Introduction to the GMRT

Yashwant Gupta

Centre Director

National Centre for Radio Astrophysics

Tata Institute of Fundamental Research

Outline of today's talk

Part I : Radio telescope basics : a review

Part II : The GMRT : early history and development

Part III : The GMRT : upgrade and current status

Part IV : Some science highlights and future potential with the GMRT

Part I

Radio Telescope Basics

Radio Telescopes : Basics

It is like your satellite dish, but there is a challenge :

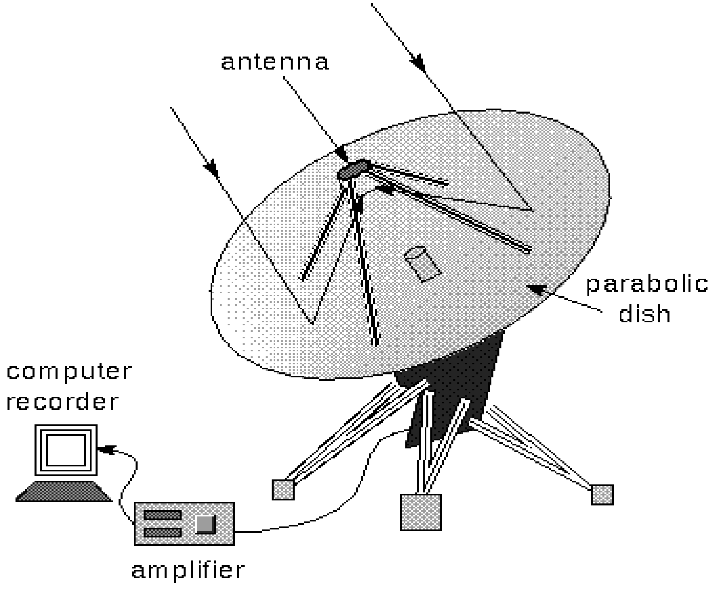
- Celestial radio signals are VERY weak (& there is corruption due to noise !) ; unit of flux used is :

  1 Jy = 10^{-26} W / m^2 / Hz
- Input radio power into a typical telescope is

  ~ -100 dBm !

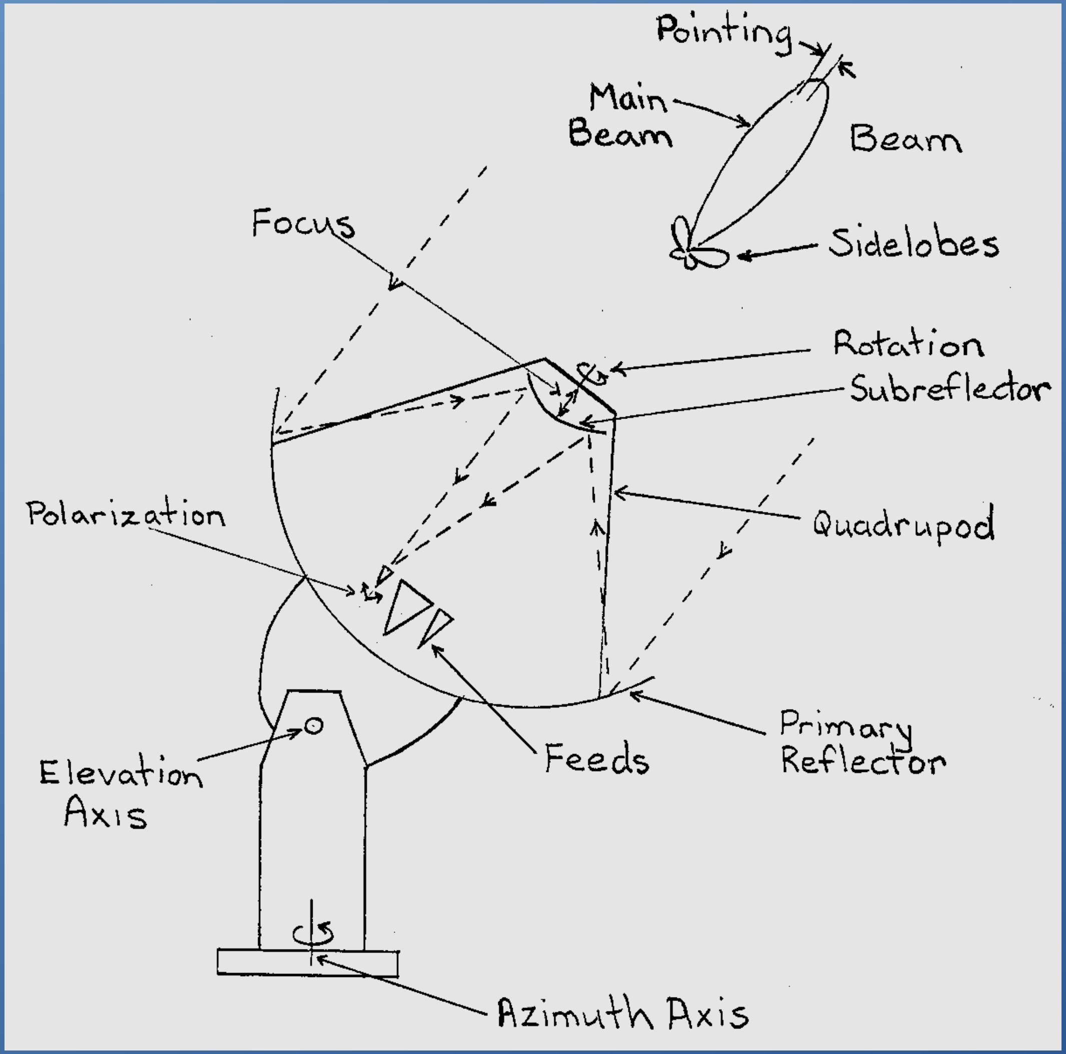
  (would take 1000 years of continuous operation to collect 1 milliJoule of energy !!)

- For high sensitivity (to see faint sources out to the distant reaches of the Universe) :
  - large dishes (several 10s of metres in diameter)
  - high quality, low noise electronics in the receivers
  - large bandwidth of observation
  - long integration times of observation



A radio telescope reflects radio waves to a focus at the antenna. Because radio wavelengths are very large, the radio dish must be very large.

Main features of an antenna



Courtesy : Synthesis Imaging Summer School, NRAO

Single Dish Radio Telescopes

- Resolution and sensitivity depend on the physical size (aperture) of the telescope
- Due to practical limits, fully steerable single dishes of more than ~ 100 m diameter are very difficult to build
  $\Rightarrow$ resolution (λ / D) ~ 0.5 degree at 1 m (very poor compared to optical telescopes)
- Simplest way to improve resolution or directivity is to use arrays of antennas

The 100-m Greenbank Telescope

Low and High Resolution Images

The 300-m Arecibo Radio Telescope

Multi-Dish Array Radio Telescopes

- To synthesize telescopes of larger size, many individual dishes spread out over a large 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

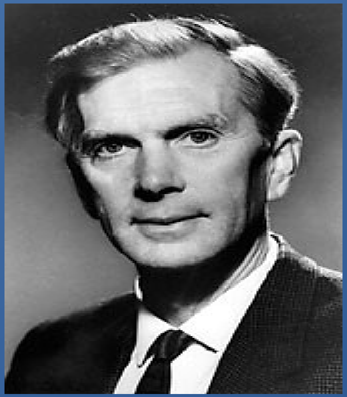
$\Rightarrow$ resolution $= \lambda / D_s$, D_s = largest separation

- This allows radio astronomy telescopes to be competitive in resolution to telescopes at shorter wavelengths (like optical)

The 100-m Greenbank Telescope

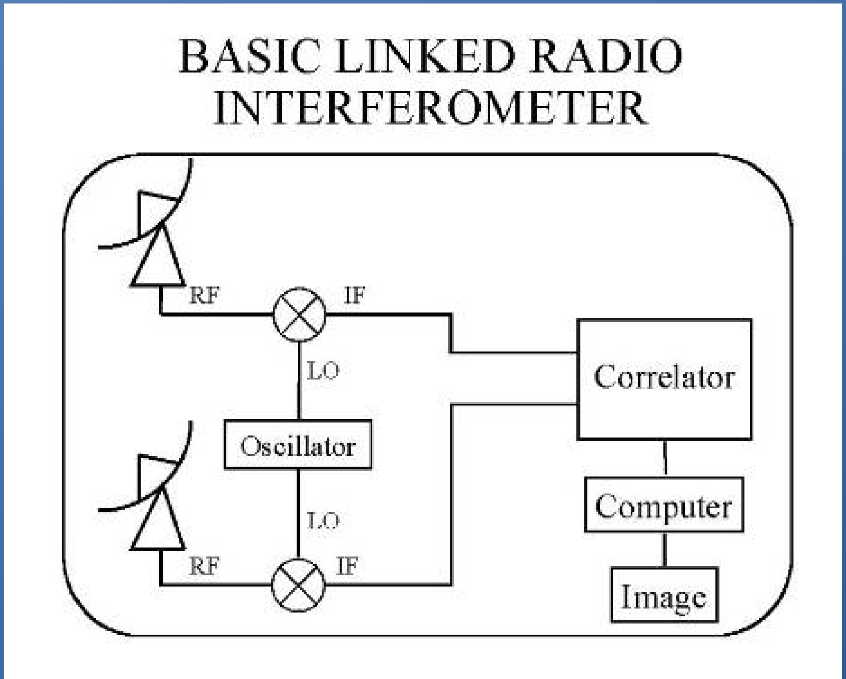
The Very Large Array Telescope, USA

Sir Mrtin Ryle -- pioneer in radio astronomy



Radio Interferometry & Aperture Synthesis

- Signals from a pair of antennas are cross-correlated (cross-spectrum is obtained)
- This functions like a Young's double slit, multiplying the sky brightness distribution by a sinusoidal response pattern
- Thus, an interferometer measures one Fourier component of the image
- 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

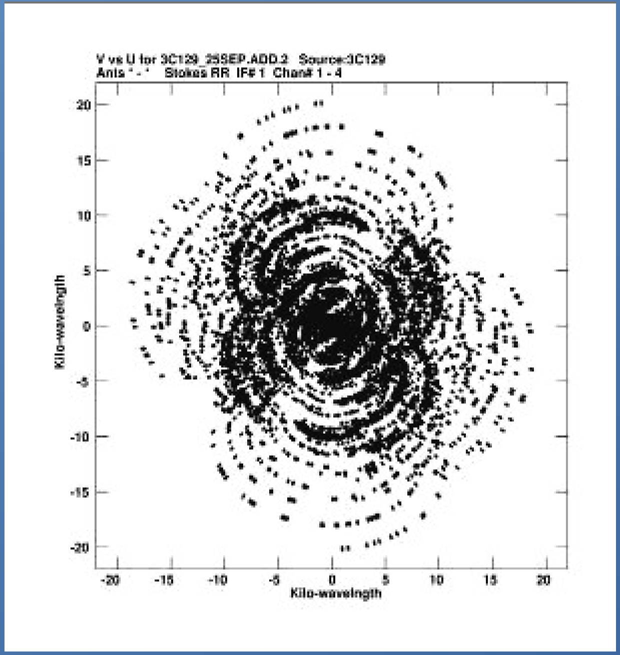


The signal processing has both real time and off-line components

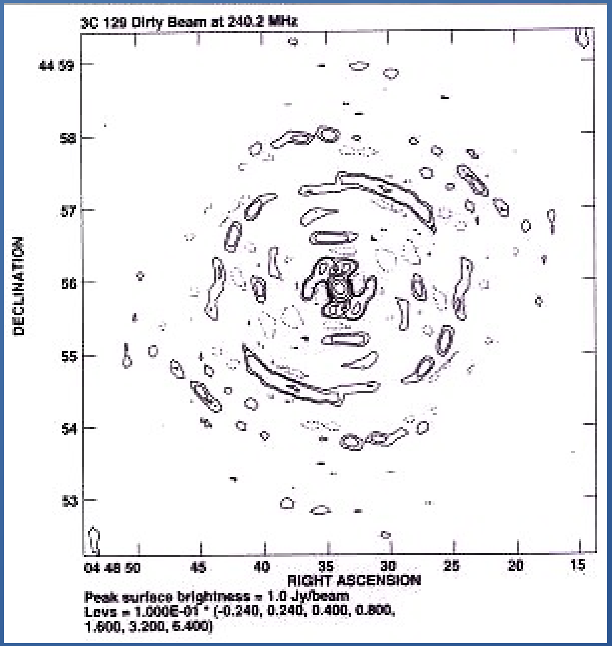
Aperture Synthesis in Radio Astronomy

Fourier Plane Coverage and "Dirty Beam"

- The finite number of baselines leads to an incomplete sampling, in the 2-D Fourier domain, of the Fourier components of the intensity distribution of the radio image
- As a result, the effective "point spread function" of the telescope is smeared out (called the "dirty beam")



Sampling function in the Fourier domain (UV plane)

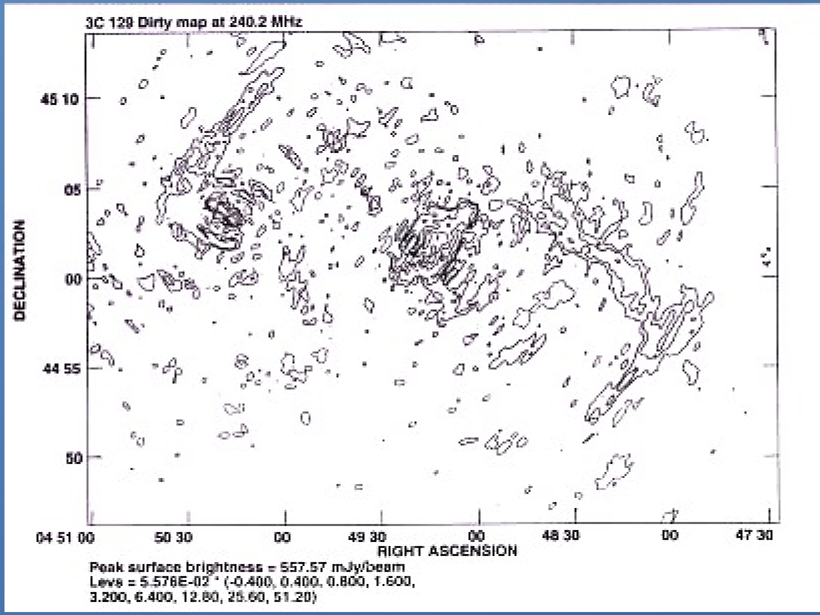


The "dirty beam" : the smeared out point spread function

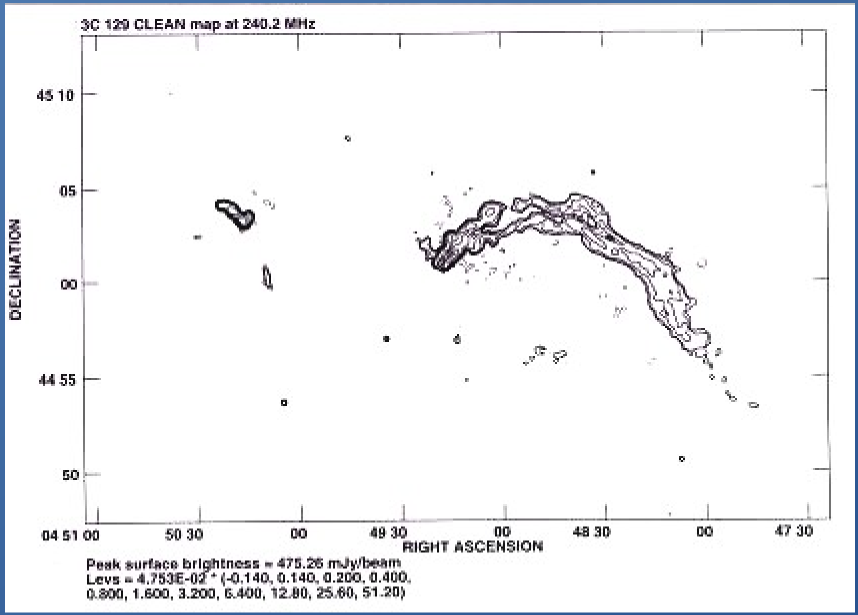
Aperture Synthesis Imaging Results

The “Dirty” and “Clean” Maps

- The raw image (“dirty map”) is the convolution of the true image with the PSF (“dirty beam”) – has many artificial features in it.
- Special signal processing techniques, such as “CLEAN” and “SELF-CAL”, are applied to correct the raw image and obtain the final processed image (“clean map”)



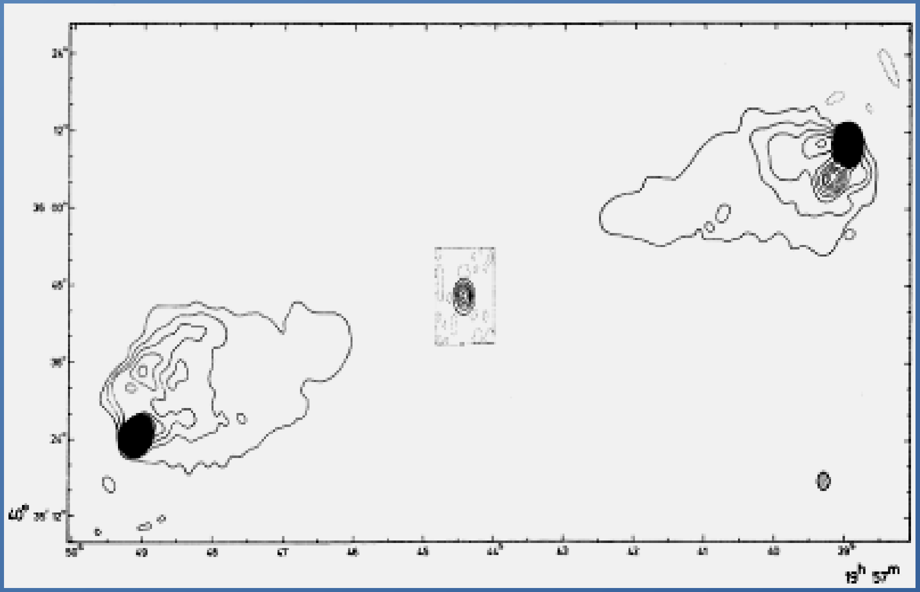
The “dirty map” from the raw inverse transform of the Fourier data



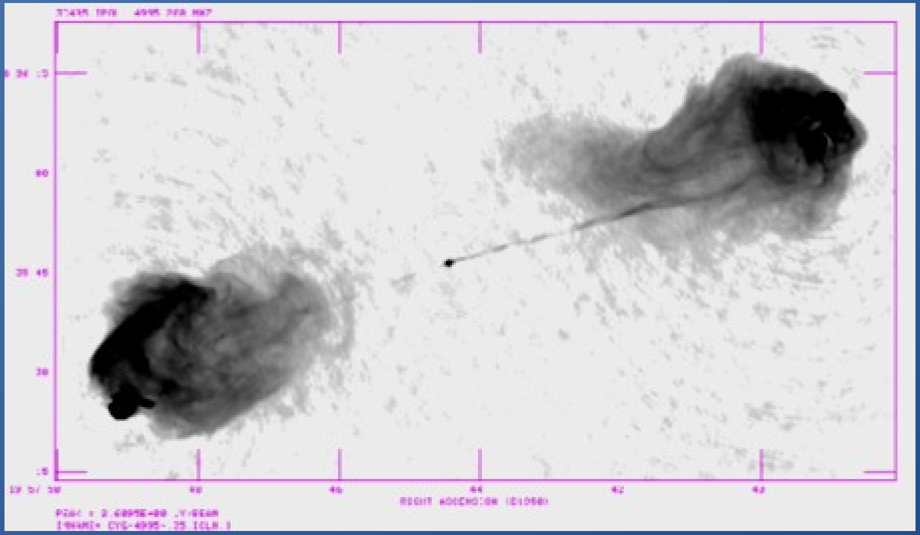
The final “clean map” after processing the data with CLEAN and SELF-CAL

The power of Array Telescopes

- The radio galaxy Cygnus-A : best pre-VLA image



- The radio galaxy Cygnus-A : new image using the VLA

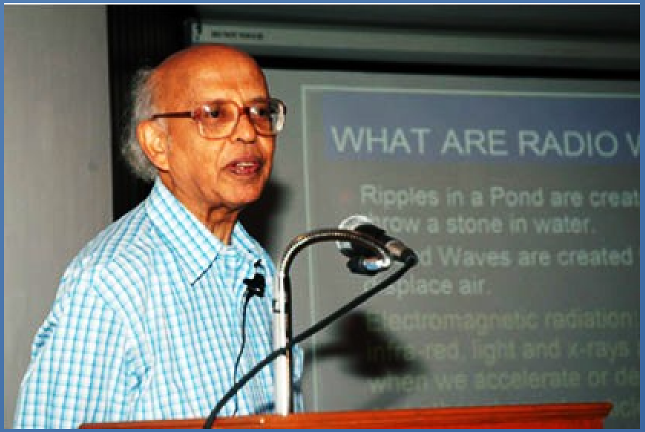


Part II

Case study of a modern radio observatory : the GMRT

A typical modern radio telescope : The GMRT

- The Giant Metre-wave Radio Telescope (GMRT) is a world class facility for studying astrophysical phenomena at low radio frequencies (50 - 1450 MHz)
- Array telescope consisting of 30 antennas of 45 m diameter, operating at metre wavelengths -- the largest in the world at these frequencies !
- Designed & built by NCRA, during the 1990s.
- Just completing a major upgrade to next generation receivers & signal processing to handle 400 MHz BW



Prof. Govind Swarup – father of Indian radio astronomy

The Giant Metrewave Radio Telescope of NCRA

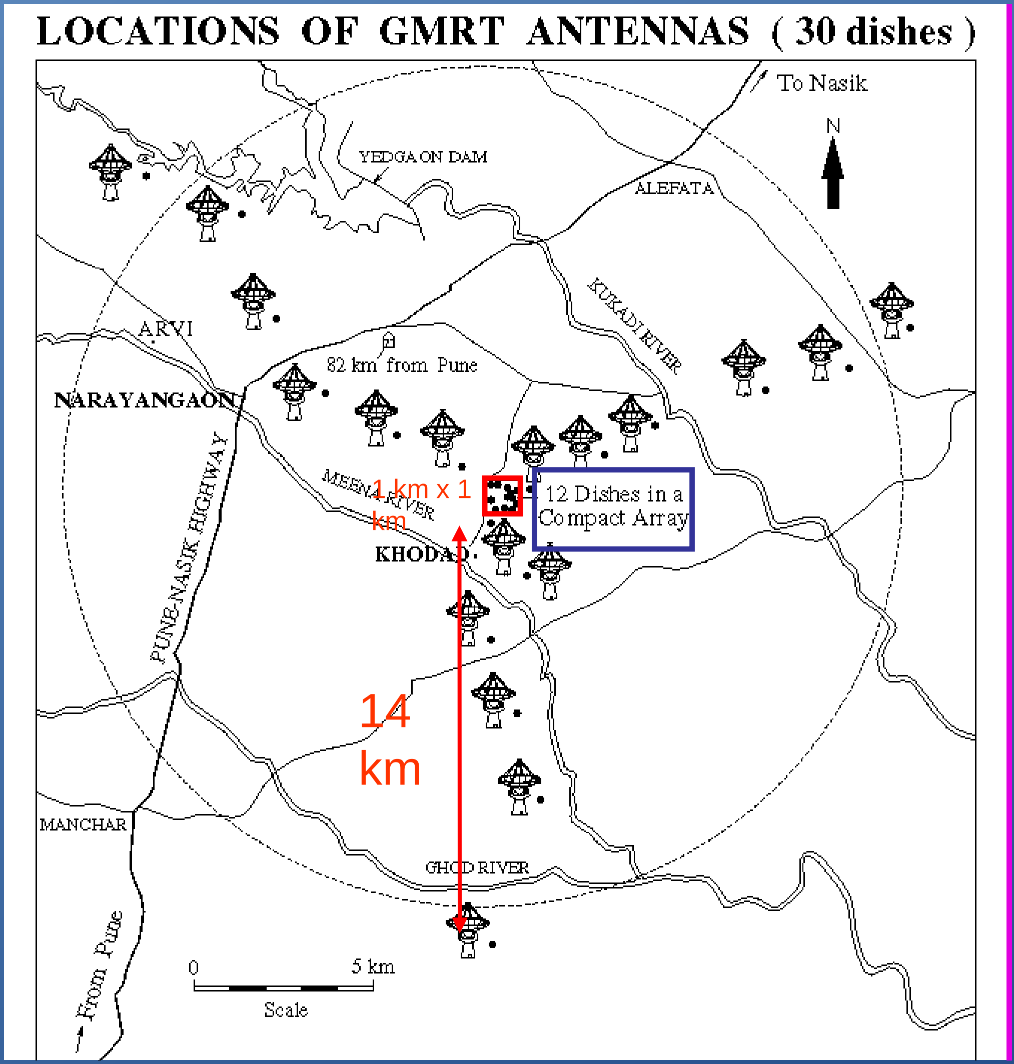
Location and Configuration of the GMRT

- Latitude : 19 deg N
- Longitude : 74 deg E

- About 70 km N of Pune,
  160 km E of Mumbai.

- 30 dishes; 45 m diameter
  - 12 dishes in central compact array
  - Remaining along 3 arms of Y-array

- Total extent : 14 km radius
  ⇒ resolution of a 28 km size antenna is achieved



The Giant Metre-wave Radio Telescope
A Google eye view

The Giant Metre-wave Radio Telescope
A Google eye view

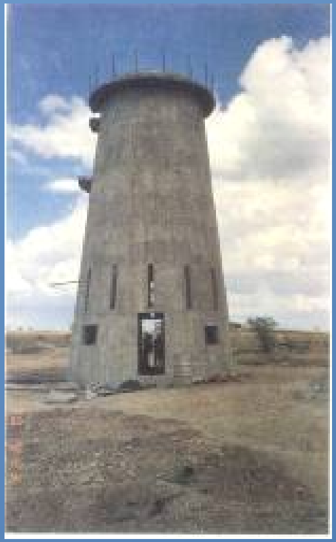
The Giant Metre-wave Radio Telescope
A Google eye view

The Giant Metre-wave Radio Telescope
A Google eye view

Panoramic View of Central Array of the GMRT

Individual antennas are very big : 45 m diameter

Construction of a GMRT antenna






Dedication of the GMRT

The Giant Metrewave Radio Telescope was dedicated to the World Scientific Community by the Chairman of TIFR Council, Shri Ratan Tata.

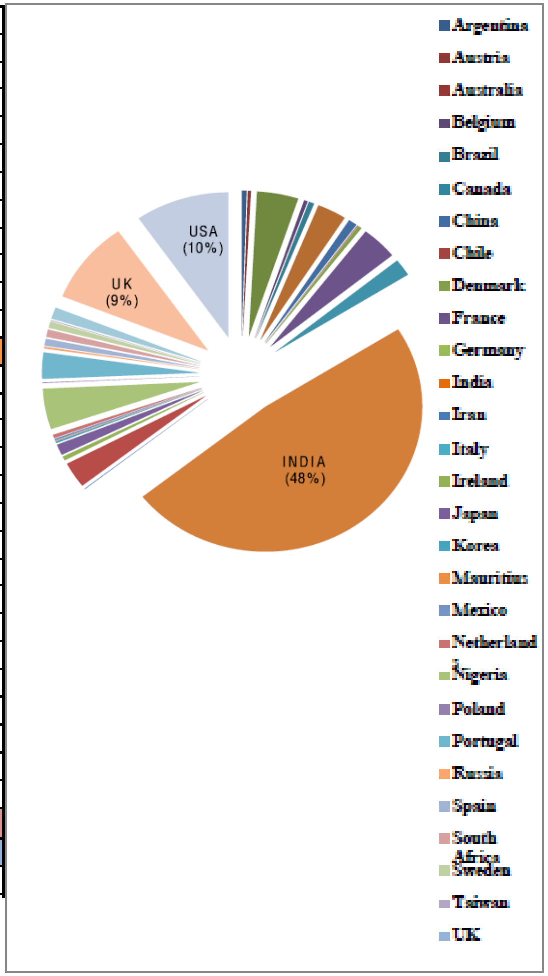
October 4, 2001

GMRT : Operations & Usage Statistics

- The GMRT is open to international participation via a formal proposal system
- Proposals are invited twice a year and reviewed by the GMRT Time Allocation Committee
- Observations are scheduled for 2 cycles of 5 months each
- The GMRT is presently oversubscribed by a factor of 2.5
- Distribution of Indian vs Foreign users : close to 50:50

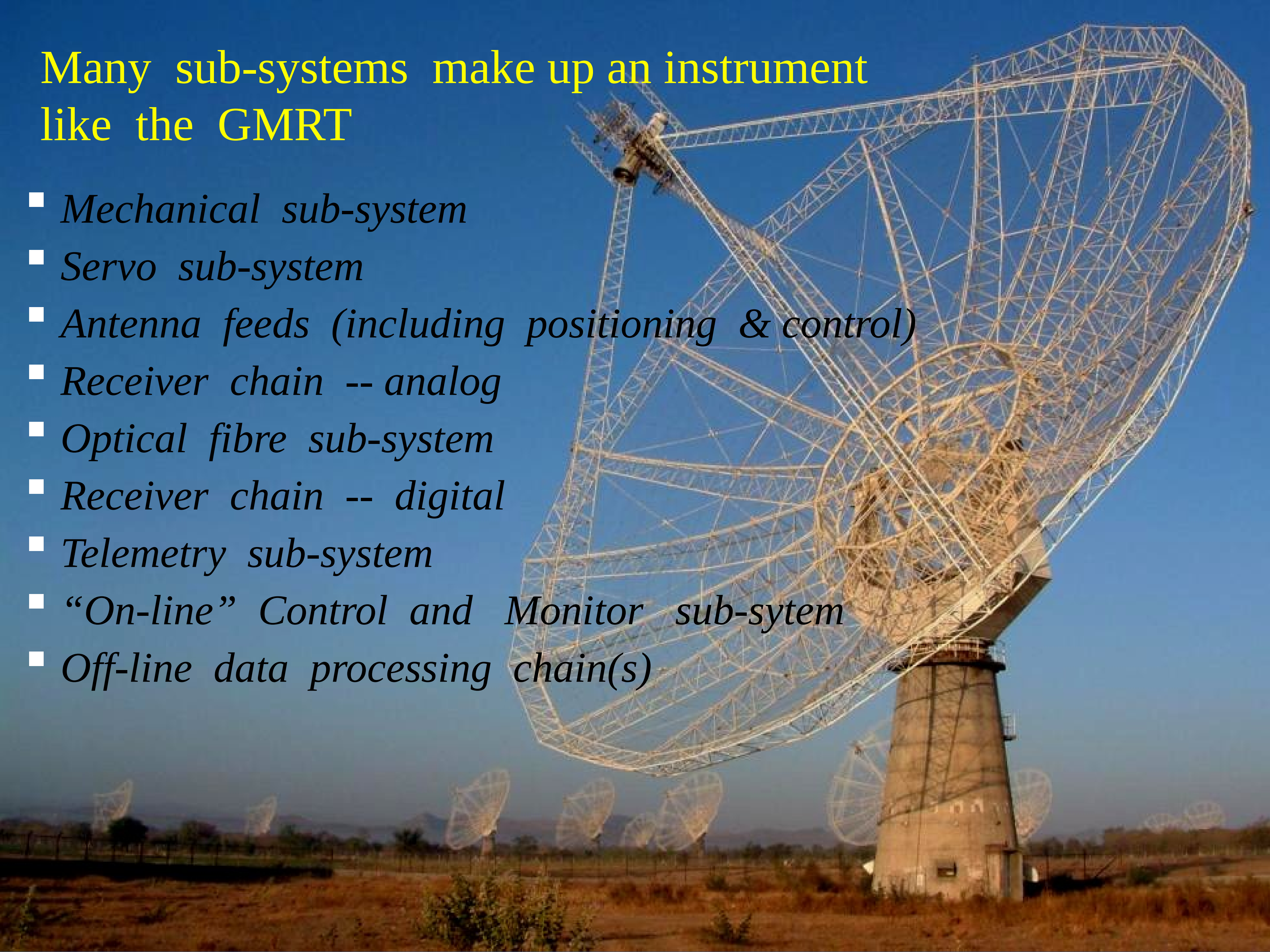
Cycle 1 to 23- PI - Countrywise distribution of proposals

Country	Nos
Argentina	7
Austria	5
Australia	61
Belgium	6
Brazil	8
Canada	43
China	12
Chile	1
Denmark	6
France	55
Germany	24
India	716
Iran	1
Italy	44
Ireland	3
Japan	16
Korea	1
Mauritius	2
Mexico	6
Netherlands	61
Nigeria	1
Poland	42
Portugal	3
Russia	11
Spain	13
South Africa	11
Sweden	1
Taiwan	18
UK	140
USA	141
Total	1459



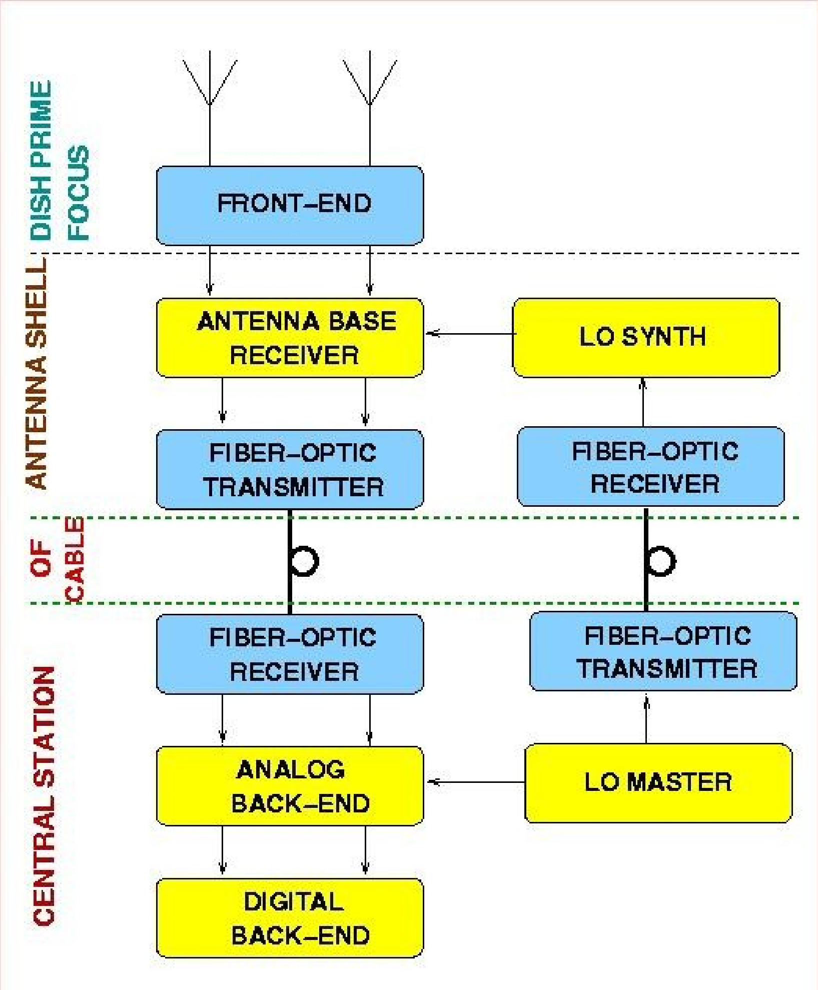
Many sub-systems make up an instrument like the GMRT

- *Mechanical sub-system*
- *Servo sub-system*
- *Antenna feeds (including positioning & control)*
- *Receiver chain -- analog*
- *Optical fibre sub-system*
- *Receiver chain -- digital*
- *Telemetry sub-system*
- *"On-line" Control and Monitor sub-sytem*
- *Off-line data processing chain(s)*



GMRT Legacy Receiver System : Overview

- Dual polarized feeds
- Low Noise GasFET amplifiers at front-end
- Optical fibre link from each antenna to central receiver room
- Super-heterodyne receiver to convert to baseband signal
- Tunable LO *(30 – 1700 MHz)* with low phase noise *(~2° @1 GHz ; -50 dBc/ Hz at 1 Hz offset) ;* locked to reference from central frequency standard
- Maximum baseband bandwidth : 400 MHz
- Full polar correlator for aperture synthesis mode and beamformer for array mode (supports incoherent & coherent array modes)



GMRT RECEIVER BLOCK SCHEMATIC

GMRT Legacy Receiver System : Overview

Real-time processing from multiple antennas involves :

(i) time alignment of the signals

(ii) FFT to get the spectra

(iii) phase corrections

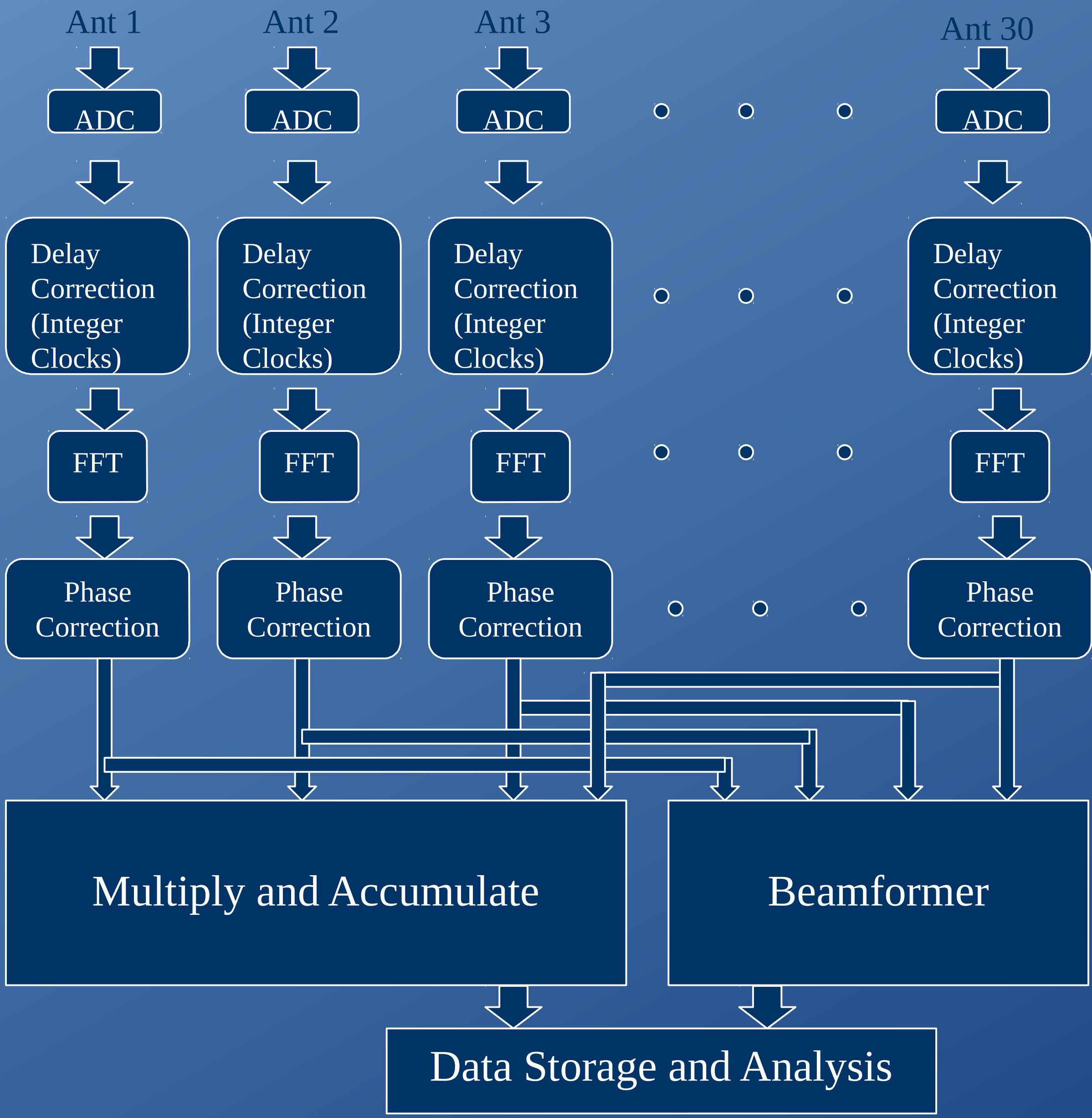
(iv) cross-spectra between every pair of antennas

(v) integration over multiple spectra

(vi) recording to disk

Total computing requirement :
~ 1.5 Tflops

Total input data rate :
4 Gsamples/sec



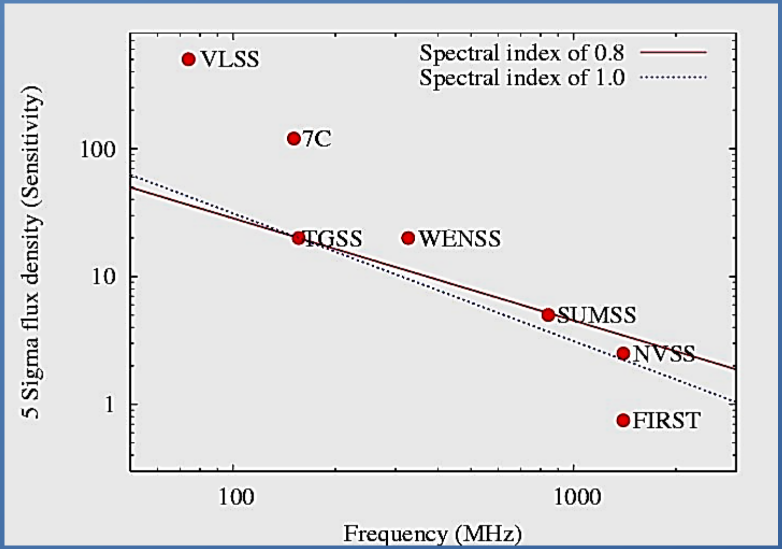
GMRT : Range of Science

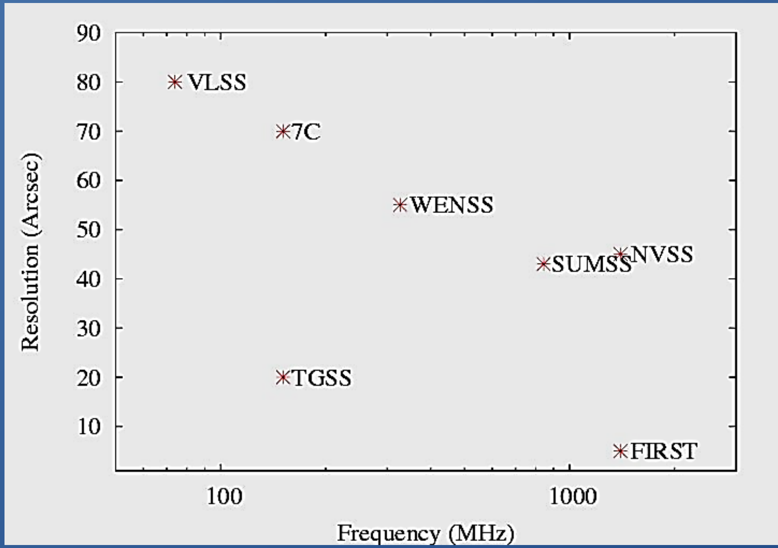
- The GMRT is a powerful instrument to probe several astrophysical objects :
  - The Sun, extrasolar planets
  - Pulsars : rapidly rotating neutron stars
  - Other Galactic objects like : supernova remnants, microquasars etc
  - Other explosive events like Gamma Ray Bursts
  - Ionized and neutral Hydrogen gas clouds (in our Galaxy and in other galaxies)
  - Radio properties of different kinds of galaxies; galaxy clusters
  - Radio galaxies at large distances in the Universe
  - Cosmology and the Epoch of Reionization
  - All sky surveys such as the 150 MHz TGSS

  - …and many interesting new results have been produced.

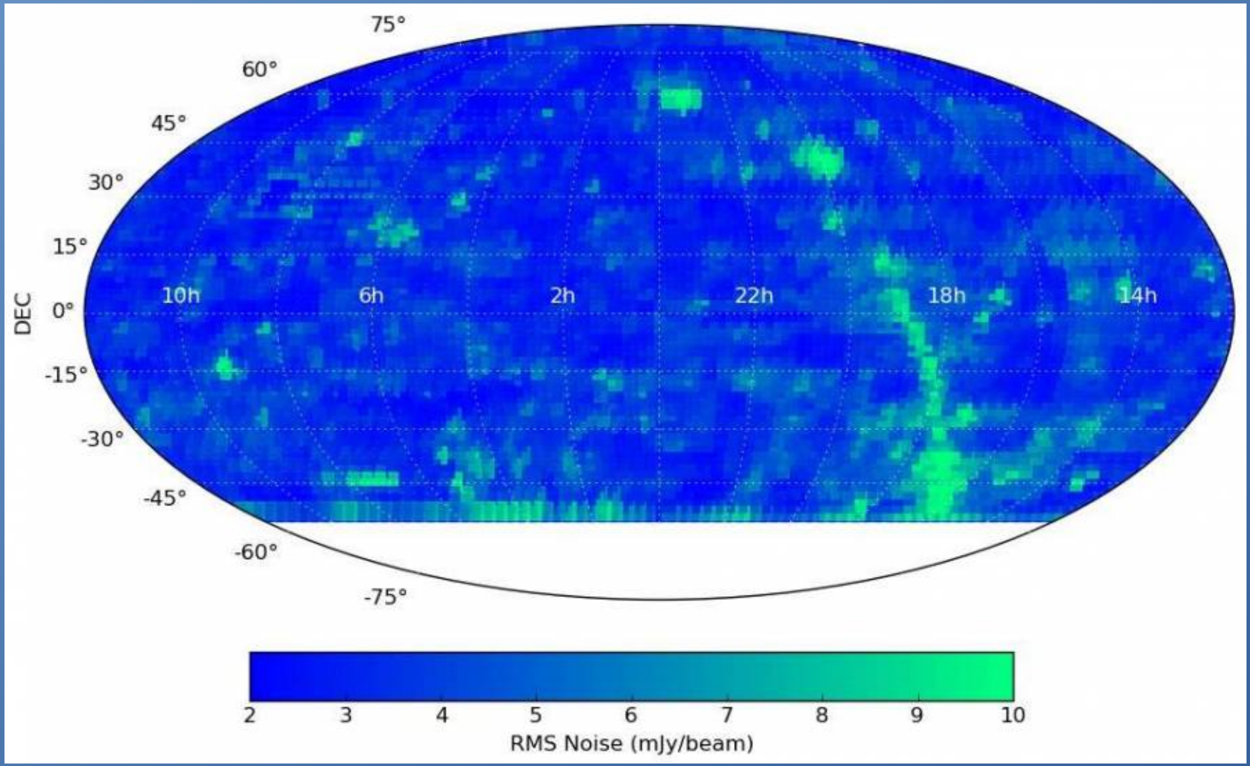
All Sky Surveys : TGSS

- All sky survey at 150 MHz
- Metrewave counterpart of NVSS (spectrally matched)
- 20" resolution (~ 5x better than NVSS)
- Median noise ~ 3.5 mJy/beam achieved
- 0.6 million sources already catalogued
- 5336 mosaic images of 5x5 sq deg





All Sky Surveys : TGSS



- Sky covered by the TGSS survey at 150 MHz : all sky > -53 dec.
- TGSS results and data products are proving very useful and popular – this is just what astronomers needed at low frequencies.

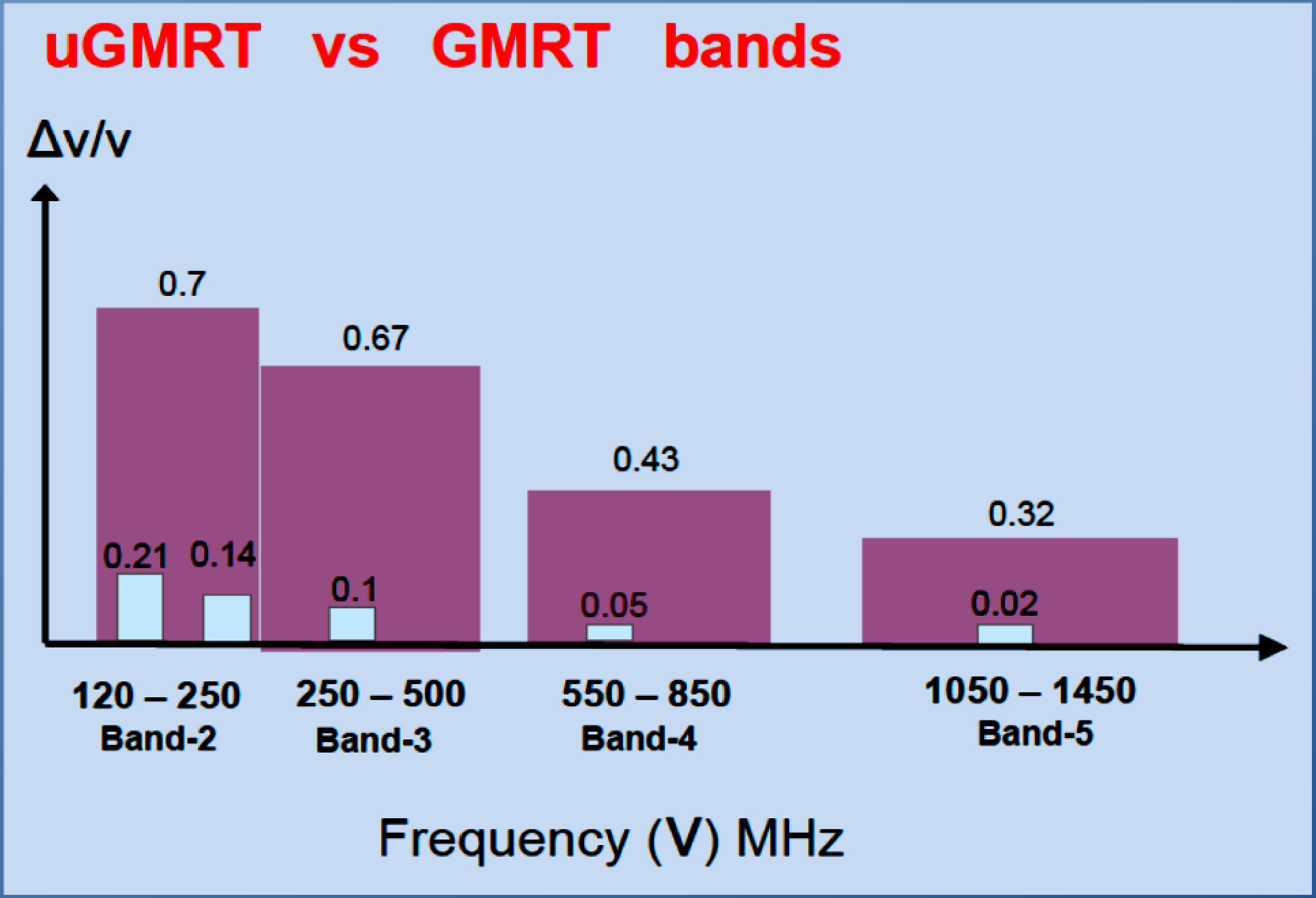
Part III

The GMRT : upgrade and recent status

GMRT : Current Status & Future Prospects

- The GMRT has produced several interesting and exciting new results in the 15 years that it has been functioning as an international facility
- We have just completed an upgrade of the GMRT to improve its sensitivity by more than a factor of two, and also make it a much more versatile instrument – to keep it on the fore-front of the global scenario for the next decade or so
- The upgraded GMRT provides near seamless frequency coverage from 120 to 1450 MHz at present (likely to be extended down to 50 MHz), with a maximum instantaneous bandwidth of 400 MHz (replacing 32 MHz of the legacy system), with improved sensitivity receivers.

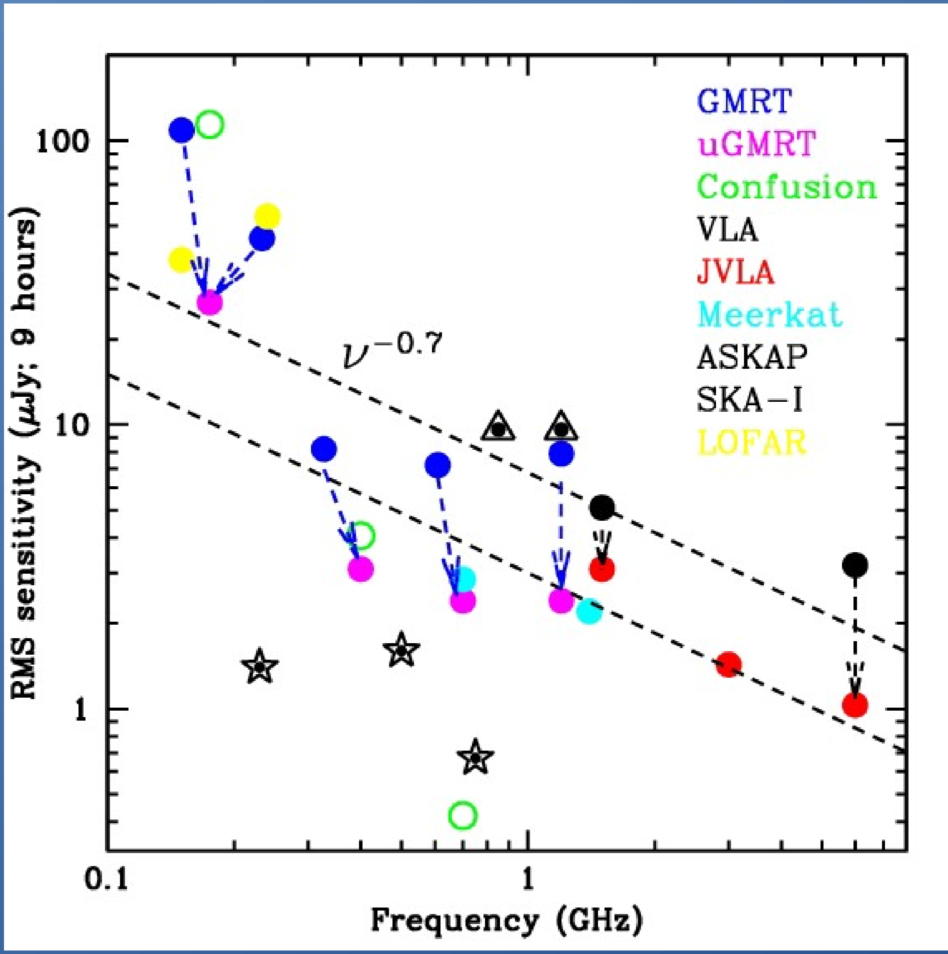
GMRT vs uGMRT : Frequency Coverage



courtesy : Ruta Kale (NCRA)

uGMRT : Expected Performance

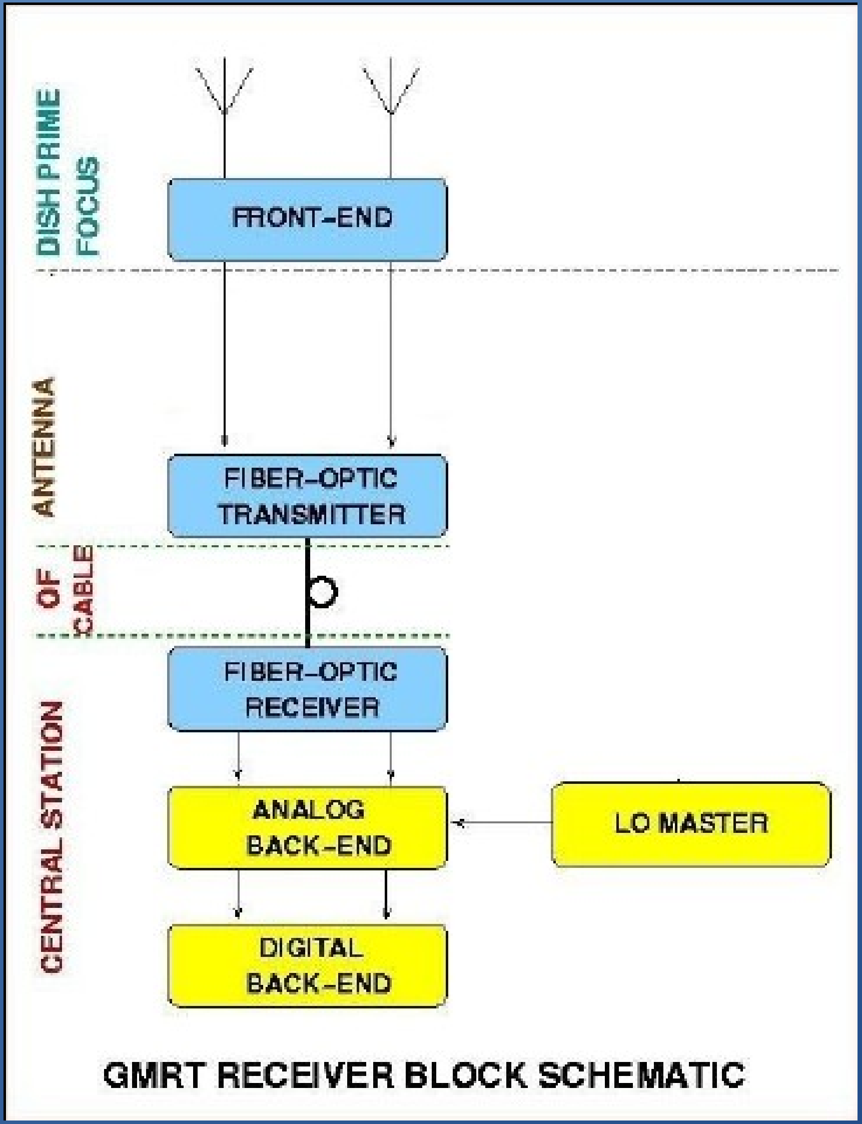
- Spectral lines : broadband coverage will give significant increase in the redshift space for HI lines + access to other lines
- Continuum imaging sensitivity will improve by factor of 3 or so.
- Sensitivity for pulsar observations will also improve by factor of 3.
- Only SKA-I will do better then uGMRT at centimeter wavelengths



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

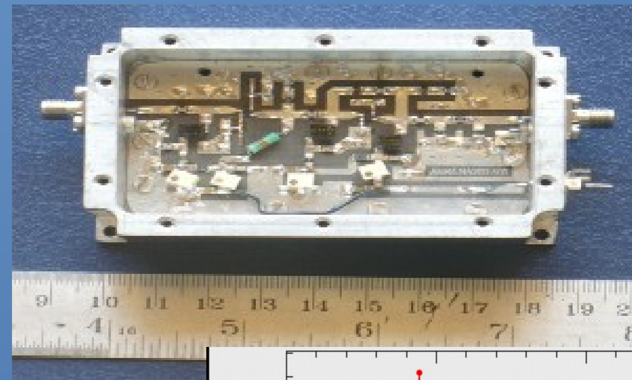
Overview of uGMRT Receiver System

- Broad-band feeds + FE (in octaves) :
  - 1000 – 1450 MHz (updating L-band)
  - 550 – 850 MHz (replacing 610)
  - 250 – 500 MHz (replacing 325)
  - 120 – 250 MHz (replacing 150)
- Modified optical fibre system to cater to wideband (50 to 2000 MHz) dual pol RF signals (while allowing existing IF signals)
- Analog back-end system to translate RF signals to 0 - 400 MHz baseband
- Digital back-end system to process 400 MHz BW for interferometric and beam modes

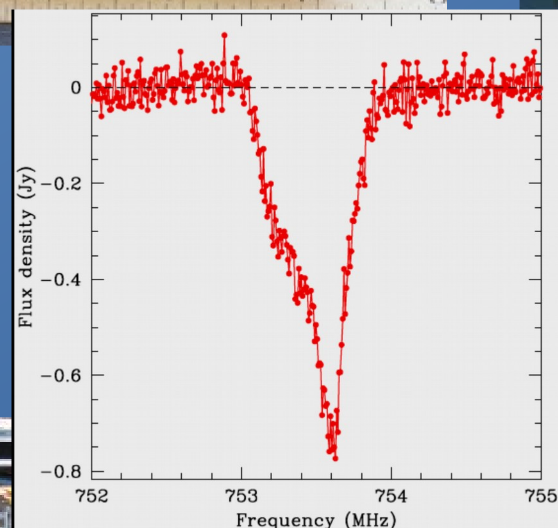


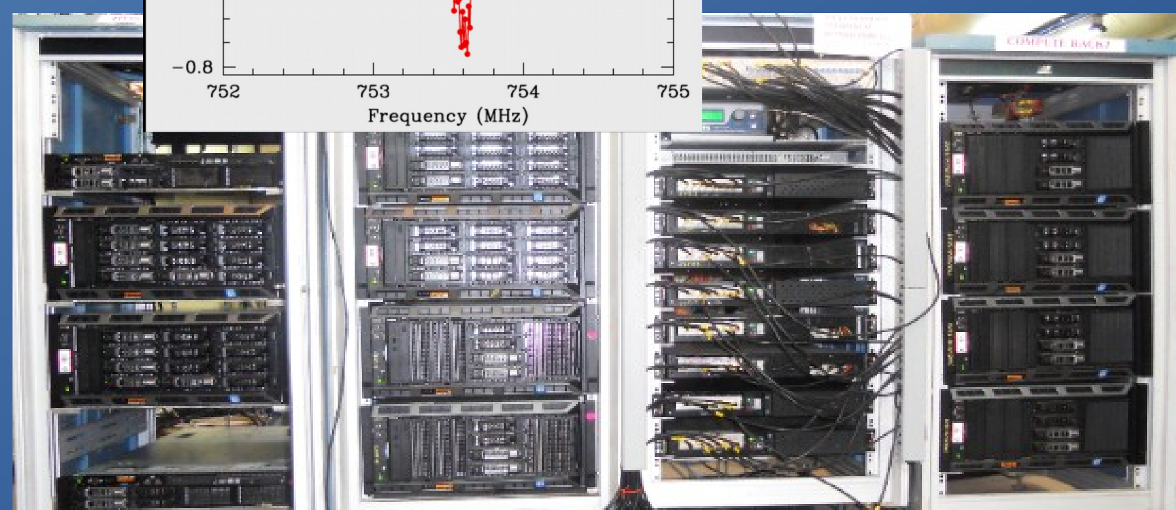
NCRA • TIFR

The Upgraded GMRT : in a Nutshell

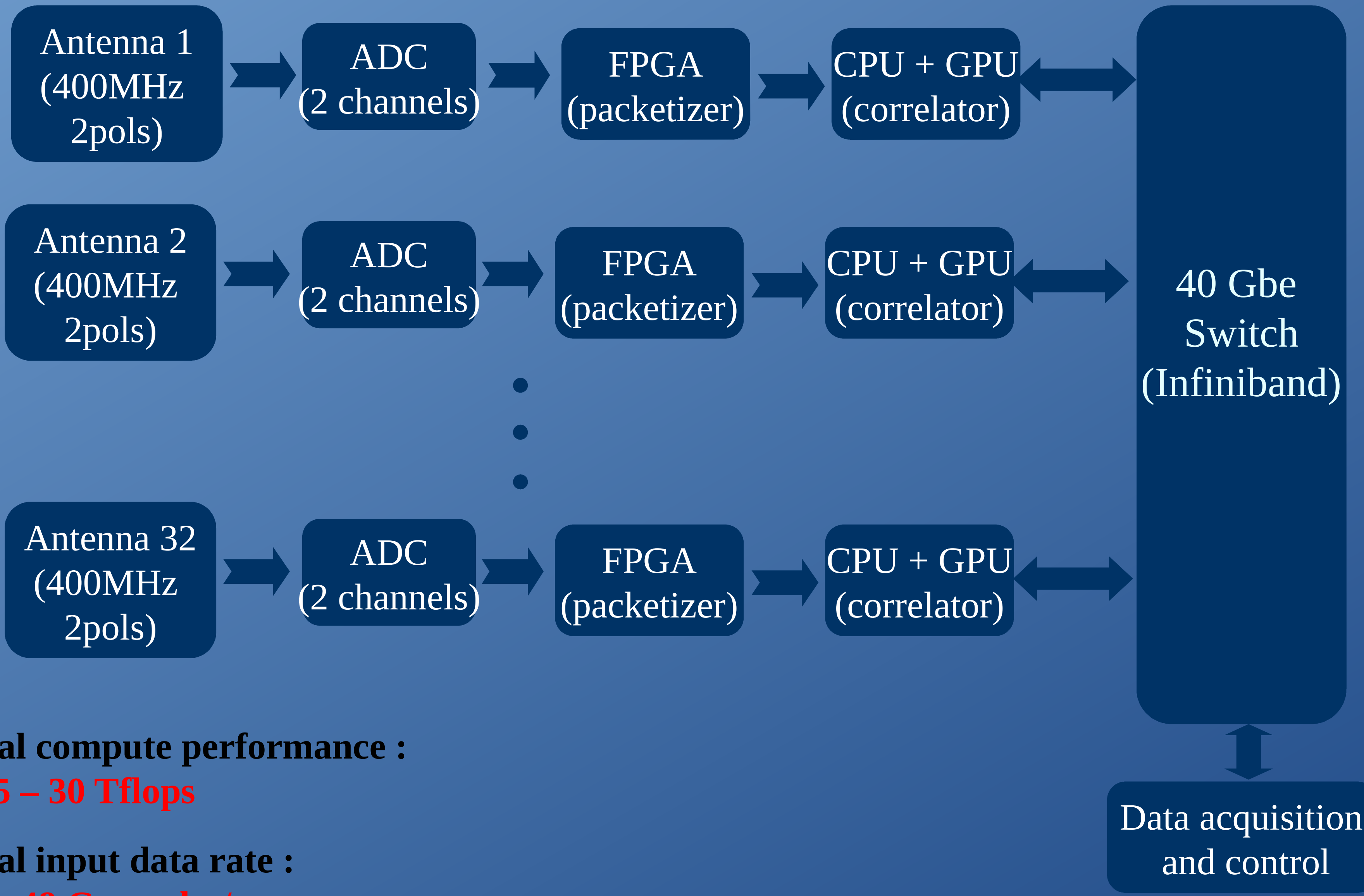


- wideband RF electronics;
- improved optical fibre system;
- next gen digital processing;
- revamped servo systems;
- smart interference rejection;
- exciting, new results !





GMRT Receiver System : Overview



Total compute performance :
~ 15 – 30 Tflops

Total input data rate :
24 – 48 Gsamples/sec

Challenges on the Road to uGMRT

The main challenges that we have encountered have been :

- Technological : design of the wideband receiver systems was a major challenge

- Operational : keeping the existing GMRT working for our regular users while upgrading simultaneously took some effort

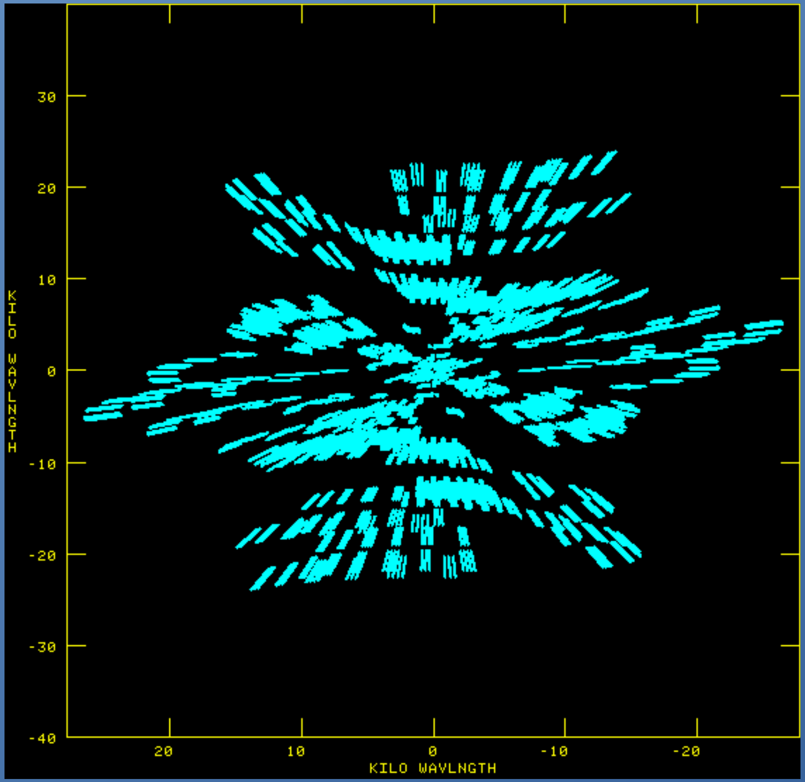
- Taking care of man made Radio Frequency Interference (RFI) is and remains our biggest challenge !
  - Containing self generated RFI
  - Mitigating RFI from external sources :

    (i) broadband impulsive (ii) spectral line

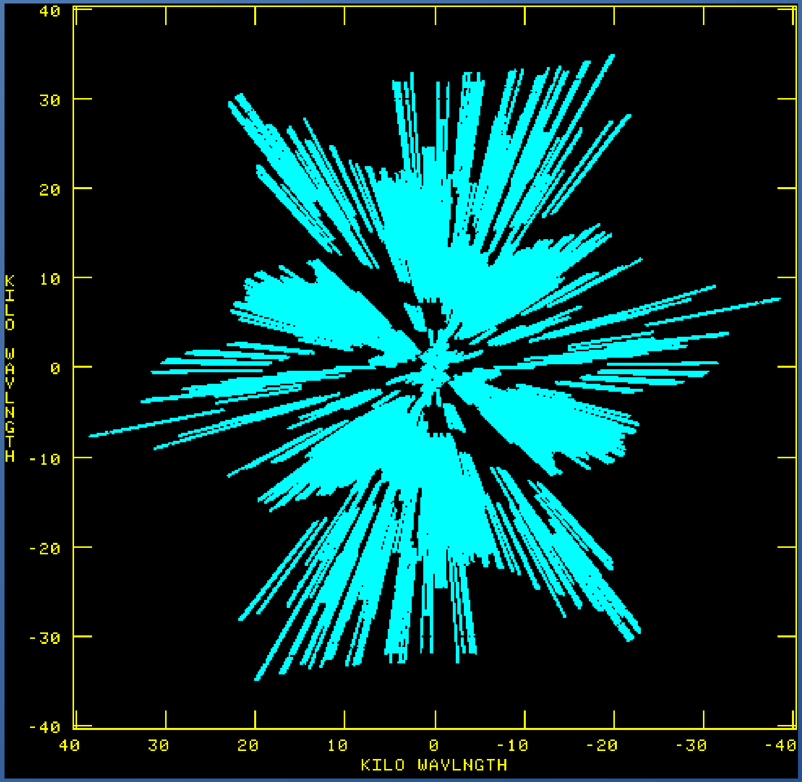
Improved imaging with uGMRT

- Large bandwidth of observations leads to improved uv-coverage and hence better imaging quality

Legacy GMRT : 325 +/- 16 MHz

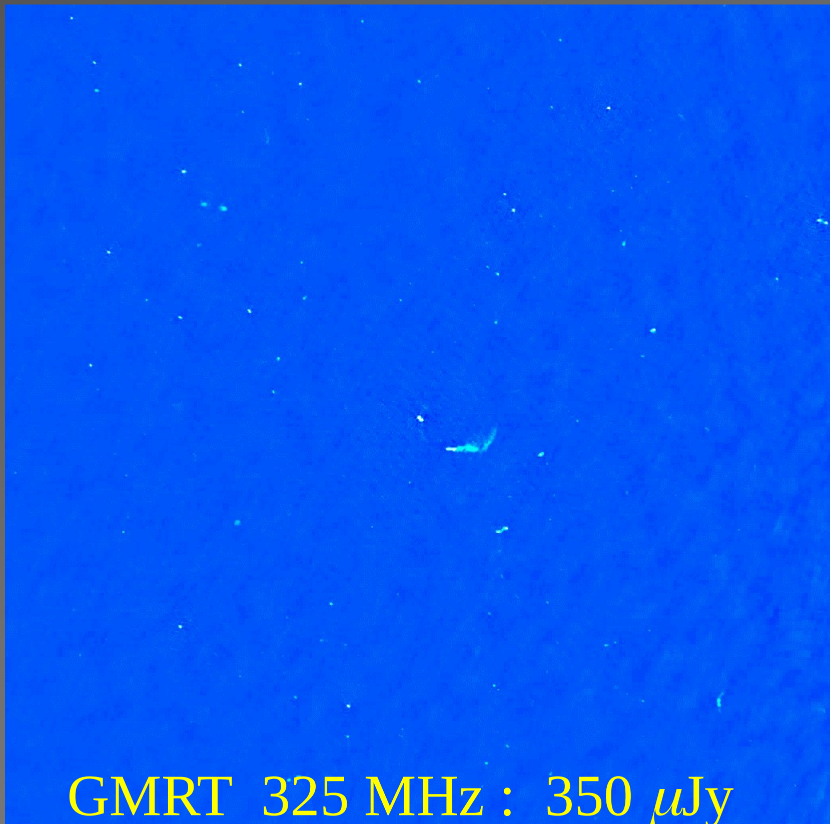


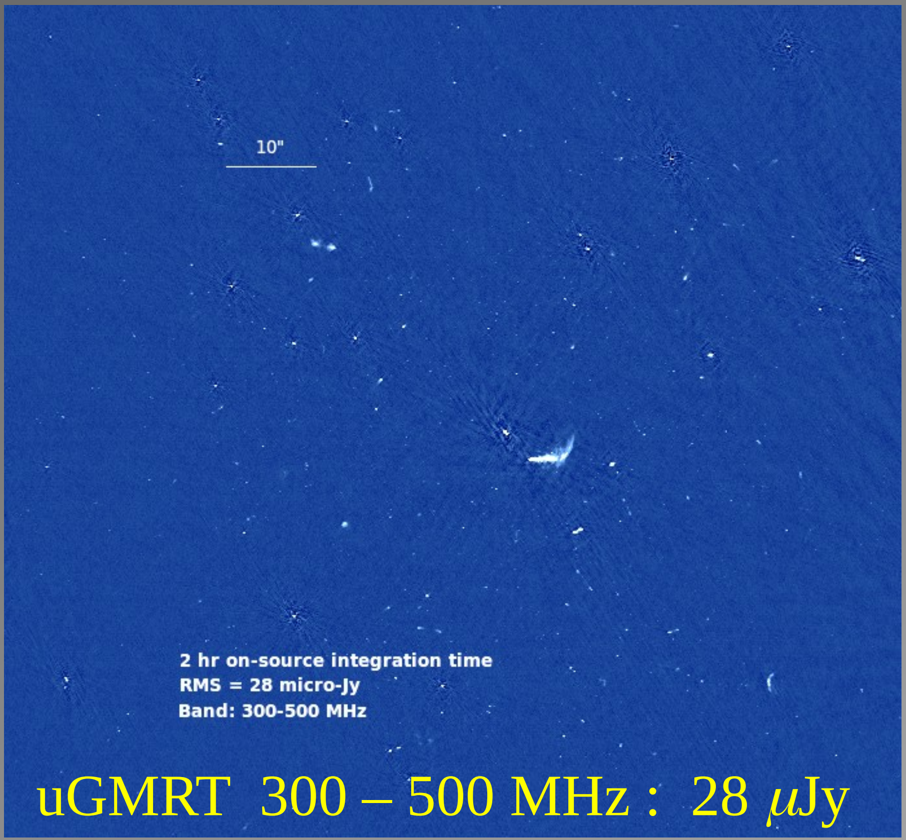
Upgraded GMRT : 400 +/- 100 MHz



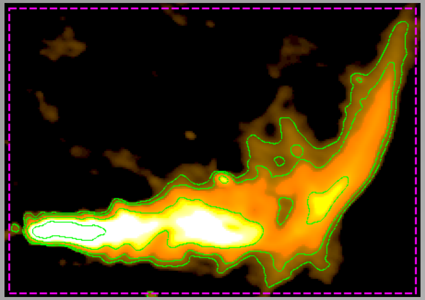
Courtesy : D.V. Lal

Improved imaging with uGMRT





- 10x lower noise RMS in uGMRT image for similar observing times
- Could detect 30 radio galaxies in the Coma cluster, some for the first time



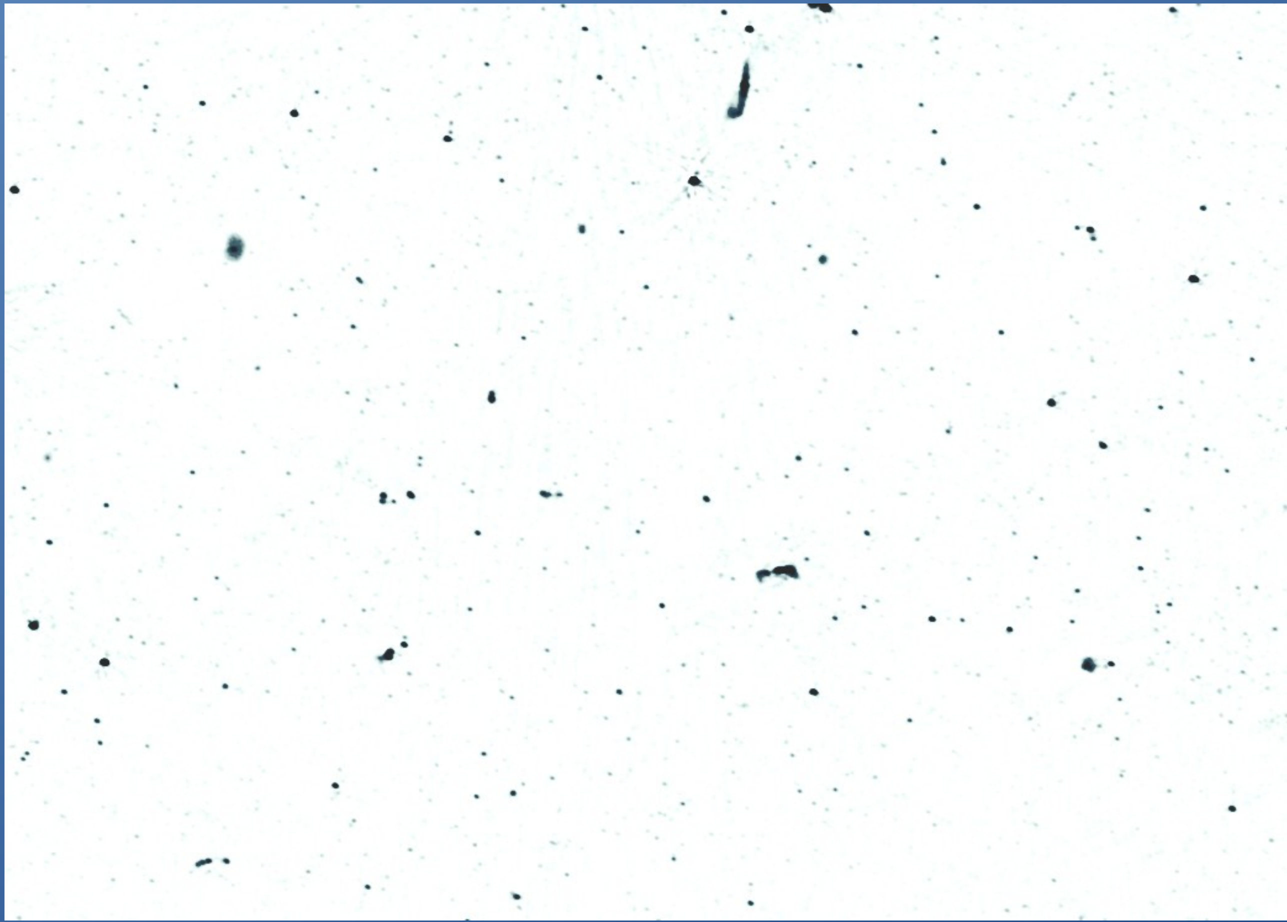
Courtesy : Lal & Ishwar-Chandra

Part IV

The GMRT : sample new results and science potential for future

Deep field imaging with the uGMRT : XMM-LSS at Band-3 (300-500 MHz)

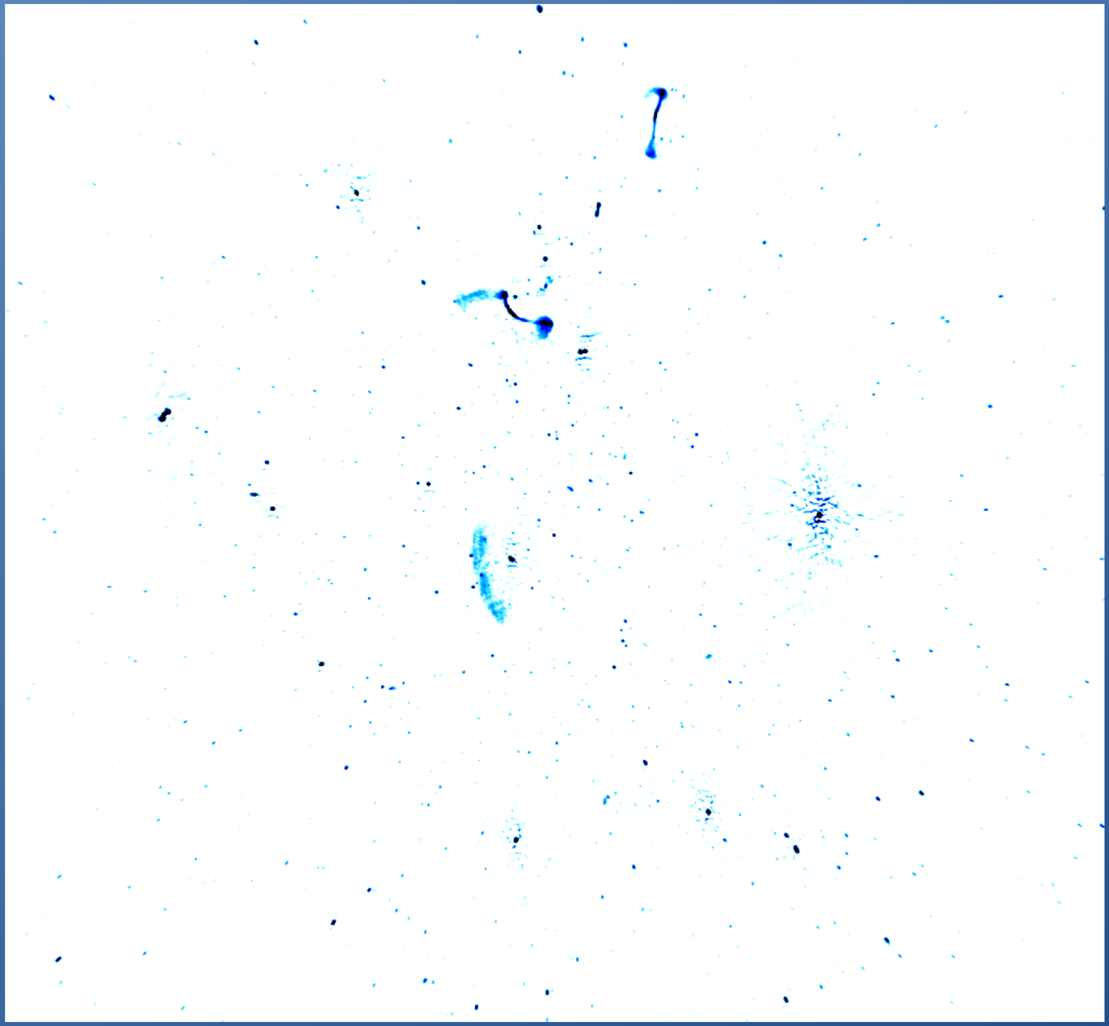
- Deepest ever (most sensitive) image made at 400 MHz by any telescope !
- 200 MHz BW
- 20 hrs on-source time
- 6.7”x5.8” resolution
- 14 microJy / beam noise
- Over 1600 sources per sq deg !



Ishwar-Chandra & collaborators

Deep imaging with the uGMRT : Abell 521 at Band-4 (550-850 MHz)

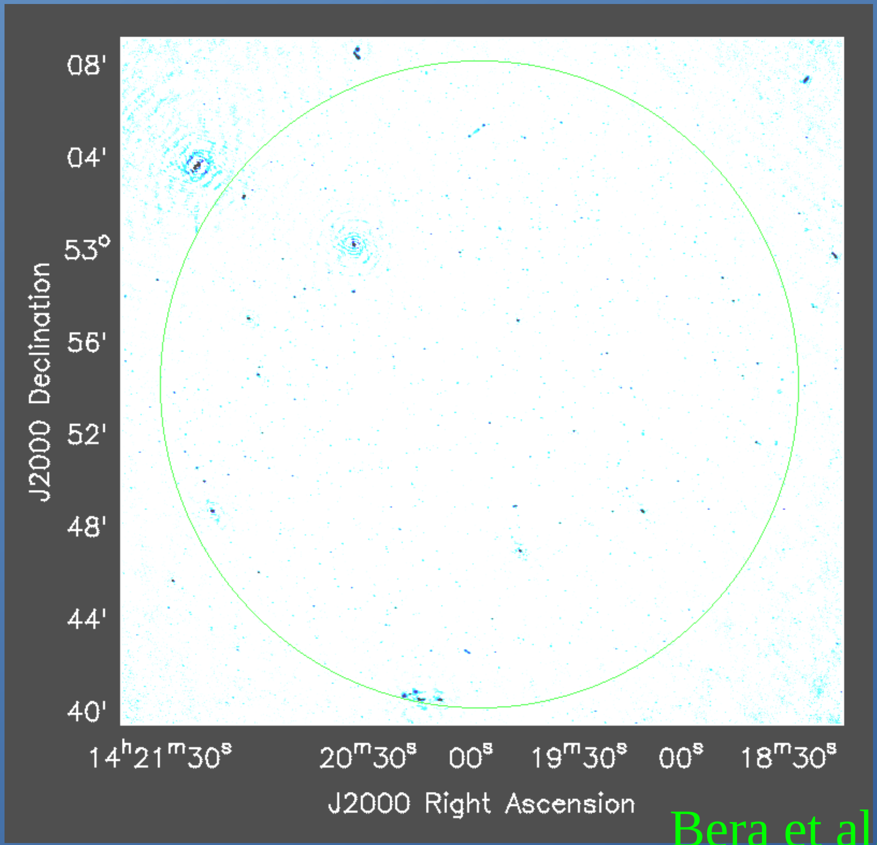
- Deepest image at Band-4 so far
- 10 microJy / beam noise !
- Arc like shock relic
- Faint central radio halo
- Radio lobes of some of the galaxies – new detections

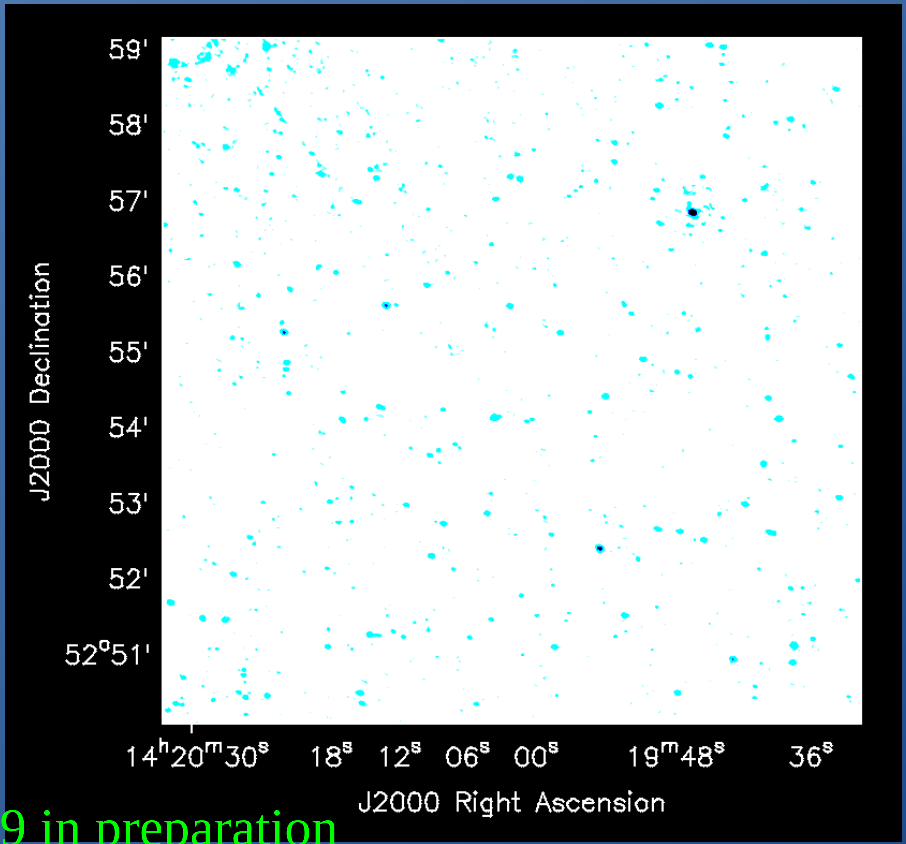


Kale & collaborators, 2019

Deep fields with the GMRT : Best image at Band-5 (1000-1460 MHz)

- Recent result from L-band (1000 – 1460 MHz) study of the Extended Groth
- Strip (EGS) field with the uGMRT
- Reached noise level of 2.3 microJy in ~ 110 hrs of on source observing
- Deepest image of the EGS ! deepest image with the uGMRT so far !!
- 2nd deepest image at L-band EVER (only JVLA has one deeper) !!!

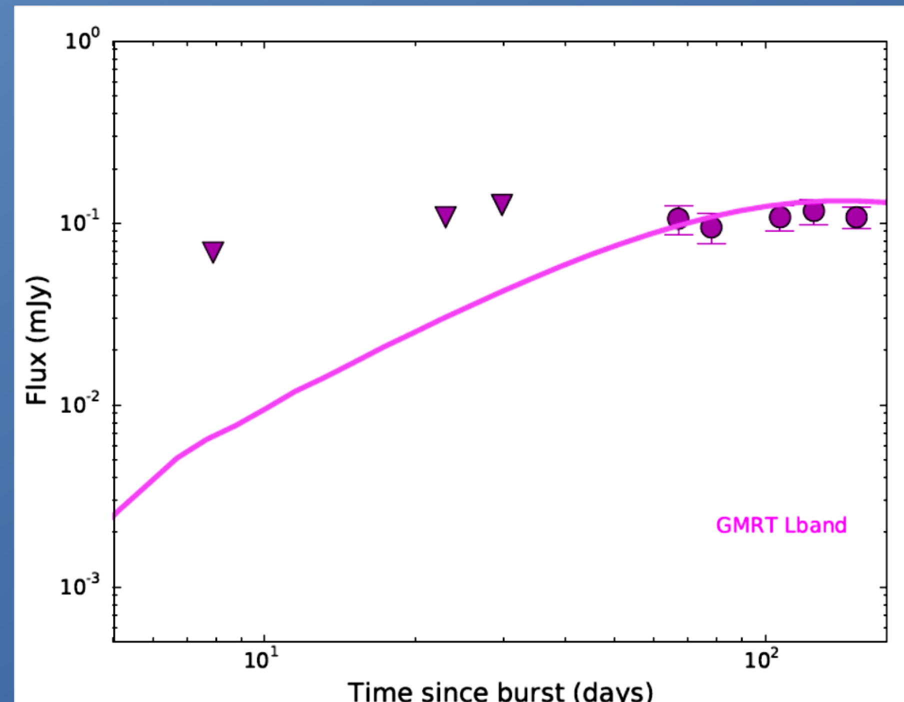




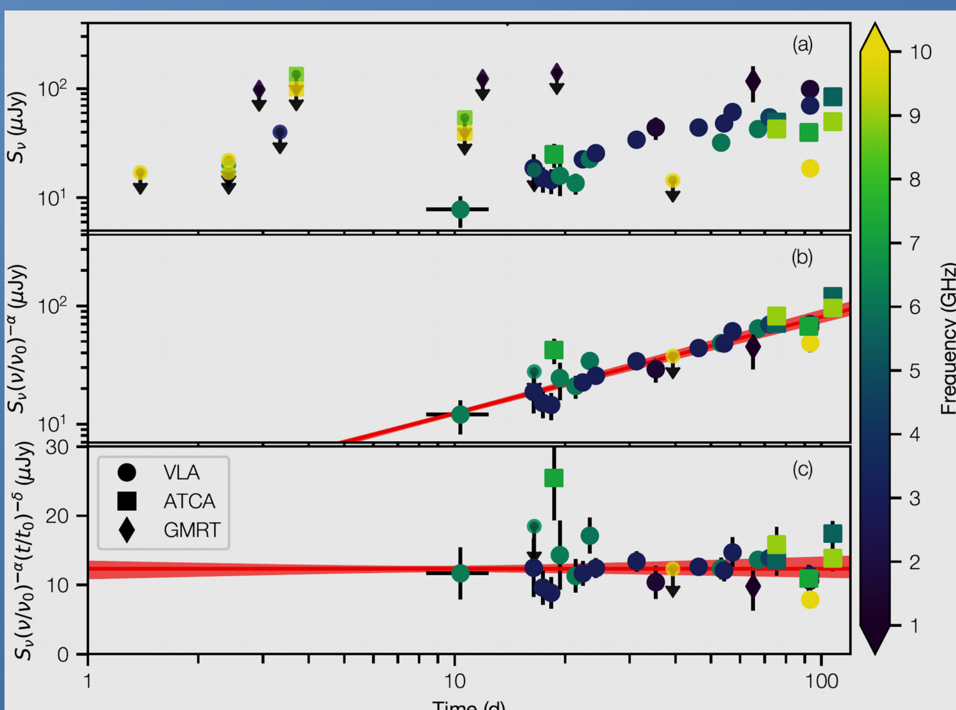
Bera et al, 2019 in preparation

GW170817 : neutron star merger event with the uGMRT

- uGMRT played an important role in the multi-messenger observations of the GW event of 17 Aug 2017.
- Two groups followed the source with the uGMRT – helped constrain the models for the structure of the event.

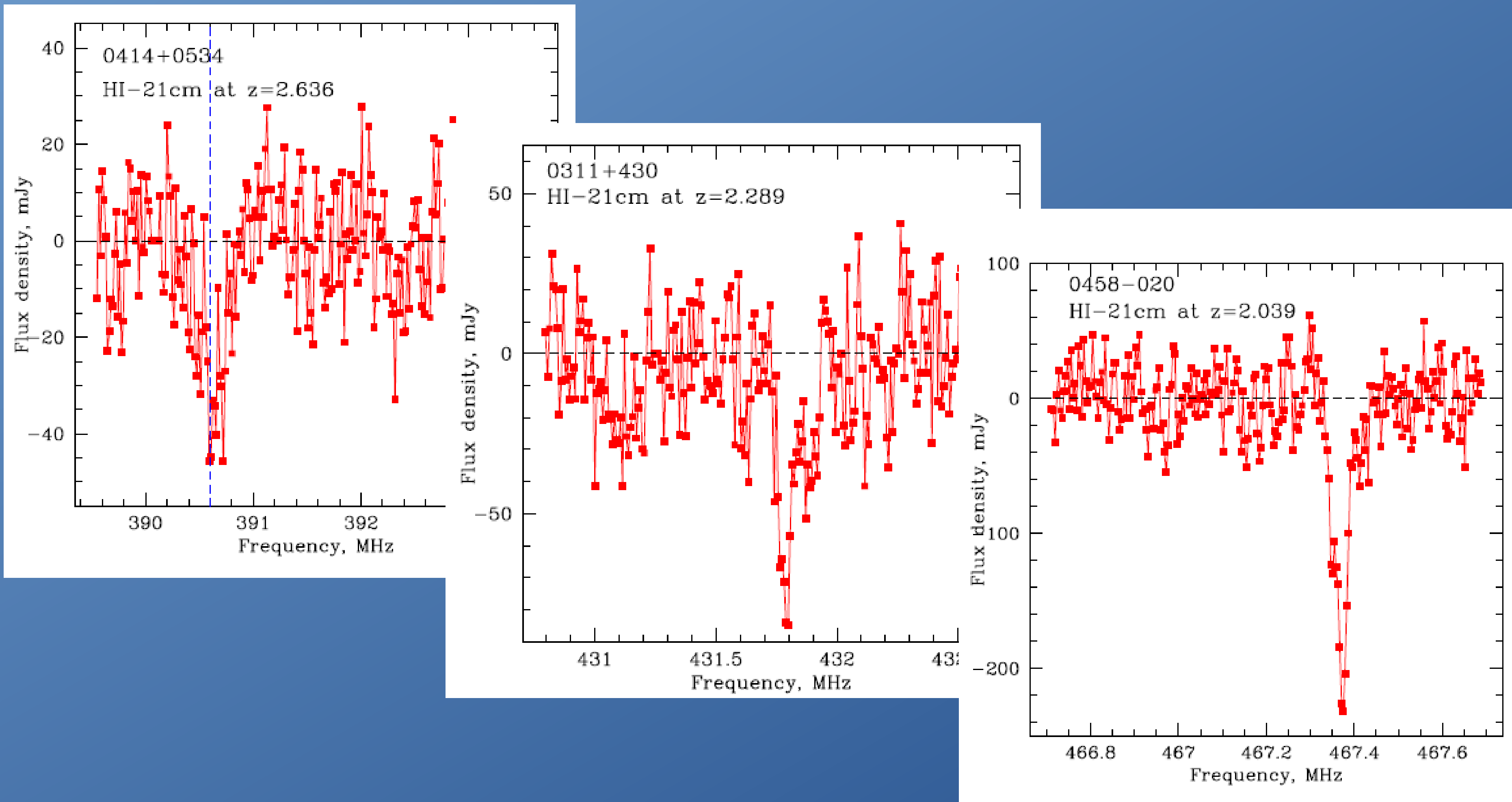


Resmi et al 2018



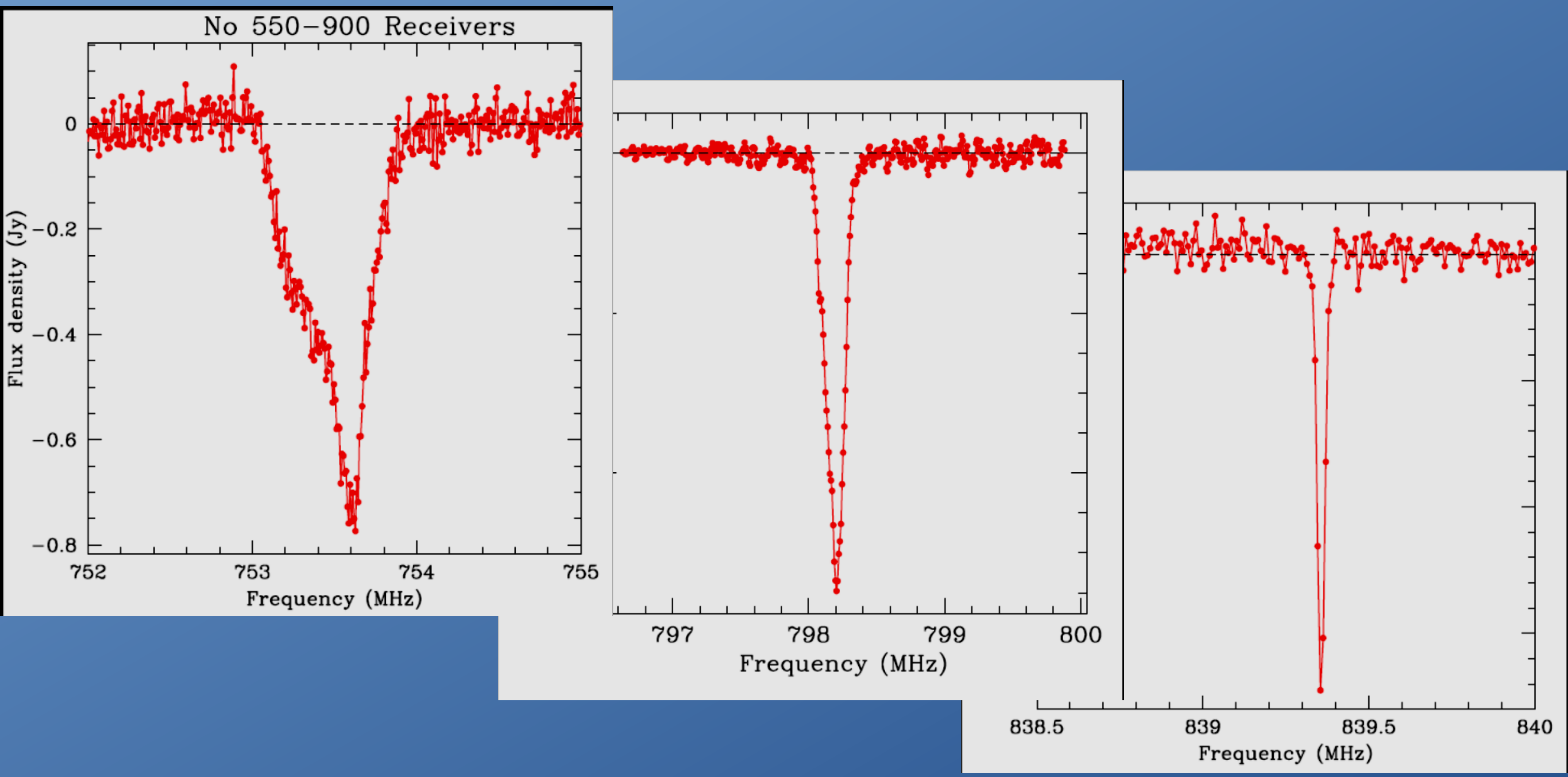
Hallinan et al 2017

Upgraded GMRT : opening new windows – Band 3 (250-500 MHz)



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

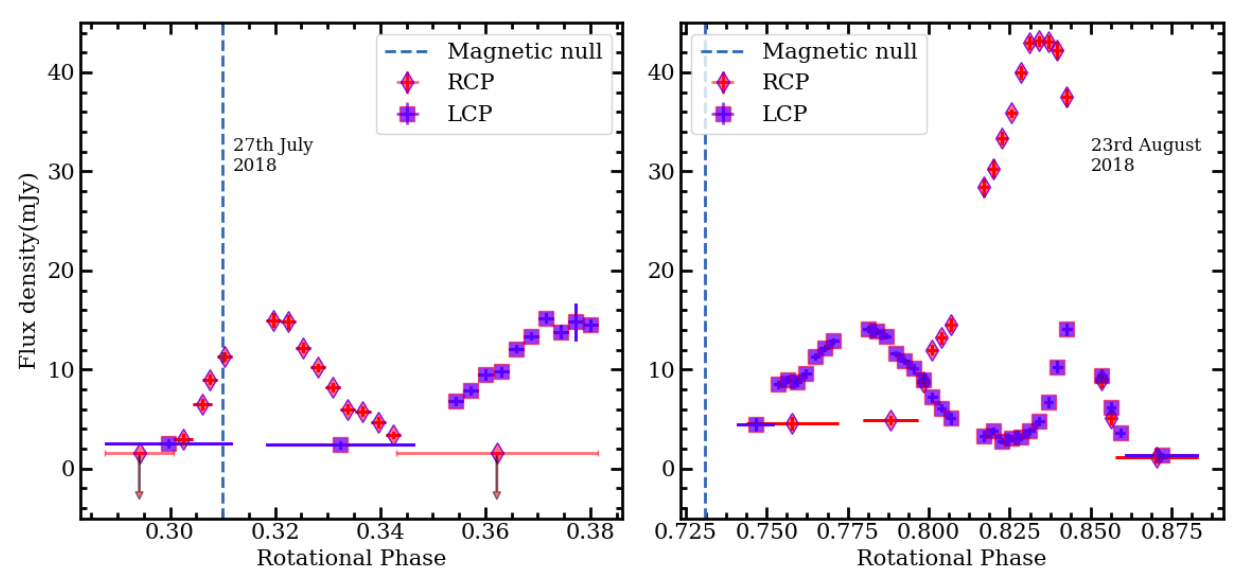
Upgraded GMRT : opening new windows – Band 4 (550-850 MHz)



First light results : spectral lines from different sources, at different parts of the 550-900 MHz band (Nissim Kanekar)

Magnetic stars with the uGMRT

- Coherent radio emission from hot stars with ordered magnetic fields
- Electron Cyclotron Maser Emission thought to be the likely candidate
- Only 1 star was known before GMRT jumped into the field
- 3 new discoveries with uGMRT in last couple of years – natural advantages
- Excellent probe of stellar magnetoshpere at different heights
- Now looking at a wider survey to better understand this new field



Das & Chandra 2017 onwards

Wideband pulsar observations : improved sensitivity with uGMRT

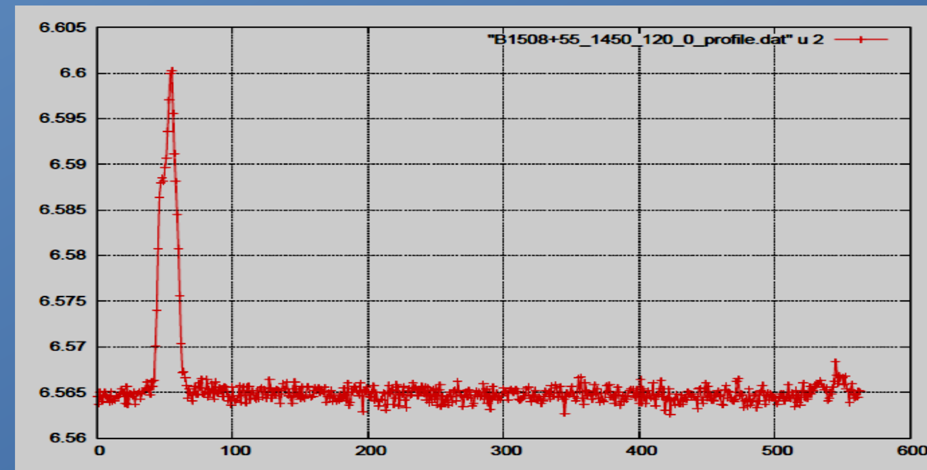
PSR B1508+55

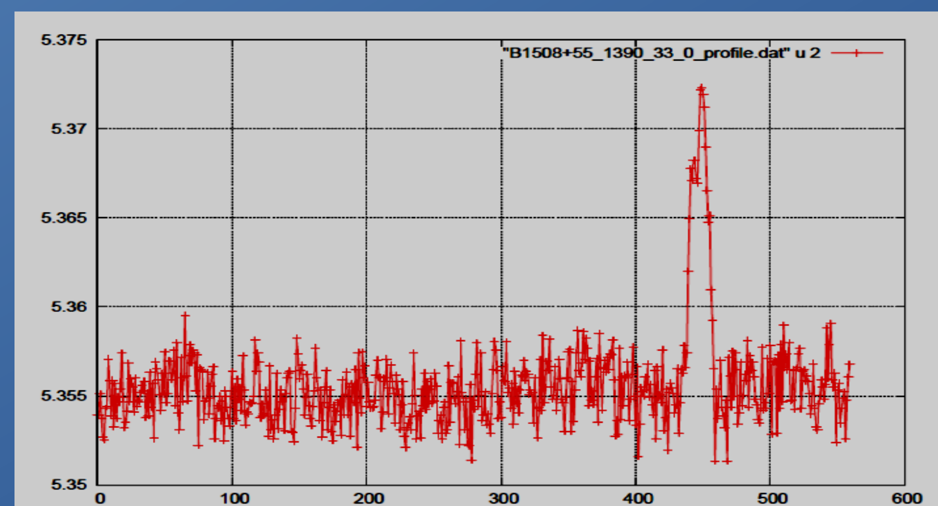
120 MHz at Lband (1330-1450)

vs

33 MHz at Lband (1390 sub-band)

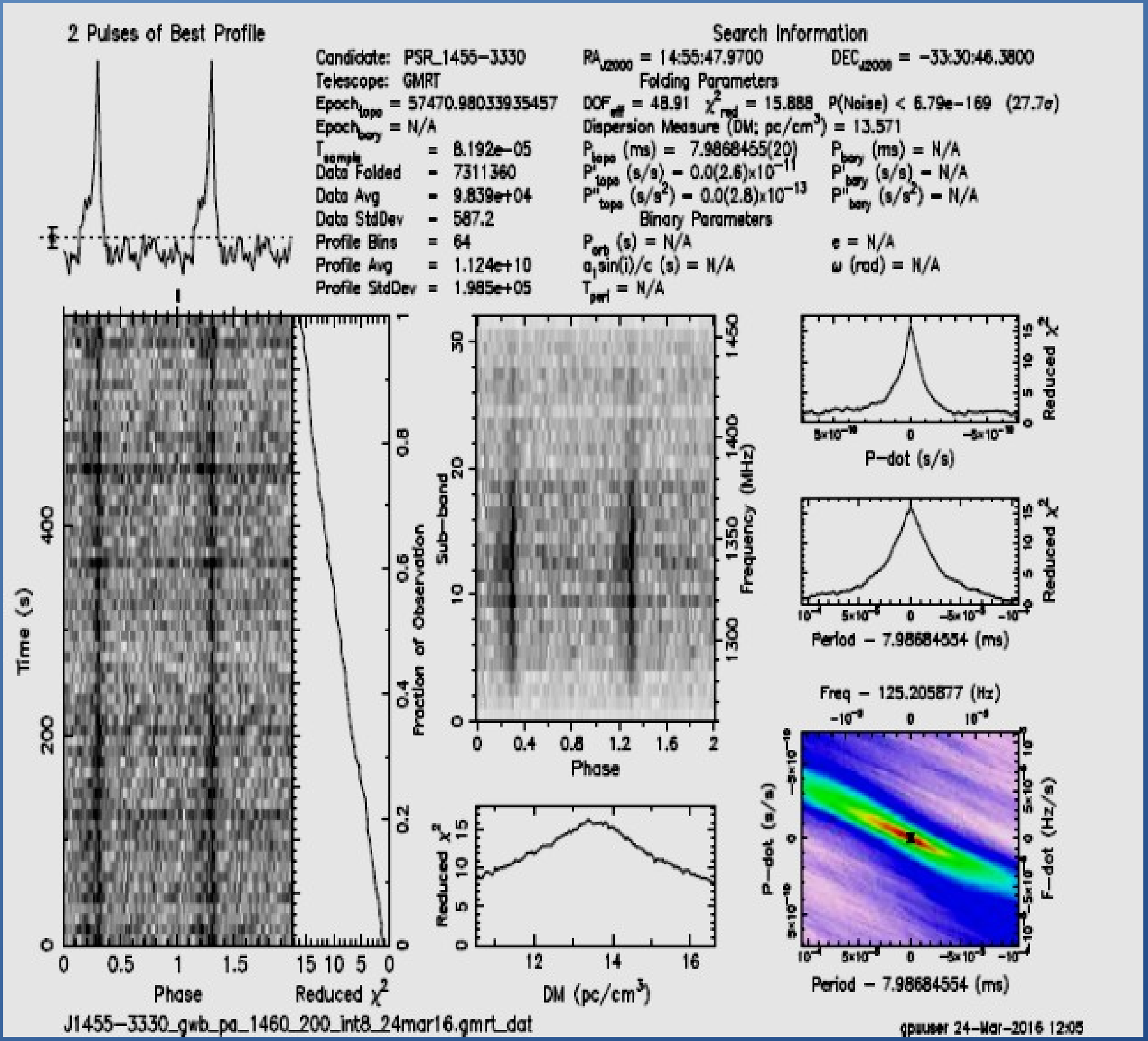
Simultaneous observations using same # of antennas in phased array mode.





Pulsars with uGMRT : improved sensitivity at Lband (Band-5)

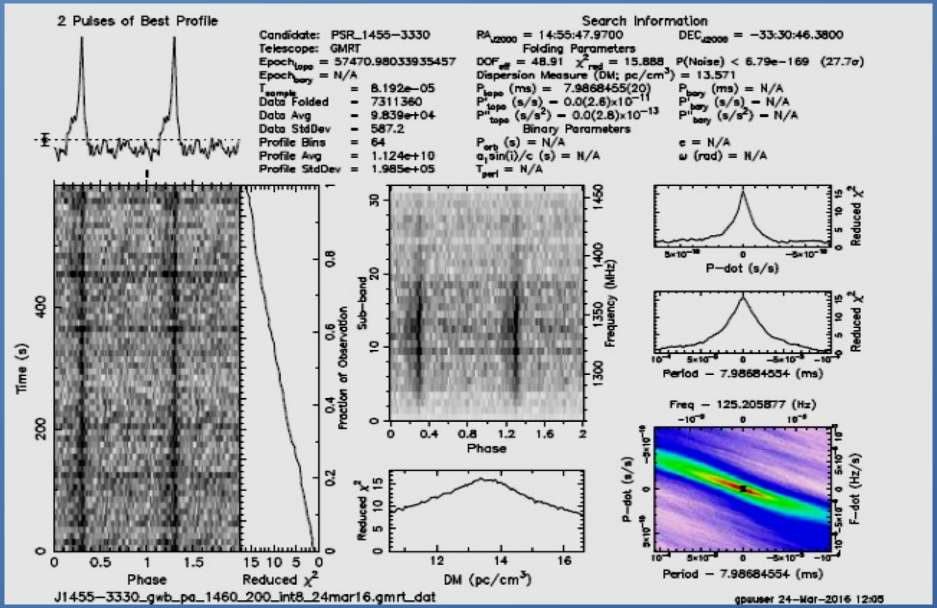
- J1455-3330
- S_1400 = 1.2 mJy
- Band-5
  (1260 to 1460 MHz)
- 10 mins scan
- 12 antennas



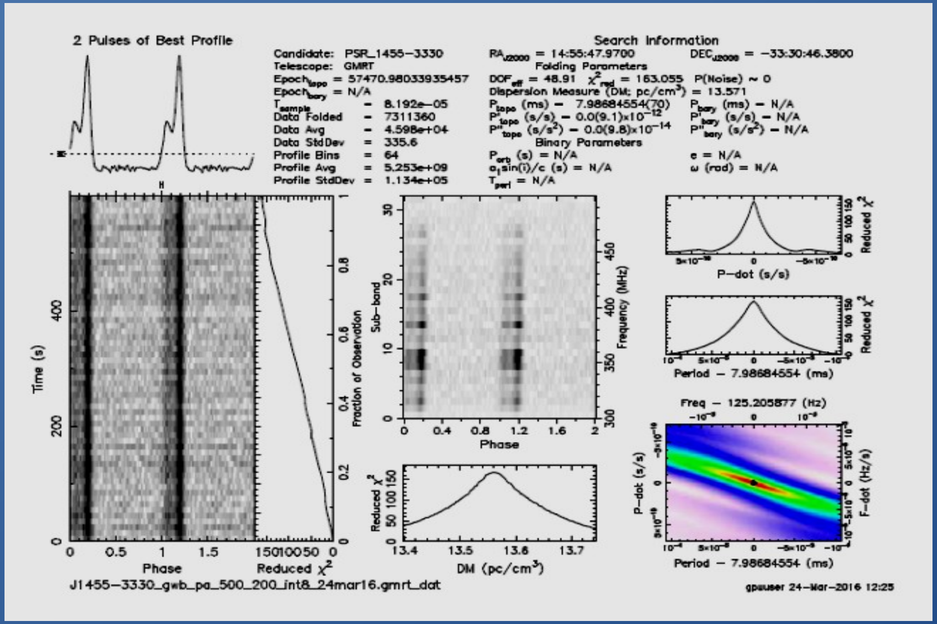
Simultaneous multi-frequency observations

Example with 2 beams :

- J1455-3330
- S_1400 = 1.2 mJy
- Band-5 (1260 to 1460 MHz)
- 10 mins scan
- 12 antennas

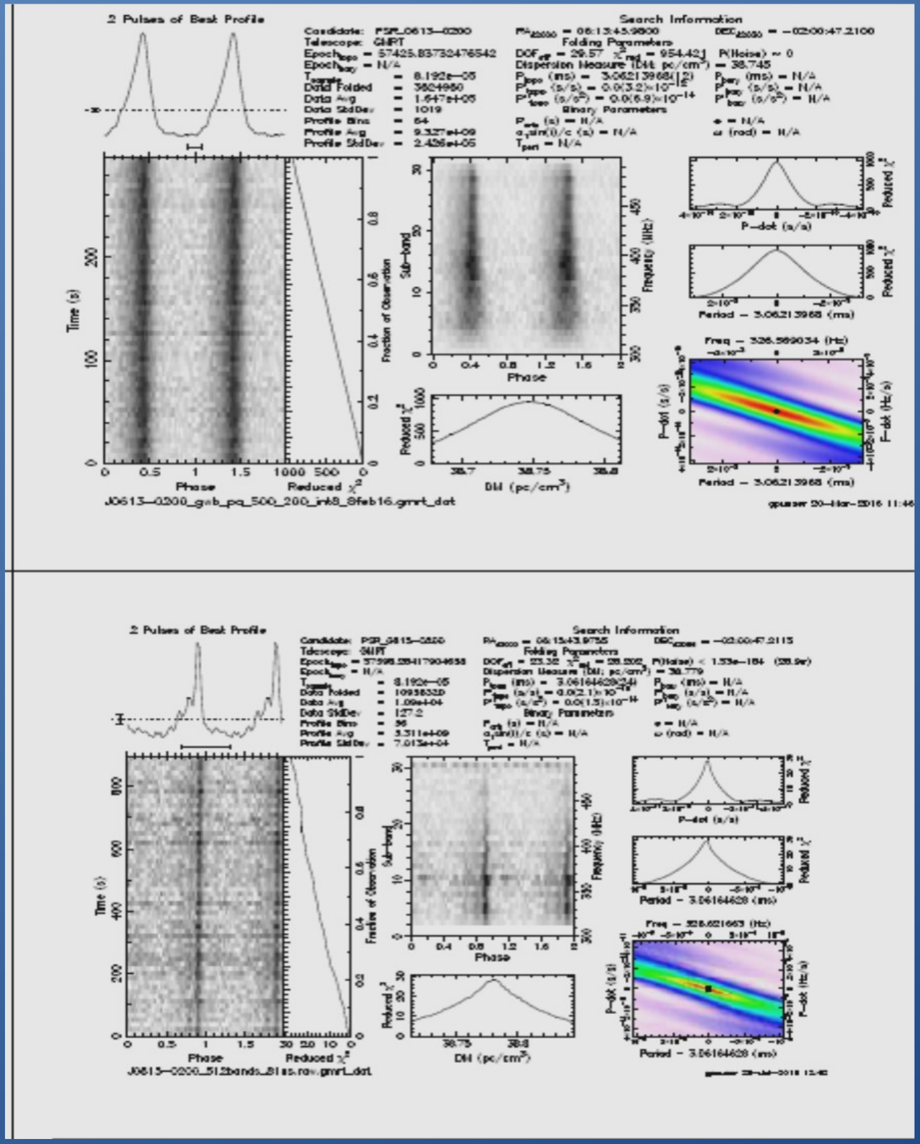


- MSP : J1455-3330
- S_400 = 9 mJy
- Band-3 (300 to 500 MHz)
- 10 mins scan
- 4 antennas (only)



Wideband Coherent Dedispersion for the uGMRT

- Coherent Dedispersion on voltage output of phased array mode of uGMRT
- Working in real-time (GPUs), for 100 to 200 MHz BWs, at low frequencies.
- Will be released soon for the general user community.
- Will increase the quality of pulsar studies with the uGMRT



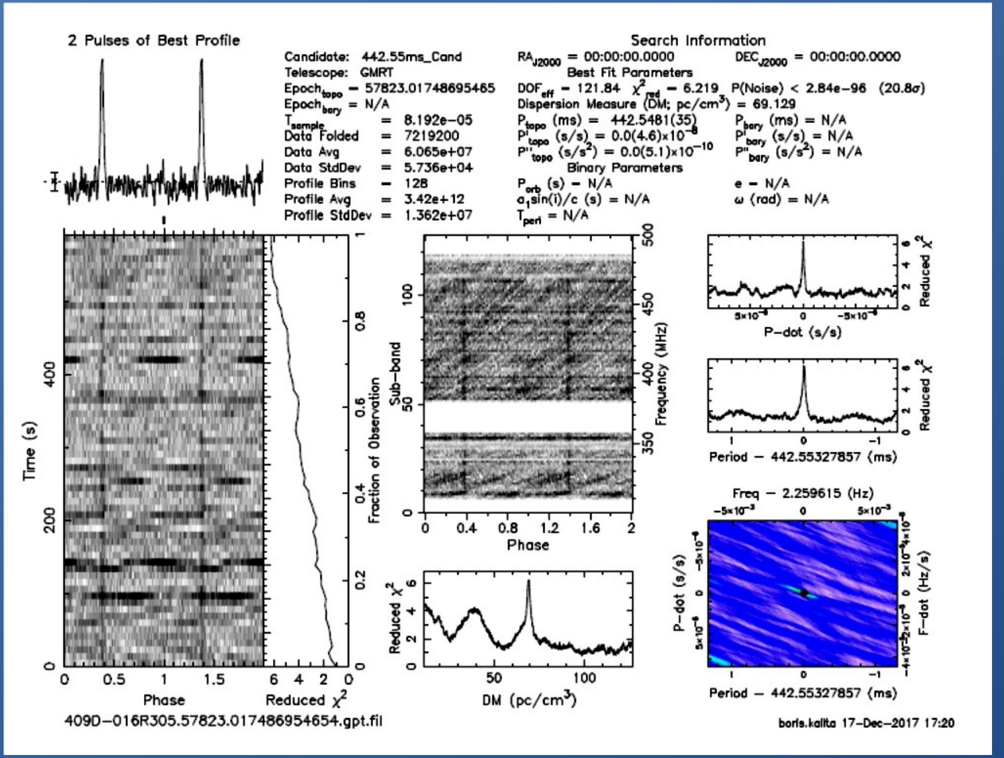
Comparison of
regular phased array beam output
with
coherent dedispersion output
for 300 to 500 MHz band of the uGMRT, for PSR J0613-0200

courtesy : Kishalay De & Y. Gupta

Finding new pulsars with the uGMRT

- uGMRT has significant potential for new pulsar discoveries (0.5 mJy in 10 mins in incoherent array mode)
- Some of the ongoing / planned pulsar searches are :
  - GHRSS : legacy GMRT + upgraded GMRT
  - uGMRT pilot survey for pulsars (PuGMaRK)
  - Targeted search in selected globular clusters
  - Targeted search in TGSS steep spectrum sources

First new pulsar discovery with the uGMRT !



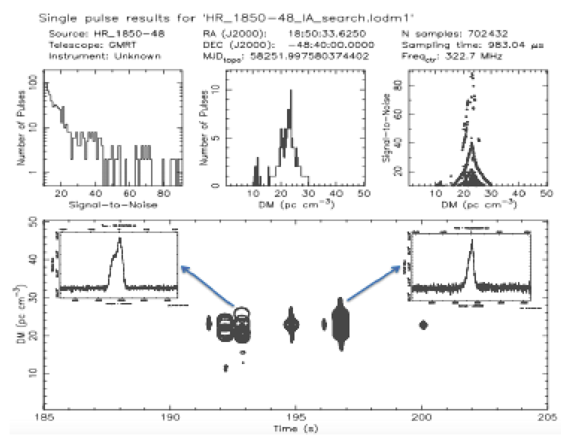
PuGMaRK team
December 2017

Finding new pulsars with the uGMRT

- uGMRT has significant potential for discoveries of new pulsars (0.5 mJy in 10 mins in incoherent array mode) and transients
- Some of the ongoing / planned pulsar searches are :
  - GHRSS : legacy GMRT + upgraded GMRT
  - uGMRT survey for pulsars (PuGMaRK)
  - Targeted search in selected globular clusters
  - Targeted search in TGSS steep spectrum sources

First new RRAT discovery with the uGMRT !

1st RRAT discovered with the GMRT



Credit : GHRSS team

J1850-48 at DM of 23 pc cm^{-3} and period of 327 ms is a RRAT discovered from the GHRSS survey

7 pulses (< 10 ms wide) see over 10-mins. The strongest pulse is at ~ 3 Jy

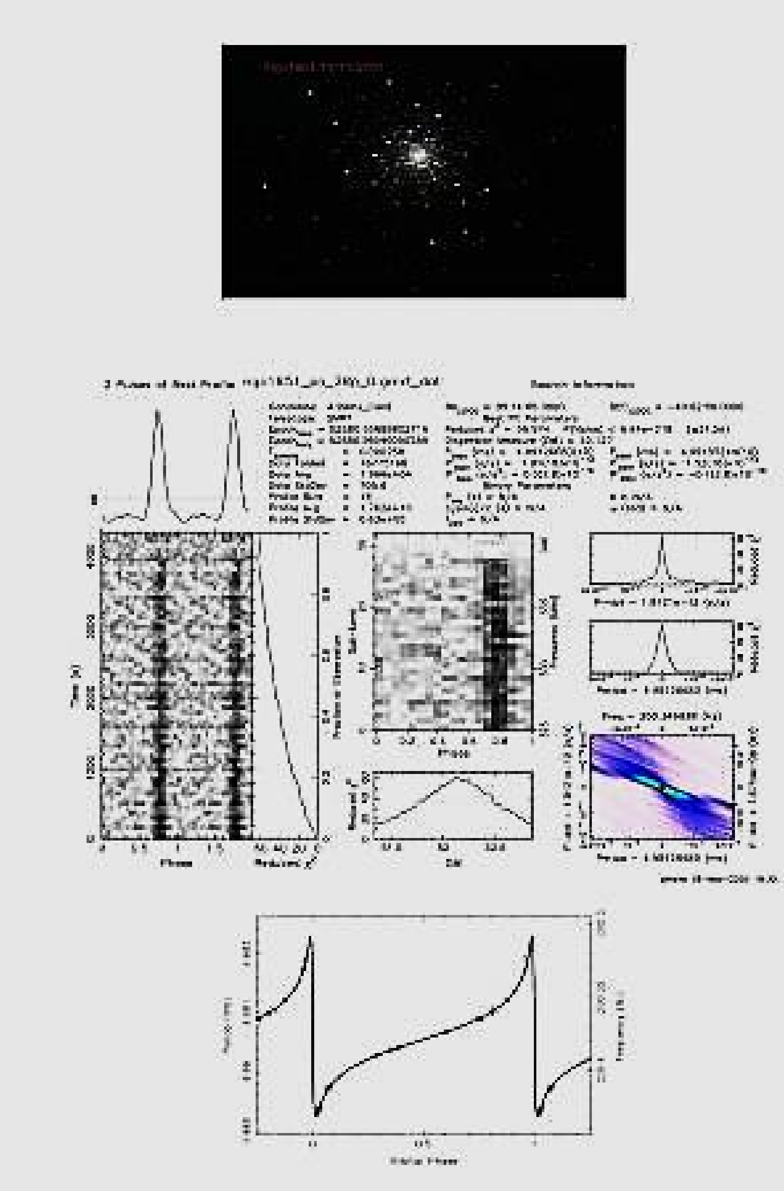
One of the nearby RRAT @ 0.8 kpc

GHRSS team

Jan 2019

Improved timing with uGMRT : the case of PSR J0514-4002A

- Discovered with the GMRT back in 2004 in globular cluster NGC1851
- Binary pulsar with *very eccentric orbit (e = 0.89) !* -- was record holder for many years.
- Initial timing observations determined advance of periastron : constrainted total mass of system :
  2.453 +/- 0.014 M_sun

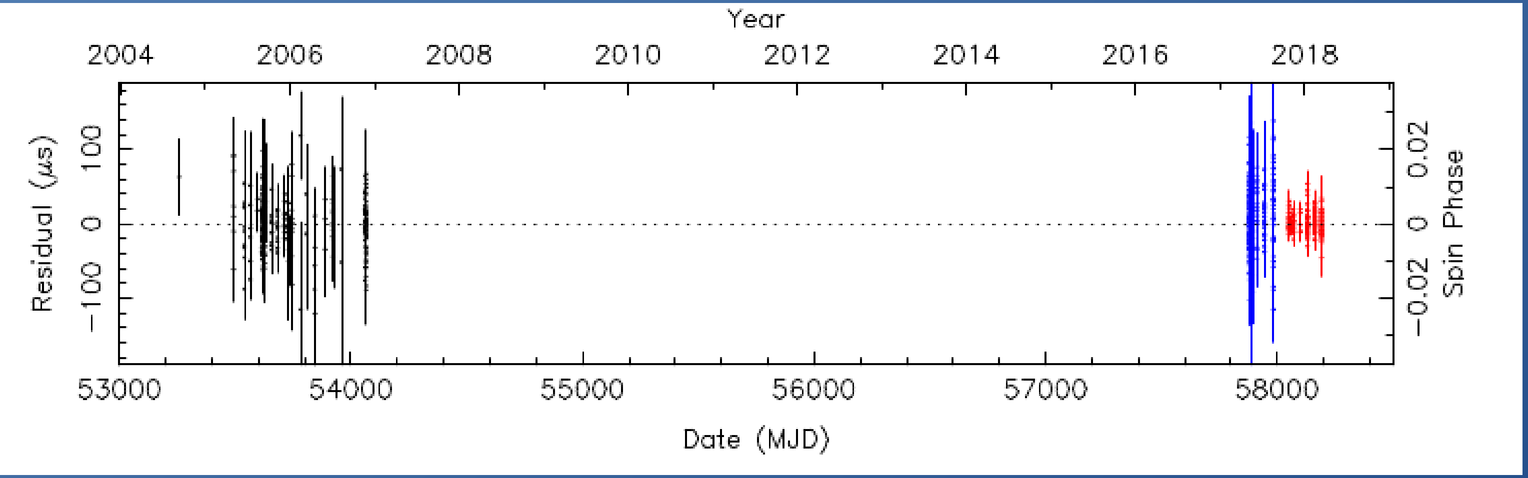


Freire et al (2004)

NCRA • TIFR

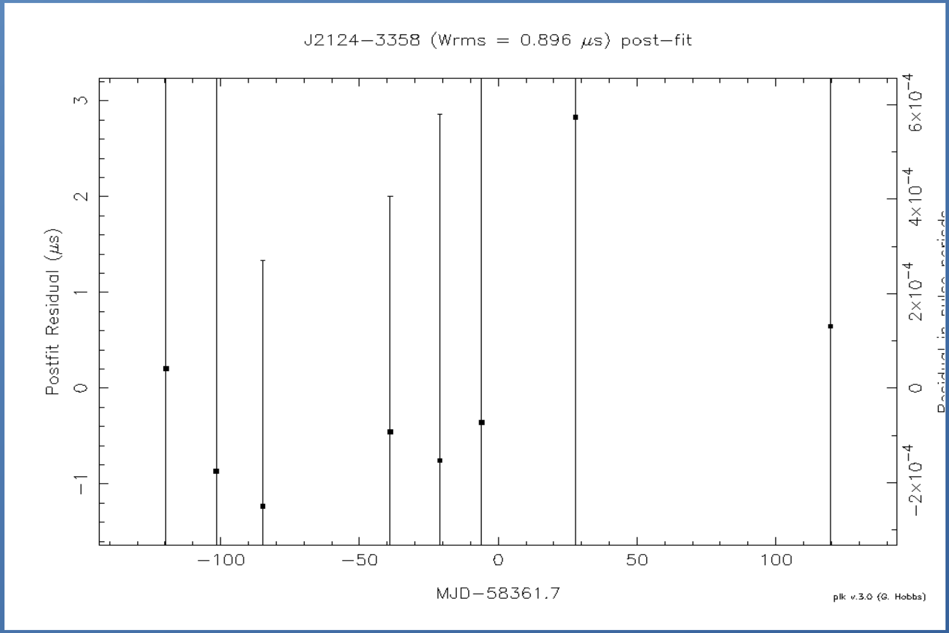
PSR J0514-4002A : improved timing with uGMRT

- More accurate & sensitive observations with uGMRT allow timing baseline to be extended over the 13 years interval
- Could measure a 2nd post-Keplerian parameter – the Einstein delay – with a 20-sigma significance
- Independent estimates of masses of neutron star and companion : 1.266 +/- 0.044 & 1.207 +/- 0.044 M_sun
- This may be the lightest millisecond pulsar with precisely measured mass
- Also, companion may also be a neutron star ?

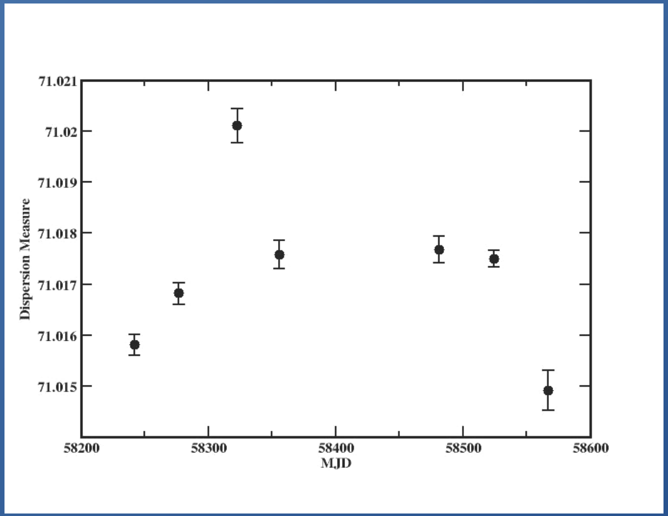


Precision timing with the uGMRT

- Regular observations for a few well known MSPs – InPTA
- Simultaneous dual-frequency observations with uGMRT :
  Band-5 (1260-1460 MHz) and Band-3 (300-500 MHz)
- Now extended to multi-frequency (3 bands) with 30 antennas
- USP : Good quality TOAs at multiple frequencies, DM & other ISM effects



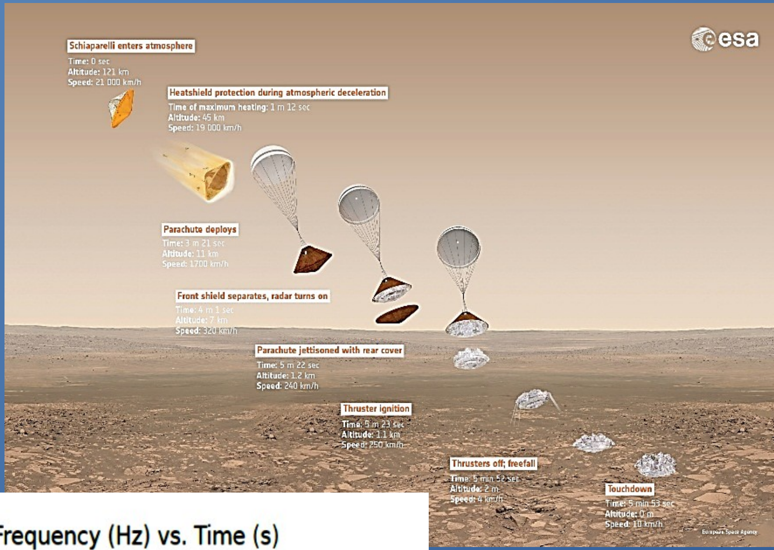
PSR J2124-3358 with uGMRT : achieving sub-microsecond residuals



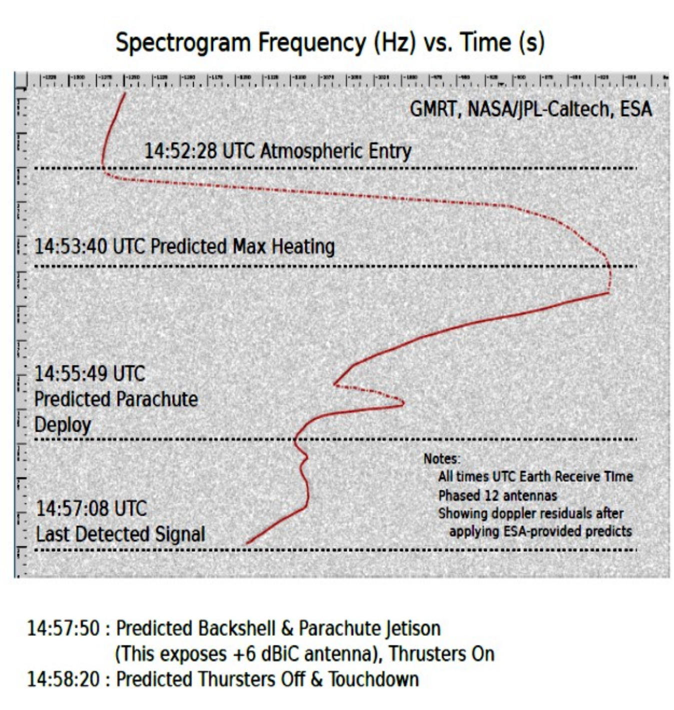
DM variations for J1939+2134

"Fringe" benefits with the uGMRT : Tracking Space Probes !

- Ground support for ExoMars mission of ESA
- GMRT + NASA collaboration
- Faithfully tracked Schiaparelli Lander module of ExoMars through "8 mins of hell"
- ~ 3 W signal @ 401 MHz from Mars !



ExoMars/Schiaparelli/EDM
Entry, Descent, Landing (EDL)
Detection at GMRT, India
2016-10-19



Summary

- Radio Astronomy is study of the Universe through the fairly wide radio window in the electromagnetic spectrum – one of the two windows that is accessible with ground based telescopes.
- Radio telescopes can be large single dishes, but are more likely to arrays of antennas spread out over large distances -- in order to achieve sufficiently high resolution.
- Many kinds of sophisticated engineering and technology are needed for building a modern radio astronomy observatory.
- The GMRT is a world class low frequency radio astronomy facility in India; has produced many interesting results in the last decade.
- The just completed upgrade will keep the GMRT on the forefront for next several years to come.