Experimental Focal Plane Array Beamforming for the Expanded GMRT

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Phased Array Feed and Advanced Receiver (PAFAR) 2022 Workshop

CSIRO, Sydney

15th November 2022

Giant Metrewave Radio Telescope (GMRT)

- One of the most sensitive telescopes for studying astrophysical phenomena at low radio frequencies (50 - 1450 MHz)
- Located in India: 80 km north of Pune, 160 km east of Mumbai
- Array telescope with 30 antennas of 45 m diameter
- 14 antennas in 1 sq. km. region, others spread in a Y-shaped array
- Upgraded GMRT (uGMRT) – near seamless observing from 120 to 1450 MHz, 400 MHz BW (max.)

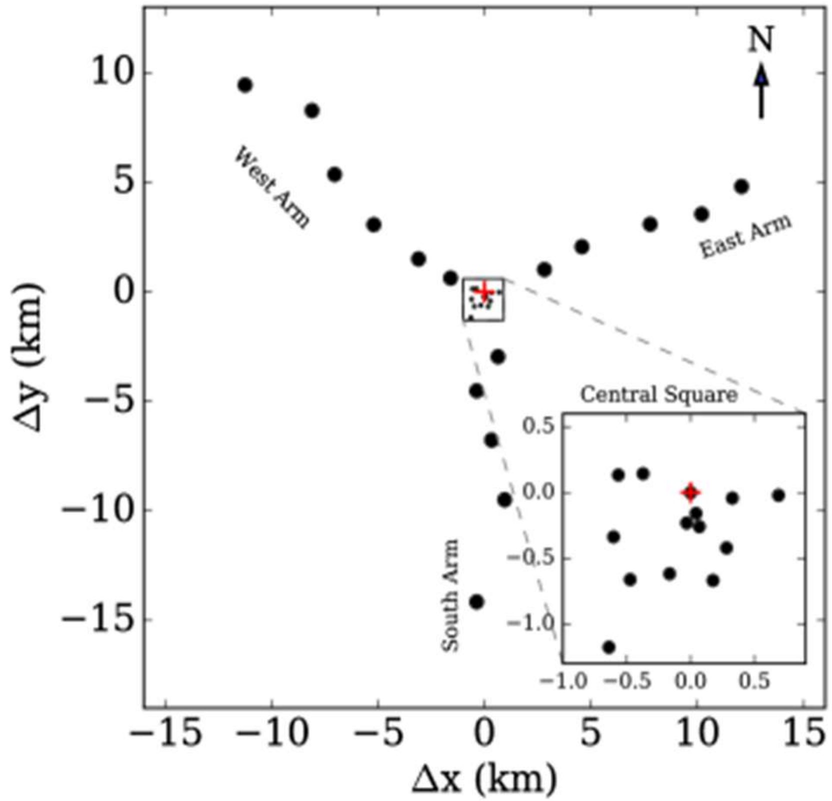


Image Courtesy: N. Patra

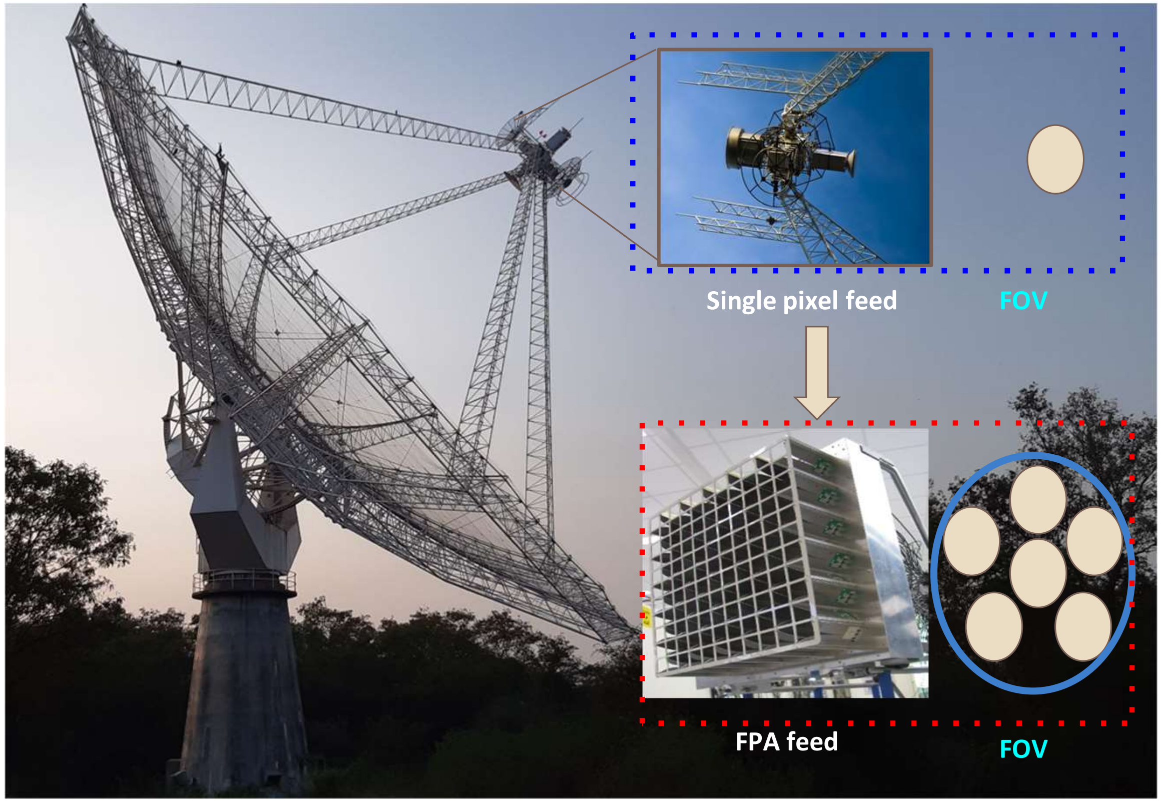
Features of the Expanded GMRT(eGMRT)

Shorter Baseline Antennas	• Better imaging of large scale structure • Improving overall sensitivity
Longer Baseline Antennas	• Improving angular resolution
Focal Plane Array Feed	• Up to 30 independent beams • Improved FOV and speed for sky surveys and transient detections.

Reference: Patra et al., "The Expanded GMRT", MNRAS, 483, 2019

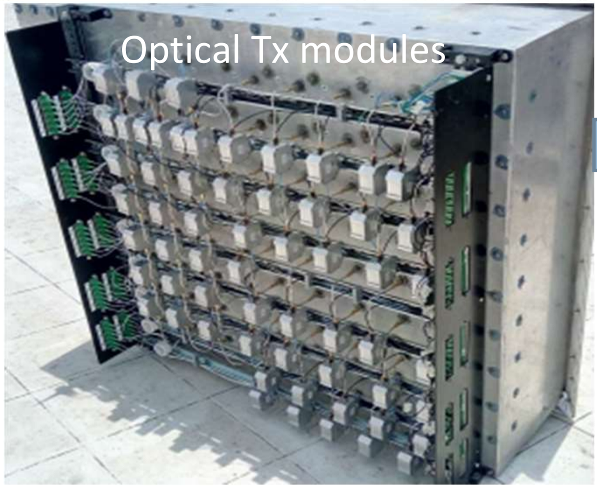
Options being explored for eGMRT Beamformer

- Dual Polarized Array 550-850 MHz
- 30 Independent Beams
- 300 MHz Bandwidth & 16384 Spectral Channels
- Optical fibre based signal transport
- Algorithms for calibration & adaptive beamforming



Prototype beamformer: L-band, 32-element, 32 MHz bandwidth, 1024 spectral channels, 5 independent beams, maxSNR beamforming

Signal Flow for the Prototype eGMRT beamformer



Optical fiber

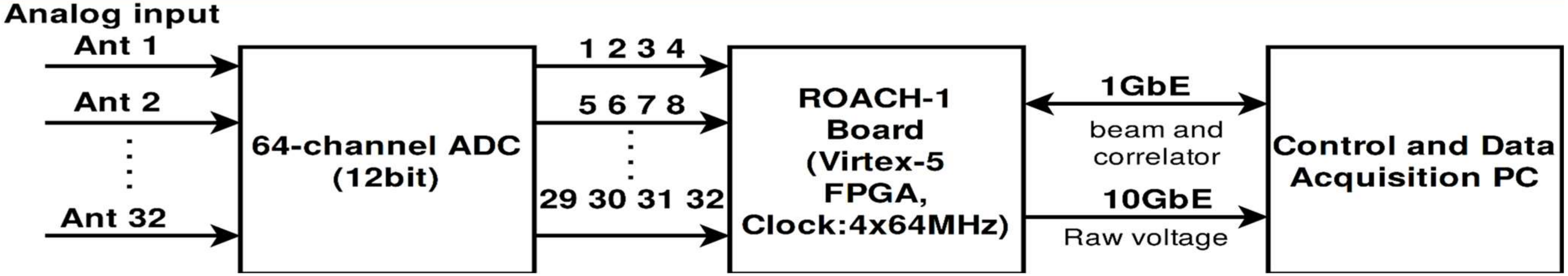
Optical Rx and Analog signal processing modules

144-element Vivaldi FPA from ASTRON

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

Acquisition and Control Computer

Narrowband FPA Beamformer



- ❑ Operates in time-multiplexed fashion
- ❑ Xilinx System Generator-Simulink used for designing
- ❑ Signal processing blocks from the CASPER open source library and toolflow
- ❑ Implemented on ROACH-1 board (Xilinx Virtex-5 FPGA) from CASPER
- ❑ Data acquisition through 1or10 Gigabit Ethernet ports
- ❑ 32-input, 32 MHz bandwidth, 1024 spectral channel, 5-beam design

Optimal reuse of hardware

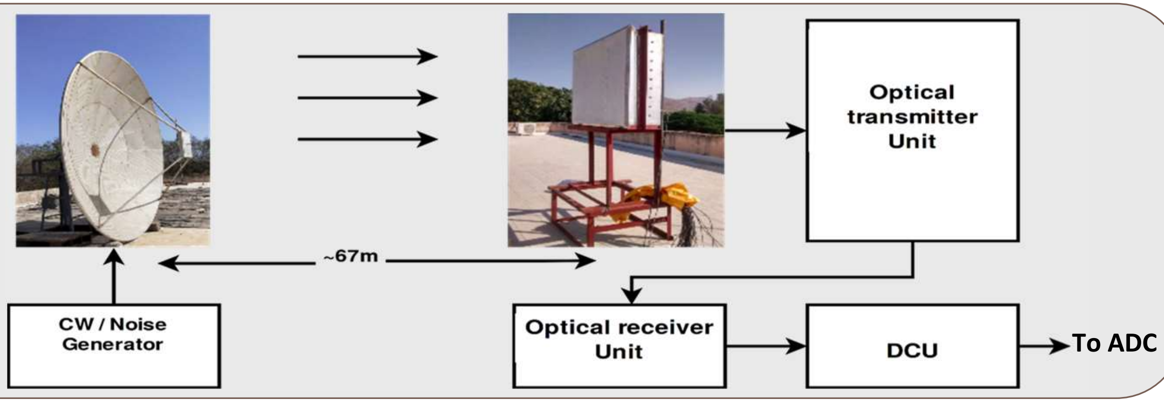
- ❑ Raw voltage acquired from FPA elements (data packetizer design)
- ❑ Offline correlation for amplitude and phase values
- ❑ Offline weight computation
- ❑ Real-time beamforming (beamformer design)

CASPER: https://casper.berkeley.edu/ | ROACH-1 board: https://casper.astro.berkeley.edu/wiki/ROACH

Testing FPA in Aperture Array Mode

Test Range Configuration

- 3m reflector test antenna,
  67 m away from FPA
- L-band cross dipole feed at prime focus
- ~15 degrees beamwidth at 1.3 GHz

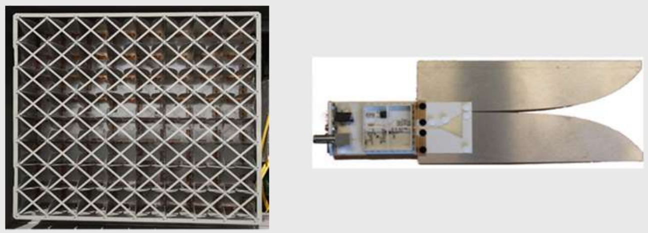


ASTRON L-band FPA used for prototyping beamformer at GMRT

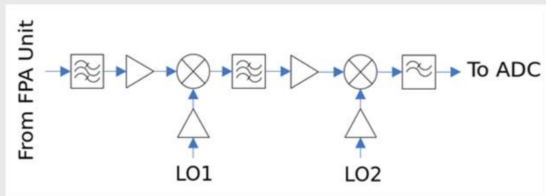
Array Configuration

A8	B8	C8	D8	E8	F8	G8	H8
A7	B7	C7	D7	E7	F7	G7	H7
A6	B6	C6	D6	E6	F6	G6	H6
A5	B5	C5	D5	E5	F5	G5	H5
A4	B4	C4	D4	E4	F4	G4	H4
A3	B3	C3	D3	E3	F3	G3	H3
A2	B2	C2	D2	E2	F2	G2	H2
A1	B1	C1	D1	E1	F1	G1	H1

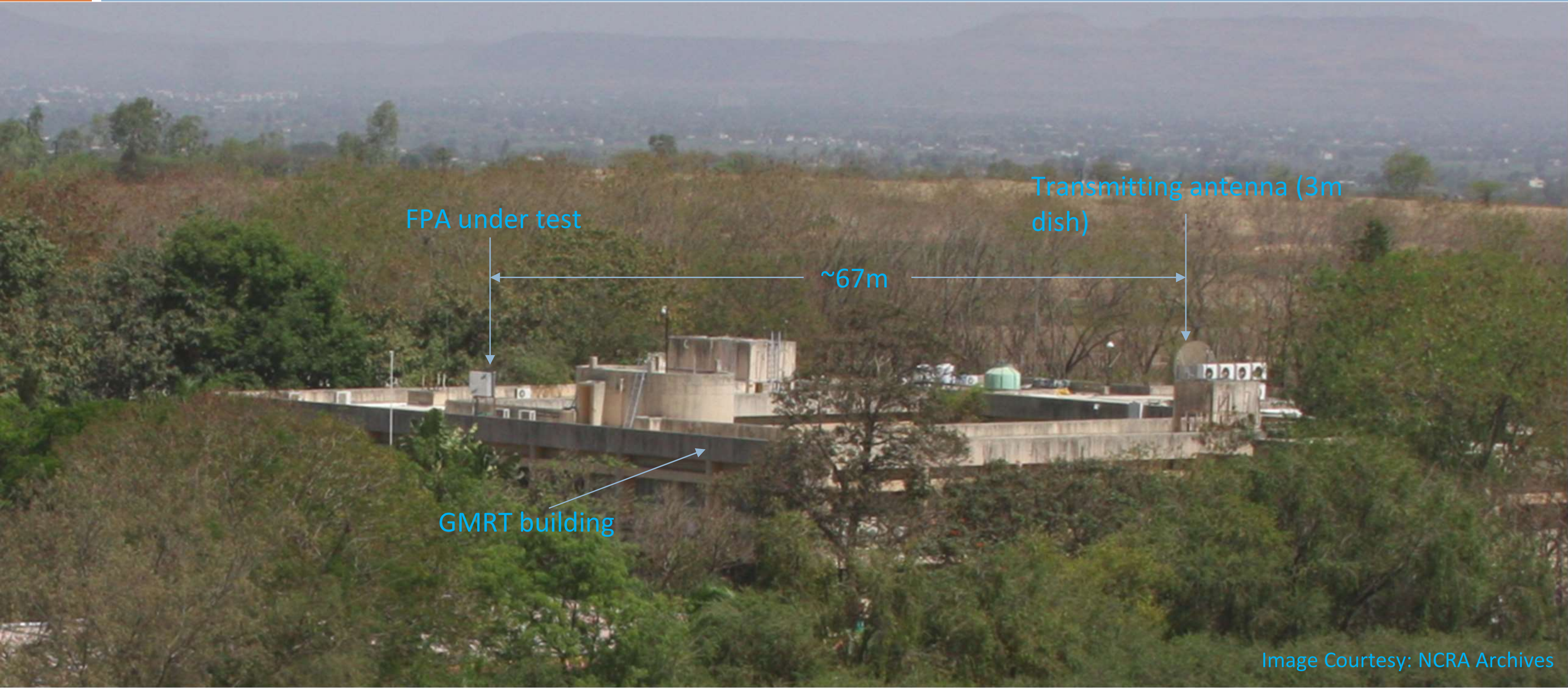
L-band FPA(8x9 Vivaldi array)



Down Converter Unit (DCU)



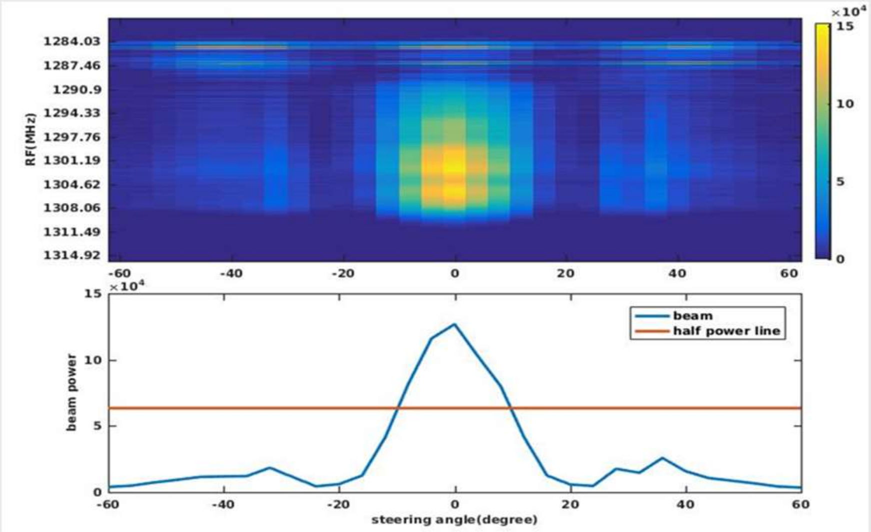
Testing beamforming in free-space test range (Aperture Array Mode)



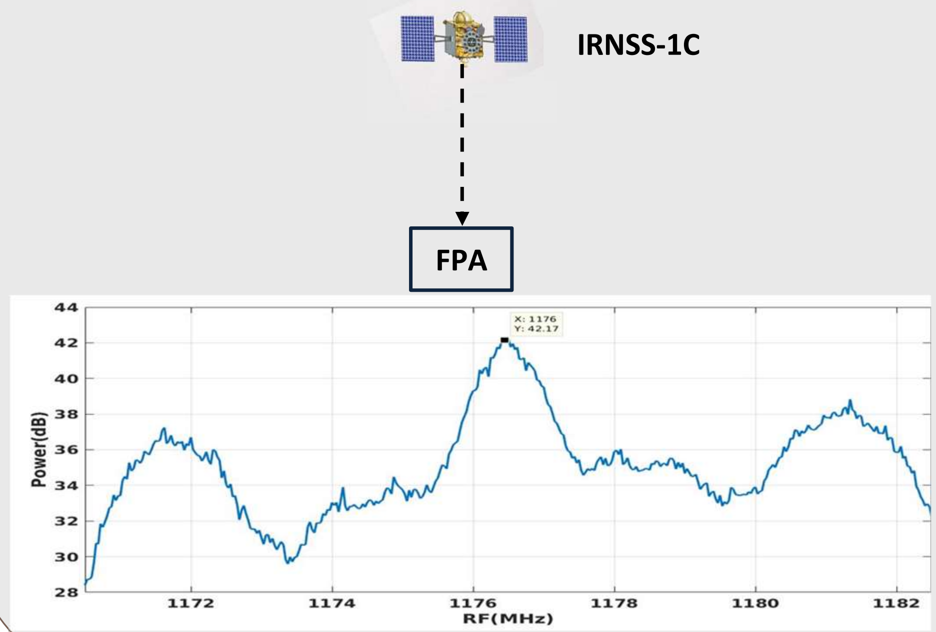
Beam Steering

Beamformer Testing in Free Test Range

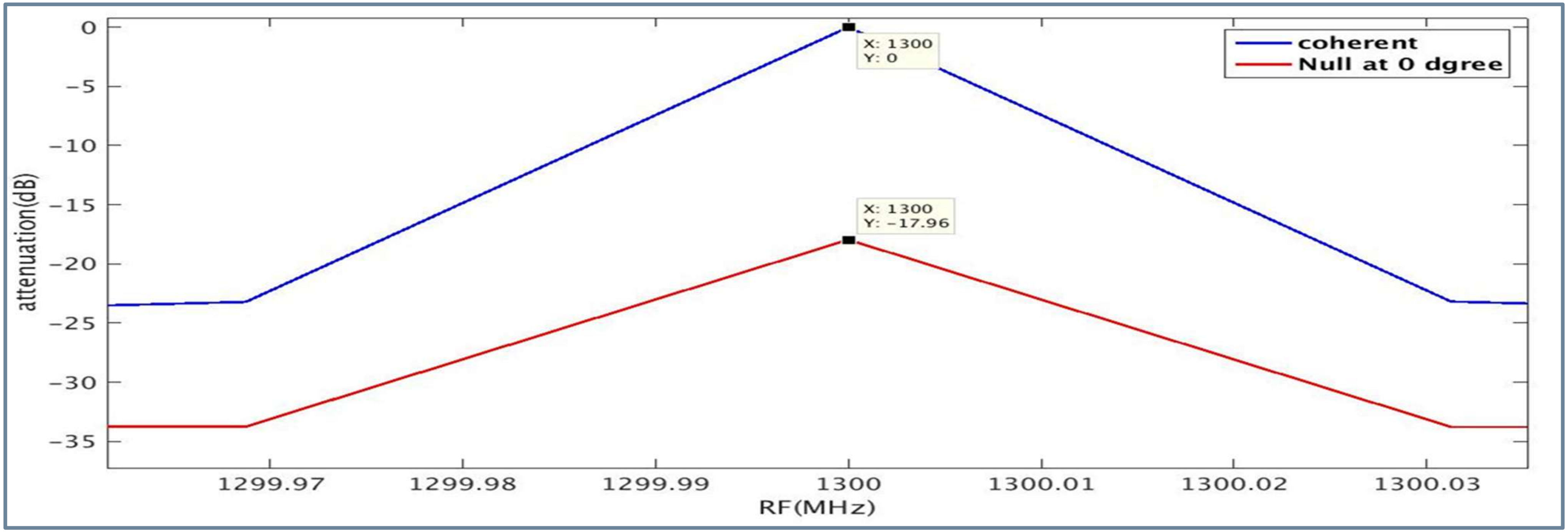
- 8-element array config. Tested (length ~ 1m)
- Theoretical BW: 15°   Measured BW: 17°



IRNSS-1C (navigational satellite) signal at 1176MHz (83 degree East)



Null Steering & Multi-beamforming

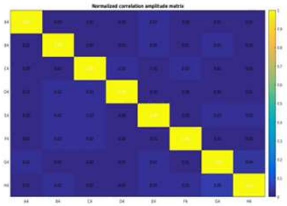


- ❑ **Beam-1:** phased array beam at boresight, **Beam-2:** nulling beamformer at boresight
- ❑ Test using tone radiation at 1300 MHz, ~18 dB null depth
- ❑ Test carried out in free-space test range

Optimal Beamforming

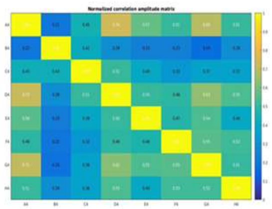
30-element beamforming

Radiation OFF

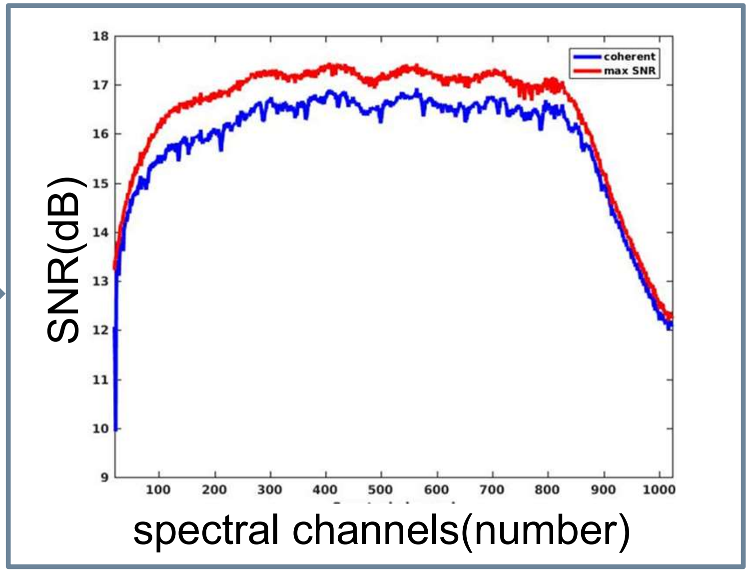


Correlation Matrices

Radiation ON



Beamformer weight optimization (Max-SNR method)



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

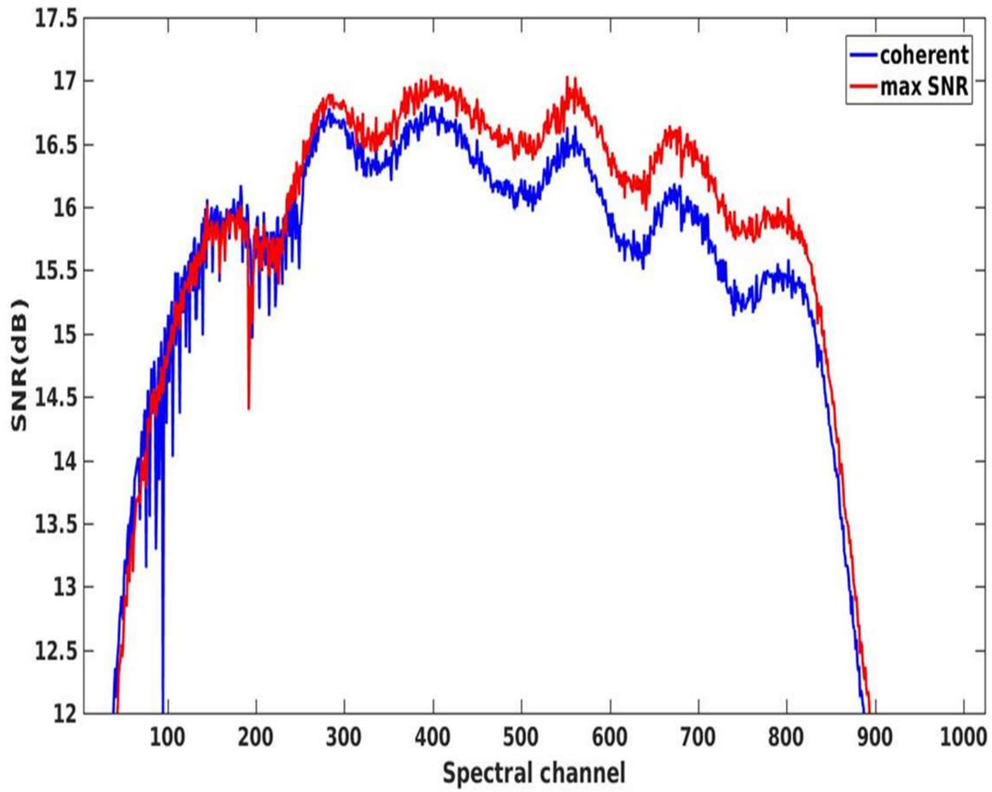
Ivashina et al., "An Optimal Beamforming Strategy for Wide-Field Surveys With Phased Array-Fed Reflector Antennas", IEEE Transaction on Antennas and Propagation, 2011

SNR Performance: Low Mutual Coupling

Cross-correlation Magnitude Matrix

	A4	B4	C4	D4	E4	F4	G4	H4
A4	1.00	0.03	0.03	0.03	0.03	0.04	0.03	0.01
B4	0.03	1.00	0.05	0.01	0.01	0.03	0.03	0.03
C4	0.03	0.05	1.00	0.07	0.03	0.05	0.05	0.05
D4	0.03	0.01	0.07	1.00	0.05	0.10	0.06	0.05
E4	0.03	0.01	0.03	0.05	1.00	0.06	0.07	0.02
F4	0.04	0.03	0.05	0.10	0.06	1.00	0.06	0.03
G4	0.03	0.03	0.05	0.06	0.07	0.06	1.00	0.05
H4	0.01	0.03	0.05	0.05	0.02	0.03	0.05	1.00

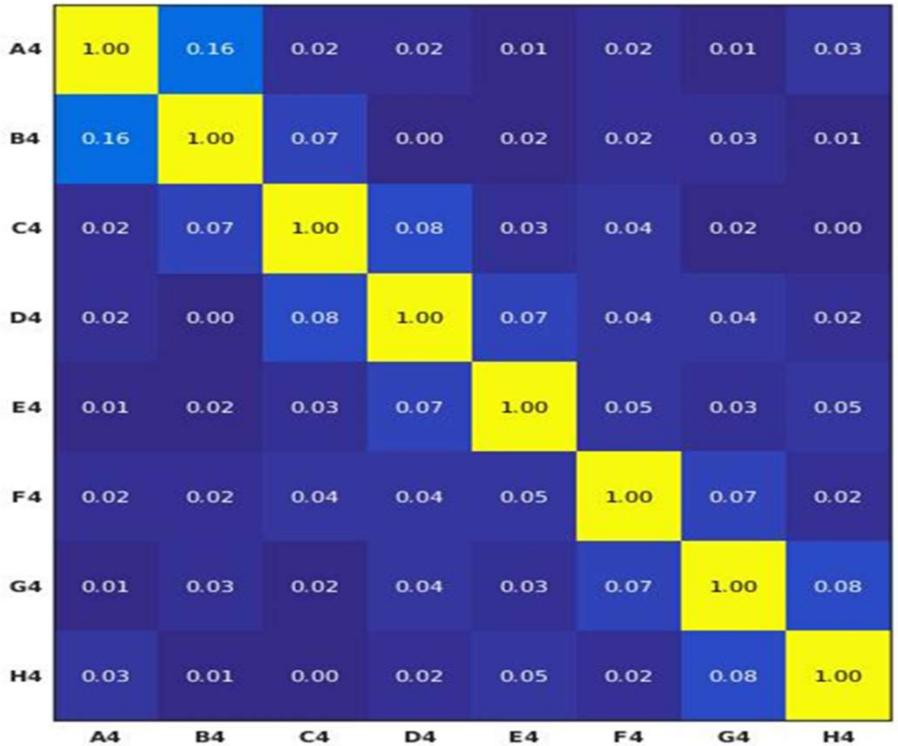
Beamformer SNR Comparison



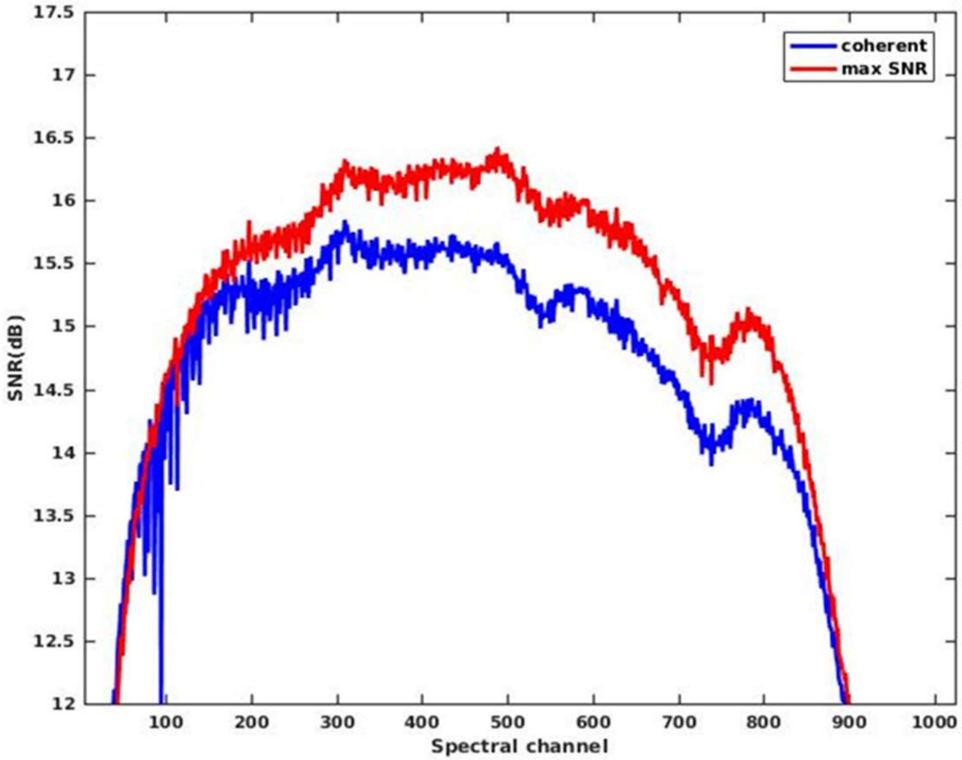
SNR performance of phased array and optimal beam are very close

SNR Performance: High Mutual Coupling

Cross-correlation Magnitude Matrix



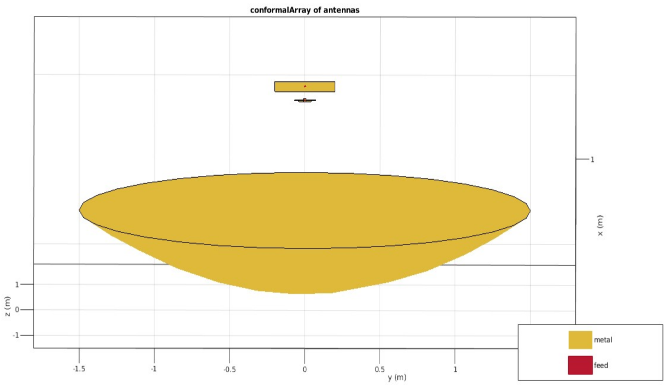
Beamformer SNR Comparison



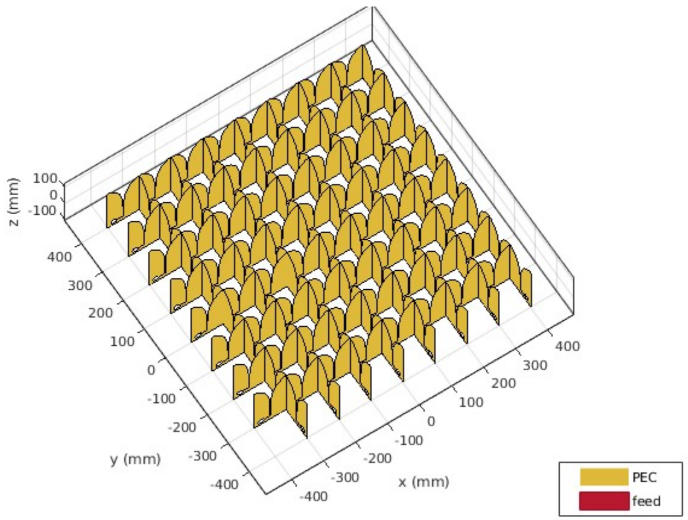
SNR performance of optimal beam is better than phased array beam

Simulation Model

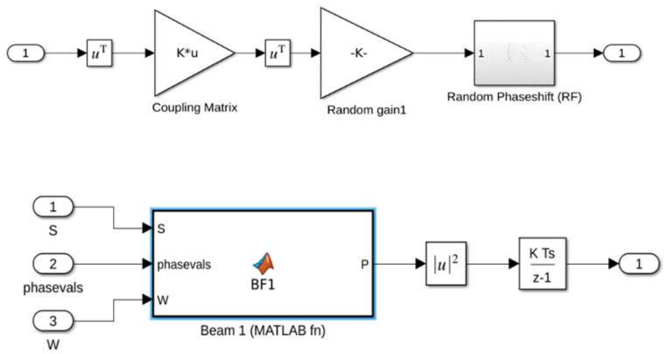
Transmit Antenna and Propagation Channel → Receive Antenna Array → RF Systems and Digital Beamformer




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



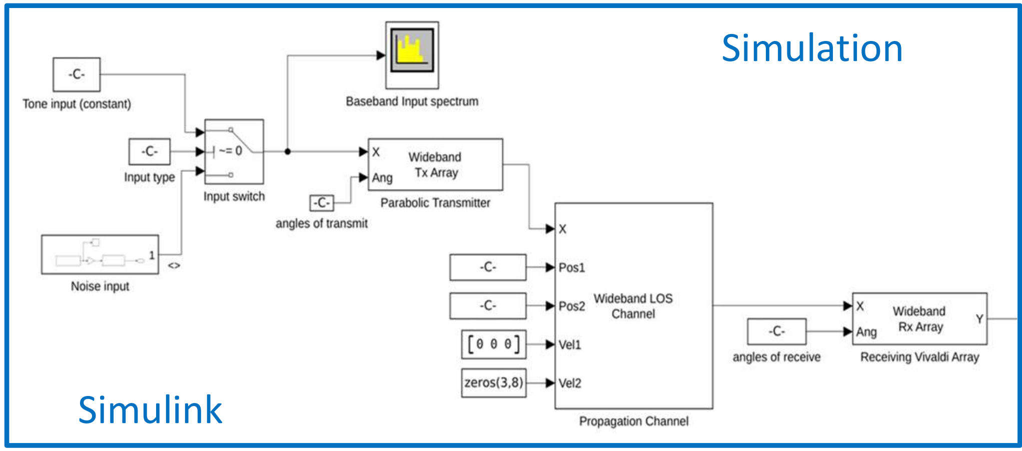

```
load('vivaldiOffset.mat','m');

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

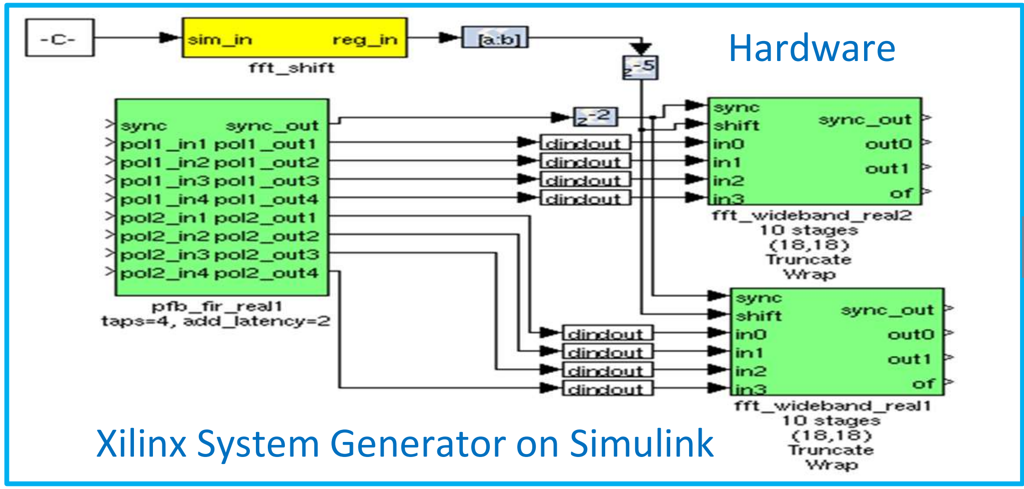


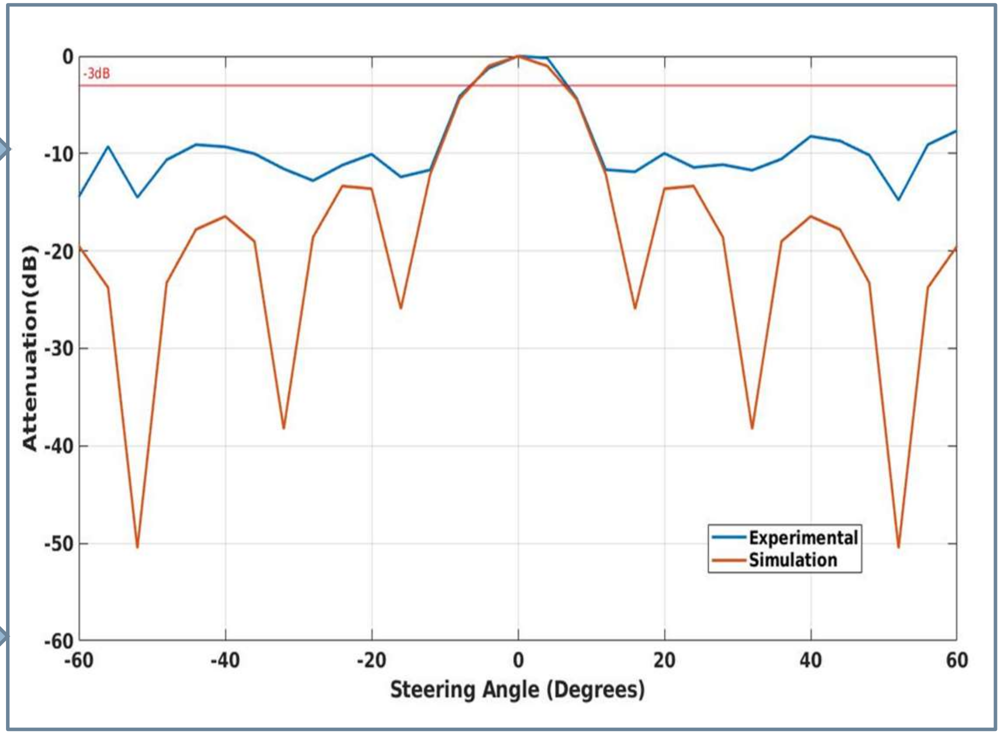
- ❑ Gain and phase modeling and randomization
- ❑ Beamformer and Correlator

Buch and Ranganathan, System-level Simulation for an Aperture Array Beamformer, MATLAB EXPO 2022

Beam-steering Comparison with Experimental Test

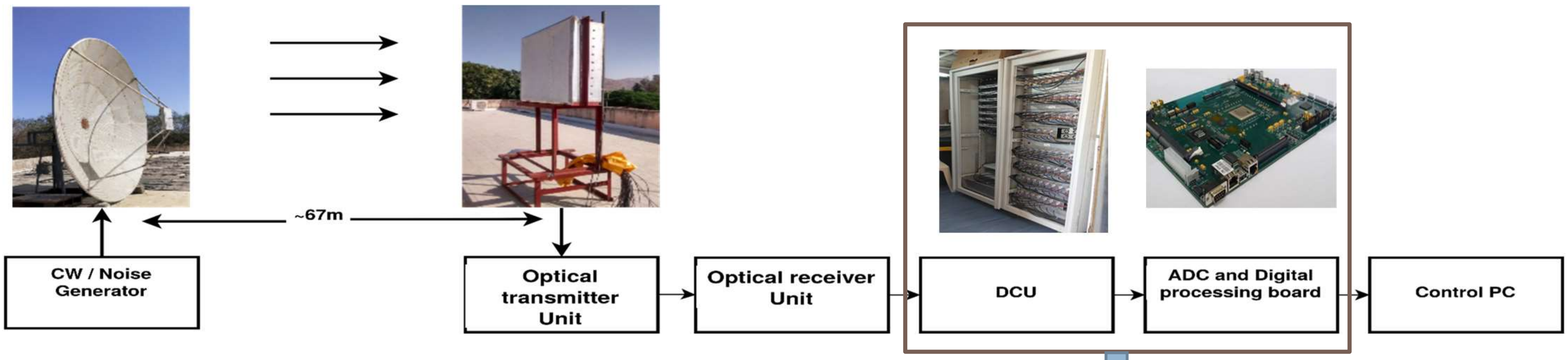




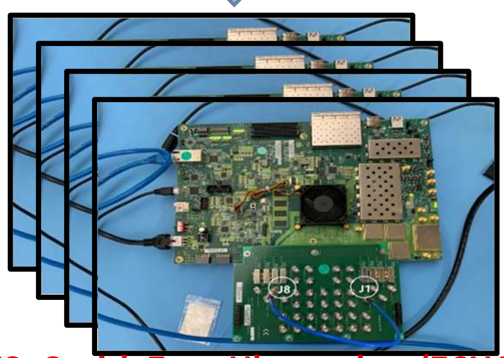


Close match with the main lobe. Side-lobe mismatch due to reflections in the test range

RFSoC for Wideband Beamformer Development



Replaced by



RFSoC with Zync Ultrascale + (ZCU111) boards

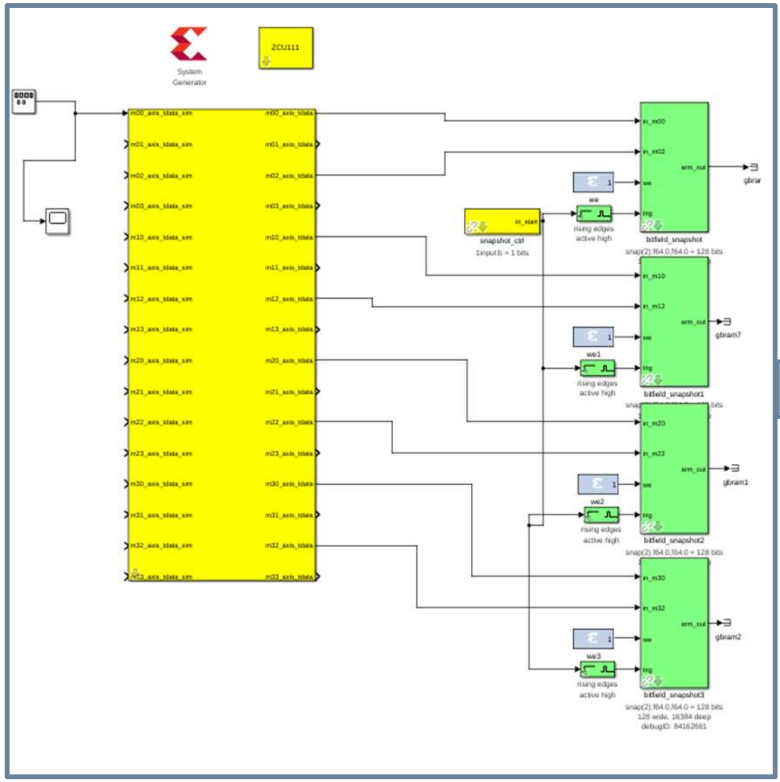
RFSoC eliminates use of bulky downconverter units!

Use the CASPER tool-flow and firmware for designing and interfacing/data acquistion

https://casper.berkeley.edu/

RFSoC Toolflow Development and Testing

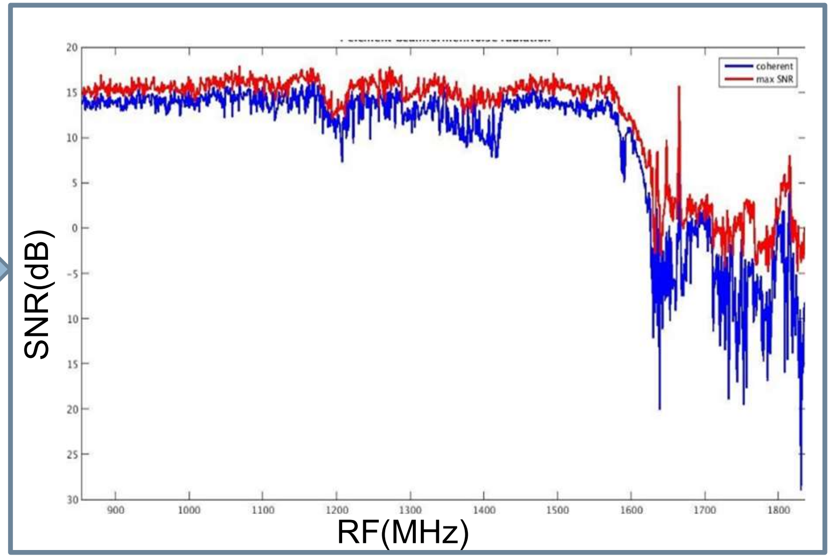
Simulink-System Generator Design using CASPER Toolflow



4-element raw voltage acquisition design

Offline Beamforming

Processing and forming beams (offline)



Frequency range: 854 to 1830MHz
Radiated signal: 800 to 1400MHz

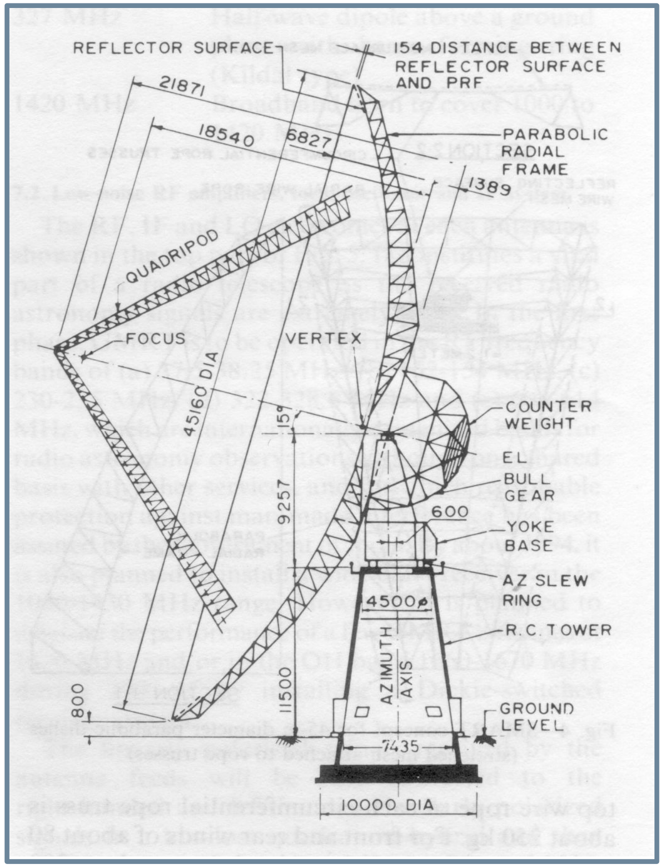
Comparison between conventional and maxSNR beams at boresight

Summary

- Prototype FPA beamformer (32 input, 5-beam, 32 MHz bandwidth) implemented on FPGA ; tested in free-space test range
- maxSNR beamforming process and testing for FPA in aperture array mode (L-band)
- Exploring various optimal beamforming and spatial RFI mitigation techniques
- FPA beamformer to be installed and tested a dish
- Wideband beamforming to be developed using RFSoC platform
- FPA beamforming through system-level simulation

Future Plans

- Testing FPA beamforming using GMRT dish
- Costing and building a dish
- Developing a wideband single pixel feed
- Designing FPA for 550-900 MHz range



GMRT dish (D=45m, f/D=0.412)

Acknowledgements

eGMRT project members/students	GMRT groups
Sudhir Phakatkar Atul Ghalame Narendranath Patra Jayanta Roy Nissim Kanekar Yashwant Gupta	Backend group Computer group Frontend & OFC group Operations group Mechanical, Electrical & Civil groups

Collaboration for Astronomy Signal Processing and Electronics Research (CASPER)

NIUS program of HBCSE-TIFR funded by DAE, Govt. Of India Grant No. RTI4001

Mitch Burnett, Brigham Young University, USA

Netherlands Institute for Radio Astronomy (ASTRON)