Array Mode of Radio Telescope

Lecture Series on Radio Astronomy and GMRT

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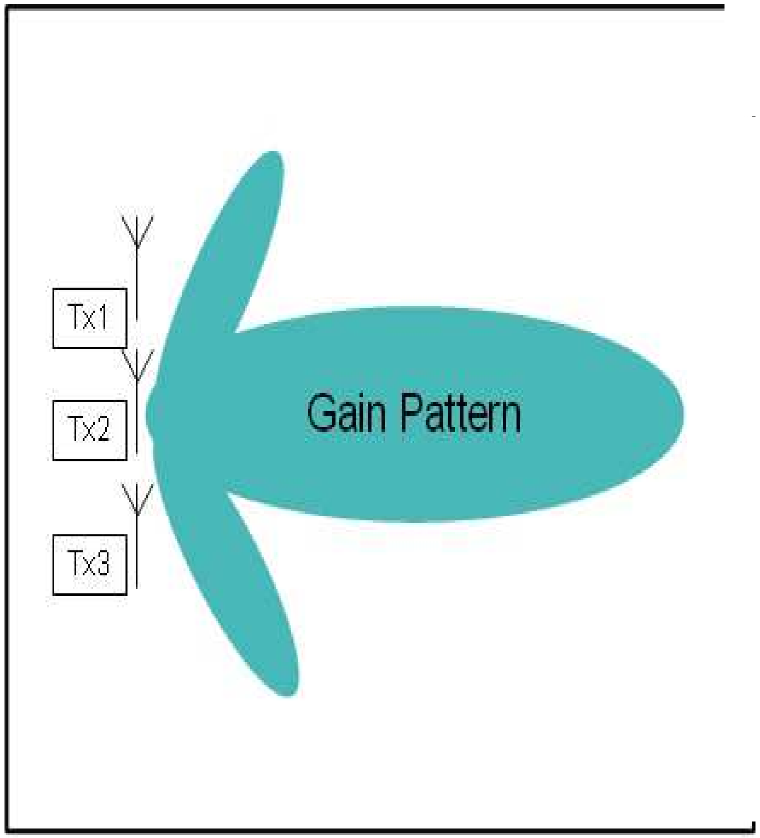
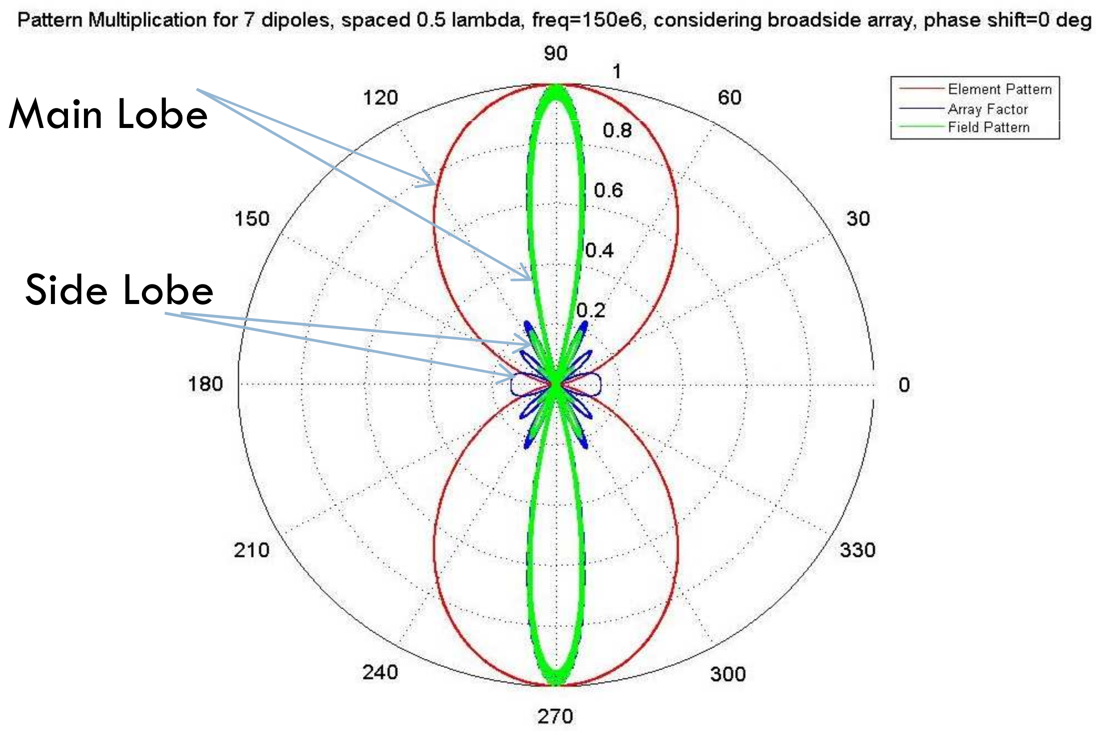
Radiation Pattern of Antenna Array

Shows sensitivity (power) of antenna with respect to the direction

Antenna with equal sensitivity in all directions – Omni-directional antenna





Array Fundamentals - 1

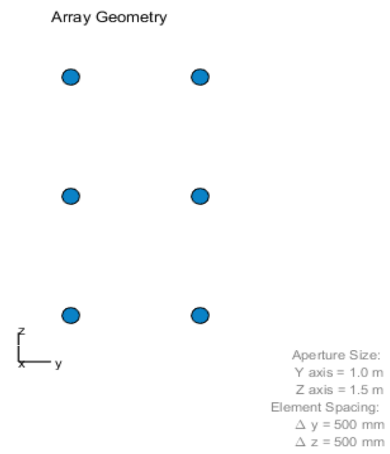
- A collection of antenna elements; each element is exited with a certain amplitude and phase to get desired response

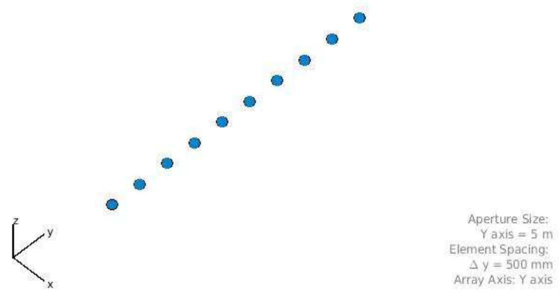
- Based on array geometry - Linear array, Rectangular array, Circular array etc.

- Based on spacing – Uniform and Non-uniform

- Based on excitation (Amplitude and Phase) – Fixed and Adaptive

- Based on beam direction – Fixed and Steerable





Array Fundamentals - 2

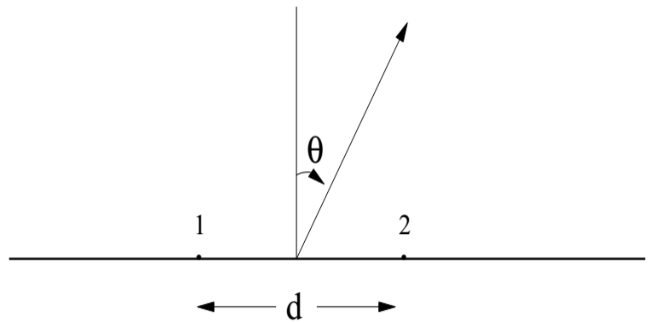
- Far field radiation pattern of two isotropic point sources separated by a distance 'd' , in direction is

$$E(\theta) = E_1 e^{i\psi/2} + E_2 e^{-i\psi/2}$$

$$\psi = kd\sin\theta + \delta$$

$k = 2\pi/\lambda$ (path difference), δ = phase difference

E_1 & E_2 are amplitudes of electric field of two sources



- The reference point for the phase (phase centre) is taken half way between the two elements

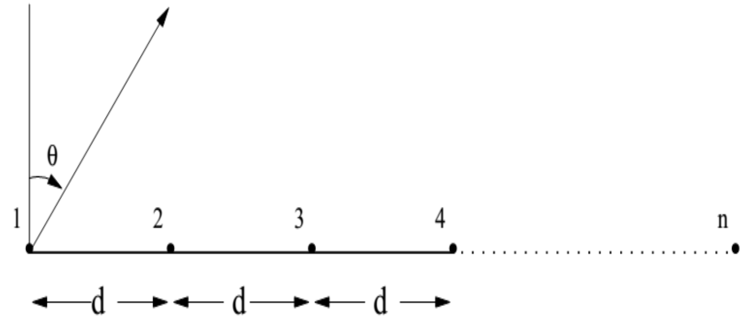
For sources with equal strength i.e. $E_1 = E_2 = E_0$

$$E(\theta) = 2 E_0 \cos(\psi/2)$$

- Extending to linear array of 'n' elements (with equal spacing and amplitude), the far-field pattern is

$$E(\theta) = E_0 [1 + e^{i\psi} + e^{i2\psi} + \ldots\ldots + e^{i(n-1)\psi}]$$

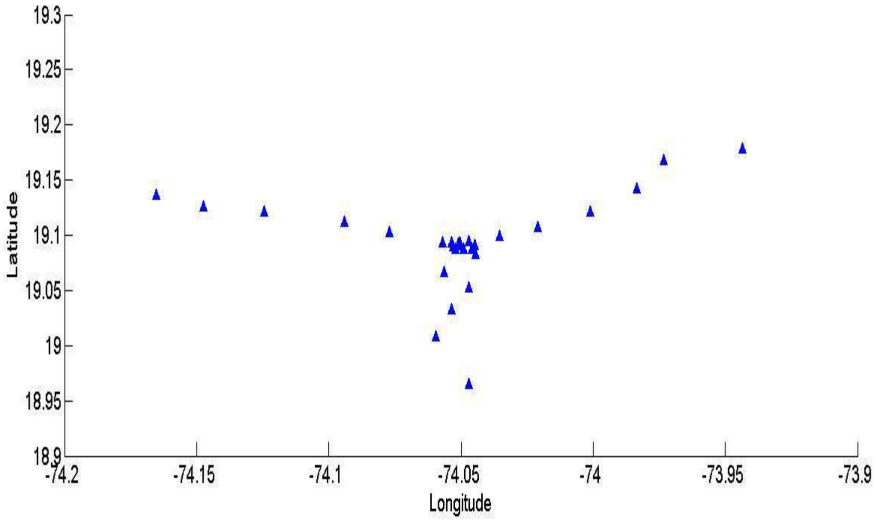
$$E(\theta) = e^{i(n-1)\psi/2} E_0 [\sin(n\psi/2)/\sin(\psi/2)]$$



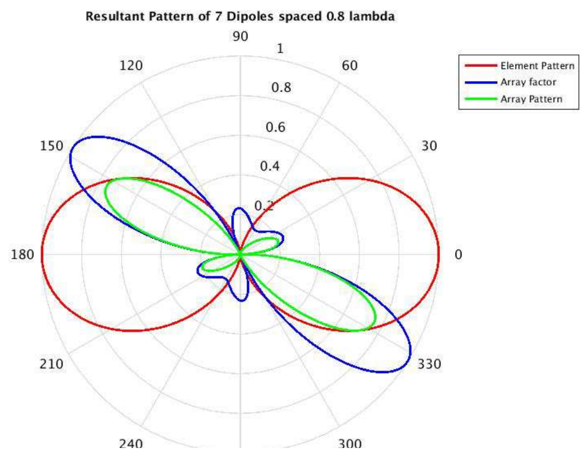
Antenna Arrays in Radio Astronomy

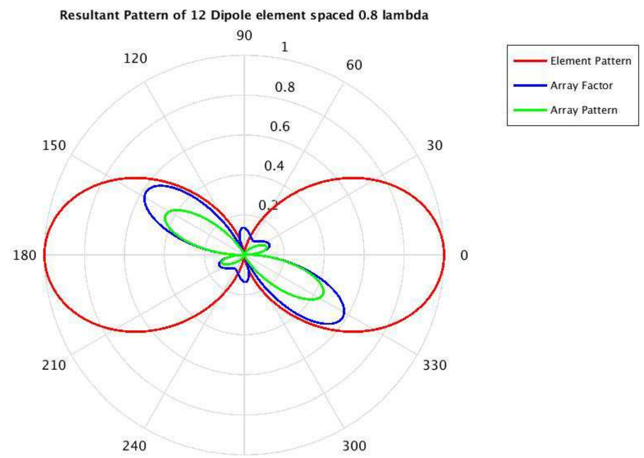
VLA, New Mexico, USA
(27 antennas)

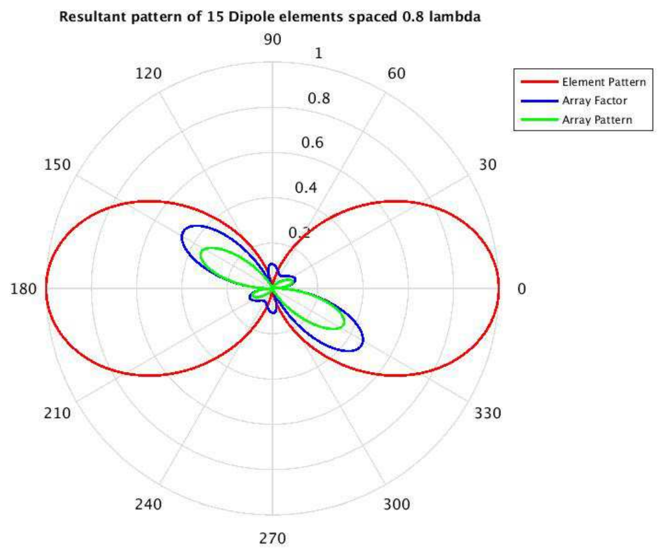
GMRT Array , India
(30 antennas)



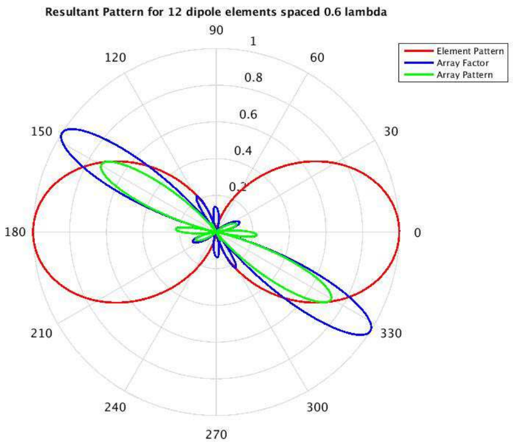
Effect of Number of Elements

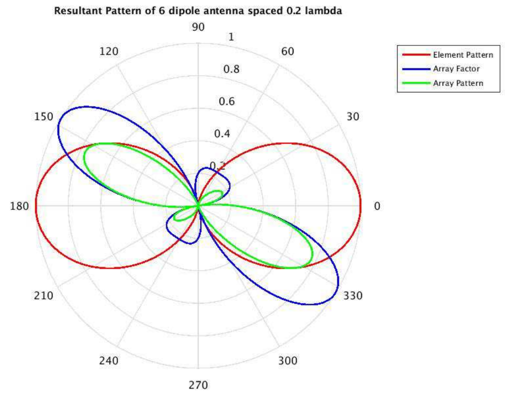


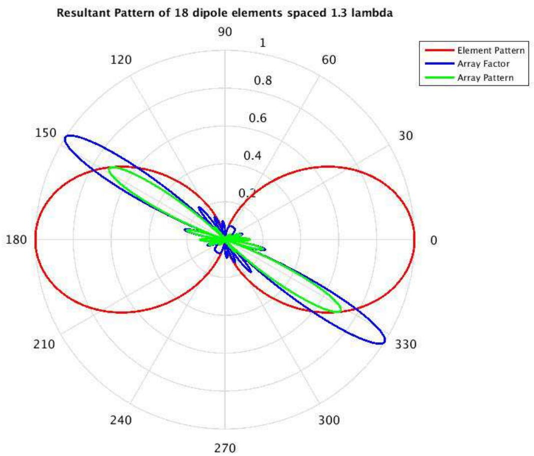


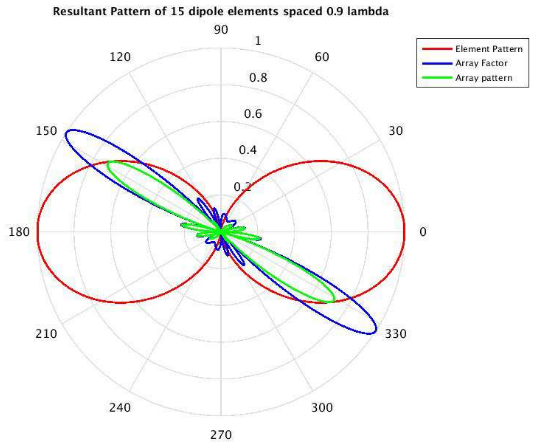


Effect of Spacing between Elements

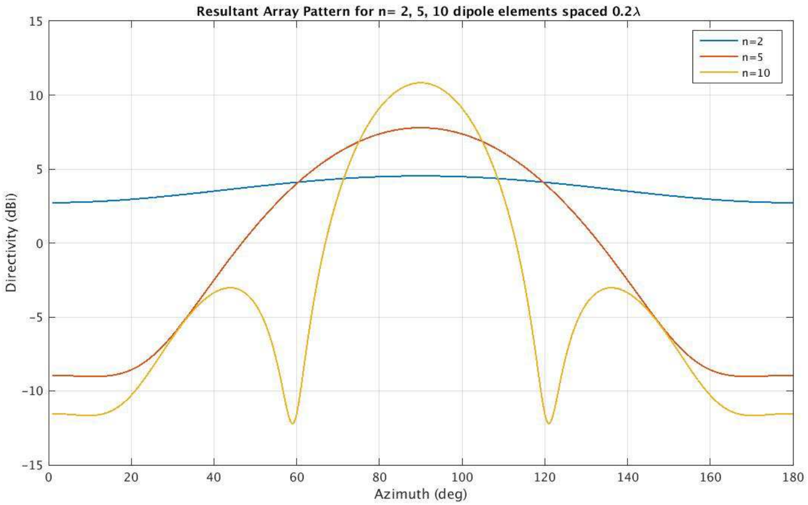


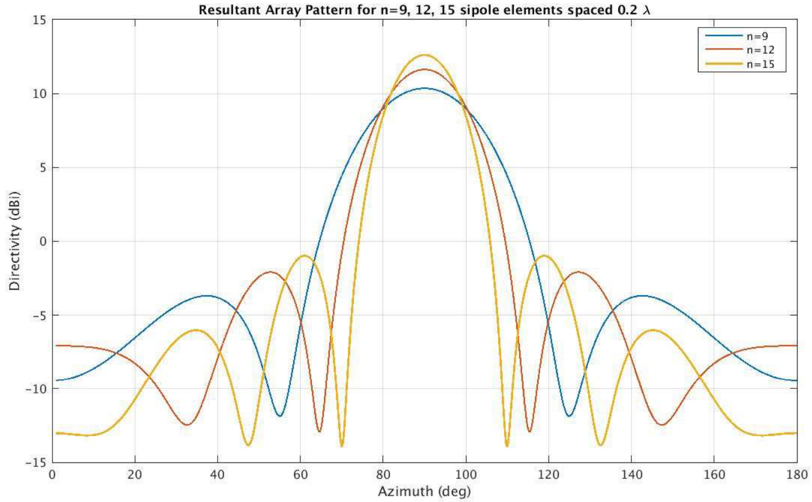


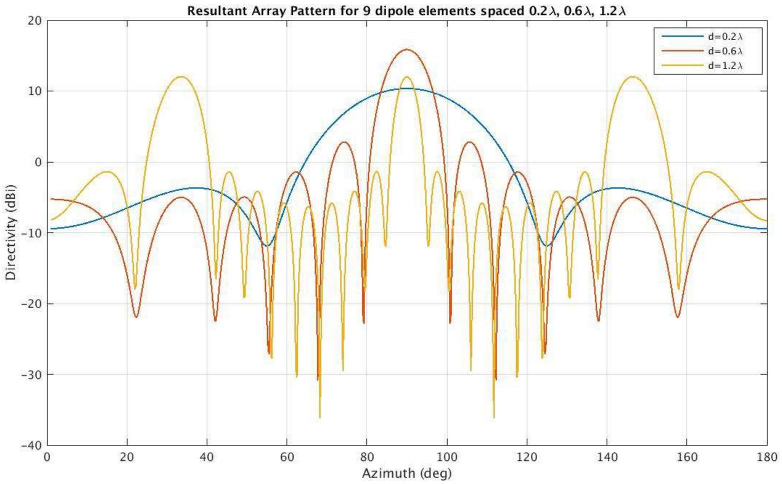


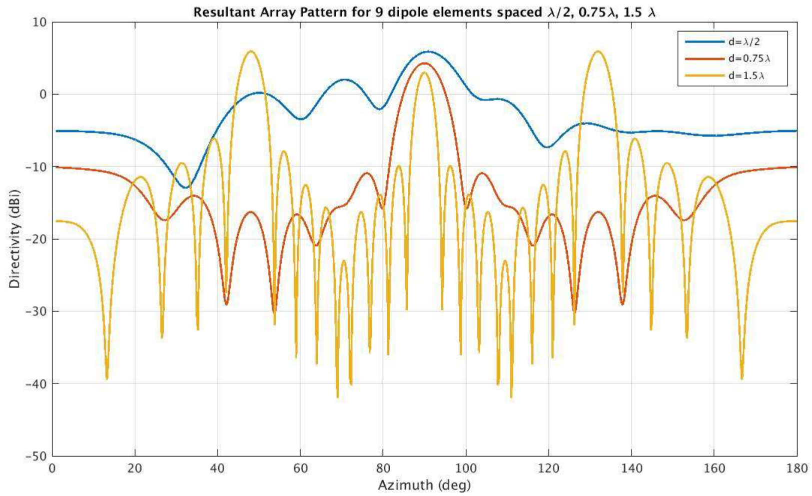


Radiation pattern









Example of beamsteering (Linear Array)

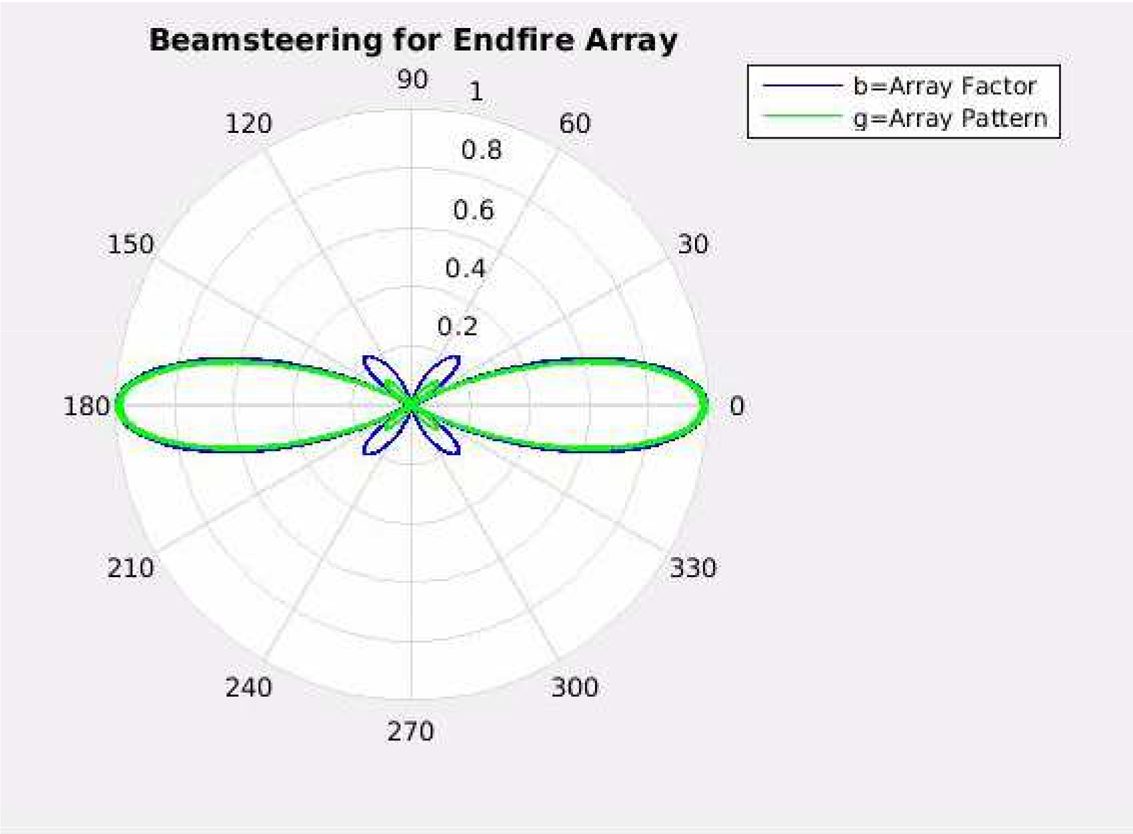
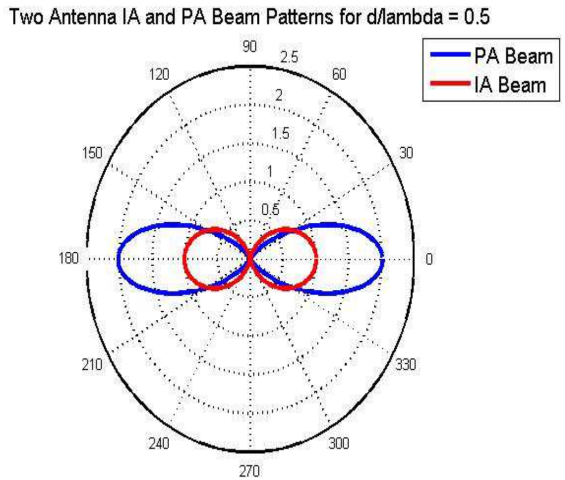


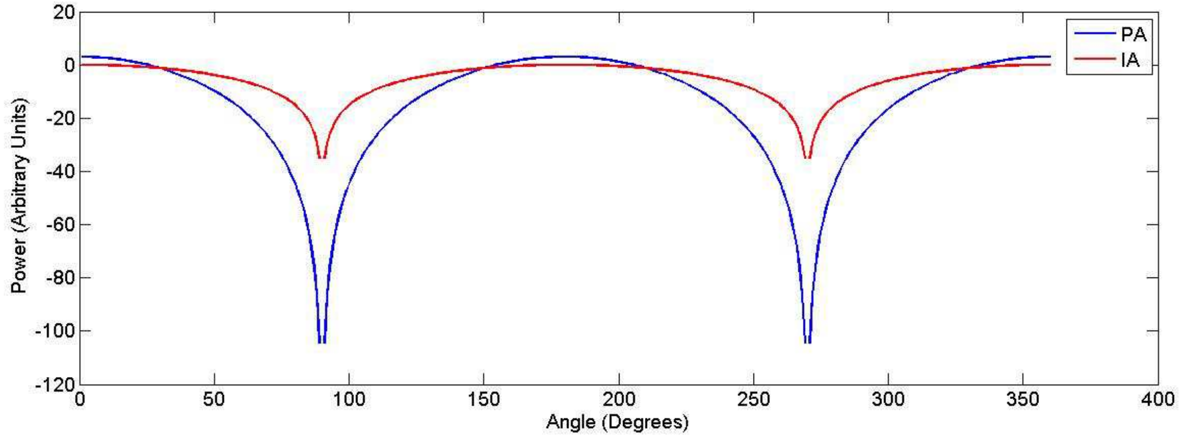
Image Courtesy: Priya Hande

Need for beamformer mode

- Improvement in the overall sensitivity & SNR by combining signal from multiple antenna

- Improvement in beam-width





Incoherent & Coherent Addition

- Power from individual antennas is added to form the incoherent beam (scalar addition)

$$B_i = \sum_{i=0}^{n} (V_1^2 + V_2^2 + \ldots\ldots + V_N^2)$$

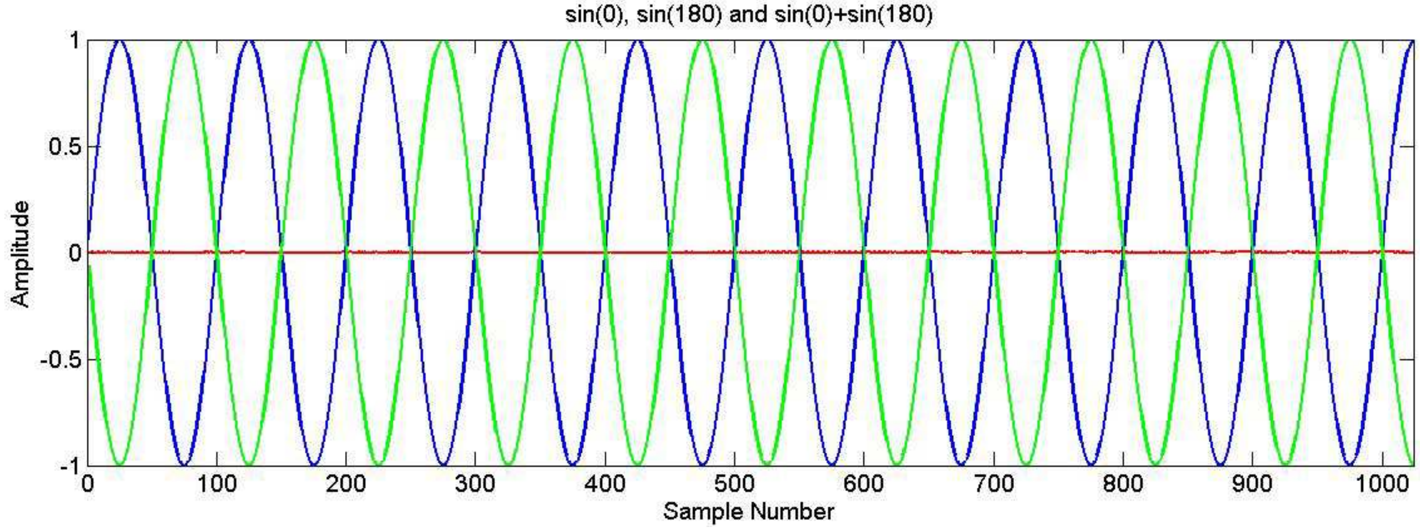
- Voltages from individual antennas are added to form the coherent beam.

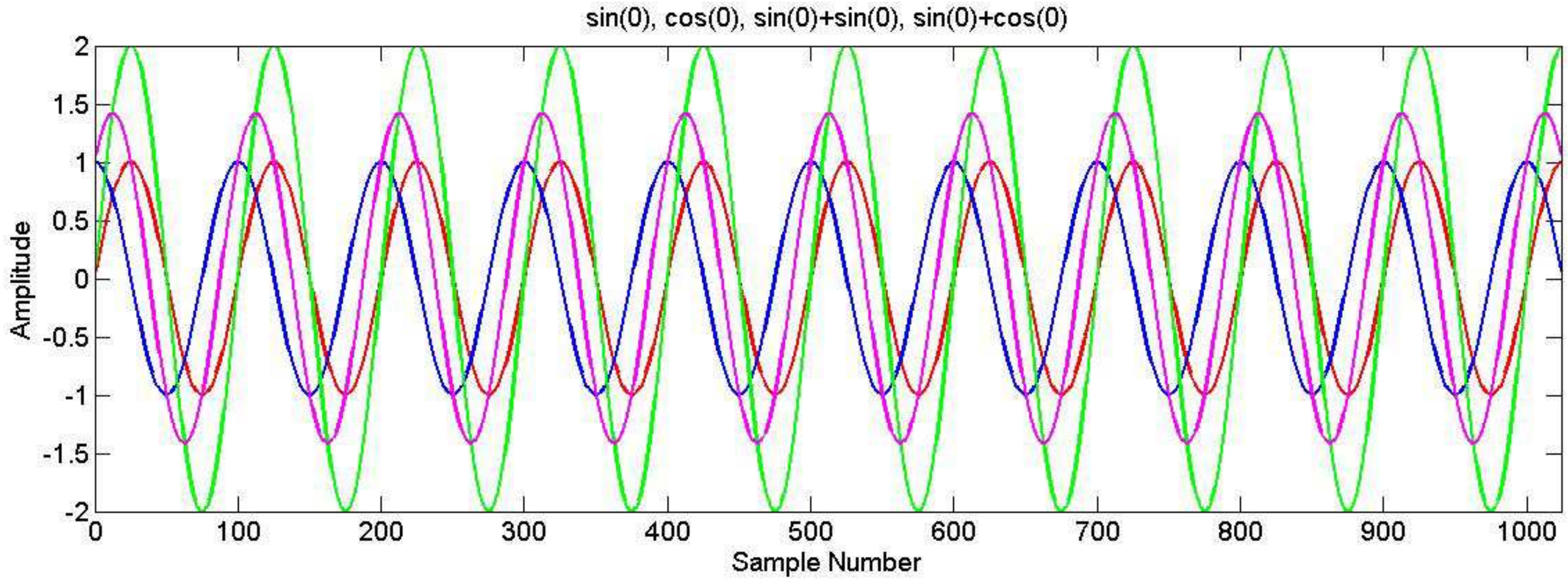
$$B_C = \sum_{i=0}^{n} (V_1 + V_2 + \ldots\ldots + V_N)^2$$

Phase is important !

In principle, if two antenna signals are added the resultant signal will cause and increase of SNR by a factor on $N^{-0.5}$ (incoherent) and N (coherent) mode

Phase addition





Phasing

Iterative phasing – shows de-phasing with time and correcting it in an iterative system

The de-phasing is large for far away antennas

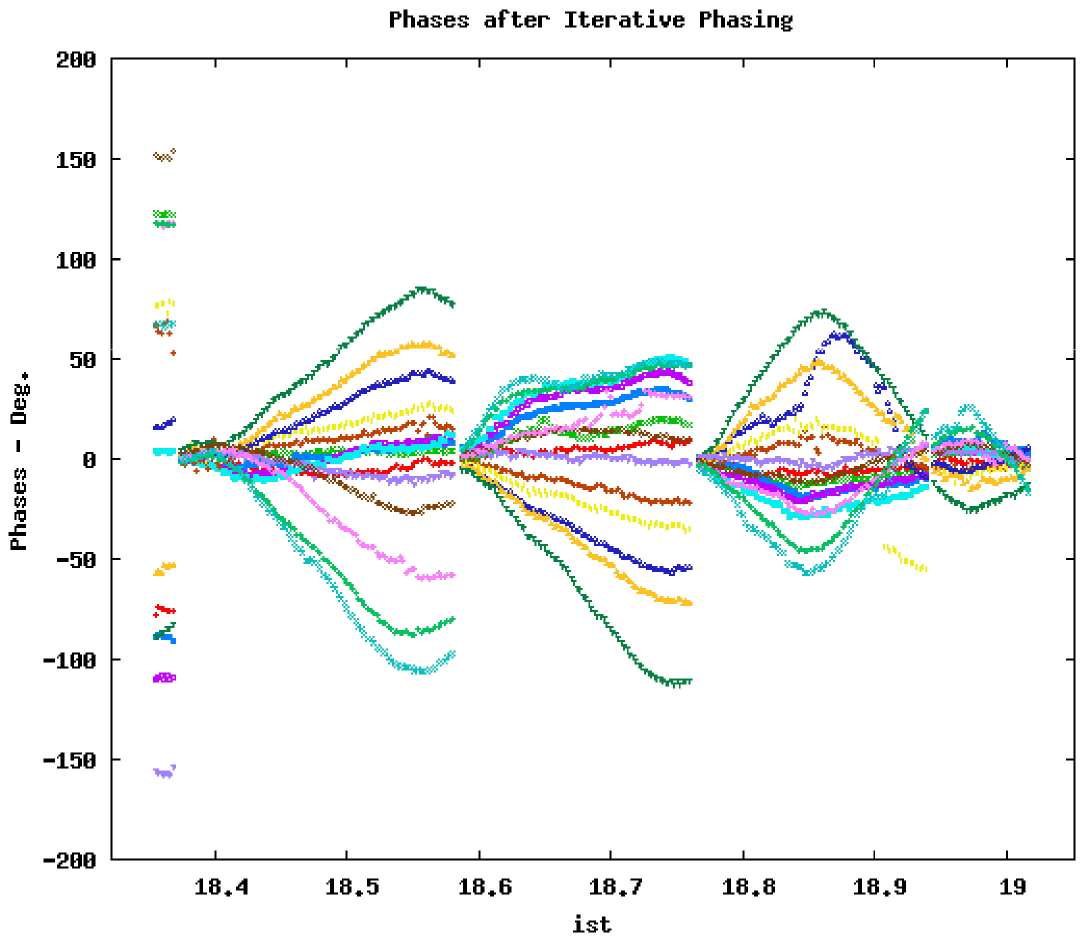
The time over which de-phasing occurs depends on

a. Ionospheric changes

b. Instrumental gain changes

De-phasing causes loss of SNR (Ruze formula)

The phase values are computed from the correlator output



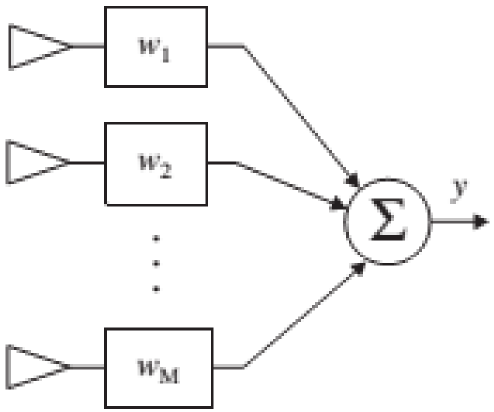
Phasing on 3C48

Image Courtesy: Sanjay Kudale

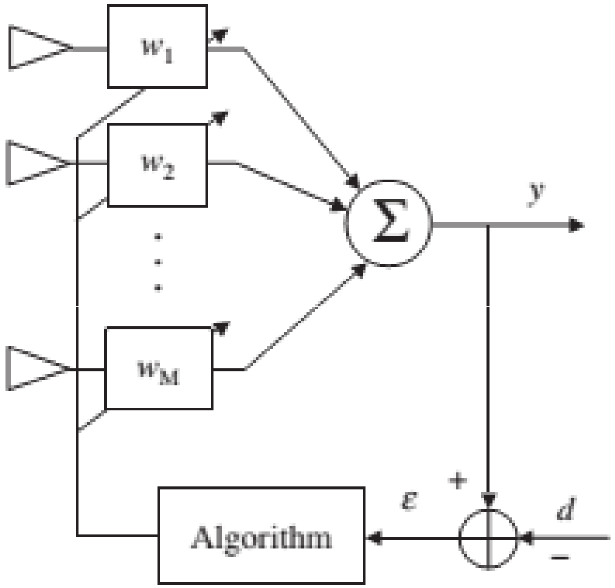
Process of phasing antenna array at GMRT

- Observe a phase calibrator and record interferometry (visibility) output
- Solving instrumental and Ionospheric gains by running 'rantsol' utility (Bad antennas are automatically removed by this utility) on the visibility outputs
- 'rantsol' provides phase as a function of frequency
- Apply the phase correction to the beamformer
- The phase calibrator has to be near the source being observed – ionosphere should not vary too much !

Types of Beamformer



Fixed-Weight



Adaptive

Beamformers can be classified as fixed-weight beamformer and adaptive weight

Fixed-weight: Weights do not adapt with changing signal environment

Adaptive: Weights are updated to optimize performance with change in signal properties.

Need advanced signal processing to compute and update weights

Analog Beamformer

Beamforming in analog domain can be done by using phase shifters, amplifiers and power combiners. Were commonly used before the digital era !

Digital beamformers are much accurate and more amenable to complicated signal processing algorithms for beamforming

Signal Processing Preliminaries - 1

- In order to reconstruct a sampled signal, the sampling frequency must be twice the maximum frequency of the signal (or the bandwidth), a.k.a. Nyquist theorem

$$f_s = 2f_m$$

- The spectral resolution f_r (width of a spectral channel) is dependent of the number of FFT points (N) and the bandwidth (Δf)

$$f_r = \Delta f \;/\; N$$

- Fourier transform of a real signal is conjugate symmetric - i.e. for a N-point FFT, only half the number of spectral channels have unique information

Signal Processing Preliminaries - 2

- Shift in time-domain (time delay) is phase shift in the frequency domain

$$x(n-d) = X(\omega)e^{-j\omega d}$$

- Convolution in time domain is multiplication in the frequency domain

$$x(t) * y(t) = X(\omega)Y(\omega)$$

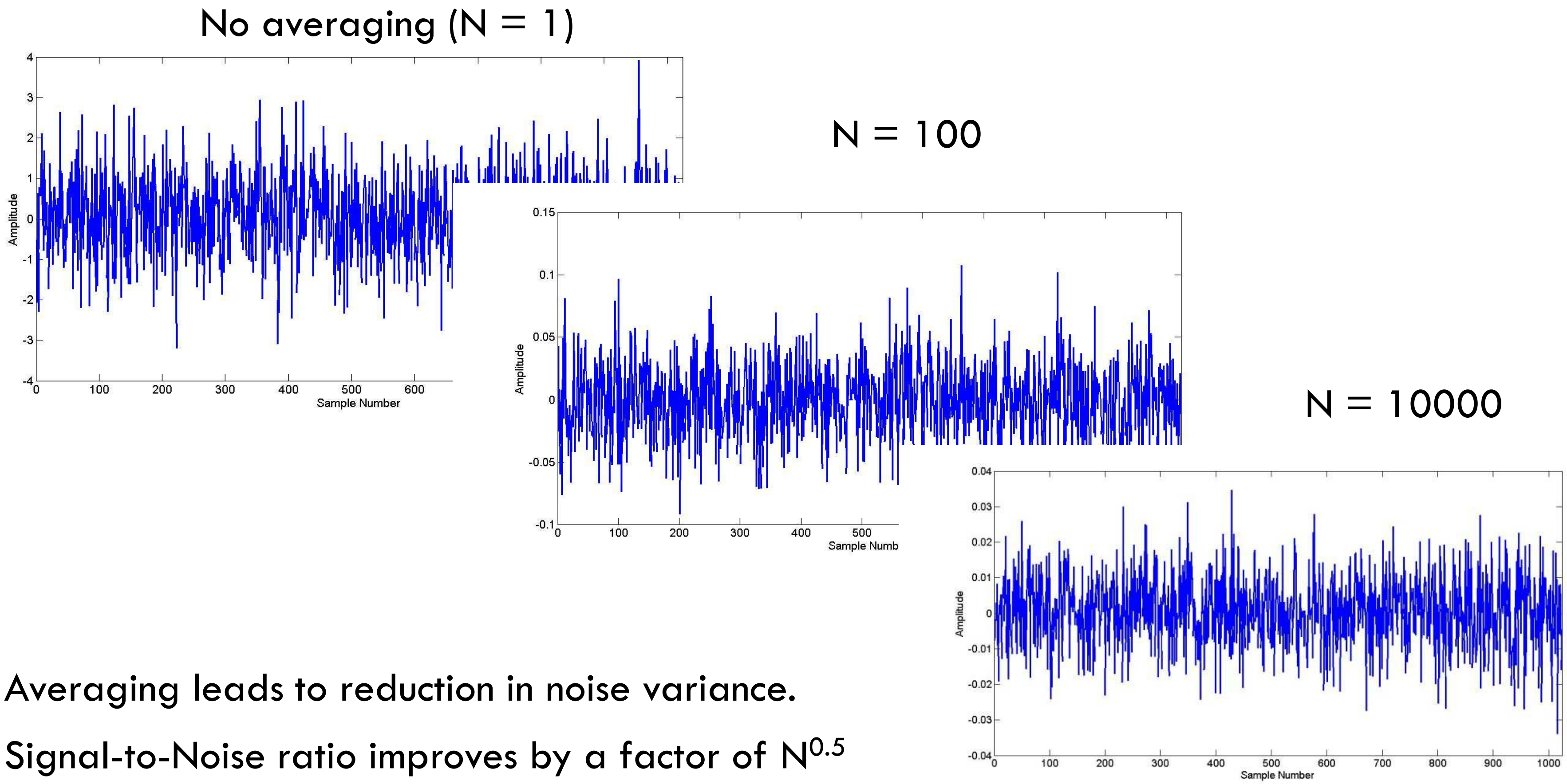
- Correlation is a measure of similarity between the two signals and it varies as a function of the lag between them.

  Even function, peaks at zero lag, reduces linearly as a function of lag

  Shows the degree of similarity between the signals

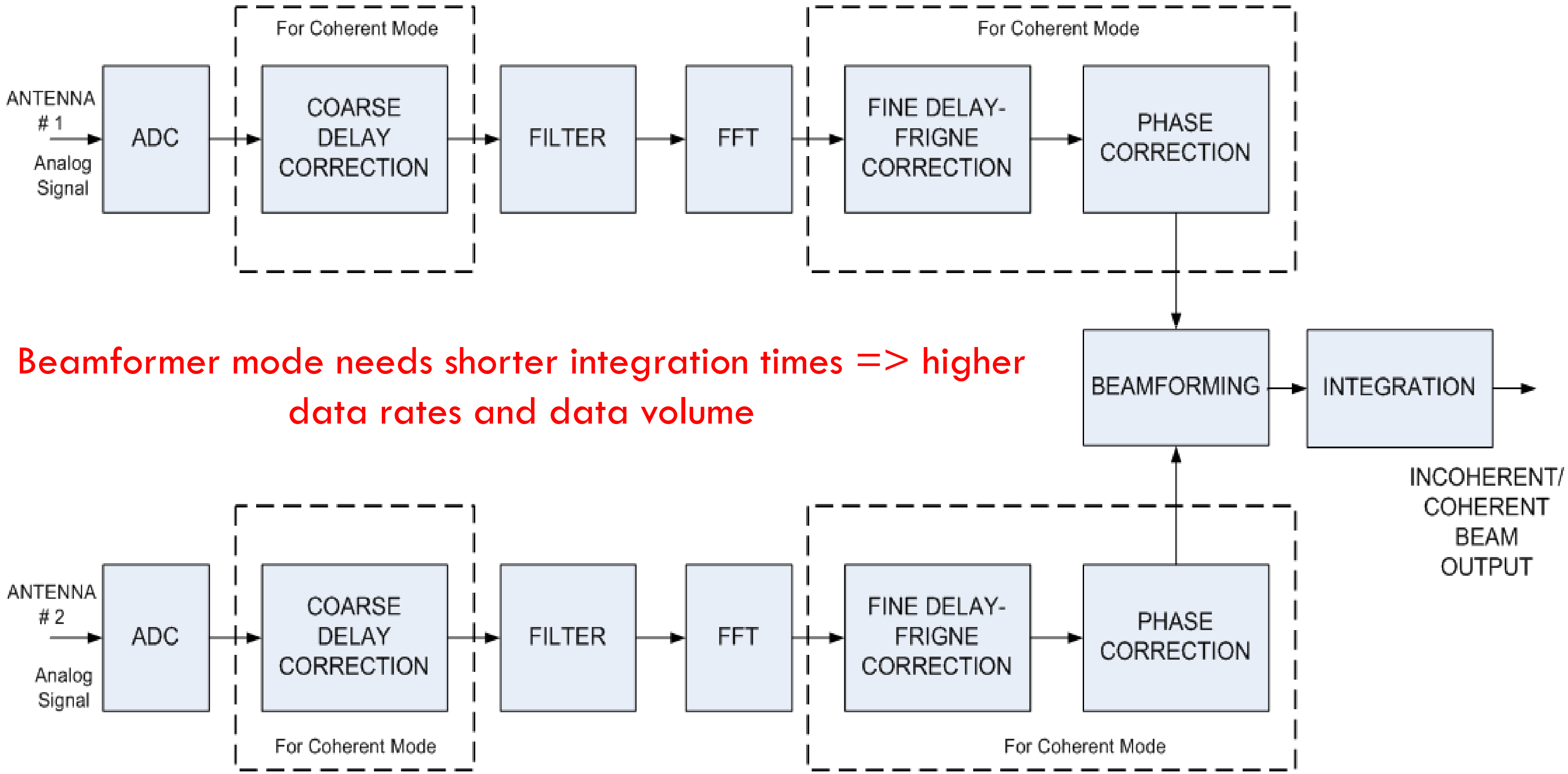
  Correlated (1), Uncorrelated (0), Partially correlated (0<R<1), Anti-correlated (-1)

Detecting Signal Buried in Noise



- Averaging leads to reduction in noise variance.
- Signal-to-Noise ratio improves by a factor of $N^{0.5}$
- Deterministic signal adds coherently while noise adds incoherently
- Increases the ability to detect a weak signal buried in noise !

Receiver Chain: IA & PA Modes

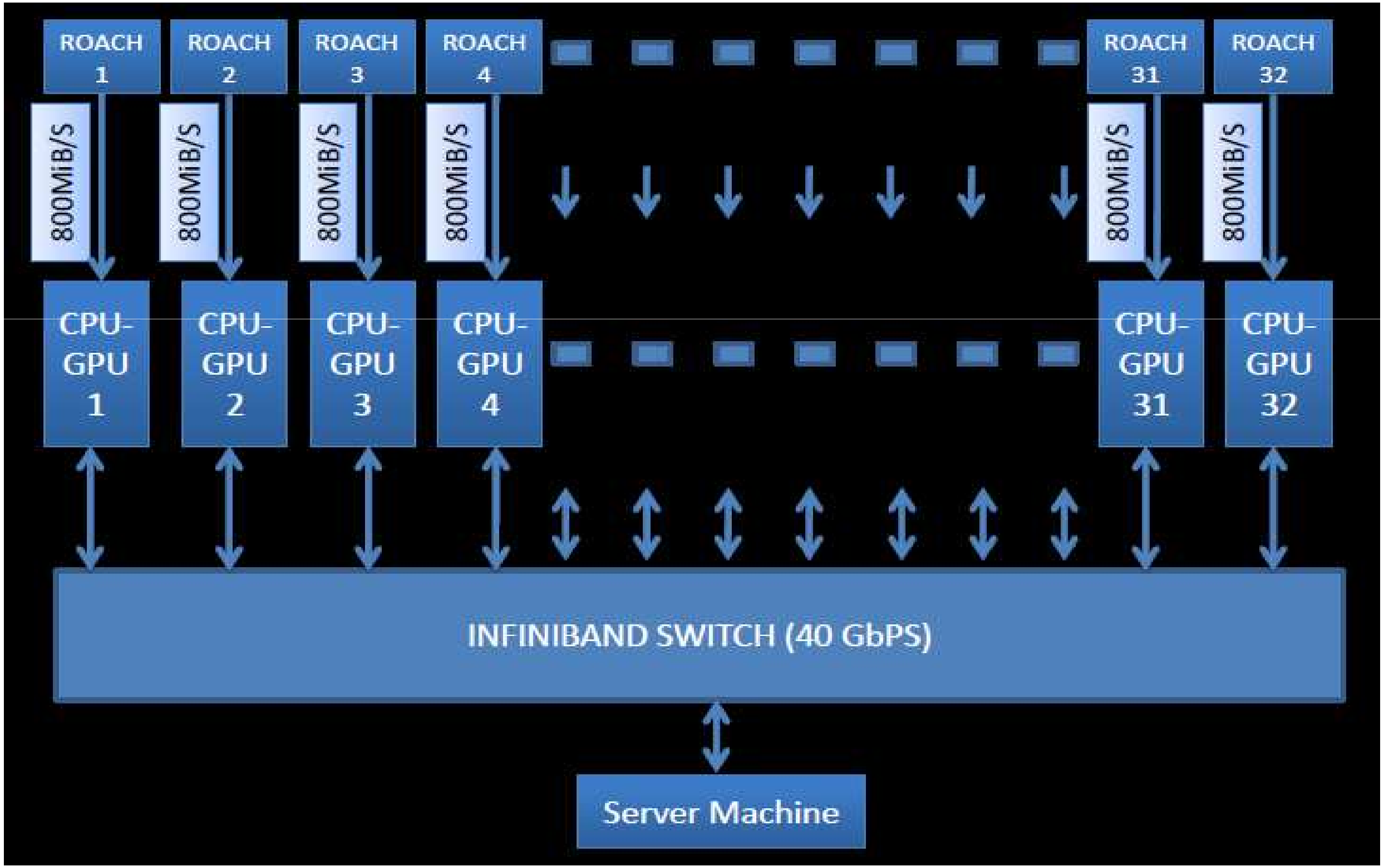


Beamformer mode needs shorter integration times => higher data rates and data volume

$$B_i = \sum_{i=0}^{n} (V_1^2 + V_2^2 + \dots + V_N^2)$$

$$B_C = \sum_{i=0}^{n} (V_1 + V_2 + \dots + V_N)^2$$

Beamformer for GMRT antennas



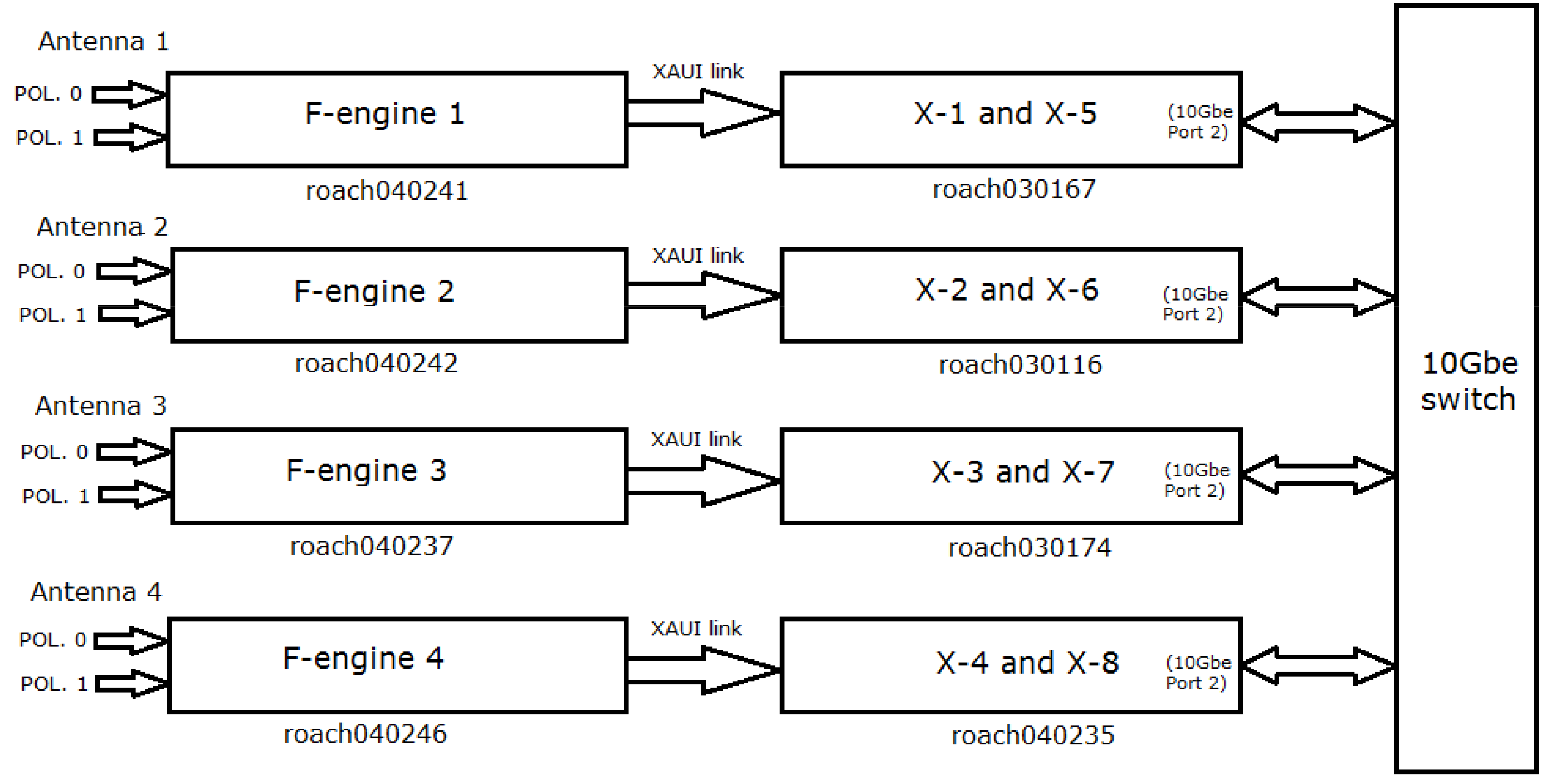
GMRT Wideband Backend (GWB) comprising of FPGAs and GPUs

GMRT Wideband Digital Backend

GMRT Wideband Digital Backend for processing 16 antenna dual polarization 400 MHz using FPGAs and GPUs

A Tflops Machine !

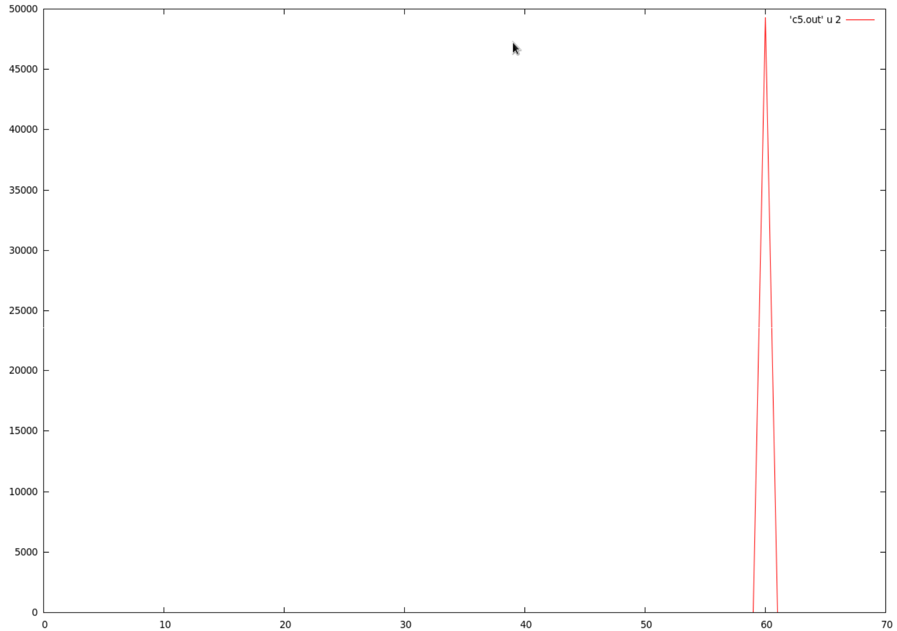
Beamformer Development: Example



Connections between F-engine and X-engine.

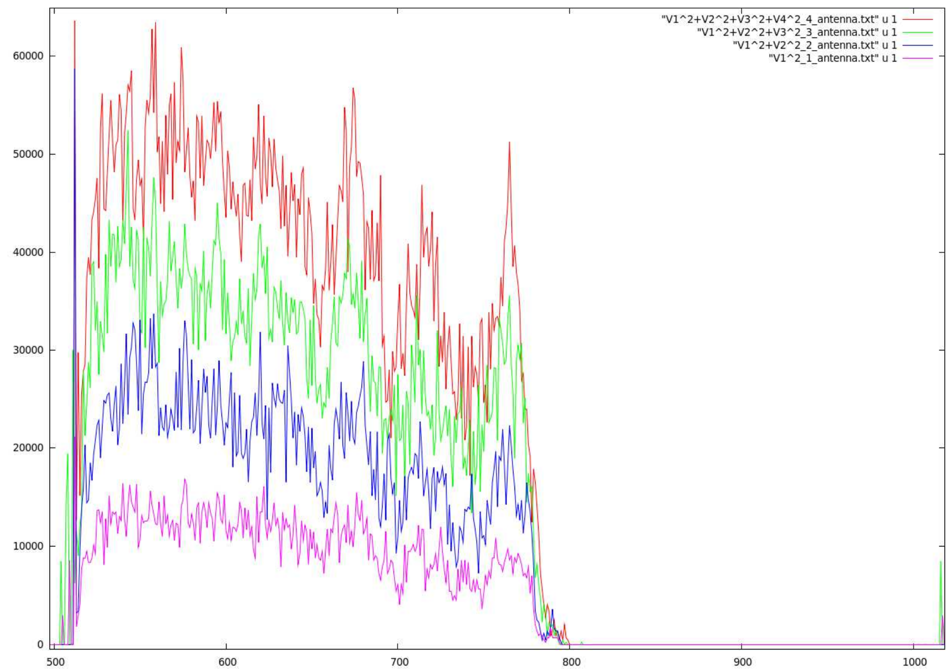
8-input Packetized Beamformer: 8 FPGA boards, 512-channel, 400 MHz, 163 us integration time

Beamformer Development: Tests



Beam output for sine (CW) input

Beam output for noise input: Adding one input at a time

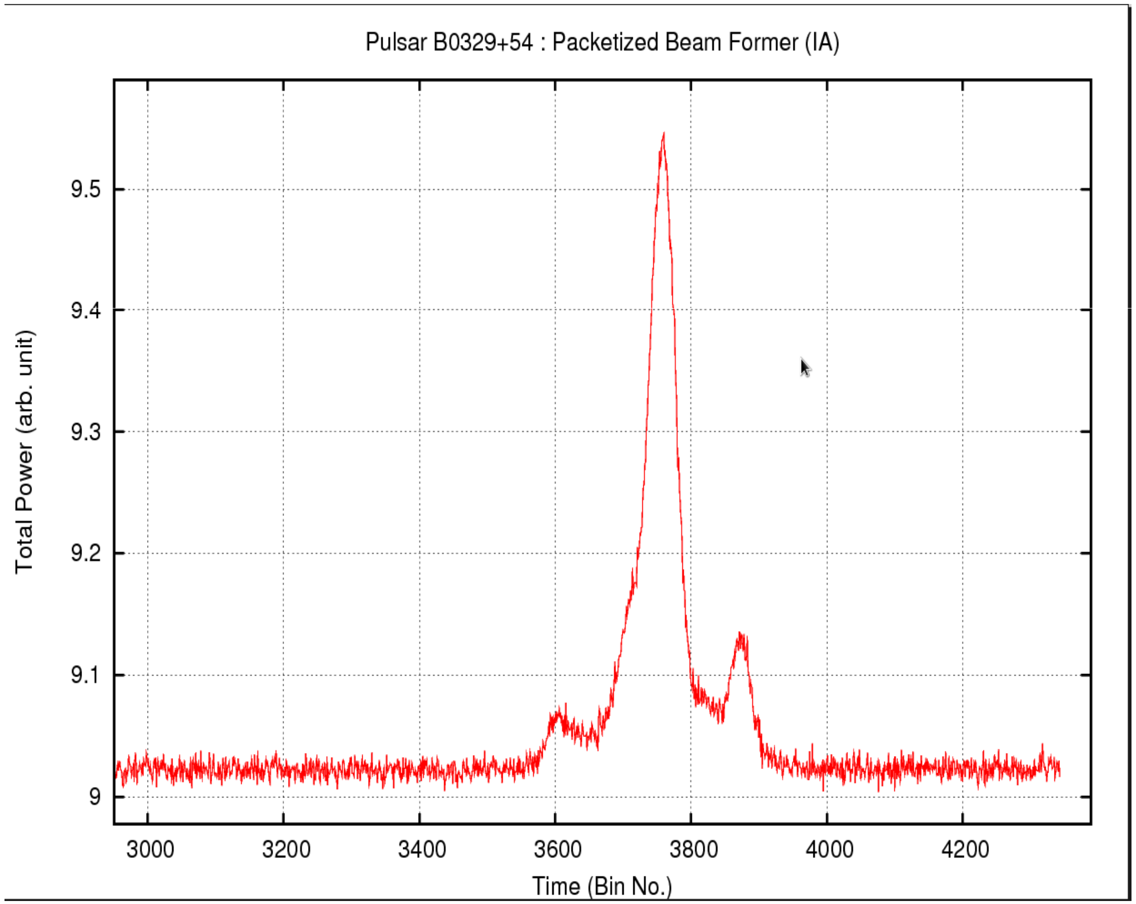


Beamformer Development: Sky tests

- <u>Date of observation</u>: 30th October 2013.
- <u>Pulsar</u>: B0329+54

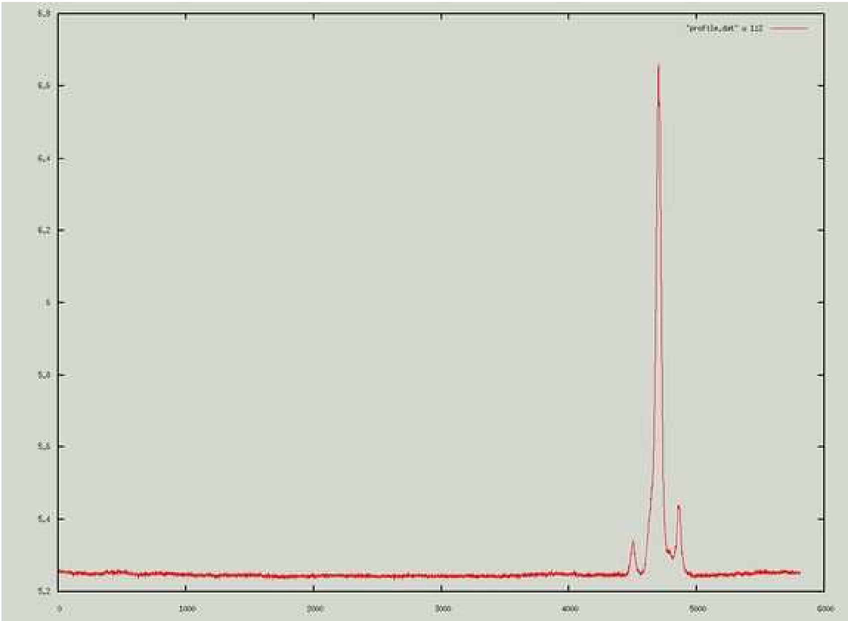
<u>Antennas</u> : 4 GMRT central square antennas.

- <u>Sampling clock</u>:800
- MHz.
- <u>Integration time</u>: 0.163 millisecond
- <u>Beamformer Bandwidth</u>: 400 MHz
- <u>RF Bandwidth</u>: 32 MHz
- <u>Number of channels</u>:512

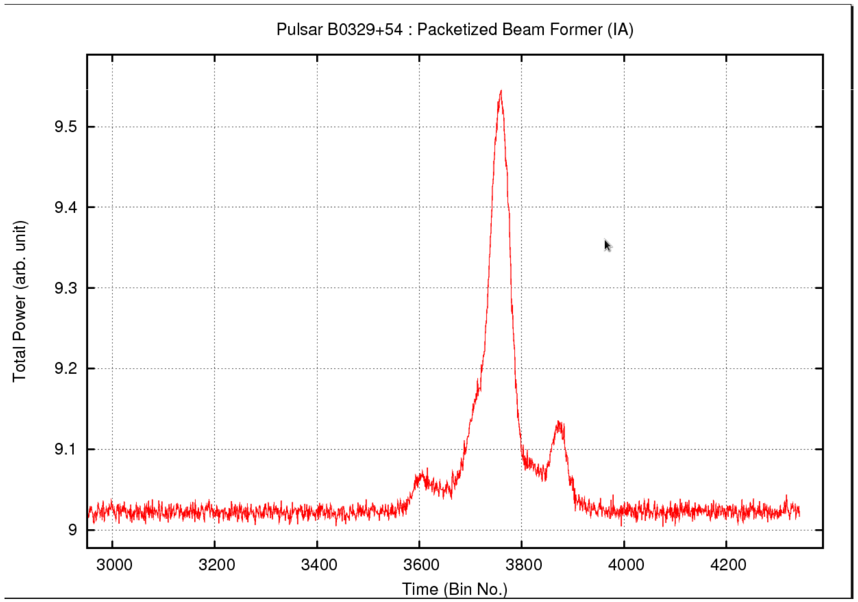


Beamformer Development: Comparison with GSB

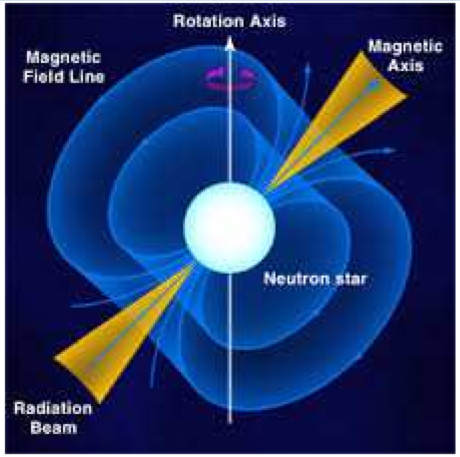
Pulsar Profile from GMRT Software Backend (GSB)



Pulsar Profile from Packetized Beamformer



Applications of Array Mode



Array mode is primarily used for Pulsar studies

Pulsars are rotating neutron stars, flux from which is detected on the Earth as periodic pulses (light house effect !)

Pulsars are compact sources (point sources for most radio telescopes)

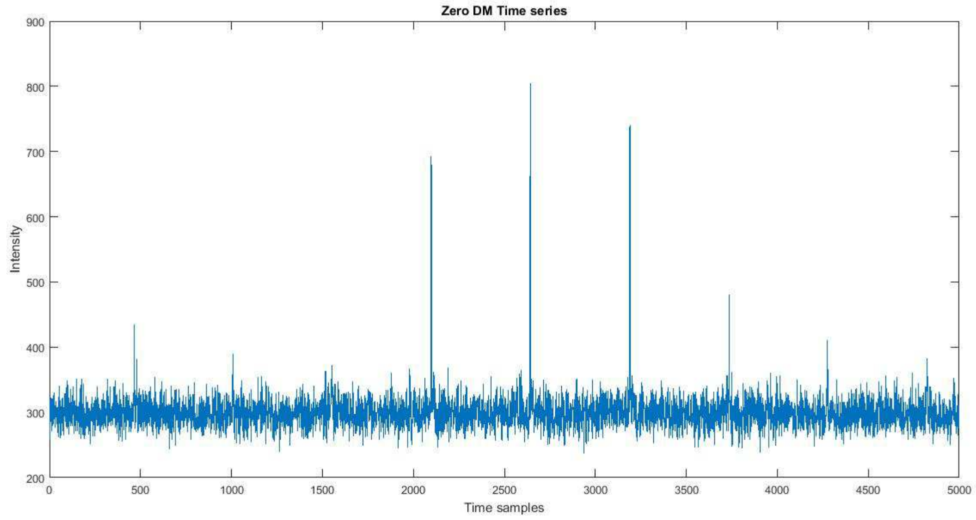
Need a sensitive radio receiver with signal processing capability to detect and study Pulsars

Improved sensitivity in the array mode helps in searching new pulsars and also studying its astrophysical properties

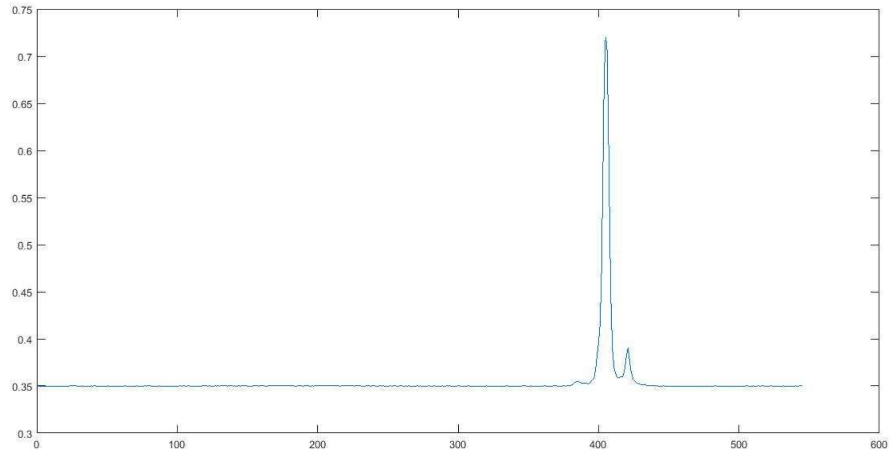
Techniques for increasing field-of-view using focal plane array use beamformer to form multiple beams in the desired directions

Image Courtesy: ASTRON

Pulsar – Single Pulse & Folded Profile



Time-series (Beamformer output) showing single pulses from pulsar B0329+54 (uGMRT 325 MHz)

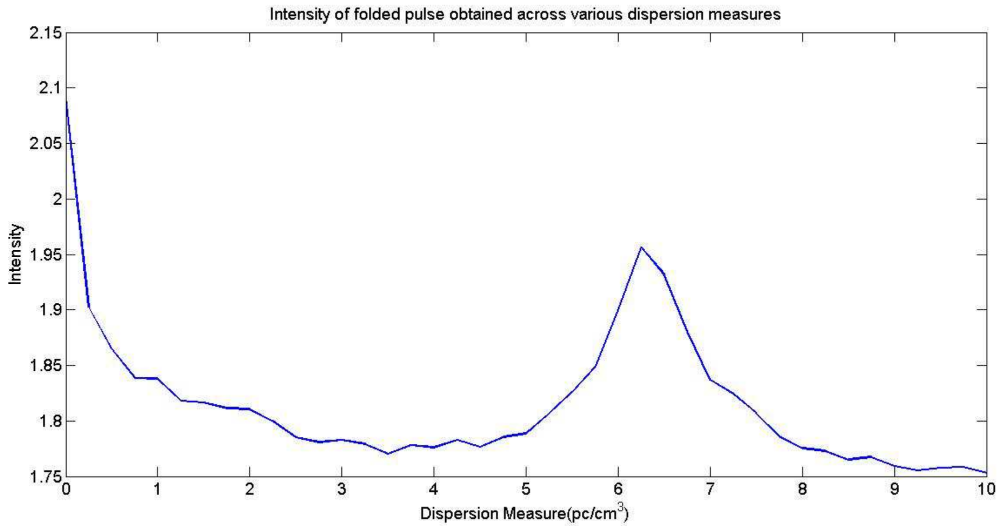


Best profile – after de-dispersion and folding for pulsar B0329+54 (uGMRT 325 MHz)

Image Courtesy: Prajwal V.P.

Offline processing of beam output

De-dispersion → Collapsing → Folding



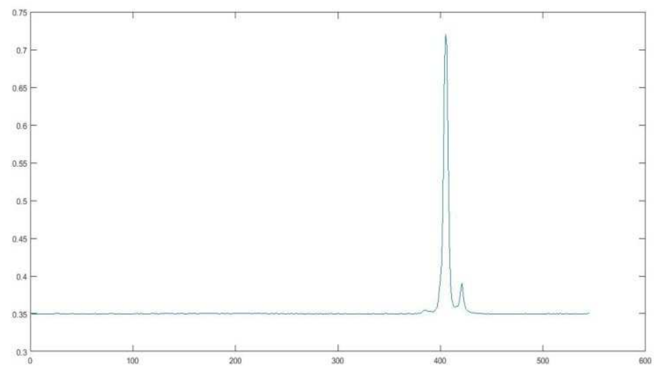
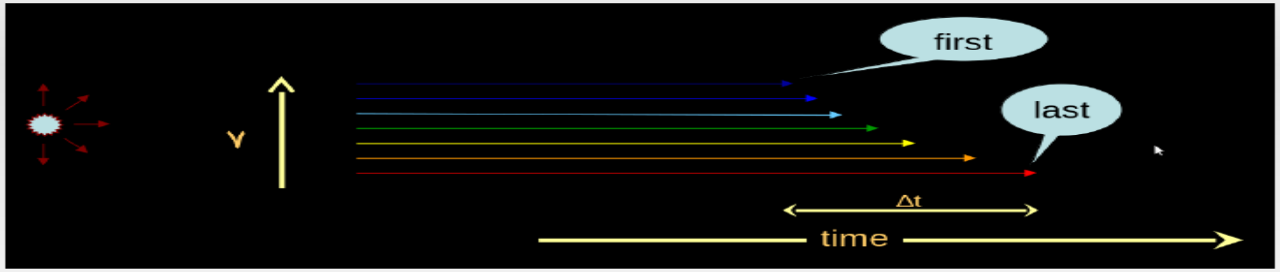


Image Courtesy: Prajwal V.P.

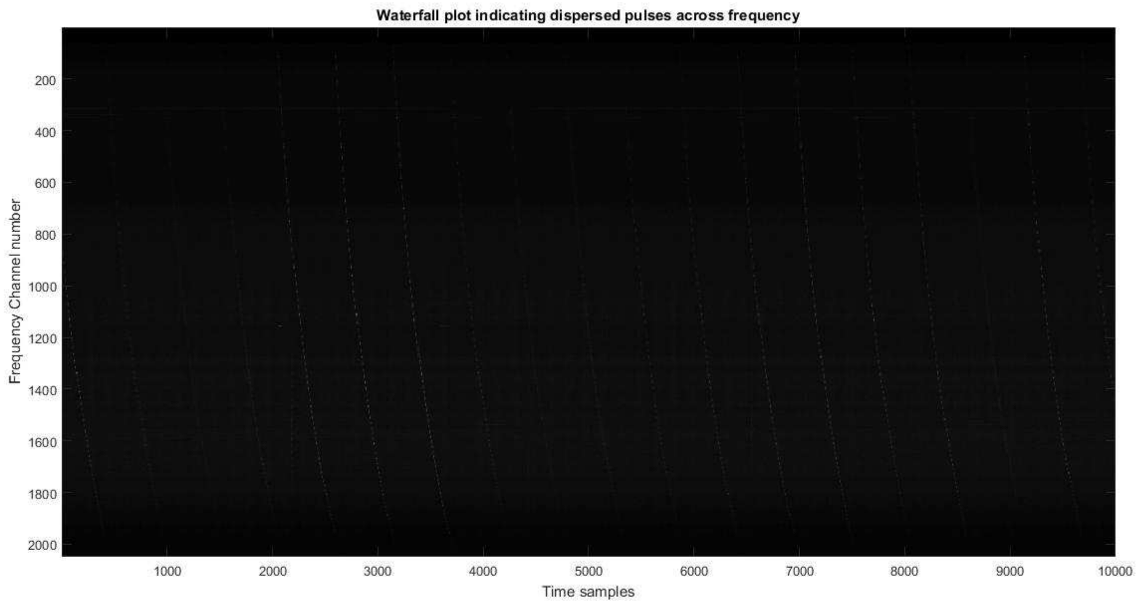
Dedispersion



$$\Delta t(ms) = 4.15 \times 10^6 \times \int n_e\, d\ell \times (\nu_1^{-2} - \nu_2^{-2})\ ; \quad \nu \text{ is in MHz}$$

$\int n_e\, d\ell$ → **Dispersion Measure (DM)**

(Electron density integrated over the distance from the source to the observer)



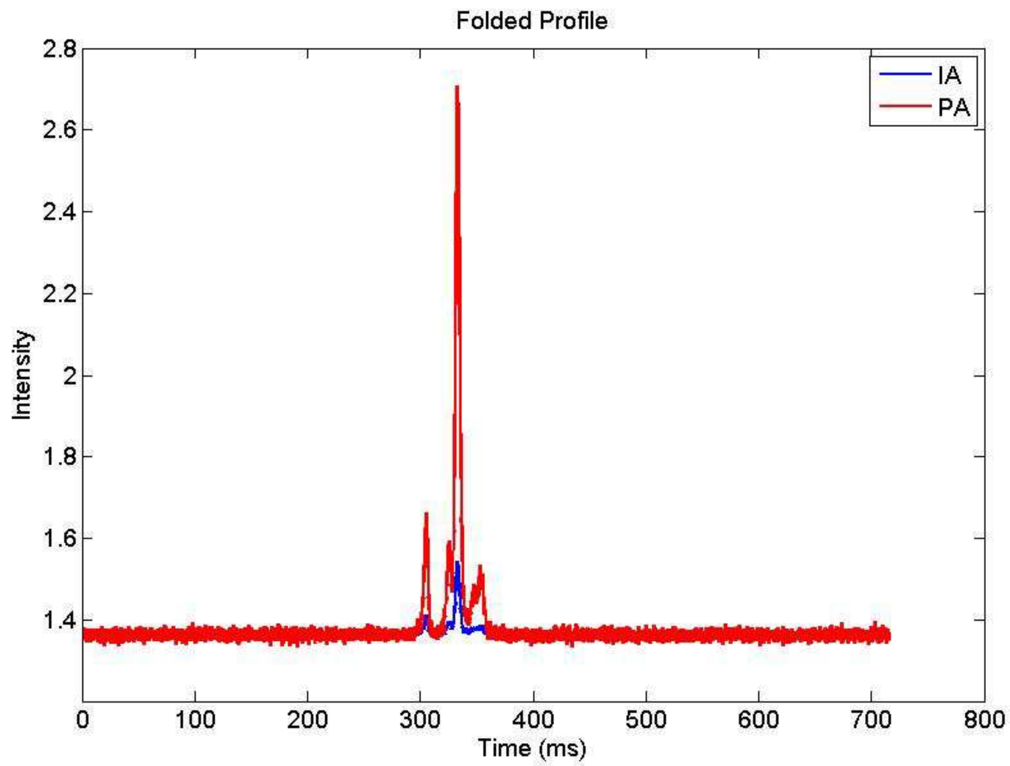
Comparison of Pulse Profile: IA and PA

Pulsar B0329+54 observed using 9 antennas of GMRT simultaneously in IA and PA modes

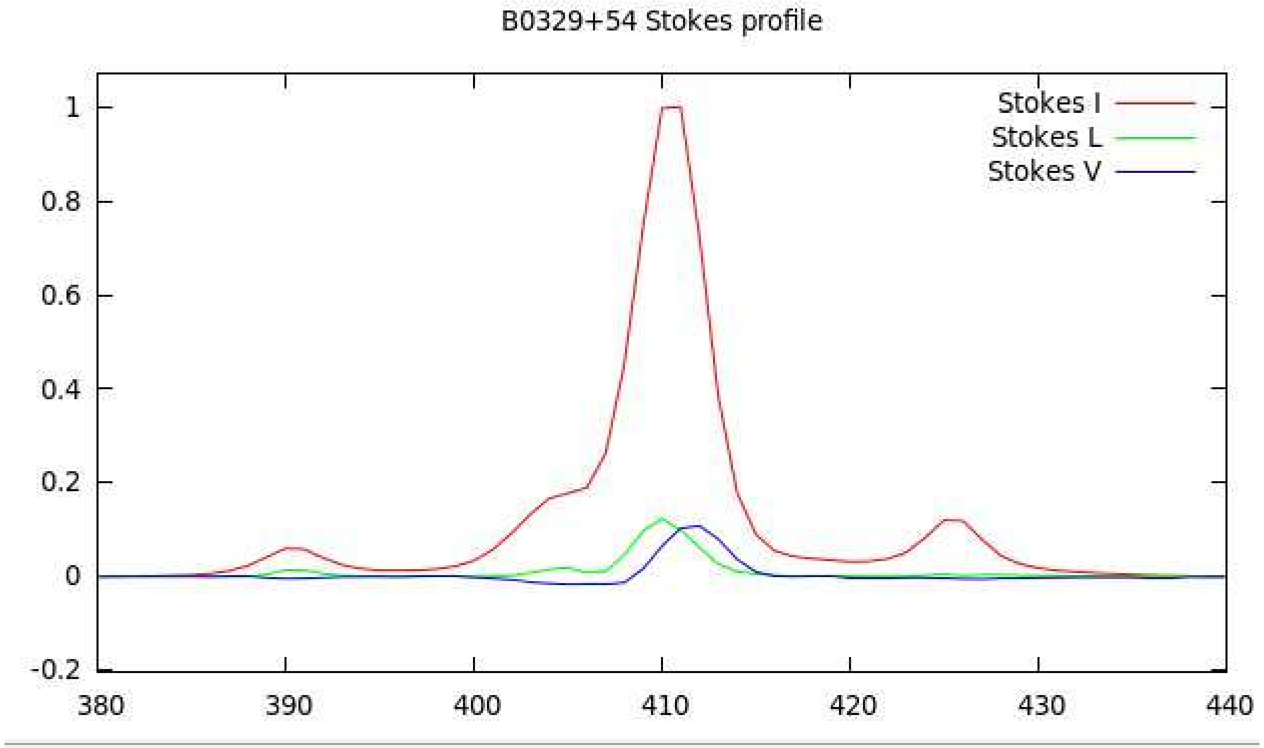
RF: 250-500 MHz
BW: 200 MHz
Sampling interval: 1.31072 ms

Improvement in the SNR for PA beam with respect to IA beam
Expected: 3 $(9^{0.5})$
Achieved: 2.7425

Mismatch in the values could be due to RFI or de-phasing



Polarization Studies using array mode



Observed with GMRT at 325 MHz; B0329+54 shows ~15 % polarized emission

Image Courtesy: Prajwal V.P.

Transient Detection Pipeline

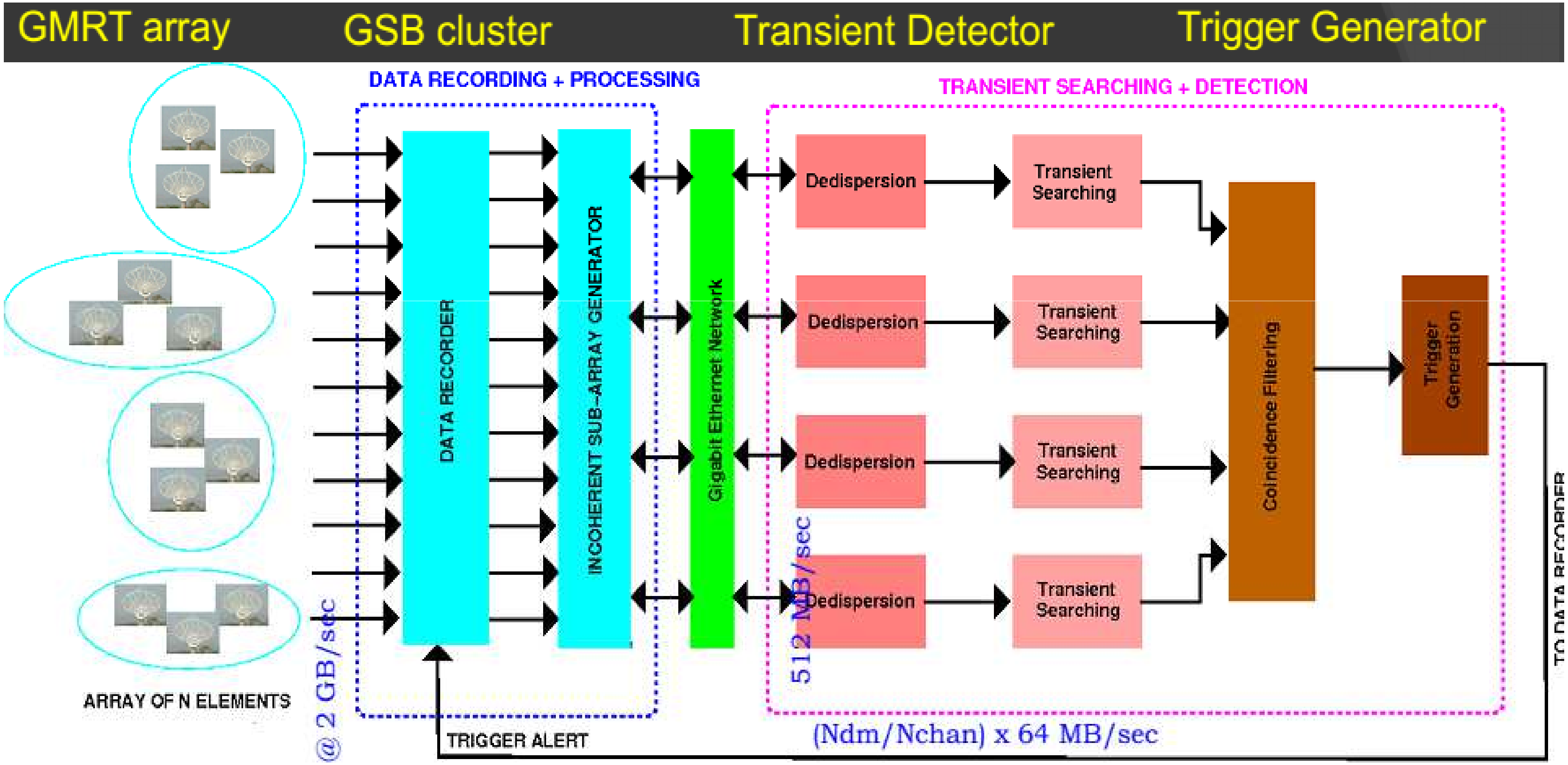
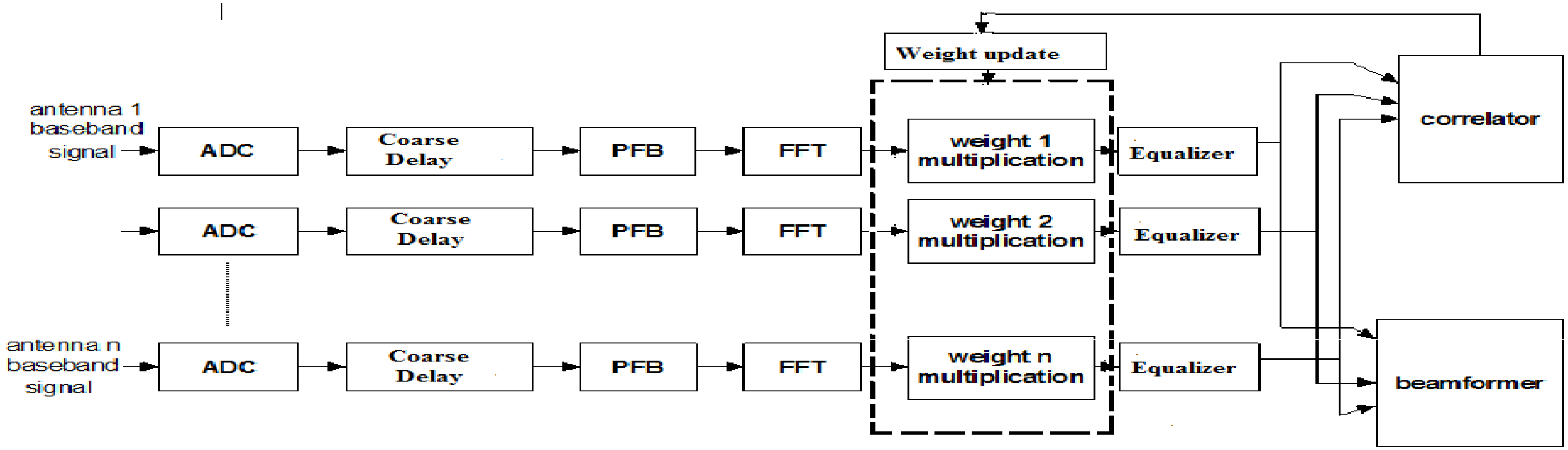


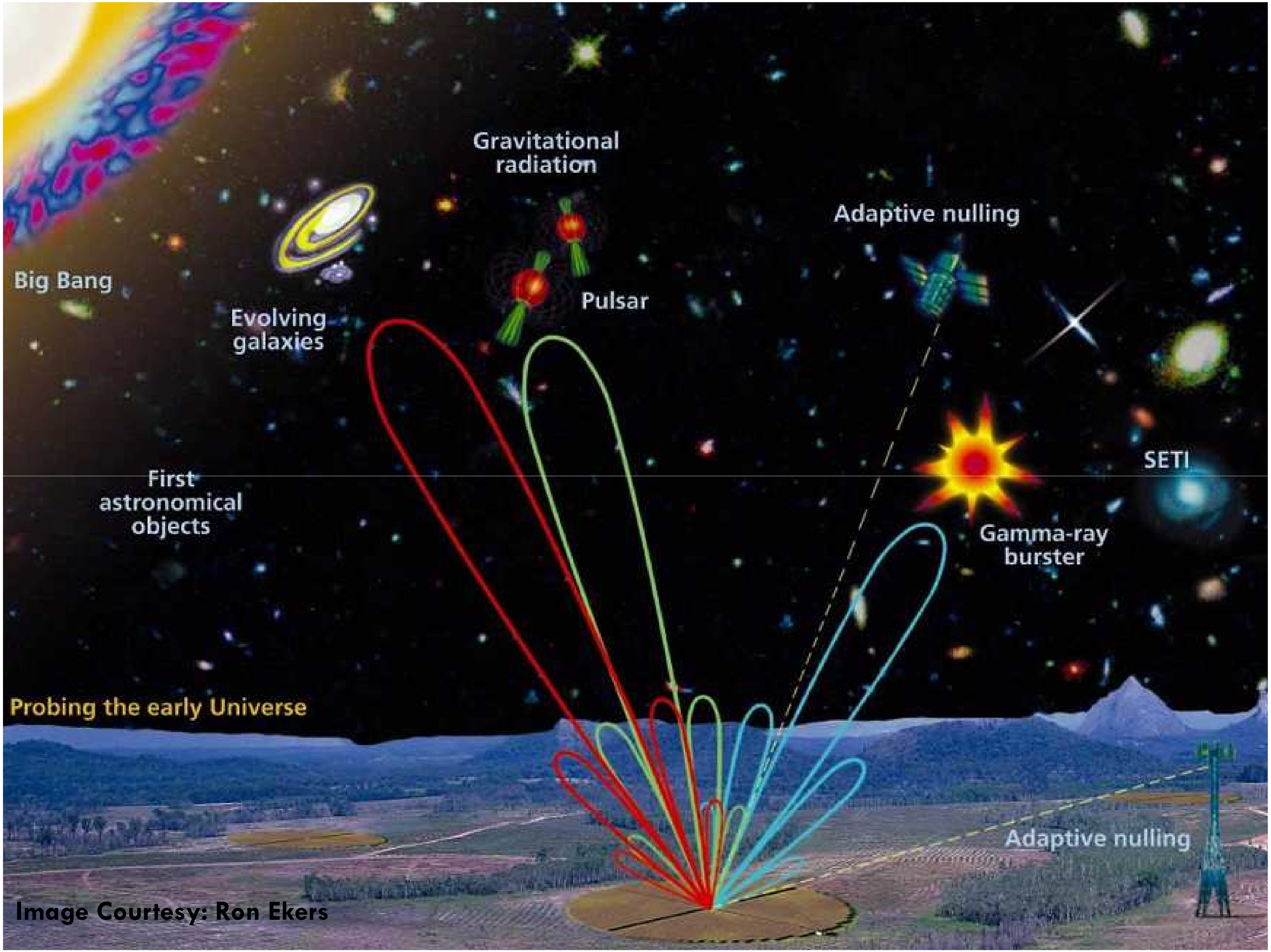
Image Courtesy: Ramesh Bhat et al.

Incoherent Beamformer for GMRT subarray

Multi-beam Beamformer for FPA



- ❑Multi-beam beamformer is used for forming multiple beams in the field-of-view of the antenna
- ❑Phase correction is different for each beam output leading to beams in different directions
- ❑Needs a correlator to compute the phase values
- ❑Delay correction is not required as the elements spacing is less


Gravitational radiation
Adaptive nulling
Big Bang
Evolving galaxies
Pulsar
SETI
First astronomical objects
Gamma-ray burster
Probing the early Universe
Adaptive nulling
Image Courtesy: Ron Ekers

Suggested Reading

- Chengalur J.N., Gupta Y., Dwarkanath K.S., "Low Frequency Radio Astronomy", NCRA, 2003
- Gross Frank, "Smart Antennas for Wireless Communications", Mc-Graw Hill, 2005
- Michael Kramer, Duncan Lorimer, "Handbook of Pulsar Astronomy"
- Thompson, A.R., Moran, J.M. & Swenson, G.W. "Interferometry and Synthesis in Radio Astronomy", John Wiley & Sons, New York, USA, 1986


Thank You!