Giant Metrewave Radio Telescope (GMRT) - Introduction, Current System & uGMRT

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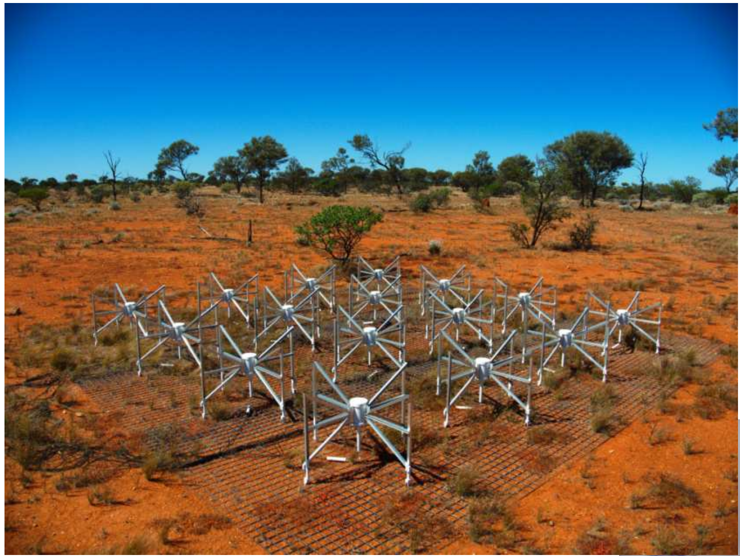
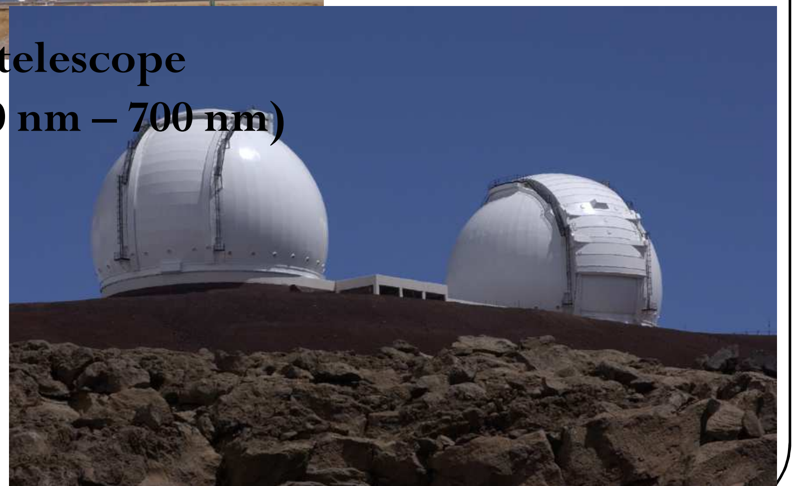


Low frequency dipole array (λ ~ 100m– 2 m)

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

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

Sub-millimeter wavelength array (λ ~ 1 cm – 10 mm)



Optical telescope (λ ~ 400 nm – 700 nm)

Image Courtesy: Wikipedia

Single Dish Radio Telescopes

Interferometric Radio Array

•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.

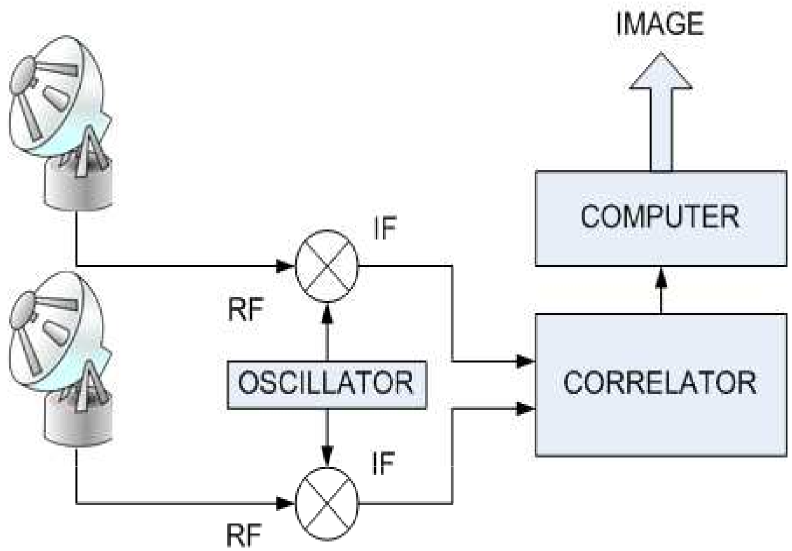
•Signals from such array telescopes are combined and processed in a particular fashion to generate a map of the source structure : EARTH ROTATION APERTURE SYNTHESIS

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

Image Courtesy: NRAO

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.

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 metres diameter, operating at metre wavelengths -- the largest in the world at these frequencies

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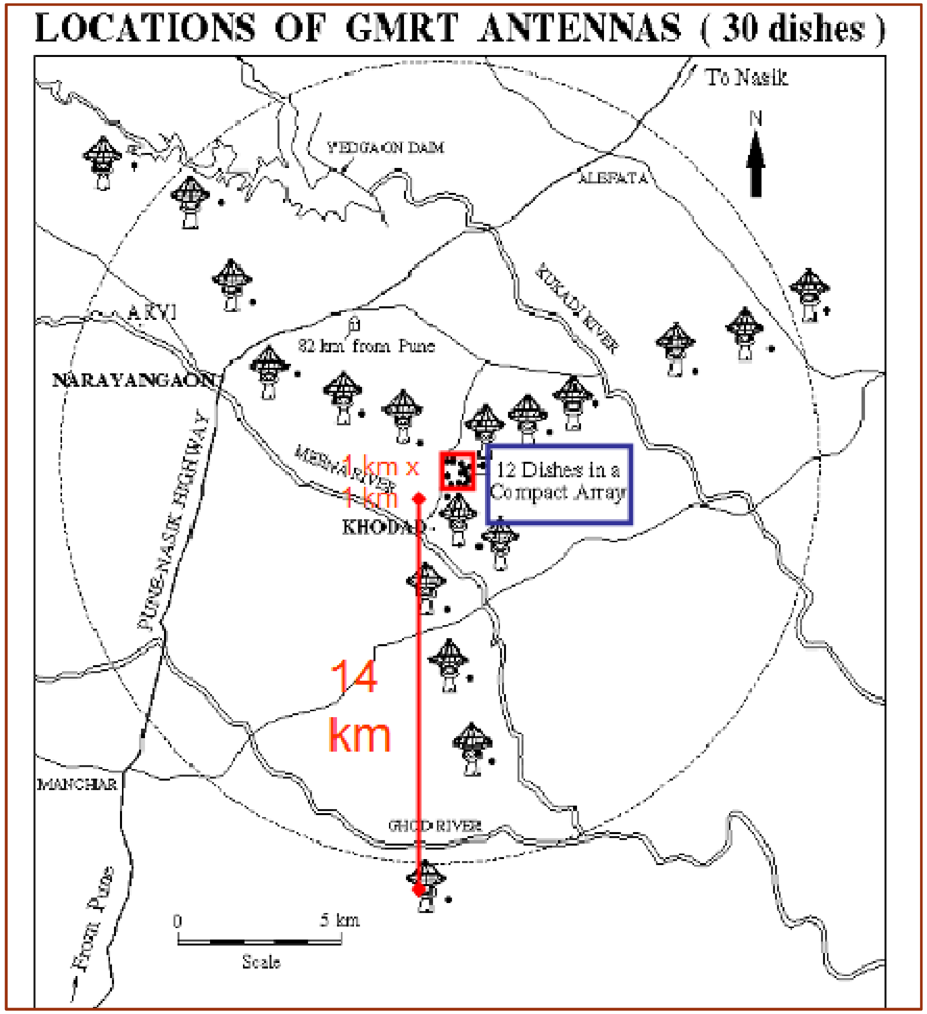
Overview of the GMRT

❑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:
130-170 MHz
225-245 MHz
300-360 MHz
580-660 MHz
1000-1450 MHz
max instantaneous processing BW = 32 MHz

❑Effective collecting area (2-3% of SKA) :
30,000 sq m at lower frequencies
20,000 sq m at highest frequencies

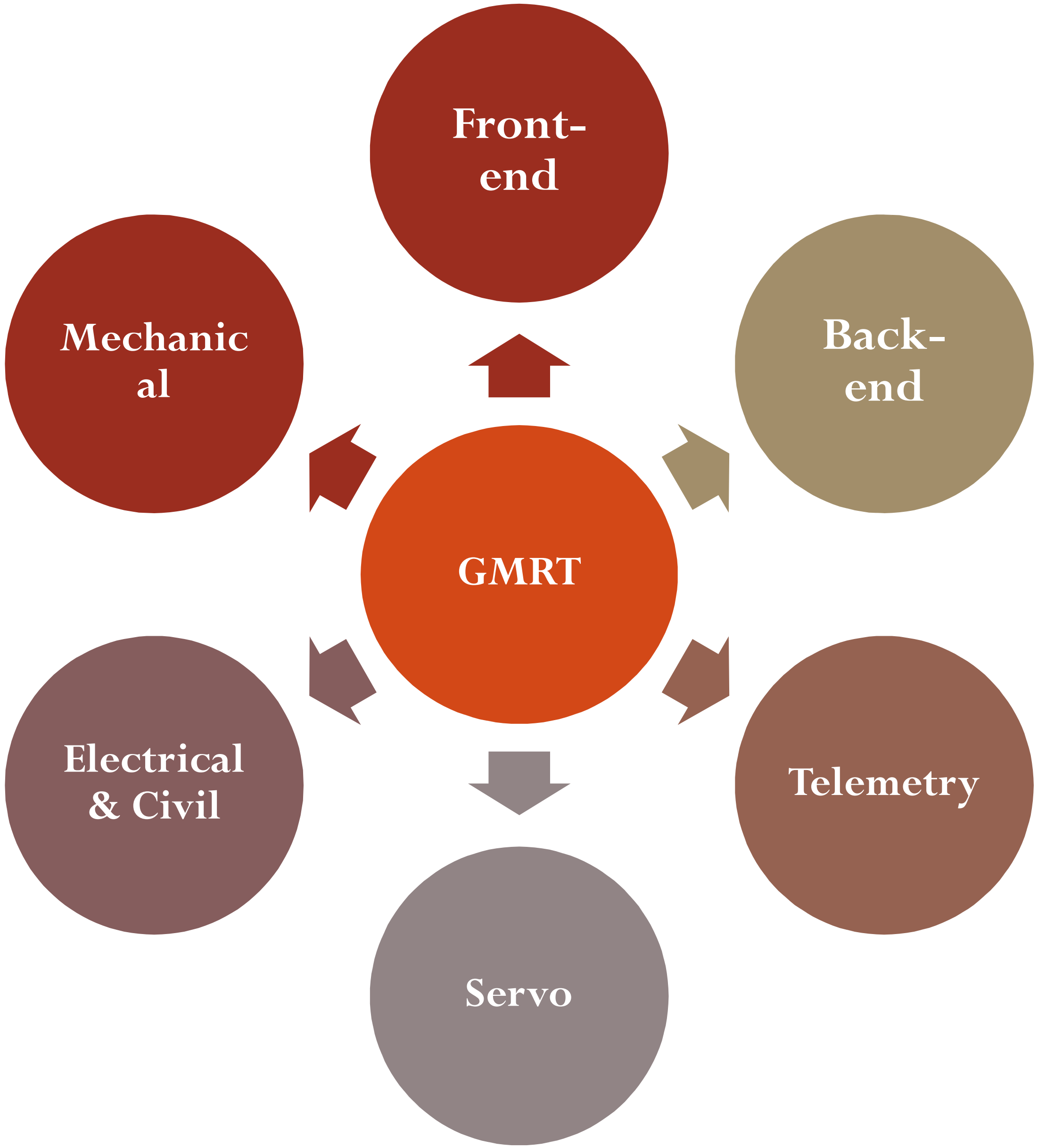
❑Supports 2 modes of operation :
Interferometry, aperture synthesis
Array mode (incoherent & coherent)



Aerial View of Central Square Antennas

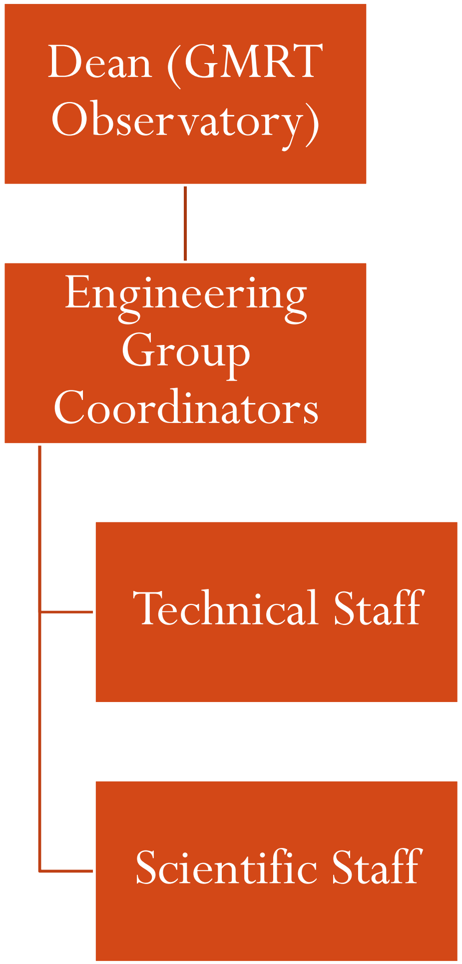
GMRT antenna: Construction Stages

GMRT: Engineering Groups



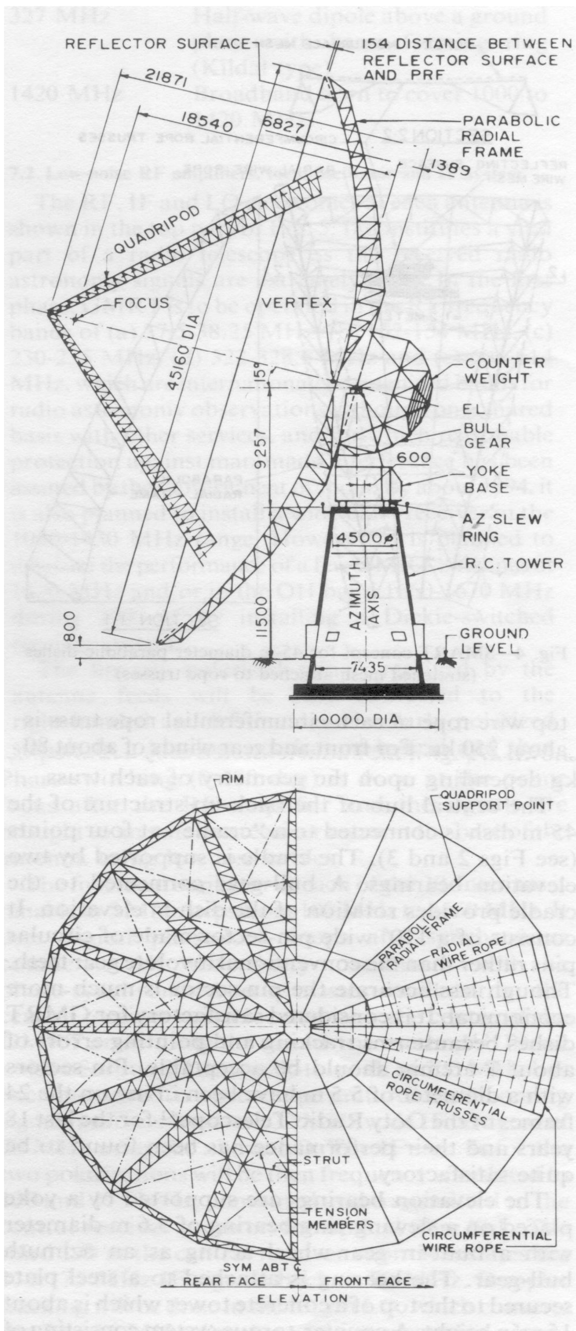
Organizational Hierarchy (Scientific & Technical)

- Total scientific and technical staff strength : 100 +
- Six Group Coordinators
- Scientific and Technical staff consists of Engineers, Technical Assistants, Lab Assistants, Scientific Officers and Telescope Operators.
- Short term positions – Visiting Engineer, Trainee Engineer, STP students



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 !

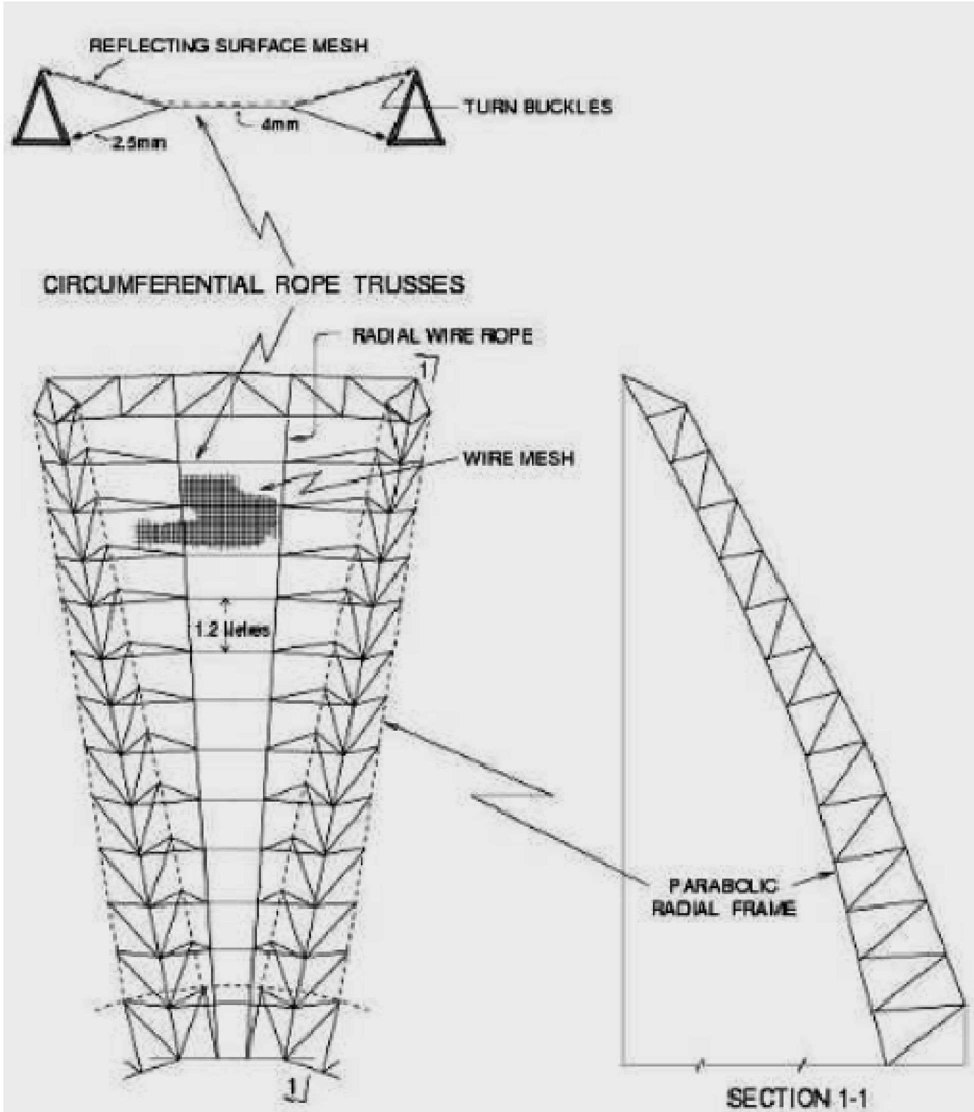
The “Invisible” Reflecting Surface

•7% solidity with 0.55 mm diameter 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 concept to form the parabola.

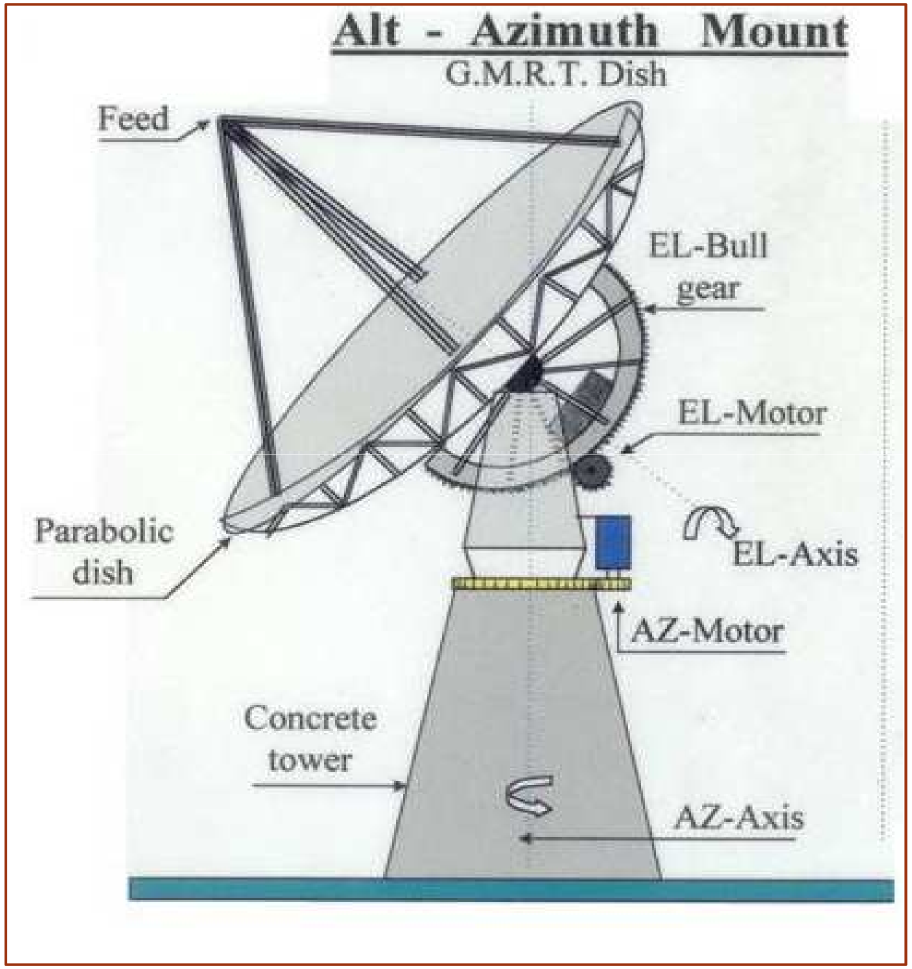
The SMART concept

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

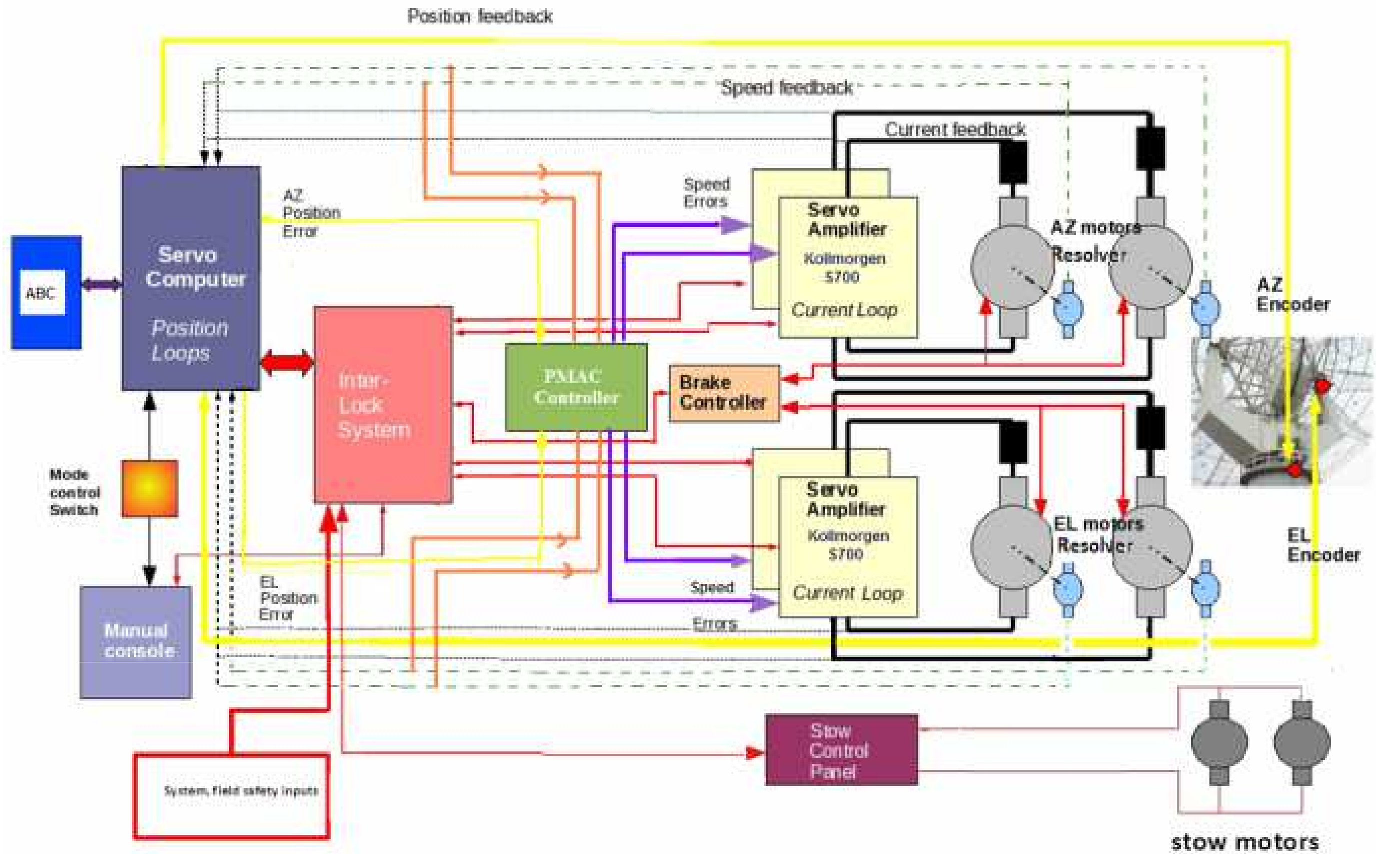


GMRT Servo System

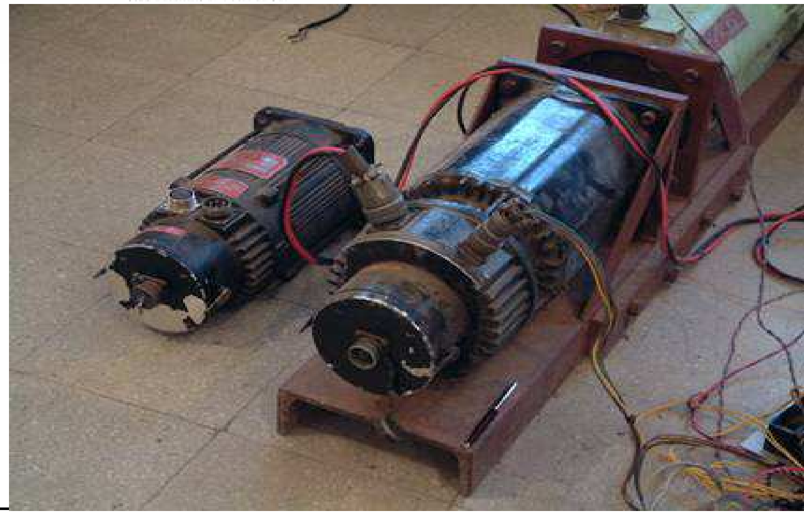
- Points the antennas to any part of the sky and tracks a source
- Being upgraded to brushless DC motors from brushed PMDC motors
- ± 270° movement around Az axis and 17 to 110° above horizon about elevation axis
- Slew speed of 30°/ min in Az axis and 20°/ min in El axis
- RMS tracking and Pointing accuracy: 1 arcmin at 20 kmph wind speed,



Servo Controller



Pair of 6 HP DC servo motors in a counter-torque system for Azimuth and Elevation axes



Feed Positioning System

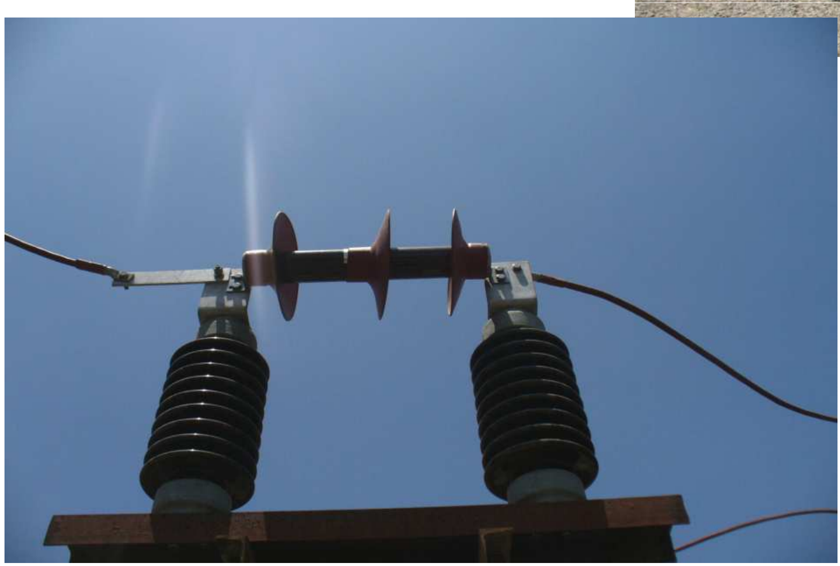
- Position Loop Control system with Incremental encoder for position feedback
- 8051 Microcontroller based system
- 0.5 hp DC servomotor
- Positioning Accuracy of 6' arc and Resolution of 1.05' arc
- Operating RF Frequency band of GMRT can be changed in about ONE MINUTE

Electrical Systems

•Power back-up (UPS and DG 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

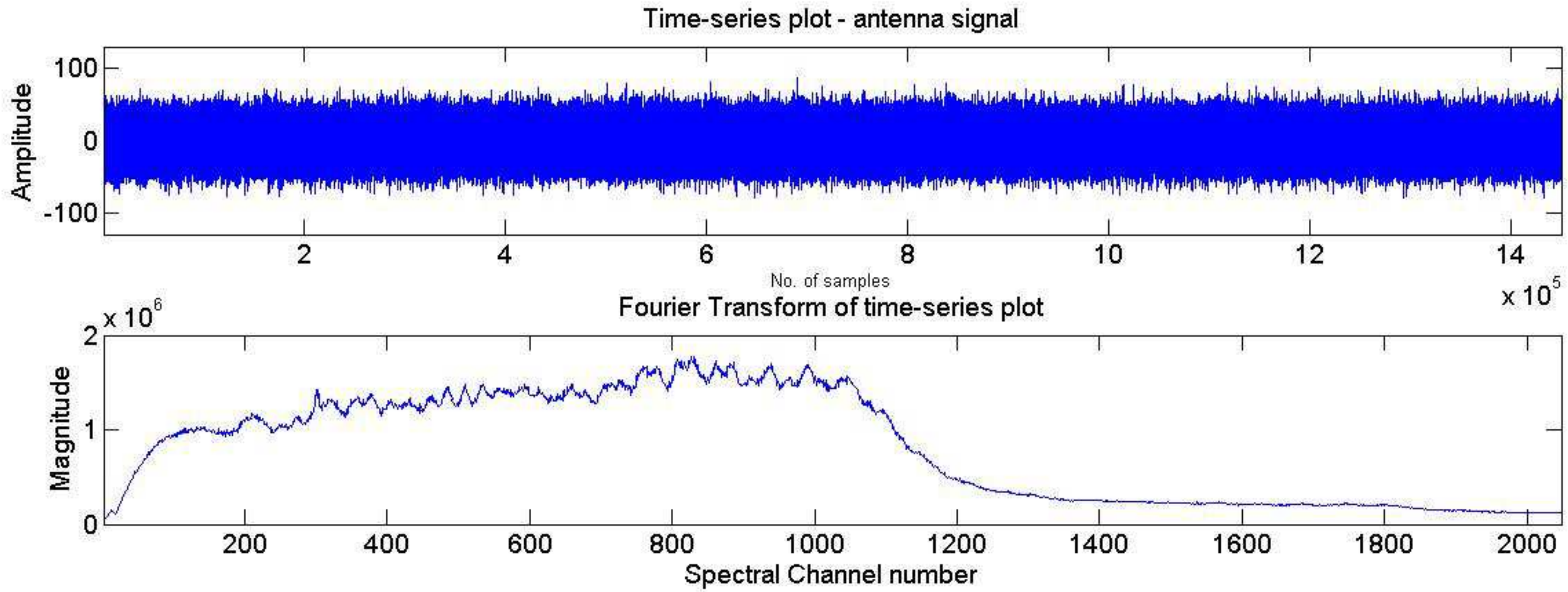
Radio Telescope Receiver

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 !*

Astronomical Signal Characteristics

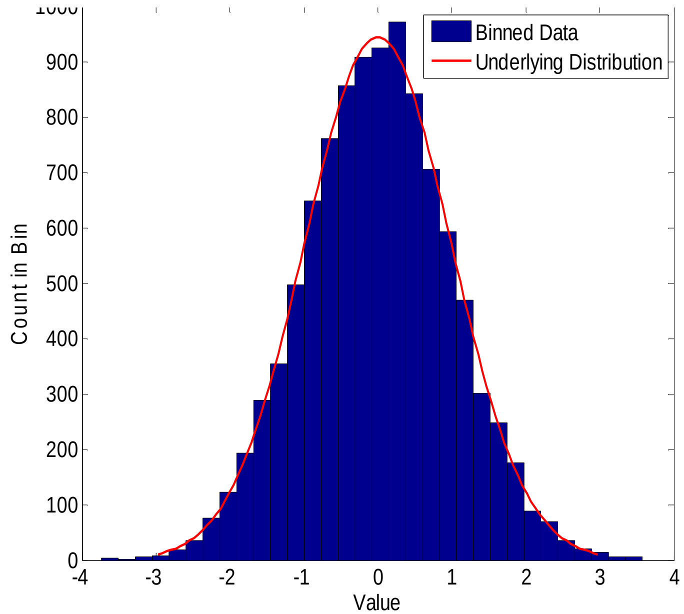


- Zero mean Gaussian distributed random signal

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

- Noise power measured over bandwidth

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



GMRT Receiver: Basic Block Diagram

•Each antenna has five wave bands, each having two polarization.

•Multi-frequency receiver uses low noise amplifiers and post amplification at the prime focus.

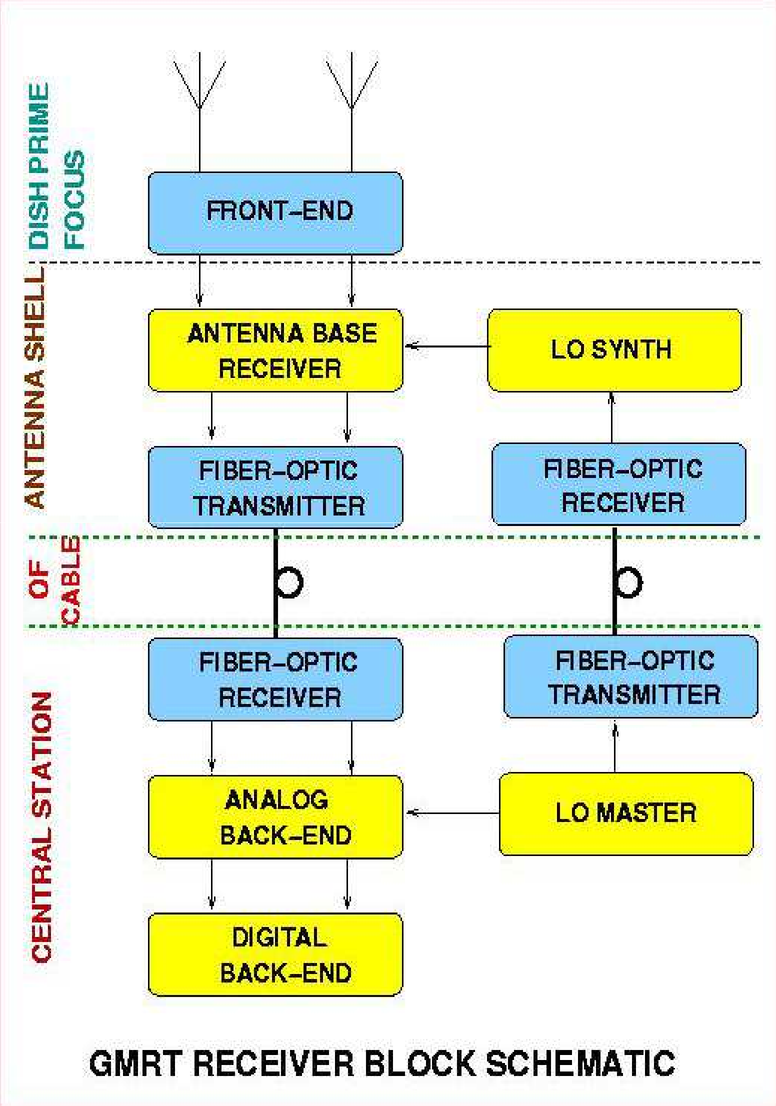
•Superheterodyne receiver: Converts RF to IF using phase coherent oscillators – locked to stable GPS disciplined Rubidium clock reference.

•IF signals transported to the Central Station using fiber optic cables.

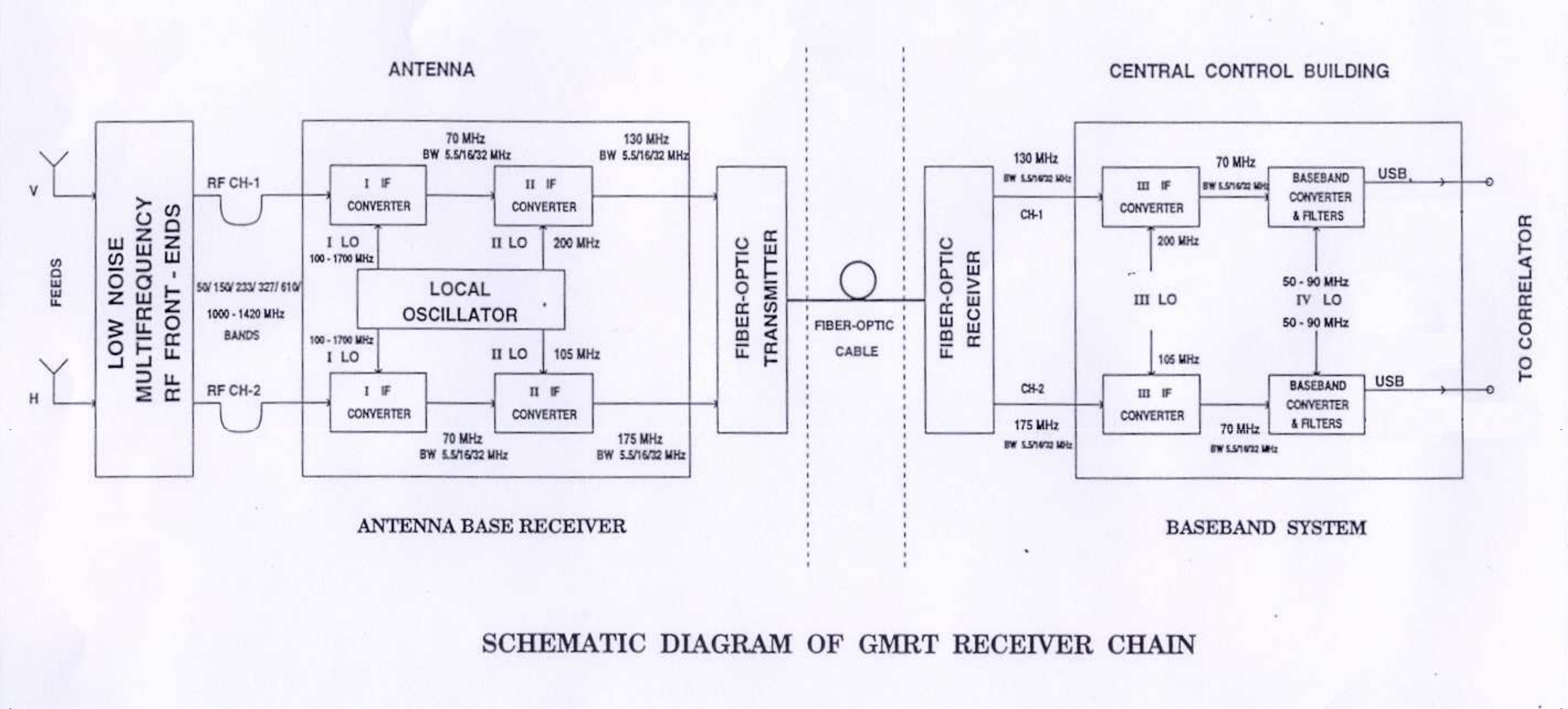
•IF signals conditioned and down-converted to base-band frequency.

•Signals are digitized and processed for computing visibilities, beam outputs and power spectra.

•Highly configurable receiver chain fully controllable from central station through telemetry system



Simplified Schematic of GMRT Receiver



- The Forward Broadcast optical fiber link sets the parameters and transfers LO Reference
- All LOs phase locked to a common stable frequency reference

Feeds of the GMRT

- Dual Polarized Prime-focus feeds to cover the six bands of operation of GMRT
- Dual Frequency operation in 233 and 610 MHz bands
- Matched E and H plane patterns with ~10 dB edge-taper and ~20% bandwidth

Feeds convert EM energy to electrical signal

Operating Frequencies of the GMRT

40 – 60 MHz	300 – 360 MHz
120 – 180 MHz	580 – 650 MHz
225 – 245 MHz	1000 – 1430 MHz

325 MHz

Antenna primary feeds
are
placed on
a rotating turret
near the
focus of the dish

235 / 610 MHz

150 MHz

GMRT Front-end

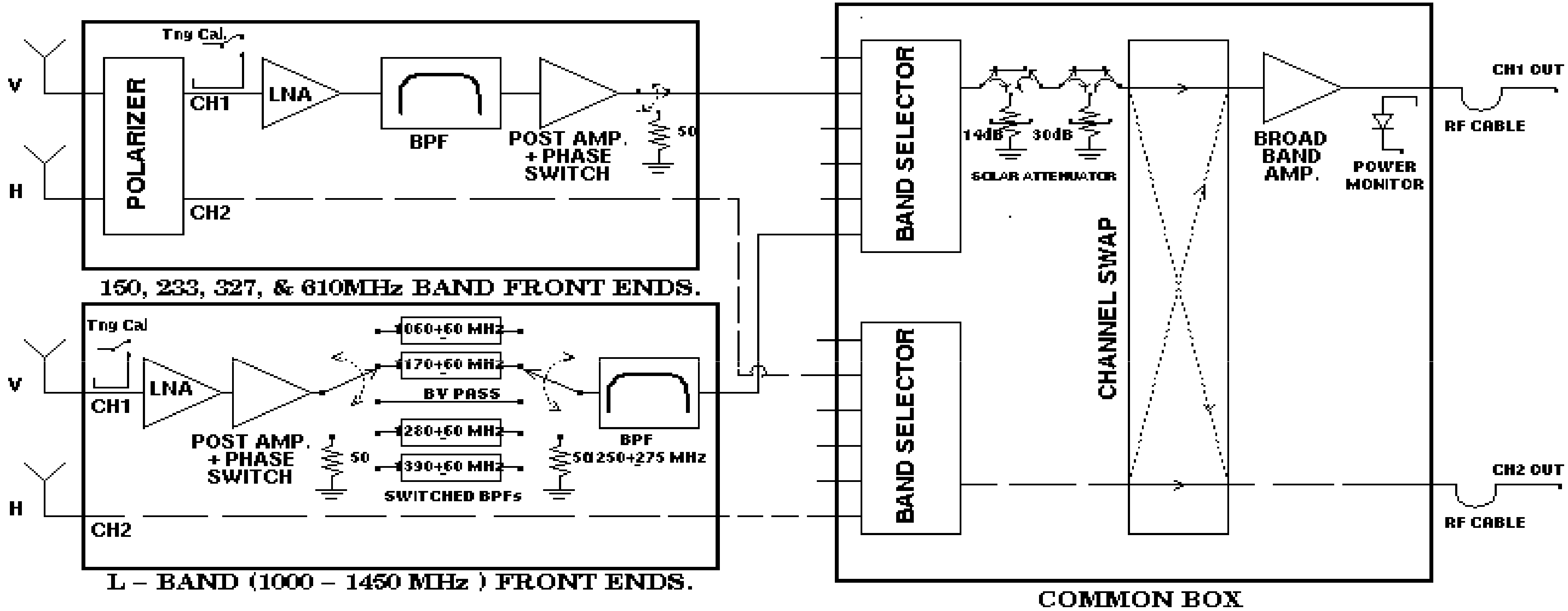


Fig : MULTIFREQUENCY RF FRONT – ENDS FOR GMRT.

~60 dB gain provided by the front end system

Receiver temperature varies from 260 K (150 MHz) to 45 K (1400 MHz)

Installing and Servicing

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

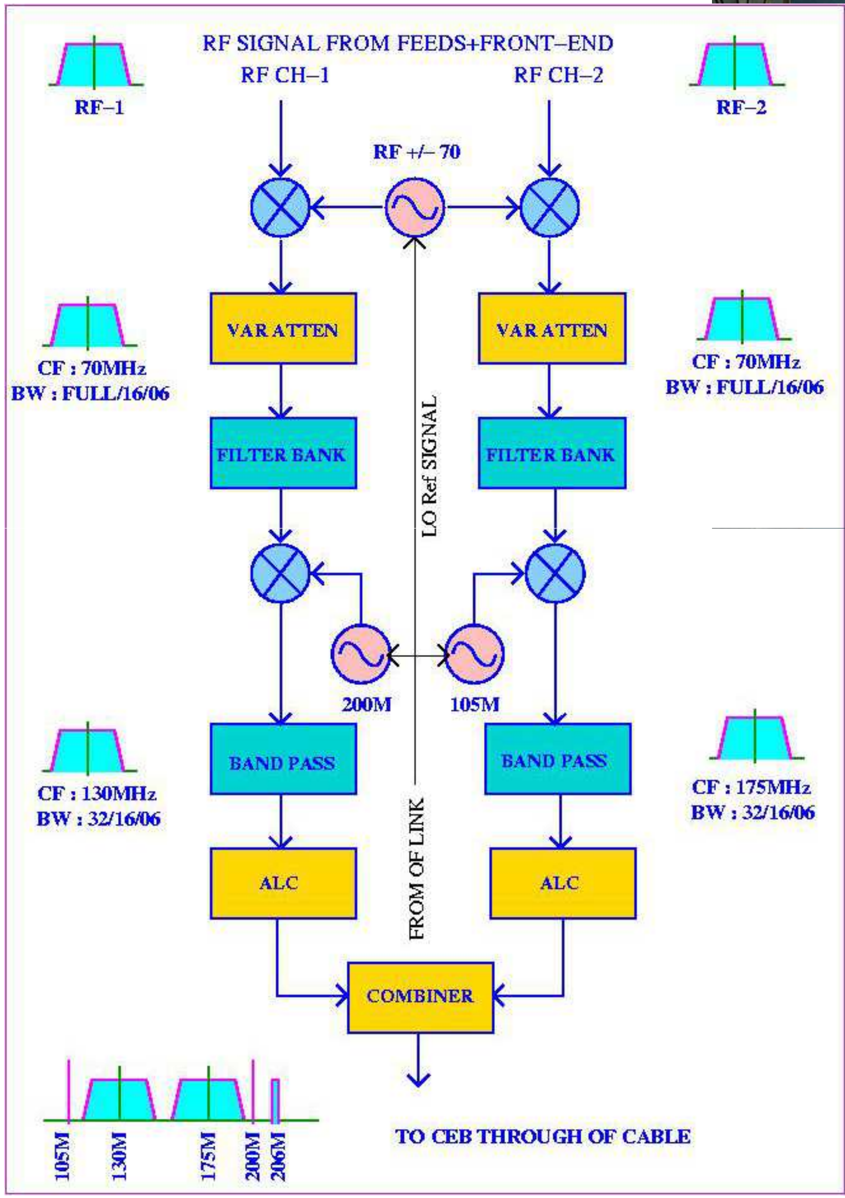
Signal Processing in IF systems

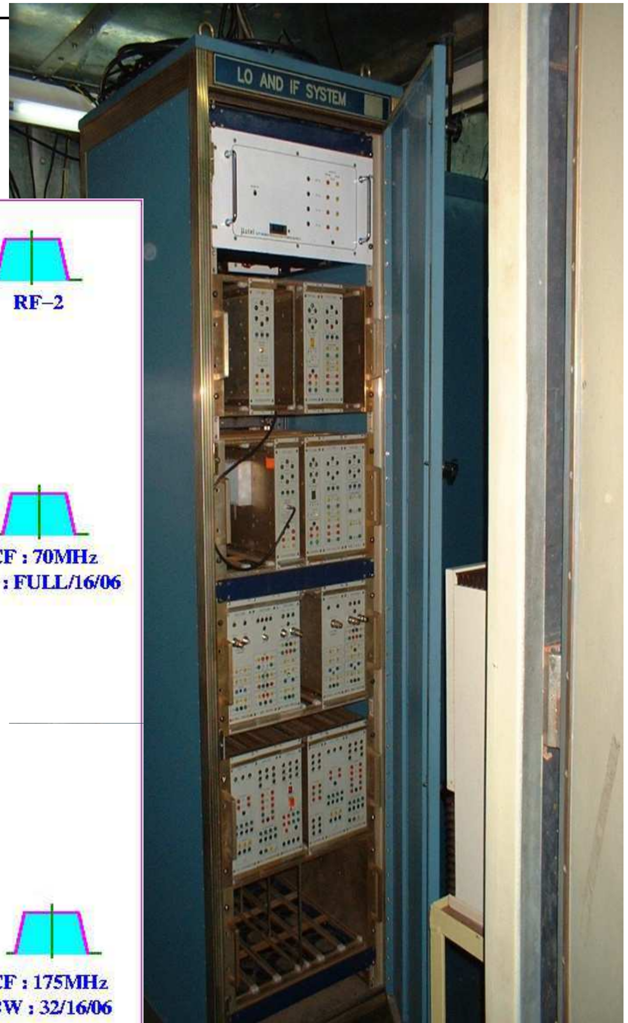
- Conversion of RF to common IF of 70 MHz

- SAW (Surface Acoustic Wave) filters used for band shaping of signals at 70 MHz

- IF signals are up-converted to 130 MHz and 175 MHz for Ch-1 and 2 respectively for transmission over optical fiber link

- High dynamic range ALC circuits are used before the signal is given to OF Transmitter to maintain a constant power.

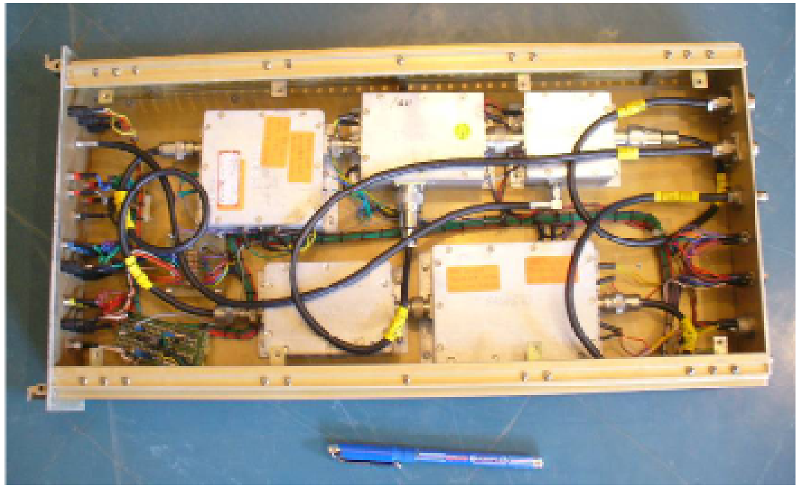




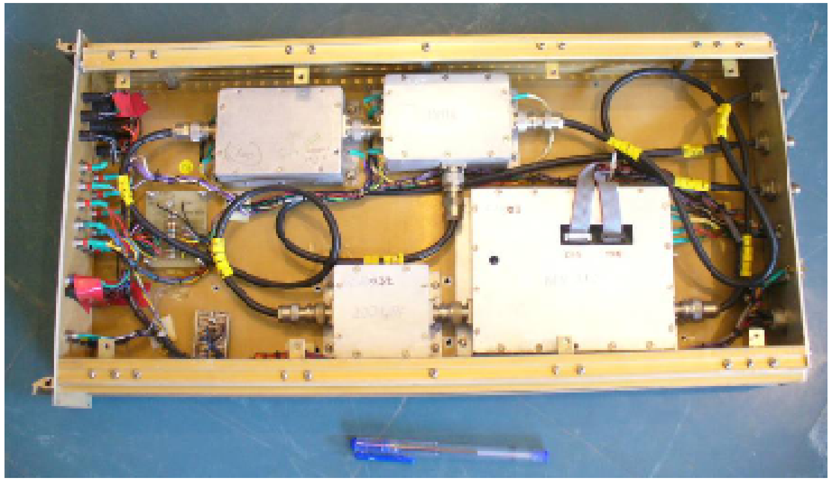
IF system installation at antenna base

Analog Receiver at Antenna - *Main Plug in Units*

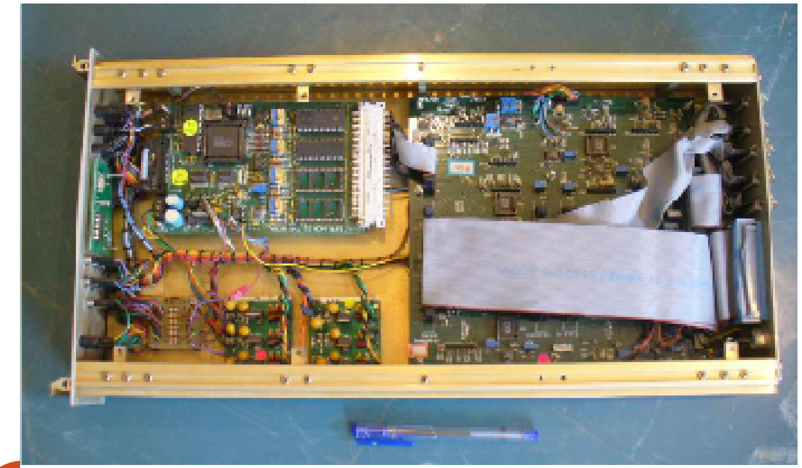
RF to 70 MHz Converter



70 to 130/175 MHz Converter



Control Unit



Monitor Unit

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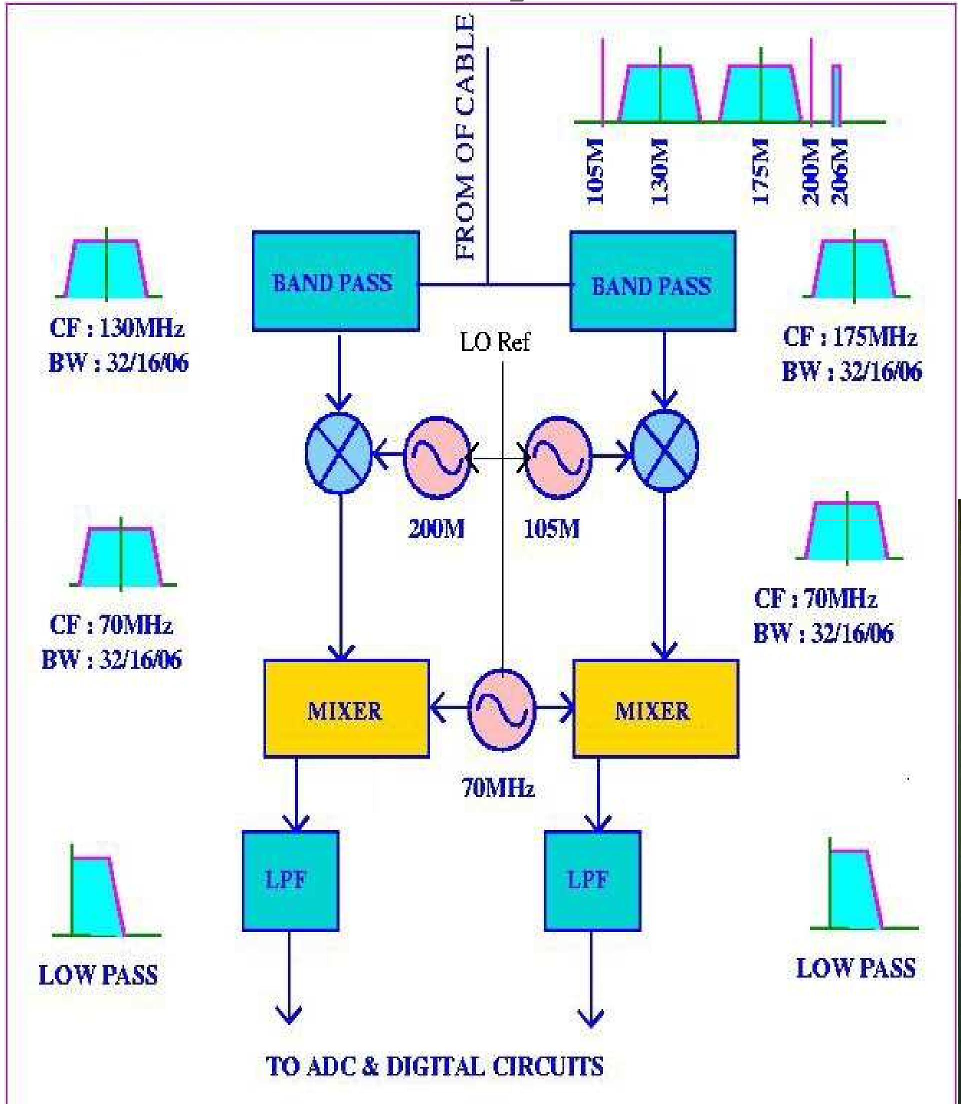
Signal Processing in Base-band System



- Converts IF Frequency signals to baseband frequency of 32 MHz.
- 30 to 1 monitoring at Central station for "live" checking of quality of signal from antennas.

Signal Processing Preliminaries - 1

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

$$f_s = 2f_m$$

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

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

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

Signal Processing Preliminaries - 2

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

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

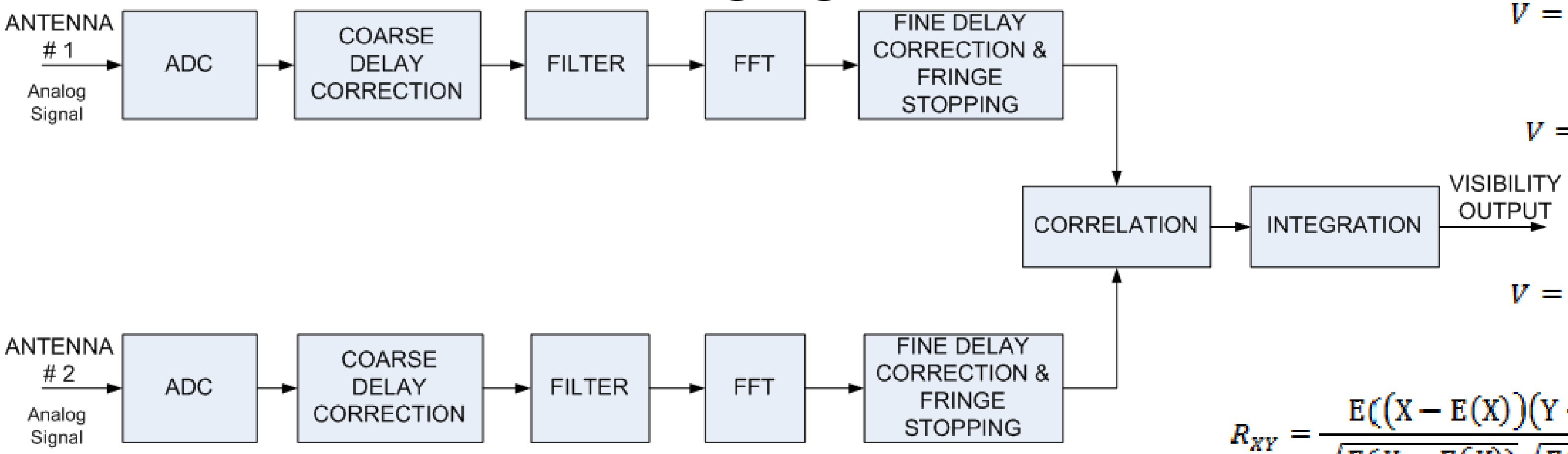
- Convolution in time domain is multiplication in the frequency domain

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

- Correlation is a measure of similarity between the two signals and it varies as a function of the lag between them.
  - Even function, peaks at zero lag, reduces linearly as a function of lag
  - Shows the degree of similarity between the signals
  - Correlated (1), Uncorrelated (0), Partially correlated (0<R<1), Anti-correlated (-1)

Digital Backend Signal Processing

Imaging Mode



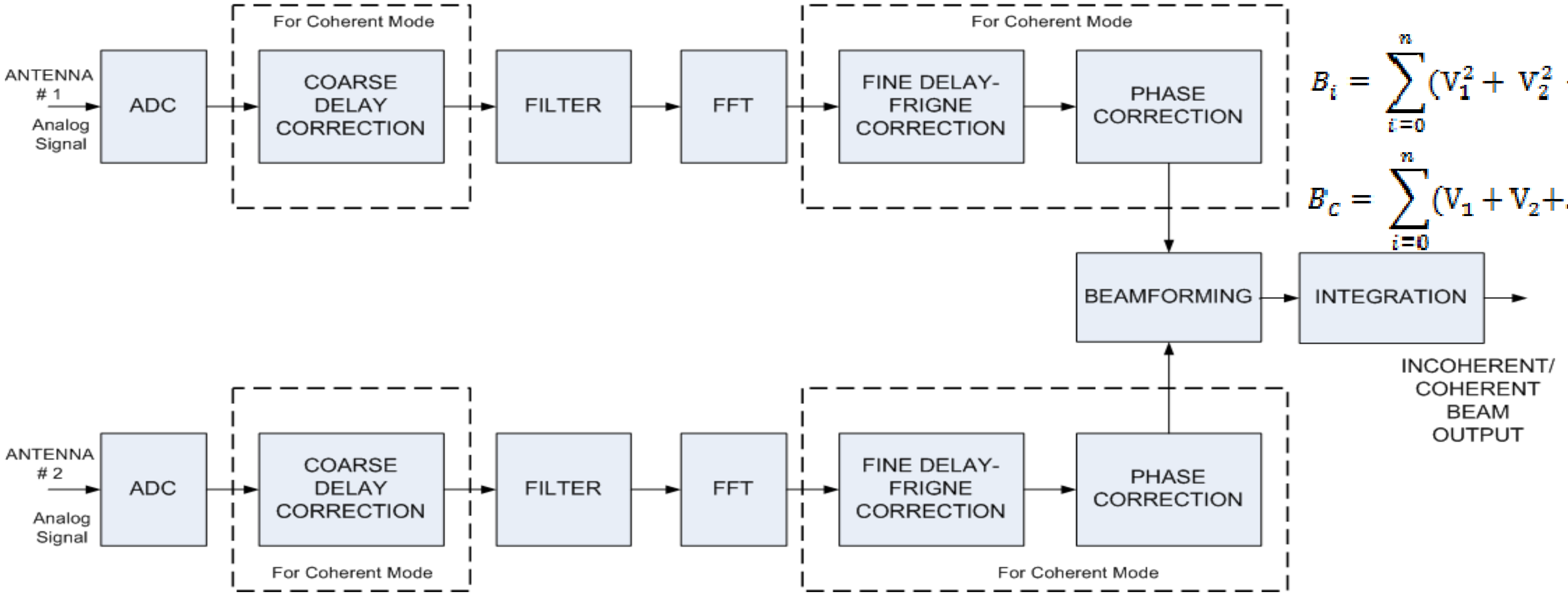
$$V = \sum_{i=0}^{n} V_1 V_1^*$$

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

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

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

Beam Mode



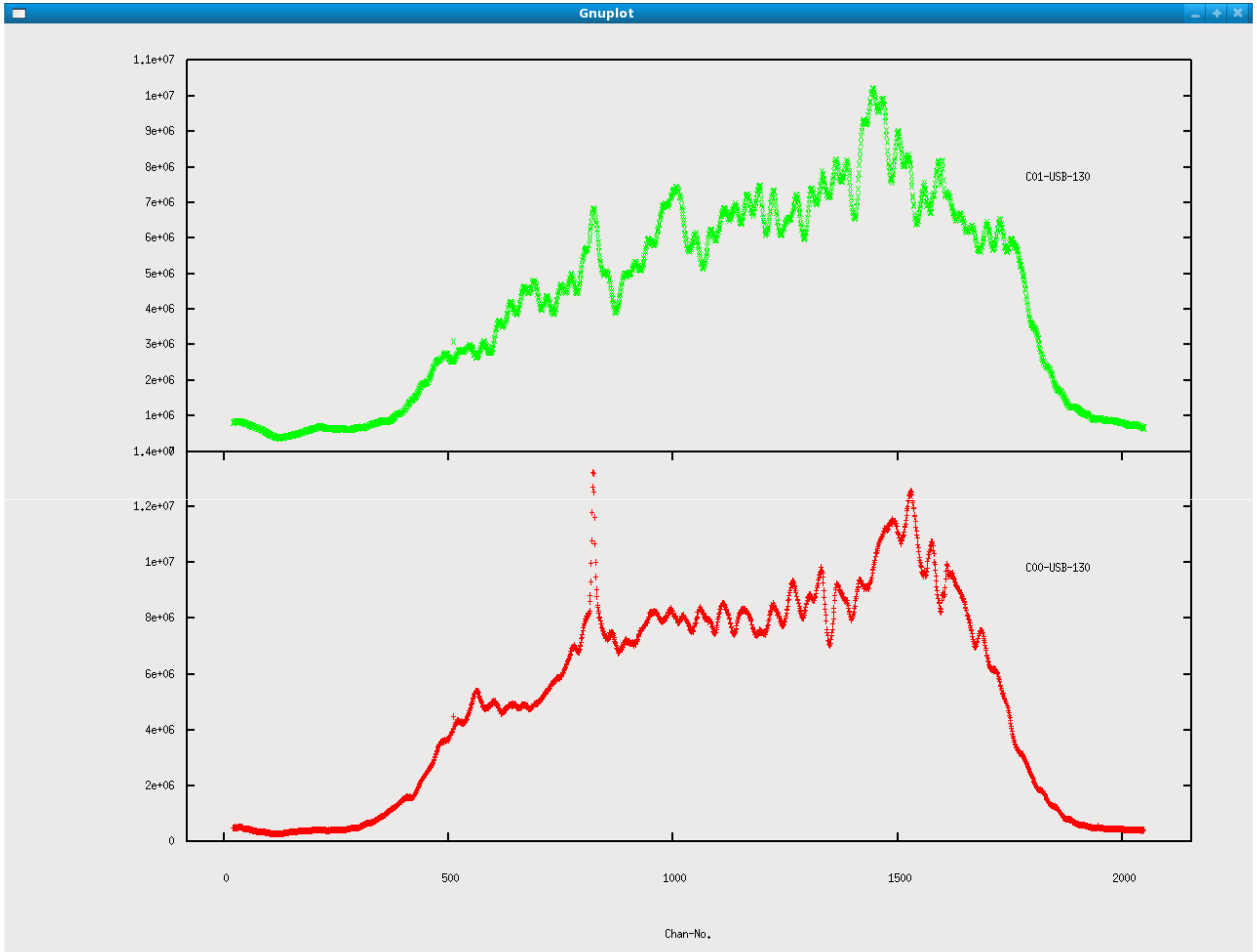
$$B_i = \sum_{i=0}^{n} (V_1^2 + V_2^2 + \ldots + V_N^2)$$

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

GMRT Software Backend (GSB)

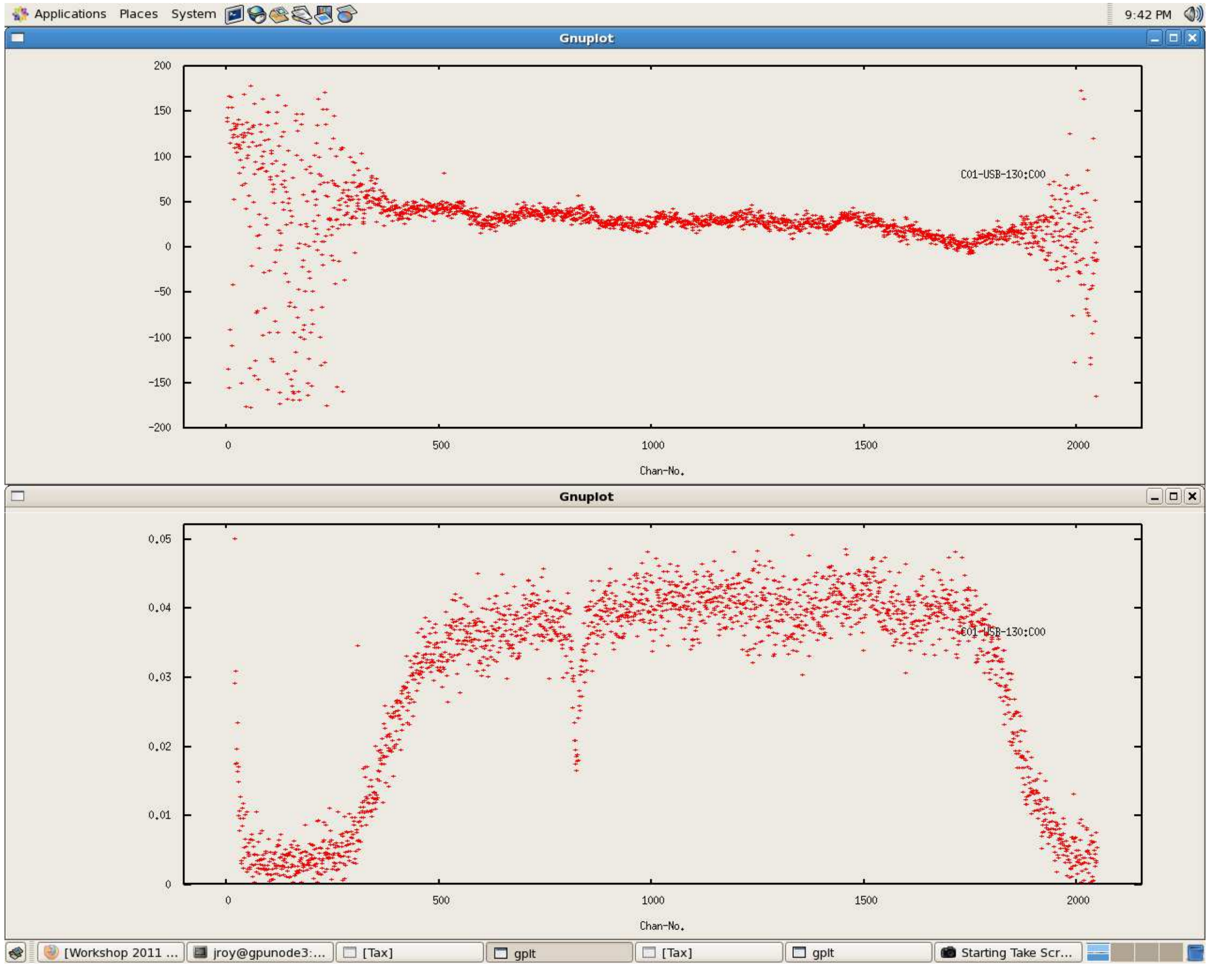
- 32 antennas
- 32 MHz bandwidth, dual polarization
- Net input data rate : 2 Gsamples/sec
- FX correlator + beam former + pulsar receiver
- Uses off-the-shelf ADC cards, CPUs & network switches to implement a fully real-time back-end

Final Outcome from the receiver chain



Self spectra of two GMRT antennas at 1.4 to 1.2 GHz RF on source 3C286, Spectral channels :2048,
Integration time : 0.671s

Final Outcome from the receiver chain



Cross correlation and phase spectrum of two GMRT antennas at 1.4 to 1.2 GHz RF on source 3C286, Spectral channels :2048, Integration time : 0.671s

The uGMRT

The Upgraded GMRT (uGMRT)

A major upgrade is underway now at the GMRT with focus on:

- 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**

Features : Comparison with Current System

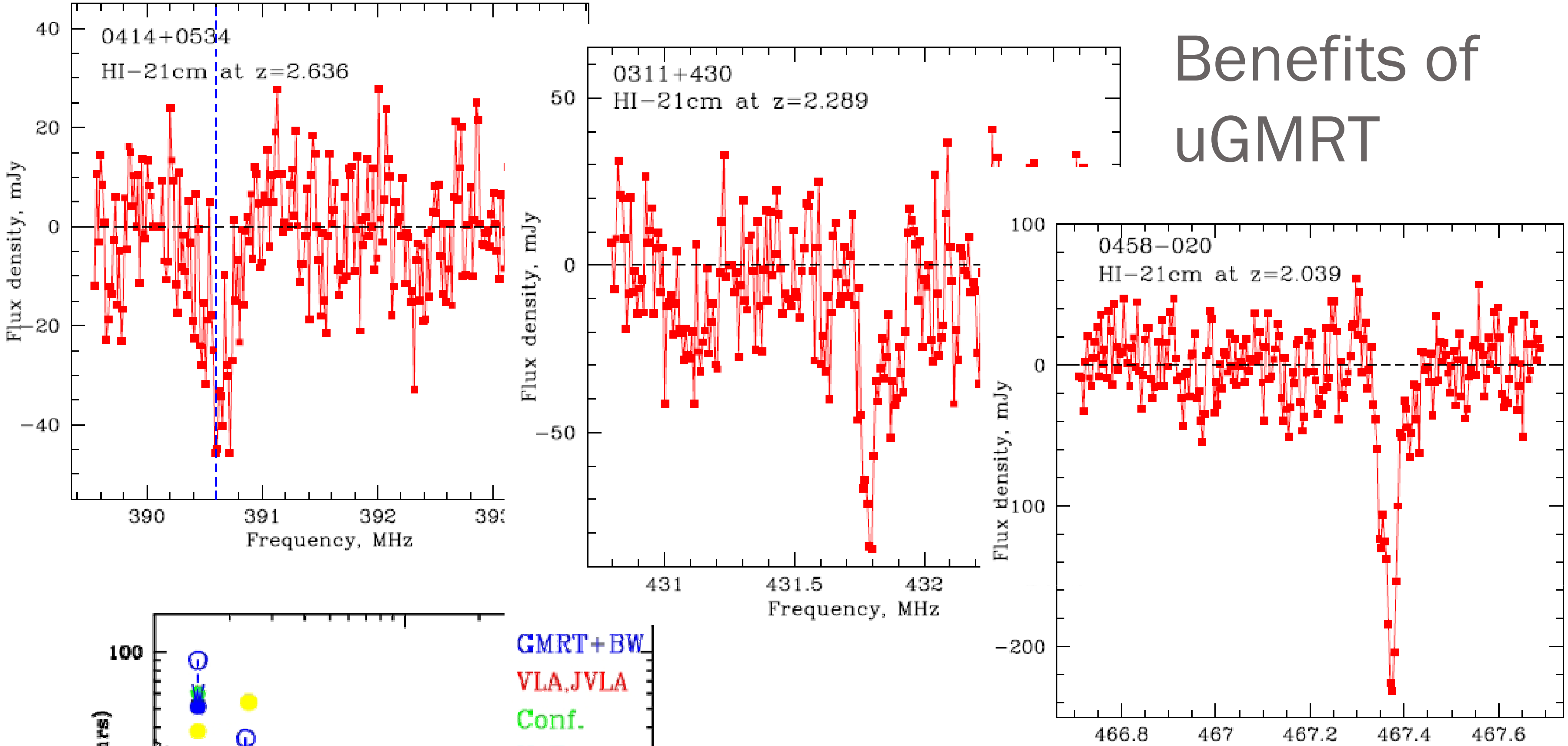
Current system

- Supports observation at specific frequency bands in 50 to 1500 MHz.
- Instantaneous bandwidth of 32 MHz in each polarization.
- Facility for dual frequency observations with 32 MHz in each band.
- Low dynamic range & RFI rejection capabilities.
- Power Level monitoring available at few stages in the receiver chain.

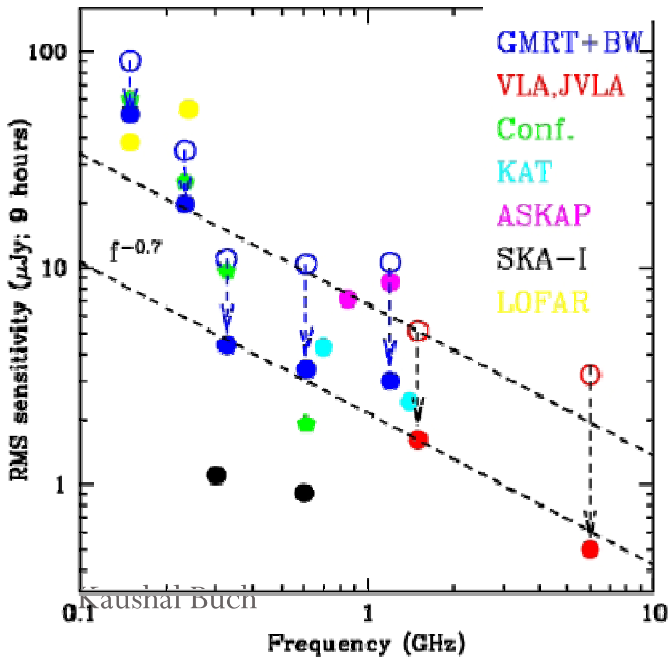
Upgraded system

- Seamless Coverage from 30 to 1500 MHz.
- Supports instantaneous bandwidth of 400 MHz in each polarization.
- Possible only if the frequency bands are within same feed bandwidth.
- Improved dynamic range and in-built RFI cancellation scheme.
- Integrated Power Level Monitoring Circuits for easy trouble shooting.

Benefits of uGMRT



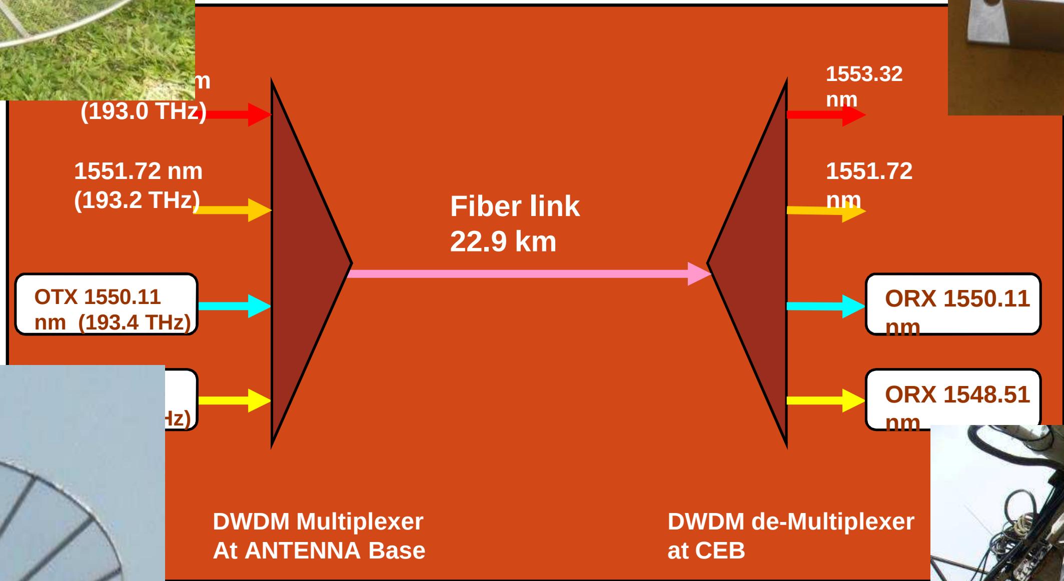
First light results: spectral lines from different sources, at different parts of the 250-500 MHz band (courtesy : Nissim Kanekar)

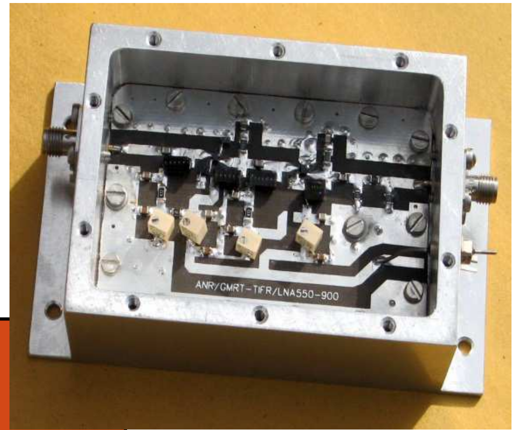


Expected sensitivity of the uGMRT compared to other major facilities in the world, present and projected (courtesy : Nissim Kanekar)

Components of Upgraded GMRT Frontend

130 - 260 MHz feed





500 – 900 MHz LNA

250 – 500 MHz feed

550 – 900 MHz feed

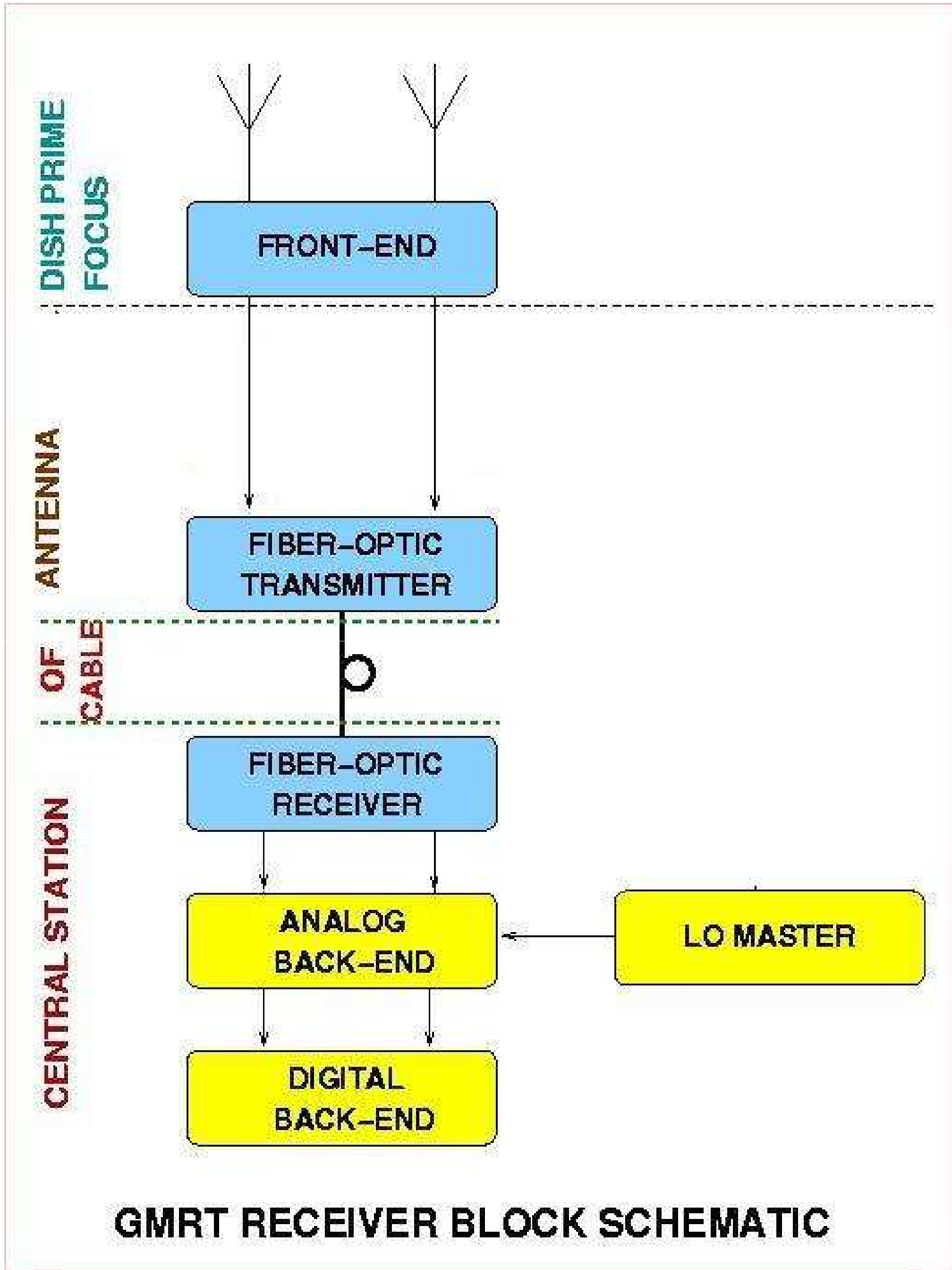
uGMRT Receiver Block Diagram

•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

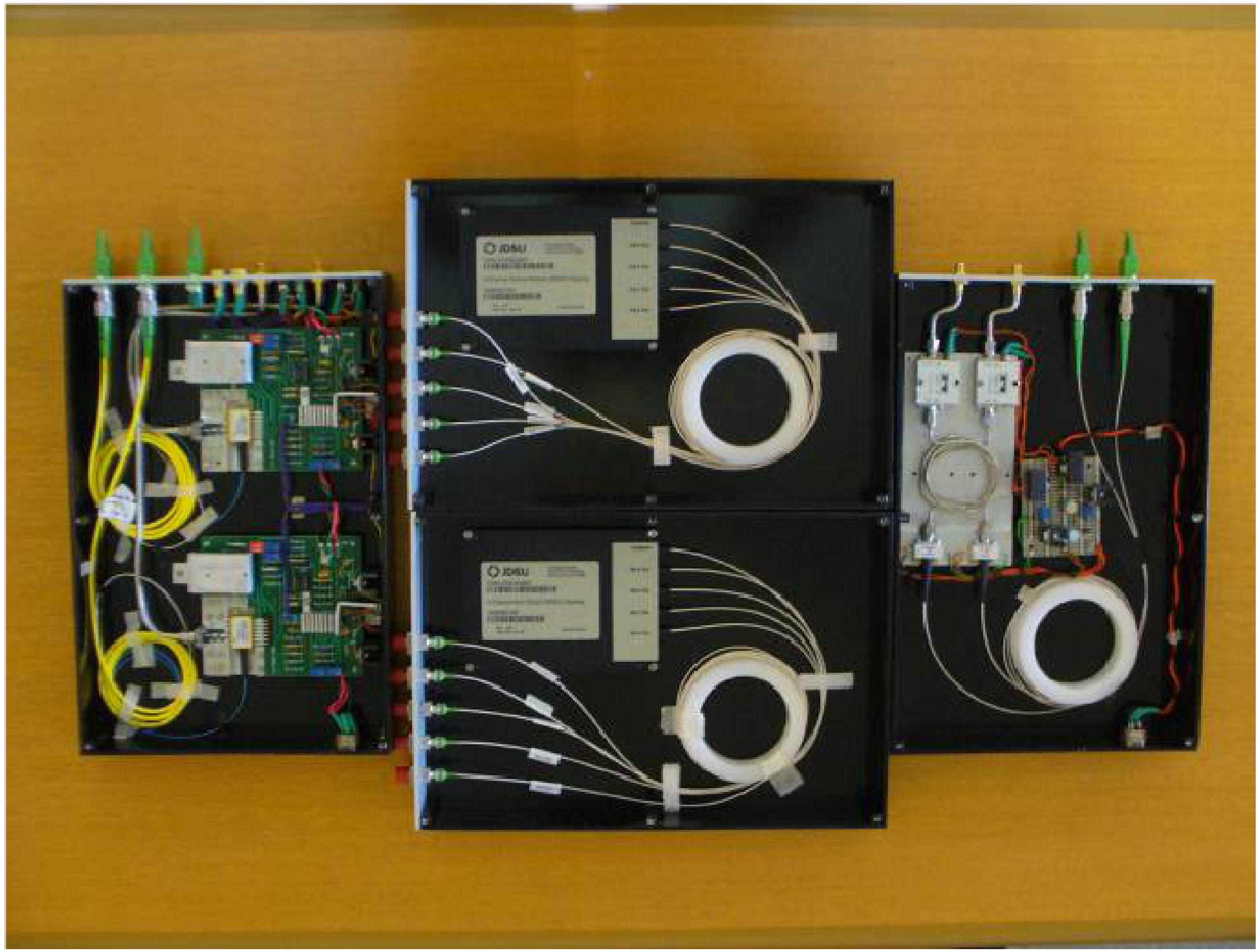
•RF signal is directly transported to the central station using a broadband analog fiber

•Reduced electronics at antenna sites



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 wavelength division multiplexing to accommodate multiple data and control channels on a single fiber.

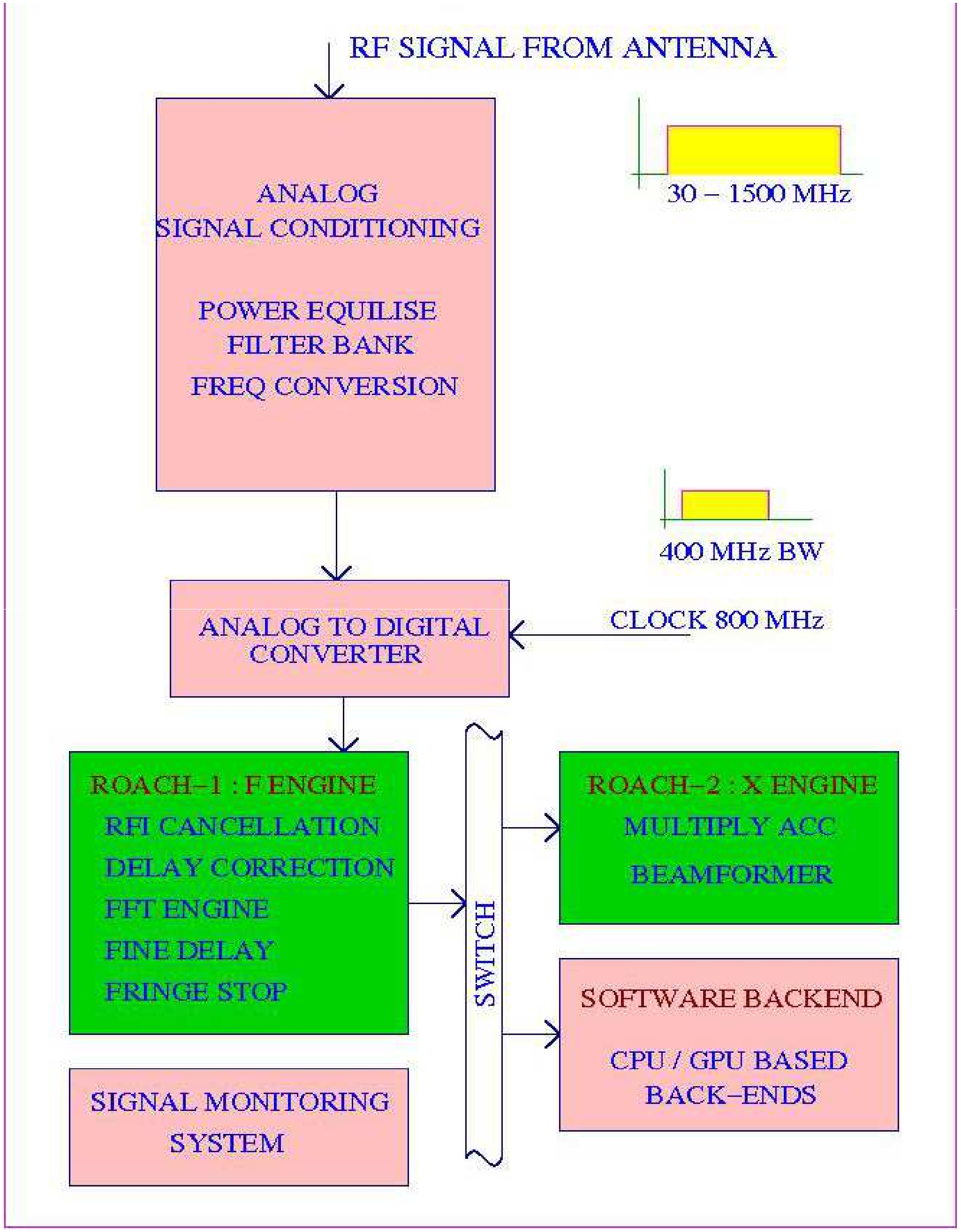


LASER Transmitter, Optical Multiplexer, Optical receiver DWDM based system

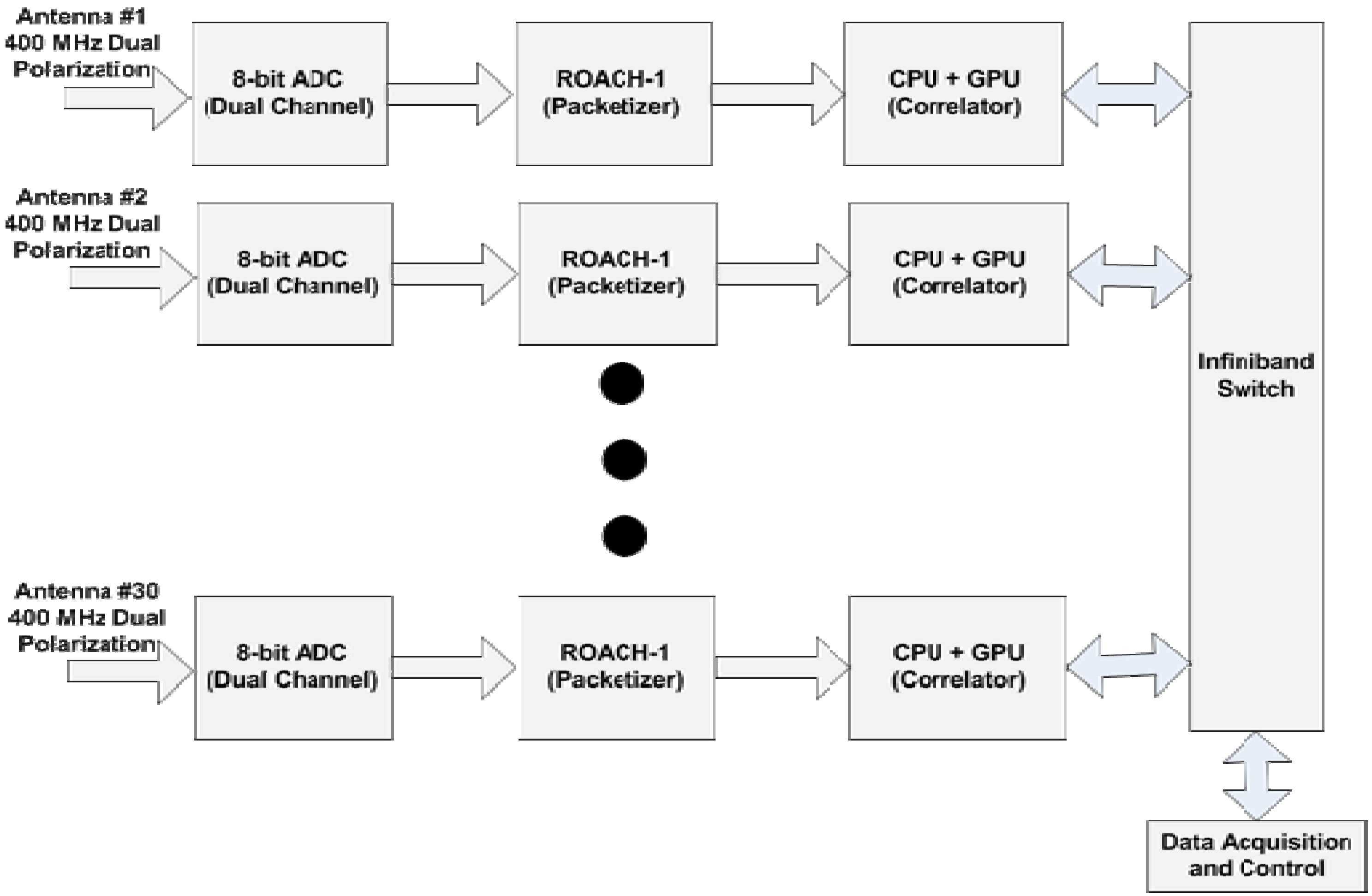
Upgraded Backend - Schematic

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

- Analog Processing
- Digitization
- Digital Processing
- RFI Excision
- Signal Monitoring



Digital Backend using FPGAs and GPUs



ROACH Board

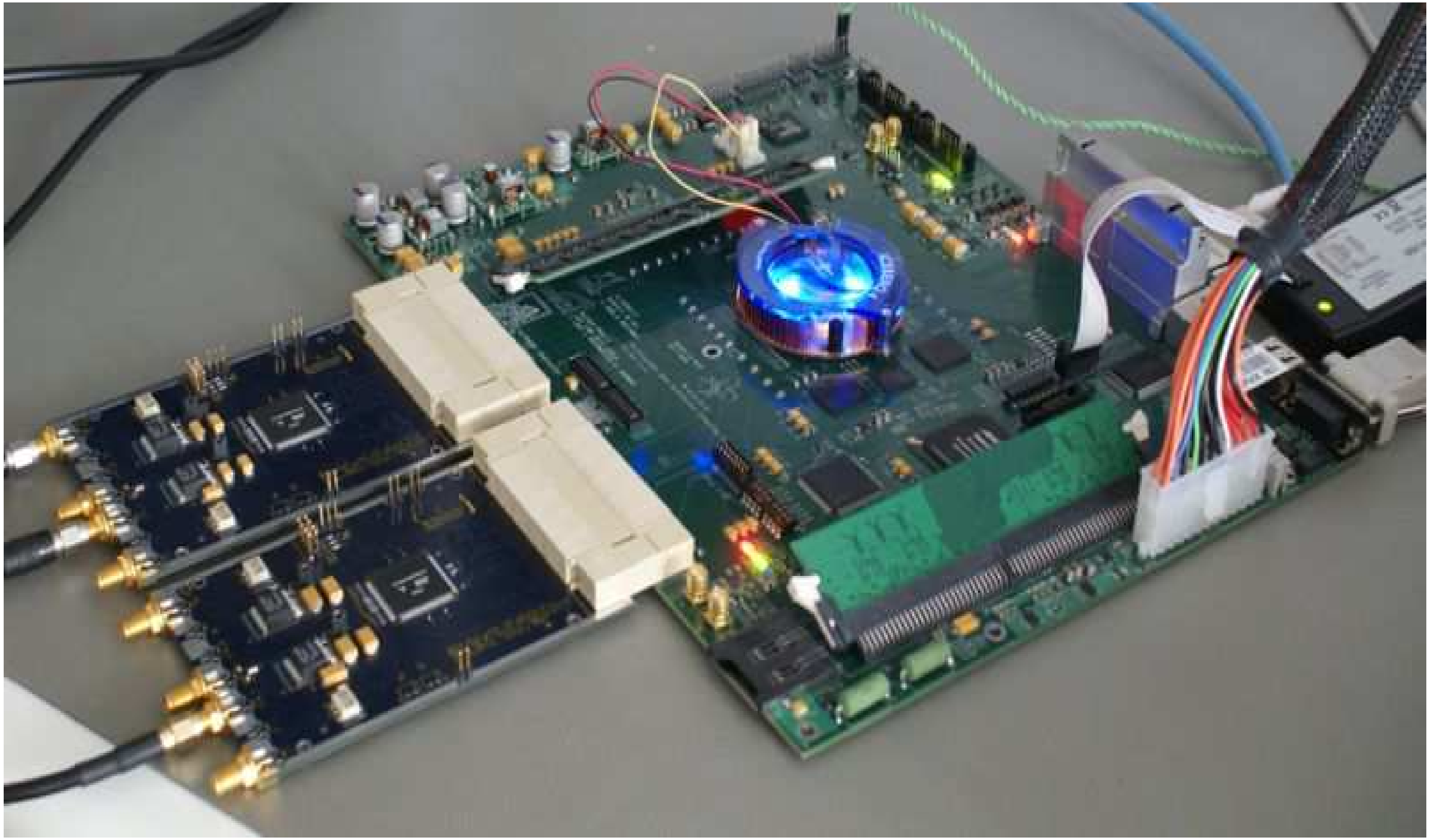


Image Courtesy: CASPER

GMRT Wideband Digital Backend

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

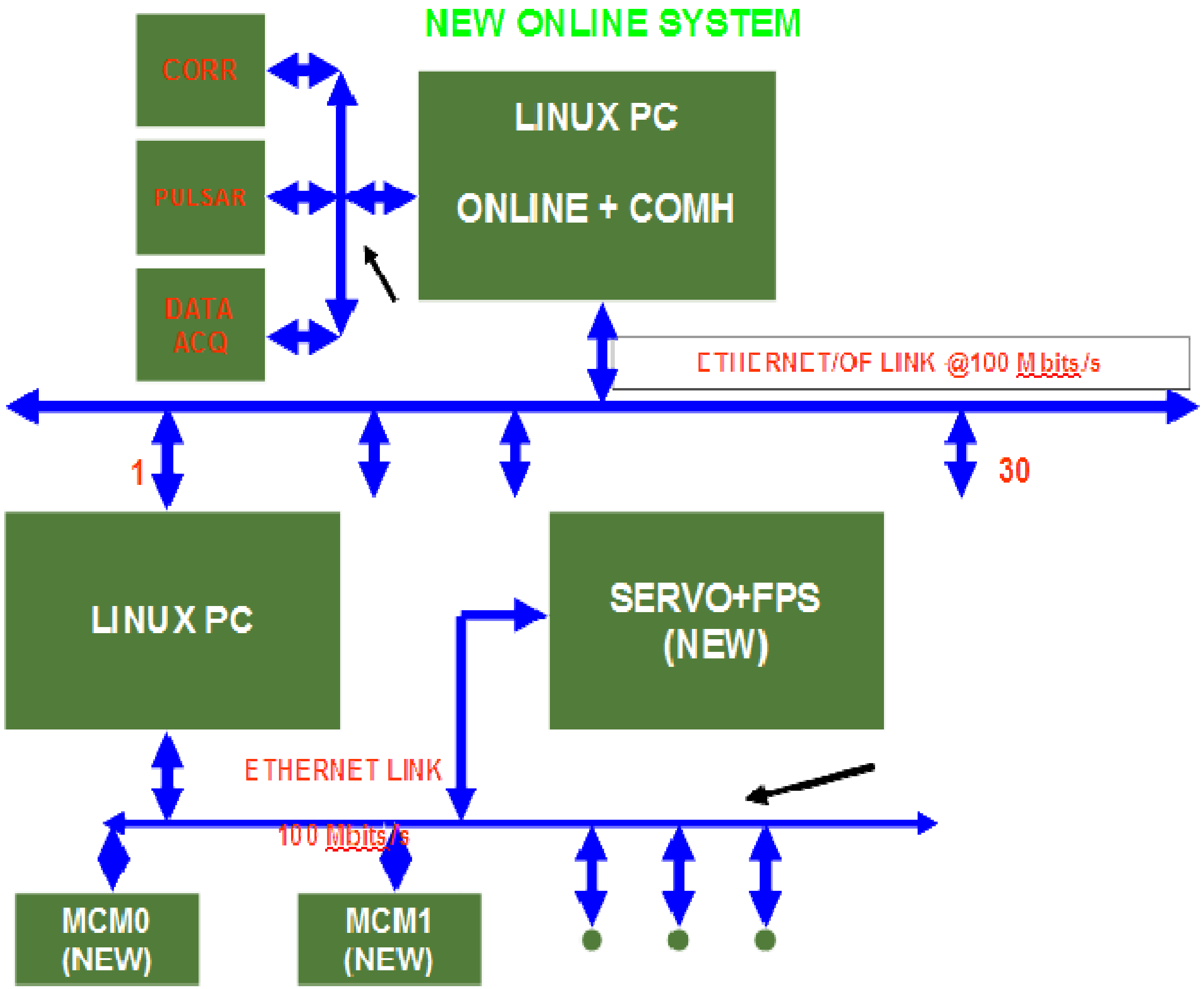
Upgraded Telemetry System

•New station control computer

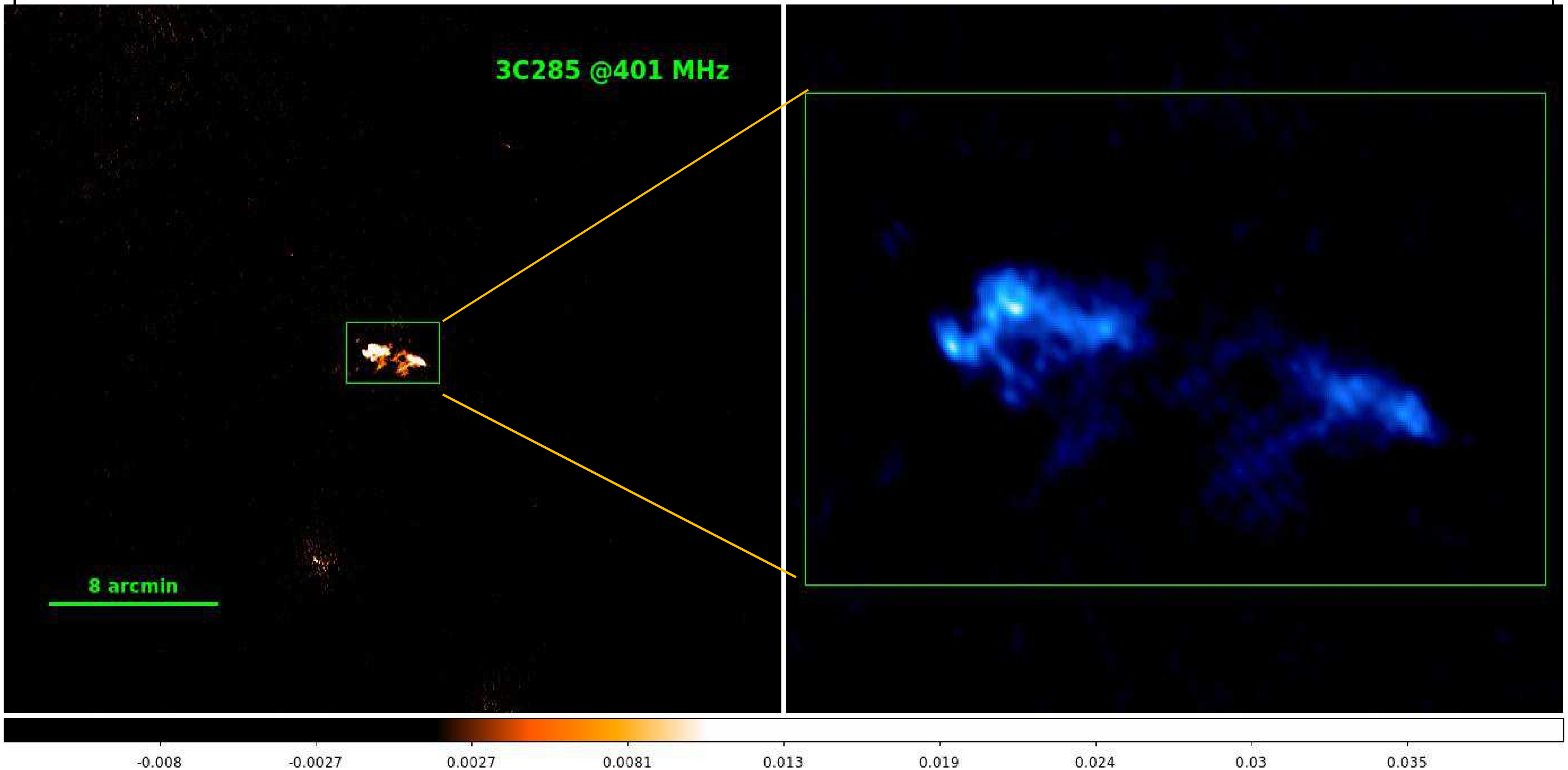
•Ethernet link from central station to each antenna, via the optical fiber

•New generation monitor and control modules using modern microcontroller

•Improved control room software running on Linux platform



Results from the uGMRT

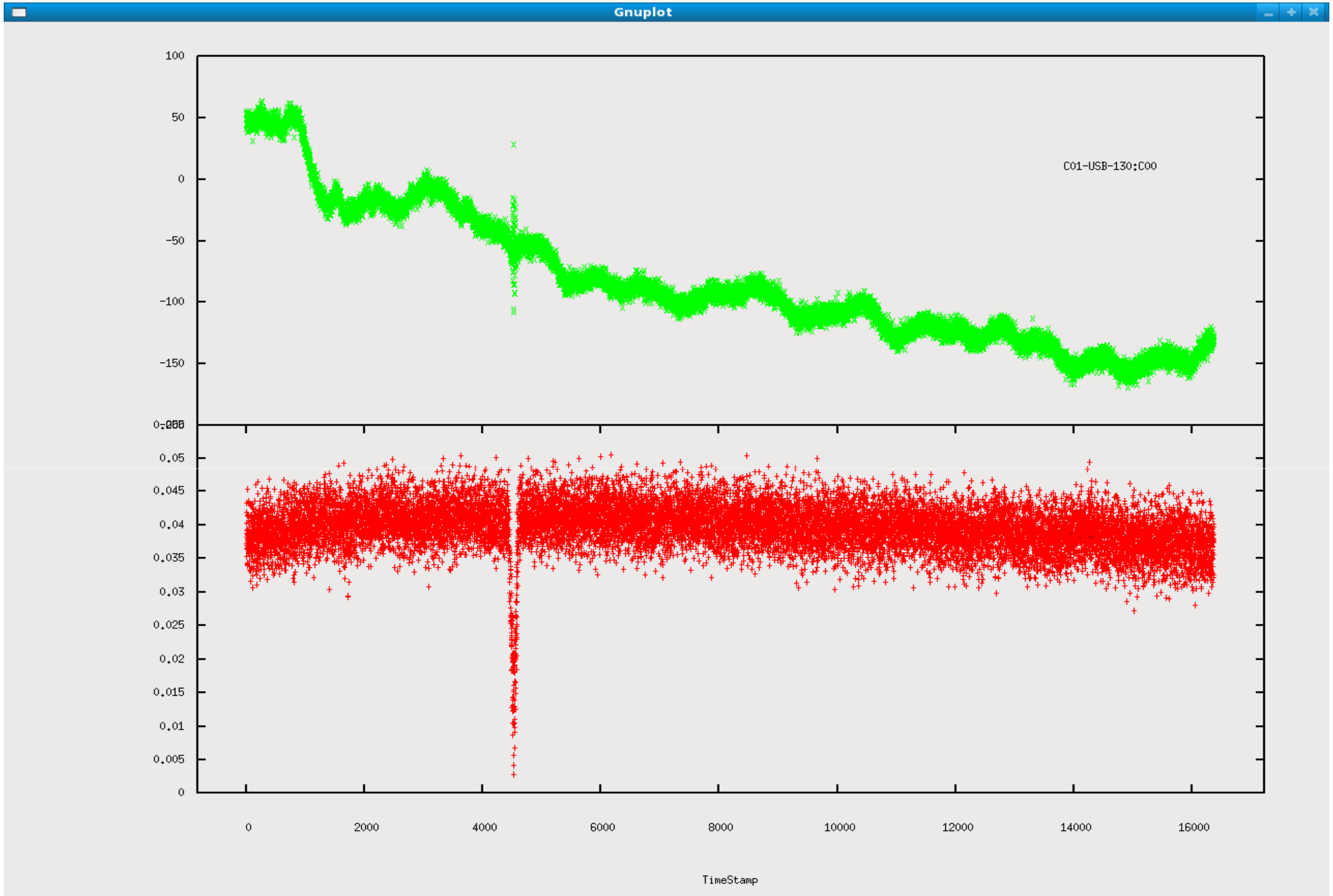


3C285 observed for about 3 hours using 11 broadband antennas, 300 MHz RF, 200 MHz bandwidth, 2048 spectral channels. RMS noise: 0.6 mJy, ~5.4 arcsec resolution

Image Courtesy: Dharam Vir Lal

Challenges for Radio Telescopes

Receiver Stability



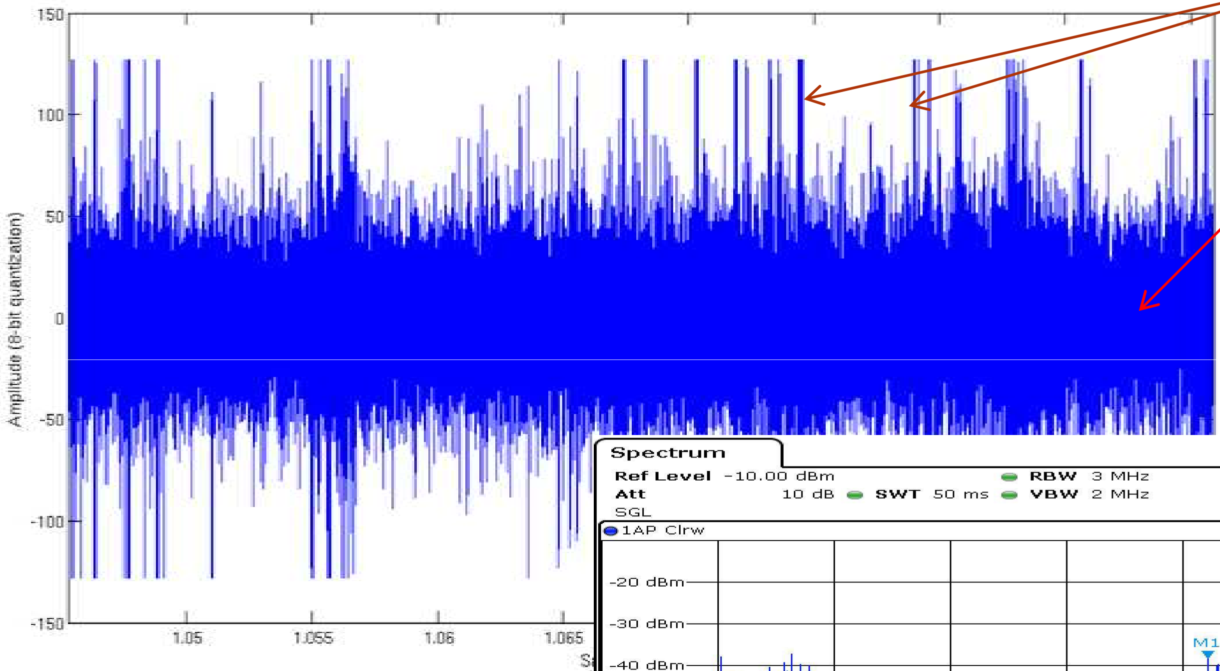
Phase Stability: A single frequency channel's cross amplitude and phase plotted over time for nearly three hours

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 than astronomical signal
- RFI has a non-random distribution
- RFI mitigation – very important problem (challenge) for contemporary radio telescopes

Broadband RFI

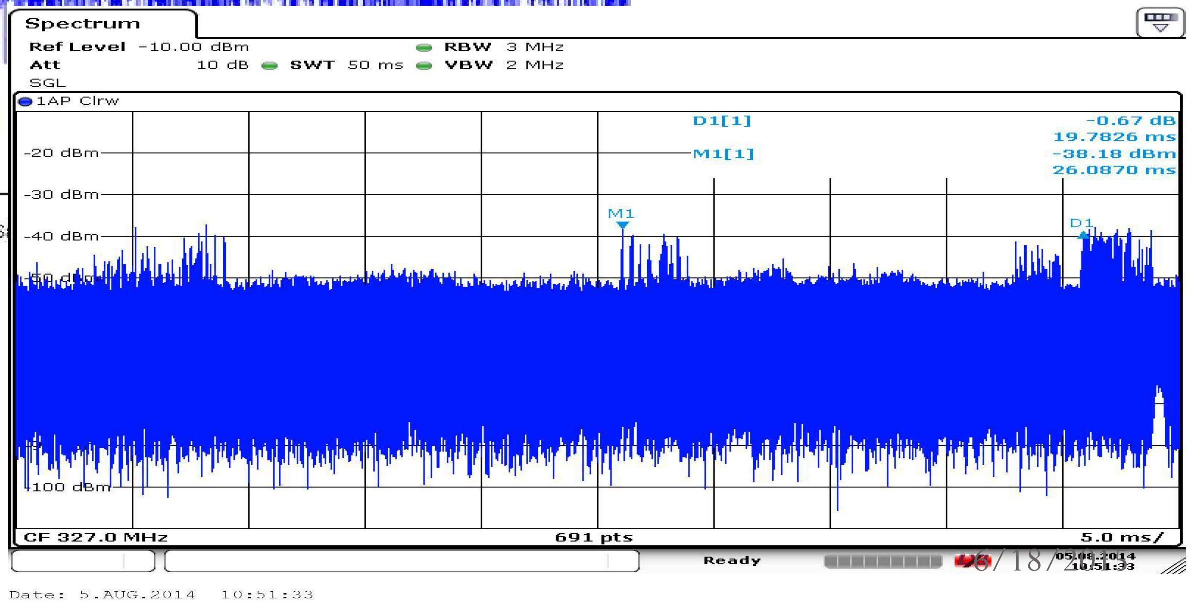
Digitized Time Series with Impulsive RFI



RFI

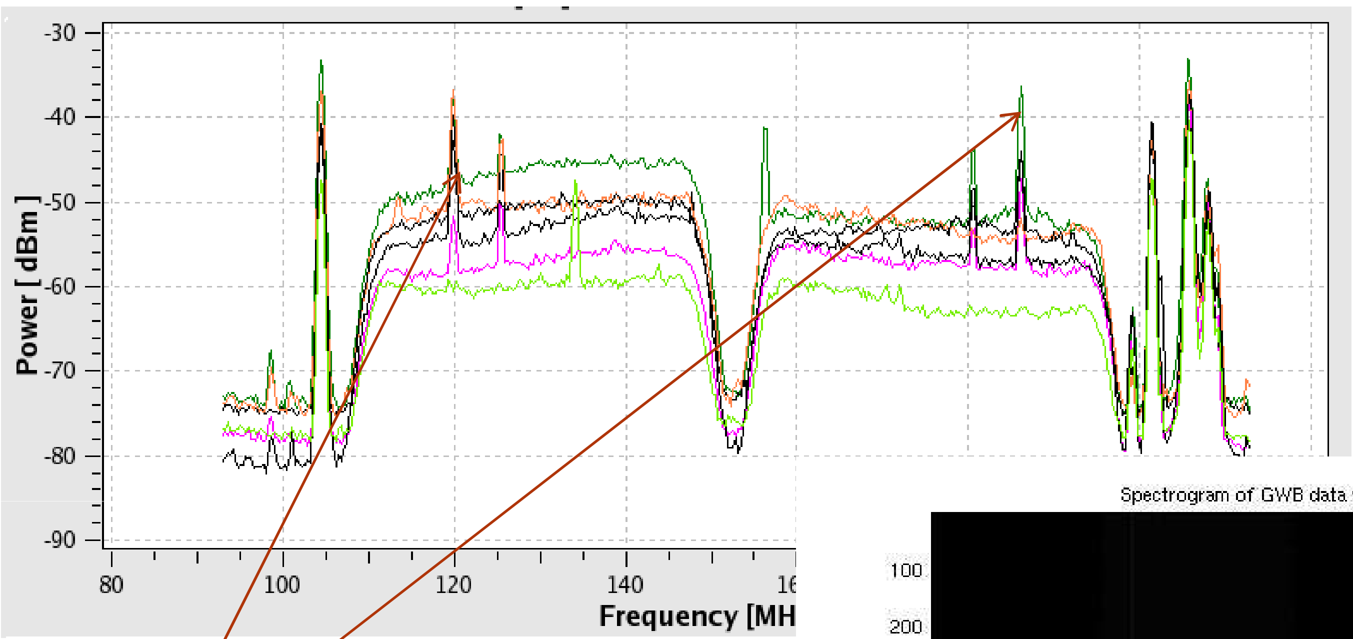
Signal

Magnitude Spectrum of Broadband RFI

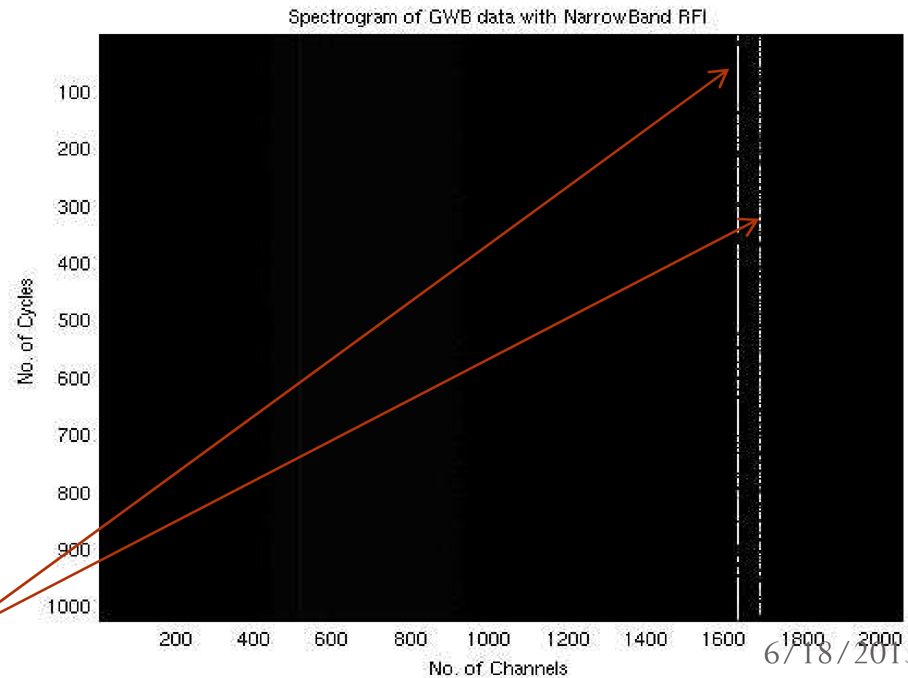


Referred to as time-domain RFI

Narrowband RFI



RFI



Referred to as frequency-domain RFI

RFI

Additive Effect of RFI

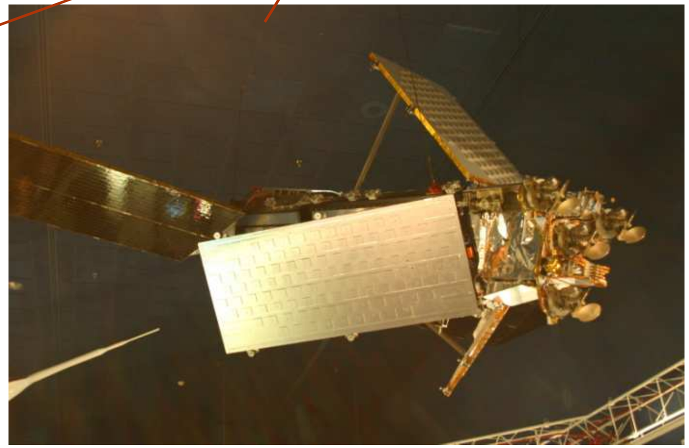
- Generalized time-domain signal model (with RFI) for a radio telescope

$$x(t) = x_{src}(t) + x_{sys}(t) + x_{RFI}(t)$$

- x_{src} is the contribution due to astronomical source (desired signal), x_{sys} is the system noise (undesired signal) and x_{RFI} is the radio frequency interference signal (undesired signal)

Typical Sources of RFI at GMRT

Narrowband RFI



Sparking

Broadband RFI

Narrowband RFI

Image Courtesy: Wikipedia

Effects of RFI

- Presence of RFI
  - Signal fluctuations do not integrate down as $t^{-0.5}$ upon temporal averaging
  - Leads to reduced signal to noise ratio (SNR) and sensitivity
- Strong narrowband RFI lines
  - Produces harmonics
  - Pronounced effects due to spectral leakage
    - Increased side-lobe levels
    - Reduced dynamic range
- Limits detection and analyses of weak radio sources, temporal events and transients

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Thank You!