



Giant Metrewave Radio Telescope (GMRT): A System Overview

Kaushal D. Buch

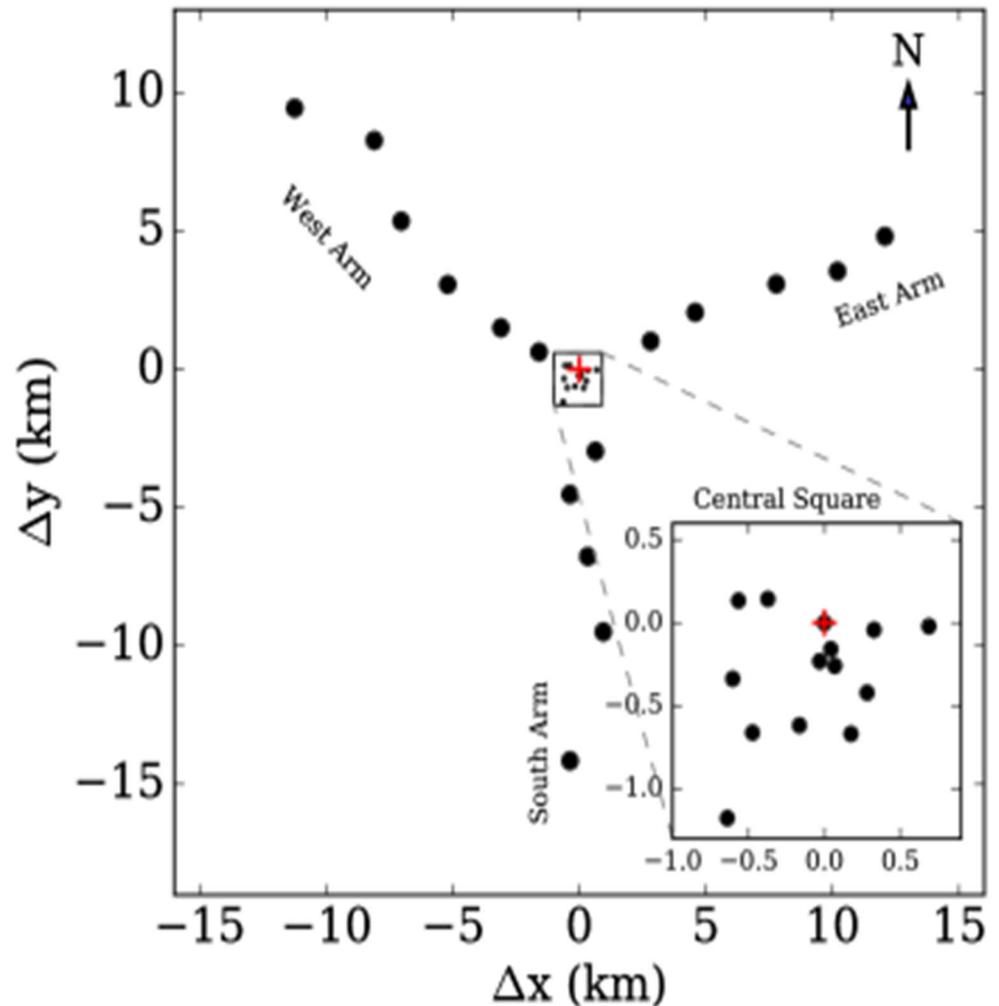
Giant Metrewave Radio Telescope (GMRT), NCRA,
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June 09 2022

GMRT

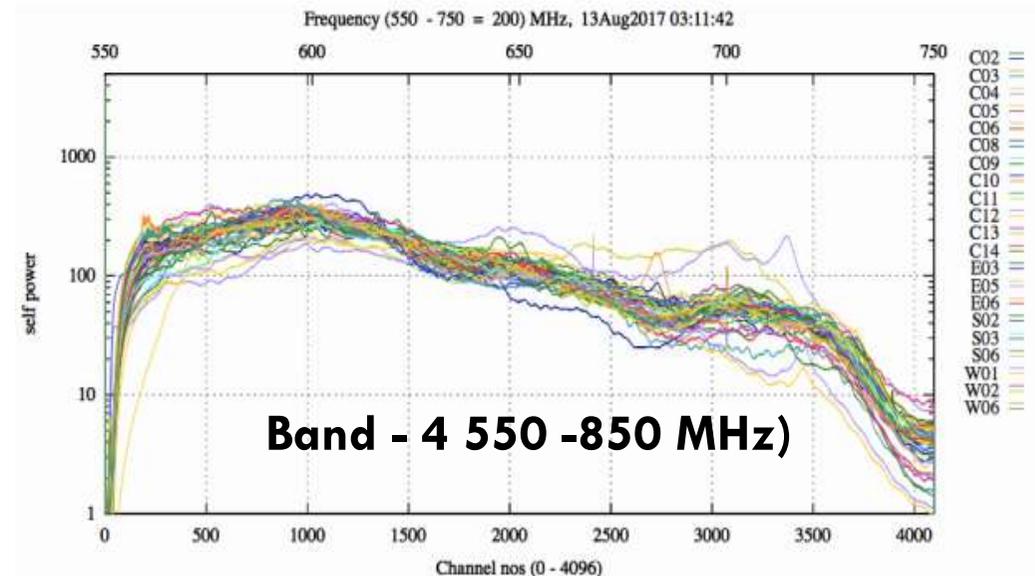
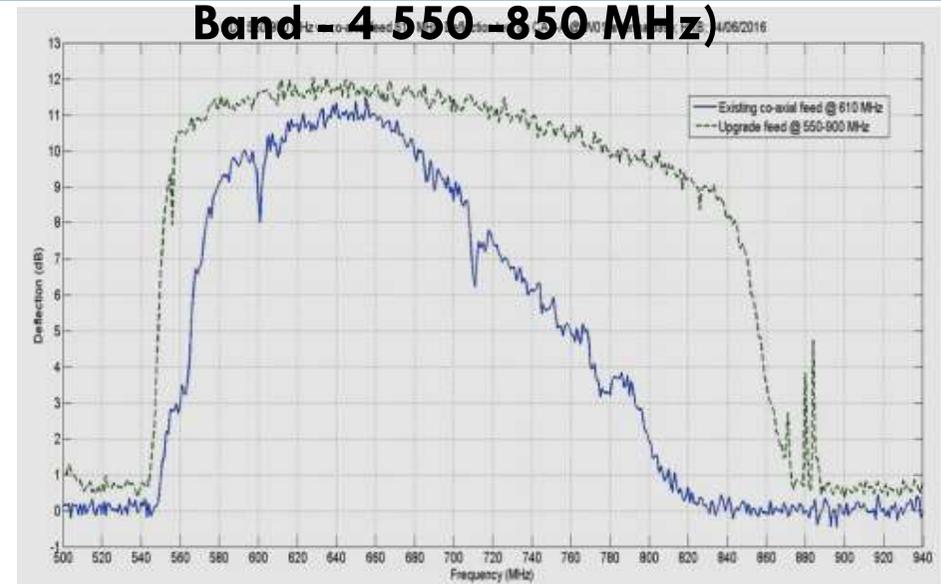
Giant Metrewave Radio Telescope

- ❑ Sensitive telescope operating between 150 to 1450 MHz. A national project of the Govt. of India
- ❑ Located 80 km north of Pune, 160 km east of Mumbai
- ❑ Array telescope: 30 antennas, each of 45 m diameter 14 antennas in 1 sq. km. region, other spread in a Y-shaped array
- ❑ Central square (C00 – C14, except C07), E-arm (E02-E06), W-arm (W01-W06), S-arm (S01-S06, except S05)



The Upgraded GMRT

- Near seamless observing (120 – 1450 MHz)
- Four observing bands:
 - ▣ Band -2 (120 – 240 MHz)
 - ▣ Band -3 (250-500 MHz)
 - ▣ Band -4 (550-850 MHz)
 - ▣ Band -5 (1050-1450 MHz)
- 400 MHz instantaneous bandwidth
- Improved sensitivity ($P=kTB$ watts, for noise-like signals)



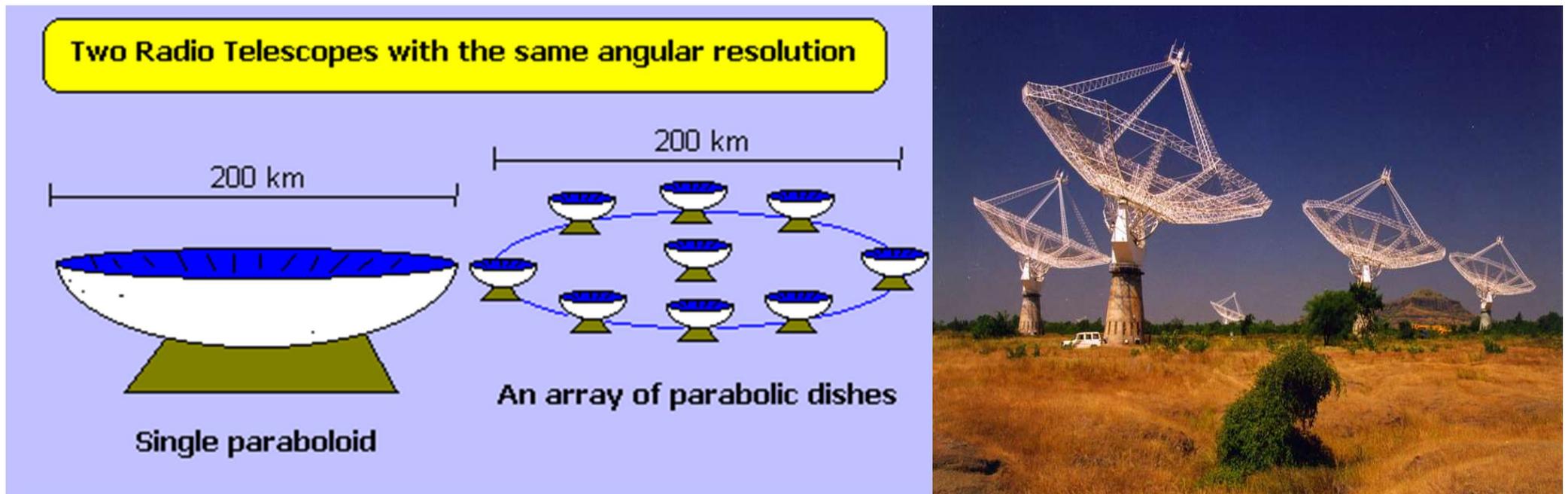
Angular Resolution: resolving distant objects

Resolve two distant objects in the sky

$$\theta \sim \lambda / D$$

For a given wavelength, depends on the diameter of the telescope or maximum separation between two antennas

GMRT best resolution (L-band Synthesized beam): $\sim 2''$



Sampling the source signal through different apertures

Short Spacing Antennas of GMRT



Shortest spacing $\sim 100\text{m}$; largest spacing $\sim 25\text{km}$

Image Courtesy: NCRA Archives

GMRT Systems

GMRT Engineering Groups

Front-End

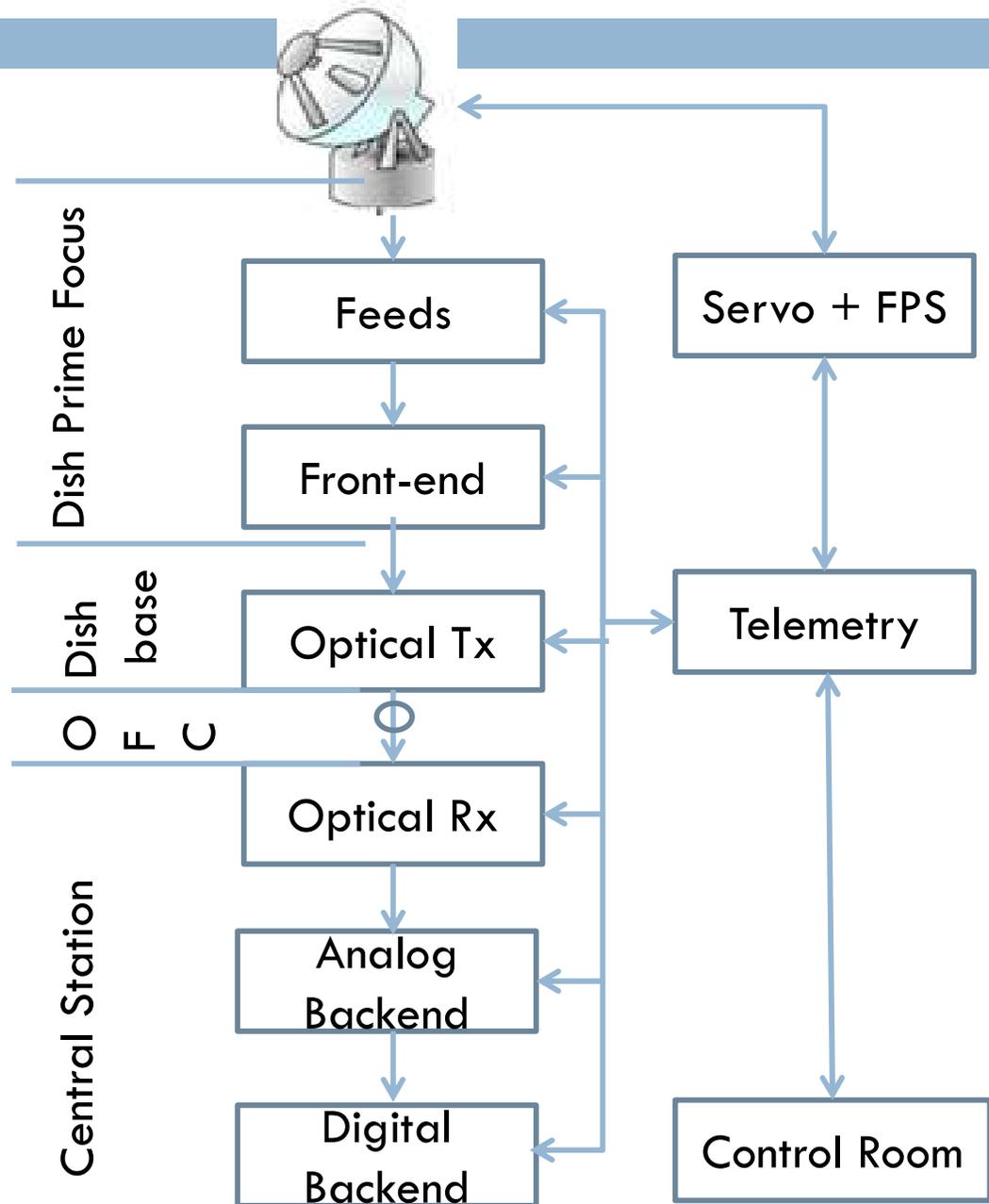
Backend

Servo

Mechanical

Electrical and Civil

Telemetry



GMRT Antenna

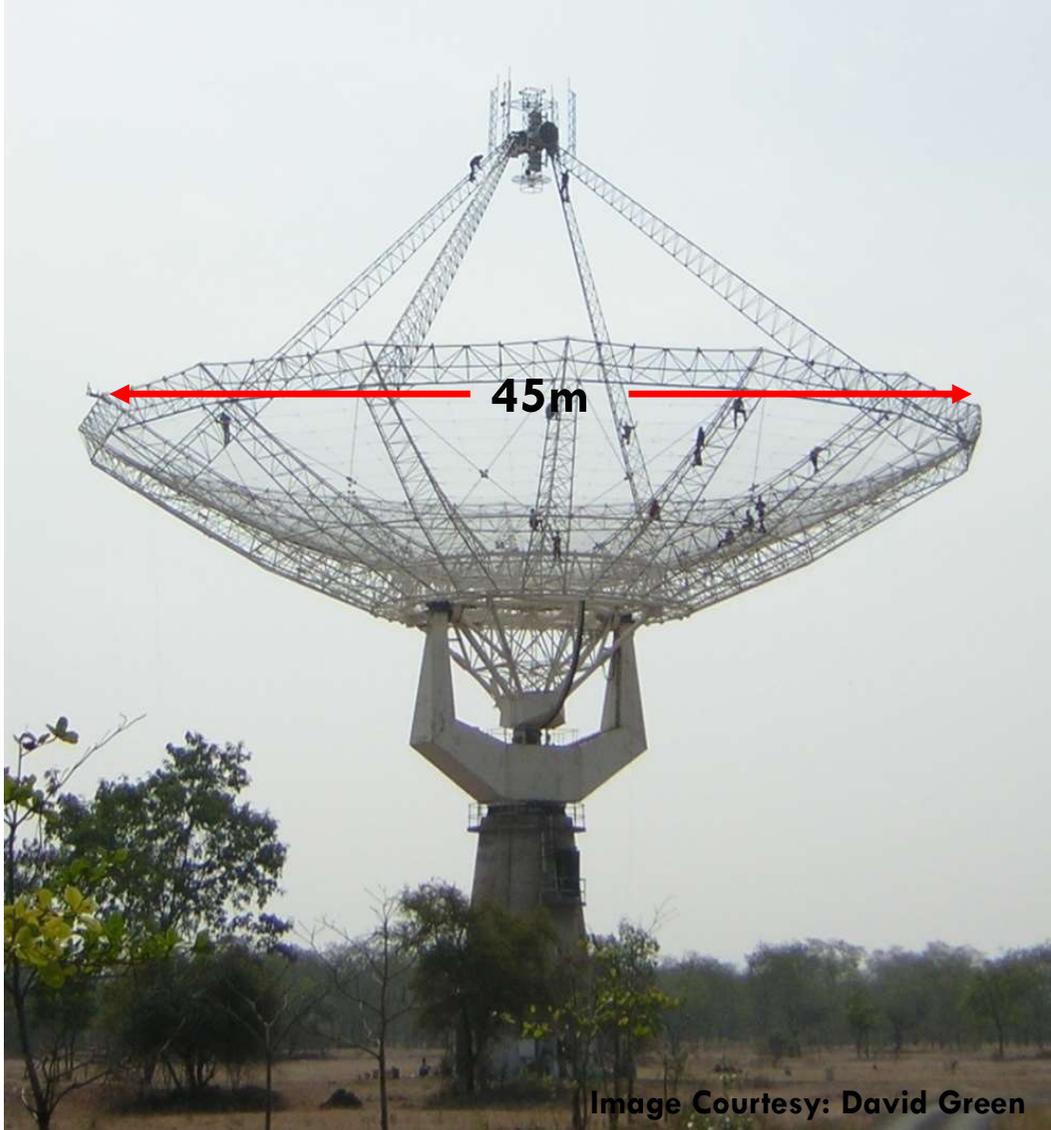


Image Courtesy: David Green

One of the 30 dishes of GMRT

- ❑ Prime-focus parabolic reflector dish antenna of 45m diameter
- ❑ Physical aperture depends on the dish area illuminated by the feed – ~60% up to L-band; ~40% in L-band
- ❑ Wire mesh as reflecting surface
- ❑ Three sectors with different mesh sizes: 10x10 mm (innermost), 15x15 mm and 20x20 mm (outermost)
- ❑ Effective collecting area (GMRT)
30,000 sq m at lower frequencies
20,000 sq m at highest frequencies
- ❑ Four feeds mounted on a turret

GMRT Antenna Parameters

Parameter	Value
Focal Length	18.54 m
Physical Aperture	1590 m ²
f/D ratio	0.412
Mounting	Altitude – Azimuth
Elevation Limits	17 to 110 degrees
Azimuth Range	± 270 degrees
Slew Rates	Alt – 20 degree / min Az - 30 degree / min
Weight of moving structure	82 tons + counter weight of 34 tons
Survival wind speed	133 km/hour
RMS surface error	10 mm (typical)
Tracking and Pointing Error	< 1' arc (up to 20 kmph) Few arc min(> 20 kmph)

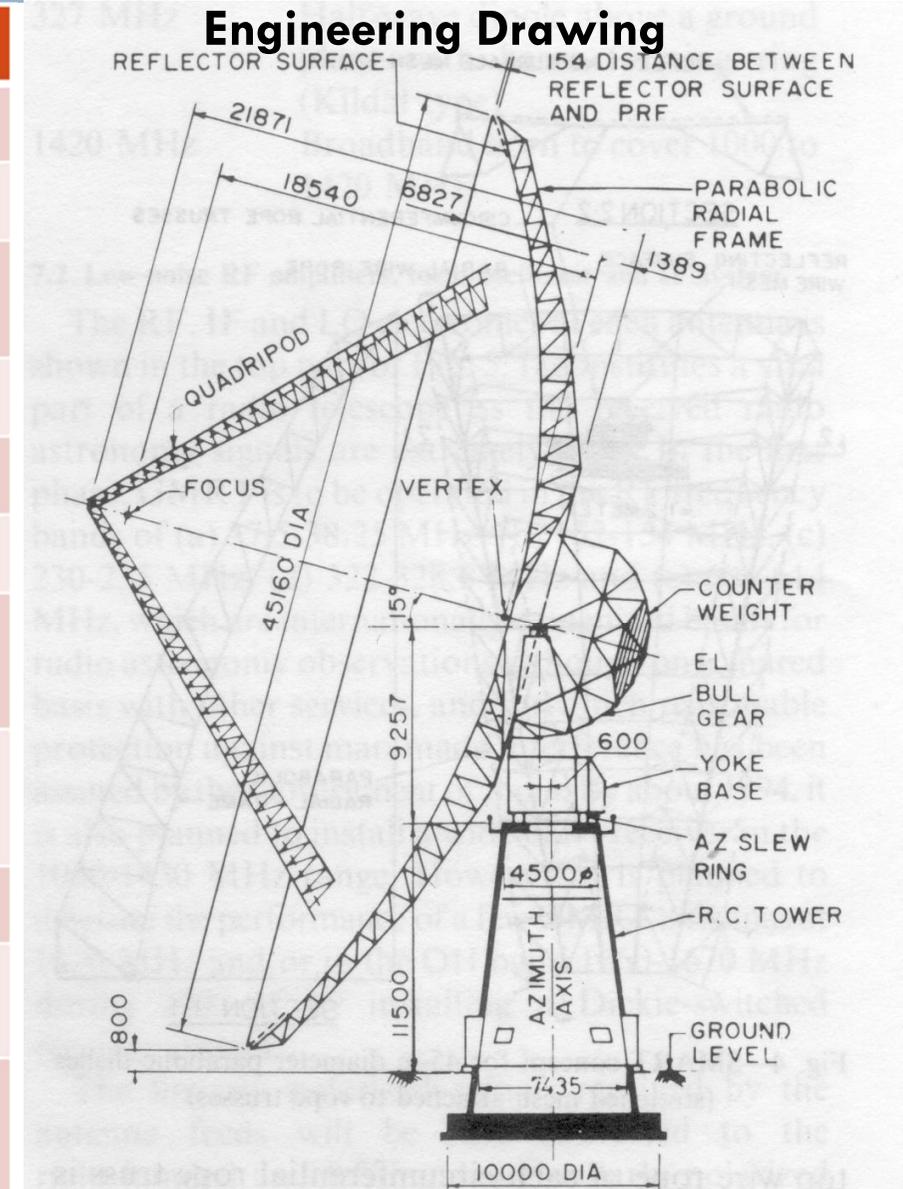


Image Courtesy: Mechanical Group

Dish and Reflecting Surface



- 7% solidity with 0.55 mm diameter Stainless Steel (SS) wires spot-welded at junction point to form a surface with 10x10 / 15x15 / 20x20 mm wire-grid.

- Mesh panel supported by SS rope trusses attached to tubular parabolic frame: SMART (Stretched Mesh Attached to Rope Trusses) concept to form the parabola.

Radio Telescope: Overall Picture

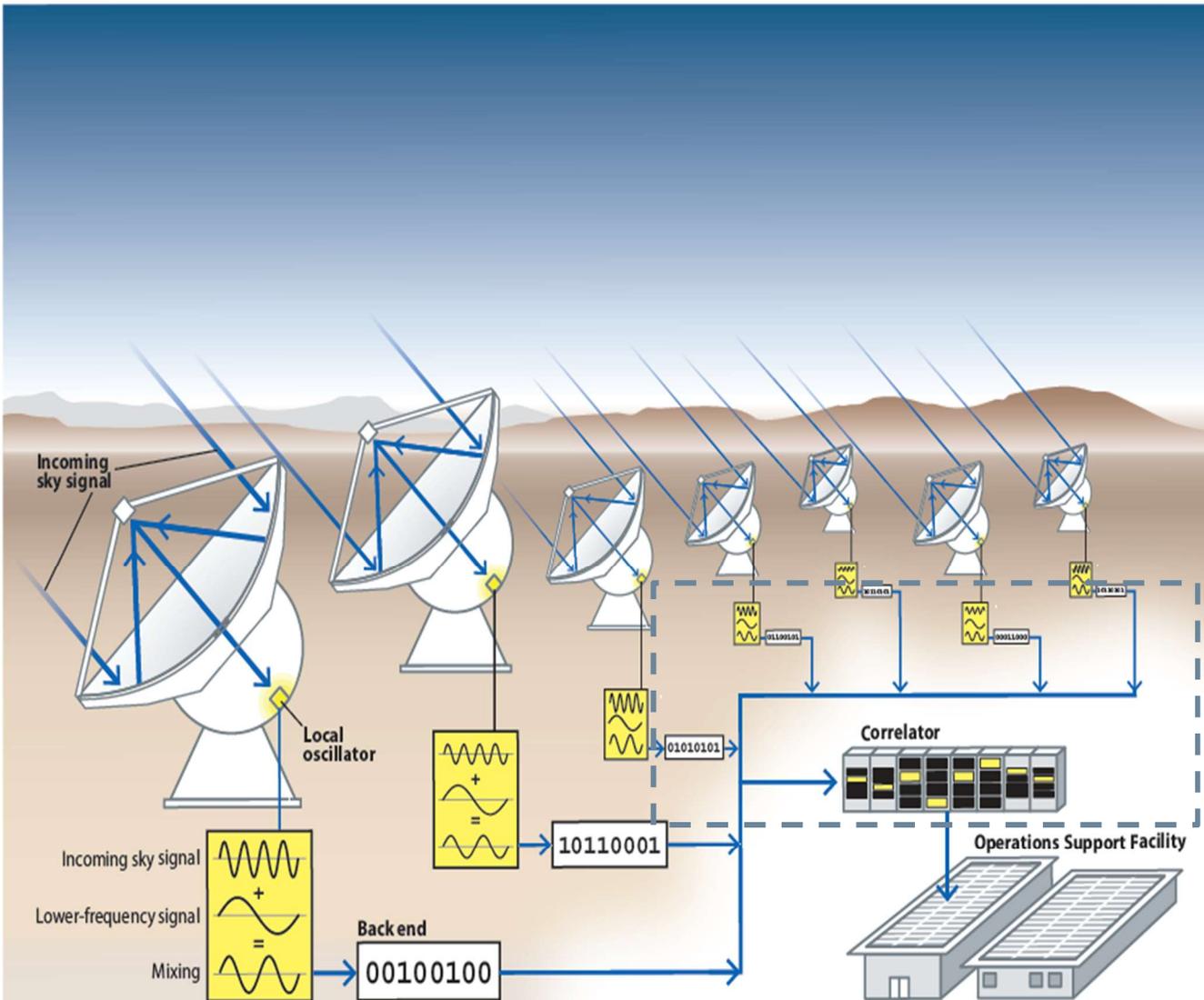


Image Source: Internet

- Converting EM to electrical signals
- Signal Conditioning (amplification, filtering, frequency down-conversion)
- Signal transport (optical fiber) to a common location
- Digitization
- Correlation
- Beamforming
- Recording

Additional systems:

- Servo rotation – accurate pointing
- Telemetry – remote control of various systems from a common location

Feeds and Front-end Electronics



**130 - 260 MHz
(Dual Ring Feed)**

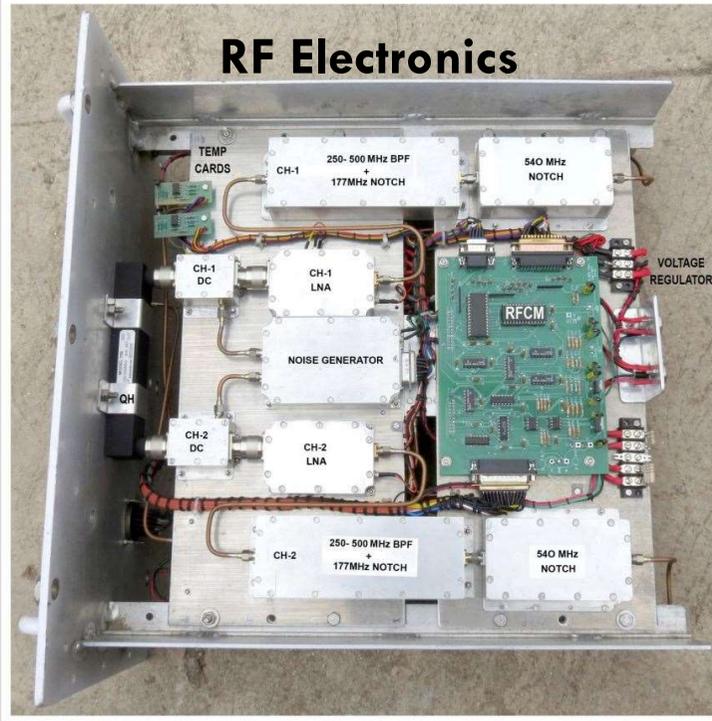
Feeds convert EM waves to electrical signal
Electrical signal amplified using low-noise amplifiers (first stage)



**550– 900 MHz
Cone Dipole feed**



**250 – 500 MHz
(Cone Dipole feed)**



Multi-stage amplification (~60 dB) at prime-focus

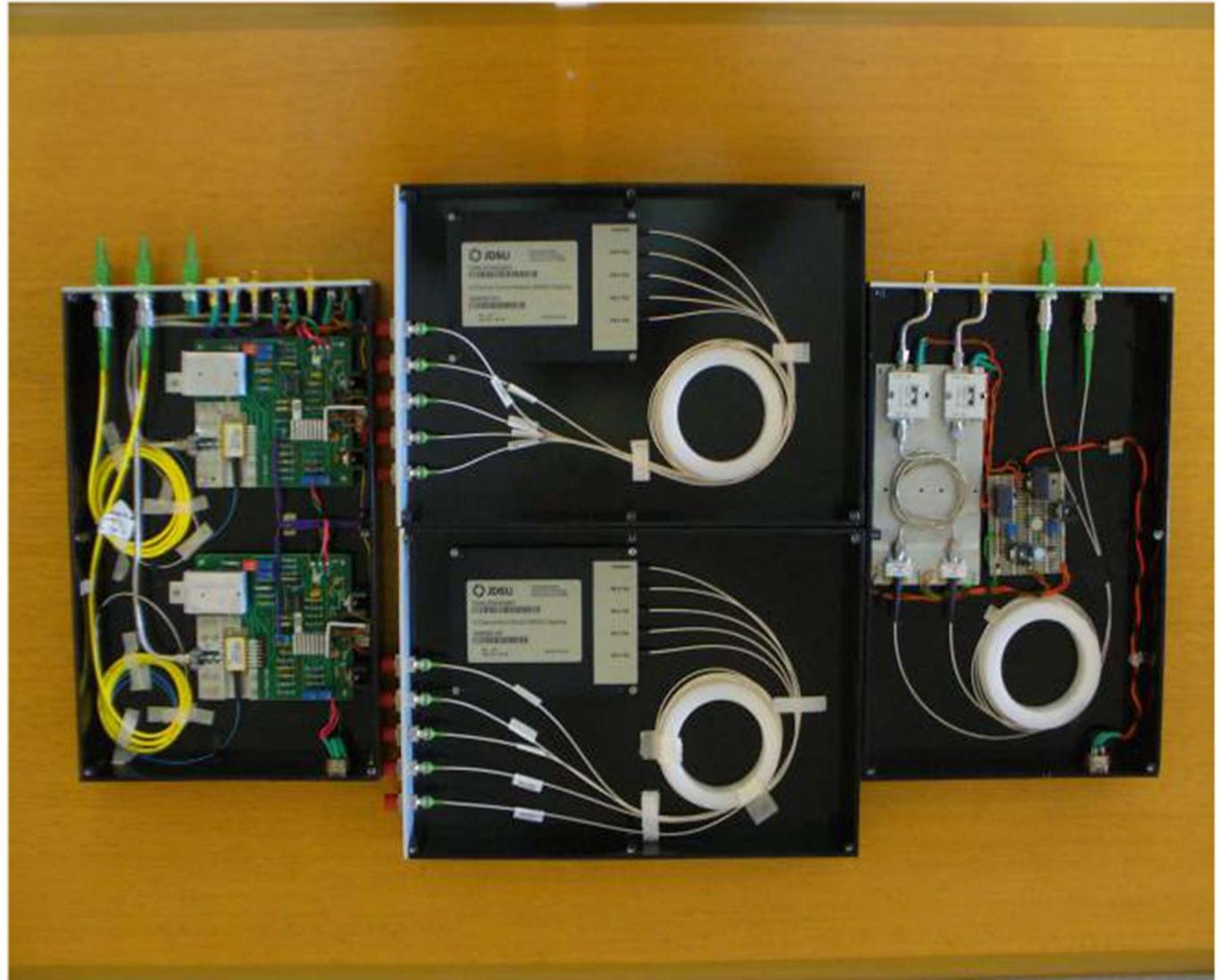
Image Courtesy: FE Group



**1000– 1450 MHz
Horn Feed**

Fiber Optics System

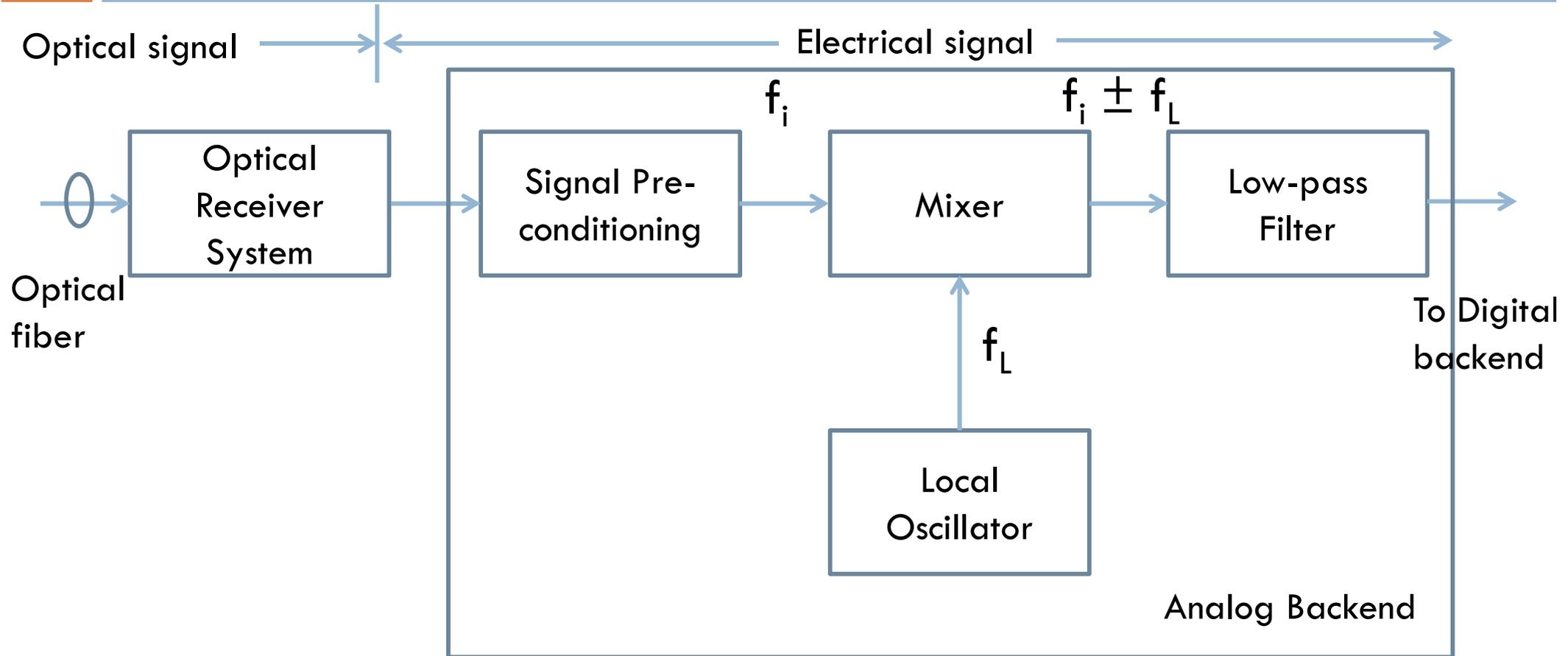
- First radio telescope to use analog fiber optic link for signal transport.
- Fiber buried at a depth of 1.5m below the ground to reduce the effect of temperature on phase stability of the link.
- Link distances vary from 200 m to 22 km.
- Dense wavelength division multiplexing (DWDM) to accommodate multiple data and control channels on a single fiber.



Signal Processing in the Central Electronics Building



Signal Processing in Receiver Room



Analog backend amplifies the signal, converts from radio frequency to baseband through frequency heterodyning and provides desired bandwidth signal to the digital system

Baseband System - Installation

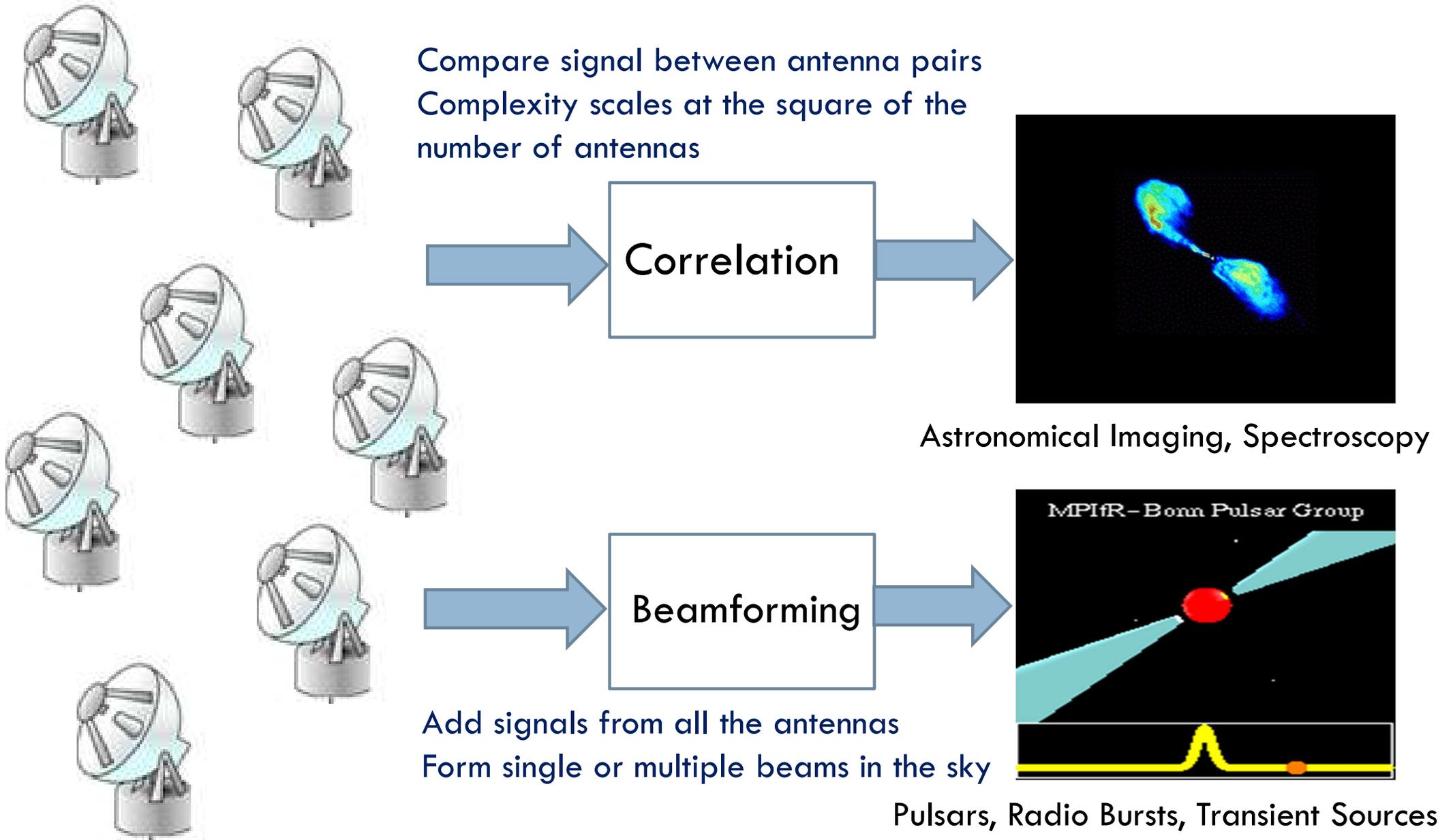


Plug-in Units



Image Courtesy: Analog Backend Group

Correlation & Beamforming



Signal Correlation

Radio Source



Digitized signal from Antenna#1



Digitized signal from Antenna#2

$$R_{xy}(\tau) = \sum_{n=0}^T x[n]y[n + \tau]$$

Cross Correlate signals from antennas after correcting for the delay between them (τ).

For N antennas, $n(n-1)/2$ cross-correlation operations are required. That makes it really complicated!

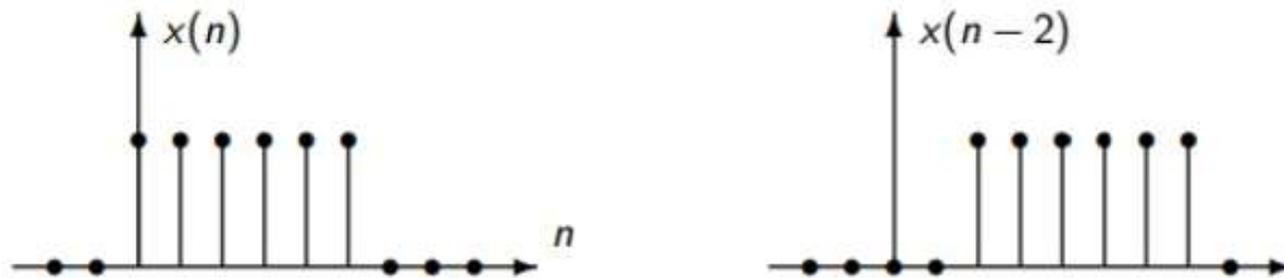
A computationally efficient method is to transform signals to frequency domain and multiply

Correlation gives information about the similarity between two signals - the common component contributed by the source

Delay Correction

(A)

Time delay can be corrected by appropriately sliding the sequences in time domain
Useful when the delay is integer multiple of the clock period



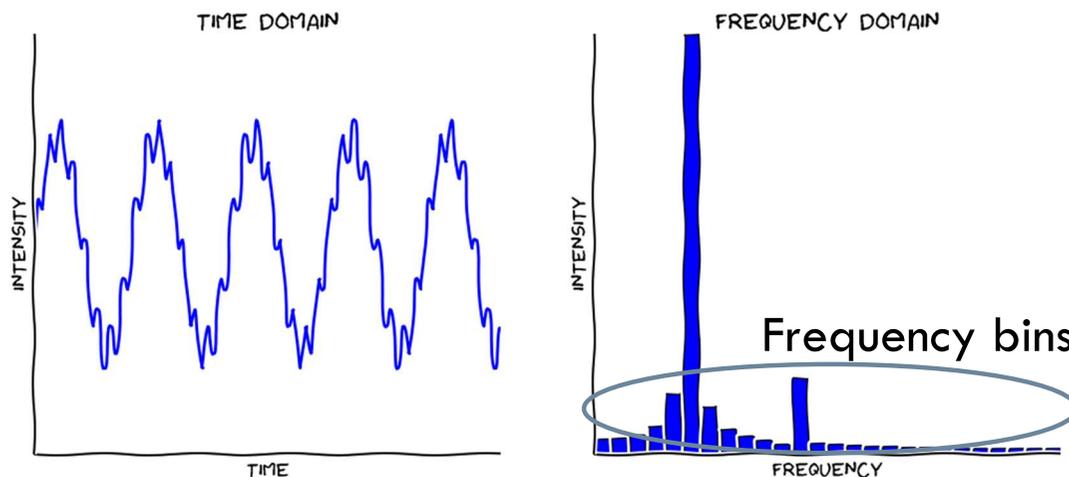
(B)

Can also be corrected by phase multiplication in the frequency domain
Useful for correcting delays that are sub-multiple of the clock period

$$x(t - t_0) \xleftrightarrow{FT} e^{-j\omega t_0} X(j\omega)$$

Correlation in the Fourier Domain

- ❑ Perform Discrete Fourier Transform (DFT) on the antenna signals
- ❑ Fast Fourier Transform – computationally efficient algorithm for computing DFT (N^2 vs $N \log_2 N$)
- ❑ N-point transform provides a frequency resolution of (sampling freq. / N) Hz.



- ❑ Implementation resources and complexity increases with the number of points
- ❑ Frequency resolution depends on the type of observation. Usually the no. of points is of the range of 2048 to 32768 for wideband receivers

Signals in the Fourier domain are multiplied $X(\omega)Y(\omega)$ for getting the cross-correlation – this is done for each bin of antenna#1 with antenna#2 and so on.

Correlation of Complex Signals

- ❑ The output of FFT is complex number
- ❑ Complex multiplication is required for this - each operation needs 4 multiplications and 2 additions

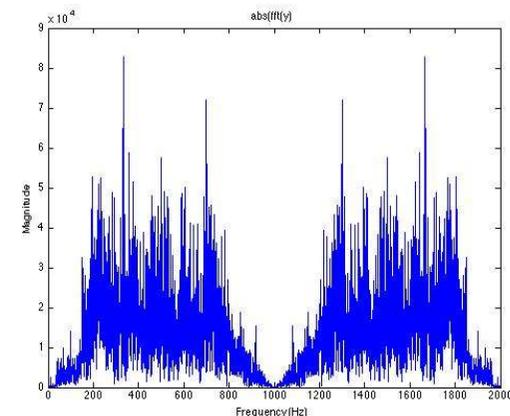
$$\begin{aligned}z_1 z_2 &= (x_1 + iy_1)(x_2 + iy_2) \\ &= x_1 x_2 + ix_1 y_2 + ix_2 y_1 + i^2 y_1 y_2 \\ &= (x_1 x_2 - y_1 y_2) + i(x_1 y_2 + x_2 y_1)\end{aligned}$$

Image courtesy: <http://www.thefouriertransform.com/math/complexmath.php>

- ❑ Since the input signal is real, the number of frequency bins contain redundant information are not used for further processing or correlation (conjugate symmetry property of DFT)

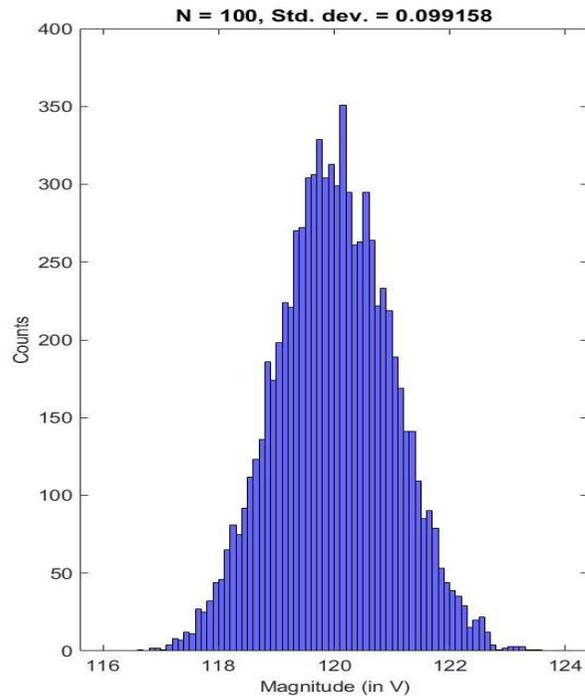
$$X(j\omega) = X^*(-j\omega)$$

- ❑ Note: The above property does not hold if the input is a complex signal

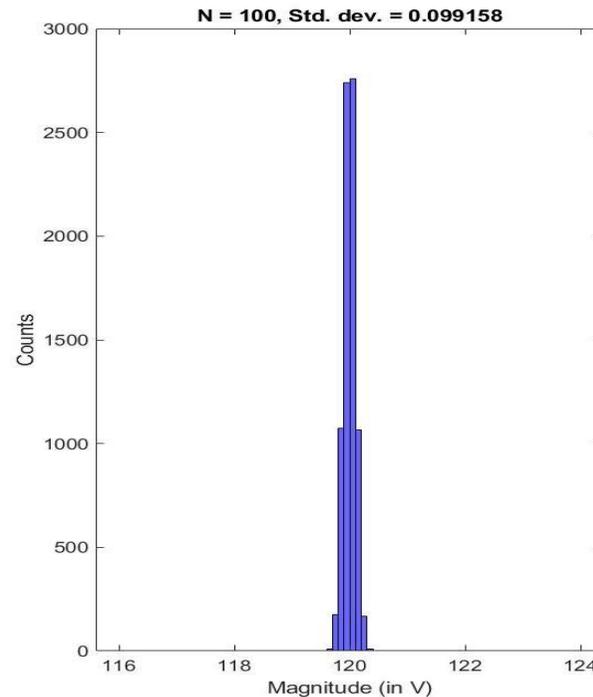


Integration

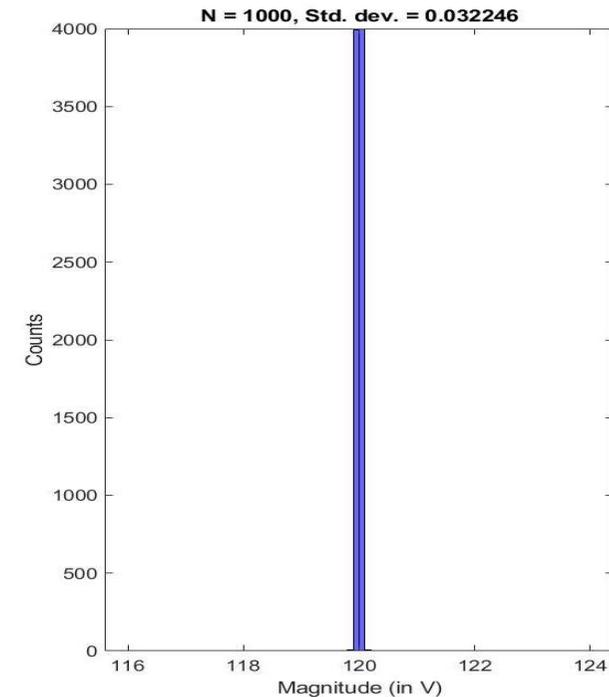
$N = 1, \sigma = 0.99$



$N = 100, \sigma = 0.1$



$N = 1000, \sigma = 0.03$



- 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 !

Reduces uncertainty in the measurement parameter

Beamformer

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

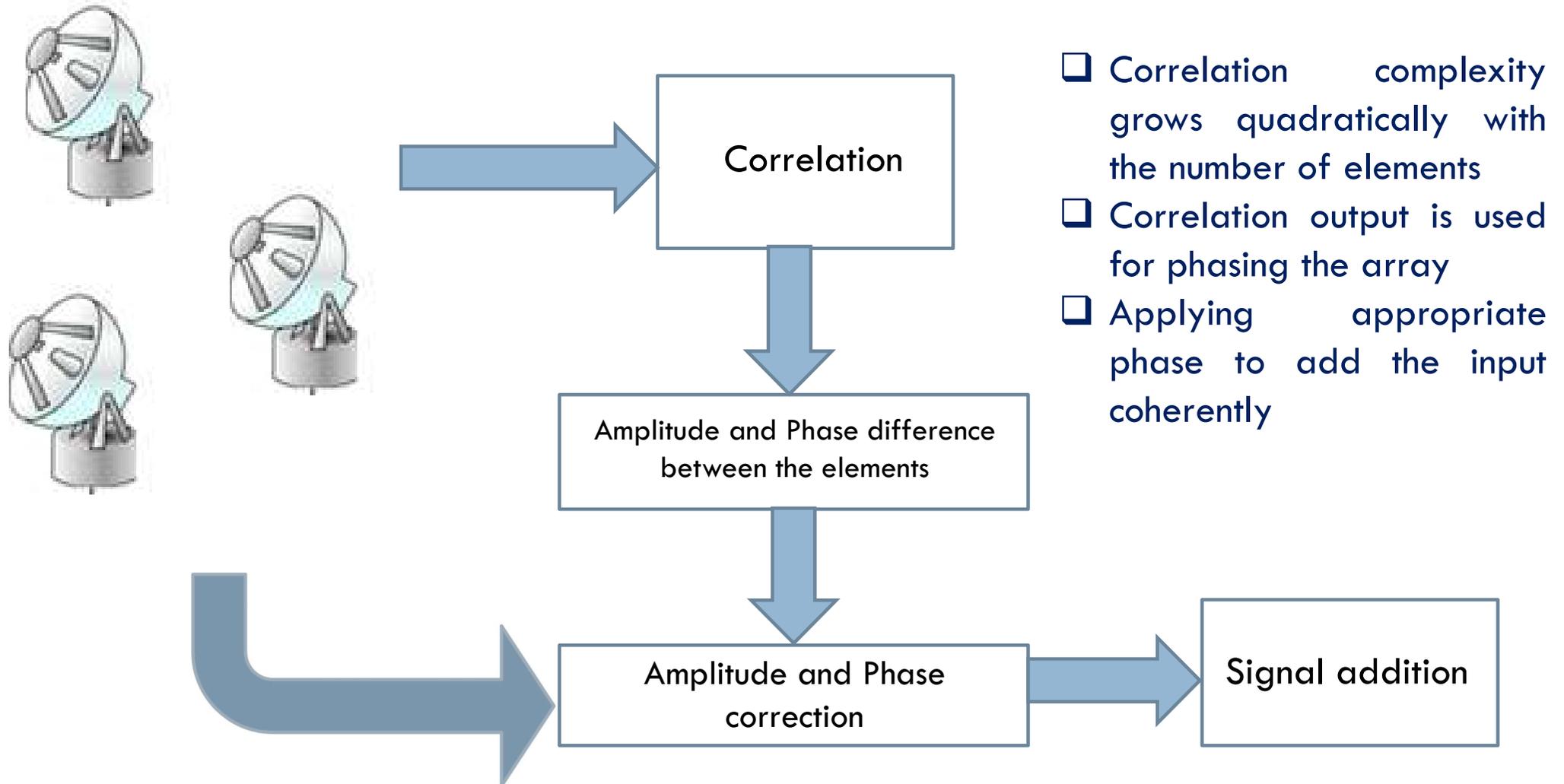
$$B_i = \sum_{i=0}^n (V_1^2 + V_2^2 + \dots + V_N^2)$$

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

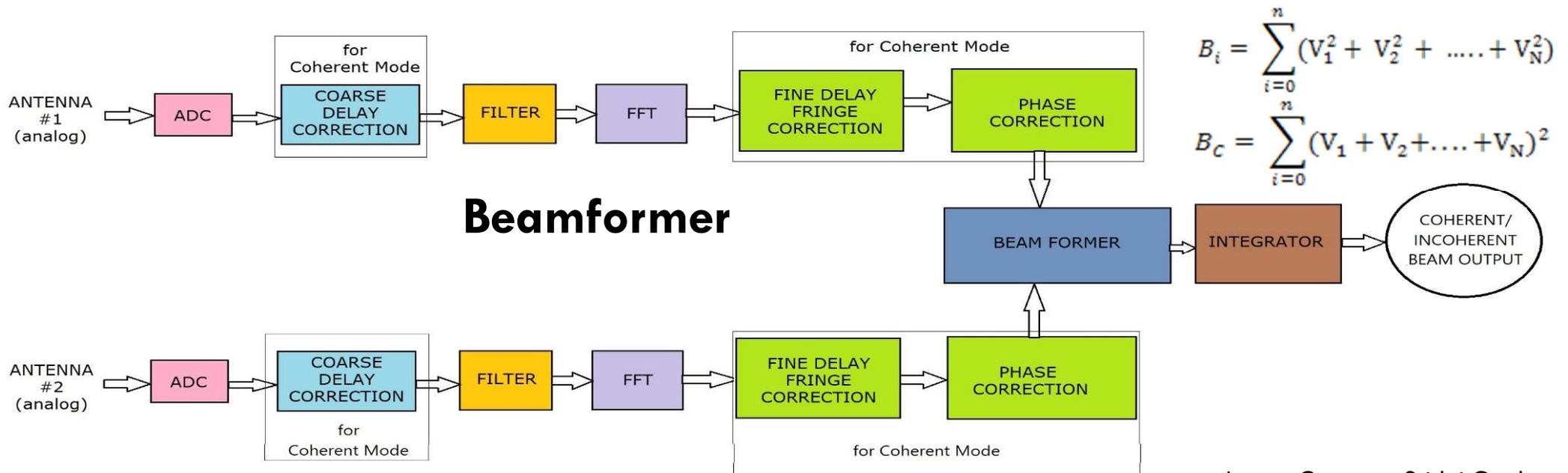
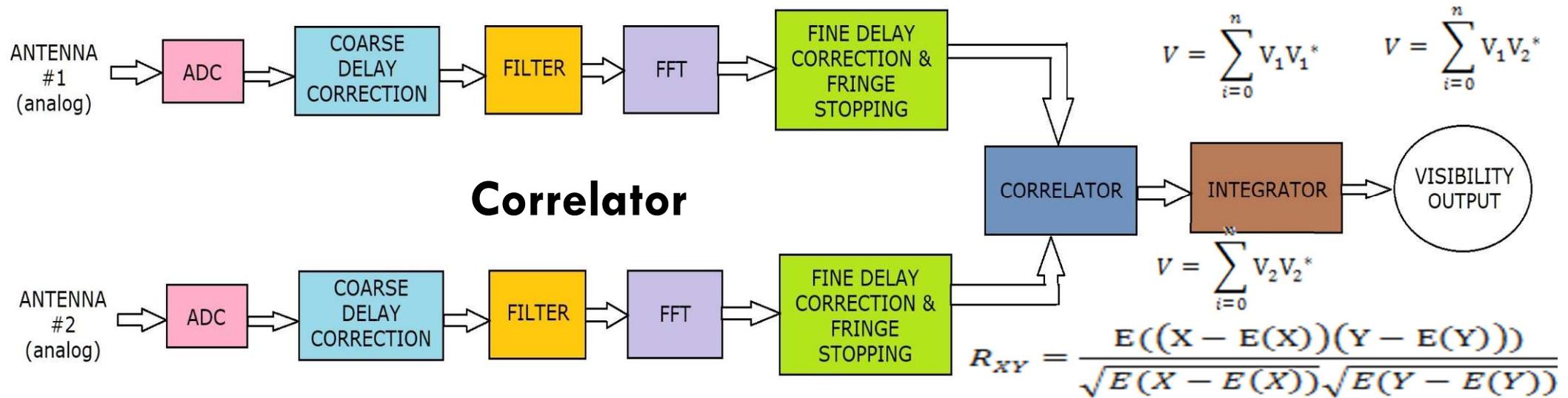
$$B_c = \sum_{i=0}^n (V_1 + V_2 + \dots + V_N)^2$$

Phase is important !

Beamforming in practice



Digital Processing: Block Diagram



Modern Correlators: Example

Correlators consist of signal processing component and networking component

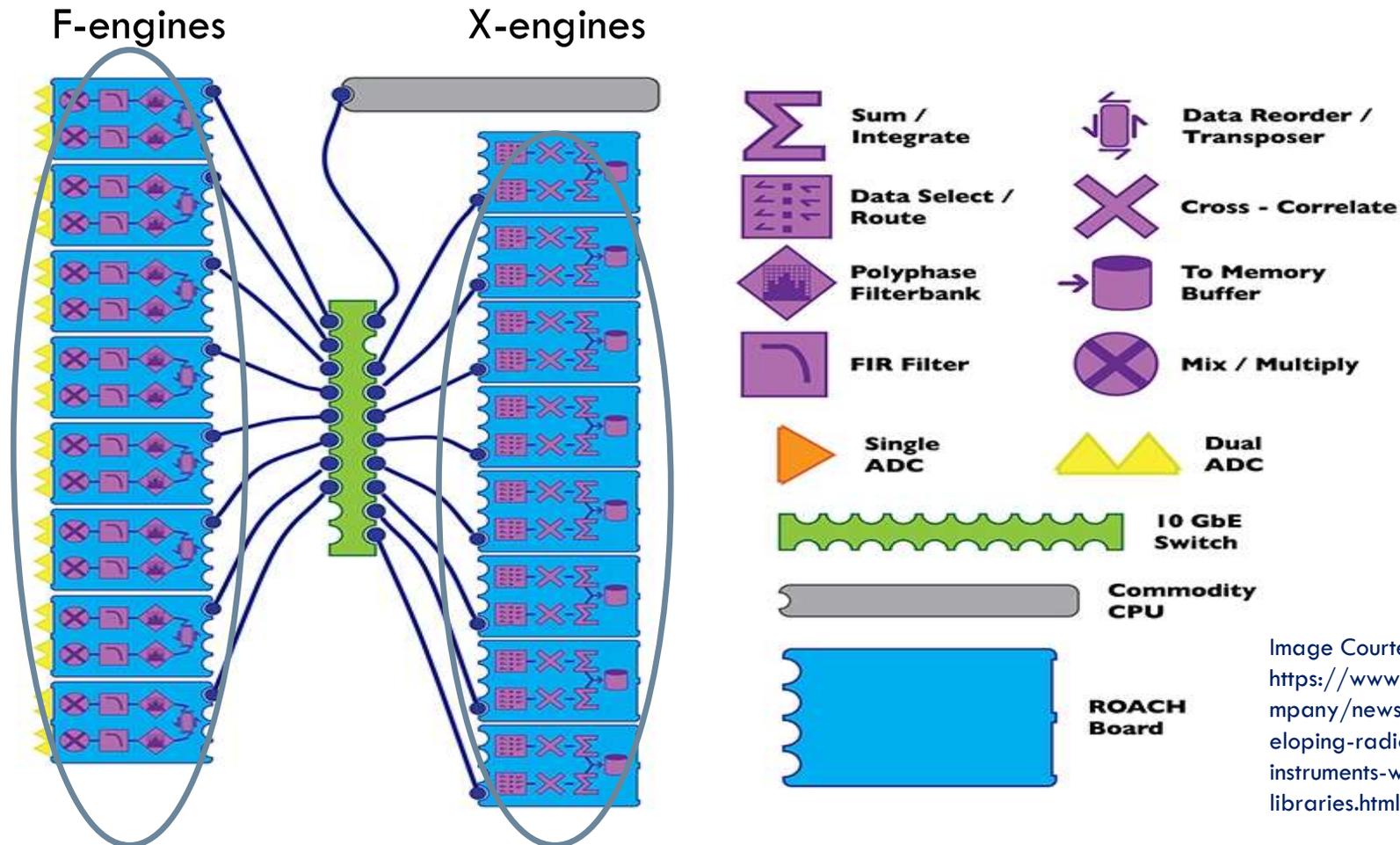


Image Courtesy:
<https://www.mathworks.com/company/newsletters/articles/developing-radio-astronomy-instruments-with-simulink-libraries.html>

Commonly used method is to carry out digitization, delay correction, FFT in F-engine and multiplication and accumulation in X-engine. High speed data connectivity is required between the F & X engines

uGMRT Correlators: Installation

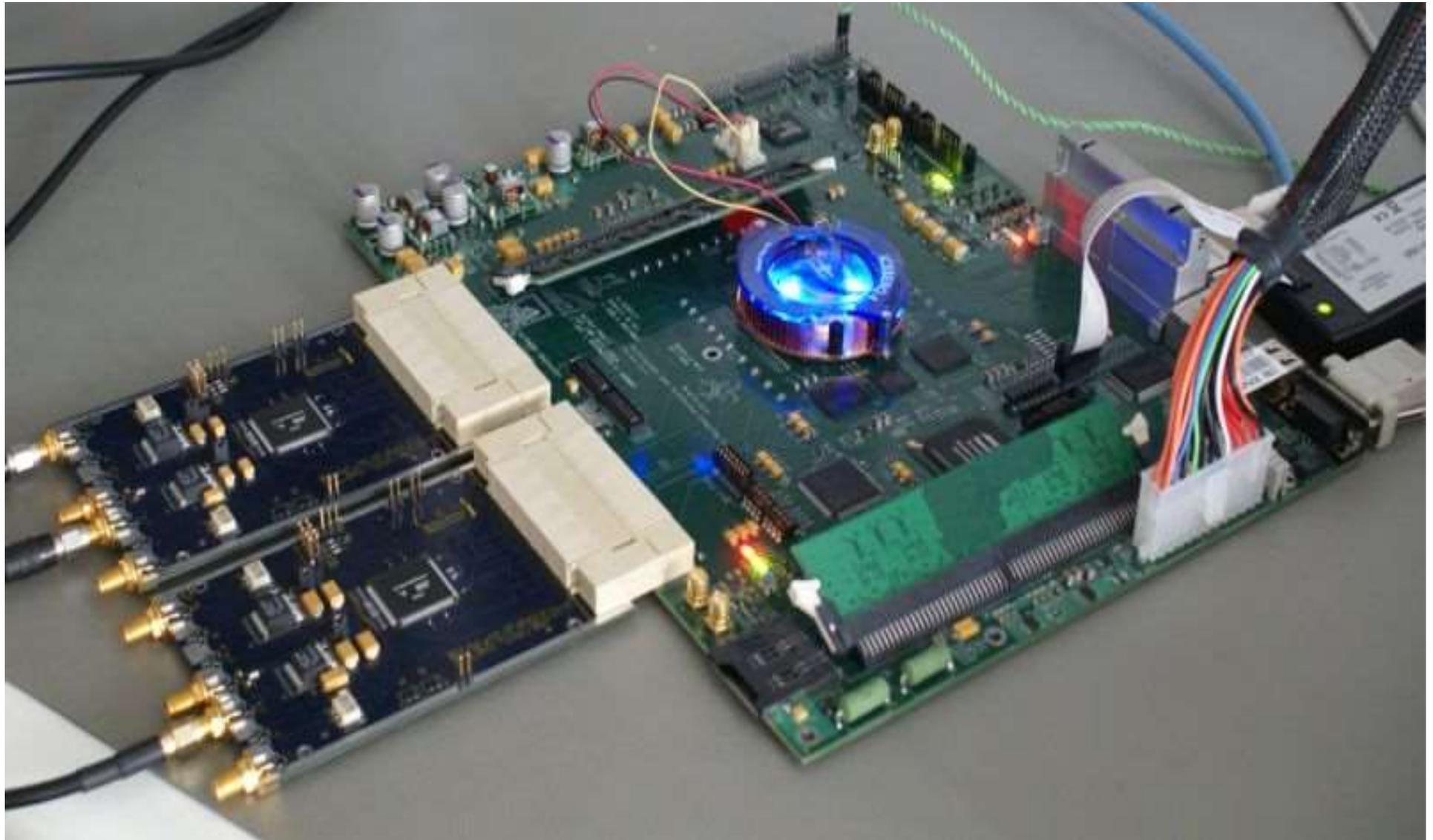


uGMRT correlator and beamformer : a combination of Field Programmable Gate Array (FPGA) and Graphics Processing Unit (GPU).

16-node cluster, computation of the order of ~10TFlops. Power consumption: ~20 kW



ROACH board



FPGA and GPU

- ❑ **Field-programmable gate array (FPGA)** is an integrated circuit designed to be configured by a customer or a designer after manufacturing
- ❑ Configurable logic blocks and programmable interconnections for implementing digital circuits
- ❑ Generic design – can be reconfigured to implement desired functionality
- ❑ **Graphics Processing Unit (GPU)** consists of many processor cores, much more than a CPU.
- ❑ Uses parallel processing to achieve high computational performance
- ❑ Performance usually measured in Floating Point Operations Per Second (FLOPS)

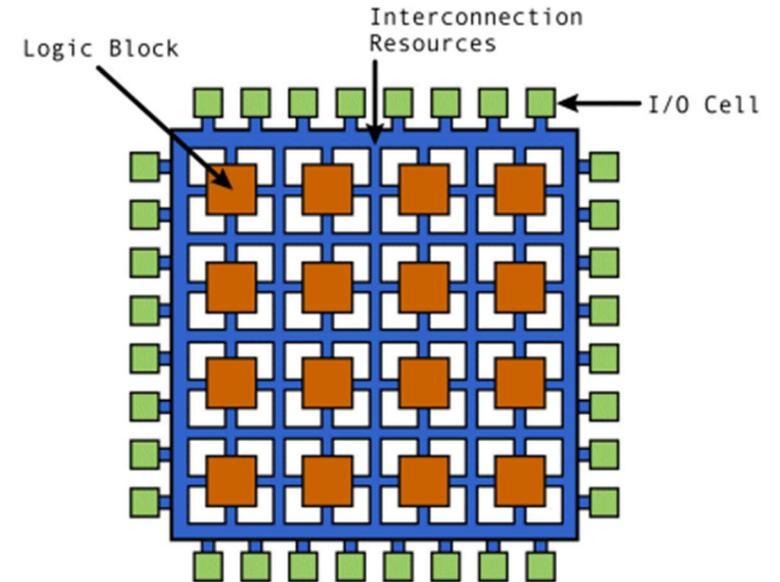


Image Courtesy: EE Times

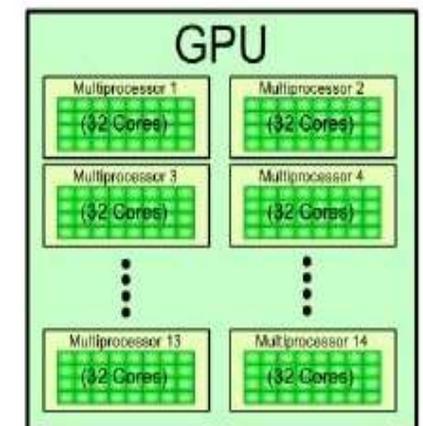
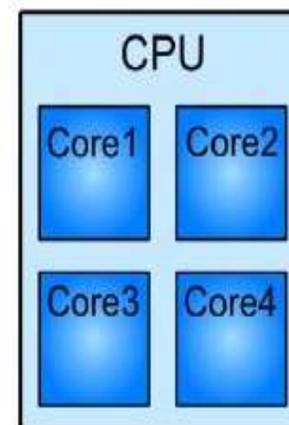
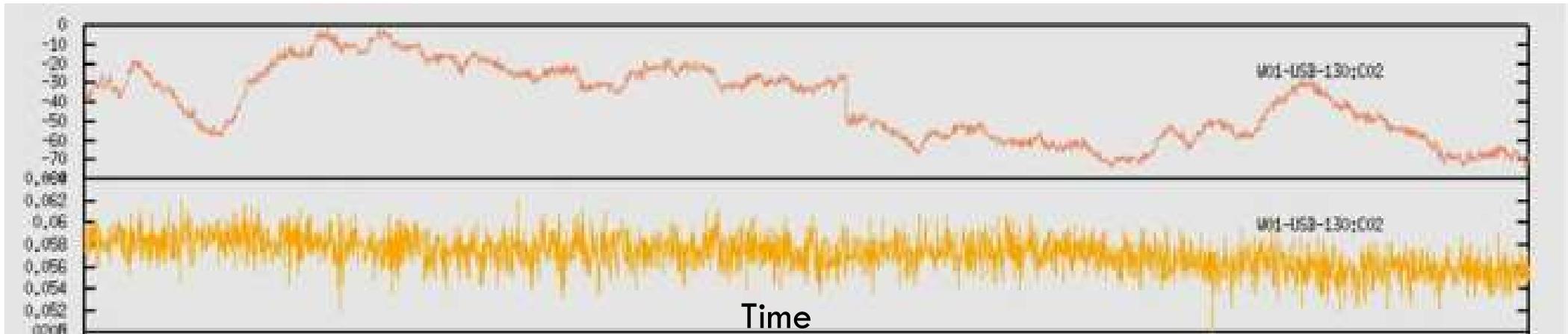


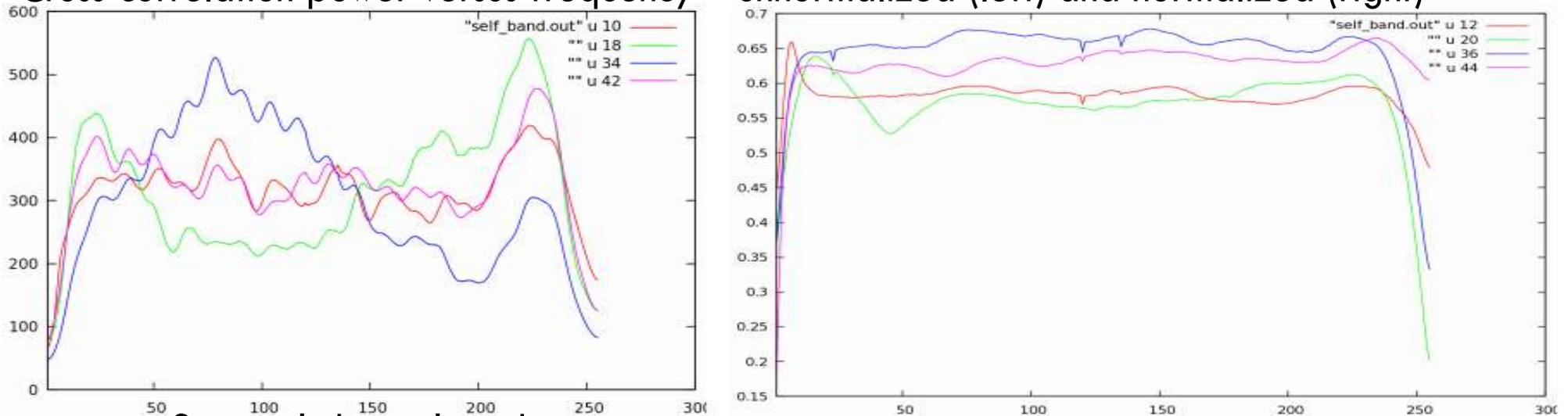
Image Courtesy: <https://www.tutorialspoint.com/>

Correlator output (Example)

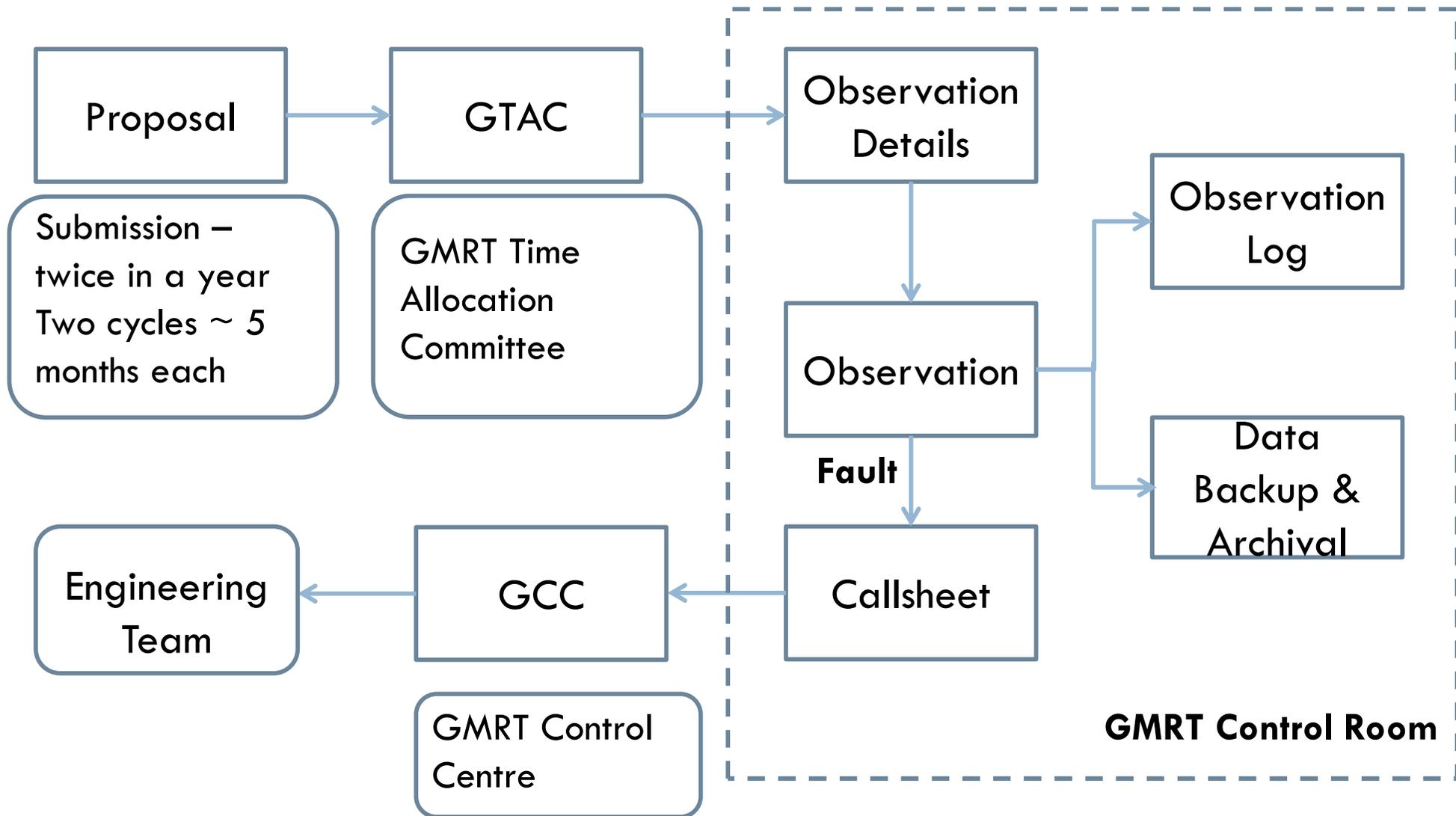
W01-C02 baseline cross-correlation amplitude (normalized) and phase for a single spectral channel (frequency) as a function of time



Cross-correlation power versus frequency – unnormalized (left) and normalized (right)

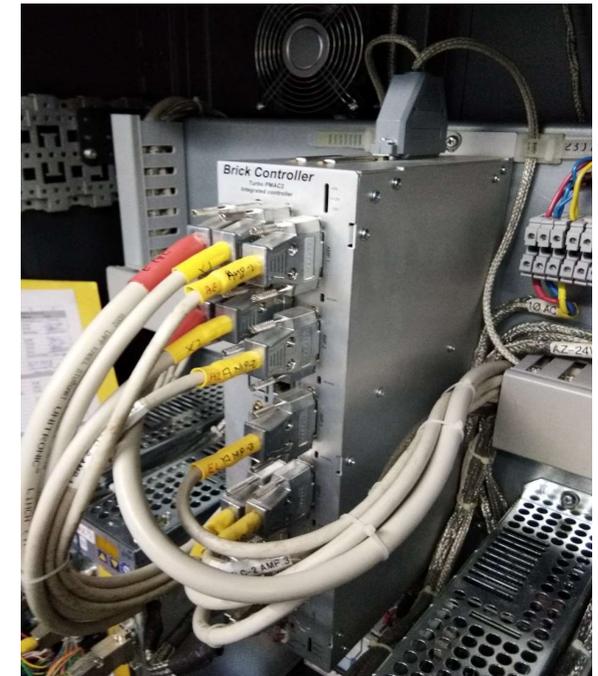
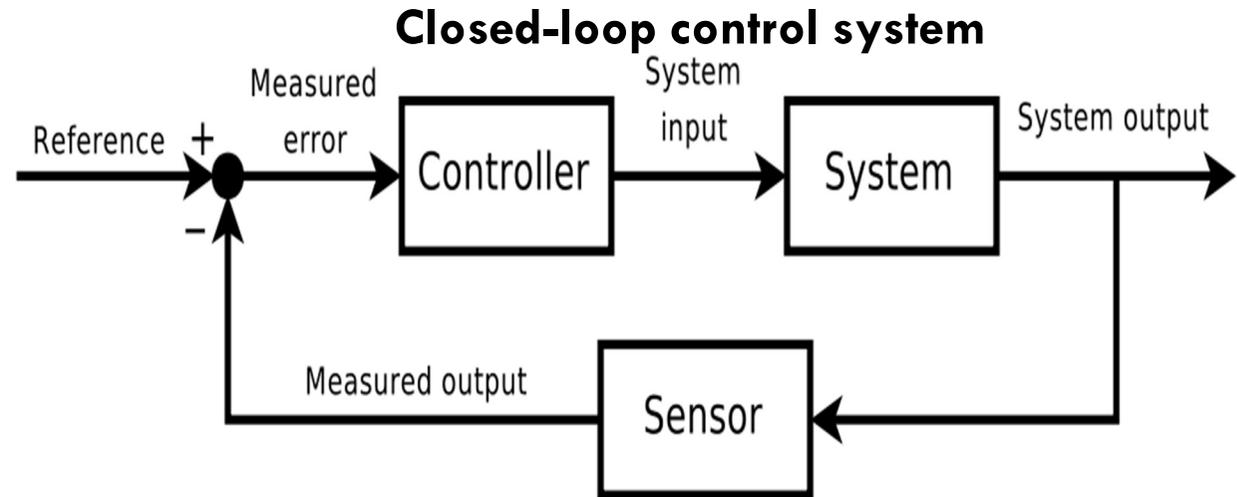


Control Room



Servo System

- Points the antennas to any part of the sky and tracks a source
- $\pm 270^\circ$ movement around azimuth axis and 17 to 110° above horizon about elevation axis
- Slew speed of $30^\circ / \text{min}$ in Az axis and $20^\circ / \text{min}$ in El axis
- RMS tracking and Pointing accuracy: 1 arcmin at 20 kmph wind speed
- Feed rotation and positioning system



Maintaining and Upkeeping



High Lift Platform for servicing front-end amplifiers, electronics and structural maintenance

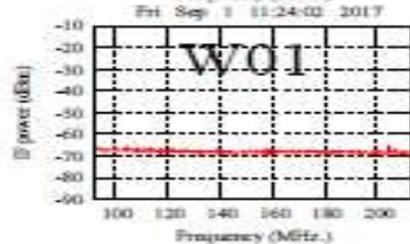
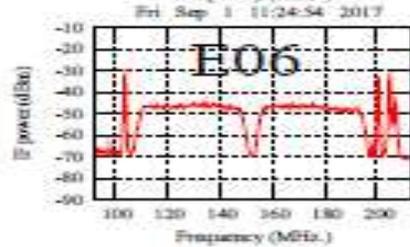
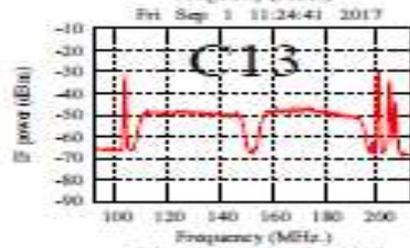
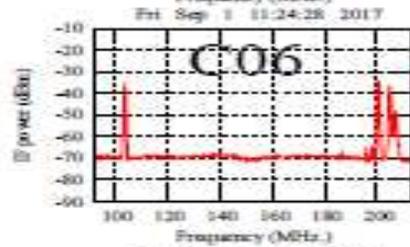
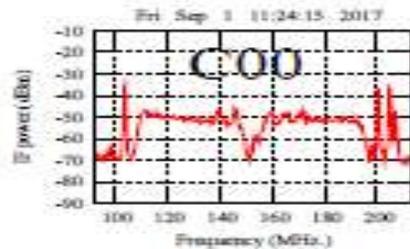
Need a minimum number of antennas (26) for a fruitful scientific observation

Day to day problem solving and long-term maintenance!

Painting: Very important for maintaining the health of the mechanical structure
Takes ~3 months to paint one GMRT dish !



Diagnostic Tools



User Documents <http://gmrt.ncra.tifr.res.in/~astro supp/>

GMRT Observer's Manual
 System Parameters and Current Status
 Polarisation observations with GMRT (V2)
 Dual band multi-pointing with GMRT (V2)
 GMRT Software Backend Documents
 uGMRT upgrade status

Before Observations

GTAC Schedule [NCRA] [GMRT]
 White Slot Request [NCRA] [GMRT]
 Command file Creator and Observations Setup
 Line Observations Frequency Setup (tune)
 Source(s) Rise and Set Time
 Observing Time Calculator
 VLA Calibrator Search
 Dual band multi-pointing coordinates
 Online Archive (GOA)

During Observations

Antenna Tracking Status
 Corr band shapes and Project State *
 Gain-amplitude and Phase (rantsol)
 Visibility - amplitude and phase (xtract)
 Antenna Wind Status
 Satellite passes

After Observations

LTA to FITS conversion:
 AIPS help:
 RFI Plots:
 GDDP summary:

Antenna Systems

Ondisplay Antenna Tracking Status
 Ondisplay History
 Feed position status
 Pointing Offsets
 Wind Monitoring Station
 Antenna Wind Status
 Temperature Status
 Servo data
 Electrical Power Status

Analog Backend

GAB Status
 IF Band Shapes and Deflection data
 Gray Plots

Digital Backend

Corr band shapes and Project State
 Fringe Status (rantsol amp-gain)
 Gain-amplitude and Phase (rantsol)
 Visibility - amplitude and phase (xtract)
 Correlator Room Temperature

Gmon Tools, Logs

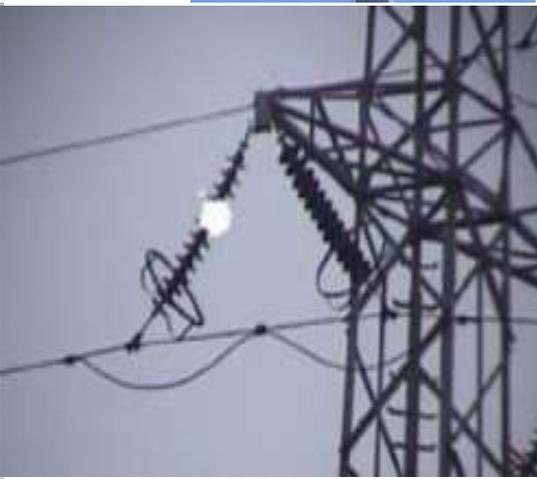
Test Results, Callsheets and Schedules

Useful scripts
 Recent Callsheets
 GMRT Upgrade Status
 Results of Weekly PMQC tests
 GDDP, RFI status gray plots
 Antenna Beam Width Plots
 Schedules and white slot request

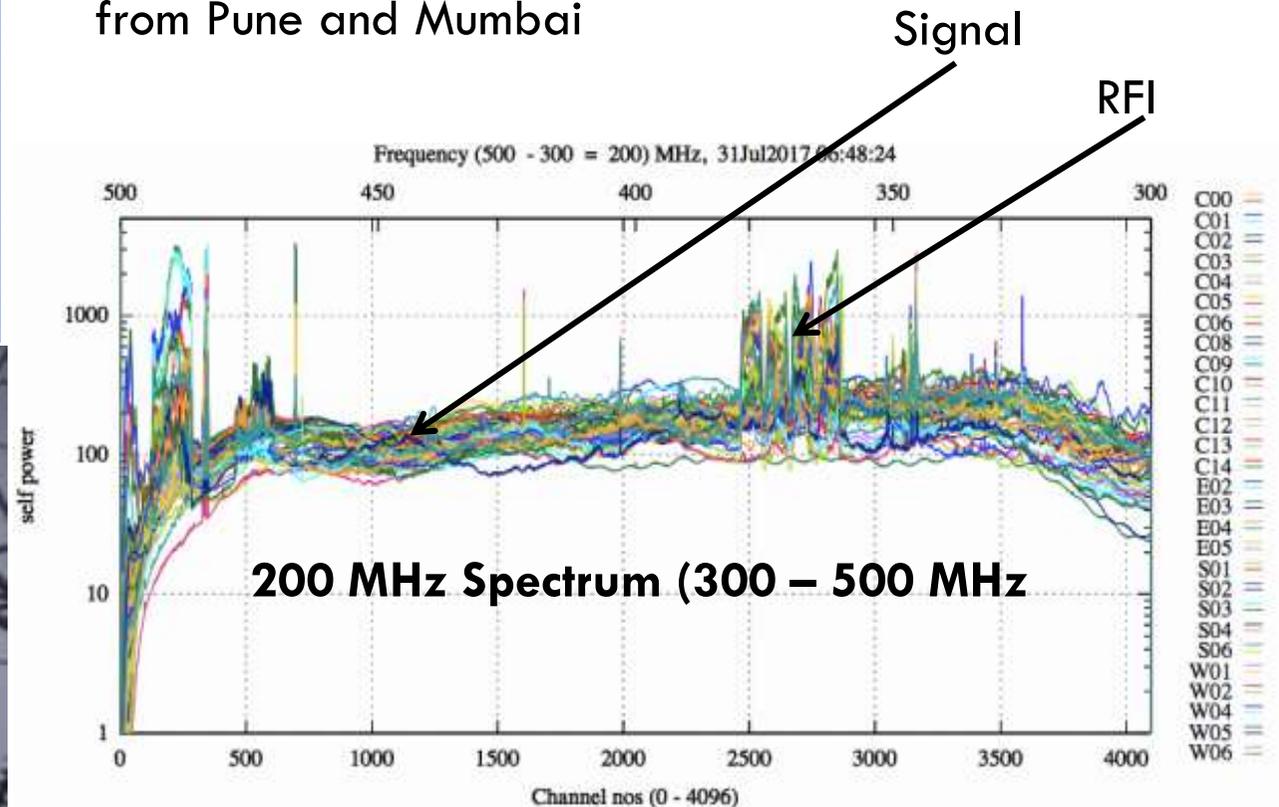
Challenge: Radio Frequency Interference



Image Courtesy: Wikipedia



- ❑ GMRT is a passive service receiver
- ❑ Due to large bandwidth and sensitive receiver systems, it is vulnerable to interference generated by various terrestrial and extra-terrestrial sources
- ❑ Radio Quiet zone around the array
- ❑ Located in a valley – mountains provide RFI shielding from Pune and Mumbai



RFI at GMRT: Coexistence



Coexisting with surrounding villages, farmlands and other industries – the potential sources of RFI

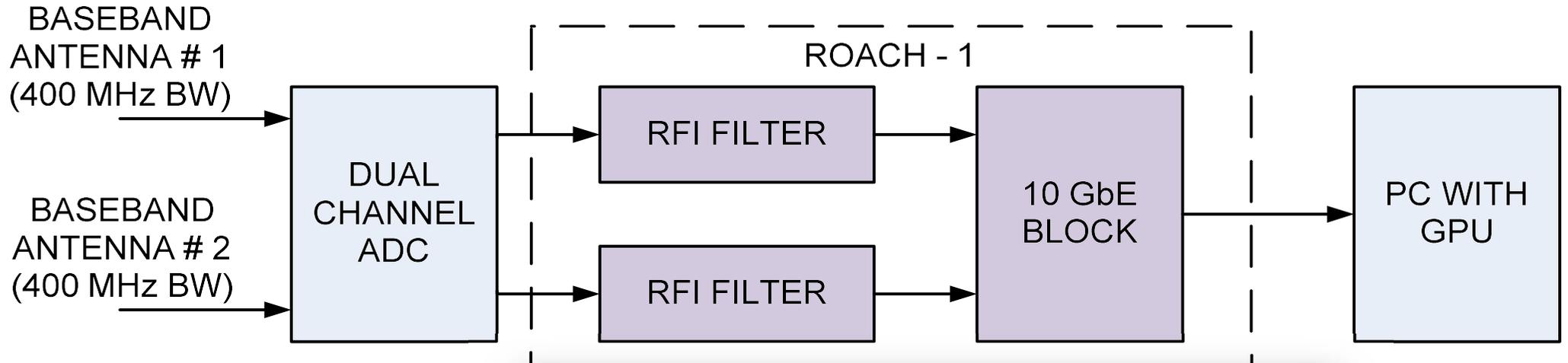
Image Courtesy: NCRA Archives

Mitigating Internal & External RFI



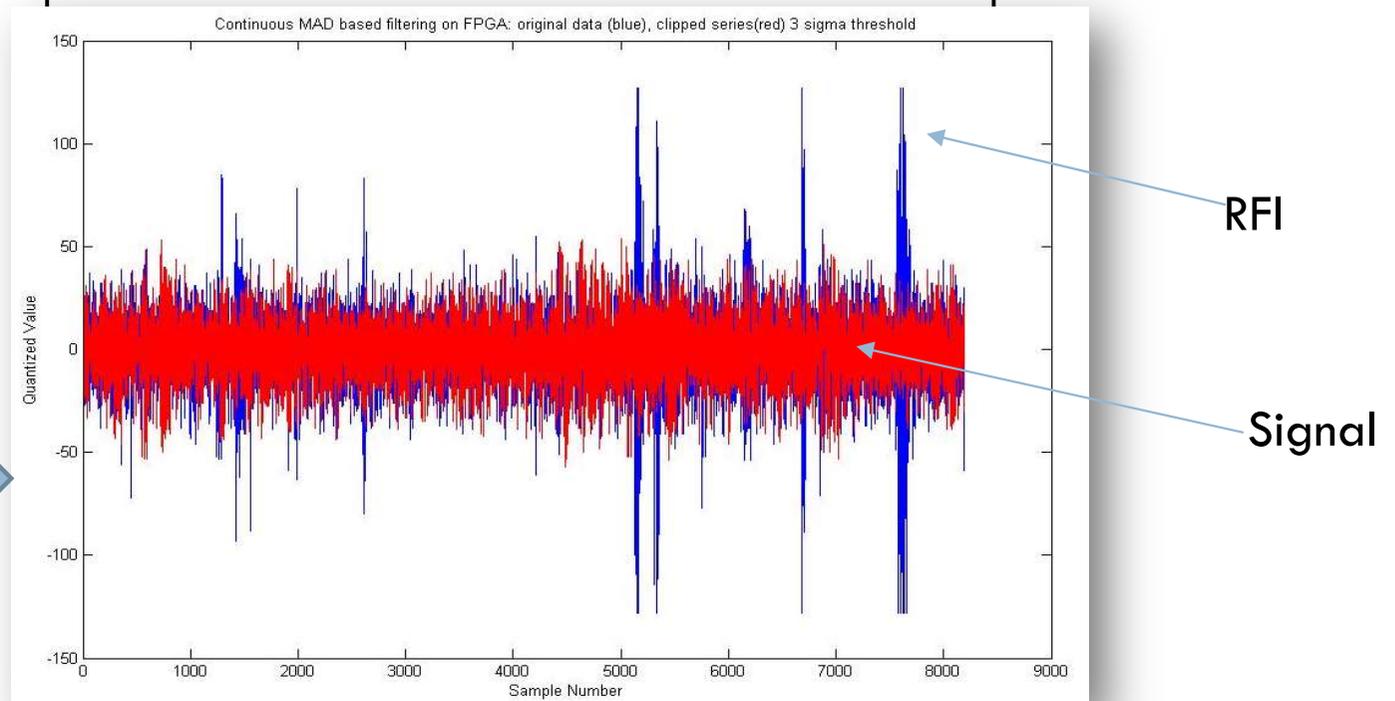
RFI Mitigation in digital system

Inside Programmable Silicon Chips



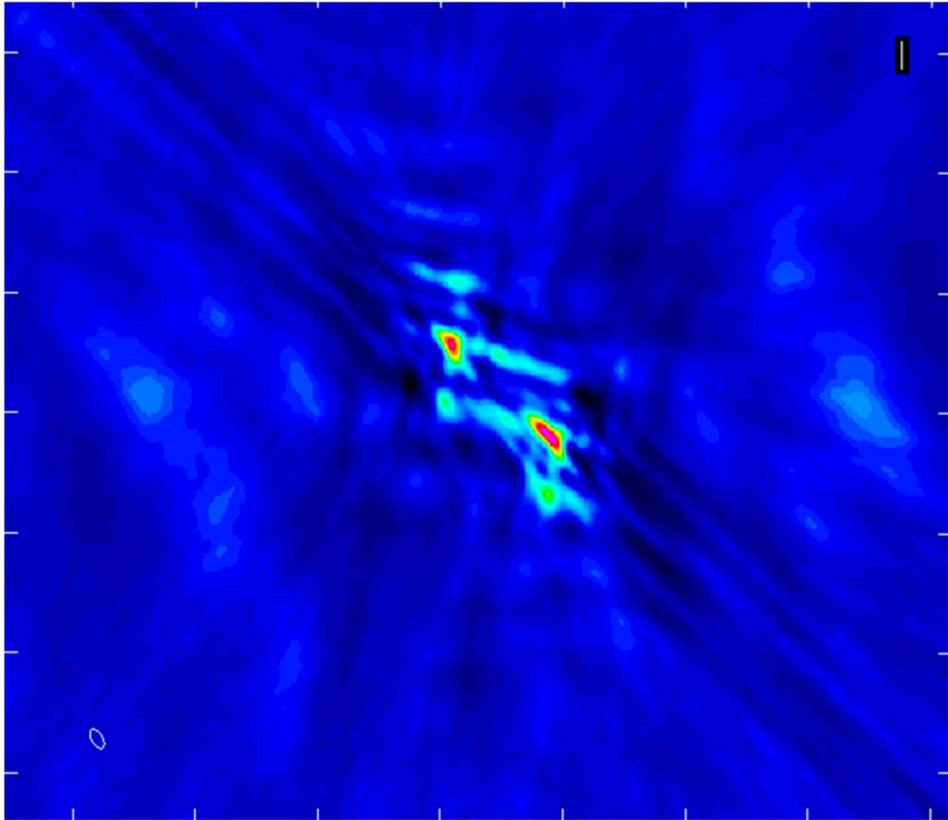
Strong power-line RFI detected through statistical techniques and filtered right after digitization (before processing)

GMRT 150 MHz time-series: blue (unfiltered), red (filtered)

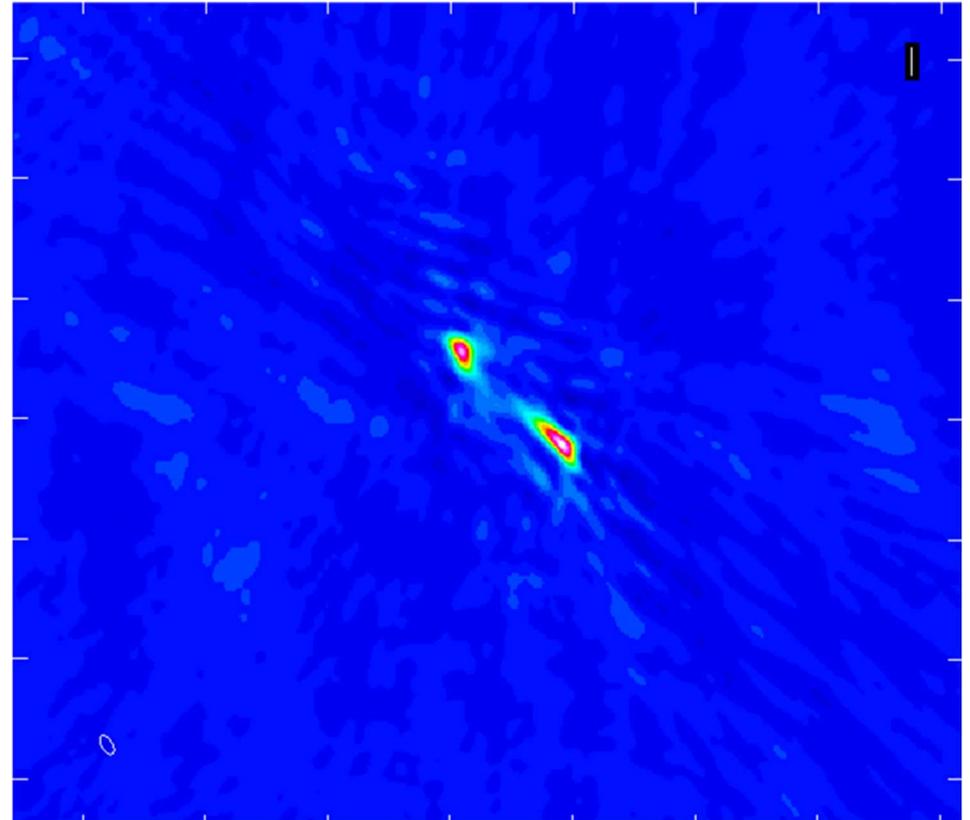


Imaging: Extended Source

Unfiltered



Filtered

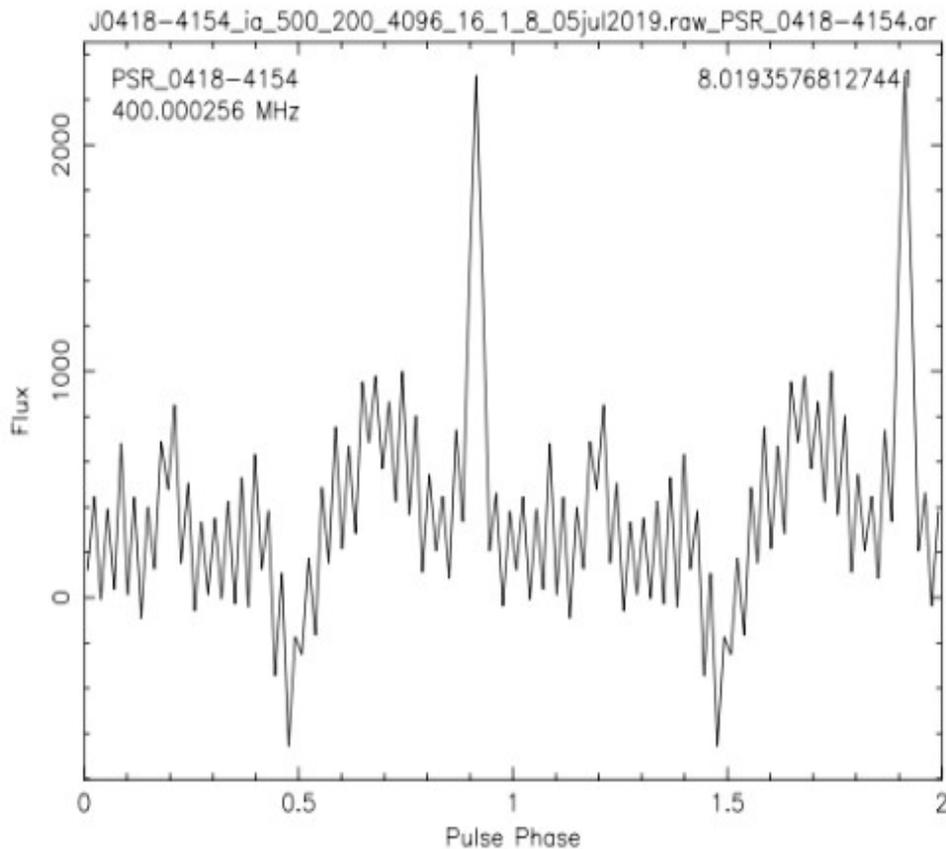


- uGMRT Band-4, 550-850 MHz , 200 MHz RF bandwidth, 2048 spectral channels
- Imaging for baselines < 1 kilolambda (~ 0.5 km)
- Noise RMS - 1.6 mJy/beam (Unfiltered) 0.52 mJy/beam (Filtered)
- Average Flagging: $\sim 2.5-3\%$

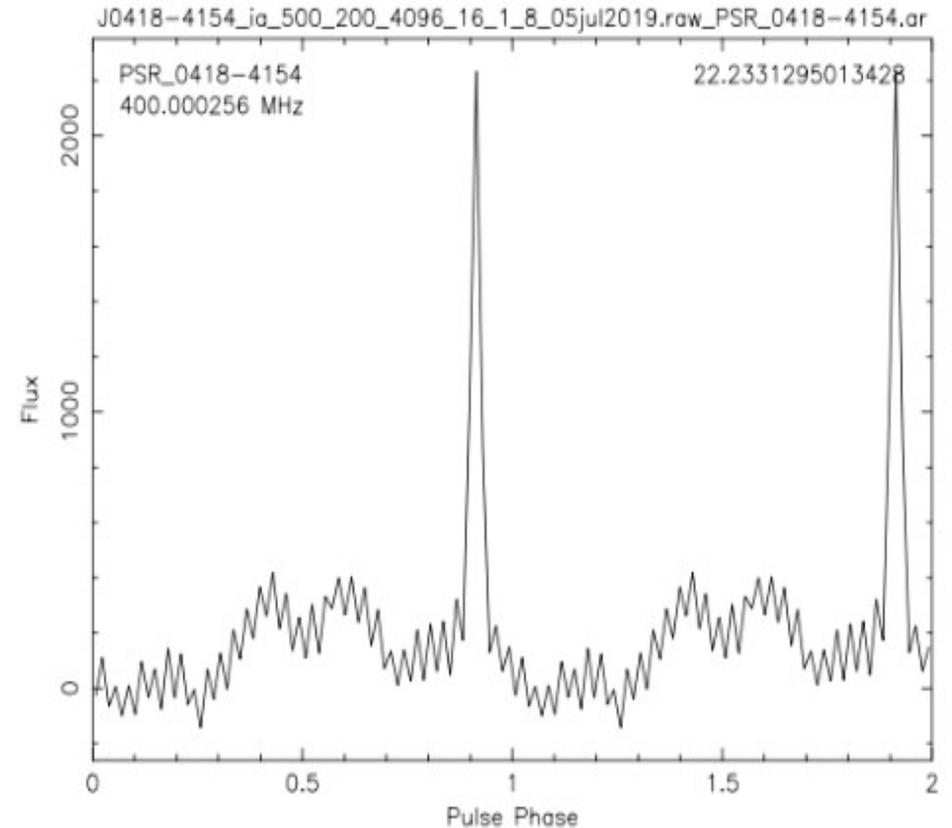
Image Courtesy: Ruta Kale, NCRA

Time-domain Astronomy

Unfiltered



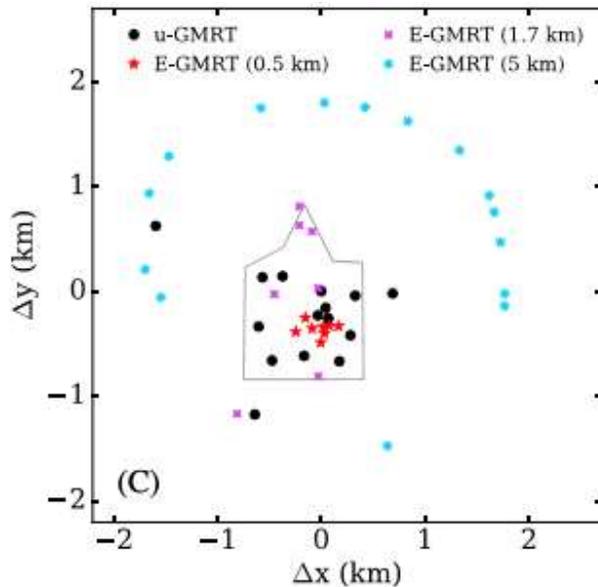
Filtered



- Pulsar (J0418-4154) profile comparison: Incoherent Array beam - 4096 spectral channels
327.68 μ s integration time.
- SNR improvement by factor of 3; Average Flagging \sim 3%

Expansions to the existing uGMRT: eGMRT

Adding more antennas for
baselines < 5 km



Improved sensitivity

Increase in Field-of-View
depends on number of
independent beams

The Expanded GMRT (eGMRT)

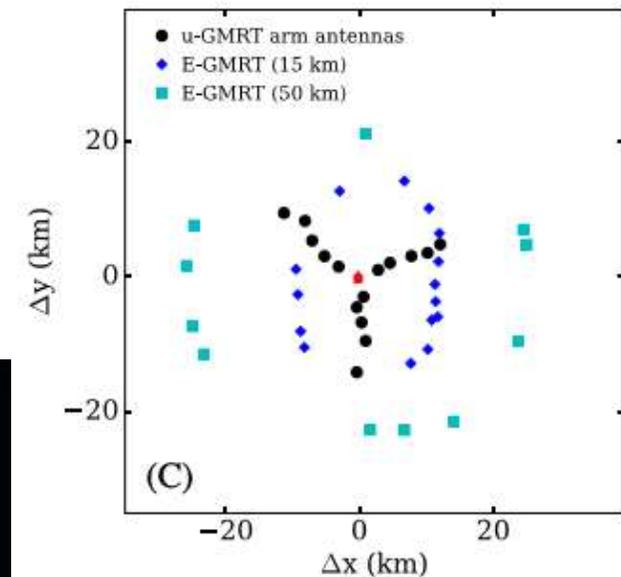
Adding focal plane array on
the GMRT antennas



Image Courtesy: K. Hariharan

Increased Field-of-View

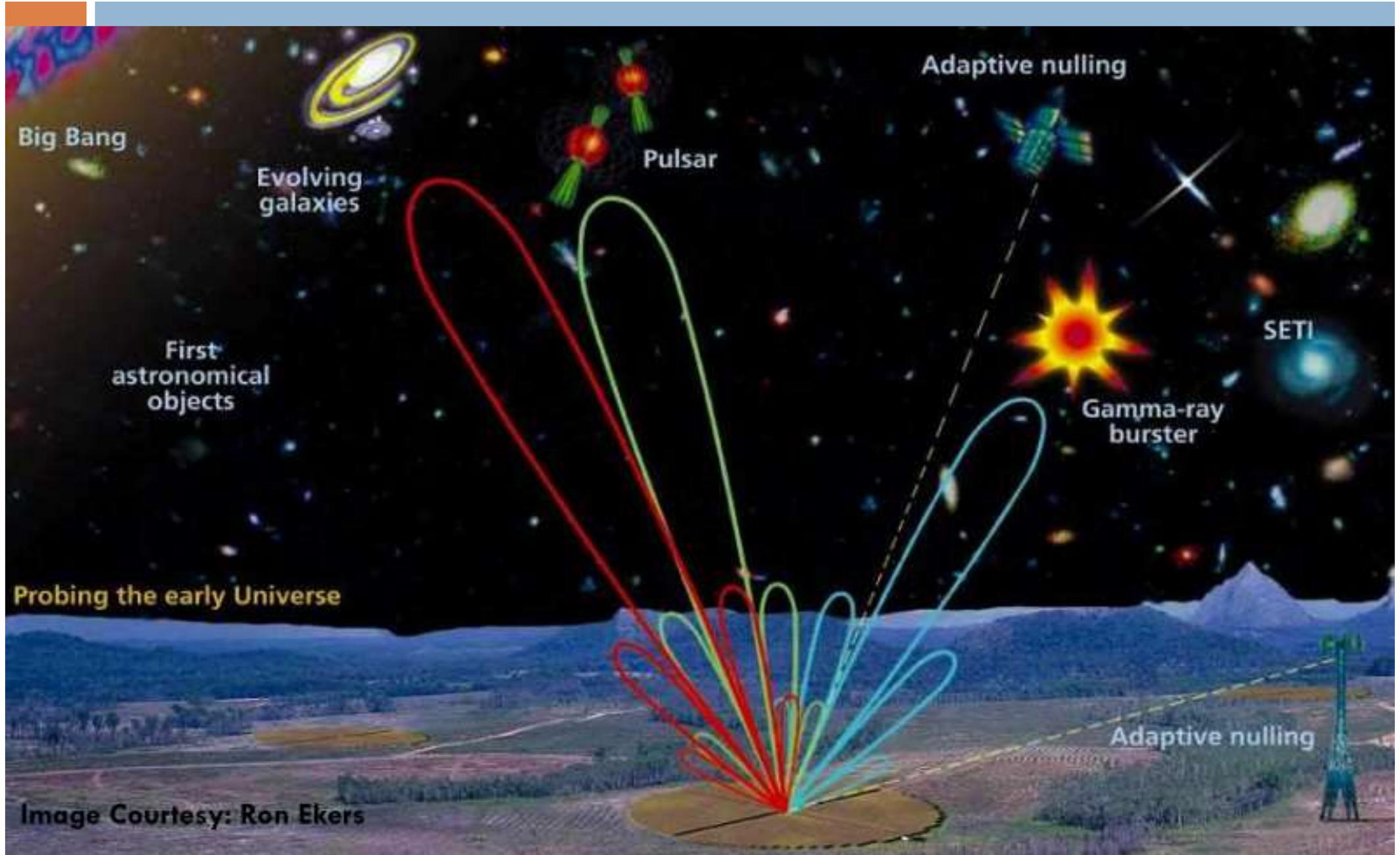
Adding more antennas for
baselines > 5 km and up to 50 km



Improved angular resolution,
lower confusion limit

Field-of-view is
measured in degrees²

Forming multiple beams: Advantages



References

1. Lecture series on "Techniques of Radio Astronomy and GMRT", February-May 2016
<https://www.gmrt.ncra.tifr.res.in/doc/Lectures/lectures.html>
2. Low Frequency Radio Astronomy, 1997,
<https://www.gmrt.ncra.tifr.res.in/doc/WEBLF/LFRA/index.html>
3. http://gmrtscienceday.ncra.tifr.res.in/gsd2021/engineering_posters.php