Giant Metrewave Radio Telescope (GMRT): A System Overview

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Astronomical Techniques II course

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GMRT

Giant Metrewave Radio Telescope

- Sensitive telescope operating between 120 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)

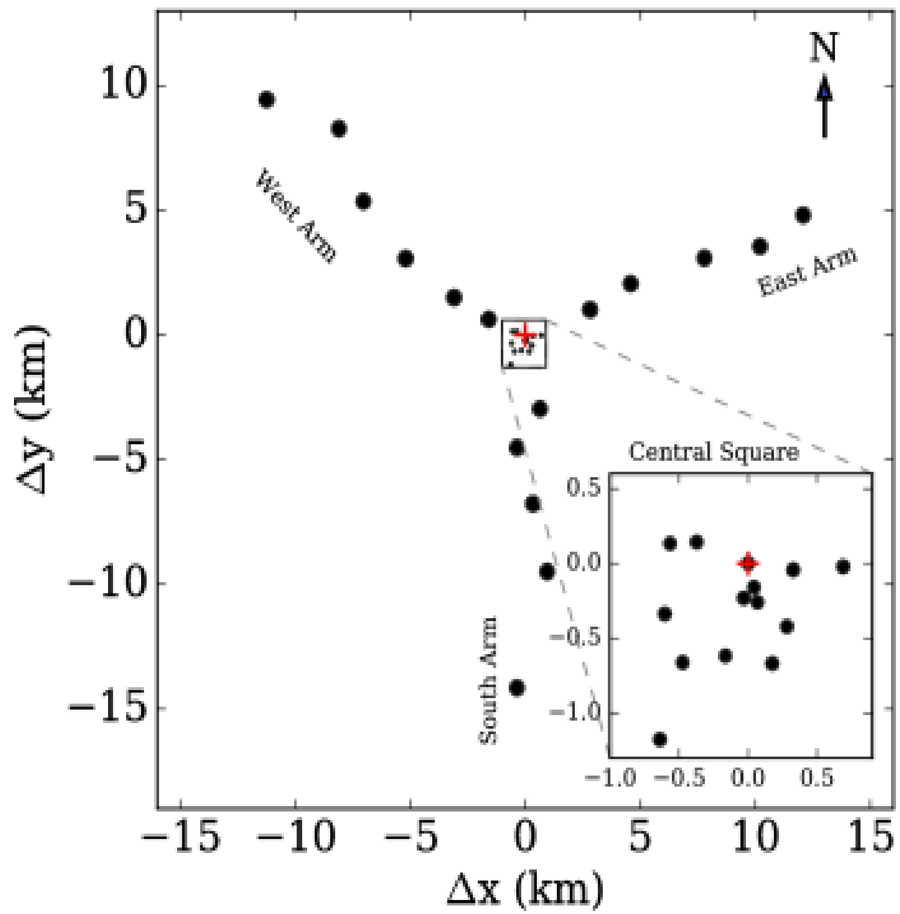
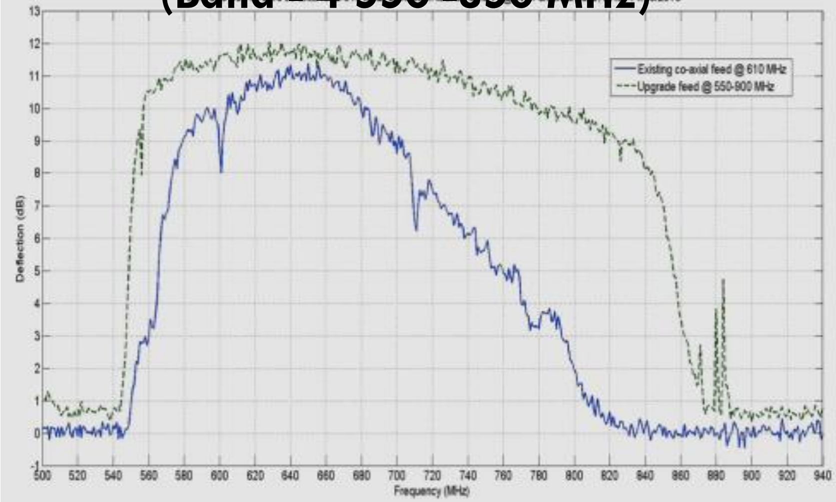


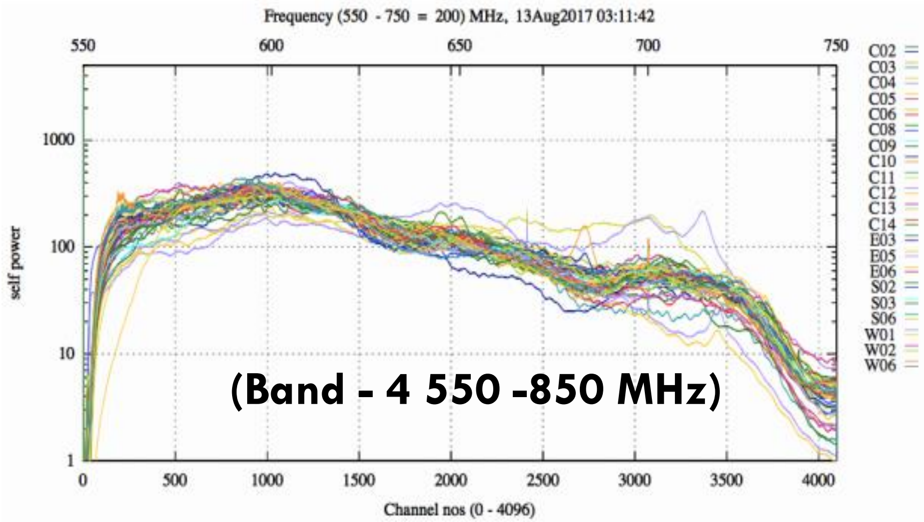
Image Courtesy: N. Patra

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)

(Band – 4 550 –850 MHz)





(Band - 4 550 -850 MHz)

Image Courtesy: FE group + Control room

Short Spacing Antennas of GMRT

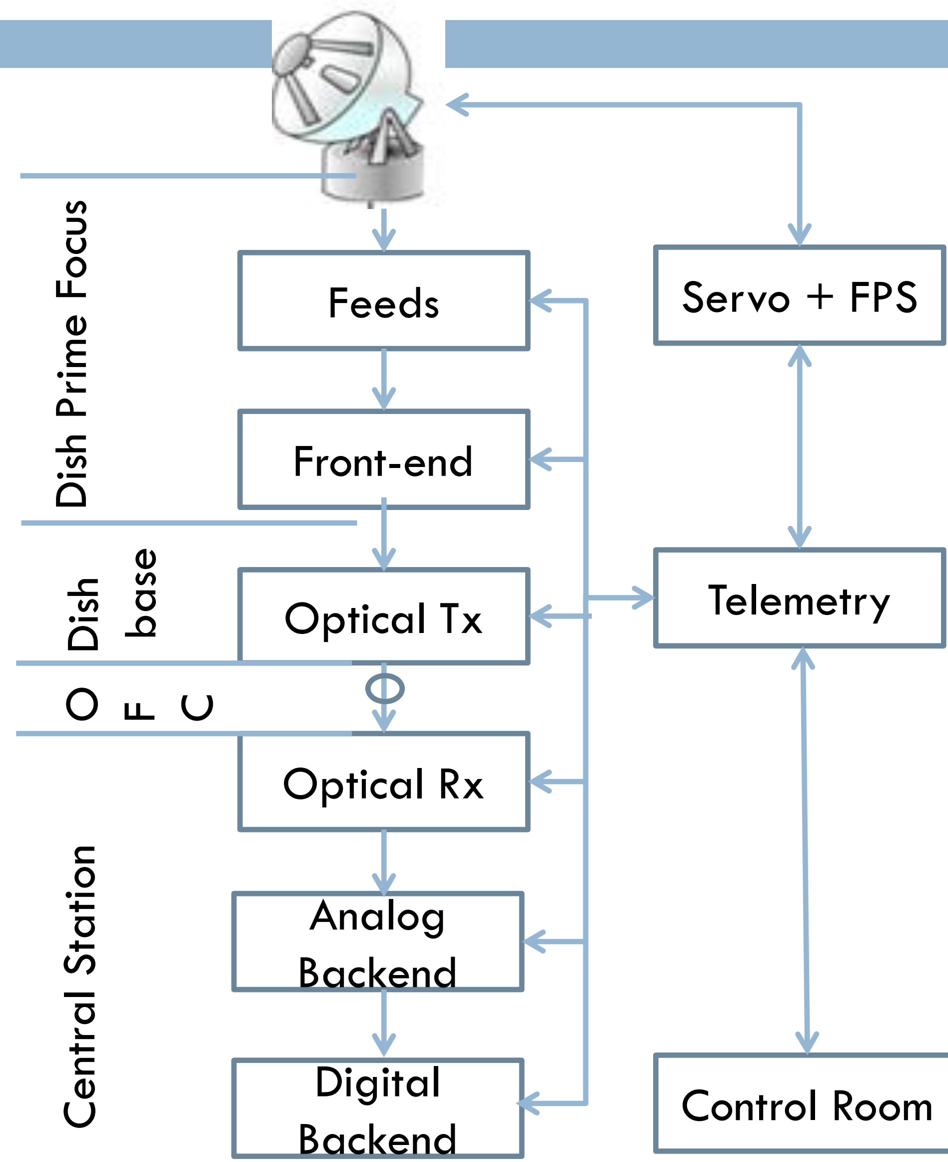
Shortest spacing ~ 100m; largest spacing ~ 25km

Image Courtesy: NCRA Archives, Google Arts and Culture, APS TV

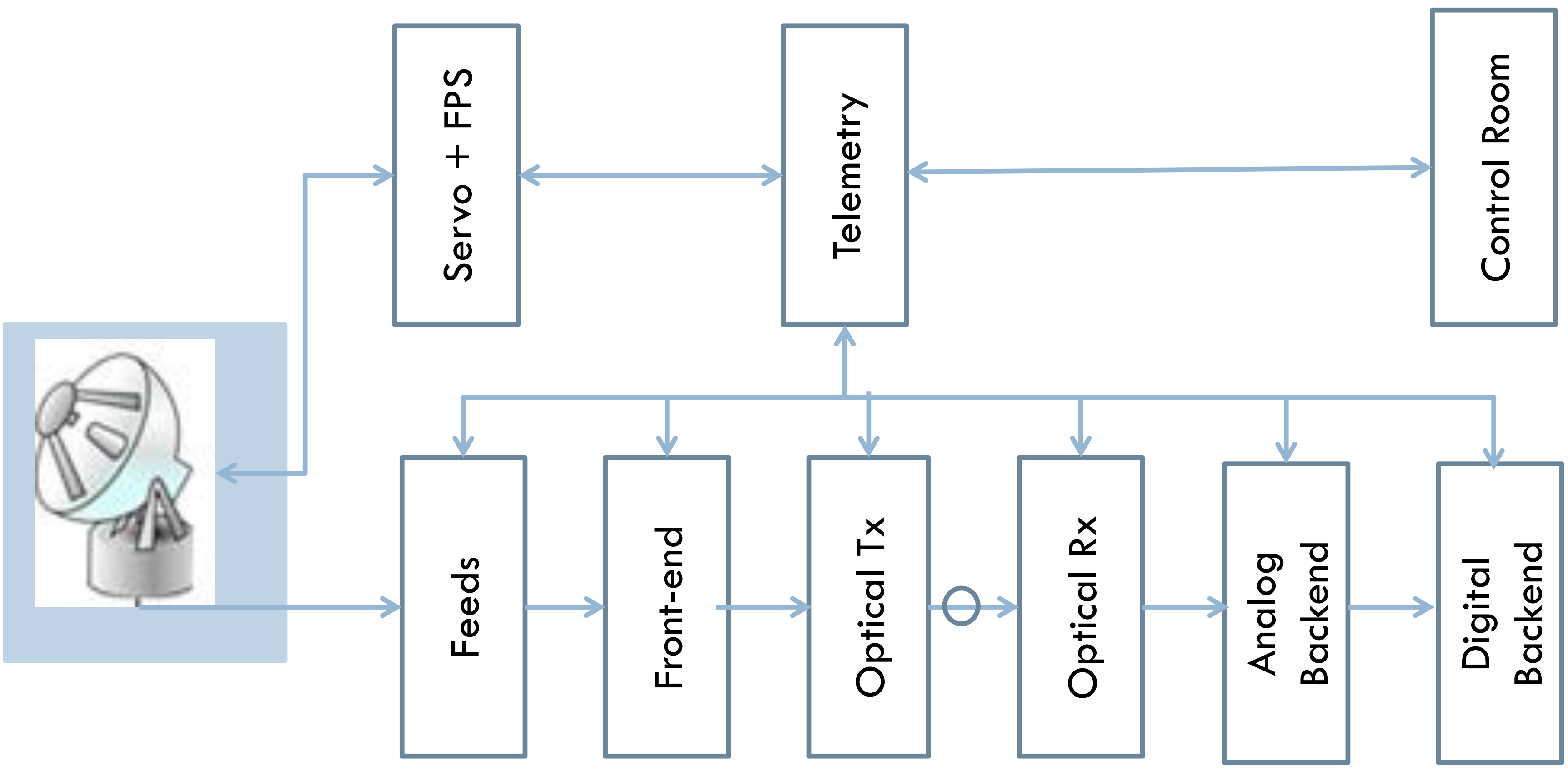
GMRT Systems

<u>GMRT Engineering Groups</u>

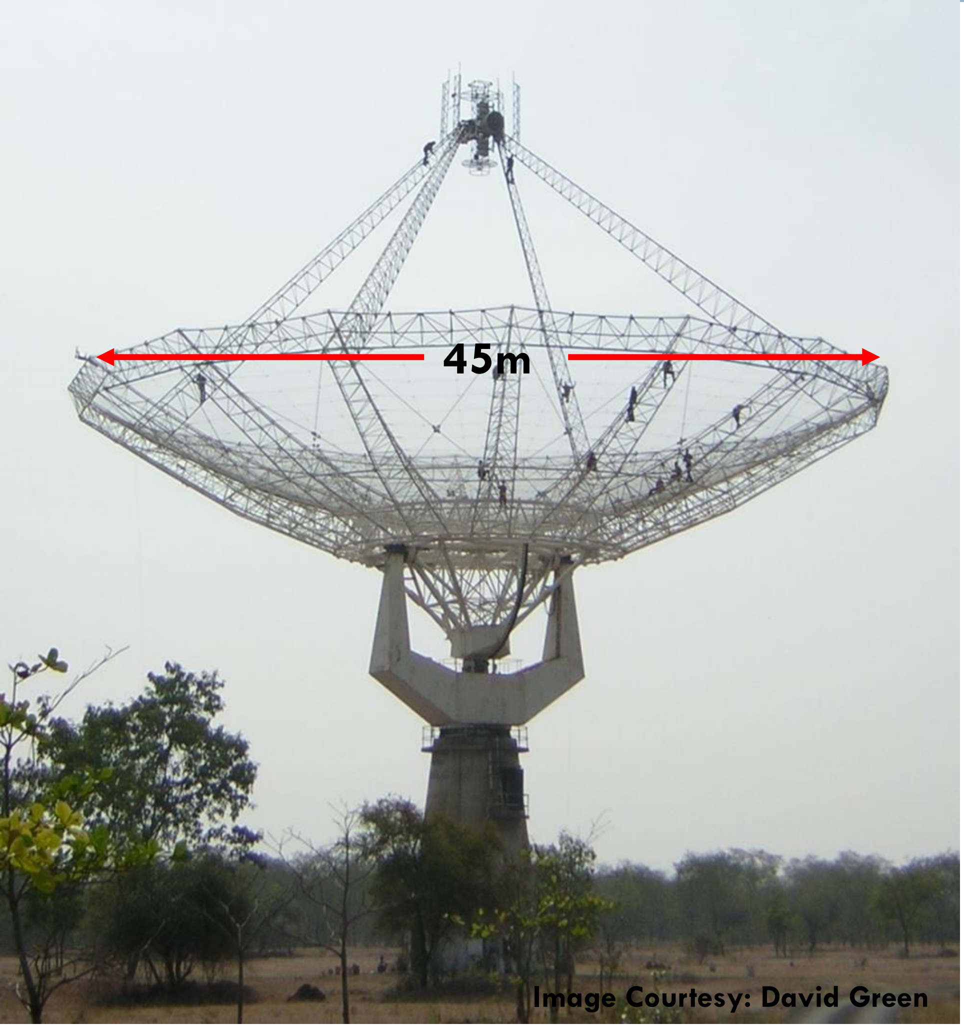
- Front-End
- Backend
- Servo
- Mechanical
- Electrical and Civil
- Telemetry



GMRT Systems



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

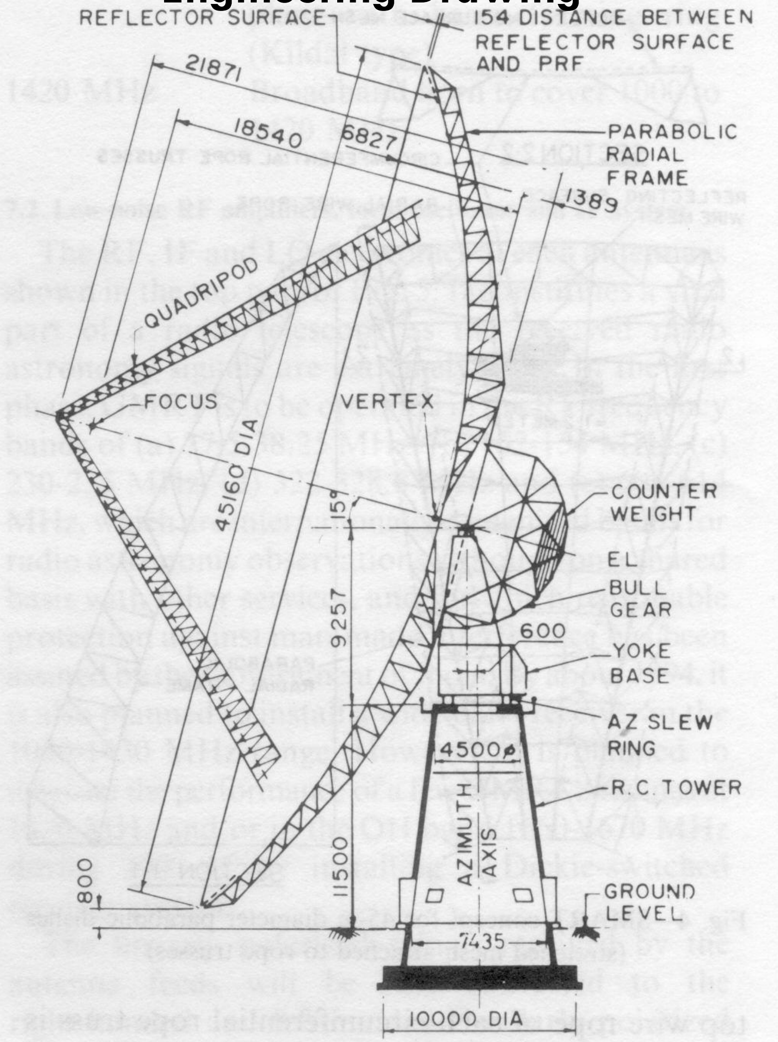


Image Courtesy: Mechanical Group

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

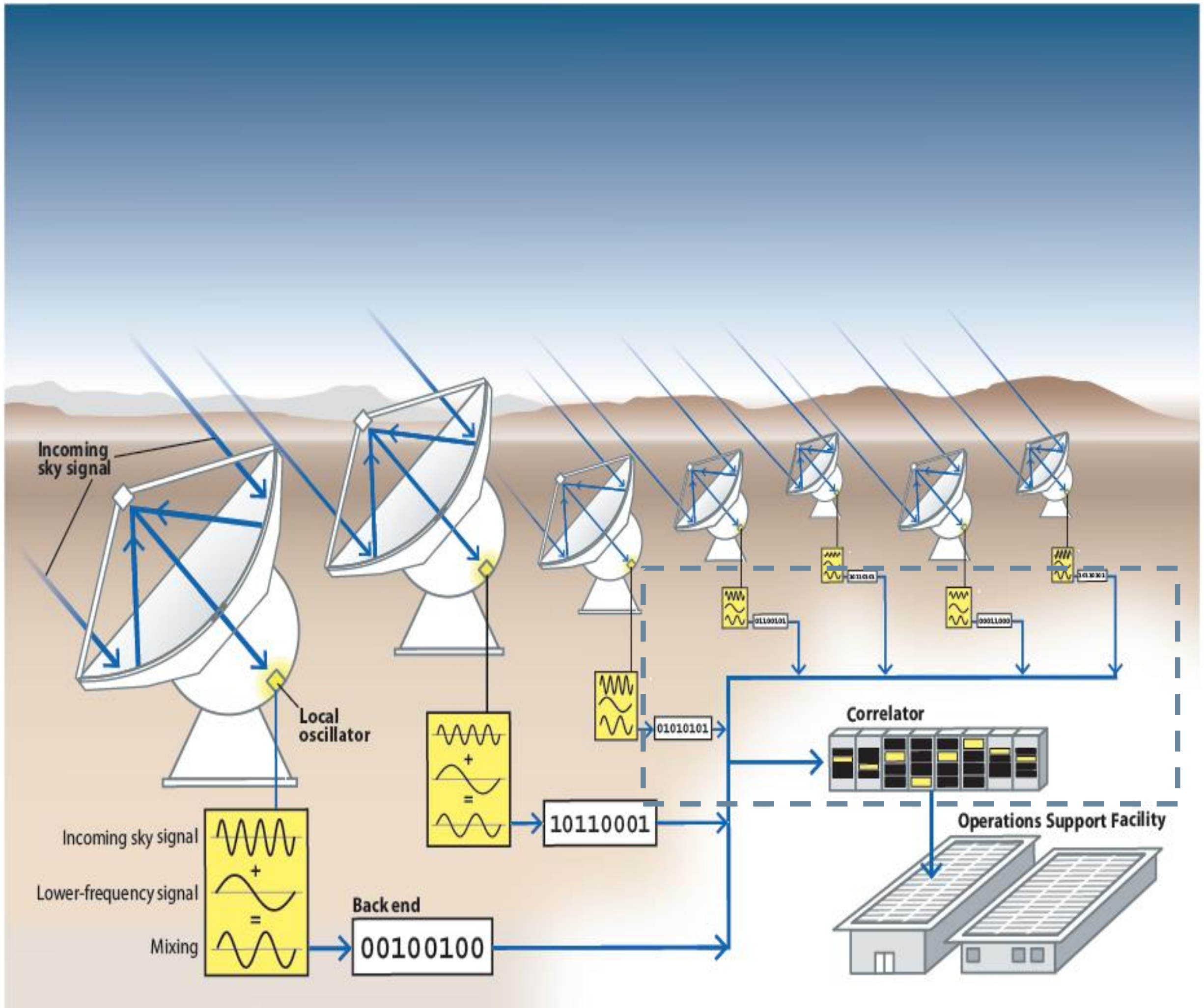


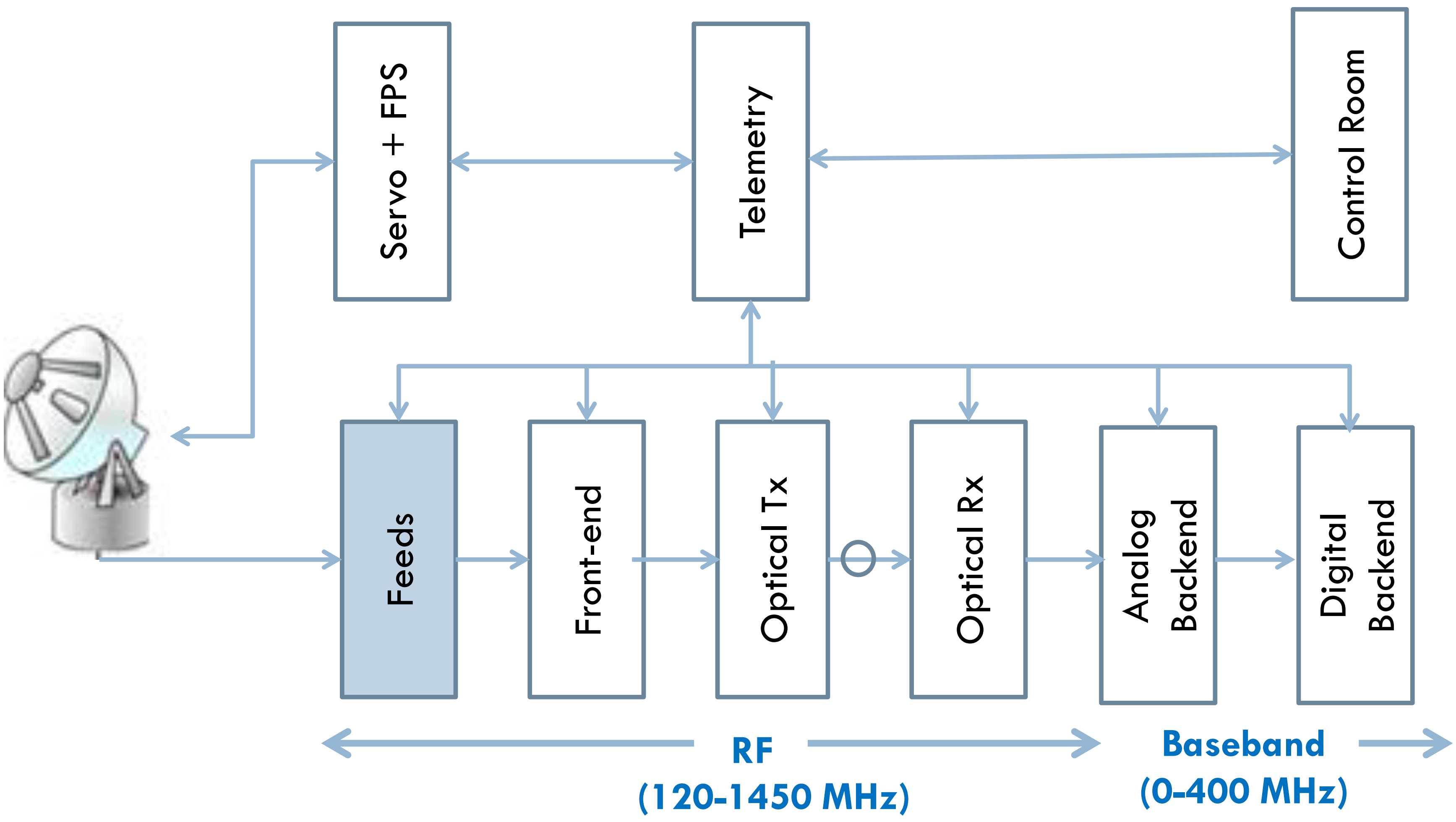
Image Source: Internet

- ❑ 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

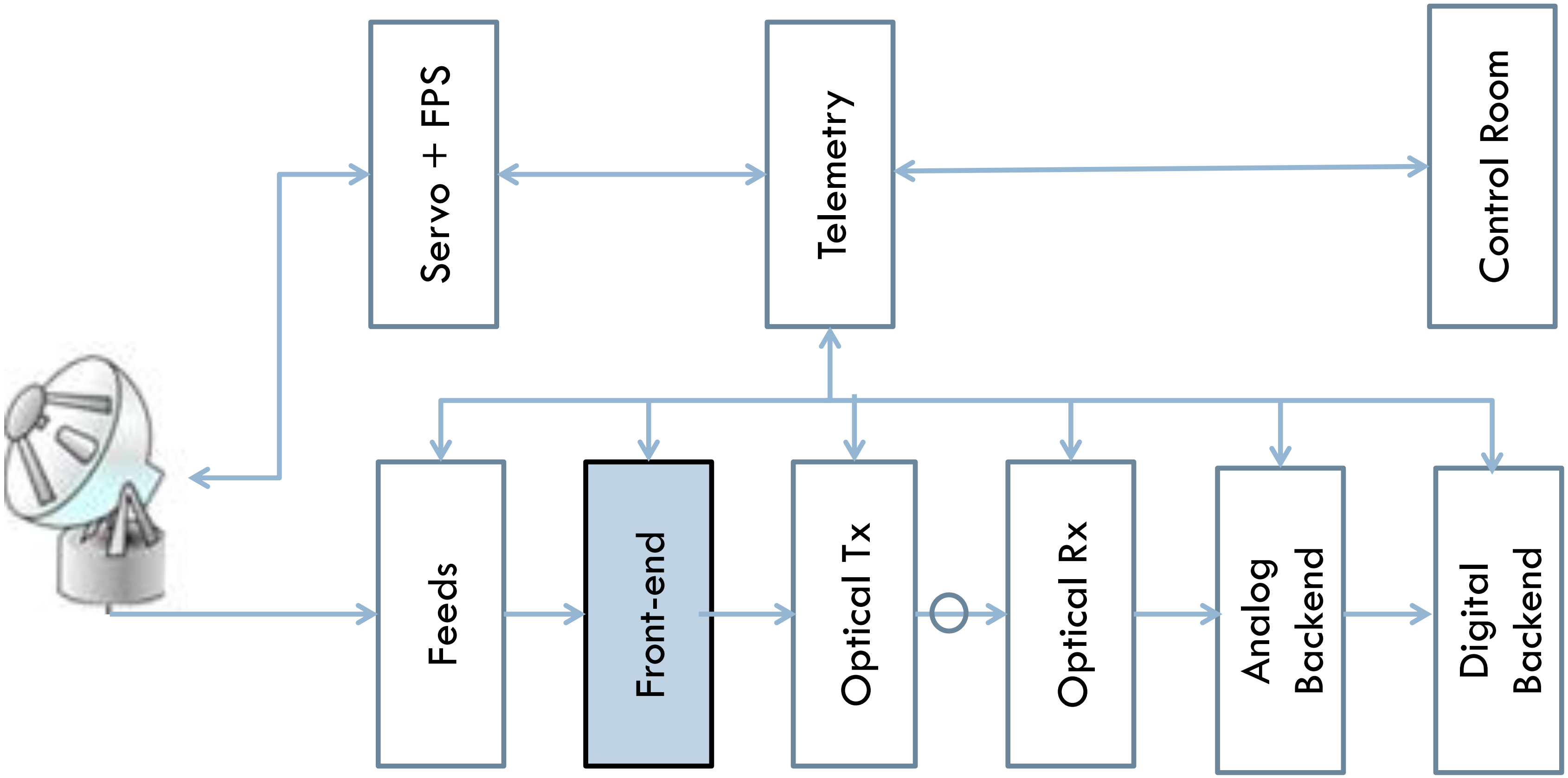
GMRT Systems



Feeds and Front-end Electronics

Image Courtesy: FE Group

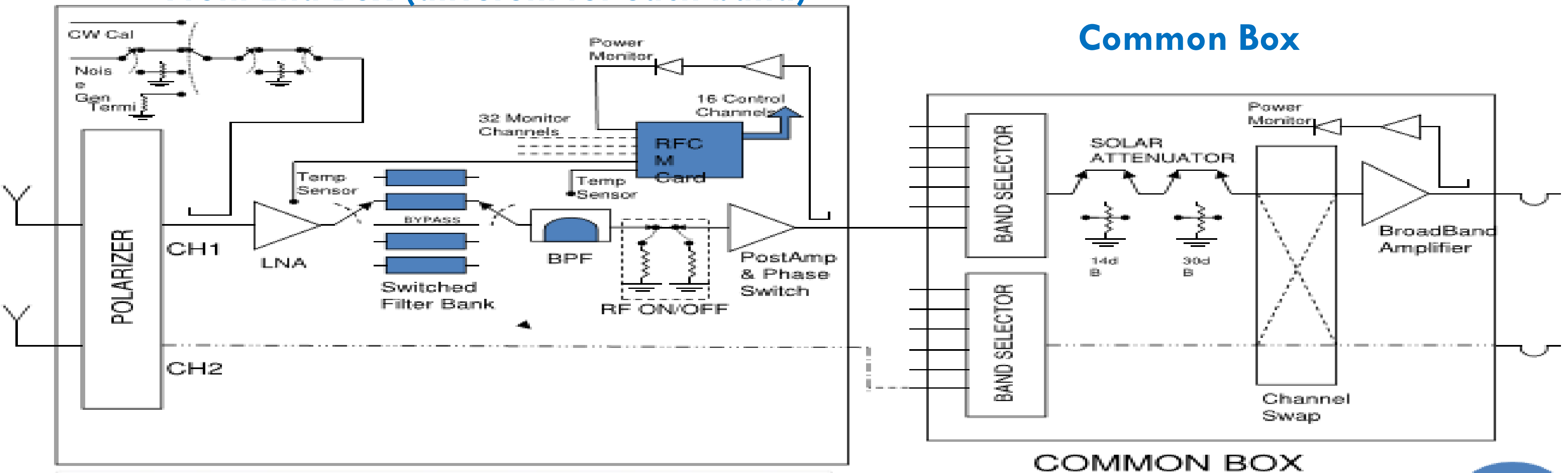
GMRT Systems

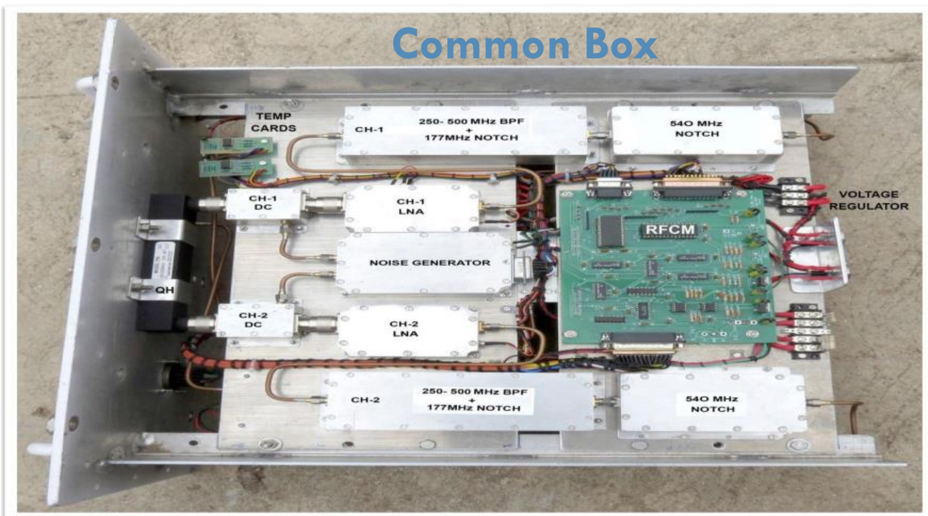


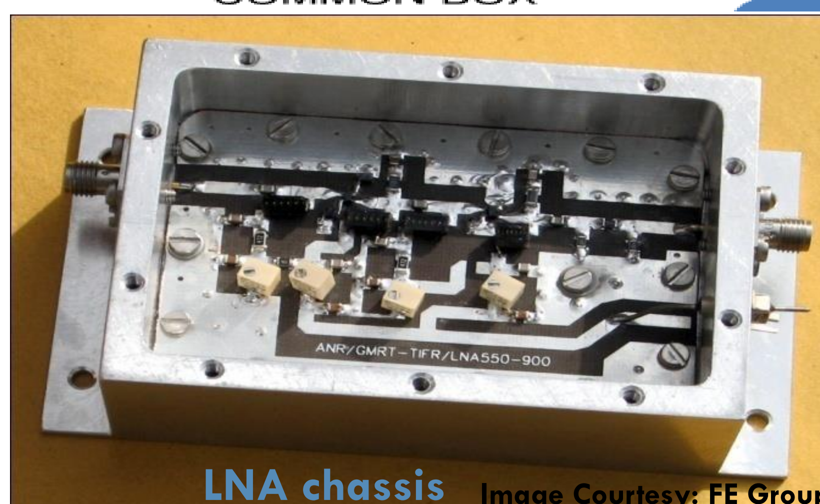
Front-end Systems

Front End Box (different for each band)

Common Box



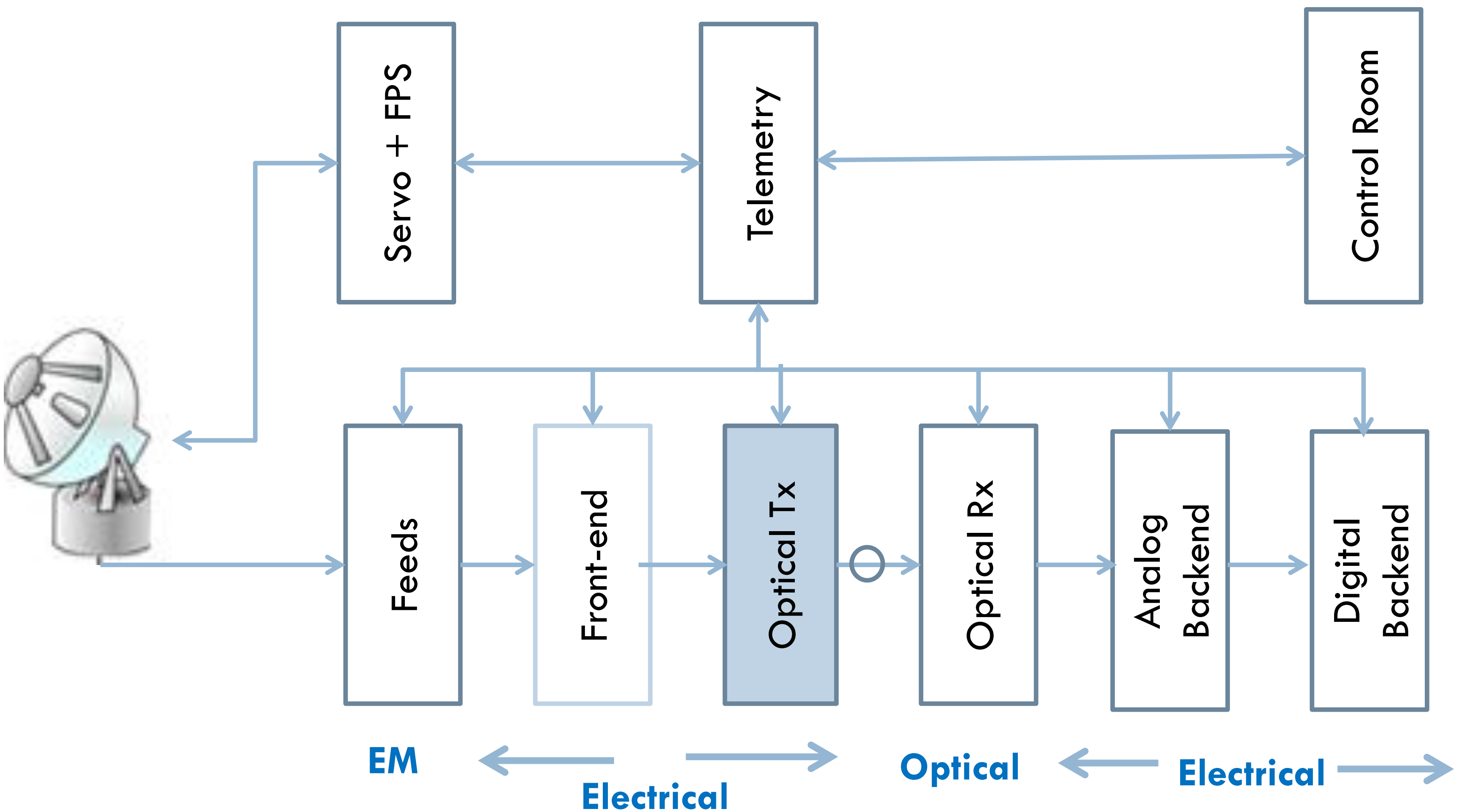




LNA chassis

Image Courtesy: FE Group

GMRT Systems



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.

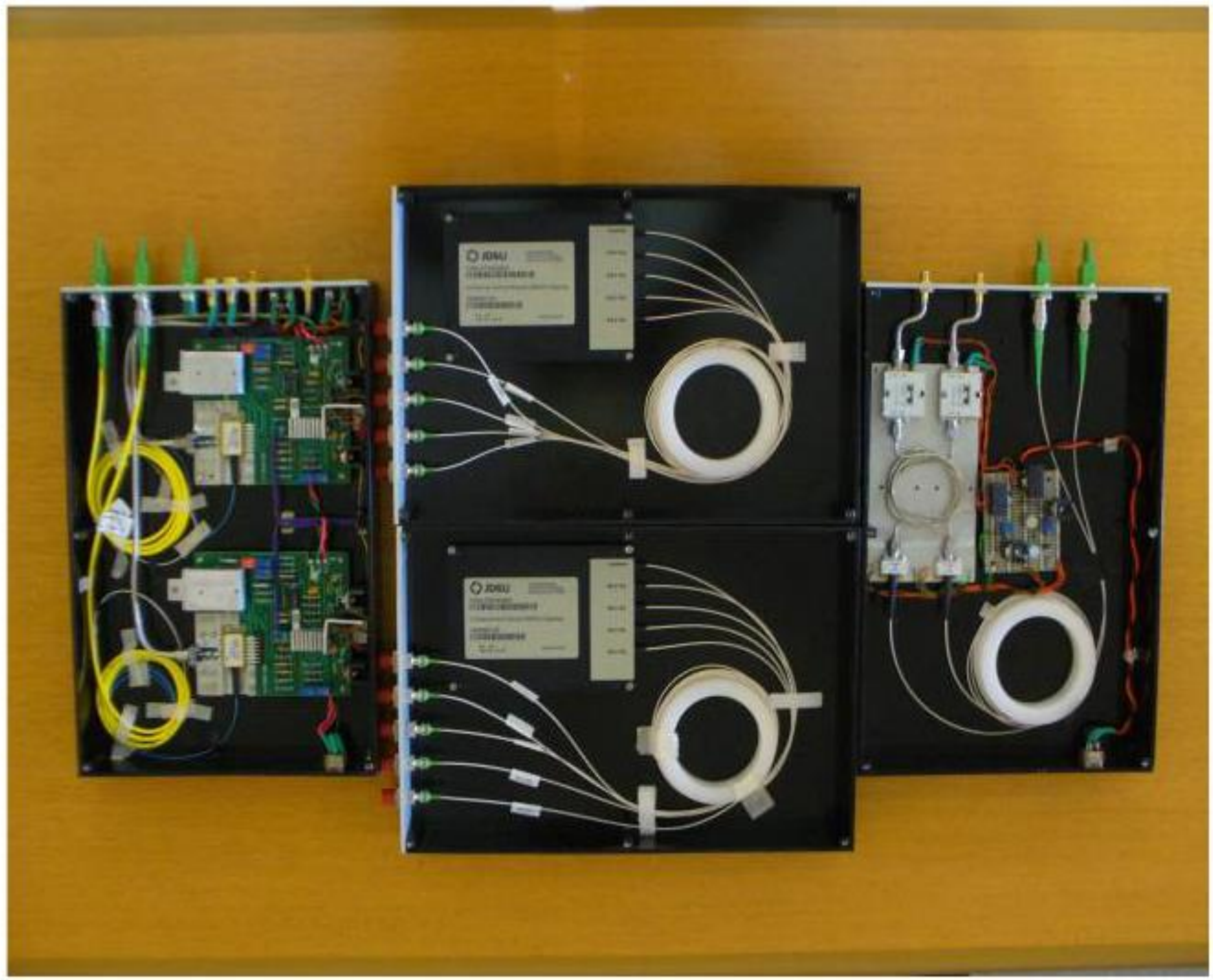
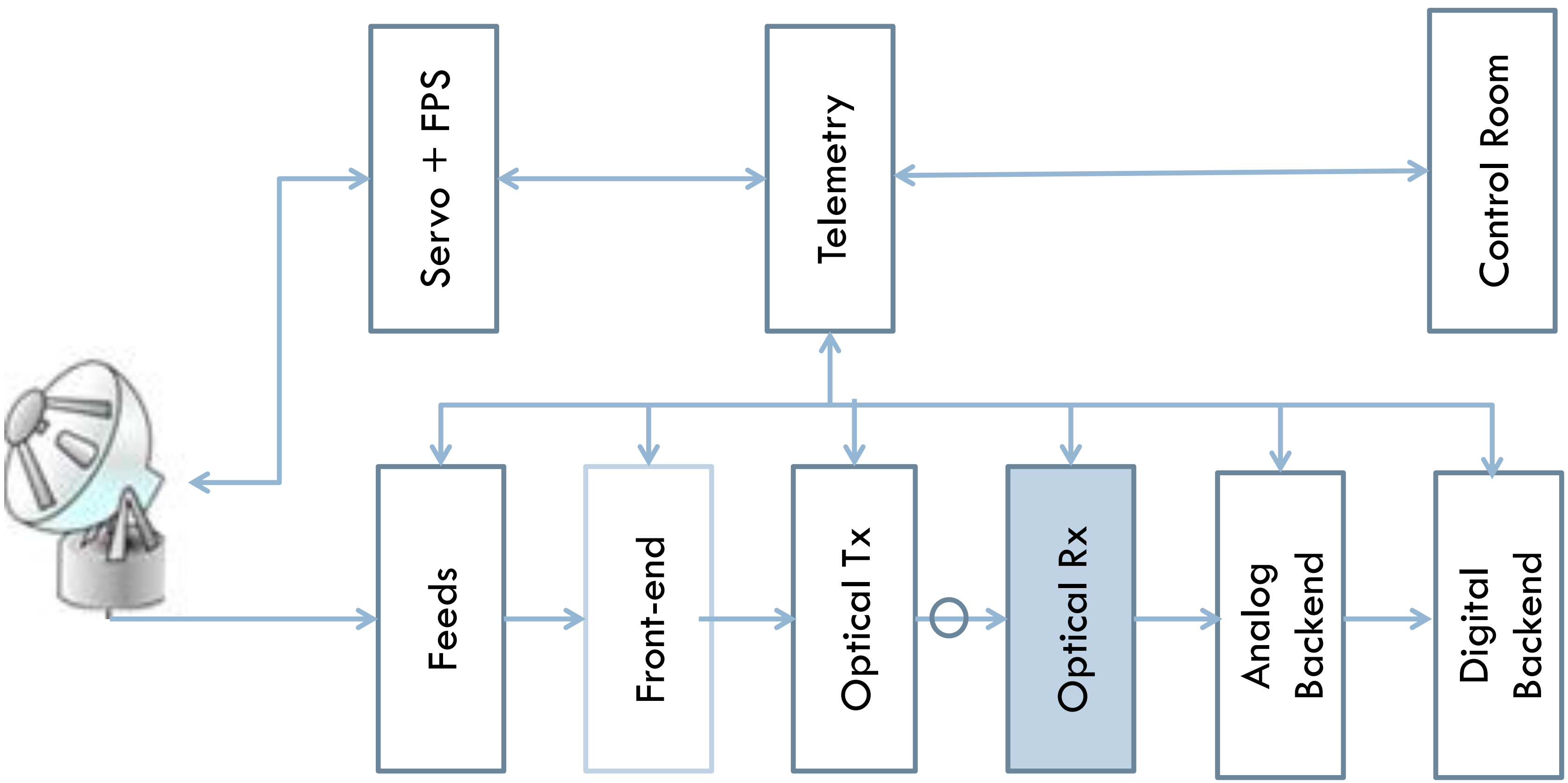


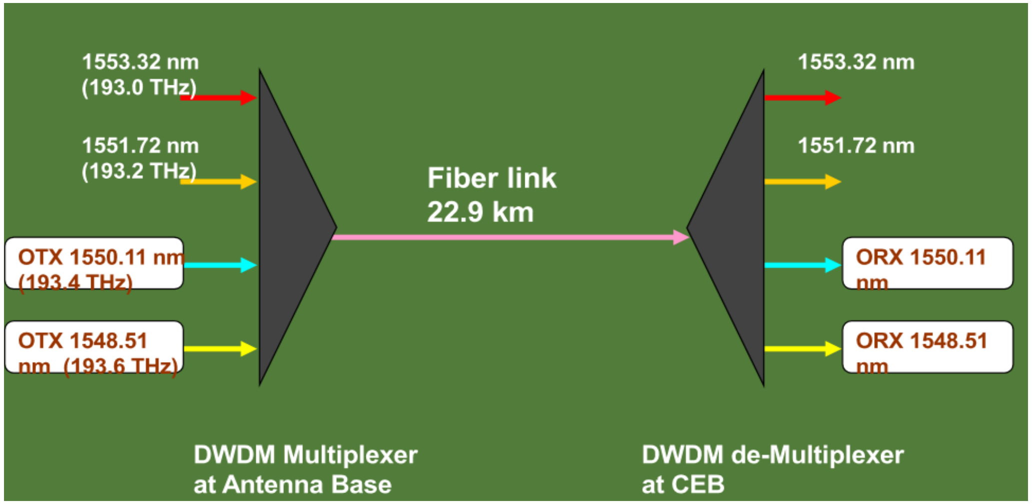
Image Courtesy: OFC Group

Signal Processing in the Central Electronics Building

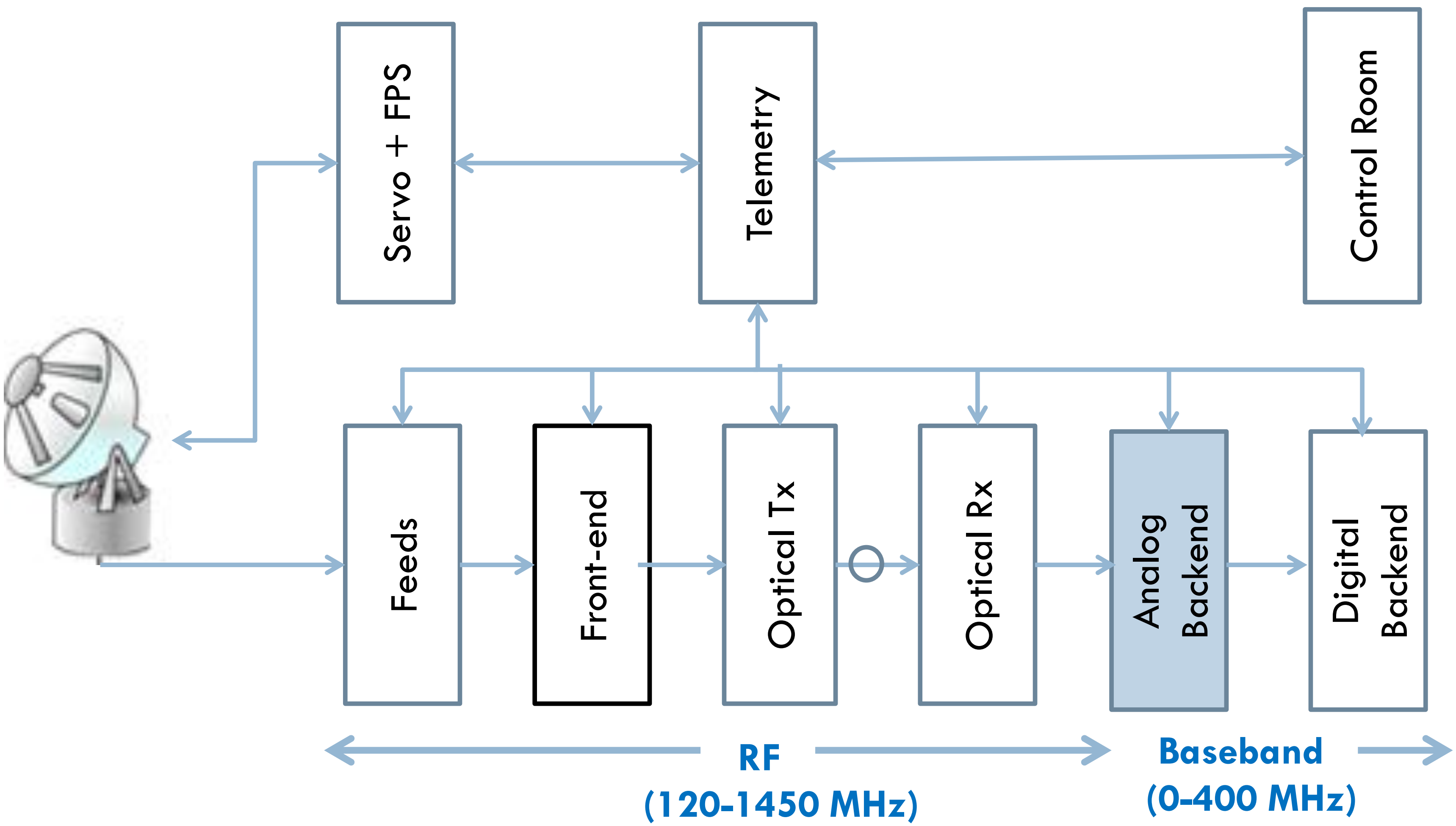
GMRT Systems



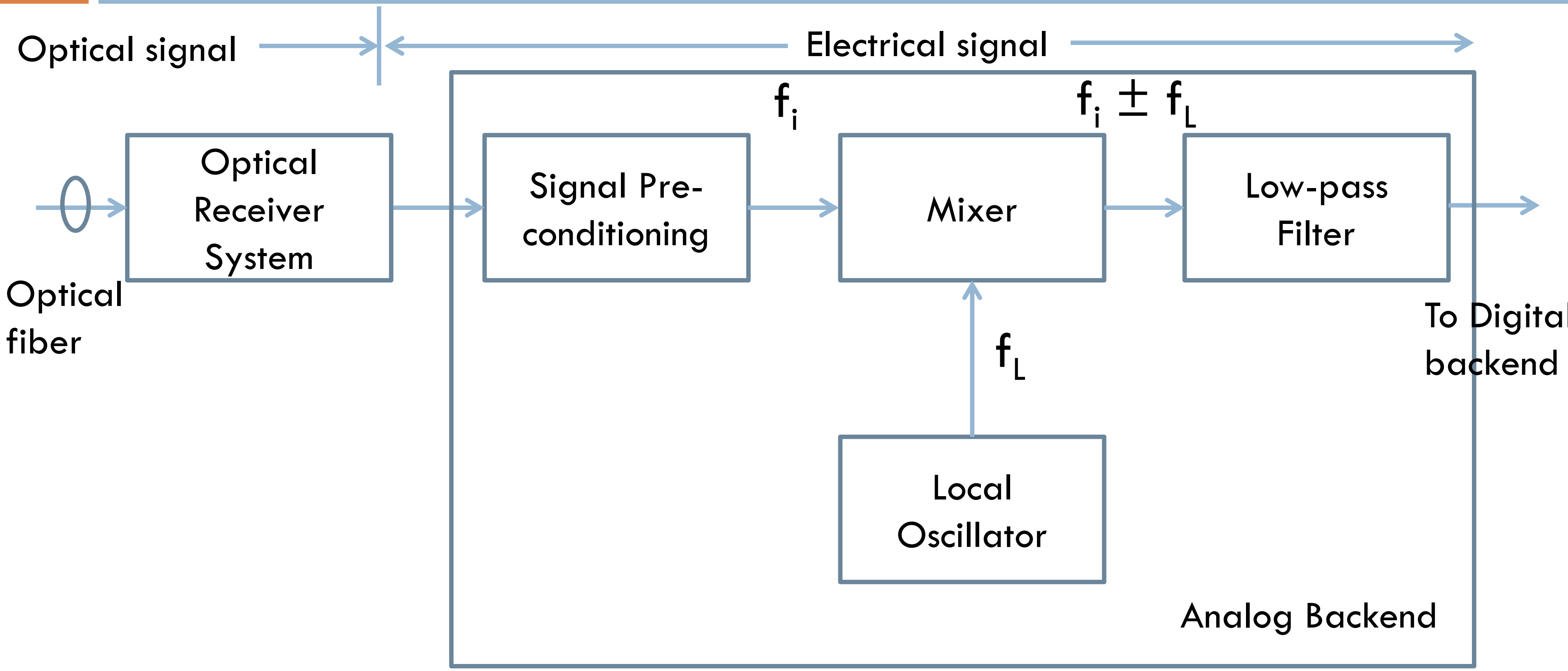
Optical Receiver System



GMRT Systems



Signal Processing in Receiver Room



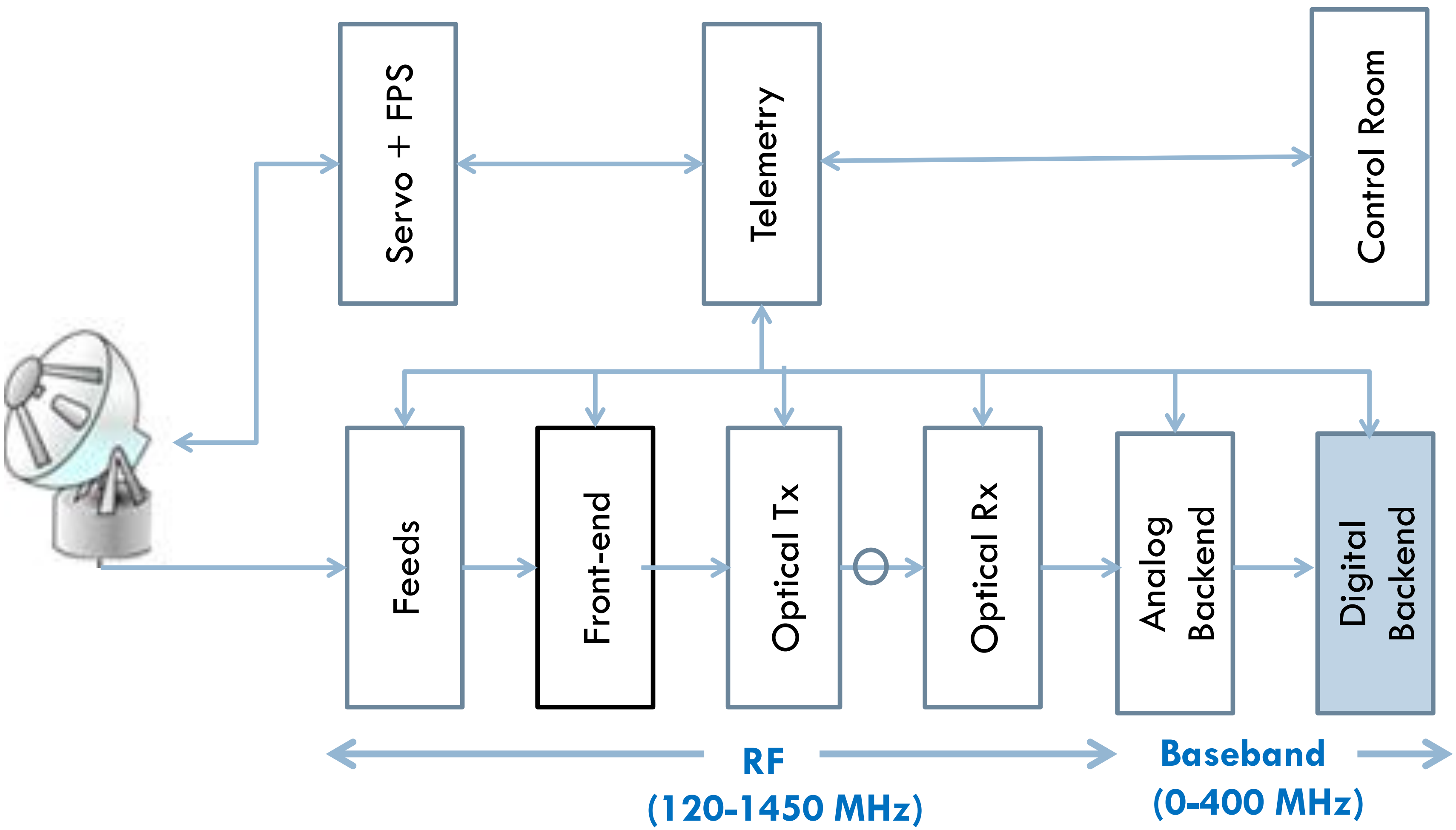
Analog backend amplifies the signal, converts from radio frequency (120 -1450 MHz) to baseband (0-400 MHz) through frequency heterodyning and provides desired bandwidth signal to the digital system

Baseband System - Installation

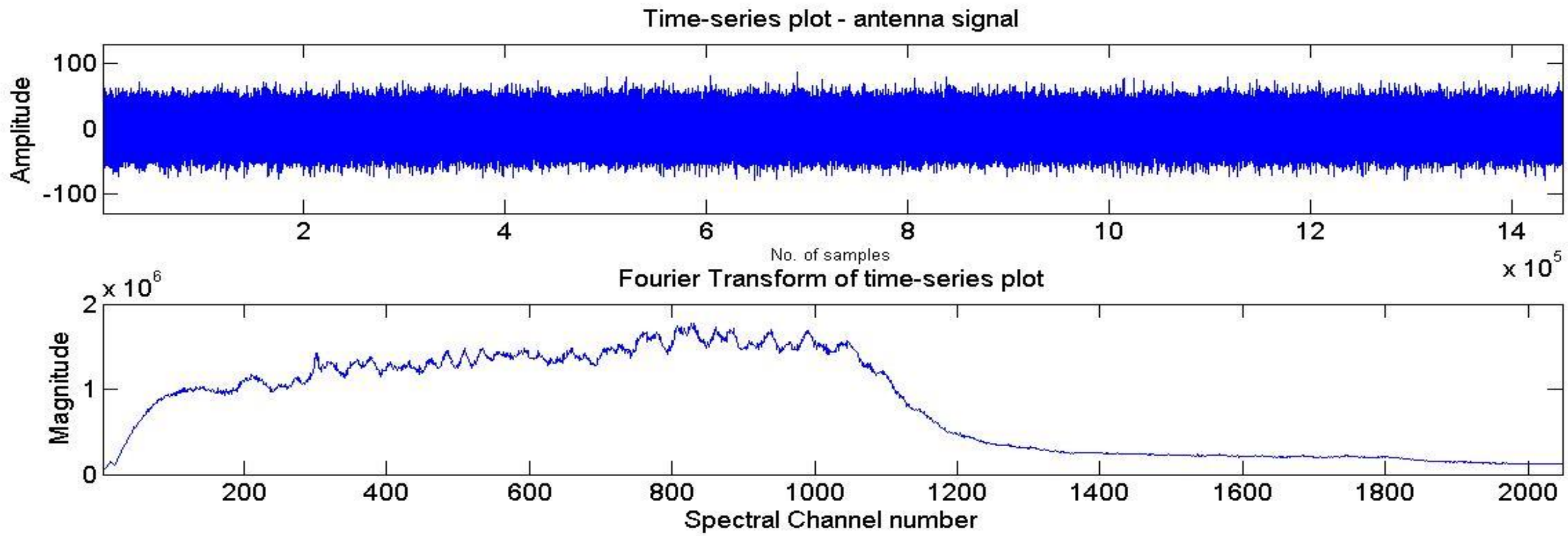
Plug-in Units

Image Courtesy: Analog Backend Group

GMRT Systems



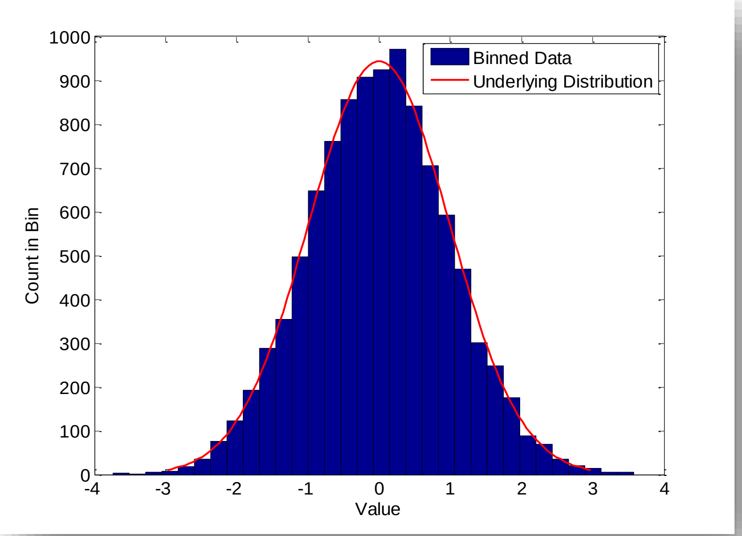
Astronomical Signal



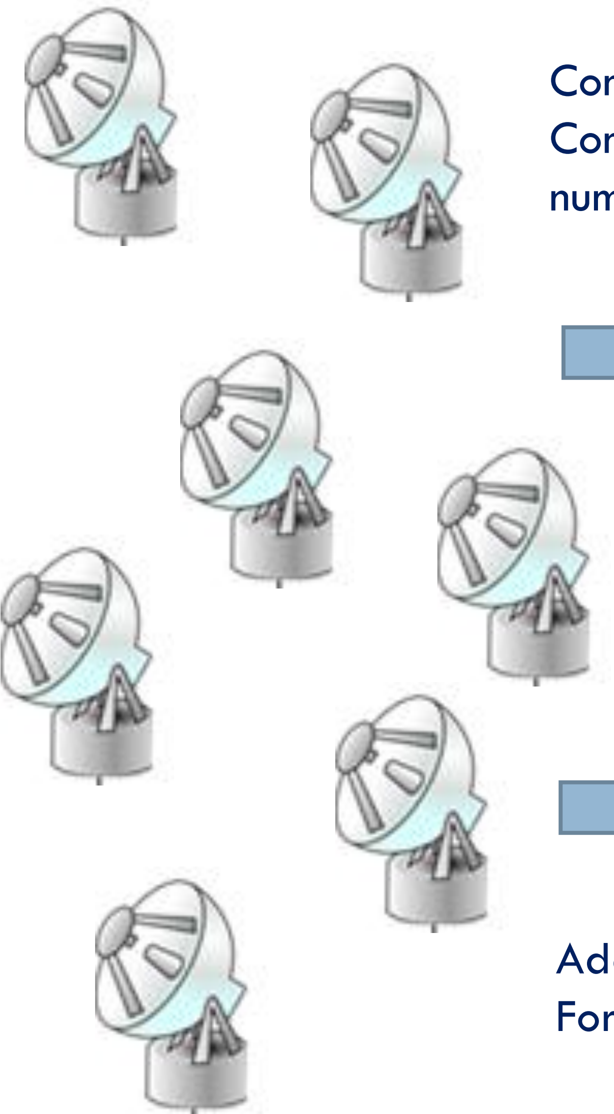
- Zero mean Gaussian distributed random signal
- Stationary random process – mean and autocorrelation do not change with time (under ideal conditions)
- Noise power measured over bandwidth

P = kTB Watts

K = Boltzmann constant, T = Temperature, B = Bandwidth

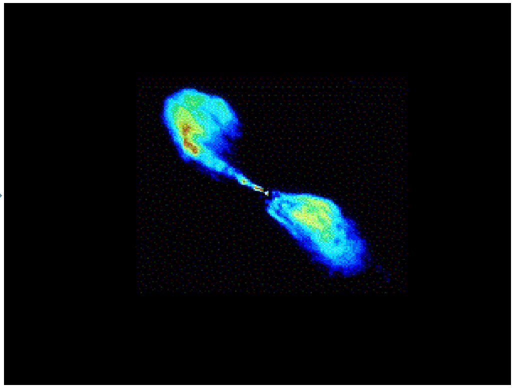


Correlation & Beamforming



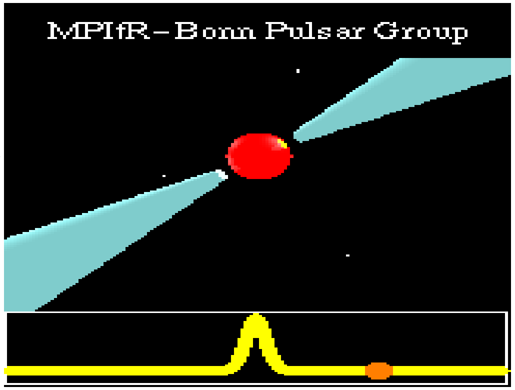
Compare signal between antenna pairs
Complexity scales at the square of the number of antennas

Correlation



Astronomical Imaging, Spectroscopy

Beamforming



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

Pulsars, Radio Bursts, Transient Sources

Digital Processing: Block Diagram

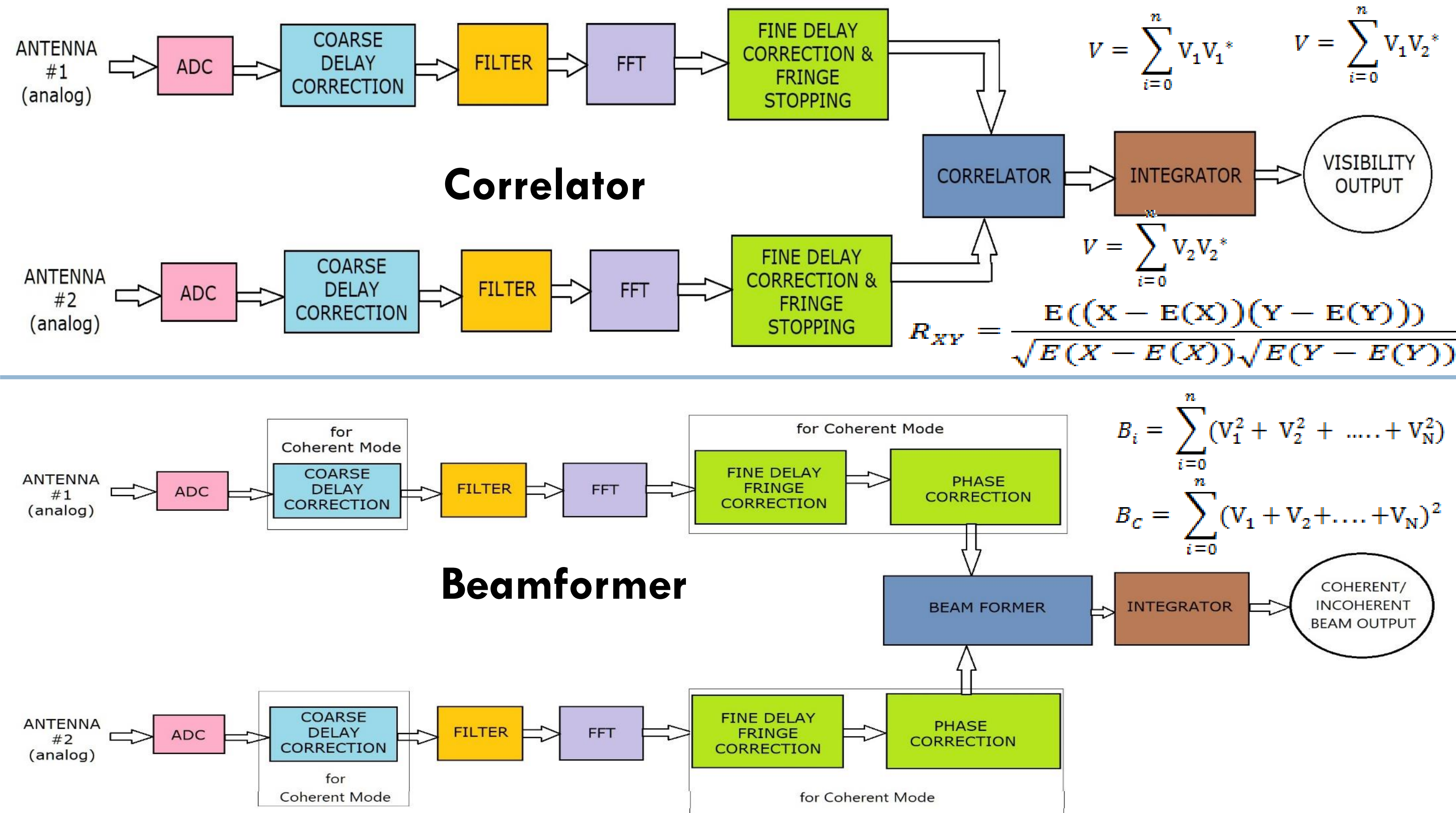


Image Courtesy: Srishti Goel

Signal Correlation

Radio Source

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

Digitized signal from Antenna#1

Digitized signal from Antenna#2

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

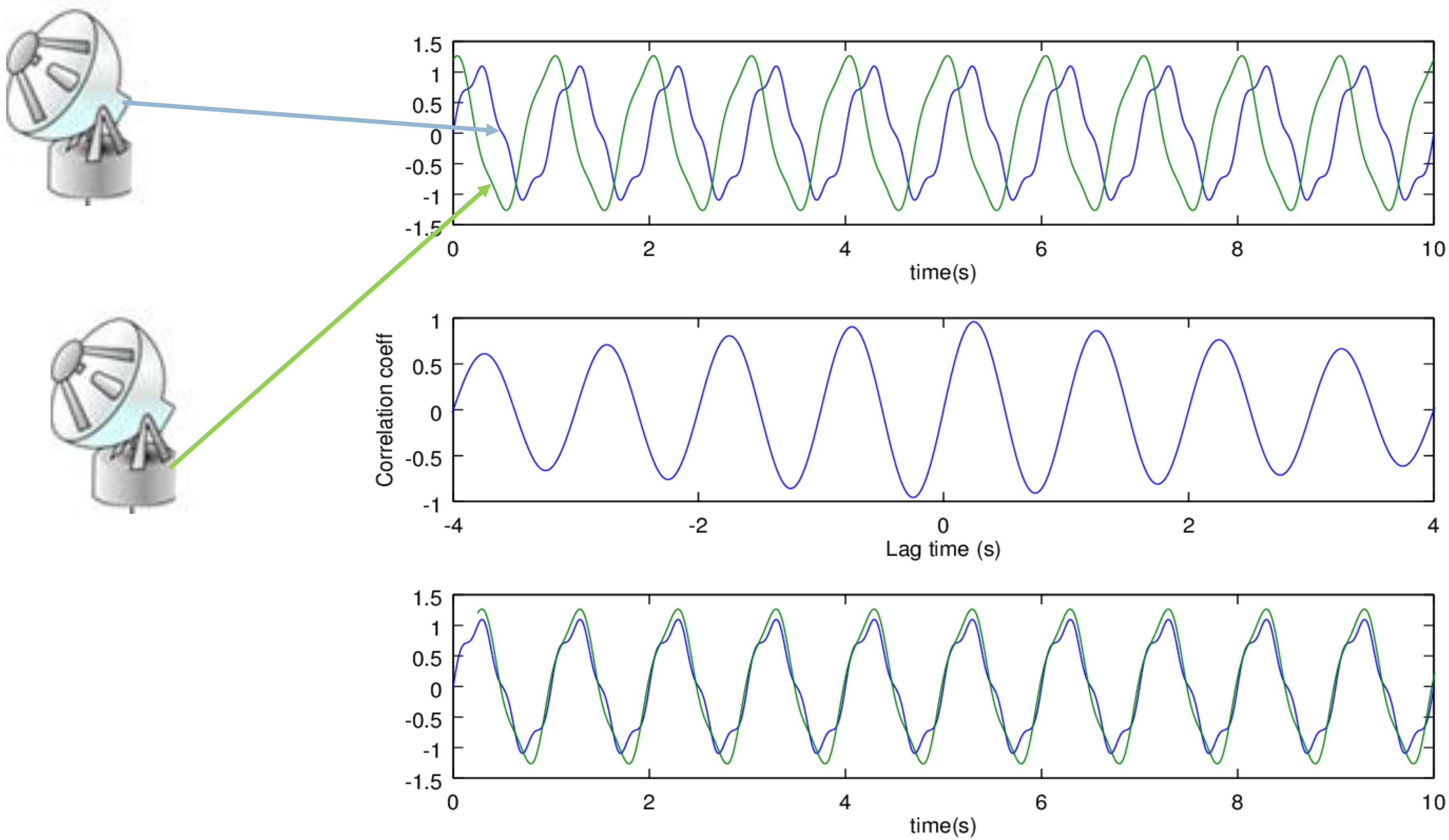
Cross Correlate signals from antennas after correcting for the delay between them (τ).

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

FX or XF (F = Fourier transform, X = Multiplication)

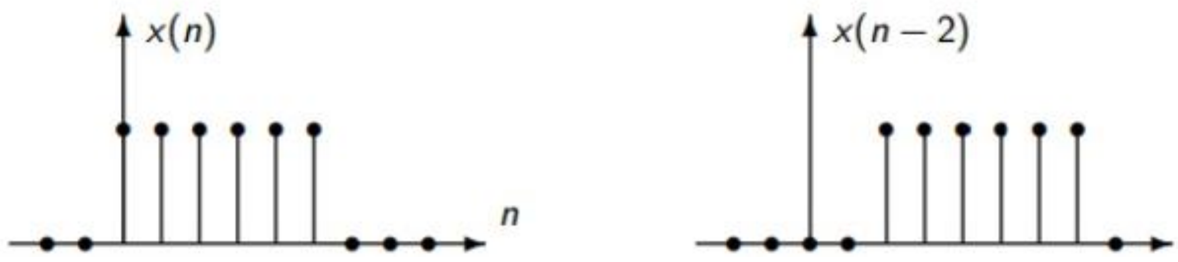
Correlation as a function of lag: An Example of Sine Wave



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)

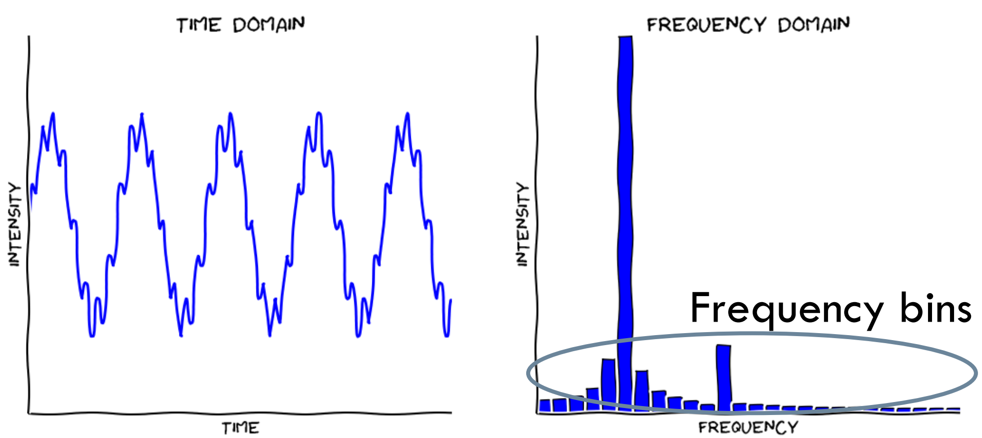
Can also be corrected by phase multiplication in the frequency domain
Useful for correcting delays that are sub-multiple of the clock period

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

Phase correction is applied for each frequency component

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.



Continuous → Discrete

- ❑ 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

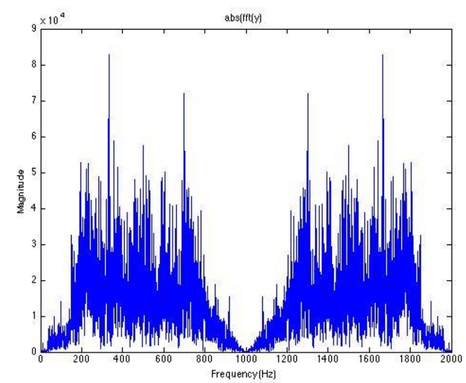
$$
\begin{aligned}
z_1 z_2 &= (x_1 + iy_1)(x_2 + iy_2) \\
&= x_1 x_2 + i x_1 y_2 + i x_2 y_1 + i^2 y_1 y_2 \\
&= (x_1 x_2 - y_1 y_2) + i(x_1 y_2 + x_2 y_1)
\end{aligned}
$$

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)

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

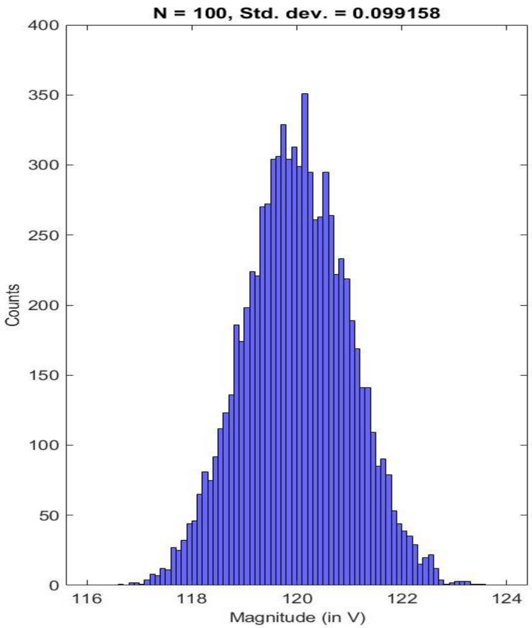
- Note: The above property does not hold if the input is a complex signal



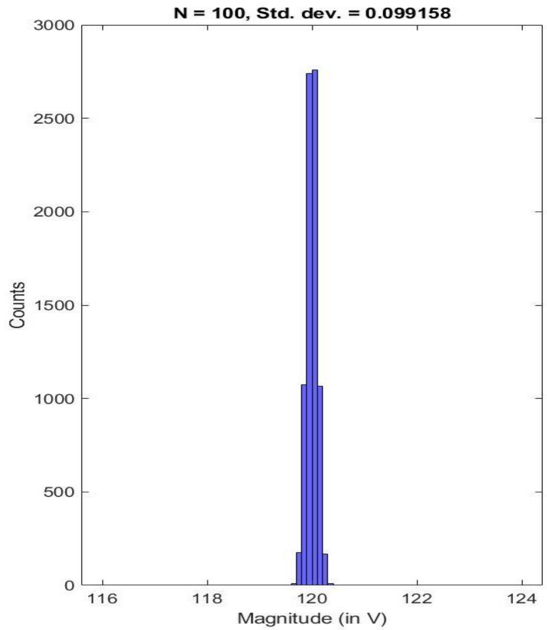
https://dsp.stackexchange.com/questions/8567/

Integration

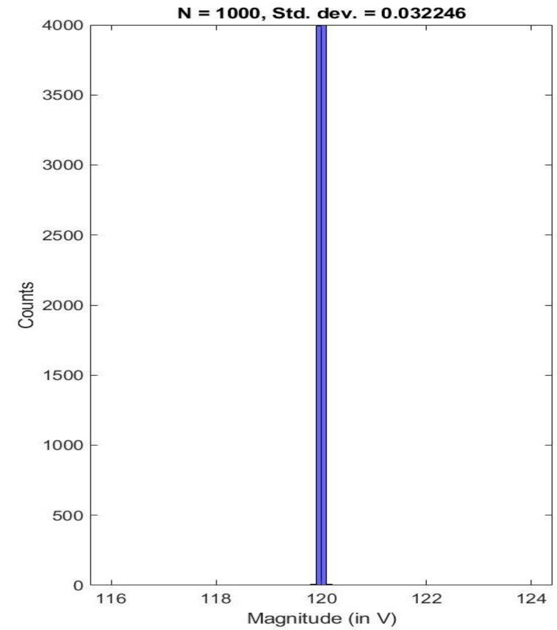
N = 1, σ=0.99



N = 100, σ=0.1



N = 1000, σ=0.03



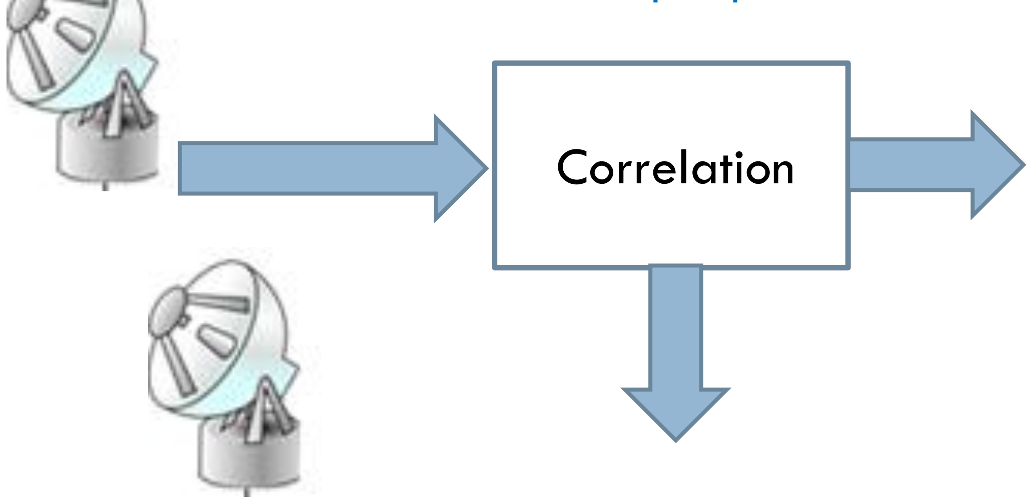
- Averaging leads to reduction in noise variance.
- Signal-to-Noise ratio improves by a factor of $N^{0.5}$
- Deterministic signal adds coherently while noise adds incoherently
- Increases the ability to detect a weak signal buried in noise !

Reduces uncertainty in the measurement parameter

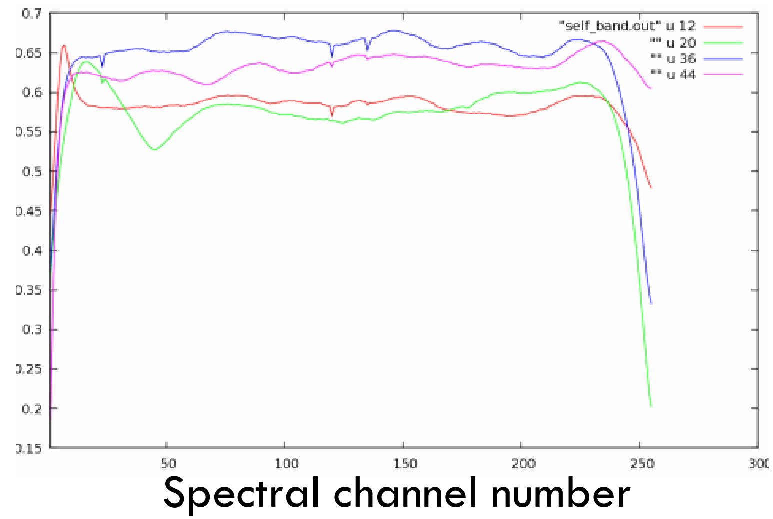
Image Courtesy: Srishti Goel

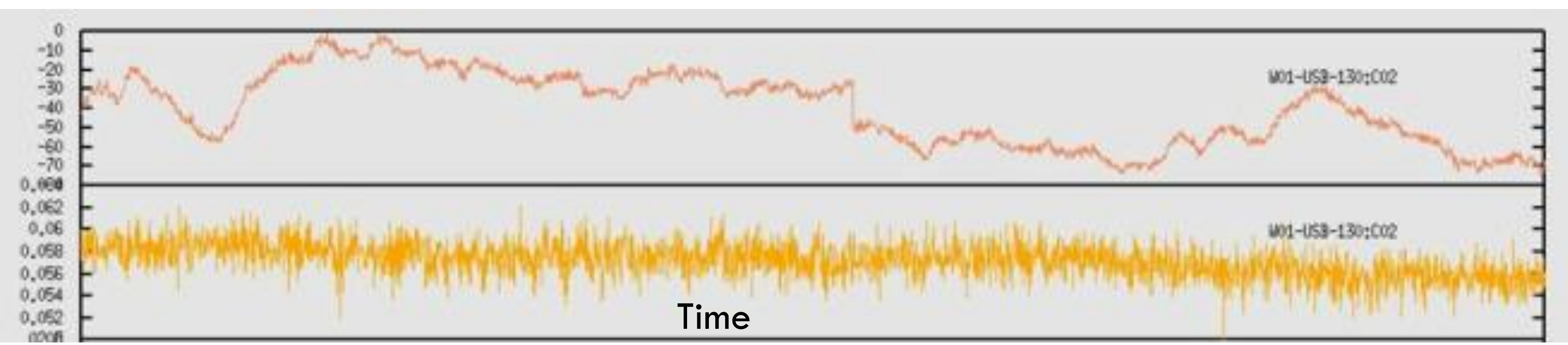
Correlation: Typical Output

GMRT: 435 visibilities per polarization



Magnitude Spectrum (Normalized)





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

Beamformer

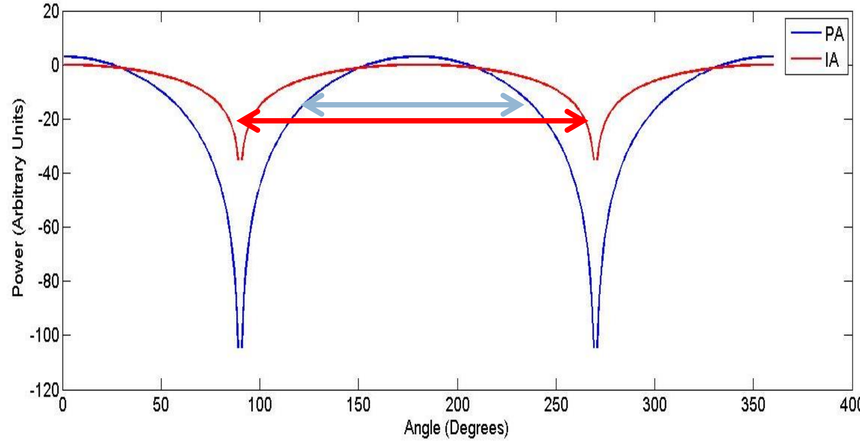
- Power from individual antennas is added to form the incoherent beam (scalar addition)

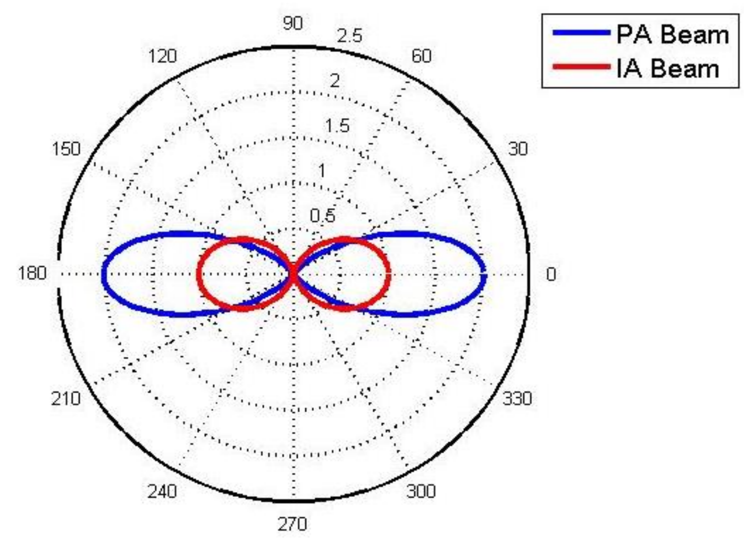
$$B_i = \sum_{i=0}^{n} (V_1^2 + V_2^2 + \ldots\ldots + V_N^2)$$

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

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

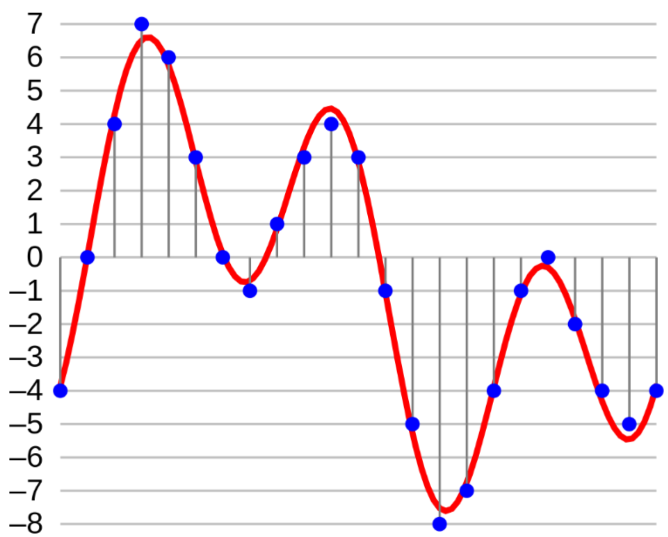
Phase is important !



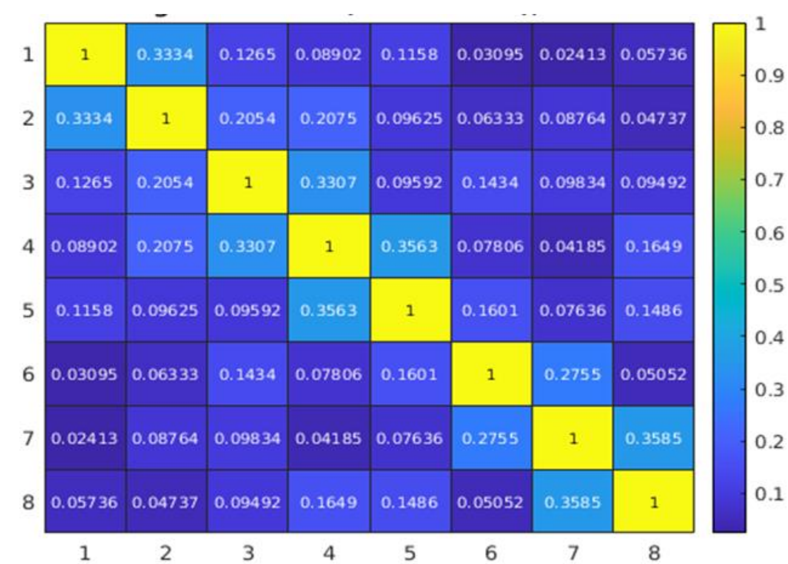


Major Challenges for Real-time Processing

- Sampling frequency: 2x the signal bandwidth
  - Faster processing
- Algorithmic complexity grows as N^2
  - Parallel Computing



8-element correlation matrix



Modern Correlators: Example

Correlators consist of signal processing component and networking component

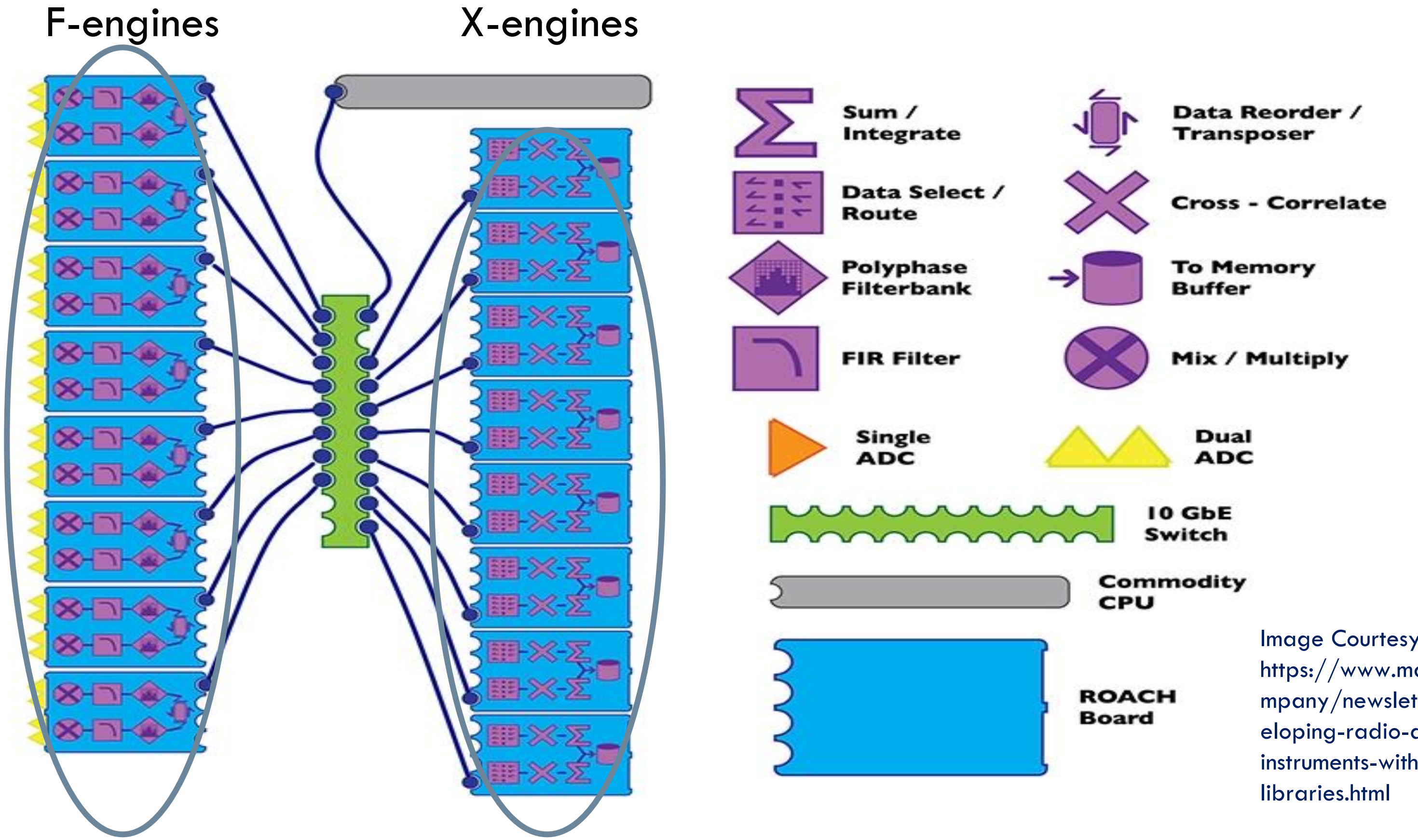


Image Courtesy: https://www.mathworks.com/company/newsletters/articles/developing-radio-astronomy-instruments-with-simulink-libraries.html

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

Image Courtesy: Digital Backend Group

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

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

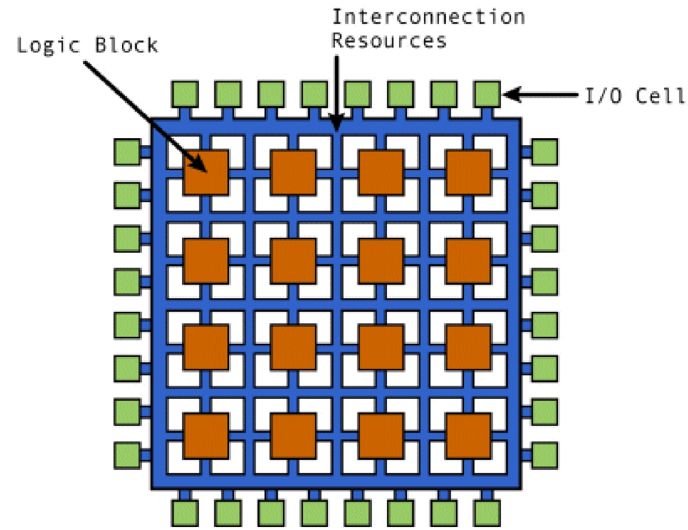


Image Courtesy: EE Times

- **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)

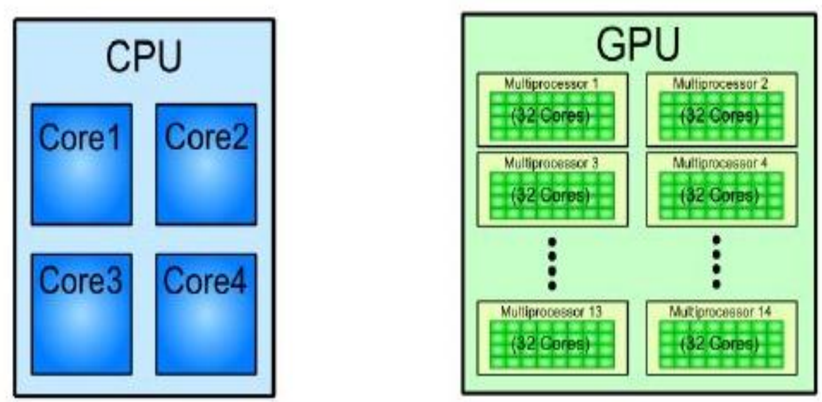
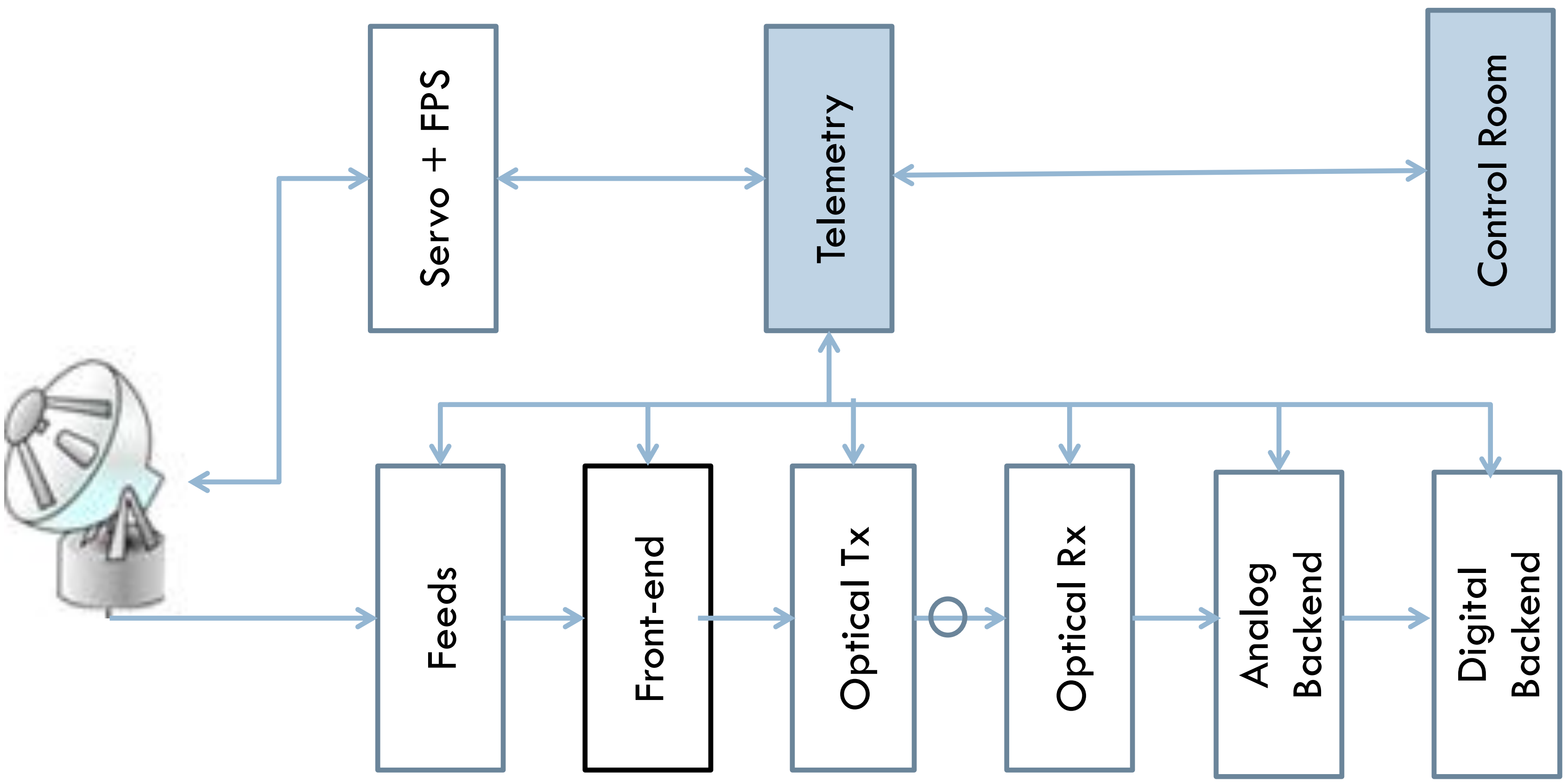
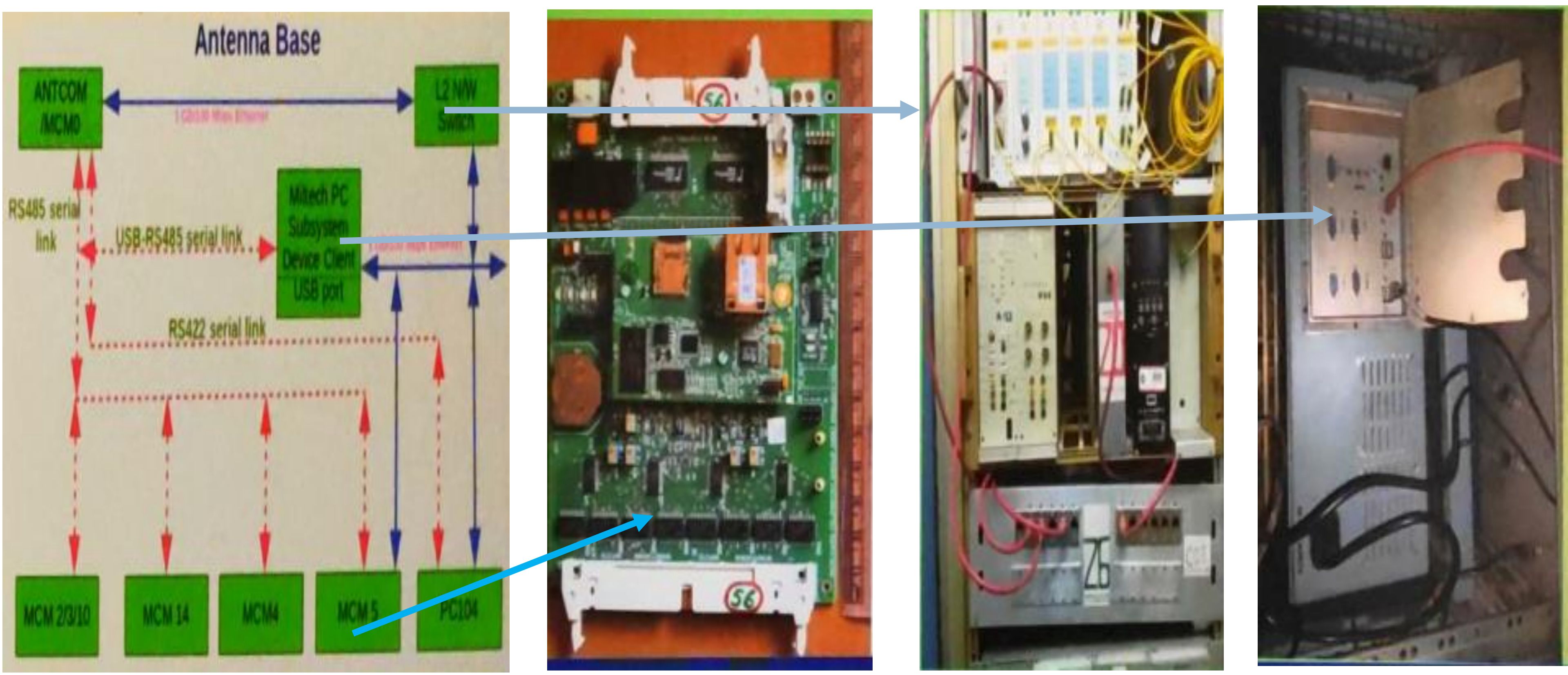


Image Courtesy: https://www.tutorialspoint.com/

GMRT Systems



Telemetry

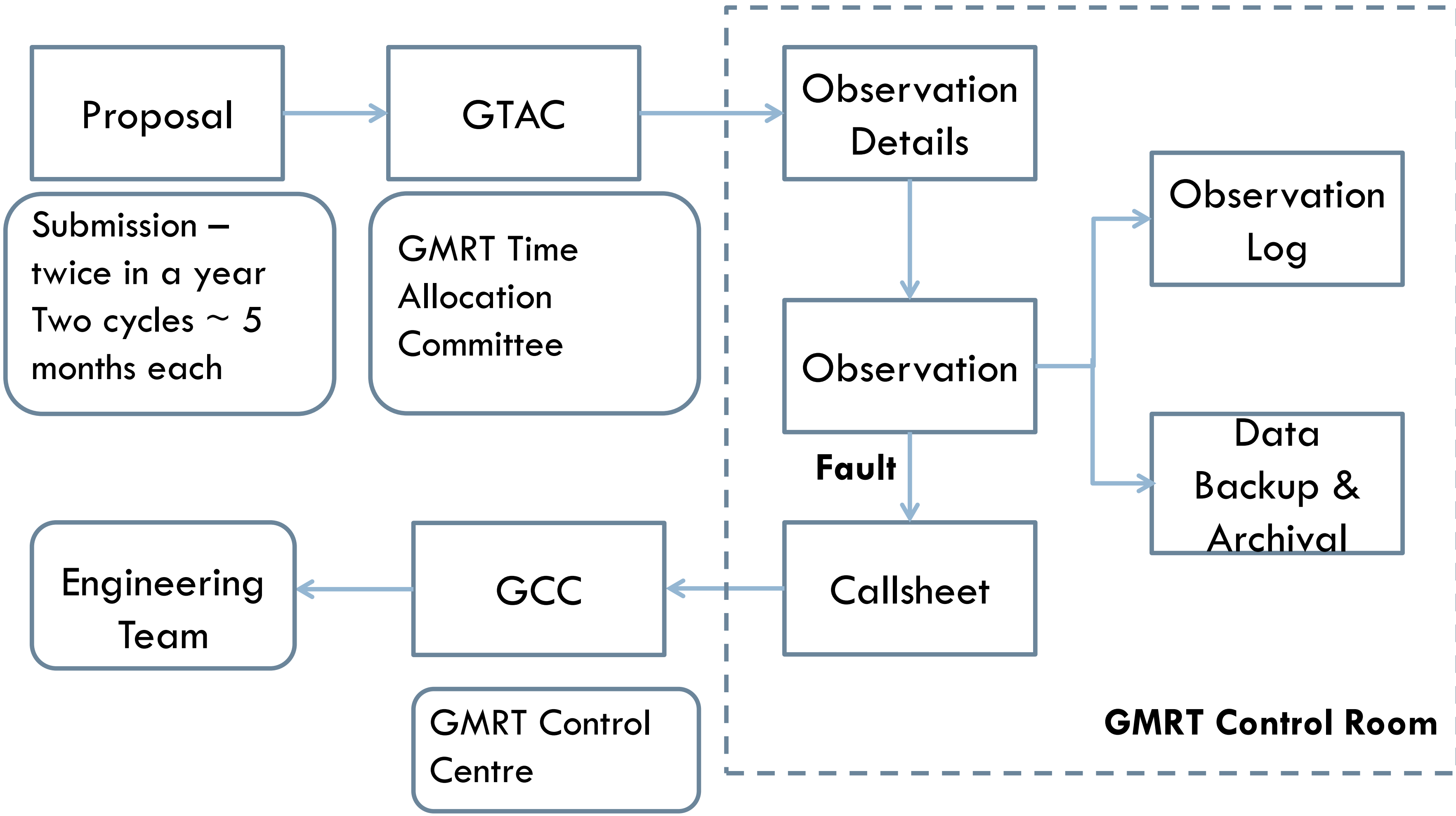


Block Diagram | MCM Unit | Switch | Miltech PC

Control & monitoring between the control room and other subsystems of the antenna and receiver

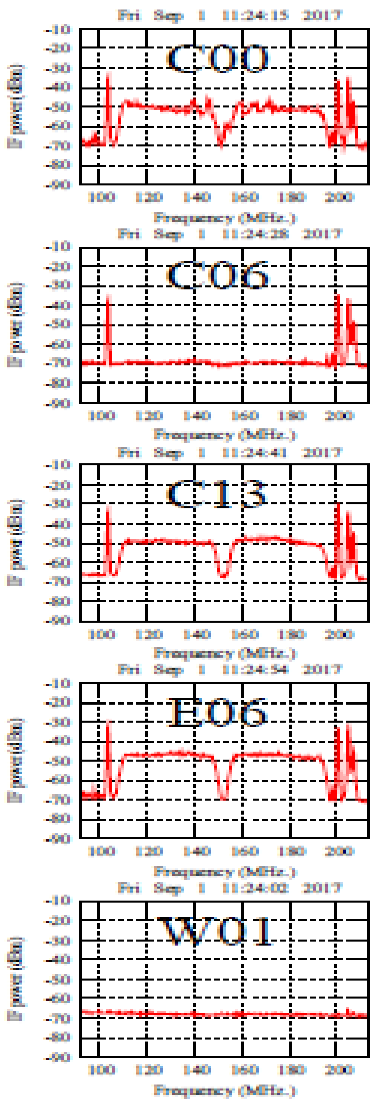
Image Courtesy: Telemetry Group

Control Room and Operations



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

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

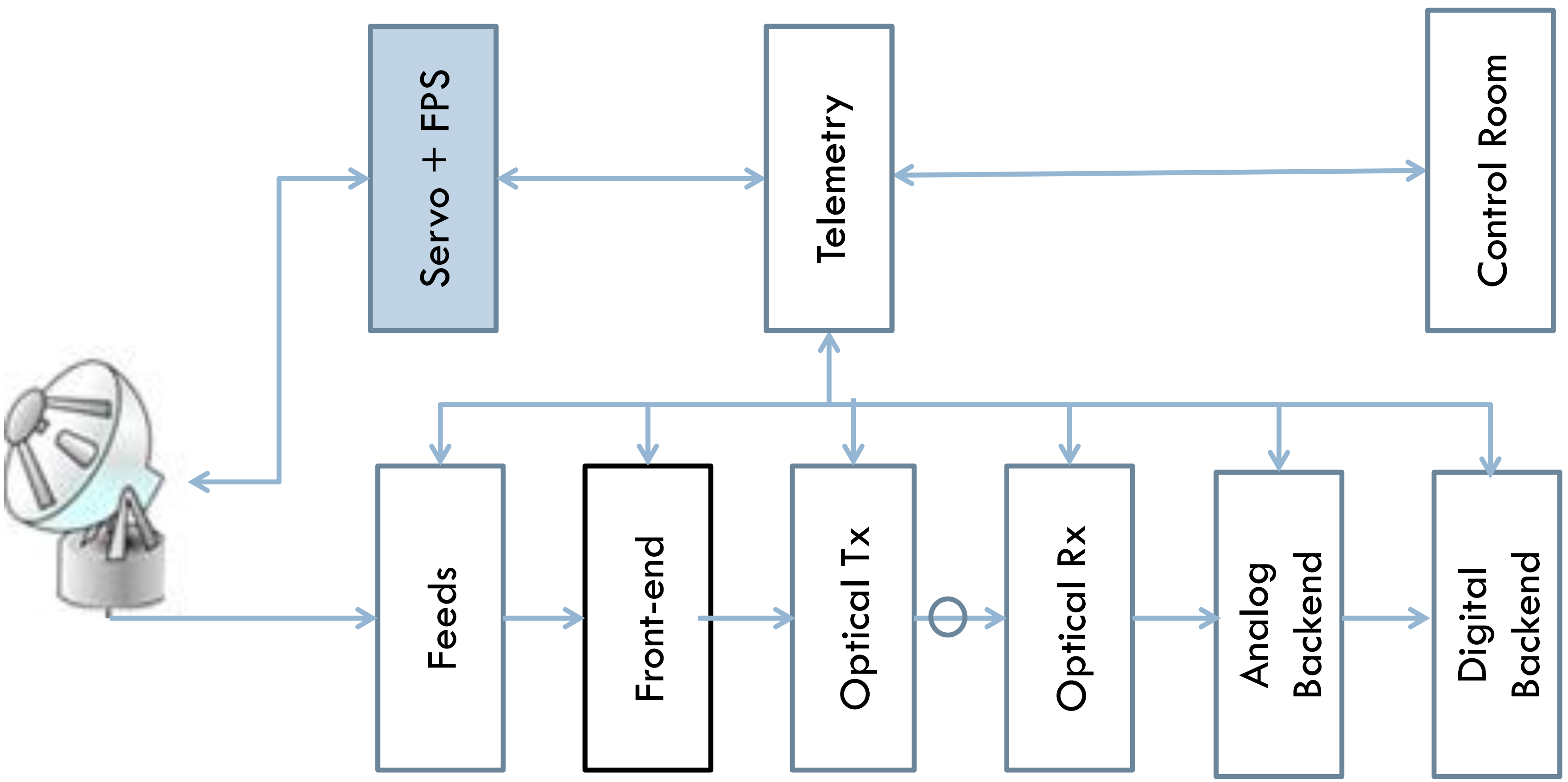
Corr band shapes and Project State
Fringe Status (rantsol amp-gain)
Gain-amplitude and Phase (rantsol)
Visibility - amplitude and phase (xtract)
Correlator Room Temperature

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

GMRT Systems



Servo System

•Points the antennas to any part of the sky and tracks a source

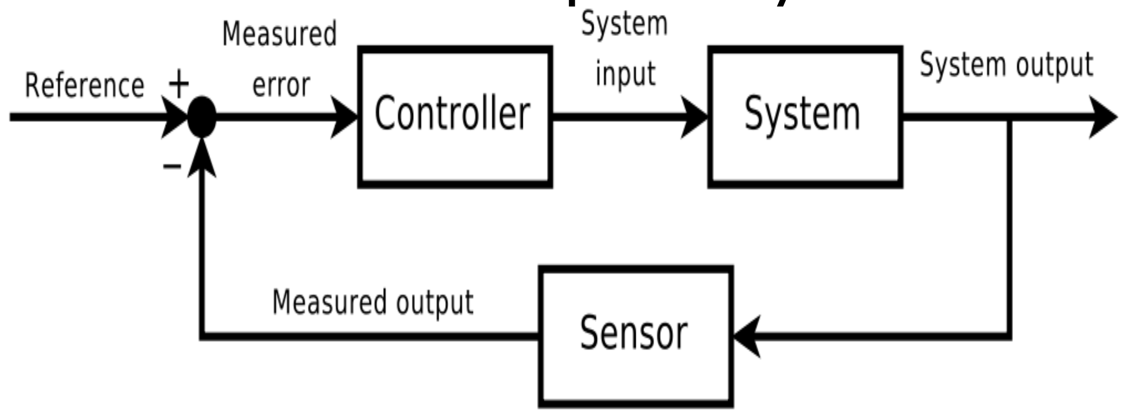
•± 270° movement around azimuth axis and 17 to 110° above horizon about elevation axis

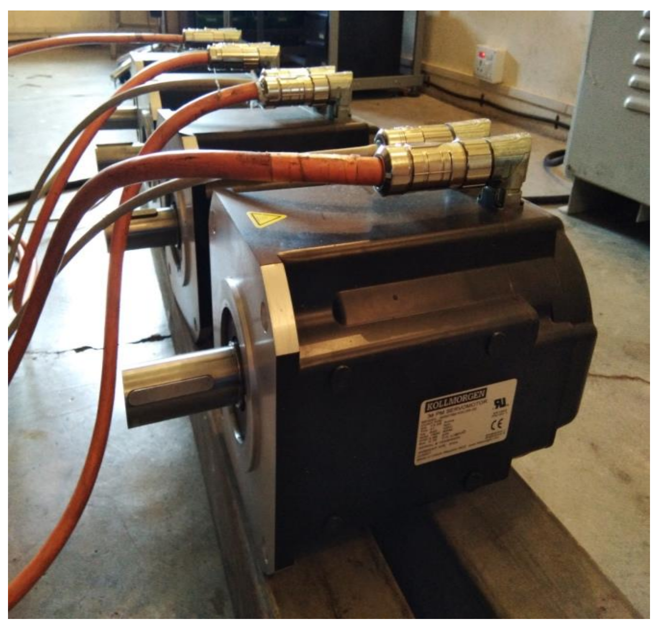
•Slew speed of 30°/ min in Az axis and 20°/ min in El axis

•RMS tracking and Pointing accuracy: 1 arcmin at 20 kmph wind speed

• Feed rotation and positioning system

Closed-loop control system





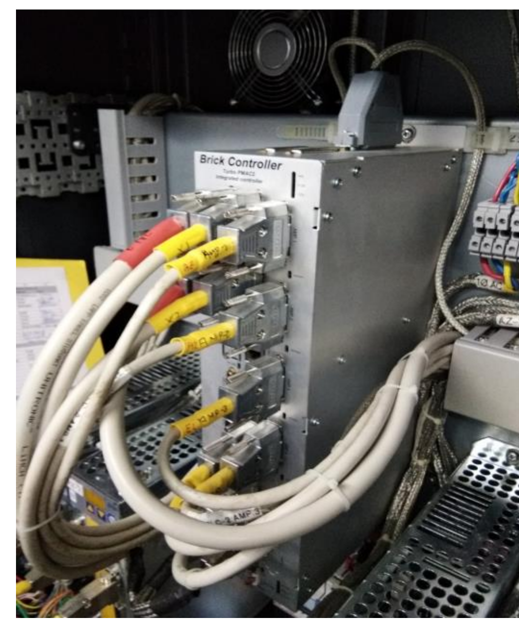


Image Courtesy: Servo Group

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 !

Image Courtesy: GMRT Archives

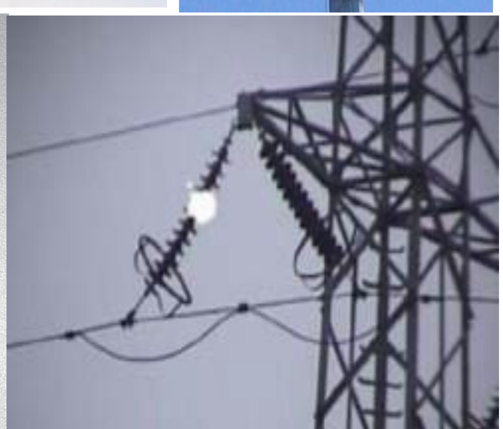
High Lift Platform for servicing front-end amplifiers, electronics and structural maintenance

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

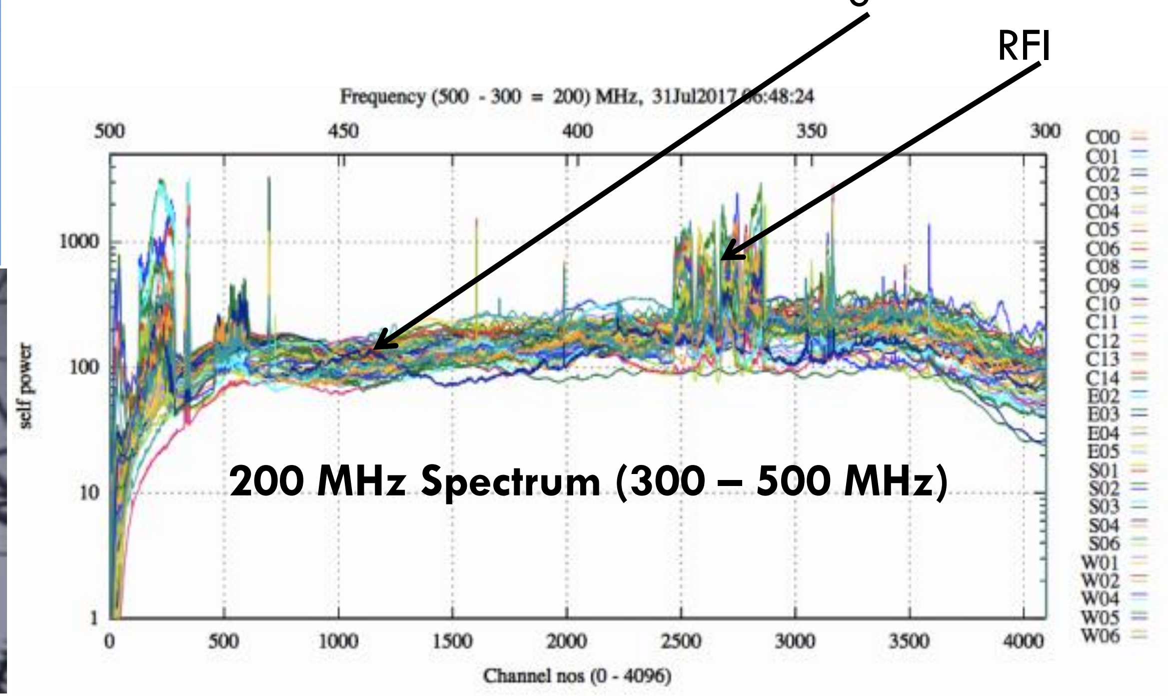
Image Courtesy: David Green

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

Image Courtesy: RFI + Electrical group

Signal Model and RFI Detection

Signal = Source + System + RFI

Source

- Astronomical source
- Weak
- Gaussian distributed noise

System

- Receiver System
- Stronger
- Gaussian distributed noise

RFI

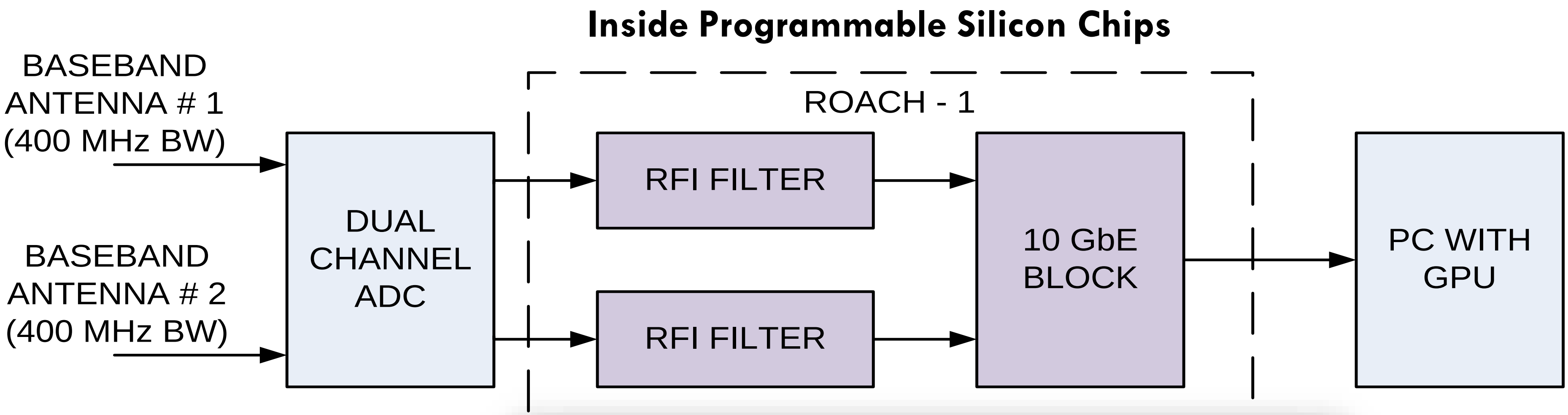
- Manmade/natural sources
- Very strong
- Non-Gaussian

RFI → Very Strong → Outlier Detection

RFI → Non-Gaussian → Non-normality Detection

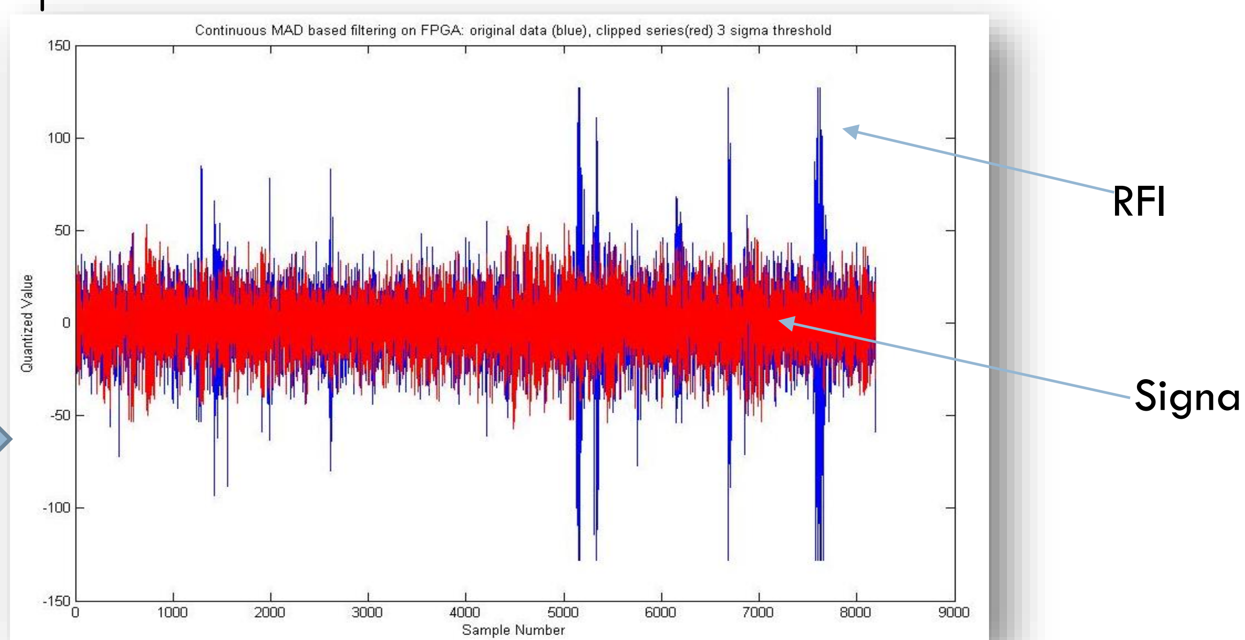
Mitigation

RFI Mitigation in digital system



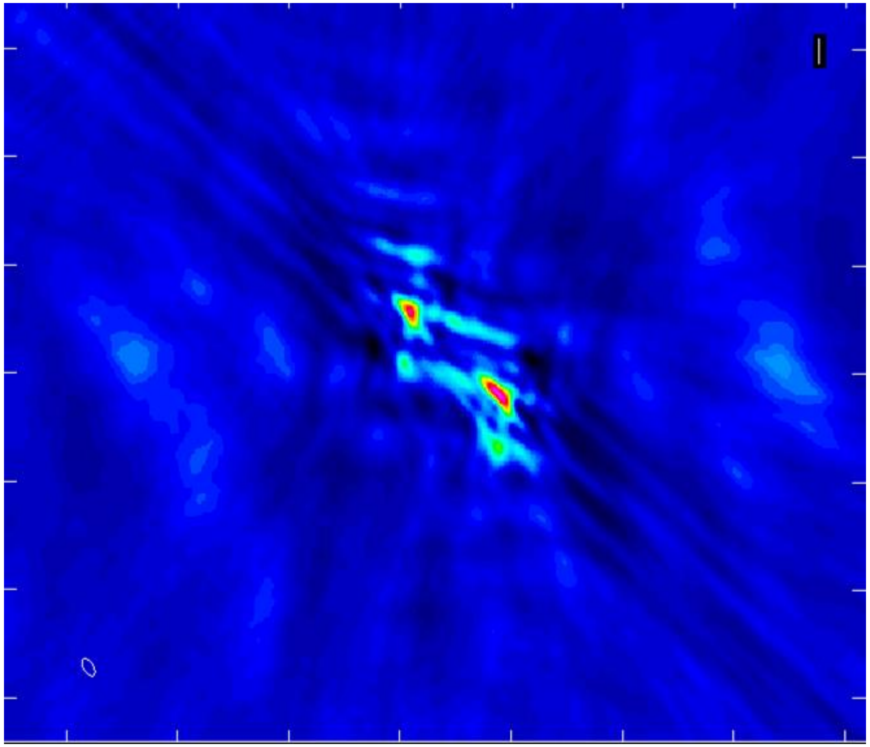
Strong power-line RFI detected through statistical techniques and filtered right after digitization (before processing)

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

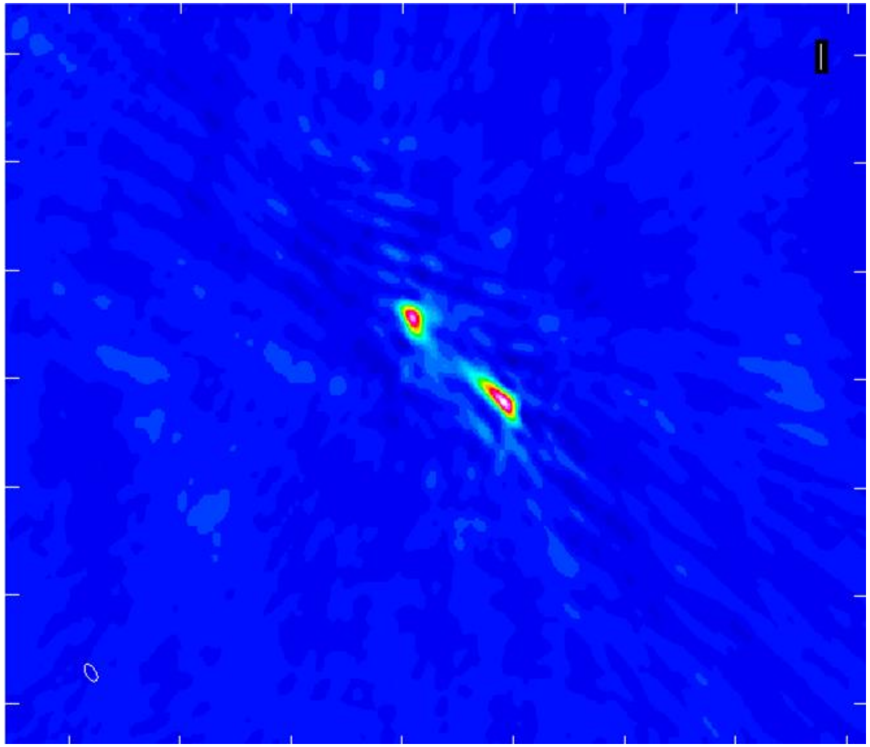


Imaging: Extended Source

Unfiltered



Filtered

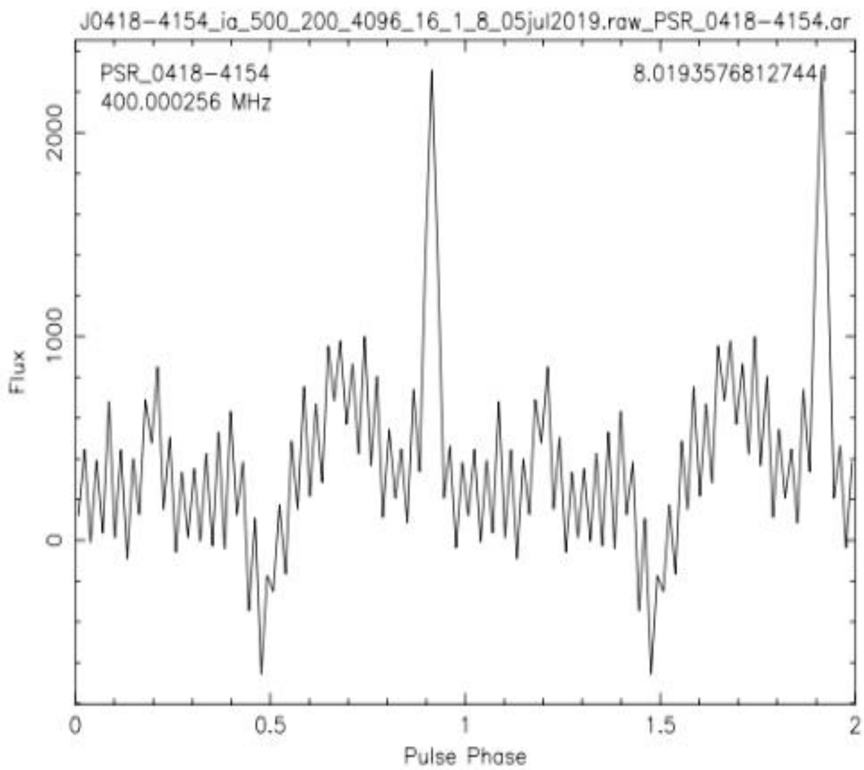


- uGMRT Band-4, 550-850 MHz , 200 MHz RF bandwidth, 2048 spectral channels
- Imaging for baselines < 1 kilolambda (~0.5 km)
- Noise RMS - 1.6 mJy/beam (Unfiltered) 0.52 mJy/beam (Filtered)
- Average Flagging: ~2.5-3%

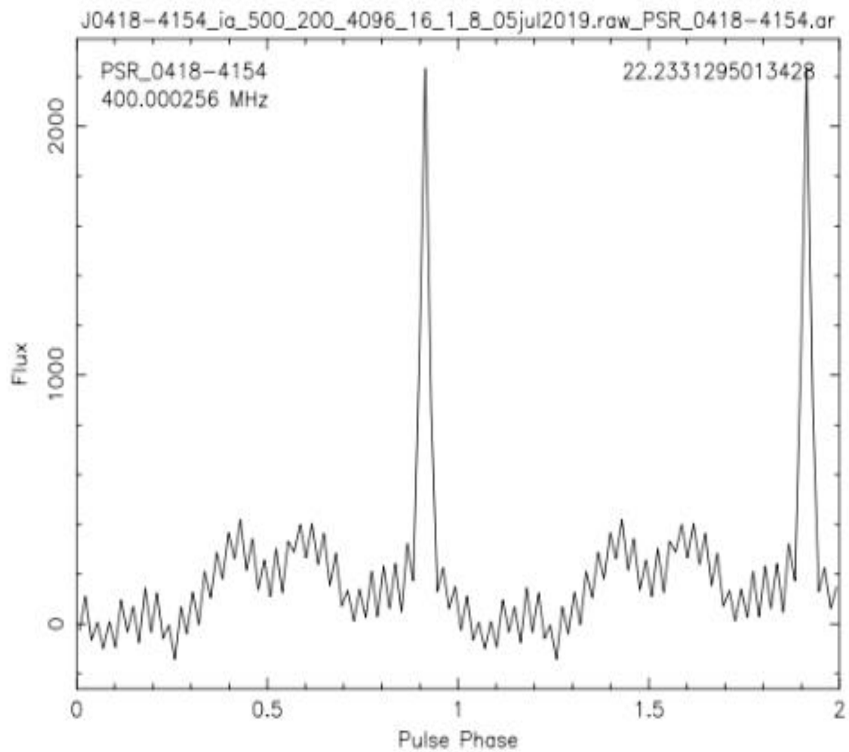
Image Courtesy: Ruta Kale, NCRA

Time-domain Astronomy

Unfiltered



Filtered



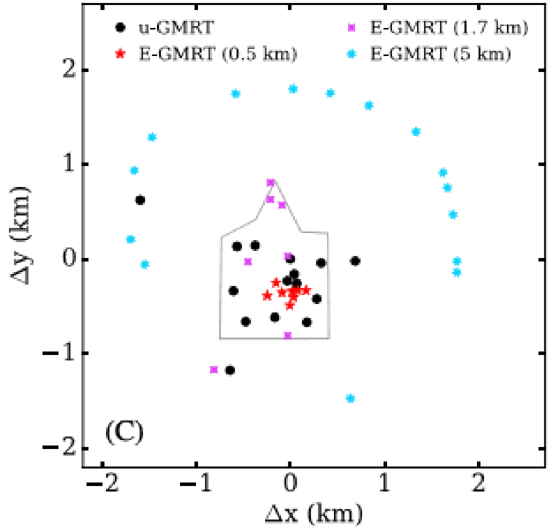
- Pulsar (J0418-4154) profile comparison: Incoherent Array beam - 4096 spectral channels 327.68μs integration time.
- SNR improvement by factor of 3; Average Flagging ~3%

Image Courtesy: J. Roy and B. Bhattacharyya, NCRA

Expansions to the existing uGMRT: eGMRT

The Expanded GMRT (eGMRT)

Adding more antennas for baselines < 5 km



Improved sensitivity

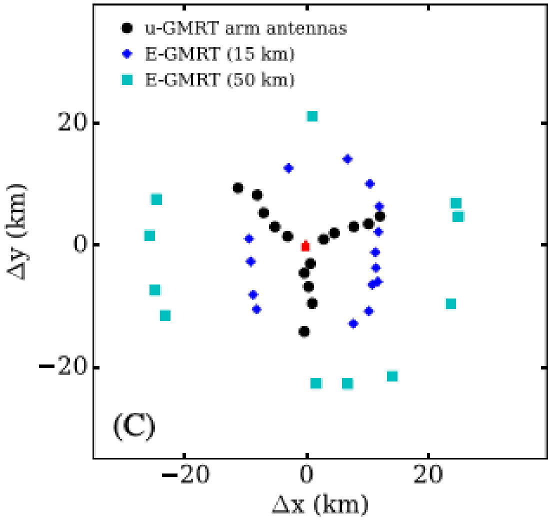
Increase in Field-of-View depends on number of independent beams

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

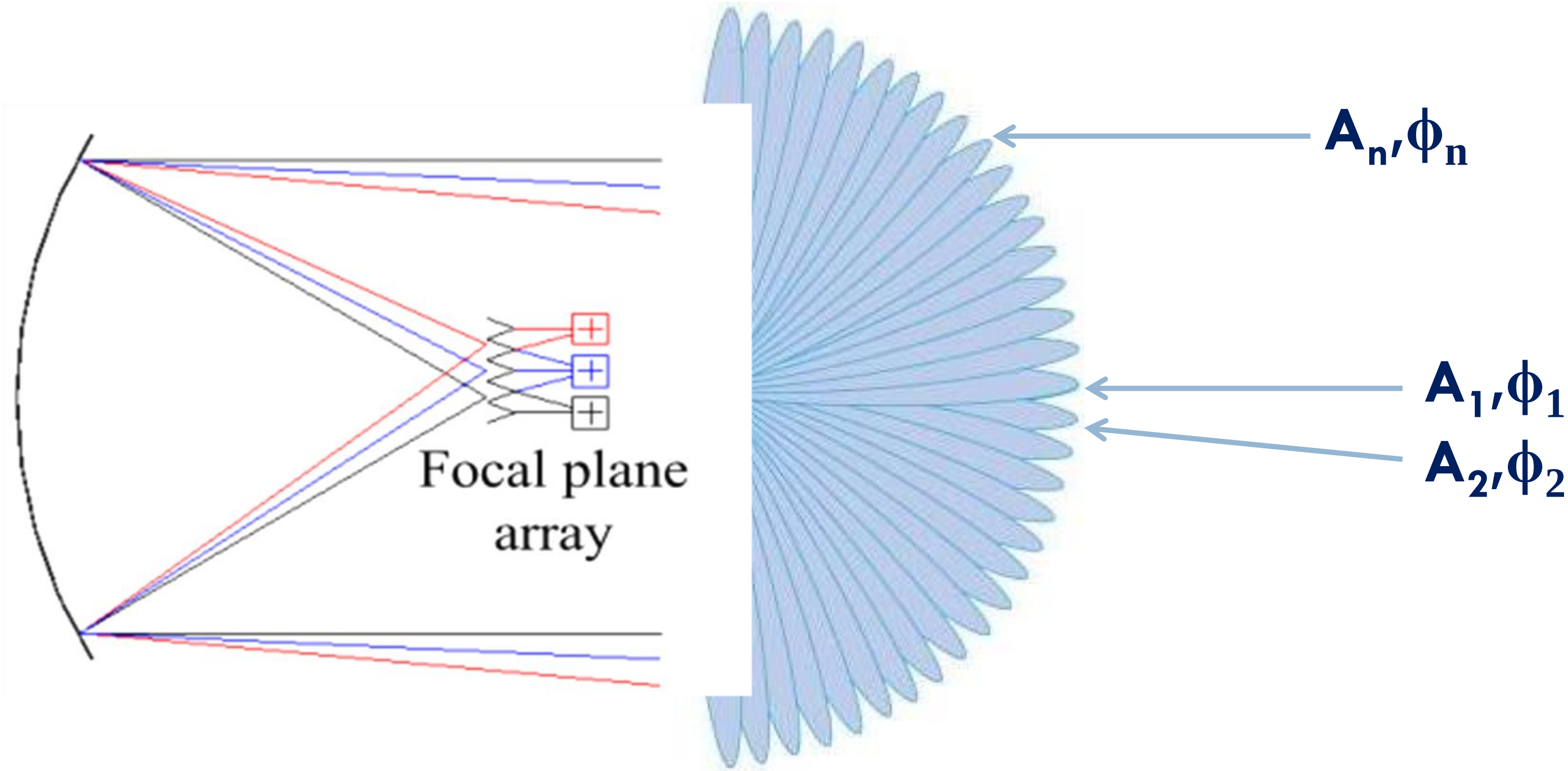


Improved angular resolution, lower confusion limit

Field-of-view is measured in degrees^2

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

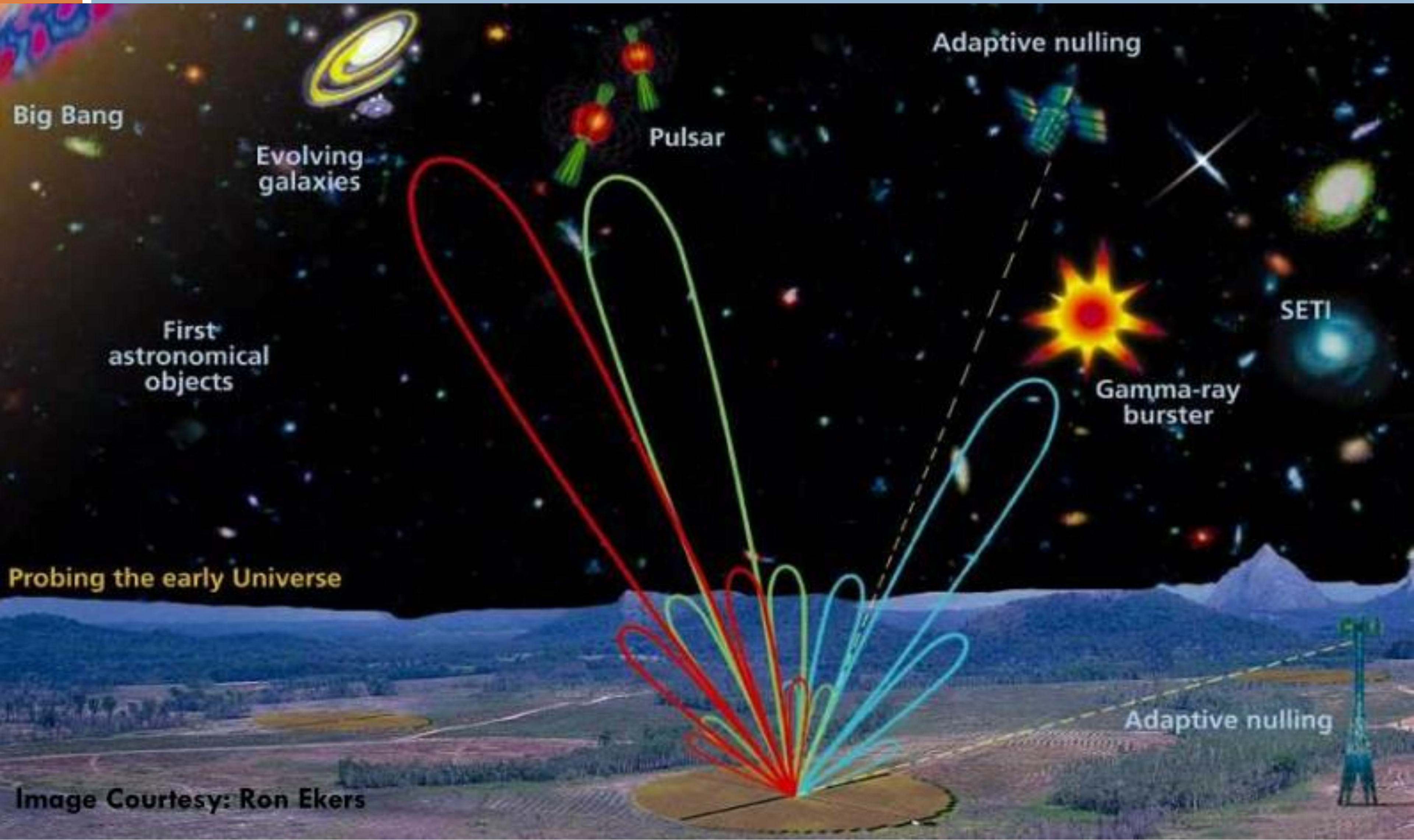
Focal Plane Array Beamforming



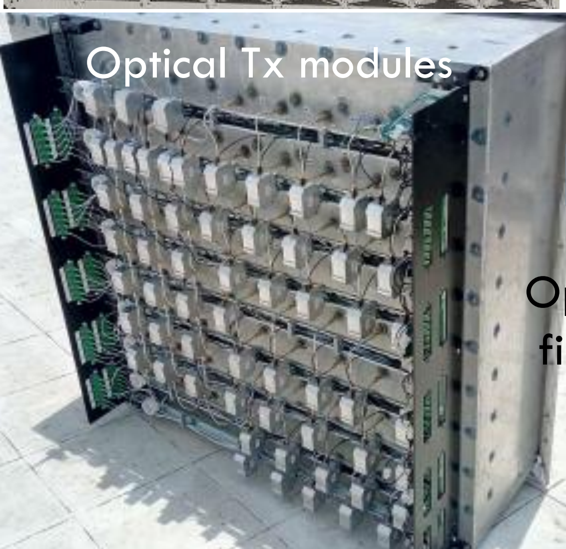
- N independent beams; increases the Field-of-View
- Changing the amplitude and phase of each element
- Combine signals from different elements

Image Courtesy: Internet

Forming multiple beams: Advantages



Experimental eGMRT beamformer



Optical fiber

Optical Rx and Analog signal processing modules

144-element L-band Beamformer (1.1 – 1.7 GHz)

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

Acquisition and Control Computer

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, ttps://www.gmrt.ncra.tifr.res.in/doc/WEBLF/LFRA/index.html
3. http://gmrtscienceday.ncra.tifr.res.in/gsd2021/engineering_posters.php