IMPORTANT CONSIDERATIONS MADE WHILE DESIGNING SINGLE DISH RADIO TELESCOPES

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Abstract

In this paper we discuss the important concepts and considerations while designing single dish radio telescopes, with emphasis laid on its antenna system. We discuss the filled aperture radio telescopes beginning with its angular resolution. The Raleigh criterion in resolving two point stars has been extended to a dish antenna. We then discuss the aperture illumination of dish antenna and evaluate the various temperature contributions. We also present some antenna deflection results using one of the GMRT dishes.

Keywords: *Dish radio telescopes, Antenna system, Stars, Antenna-feeds, GMRT antenna, Paraboloid reflector.*

1 Introduction

While designing single antenna radio telescopes, preference is given to paraboloid dishes. However, while designing such an instrument, care is to be taken for maintaining good directivity for resolution of the radio sources on the sky. For this purpose we first explain the Raleigh criterion and then extend it from optical to a single dish radio telescope. The paraboloid dish antenna is limited by aperture illumination caused by the antenna-feed at its focus. All of these are explained and estimation of antenna temperature has been made. Overview of recent types of antenna-feeds tested on a GMRT[1] radio telescope antenna has been produced along with some tested results with the astronomical radio source Cygnus-A.

2 Scope of the Radio Telescope

Before designing the radio telescope, the astronomical sources which are supposed to be the target of observation must be specified in terms of flux-density and angular width. Also the brightness temperature of the background sky within the vicinity of these targeted sources must be studied. The system temperature of the radio telescope should be decided based on this. The integration time of the signals in the receiver should be adjusted such that the signal to noise ratio of system is reasonably good and the system responds to the source. Usually a typical receiver temperature of 40 K is practically achieved with moderate efforts. The antenna temperature when pointed to background sky combined with the receiver temperature must be estimated which is known as the system temperature. When the telescope antenna is pointed to the source, the system temperature should increase significantly. With this background work on paper, the resolution of the telescope which is usually a dish antenna is estimated [1, 2, 3].

[1]Giant Meterwave Radio Telescope, Narayangaon, Pune, Maharashtra. It is an array of 30 dish antennae operating between 0.1 GHz and 1.8 GHz. It is used for detecting and mapping astronomical objects that also emit in radio in the given frequency band. Each of these GMRT dishes has a diameter of 45 meters.

3 Estimating the resolution of a Dish Antenna Telescope

The resolution of a dish can be determined by extending the Rayleigh criterion. It states that two point monochromatic light sources can be resolved with a lens provided the angular separation between the two sources is at least equal to or greater than $1.22\lambda/D$ as expressed in equation (1), where λ is the wavelength, D is the aperture diameter of the telescope and α' is the minimum angle between the two point sources in radians [1, 2].

$$\alpha' = 1.22\ \lambda/D \approx \lambda/D \quad \dots (1)$$

For a better understand, consider a simple optical convex lens having a diameter *D* and a focal length *F*. It forms an image of a distant monochromatic star operating at a wavelength *λ as* shown in Figure 1(a). The diffraction pattern of the lens, causes the image of the star to have an intensity variation as shown in Figure 1(b) and 1(c). This is known as "point spread function".

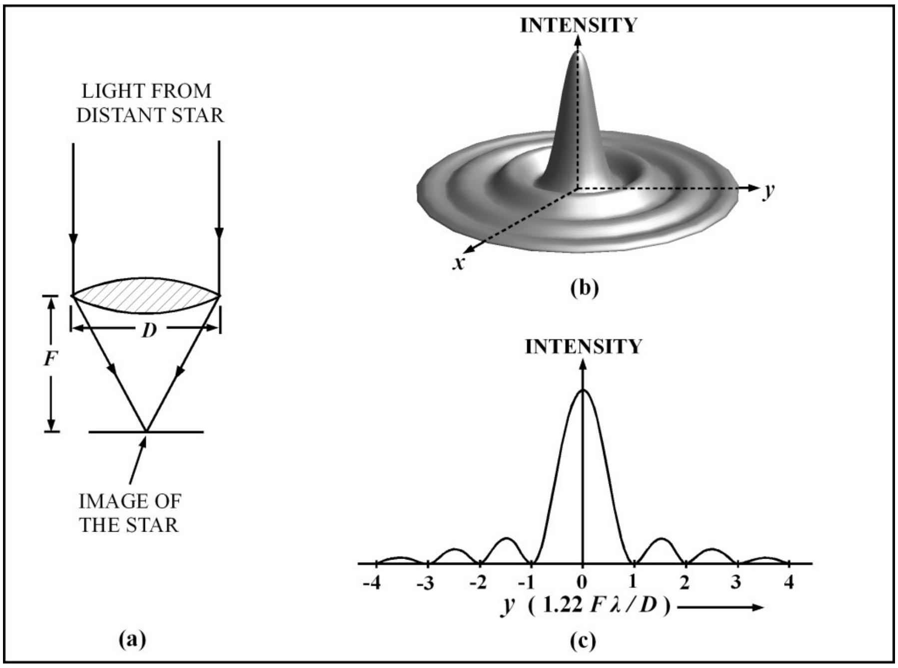


Figure 1 Image intensity distribution of a point monochromatic source formed using a convex lens. (a) Light from a distant monochromatic star is focused. (b) Image intensity distribution on the screen. (c) Image intensity distribution along one axis.

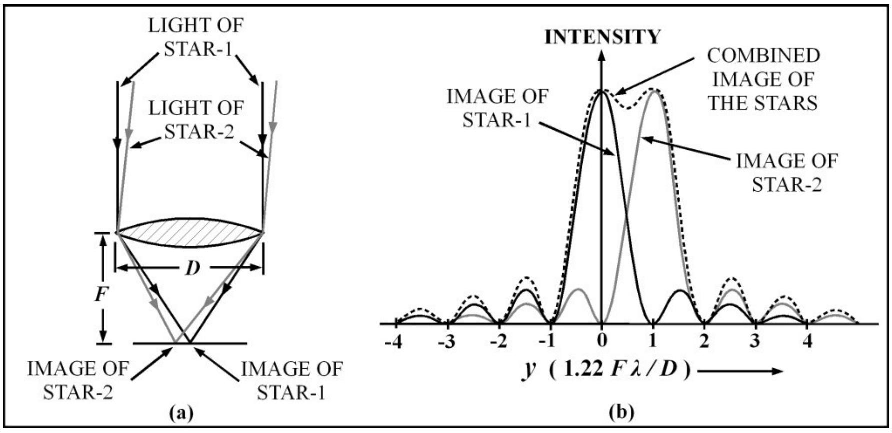


Figure 2 Monochromatic light from two point sources (two stars) forming an image. (a) Arrangement to form the image. (b) Intensity distribution due to overlapping of the two images.

If there exists another similar monochromatic star at same wavelength λ and subtending at an angle α with respect to the previous star as shown in Figure 2(a), then the two resulting image patterns gets superimposed as shown in Figure 2(b). The effective image is marked by dotted lines. When the angle α meets the Rayleigh criterion, the maxima of one image lies over the first minima of the other and the two point sources can be identified in the effective image. If the angle is reduced, the two point sources are difficult to identify because the two images tend to overlap more on each other. On the other hand, if the angle between the sources gets larger, the point sources become more prominent in the image. It must be noted that the diffraction pattern is also a function of wavelength. If the stars emit light over a band of frequencies, then more and more images will result corresponding to each frequency/wavelength and the image will get blurred.

The Raleigh criterion varies with wavelength. It is extensively used in radio astronomy as well. Since, most of the large radio astronomy antennae are paraboloid dishes, they may be compared with a convex lens and thereby opening the door to apply Raleigh criterion in radio astronomy. We obtain the resolution of a single dish radio telescope using equation (1) by simply replacing the diameter of the lens by the diameter D of the dish antenna. Figure 3 shows the resolution of a single 45 meter GMRT dish as a function of frequency.

4 Aperture Illumination of a Paraboloid Dish

The aperture area of dish is equal to the cross sectional area of the dish in one plane. Ideally, this is the effective aperture area, provided no losses occur for any reason. Practically, because of obscuring of the dish area by the shadow of the antenna feed and its mechanical supports and also due to non-uniform illumination of the dish by the antenna-feed, the effective aperture area is always less than the dish cross sectional area. Figure 3(a) shows an ideal type dish illumination where the pattern of antenna-feed is such that all energy from the dish is uniformly collected by it at the focus. Practically, this is not the case since the feed being an antenna by itself does have a pattern consisting of major and side lobes, the effect of which is visible in Figure 3(b). Apart from this the discontinuity at the edges of the reflector (dish) itself generates side lobes which may be reduced to some extent by increasing the ratio of diameter of the dish to wavelength [1, 2].

The radiation pattern of any antenna always contains undesirable side lobes and a back lobe. They may be reduced to some extent but cannot be eliminated. These useless lobes pick up unwanted signals from undesired directions. Since the antenna-feed's main beam does not illuminate the dish uniformly, it results in less efficient usage of the dish aperture area. As shown, the central zone of the dish is illuminated with highest intensity and gradually decreases towards the edges. This is termed as "*inefficient dish illumination*". Also some small amount of energy gets spilled out the dish which is termed as "*dish spill over*". If the dish is pointed vertically up towards the zenith, the antenna temperature gets contribution from the dish spill over over the ground, through some side lobes and back lobe as well. Sometimes to reduce cost and weight, the dishes use metallic mesh as its reflecting surface; thereby some amount of illumination is lost as mesh leakage. The mesh aids to picking the ground temperature and also reduces the effective aperture area of the antenna system. Effectively, the combined pattern (antenna-feed and dish together) develop side and back lobes whose shape and size depend on the angle of the radio source with respect to the zenith. If the beam width of antenna-feed is broadened, the spill over increases and it may be said that the dish is "*over illuminated*". If it is aimed to avoid the spill-over, the antenna-feed beam width should be reduced resulting in "*under illumination*". The dish surface roughness causes phase mismatch at the focus further reducing the signal strength. By comparing the two dish illuminations (ideal vs. practical) from Figure 4, we find that side lobes are much less in the latter, but dish efficiency gets sacrificed [3].

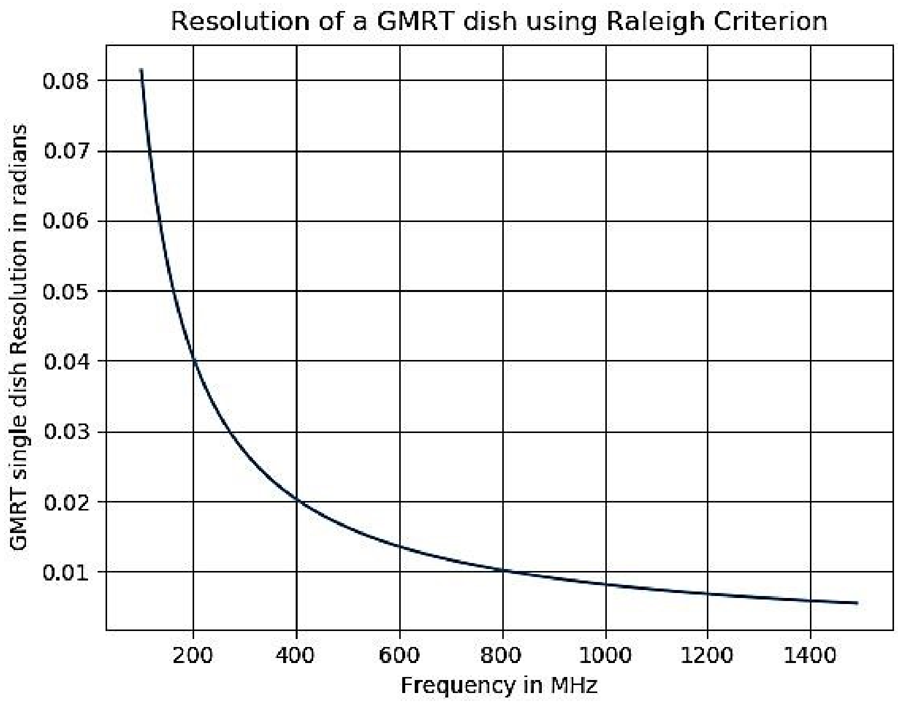


Figure 3 Variation in resolution of a single GMRT dish antenna as a function of frequency estimated using Raleigh Criterion. The resolution increases with frequency.

We now quantify the six major efficiency factors governing the performance of a dish antenna system which is defined below. Each of these efficiencies ranges between zero and unity [1,2].

(i) Antenna-feed efficiency η_a:

It is the ratio of power radiated by the antenna-feed to the power consumed by the antenna-feed.

(ii) Dish spill over efficiency η_{sp}:

It is defined as the ratio of the actual power falling on the dish surface from the antenna-feed to the total power radiated by the antenna-feed.

(iii) Dish leakage efficiency η_{msh}:

It is defined as the ratio of the amount of power reflected by the dish surface to the amount of power falling on the dish surface. It depends on the quality of the mesh.

(iv) Dish surface smoothness efficiency η_{rms}:

It is defined as the ratio of actual power available at the focus to the theoretical power that would be available at the focus if a plane wave front illuminates the dish surface with conditions that the dish is leak proof. It depends on the root mean square variations on the surface of the dish.

(v) Illumination efficiency η_{ill}:

It is considered here as the ratio of total power illuminating the dish to the total power required for illuminating the dish uniformly with peak intensity of the antenna-feed pattern. It depends on the intensity variation of the signal on the dish.

(vi) Polarization efficiency η_{pol}:

It is defined as the ratio of power actually received to the maximum power that could be received if the antenna had optimum polarization with the received wave.

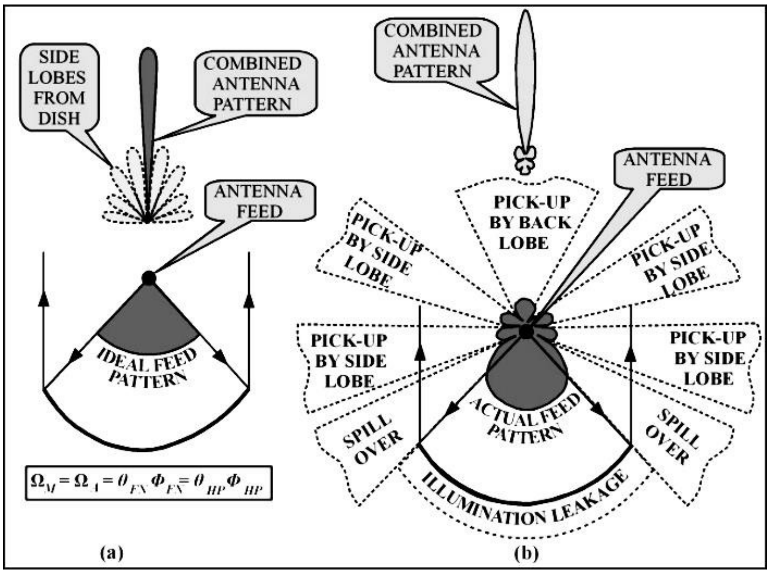


Figure 4 Ideal vs. actual dish illumination. (a) An ideal antenna-feed illuminates the dish uniformly. Large side lobes result from dish-edge discontinuity. (b) A practical antenna-feed pattern causes non uniform dish illumination. Part of energy goes out of the dish called *spill over*. Minor lobes pick up power from undesired directions. The dish surface may not be 100% reflecting resulting in illumination leakage. The resulting antenna pattern has relatively smaller side and back lobes.

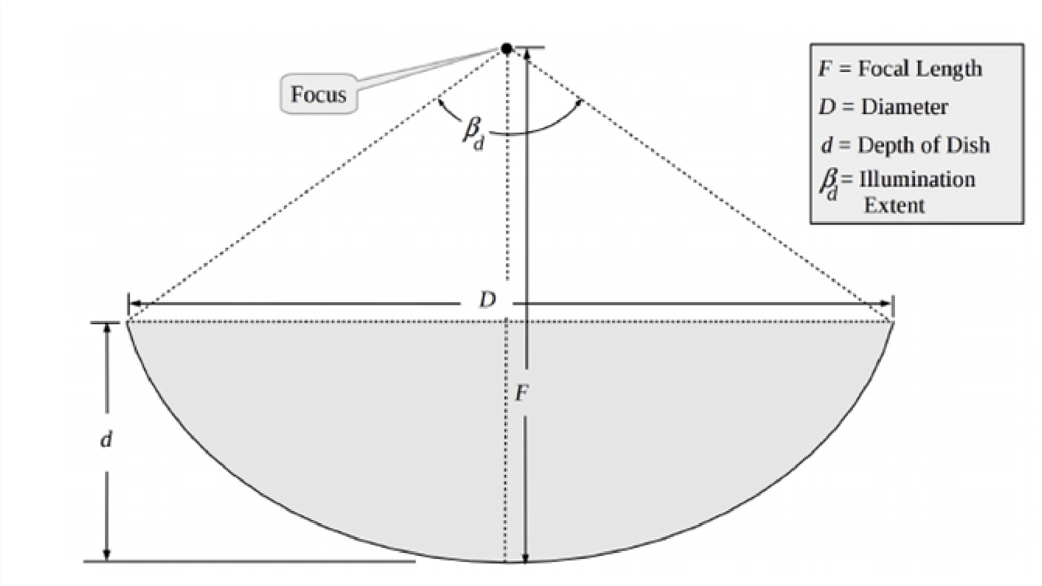


Figure 5 Basic geometry of a dish antenna for estimating the aperture area.

5. Analysis of Gain and Aperture Area

Consider the dish geometry shown in Figure 5. Let K_{FD} be the ratio of focal length *F* to dish diameter *D*. Based on the dish illumination by the antenna-feed, the value of K_{FD} is selected. For most practical designs, K_{FD} is kept near about 0.4, since antenna feeds are designed accordingly [1, 2]. The dish diameter *D* is given by Eq. (2). The depth d of the dish is obtained from *D* using Eq. (3). The illumination extent angle β_d of the dish is obtained from Eq. (4). The aperture efficiency $A_e$is expressed in Eq. (5). Eq. (6) further expresses η_A in terms of the several other efficiencies described earlier. The effective gain G_{eff} of the antenna system (dish plus antenna-feed) is expressed in Eq. (7). It is dependent on η_A. Using G_{eff} we obtain the effective half power beam-width θ_{effHP} as expressed in Eq. (8).

$$D = \frac{F}{K_{FD}} \dots (2)$$

$$d = \frac{D^2}{16F} \dots (3)$$

$$\beta_d = 2tan^{-1}\left(\frac{D}{F-d}\right) \dots (4)$$

$$A_e = \eta_A \frac{\pi D^2}{4}, where \eta_A < 1 \dots (5)$$

$$\eta_A = \eta_a \eta_{sp} \eta_{msh} \eta_{rms} \eta_{ill} \eta_{pol} \dots (6)$$

$$G_{eff} = \eta_A \left(\frac{\pi D}{\lambda}\right)^2 \dots (7)$$

$$\theta_{effHP} = \sqrt{\frac{40000}{G_{eff}}} \dots (8)$$

5.1 Analysis of Antenna Temperature

Let a paraboloid dish be pointed to an astronomical radio source at the zenith as shown in Figure (5) [1-3]. This is shown in Figure 6. Assume the source to be randomly polarized and let the polarization efficiency be $\eta_{pol} = 1$. Contribution to the antenna temperature comes from (*i*) source, (*ii*) spillover, (*iii*) sky and (*iv*) leakage through the dish. The angles $\beta_d \beta_{SP} = \beta_{S1} + \beta_{S2}$ and β_{Sky} respectively represent the distribution of feed pattern towards the dish, ground spillover and sky. Assuming that the beam pattern is symmetric around the zenith, the beam solid angle $\Omega_{Dish}$of the dish antenna system is expressed in equation (9). Let $P_n(\theta, \phi_0)$ be the normalized power pattern of the antenna-feed on the plane $\phi = \phi_0$. Note that $P_n$is maximum at $\theta = \pi/2$. The effective beam solid angle Ω_{12} of the antenna-feed facing the sky can then be expressed as in equation (10).

$$\Omega_{Dish} \approx \left(\theta_{effHP}\right)^2 \dots (9)$$

$$\Omega_{12} = \int_0^{2\pi} \int_{\theta_1}^{\theta_2} P_n\,(\theta, \phi) sin\theta d\theta d\phi \dots (10)$$

Since θ lies between 0 and π/2, we have, $0 \le \theta_1 \le \pi/2\,, 0 \le \theta_2 \le \pi/2$. We also have $\theta_1 < \theta_2$. From our assumption of cylindrical symmetry around z-axis, Eq. (10) can be simplified to Eq. (11). Using Eq. (11), the effective portion of beam solid angle $\Omega_{Sky}$of the antenna-feed looking towards the sky (side and back-lobes) can be written as in Eq. (12). In a similar manner, the effective beam solid angle Ω_d illuminating the dish is written as Eq. (13), where $\beta_{S1} = \beta_{S2} = \beta_{SP}/2$. The effective beam solid angle Ω_{SP} responsible for spill-over is given in Eq. (14).

$$\Omega_{12} = 2\pi \int_{\theta_1}^{\theta_2} P_n\,(\theta, \phi) sin\theta d\theta \dots (11)$$

$$\Omega_{Sky} \approx 2\pi \int_0^{\frac{\pi}{2}} P_n\,(\theta, \phi_0) sin\theta d\theta \dots (12)$$

$$\Omega_d \approx 2\pi \int_{\frac{\pi}{2}+\frac{\beta_{SP}}{2}}^{\pi} P_n\,(\theta, \phi_0) sin\theta d\theta \dots (13)$$

$$\Omega_{SP} \approx 2\pi \int_{\frac{\pi}{2}+\frac{\beta_{SP}}{2}}^{\pi} P_n\,(\theta, \phi_0) sin\theta d\theta \;\dots (14)$$

The temperature contribution to the antenna system from the dish alone is expressed in equation (15), where, Ω_s is the beam solid angle subtended by the source, and $\bar{T}_{Src}$ is mean temperature of the source over Ω_s. The overall antenna temperature $\theta_{effHP}$is expressed in equation (16), where $T_{SkyPickup} = \Omega_{Sky} T_{Sky}$, $T_{GndPickup} = \Omega_{SP} T_{Gnd}$ and $T_{GndLeakage} = \Omega_d T_{Gnd}(1 - \eta_{msh})$.

$$T_{Dish} = \eta_{msh}\eta_{rms}\Omega_s \bar{T}_{Src} + \left(\Omega_{Dish} - \Omega_{Sky}\right) T_{Sky} \dots (15)$$

$$T_A = T_{Dish} + \eta_a\left[T_{SkyPickup} + T_{GndPickup} + T_{GndLeakage}\right] \dots (16)$$

Above concludes the antenna temperature with dish pointing towards zenith. In reality, the antenna position keeps changing since it tracks a moving radio source across the sky. The current estimate gives us a feeling of good observation, and is useful roughly within 45 degrees around the zenith.

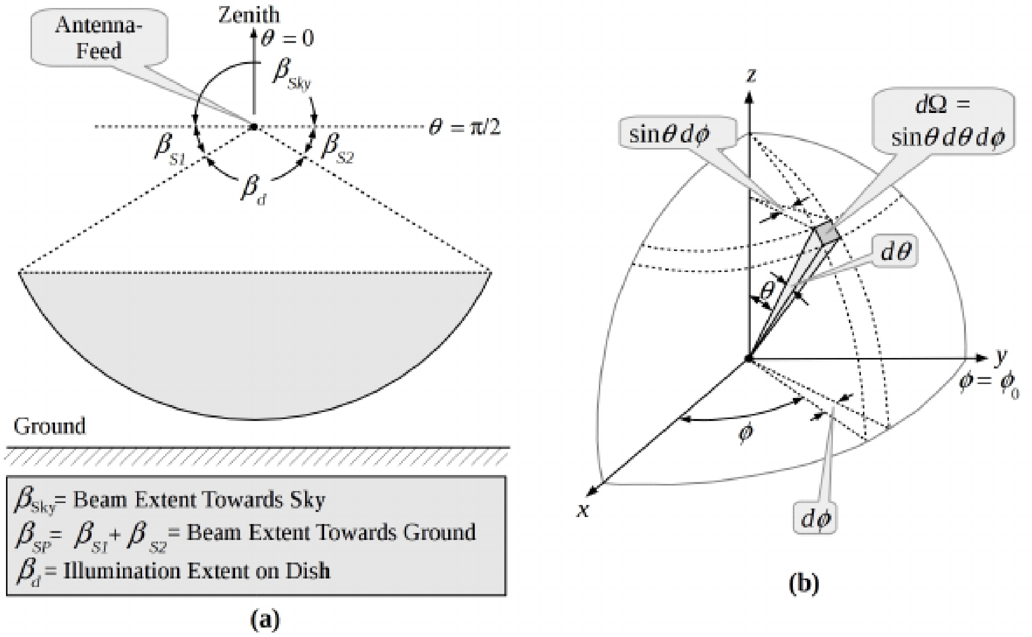


Figure 6 (a) A dish pointed to zenith having an antenna-feed at its focus. The angular extents indicate beam pattern distribution from the antenna-feed. (b) A three dimensional coordinate system used for analysis.

5.2 Reduced Aperture Illumination

The coordinates of the dish keep changing with time while it tracks the astronomical radio source. These changes get reflected in Ω_{Sky} and Ω_{SP}. As understood from Figure 6b, although the antenna-feed beam intensity is less across spill-over regions, it could be reasonably larger than the side-lobes, especially at the edges of the dish. The spill-over can be reduced by increasing the gain of the antenna-feed so that its beam becomes narrow thereby causing reduced aperture illumination. Under such conditions, the unwanted temperature contributions comes from the side and back-lobes. If these lobes are uniformly distributed, the unwanted temperature contributions will remain more or less same. This is because, as the antenna moves away from the zenith, the ground contribution reduces from one side and increases on the other side and vice versa.

However, reduced dish illumination reduces aperture efficiency η_A of the dish. For any angle of inclination, the above equations hold reasonably good provided the dish leakage efficiency i.e. mesh efficiencyη_{msh} is close to unity [1-3].

As the dish moves away from the zenith, the angle of the side lobes changes which are free to pick up any unwanted signal aligned towards them. These are generally ground based man made signals for communications called "radio frequency interference" or 'RFI'.

Thus the RFI appears at certain inclinations of the dish.

6. Antenna-feeds for Radio Telescope Antenna

There are several types of antenna-feed available today. Each has its own advantages and disadvantages in respect of gain, bandwidth, efficiency and side lobes etc. Here we begin with a simple dipole feed for creating a background of understanding the concepts. Then we move out to ultra wide band antenna-feeds, since they look more promising for the future ultra wide band technology of the radio telescopes [4, 5, 11, 12].

6.1 The basic concept of Antenna-feed (Cross-Dipole)

It is advantageous to have both polarized components in radio astronomy for improving the signal to noise ratio. A simple dipole-cross shown in Figure 6 may be used, though not preferable because (*i*) it doesn't illuminate the dish properly and (*ii*) it possess large back lobes. The two dipoles can be mounted at the focus of the paraboloid reflector shown in Figure 7(a). These are half wave dipoles whose thickness may be increased to improve the bandwidth. The maximum band width that can be achieved is roughly 5% of the center frequency. The directivity of a dipole antenna is about 2.15 dBi and the radiation resistance is roughly 73 ohms. The dipoles are fed from a coaxial transmission line having a characteristic impedance of 75 ohms through a balun[2]. The radiation patterns of the dipole-cross from various angles are shown in Figures 7(b), 7(c) and 7(d). Each dipole picks up one polarization component of the signal. The dipole-feed is inefficient in several respects like (*i*) narrow band width, (*ii*) large back lobes and (*iii*) poor directivity. Though the back-lobe may be reduced by using a reflector at the back of the cross, but major advantages of the dish are not achievable. Several other antennae like log periodic antenna, reflector based bow tie antenna, horn antenna, helical antenna etc. which have much higher directivities and bandwidth may be used, but care must be taken to extract the complete polarization of information from the astronomical signals. Thus these antenna-feeds should be dual polarized.

6.2 Typical ultra Wide Band Antenna-feeds

Several other antenna-feeds are used in radio telescopes. Usually they are log-periodic frequency independent in nature. The bandwidth could be as large as 1:10 or more. The dual polarized planar log periodic antenna structures associated with a Step-Lane Reflector developed in GMRT shown in Figure 8 [6-10] is a good example. Along with this an alternate model is also shown using pyramidal reflector. The latter has a less geometrical and fabrication complications, without compromise in performance. The construction was made with aluminum sheets fitted over FR4 (glass-epoxy) substrate. The reflector was fabricated using aluminum sheets. The simulated directive gain patterns of the indigenously designed antenna-feed is shown in Figure 9. The details of mounting of test model over one of the GMRT antennas are shown in Figure 10 [3].

7. Test results from Cygnus-A

The GMRT antenna was pointed to an astronomical radio source Cygnus-A [13] and measurements were made over different frequency bands. These are shown in Figure 11 [3]. This is also known as deflection test where two measurements are made by (*i*) pointing the radio telescope to the background sky, and then (*ii*) pointing to the astronomical radio source.

[2] A balun is the short form of balance to unbalance transformation. The dipole is symmetric on both sides from the center and hence is balanced at its terminals, whereas a coaxial transmission line is unbalanced since the center conductor is enclosed within the shield. An electrical network interfacing these two is a balun.

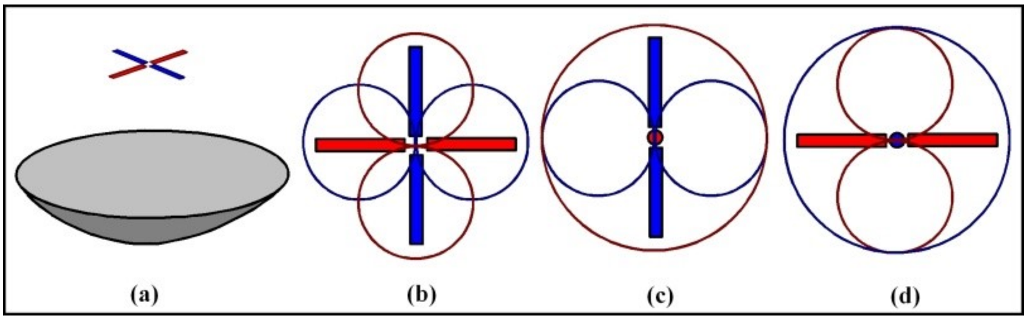
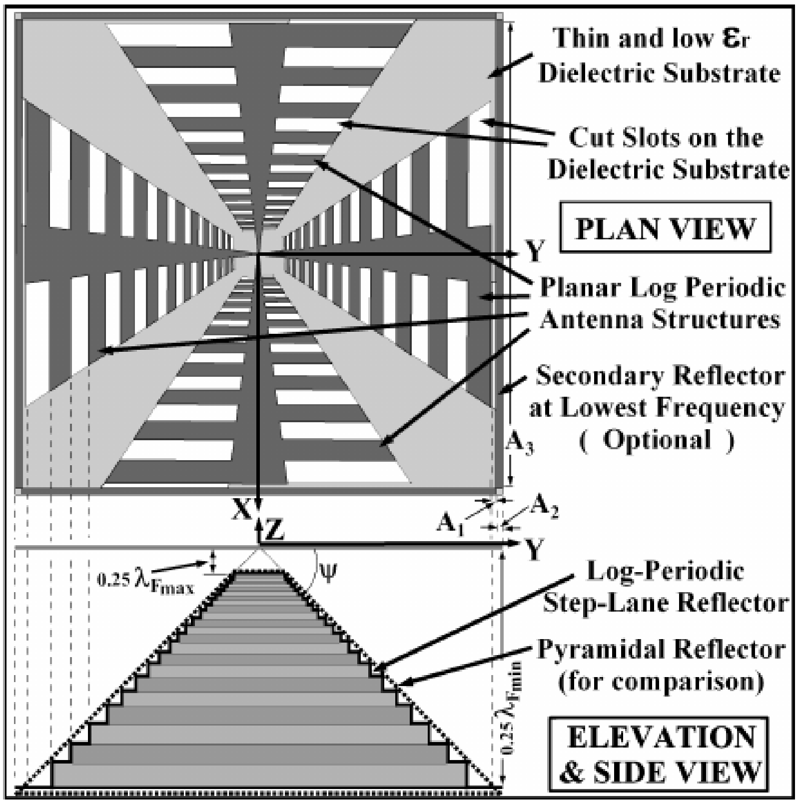


Figure 7 A simple dipole-cross antenna-feed. (a) A dipole-cross at the focus of a parabolid dish. (b) Radiation pattern of the dipole-cross as observed from top. (c) Radiation pattern of the dipole-cross as observed along the red dipole. (d) Radiation pattern of the dipole-cross as observed along the blue



dipole.

Figure 8 Elevation and plan of a dual polarized planar log periodic antenna structures associated with a Step-Lane Reflector (dark lines) or a Pyramidal Reflector (dotted lines). An optional secondary reflector is provided for improving the gain at the lowermost frequencies.

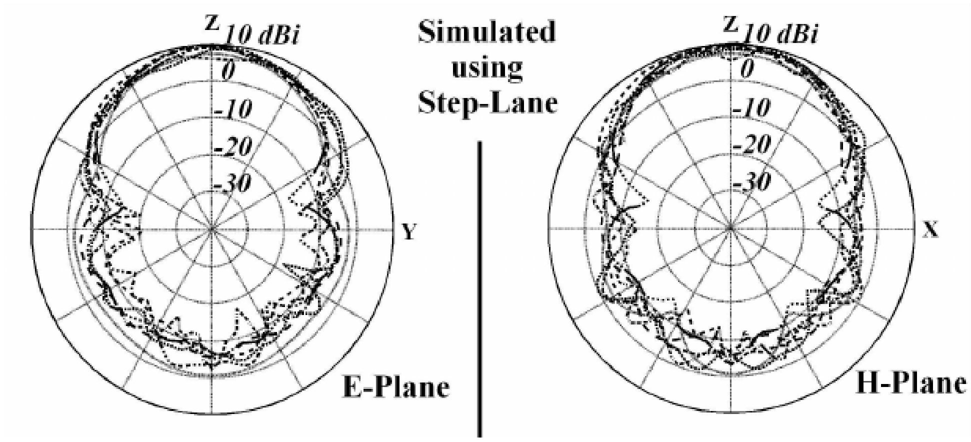


Figure 9 Simulated E and H directive gain patterns for discrete frequencies of the Planar Log-Periodic antenna backed by the two different Frequency-Independent Reflectors.

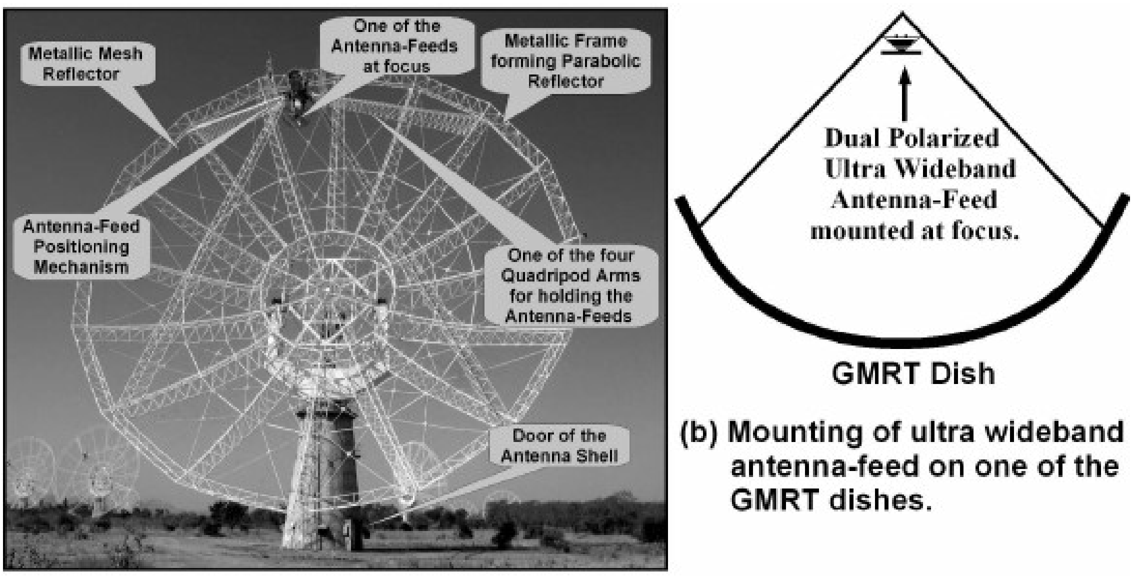


Figure 10 (a) Physical details of a GMRT dish antenna and (b) mounting outline of the ultra-wideband antenna-feed at its focus.

The incremental power from background sky to source is termed as *deflection*. Signals represented in black and gray are obtained by pointing the dish toward Cygnus A and zenith (sky) respectively. Some undesirable narrow-band radio interference from distant radio transmitters are also seen.

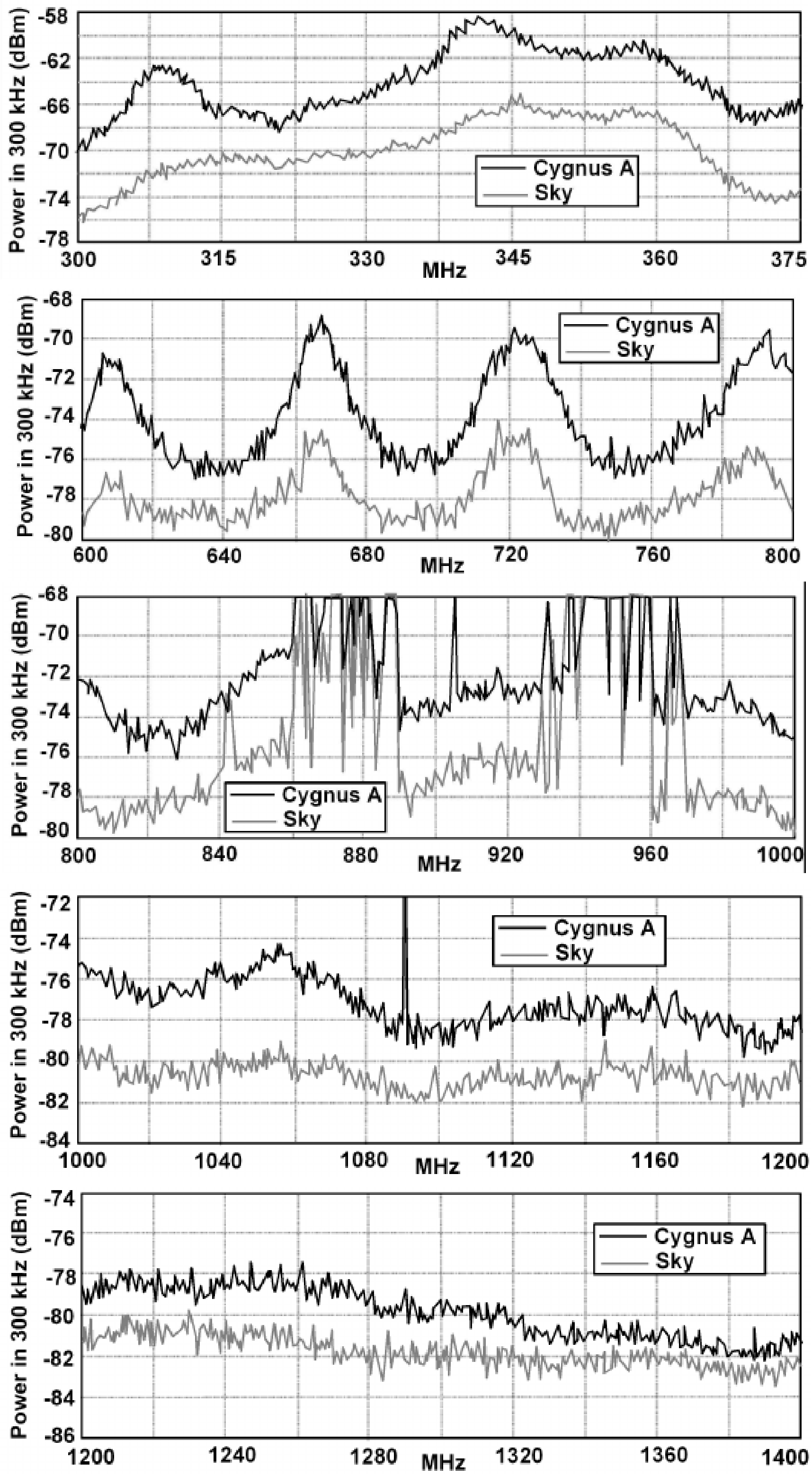


Figure 11 Signals represented in black and gray are obtained by pointing the GMRT dish toward Cygnus A and zenith (background sky) respectively. Thin tall lines and buildings are radio interference from distant transmitters.

8. Conclusions

From the GMRT antenna observation results the following points are drawn.

(*i*) For frequencies below 1 GHz, the optimized dish illumination (beam pattern falling by 10 dB at the edges of the dish) could be safely used in radio astronomy.

(*ii*) At higher frequencies, dish illumination by the feed must be reduced to avoid ground pickup.

(*iii*) The mesh and RMS efficiencies of the GMRT dishes deteriorate significantly at higher frequencies.

It is concluded that size of the holes on the metallic mesh (surface of the paraboloid dish) must be reduced to improve higher frequency signals. The overall performance of the antenna could be further improved if the side-lobes and the back-lobes of the antenna-feed are further reduced [3].

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