The GMRT : System Parameters and Current Status

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Overview

The Giant Metrewave Radio Telescope (GMRT) consists of thirty 45 m diameter antennas spread over a 25 km region, about 80 km north of Pune, India. Fourteen antennas are in a compact, quasi-randomly distributed array, in a region of size about 1 km (called the Central Square). The remaining sixteen antennas are on the 3 arms of a "Y" (North-West, North-East, and South), each of length $\approx$ 14 km, with 5 or 6 antennas on each arm. The longest baseline is about 25 km and the shortest is about 100 m, without foreshortening. More details about the general aspects of GMRT are given in the appendix.

Since the completion of a major upgrade in March 2019, the upgraded GMRT (uGMRT) has been available for observations with the full array of 30 antennas supporting 4 upgraded wideband receiver systems: 125−250 MHz (Band-2), 250−500 MHz (Band-3), 550−850 MHz (Band-4) and 1000−1460 MHz (Band-5), in regular release mode. Rotation of the feed system to change the frequency of observations is routinely possible. In the new Tango-based GMRT Control and monitor system (TGC), the antenna pointing model is by default applied to all the observations.

The GMRT wide band backend, aka GWB is the observatory default backend for the GMRT, though the GMRT software backend, aka GSB, continues to be available for supporting the legacy system modes. All the uGMRT observations are carried out with the 30-antenna back-end supporting a choice of 100, 200 or 400 MHz processing bandwidth for the correlator (along with a zoom mode for spectral line observations), with the choice of 2048, 4096, 8192, or 16384 channels, as well as the corresponding IA/PA beamformer outputs for pulsar observations. The GMRT is now formally available for VLBI observations in collaboration with the European VLBI Network (EVN). However, the approved EVN proposals that request GMRT time will undergo independent evaluation for technical feasibility and potential conflicts with regular GTAC observations and will be scheduled on a best-effort basis. Section 1 describes some details on observations with the upgraded GMRT, whereas Section 2 details observations with the legacy GMRT. A more detailed general overview on the system can be found in the appendix (Section 3).

1. Observing with the upgraded GMRT

The distribution of the observing slots over the duration of Cycle 46 is shown in the dummy schedule at `http://www.ncra.tifr.res.in/ncra/gmrt/gtac`. Note that the slot from Wednesday 09:00 hours to Thursday 18:00 hours every week is set aside for maintenance and improvement activities, as well as system tests, and no regular science observations are scheduled during this slot. Ongoing maintenance and long-term upgrade activities will have some effect on the observing capabilities of the GMRT. Specifically,

(i) Upgrades of the feed positioning servo system may result in downtime of one antenna up to one week at any given time.

(ii) Antenna structure and surface improvement activities may result in up to two antennas being down during the daytime for a week to one month (or more in rare cases) depending on the nature of the repair work.

A new command file creator user interface to directly create command files in the format needed for the TANGO-based control and monitor system (TGC), including the setup for interferometric and beamformer observations is now available at `http://www.ncra.tifr.res.in/~secr-ops/cmd/cmd.html`. Users are requested to make and share the output from this command file creator with the GMRT operations gmrtoperations@ncra.tifr.res.in.

Users can also find several useful tools in `http://www.gmrt.ncra.tifr.res.in/gmrt_users/help/help.html` for creating command files, setup files, calculation of source rise and set times, selecting phase calibrators from the VLA calibrator list, etc. These are especially useful for users who are availing of the absentee observing facility at GMRT.

The GMRT observatory will try its best to maximise the number of antennas available for science observations, by coordinating the various upgrade, test, and maintenance activities. However, due to various issues, some individual antennas may not be available at different points in time. The observatory will strive to guarantee a minimum of 26 working antennas for all science observations. Programs that critically depend on specific antennas (e.g. the longest baseline antennas such as W06, E06, or S06, or the short spacing antennas C05, C06, and C09, etc) should clearly indicate this in the observing proposal.

A brief description of the available modes and the system is given below. For further details users are requested to refer to the Appendix and/or contact GMRT operation's group at gmrtoperations@ncra.tifr.res. Following are the specifications for the Front-End and Back-End systems for the GMRT wide bandwidth system.

1.1. Overview of the system

1.1.1. Front-End (FE) + Optical Fibre (OF) systems

Following are few features of the Front-End system.

(i) All 30 antennas with the Band-5 (1000−1460 MHz) FE receivers, with a choice of full band or one of four 120 MHz wide sub-bands, in regular release mode.

(ii) All 30 antennas with the Band-4 (550−850 MHz) FE receivers, with a choice of a full band or one of four 100 MHz wide sub-bands in regular release mode.

(iii) All 30 antennas with the Band-3 (250−500 MHz) FE receivers, with a choice of a full band or one of four 100 MHz wide sub-bands, in regular release mode.

(iv) All 30 antennas with the Band-2 (125−250 MHz) FE receivers, with an in-band notch filter for television transmitters ∼175 MHz, in regular release mode.

(v) All the FE receivers have additional features such as noise injection, temperature, and total power monitoring facilities, which will continue to be available in shared risk mode.

(vi) All 30 antennas with high dynamic range wideband OF system, delivering the full wideband signals to the back-end system.

1.1.2. Back-End (BE) systems

GMRT Back-end system comprises analog and digital sections described below.

Analog section: GMRT Analog Backend (GAB) for all 30 antennas.

(a) Converts the selected RF band to the baseband, with the final BW of 100/200/400 MHz.

(b) Local Oscillator (LO) settings for all antennas (both polarisations) in 100-1500 MHz range, with 10 kHz step.

(c) Variable attenuation control for power equalisation.

Digital section : GMRT Wideband Backend (GWB) for all 30 antennas, operates in interferometric mode and beam mode. In the following, we detail some specific features of these modes.

(i) Interferometric modes: Please note the following details regarding the interferometric modes available with the upgraded GMRT.

(a) Total intensity mode for 100/200/400 MHz BW choices with up to 8192 channels in regular release mode.

(b) Full polar mode for 100/200 MHz BW with up to 8192 channels and 400 MHz BW with up to 4096 channels in regular release mode. In both (a) and (b), a combination of short integration and a higher number of channels may not be possible due to the resultant high data rate. For example, while 0.6s integration is okay for 2048 channels, an integration time of 5s is recommended for 8192 channels.

(c) Narrow bandwidth spectral-line modes (in total intensity) with BW ranging from 100 MHz down to 0.390625 MHz in steps of factors of 2, with up to 16384 channels in regular release mode.

(d) Frequency-switching for narrow-bandwidth spectral-line observations is available, in shared-risk mode from Cycle 40. Users who would like to use this mode should get in touch with Nissim Kanekar (nkanekar@ncra.tifr.res.in) for observing details and possible issues.

(e) Option for Polyphase Filter Bank (PFB) instead of regular FFT in the F stage of the FX correlator, as the default option.

(f) Option for equalisation of the power across the band for each antenna individually.

(g) A release of the Walsh switching scheme for the GMRT Band-3, Band-4, and Band-5 is available from Cycle 45. This scheme consists of antenna-based Walsh modulation and demodulation at the backend. GMRT legacy system will not be available while enabling the Walsh for the uGMRT signal path. The number of antennas with the proper functioning of the Walsh switching can vary and will be checked at the beginning of observations to generate an antenna-based mask for enabling modulators and demodulators for a set of antennas.

(h) A high-time resolution total intensity visibility recording facility allowing up to 1024 channels at 83 ms time resolution for 200 MHz bandwidth is now available on a shared risk basis.

(ii) Beam modes: Beam modes can be operated in parallel with the interferometric modes.

(a) Option for up to 4 total intensities for incoherent array (IA) or phased array (PA) beams for a choice of bandwidth 100/200/400 MHz.

(b) Option for PA voltage beam on 2 out of the 4 beams for bandwidths of 100/200 MHz with real-time coherent dedispersion (CD) resulting in multi-channel intensity data at desired time resolution. At present one can record either one CD beam for 200 MHz bandwidth (along with PA and IA beams) or up to 2 CD beams for 100 MHz bandwidth (along with PA and IA beams) in total intensity. Simultaneous IA/PA and CD beam recording is possible at chosen bandwidth with a combination of time and frequency resolution satisfying the maximum allowed data recording rate of 48 MB/s per beam.

(c) Full polar mode for 2 PA beams for a bandwidth of 100/200 MHz. Option for 400 MHz BW in shared risk mode. Observing the CD beam is not possible if the GWB is configured in full-polar mode.

(d) Range of choices for time/frequency resolution - time resolution from 81 μs onwards and the number of frequency channels - from 2048 to 16384 over 200/400 MHz for the IA/PA modes.
The allowed time-frequency resolution for the IA, PA, and CD modes are summarised in Table 1 of "Manual for observations in beam-former mode" which can be found in,
`http://www.gmrt.ncra.tifr.res.in/gmrt_users/help/help.html`.

(e) Phased Array Spectral Voltage (PASV) baseband data from the GMRT Wideband Backend (GWB) is available in full-release mode for 25/50/100/200 MHz bandwidths with 4/8-bit sampling and 400 MHz with only 4-bit sampling. These modes can be used for VLBI experiments, as well as for specific science experiments that demand high time and/or frequency resolution. Diagnostic tools for quick data quality and sanity checks are available at the Observatory. There is a data limit of $\lesssim$ 2 hours with the 200-MHz/8-bit and $\lesssim$ 4 hours for 100-MHz/8-bit modes, which can be scaled for the digitally downconverted mode (DDC mode) bandwidths, as well as bit depth (4- vs 8-bit). Currently, available CD, PA, and IA modes of the beamformer already provide 10.24 μs sampling for high-time resolution pulsar and transient studies. Therefore, any proposal for using the PASV modes has to be backed by strong scientific motivation. Proposers must note that they have to provide a statement on how they intend to move the data out of the recording disks within 24 hours (e.g. they could mail their own portable disks beforehand), beyond which there is no guarantee of data retention. Note that the bandwidth requested for the PASV mode is set at the GWB and will therefore apply across all concurrent beam and interferometric data. Write to Viswesh Marthi/Sanjay Kudale (vrmarthi/ksanjay@ncra.tifr.res.in) for additional details.

(f) The GMRT can now be requested as part of European VLBI Network (EVN) observations. Any proposal to include the GMRT will undergo an independent technical feasibility assessment. The GMRT baseband data will be sourced from the PASV tied-array beam, with an option to record a single-antenna beam. Upon request, the GMRT interferometric visibilities can be made available, subject to non-conflict with ongoing observations on identical sources with similar science cases or with data from observations within the proprietary period. More details can be found in the latest EVN Newsletter. For assistance or clarifications, write to Viswesh Marthi (vrmarthi@ncra.tifr.res.in).

(g) A reduced-bit 8-bit mode for IA/PA total intensity beam will be available to record high time/frequency resolution data. Please refer to Table 1 of
`http://www.gmrt.ncra.tifr.res.in/doc/GTAC_obs_beamformer_ver4.pdf`
for the maximum allowed resolution.

(h) Online coherent dedispersion pipeline (CDP) for 4-bit voltage beam supporting quad-beam each with 100 MHz bandwidth or dual-beam each with 200 MHz bandwidth is available in Cycle 45.

(i) Phasing of the antennas using a standard procedure (regular release mode); an additional mode called "wideband phasing" (shared risk mode).

(j) PA-IA total intensity beam (or Post-Correlation beam) for the 8-bit and 16-bit recording is available in shared risk mode from cycle 45.

(k) A band equalisation facility with a configurable choice of frequency-window size, roll-off and number of taps is now available. This allows for the correction of the slow spectral variations and can be effective for beamforming observations at band-4 with a reduced bit (i.e. 8-bit beam). This facility is now available in shared risk mode.

(l) A reduced 8-bit CD total intensity beam recording for 200 MHz bandwidth with an 8-bit voltage beam allowing higher time-frequency resolution is now available in shared risk.

Moreover, the following are some common features that are applicable to the interferometric as well as the beam modes.

(a) Upto 8192 spectral channels for most of the above modes in regular release mode; for other extreme combinations of the number of channels and integration times, the system is available in shared risk mode – system may not work reliably for lack of adequate data I/O or recording capabilities at higher channels and shorter integration time.

(b) Standard power equalisation scheme for balancing the power levels for all working antennas, using the GAB attenuators (regular release mode); more advanced power equalisation schemes to facilitate Galactic plane / Galactic centre observations (shared risk mode). Users observing near the Galactic plane should power equalise at the target location before the start of the observations to avoid saturation and non-linearity. A scheme for automatic adjustment of power levels for observations in the Galactic plane regions is available. More information about this scheme can be found at
`http://www.ncra.tifr.res.in/ncra/gmrt/gmrt-users/galactic-plane`.
For additional details, please contact Subhasis Roy (roy@ncra.tifr.res.in)

(c) A scheme for real-time broadband RFI excision at the pre-correlation (voltage) stage for each polarisation of all antennas is available (released) for Band-3 and Band-4. However, the scheme for Band-2 is still under development and is available in shared risk mode. The scheme is not recommended for Band-5 and users who would like to use the scheme in Band-5 may do so under shared risk. While this mode has undergone a reasonable amount of testing, the artifacts it can introduce during severe RFI conditions are not fully understood. Users interested in using the filter during their observations are requested to go through the document
`http://www.ncra.tifr.res.in/ncra/gmrt/gmrt-users/online-rfi-filtering`
to see the features provided by the system. Users opting to use the system should get in touch with the RFI excision team (onlinerfi@ncra.tifr.res.in) well in advance. A web-based tool for analyzing the real-time broadband RFI flagging percentage in a GTAC observation has been released on a shared risk basis. This tool allows accessing the specific file based on the observation date, plotting the percentage flagging across the antennas, calculating and plotting average flagging for each antenna for an observation, including the overall flagging across all the antennas.

It is to be understood that not all the modes and combinations specified above under shared risk release have been tested thoroughly, and there may be undiscovered issues in some of these. The aim of the shared risk release is to allow users to exercise the system for a thorough shake-down of such modes.

1.2. Details on data acquired

Data quality: It is to be noted that not all the modes and combinations specified above under shared risk release have been tested thoroughly, and there may be undiscovered issues in some of these. The aim of the shared risk release is to allow users to exercise the system for a thorough shake-down of such modes. In addition, the acquired data could be affected by radio frequency interference and ionospheric scintillation.

(a) **Effect of radio frequency interference:** The radio frequency interference (RFI) environment can occasionally be poor at Band-2 and Band-3; the situation is usually better at night than during day time.

It is recommended to use the solar attenuators in the common box for Band-2, to reduce the possibilities of saturation of the downstream electronics chain due to RFI. Observations at Band-3 can be hampered sometimes due to RFI from nearby aviation-related activity (especially during daytime), as well as from some satellites such as the MUOS which have very strong transmissions in this band. A set of tools are available for predicting satellite interference in planned observations (which can be used for improved planning of observations by users) and also for checking the same post-facto after observations, at
`http://www.gmrt.ncra.tifr.res.in/gmrt_users/help/help.html`
under "Satellite Tools". A real-time version of the tool runs in the control room and produces warnings for satellite interference during the observations, which can be monitored by the operator on duty. Due to increasing interference from mobile phone signals around 950 MHz, some observations in Band-4 and Band-5 can be affected.

(b) **Effect of ionospheric scintillation:** Ionospheric scintillation is common near the solar maximum, even at Band-5. The probability of scintillation is higher closer to the equinoxes. High winds can halt observations in the pre-monsoon months of April – June and also sometimes in October and November. During the monsoon months of June and July, the antennas on the arms sometimes fail due to power outages.

uGMRT system parameters and primary-beam shape parameters: Tables 1.2 and 1.2 provide uGMRT system parameters and primary-beam shape parameters, respectively. The primary-beam shape parameters have been determined by fitting an even polynomial (of 8th order) to the measured antenna response. A short note (dated 9 September 2022) providing some of the details is available at
`http://www.ncra.tifr.res.in/ncra/gmrt/gmrt-users/observing-help/beam-shape-v1-09sep2022.pdf`.

Table 1: uGMRT System Parameters

Band	Frequency range MHz	Gain (K/Jy)	T_{sys} K	RMS noise† μJy/Bm	Primary Beam$ ′	Synth. beam$ ″
Band-2	125 – 250	0.33	760 – 240	500	120	17.3
Band-3	250 – 500	0.38	165 – 100	10	75	8.3
Band-4	550 – 850	0.35	≈ 100	6	38	4.3
Band-5	1000 – 1460	0.22–0.28	≈ 75	2.5	23	2.3

† The quoted RMS noise values are the deepest obtained known to us so far with the different uGMRT bands, in continuum mode.
$ The values for primary and synthesised beams are at the centre frequency of the band.

Table 2: Coefficients of an 8th order polynomial fit to the antenna primary beam.

observing band		polynomial coefficients			
		a	*b*	*c*	*d*
	(MHz)	PBPARM(3)	PBPARM(4)	PBPARM(5)	PBPARM(6)
Band–2	125–250	−3.089	39.314	−23.011	5.037
Band–3†	250–500	−2.939	33.312	−16.659	3.066
Band–4	550–850	−3.263	42.618	−25.580	5.823
Band–5	1050–1450	−2.614	27.594	−13.268	2.395

†: (old) polynomial coefficients at band-3 from the earlier (1 December 2018) note.

Offline data analysis and data back-up : The existing offline programs such as listscan and gvfits have been upgraded to make them compatible with the wideband uGMRT data. All interferometry data acquired will be formally archived in the GMRT Observatory Archive (GOA). A CASA based Pipeline-cum-Toolkit for producing quick-look continuum images from the uGMRT is now available at `https://github.com/ruta-k/uGMRT-pipeline`. Note that beamformer data are presently not archived in GOA, and the user is responsible for their own back-up of such data. For details on back up of beam former data please refer to Section 4 of "Manual for observations in beam-former mode" that can be found in `http://www.gmrt.ncra.tifr.res.in/gmrt_users/help/help.html`. Users with approved uGMRT proposals are allowed to record and use data from both the GWB and the legacy GSB system.

2. Observing with the legacy GMRT

Some of the observation modes in the legacy GMRT system have been affected by the changes implemented as part of the upgrade activities. These include the following :

(i) With all antennas now having the new Band-4 feed and receiver, the dual frequency 235−610 feeds and receivers of the legacy system are no longer available; hence simultaneous dual frequency observations at 235 & 610 in the legacy mode, are no longer possible.

(ii) For some observing frequencies, the choice of 1^{st} LO $>$ RF might not be possible when observing in 250−500 MHz (Band-3) and 550−850 MHz (Band-4). In such cases, observations in legacy mode can still be possible, with the choice of 1^{st} LO $<$ RF.

GSB overview : The main back-end for the legacy system is the GMRT Software backend (GSB). The GSB handles the full 32 MHz baseband signals from each of two polarisations for all 30 antennas, which are digitised and sent to a networked cluster of computers that performs all the operations needed to realise a correlator and a pulsar receiver, in real-time. The standard processing features include gain equalisation, integer and fractional delay correction, and fringe stopping for the signals from each antenna. The GSB implements a FX type correlator, with user selectable number of spectral channels across the band. Operation over narrower bandwidths is supported by use of a digital filter followed by desampling to the required Nyquist rate, inside the GSB. Though the GSB works for 32 MHz input bandwidth (with an exact sampling rate of 66.666 MHz and 4 bits per sample), it can also run in 33.333 MHz sampling rate (with 8 bits per sample), which is useful for cases where the input bandwidth is limited (at the IF stages) to 16 MHz or less. These two modes of operation of the GSB are referred to as "32 MHz" and "16 MHz" modes. In both these modes, the GSB can be run either in total intensity mode or in full polar mode. In the latter, the GSB provides the intensity for each polarisation and the real and imaginary parts of the cross-term. Both interferometric and beamformer mode observations can be conducted using the GSB. The visibilities are output from the GSB cluster at a nominal rate of 2 seconds and are further processed by a software chain which allows real-time monitoring of the data products, before recording to disk with a default integration time of 16 seconds. The GSB also has a beam former, running concurrently with the FX correlator, which produces incoherent array (IA) and phased array (PA) beam outputs for a user selectable set of antennas, which can be chosen independently for the IA and PA modes. The GSB also has an offline mode, where the raw voltage data from all the antennas can be recorded on an array of SATA disks attached to the GSB cluster, for offline processing. In this mode, the GSB can record data samples at reduced bit resolution, typically 4 bits per sample (for the "16 MHz" mode) and 2 bits per sample (for the "32 MHz" mode).

For further details and clarifications please contact
GMRT Operations (`gmrtoperations@ncra.tifr.res.in`).

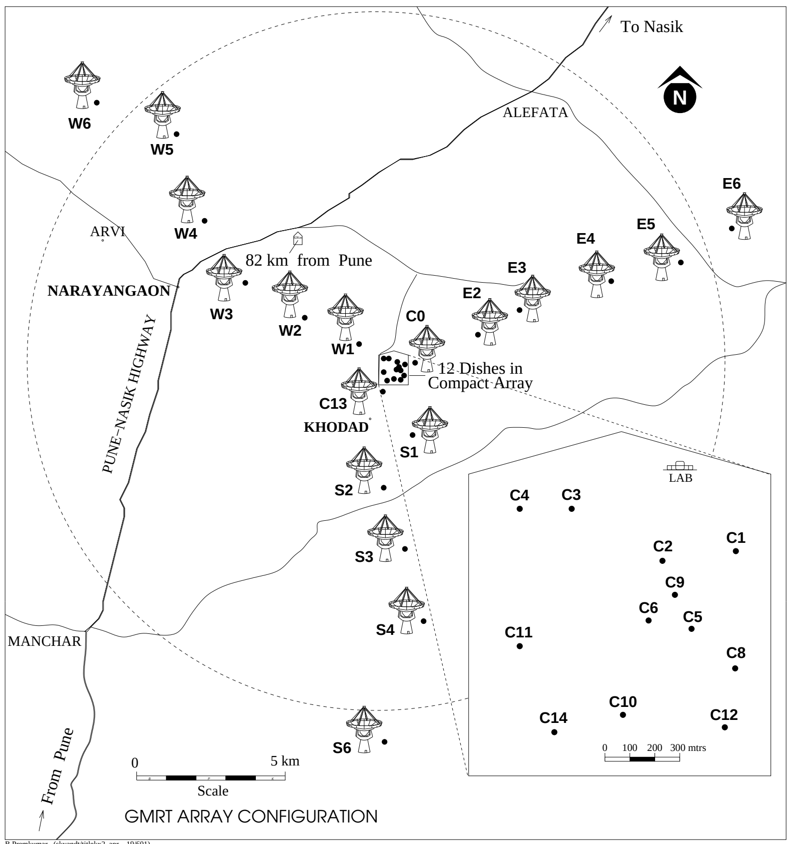

Fig. 1.— GMRT Array configuration: 30 antennas each of 45 m diameter spread 25 km, central square consists of 12 antennas in 1 km.

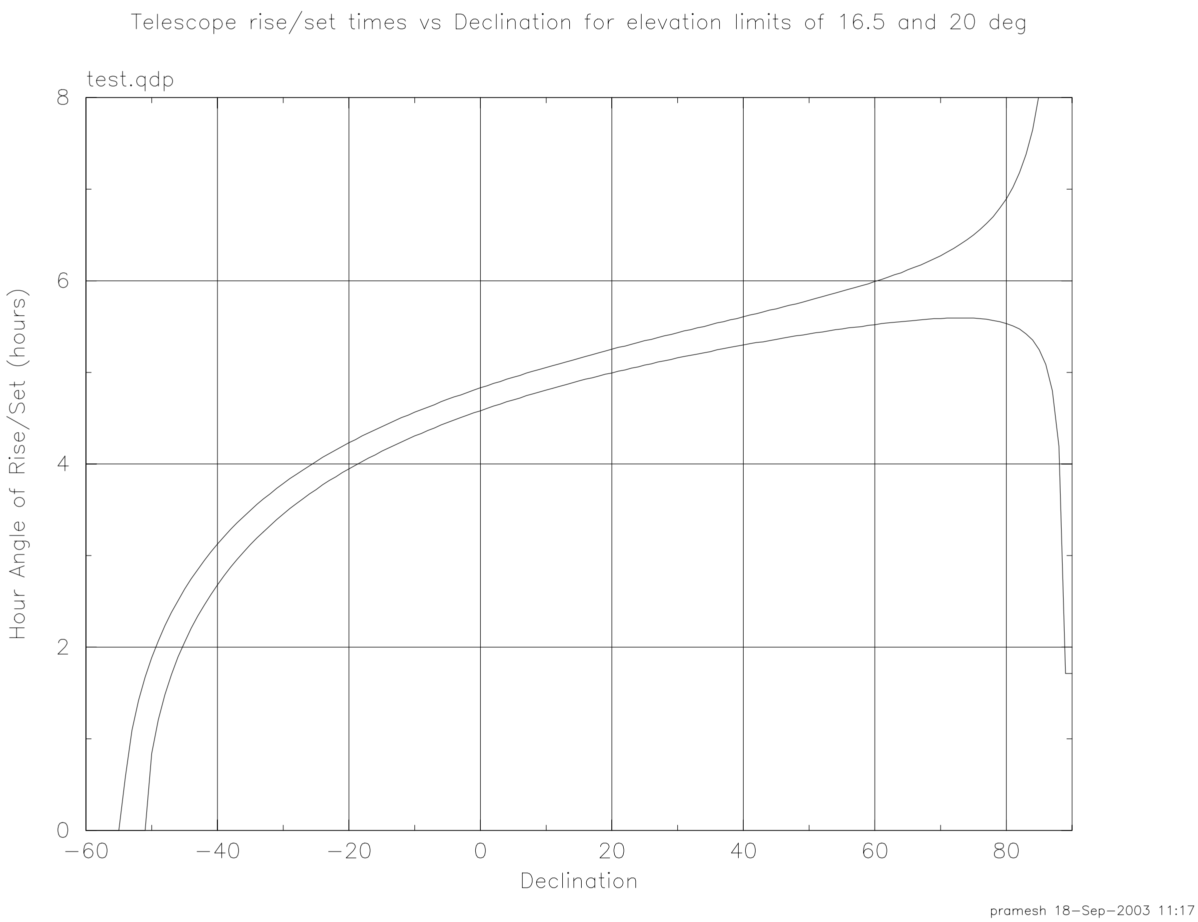

Fig. 2.— Hour Angle at which sources at different declinations rise and set for GMRT antennas - upper curve if for elevation limit of 16° and the lower for 20°

Table 3: Relative locations of GMRT Antennas. Coordinate system is as defined in “Interferometry and Synthesis in Radio Astronomy” by Thompson, Moran and Swenson (1985), p87 : *bx* and *by* in the equatorial plane with *by* to the East.

AntId	Name	bx (m)	by (m)	bz (m)
ANT00	C00	40.48	687.87	-8.43
ANT01	C01	41.47	326.43	-30.57
ANT02	C02	0.00	0.00	0.00
ANT03	C03	-41.88	-372.72	136.82
ANT04	C04	-42.21	-565.94	126.46
ANT05	C05	84.47	67.82	-244.74
ANT06	C06	80.11	-31.44	-217.50
ANT07	C08	139.65	280.67	-397.25
ANT08	C09	77.40	41.94	-141.69
ANT09	C10	200.22	-164.86	-584.43
ANT10	C11	135.99	-603.94	-309.88
ANT11	C12	214.67	174.85	-633.66
ANT12	C13	402.19	-639.50	-1106.31
ANT13	C14	229.27	-474.67	-621.28
ANT14	E02	-319.41	2814.54	963.63
ANT15	E03	-698.30	4575.99	1935.69
ANT16	E04	-1009.37	7780.52	2913.07
ANT17	E05	-1177.96	10199.78	3343.16
ANT18	E06	-1550.28	12073.19	4550.70
ANT19	S01	971.77	633.92	-2795.96
ANT20	S02	1462.21	-367.08	-4275.93
ANT21	S03	2212.71	333.12	-6395.07
ANT22	S04	3072.97	947.47	-8979.47
ANT23	S06	4614.59	-369.05	-13374.92
ANT24	W01	-167.79	-1591.91	602.93
ANT25	W02	-453.65	-3099.40	1429.36
ANT26	W03	-982.31	-5199.93	2902.34
ANT27	W04	-1705.86	-7039.01	5077.25
ANT28	W05	-2705.66	-8103.19	7817.06
ANT29	W06	-3079.50	-11245.58	8923.76

3. Appendix

This section gives an overview of the latest status of the GMRT and relevant system parameters useful for planning GMRT observations. Section 1 gives the background and an overall description of the GMRT, covering the legacy system and the upgraded GMRT.

3.1. General Overview

The GMRT consists of thirty 45 m diameter antennas spread over a 25 km region. Fourteen antennas are in a compact, quasi randomly distributed array, in a region of size about 1 km (called the Central Square). The remaining sixteen antennas are on the 3 arms of a "Y" (NorthWest, NorthEast and South), each of length $\approx$ 14 km, with 5 or 6 antennas on each arm. The longest baseline is about 25 km and the shortest is about 100 m, without foreshortening. The array configuration is shown in Fig. 1.

The telescope (Latitude=$19.1^{\circ}N$, Longitude = $74.05^{\circ}E$) is located near Khodad village, which is about 80 km north of Pune. The telescope site houses laboratories, a guest house, a library and a canteen. The observatory can be reached using the daily shuttle service that starts from NCRA, Pune at 7 AM in the morning and return from GMRT at 5:30 pm (all days including holidays and weekends), or by a direct taxi from Mumbai or Pune. The closest town, Narayangaon, is about 14 km from the observatory and is connected to Pune and Mumbai by a public bus transport system. If advance information is given, arrangements can be made to transport observers from the Narayangaon bus stand to the observatory. See `http://www.ncra.tifr.res.in` for more details on various general aspects of observing at the GMRT, including a road-map for travel to the observatory.

The GMRT antennas are 45 m alt-azimuth mounted parabolic prime-focus dishes. While the dishes can go down to an elevation of 16°, at present, the elevation limit has been set at 17°, giving a declination coverage from -53° to $+90^{\circ}$. The usable hour-angle range for different declinations is shown in Fig. 2. The slew speed of the antennas is 20°/min on both axes and they can be operated upto wind speeds of 40 km/h (for safety, the antennas are parked at higher wind speeds). There is a rotating turret at the focus on which the different feeds are mounted. The feeds presently available are the Band-5 (1000$-$1460 MHz), Band-4 (550$-$850 MHz), Band-3 (250$-$500 MHz) and Band-2 (125$-$250 MHz) feeds. The reflecting surface is formed by a wire mesh and the efficiency of the antennas varies from about 60% to about 40%, from the lowest to the highest frequency. Signals from two orthogonal polarisations are brought to the control room from each antenna, over optical fiber. The native polarisations for all receiver systems are circular, except for the Band-5, which delivers linear polarisations.

The GMRT has been open to the international community of users since early 2002, via a proposal submission and approval scheme that presently runs two observing cycles in each year. After over a decade of operations, the GMRT has recently undergone a major upgrade of its capabilities, whose main goals have been to provide (i) near-seamless frequency coverage from $\sim$ 100 MHz to $\sim$ 1500 MHz (ii) improved sensitivity with better quality receivers (iii) a maximum instantaneous usable bandwidth of 400 MHz along with high spectral resolution (iv) a revamped and modern servo system (v) a next-generation monitor and control system (vi) improvements in the antenna mechanical structure and (vii) matching improvements in infrastructure and computational facilities. The upgrade has resulted in significant changes to almost all aspects of the GMRT receiver chain and other systems. However, full care was taken in the design of the new systems to ensure that the performance of the existing legacy GMRT system is not affected as the upgrade is implemented. The upgraded GMRT (hereafter, the "uGMRT"), now fully complete, has been made available in an incremental fashion to the user community since GMRT Cycle 30, and Cycle 36 marked the full release of the final uGMRT.

3.2. Overview of the uGMRT

The uGMRT replaces the narrow band feed and front-end receiver systems of the legacy system with wide-band receivers. The legacy 150 MHz feed has been replaced with a wider bandwidth feed, covering 125 to 250 MHz (Band-2). The legacy 325 MHz feed has also been replaced with a broadband feed operating from 250 to 500 MHz (Band-3), along with a broadband low noise amplifier with improved noise temperature. A new feed operating from 550 to 850 MHz (Band-4) has replaced the legacy 610/235 MHz co-axial feed, also with a matching LNA with improved noise figure. Due to this, the 235 MHz band of the legacy system is no longer available from Cycle 34 onwards. Both band-3 and band-4 have the provision to select sub-bands of 100 MHz bandwidth with significant overlap for each sub-band. The L-band feed (Band-5) has been upgraded with a better dynamic range front-end receiver system, covering the frequency range of about 1000 to 1460 MHz, along with four sub-bands, each of 120 MHz bandwidth.

As part of the upgrade, the optical fiber link to each antenna has been modified to provide additional wavelengths to bring back the dual polarisation broadband RF signals from the new front-end receivers directly to the Central Electronics Building (CEB), without disturbing the existing narrow bandwidth path for the legacy system that brings back the two polarisations on IF signals with a maximum bandwidth of 32 MHz. In the CEB, a new signal chain has been developed in parallel to the existing system that handles the narrow-band signals of the legacy GMRT, for catering to the broadband signals of the upgraded GMRT. The broadband RF signals are converted to baseband signals with a maximum bandwidth of 400 MHz, which are then processed with the new digital back-end system, the GMRT Wide-band Backend (GWB), consisting of a correlator, a beam-former, and a pulsar receiver, that can handle the full 400 MHz bandwidth. Both these signal paths run independently and in parallel, without affecting each other.

The servo system for all 30 antennas has been upgraded with new brush-less DC motor system along with a new servo computer. A new Tango based GMRT Control and monitor system (TGC) with improved hardware at each antenna connected to the central station via Ethernet, and improved software and user interface, replaces the current control and monitor system. Several improvements to the mechanical structure and reflecting surface of the antennas have been carried out, and continue to be undertaken. Matching enhancements in computing resources and data archiving capabilities are being implemented.

These upgrade activities are now complete and the full uGMRT was released to users from Cycle 36 (April 2019) onwards.

3.3. Front-end Receiver Systems

At the focus of each antenna, the front-end system for each feed has 2 low noise amplifiers (LNAs) (one for each polarisation), with a noise injection facility where the user can select one of 4 levels of injected noise power. For all the bands (except Band-5), the linear polarisation signals from the feeds are converted to circular polarisation signals just before the LNAs. The two polarisations signals from the front-end receivers of all the bands go to a common box (also located on the feed turret) where the user has to select one of the frequency bands for onward transmission, as only two RF cables go down to the antenna base. The common box also has facilities to select solar attenuators (0, 14, 30 or 44 dB), enable/disable noise and Walsh modulation, and swap the signals between the two polarisation channels.

Legacy GMRT system : In the legacy system, at the antenna base, the RF signals are mixed with a pair of coherent local oscillator signals (the 1^{st} LO) to give two 70 MHz IF signals. The user can select the 1^{st} LO frequency (1 MHz steps upto 350 MHz and 5 MHz steps from 350 to 1700 MHz), IF attenuators (0 to 64 dB in 0.5 dB steps) and the IF bandwidth (6, 16 or 32 MHz) independently for each IF. The IF signals from each antenna are transmitted on optical fibre to the CEB. There is a facility at each antenna to turn on or off an Automatic Level Controller (ALC) before the optical modulator. At the CEB the IF signals for the two polarisations from each antenna are converted to corresponding baseband signals. In the present arrangement, the signals are first converted to a common 70 MHz IF (using a different 3^{rd} LO for each polarisation), and then to baseband using a single oscillator (the 4^{th} LO), which the user can set from 50 to 90 MHz in steps of 0.1 KHz. For simplicity, for each polarisation, an effective value of the LO signal down conversion is specified (called the 5^{th} LO).

Upgraded GMRT system : In the upgraded system, the RF signals are directly transmitted to CEB using high dynamic range fibre optics system; these form the input to the GMRT Analog Backend (GAB). The GAB converts any of the RF bands to baseband, with a final bandwidth of 100/200/400 MHz. The LO settings for all antennas (both polarisations) can be set independently to any value in the range 100-1700 MHz, with a step size of 10 kHz. Variable attenuation control for power equalisation is available in both polarisations.

3.4. Backend Systems

The backend systems are housed at the CEB, with separate systems for processing the legacy and upgraded GMRT signals. The first stage of these systems is the analog processing chain that provides the final baseband signals, which are then digitised and processed by the digital backend systems – the GMRT Software Backend (GSB) for the legacy GMRT, and the GMRT Wideband Backend (GWB) for the upgraded GMRT.

GMRT Wideband Backend (GWB): The GWB processes a maximum of 400 MHz band for each of two polarisations for all the GMRT antennas. It implements an FX correlator for interferometry mode, supporting both total intensity and full polar mode processing. It also has narrow-band spectral zoom modes that are useful for spectral line observations. The maximum number of spectral channels that the GWB provides goes up to 16384 (the default is 2048), though some modes may support a smaller value for the maximum number of spectral channels. The range of integration for the final recorded visibility data is between 0.6 and 16 secs.

In parallel with the correlator, the GWB also has incoherent array (IA) and phased array (PA) beamformers for the array mode, which are useful for observations of sources such as pulsars and fast transients. In addition, the beamformer has an option for providing the phased array voltage beam, at Nyquist rate, followed by real-time coherent dedispersion (CD) resulting in multi-channel intensity data at desired time-frequency resolution. A total of 4 beams can be formed simultaneously, with completely independent control over the choice of antennas to be used for each beam. These 4 beams can be any combination of IA, PA or CD beams at single or multiple frequency bands. However, at present one can record either one CD beam for 200 MHz bandwidth (along with PA and IA beams) or upto 2 CD beams for 100 MHz bandwidth (along with PA and IA beams) in the 8-bit mode (see 2.2.2(h) for newly available 4-bit CDP). Observation with CD beam is not possible if the GWB is configured in full-polar mode. The beam data (total intensity or Stokes parameters) can be recorded with different combination of allowed time frequency resolutions determined by the maximum allowed data rate of 48 MB/s par beam. The allowed time frequency resolution for the IA, PA and CD modes are summarised in the Table 1 of "Manual for observations in beam-former mode" that can be found in `http://www.gmrt.ncra.tifr.res.in/gmrt_users/help/help.html` . Any question regarding the choice of observing modes for the beamformer observations can be directed to Bhaswati Bhattacharyya (bhaswati@ncra.tifr.res.in).

3.5. Control and Monitor System

The Control and Monitor System issues commands to set the parameters of the electronics, to slew and track the antennas and to enable the recording of data. As part of the GMRT upgrade, the control and monitor system has been fully migrated to a new Tango based GMRT Control (TGC) system since January 2021. Observations of targets which moves in the sky during the course of observations (eg: Solar system objects) are possible, but users should provide the necessary ephemeris required for this kind of special observations. The control and monitor system also provides facilities for monitoring a wide range of parameters.

In practice, the GMRT is controlled by the telescope operator on duty. The responsibility of the user is limited to (1) providing the operator with the observing plan, the settings, and the command file, and (2) ensuring that the data quality is satisfactory. In the new TGC system, the format and syntax of the command files will be different from those in the legacy control system. Detailed explanation of the syntax can be found in `http://www.ncra.tifr.res.in/~secr-ops/cmd/cmd.html`.

Several useful tools for preparing observing files or command files, setup files, calculation of source rise and set times, selection of phase calibrators etc, are available at `http://www.gmrt.ncra.tifr.res.in/gmrt_users/help/help.html`. Users are encouraged to use these tools to prepare the observing files and mail them to gmrtoperations@ncra.tifr.res.in well in advance.