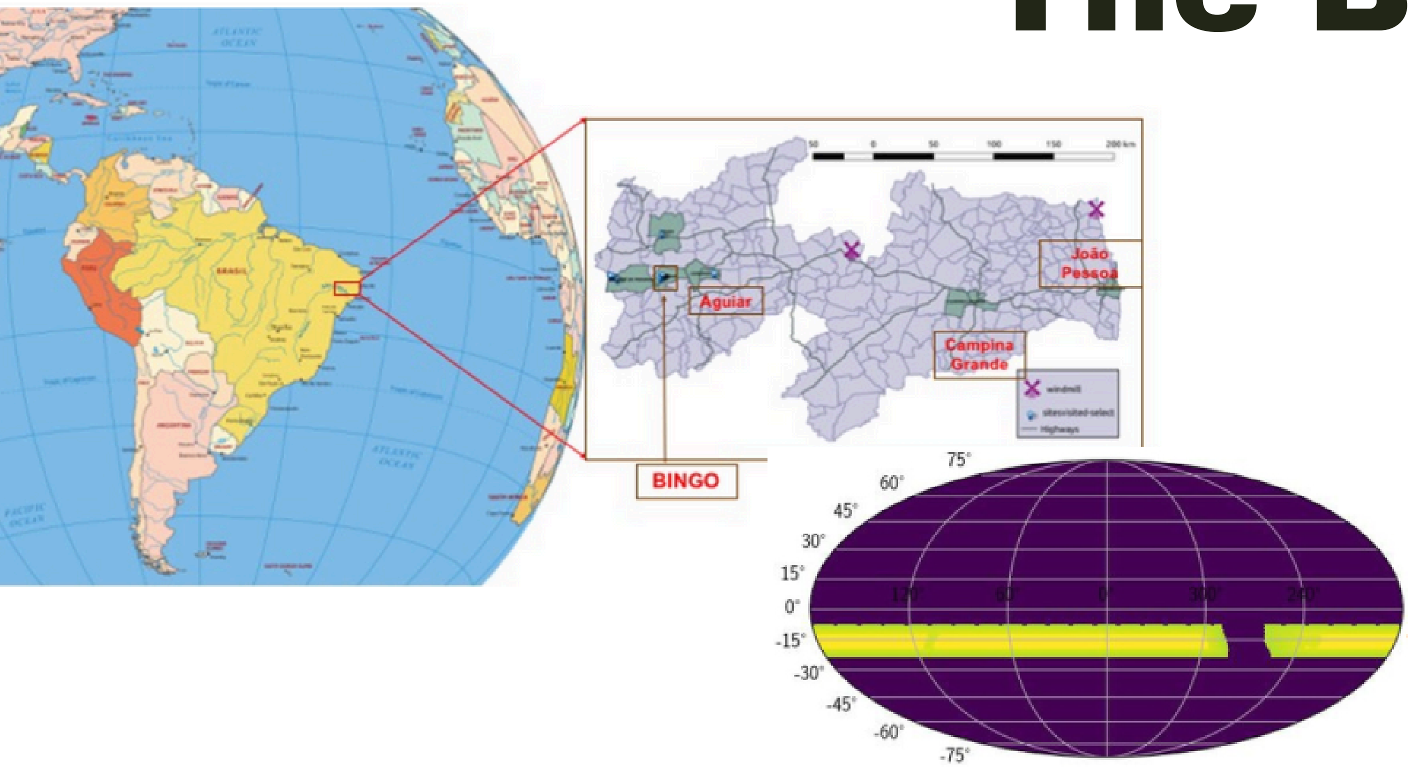
A Connected Vivaldi Aperture Array Outrigger station for the BINGO radiotelescope

Pablo Motta,

On behalf of the BINGO collaboration

ICEAA, Lisbon 2024

The BINGO instrument



- **Location:** Aguiar, Paraíba, Brazil
- **Frequency:** 980MHz - 1220MHz
- **Redshift:** 0.127 to 0.449
- **Declination:** -25° to -10°

- **Coverage:** 5324 deg^2
- **System temperature:** 70K
- **Resolution:** 40'
- **Number of beams:** 5x28

Design

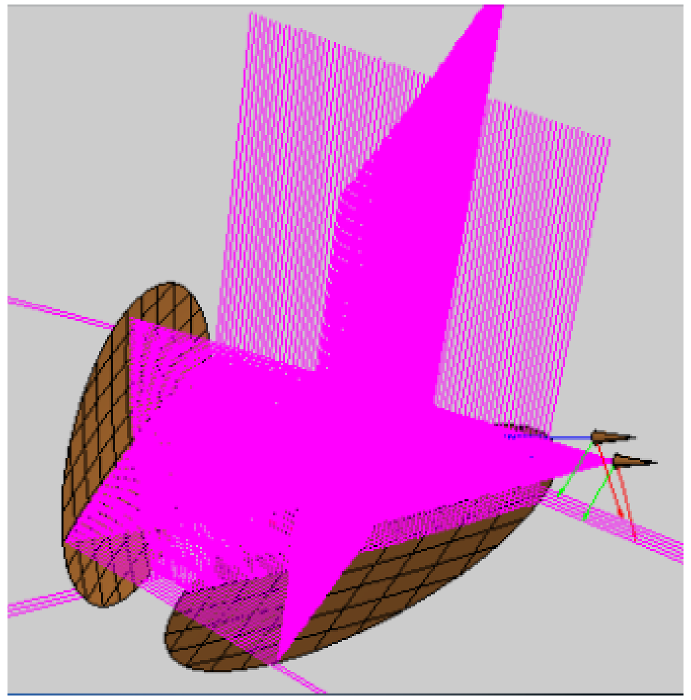
- Two mirror off-axis, crossed Dragonian
- Primary mirror: parabolic of 40m of diameter, focal length 140m
- Secondary Mirror: hyperbolic of 40m of diameter
- Very low polarization leakage

Horns

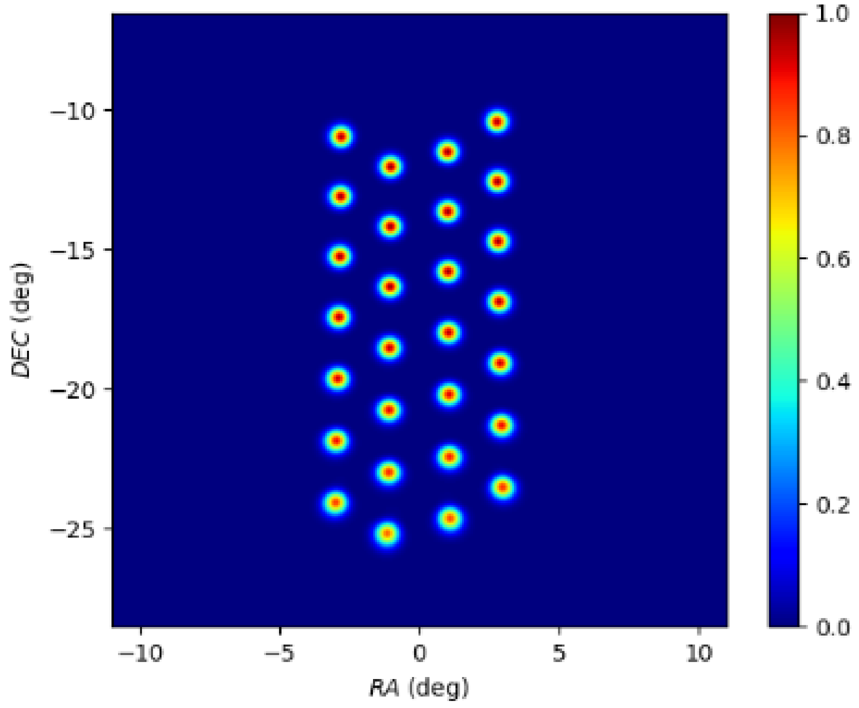
- Aluminum ~800Kg
- 1.7 m diameter x 4.9 m length
- 28 horns arranged in 4 vertical columns
- Each horn assuming 5 different vertical positions

BINGO optics

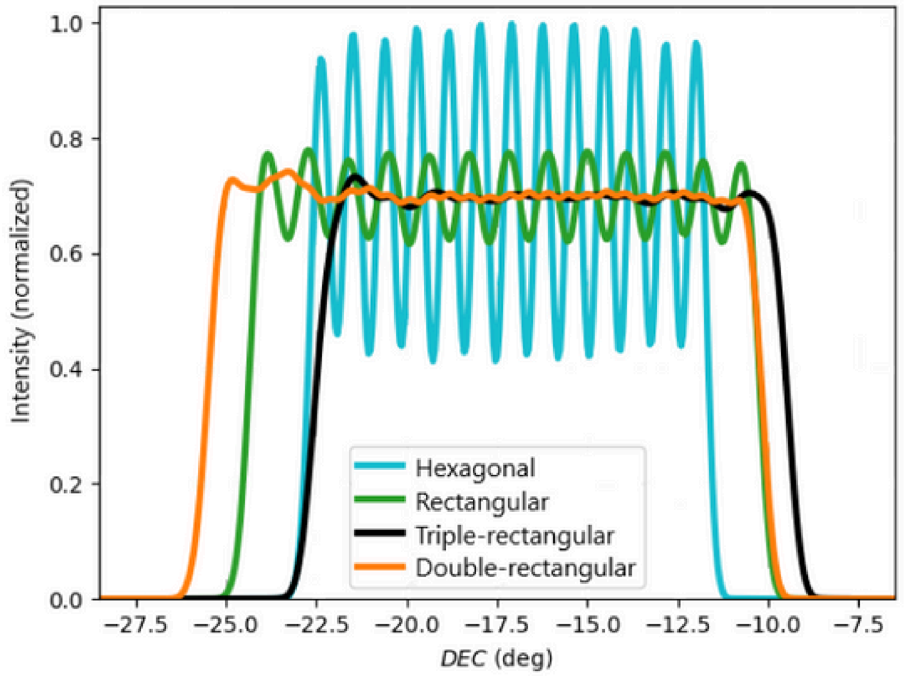
Simulations with GRASP



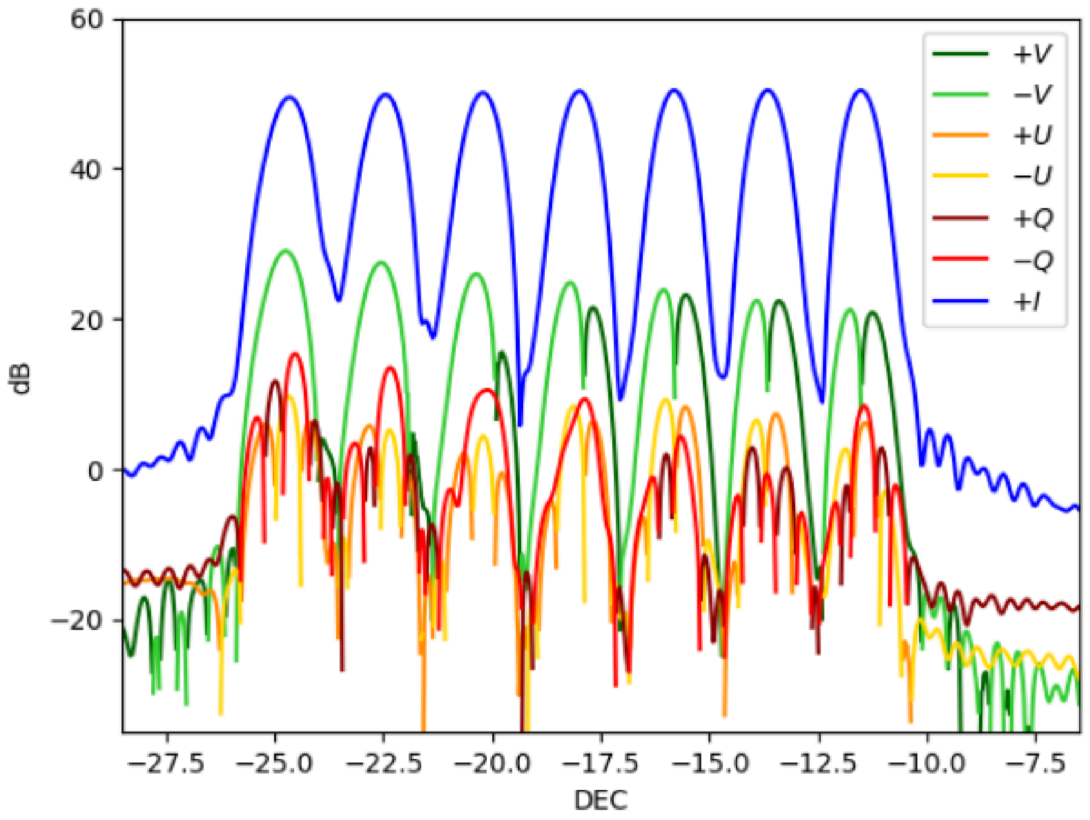
Beam - sky projection



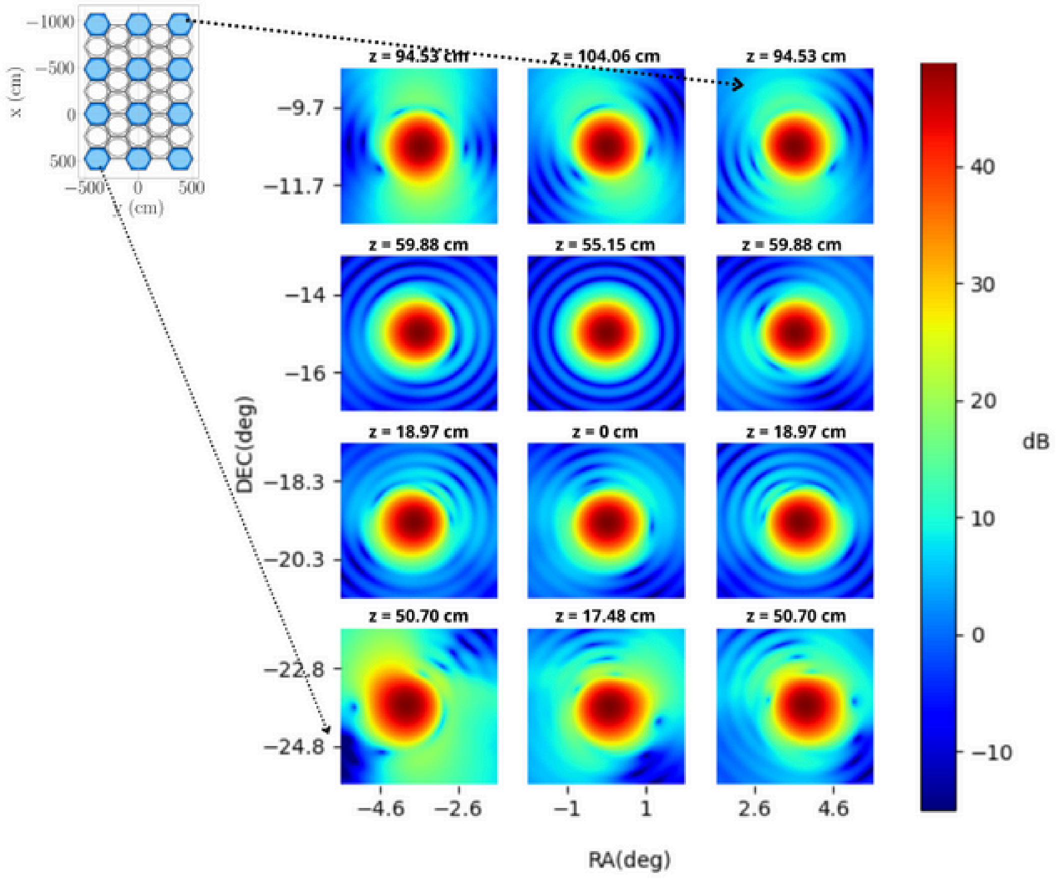
Continuous sky coverage



Low polarization leakage



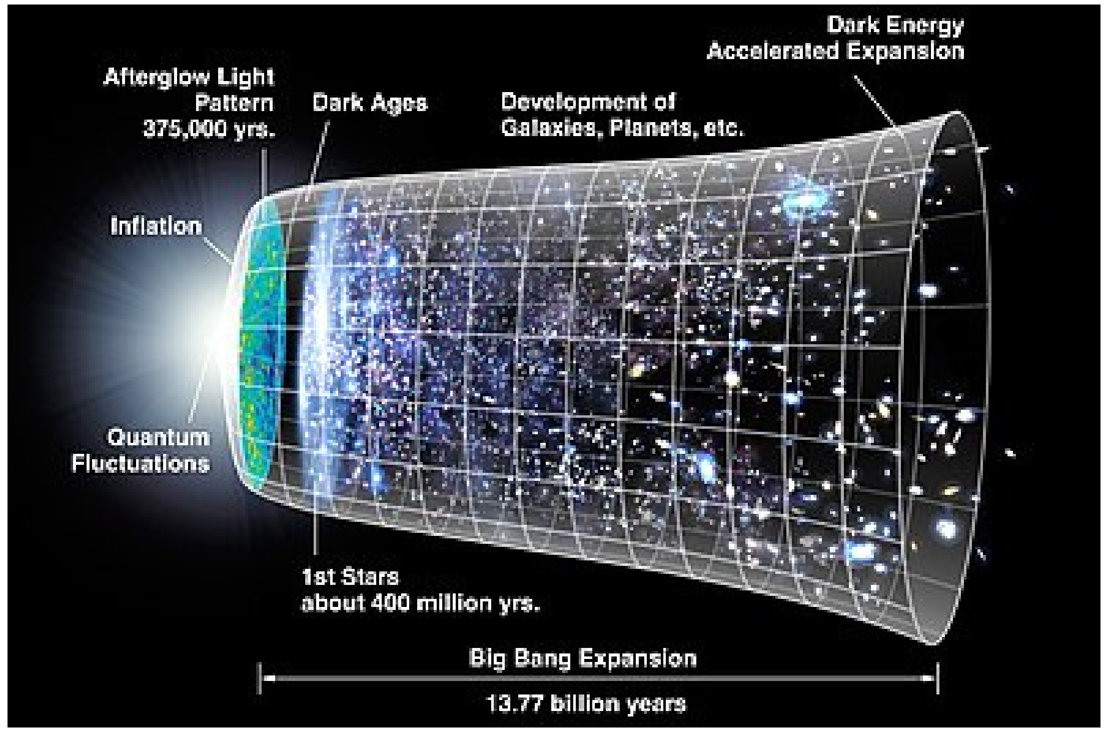
Aberrations



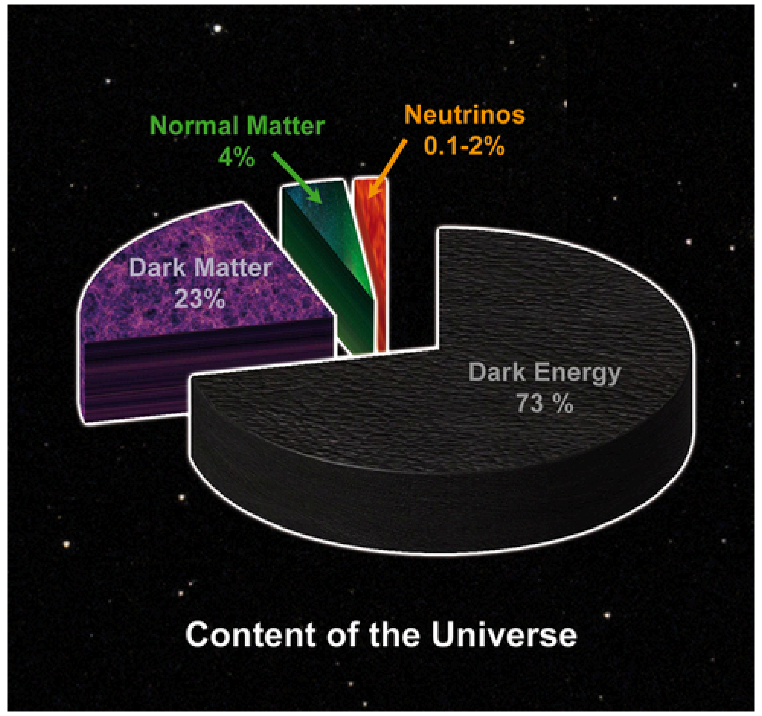
F. Abdalla, A. Marins, P. Motta et al
DOI: 10.1051/0004-6361/202141382

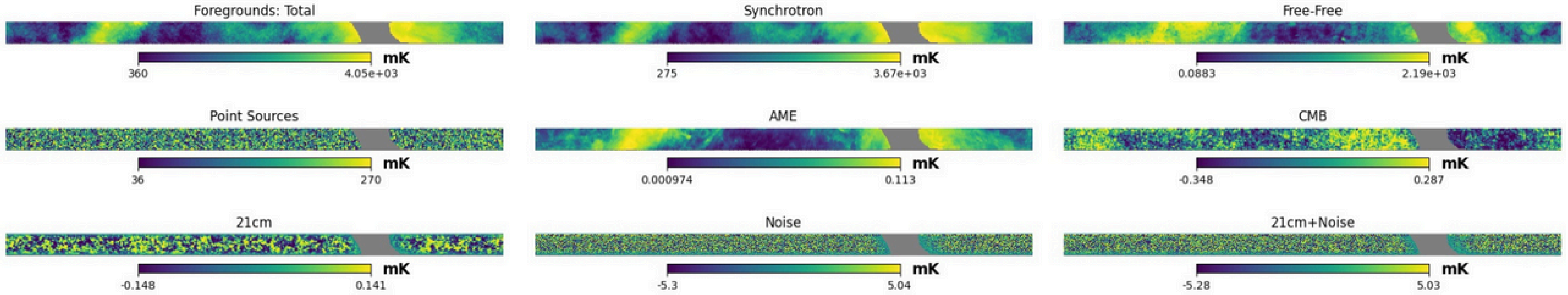
BINGO science - Cosmology

Dark Energy drives cosmic expansion in late universe



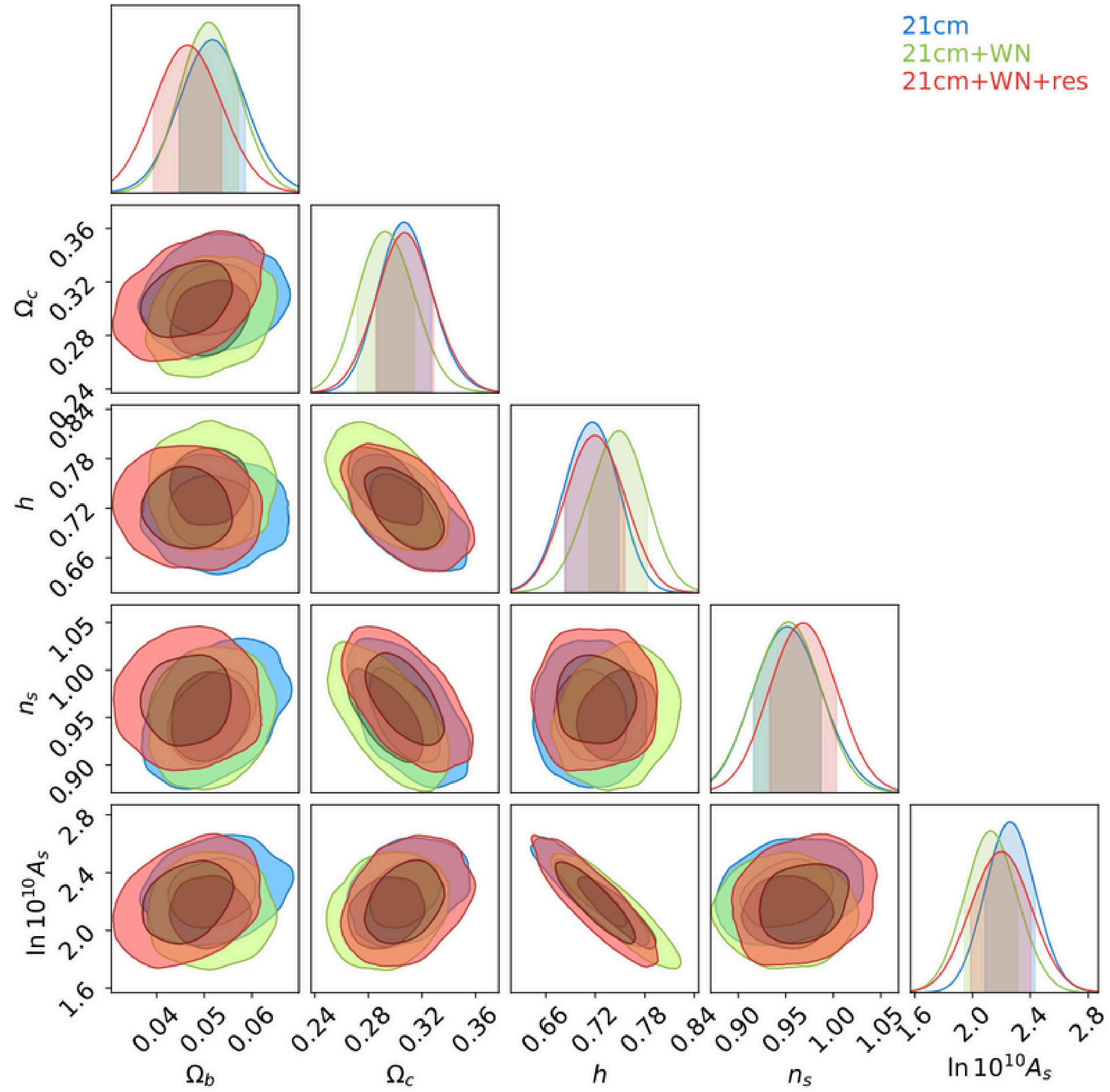
Most of the universe is dark





A Marins et al, arXiv:2209.11701

The 21cm line emission is tracer of matter. However it is contaminated with other extragalactic/galacitic sources

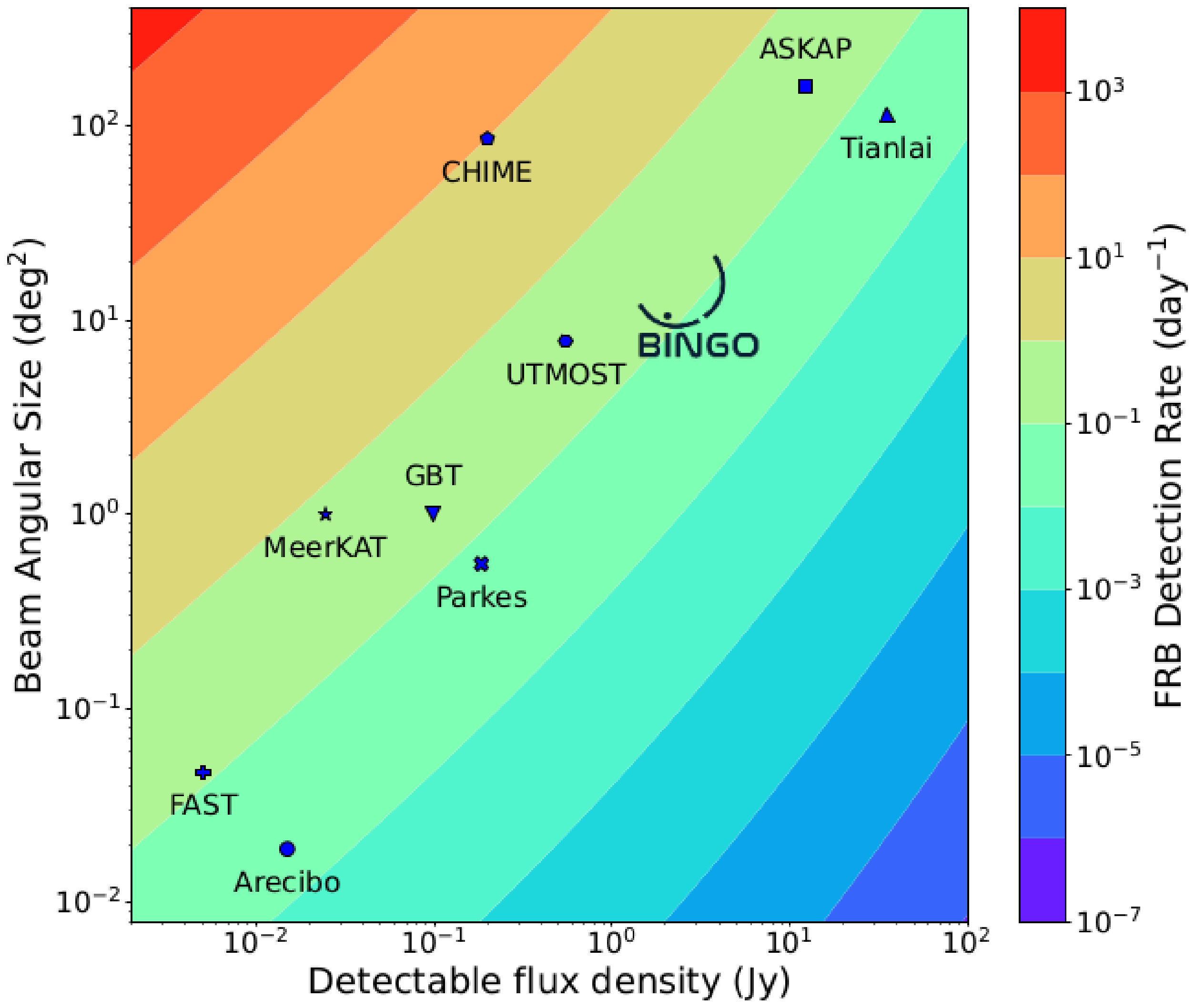


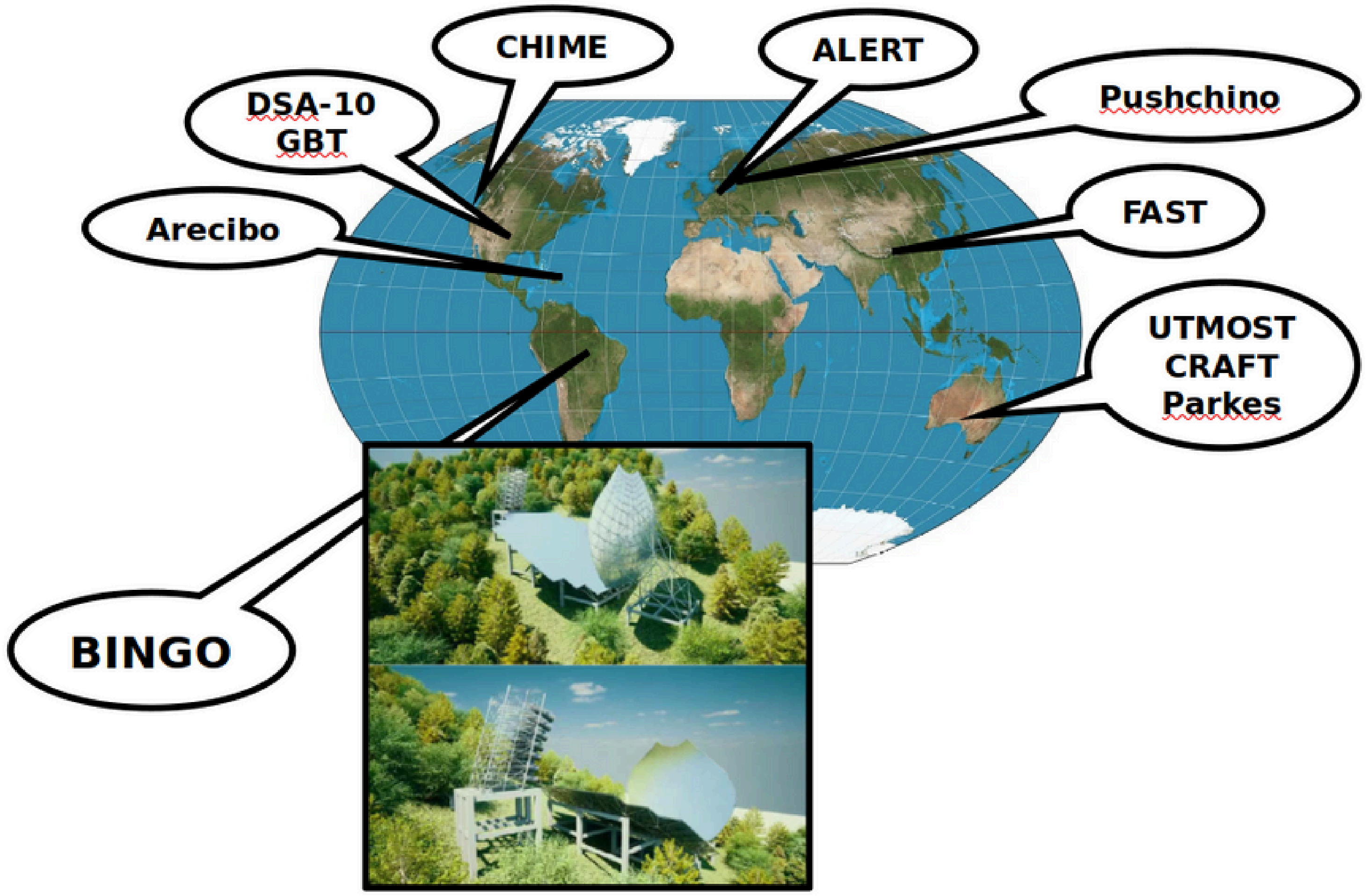
P. Motta et al, in prep.

With statistical tools we can fit cosmological models from the 21cm Intensity Maps.

BINGO science - FRB

- **Radio transients.** Point sources that commonly come from outside the galaxy.
- **Fast:** duration range from μs to ms.
- **Radio:** frequency: 300 MHz — 8 GHz.
- **Bursts:** energy 10^{33} J (power of 10^9 Suns).

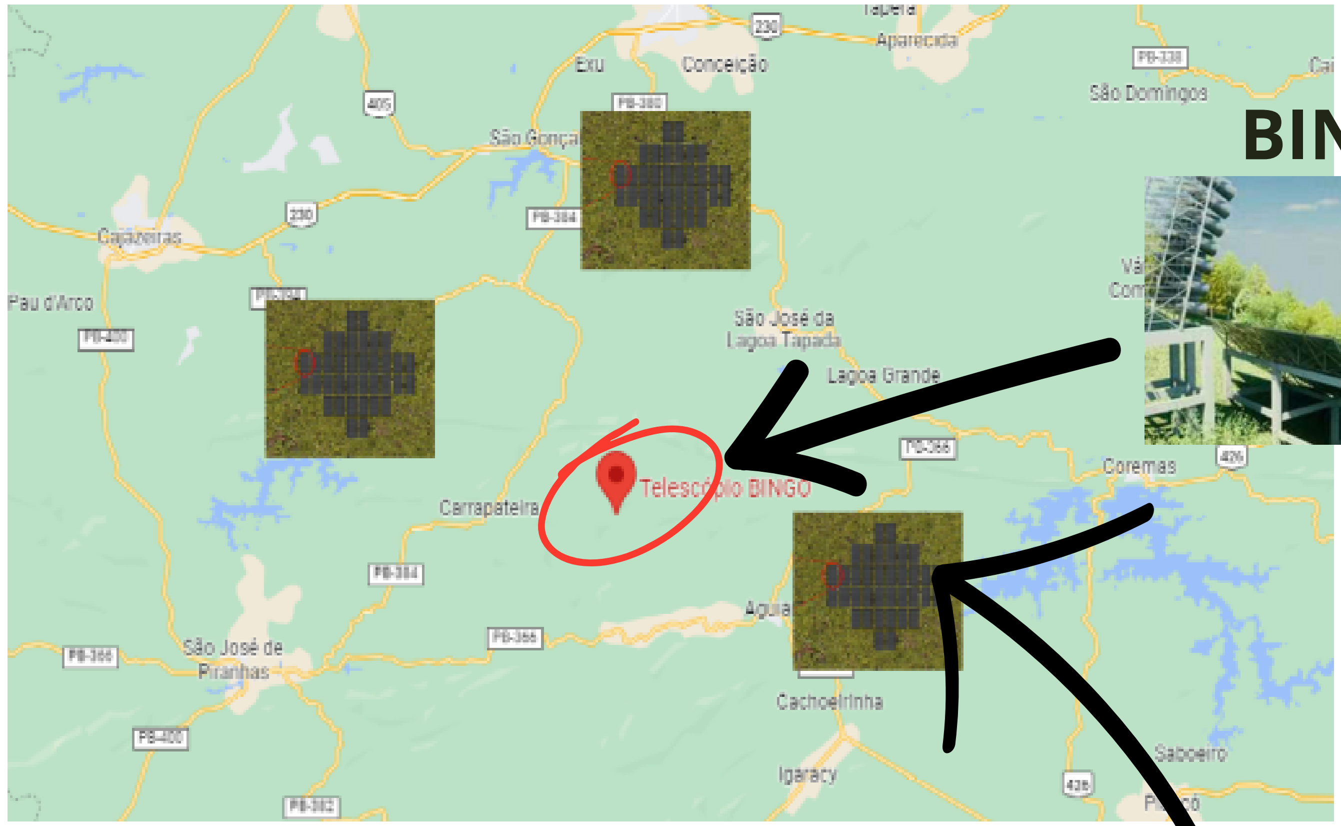




BINGO/ABDUS interferometry system

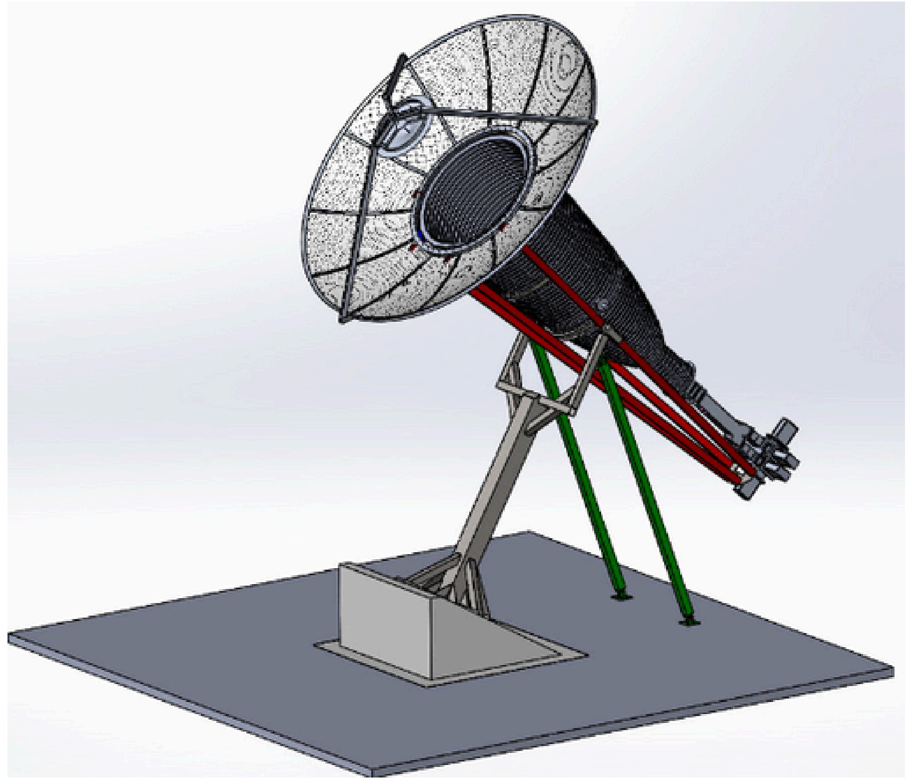
- An interferometry system is need for localizing FRBs.
- It is composed by BINGO and some small telescopes called outriggers.
- The outriggers can be either **single-dished** telescopes or **phased array stations**.
- We plan to use two or three phased array stations, 40km away from the main telescope.

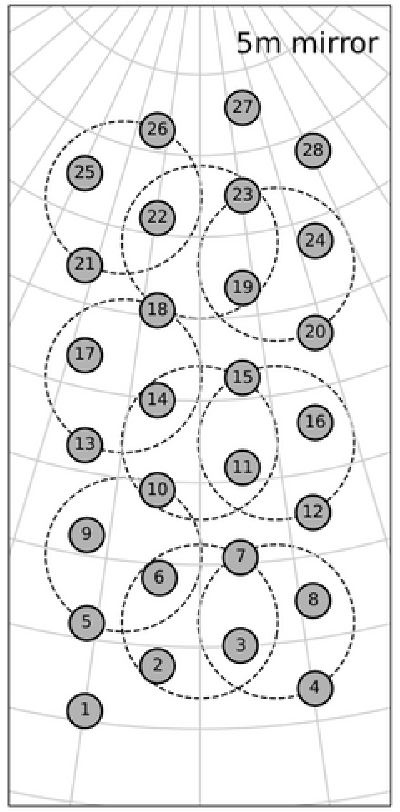
Scheme of interferometry system



BINGO

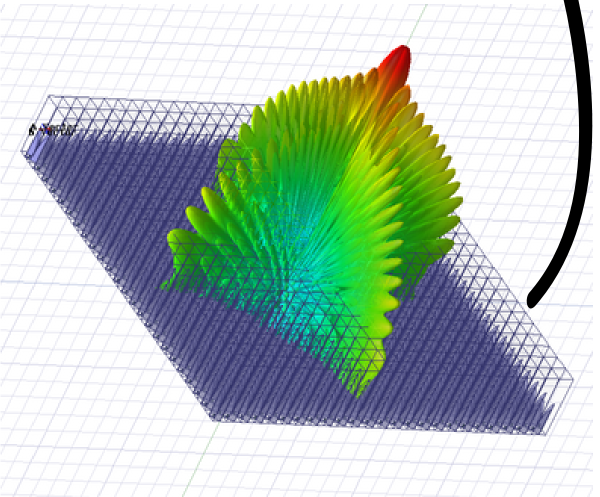
Single-dished outrigger





Tile for phased array

Phased array station

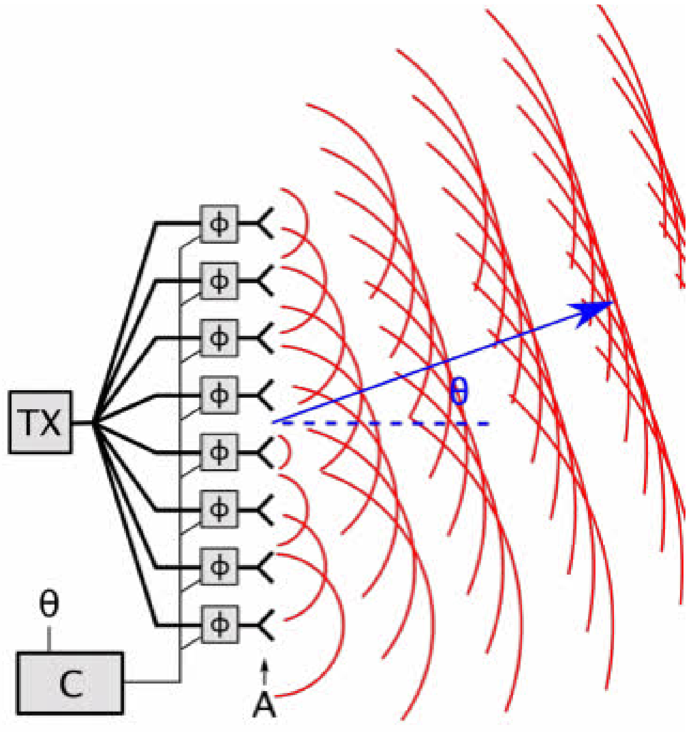


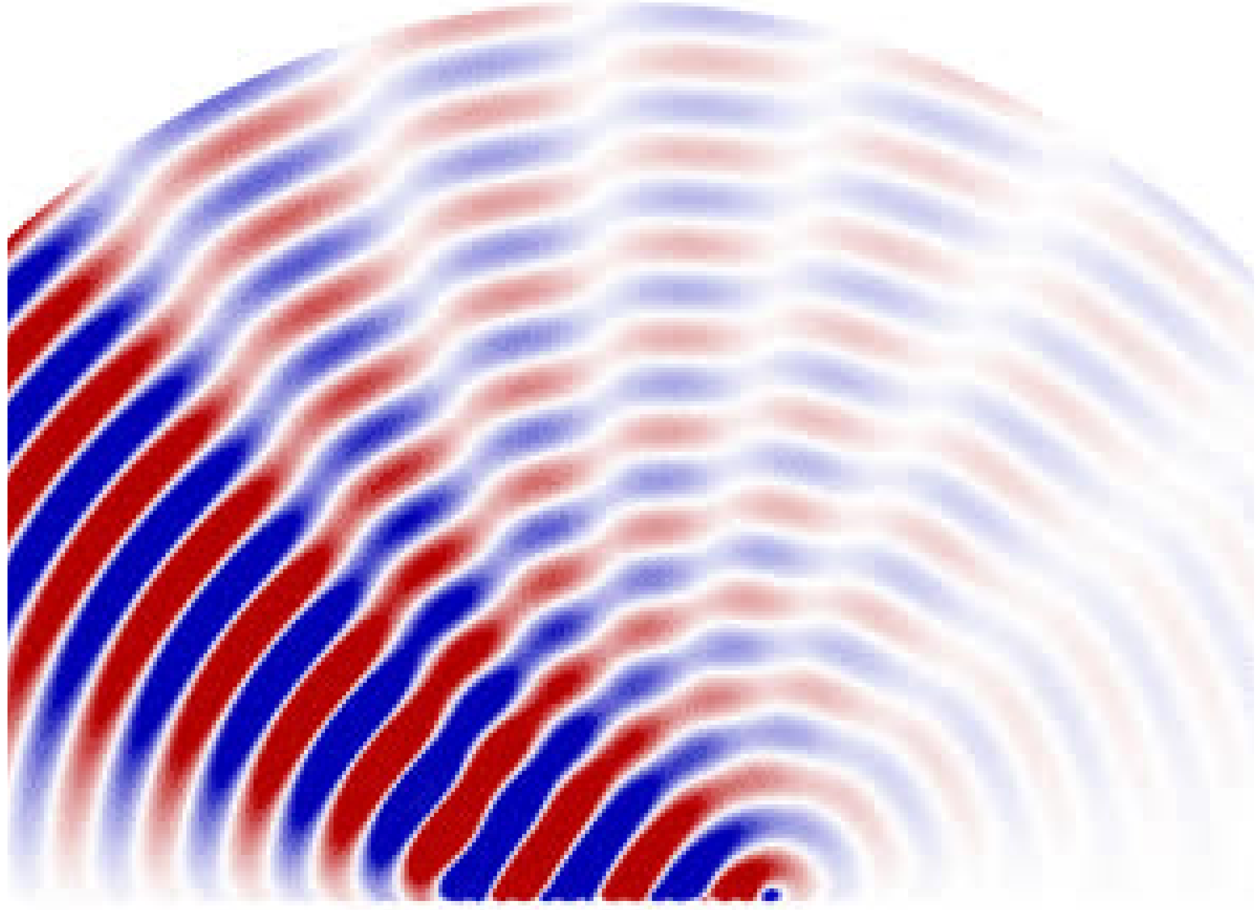
Phased Array

- Array of antennas which creates a beam of radio waves that can be electronically steered to point in different directions.
- A given direction is obtained with a specific setup of phases.
- The electric field of an array can be estimated using array factors.

$$\mathbf{E}_{array}(\theta,\phi) = AF(\theta,\phi)\,\mathbf{E}_{element}(\theta,\phi)$$

$$AF(\theta,\phi) = \sum_{n}^{N} e^{jk\mathbf{r}_n\cdot\left(\hat{r}(\theta,\phi)-\hat{r}_S\right)}$$

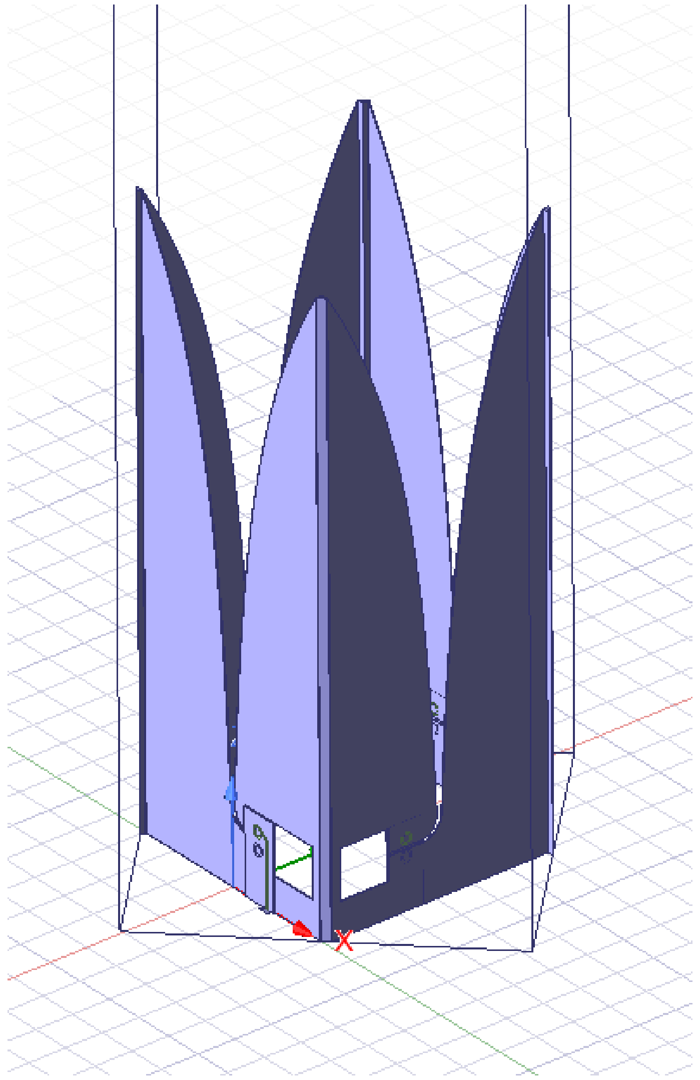




The Thechnology

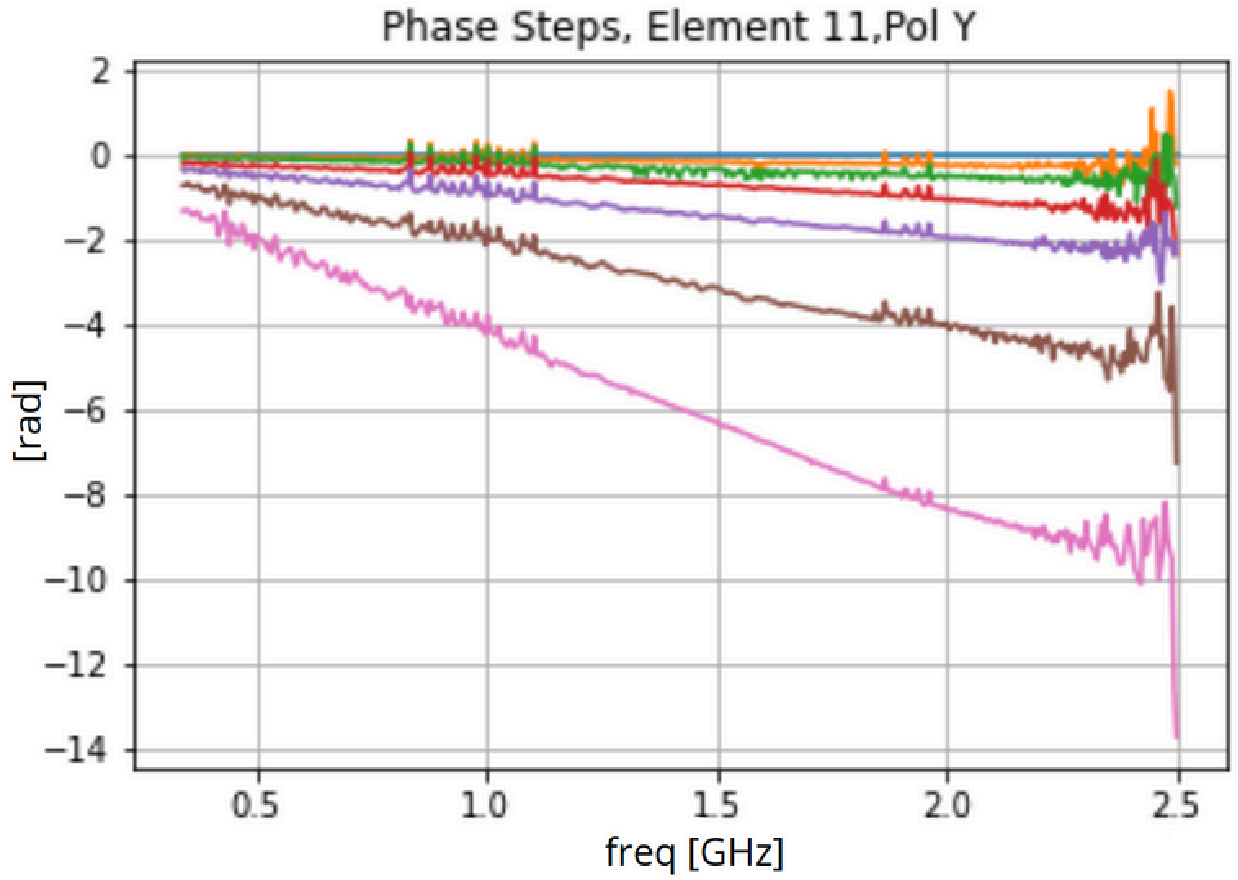
- **Vivaldi antenna:** This tapering design helps provide a wide bandwidth and directional radiation pattern.
- **Beamforming:** performed in two steps: the first is **analog** on the tile and the second is **digital**. The digital step form multiple directed beams at the same time.
- **True-time delay:** exhibit constant phase slope over frequency.

Frequency: 500MHz to 1500MHz **Polarization:** dual linear
Nr. of analog beams: 2 **Dimensions:** 35cm x 134cm



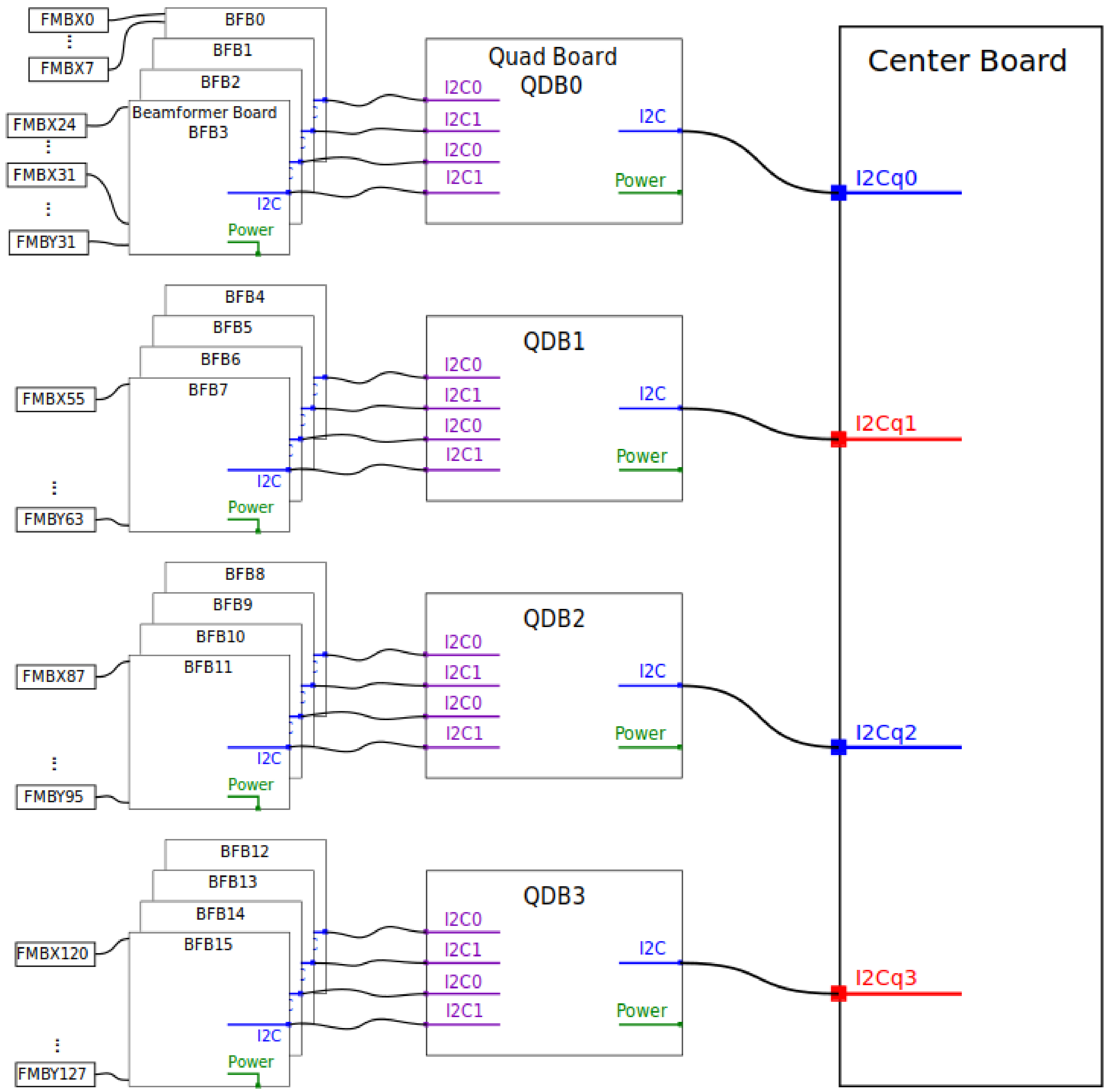
Vivaldi antenna

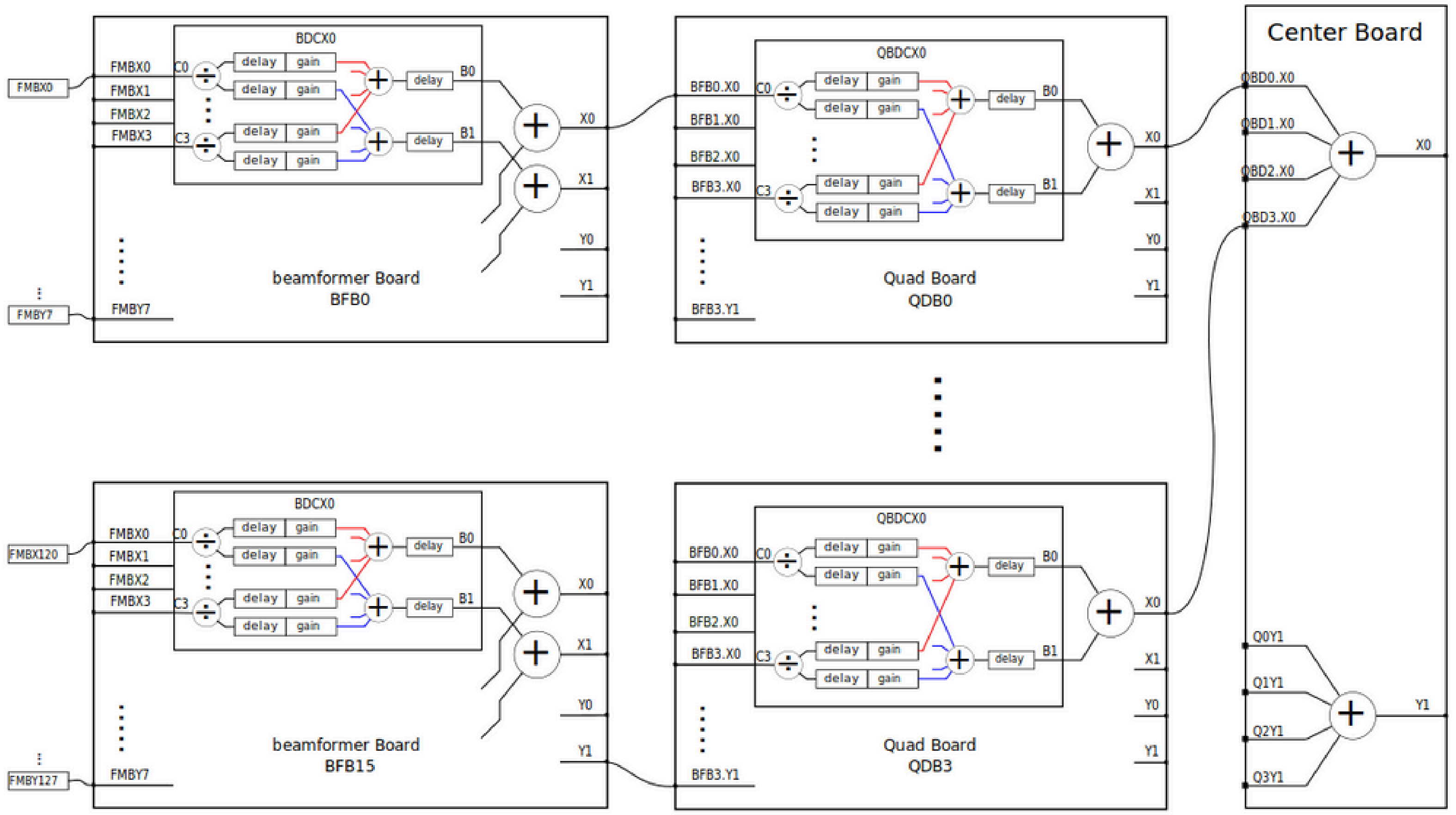
Tile

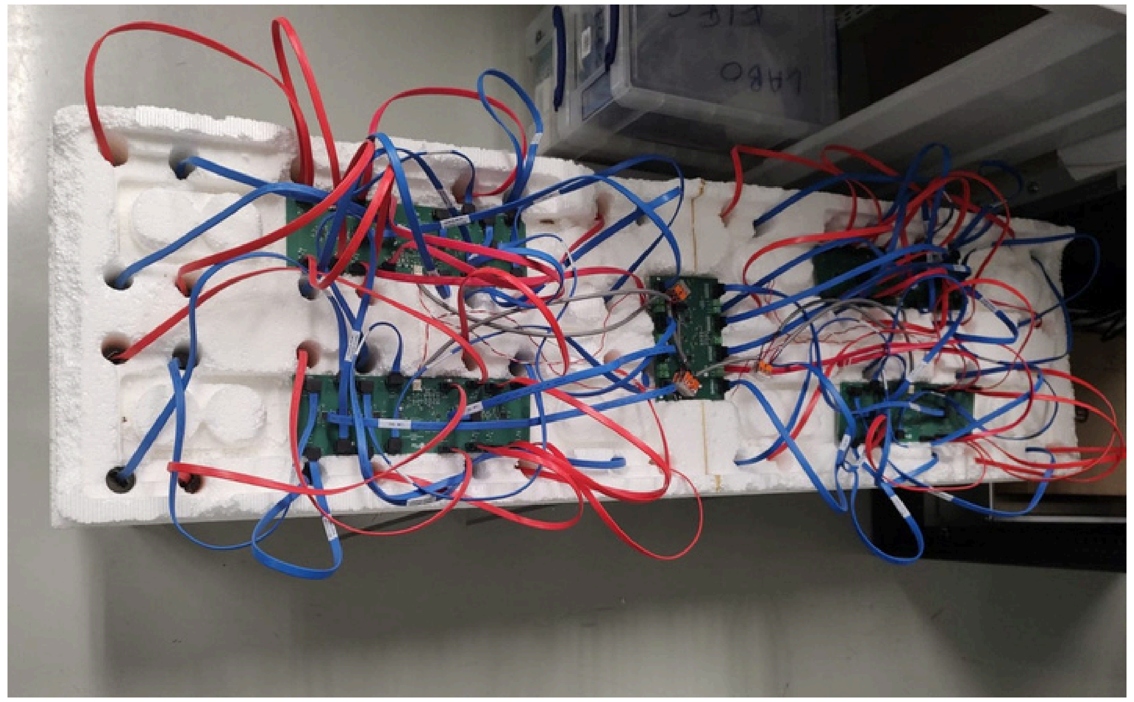


Time delay

Architecture of the tile

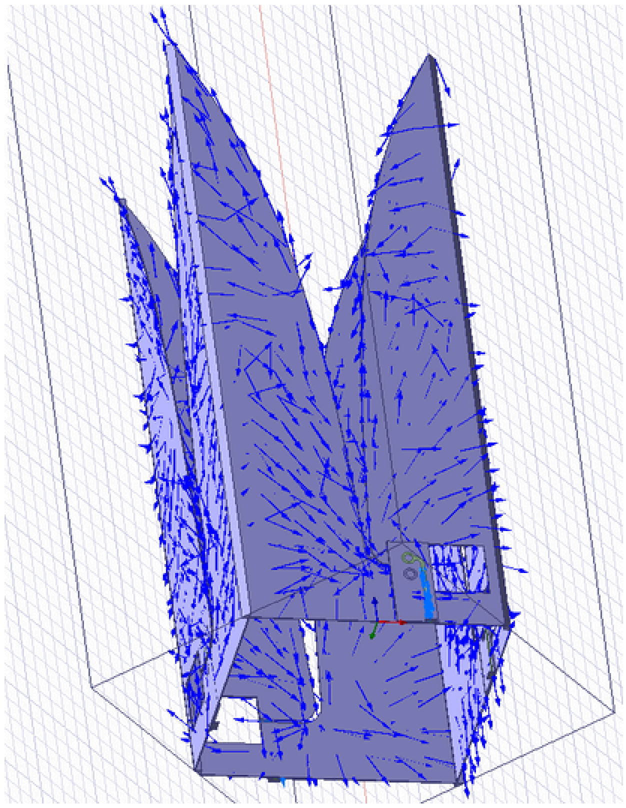




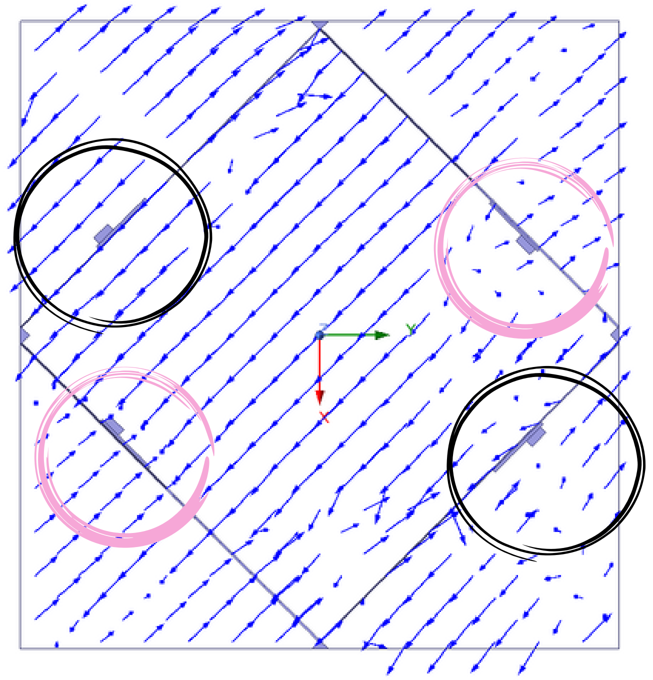


HFSS simulations

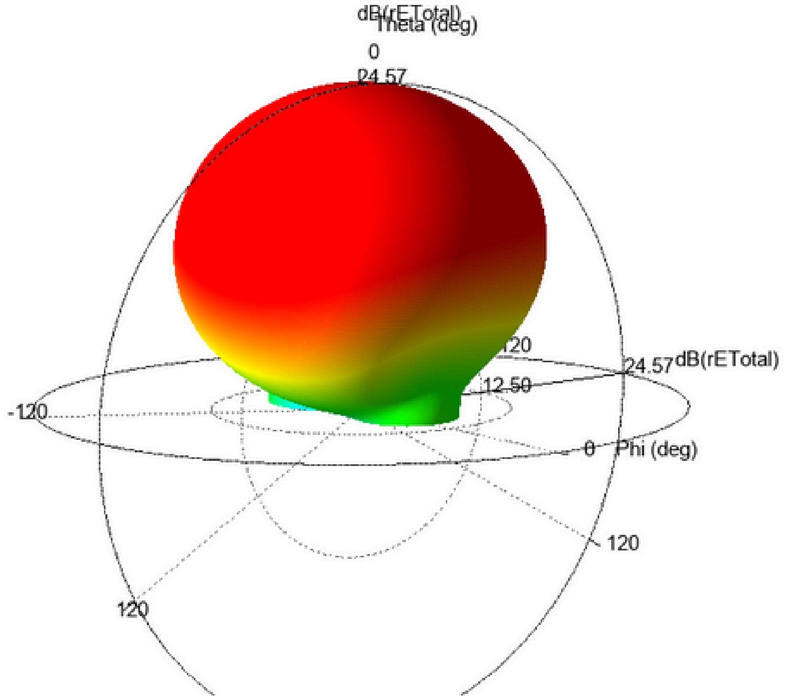
One cell - 4 antenna elements



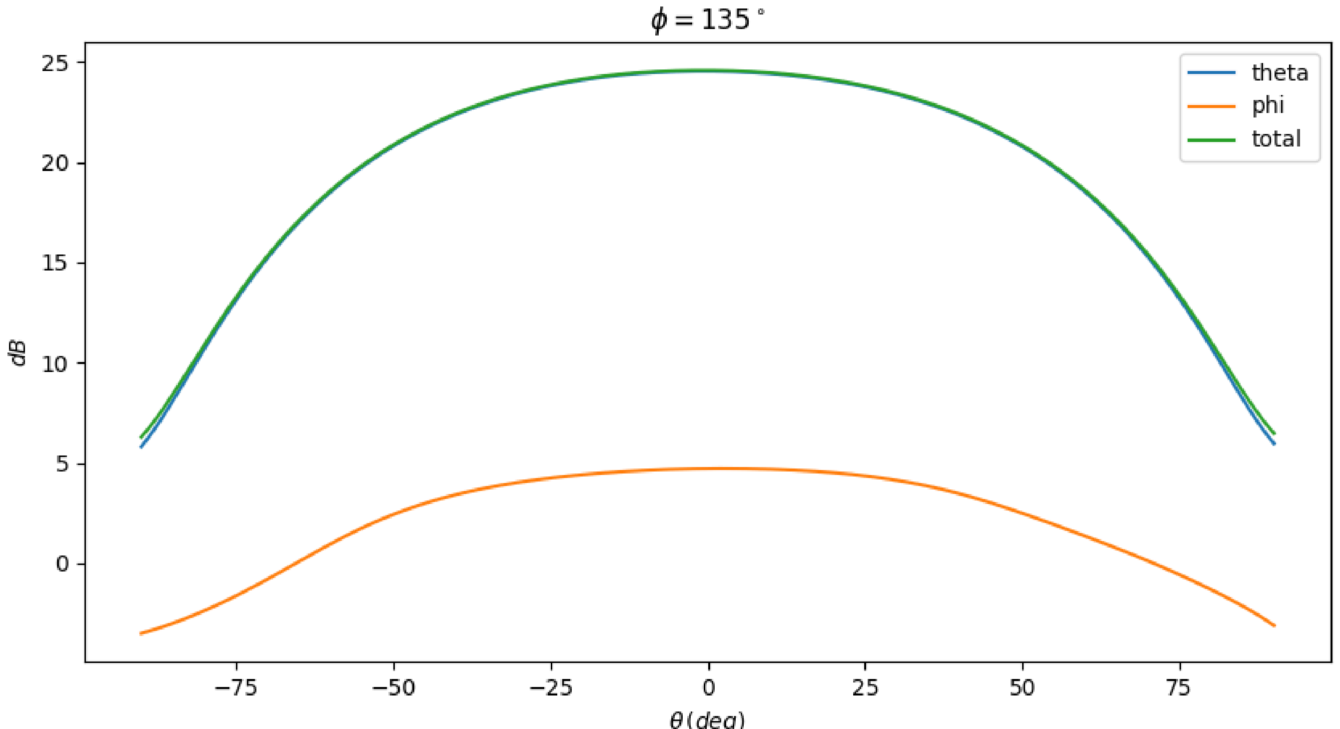
Sources - dual polarization



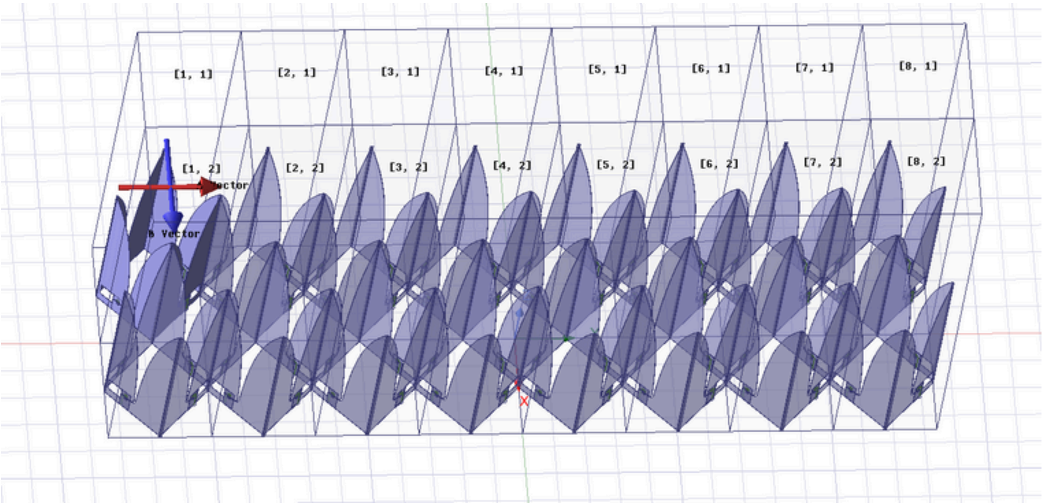
Broad far-fields

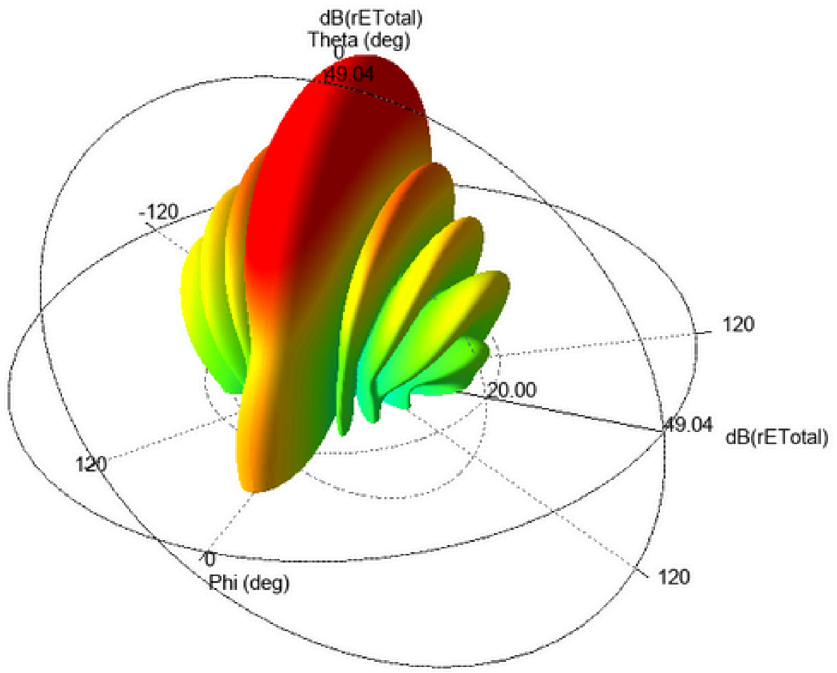


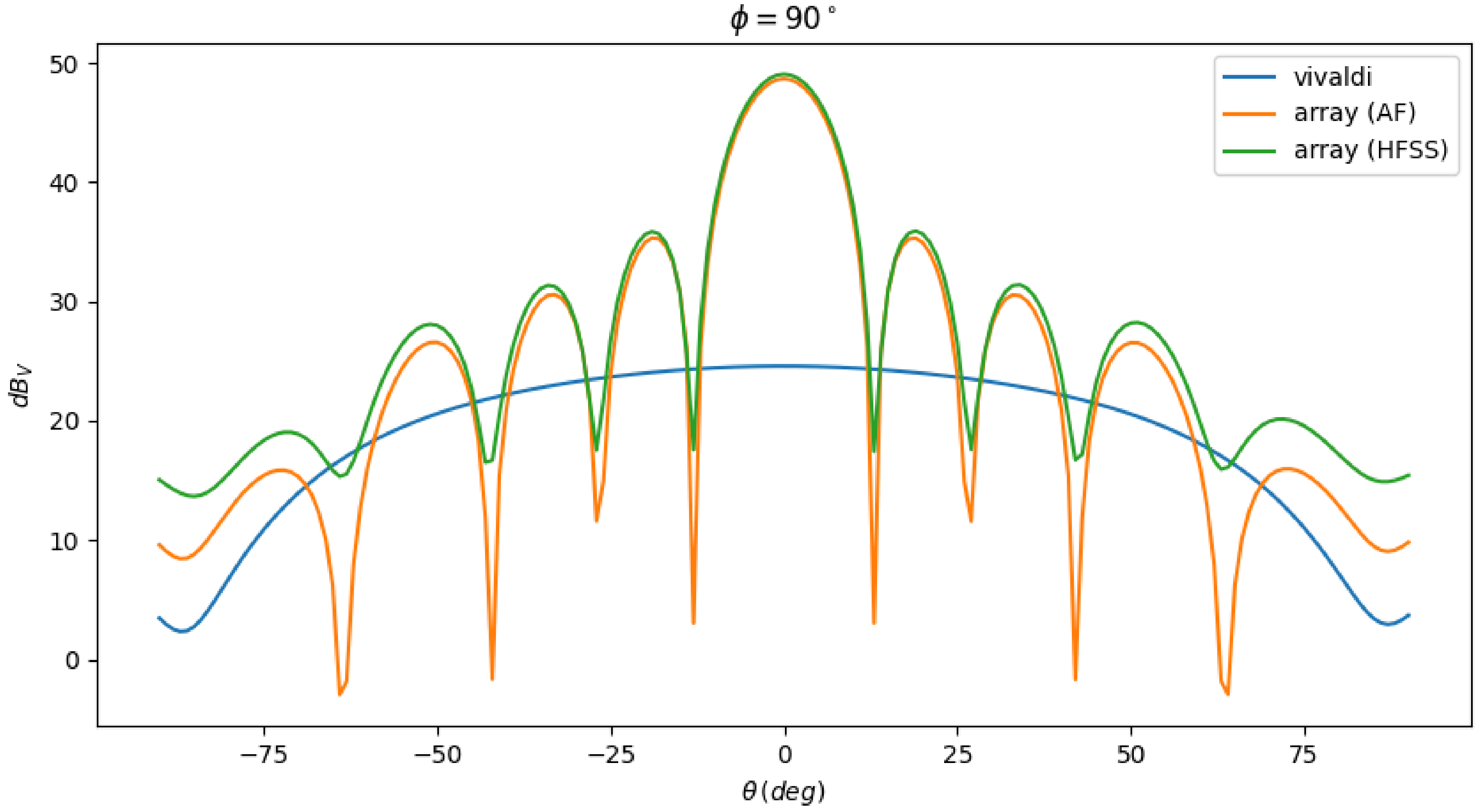
Low cross-polarization

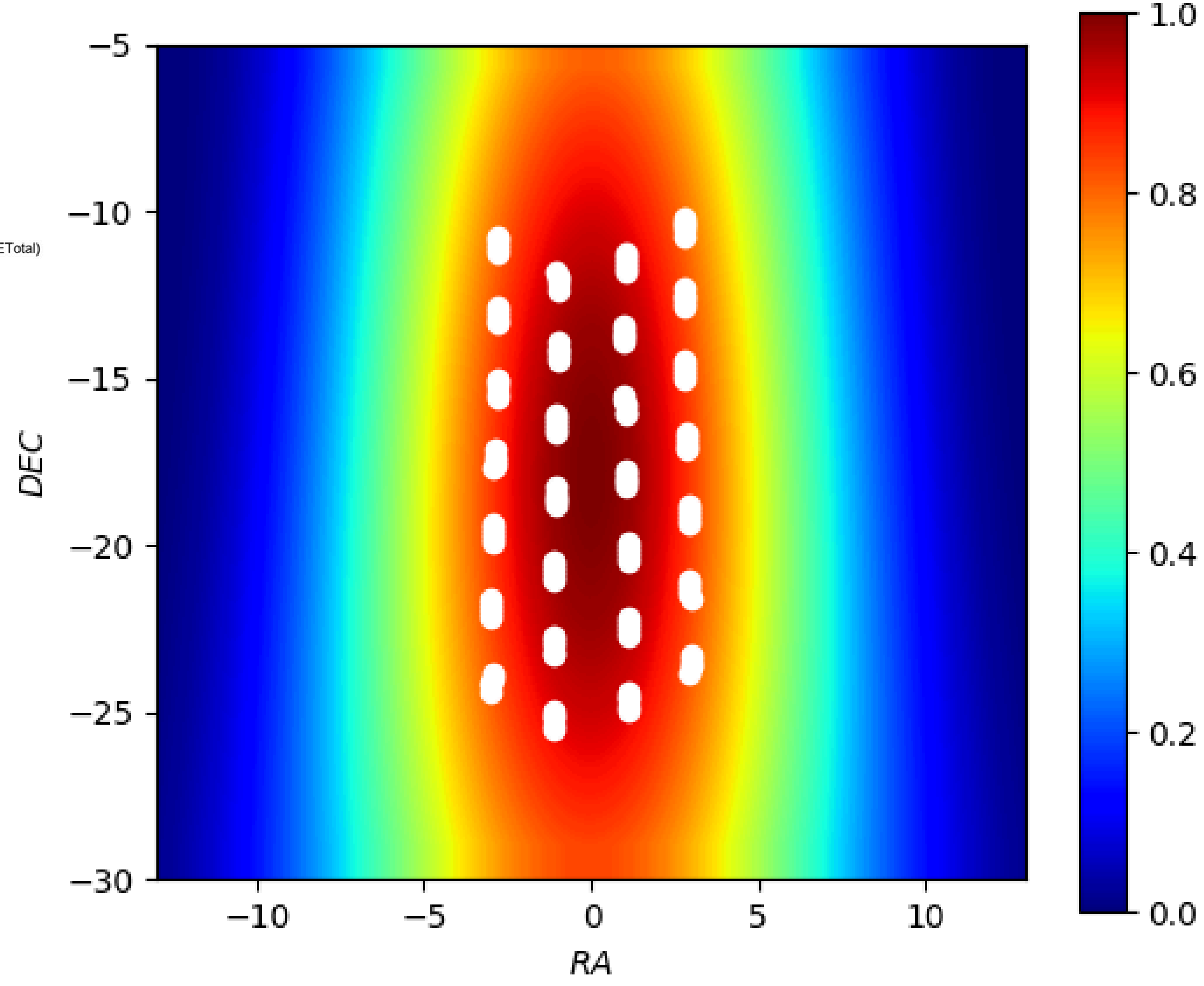


Vivaldi tile simulation

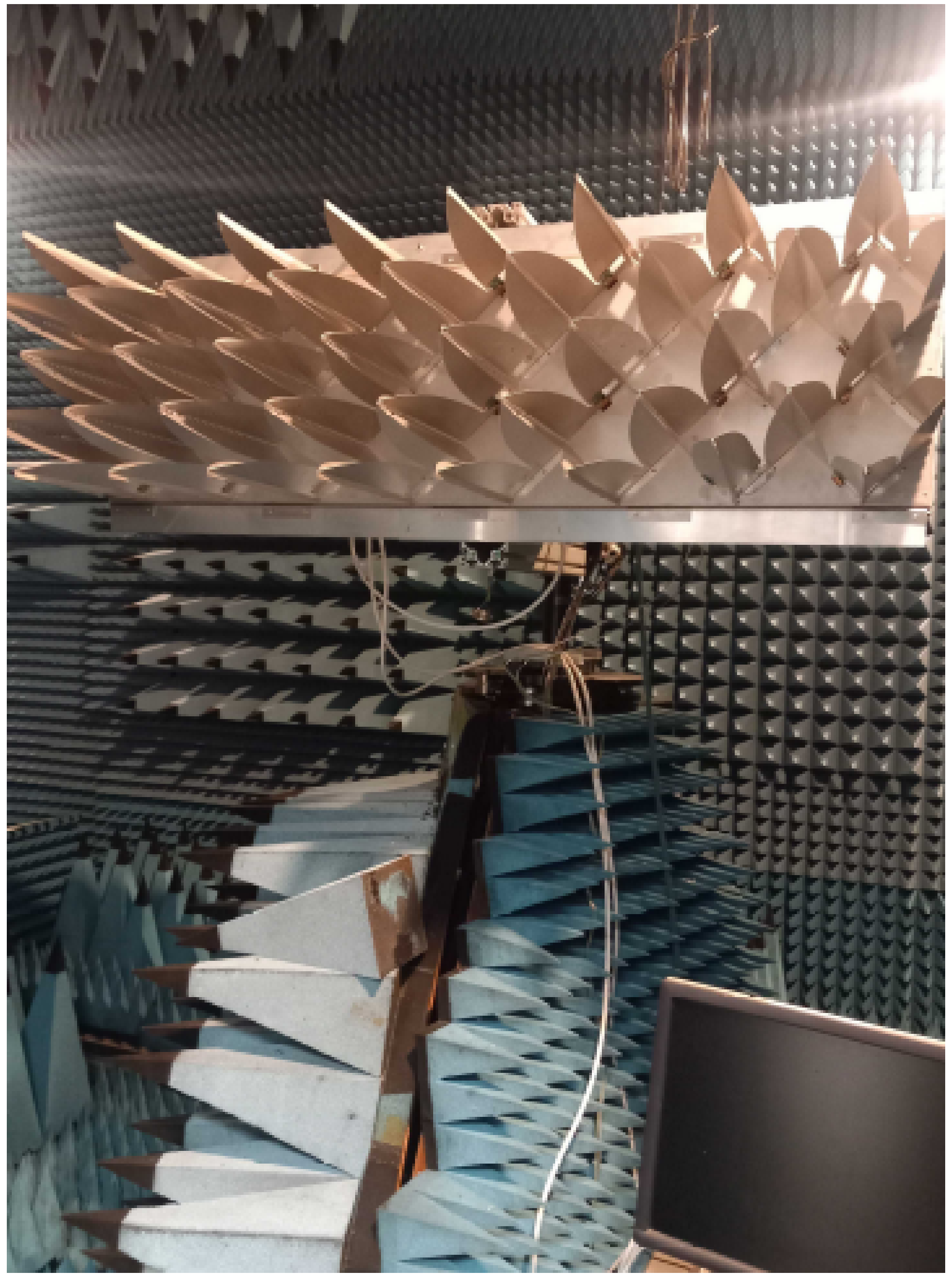


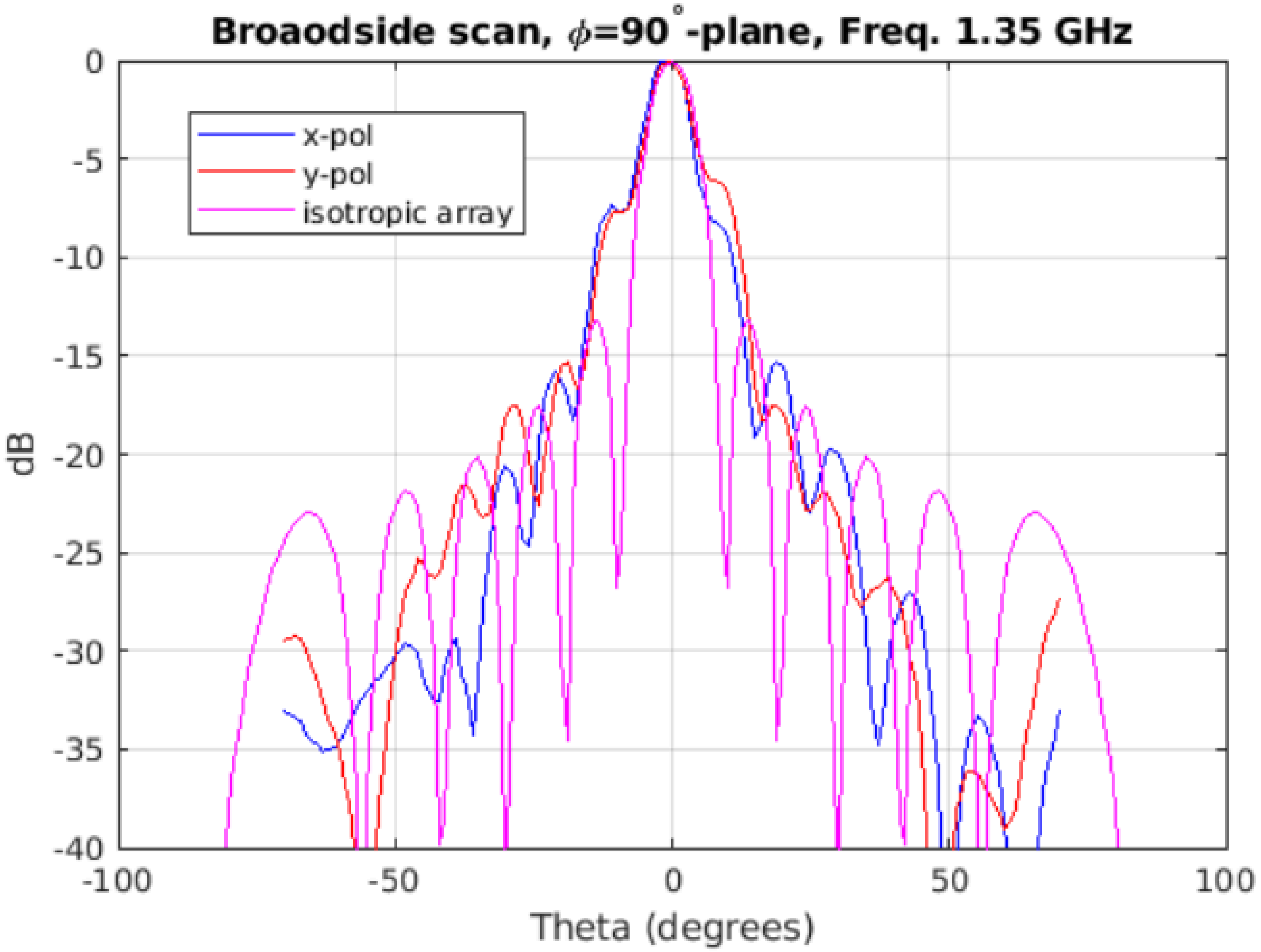




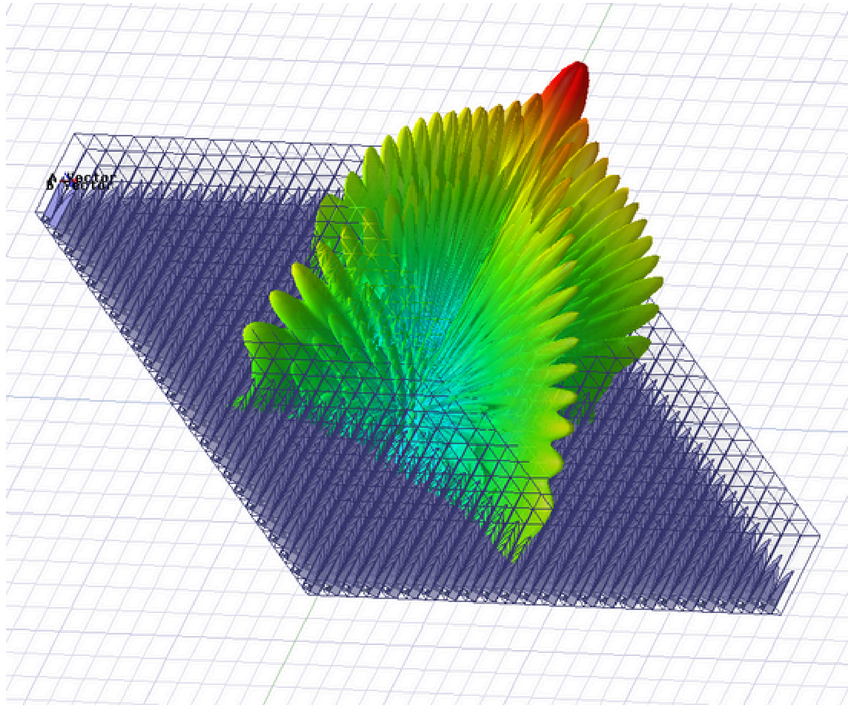


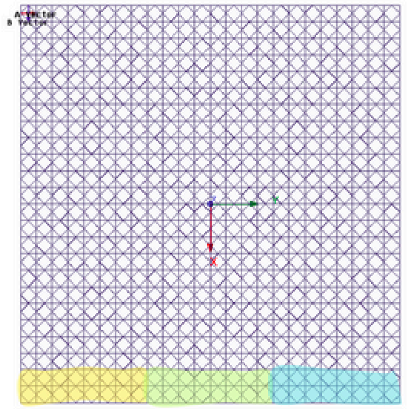
Tile measurements in antenna room

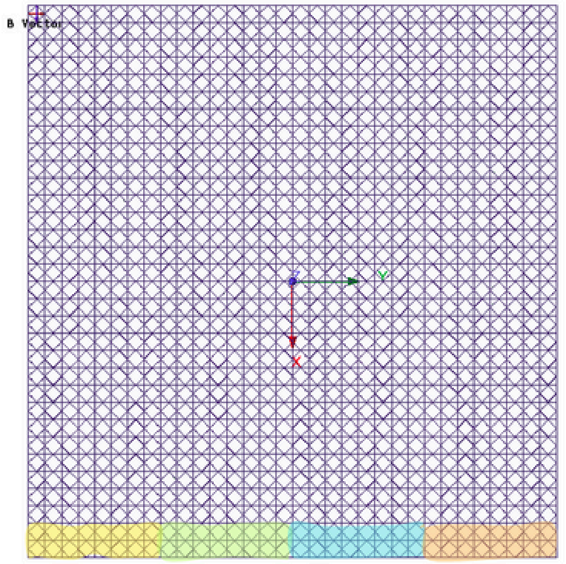




Simulating stations





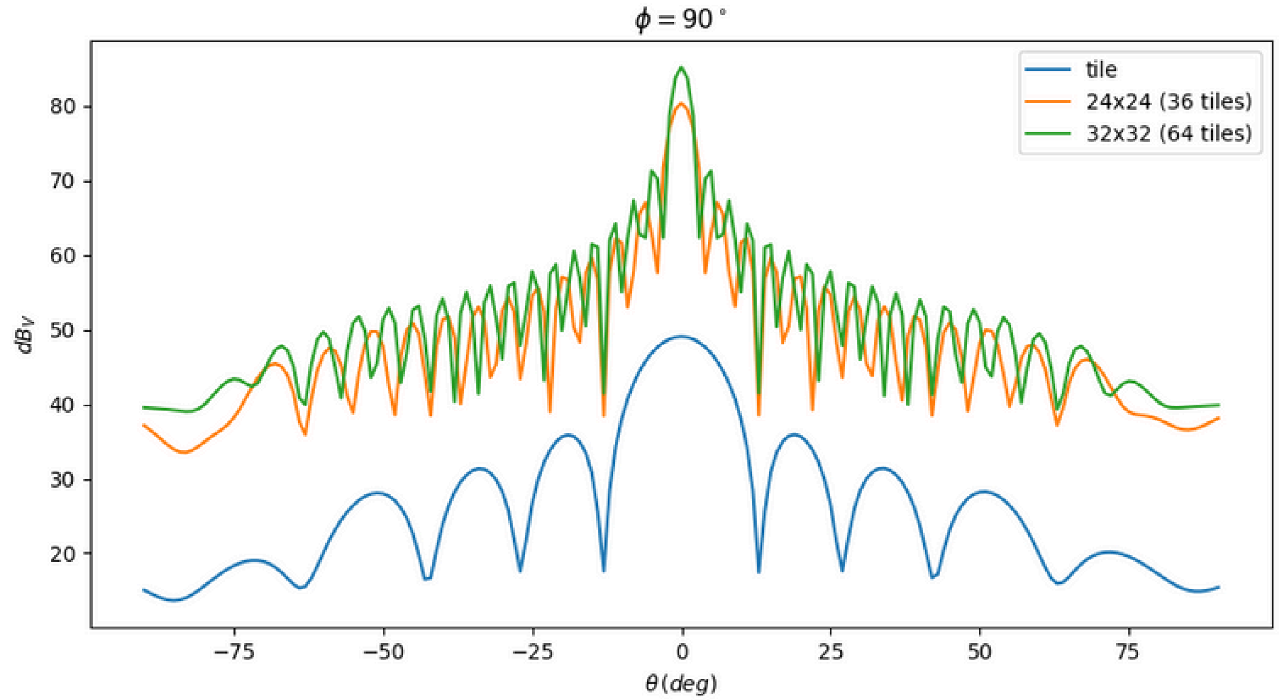


- 24x24 unit cells
- 36 tiles
- 422cm x 402cm
- Physical area: 17m2
- Effective area: 16.24m2

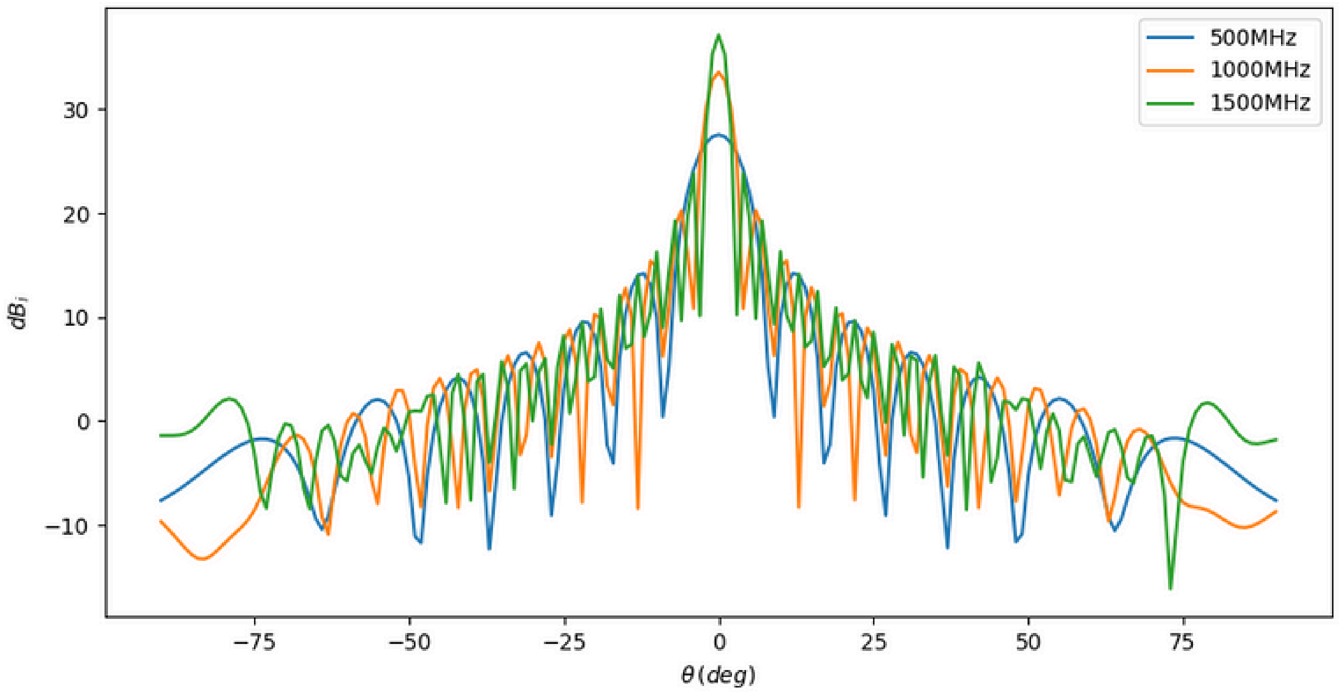
- 32x32 unit cells
- 64 tiles
- 563cm x 536cm
- Physical area: 30.21m2
- Effective area: 28.84m2

The required effective area is obtained with 36~64 tiles

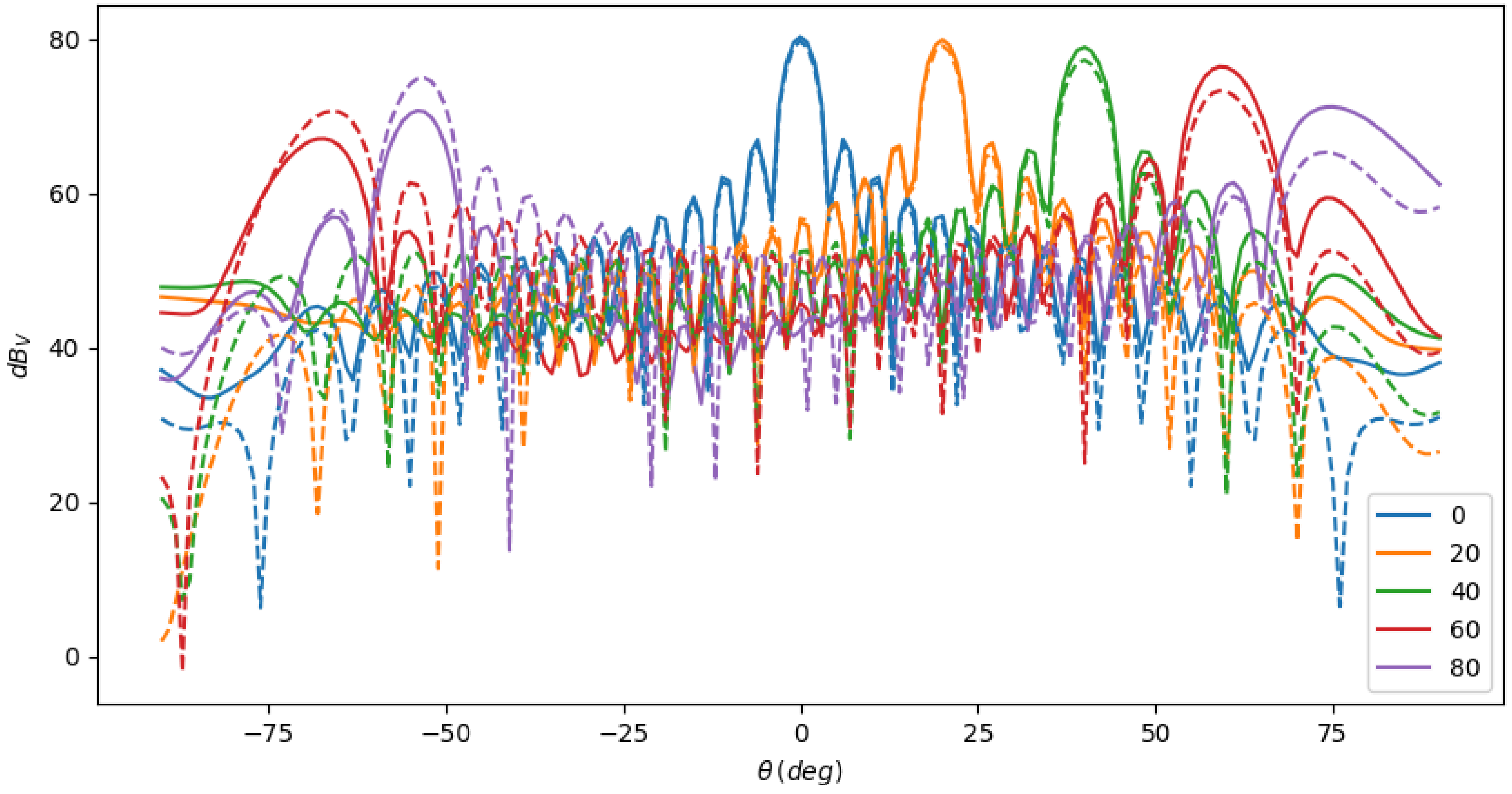
Smaller beamwidth for bigger stations



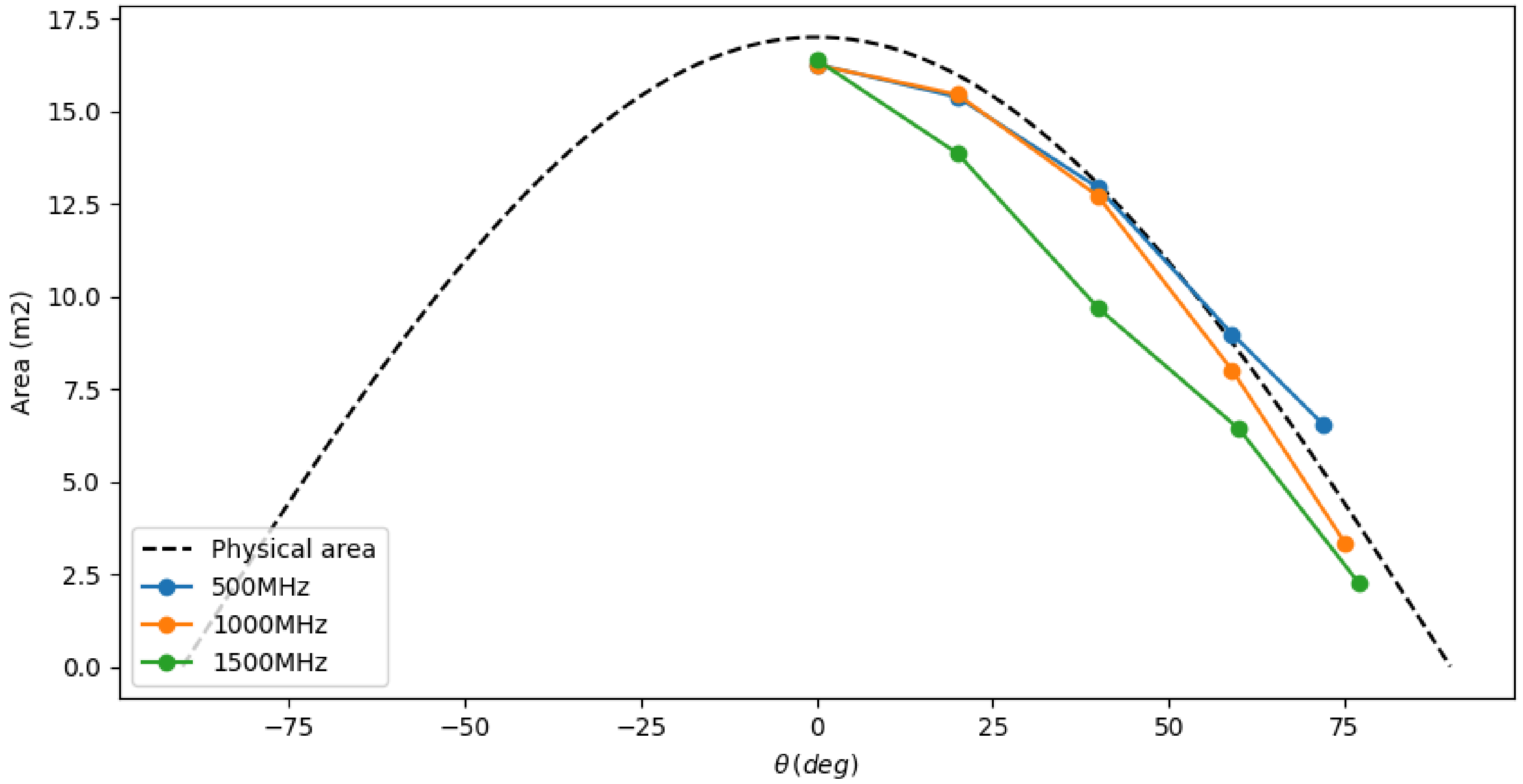
Smaller beamwidth at higher frequencies



Beam steering and effective area



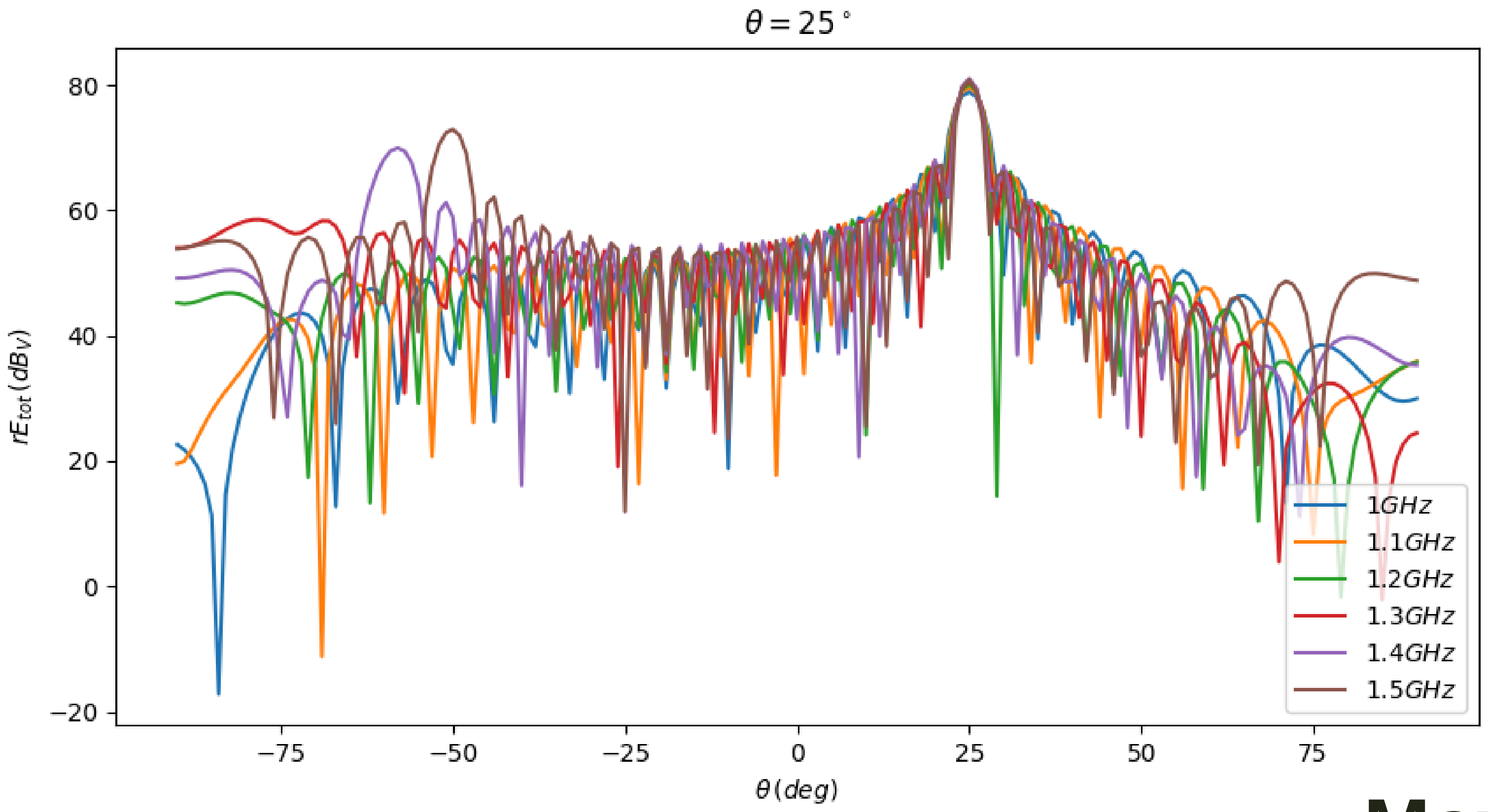
- Gain decreases with scan angle
- Grating lobes appear at high scan angles
- AF computation overestimates grating lobes



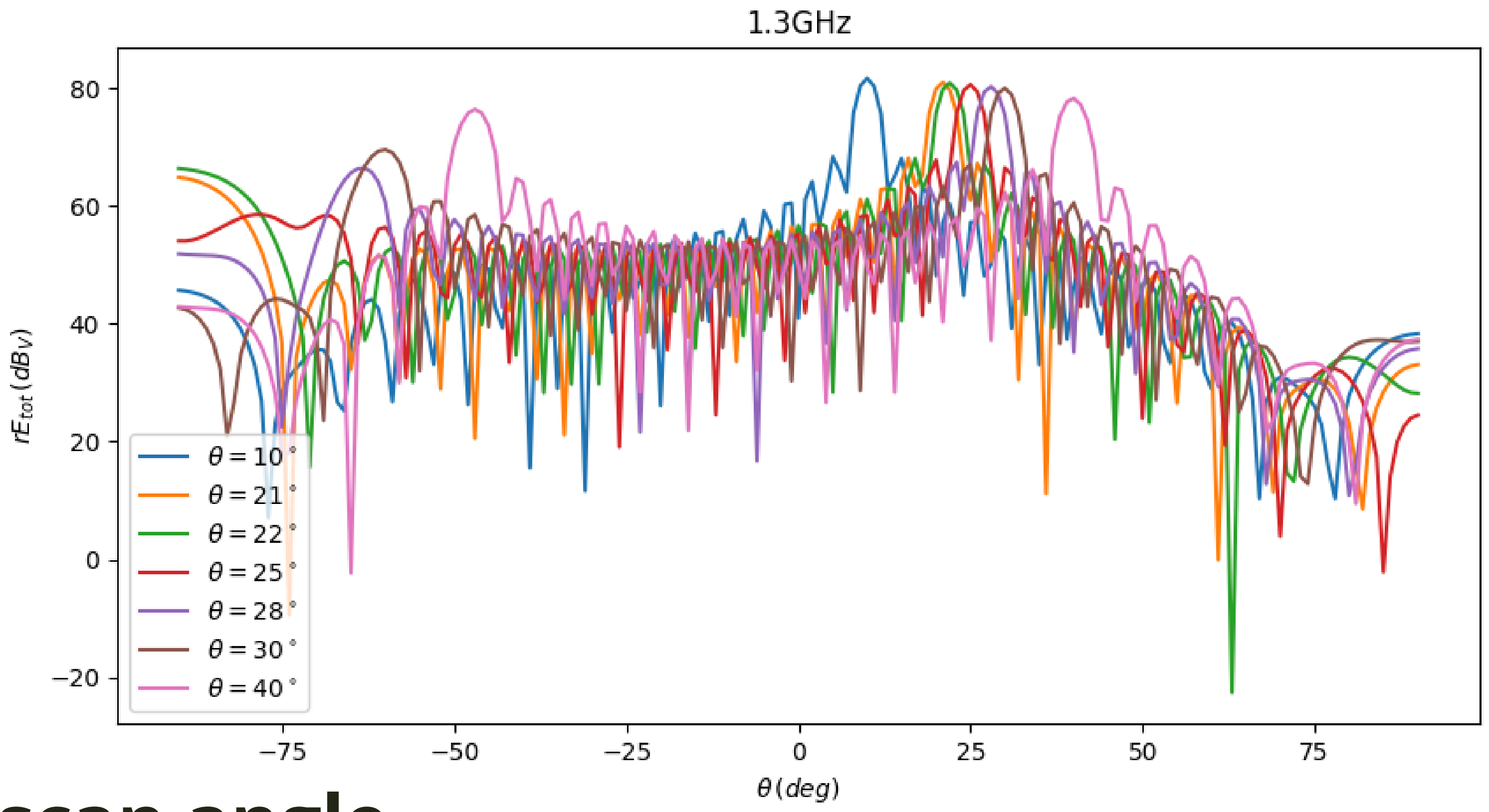
- Multi-frequency analysys
- Efffective area is smaller at high frequencies at high scan angles

Grating lobes

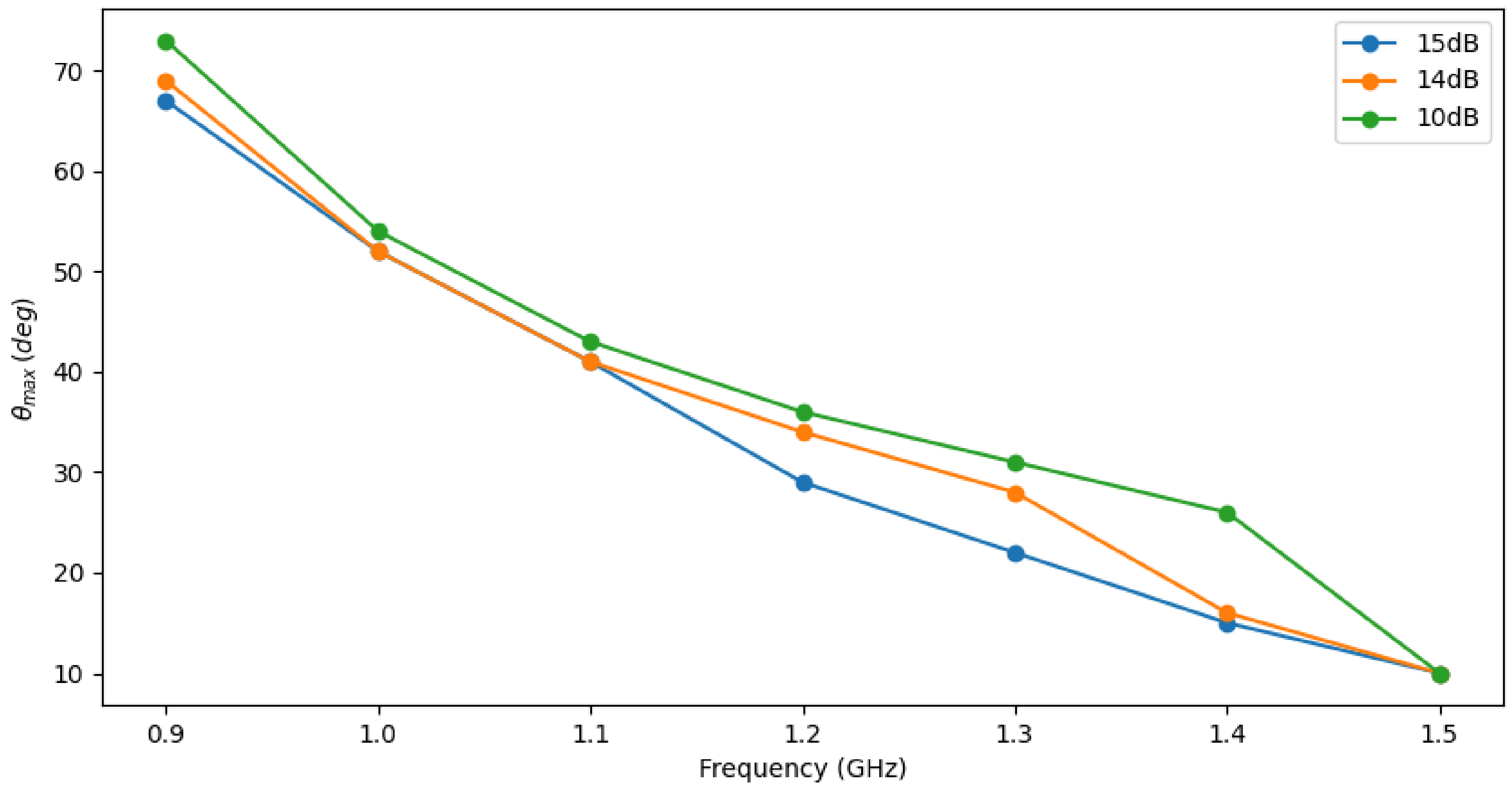
Appear at higher frequencies



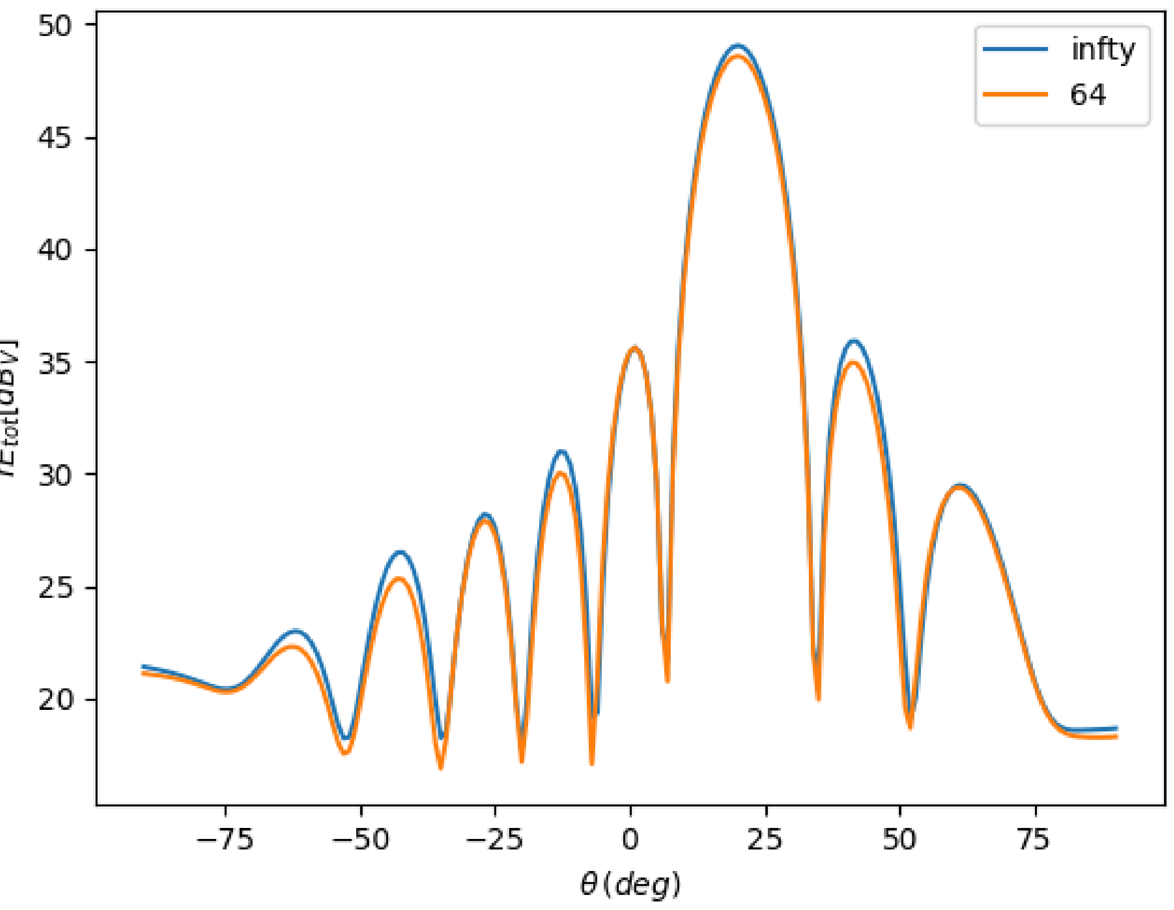
and higer scan angles

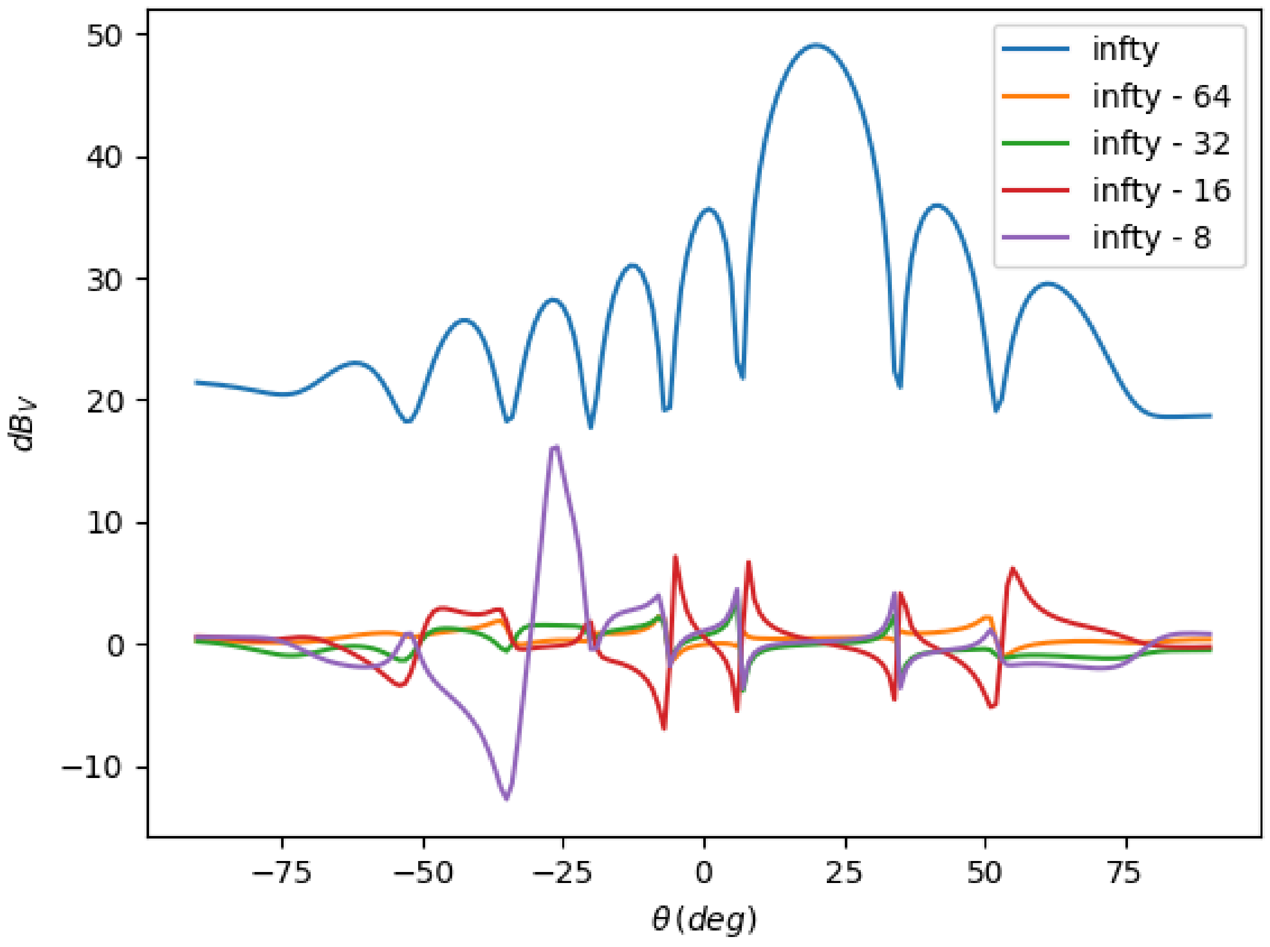


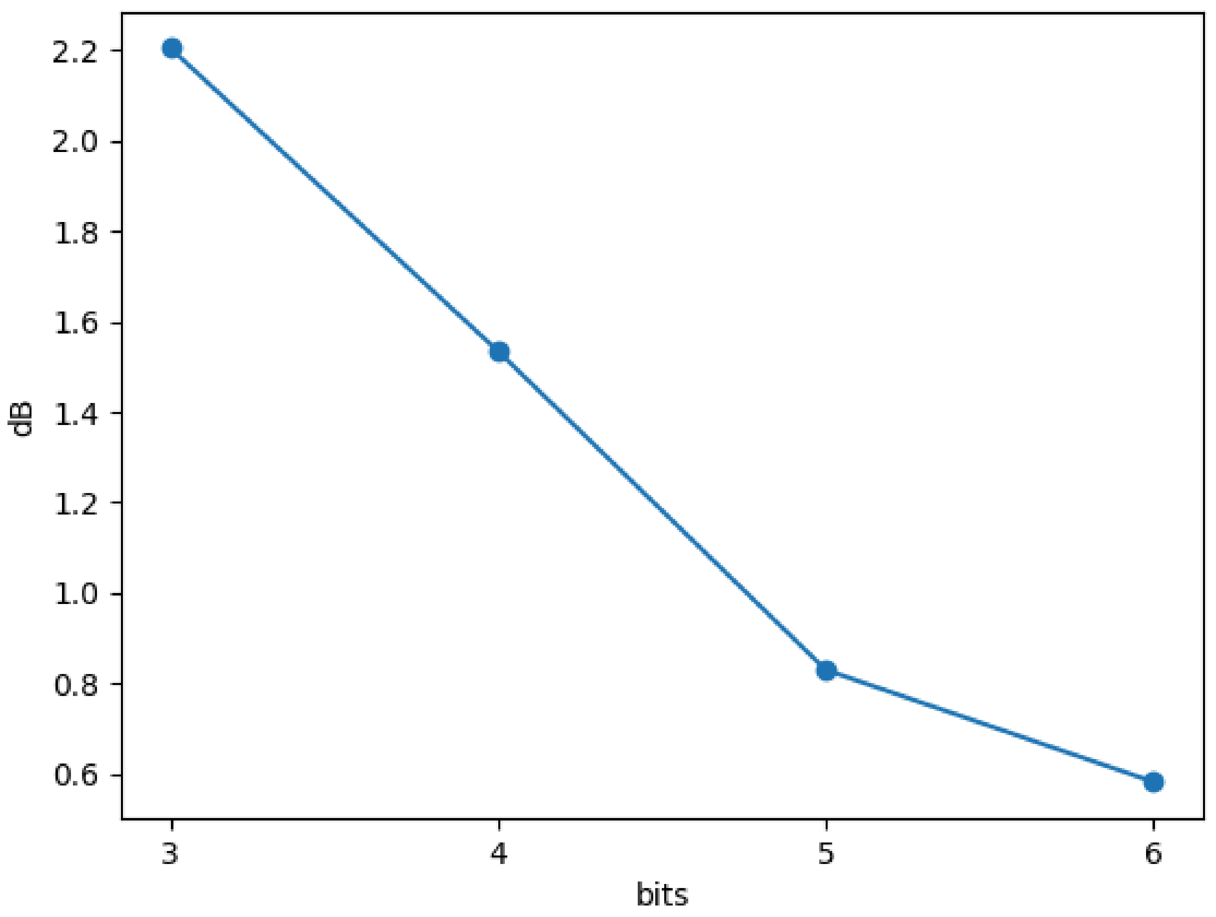
Maximum scan angle



Phase quantization







- The smaller the phase steps, the finer the control over the direction of the beam
- 64 phase steps leads to a good resolution on the beamforming

Conclusions

- We did EM simulations of the tile prototype and aperture array outrigger station with HFSS.
- The analog beam have a normalized gain >0.75 at the BINGO area, suitable for interferometry.
- A station with 36 (64) tiles gives an effective area of 16.2m^2 (28.8m^2) and FWHM of 4deg (2deg) at 1GHz, which satisfy the scientific requirements for FRB localization.
- Grating lobes appear at scan angles lower than 40deg at frequencies higher than 1.1GHz. The maximum scan angle reaches 10deg at 1.5GHz

ASTRON

BINGO

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Shanghai Astronomical Observatory,CAS

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University of Science and Technology of China

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Universidade de São Paulo

UFCG
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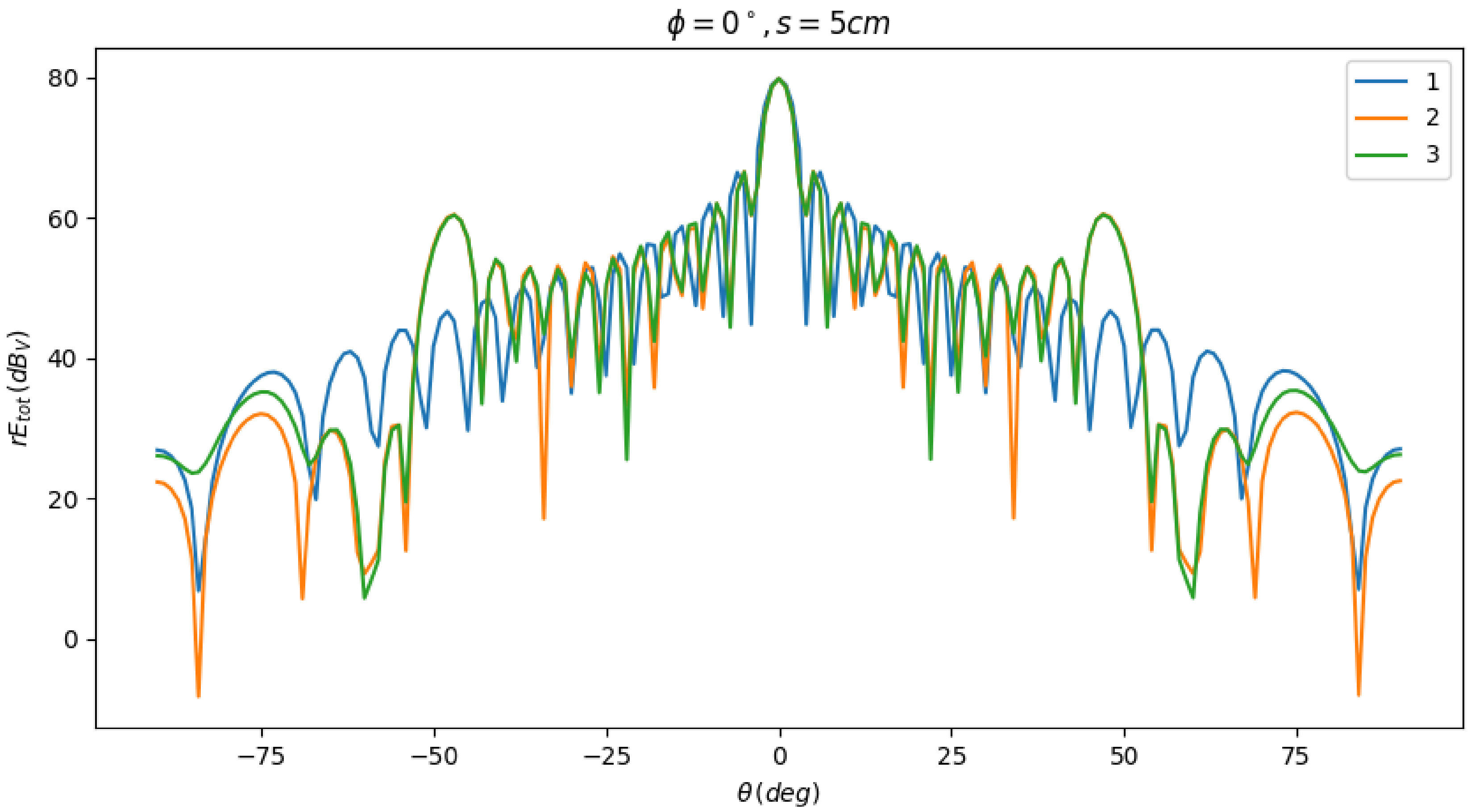
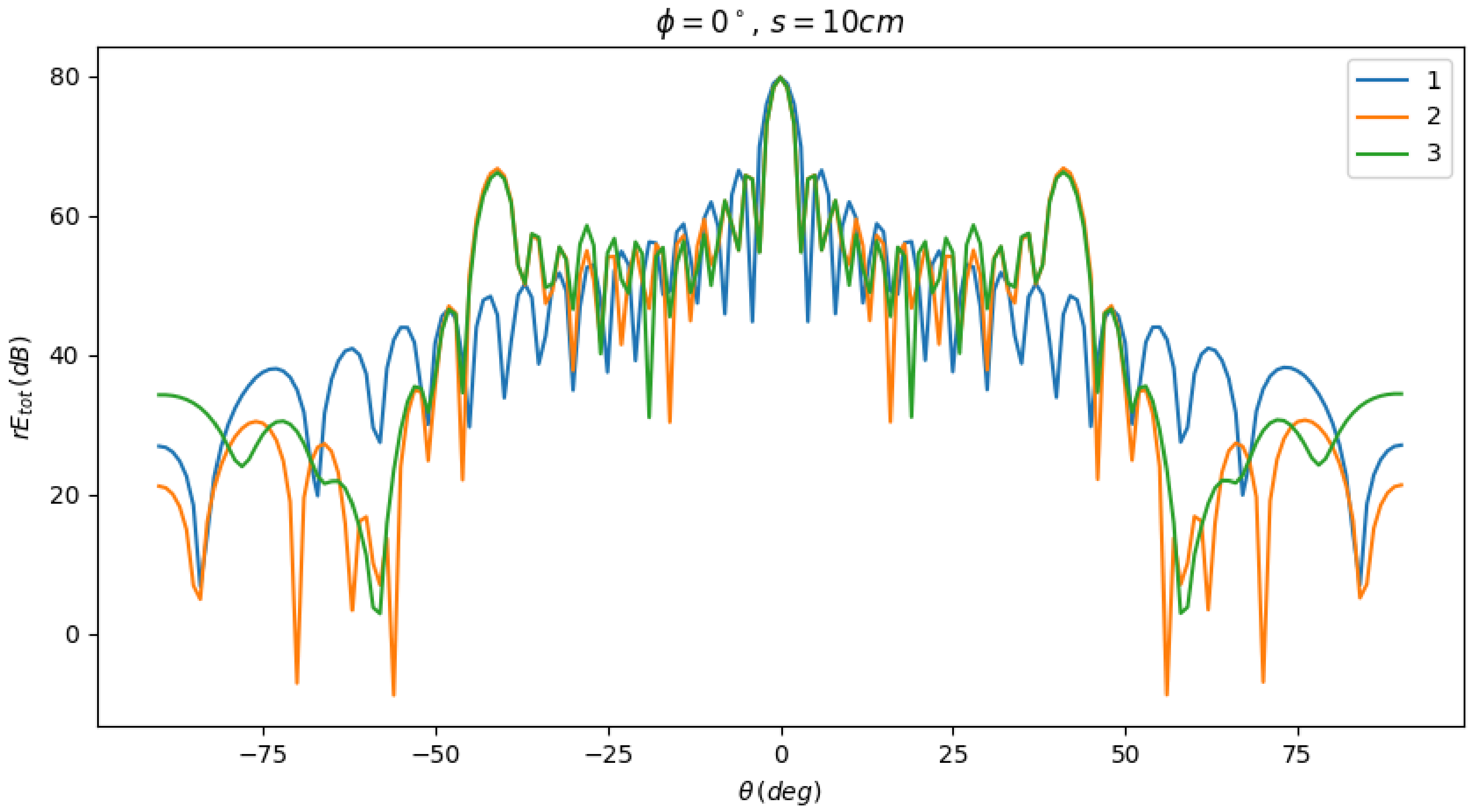


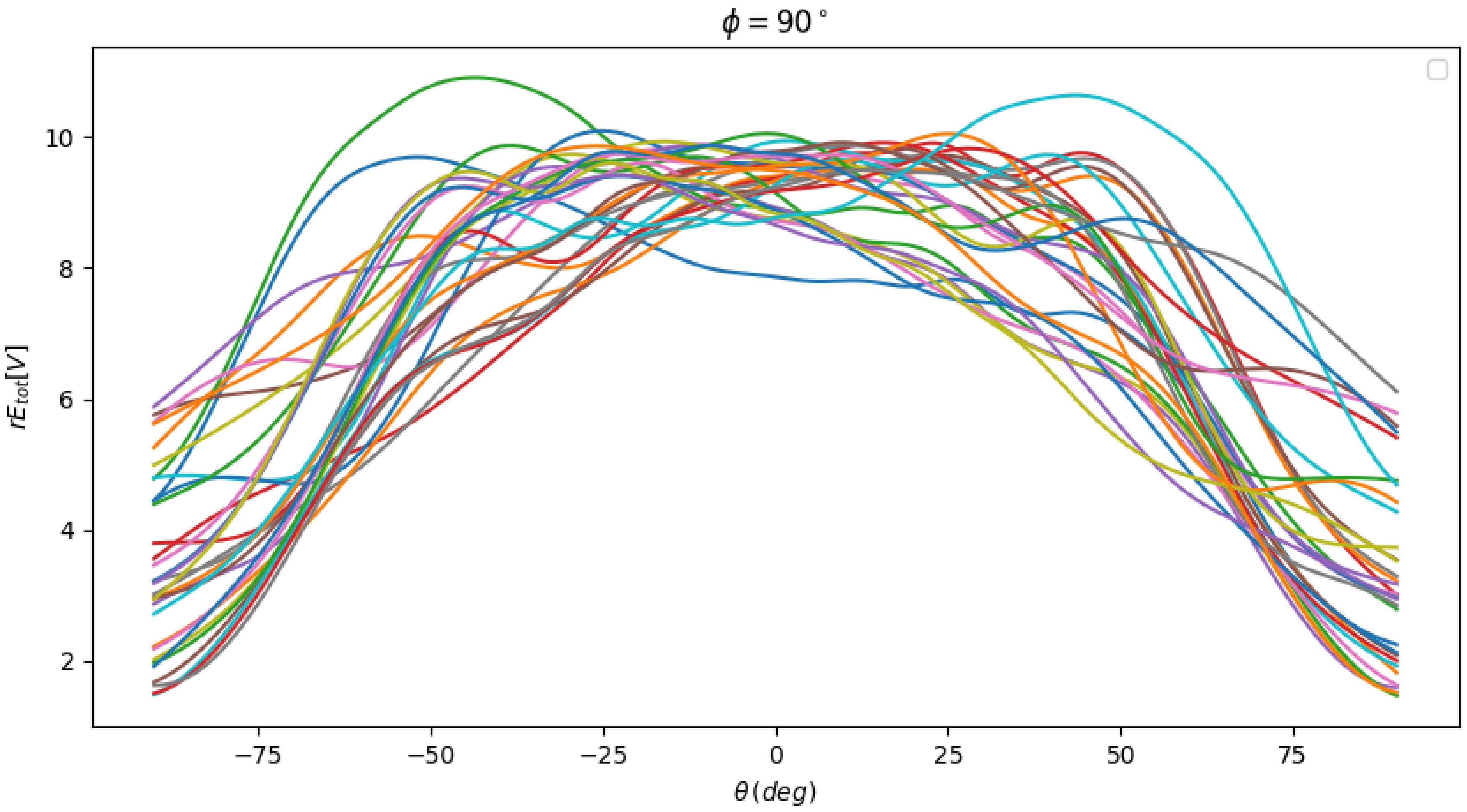
$\phi = 0^\circ, s = 5cm$
1
2
3
80
60
40
20
0
$rE_{tot}(dB_V)$
−75
−50
−25
0
25
50
75
$\theta(deg)$



$\phi = 0^\circ, s = 10cm$
1
2
3
80
60
40
20
0
$rE_{tot}(dB)$
−75
−50
−25
0
25
50
75
$\theta(deg)$

	01 tile	36 tiles	64 tiles
Size (m x m)	0.35 x 1.34	4.22 x 4.02	5.63 x 5.36
Gain (dBi)	5.02	33.6	36.1
Phis. area (m2)	0.47	17	30.2
Eff. area (m2)	0.45	16.2	28.8
FWHM (deg)	10 (42)	4	2
First side lobe (deg)	-13.3	-13.3	-13.9

Table 1. Technical data for the tile and for the 36-tile and 64-tile station. All the quantities except the size and physical area were computed from the HFSS simulations.



$\phi = 90^\circ$
10
8
6
4
2
$rE_{tot}[V]$
−75
−50
−25
0
25
50
75
$\theta(deg)$