Technological Innovations & Historical Impact of the GMRT : a IEEE Milestone Facility

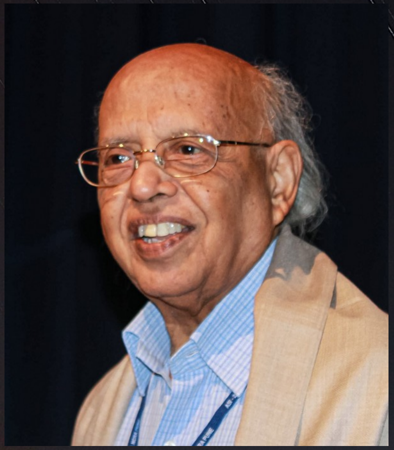

IEEE MILESTONE

Giant Metrewave Radio Telescope (GMRT), 1994

GMRT, consisting of thirty antennas of 45 m diameter each, spanning 25 km near Pune, India, is one of the largest and most sensitive low frequency (110-1460 MHz) radio telescopes in the world. It pioneered new techniques in antenna design, receiver systems, and signal transport over optical fibre. GMRT has produced important discoveries in domains such as pulsars, supernovae, galaxies, quasars, and cosmology, greatly enhancing our understanding of the Universe.

March 2021

IEEE


Prof. Govind Swarup (1929–2020)

Photograph courtesy : Shilkumar Meshram & Divya Oberoi (NCRA)

Yashwant Gupta

National Centre for Radio Astrophysics (NCRA), Pune

IEEE HISTELCON 2023 over zoom from Pune, India on 8th Sep 2023

Plan for today's talk

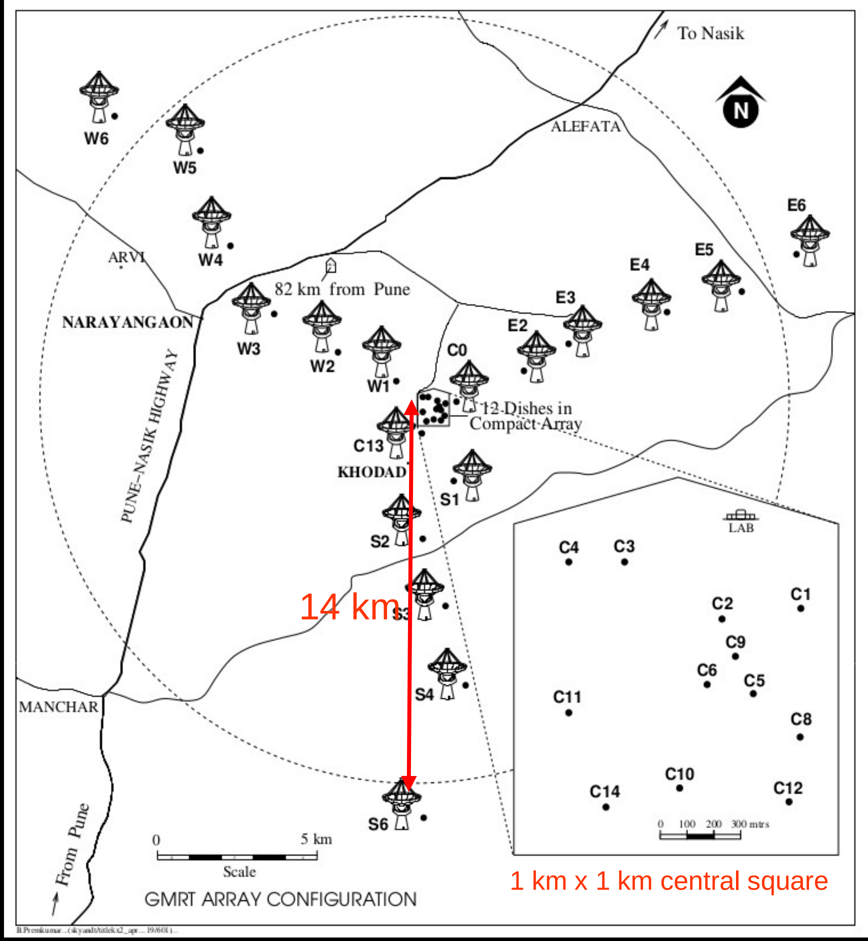
1. Introduction to the GMRT
2. GMRT : key features and innovations
3. GMRT : challenges along the way
4. GMRT : impact over the years
5. IEEE Milestone status
6. Summary

The GMRT : an overview

- One of the largest low frequency radio astronomy facility in the world
- Located in western part of India, about 80 km from Pune and 120 km from Mumbai
- Conceived in the 1980s
- Built during the 1990s
- Operational since 2001
- Completed a major upgrade in 2019
- Many technological innovations
- Lots of interesting new results
- Major regional and global impact
- A IEEE Milestone facility

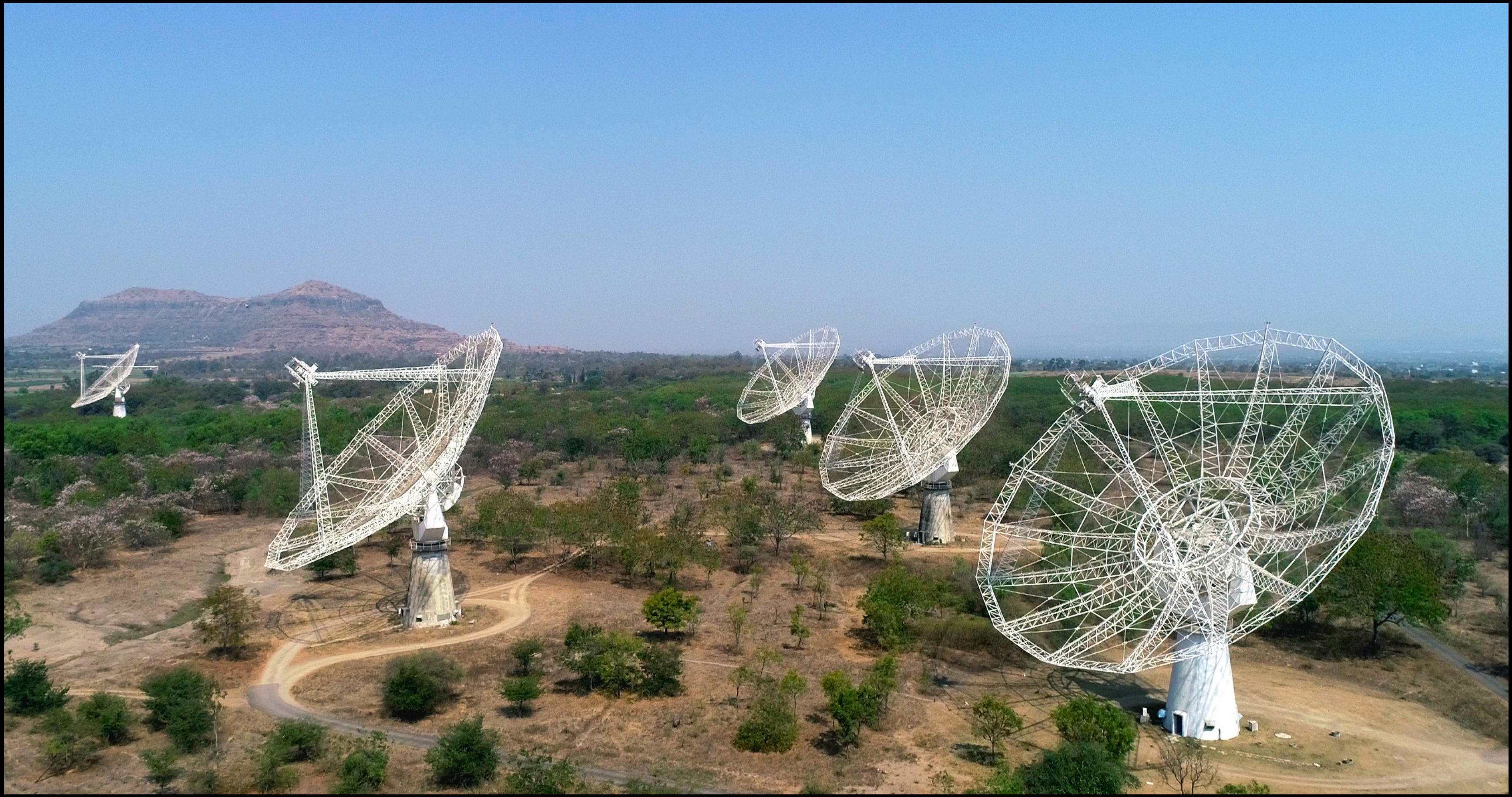
The GMRT : main features

- 30 dishes, 45 m diameter each
  - 12 dishes in a central 1 km x 1 km region (central square)
  - remaining along 3 arms of Y-shaped array
  - baselines : ~ 200 m (shortest);
    ~ 30 km (longest)
- Frequency range (after upgrade) :
  - 110-250 MHz (Band-2)
  - 250-500 MHz (Band-3)
  - 550-850 MHz (Band-4)
  - 1000-1450 MHz (Band-5)
  - max instantaneous BW = 400 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)



The GMRT : a Google eye view showing the central compact array

GMRT : central array antennas

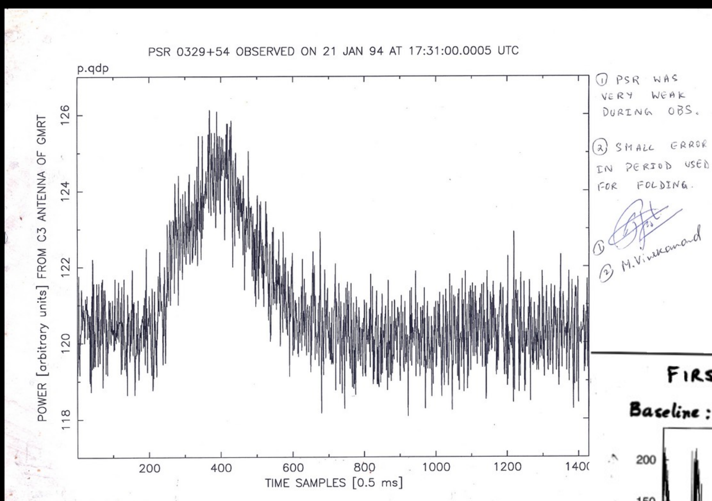


A brief look at the GMRT over the years

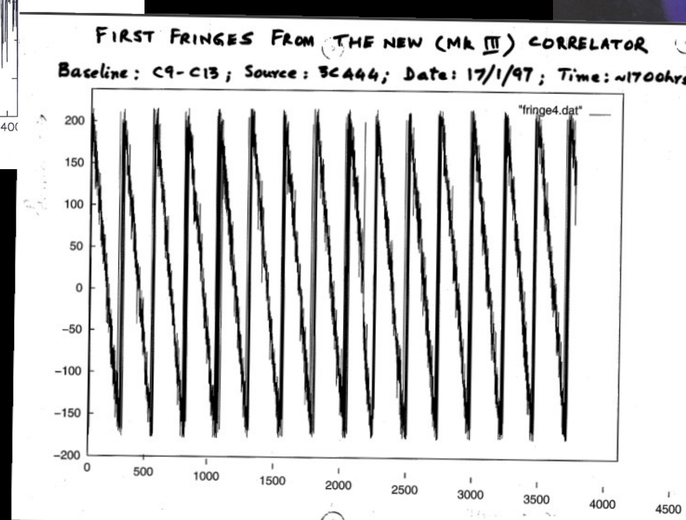
Early days : construction of GMRT antennas (1990s)

Early Days : First light signals (1990s)

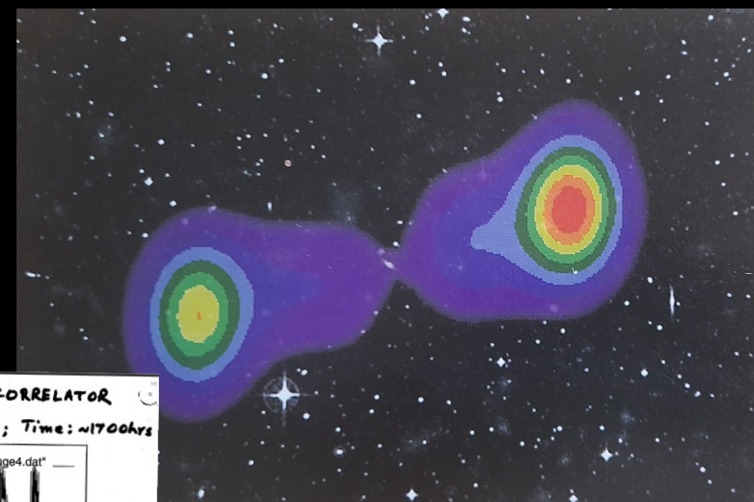
From the first reception of a celestial signal (pulsar) with a single dish of GMRT (Jan 1994) to the first image with 8 antennas of GMRT (June 1997)



First pulsar observed with GMRT, using a single antenna (Jan 1994)



First fringes with the 8-antenna correlator of final design (Jan 1997)



First image with GMRT using the 8-antenna system (June 1997)

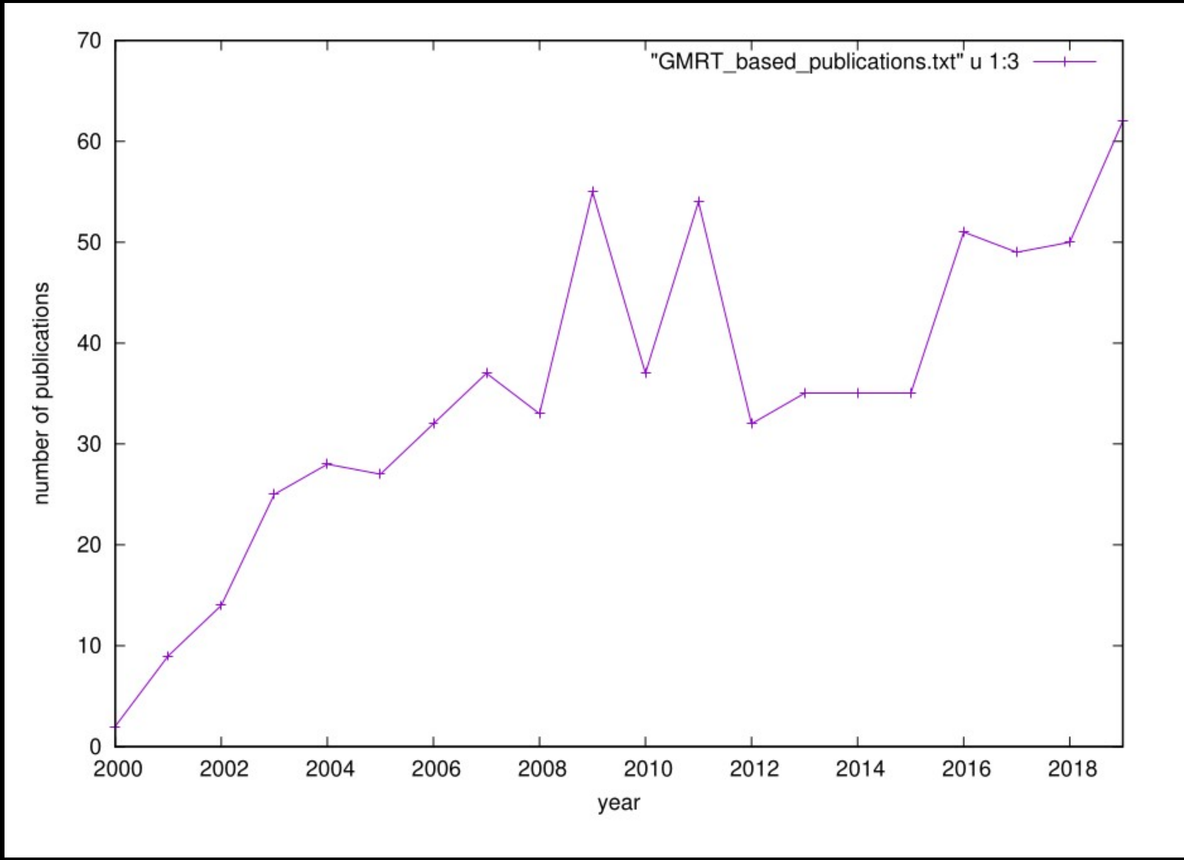
Coming of age : 2001-2002

After the formal dedication ceremony on 4th Oct 2001, GMRT became available to the international community from Jan 2002

The GMRT was formally inaugurated and dedicated as an international facility on 4th October 2001 by the Chairman of the TIFR Council, Shri Ratan Tata

Productivity of the GMRT

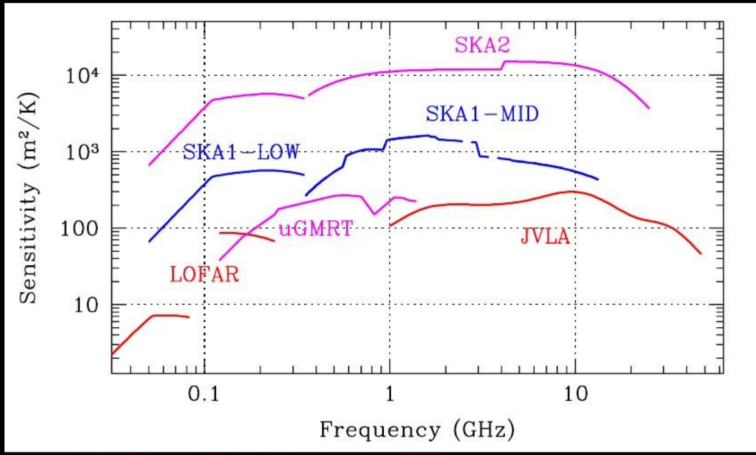
The GMRT saw a steady growth of science results over the years



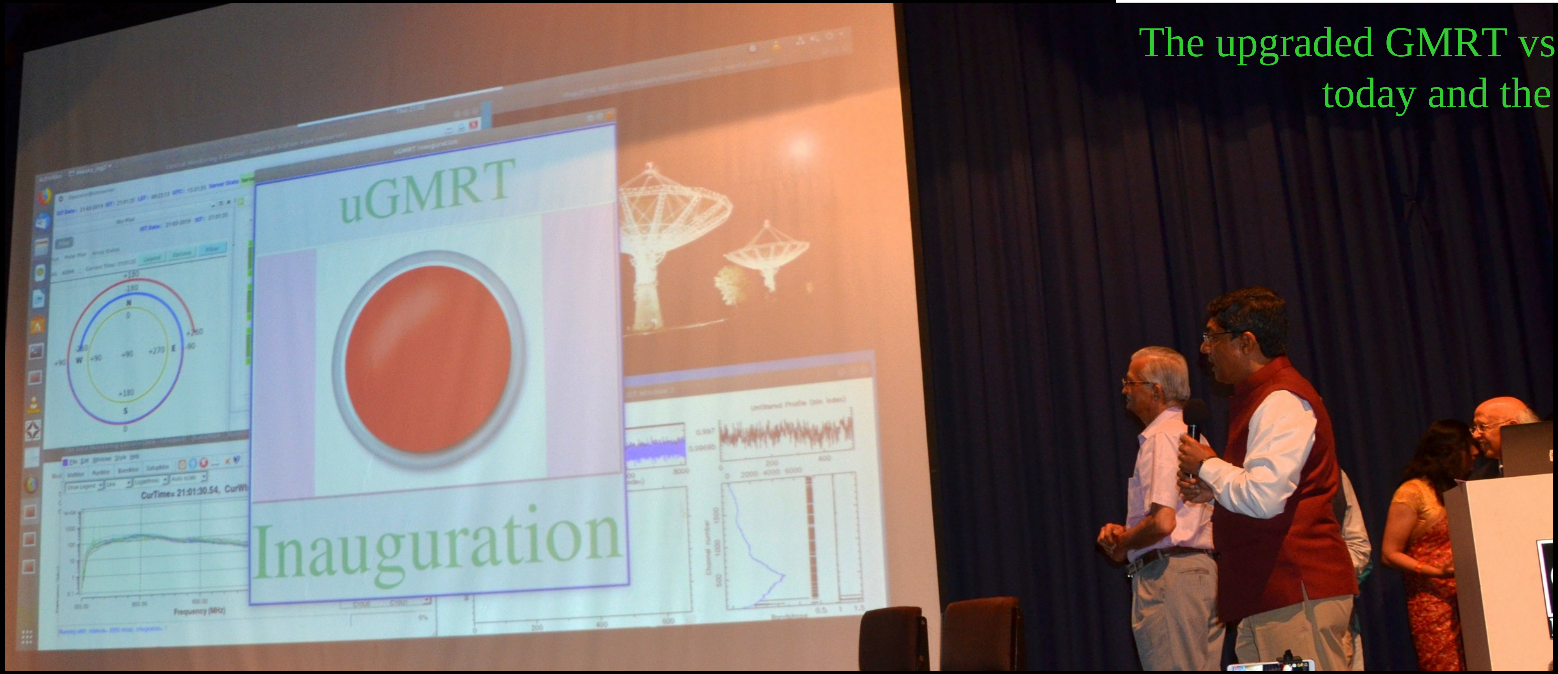
Growth of GMRT based publications over the years (2000 to 2019)

Recent developments : upgraded GMRT (2019)

- After over 15 years of operation, the GMRT was upgraded to a more sensitive and versatile facility, and released to the international community in March 2019
- This has led to a new spurt in productivity !



The upgraded GMRT vs other facilities of today and the future



The upgraded GMRT was formally inaugurated by Prof Govind Swarup on 26th March 2019

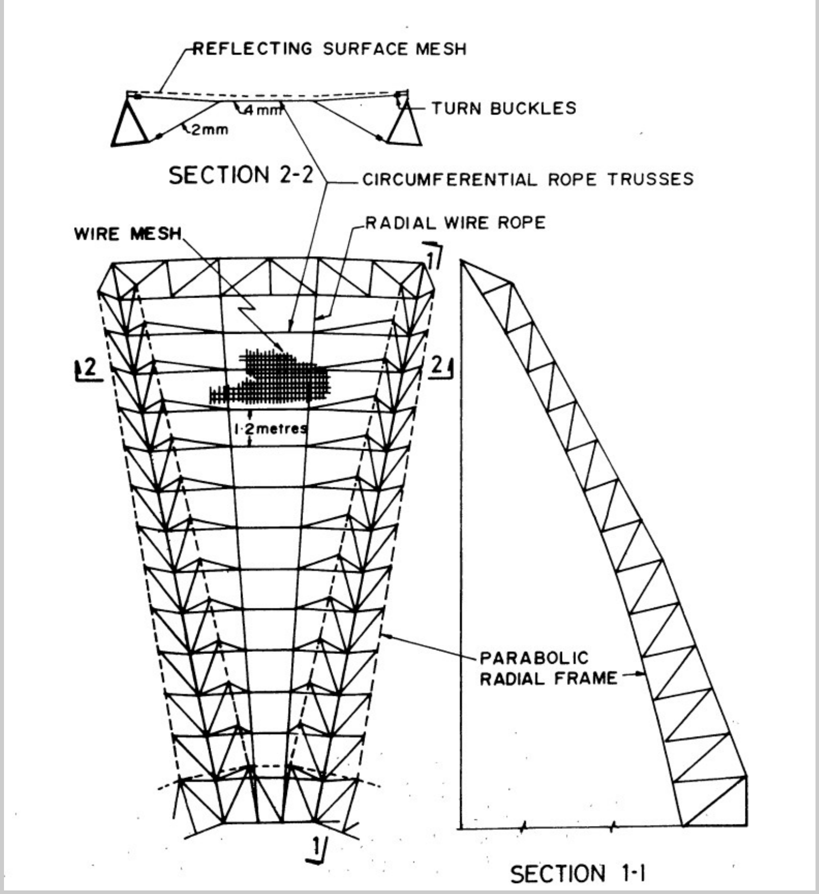
Some unique features of the GMRT

The GMRT : some unique features

- Antennas : very large (45-m diameter) but light weight (100 tons) due to the unique SMART concept (optimised for the frequency range of interest)

GMRT unique features : SMART concept

- SMART : Stretched Mesh Attached to Rope Trusses



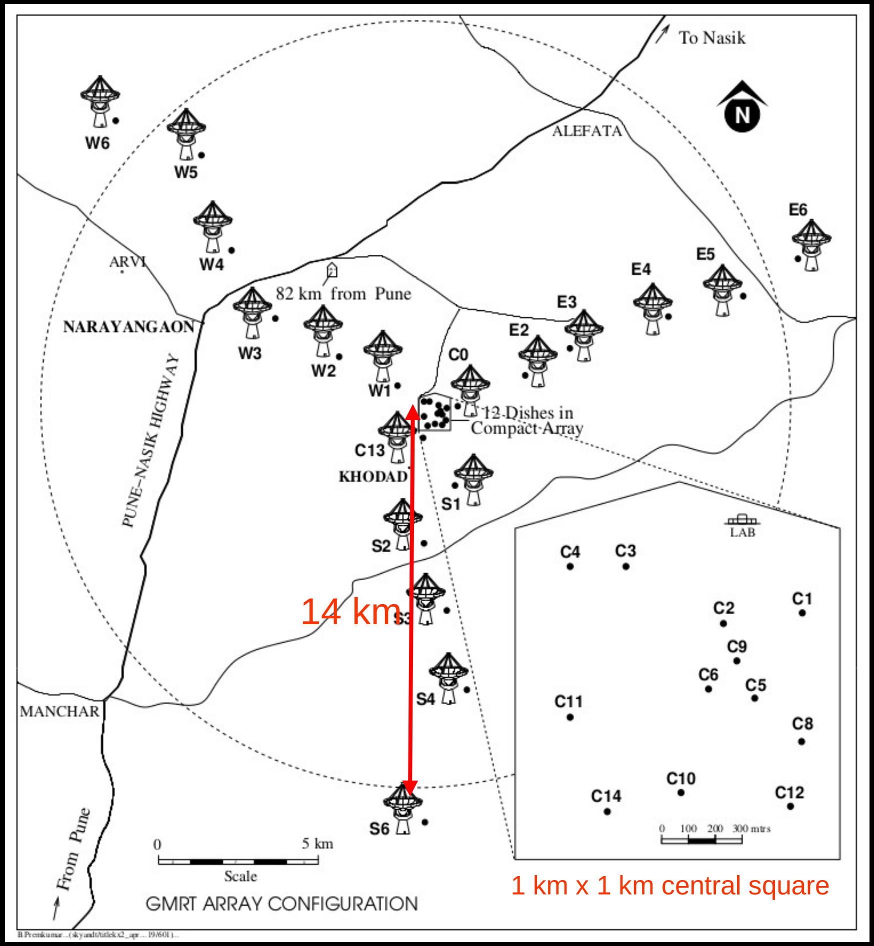
The SMART design allowed for large antennas (45 m diameter) to be very light (only ~ 100 tons) and easy to fabricate, while meeting performance requirement upto 1450 MHz

The GMRT : some unique features

- Antennas : very large (45-m diameter) but light weight (100 tons) due to the unique SMART concept (optimised for the frequency range of interest)
- Hybrid array configuration : dense core + extended arms => optimized sensitivity to compact & extended radio sources (now widely adopted)

GMRT unique features : hybrid array layout

- Antennas in a central dense core (1 km x 1 km) and extended arms
- Optimised to give good response for imaging of compact as well as diffuse sources
- Concept now adopted by most of the large arrays including the SKA



The GMRT array configuration showing the full array over a ~ 30 km diameter region, as well as the central core (inset)

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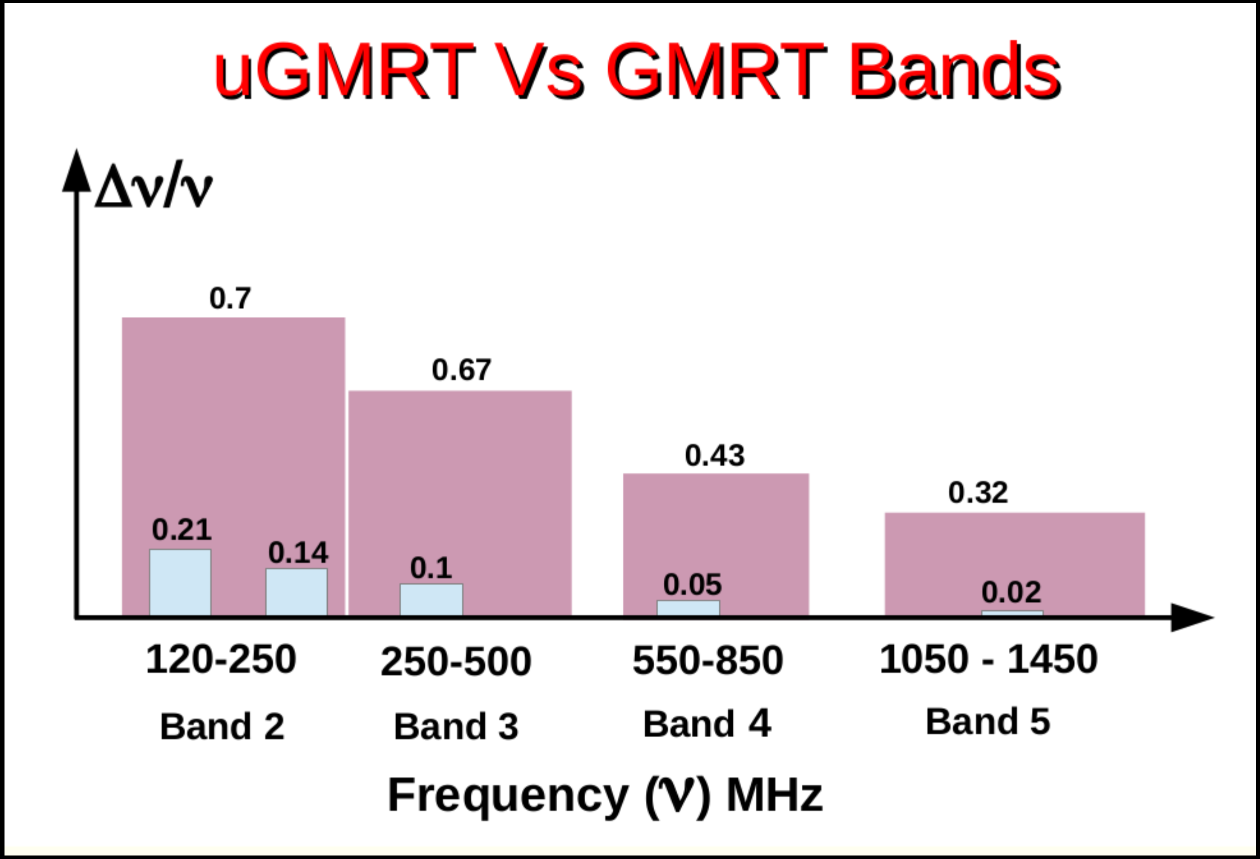
GMRT unique features : frequency coverage

- The upgraded GMRT provides almost seamless frequency coverage between 110 and 1450 MHz, using 4 main bands
- Using sub-array mode, simultaneous multi-frequency observations across more than one band can be carried out => many useful science cases



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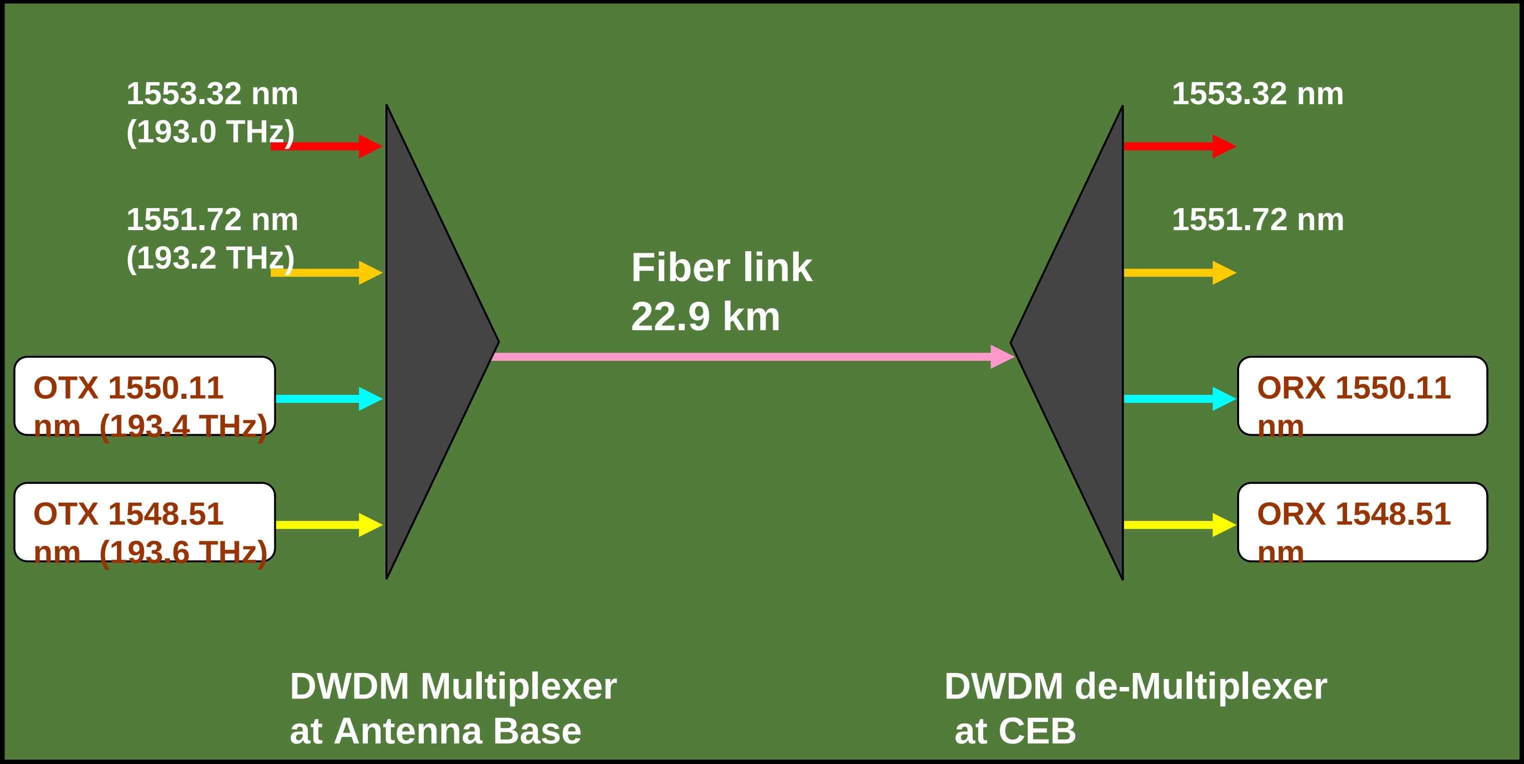
GMRT unique features : use of optical fibre

- One of the first radio observatories to use optical fibres for signal transport (today it is the de facto norm in all modern observatories)
- DWDM based, broad-band (2.5 GHz), analog optical fibre transmission scheme; features : 20 dB S/N; 40 dB dynamic range
- Also supports the telemetry and monitor & control communication to antennas



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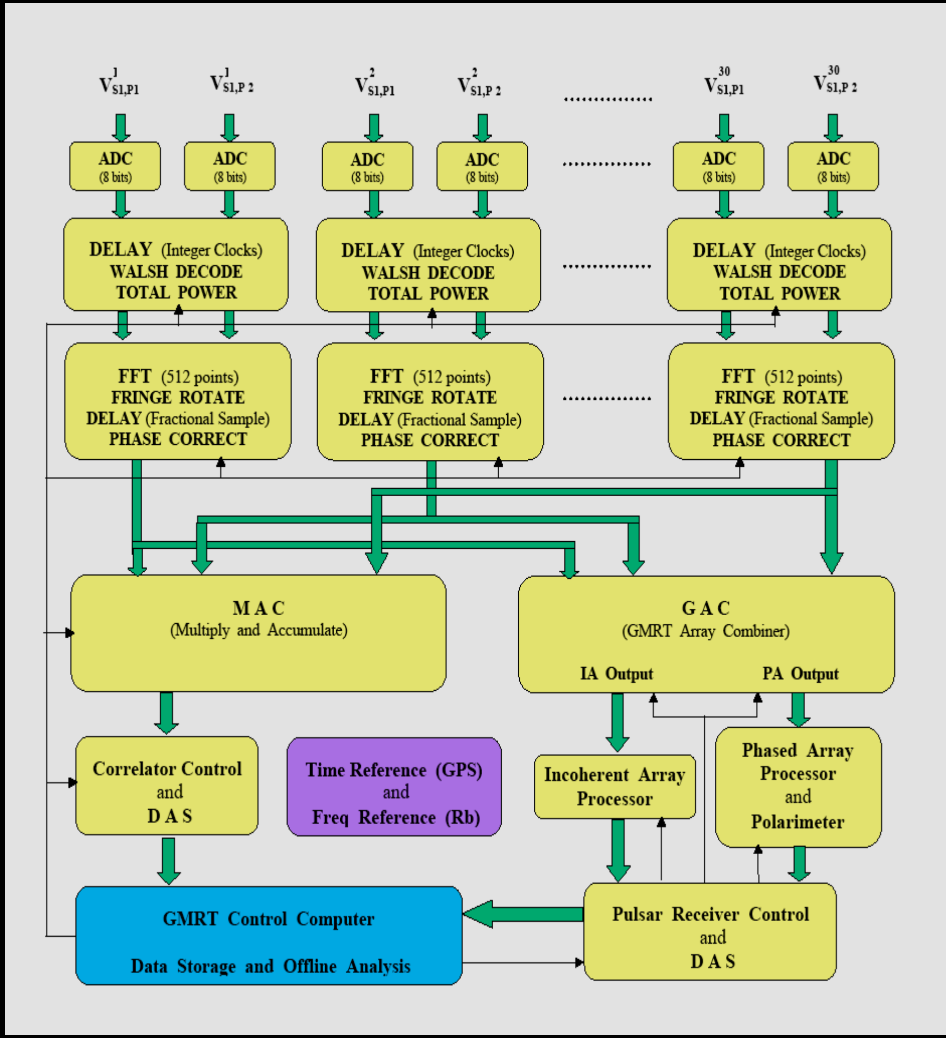
GMRT unique features : beamforming simultaneous with interferometry

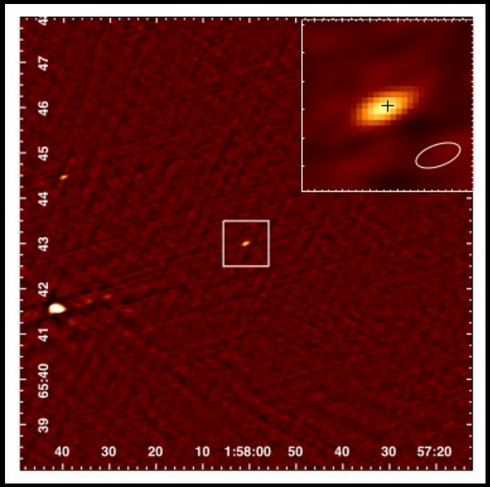
- Main components :
  - FX Correlator : correlates signals between every pair of antennas
  - Beamformer : adds signal from all antennas and gives high time resolution output
- can operate simultaneously, over full bandwidth and in sub-array mode
- Common signal processing stages: sampling, delay correction, fringe stopping and FFT
- Input data rate : 20 Gsamples/s
- Output data rate : 10s of MBytes/s
- Total real-time compute load : ~ 15 TFlops
- Based on FPGAs and CPU+GPU computing – software backend

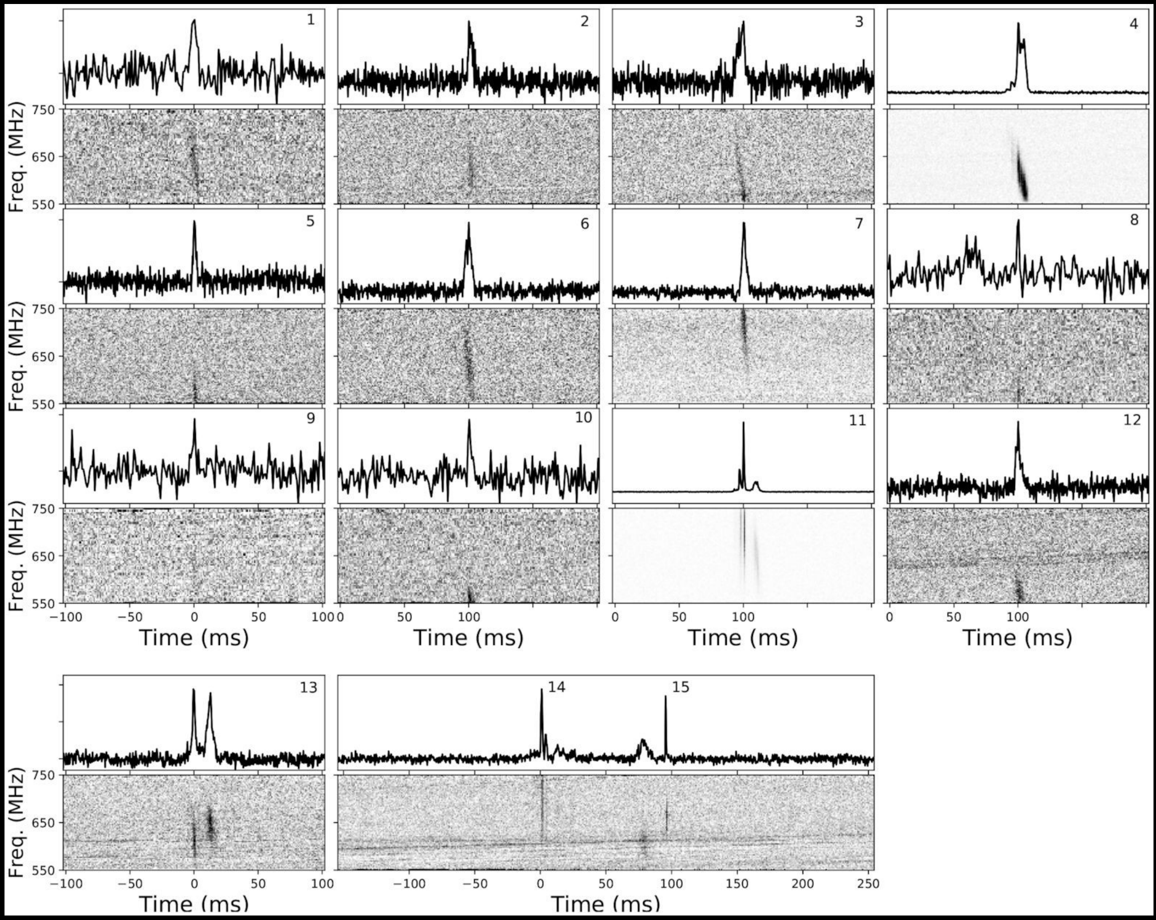


Schematic block diagram of the GMRT backend receiver showing interferometry and beamformer modes operating in parallel

Simultaneous beamforming & imaging : Bursts from FRB180916.J0158+65 (R3)

- 15+ bursts from R3 in 3 epochs
- 12 in one epoch – highest in a session
- Lowest fluence detections : 0.1 Jy ms – only 10-20 times SGR1935 +2154
- Commensal imaging for localising ==> significant value addition with uGMRT





from Marthi et al 2020

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- In summary : a relatively low cost but very sensitive and highly effective world-class radio observatory !

The GMRT was a big and bold step, but not without its fair share of challenges (and achievements) !

Challenges on the road to the GMRT

- Coming up with a viable (indigenous) design for the GMRT, being aware of : technological capabilities, manpower resources, funding limitations
- Getting the proposal approved and securing the funding (very large amount) : led to some rescoping, but still remained a worthwhile goal
- Finding a suitable site for locating the array : wide ranging search
- Acquiring land at the chosen site location(s) : easier said than done !
- Designing and building the antennas : SMART idea was a game changer; but still lot of difficulties in implementing on shoe-string budget with inexperienced contractors => ingenious, simple optimisation techniques
- Making the electronics : a significant indigenous effort, all the way from the feeds to the digital back-end; mass production and commissioning was an arduous task, group was short on experience of this scale, but we managed it !

Challenges on the road to the GMRT

- Stabilising the functioning towards regular operations : slow but steady progress over 4-5 years from 2001 onwards
- Choosing a path for the upgrade : how to maximise the bang for the buck
- Executing the upgrade without shutting down the GMRT : required some clever designs + a modified operating model (and some increased cost!)
- Creating and maintaining a RFI quiet environment at the observatory : significant challenge as it is (now) a fairly well populated region and development aspirations of the people have to be kept in mind
  => lots of discussions and negotiations with various agencies !

What has been achieved ? What has been the impact of the GMRT ?

Achievements and Impact of the GMRT

- A world-class radio astronomy facility in India that came online at the right time => many new science results, in various areas of astrophysics...

GMRT : Range of Science

The GMRT has produced interesting results related to several different astrophysical objects and phenomena :

- 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 & neutral Hydrogen gas clouds (our Galaxy & 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 survey at 150 MHz – TIFR GMRT Sky Survey

…and many interesting new results have been produced, with more than 50 papers per year now-a-days based on GMRT data

Furthest detection of HI in emission (z ~ 1) : Galaxies running out of gas…

- Deep observations of DEEP2 fields covering z ~ 0.74 – 1.45
- Using Band-4 (550-850 MHz) of uGMRT
- Stacking of 11,394 blue star-forming galaxies over 1.7 sq deg
- Extended survey of 520 hrs ==> noise keeps going down as expected !

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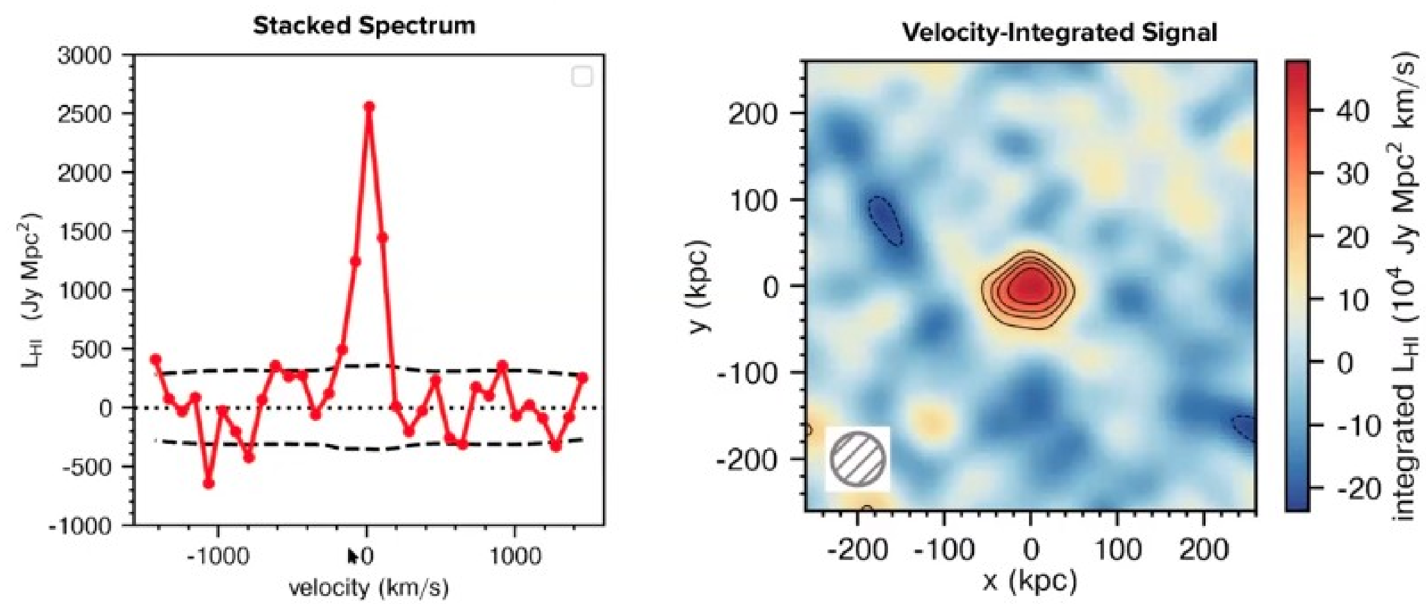

- Average HI Mass : **(8.8 ± 1.2) × 10^9 $M_\odot$**
- Noise has gone down as expected; signal consistent with than from pilot survey.

Choudhury et al 2020a & 2021

Precision pulsar timing with uGMRT

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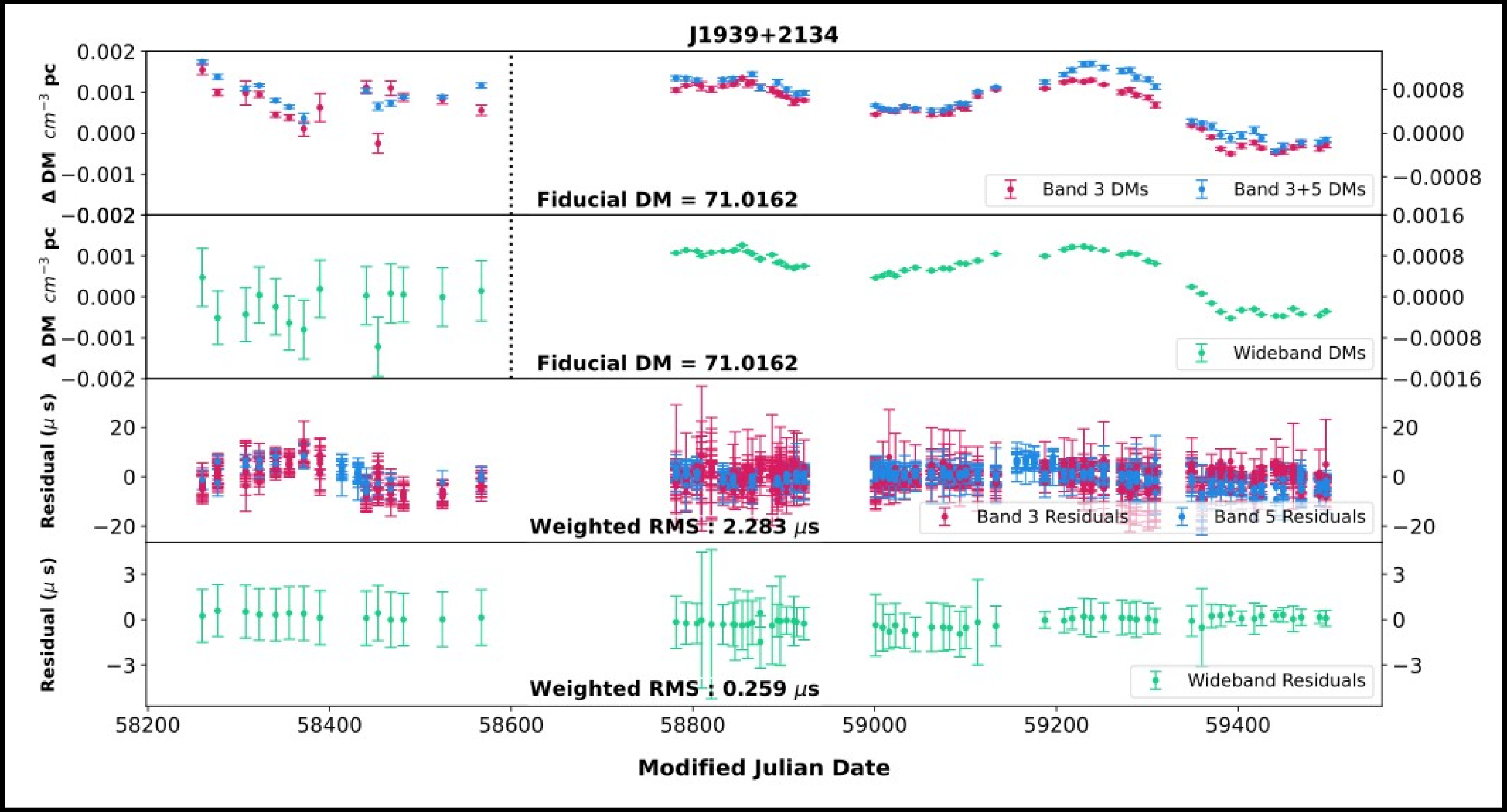
- Accurate estimates of DM variations : 1 part in 10^5 ==> excellent ability to correct for ISM distortions in precision timing experiments
- Timing residuals ~ microsec and better using wideband timing technique
- First data release in 2022 from Indian Pulsar Timing Array (InPTA) collaboration
- uGMRT contributed to the recent result (2023) on first sign fo detection of GWs!



InPTA papers :

Krishnakumar et al 2021;

Nobleson et al 2022;

Tarafdar et al 2022;

Paladi et al 2023.

InPTA
Indian Pulsar Timing Array

Achievements and Impact of the GMRT

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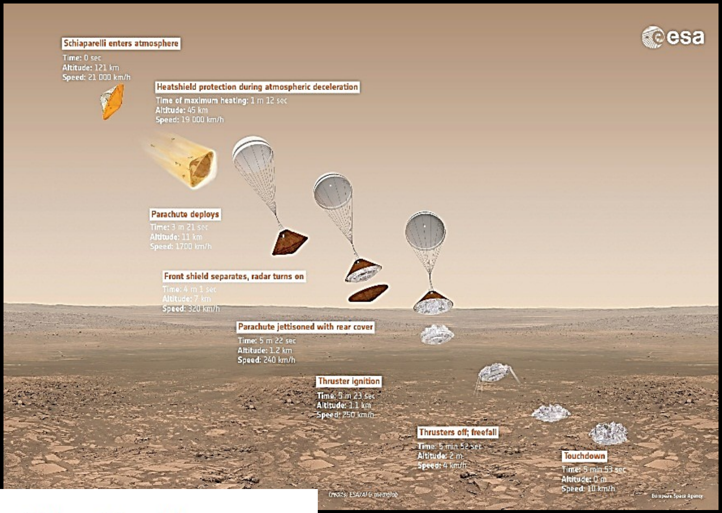
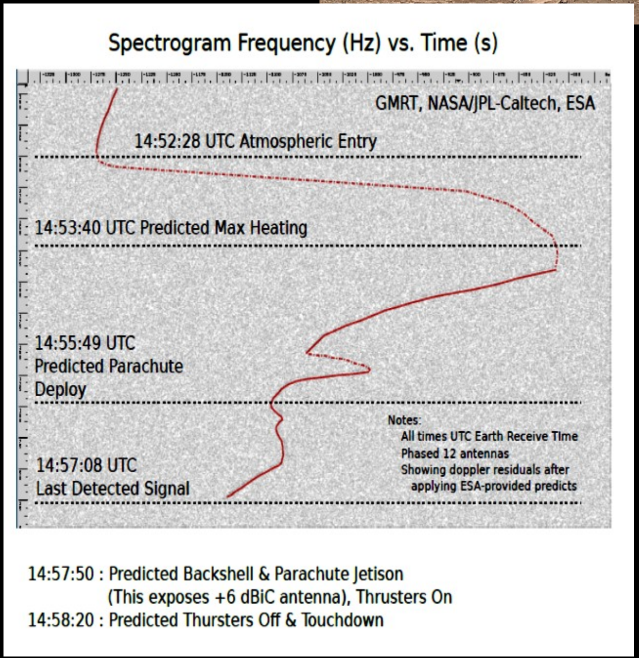
- ...and some interesting contributions in other aspects of space exploration!

“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

Doppler tracking of the motion of the lander module, using the GMRT

Achievements and Impact of the GMRT

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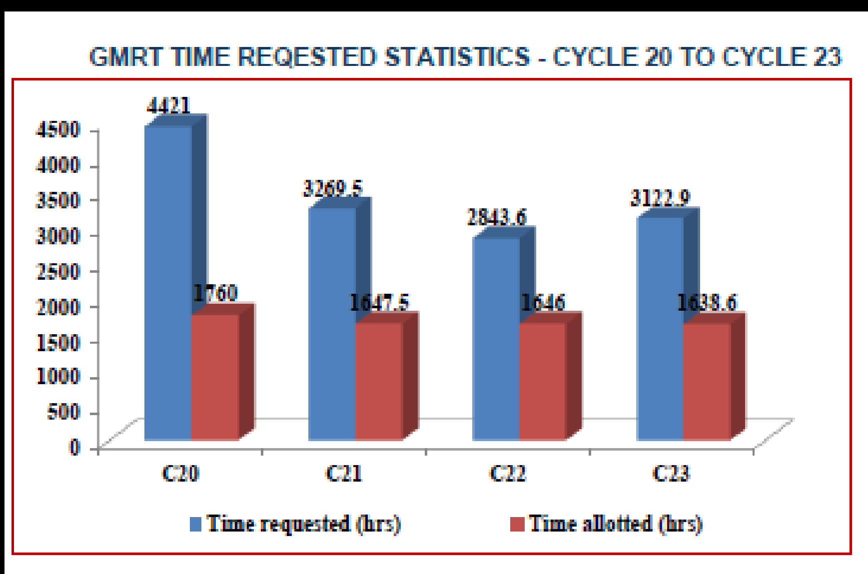
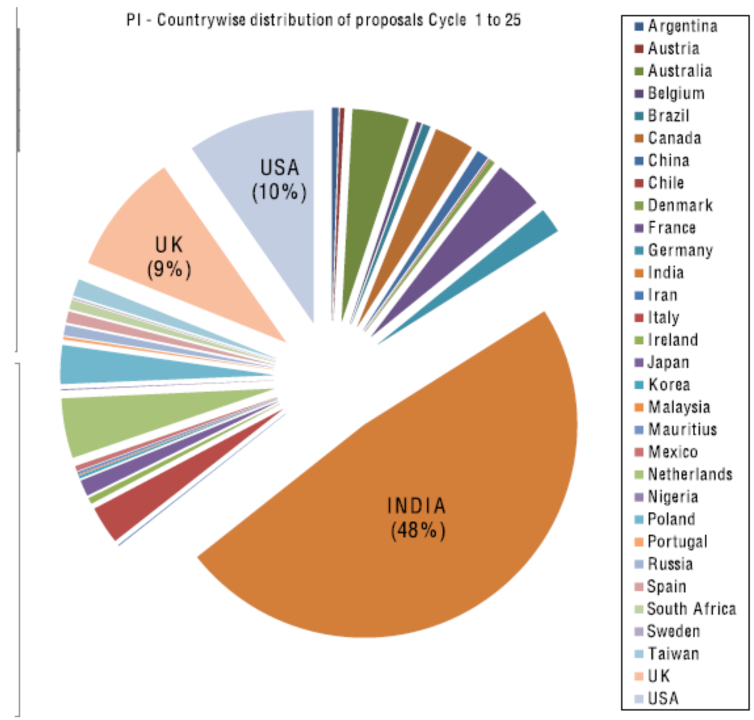
- A largely indigenous effort (some consultancy with international experts) : built up the community in India, while serving the global community

GMRT : Usage Statistics

- GMRT sees users from all over the world : distribution of Indian vs Foreign PIs is close to 50:50

- The GMRT has been typically oversubscribed by a factor of 2 or more





Country	Nos	Country	Nos	Country	Nos	Country	Nos	Country	Nos
Argentina	8	China	14	Iran	1	Mauritius	3	Russia	12
Austria	5	Chile	1	Italy	45	Mexico	6	Spain	13
Australia	67	Denmark	6	Ireland	7	Netherlands	71	South Africa	11
Belgium	6	France	59	Japan	19	Nigeria	1	Sweden	1
Brazil	9	Germany	30	Korea	3	Poland	46	Taiwan	20
Canada	47	India	758	Malaysia	1	Portugal	3	UK	145
								USA	152
Total Proposals Received					1570				

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- Nucleated a strong group in radio astronomy in India
- Also a source of trained human resources (science and technology) at national and international level

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- Ushered in a renaissance in low frequency radio astronomy in the world!
- Nucleated a strong group in radio astronomy in India
- Also a source of trained human resources (science and technology) at national and international level
- Spurred the growth of radio technology in the country, laying the roots for India's participation in large international projects such as the Square Kilometre Array (SKA)

GMRT and the IEEE Milestone connection

The year 2021 was momentous for the GMRT

Marking 20 yrs of the GMRT : 4-5 Oct 2021

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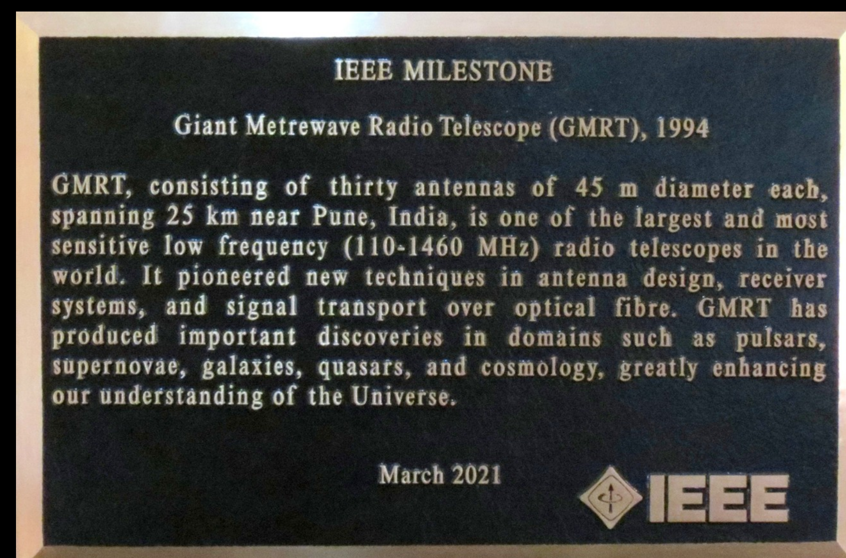
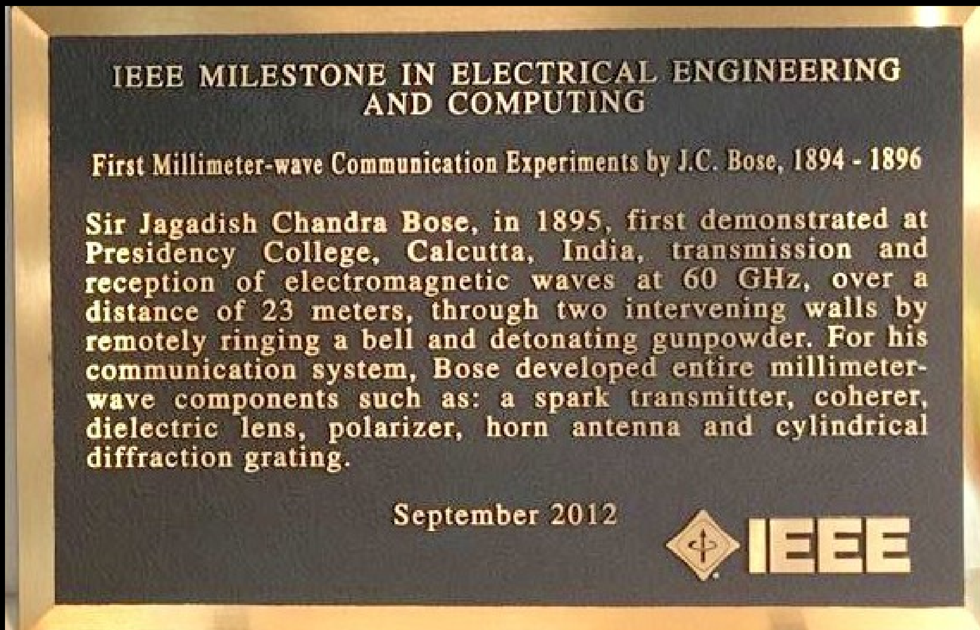
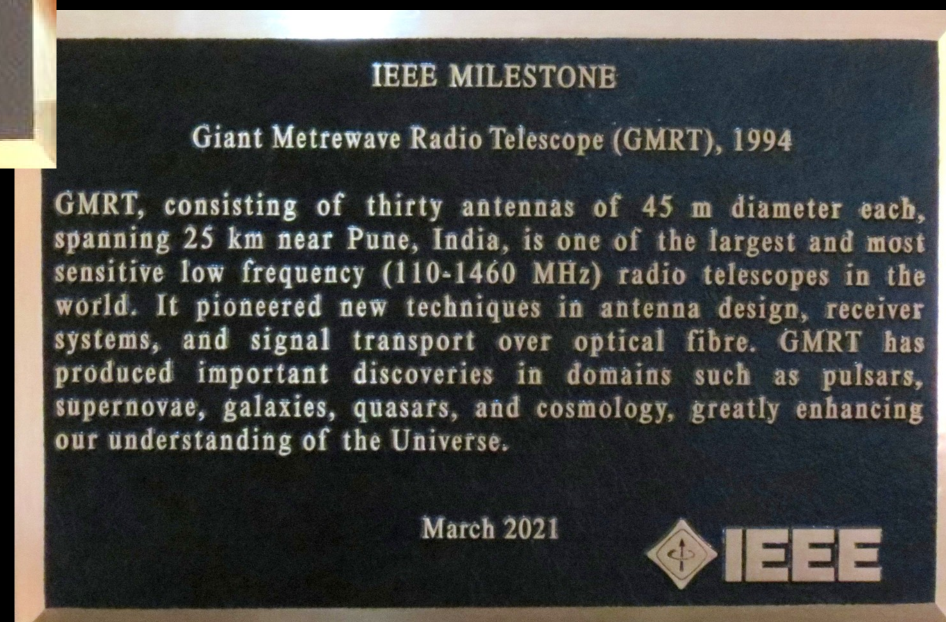


GMRT awarded IEEE Milestone : March 2021

A tale of two IEEE Milestones in India



IEEE Milestone commemorating the first radio communication experiment by Sir J.C. Bose in Calcutta, India, in 1895 !



IEEE Milestone commemorating the achievements of the GMRT : March 2021

Summary and closing thoughts

- The GMRT, built during the 1990s and upgraded during 2013-19, has been a major achievement in global low frequency radio astronomy.
- It is a culmination of the efforts of the radio astronomy activities started by late Prof. Govind Swarup in India, in1963.
- The GMRT has to its credit several unique and innovative technology features that have contributed to the growth of radio astronomy.
- The GMRT, used by astronomers from all over the world, has produced many exciting new results, in a diverse range of topics in astrophysics.
- The GMRT has also had a major impact on the growth of science and technology in India.
- The award of IEEE Milestone status to the GMRT in India (in 2021) connects deeply with the similar recognition given by the IEEE to the pioneering work of Sir J.C. Bose in India (in 1895) !

Thank you for your attention

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