Giant Metrewave Radio Telescope (GMRT): A System Overview

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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 diameter14 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)

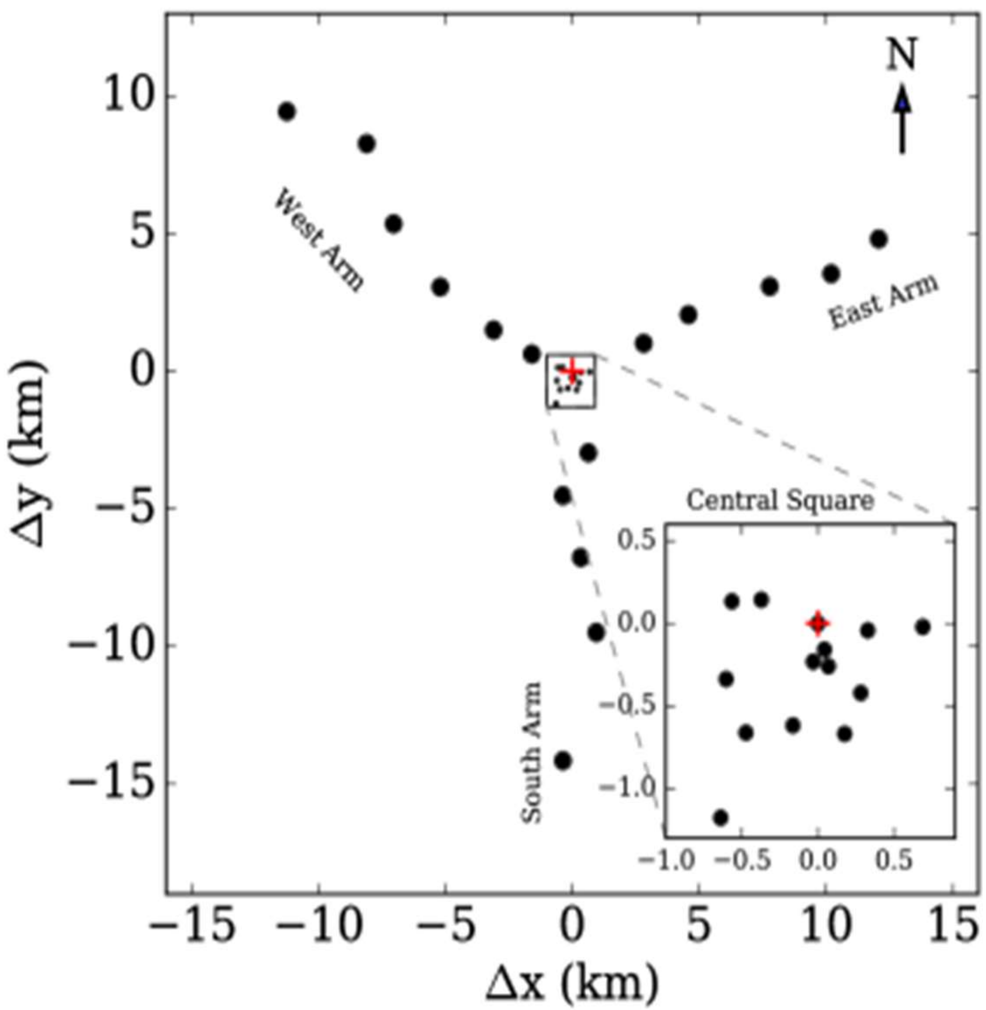
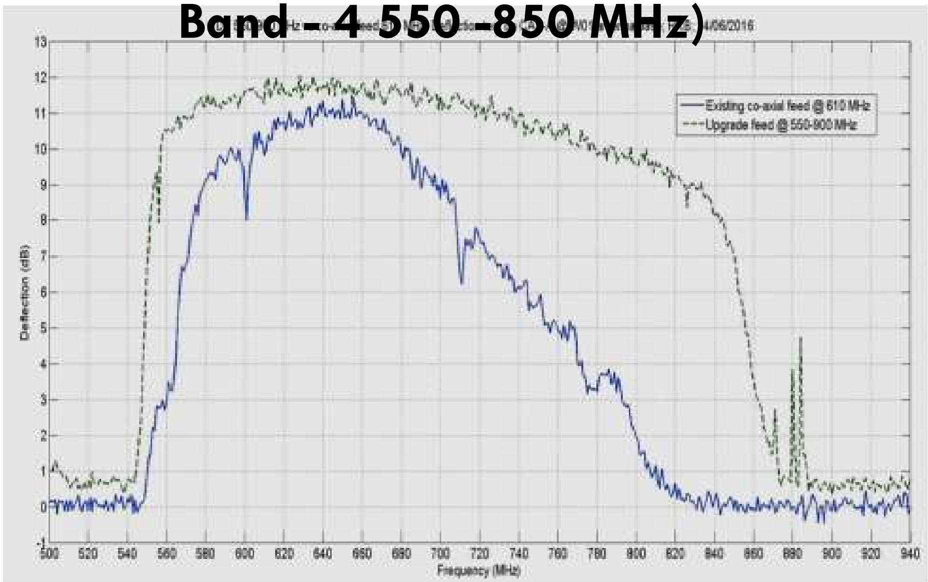


Image Courtesy: N. Patra

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)



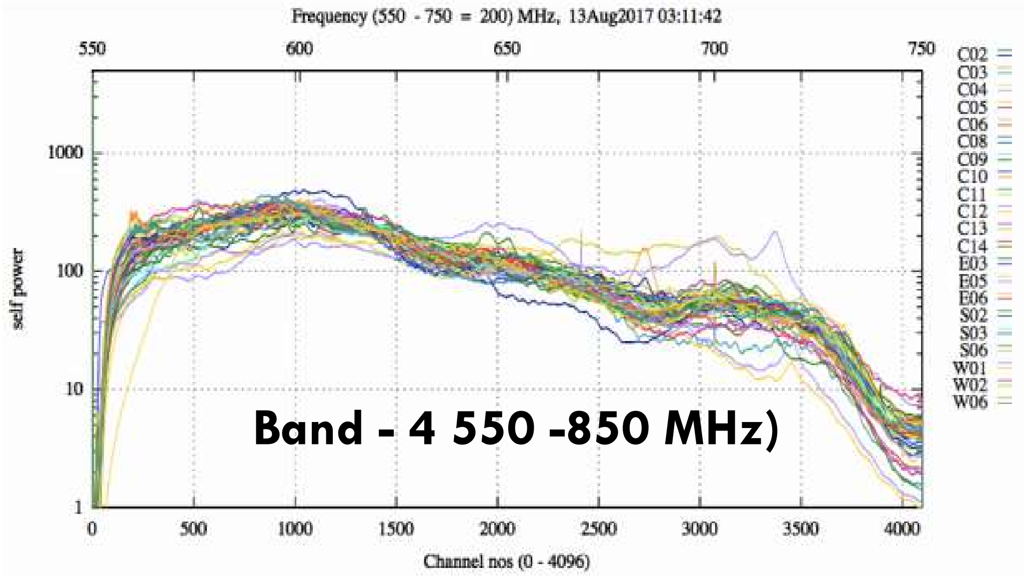


Image Courtesy: FE group + Control room

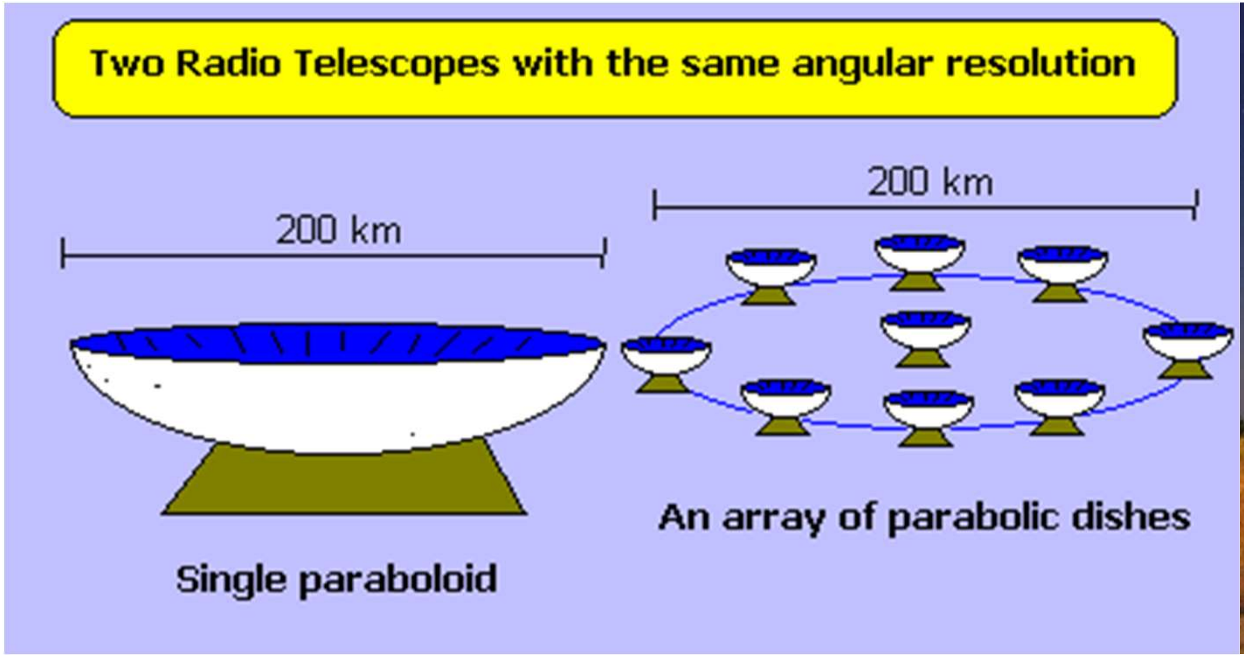
Angular Resolution: resolving distant objects

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): ~ 2”



Sampling the source signal through different apertures

Short Spacing Antennas of GMRT

Shortest spacing ~ 100m; largest spacing ~ 25km

Image Courtesy: NCRA Archives

GMRT Systems

GMRT Engineering Groups

Front-End

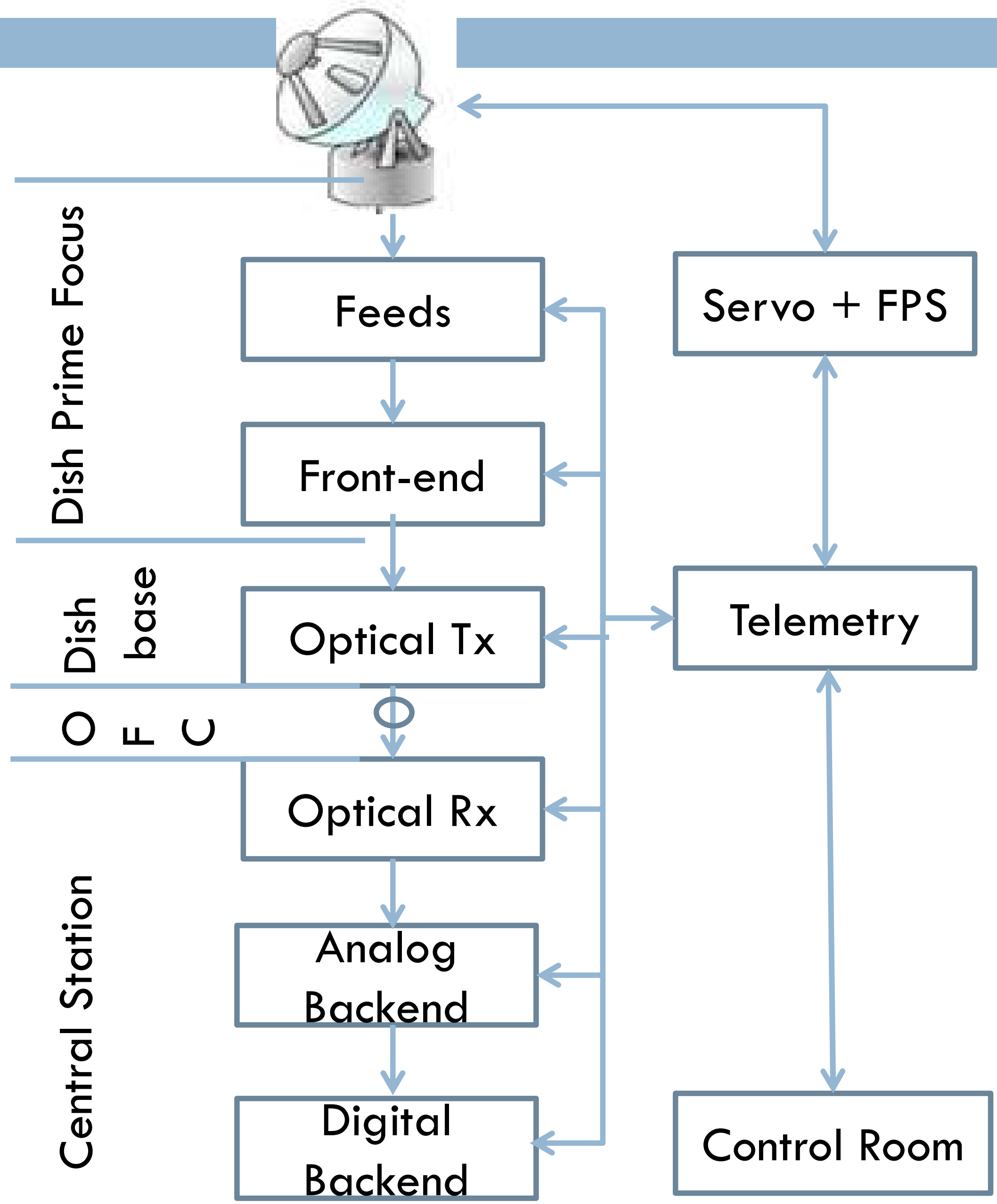
Backend

Servo

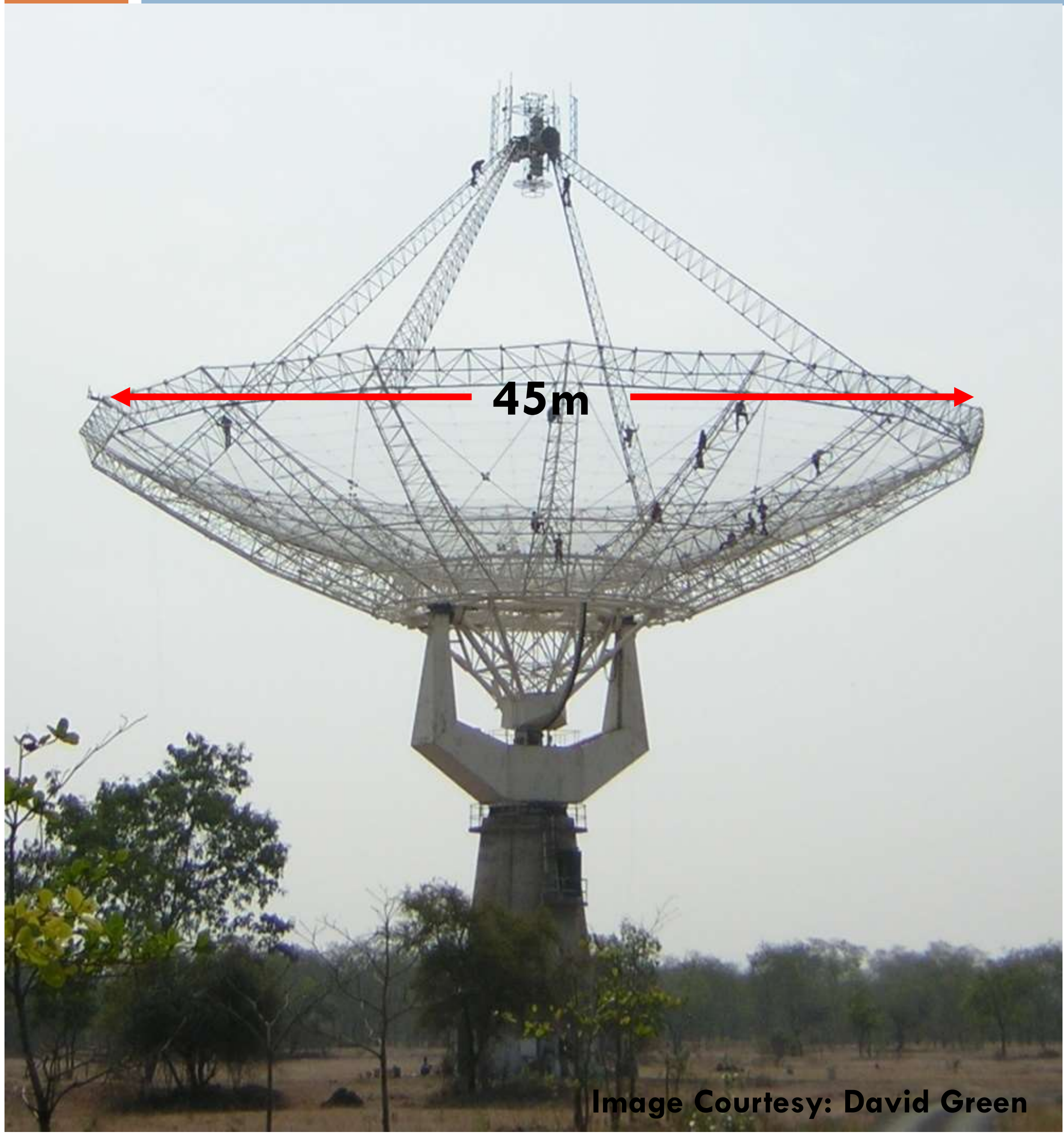
Mechanical

Electrical and Civil

Telemetry



GMRT Antenna



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)

Engineering Drawing

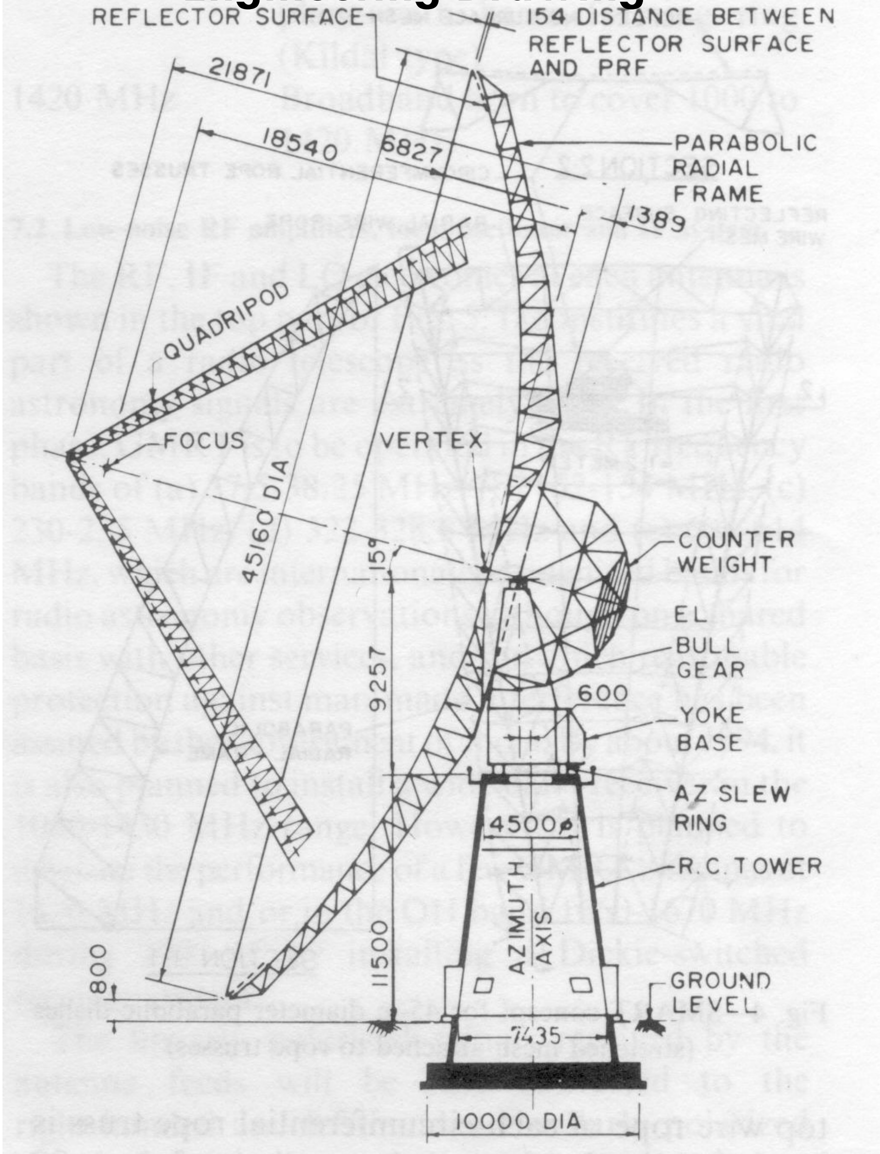


Image Courtesy: Mechanical Group

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

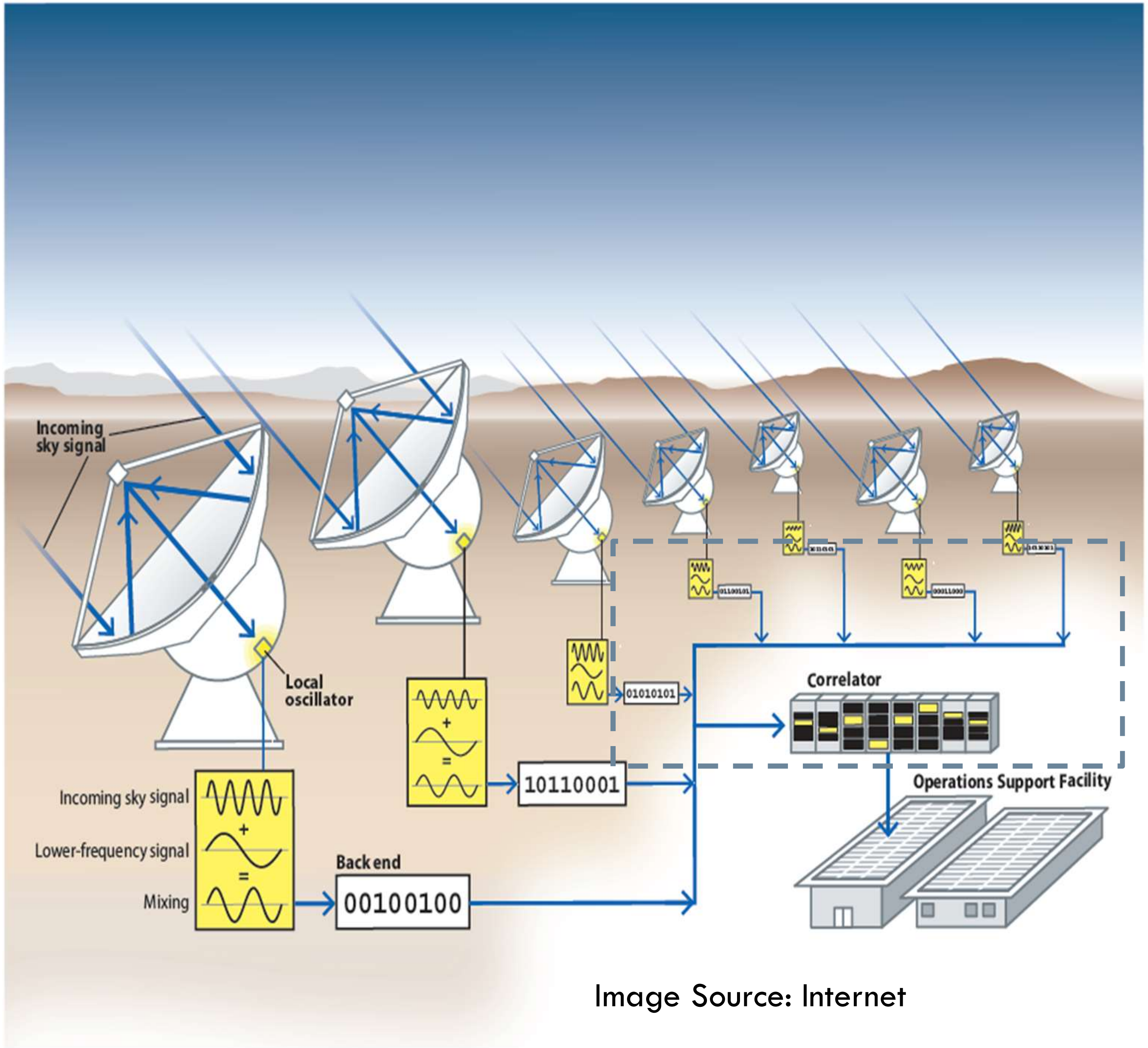


Image Source: Internet

- 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:

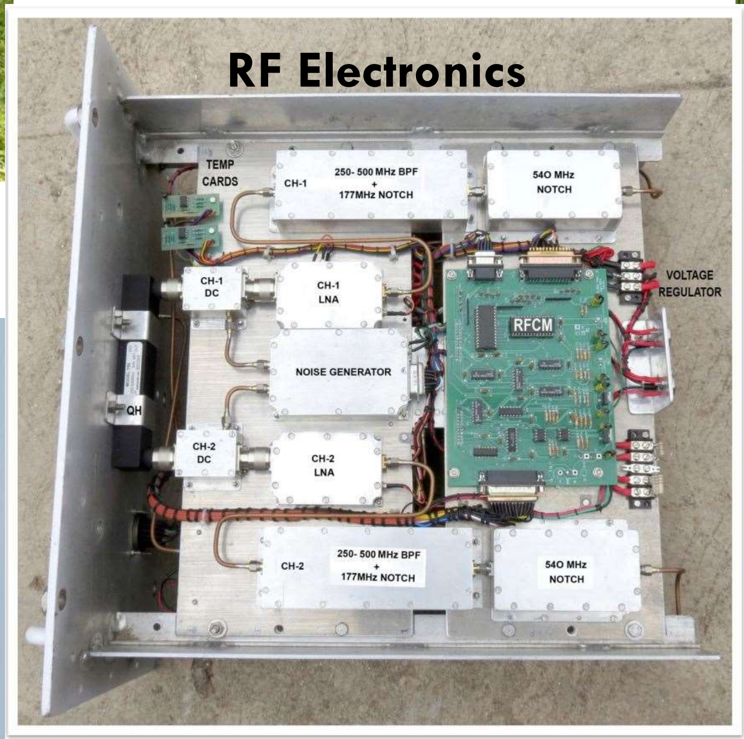
- Servo rotation – accurate pointing
- Telemetry – remote control of various systems from a common location

Feeds and Front-end Electronics

130 - 260 MHz
(Dual Ring Feed)

250 – 500 MHz
(Cone Dipole feed)

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



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

Image Courtesy: FE Group

550– 900 MHz
Cone Dipole feed

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.

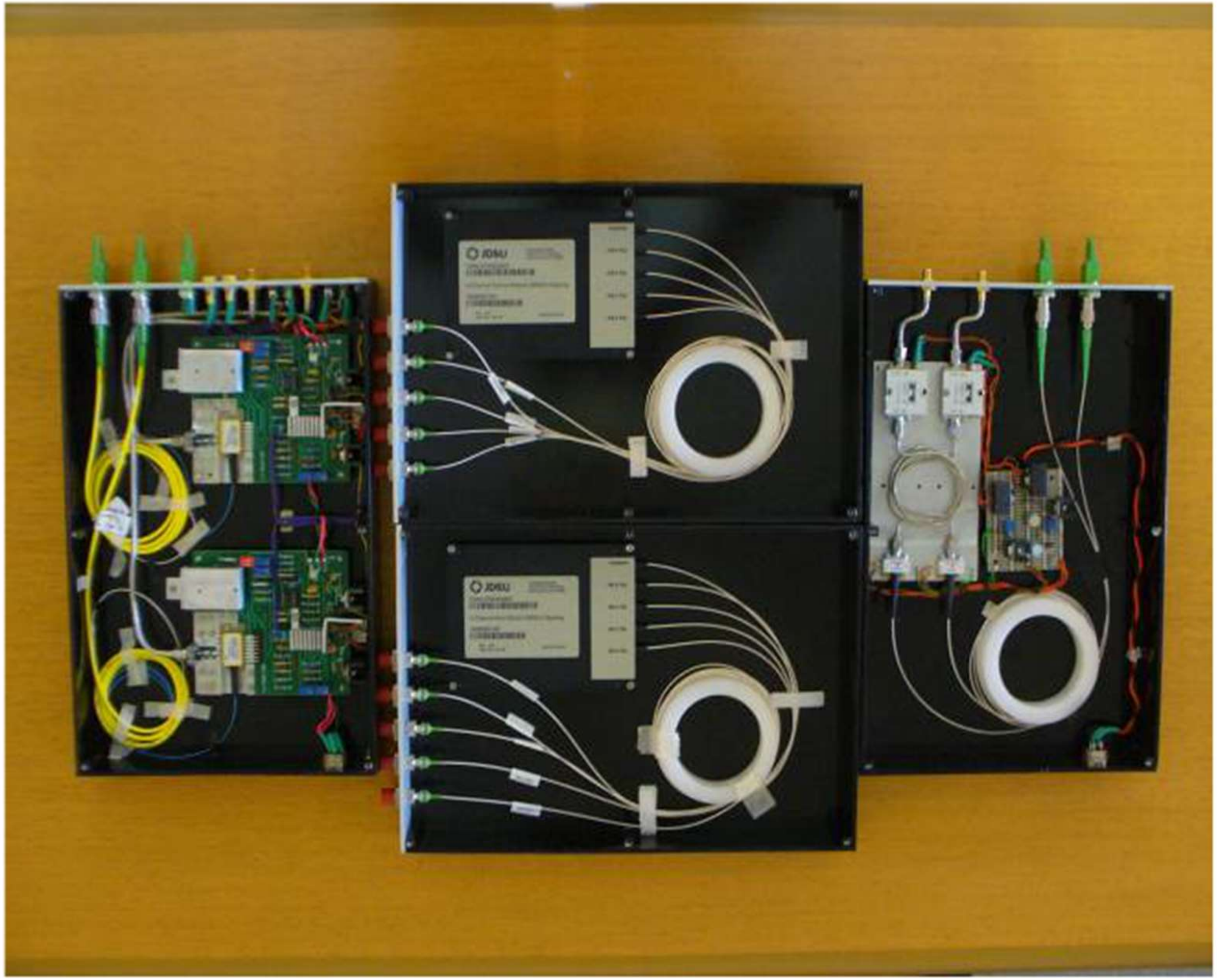
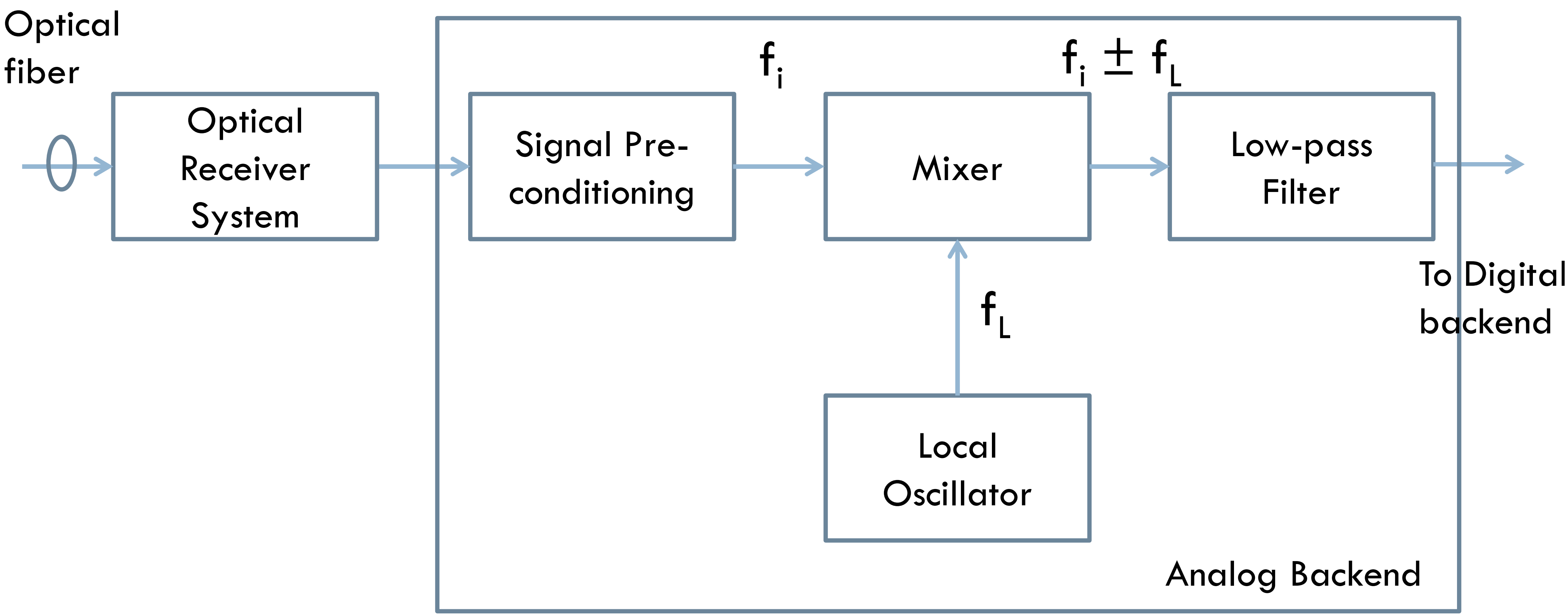


Image Courtesy: OFC Group

Signal Processing in the Central Electronics Building

Signal Processing in Receiver Room



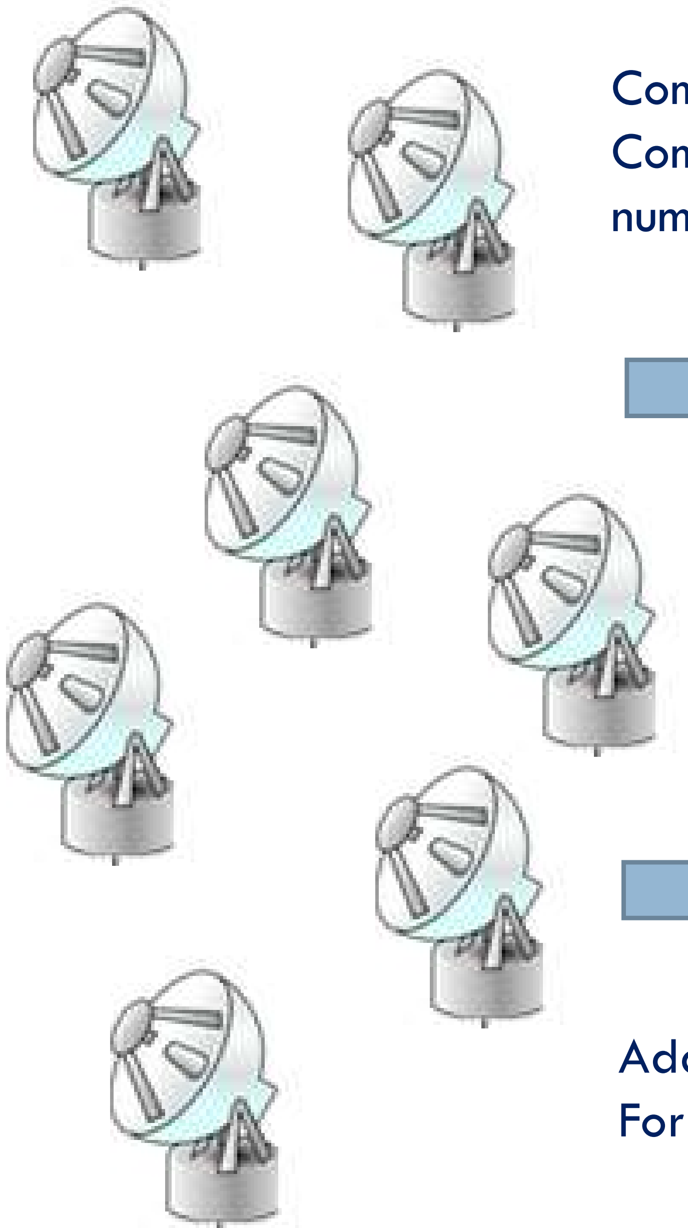
Analog backend amplifies the signal, converts from radio frequency to baseband through frequency heterodyning and provides desired bandwidth signal to the digital system

Baseband System - Installation

Plug-in Units

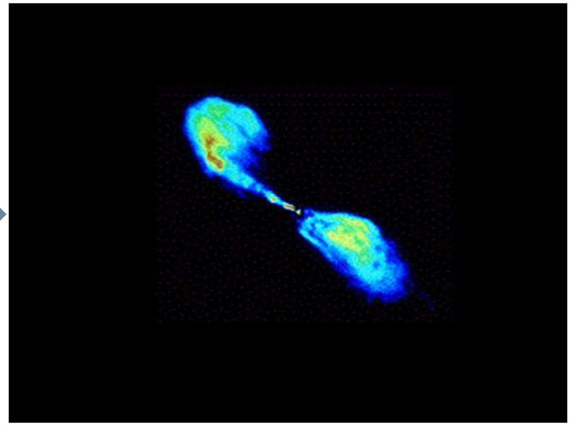
Image Courtesy: Analog Backend Group

Correlation & Beamforming



Compare signal between antenna pairs
Complexity scales at the square of the number of antennas

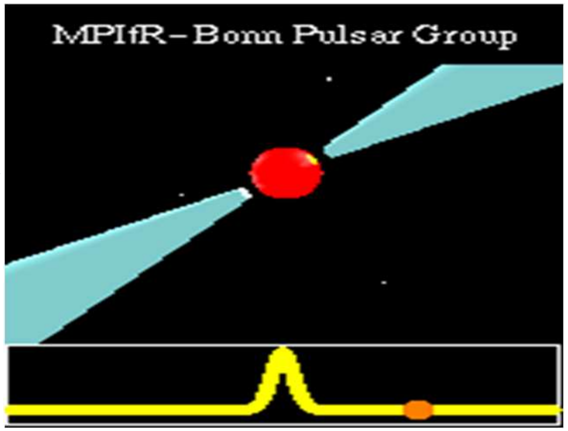
Correlation



Astronomical Imaging, Spectroscopy

Beamforming

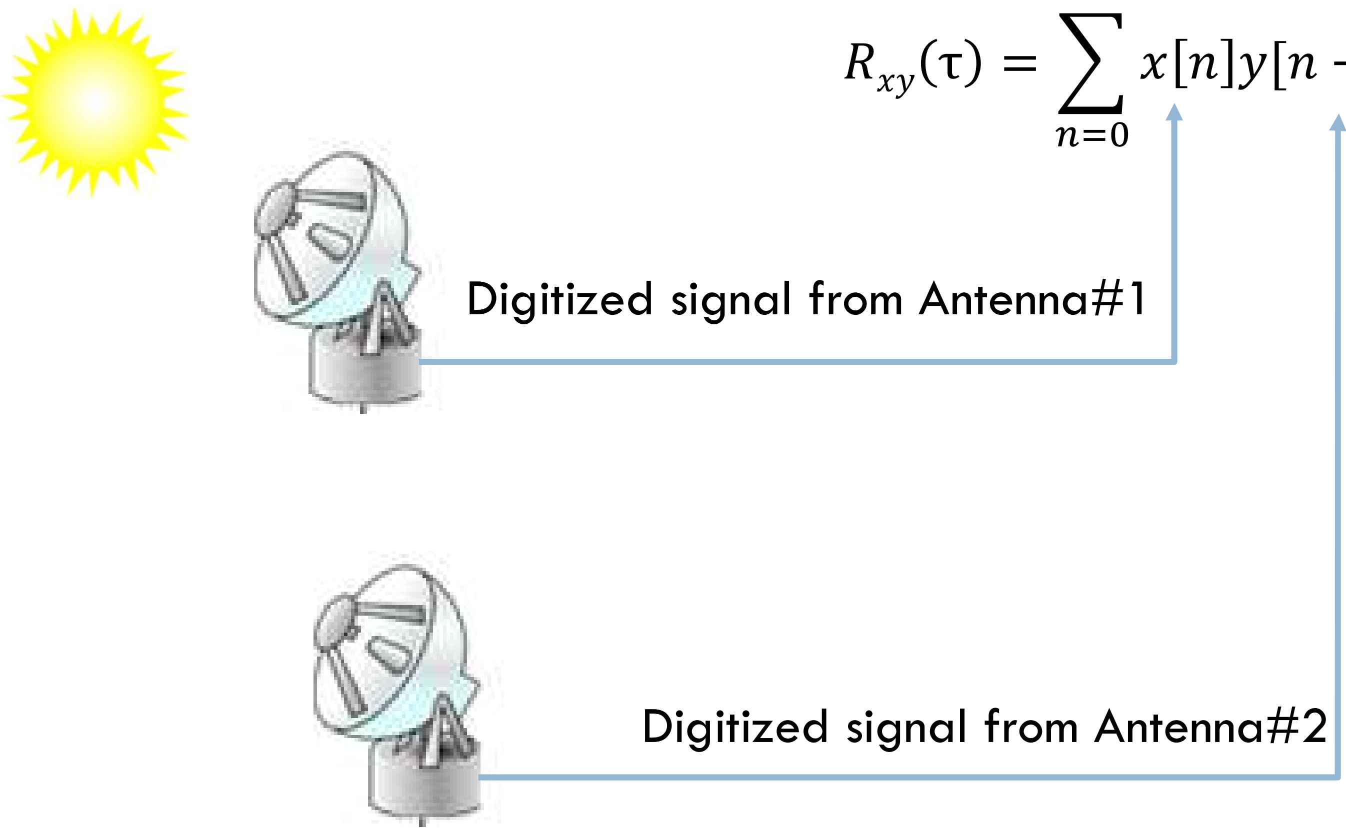
Add signals from all the antennas
Form single or multiple beams in the sky



Pulsars, Radio Bursts, Transient Sources

Signal Correlation

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



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

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

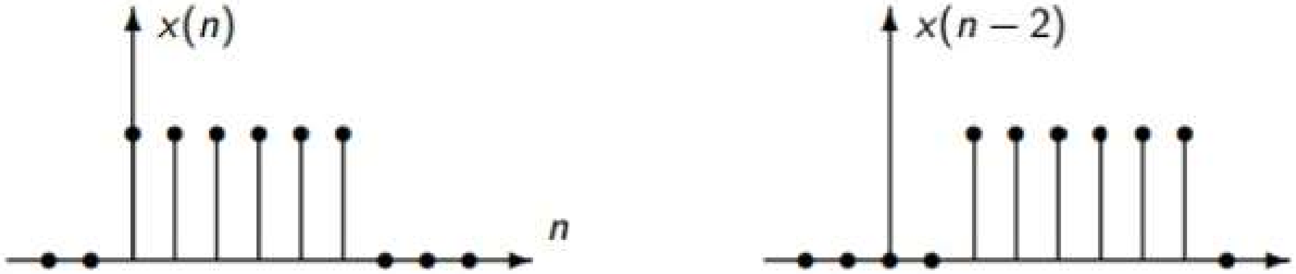
For N antennas, n(n-1)/2 cross-correlation operations are required. That makes it really complicated!

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

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



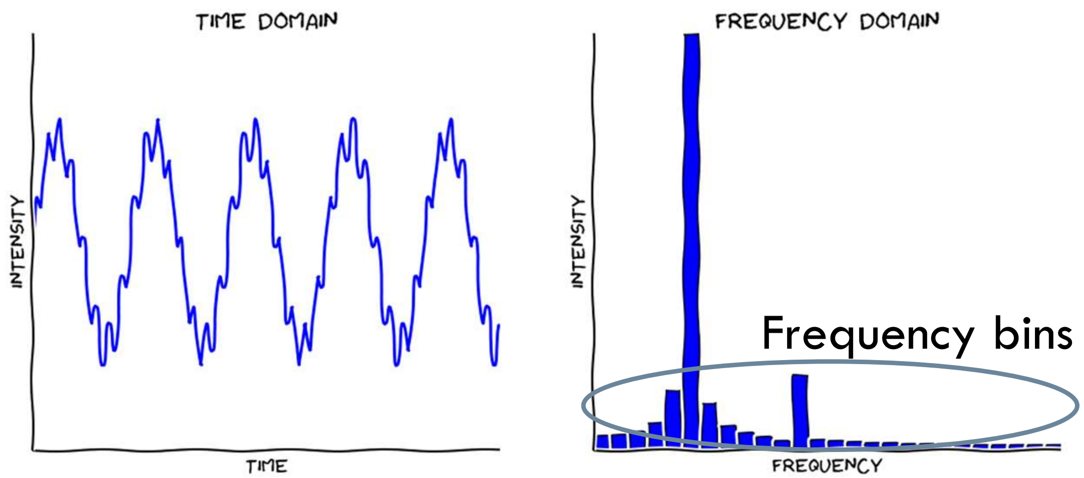
(B)

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

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

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.

Image Courtesy: https://learn.adafruit.com/fft-fun-with-fourier-transforms/background

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

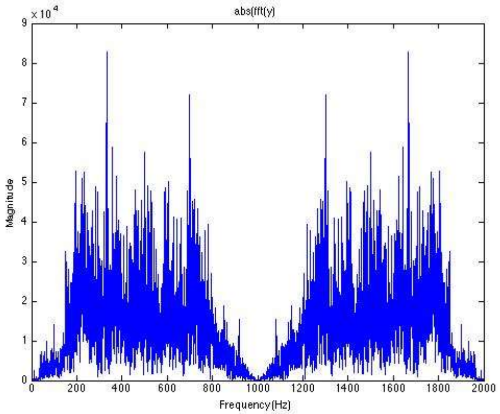
$$
\begin{aligned}
z_1 z_2 &= (x_1 + i y_1)(x_2 + i y_2) \\
&= x_1 x_2 + i x_1 y_2 + i x_2 y_1 + i^2 y_1 y_2 \\
&= (x_1 x_2 - y_1 y_2) + i(x_1 y_2 + x_2 y_1)
\end{aligned}
$$

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)

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

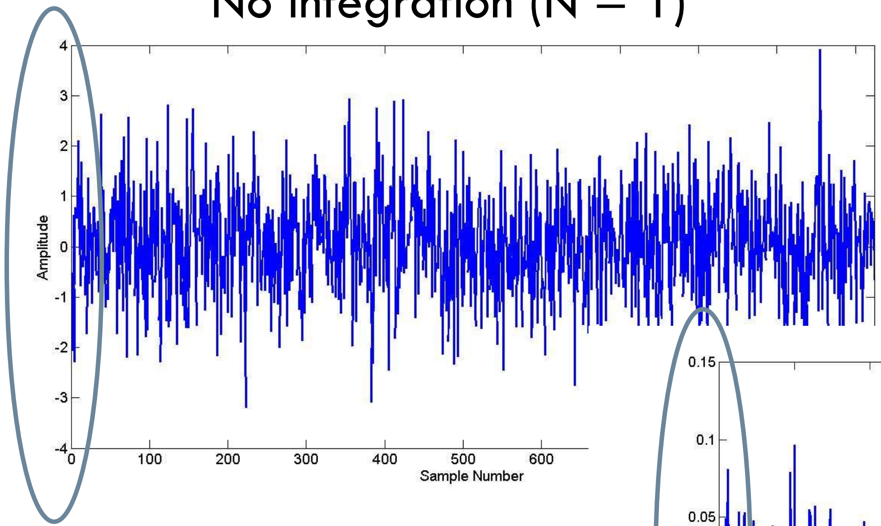
- Note: The above property does not hold if the input is a complex signal



https://dsp.stackexchange.com/questions/8567/

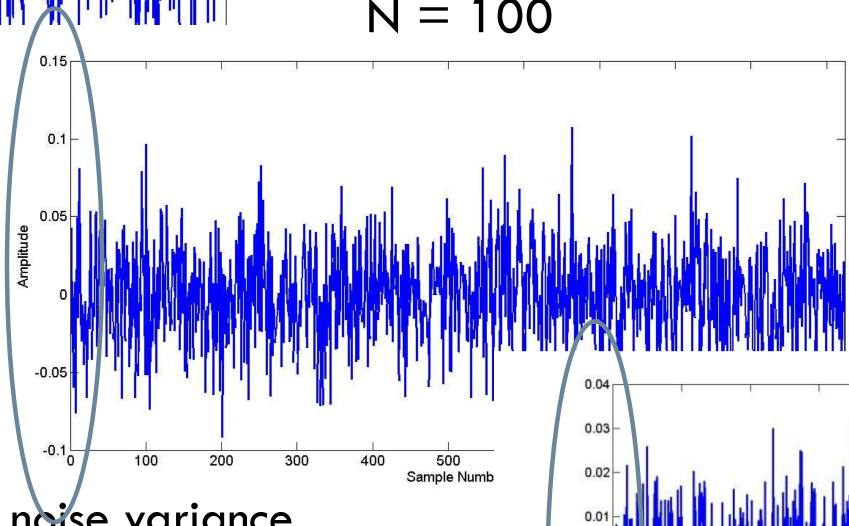
Integration

No integration (N = 1)

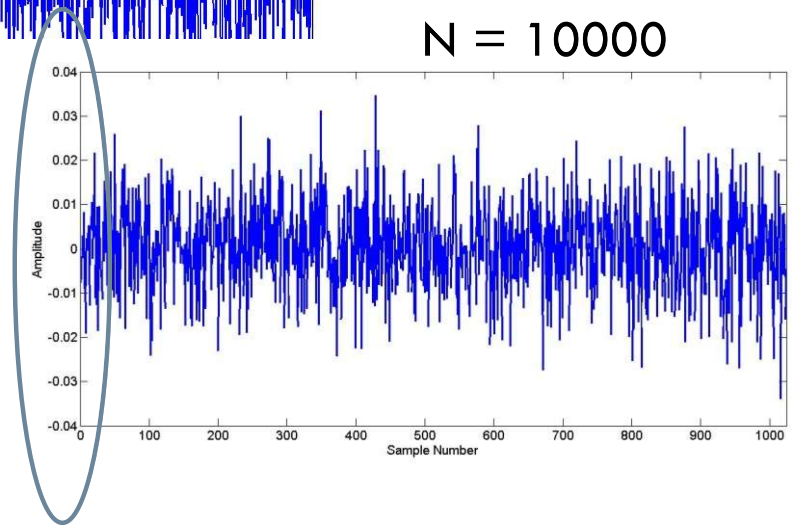


Reduces uncertainty in the measurement parameter

N = 100



N = 10000



- 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 !

Beamformer

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

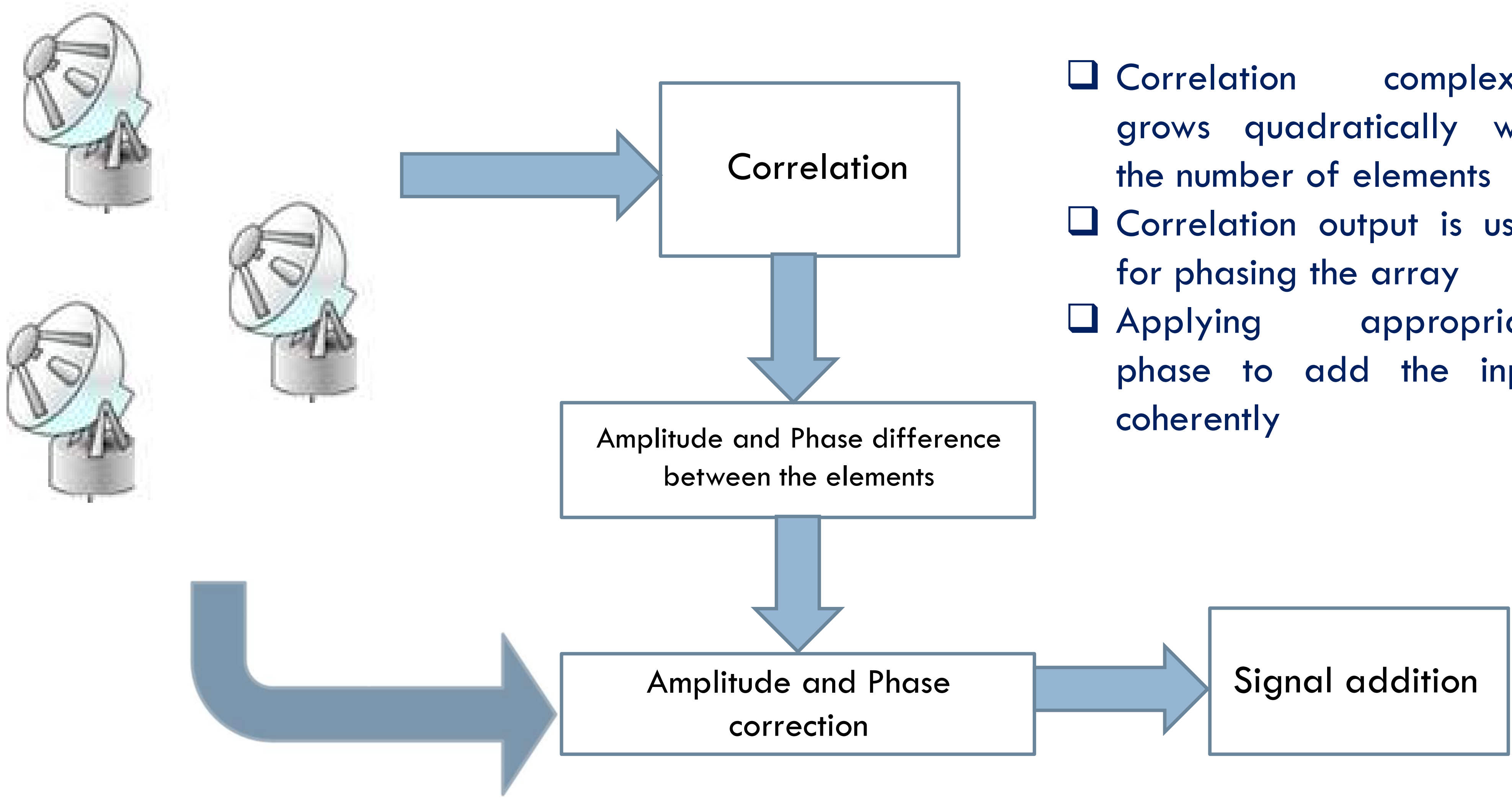
$$B_i = \sum_{i=0}^{n} (V_1^2 + V_2^2 + \ldots.. + V_N^2)$$

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

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

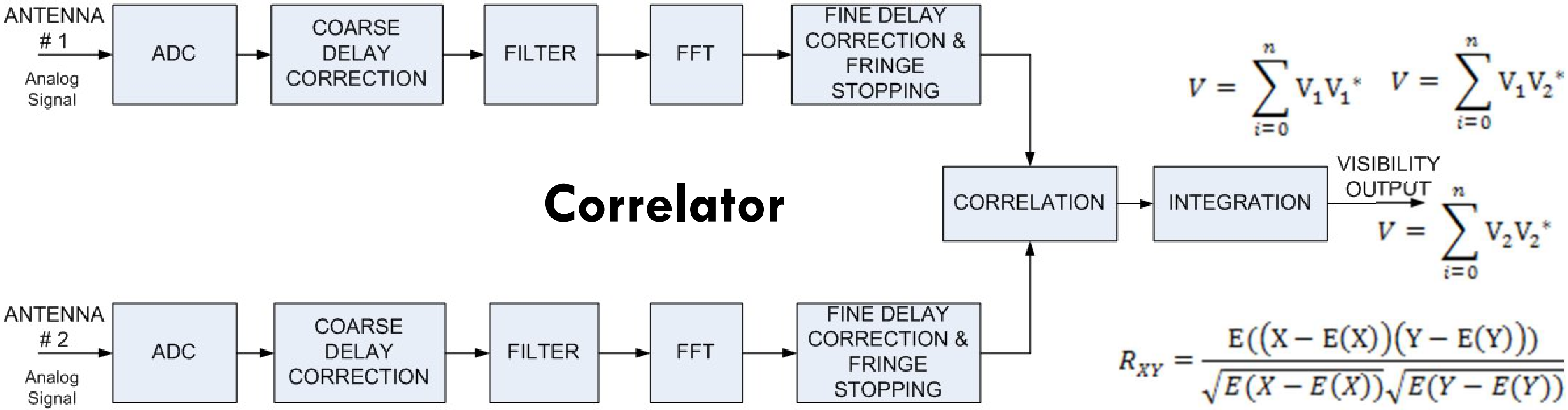
Phase is important !

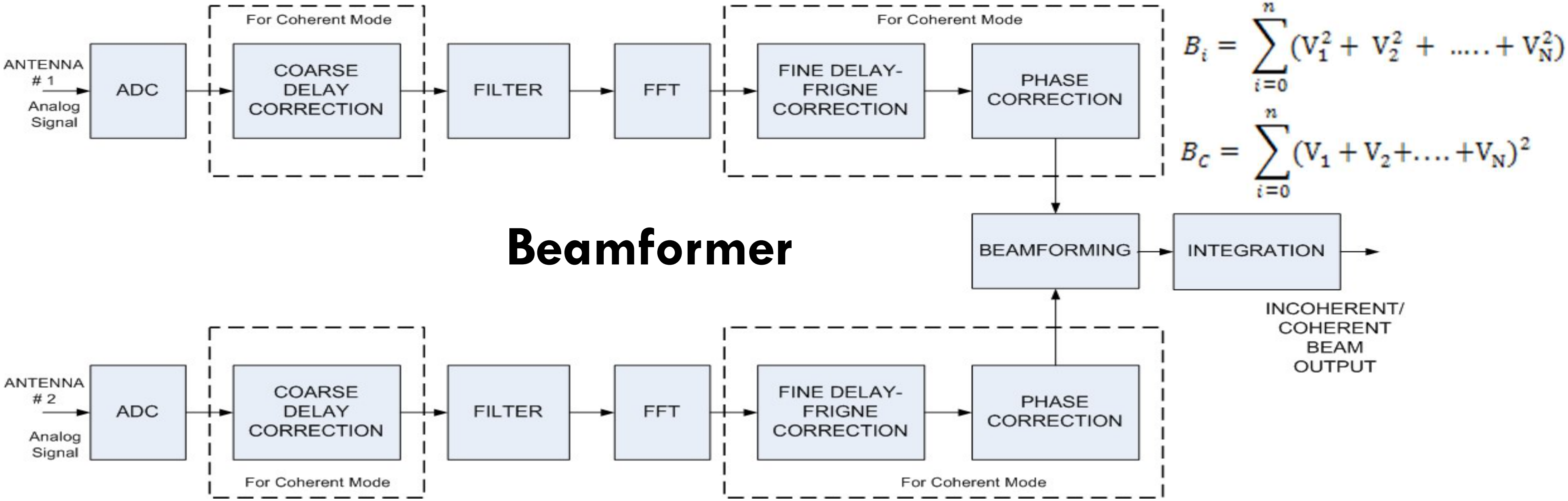
Beamforming in practice



- Correlation complexity grows quadratically with the number of elements
- Correlation output is used for phasing the array
- Applying appropriate phase to add the input coherently

Digital Processing: Block Diagram





Modern Correlators: Example

Correlators consist of signal processing component and networking component

F-engines X-engines

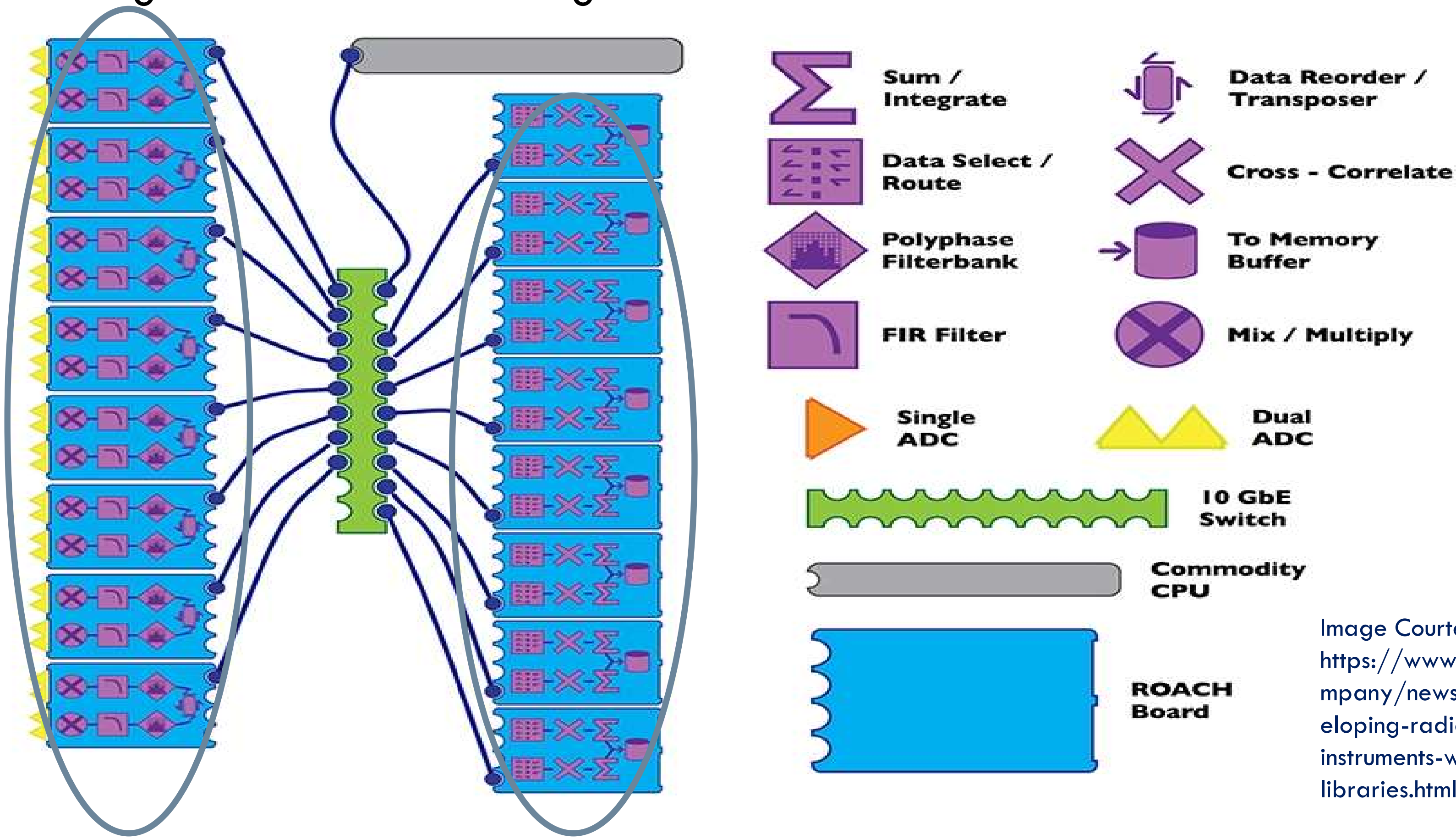


Image Courtesy: https://www.mathworks.com/company/newsletters/articles/developing-radio-astronomy-instruments-with-simulink-libraries.html

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

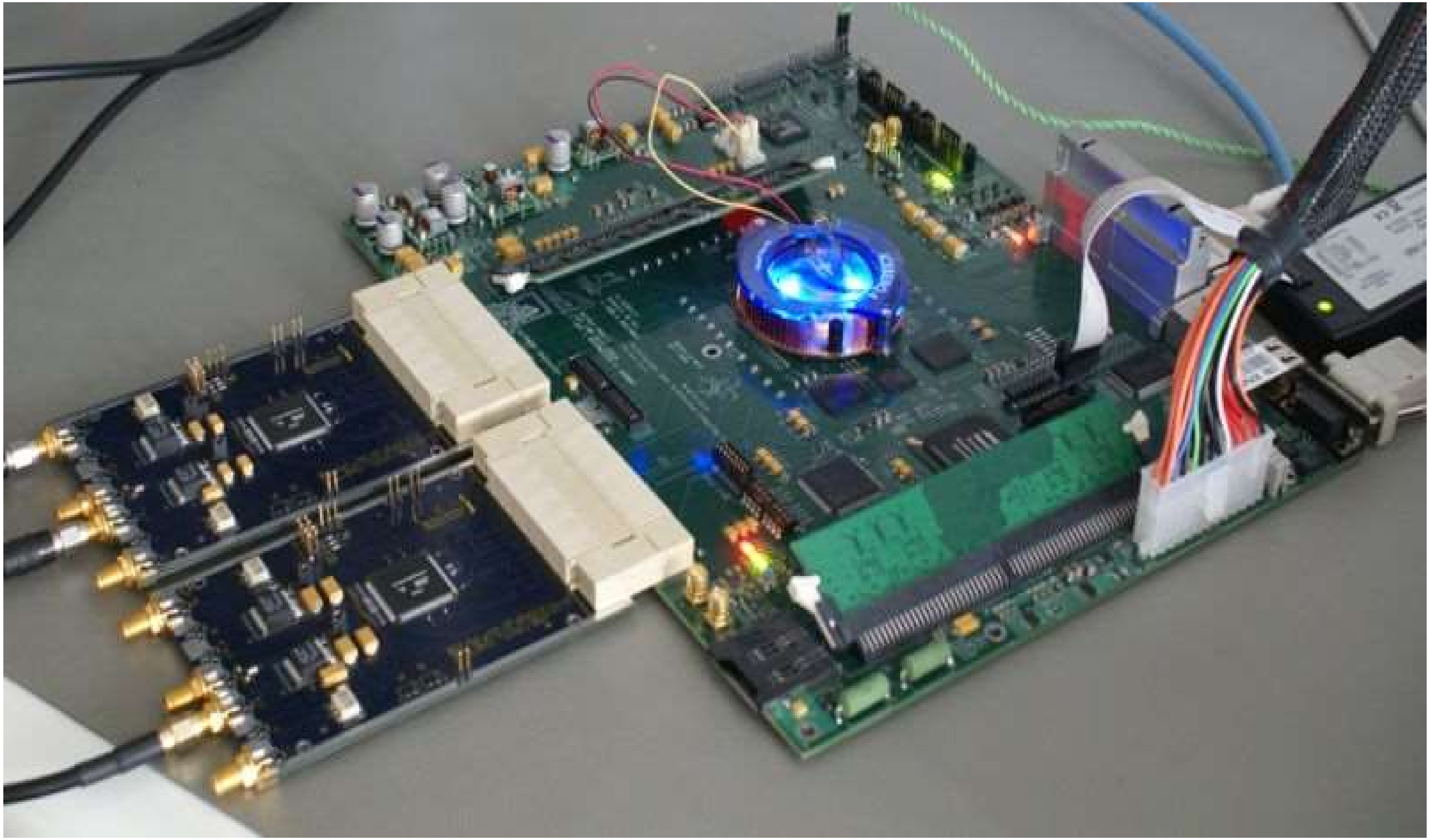


Image Courtesy: CASPER

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

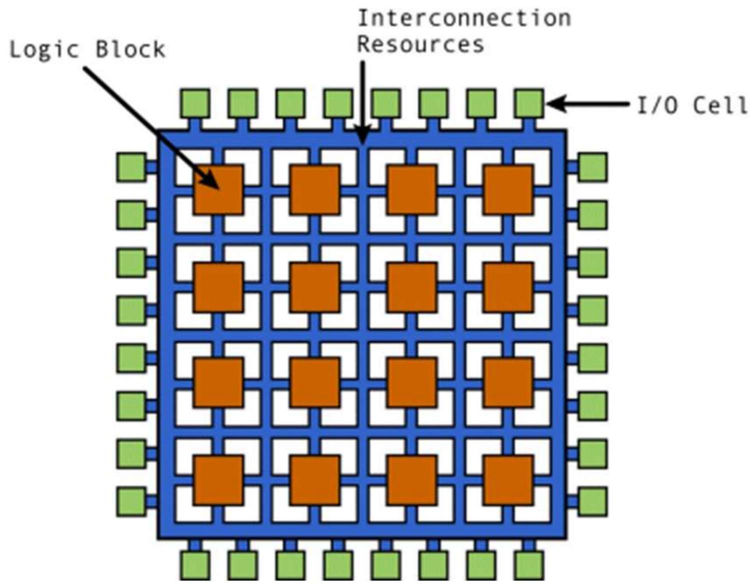


Image Courtesy: EE Times

- **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)

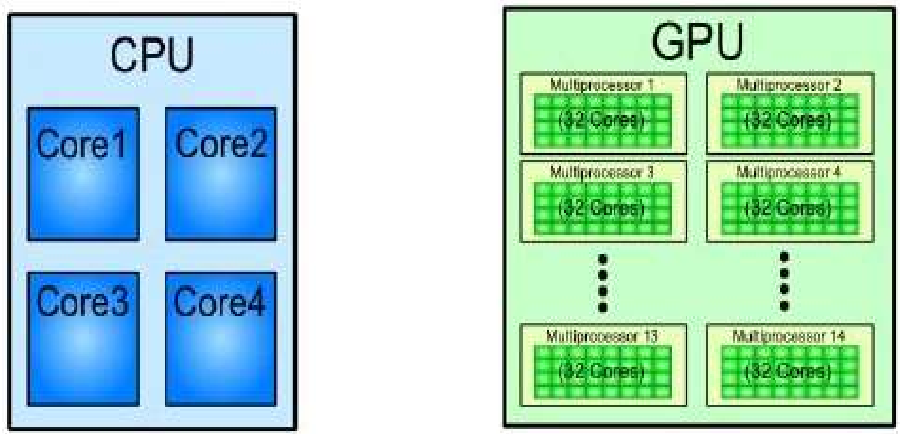
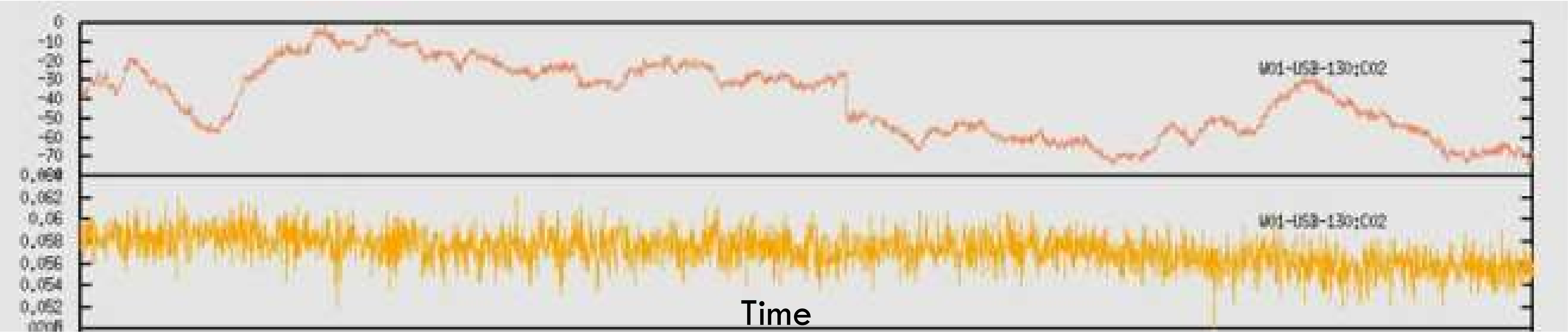


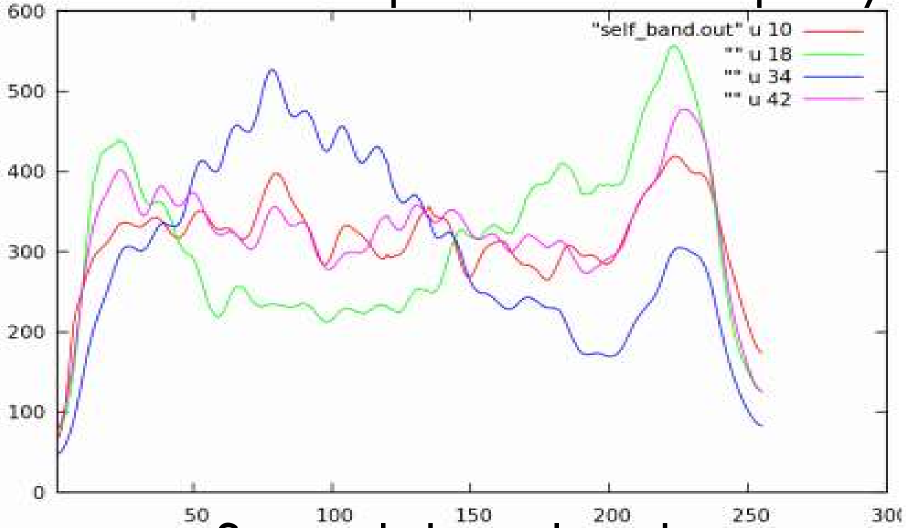
Image Courtesy: https://www.tutorialspoint.com/

Correlator output (Example)

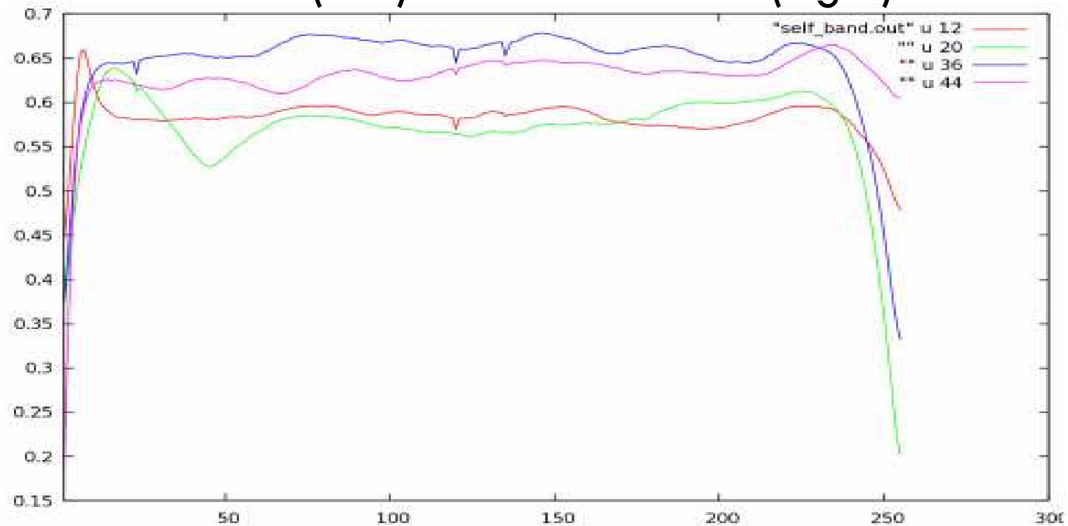
W01-C02 baseline cross-correlation amplitude (normalized) and phase for a single spectral channel (frequency) as a function of time



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

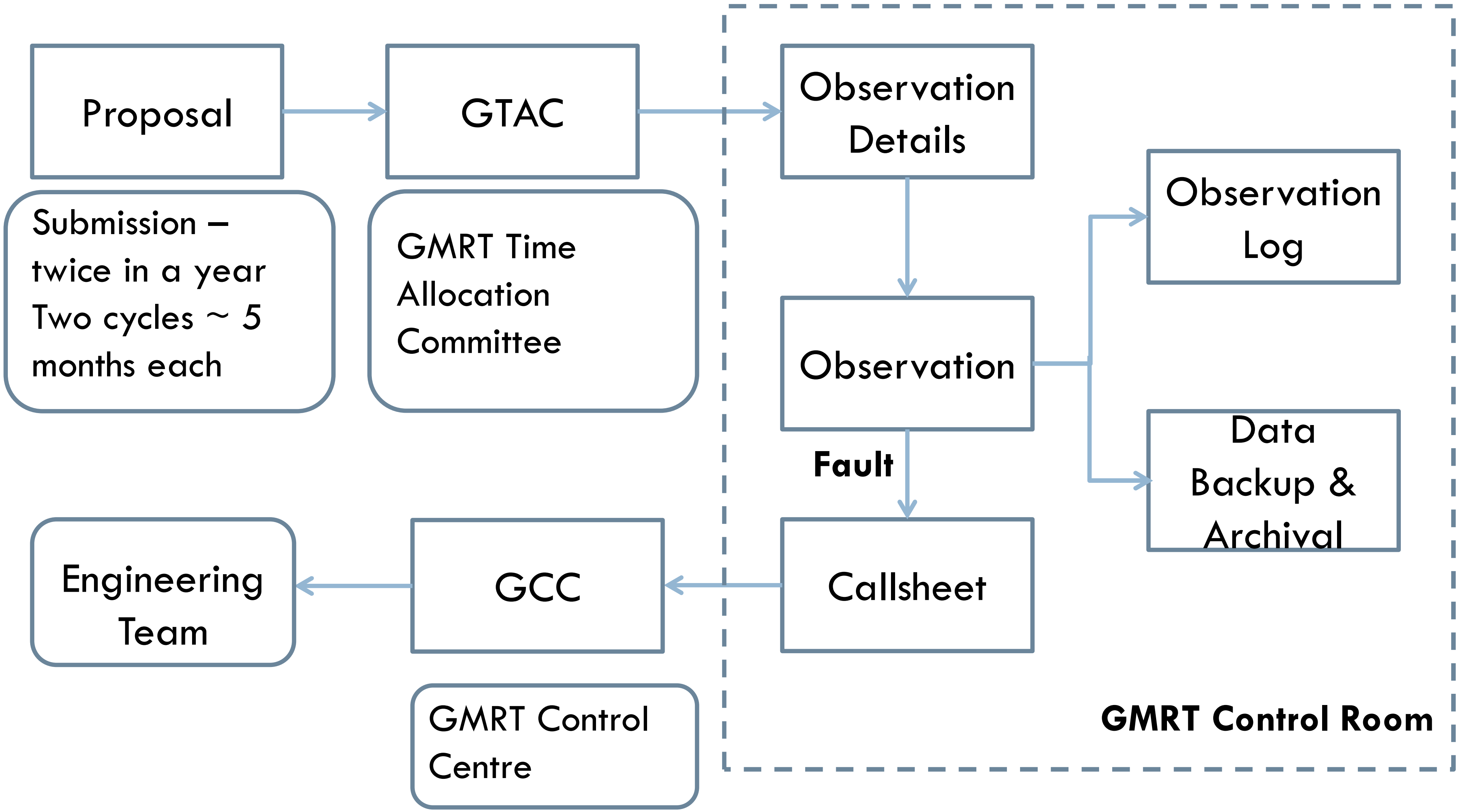


Spectral channel number



Spectral channel number **Image Courtesy: J. Roy**

Control Room

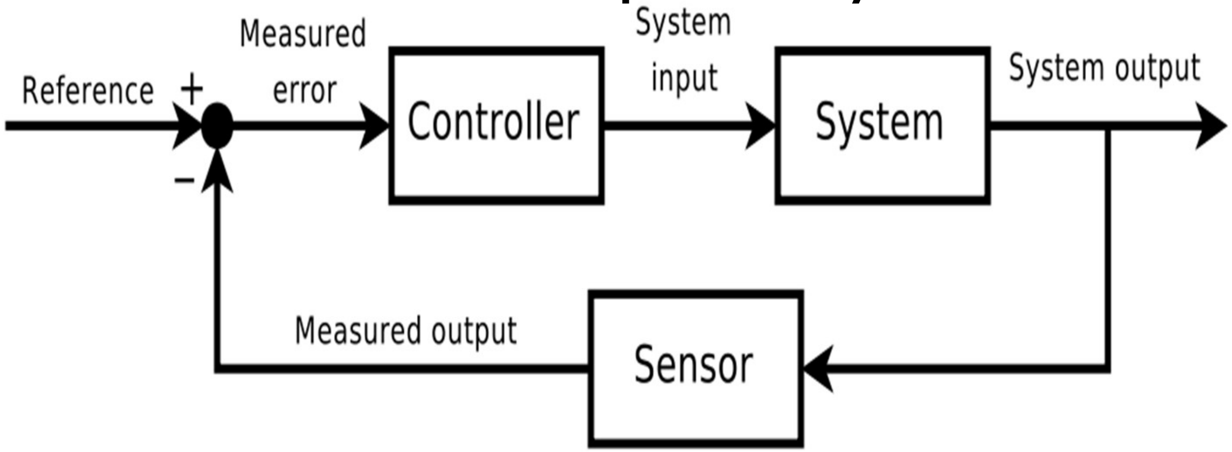


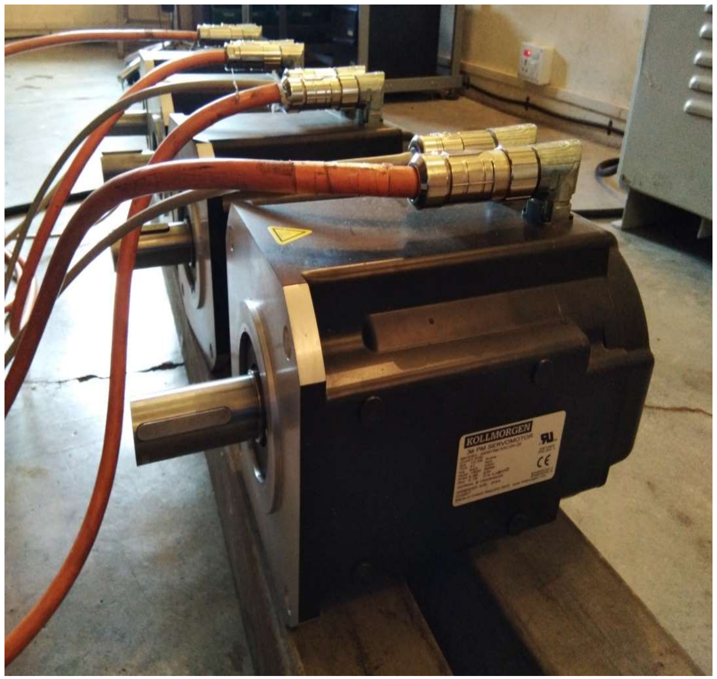
NCRA Archival and Proposal System (NAPS) https://naps.ncra.tifr.res.in/naps/login

Servo System

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

Closed-loop control system





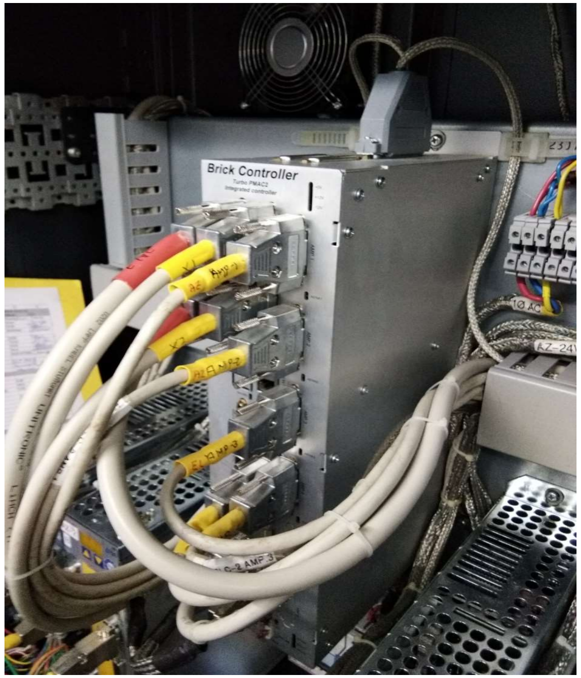


Image Courtesy: Servo Group

Maintaining and Upkeeping

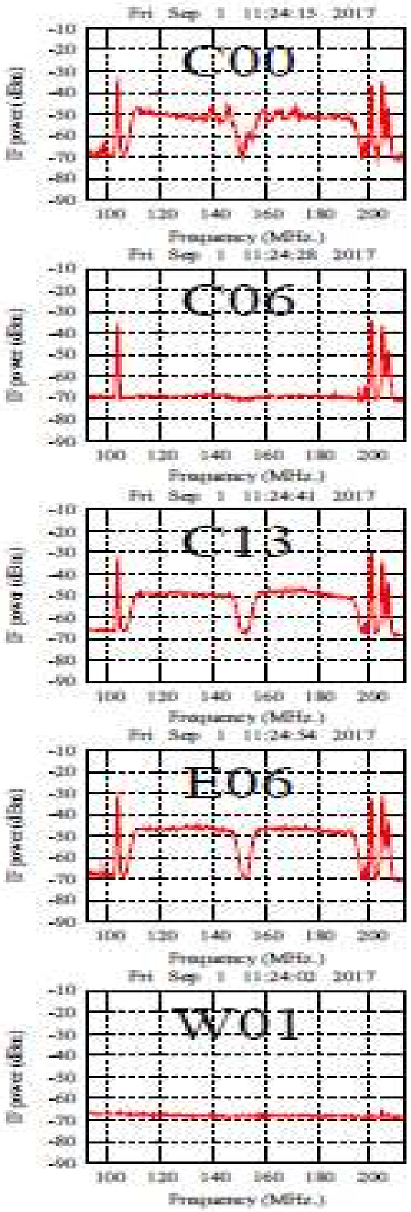
Day to day problem solving and long-term maintenance!

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

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

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

Diagnostic Tools



http://gmrt.ncra.tifr.res.in/~astrosupp/

User Documents
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 Creater 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

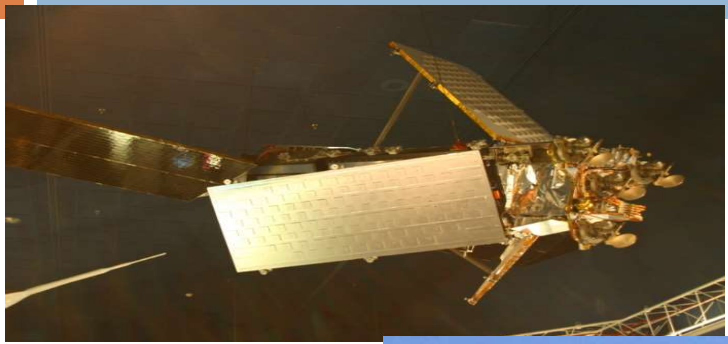
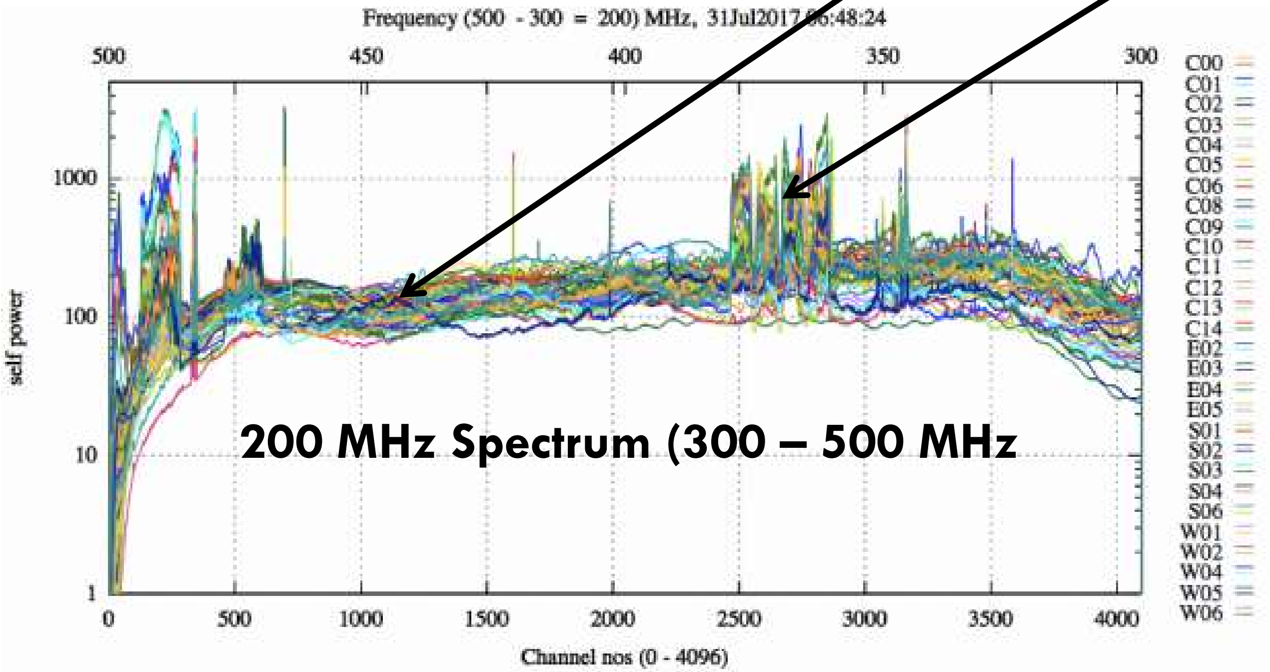


Image Courtesy: Wikipedia

- 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

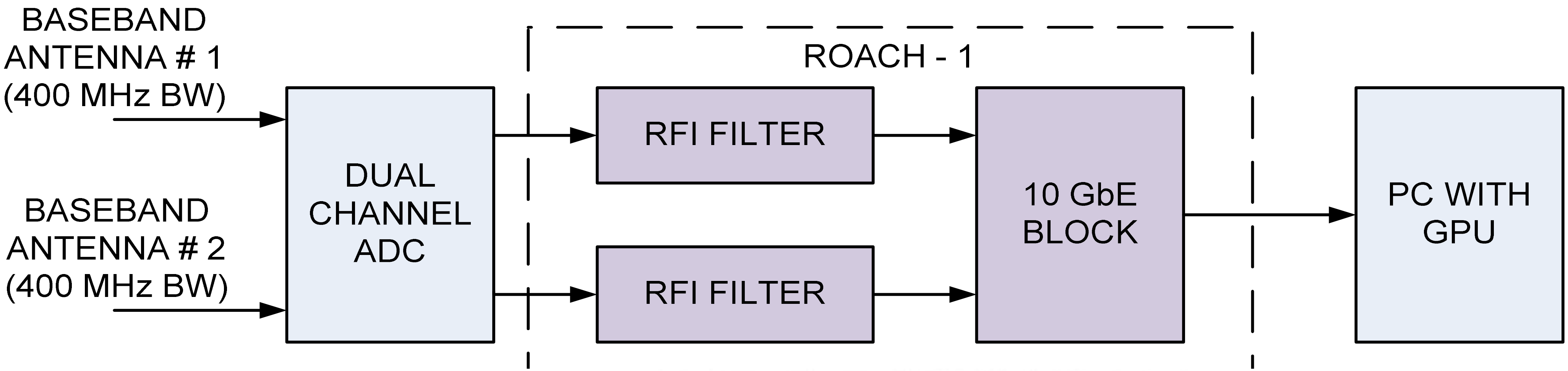
Coexisting with surrounding villages, farmlands and other industries – the potential sources of RFI

Image Courtesy: NCRA Archives

Mitigating Internal & External RFI

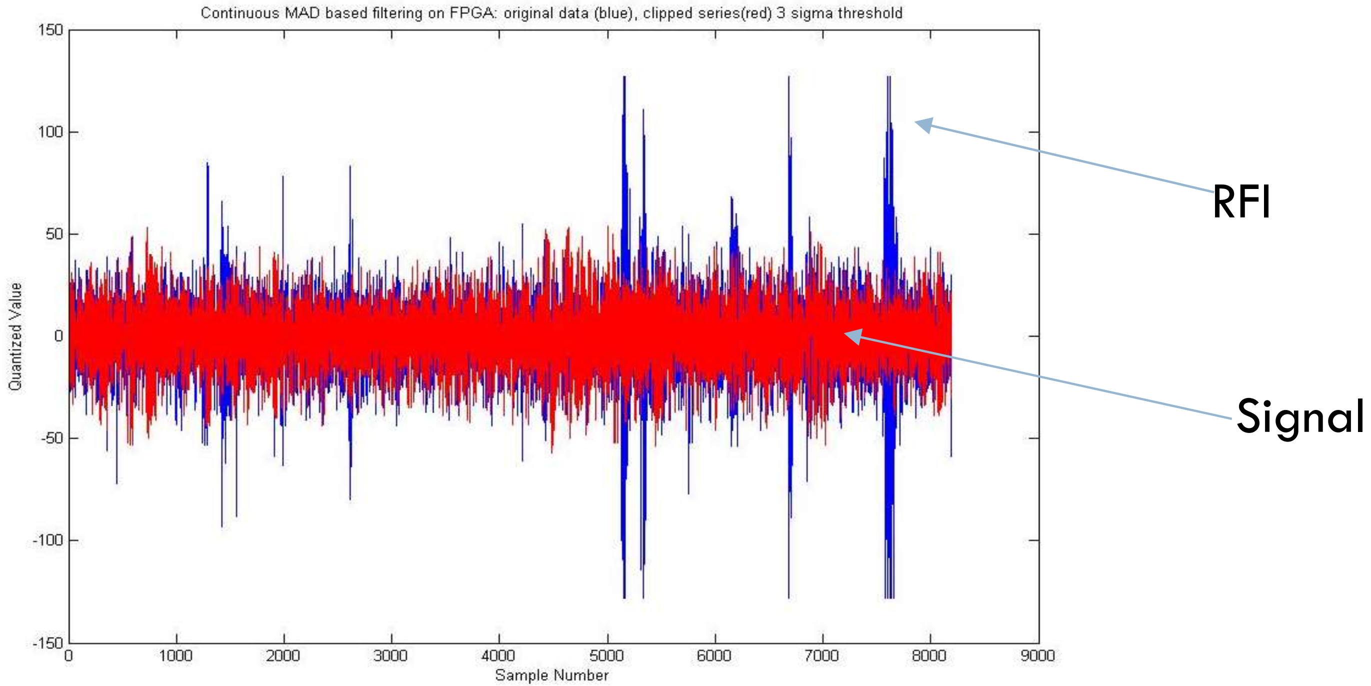
RFI Mitigation in digital system

Inside Programmable Silicon Chips



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

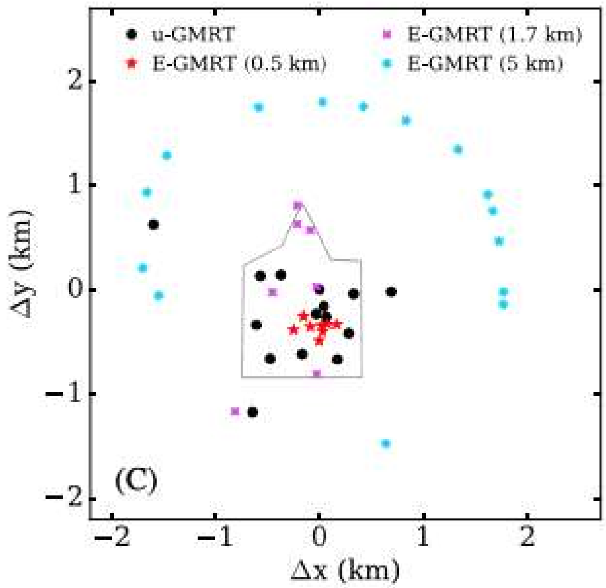
GMRT 150 MHz time-series: blue (unfiltered), red (filtered)



Expansions to the existing uGMRT: eGMRT

The Expanded GMRT (eGMRT)

Adding more antennas for baselines < 5 km



Improved sensitivity

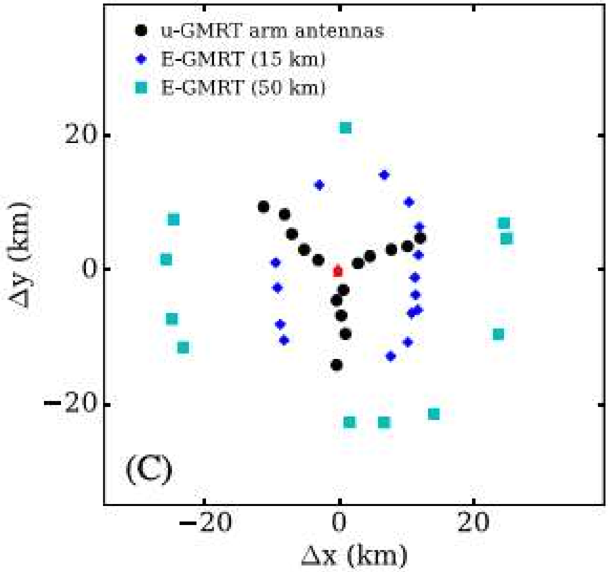
Increase in Field-of-View depends on number of independent beams

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

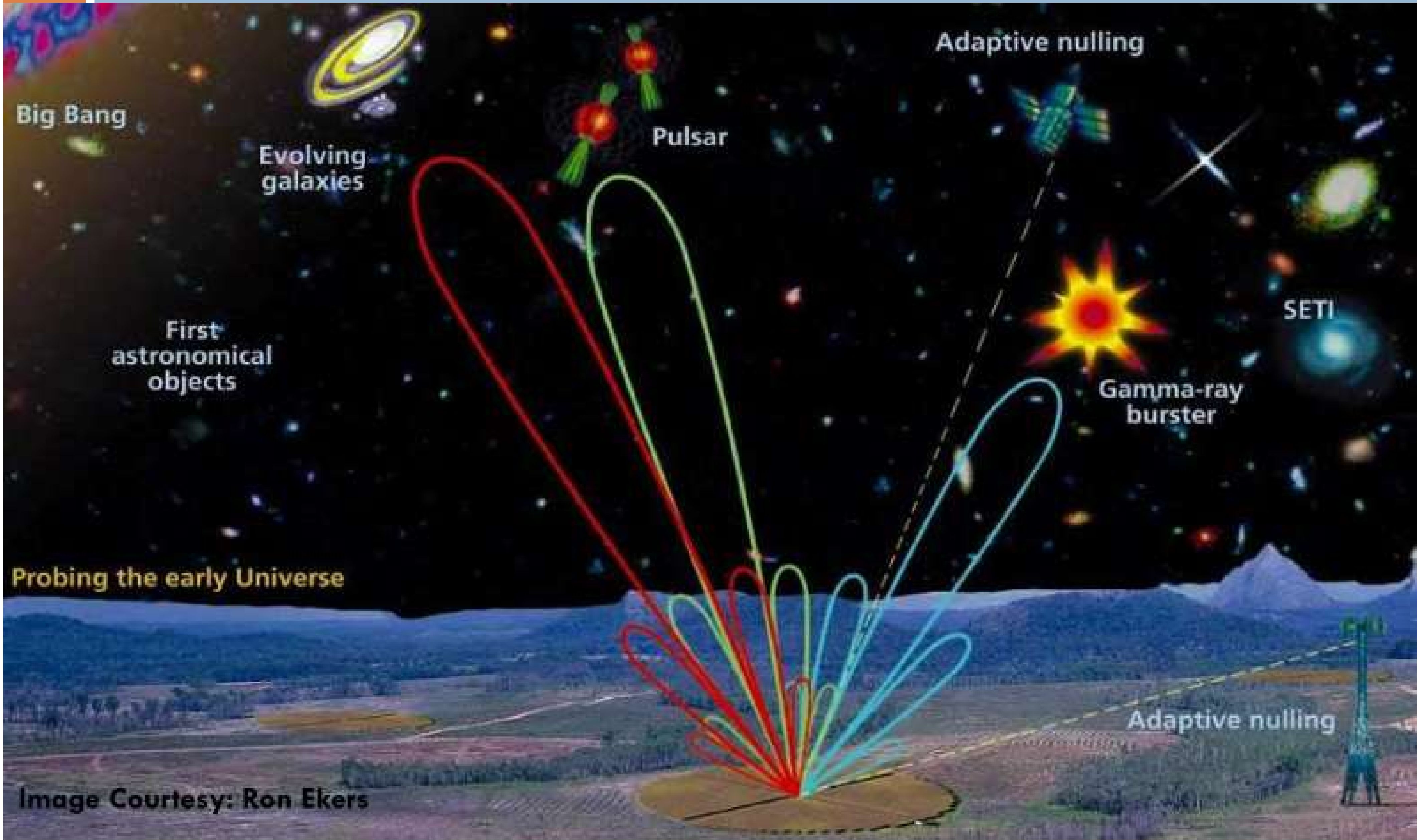


Improved angular resolution, lower confusion limit

Field-of-view is measured in degrees^2

Source: Patra et al., EGMRT, MNRAS, 2019

Forming multiple beams: Advantages



References

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2. Low Frequency Radio Astronomy, 1997, ttps://www.gmrt.ncra.tifr.res.in/doc/WEBLF/LFRA/index.html
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