Fast Numerical Methods for the Simulation Focal Plane Array

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- ASM-MBF for Large Array Simulation
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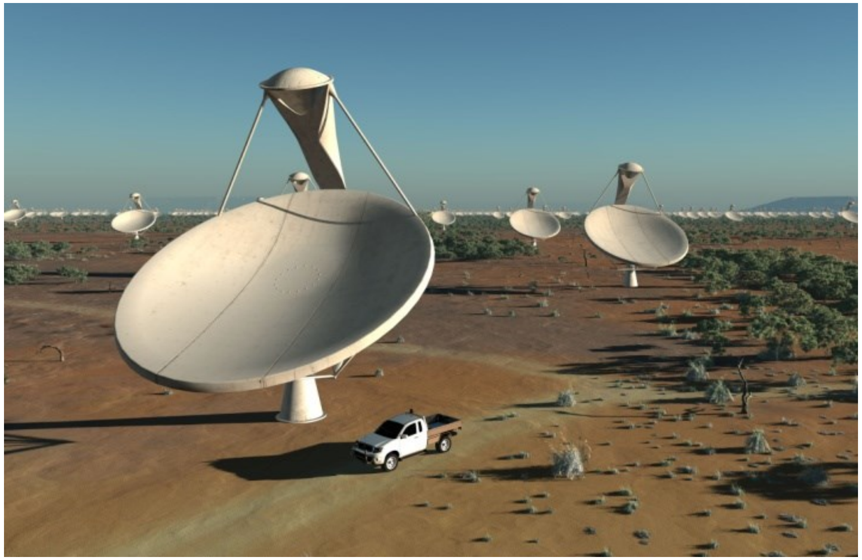
Next-generation Radio Telescopes: SKA

1937

Grote Reber, built a parabolic, 9.5-m diameter, reflector dish in his backyard

2016



SKA antennas will extends over thousands of Kilometers in SA and Australia.

Advanced Focal Array Demonstrator

Bruce Veidt (NRC-DRAO, Canada)

Bruce Veidt (NRC-DRAO, Canada)

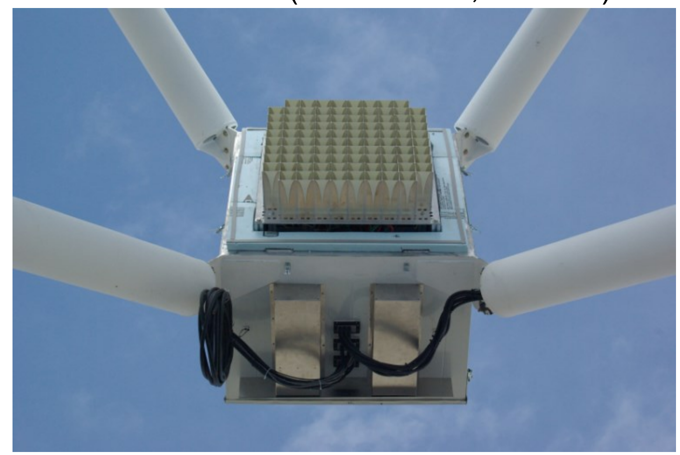
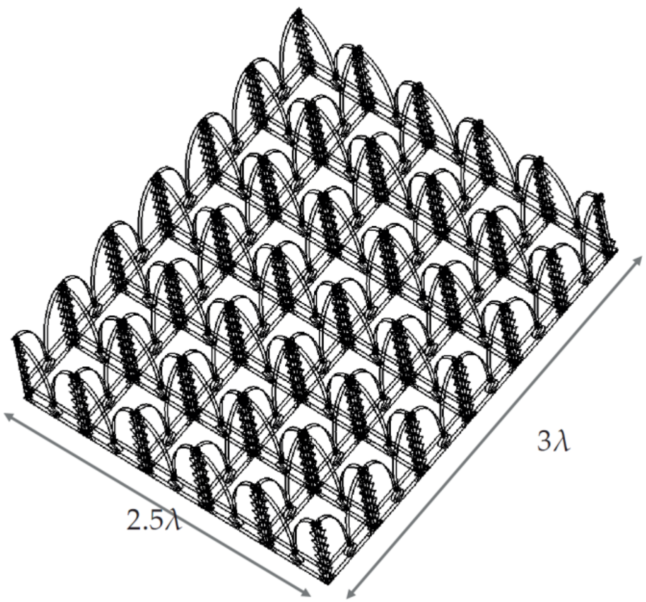


Table: 3D Array specifications

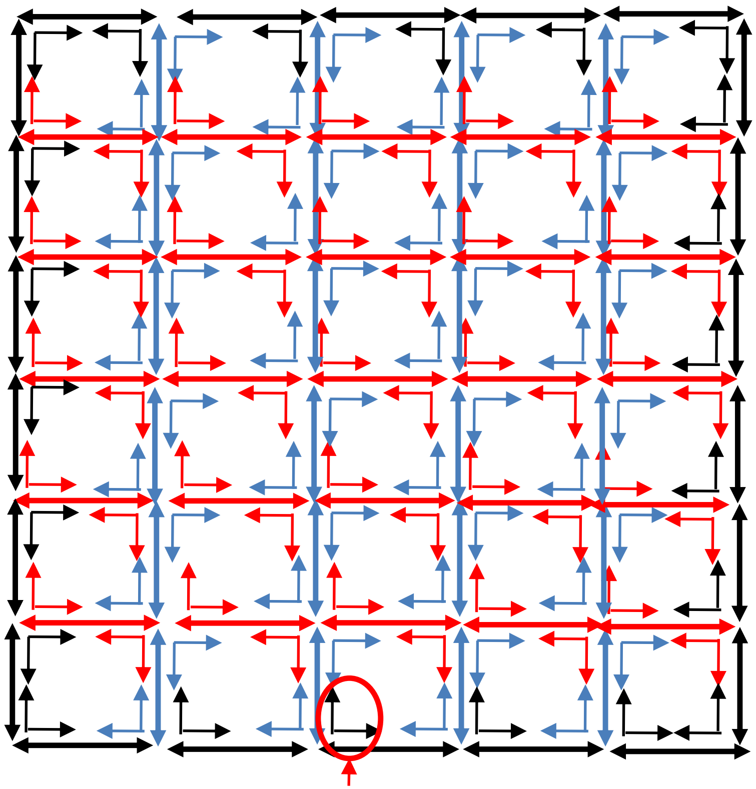
Frequency range	$0.7 - 1.5GHz$
Element spacing	$\lambda/2 = 10cm$
Array size	$\leq 1m \times 1m$
Element dissipative loss	$< 0.1dB$
T_{LNA}	$< 15k$
G_{LNA}	$25 - 35dB$
Array mass	$< 50kg$

Goal: Simulation and design of Focal Plane Array of 71 antennas.

Large Focal Plane Array



Array periodic structure construction



Connecting basis functions

- 5 × 7 antennas polarized along x axis
- 6 × 6 antennas polarized along y axis.

ASM-MBF Goal

- Goal: Large array analysis with Method-of-moments

MoM System

$$\bar{\bar{Z}}\ \bar{x} = \bar{V} \quad (1)$$

MoM Matrix

For large antenna arrays, $\bar{\bar{Z}}$ matrix's size increases(Gbytes).
The inversion of $\bar{\bar{Z}}$ needs:

- Powerful computers (Processor)
- Large memory capacity (RAM)

Basis functions

Weight associated with each basis functions f_i

Excitation

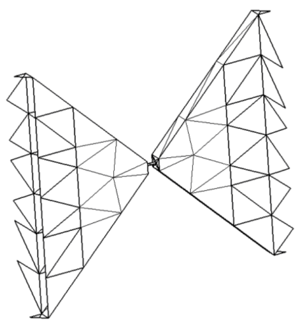
Delta gap excitation vector

- Idea: Compress the MoM matrix using set of current distributions from the solution of smaller problems.

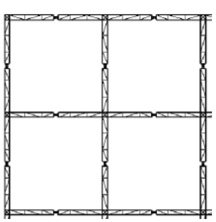
ASM-MBF Principle

Simulation of smaller problem

Array Scanning Method (ASM).
Small Finite Array.



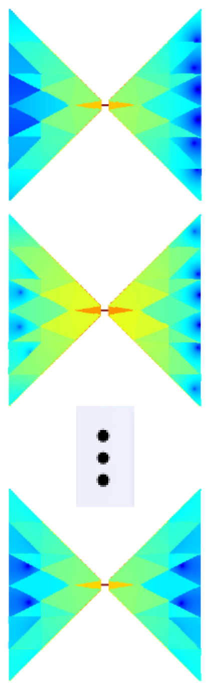
Infinite simulation



Finite simulation

Current Extraction

Extract L current distributions
$\bar{J}_i = \bar{Q}_i \bar{f}$.



$\bar{J}_1 = \bar{Q}_1 \bar{f}$

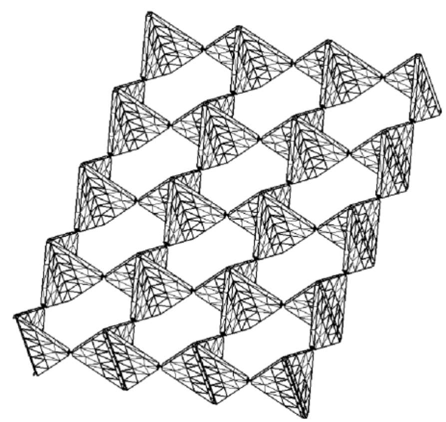
$\bar{J}_2 = \bar{Q}_2 \bar{f}$

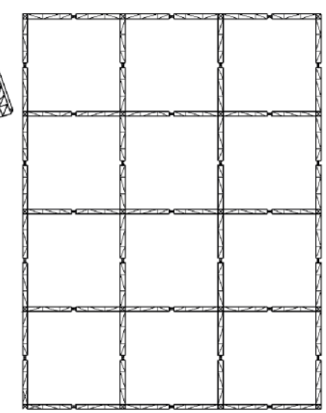
$\vdots$

$\bar{J}_L = \bar{Q}_L \bar{f}$

Compress & Solve System

- Express current distribution as linear combination of the obtain set of currents from smaller problems.
- Compress the system matrix using Q_i.
- Solve the compressed system.
- Decompress the current solution.





ASM-MBF Formulation

Set of current distributions

$$\bar{\bar{Q}}_i = \left[\bar{\bar{Q}}_{ASM} \quad \bar{\bar{Q}}_{small\ array} \right]$$

All the sets of current distributions are concatenated in $Q_i matrix$.

Linear Combination

$$\bar{x}_i = \bar{\bar{Q}}_i \, \bar{y}_i$$

Then any current distribution can be expressed as a linear combination of these current sets.

Compress & Solve System

The MoM system of equation is compressed as shown:

$$\underbrace{\begin{pmatrix} Q_1^T & \cdots & 0 & 0 \\ 0 & Q_2^T & \cdots & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & \cdots & Q_M^T \end{pmatrix} \bar{\bar{Z}} \begin{pmatrix} Q_1 & \cdots & 0 & 0 \\ 0 & Q_2 & \cdots & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & \cdots & Q_M \end{pmatrix}}_{\bar{\bar{Z}}_{Compressed}} \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_L \end{pmatrix} = \begin{pmatrix} Q_1^T & \cdots & 0 & 0 \\ 0 & Q_2^T & \cdots & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & \cdots & Q_M^T \end{pmatrix} \bar{V}$$

M is the number of basis functions
L is the number of current distributions
N is the number of the array antennas

Size of Z is (N*M)x(N*M)
Size of $Z_{compressed}$ is (N*L)x(N*L)
Compression ratio = (M/L)

M = 838
L = 28
Cr= 30

ASM-MBF Validation & Discussions

3D Bowtie antenna:

- Meshed by M = 180 basis functions
- And compressed by ASM (3x3) L = 9
- Compression ratio is 20.

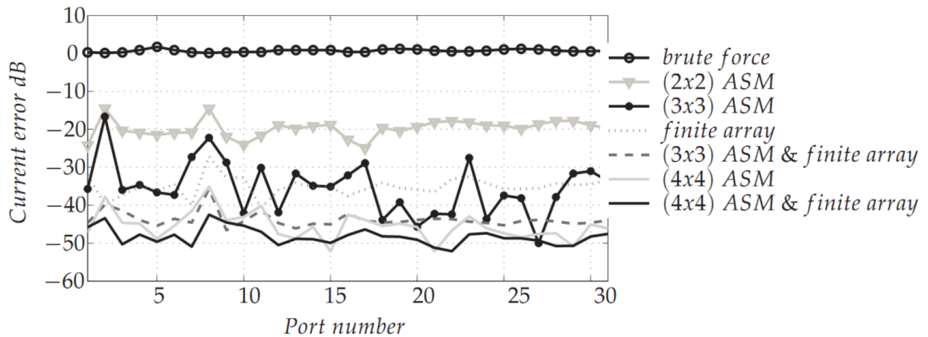
We compare the CPU time:

Brute-force

C-code program
Pentium (R) 4 CPU 3,06 GHz 1,5 GB of RAM
CPU time:4h 21min

ASM-MBF

Matlab program
Pentium (R) 4 CPU 3,06 GHz 1,5 GB of RAM
CPU time:1h 19min

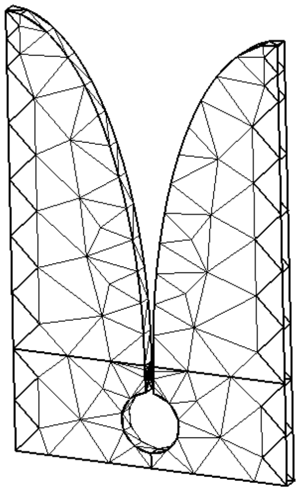


Conclusion

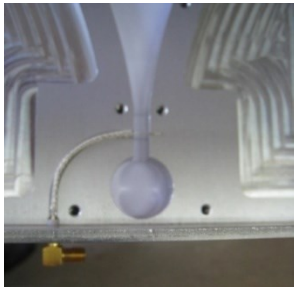
- Matrix interaction calculation represents an important share of time. This is proven to be reduced using Multipoles [2].
- This method is interesting for Very Large Array where memory resources needed bypass the available memory capacity.
- The most important thesis of this method is the complexity reduction of the problem and the quality of the results. Error below −40 db using only ASM (4x4).
- This ASM-MBF method stays applicable with dielectric structures. Further works has been done in [1].

[1] Ozdemir N. A. and Craeye C., Efficient analysis of periodic structures involving finite dielectric material based on the array scanning method," Int. Conf. on Electromagnetics in Advanced Applications, Torino, Italy, Sept. 14-18, 2009.
[2] C. Craeye, “A fast impedance and pattern computation scheme for finite antenna arrays,” Antennas and Propagation, IEEE Transactions on, vol. 54,no. 10, pp. 3030 –3034, oct. 2006.

Potential of 3D TSA



Layout of 3D TSA

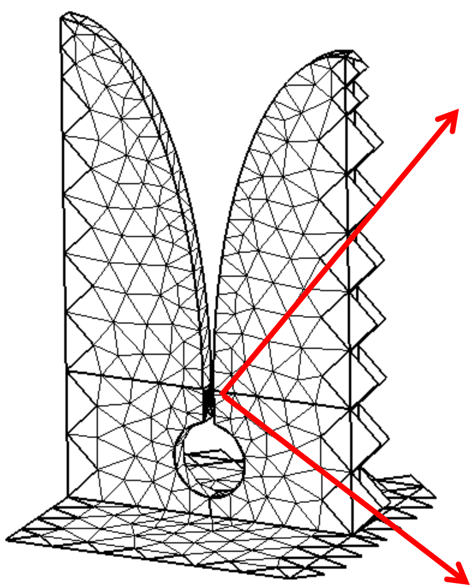


Feed inside the structure

Advantages of Metal only Vivaldi:

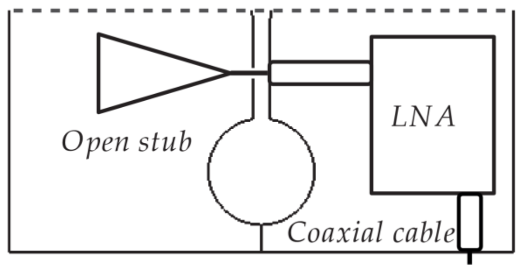
- Direct feed almost no soldering required.
- No dielectric material: dielectric loss elimination.
- Host LNA as near as possible to feed: reduced noise level.
- Highly modular -> easy upgrade of the system since each element can be treated alone.
- Easy to manufacture and mount.
- Stability and reproducibility of the array.
- Cost becomes fair for mass production.

Feed types investigations

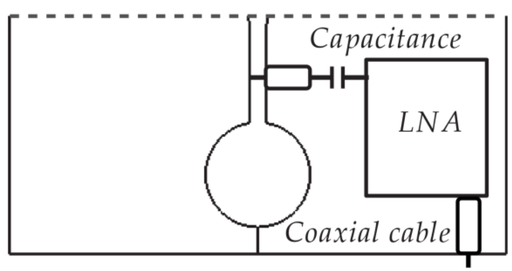


Infinite array simulation
with connecting basis functions

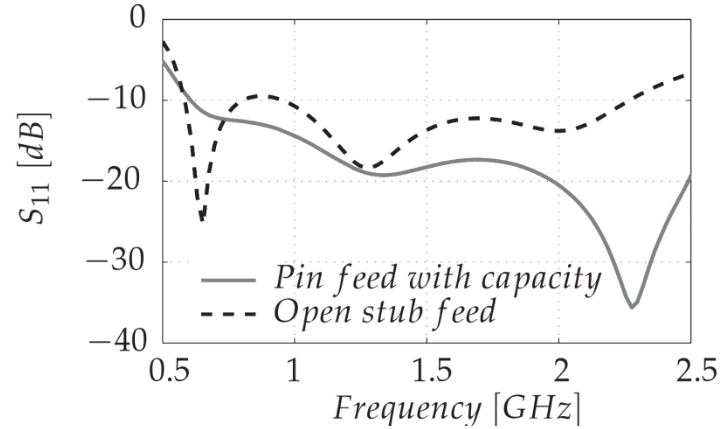
Open stub feed



Pin feed with series capacity



Reflection coefficient



With reference to 85 Ohms

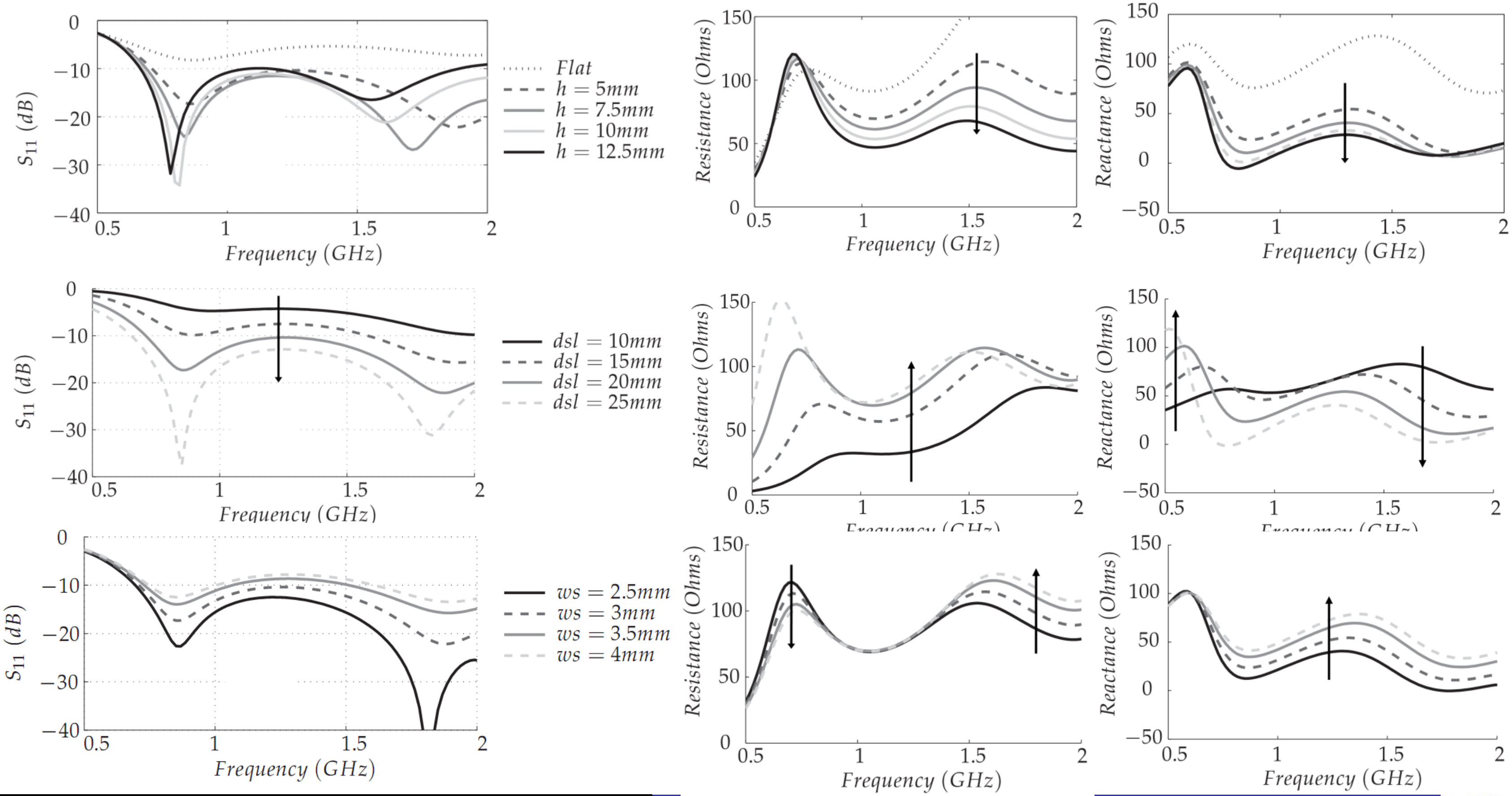
Optimization of the 3D Vivaldi Antenna

Reflection coefficient | **Real part of Z** | **Imag part of Z**

Sweep thickness

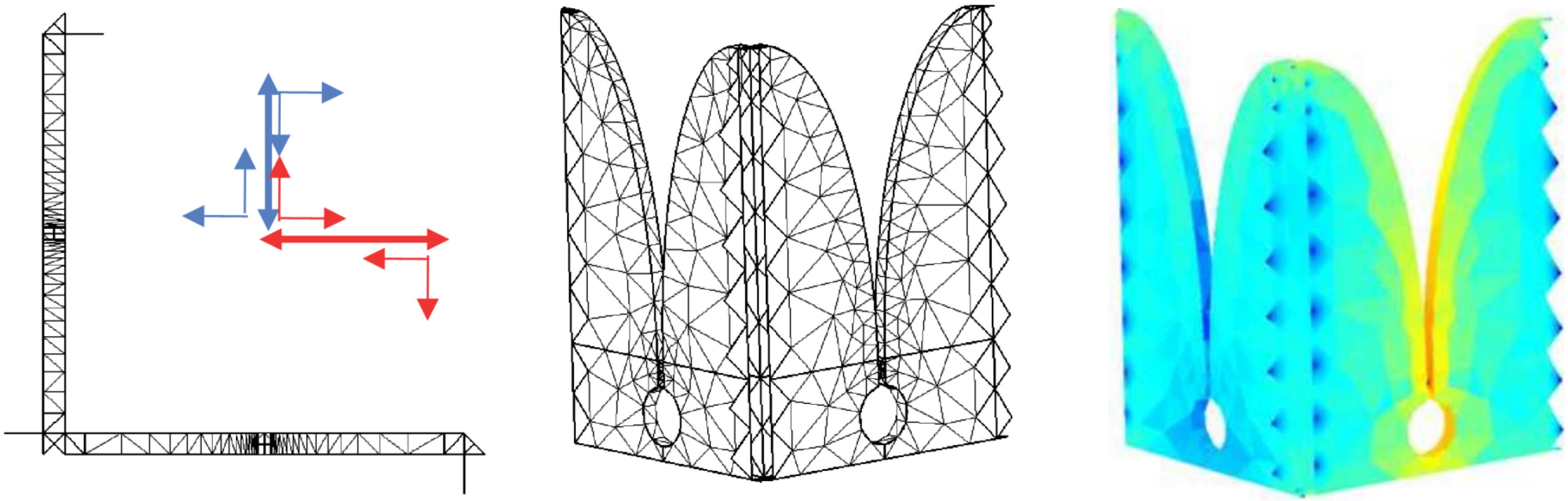
Sweep balun

Sweep balun



(4x4) ASM current distributions

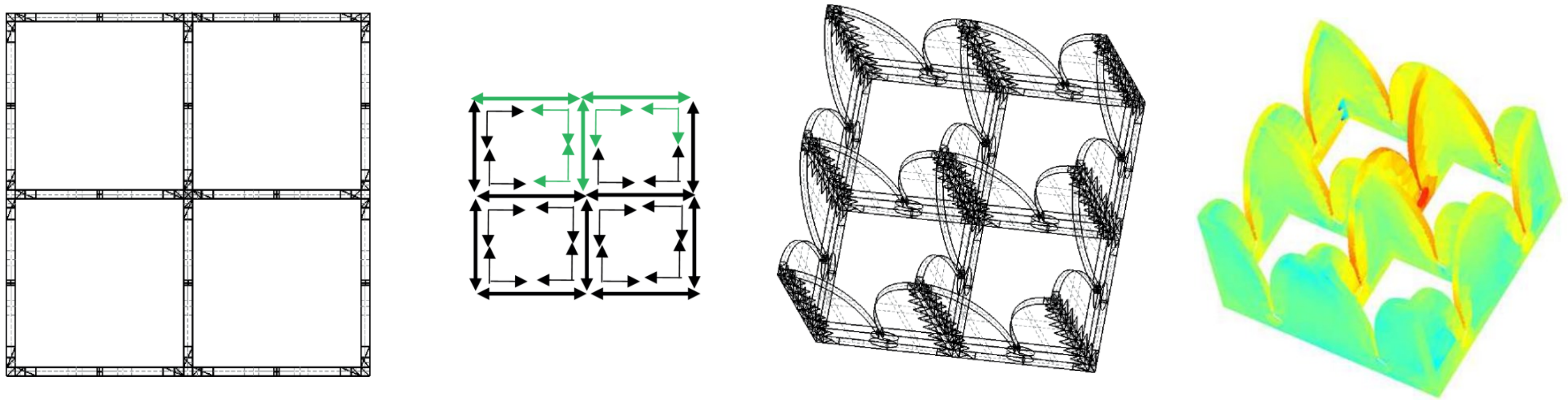
- Infinite simulation



- We extracted 16 current distributions from the ASM simulations.

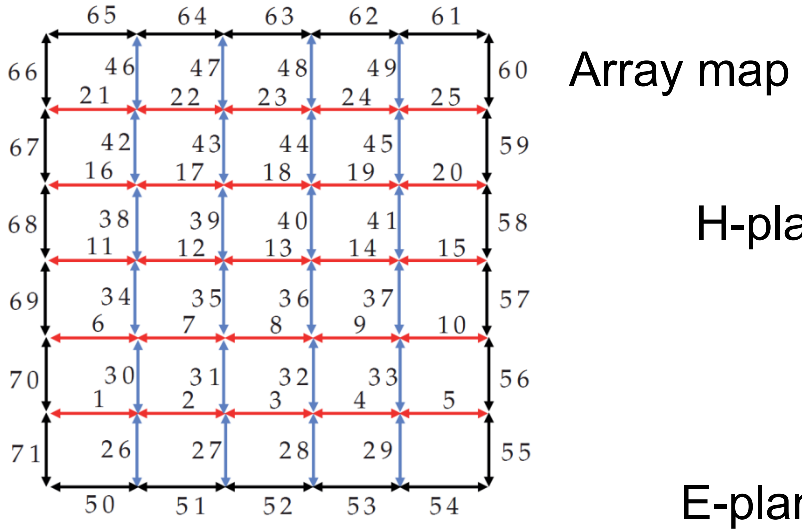
Small Finite Array

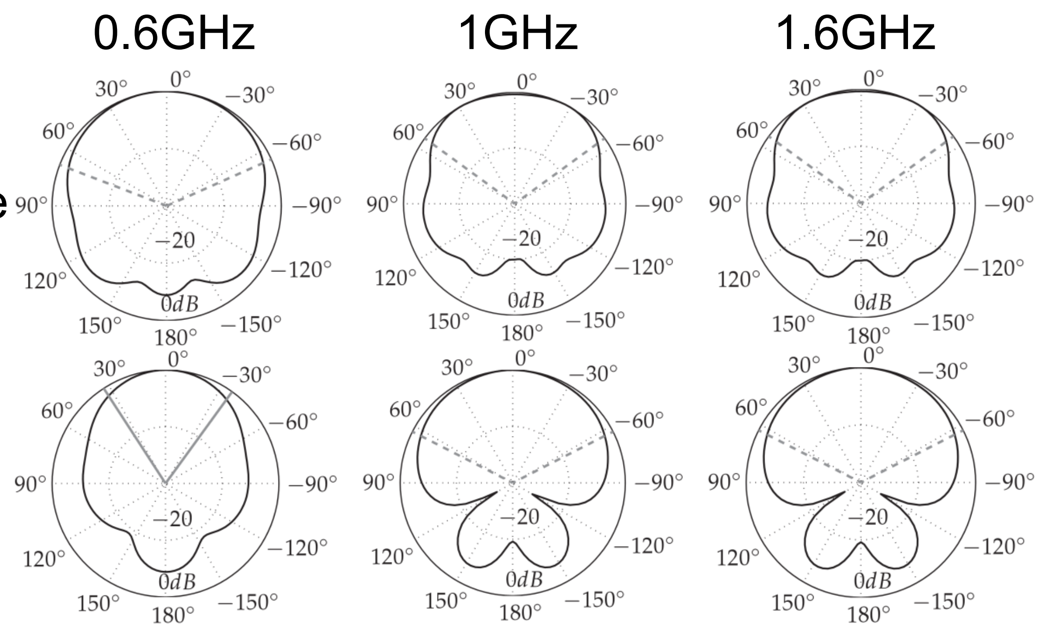
- Finite Simulation



- We extracted 12 current distributions from the simulation of this array.

71 Antenna Array Simulation Results





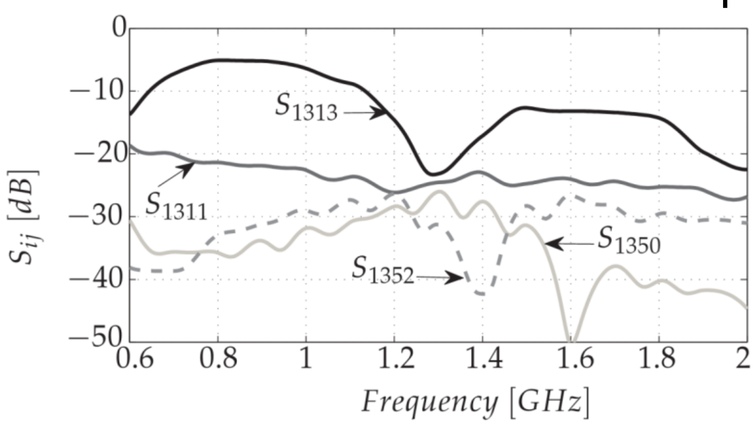
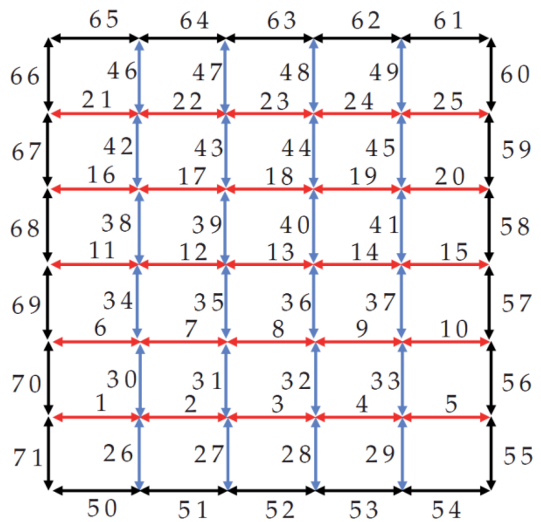


Table: Half Power Beam Width of the center element of the array.

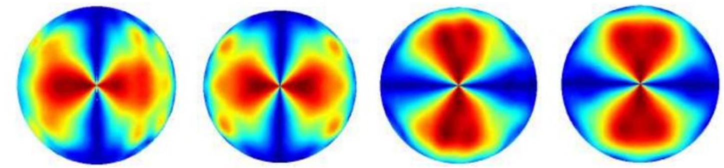
	$H - plane$ ($\phi = 0°$)	$E - plane$ ($\phi = 90°$)
At 0.6 GHz	135°	69°
At 1 GHz	108°	126°
At 1.6 GHz	111°	111°

Truncation Effects at Array Borders

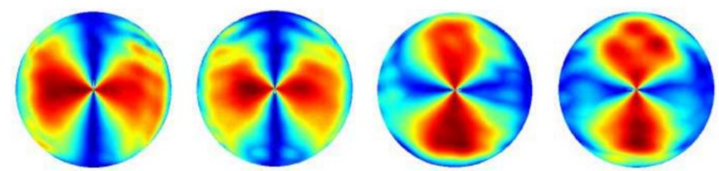
Array map



1GHz

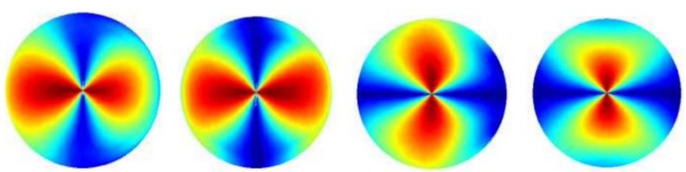


(a) *Hpol Antenna* 11 (b) *Hpol Antenna* 13 (c) *Vpol Antenna* 11 (d) *Vpol Antenna* 13

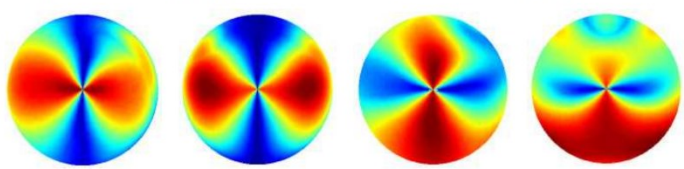


(e) *Hpol Antenna* 50 (f) *Hpol Antenna* 52 (g) *Vpol Antenna* 50 (h) *Vpol Antenna* 52

0.6 GHz

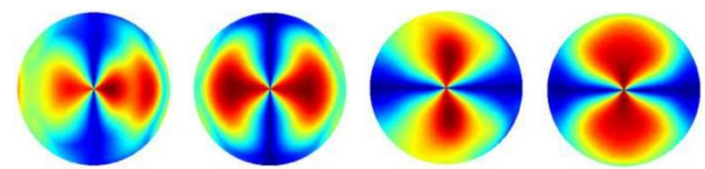


(a) *Hpol Antenna* 11 (b) *Hpol Antenna* 13 (c) *Vpol Antenna* 11 (d) *Vpol Antenna* 13

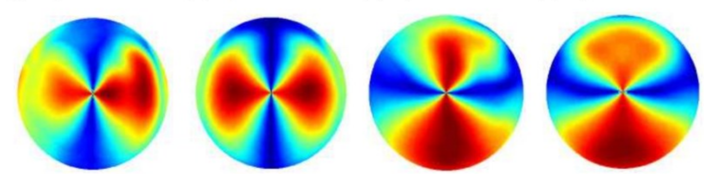


(e) *Hpol Antenna* 50 (f) *Hpol Antenna* 52 (g) *Vpol Antenna* 50 (h) *Vpol Antenna* 52

1.6GHz

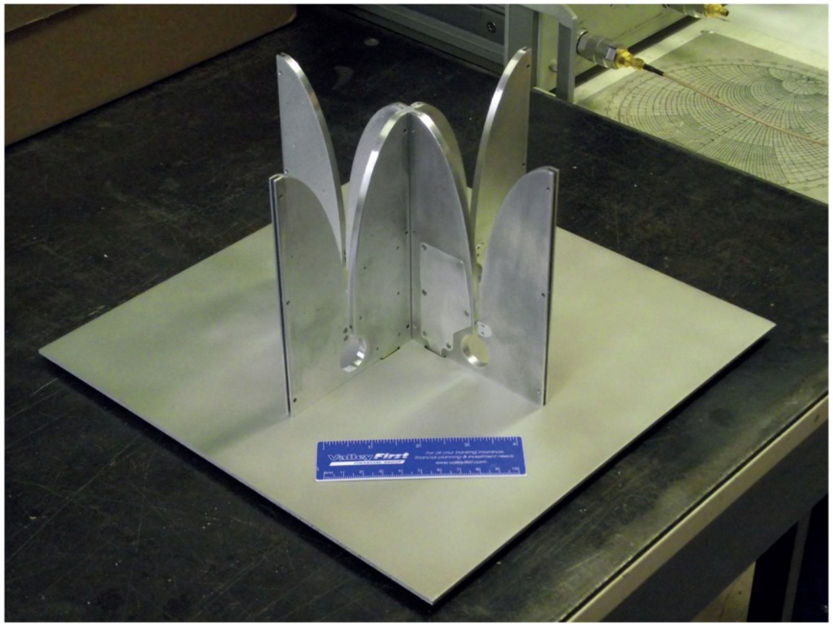


(a) *Hpol Antenna* 11 (b) *Hpol Antenna* 13 (c) *Vpol Antenna* 11 (d) *Vpol Antenna* 13



(e) *Hpol Antenna* 50 (f) *Hpol Antenna* 52 (g) *Vpol Antenna* 50 (h) *Vpol Antenna* 52

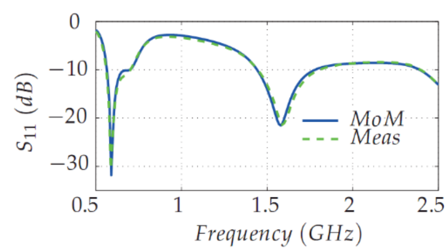
Simulation vs. Measurements



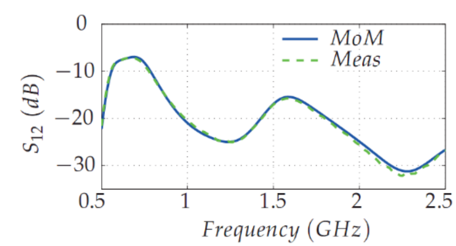
Vivaldi 3D dimensions

- Width a = 10 cm
- Height b = 14 cm
- Cavity diameter c = 2 cm
- Slot Width d = 0.3 cm
- Thickness = 0.5 cm

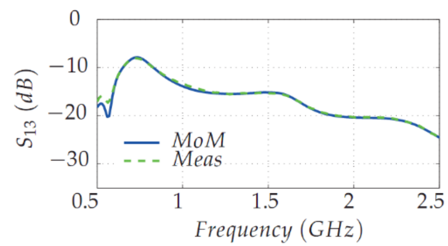
S-parameters Simulations vs. measurements



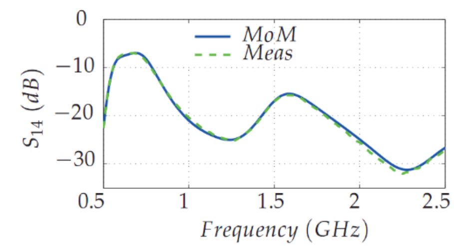
(a) S_{11} simulation vs. measurements.



(b) S_{12} simulation vs. measurements.



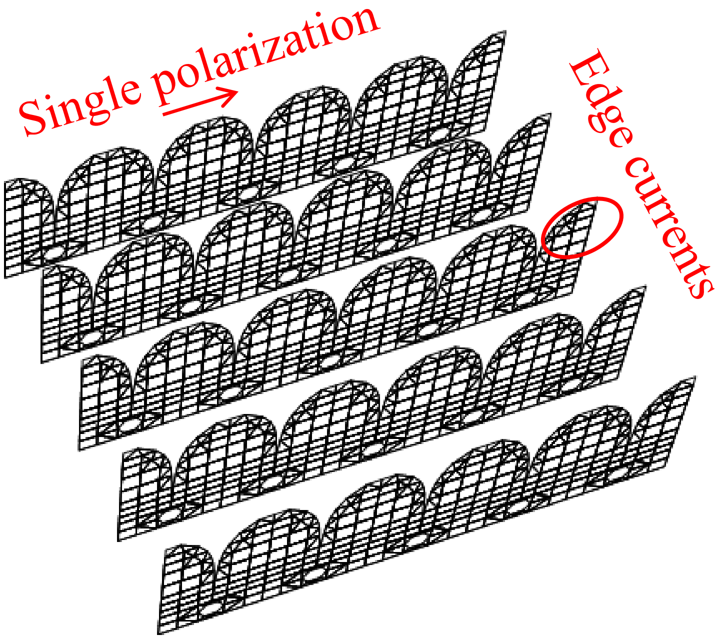
(c) S_{13} simulation vs. measurements.

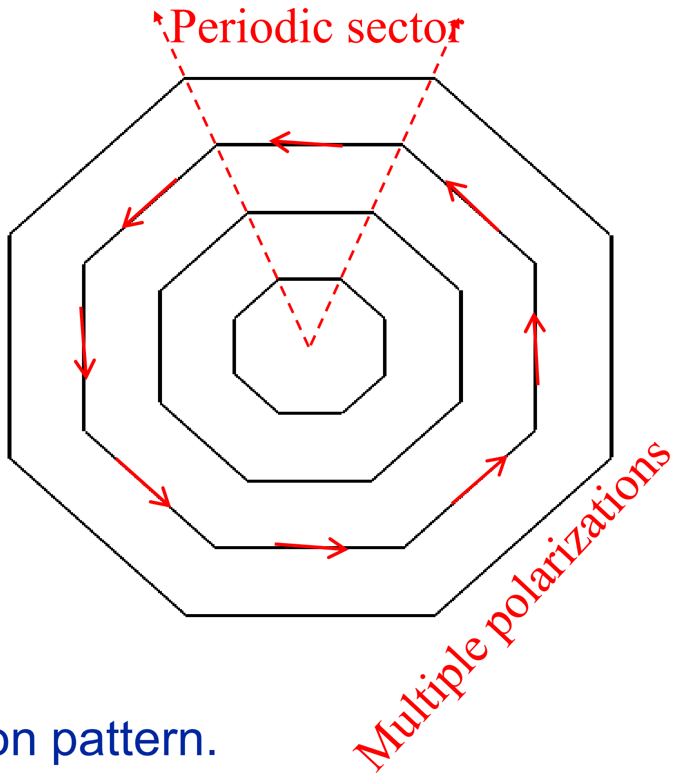


(d) S_{14} simulation vs. measurements.

- Excellent agreement between the simulation and measurements.

Rectangular Arrays Vs Circular Arrays





- Less truncation effect at the border of the array.
- Advantage of the rotation similarity of the radiation pattern.
- Polarimetric advantage using different polarizations.
- Rotational symmetry: pattern calibration is made easier.

Array Scanning Method (ASM)

Current Distribution

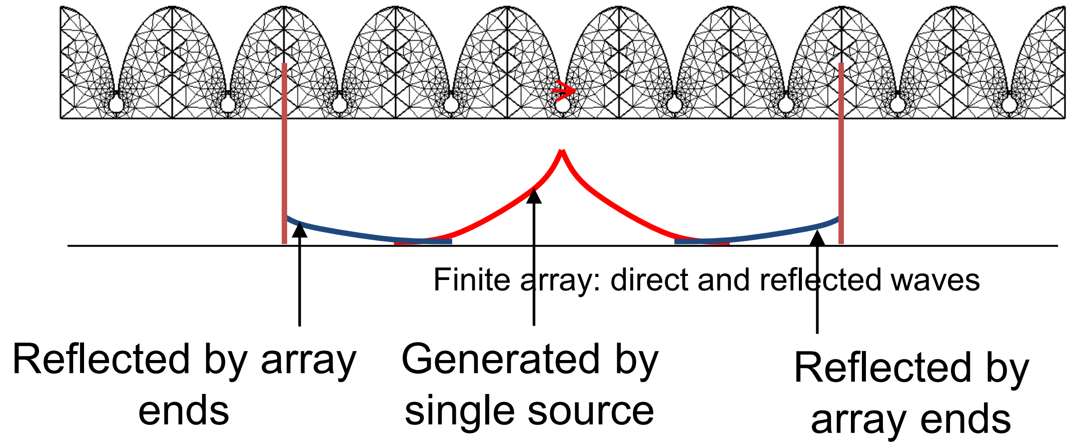
$$I(m) = \frac{1}{2\pi}\int_0^{2\pi} I^{\infty}(\psi)e^{-jm\psi}d\psi \quad (1)$$

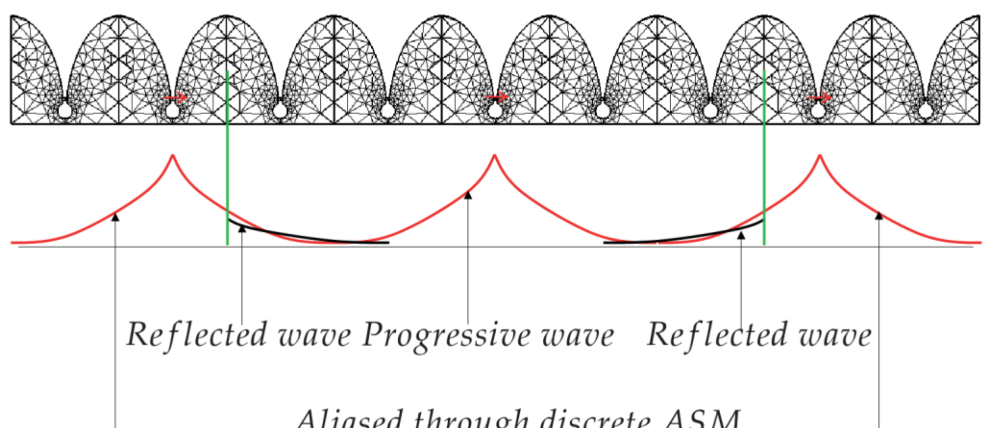
Array Scanning Method

$$I(m) \approx \frac{1}{N}\sum_{p=0}^{N-1} I^{\infty}(\psi_p)e^{-jm\psi_p} \quad (2)$$

where $\psi_p = p\frac{2\pi}{N}$

with $(0 < p < N-1)$





ASM for Circular Array

MoM System

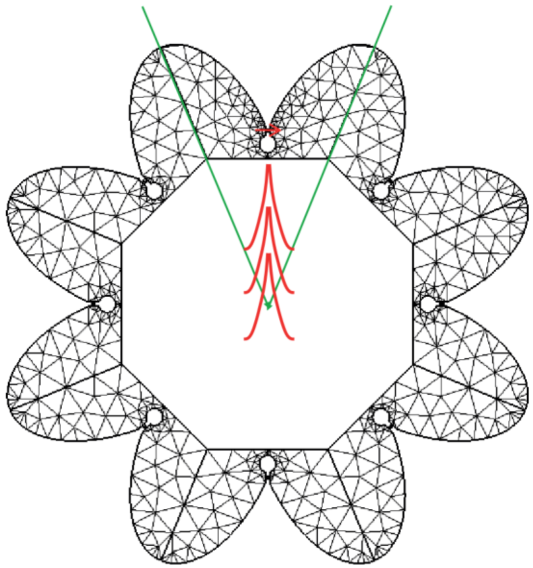
$$\begin{pmatrix} Z_{1,1} & Z_{1,2} & \dots & Z_{1,N} \\ Z_{2,1} & Z_{2,2} & \dots & Z_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{N,1} & Z_{N,2} & \dots & Z_{N,N} \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{pmatrix} = \begin{pmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{pmatrix} \quad (1)$$

ASM for Circular Array

$$\begin{pmatrix} Z_{1,1} & Z_{1,2} & \dots & Z_{1,N} \end{pmatrix} \begin{pmatrix} I^{\infty}_{\psi_p} \\ I^{\infty}_{\psi_p} e^{jm\psi_p} \\ \vdots \\ I^{\infty}_{\psi_p} e^{j(N-1)\psi_p} \end{pmatrix} = \left(V_1(\psi_p)\right) \quad (2)$$

$$\begin{pmatrix} Z_{1,1} & Z_{1,2}e^{j\psi_p} & \dots & Z_{1,N}e^{j(N-1)\psi_p} \end{pmatrix} \left(I^{\infty}_{\psi_p}\right) = \left(V_1(\psi_p)\right) \quad (3)$$

$$\left(\sum_{m=0}^{N-1} Z_{1,m+1} e^{jm\psi_p}\right) \left(I^{\infty}_{\psi_p}\right) = \left(V_1(\psi_p)\right) \quad (4)$$

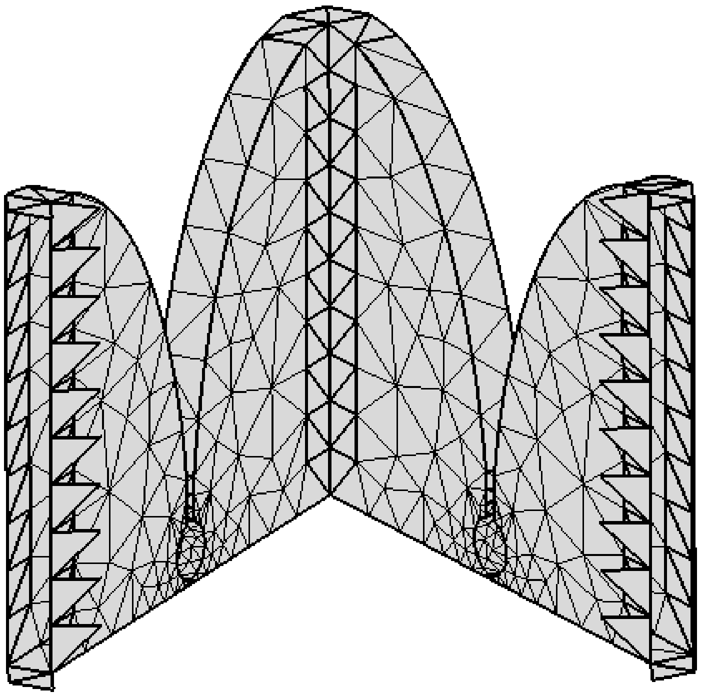


ASM yields exact solution

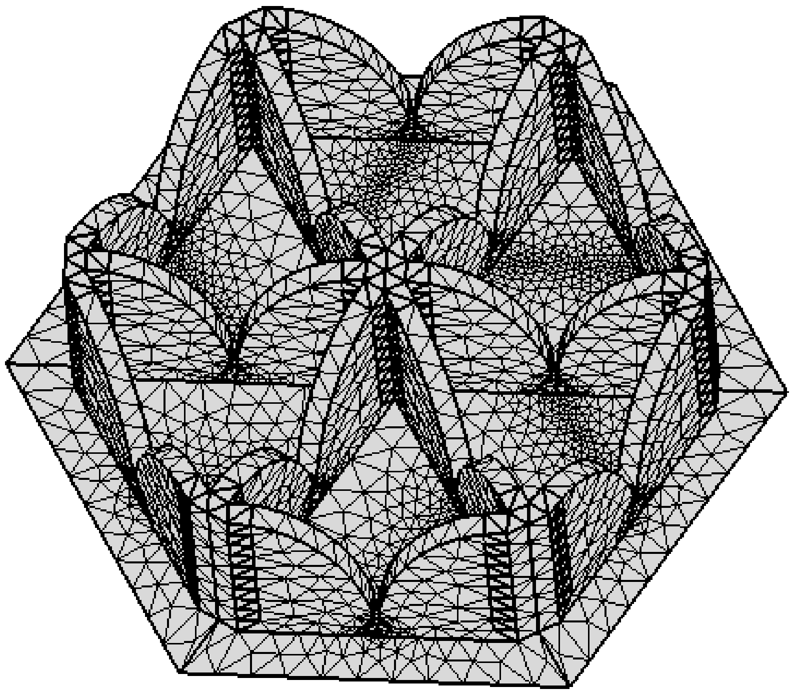
$$I(m) \approx \frac{1}{N} \sum_{p=0}^{N-1} I^{\infty}(\psi_p) e^{-jm\psi_p} \quad (5)$$

- MoM system (N*M)x(N*M) solution is reduced to N*(MxM) systems
- N antennas and M basis functions to discretize each antenna,

Dense Hexagonal Array

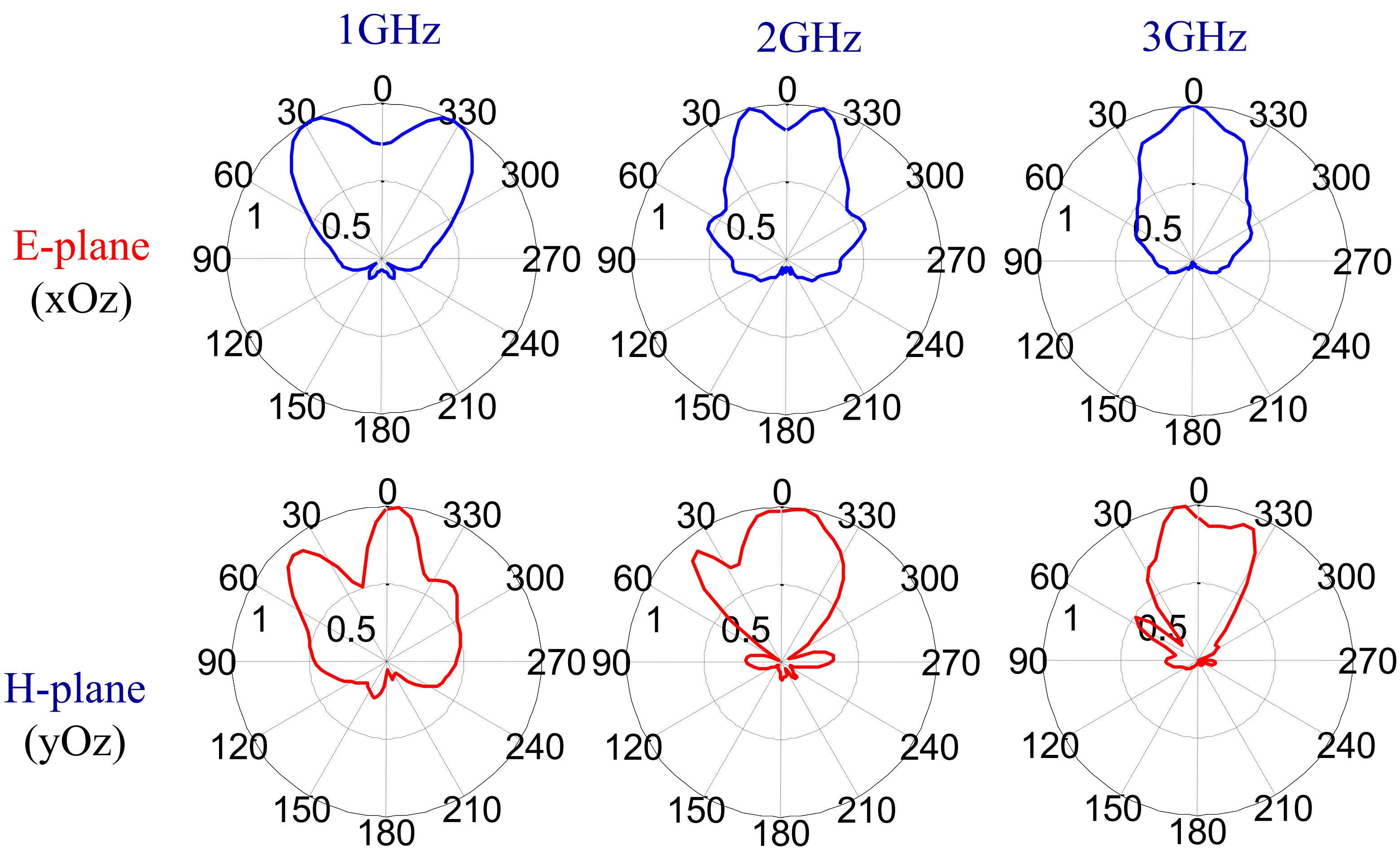


Periodic element of the array

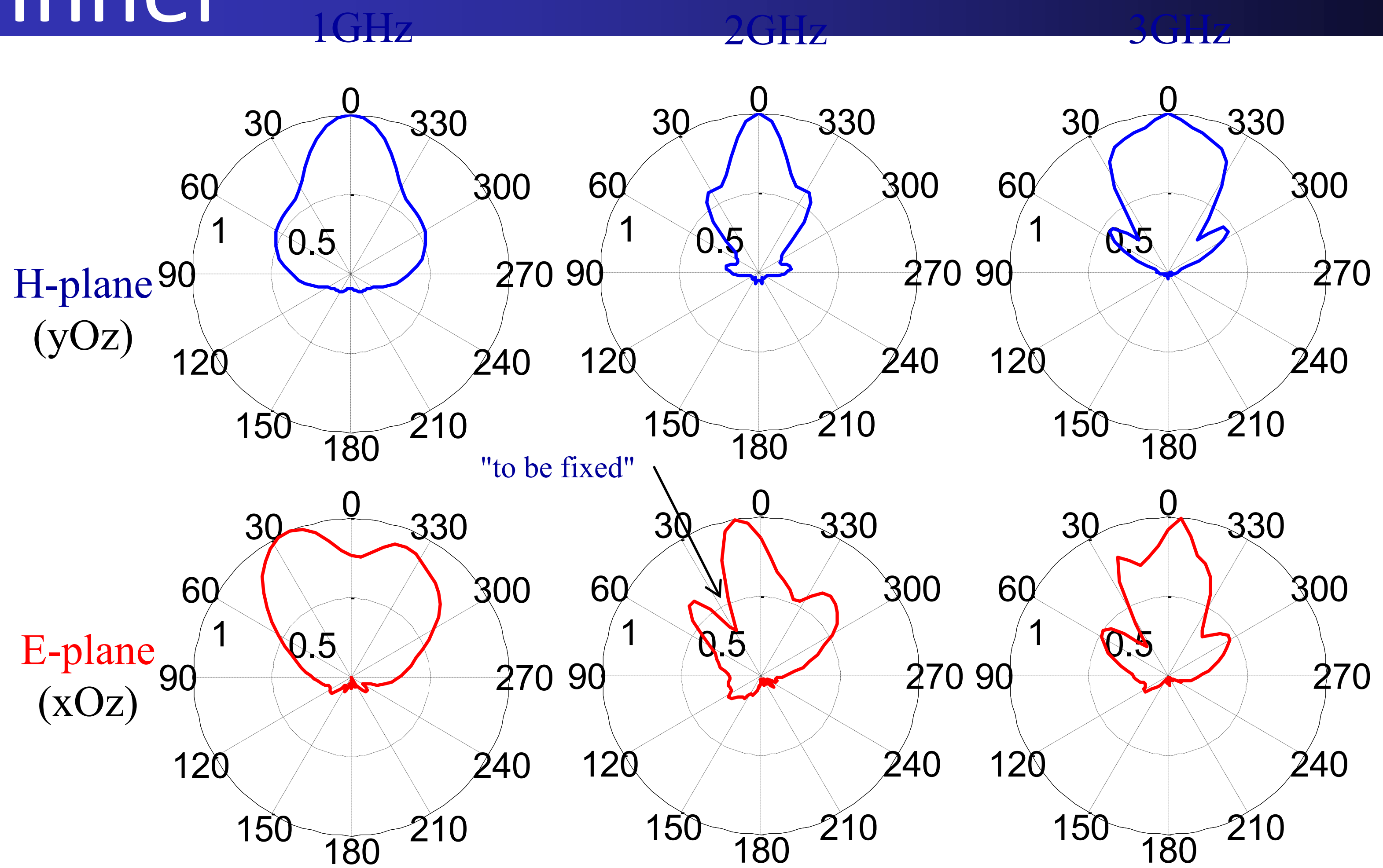


Dense Hexagonal Array

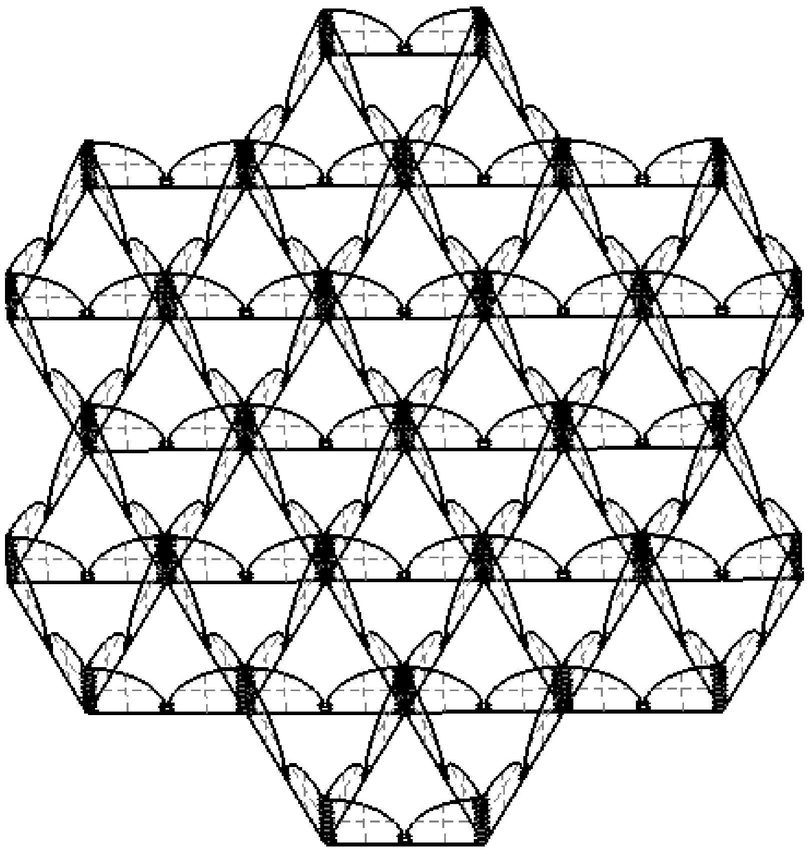
Outer


1GHz
2GHz
3GHz
E-plane
(xOz)
H-plane
(yOz)
0
30
330
60
300
90
270
120
240
150
210
180
0.5
1

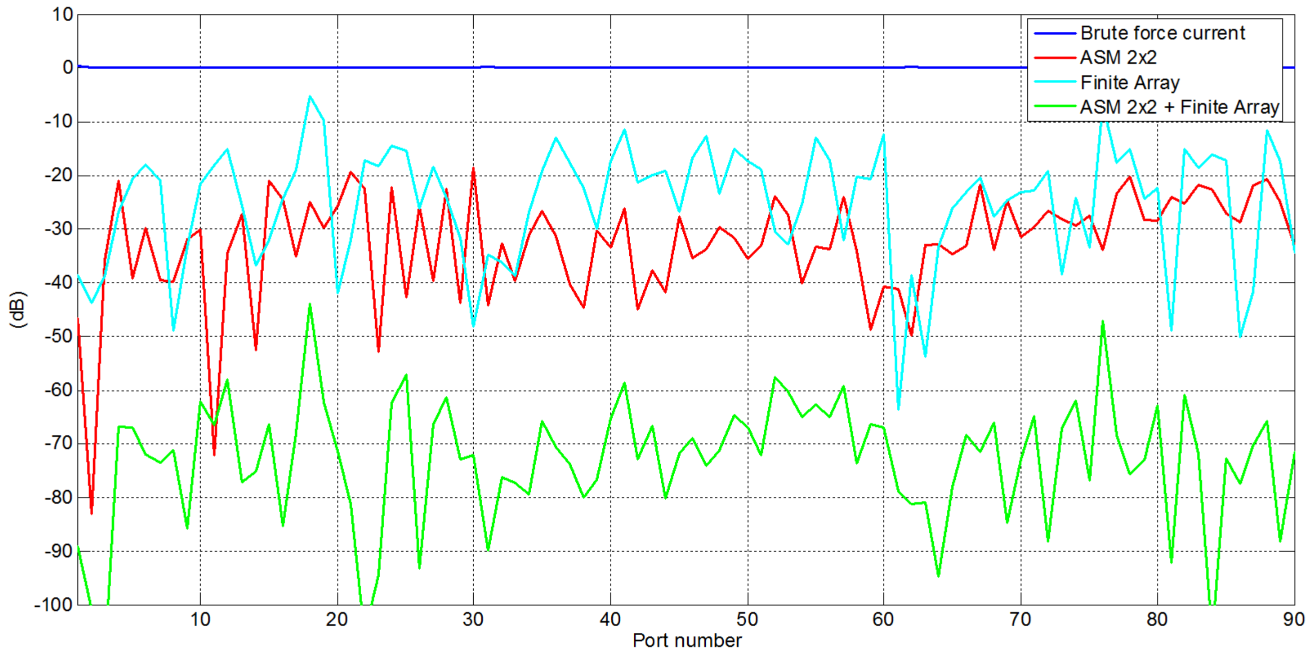
Inner


1GHz
2GHz
3GHz
H-plane
(yOz)
E-plane
(xOz)
"to be fixed"
0
30
330
60
300
90
270
120
240
150
210
180
1
0.5

Large Hexagonal Array



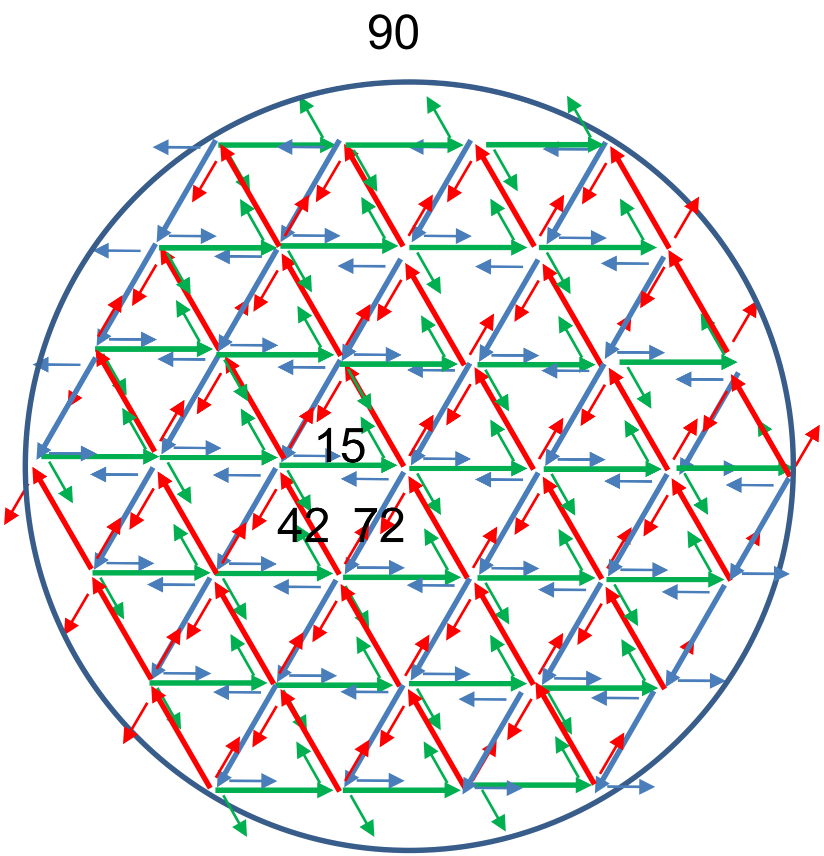
ASM-MBF for Large Hexagonal Array

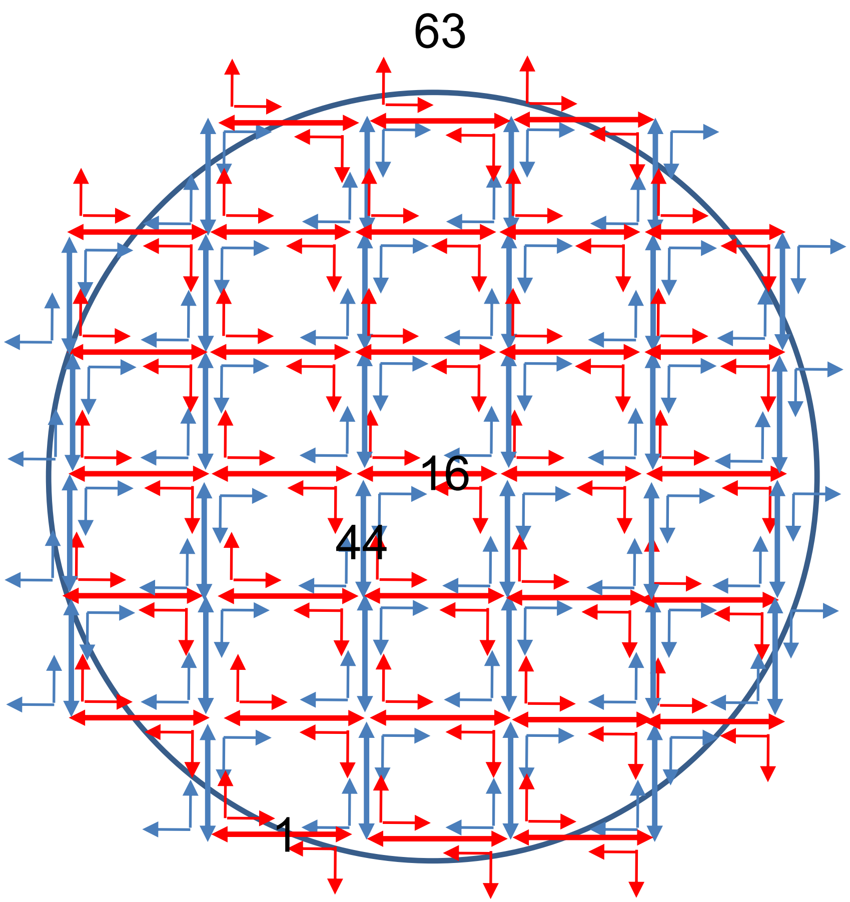


2x2 ASM combined with 12 elements finite array

Current error is below 40dB

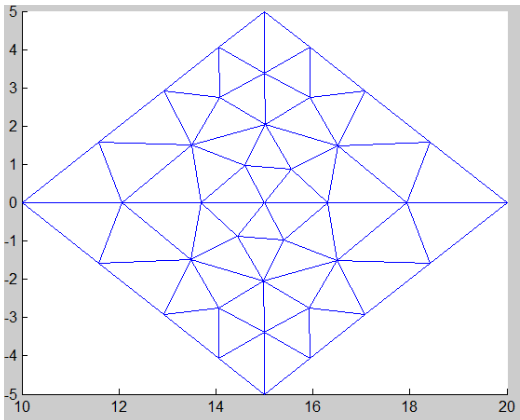
Hexagonal Vs. Rectangular Array



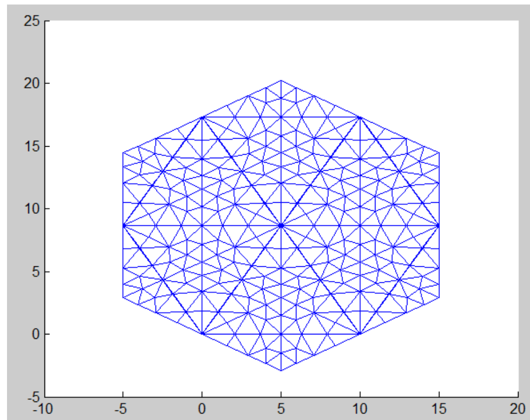


Large Hexagonal Array

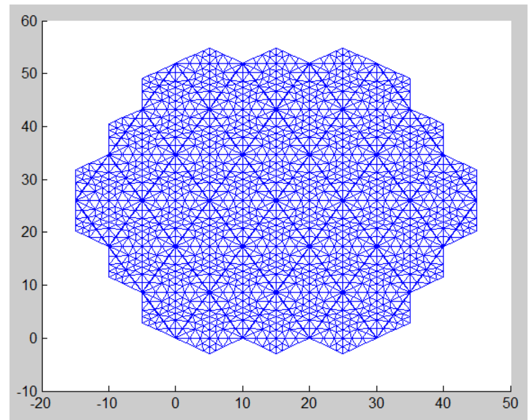
Single antenna

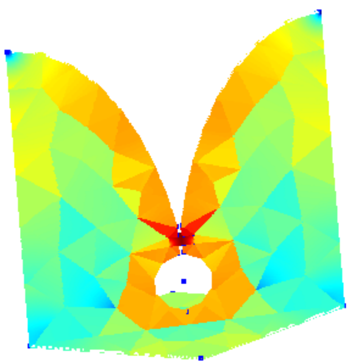


12 element array

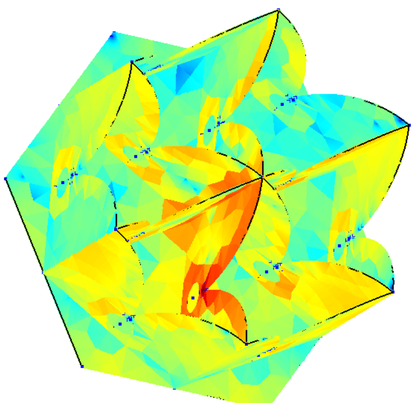


90 elements Hexagonal Array





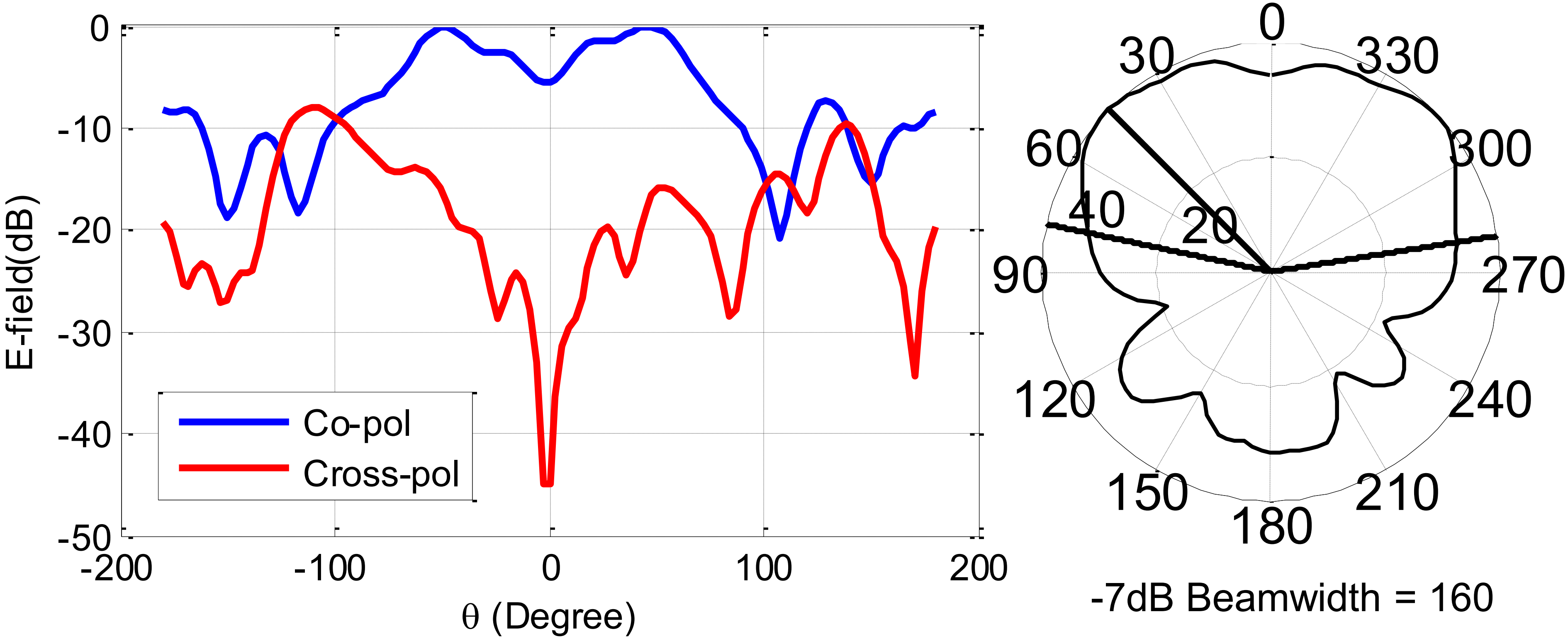
Infinite simulation



Finite simulation

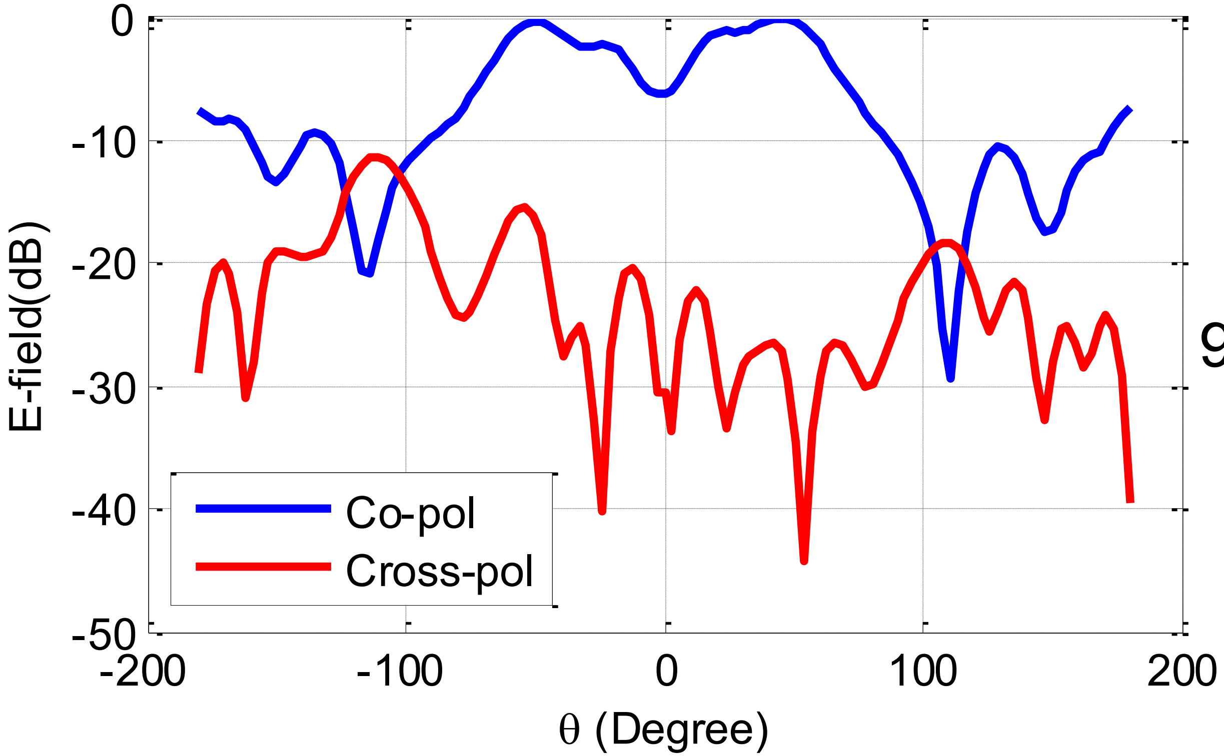
ASM-MBF

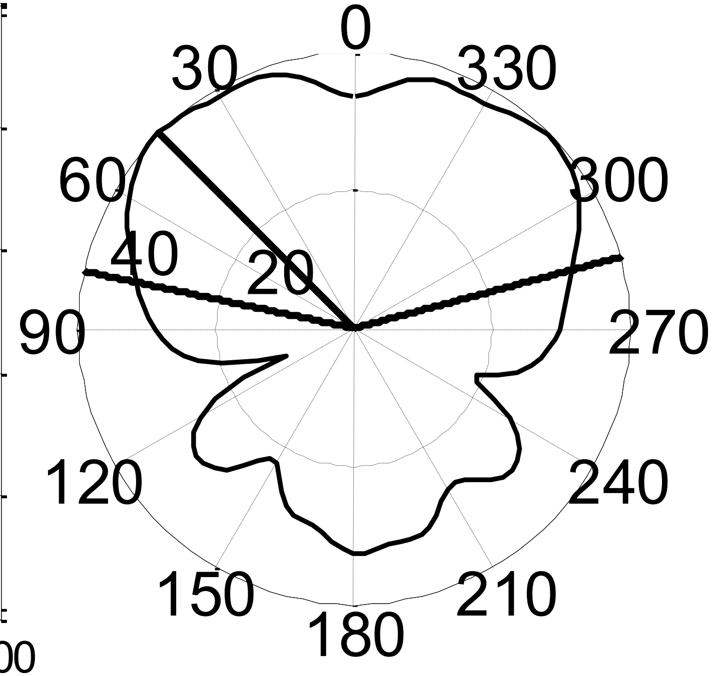
Center element antenna 15 Pol1



-7dB Beamwidth = 160

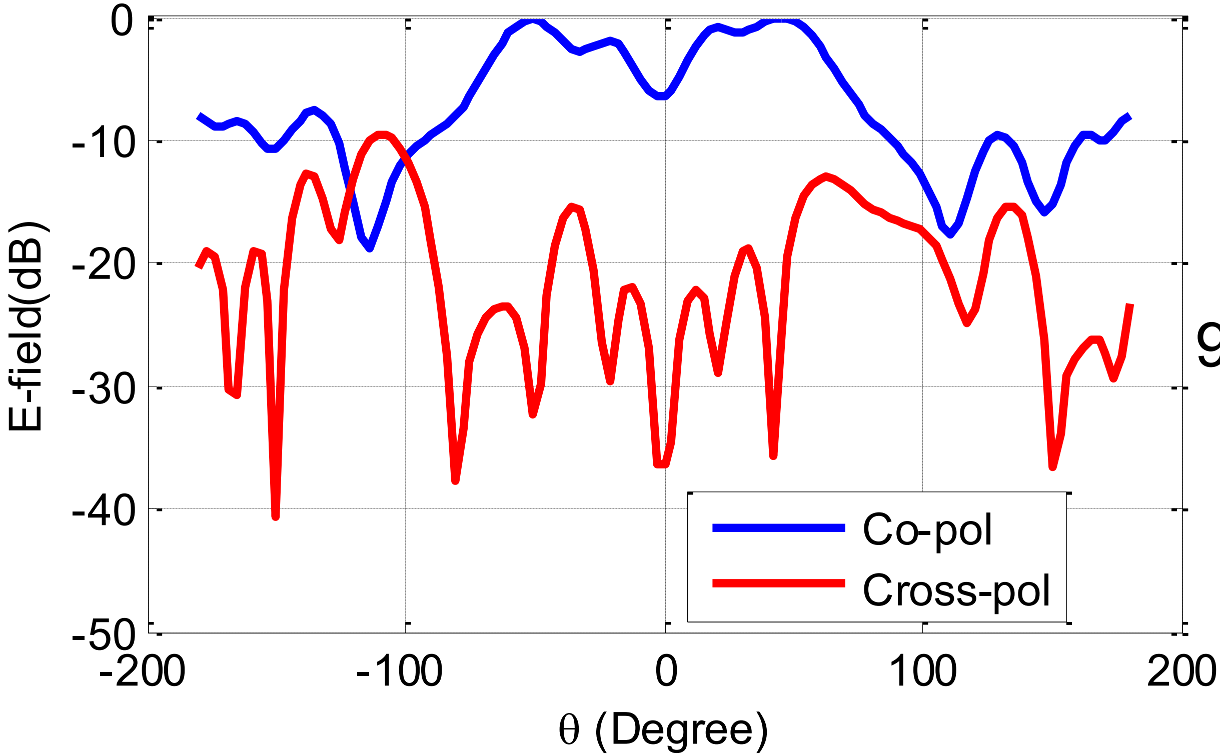
Center element antenna 42 Pol2

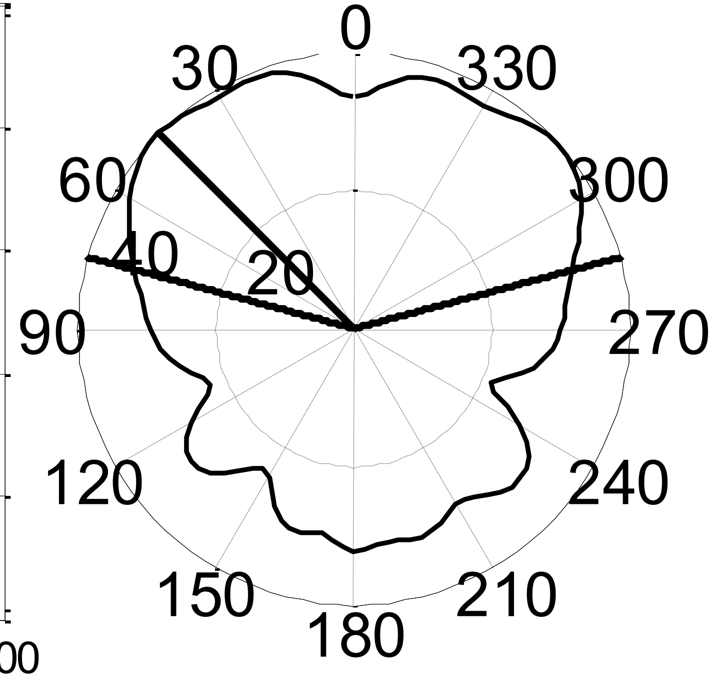




-7dB Beamwidth=153

Center element antenna 72 Pol3

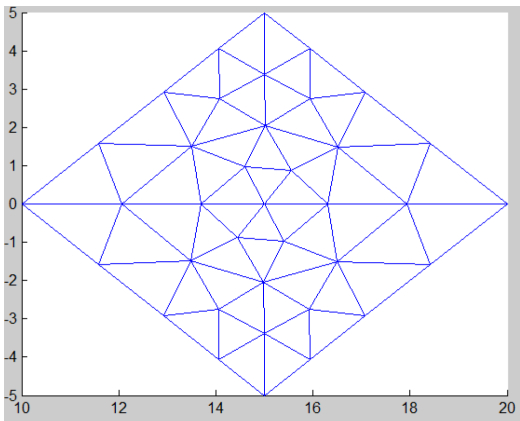




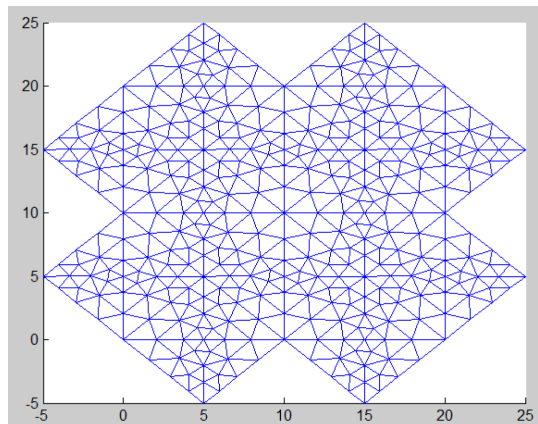
-7dB Beamwidth=150

Large Rectangular Array

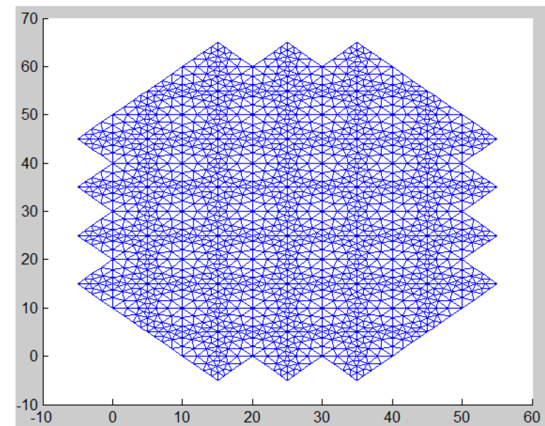
Single antenna

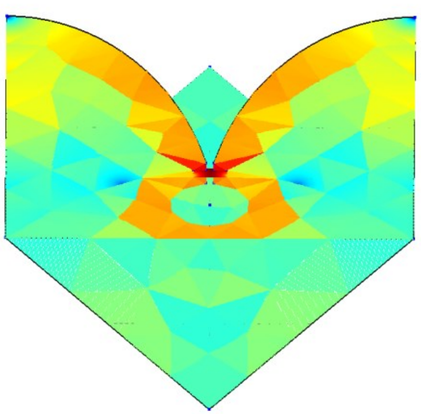


12 elements array

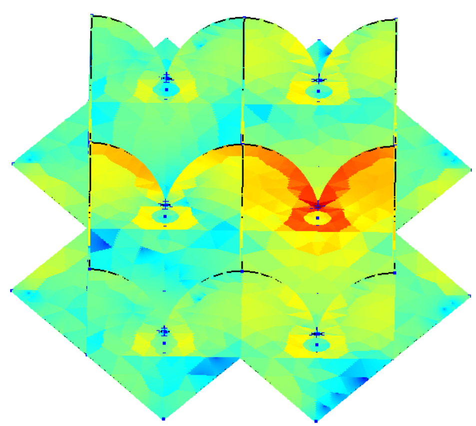


63 elements rectangular array





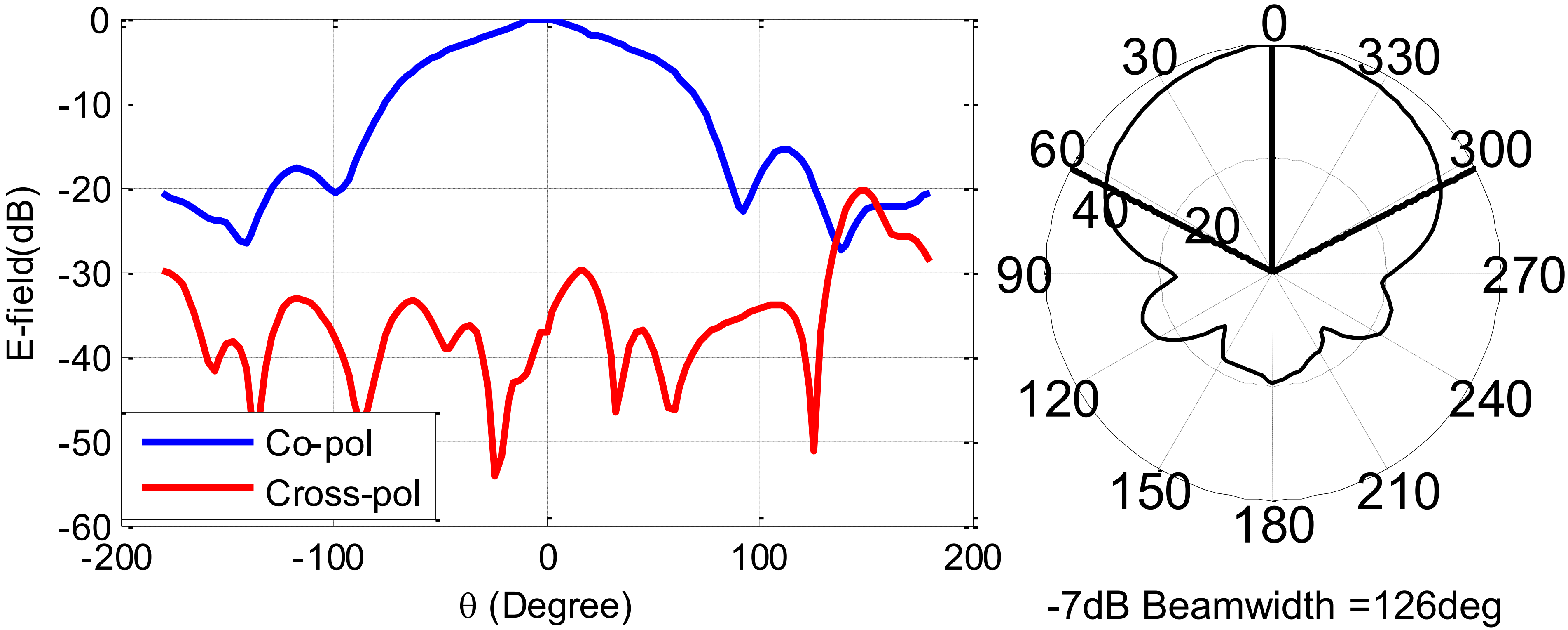
Infinite antenna



Finite antenna

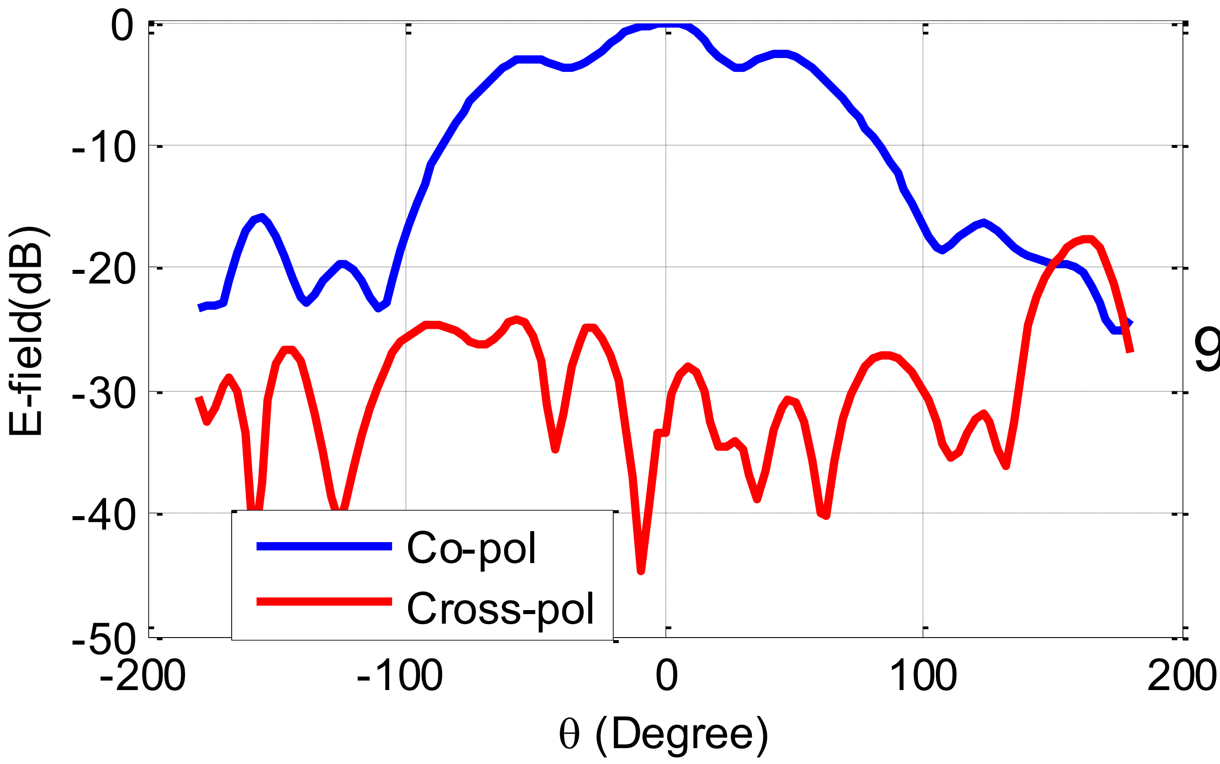
ASM-MBF

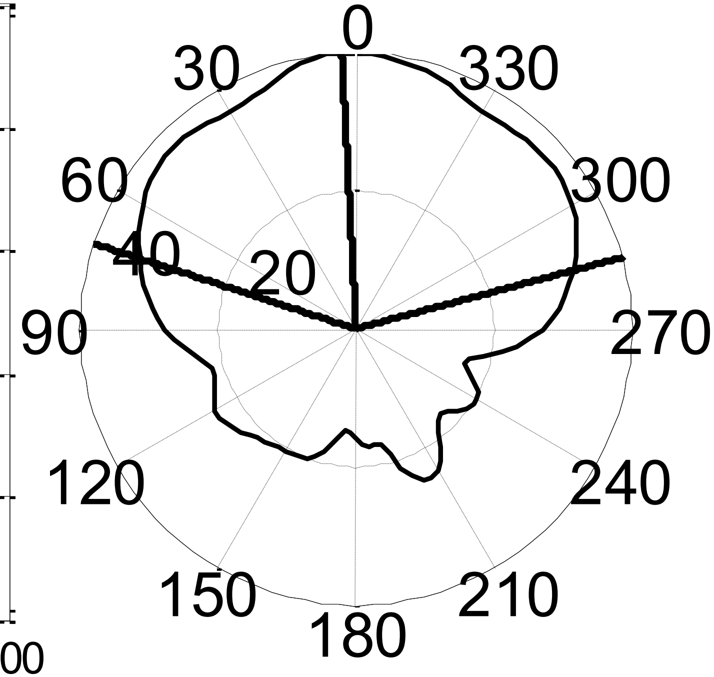
Center element 16 Pol1



-7dB Beamwidth =126deg

Center element 44 Pol2





-7dB Beamwidth=147deg

Conclusion

- We presented ASM-MBF for the simulation of Large Focal Plane Array
- Link between ASM and Block circulant matrix solution.
- Novel design of 3D Vivaldi antenna
  - Light weight of the antenna.
  - Precise fabrication technology.
  - Suitable to host LNA.
- Study of different circular array structures
  - Dense and Concentric Hexagonal arrays.
  - Easier Calibration: Radiation pattern can be compensated.