Holographic field-retrieval method of near-field measurements of wide field-of-view millimeter-wave telescopes using reference phase steps

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Background

CMB Telescopes

・Low noise and high throughput

→Broad frequency coverage and wide field of view telescopes equipped with bolometer detector arrays such as TES.

・It is necessary to accurately evaluate the far-sidelobes of the beam pattern $f(\boldsymbol{k})$

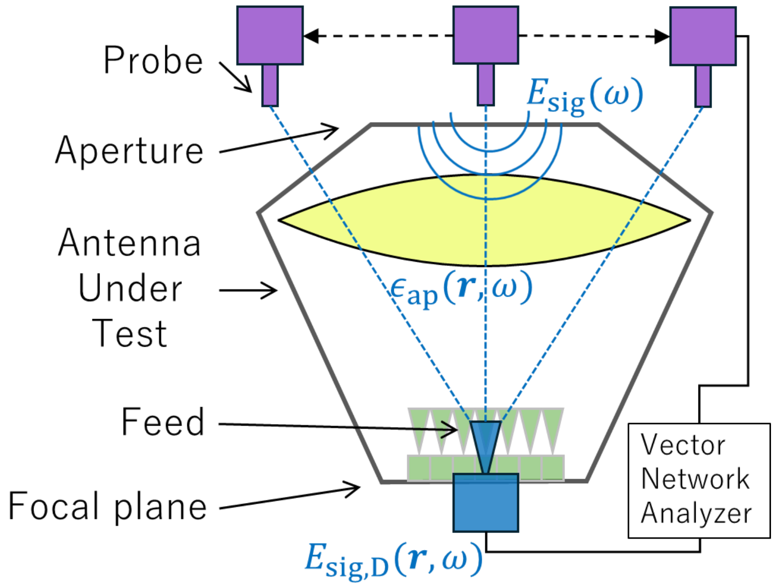
Near-field antenna measurements (Vector)[1]

・$f(\boldsymbol{k}) = \iint_{-\infty}^{\infty} \epsilon_{\mathrm{ap}}(\boldsymbol{r}) e^{-i(\boldsymbol{k}\cdot\boldsymbol{r})}\, d\boldsymbol{r}$

$E_{\mathrm{sig,D}}(\boldsymbol{r}) = \epsilon_{\mathrm{ap}}(\boldsymbol{r}) E_{\mathrm{sig}}$

ϵ_{ap} : normalized aperture field

・Need **phase and intensity** of the aperture field



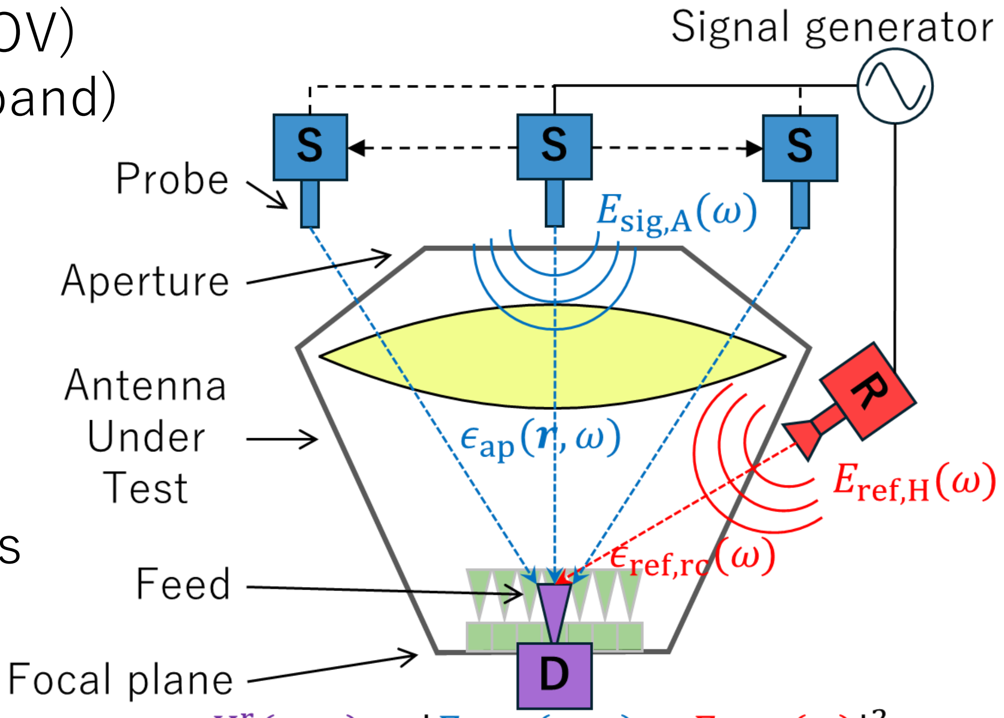
Our goal is to measure $f(\boldsymbol{k})$ of the telescope using bolometer-coupled feeds (not sensitive to phase)

[1] Takakura, H. et al. 2019. IEEE TST 9, 598–605

Holographic field retrieval near-field measurements

We have developed an antenna measurement method for future CMB telescopes.

①With bolometer-coupled feeds (①phaseless)
②Measure across the entire focal plane (②Wide FOV)
③Be applicable to a broad frequency bandwidth (③Broad band)
④Be applicable to a cryogenic measurements (④Cryo)



$H^{\mathrm{r}}(\boldsymbol{r},\omega) = |E_{\mathrm{sig,D}}(\boldsymbol{r},\omega) + E_{\mathrm{ref,D}}(\omega)|^2$

S : Signal waves emitter
R : Reference waves emitter
D : Detector

Retrieve the aperture field (amplitude and phase) from **intensity-only** measurements

The coherent signal is divided into two parts

⇩

Two waves are interfered

The intensity distribution of the interference fringes (Hologram H)

$$H = |E_{\mathrm{sig,D}}(\boldsymbol{r},\omega) + E_{\mathrm{ref,H}}(\omega)|^2$$
$$= |E_{\mathrm{sig,D}}(\boldsymbol{r},\omega)|^2 + |E_{\mathrm{ref,H}}(\omega)|^2 + E_{\mathrm{sig,D}}(\boldsymbol{r},\omega)E^{*}_{\mathrm{ref,H}}(\omega) + E^{*}_{\mathrm{sig,D}}(\boldsymbol{r},\omega)E_{\mathrm{ref,H}}(\omega)$$

Holographic field retrieval algorithms

Hologram

$$H = |E_{\mathrm{sig,D}}(\boldsymbol{r},\omega)|^2 + |E_{\mathrm{ref,H}}(\omega)|^2 + \underbrace{E_{\mathrm{sig,D}}(\boldsymbol{r},\omega)E^*_{\mathrm{ref,H}}(\omega) + E^*_{\mathrm{sig,D}}(\boldsymbol{r},\omega)E_{\mathrm{ref,H}}}_{\text{Modified hologram } H_{\mathrm{m}}}(\omega)$$

Algorithms to retrieve $E_{\mathrm{sig,D}}(\boldsymbol{r},\omega)$

1 Retrieval in the spatial-frequency domain[4]

- $\hat{H}_{\mathrm{m}}(\boldsymbol{k}) = \mathcal{F}_{\boldsymbol{r}\to\boldsymbol{k}}[H_{\mathrm{m}}(\boldsymbol{r})] = \underbrace{\hat{E}_{\mathrm{sig,D}}(k)\hat{E}^*_{\mathrm{ref,H}}}_{\propto \text{ antenna pattern}} + \hat{E}^*_{\mathrm{sig,D}}(-\boldsymbol{k})\hat{E}_{\mathrm{ref,H}}$
- Not suitable for evaluating far-sidelobes of the beam patterns

2 Retrieval in the time domain[2,3]

- $\bar{H}_{\mathrm{m}}(\boldsymbol{r},t) = \mathcal{F}_{\omega\to t}[H_{\mathrm{m}}(\boldsymbol{r},\omega)] = \bar{E}_{\mathrm{sig.D}}(\boldsymbol{r},t)\bar{E}^*_{\mathrm{ref,H}}(-t) + \bar{E}^*_{\mathrm{sig,D}}(\boldsymbol{r},-t)\bar{E}_{\mathrm{ref,H}}(t)$
- $E_{\mathrm{sig,D}}(\boldsymbol{r},\omega) \propto \mathcal{F}_{t\to\omega}[w(t)\bar{H}_{\mathrm{m}}(t)]$
- 2 aperture scan
- Fine frequency tuning
- This method requires a spectrum for field retrieval, so it is easily affected by standing waves.

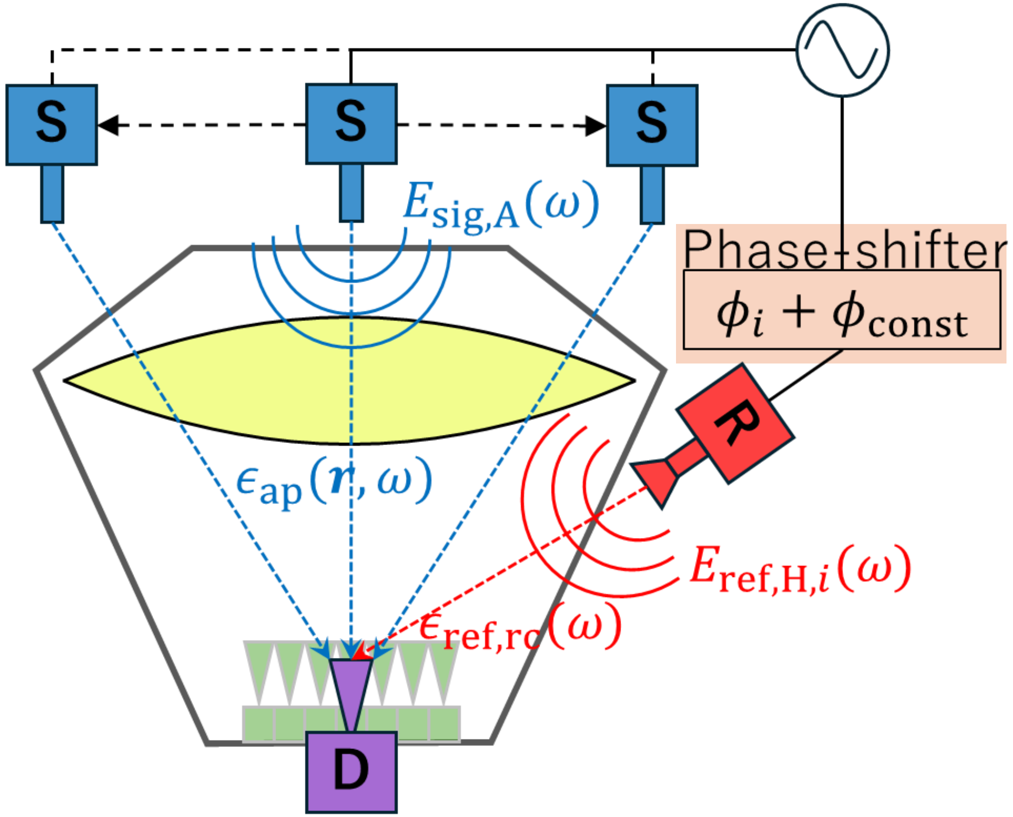
[2] A. Arboleya+, IEEE Trans Ant Prop 2016 [3] Nakano. R., et al. 2023. JATIS. 9. 2. 28003 [4] D. Smith+, IEEE Ant Prop Mag 2007

Phase step holography

Phase step holography

$$H_i^{\mathrm{r}}(\boldsymbol{r},\omega) = |E_{\mathrm{sig,D}}(\boldsymbol{r},\omega) + E_{\mathrm{ref,D},i}(\omega)|^2$$

$$E_{\mathrm{ref,D},i} = \epsilon_{\mathrm{ref,rc}} E_{\mathrm{ref,H},i} = \epsilon_{\mathrm{ref,rc}} \tau_i e^{j\phi_i} E_{\mathrm{ref,H}}$$
$$(\tau_0 = 1, \phi_0 = 0)$$



Measurement parameters
Holograms : H_0, H_1, H_2
Phase steps : ϕ_1, ϕ_2 (be characterized in advance)
Insertion loss of the phase shifter : τ_1, τ_2 (~1)

Proposed algorithm[5]

$$\epsilon_{\mathrm{ap}}(\boldsymbol{r},\omega) \propto \frac{\left(\tau_2(\omega)e^{j\phi_2(\omega)} - 1\right)\left\{H_1(r,\omega) - H_0(r,\omega) - (\tau_1^2(\omega) - 1)\left|E_{\mathrm{ref,D},0}\right|^2\right\} - \left(\tau_1(\omega)e^{j\phi_1(\omega)} - 1\right)\left\{H_2(r,\omega) - H_0(r,\omega) - (\tau_2^2(\omega) - 1)\left|E_{\mathrm{ref,D},0}\right|^2\right\}}{(\tau_1(\omega)e^{-j\phi_1(\omega)} - 1)(\tau_2(\omega)e^{j\phi_2(\omega)} - 1) - (\tau_1(\omega)e^{j\phi_1(\omega)} - 1)(\tau_2(\omega)e^{-j\phi_2(\omega)} - 1)}$$

By modulating the phase of the reference waves and taking the difference between them, the effect of the reference fluctuation is reduced.

[5] Takahashi. R. et al. 2024. SPIE. 13102. 663-676

Measurement set-up

Frequency $f = 140$ GHz → 220 GHz $df = 1.0$ GHz

Antenna Under Test：*LiteBIRD* LFT 1/4-scaled antenna

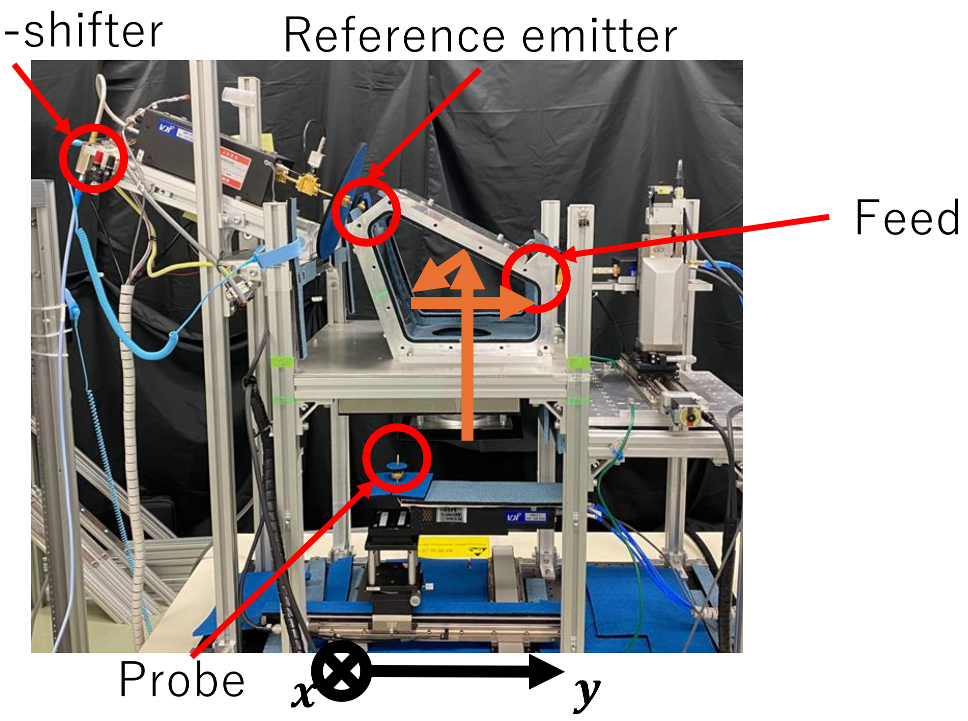
Use a vector network analyzer(VNA)

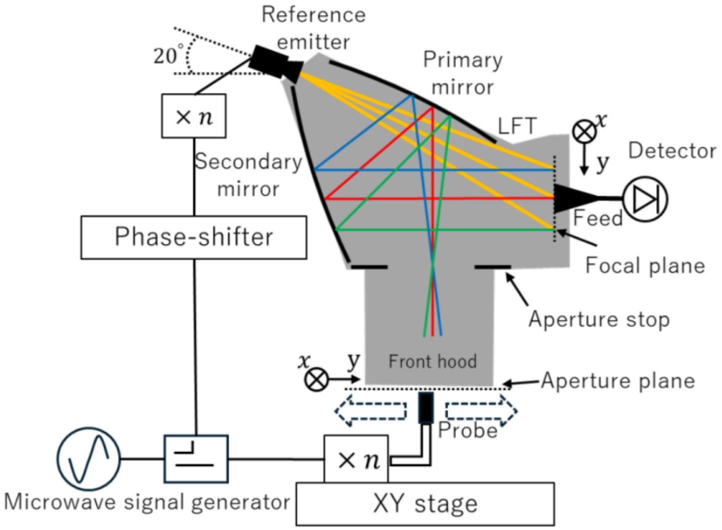
The phase shifter is placed before frequency-multiplying the signal from the signal generator.

The position and angle of the reference emitter was adjusted so that the entire focal plane was illuminated by the reference waves.

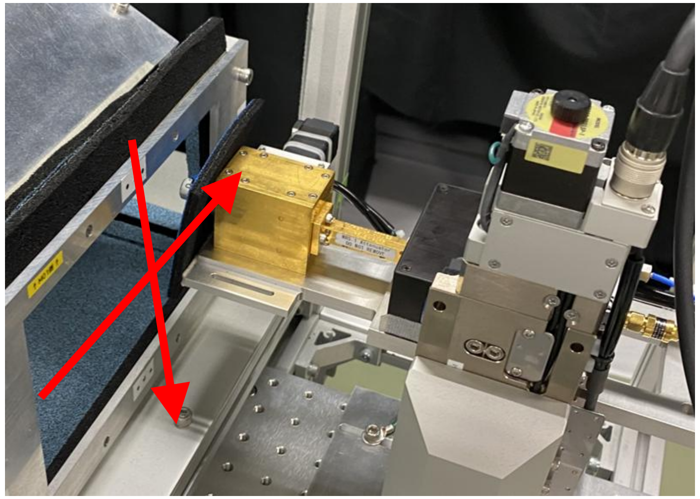
Vector near-field measurements

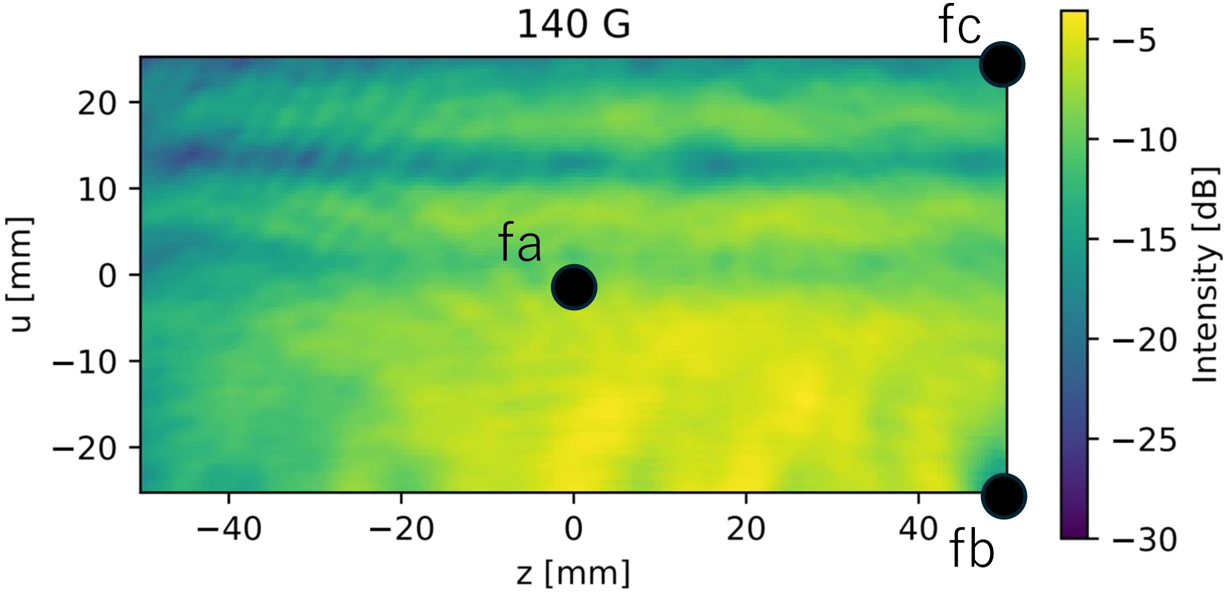
Measurement of the waves from the probe without the reference waves





Reference waves on the focal plane





The intensity distribution on the focal plane

The intensity and phase intervals of the reference waves (140 GHz)

	$\|E_{\mathrm{ref,D,0}}\|^2$ [dB]	$\|E_{\mathrm{ref,D,1}}\|^2$ [dB]	$\|E_{\mathrm{ref,D,2}}\|^2$ [dB]	ϕ_1 [deg]	ϕ_2 [deg]
fa	−8.305	−8.300	−8.300	75.8	149.3
fb	−18.03	−18.04	−18.04	75.9	149.4
fc	−16.65	−16.65	−16.64	75.9	149.4

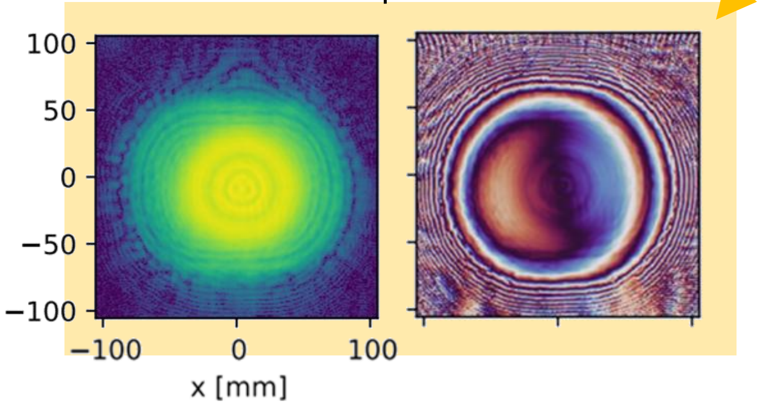
The intensities are normalized by the maximum values of the aperture field measured at position fa, respectively.

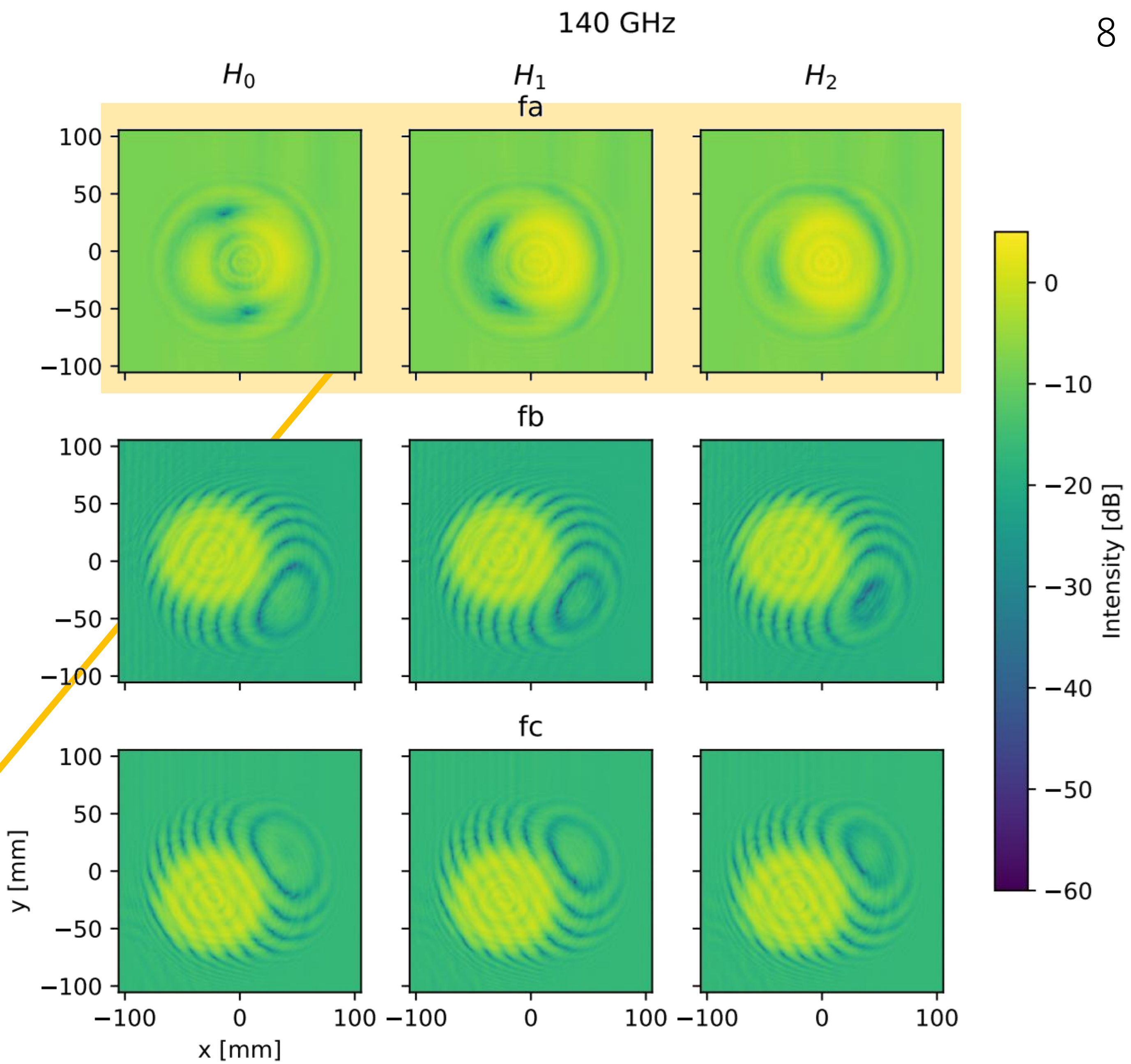
Holograms

Measurement of 3 holograms using reference waves with 3 different phases by single aperture scan
Only the intensity was measured

Aperture scan
(x, y)
$= (-105\ \text{mm}, -105\ \text{mm}) \rightarrow (105\ \text{mm}, 105\ \text{mm})$
$dx, dy = 1.0$ mm
fast axis is y

Retrieve aperture field





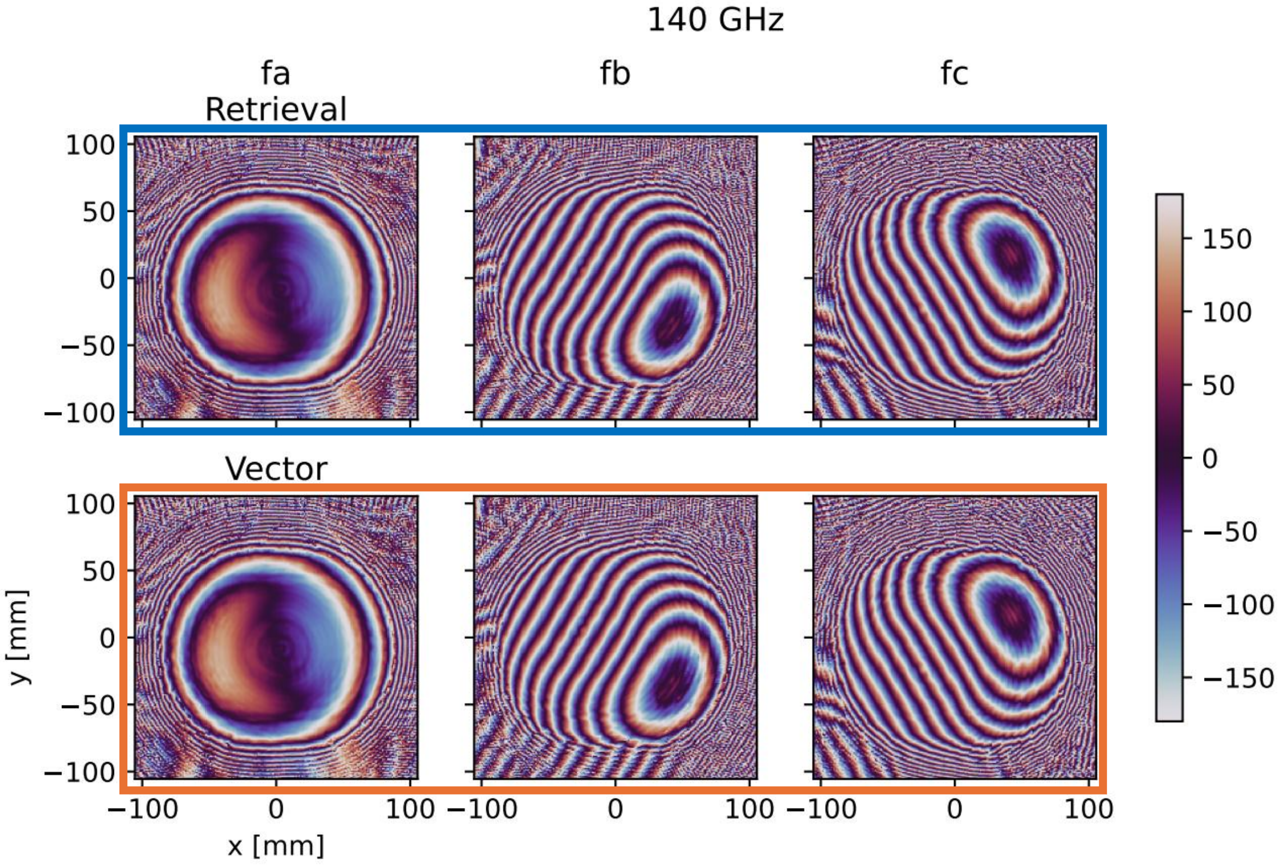
The intensities are normalized by the maximum values of the aperture field measured at position fa, respectively.

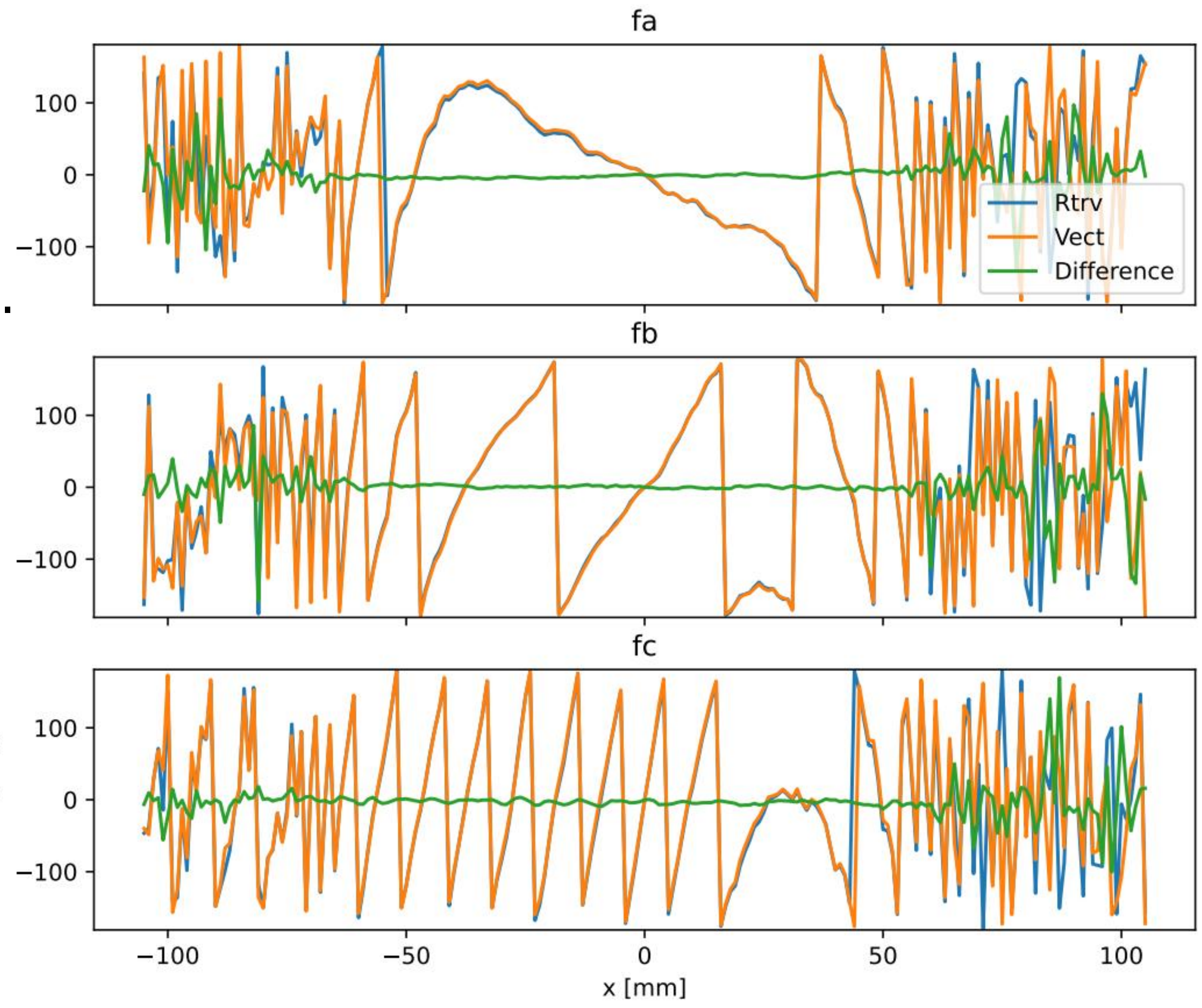
Near-field (Phase)

ϕ_{rtrv} : Phase distribution on the aperture plane retrieved from holograms

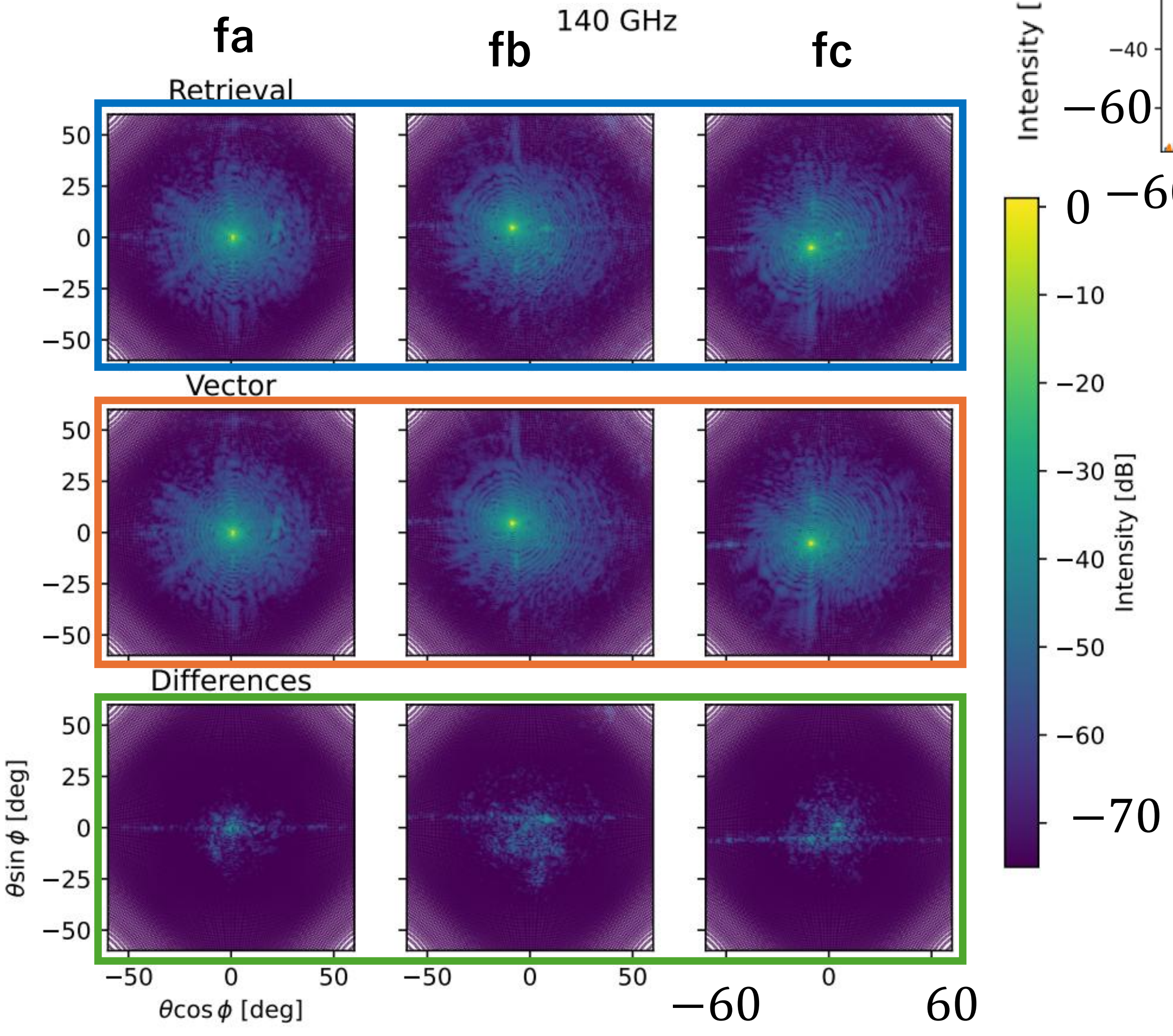
ϕ_{vect} : Phase distribution obtained by vector near-field measurements

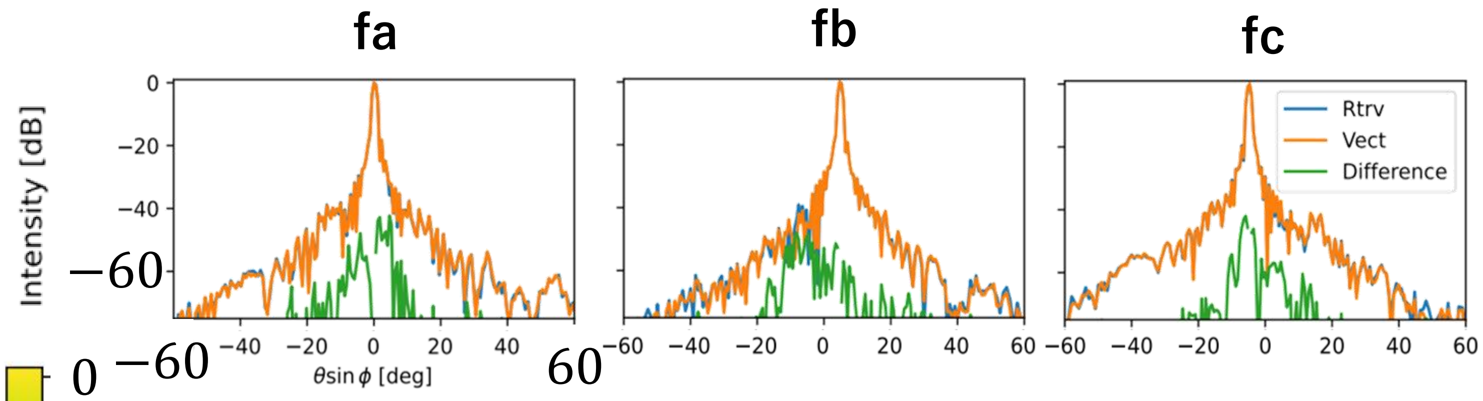
These are normalized to be 0 degree at $(x, y) = (0, 0)$.





Beam patterns





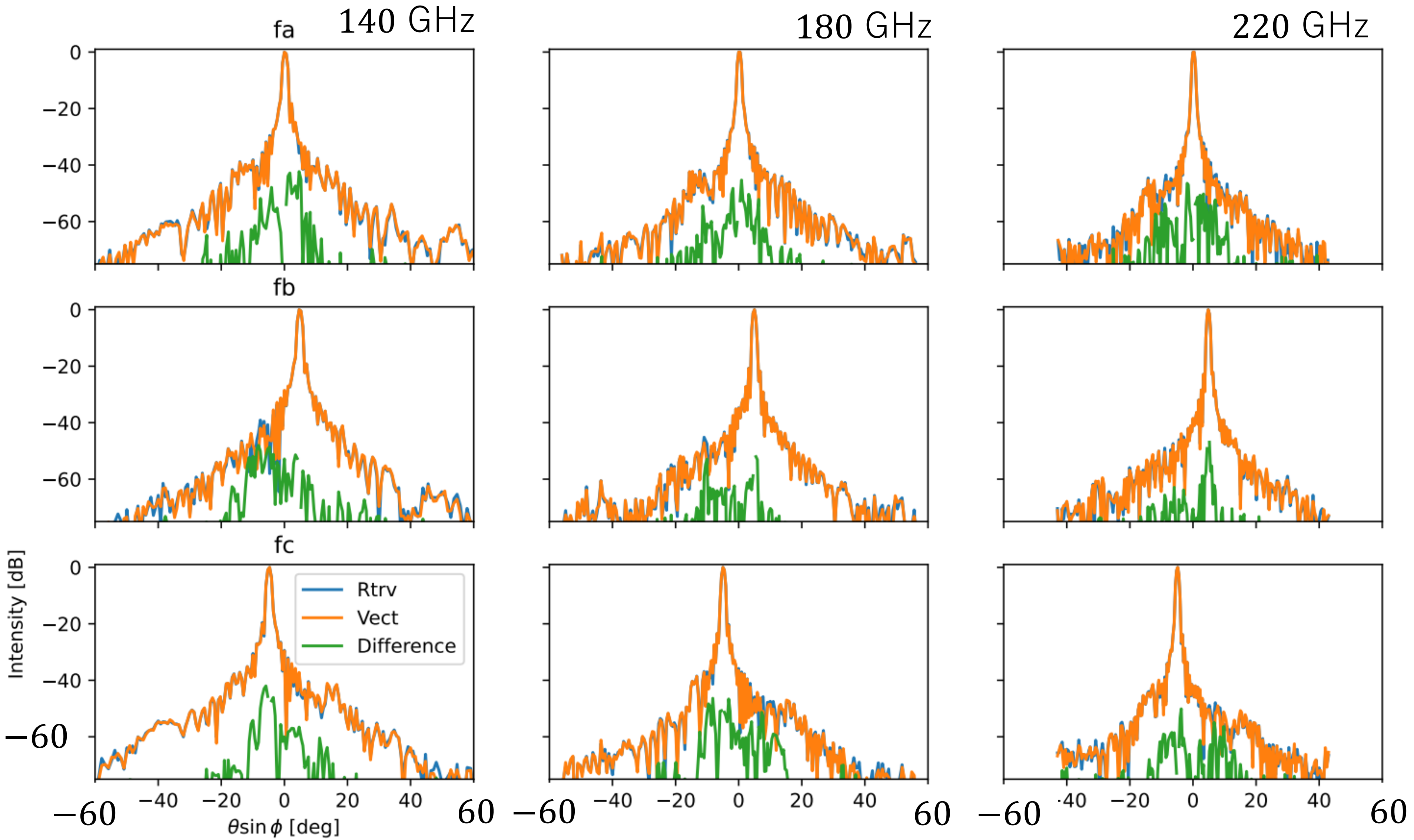
Differences $= 20\log_{10}|10^{\frac{f_{\mathrm{rtrv}}}{20}} - 10^{\frac{f_{\mathrm{vect}}}{20}}|$

The far sidelobes of the beam patterns computed from the retrieved aperture fields and those directly measured by the vector near-field measurements agreed at the −60 dB level.

We confirmed that the patterns are retrieved at a similar precision **among the focal positions**.

Far-field beam patterns

We confirmed that the patterns are retrieved at a similar precision at the edges and center of the measurement frequency band.



Conclusion

- We developed the aperture field retrieval algorithm using reference phase steps, and demonstrated the retrieval of the aperture field and the antenna patterns measurements using this algorithm with the LFT 1/4-scaled antenna.
- The far-sidelobes of the beam patterns (Retrieved - Vector) are agreed at -60 dB level. → (① Phaseless)
- By measuring at the edges of the focal plane, we confirmed that this method can be applied to wide field of view telescopes. → (② Wide FOV)
- Even at the edges of the measurement frequency band, it is possible to retrieve the aperture field and measure the antenna patterns. → (③ Broad band)
- Cryogenic measurement using this method has been demonstrated. (H. Takakura's talk) → (④ Cryo)