System-level Simulation of an Aperture Array Beamformer

Kaushal D. Buch[1], Sreekar Sai Ranganathan[2], and Bela S. Dixit[1]

[1]Giant Metrewave Radio Telescope (GMRT), NCRA-TIFR, Pune, India

[2]Indian Institute of Technology Madras, India

kdbuch@gmrt.ncra.tifr.res.in

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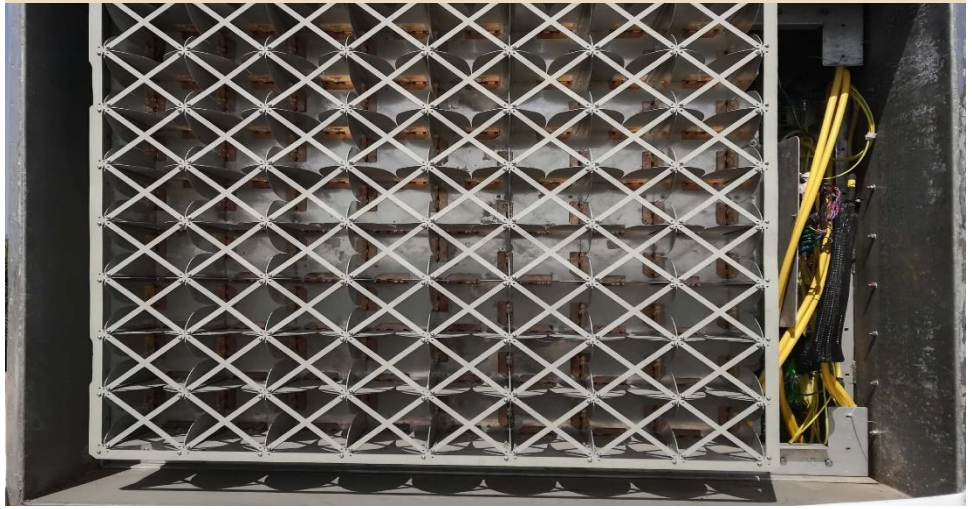
Aperture Arrays

- Beamforming & spatial filtering using array of antenna elements along with associated RF & digital signal processing systems
- Applications: Communication, array signal processing, radar signal processing, radio astronomy
- Challenges: Calibration in presence of Mutual Coupling, Complex signal processing

Vivaldi Array Element

144 Element Vivaldi Antenna Array



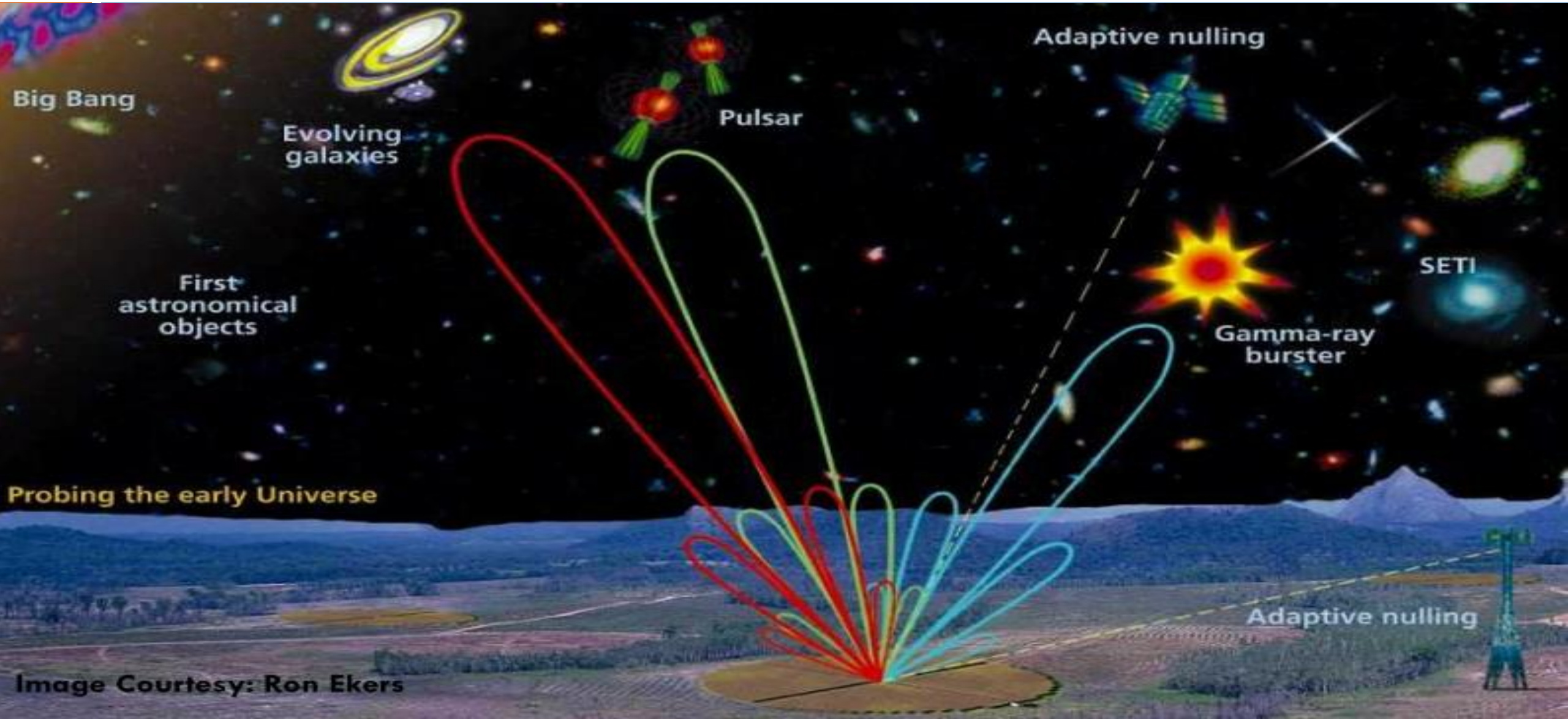
Aperture Arrays in Radio Astronomy

- Radio telescopes detect radio emissions from the stellar objects
- Aperture arrays provide Wider Field-of-View (FoV), Increased Survey Speed, and Better Sensitivity

Image Courtesy: ASTRON

Image Courtesy: ASKAP

Aperture Arrays in Radio Astronomy



Expanded GMRT: Aperture Array Development

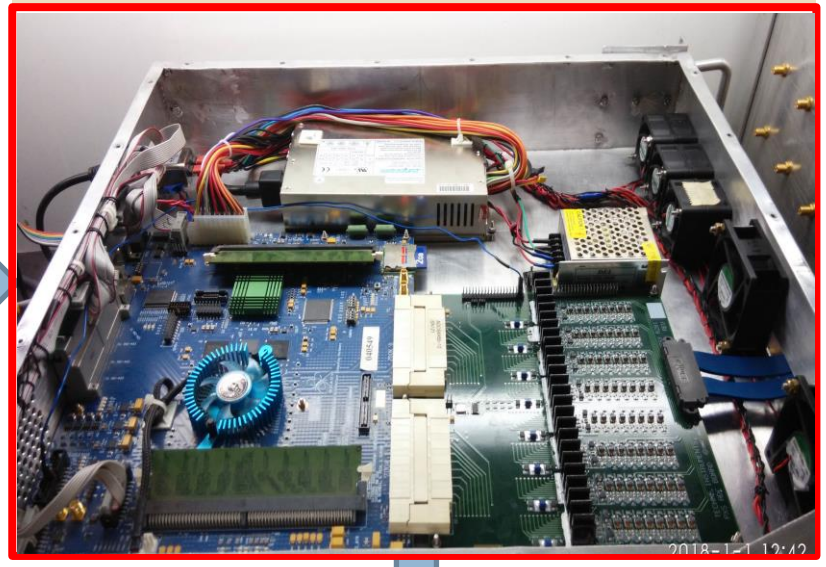
144-element Vivaldi Array

Optical Transmitter Modules

Optical Fiber

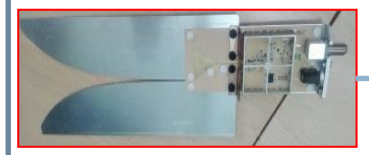
Optical Receiver and Analog Front-End

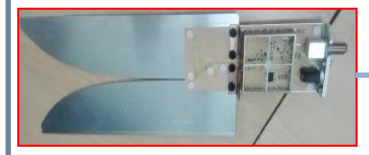
32-element, 5-beam, FPGA-based digital beamformer

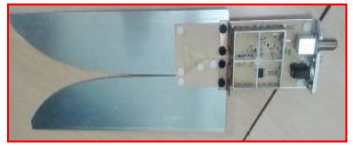


Acquisition and Control Computer

Aperture Array Beamformer Simulation







Antenna & Phased Array Toolbox *(Element and Embedded Pattern)*

Amplifier

Amplifier

RF Toolbox *(Gain & Phase Variations, Coupling)*

Digitization

Digitization

FFT

FFT

Signal Processing Toolbox
Simulink
MATLAB

(Hardware Imperfections, Finite Arithmetic)

A_1 φ_1 Weight Multiplication

A_1 φ_1 Weight Multiplication

A_2 φ_2 Weight Multiplication

A_2 φ_2 Weight Multiplication

Correlator

A_1
A_2
φ_1
φ_2

Beam-1

Beam-2

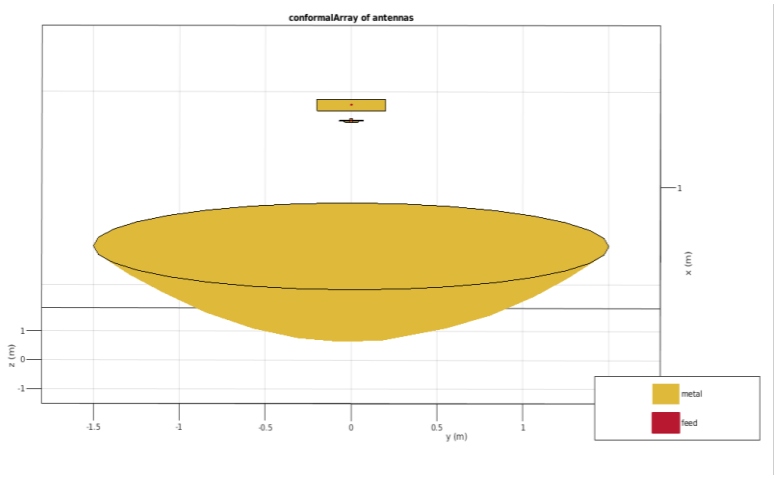
Simplified block diagram of a 2-element 2-beam beamformer

Free-space Test Range

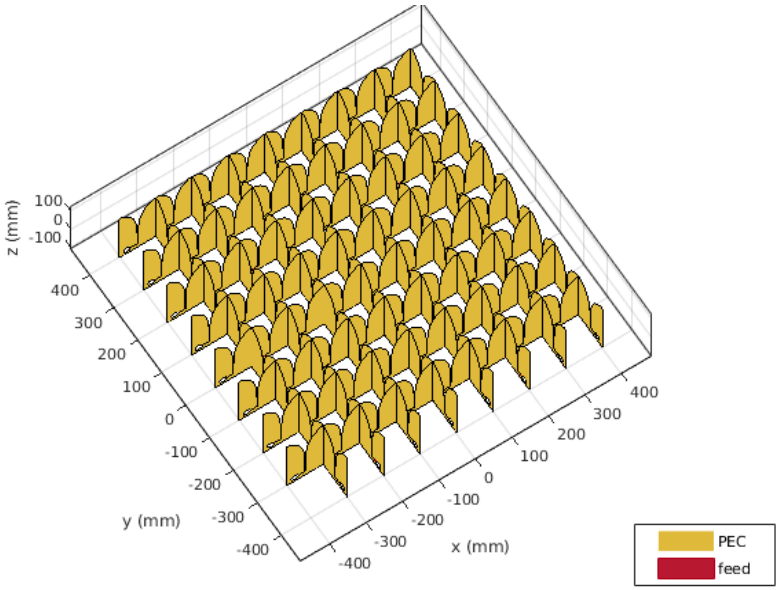
Image Courtesy: NCRA Archives

Major Components of Simulation Model

Transmit Antenna and Propagation Channel → Receive Antenna Array → RF Systems and Digital Beamformer

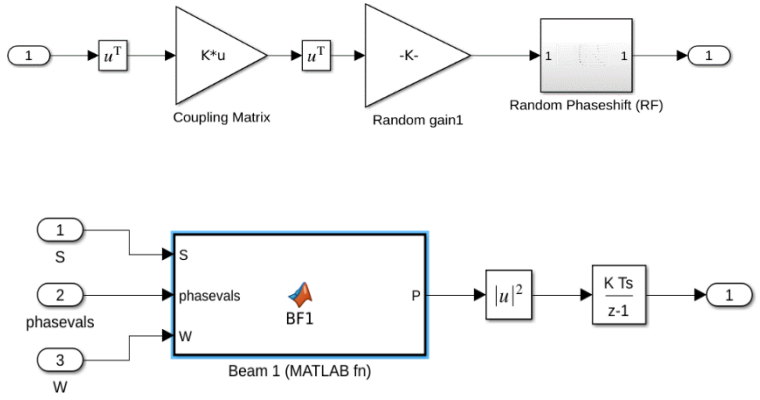



```
refl = reflectorParabolic('Exciter',rect_ant,...
    'FocalLength',f_len,...
    'Radius',parab_rad);
figure('Name','square antenna with parabolic reflector');
show(refl);
```




```
load('vivaldiOffset.mat','m');

a = eggCrate('Element',m,...
    'Size',[8 8],...
    'Gap',[0 0]);
show(a);
```



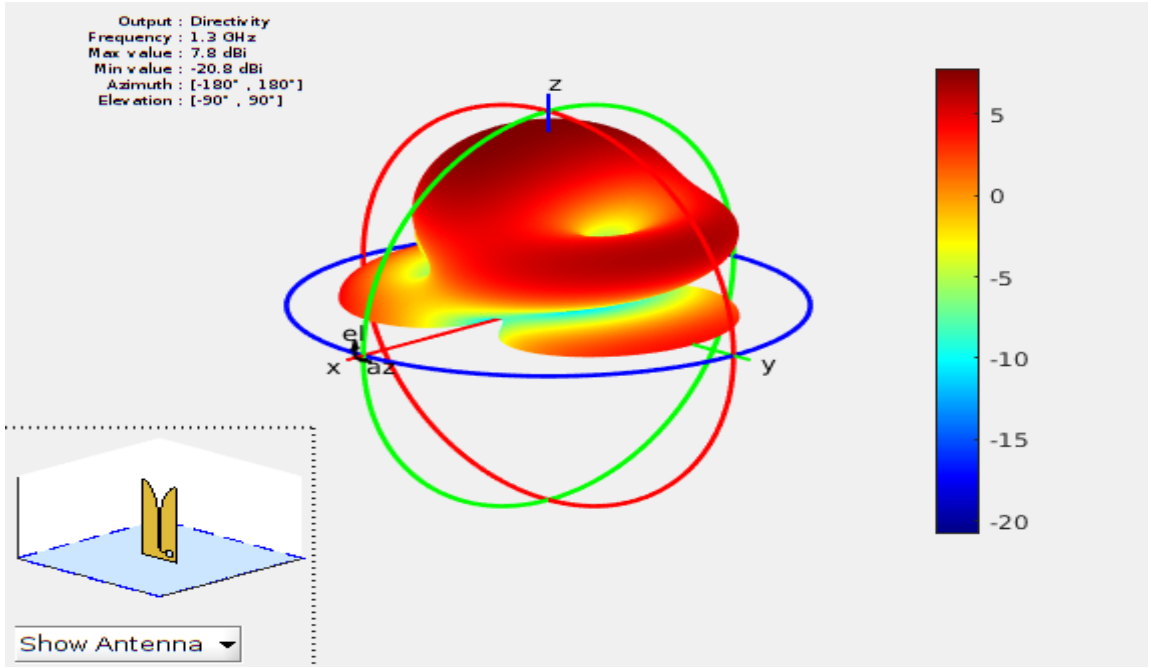
- Gain and phase modeling and randomization
- Beamformer and Correlator

Modeling Vivaldi Antenna Array

```
m=vivaldiOffsetCavity('TaperLength', h1,...
    'ApertureWidth', wh,...
    'OpeningRate', R,...
    'TaperedSlotWidth',ws,... %dunno why added 5e-3
    'TaperOffset',0,...
    'CrossTaperLength',0.1e-3,... %no crossing needed
    'SlotLineWidth', ws,...
    'CavityToTaperSpacing', ls1 + rs1,... % check ifs correct value
    'CavityShape','Circular',...
    'CavityOffset',[rs2 dmc],...
    'GroundPlaneLength', Lground,...
    'GroundPlaneWidth', Wground,...
    'FeedOffset', rs1 + ls2 - dmc,... % correct
    'Conductor',metal('PEC'),... % an also use specific metals
    'CavityDiameter', cavity_dia);

save('vivaldiOffset.mat','m');

show(m);
```



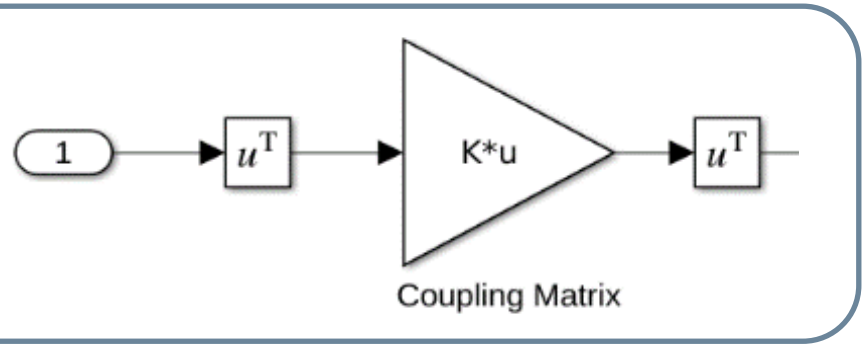
The geometry of the array can be selected through a mask file e.g. C3-F3, C4-F4, C5-F5, and C6-F6

	A	B	C	D	E	F	G	H
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0	1	1	1	1	0	0
4	0	0	1	1	1	1	0	0
5	0	0	1	1	1	1	0	0
6	0	0	1	1	1	1	0	0
7	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0

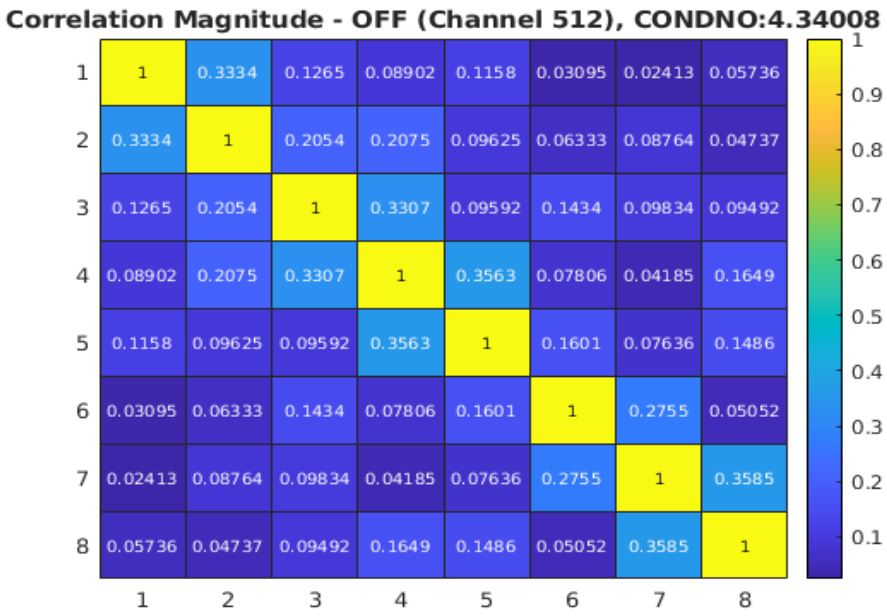
- Individual Vivaldi element pattern implemented using Antenna Toolbox
- Mutual coupling added in the receiver chain

Adding Mutual coupling

- Coupling matrix is based on impedance parameters of the N-element array.
- Data from the phased array is pre-multiplied by the coupling matrix.



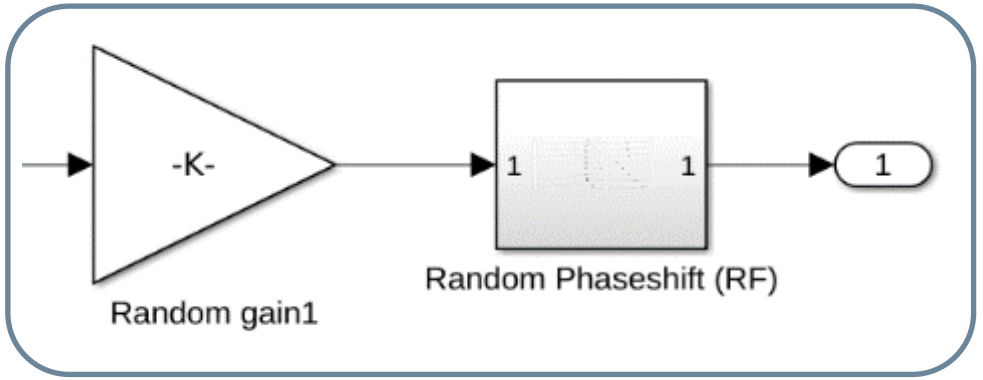
Cross-correlation



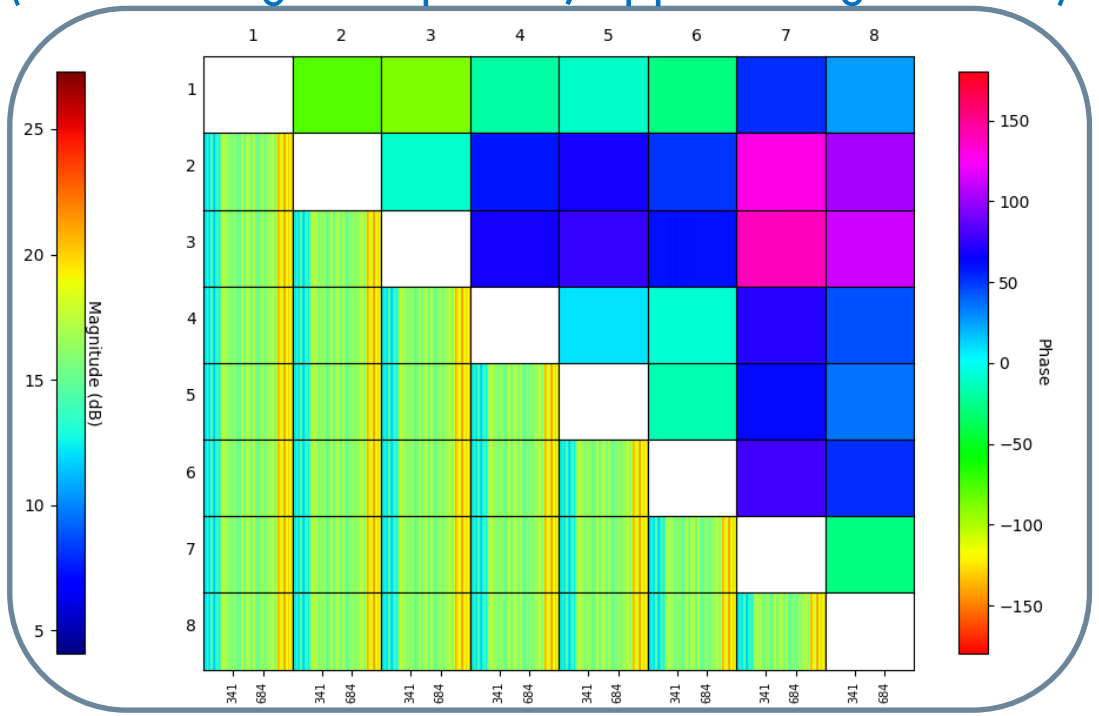
Cross-correlation between the elements resulting from mutual coupling (8x1 linear array). Diagonal represents auto-correlation

Pratschner, Stefan, et al. "A mutual coupling model for massive MIMO applied to the 3GPP 3D channel model." 25th European Signal Processing Conference (EUSIPCO). IEEE, 2017.

Adding Gain & Phase Variations

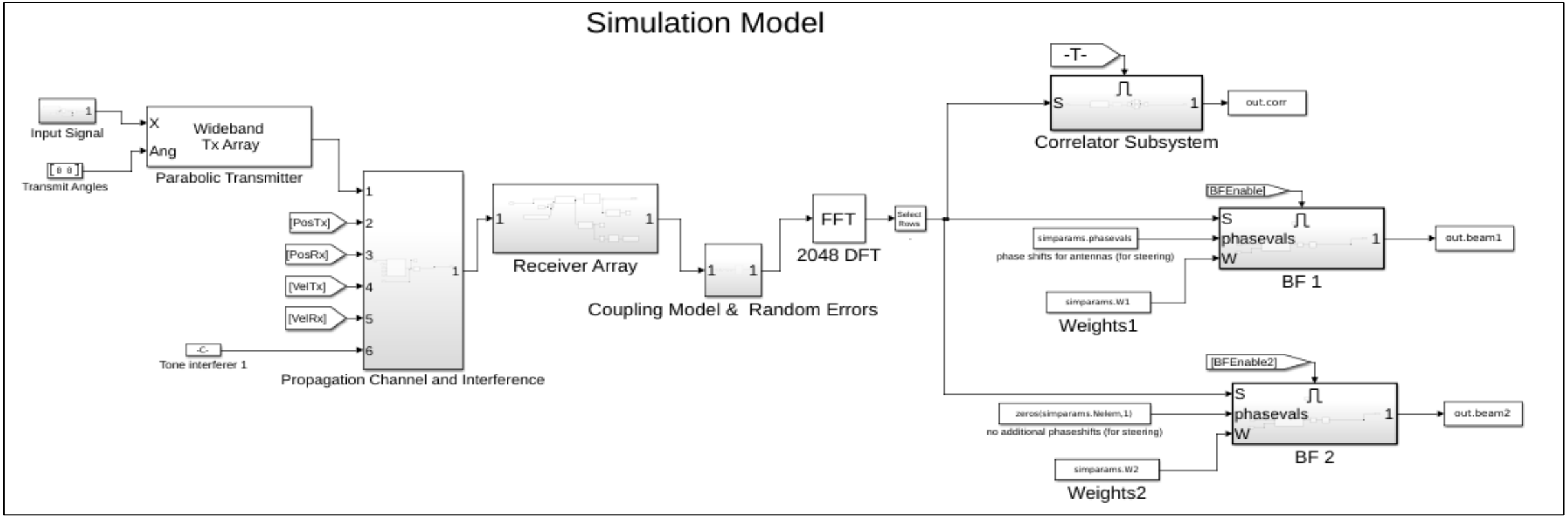


8-element cross correlation matrix
(Lower triangle: Amplitude, Upper triangle: Phase)



- Randomized gain is implemented through a multiplying factor
- Randomized phase is implemented via RF phase shifters (RF Toolbox)

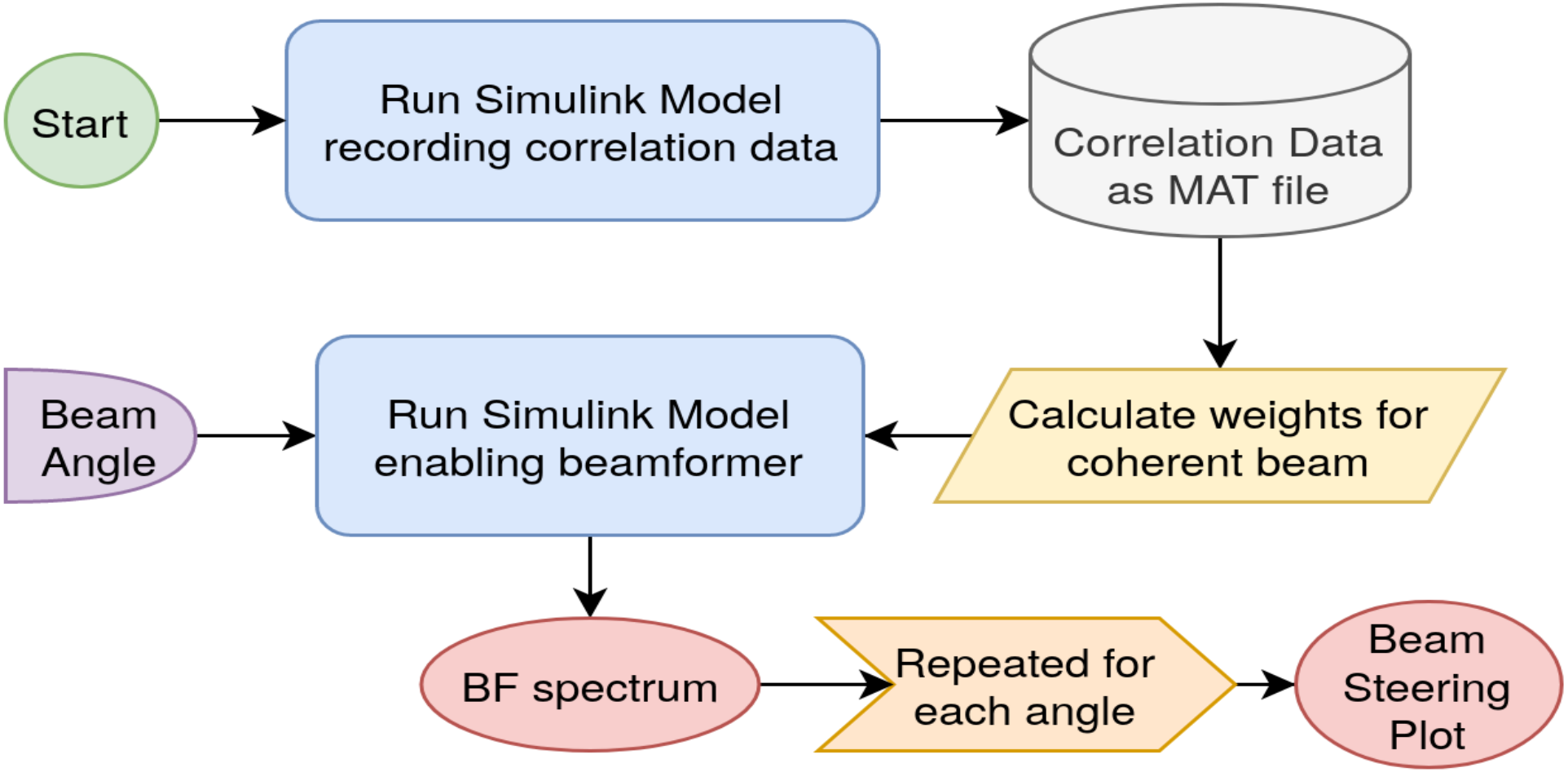
System Simulation Model



- ❑ Transmit tone or broadband noise
- ❑ Multiple transmitters
- ❑ Variable array elements & array config.

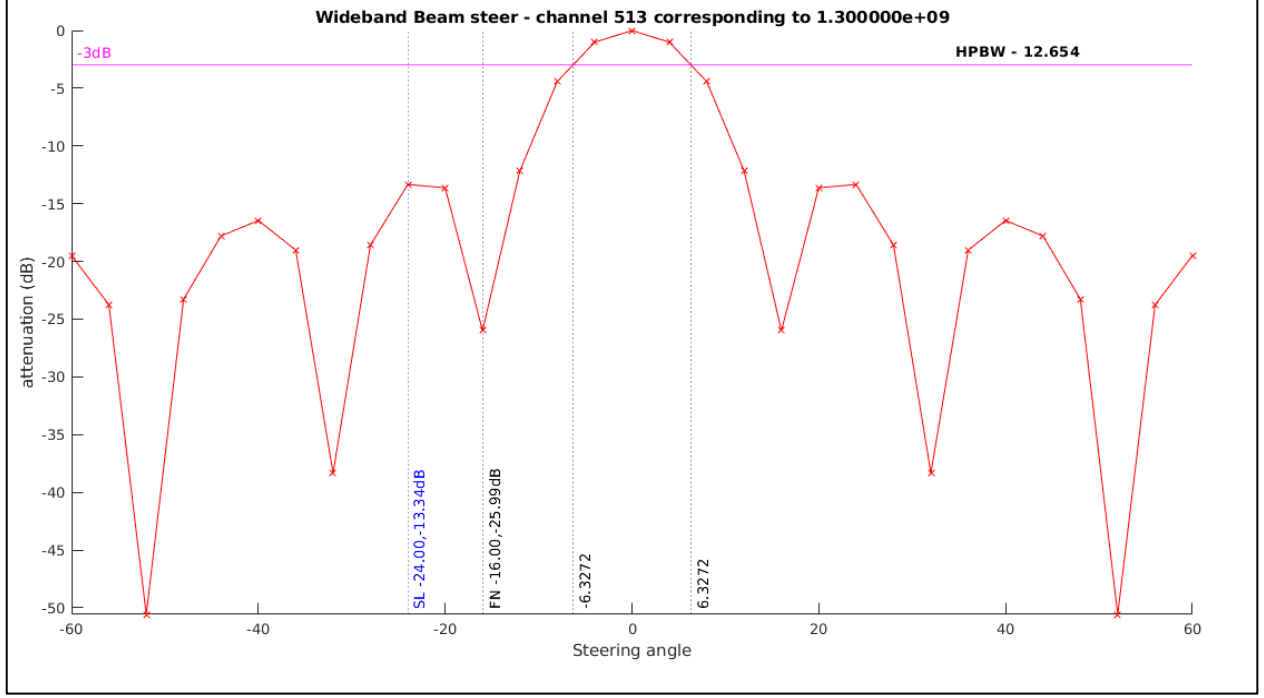
- ❑ Randomized receiver gain and phase
- ❑ Programmable mutual coupling
- ❑ Multi-beam beamformer and correlator

End-to-End System-level Simulation

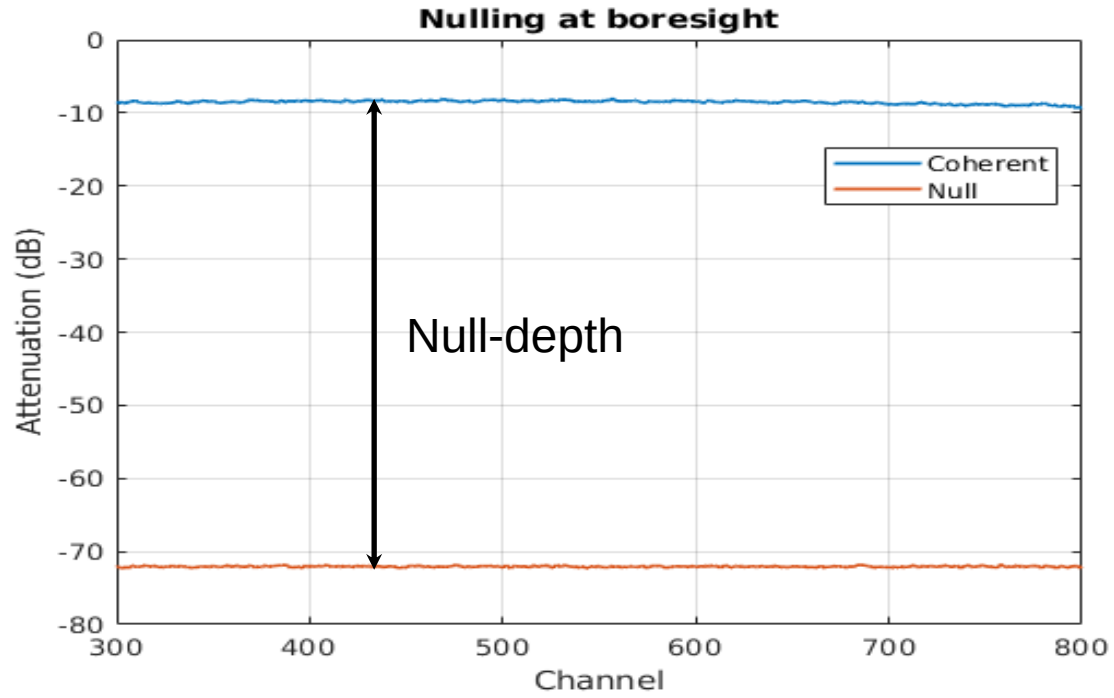


Beam-steering & Multi-beamforming

Beam-steering from -60 to 60 degrees
Single frequency channel
Broadband noise radiation (32 MHz)



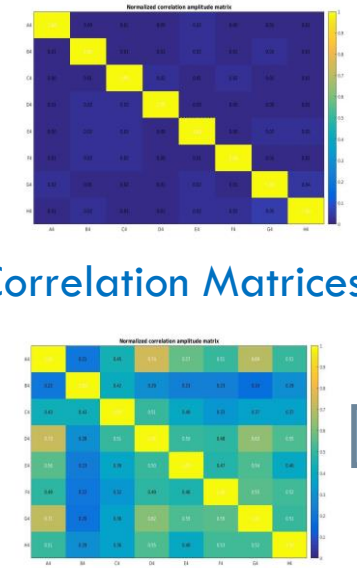
Phased-array beam at boresight (B-1)
Null-steering at boresight (B-2)
32 MHz bandwidth; C.F: 1.3 GHz



Optimal Beamforming

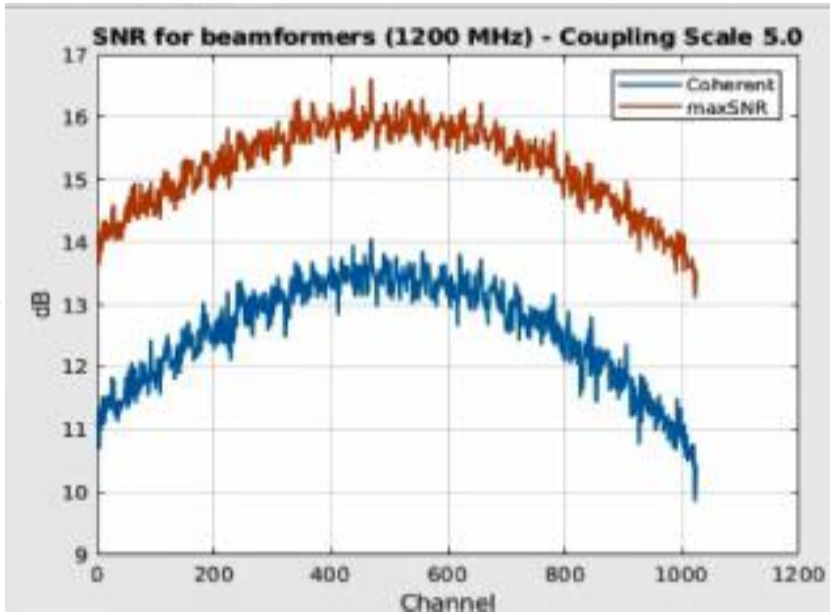
Radiation OFF

Radiation ON



Correlation Matrices

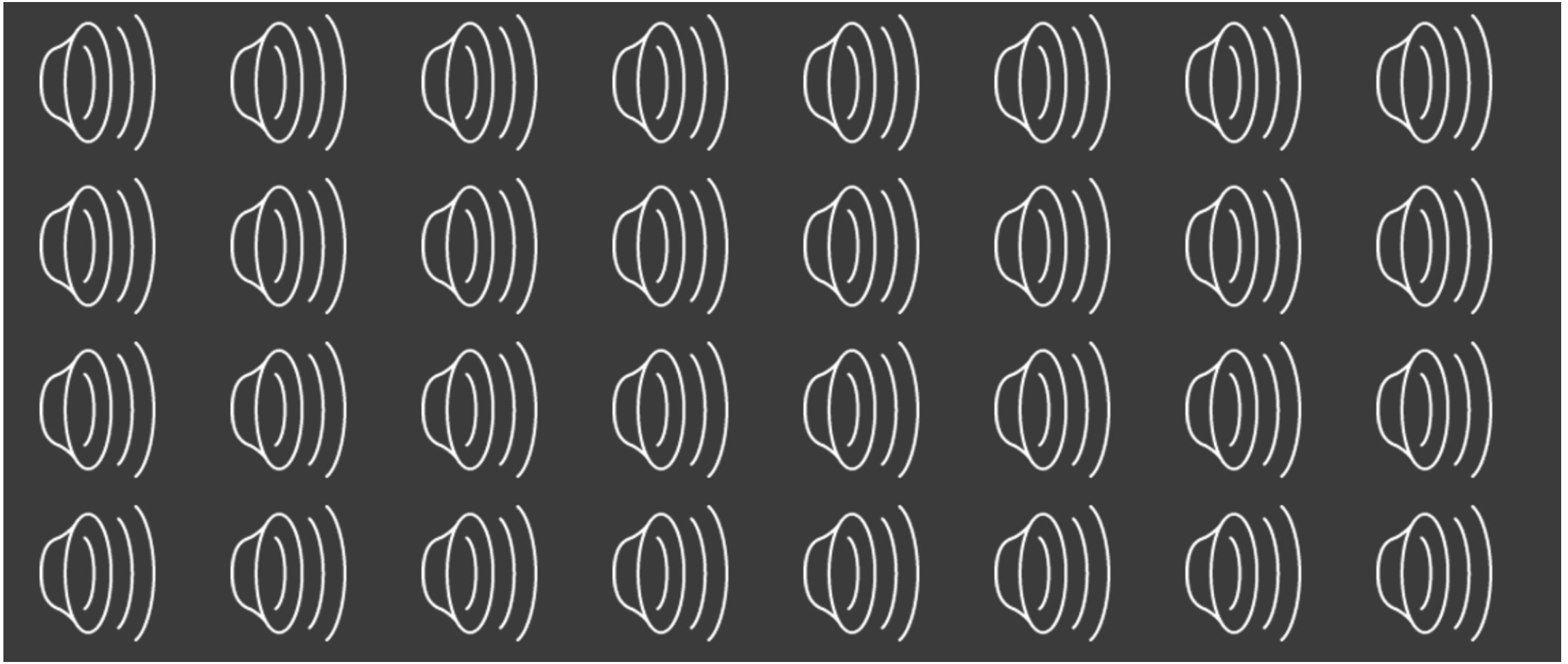
Beamformer weight optimization (Max-SNR method)



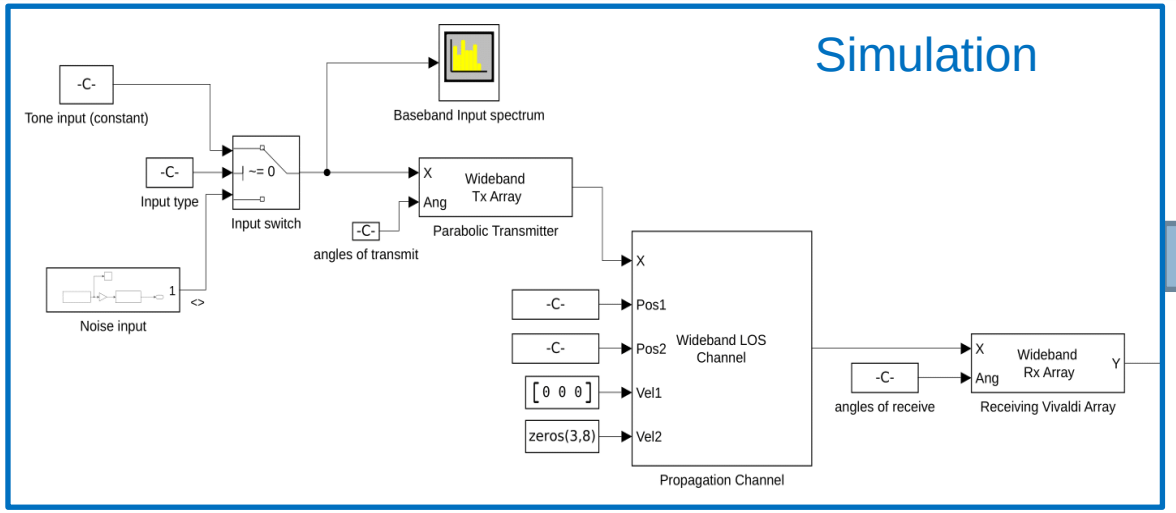
ACM values from correlator → Optimum Weight Calculation → Applying Weights to the beamformer → SNR Comparison with Coherent Beam

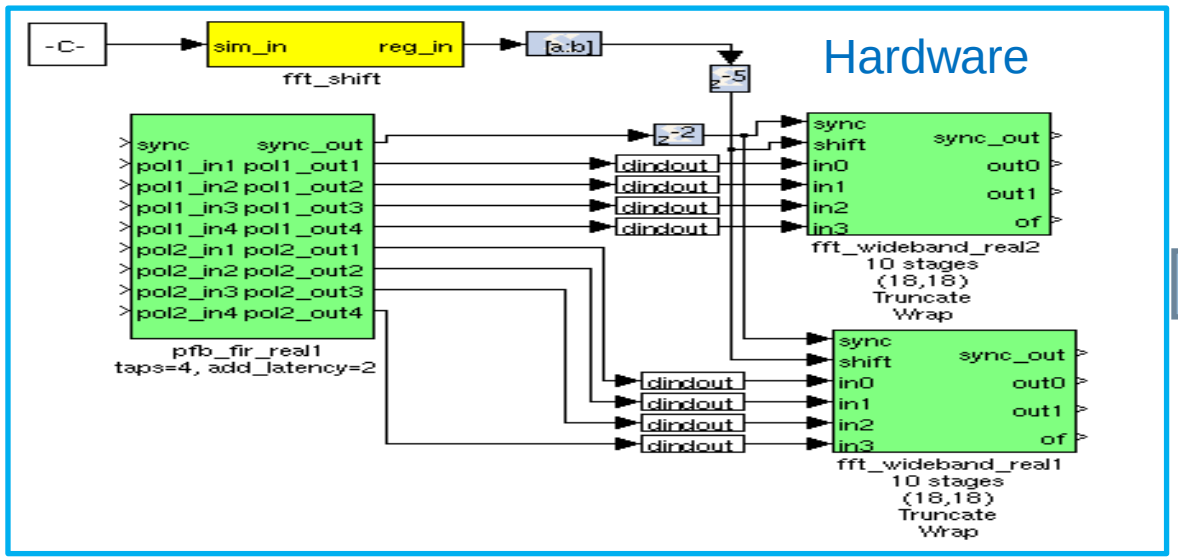
M. V. Ivashina et al., "An Optimal Beamforming Strategy for Wide-Field Surveys With Phased Array-Fed Reflector Antennas", IEEE Transaction on Antennas and Propagation, July 2011

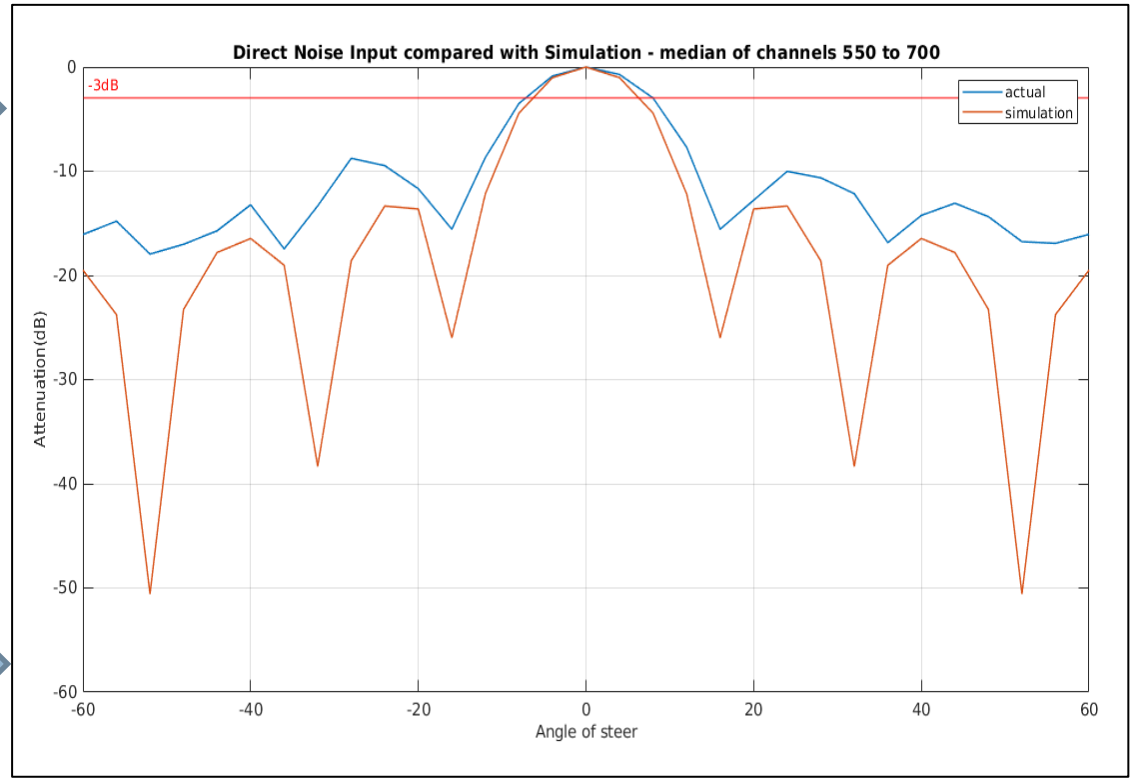
maxSNR Algorithm: Simulation Video



Beam-steering Comparison with Experimental Test







Close match with the main lobe. Side-lobe mismatch due to reflections in the test range

Summary

- Aperture array beamforming simulator developed using toolboxes of MATLAB & Simulink
- Beam-steering and beamforming tested for different RF and antenna configurations.
- Simulation results provided insight on implementation trade-offs for calibration & beamforming prior to the actual experiment.
- Future Work: HDL code generation and testing