The Giant Metre-wave Radio Telescope

G. Swarup, S. Ananthakrishnan, V. K. Kapahi, A. P. Rao, C. R. Subrahmanya and V. K. Kulkarni

The Giant Metre-wave Radio Telescope, an aperture-synthesis array consisting of 30 fully steerable parabolic dishes of 45-m diameter each, is being set up about 80 km north of Pune as a national facility for frontline research in radio astronomy in the frequency range 38 MHz to 1420 MHz. The new and novel design of a low-solidity dish for metre-wave operation, in which a thin wire mesh (varying in size from 10 mm × 10 mm to 20 mm × 20 mm and made of 0.55 mm diameter stainless-steel wire), which constitutes the reflecting surface, is stretched over a parabolic surface formed by rope trusses, has made it possible to build a large collecting area (total effective area of about 30,000 m^2, over three times that of the Very Large Array in the USA) at modest cost. It will be a major new instrument designed to fill the existing world-wide gap in powerful radio telescopes operating at metre wavelengths, where there are many exciting and challenging astrophysical problems and phenomena to be investigated. Two of the primary scientific objectives of the telescope are to detect the highly redshifted '21-cm' line of neutral hydrogen from protoclusters or protogalaxies in the early epochs of the Universe before galaxy formation and to detect and study a large number of millisecond pulsars in an attempt to detect the primordial background of gravitational radiation.

MUCH of the early and pioneering work in radio astronomy after World War II was carried out at metre wavelengths. But the development of interferometric techniques and low-noise receivers and electronics saw a steady shift in emphasis towards shorter wavelengths, where the Galactic background noise is smaller and higher angular resolutions can be attained for a given antenna size or interferometer baseline. The most powerful radio-astronomical facilities in the world today operate mainly in the centimetre and decimetre part of the radio spectrum even though there are many exciting and challenging astrophysical problems that are best studied at metre wavelengths. The importance of this part of the radio spectrum has been well highlighted by the variety of astronomical research carried out using the few instruments built specially for metre-wave operation[1–7]. Much of the potential has however remained unexploited as these instruments have been limited by sensitivity and resolution, as well as the limited frequency coverage and the inability of many of them to track radio sources for long periods of time.

The more widespread prevalence of man-made radio interference at metre, compared to centimetre wavelengths in the Western world and the increasing distortions at longer wavelengths in the incoming wave fronts caused by ionospheric irregularities have also possibly been responsible for the present neglect of metre-wave radio astronomy. Fortunately, radio interference is not a serious problem in India and the harmful ionospheric effects can be largely overcome or greatly reduced through the use of powerful self-calibration techniques[8] that have been developed over the last decade or so.

The Giant Metre-wave Radio Telescope (GMRT) has been designed as a major new instrument that would fill the existing gap in radio-astronomy facilities at metre wavelengths. Now under construction near Khodad, about 80 km north of Pune (site latitude 19° 06′ N, longitude 74° 03′ E, altitude 650 m), GMRT will be the world's largest aperture-synthesis array. It will have over three times the collecting area of the Very Large Array[9] (VLA) in New Mexico, USA. At 327 MHz its sensitivity will be about eight times higher than that of the VLA because of larger area, 1.6 times higher efficiency of the antennas, and at least four times wider usable bandwidth.

Since the original proposal[10] in 1984, which was to build a total collecting area of about 100,000 m^2 in the form of 34 parabolic cylinders operating at four different frequencies in the range 38 to 610 MHz, the design of GMRT has undergone several important changes as a result of extensive investigations to optimize the antenna design and array configuration. The most important change is that parabolic cylinders have been replaced by parabolic dishes[11]. For a given collecting area the conventional design of a dish is several times more expensive than that of a cylinder. But the development of a new and novel design for metre-wavelength parabolic dishes has made it possible to cut costs drastically, as a result of which it has

The authors are in the National Centre for Radio Astrophysics, TIFR, Pune 411 007.

become feasible, within the available budgets, to build a total collecting area in the form of dishes that is only about a factor of 2 smaller than proposed originally in the form of parabolic cylinders. The reduction in collecting area should, however, be compensated by the reduced system temperatures, the much greater versatility and flexibility of the array in terms of its improved scientific performance, and greater reliability and ease of larger frequency and sky coverage.

Another important change from the original proposal is the decision to extend the high-frequency coverage from 610 to 1420 MHz, which will greatly enhance the scientific potential of the telescope.

The final design of GMRT, as currently under execution, consists of an array of 30 fully steerable parabolic dishes, each 45 m in diameter, installed over a region of about 25 km. The feed and receiver systems will allow observations in six different wave bands between 38 and 1420 MHz. The achievable angular resolution (given by the half-power width of the synthesized beam) will vary from about 2 arcsec at 1420 MHz to 75 arcsec at 38 MHz. The array is being built as a national project by TIFR for which an academic centre has been set up in the campus of Poona University.

Astrophysical objectives

GMRT is designed to cover a wide region of the radio spectrum in the wavelength range of about 20 cm to 8 m. Some aspects of its design features were motivated by the important astrophysical objectives of (i) searching for the highly redshifted line of neutral hydrogen from protoclusters or protogalaxies in an attempt to determine the epoch of galaxy formation, and (ii) searching for new short-period pulsars. However, GMRT will still be a very versatile and general-purpose astronomical facility for both continuum as well as spectral-line observations. Because of its high sensitivity and angular resolution, it will be useful for investigations of almost every type of celestial object that emits radiation at radio wavelengths. With a view to informing potential users of the telescope, a brief account of some of the areas where GMRT will have the capability of making outstanding contributions is given below. It should be emphasized, however, that the list is by no means exhaustive and major advances in totally unforeseen areas cannot be ruled out.

Continuum studies

The Solar System. The provision of high time-resolution capability (40 msec; about an order of magnitude higher than available with VLA) will allow GMRT to be very effectively used for studying a variety of solar and planetary radio bursts, including those from Saturn discovered by the *Voyager* spacecraft[12]. Observations of interplanetary scintillations (IPS) of distant radio sources provide valuable information on solar wind velocity. Such studies have recently been extended to much weaker sources using the Ooty Radio Telescope[13]. By combining high-resolution maps of solar active regions made using GMRT with IPS observations made at Ooty as well as at observatories elsewhere, it should be possible to obtain a better understanding of the complex relationship between solar activity (flares, prominences, coronal holes, etc.) and disturbances in the interplanetary medium[14, 15]. It may also become possible to probe the ionospheres and magnetospheres of some planets other than Earth by observing scintillations of radio sources passing close to the planets.

Galactic plane surveys. With its multifrequency coverage at metre wavelengths, continuum surveys of the Milky Way and detailed imaging of interesting sources with GMRT should lead to deeper insights into the physics and evolution of HII regions, planetary nebulae, supernova remnants, voids, spurs and other phenomena in our galaxy. Of particular value will be a search for young supernova remnants[16] or plerions (Crab-nebula type).

Radio stars. During the last two decades, radio emission has been detected from many different types of stars[17]. The most prominent at metre wavelengths are the red-dwarf flare stars of UV Ceti type, of which over twenty have been found to give rise to frequent radio flares. Other types are radio-active binaries, cataclysmic variables and radio-emitting X-ray binaries such as Sco X-1, Cyg X-3, and SS 433. Observations of the dynamic spectra of flare stars and the extension to metre wavelengths of continuum spectra of other types of radio stars will be important in understanding the plasma processes that give rise to these highly intense radio emissions, often hundreds of times stronger intrinsically than those from the Sun.

Pulsars. With its large collecting area and extensive sky coverage, GMRT will be one of the most powerful telescopes for the study of pulsars associated with rotating neutron stars. It will have the capability of bringing about a three- or four-fold increase in the total number of pulsars (about 450) that are currently known[18] in the Galaxy. This will allow many important statistical investigations into the origin and evolution of pulsars. Observations of sets of individual pulses from known pulsars with the 30 antennas of GMRT used in the phased-array mode will also be valuable in extending the study of a variety of features, such as pulse shapes, pulse microstructure, polarization properties, drifting subpulses, mode changing and scintillations in the interstellar medium, to a large number of objects. A particularly important programme in pulsar research will be the search for fast-period or the so-called millisecond pulsars. Only about a dozen such objects (with periods smaller than ~ 10 msec) are presently known and five of these are members of binary star systems[19]. Systematic timing measurements of binary pulsars in eccentric orbits can be used to make sensitive tests of gravitational theories[20] like the general theory of relativity.

Accurate timing measurements of millisecond pulsars have also been used to place limits on the presence of gravitational background radiation of primordial origin[21] thought to have arisen during the early inflationary phase of the Universe. GMRT will have the potential of greatly improving the present limits on the long-wavelength gravitational radiation (equivalent to about 10^{-6} of the closure density of the Universe) because of its ability to find and monitor many new pulsars well distributed over the sky. Most known millisecond pulsars have been discovered using the Arecibo radio telescope[22], which has a restricted declination coverage. The detection of background gravitational radiation will clearly provide a very important new input to the physics of the early Universe.

Variability of radio sources at metre wavelengths. GMRT would be a powerful tool for investigating the origin of low-frequency variability of extragalactic sources and to monitor transient sources in the Galactic plane and supernovae in external galaxies. There is considerable uncertainty about the extent of low-frequency variability of extragalactic sources[23, 24] and the contribution made by refractive interstellar scintillations[25] and intrinsic effects to such variability[26, 27]. Simultaneous flux-density measurements at both metre and decimetre wavelengths as well as monitoring of complete samples are clearly important but have not been pursued extensively so far. Such observations are vital for understanding of the nature and cause of variability as well as plasma irregularities in the interstellar medium.

Extragalactic radio sources and cosmology. Continuum studies of normal and active galaxies at metre wavelengths would address several basic issues, such as the bivariate optical–radio luminosity function, the existence of nonthermal radio haloes around spiral galaxies, and the presence of thermal plasma in such galaxies. Investigations of giant radio galaxies[28], the largest individual structures in the Universe, could be very profitably undertaken with the wide-field high-resolution capabilities of GMRT. Rich clusters of galaxies are often found to contain extended 'tailed' radio galaxies or sometimes the so-called 'relic' radio sources[29, 30], which have unusually steep radio spectra. Metre-wave studies are highly complementary to those made at X-rays and optical wavelengths for investigating the nature of such radio sources.

Metre wavelengths are also appropriate to investigate synchrotron emission from the oldest population of relativistic electrons in radio galaxies and quasars, allowing the ages of the emission regions to be derived from their spectral forms[31]. The different individual components in these sources, such as the compact cores, jets or beams emanating from the nuclei, hot spots where the beams are believed to be interacting with the intracluster/intergalactic medium, and the diffuse lobes or cocoons of material 'flowing back' from the hot spots, will all be studied by GMRT at the highest resolution both by aperture synthesis as well as by techniques of lunar occultation and interplanetary scintillation (particularly at the lowest frequencies of 38 and 150 MHz) to obtain valuable spectral information.

The study of the magneto-ionic content in the diffuse radio regions of clusters and radio galaxies by measuring the weak Faraday rotation caused by it is also a vital area, which GMRT will be able to probe extensively for the first time. When combined with X-ray data, such information can yield a direct estimate of the magnetic field in diffuse radio sources, which is a key parameter that is poorly known.

In the phased-array mode, GMRT could form the dominant element in a global network of very-long-baseline interferometry (VLBI). This world-wide collaborative effort, which by the mid-nineties may also include antennas in space, would enable very-high-resolution ($\lesssim 1$ milliarcsec) imaging to be extended to extremely weak cores in a variety of radio sources. Such observations are our best source of information on the workings of the compact central engines that power radio galaxies and quasars, but are currently limited to sources of relatively strong radio cores and therefore may not represent an unbiased sample of jet orientations because of relativistic beaming effects[32].

In the area of observational cosmology, deep radio surveys using GMRT will be capable of extending the number–flux density counts of radio sources at metre wavelengths to flux levels about 10 times fainter than at present[33] and the angular size–flux density relation[34] to even 100 times fainter levels than at present. Together with deep-optical identifications and spectroscopy, this data would be very valuable in constraining models of cosmic evolution in the properties of radio sources over a wide range of radio luminosity[35, 36].

Spectral-line studies

Neutral hydrogen (HI). The 21-cm line of HI plays an extremely important role in studies of the distribution of hydrogen in our galaxy[37, 38] and in many external galaxies[39]. Mapping of HI gas associated with dense molecular clouds (which can be regarded as stellar 'nurseries') and HII regions should greatly further our understanding of the processes of star formation and early stellar evolution. In the phased-array mode, it should be possible to observe HI-absorption spectra of interstellar gas against a background of numerous compact extragalactic radio sources and pulsars. Such absorption spectra sample the structure of interstellar clouds on scales down to milliarcseconds and are an important source of information on physical conditions in the interstellar medium.

In the case of external galaxies, HI studies will allow determination in a large number of galaxies of velocity fields and rotation curves, which provide important input for studying the dynamics of the galaxies[40] and the distribution of dark matter[41]. The observed velocity width in HI provides a very useful distance indicator through the Tully Fisher relation[42] (between velocity width and galaxy luminosity), which has contributed significantly in recent years to inferring the presence of large and systematic streaming motions in the nearby Universe that can be attributed to a so-called Great Attractor[43], whose nature and location are still controversial. GMRT will have the potential to extend such studies to greater distances and over larger areas of the sky. This is important for a better understanding of the deviations from a uniform Hubble flow.

With the aid of wide-band feeds and receivers, GMRT will be a very powerful tool to probe the properties of intergalactic HI clouds or HI-rich galaxies out to cosmological distances through detection of the redshifted HI absorption by these intervening clouds of the continuum radiation from distant quasars. Only a handful of such absorption lines have so far been detected[44].

Search for protoclusters. Perhaps the most exciting prospect with GMRT is the detection of the highly redshifted 21-cm line of neutral hydrogen arising in primordial clouds, representing protogalaxies and protoclusters in the early Universe[45,46]. The line is expected to be greatly redshifted into the metre-wave band because of the expansion of the Universe between emission, at an early epoch, and detection, at the present epoch. For hydrogen clouds at redshifts between $z = 3$ and $z = 10$, the line should be observable at frequencies between about 350 and 130 MHz. A positive detection of such clouds would be of immense importance to our understanding of the epoch of formation of galaxies and clusters that constitute the principal units of the present-day Universe. Even the lack of detection[47,48] would yield very important constraints to theoretical models of galaxy formation.

Deuterium line. GMRT should have sufficient sensitivity to justify a fresh deep search for the hyperfine line emission from deuterium atoms at 327 MHz (refs. 49, 50). It should be possible to detect the line if the general deuterium-to-hydrogen ratio is about 2×10^{-5}, as has been found towards nearby stars by the *Copernicus* satellite[51]. Radio detection of the line would be of fundamental cosmological significance as deuterium is likely to have been produced in the first few minutes of the big bang, and its abundance is a sensitive function of the baryonic matter density in the Universe.

Recombination lines. The spectral resolution of GMRT will permit detailed observations of a host of recombination lines in the interstellar medium, including lines that have been shown to change from emission to absorption at metre wavelengths[52]. Since recombination lines are weak, the large collecting area of GMRT will make it one of the world's best telescopes for such studies at low frequencies with high spectral and spatial resolution.

The parabolic dish antenna

Conventional parabolic dishes have generally been built for operation only at centimetre and decimetre wavelengths ($\gtrsim 1$ GHz), and their high cost can in part be attributed to the need to maintain high surface accuracy in the presence of gravity deflections and large wind forces because of their solid surfaces. Even for mesh surfaces, large wind forces have to be allowed for in the event of snowfall. Although the structural specifications for GMRT antennas could be relaxed considerably because of the longer wavelengths of operation and the total absence of snowfall in the plains

Figure 1. Artist's sketch of the 45-m diameter parabolic dish antenna based on the SMART design.

of India, it was hard to estimate the potential savings in cost as no large antennas specifically designed for metre-wave operation have previously been built anywhere. It was clear therefore that new and innovative designs with a much lower solidity, would have to be developed if the requirement of a total physical area of $\sim 50{,}000\ m^2$ with about 30 elements had to be met within the limited available budget. To meet this challenge, several different approaches were investigated in considerable detail, as described elsewhere[53].

The design finally adopted as one meeting both technical and budgetary requirements is a 45-m-diameter dish based on a novel concept that was nicknamed SMART, for stretched *m*esh *a*ttached to *r*ope *t*russes. Basically, very low weight and solidity are achieved in this concept by replacing the conventional back-up structure in a dish by a series of rope trusses (made of thin stainless-steel wire ropes) stretched between radial parabolic frames and suitably tensioned to form a parabolic surface. A very-low-solidity wire mesh (made of thin stainless-steel wire) stretched over the rope trusses forms the reflecting surface of the dish. An artist's sketch of one of the 45-m dishes based on this concept is shown in Figure 1 and a section drawing in Figure 2. Some details of the design are discussed below.

The 16 radial parabolic frames made of tubular steel

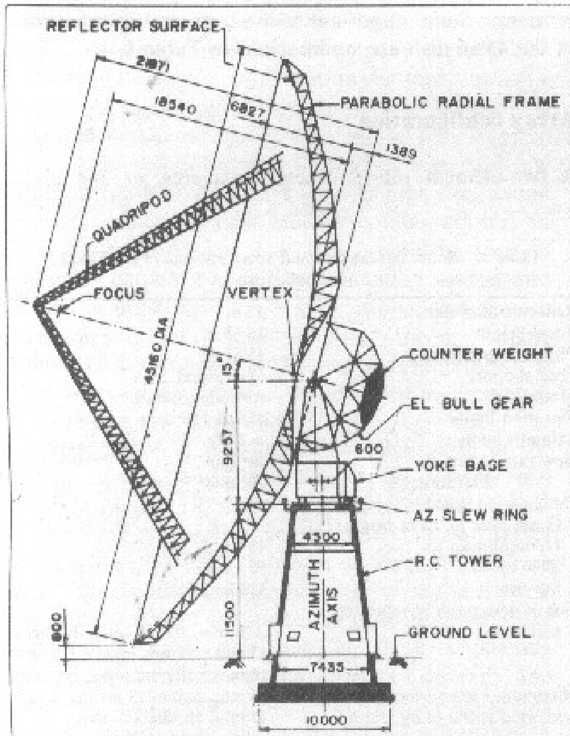

Figure 2. Sectional elevation of the parabolic dish.

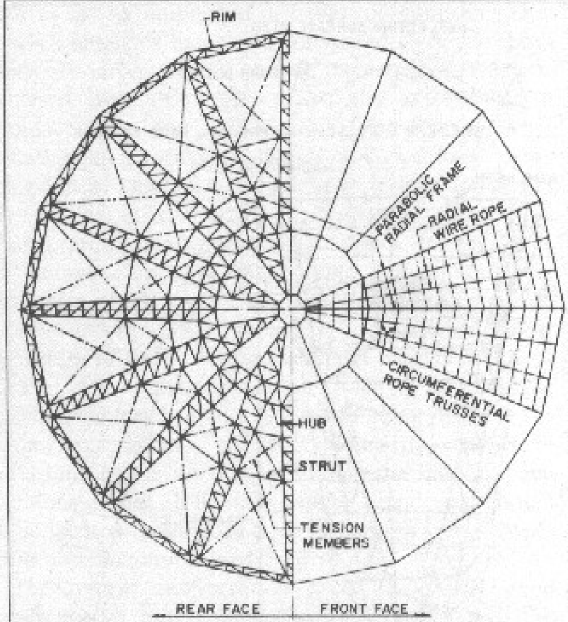

Figure 3. Front and rear schematic views of the parabolic dish.

are connected to a 12-m-diameter central hub (Figure 3). As shown in Figures 3 and 4, circumferential rope trusses made of 4-mm- and 2.5-mm-diameter wire ropes are stretched between adjacent parabolic frames to form the curved back-up surface on which the fine wire mesh that forms the reflecting surface can be supported. At their two ends, the rope trusses are connected to anchor blocks of adjustable height, which are welded to the parabolic frames at spacings of about 1.2 m. Turn-buckles at each end are used to provide the correct shape and tension. Each dish uses about 1200 turn-buckles.

The outer ends of the radial parabolic frames are connected together by triangular rim trusses made of tubular steel. The rim restricts variation of the circumferential distance between the support points of the rope trusses and prevents their becoming slack during high winds. It also provides stiffness to the structure and allows the placing of two radial wire-rope trusses between adjacent parabolic frames to provide transverse stiffness to the circumferential rope trusses. The initial tension in the top wire rope of each circumferential rope truss is about 250 kg. For front and rear winds of about 80 kmph the tension in the top wires changes to about 280 kg and 230 kg respectively. For the lower ropes, shown in Figure 4, the initial tension is only about 15 to 40 kg depending upon the geometry of each truss.

The wire mesh of the reflecting surface is stretched in both circumferential and radial directions before being tied to the rope trusses. Because of the shape of the

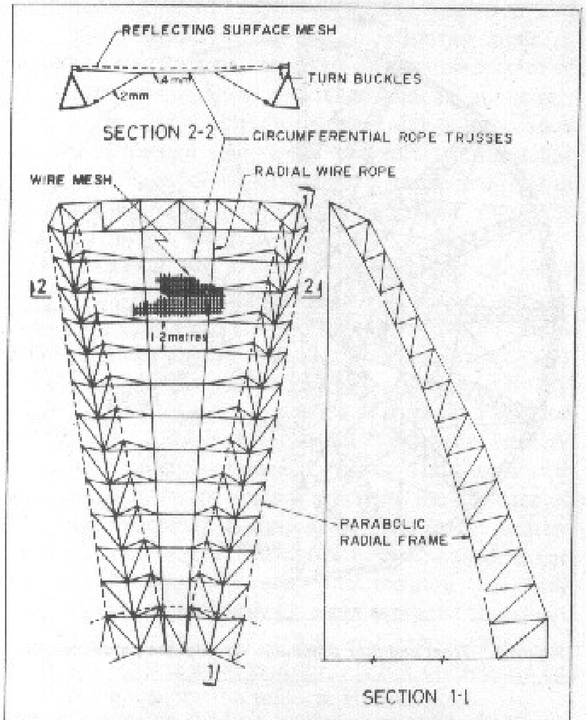

Figure 4. A section of the dish, illustrating the SMART concept.

rope trusses the parabolic reflecting surface of the dish is approximated by a series of plane facets with dimensions of about 1.2 m × 2.9 m near the outer parts of the dish and 1.2 m × 0.8 m near the central hub. The root-mean-square deviation of the actual surface from a true paraboloid is estimated to be about 8 mm. The wire mesh is made up of 0.55-mm diameter stainless-steel wire with a size of 10 mm × 10 mm in the central one-third area of the dish, 15 mm × 15 mm in the middle one-third, and 20 mm × 20 mm in the outer parts of the dish. At the highest operating frequency of 1.4 GHz the mesh surface will have an estimated leakage of about 5%.

The central hub of the back-up structure is connected to a 'cradle' at four points. The cradle is supported by two elevation bearings. The bull-gear connected to the cradle for rotation of the dish in elevation consists of a sector with an opening angle of 110° and with pins of circular cross-section rather than the conventional involute gear teeth. Though less accurate, the pin sector is much more economical. It is considered satisfactory for GMRT dishes because r.m.s tracking and pointing errors of about 1 arcmin should be acceptable. Pin sectors with a diameter of 5.5 m have been in use on the 24 frames of the Ooty Radio Telescope for the last 20 years and their performance has been found to be quite satisfactory.

The elevation bearings are supported by a yoke placed on a slewing-ring bearing of 3.6-m diameter with a built-in gear-wheel acting as an azimuth bull-gear. The bearing is attached to a steel plate secured to the top of a concrete tower which is about 15 m in height. A counter-torque system consisting of a pair of 5 kVA DC servo motors will be connected to the elevation bull-gear, and similarly to the azimuth slew ring, through a pair of gear boxes with overall gear reduction of 25,000 : 1 and 18,000 : 1 respectively.

The total tonnage of the back-up structure of the dish, the quadripod which supports the feed system at the focus of the dish, the elevation bull-gear structure, the yoke and the azimuth bearing support (excluding counterweight of 34 tonnes) is only about 82 tonnes. In contrast, the tonnage of a typical 25-m dish for use at centimetre wavelengths is about 250 tonnes (excluding counterweight). For a front wind speed of 133 kmph at a 10-m height (increasing to 155 kmph at 45-m height), the total force on the dish is only about 50 tonnes. For the elevation axis the maximum torque gets applied near the zenith position of the dish, and is estimated to be 189,000 kg m at 133 kmph wind speed; for the azimuth axis, the same occurs near the horizon position of the dish and is about 206,000 kg m. The overall wind forces and rotational moments of the 45-m dish based on the SMART concept are thus similar to those of only a 22-m conventional dish, resulting in considerable economy. Some important parameters and specifications of the 45-m dish are summarized in Table 1.

Array configuration

A two-element interferometer measures, at any given

Table 1. Some parameters and specifications of the GMRT parabolic dish.

Reflector diameter	45 m
Focal length	18.54 m
Physical aperture	1590 m^2
Feed support	Quadripod
Mounting	Altitude-azimuth
Elevation limits	15° to 110°
Azimuth limits	± 270°
Slew rate: Azimuth	30° min^{-1}
Elevation	20° min^{-1}
Design wind speeds (3 sec peak at 10-m height):	
Operation up to	40 kmph
Slew up to	80 kmph
Survival	133 kmph
Size of wire mesh of reflecting surface	20 mm × 20 mm, outer 1/3 area 15 mm × 15 mm, middle 1/3 area 10 mm × 10 mm, inner 1/3 area
Maximum r.m.s surface errors, at wind speed of 40 kmph	20 mm, outer 1/3 area 12 mm, middle 1/3 area 8 mm, inner 1/3 area
Tracking and pointing accuracy	1 arcmin r.m.s. at winds of < 20 kmph

instant, one spatial Fourier component (called the visibility function) of the source brightness distribution. The spatial frequency of the Fourier component being measured depends on the relative position of the antennas (the baseline vector), the geographical latitute of the antennas, and the hour angle (H) and declination (δ) of the source being observed. The spatial frequencies, u and v, of the Fourier component being measured at any instant are given by

$$u = b_x \sin H + b_y \cos H,$$
$$v = -b_x \cos H \sin \delta + b_y \sin H \sin \delta + b_z \cos \delta,$$

where b_x, b_y and b_z are the components of the baseline vector (measured in wavelengths) in a coordinate system with x pointing to ($H=0$, $\delta=0$), y to ($H=-6^h$, $\delta=0$) and z to ($\delta=90°$). As the hour angle of the source changes owing to the rotation of the Earth, a two-element interferometer measures the Fourier components along an elliptical track in the $u-v$ plane. To determine the source structure one has to measure all the spatial Fourier components and perform an inverse Fourier transform. The different Fourier components can be measured either by changing the baseline vector by moving one of the antennas, or by having many (N) antennas, so that a large number of baselines ($N(N-1)/2$) are present at any instant.

With its 30 antennas, GMRT would measure 435 Fourier components at any instant. The decision on where these 30 antennas should be located is a complex one that requires consideration of many factors. The most straightforward consideration is that the $u-v$ plane should be covered as completely as possible up to the desired maximum values of u and v. This leads to different strategies for arrays located at high and low latitudes. High-latitude arrays look at high declination sources, for which the most efficient configuration is an east–west array. At low latitudes (as in the case of GMRT) the emphasis is on low-declination sources and such arrays must have a two-dimensional distribution of antennas if they have to cover the $u-v$ plane adequately. A three-armed 'Y'-shaped configuration is well known to give a good coverage of the $u-v$ plane at both high and low declinations[54].

Another factor in deciding the configuration of the antennas is the nature and size of the sources one intends to study. To study small sources one should have as long a baseline as possible, but for larger sources whose visibility function is zero at baselines longer than (wavelength/source size in radians), it is more useful to have the antennas in a more compact configuration. One way out of these conflicting requirements is to mount the antennas on rails and change the configuration depending on the nature of the observations, as in the case of the VLA[9]. However, since this was not a cost-effective solution for GMRT, and because, at low frequencies, the study of extended sources is as important as that of compact ones, GMRT antennas had to be configured to handle both kinds of sources without moving the antennas. This was achieved by putting about half the antennas in a compact array and half in an extended array. After investigating a variety of possible configurations[55] from the point of view of $u-v$ coverage, sidelobe levels and logistics of access roads and cabling work, the configuration finally selected is shown in Figure 5. Six antennas are distributed along each of the three arms of a rough Y and the remaining 12 antennas are more or less randomly placed in a compact cluster near the centre of the Y, with a maximum baseline of about 1.1 km. The maximum baseline length among the distant antennas is about 25 km. Note that, because the optimizing function is fairly insensitive to small variations in the antenna positions, the final antenna locations do not all lie on a regular Y and were chosen to be located reasonably close to existing village roads or in nonagricultural lands and so on.

The hybrid configuration gives reasonably good sensitivity for both compact and extended sources (of the order of 20 arcsec and 5 arcmin respectively at 150 MHz). The shortest spatial frequency that can be measured corresponds to baselines of about 100 m. Figure 6 shows the Fourier components that would be measured instantaneously by GMRT ($H = 0^h$), while Figures 7 and 8 show all the Fourier components, up to baselines of 25 km and 1 km respectively, that can be measured by tracking a source for the full range of

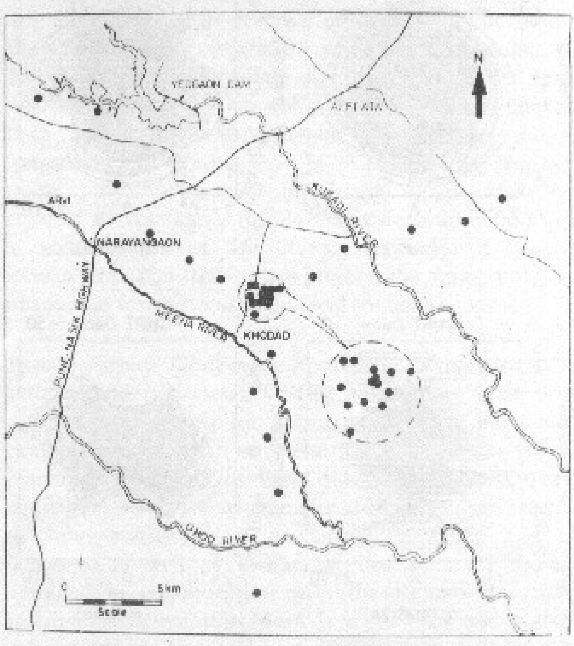

Figure 5. The locations of the 30 parabolic dishes of GMRT.

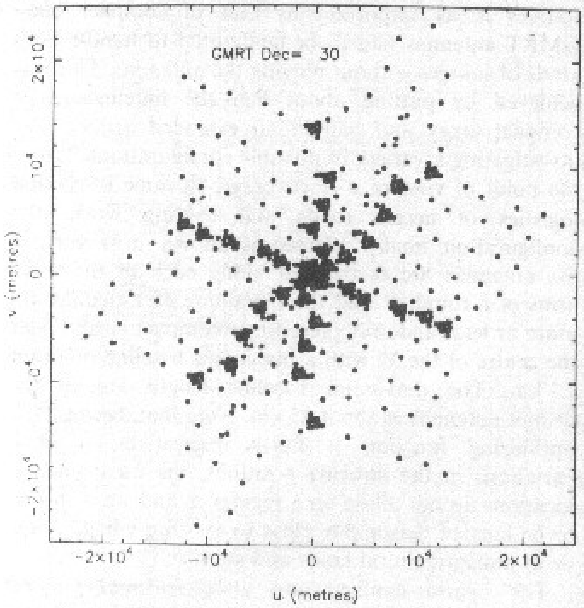

Figure 6. The instantaneous *u–v* coverage of GMRT, at H = 0^h for a source at a declination of +30°.

observable hour angles. As can be seen, very good coverage of spatial frequencies corresponding to antenna separations of 100 m to 25 km is achieved.

The electronics system

Optimum sensitivity, economy, reliability and ease of maintenance were the primary criteria in the design of a stable electronics system for GMRT to provide observing capability at six different frequency bands with a maximum bandwidth of 32 MHz. Some of the important design aspects considered were (i) phase switching using Walsh functions to minimize any coupling between antenna electronics, (ii) adequate image rejection, (iii) a flexible local-oscillator (LO) system that provides a tunable LO frequency in 5-MHz steps to cover the 30–1700 MHz range, (iv) Doppler tracking for line observations, and (v) low phase ripples across the passband of the system.

A simplified block diagram of the electronics system is shown in Figure 9. The antennas will have dual polarized feeds at all the six frequencies. The feeds will be mounted on the four faces of a computer-controlled rotating turret near the prime focus. While two faces will have feeds operating at 153 and 327 MHz, the other two faces will have dual frequency feeds at 233/610 MHz and 38/1420 MHz. As a joint programme with the Raman Research Institute, Bangalore, a dual-horn broad-band feed covering 1000–1450 MHz is also being developed for installation at a later stage. A few of the antennas may also be operated in the OH band (1660–1670 MHz). The types of feeds presently being

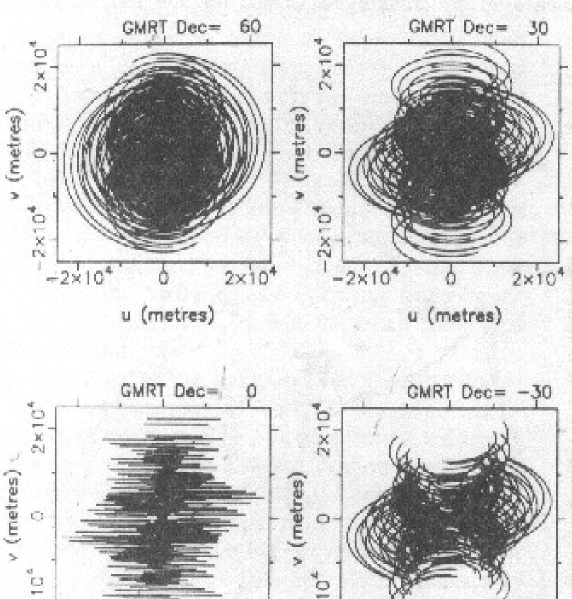

Figure 7. The full *u–v* coverage of GMRT at four different declinations.

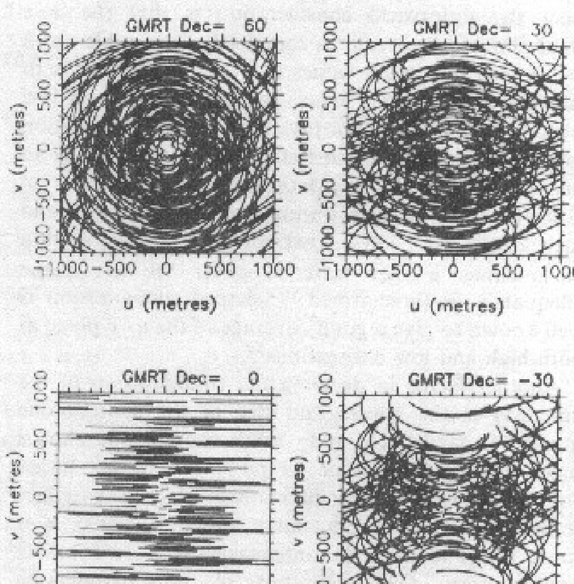

Figure 8. The *u–v* coverage for full synthesis, but restricted to baselines less than 1 km in length.

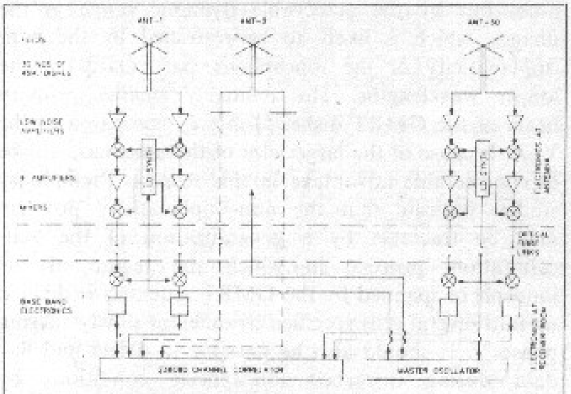

Figure 9. A block diagram of the main elements of the receiver system of GMRT.

developed for the different frequency bands are listed in Table 2.

The front end consisting of RF, LO and IF electronics (Figure 9) is designed for low system temperature and good phase stability. The linearly polarized signals are first converted to right-hand and left-hand circularly polarized signals in low-noise quadrature hybrids and then amplified in low-noise RF amplifiers. After phase switching, signals are brought through low-loss cables to the base of the antenna. The RF signals are converted to a 32-MHz-wide intermediate frequency (IF) centred at 70 MHz using LO signals tied to a central frequency standard. All LO signals will be phase-synchronized using a round-trip phase-modulation method[56]. The LO and IF signals as well as control and monitor telemetry and voice signals are transmitted from and to the central electronics building on a low-loss fibre-optic link. For each of the two polarizations, the 32-MHz-wide IF signals are further down-converted to two baseband signals, each of 16-MHz bandwidth. There will be a choice of RF, IF and video filters to select any desired bandwidth from 0.0625 to 32 MHz in binary steps.

The back end will consist of a large state-of-the-art FX-type[57] correlator system which uses about 1650 special-purpose high-speed FFT and multiplier chips (these VLSI chips have been developed by the National Radio Astronomy Observatory, USA, for the VLBA project). A 256-spectral-channel cross-correlator has been designed for the 30 antennas of GMRT, which gives $(30 \times 31/2) \times 256 \times 2 = 238{,}080$ correlated outputs, each of which is a complex number to be averaged over integration times selectable from 0.04 to 10 sec. The maximum bandwidth of the system is 16 MHz. The correlator will allow measurement of all four Stokes' parameters with 128 spectral channels.

The output from the correlator acquired by the on-line computer will lead to a data base of about 4 gigabytes for a full synthesis observation. The on-line computer will also control the synchronized rotation of the antennas, feeds, etc. and monitor the entire system besides performing preliminary analysis of the data. For more details of the electronics system the reader is referred to Swarup[53].

Table 2. Feeds under development.

Frequency (MHz)	Type of feed
38	Half-wave dipole with linear reflector
153	Two orthogonal pairs of dipole over a plane reflector
233 610	Dual concentric coaxial cavity
327	Half-wave dipole over ground plane and a beam-forming ring (Kildal feed[63])
1420	Corrugated horn

Interference monitoring and rejection. A phase-switched interferometer is less prone to local interferences[58]. However, since large bandwidths will be essential for certain scientific programmes even at 153 or 233 MHz, it will be necessary to monitor the interfering signals at various frequencies by a specially designed receiver. Our experience at the GMRT site over the last few years shows that there are only two or three strong interfering signals in a 16-MHz bandwidth at 150 MHz such that their strength exceeds about 10% of the receiver noise. There are even fewer interfering signals at higher frequencies. In order to keep the interference rejection capability high, the overall dynamic range of the IF chain, fibre-optic link and correlator system for any intermodulation product is designed to be better than 35 dB. For example, the correlator system has 4-bit sampling rather than the usual 2-bit, so that narrow-band signals do not produce harmonics higher than −50 dB. Thus it is possible to reject weak radio-frequency interference that is $< 1\%$ of the receiver noise; but any stronger interfering signals must be rejected by restricting the RF bandwidth and choosing a suitable set of IF filters. Similarly, if severe ionospheric scintillations are present, the data would be unsuitable for radio-astronomical imaging.

Special purpose hardware. Apart from being used as a synthesis interferometer, GMRT will also be used as a phased array mainly for pulsar, VLBI, IPS and lunar occultation observations. The outputs of the FFT machines can be added digitally to give a phased array equivalent to a 250-m-diameter dish. A pulsar search machine consisting of an array combiner and a coherent as well as incoherent dedisperser is being designed in collaboration with the Raman Research Institute. A two-station Mark-II VLBI back end is also being planned. The frequency reference for these would be an atomic standard backed by a high-stability crystal oscillator, while the time would be referenced by combining a GPS system with the atomic standard.

Off-line analysis. The computing requirements of GMRT are very high, both because of the large data base and owing to the extensive data processing required at low frequencies to correct the ionospheric phase variations over the full field of view of each antenna. For this purpose, we are collaborating with the Centre for Development of Telematics (C-DoT), Bangalore, to build a special-purpose parallel-processing computer. The system will consist of up to 256 processing elements, each of which is a Transputer T800 with 4 MB local memory. A 16-element system is currently operational at Pune[59]. The parallel processor will be networked to a file server and a set of workstations to provide a powerful computer system for image processing.

System parameters

For the feeds presently under development, it is estimated that the aperture efficiency of the GMRT dishes would be about 65% at frequencies between 153 and 610 MHz and about 40 to 50% at 38 and 1420 MHz. Typical values of the predicted total system temperature (T_{sys}) at different frequencies together with the contributions to T_{sys} by different factors are listed in Table 3, which also gives the resulting values of the theoretical r.m.s thermal noise limits in the synthesized images (for 10 h of integration) using natural weighting. At frequencies higher than 233 MHz, the noise limits are seen to be in the region of only 10 to 20 μJy.

For continuum mapping the minimum detectable signals will generally be governed not by the thermal noise but by the achievable dynamic range in the images, which is likely to be restricted by the non-isoplanaticity of the ionosphere, particularly at the longer wavelengths. The relatively smaller primary beam of the GMRT dishes (Table 3), compared to the VLA, because of the larger size of the antennas, will be of considerable advantage in this respect. Preliminary studies indicate that the non-isoplanaticity problem may be tractable by a generalization of the 'self-calibration' process, in which the region of the ionosphere spanned by the GMRT antennas is divided up into several cells specified by different slowly varying phases[60]. It should also be possible to detect and flag data during disturbed ionospheric conditions by looking at the phases of a few relatively strong sources in the field of view during the off-line reduction[61].

Another problem[62, 63] that can impose a considerable limitation on the achievable dynamic range at low frequencies because of the large primary beams is that the *w*-term in the Fourier-transform relationship between the visibility and brightness distribution cannot be ignored when the antennas are non-coplanar as in GMRT or VLA. Solutions to this problem, as to the problem of non-isoplanaticity, are computationally expensive[62]. However, the problems are well suited to special-purpose computers utilizing the parallel-processing technique. The 256-element parallel-processing machine currently being designed for GMRT will hopefully make it practical to solve the above problems[59].

Table 3. Some estimated system parameters for GMRT.

	Frequency (MHz)					
	38	150	233	327	610	1420
Primary beam (deg)	15	3.8	2.5	1.8	0.9	0.4
Synthesized beam						
Total array (arcsec)	80	20	13	9	5	2
Central compact array (arcmin)	28	7	4.5	3.2	1.7	0.7
System temperature (K)						
i) $T_{receiver}$ (including cable losses)	200	144	55	50	60	60
ii) $T_{ground} = T_{mesh} + T_{spillover}$	80	30	23	18	22	32
iii) T_{sky}	10,000	308	99	40	10	4
iv) Total T_{sys}	10,280	482	177	108	92	96
RMS noise in image* (μJy)	1,420	46	17	10	9	13

*For assumed bandwidth of 16 MHz, integration of 10 h, and natural weighting.

1. Wild, J. P. (ed.), *Proc. Inst. Radio Electron. Eng. Aust.*, 1967, **28**, No. 9.
2. Erickson, W. C., Mahoney, M. J. and Erle, K., *Astrophys. J. Suppl.*, 1982, **50**, 403.
3. Swarup, G. *et al.*, *Nature Phys. Sci.*, 1971, **230**, 185.
4. Sukumar, S., Velusamy, T., Rao, A. P., Swarup, G., Bagri, D. S., Joshi, M. N. and Ananthakrishnan, S., *Bull. Astron. Soc. India*, 1988, **16**, 93.
5. Baldwin, J. E., Boysen, R. C., Hales, S. E. G., Jennings, J. E., Waggett, P. C., Warner, P. J. and Wilson, D. M. A., *Mon. Not. R. Astron. Soc.*, 1985, **217**, 717.
6. Subramanian, K. R., Nanje Gowda, C. and Sastry, Ch. V., *Bull. Astron. Soc. India*, 1986, **14**, 236.
7. Mills, B. Y., *Proc. Astron. Soc. Aust.*, 1981, **4**, 156.
8. Pearson, T. J. and Readhead, A. C. S., *Annu. Rev. Astron. Astrophys.*, 1984, **22**, 97.
9. Napier, P. J., Thompson, A. R. and Ekers, R. D., *Proc. IEEE*, 1983, **71**, 1295.
10. Swarup, G., *Giant Metrewave Radio Telescope—A proposal*, Radio Astronomy Centre, TIFR, Ootacamund, 1984.
11. Swarup, G., Kapahi, V. K. and Ananthakrishnan, S., *Giant Metrewave Radio Telescope—Status Report*, TIFR, Bangalore, 1987.
12. Evans, D. R., Warwick, J. W., Pearce, J. B., Carr, T. D. and Schauble, T. J., *Nature*, 1981, **292**, 716.
13. Manoharan, P. K. and Ananthakrishnan, S., *Mon. Not. R. Astron. Soc.*, 1990, **244**, 691.
14. Hewish, A., *Solar Phys.*, 1988, **116**, 195.
15. Ananthakrishnan, S., *Indian J. Radio Space Phys.*, 1990, **19**, 519.

16. Helfand, D. J., Velusamy, T., Becker, R. H. and Lockman, F. J., *Astrophys. J.*, 1989, **341**, 151.
17. Hjellming, R. M., in *Galactic and Extragalactic Radio Astronomy*, (eds. Verschuur, G. L. and Kellermann, K. I.), Springer-Verlag, 1988, p. 381.
18. Lyne, A. G. and Graham-Smith, F., *Pulsar Astronomy*, Cambridge Univ. Press, 1990.
19. Backer, D. C. and Kulkarni, S. R., *Phys. Today*, 1990, **43**, 26.
20. Weisberg, J. M. and Taylor, J. H., *Phys. Rev. Lett.*, 1984, **52**, 1348.
21. Rawley, L. A., Taylor, J. H., Davis, M. M. and Allan, D. W., *Science*, 1987, **238**, 761.
22. Fruchter, A. S., Stinebring, D. R. and Taylor, J. H., *Nature*, 1988, **333**, 237.
23. Slee, O. B. and Siegman, B. C., *Mon. Not. R. Astron. Soc.*, 1988, **235**, 1313.
24. McGilchrist, M. M. and Riley, J. M., *Mon. Not. R. Astron. Soc.*, 1990, (in press).
25. Rickett, B. J., *Annu. Rev. Astron. Astrophys.*, 1990, **28**, 561.
26. Ghosh, T. and Gopal-Krishna, *Astron. Astrophys.*, 1990, **230**, 297.
27. Mantovani, F., Fanti, R., Gregorini, L., Padrielli, L., Spangler, S., *Astron. Astrophys.*, 1990, **233**, 535.
28. Saripalli, L., Gopal-Krishna, Reich, W. and Kuhr, H., *Astron. Astrophys.*, 1986, **170**, 20.
29. Slee, O. B. and Reynolds, J. E., *Proc. Astron. Soc. Aust.*, 1984, **5**, 516.
30. Joshi, M. N., Kapahi, V. K. and Bagchi, J., in *Radio Continuum Processes in Clusters of Galaxies* (eds. O'Dea, C. P. and Uson, J. M.), National Radio Astronomy Observatory, USA, 1986, p. 73.
31. Leahy, J. P., Muxlow, T. W. B. and Stephens, P. W., *Mon. Not. R. Astron. Soc.*, 1989, **239**, 401.
32. Barthel, P. D., *Astrophys. J.*, 1989, **336**, 606.
33. Oort, M. J. A., Seemers, W. J. G. and Windhorst, R. A., *Astron. Astrophys. Suppl.*, 1988, **73**, 103.
34. Kapahi, V. K., Kulkarni, V. K. and Subrahmanya, C. R., *J. Astrophys. Astron.*, 1987, **8**, 33.
35. Kapahi, V. K., *Astron. J.*, 1989, **97**, 1.
36. Dunlop, J. S. and Peacock, J. A., *Mon. Not. R. Astron. Soc.*, 1990, **247**, 19.
37. Kulkarni, S. R. and Heiles, C., in *Galactic and Extragalactic Radio Astronomy* (eds. Verschuur, G. L. and Kellermann, K. I.), Springer-Verlag, 1988, p. 95.
38. Burton, W. B., in *Galactic and Extragalactic Radio Astronomy* (eds. Verschuur, G. L. and Kellermann, K. I.), Springer-Verlag, 1988, p. 295.
39. Giovanelli, R. and Haynes, M. P., in *Galactic and Extragalactic Radio Astronomy* (eds. Verschuur, G. L. and Kellermann, K. I.), Springer-Verlag, 1988, p. 522.
40. Bosma, A., *Astron. J.*, 1981, **86**, 1791 and 1825.
41. Trimble, V., *Annu. Rev. Astron. Astrophys.*, 1987, **25**, 425.
42. Tully, R. B. and Fisher, J. R., *Astron. Astrophys.*, 1977, **54**, 661.
43. Lynden-Bell, D., Faber, S. M., Burstein, D., Davies, R. L., Dressler, A., Terlevich, R. J. and Wegner, G., *Astrophys. J.*, 1988, **326**, 19.
44. Briggs, F. H., in *QSO Absorption Lines* (eds. Blades, J. C., Tumshek, D. and Norman, C. A.), Cambridge Univ. Press, 1988, p. 275.
45. Swarup, G. and Subrahmanya, R., in *Observational Cosmology* (eds. Hewitt, A., Burbidge, G. and Fang, L. Z.), D. Reidel, Dordrecht, 1987, p. 441.
46. Scott, D. and Rees, M. J., *Mon. Not. R. Astron. Soc.*, 1990, **247**, 510.
47. Subrahmanyan, R. and Swarup, G., *J. Astrophys. Astron.*, 1990, **11**, 237.
48. Subrahmanyan, R. and Anantharamaiah, K. R., *J. Astrophys. Astron.*, 1990, **11**, 221.
49. Sarma, N. V. G. and Mohanty, D. K., *Mon. Not. R. Astron. Soc.*, 1976, **184**, 181.
50. Anantharamaiah, K. R. and Radhakrishnan, V., *Astron. Astrophys.*, 1979, **79**, L9.
51. Dupree, A. K., Balimas, S. L. and Shipman, H. L., *Astrophys. J.*, 1977, **218**, 361.
52. Anantharamaiah, K. R., Erickson, W. C. and Radhakrishnan, V., *Nature*, 1986, **315**, 647.
53. Swarup, G., *Indian J. Radio Space Phys.*, 1990, **19**, 493.
54. Mathur, N. C., *Radio Sci.*, 1969, **4**, 235.
55. Rao, A. P., Kulkarni, V. K., Singal, A. K., Salter, C. J., Ananthakrishnan, S., Rots, A. and Patnaik, A., *GMRT Array Configuration*, Technical Report, 1991, NCRA, Pune.
56. Swarup, G. and Yang, K. S., *IEEE Trans. Antennas Propag.*, 1961, **AP-9**, 75.
57. Chikada, Y. *et al.*, in *Indirect Imaging* (ed. Roberts, J. A.), Cambridge Univ. Press, 1984, p. 387.
58. Thompson, A. R., Moran, J. M. and Swenson Jr., G. W., *Interferometry and Synthesis in Radio Astronomy*, John Wiley and Sons, New York, 1986.
59. Kulkarni, V. K. and Subrahmanya, C. R., in *Proc. IAU Colloq. 131 on Radio Interferometry—Theory, Techniques and Applications* (ed. Cornwell, T. J.), ASP Conf. Ser., (in press).
60. Subrahmanya, C. R., in *Proc. IAU Colloq. 131 on Radio Interferometry—Theory, Techniques and Applications* (ed. Cornwell, T. J.), ASP Conf. Ser., (in press).
61. Rao, A. P., in *Proc. IAU Colloq. 131 on Radio Interferometry—Theory, Techniques and Applications* (ed. Cornwell, T. J.), ASP Conf. Ser., (in press).
62. Perley, R. A., in *Synthesis Imaging in Radio Astronomy* (eds. Perley, R. A., Schwab, F. R. and Bridle, A. H.), ASP Conf. Ser., 1989, p. 259.
63. Kildal, P-S., *IEEE Trans. Antennas Propag.*, 1982, **AP-30**, 529.

ACKNOWLEDGEMENTS. It is a pleasure to thank Prof. M. G. K. Menon, Prof. B. V. Sreekantan and the late Prof. Mohan Joshi for the encouragement, support and guidance given by them for the starting of this challenging project. We are grateful to all our colleagues in TIFR, too numerous to mention individually, who have put in a lot of hard work for the past six years to bring the GMRT project to its present stage. Our special thanks go to M. K. Bhaskaran, N. V. Nagarathnam, S. C. Tapde and T. L. Venkatasubramani, who, amongst a host of colleagues, are most actively involved in the various engineering aspects of the project. The engineering design of the 45-m dishes has been done by M/s Tata Consulting Engineers. Dr. Ben Hooghoudt of the Netherlands made many valuable comments concerning the design of these dishes. The Civil and Services as well as Servo Group of BARC, Bombay; C-DoT, Bangalore; and RRI, Bangalore, are the other organizations associated with the project. The help and guidance offered by many experts from within India and abroad are also gratefully acknowledged.