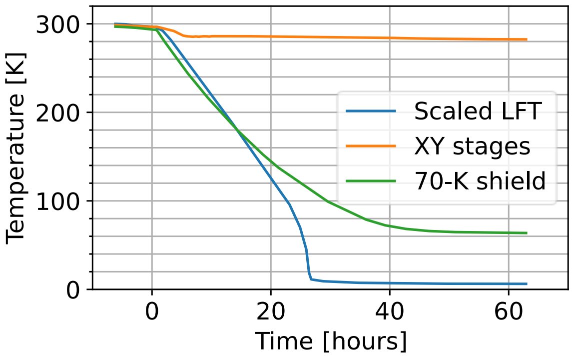


* Baffles are not attached due to the limited height of the chamber

Reference emitter
Generate interferometric fringes that contains phase information of the aperture fields

XY stages
Kept at 280 K for accurate and quick motions; moves with co-moving radiation shields

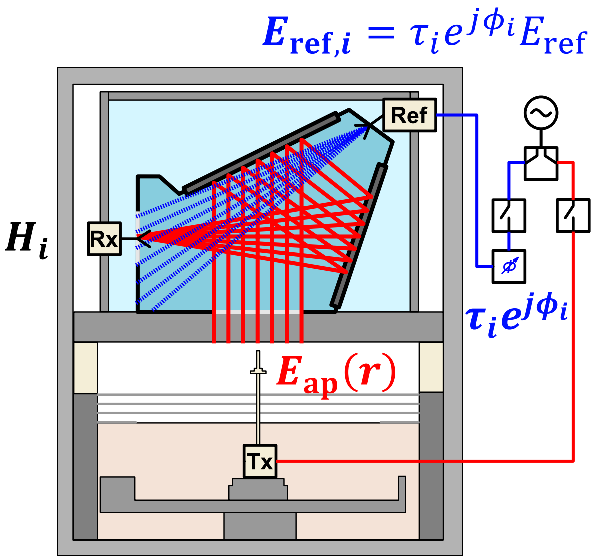




H. Takakura+, SPIE 2024

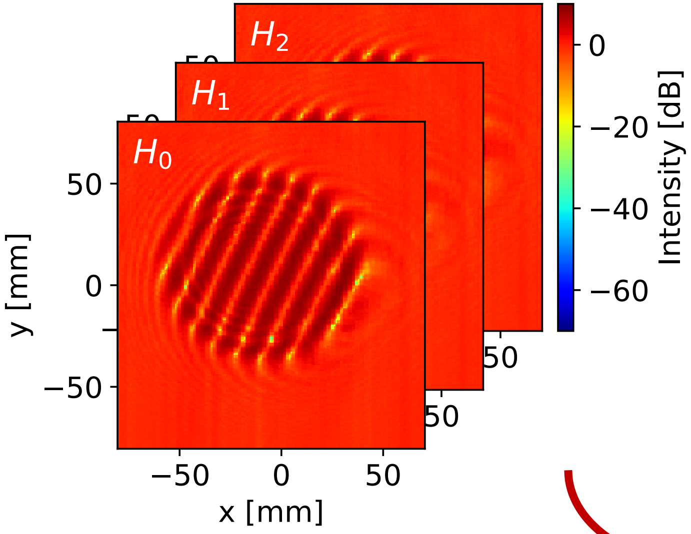
Holograms & retrieved aperture fields at 6 K

- Measured 3 holograms with different phase steps by a single aperture scan
- Retrieved and vector-measured fields are consistent, even at 6 K

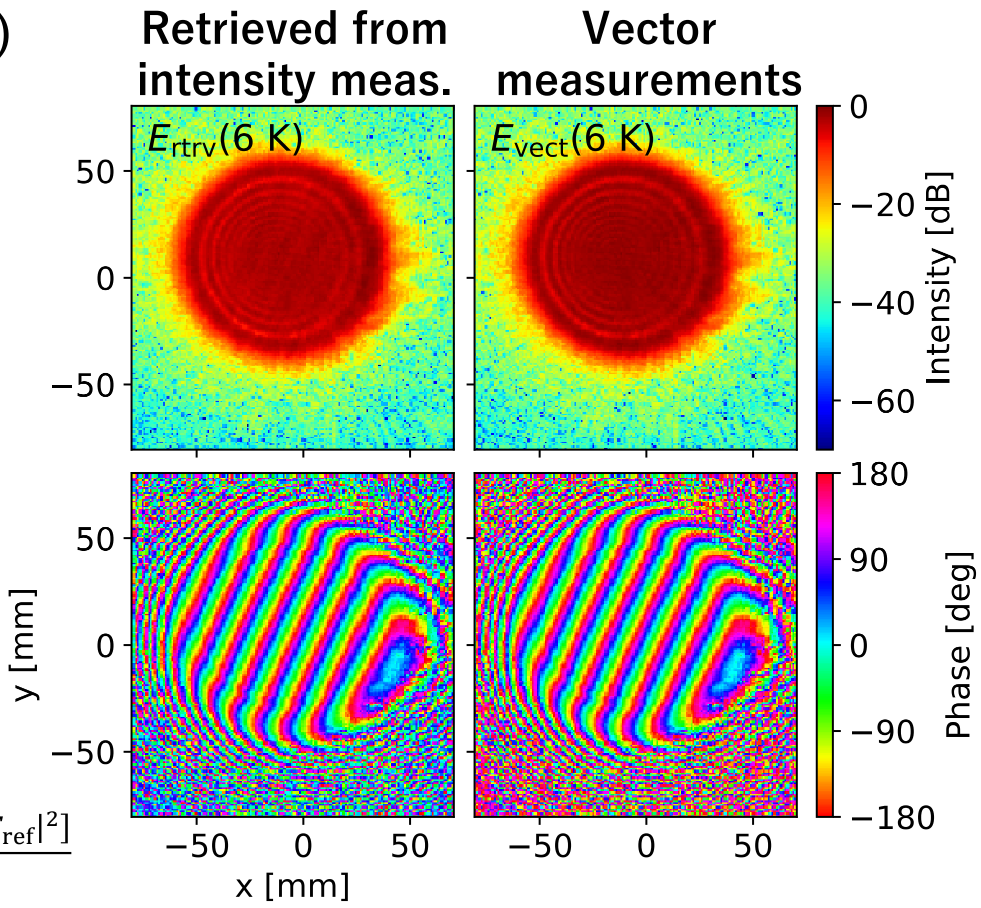


$$H_i = \left|E_{\mathrm{ap}}(r) + E_{\mathrm{ref},i}\right|^2$$

Holograms at 6 K (144 GHz)



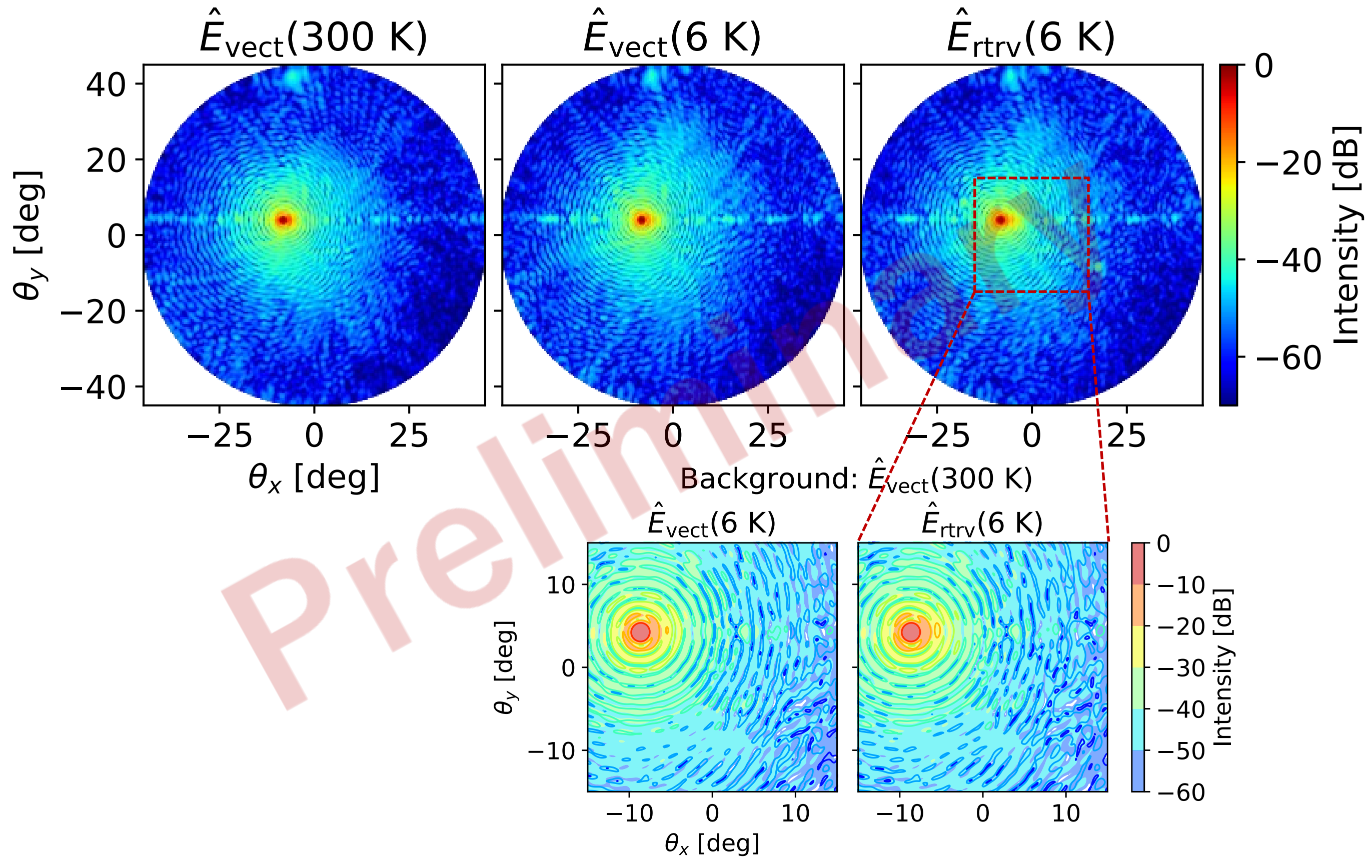
Algorithm by
[R. Takahashi, HT+, SPIE 2024]

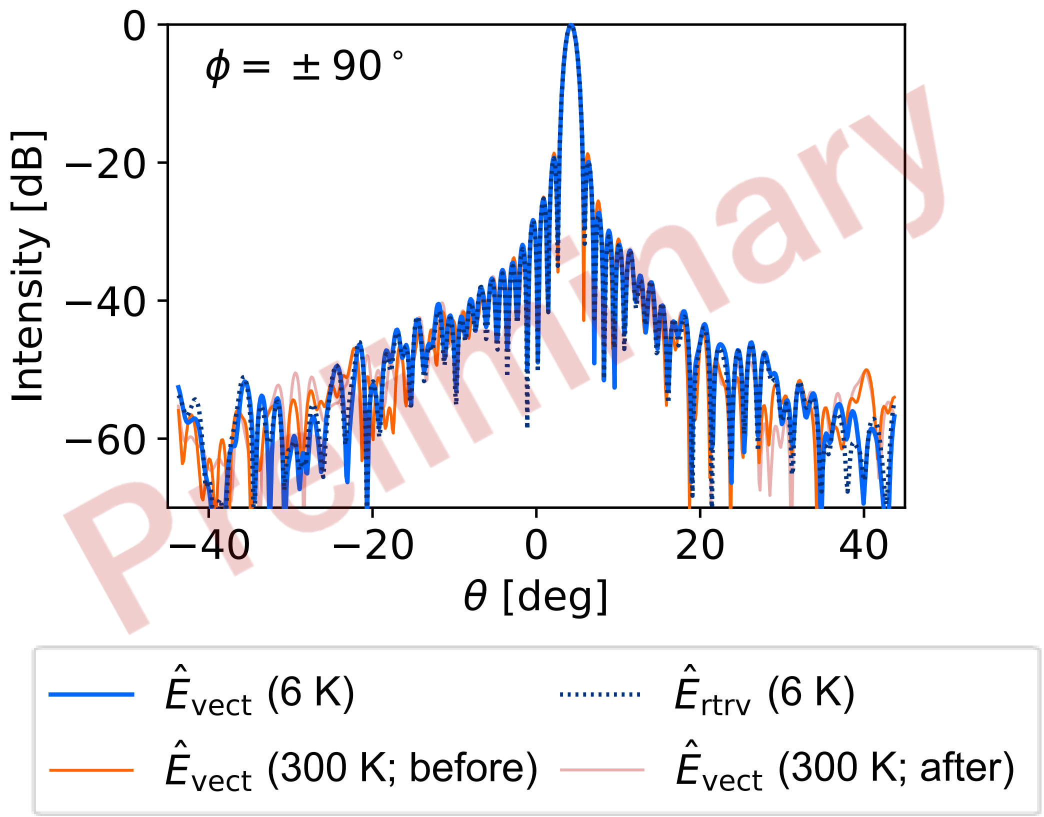


$$E_{\mathrm{ap}}^{\mathrm{rtrv}}(r) = \frac{(\tau_2 e^{i\phi_2} - 1)[H_1(r) - H_0(r) - (\tau_1^2 - 1)|E_{\mathrm{ref}}|^2] - (\tau_1 e^{i\phi_1} - 1)[H_2(r) - H_0(r) - (\tau_2^2 - 1)|E_{\mathrm{ref}}|^2]}{(\tau_1 e^{-i\phi_1} - 1)(\tau_2 e^{i\phi_2} - 1) - (\tau_1 e^{i\phi_1} - 1)(\tau_2 e^{-i\phi_2} - 1)}$$

Antenna patterns at 6 K (vector & retrieved)

- Retrieved and vector-measured patterns are consistent, even at 6 K
- Patterns at 6 K are mostly consistent with those at 300 K down to −50 dB





Summary

- Laboratory verification of wide-field optical designs for LiteBIRD telescopes
  - Polarization angles (LFT): $< 1.9'$ uncertainties **H. Takakura+, JATIS 2023**
  - Far sidelobes (LFT & HFT): -70 dB level, both for on- and off-axes

H. Takakura+, IEEE TST 2019; E. Carinos, HT+, SPIE 2024

- Experimental characterization of stray light
  - Identified stray light with a 30 mm path-length resolution **H. Takakura+, SPIE 2022**
  - Characterized 2D reflection profiles of absorbers with near-field technique

F. Miura, HT+, Appl Opt 2024; F. Miura, HT+, SPIE 2024

- Cryogenic phase-retrieval measurements towards the future ground test
  - Patterns at 6 K are mostly consistent with those at 300 K down to -50 dB
  - Retrieved and vector-measured patterns are consistent, even at 6 K

H. Takakura+, SPIE 2024 (Cf. R. Nakano, HT+ JATIS 2023; R. Takahashi, HT+, SPIE 2024)

References

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