Giant Metrewave Radio Telescope (GMRT) - A System Overview

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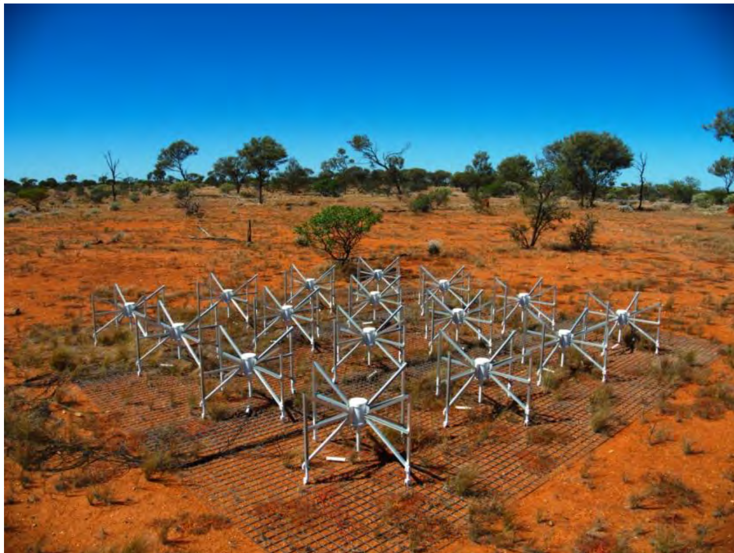
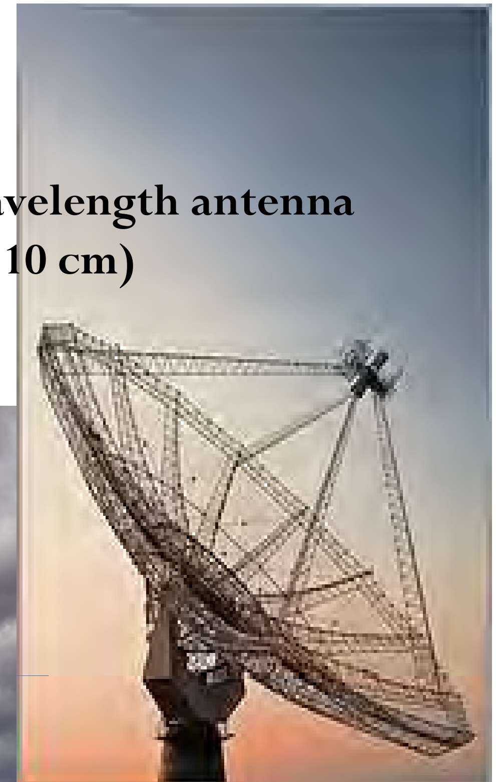
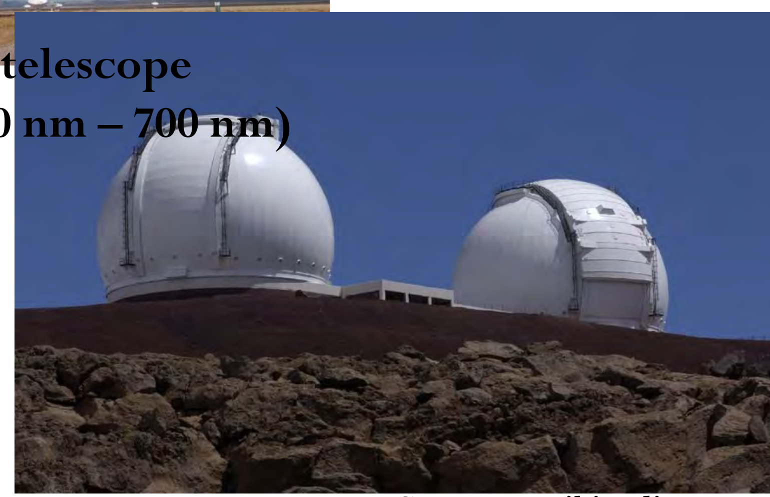


Low frequency dipole array (λ ~ 100m– 2 m)



Metre wavelength antenna (λ ~ 1m– 10 cm)

High frequency array (λ ~ 10 cm – 1 cm)



Optical telescope (λ ~ 400 nm – 700 nm)

Sub-millimeter wavelength array (λ ~ 1 cm – 1 mm)

Image Courtesy: Wikipedia

Single Dish Radio Telescopes

Interferometric Radio Array

Image Courtesy: NRAO

•Resolution and sensitivity depend on the physical size (aperture) of the radio telescope.

•Due to practical limits, fully steerable single dishes of more than ~ 100 m diameter are very difficult to build.
Resolution (λ / D) ~ 0.5 degree at 1 metre wavelength (very poor compared to optical telescopes).

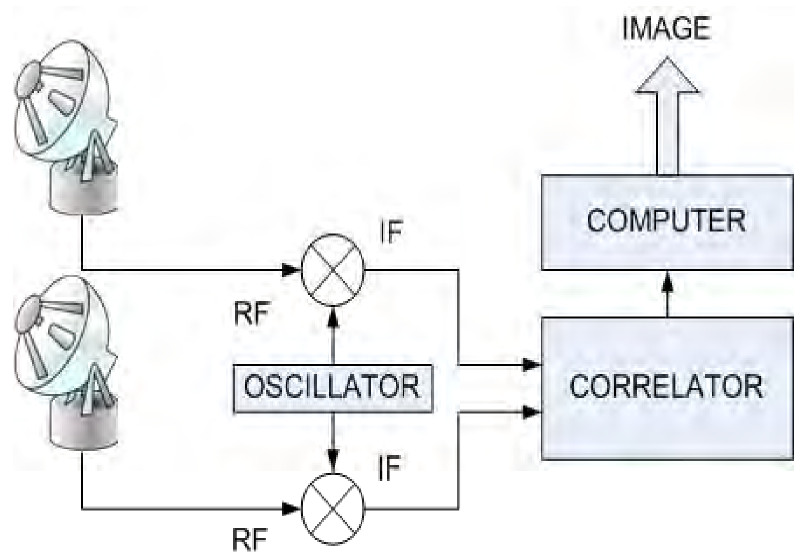
•To synthesize telescopes of larger size, many individual dishes spread out over a wide area on the Earth are used.

•Signals from such array telescopes are combined and processed in a particular fashion to generate a map of the source structure : EARTH ROTATION APERTURE SYNTHESIS

- Resolution = λ / D_s , D_s = largest separation.

Interferometry & Aperture Synthesis

- Signals from a pair of antenna are cross-correlated (cross-spectrum is obtained).
- This functions like a Young's double slit, measures one Fourier component of the image in the U,V Plane.



Basic two-element Interferometer

- From measurements using different pairs of antennas, several Fourier components of the image are obtained.
- Inverse Fourier transform of the combined "visibilities" gives a reconstruction of the original image => aperture synthesis.

Giant Metrewave Radio Telescope

GMRT - Introduction

- GMRT is a world class instrument for studying astrophysical phenomena at low radio frequencies (50 to 1450 MHz)

- Located 80 km north of Pune, 160 km east of Mumbai

- Array telescope consisting of 30 antennas of 45 m diameter, operating at metre wavelengths - the largest in the world at these frequencies

Overview of the GMRT

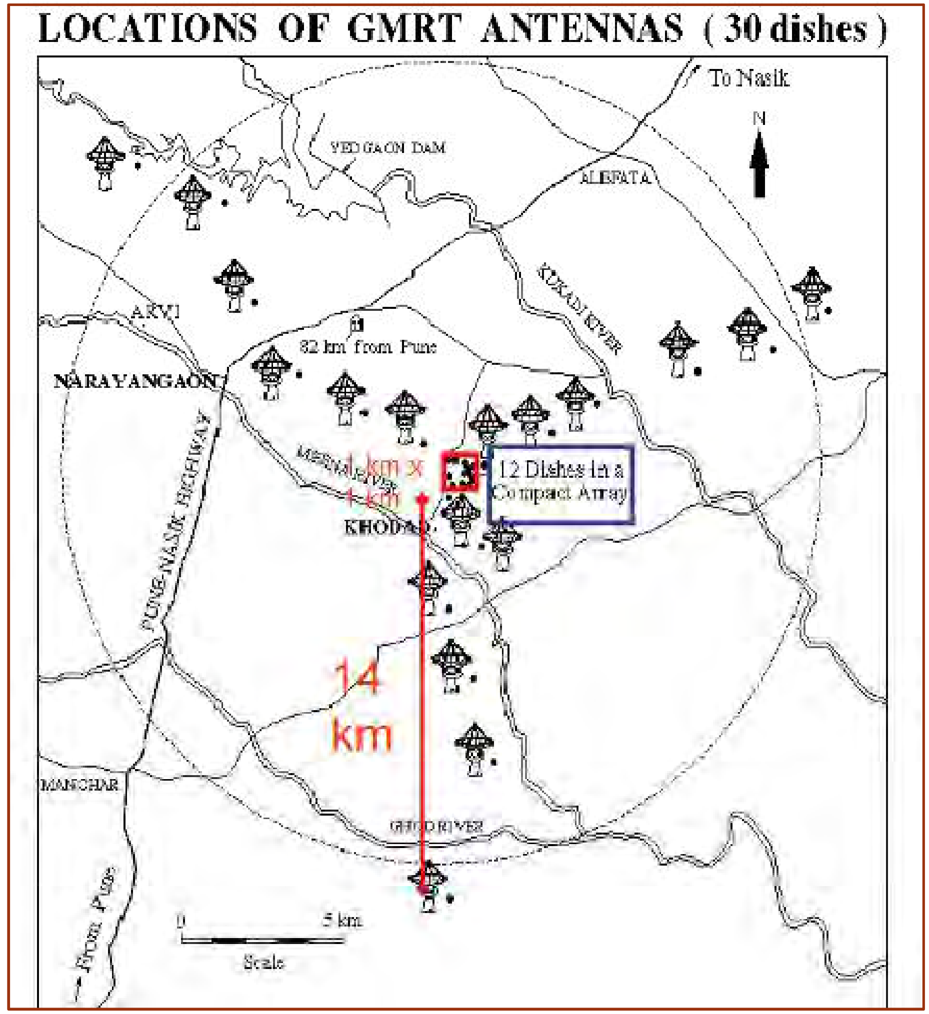
❑30 dishes, 45 m dia each
12 in a central 1 km x 1 km region
18 along 3 arms of Y-shaped array
baselines : ~ 200 m to 30 km.

❑Frequency bands (upgraded)
- ❑120-240 MHz
- ❑250-500 MHz
- ❑550-850 MHz
- ❑1000-1450 MHz

Max. processing bandwidth: 400 MHz

❑Effective collecting area:
30,000 sq m at lower frequencies
20,000 sq m at highest frequencies

❑GMRT site selection primarily based on:
- ❑Low manmade radio frequency interference
- ❑Low wind speed



GMRT observations

Two main observing modes:

1. Interferometry (Imaging, Spectral line)
2. Beam (Pulsar)

Spectral line

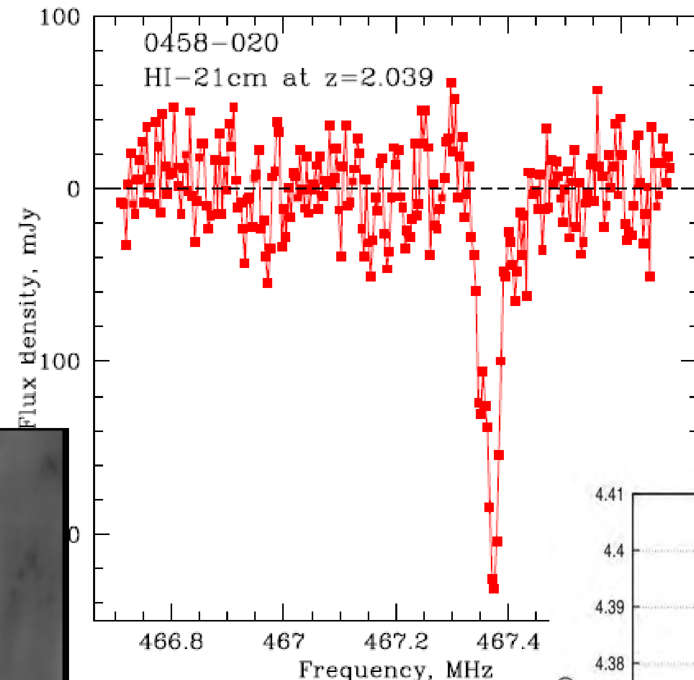
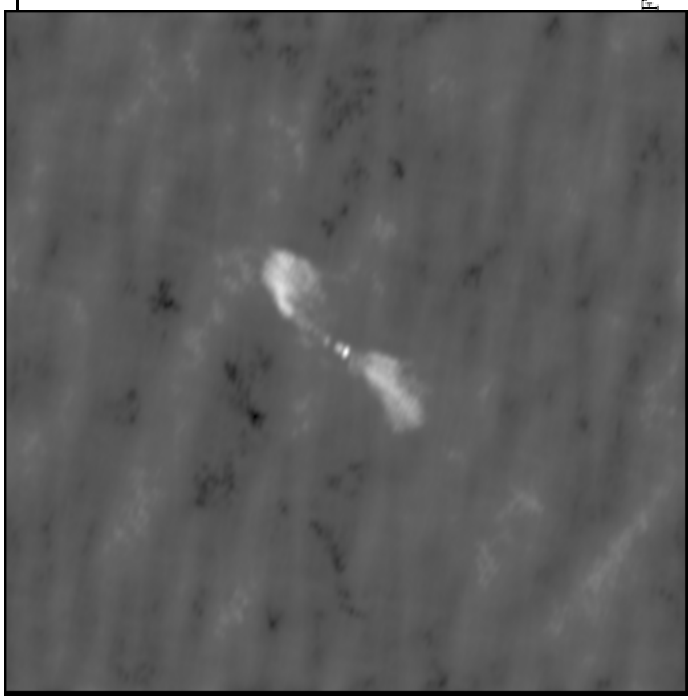
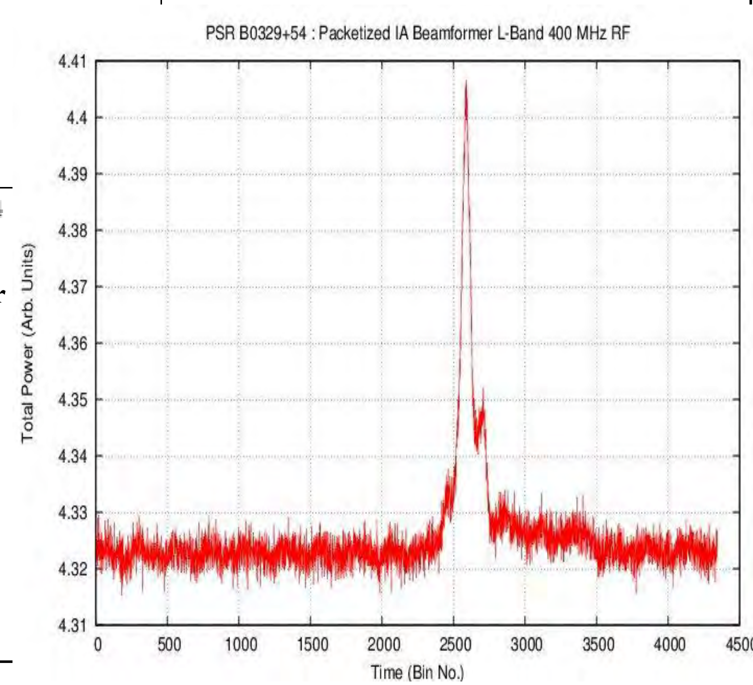


Image Courtesy: Nissim Kanekar

Imaging (Continuum)



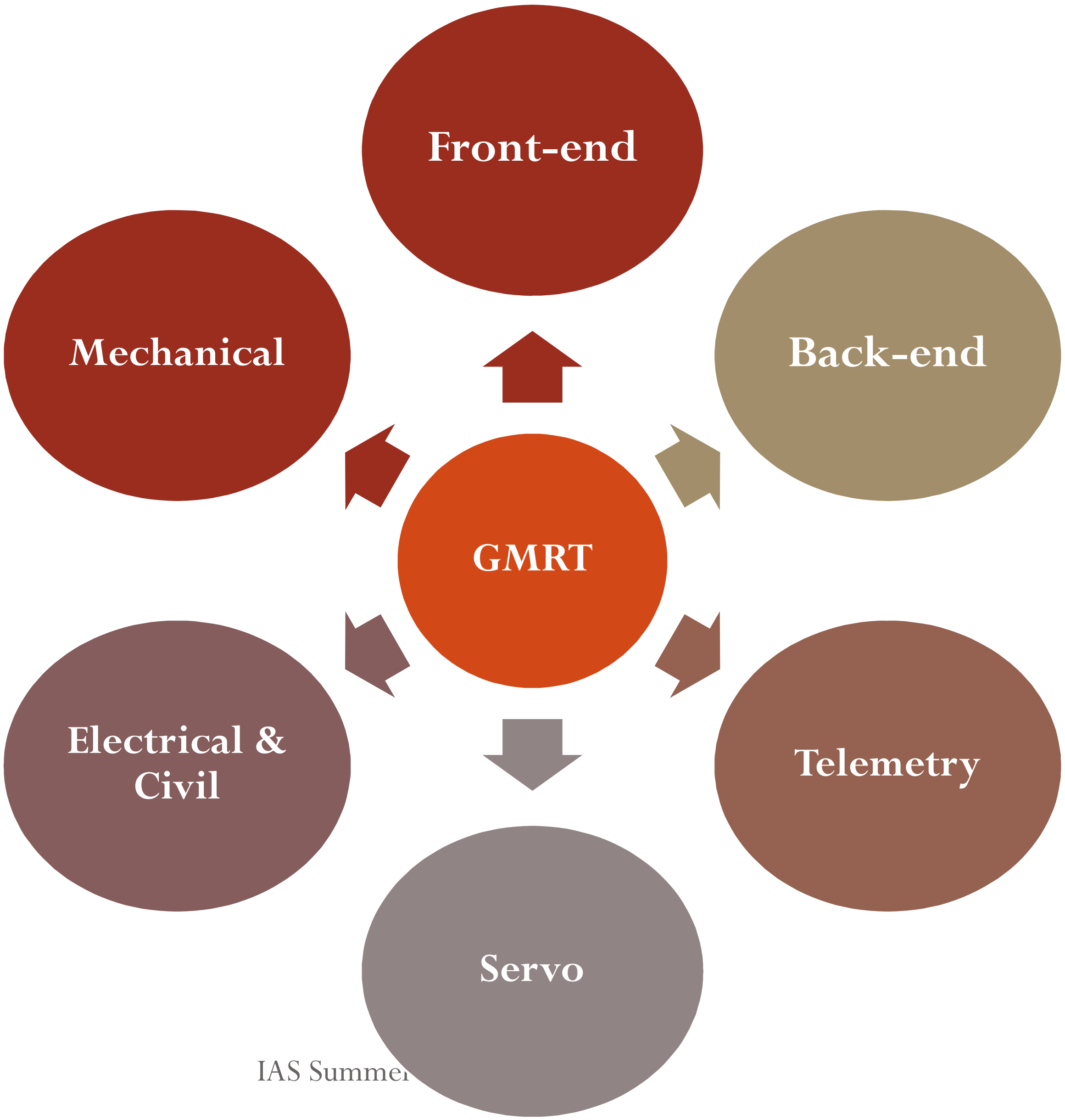
Pulsar



Aerial View of Central Square Antennas

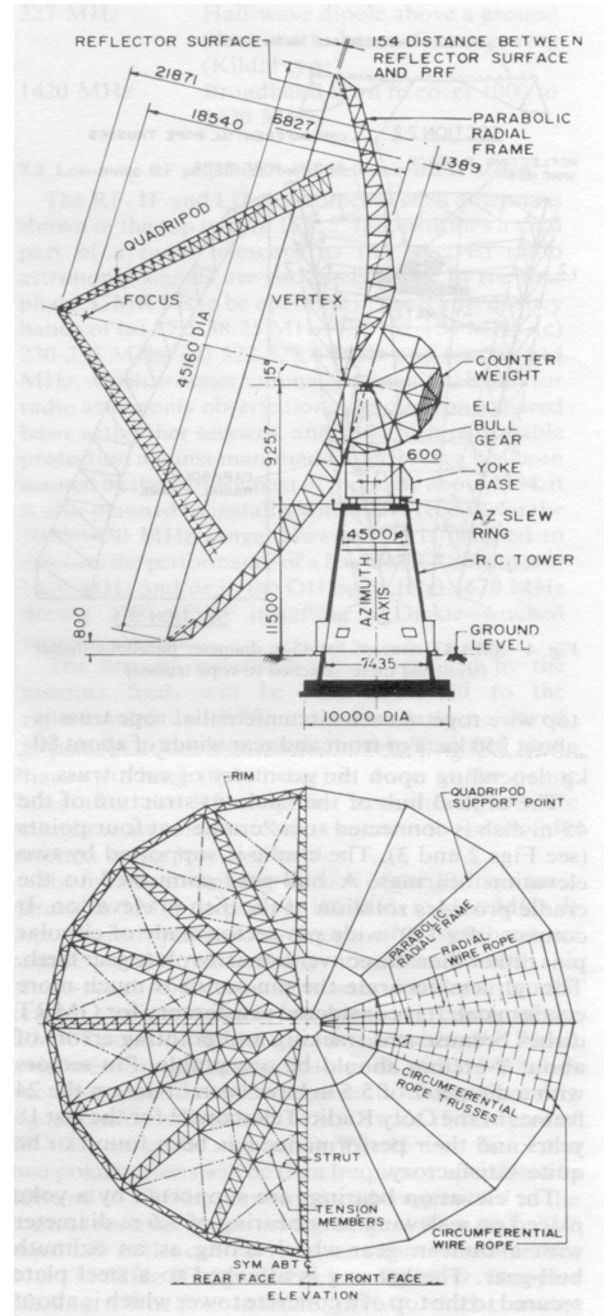
GMRT antenna: Construction Stages

GMRT: Engineering Groups



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)



Alt-Azimuth mount with ~3.5m dia azimuth bearing !

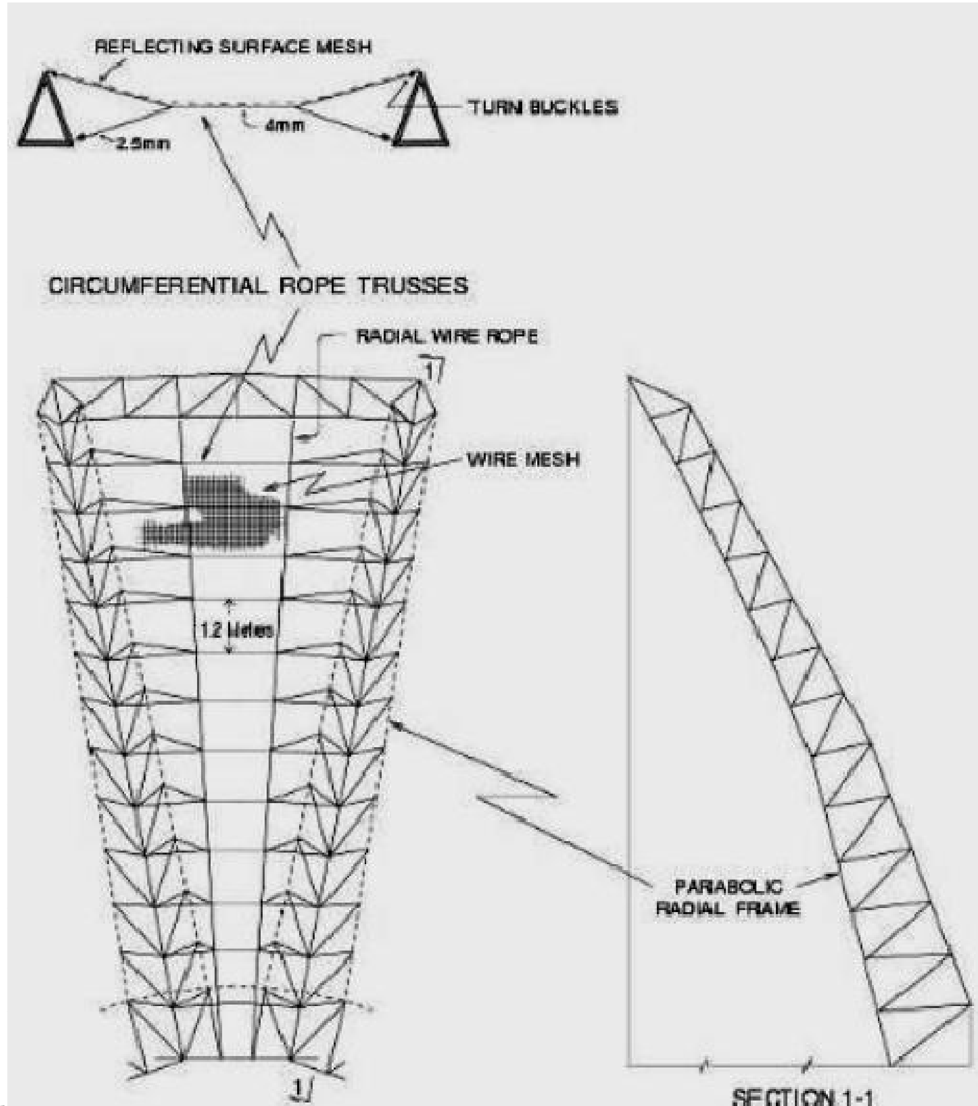
The “Invisible” Reflecting Surface

•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.

The SMART concept

- The dish has 16 parabolic frames which give the basic shape
- The reflecting surface consists of a "Stretched Mesh Attached to Rope Trusses (SMART)"
- The wire mesh size is matched to the shortest wavelengths of operation



Servo Controller

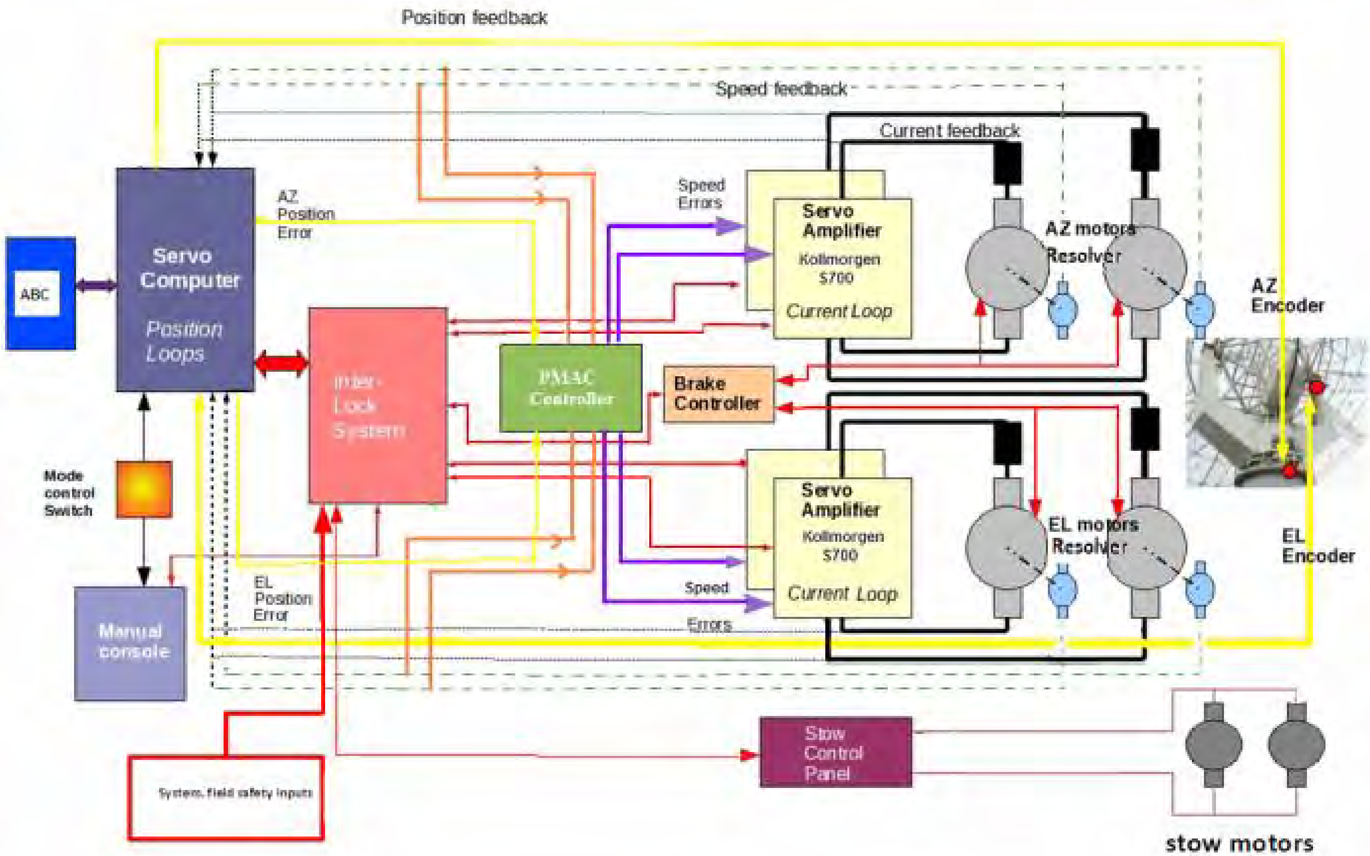
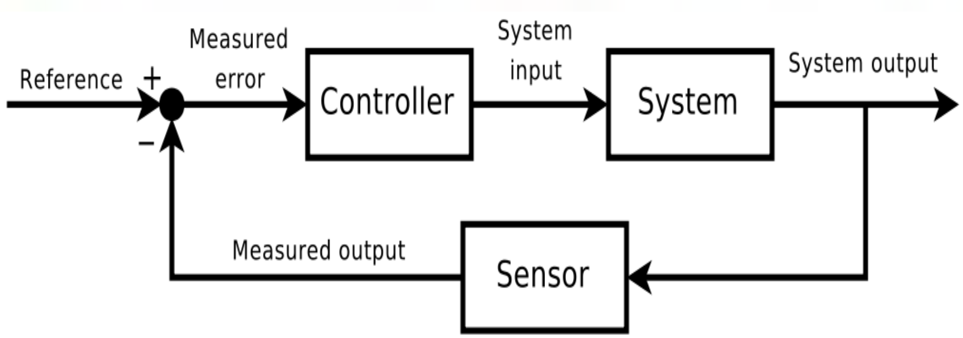


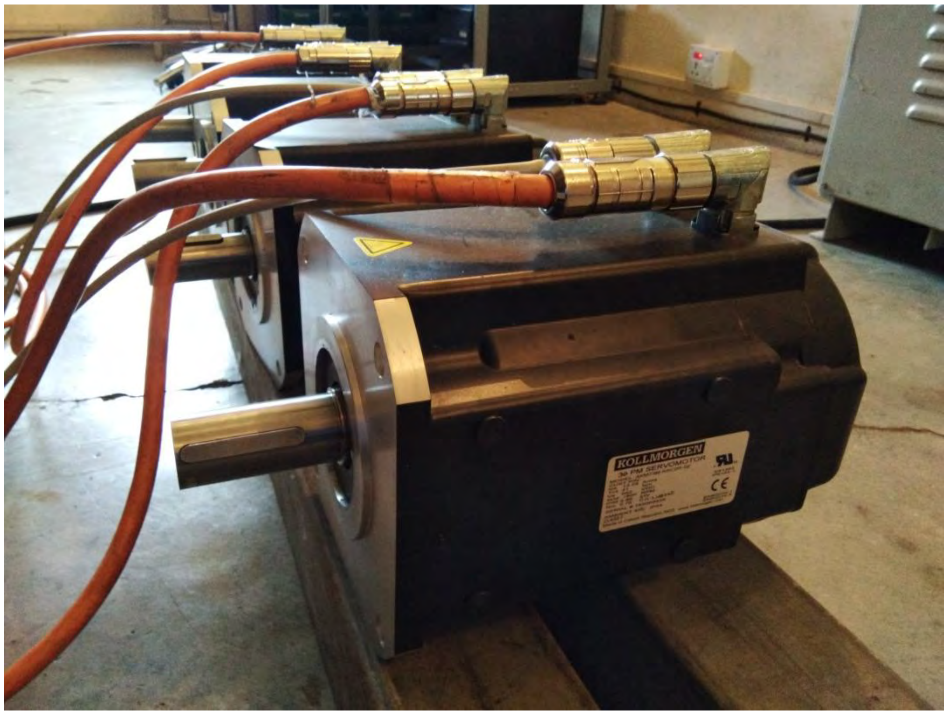
Image Courtesy: Servo group



Closed-loop control system

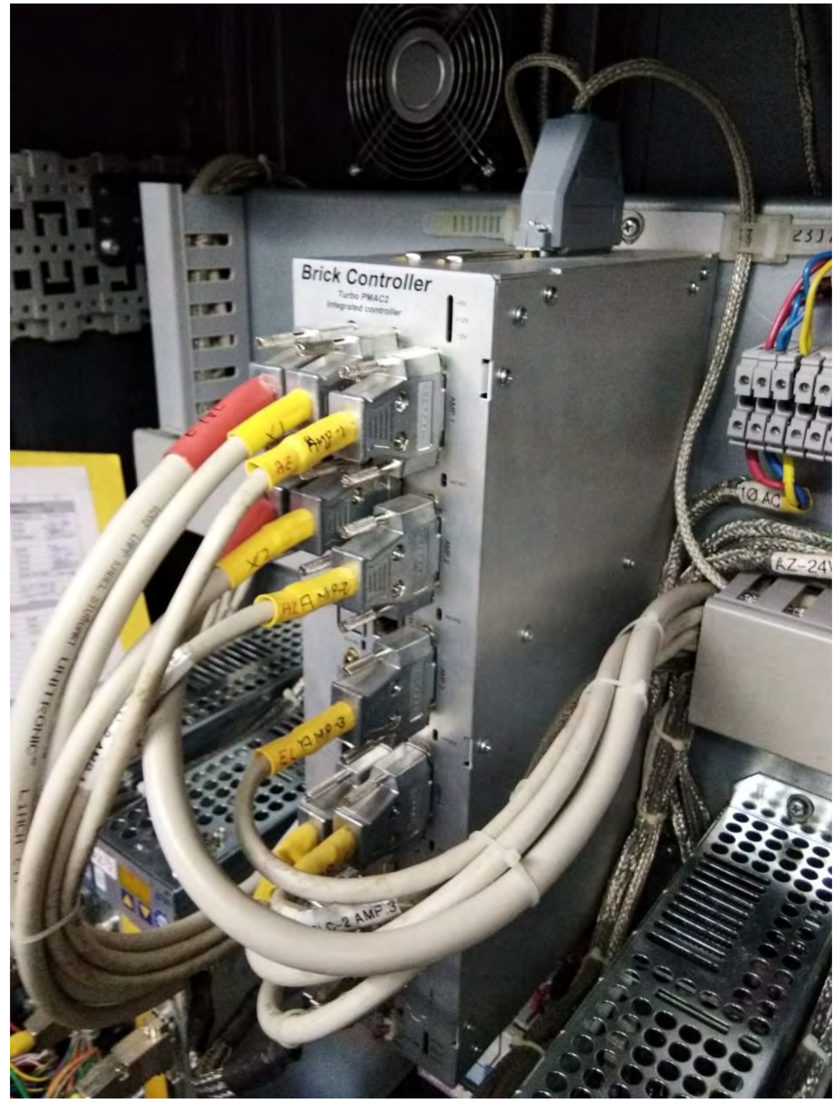
Image Courtesy: Wikipedia

BLDC motors and drives



Brushless DC motors – Azimuth and Elevation

Motors are connected to the gear box: speed-torque transformation



Drive for the BLDC motor

Image Courtesy: Amit Kumar

Feed Positioning System

•Position Loop Control system with incremental encoder for position feedback (being converted to absolute encoder for better pointing)

•8051 Microcontroller based system (being converted to contemporary microprocessor)

•0.5 hp DC servomotor

•Positioning Accuracy of 6’ arc and Resolution of 1.05’ arc

•Operating RF Frequency band of GMRT can be changed in about ONE MINUTE

Image Courtesy: Abhay Bhumkar

Electrical Systems

- Power back-up (UPS and Diesel Generator sets) to cover ALL the antennas
- Finding and eliminating sources of power-line interference
- Improved reliability of electrical sub-systems
- Approximate power consumption 20-25 KW per antenna
- Uninterrupted power to all the laboratories and facilities in the central square campus

Installing and Servicing

- High-lift platform (a.k.a. cherry picker) is used for installing and servicing feeds and front end electronics.
- It is also used for painting, electronics at the prime focus, and structural maintenance of the antenna.

Painting the GMRT antenna

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

Image Courtesy: David Green

Radio Telescope Receiver

Radio Telescope Receiver Specifications

- *IDEAL Radio Telescope Receiver: INFINITE bandwidth and ZERO noise*
- *PRACTICAL Radio Telescope:*
  - Parabolic Reflector Surface acts like a Low-Pass Filter due to surface errors and reflector dimensions (~ 2 GHz for GMRT)
  - Internationally protected frequency bands
    - For Spectral line observations
    - For Continuum Observations
- Celestial signals are very weak – measured in Jansky (Jy) (1 Jy = 10^{-26} $Wm^{-2}Hz^{-1}$)
- The input to the receiver (=kTB, ~ -100 dBm) must be amplified to around 0 dBm (=220 mV RMS) for processing by the digital electronics.

  Gain requirement of around 100 dB (10^{10}) in the receiver chain
- The above gain must be distributed among various sub-systems with a good matching between
  - Noise Figure
  - Linear Dynamic Range
  - Spurious Free Dynamic Range
  - *Ensure NO bottleneck is created by any Receiver stage*

Signal Strength

- Typical Spectral Power flux density received at the feed of the antenna is about -100 dbm over 32 MHz receiver bandwidth, which is lower than the thermal noise floor of most of the electronic instruments.

  For instance, the thermal noise floor of a spectrum analyzer is about -110 dbm over 32 MHz bandwidth

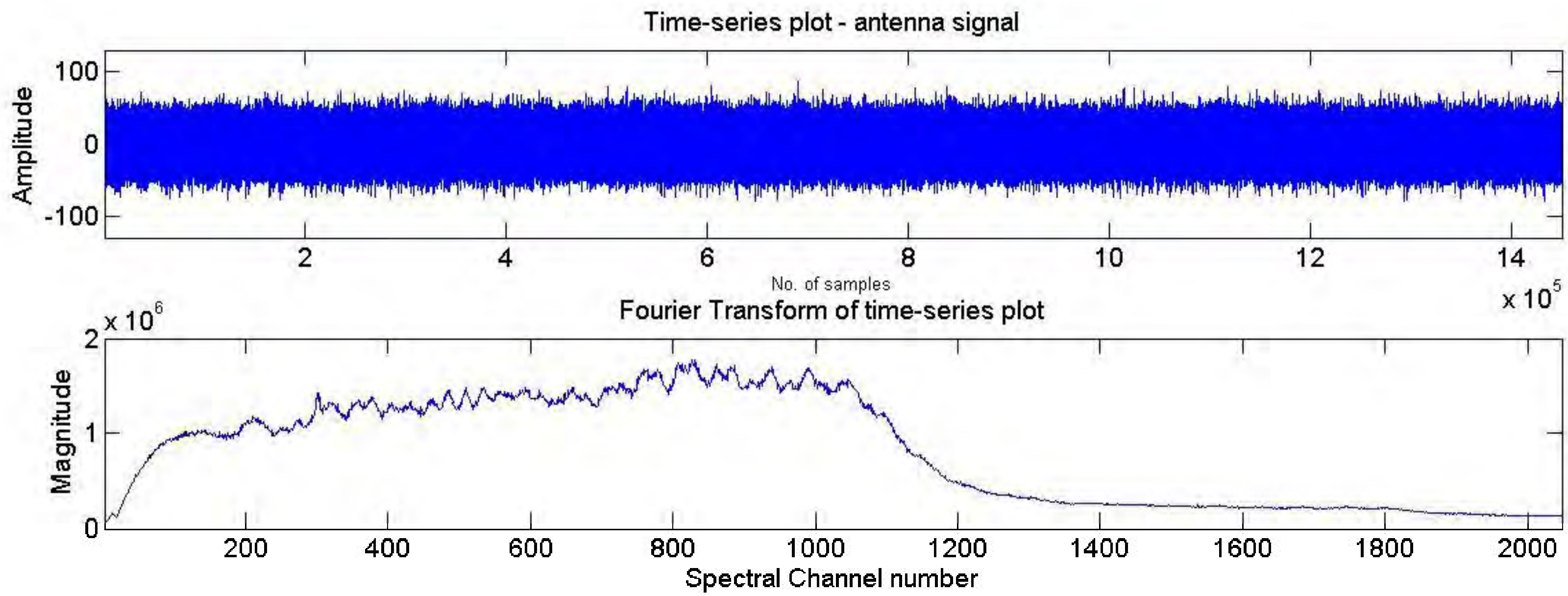
- To increase the received power and to improve the signal-to-noise ratio (G/T_{sys}):

a. Increase the receiver bandwidth => Wideband receivers

b. Reduce system noise => Low noise electronics

c. Increase collecting area => Bigger dishes

Astronomical Signal Characteristics

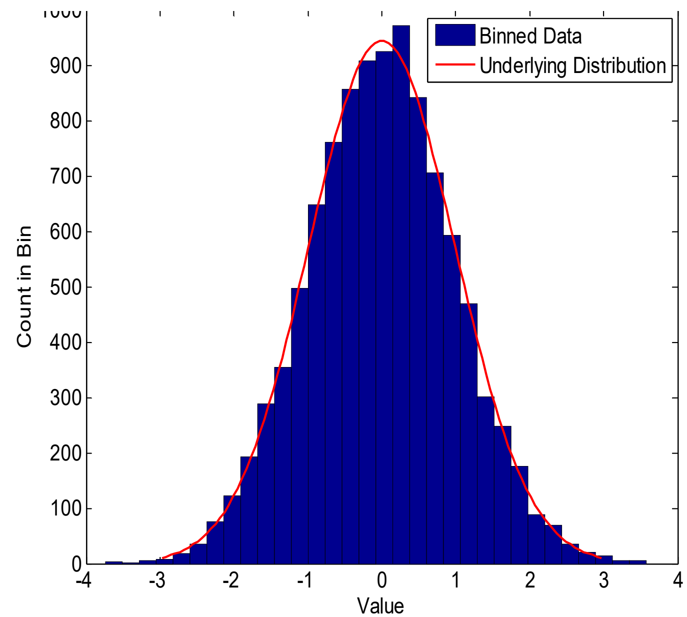


•Zero mean Gaussian distributed random signal

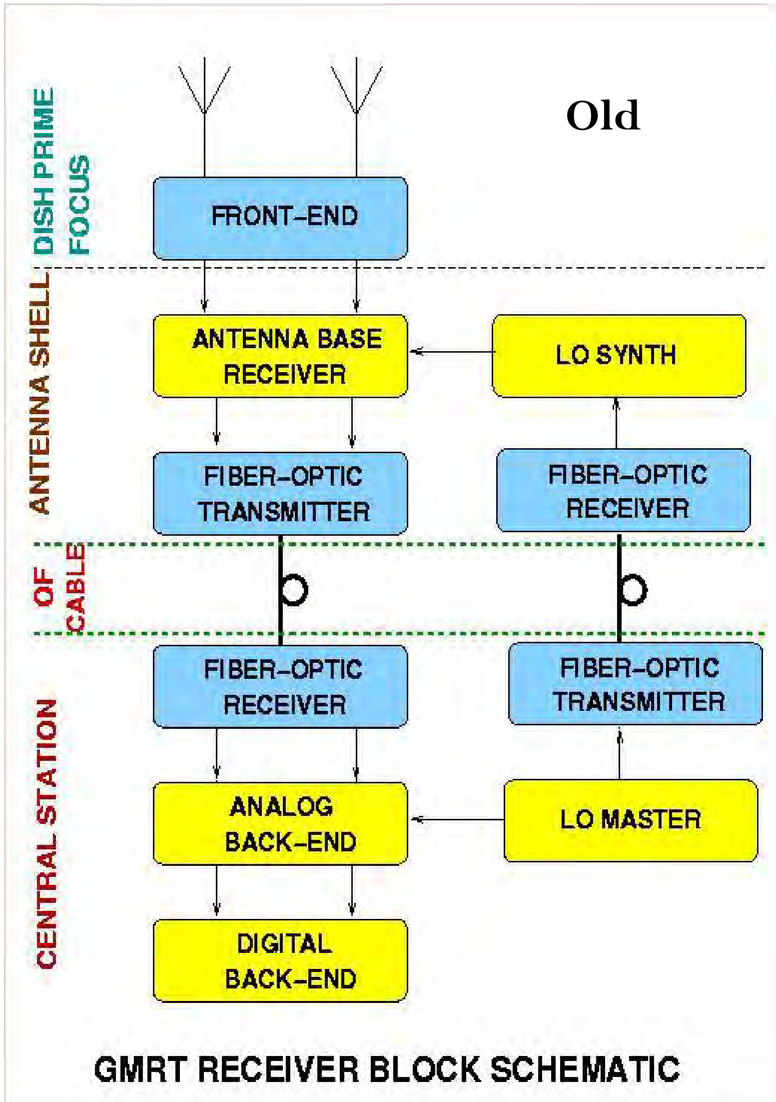
•Stationary random process – mean and autocorrelation do not change with time (under ideal conditions)

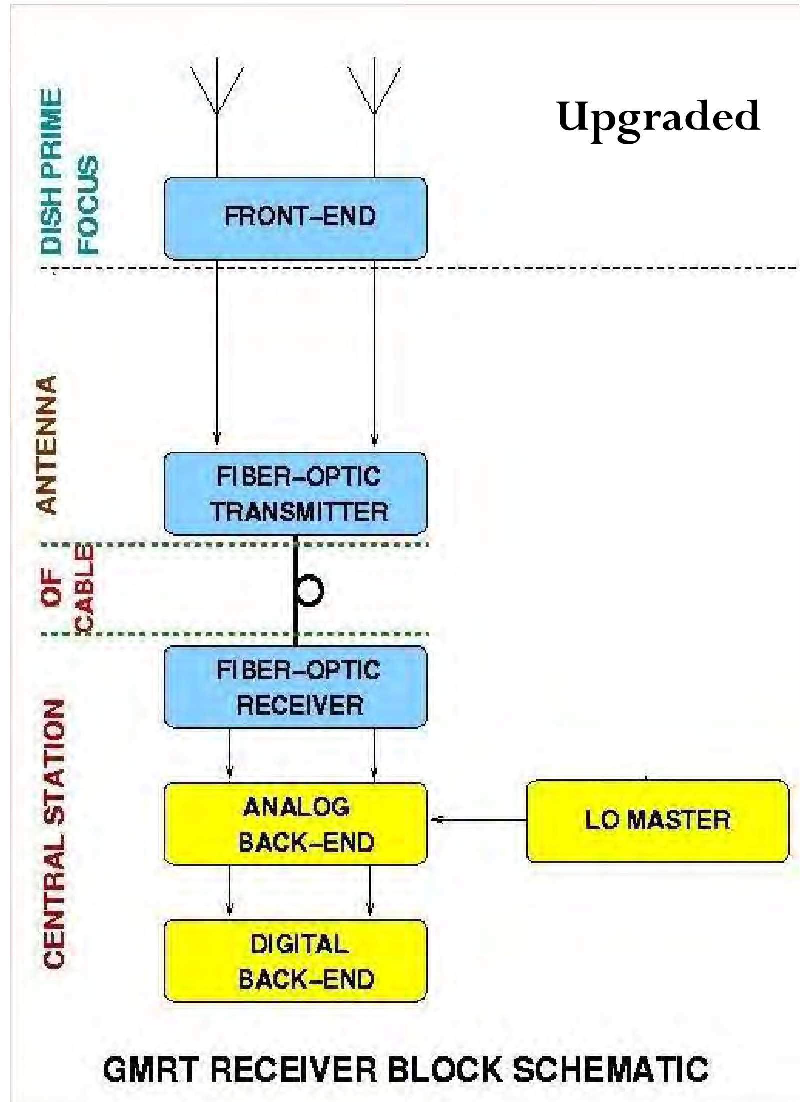
•Noise power measured over bandwidth

$$P = kTB \text{ Watts}$$



Comparison: Old versus Upgraded



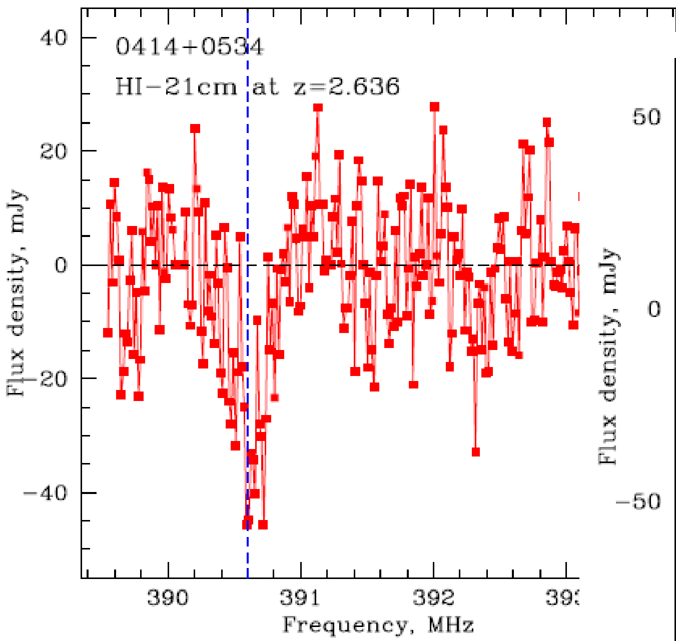


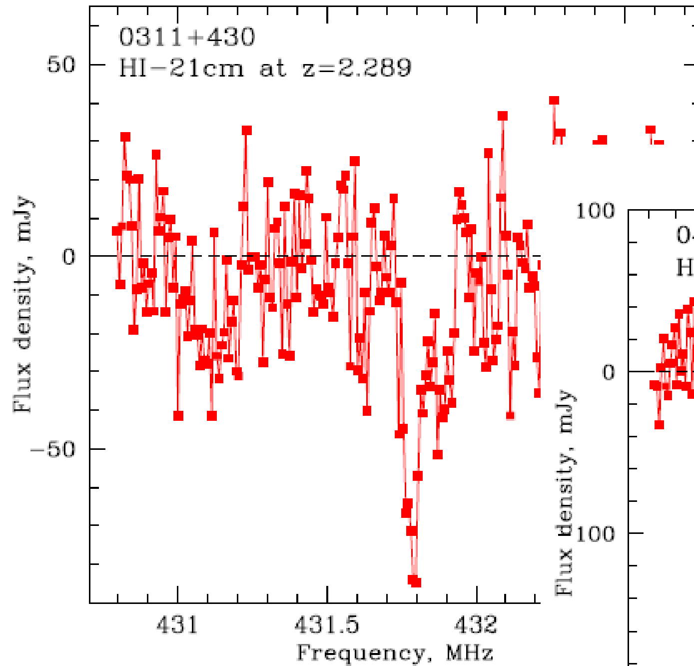
The uGMRT

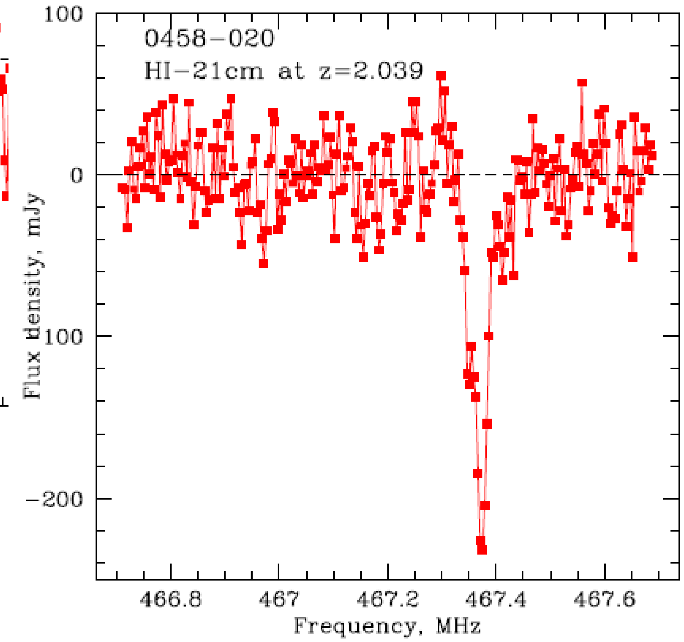
The Upgraded GMRT (uGMRT)

- Seamless frequency coverage from ~30 MHz to 1500 MHz **design of new feeds and receiver system**
- Improved G/T_{sys} by reduced system temperature => **better technology receivers**
- Increased instantaneous bandwidth of 400 MHz (from the present maximum of 32 MHz) => **modern new digital back-end receiver**
- **Revamped servo system for the antennas**
- **Modern and versatile control and monitoring system**
- **Matching improvements in offline computing facilities and other infrastructure**
- **Improvements in mechanical systems and infrastructure facilities**

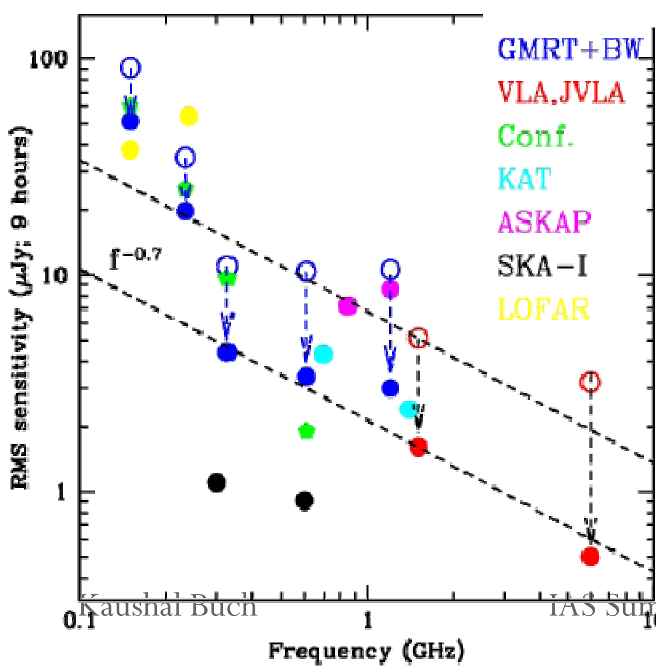
uGMRT: Benefits







First light results: spectral lines from different sources, at different parts of the 250-500 MHz band (courtesy : Nissim Kanekar)



Expected sensitivity of the uGMRT compared to other major facilities in the world, present and projected (courtesy : Nissim Kanekar)

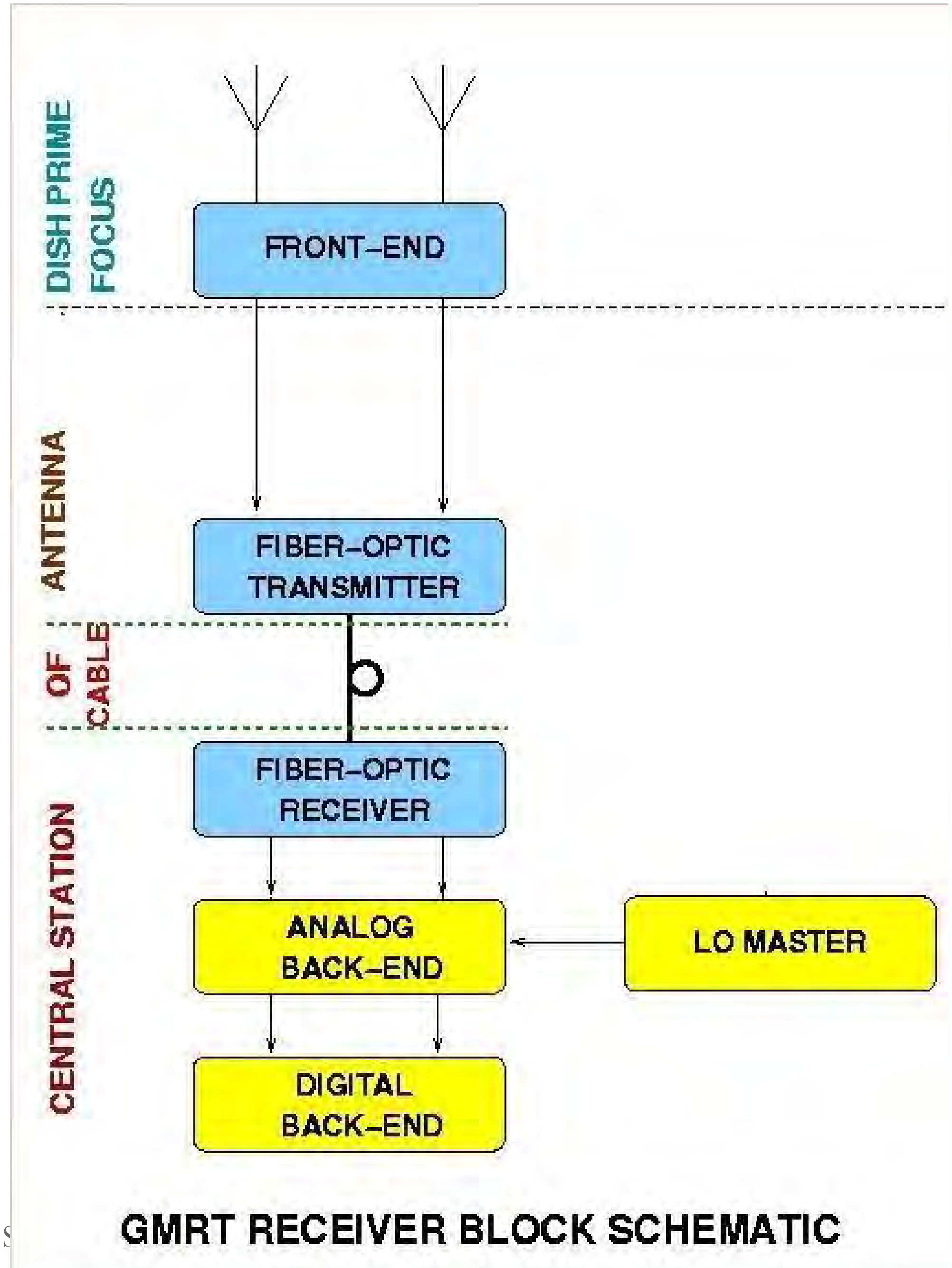
uGMRT Receiver Block Diagram

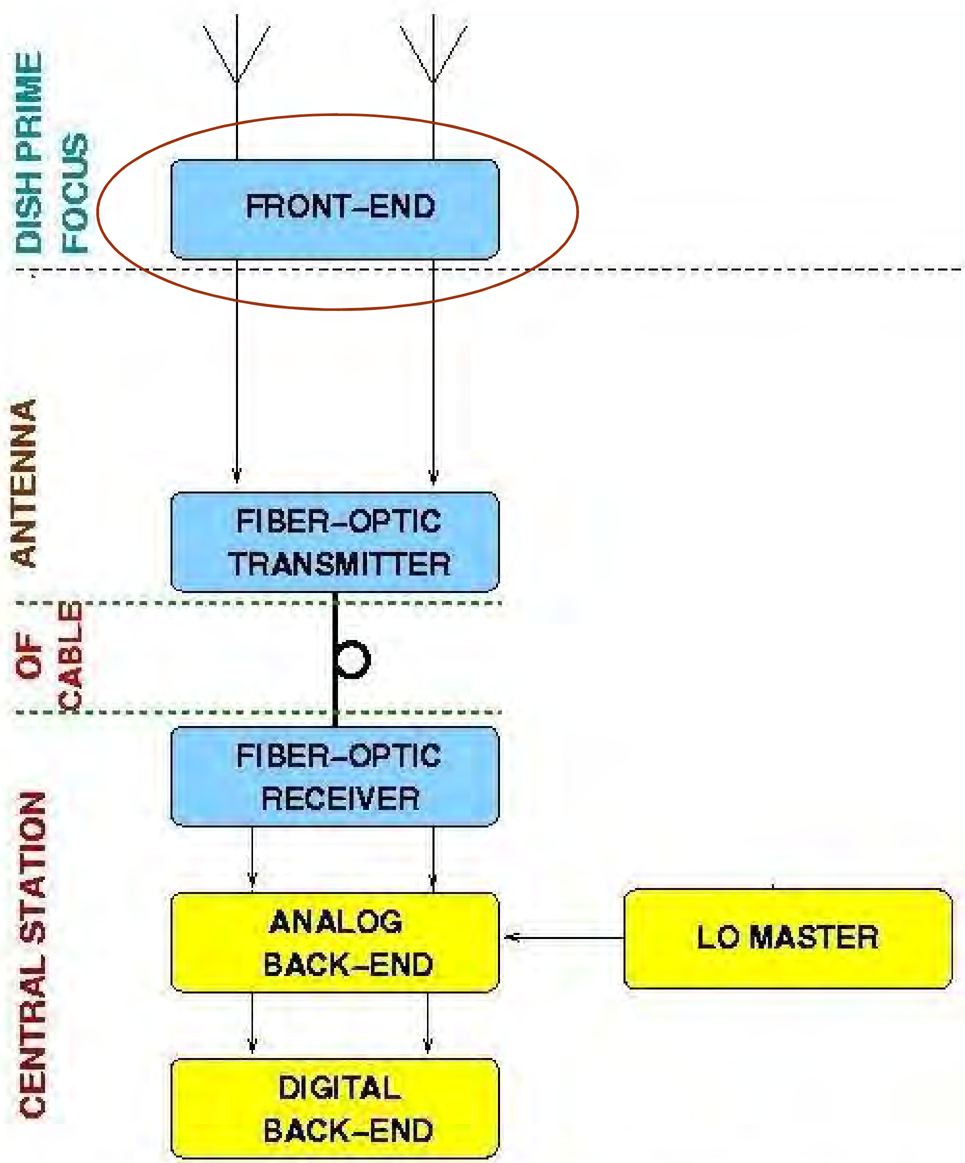
•New feeds with wider frequency coverage allowing observations from 50 to 1500 MHz band

•Improved front-end electronics with low noise and increased dynamic range

•RF signal is directly transported to the central station using a broadband analog fiber

•Reduced electronics at antenna sites

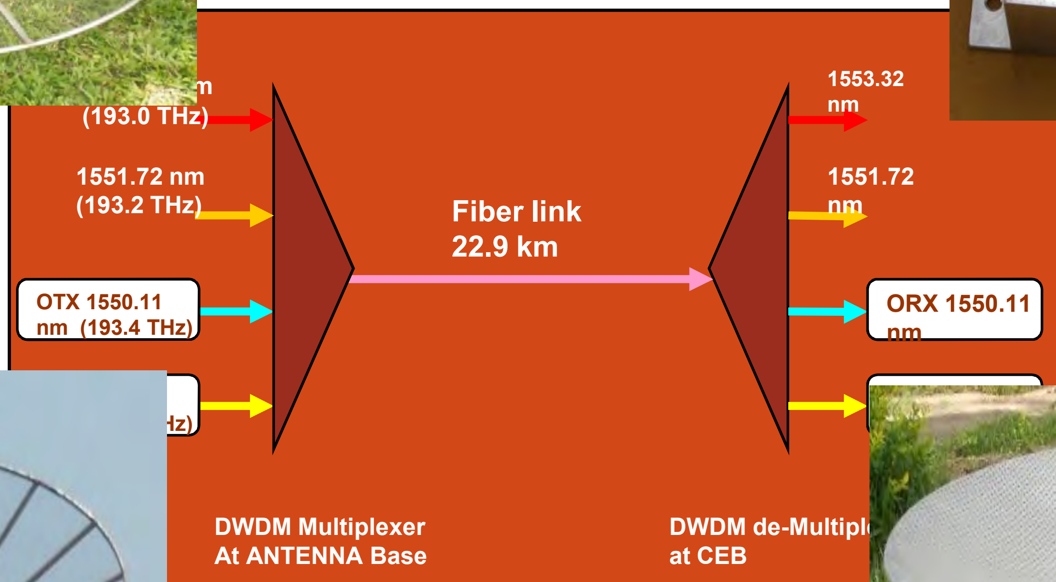


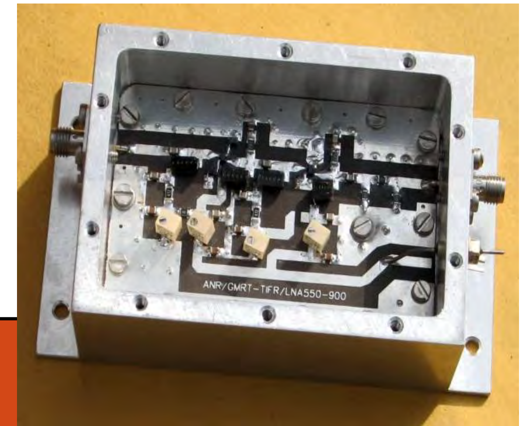


GMRT RECEIVER BLOCK SCHEMATIC

Components of Upgraded GMRT Frontend

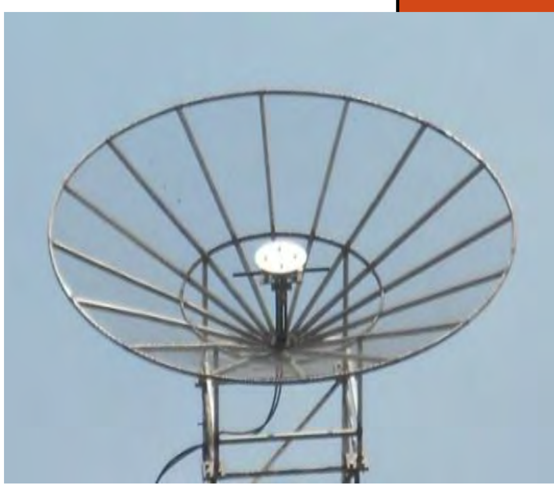
130 - 260 MHz feed





500 – 900 MHz Low Noise Amplifier

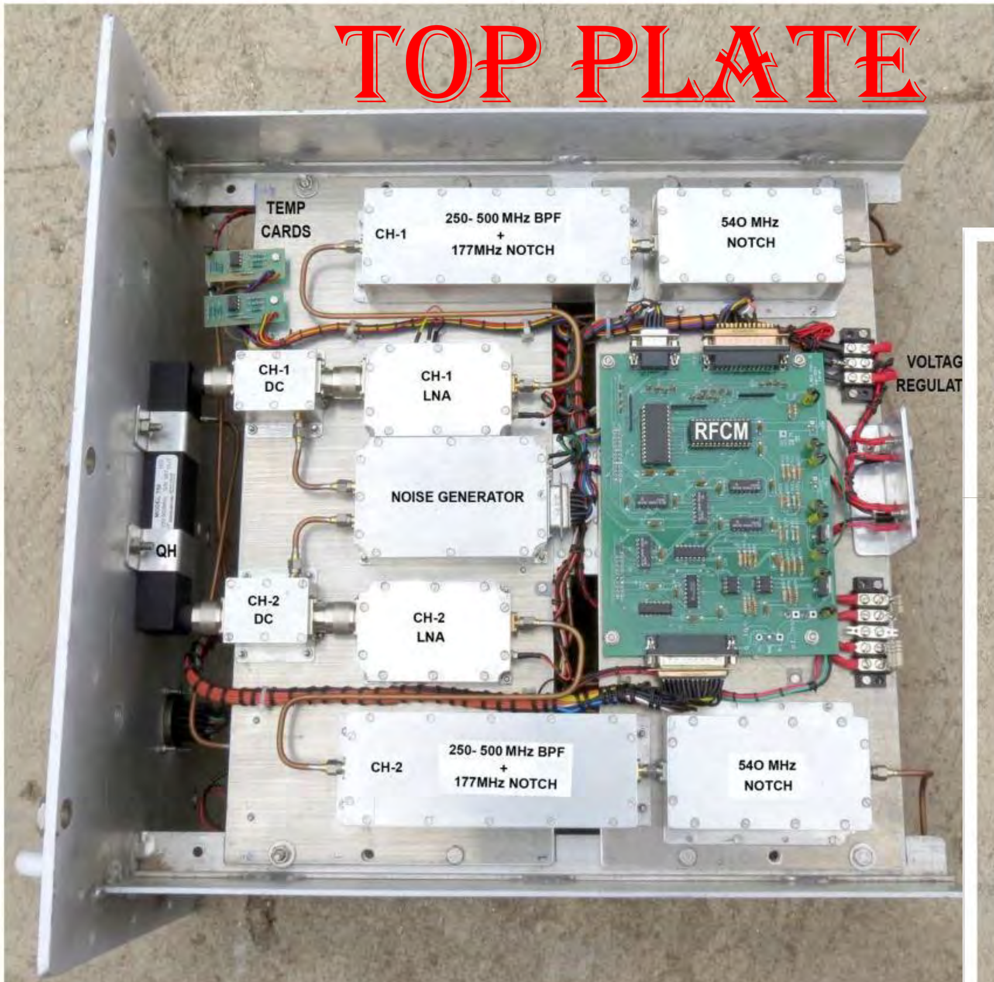
550– 900 MHz feed



250 – 500 MHz feed

Image Courtesy: Front-end Group

RF signal processing units



Front-end box installed at the prime-focus consists of polarizers, low-noise amplifiers, filters and monitoring and control circuitry

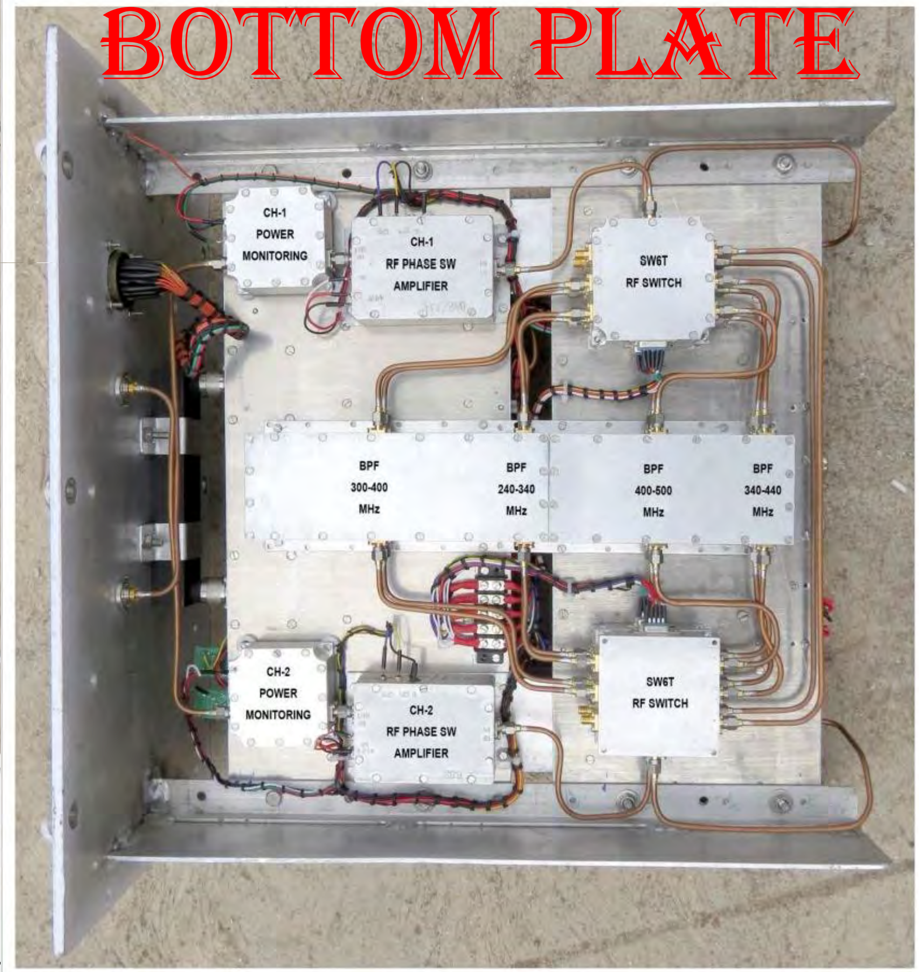
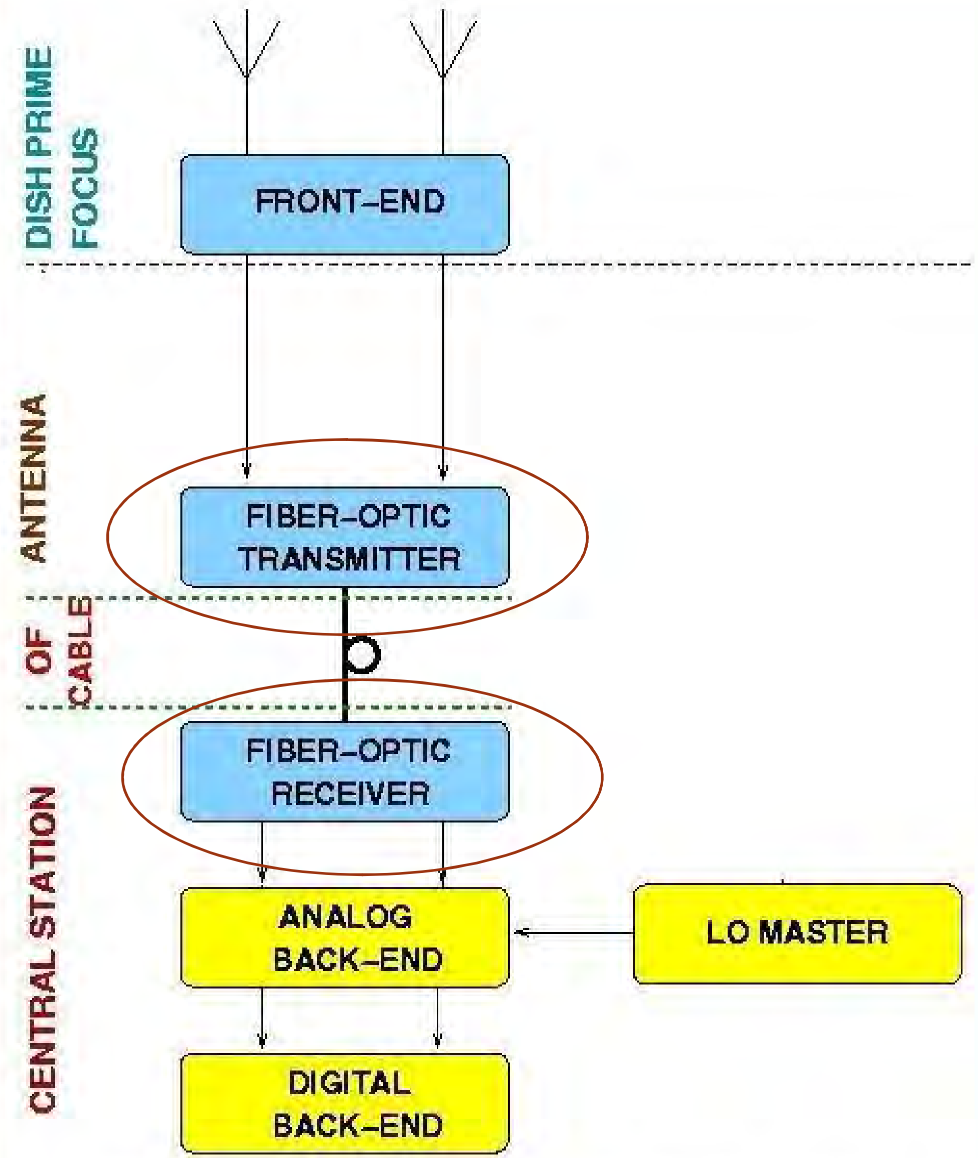


Image Courtesy: Front-end Group



GMRT RECEIVER BLOCK SCHEMATIC

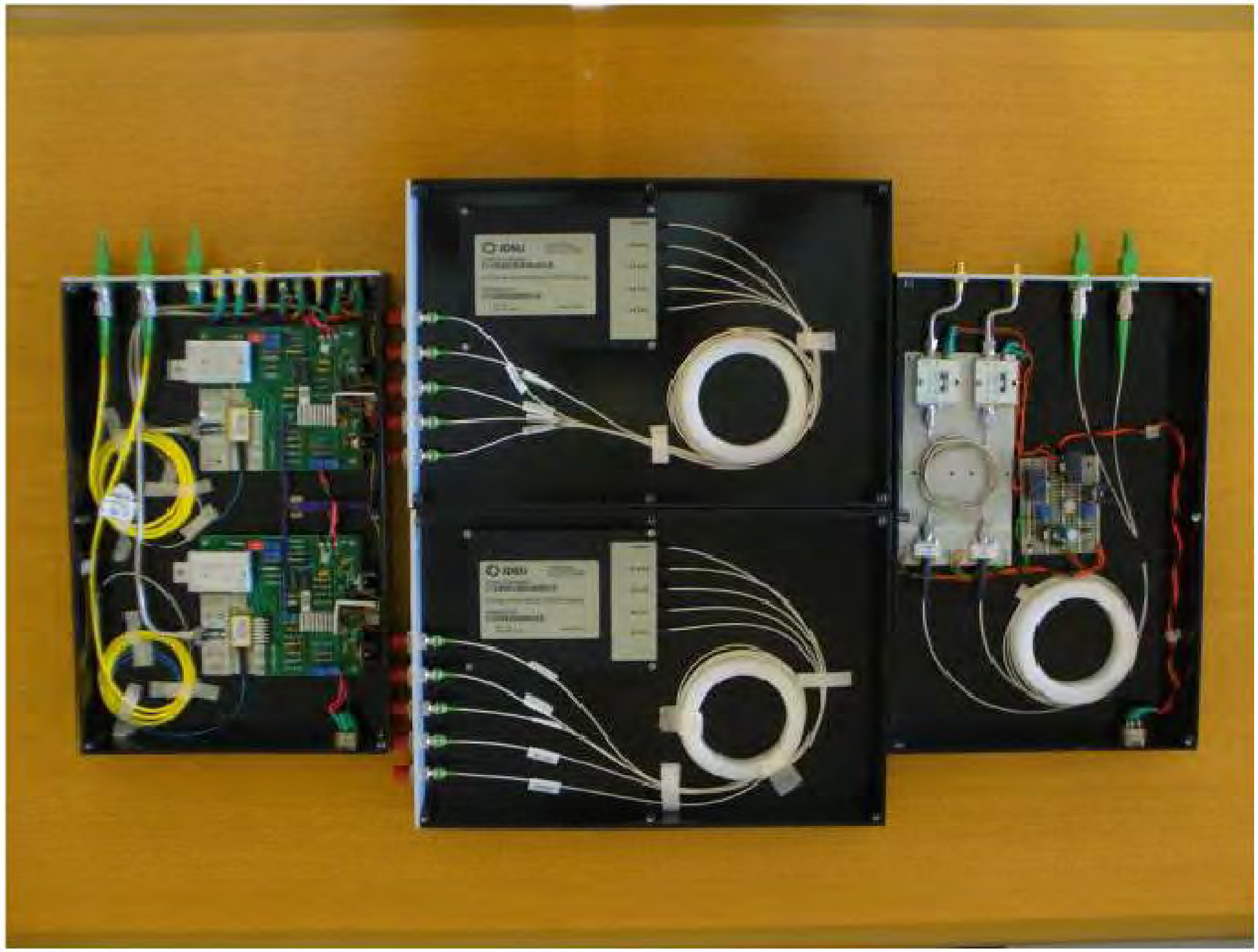
Upgraded Fiber Optic System

•GMRT is the first radio telescope to use analog fiber optic link for signal transport.

•Fiber is 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.

•Uses dense wavelength division multiplexing (DWDM) to accommodate multiple data and control channels on a single fiber.

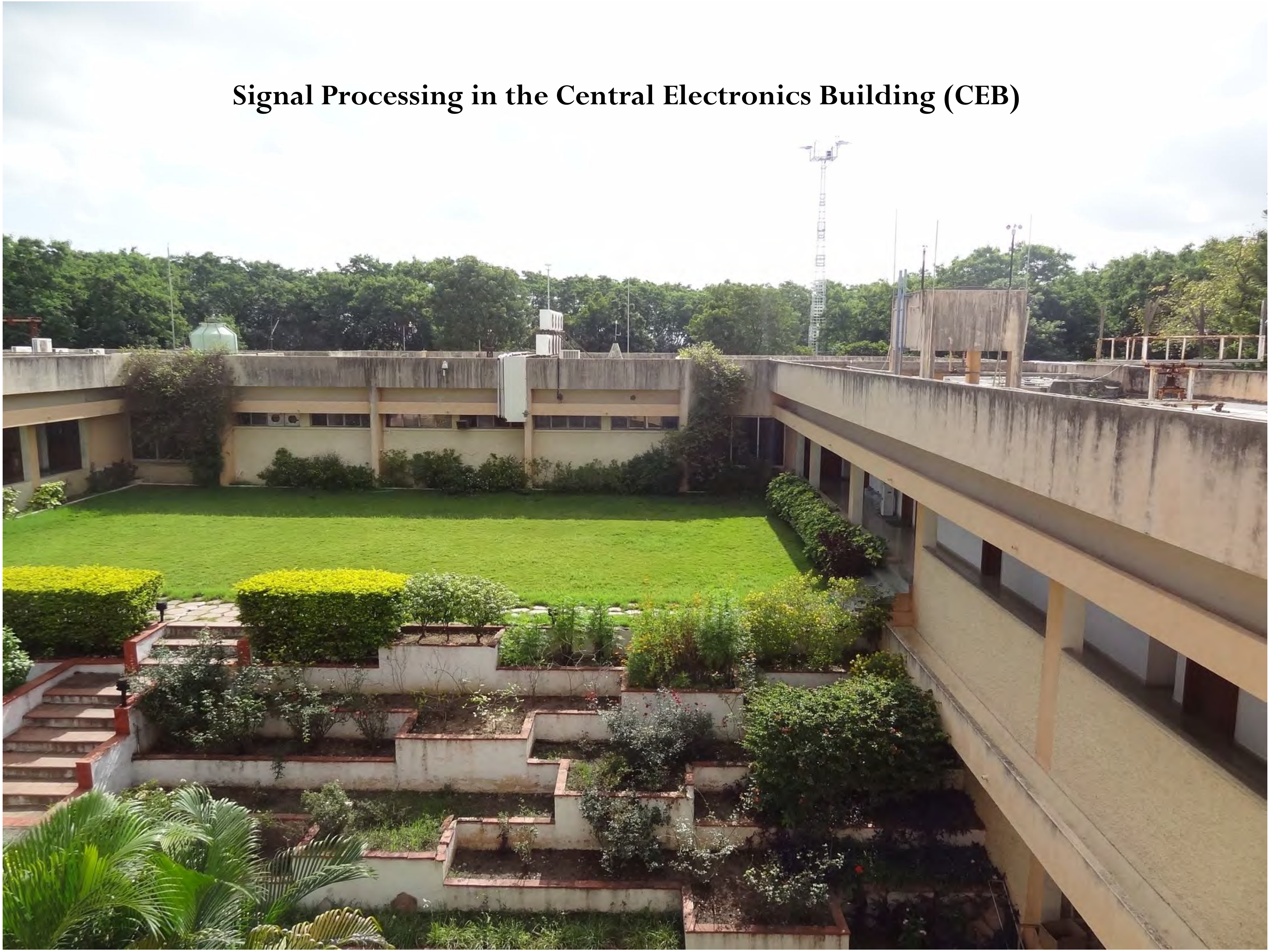


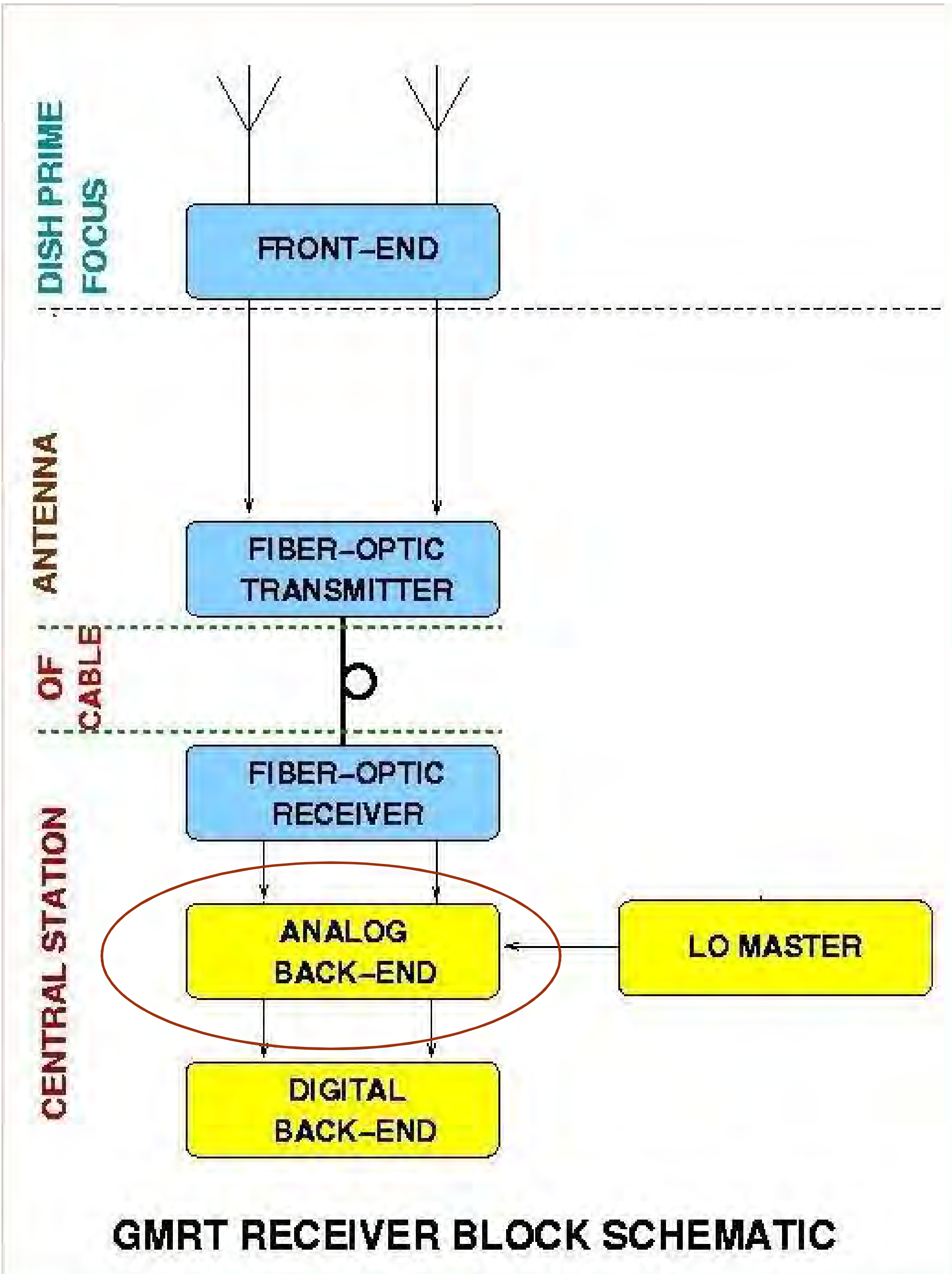
LASER Transmitter, Optical Multiplexer, Optical receiver

DWDM based system

Image Courtesy: OFC Group

Signal Processing in the Central Electronics Building (CEB)

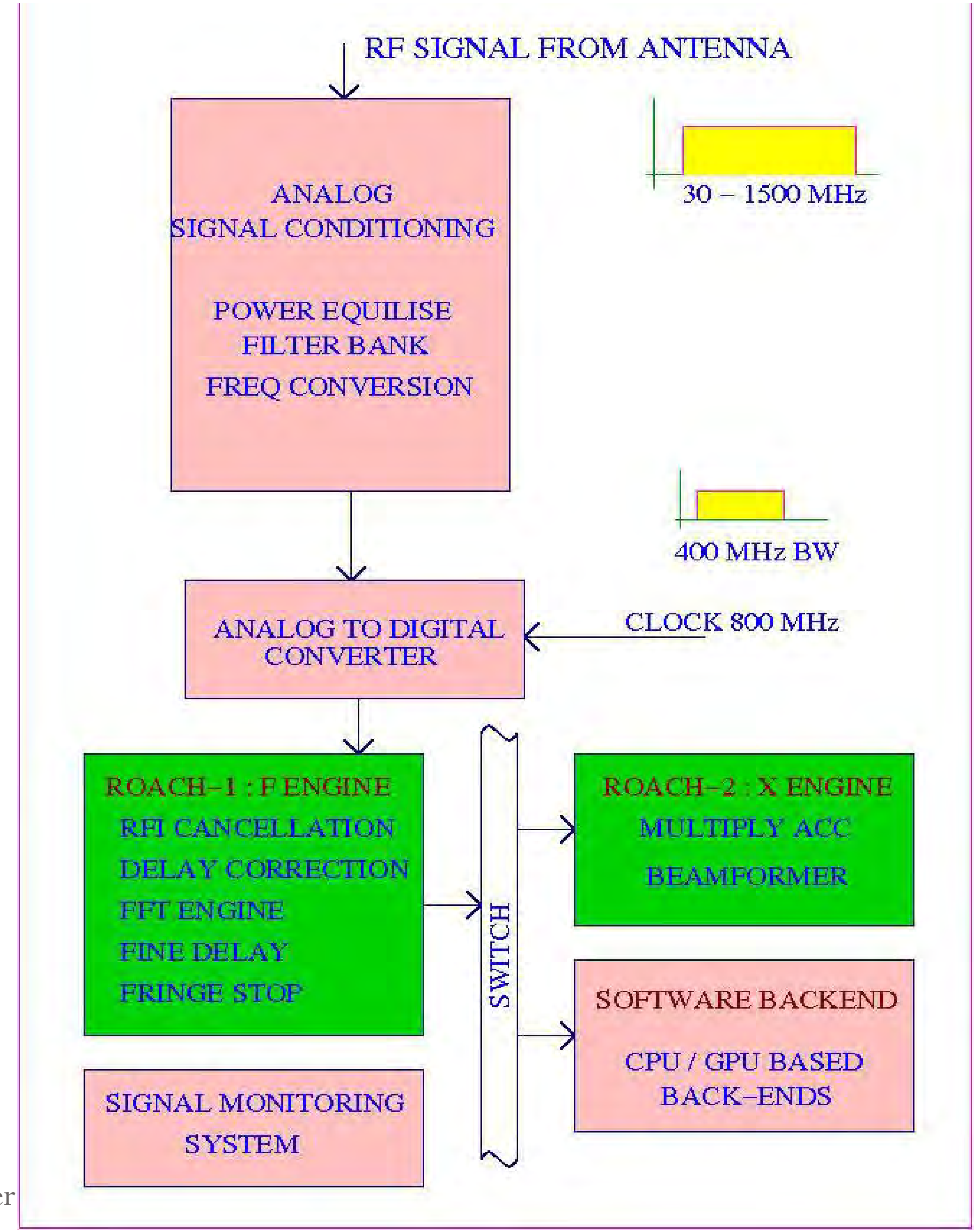



DISH PRIME FOCUS
FRONT-END
ANTENNA
FIBER-OPTIC TRANSMITTER
OF CABLE
FIBER-OPTIC RECEIVER
CENTRAL STATION
ANALOG BACK-END
LO MASTER
DIGITAL BACK-END
GMRT RECEIVER BLOCK SCHEMATIC

Upgraded Backend - Schematic

Most of the signal processing in backend receiver chain is carried out at the central station

- Analog Processing
- Digitization
- Digital Processing
- Radio Frequency Interference (RFI) Excision
- Signal Monitoring



GMRT Analog Backend (GAB)

Basic Block Diagram of System:

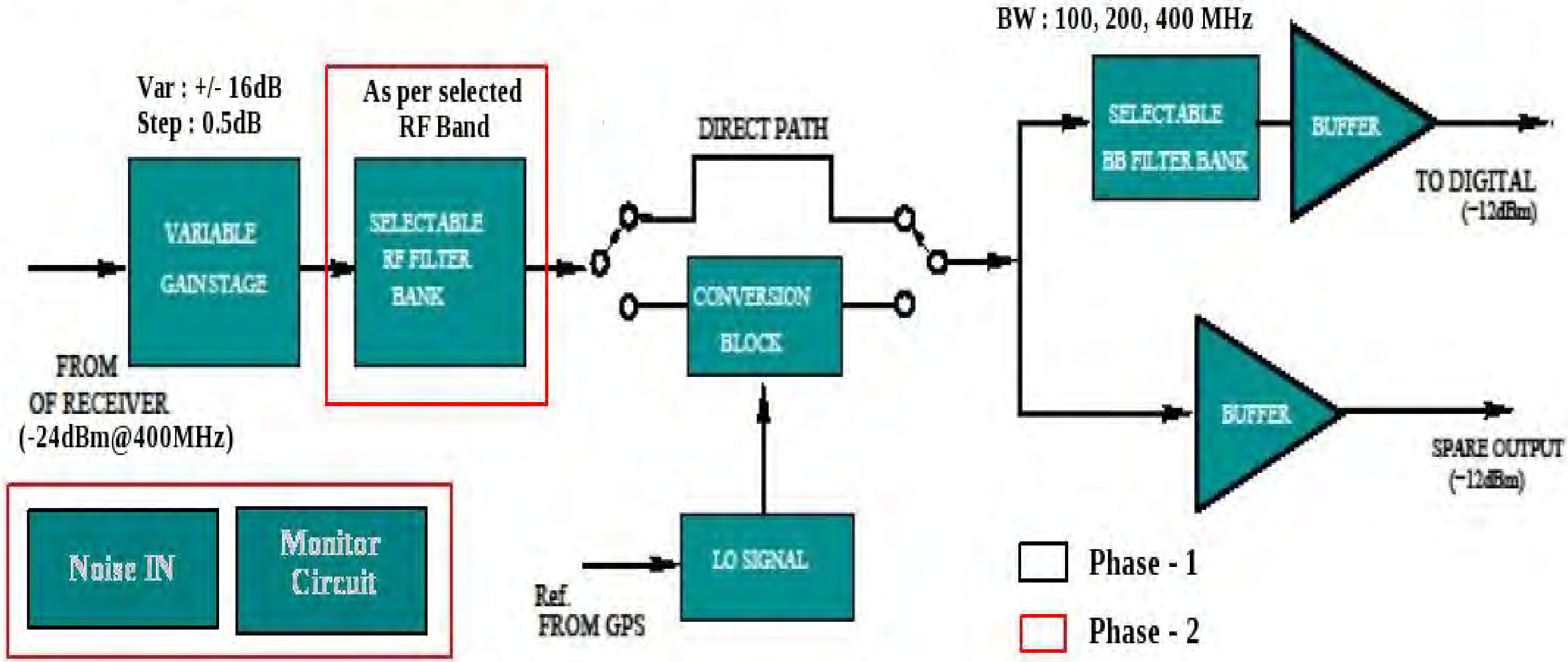


Image Courtesy: Analog Backend group

Baseband system and Plug-in Units (PIU)

Image Courtesy: Analog Backend Group

Time and Frequency Standards

Image Courtesy: Precision Test Systems

- ❑Currently GPS disciplined Rubidium frequency standard used as observatory reference
- ❑Active Hydrogen MASER (AHM) has been installed and will be operational soon.

Time & Freq Signal Connectivity for GMRT

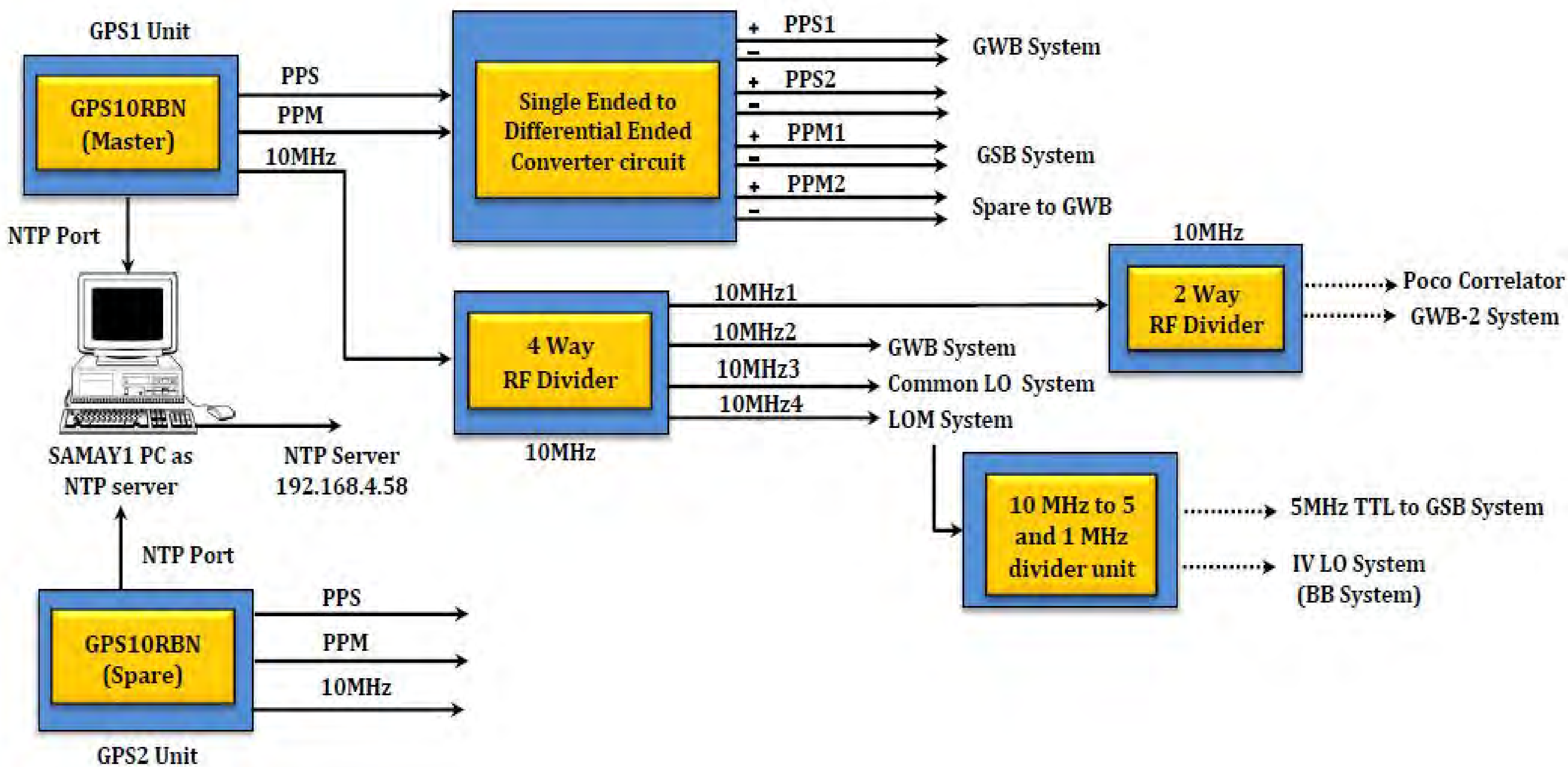
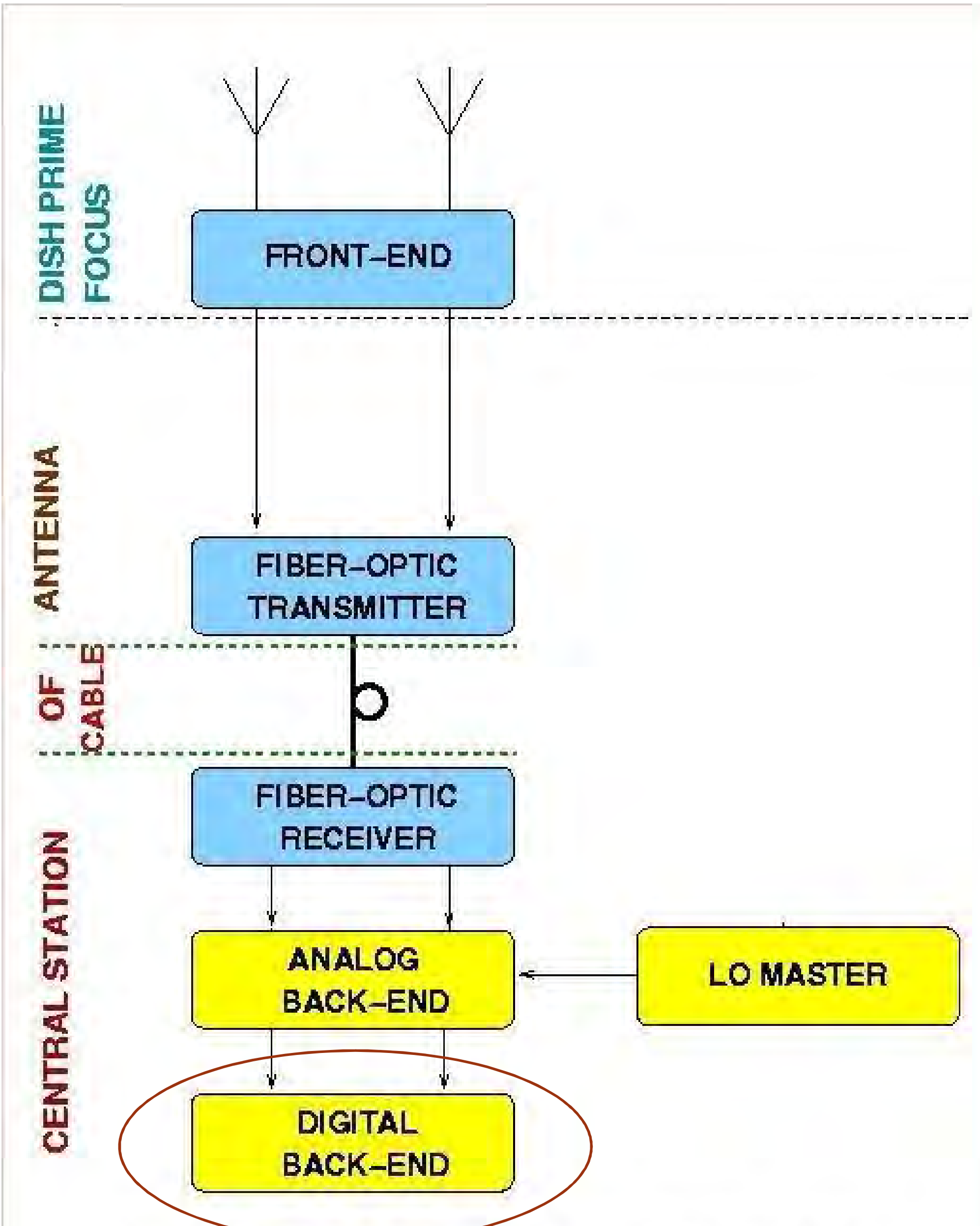


Image Courtesy: Ajay Vishwakarma



GMRT RECEIVER BLOCK SCHEMATIC

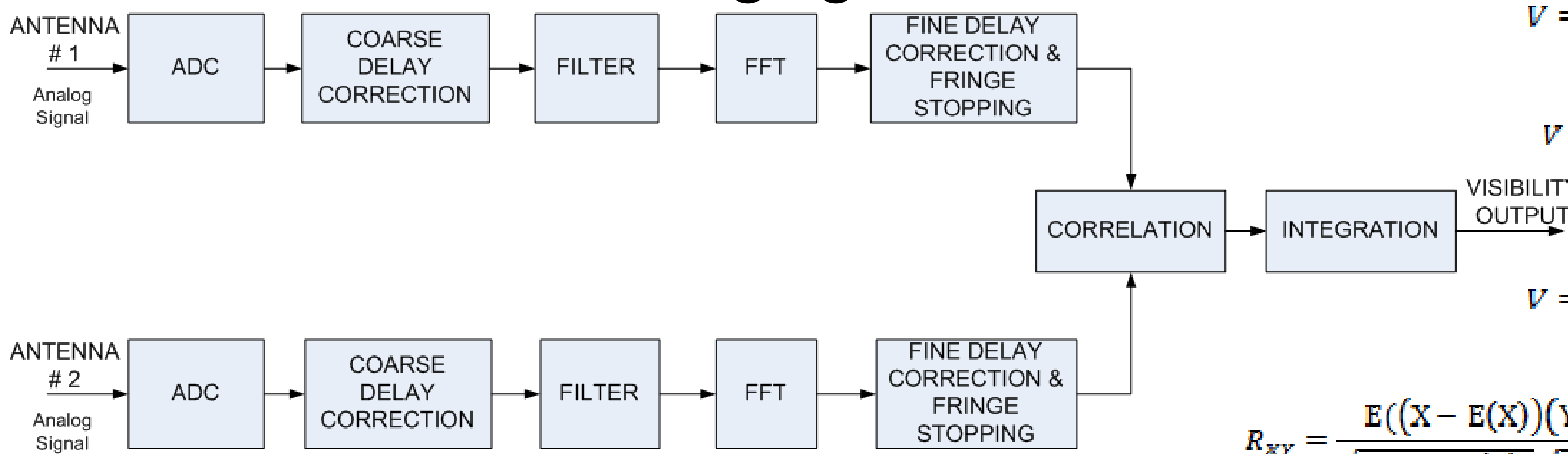
Correlation and Beamforming: Basic Steps

- Correlation: (n(n-1)/2 combinations) – Total Intensity and Full Stokes modes
    1. Delay Correction (Coarse and Fine)
    2. FFT
    3. Multiply-and-accumulate

- Beamforming: (single output stream) - Total Intensity and Full Stokes modes
    1. Delay correction (Coarse and Fine)
    2. FFT
    3. Phasing, Combining (addition) and accumulation

Digital Backend Signal Processing

Imaging Mode



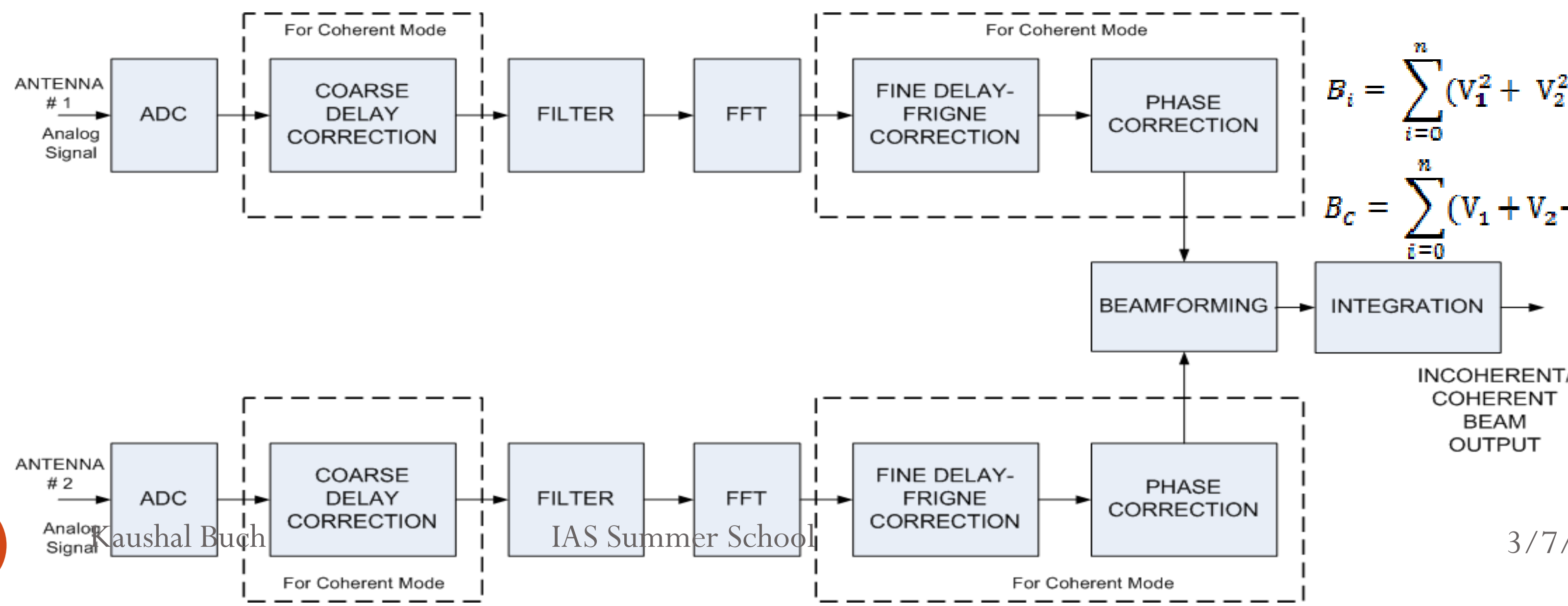
$$V = \sum_{i=0}^{n} V_1 V_1^*$$

$$V = \sum_{i=0}^{n} V_1 V_2^*$$

$$V = \sum_{i=0}^{n} V_2 V_2^*$$

$$R_{XY} = \frac{E((X - E(X))(Y - E(Y)))}{\sqrt{E(X - E(X))}\sqrt{E(Y - E(Y))}}$$

Beam Mode



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

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

Parallel Computing

- Real-time correlation and beamforming for multiple antennas is a computationally challenging problem
- Computational scales as the square of the number of antennas
- Use parallelism available on contemporary devices like Field Programmable Gate Array (programmable logic device) and Graphics Processing Unit (several thousand microprocessor cores)

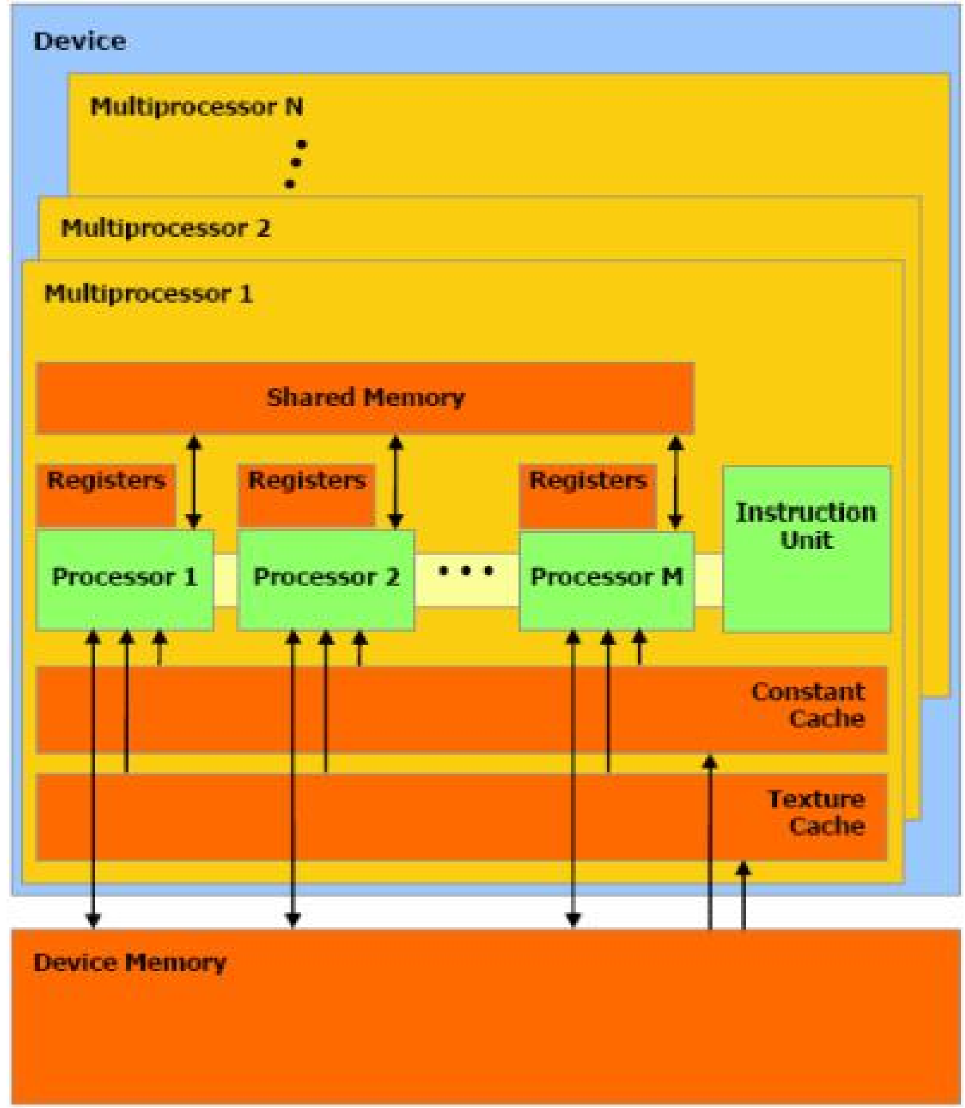
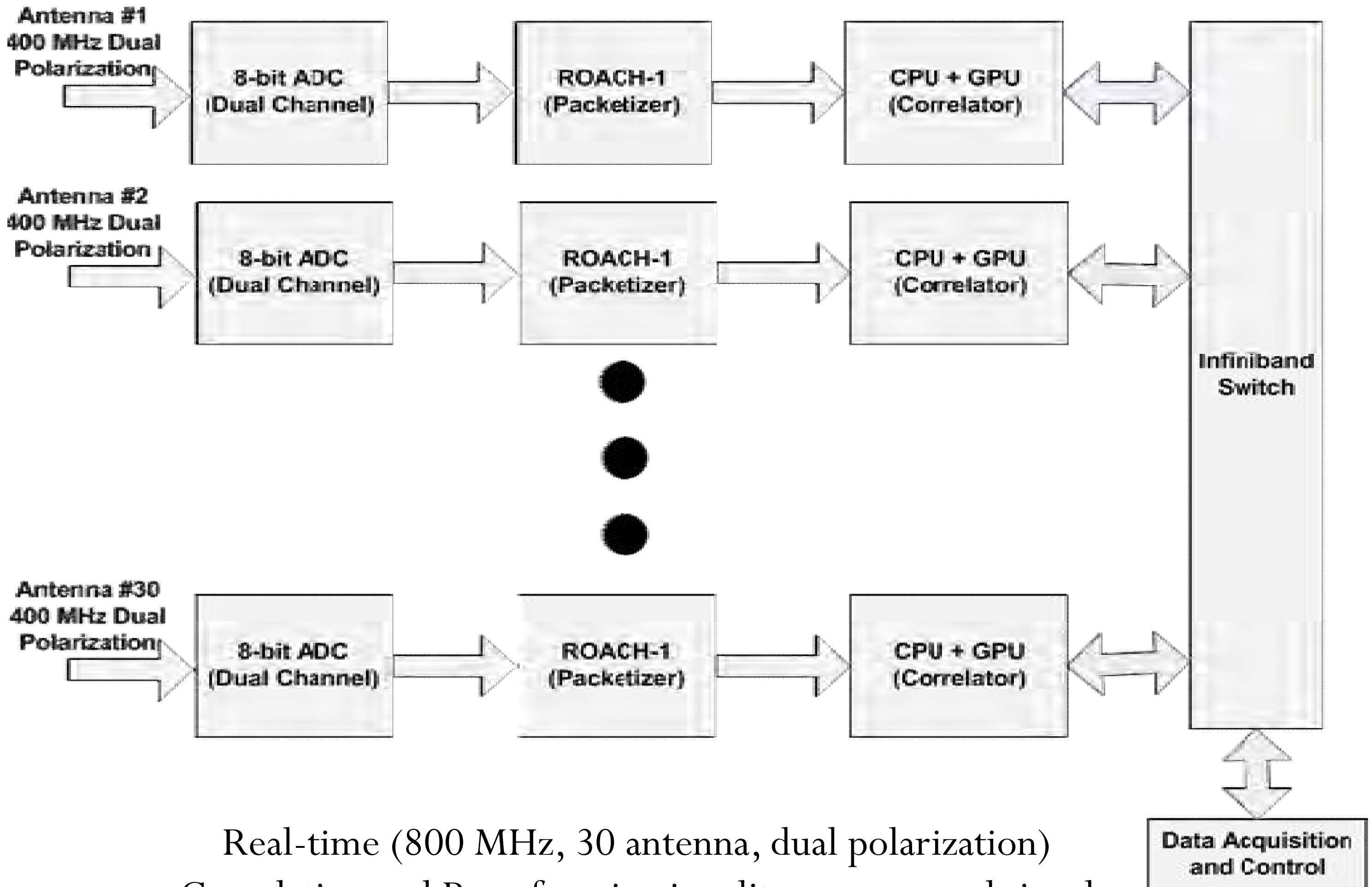


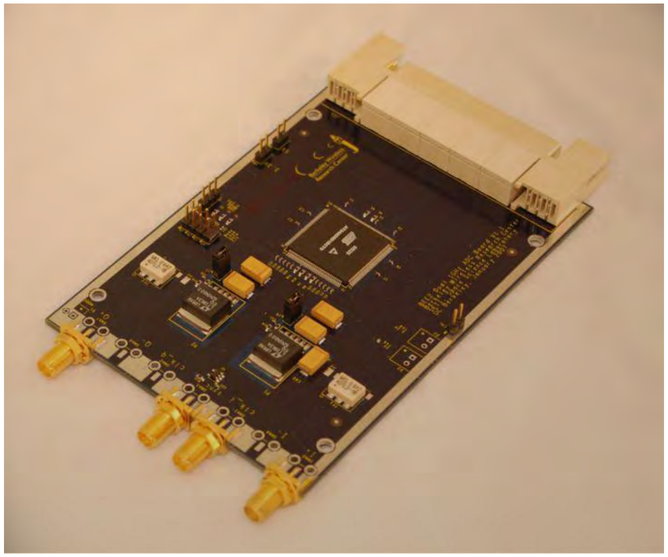
Image Courtesy: nVIDIA

GMRT Wideband Backend (GWB)

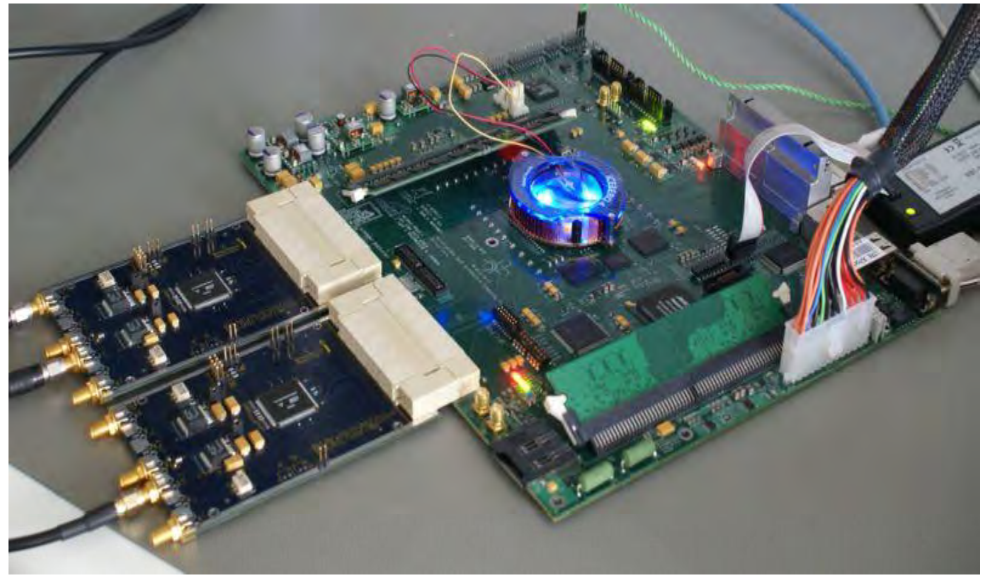


Real-time (800 MHz, 30 antenna, dual polarization) Correlation and Beamforming is split across several signal processing platforms (FPGA and GPU)

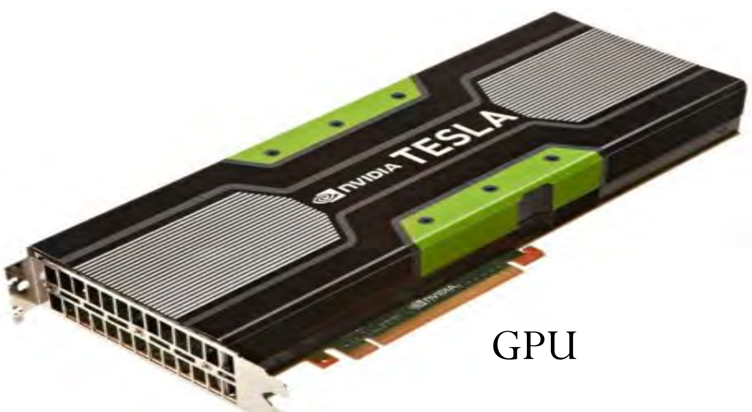
GWB Hardware



High-speed ADC



FPGA board – ROACH-1



GPU

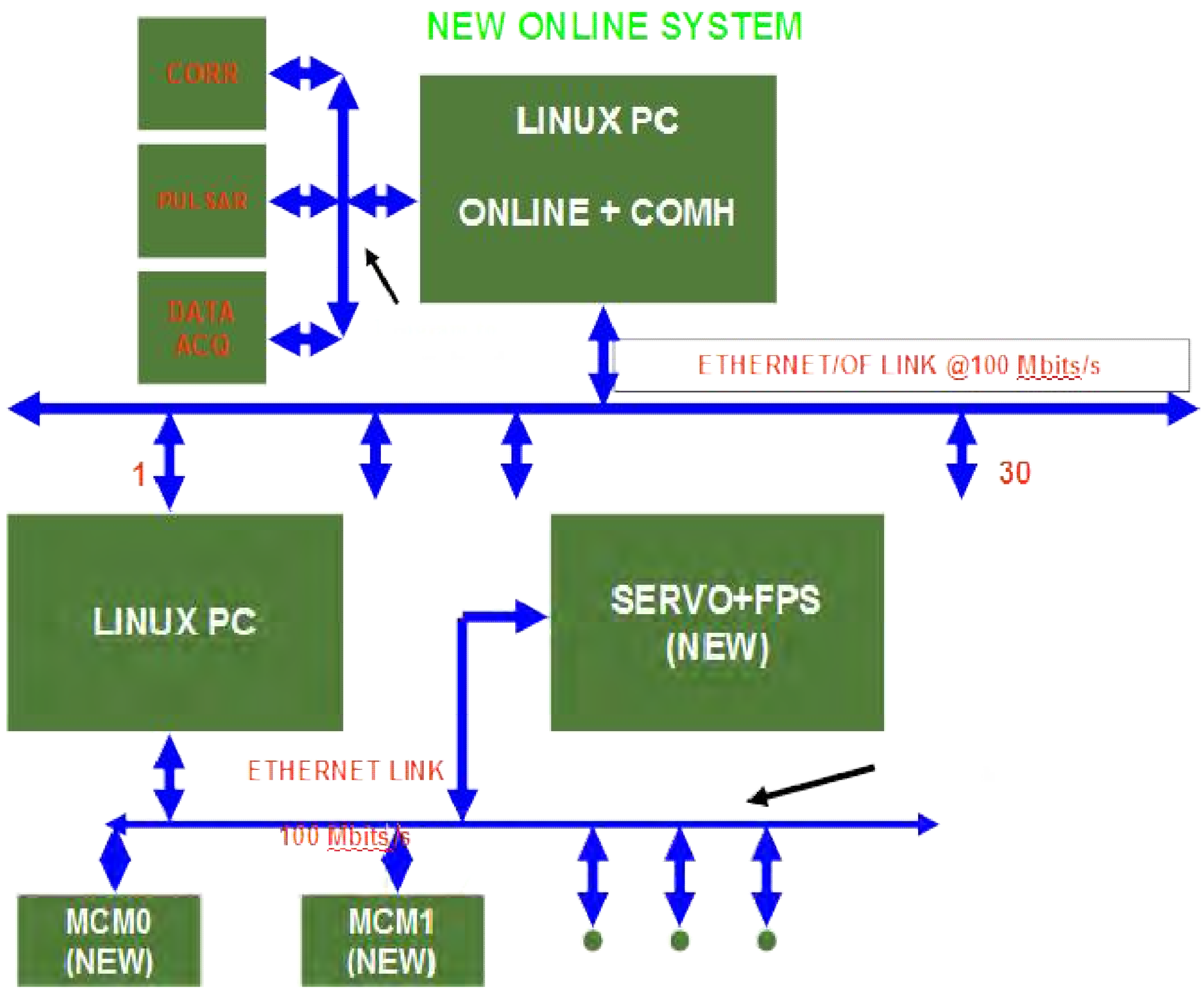
Multi-core CPU

GWB: Correlator Room

GMRT Wideband Digital Backend for processing 32 antenna (dual polarization) 400 MHz bandwidth using FPGAs and GPUs

Upgraded Telemetry System

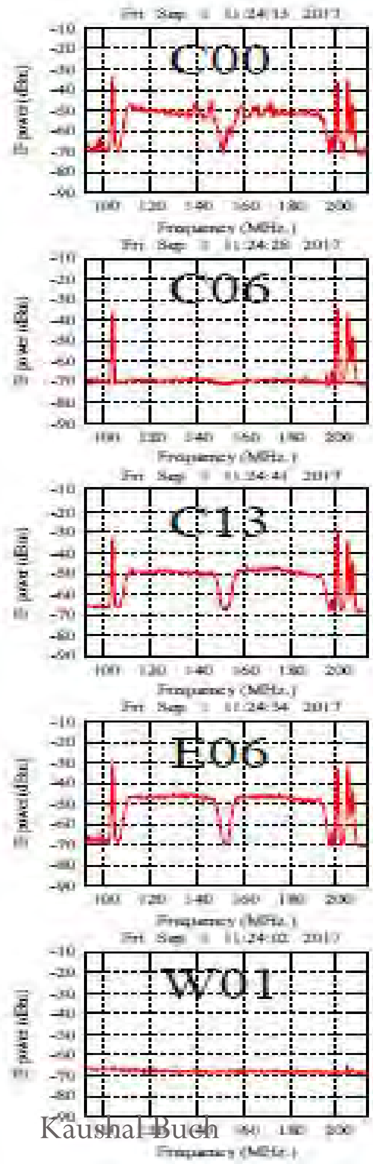
- New station control computer
- Ethernet link from central station to each antenna, via the optical fiber
- New generation monitor and control modules using modern microcontroller
- Improved control room software running on Linux platform



GMRT Control Room

Central location for monitoring and controlling antennas and subsystems, coordinating the observations
Operational: 24x7x365

Diagnostic tools



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

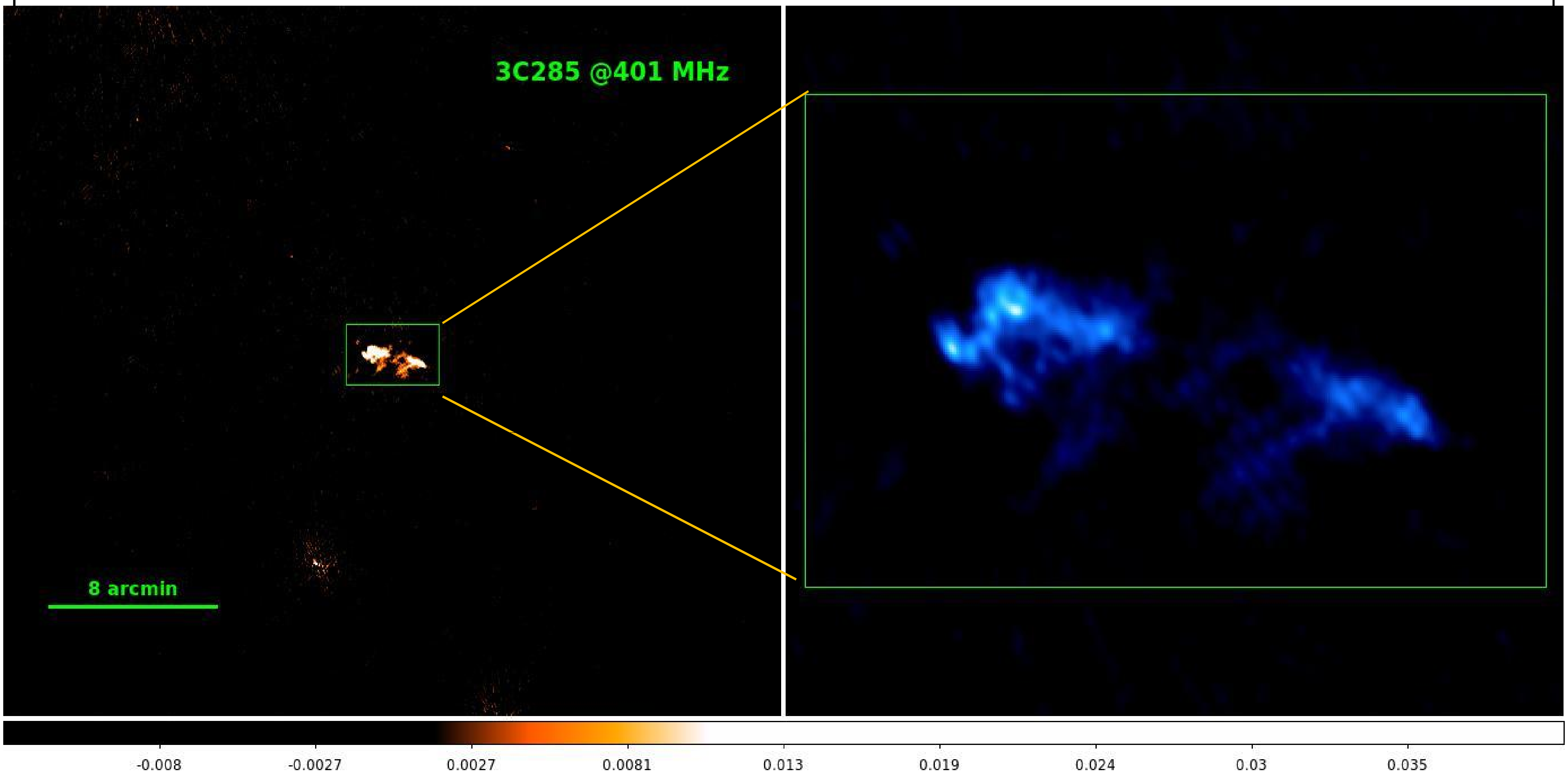
Digital Backend
Corr band shapes and Project State
Fringe Status (rantsol amp-gain)
Gain-amplitude and Phase (rantsol)
Visibility - amplitude and phase (xtract)
Correlator Room Temperature

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

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

Results from the uGMRT



3C285 observed for about 3 hours using 11 broadband antennas, 300 MHz RF, 200 MHz bandwidth, 2048 spectral channels. RMS noise: 0.6 mJy, ~5.4 arcsec resolution

Image Courtesy: Dharam Vir Lal

GMRT versus Upgraded GMRT

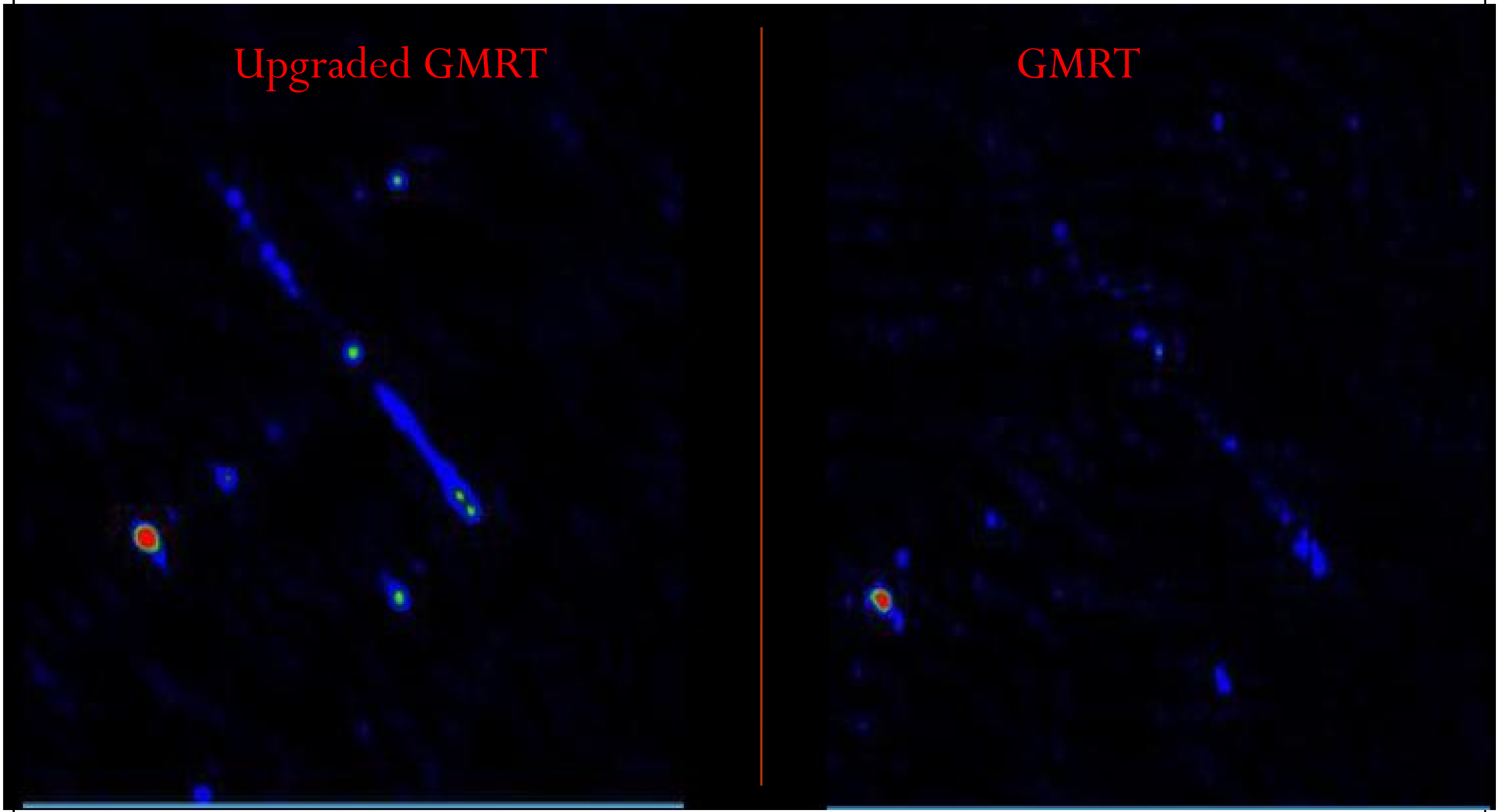
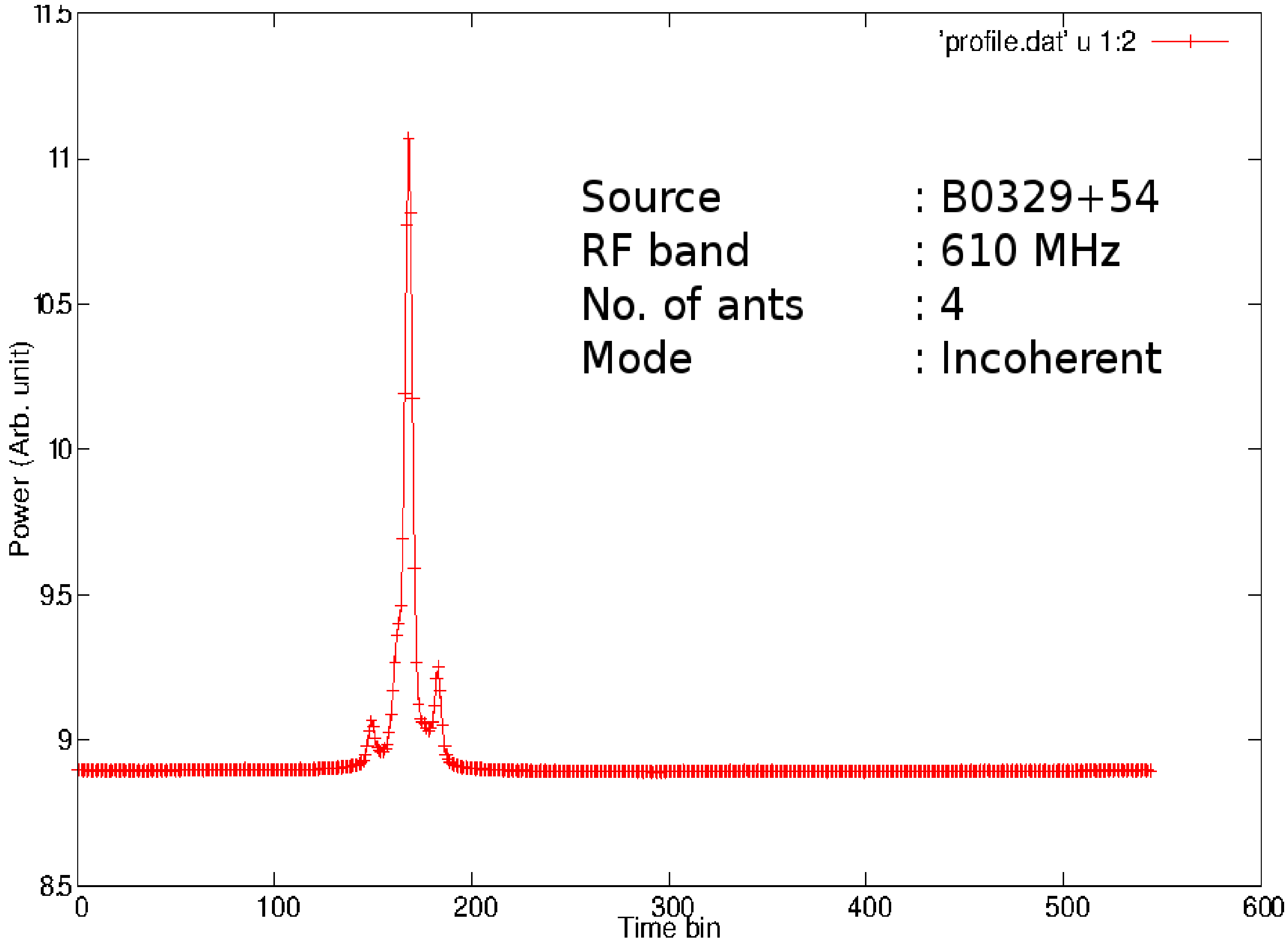


Image Courtesy: Ishwarchandra C.H. & Binny Sebastian

Improvement by a factor of 2 to 3 in the sensitivity

Pulsar Observation using uGMRT



Biggest Challenge for Contemporary Radio Telescopes

Radio Frequency Interference

- Man-made electromagnetic radiation from electronic/electrical equipments
- RFI is typically 30 to 40 dB (i.e. 1000 to 10000 times) stronger
- RFI has a non-random distribution
- RFI mitigation – very important problem (challenge) for contemporary radio telescopes
- Mitigation by creating radio quietness around the array, controlling self-generated RFI and removing interference in real-time and offline in the receiver system
- No escape from RFI on the surface of the Earth!

Typical Sources of RFI at GMRT

Narrowband RFI

Image Courtesy: Wikipedia

Sparking

Broadband RFI

Narrowband RFI

GMRT and surroundings

Nearest village: ~1 km., ~10,000 people

Very Large Array and surroundings

Very low population density – New Mexico USA

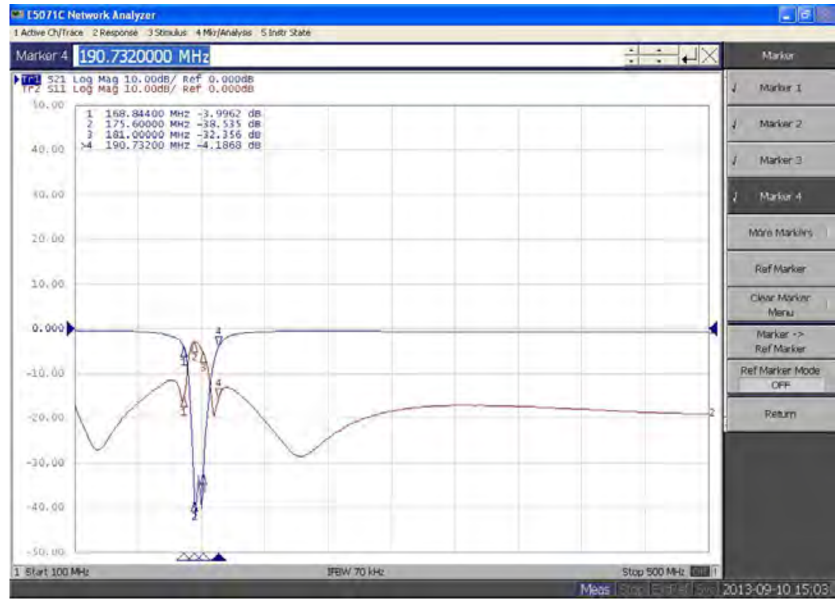
MeerKAT/SKA and surroundings

Extremely low population density – South African desert

Zoomed Image of GMRT Central Square

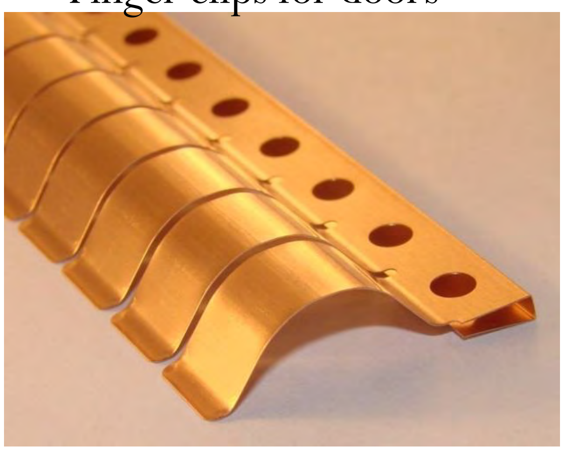
Fighting RFI

Notch filter for TV signal



Power line filter

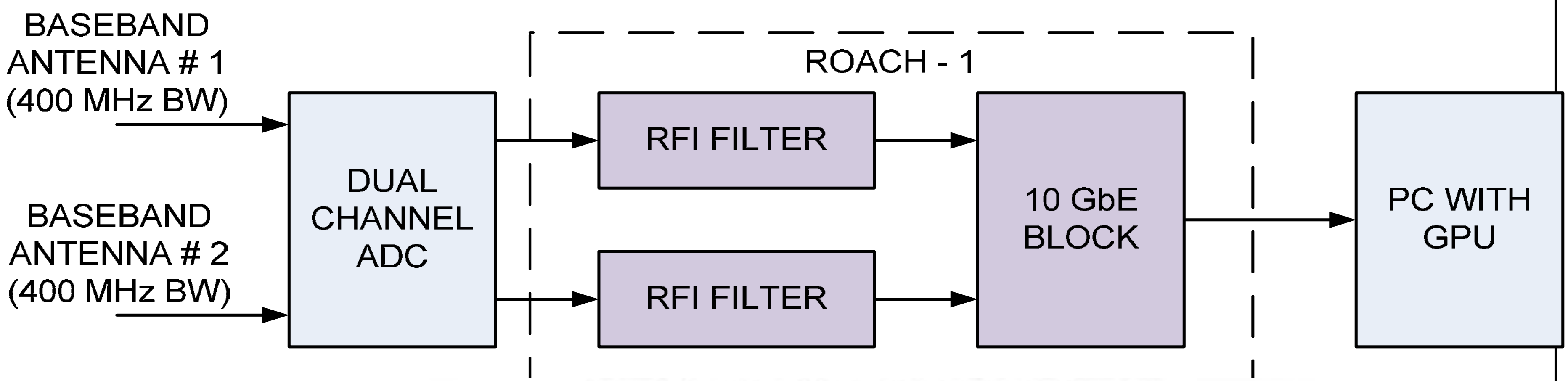
Finger clips for doors

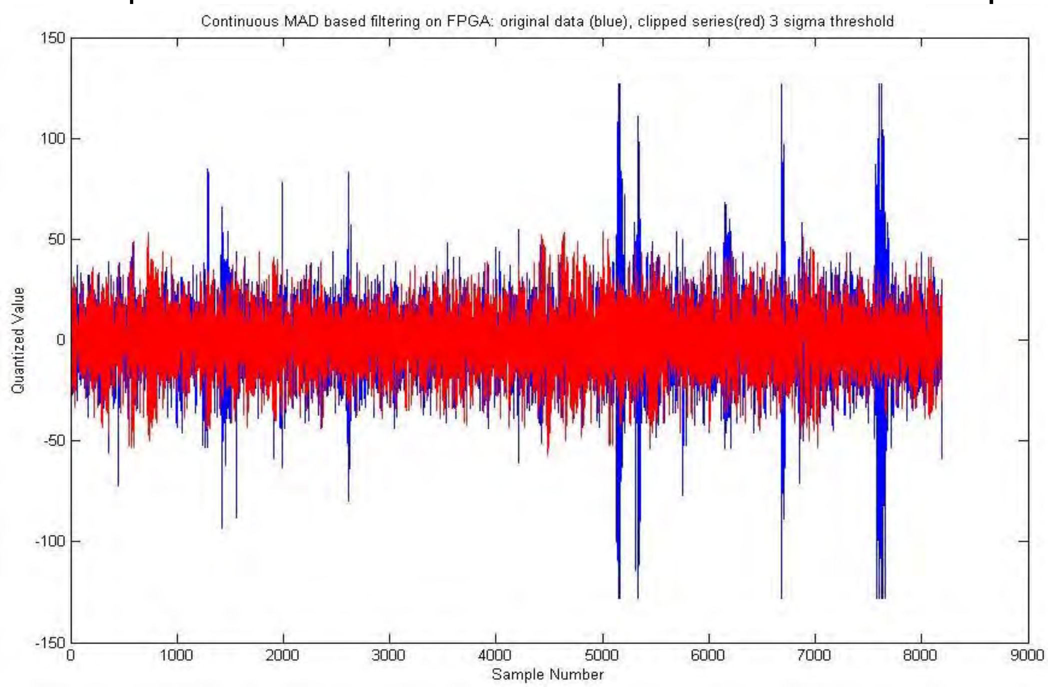


Monitoring sources of RFI

Image Courtesy: RFI / OFC Group

Fighting RFI in the digital domain





The Expanded GMRT (eGMRT)

Photo: B. Premkumar

Motivation & Proposal

1. Installing low-frequency focal plane arrays (FPA).
2. A factor of 5 increase in the angular resolution, by installing new antennas on baselines extending to 100 km.
3. An improved sensitivity to extended radio emission, by installing new antennas on very short baselines, at spacing much lower than 1 km.

- ❑ Prototyping a beam-former and a signal transport system for the FPA
- ❑ A land survey to determine possible antenna sites for the putative long baseline
- ❑ Optimal antenna configuration and the number of new antennas that would be needed to achieve the science goals for both the long- and short-baseline options.

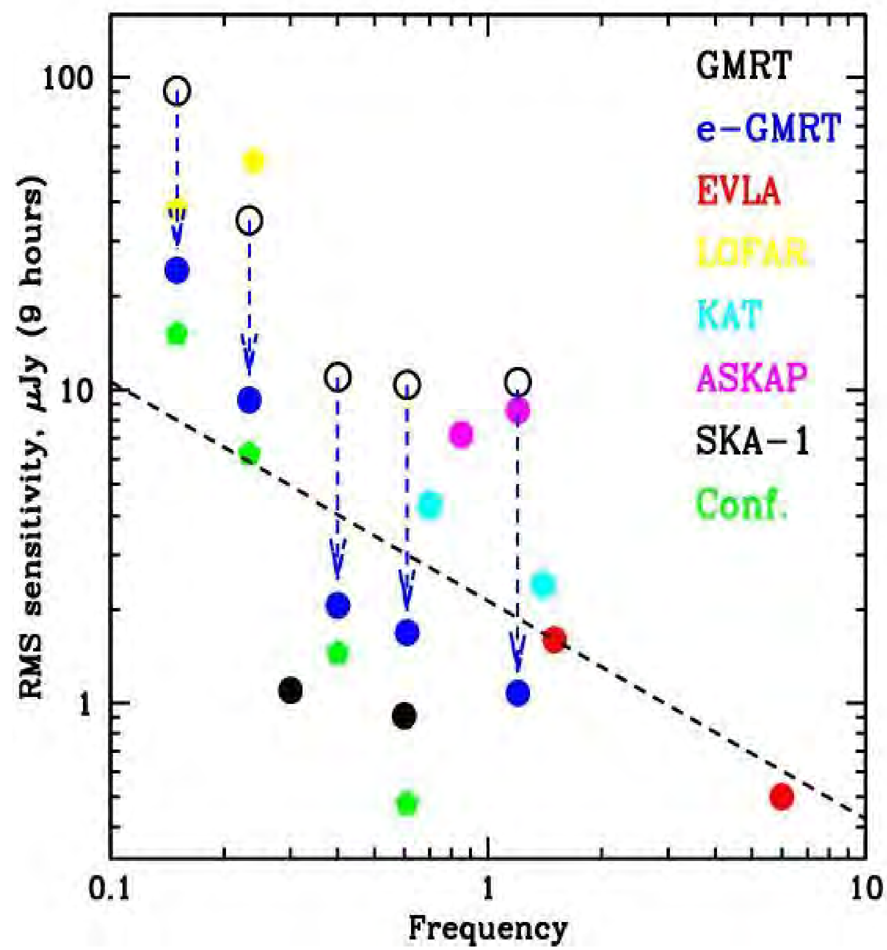


Image Courtesy: Nissim Kanekar

Summary

- GMRT has been operational since last ~15 years
- One of most sensitive (and busy) radio telescopes in the world at metre wavelengths
- A lot of diverse engineering involved – Mechanical, Electrical, Civil and almost all the major branches of Electronics
- Building, maintaining and upgrading is a coordinated effort of a huge team (with engineering, scientific and academic background)
- Upgraded GMRT uses latest technology at every level – will enable better science
- Looking in to the future – the Expanded GMRT proposal looks very promising, will help maintain GMRT's global status

Suggested Reading (GMRT)

- Low Frequency Radio Astronomy – NCRA-TIFR (Editors: Chengalur, Gupta and Dwarkanath) http://gmrt.ncra.tifr.res.in/gmrt_hpage/Users/doc/WEBLF/LFRA/index.html

- "Techniques of Radio Astronomy and GMRT" - Lecture Series conducted from February – May 2016 at GMRT http://gmrt.ncra.tifr.res.in/gmrt_hpage/Users/doc/Lectures/lectures.html (This link is accessible only from NCRA-GMRT)


Thank
You!