CHAPTER 1

INTRODUCTION AND HISTORICAL REVIEW

1.1 INTRODUCTION

In late 1967, the first detection of the clocklike radio pulses emitted by objects that have come to be called as pulsars, opened up one of the most interesting areas in astronomical research. Considerable progress has been made since then towards understanding this natural phenomenon. The present understanding of the pulsar radiation is based mainly on the extensive pulsar observations at high radio-frequencies ⊝ 100 MHz). In the first part of this chapter, a very brief account of the generally accepted scenario for the emission from these peculiar sources is given. This will be followed by a discussion on the observational properties of pulsars. We also present a brief review of the techniques employed for the related observations. In the last part of the chapter, we discuss the significance of pulsar observations at low radio-frequencies. A variety of difficulties associated with low frequency observations are also described. In the end, we review the previous work on pulsars at low radio-frequencies and underline the scope of further work.

1.2 RADIO EMISSION FROM PULSARS

Jocelyn Bell and Antony Hewish [1] discovered pulsars at Cambridge University while observing interplanetary scintillations of compact radio sources at 81.5 MHz. Initially, they had great difficulty convincing themselves that the strange periodic signals they were observing, had been emitted by naturally occurring astronomical objects. However, the other possibilities were soon systematically eliminated. By the middle of 1968, a dozen pulsars were detected, with broadly similar characteristics with periods ranging from 0.25 to 1.96 sec. Since the pulse widths were of the order of 20 milliseconds, it was concluded on the basis of light-travel-time argument that the source could not be larger than the size of the Earth. It was clear from the early work [1] that the basic periodicities were stable to a precision better than one part in 10^3 over intervals of a few months. This indicated that objects with great inertia must be involved in the time-keeping process. The short periods implied that these objects must be very compact compared to normal stellar objects. The obvious candidates [1] for these objects were white dwarf stars and the theoretically predicted neutron stars.

Several types of mechanisms were suggested for producing the periodic signals, e.g. radial pulsation, orbital motion of a satellite or a planet and rotation (spin). Various physical considerations ruled out all the above possibilities (e.g.[2,3]) except the rapid rotation of neutron stars. The discovery of two pulsars near the centres of supernova remnants [4,5] gave added strength to the argument, that the pulses were coming from spinning neutron stars.

Before the discovery of pulsars, Pacini (1967) [6] had suggested that there might be a very strong magnetic field in neutron stars and that they might be rotating so rapidly that the Lorentz force of this field would be of great importance. Gold (1968) [3] was the first to argue that due to the strong magnetic fields and high rotation speeds of neutron stars, relativistic velocities will be set up in any plasma in the surrounding magnetosphere, leading to radiation in the pattern of a rotating beacon. He also suggested that the emission derives its energy from the rotational energy of the star and predicted "a slight but steady, slowing down of the observed repetition frequency". Soon after such slowing down was indeed found in the cases of the Crab pulsar [7], the Vela pulsar [8] and also other pulsars [9,10]. The magnetic field strengths at the surface of the star are estimated using the slowing-down rates along with reasonable values of the moments of inertia for the stars and assuming energy loss mechanism to be the magnetic dipole radiation [11]. The field strengths were found to be of the order of 10^{12} Gauss.

The rate of rotational kinetic energy loss, derived from the observed slowing-down rate of pulsars, is enormously more than that required to account for the observed radio pulses. But, as yet, no mechanism for converting a part of this rotational energy into pulses we observe is universally accepted. Here we will briefly present a usually accepted theory for the emission mechanism.

The observed radio flux densities, together with reasonable estimates of distances and upper limits to the sizes of emitting regions, correspond to apparent brightness temperatures greater than 10^{30} K in some cases [12]. If any incoherent emission mechanism is to produce such temperatures, then the required particle energies turn out to be many orders of magnitude larger than that can be produced by any known process. This almost certainly suggests that the observed intensities are the result of a highly coherent emission mechanism (i.e. many particles radiating in phase).

The narrow pulse widths observed for most pulsars imply that the emission originates from a confined zone on the rotating neutron star. Observations of the Vela pulsar by Radhakrishnan et al. (1969) [8] showed that the position angle of the linearly polarized emission changes by more than 50° across the pulse profile. The continuous sweep of linear polarization was suggested [13] to be related to the dipole structure of the magnetic field in the near magnetospere. This implied that the emission region may be in the vicinity of a magnetic pole. Further support for this conclusion came from Goldreich and Julian (1969) [14] who showed that charged particles would be accelerated along the so called "open" field-lines emanating from the polar regions. As originally proposed by Radhakrishnan [15] ,these particles with relativistic speeds would emit radio-frequency radiation due to their motion along the curved field-lines (i.e. curvature radiation)[16]. The high intensities would be produced by coherence from particle bunches. This radiation would be confined to a conical beam, directed radially outward from the star and centered on the magnetic axis. The angular size of the cone is determined by the angle subtended by the open field lines in the region of emission.

Ruderman and Sutherland (1975) [17] have proposed a fairly complete model for the pulse emission process based on their theory of magnetospheric gaps, This emission mechanism does not require much surface emission of particles. They suggested that a large part of the induced electric potential in the magnetosphere is developed across a vacuum gap, possibly about 100 m thick, immediately above the star surface and in the open field line region. If a single charge is placed in this gap, it is immediately accelerated to a very high energy, and in the presence of the intense magnetic field It emits high energy gamma-rays. The gamma-ray photons have sufficient energy to produce electron-position pairs, which are themselves accelerated along the field lines, forming a cascade of particles and gamma-rays. The upper surface of the vacuum gap then becomes the effective emitting surface. The emission may be concentrated at one or more points on the surface like spark discharges, and these points may move about. These accelerated seecondary particles moving along the magnetic field lines give out the "curvature radiation" in the direction of their motion. When the star rotates, the torch of emission is swept across the line-of-sight to give one radiation pulse in each rotation period. If the particles, which are accelerated at the polar gap, are available in form of bunches with dimensions less than a wavelength, their radiation fields (rather than intensities) add to produce coherent radiation. In this model, the lower frequency radiation is produced in regions farther away from the star. This model provides plausible explanations for several observed characheteristics of pulsar radiation.

1.3 OBSERVATIONAL PROPERTIES OF PULSARS

1.3.1 Period

The outstanding result from extended timing meaurements [18,19,20] is that the arrival times of pulses are astonishingly regular. On a short time scale, i.e. over a span of a few days, the arrival time shows only a small jitter from pulse to pulse, which averages out over a few hundred pulses. Such averaged pulse arrival times, when looked at over months or years, usually show only the geometric effect of the barycentric correction (see Appendix I) and the regular spin-down represented by the first derivative ($\dot{P}$) of the period. With the recent discovery of the first "millisecond pulsar" [21], the periods of the over 400 known pulsars range from about 1.5 milliseconds to 4.3 seconds.

The first derivative of the period has been measured for most of the pulsars [18,19,20,22] and is positive in sign. In most of the cases the $\dot{P}$ values are of the order of 10^{-15} sec/sec. The second derivative ($\ddot{P}$) of the period has been measured for the Crab pulsar [23], and is negative in sign. Some discontinuous changes in the periods, known as "Glitches", were observed in a few cases [24,25,26]. The observed Glitches correspond to sudden decrements in the period, and are believed to result from internal readjustments within the Neutron star.

1.3.2 Pulse Profile

The average properties of the pulse profiles are obtained by studying the integrated profiles. These integrated profiles are obtained by adding together some hundreds of pulses. Their shapes tare known in detail at high radio-frequencies for many pulsars (e.g.[27,28,29]). The width of the integrated pulse profile, if expressed as a fraction of the period, does not depend on the period and for most pulsars it is typically in the range 0.02 to 0.05 times the period [30]. The pulse profiles in some cases are found to consist of several components or subpulses. In such cases, an Increase in the component separation has been observed towards lower radio-frequencies [29].

The pulsars are classified into two broad groups, depending on whether their pulse profile has single or multiple components. They are called Type S (Simple) and Type C (Complex) respectively (Taylor and Huguenin, 1971) [27]. This division is based on the profile shapes, observed mostly around 400 MHz, and has goad correlation with other pulsar properties [31]. The Type C pulsars tend to have long periods, in most cases greater than one second. They also have a higher magnetic field strength. The type S, on the other hand, have short periods and low values of magnetic field strength. The magnetic field strengths are estimated from the values of the product $P\dot{P}$ [11].

An interesting feature, known as 'drifting subpulses' has been observed in many pulsars, where subpulses in successive pulses drift systematically across the profile [32,33,34,35]. This drifting in the case of some pulsars is found to have highly organised patterns, leading to strong features in their fluctuation spectra [36,37]. Most of the pulsed energy is confined to a small fraction of the period, i.e. the main pulse window. However, in some cases an additional pulse component, situated approximately half-way between the main pulses, is observed [38,39,40,41]. This component, known as the 'interpulse', is believed to be due to the radiation from the other polar region of the generally accepted dipolar magnetic field of the pulsar.

Two other interesting phenomena, namely 'mode changing' [42,43] and 'Nulling' [44,45,46], have been observed. Mode changing is seen for the pulsars with complex pulse profiles, where the intensities of the subpulses in a normal mode abruptly vary to produce a new mode. The pulsar remains in the new mode typically for a few tens or hundreds of periods before abruptly reverting to its normal mode. 'Nulling' is a sudden drop in the intensity of the pulse during the nulling interval. The average frequency and the interval of nulling are seen to vary over a wide range. For some pulsars, a significant variation in the pulse intensities on time scales of the order of a few hundred microseconds has been noticed

[47,48]. Such variations are called micropulses. In addition to all this, the integrated profiles for many pulsars are seen to have quite significant polarization characteristics [28,49]. These polarization characteristics change with frequency. Some of the profiles have linear polarization as high as 70 to 95 percent.

1.3.3 Pulse Energy

Observed pulse energies vary on many different time scales. These variations can be either intrinsic to the pulsar radiation or due to the propagation effects in the intervening medium. Such variations can be studied to obtain valuable information about the intervening medium and the intrinsic radiation from pulsars. However, the task of measuring the average pulse energy and its spectrum becomes difficult in the presence of such variations.

For most of the known pulsars, spectra have been measured at high radio-frequencies [50,51]. These spectra indicate that the pulse energy decreases with increasing frequency. The spectral indices (see Appendix III) for different pulsars usually lie in the range -1 to -3 at the high frequencies [50]. The limited measurements at low frequencies show, that the average energy starts reducing instead of increasing with the decreasing frequency below a turn-over frequency [52,53]. The reasons for such turn-overs are little understood, except in the cases of some short period and distant pulsars, where the turnovers are observed to be the result of interstellar scattering (e.g.[54]).

A recent search for unpulsed radio emission from pulsars has shown the presence of significant unpulsed flux in four cases, apart from the pulsed flux [55].

1.4 PULSAR SIGNAL PROCESSING TECHNIQUES

The basic observable quantity in radio studies of pulsars is the varying voltage induced in a certain antenna-receiver combination. The center frequency f_0 and bandwidth B of the receiver, together with the polarization response of the antenna, determine the instrumental parameters. These parameters along with the pulsar parameters determine the instrumental effects. It is ideal to record the outputs of two similar antenna-receiver combinations with mutually orthogonal polarizations. However, here we will confine the discussion to the detection and recording of pulses from a single antenna-receiver combination.

Let us denote the varying voltage due to a pulsar signal by $X(t)$, which in a narrow band approximation, can be expressed as [56] ;

$$X(t) = \mathrm{Re}[V(t)\exp(i2\pi f_0 t)] \qquad \ldots\ldots(1.1)$$

where $V(t)$ = the associated complex envelope as a function of time t.

and $\mathrm{Re}[y]$ = Real part of y

In conventional observations, the voltage $X(t)$ is amplified, detected and smoothed using a postdetection filter, to obtain

$$X(t) = 1/2|V(t)|^2 * r(t) \qquad \ldots\ldots(1.2)$$

where $r(t)$ = the impulse response of the postdetection filter

$|y|$ = magnitude of y

and '$*$' means a convolution.

The filter removes the components of $X(t)$ at $\pm 2f_0$. The bandwidth of the postdetection filter determines the minimum rate for sampling and also the upper limit to the attainable time-resolution. However, in reality the effects due to the propagation (see Appendix II) of pulsar signals through the interstellar medium need to be taken into account. In the presence of the propagation effects, the output intensity $I(t)$ is given by

$$I(t) = 1/2|V(t)|^2 * s(t) * d(t) * r(t) \qquad \ldots\ldots(1.3)$$

where $s(t)$ = the impulse response due to interstellar scattering.

and $d(t)$ = the receiver bandpass converted into a time function by the dispersion law.

In this case, the time-resolution is predominantly determined by the longest of the three contributing responses. In the presence of noise, the best signal-to-noise ratio is obtained by adjusting the postdetection time-constant to match the width of $d(t)$. Wide RF bandwidths are desirable in most radio astronomical observations to obtain improvements in signal-to-noise ratios. However, in pulsar observations, if dispersion effects are not removed, wider bandwidths result in poorer time-resolution.

Therefore, an ideal pulsar receiver always includes a dispersion removal system, wherein wider bandwidths can be used effectively for achieving better signal-to-noise ratios without losing much in terms of time-resolution. Postdetection dispersion removal can be performed by dividing the receiver band into many narrow channels and then adding the detected outputs after appropriate delays. Thus the time-resolution of a single narrow channel can be retained with the signal-to-noise ratio equivalent to that attainable for the total observing bandwidth. This technique is also known as 'signal enhancement' technique. Once the output samples of different narrow channels are available, this process can easily be implemented in software. However, in such a case, the effective rate of data recording is increased proportional to the number of narrow channels. This problem can be avoided by using a suitable processor to perform the operations in real time (e.g.[57]).

For studying the finer details in pulse structure, the time-resolution can be improved considerably by removing the dispersion distortion before detection. In principle, the signal emitted by a pulsar can be recovered over a limited frequency and time interval by passing the received signal through an inverse filter, whose transfer function is equal to the complex conjugate of the transfer function representing the dispersion in the interstellar medium. The time-resolution is then limited to the inverse of the system bandwidth. The practical resolution limit is set by the widest bandwidth that can be sampled fast enough to avoid aliasing. Predetection dispersion removal can be achieved either by using a hardware dispersive filter [58] or by simulating the filter by computer software [48].

A swept-frequency dedispersion procedure has also been used for pulsar observations [59]. In this scheme a multichannel filter receiver is employed. The local oscillator frequency of the receiver is carefully controlled to sweep in synchronism with the dispersed pulse. The sweep is synchronized in time so that the pulse window is centered in the middle of the multichannel filter bank. The detected outputs of the adjecent frequency channels then correspond to the pulse amplitude at adjecent longitudes (see Appendix III for definition) within the pulse window. The time-resolution is limited by the dispersion smearing within a spectral channel. The signal-to-noise ratio attainable on any pulse depends on the square of the ratio of the pulse tracking time to the time-resolution [60].

The signal-to-noise ratio for average pulse profiles of pulsars is improved by'observing a large number of pulses and combining the data of individual pulses together in phase by making use of the known periodicities.

1.5 PULSAR OBSERVATIONS AT DECAMETRIC WAVELENGTHS

Experimental data on the basic quantities of pulsars are required to establish general laws describing the radio emission of pulsars and to identify the distinctive features of that radiation reflecting various parameters of the pulsars. The mean pulse profile and the radiant flux density of a pulsar depend on frequency unlike such quantitites as the period, its derivative and the dispersion measure. Therefore these quantities have to be investigated over as wide a frequency range as possible. Most of the available data on pulsars, numbering now over 400, are from the observations at high radio-frequencies. There is a considerable lack of observations towards lower radio-frequencies. This fact is, clearly brought out in Fig. 1.1 ,where we indicate the number of pulsars observed at different frequencies. There is a striking deficiency in the number of pulsars observed below

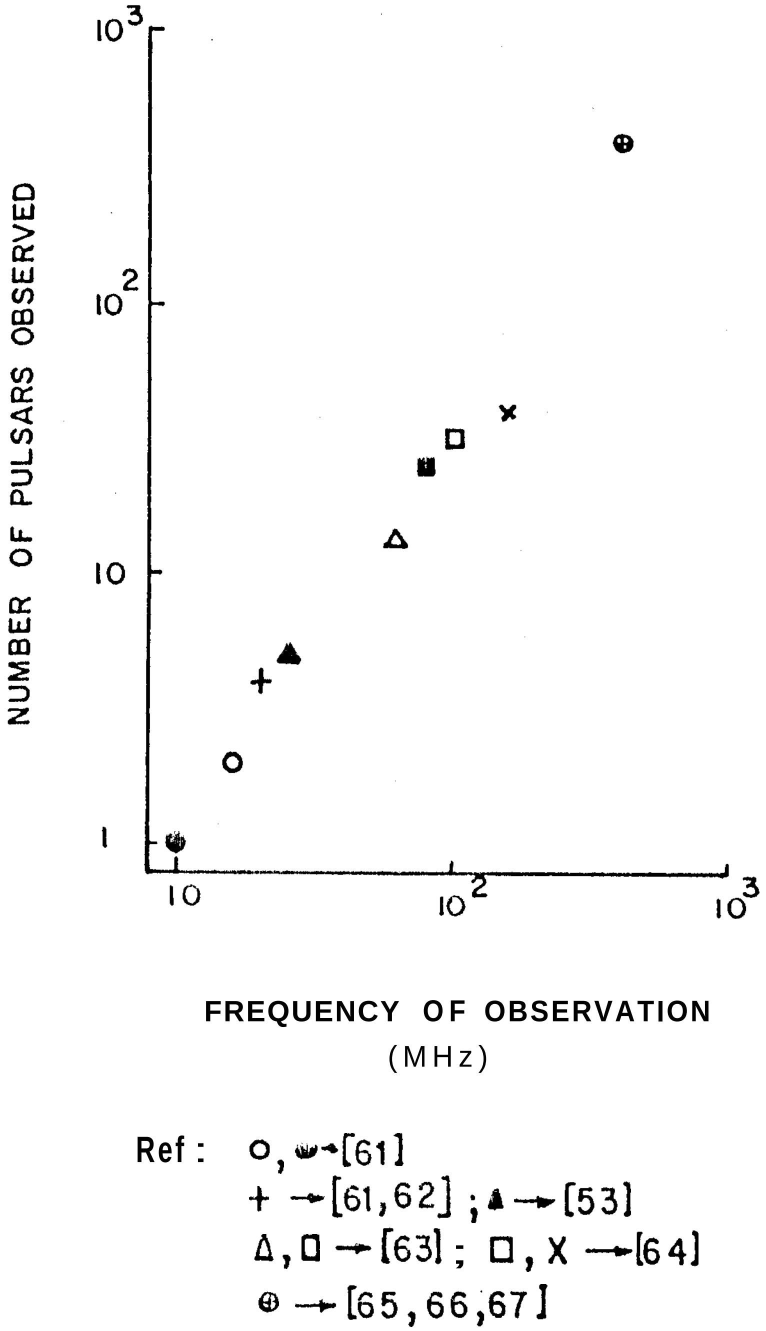

FIG. I.1 Number of pulsars observed Vs. the frequency of observation.

50 MHz. This is mainly due to various difficulties in observing pulsars at decametric wavelengths.

The difficulties arise mainly due to the effects of the propagation of pulsar signals through the interstellar medium. The dispersion of the propagating signals due to the plasma in the interstellar medium causes differential delays of the signals received at different frequencies. This results in smearing of the pulse at the receiver output. The amount of smearing is given by the difference in the pulse arrival times at the edge frequencies in the observing band. This smearing is proportional to the third power of the wavelength (see eq. II.5), consequently, observations of highly dispersed pulsar signals at decametric wavelengths are very difficult, The smearing results in an apparent reduction of the peak flux (see Appendix III) of the pulsar signal, causing reduction in signal-to-noise ratio. Such smearing also seriously affects the attainable time-resolution.

The second important effect of the propagation in the medium is that of the scattering due to density irregularities in the medium. The scattering also results in smearing of the pulses. Unlike the dispersion smearing, the smearing due to scattering cannot be reduced or avoided. This smearing is observed to increase very sharply with the wavelength of observation [68,69,70] and the dispersion measure (DM) for the pulsar [71,72] (see Appendix II). In the case of pulsars with short periods and large values of dispersion measure, the smearing due to the scattering can be larger than the pulsar period, causing drastic reduction in the effective pulsed energy. Even in the case of other pulsars, the scattering causes the peak flux to drop, apart from smoothening out narrow features in the pulsar signals. However, it should be noted that the measurements of the amount of scattering made using pulsar signals, are of great importance in studying the parameters of the interstellar medium.

Both these effects in the interstellar medium, namely dispersion and scattering, make high sensitivity and high time-resolution observations at low frequencies almost impossible for most of the distant pulsars. As the sky background becomes brighter at lower frequencies [73], additional difficulties arise if the pulse energy decreases instead of increasing towards lower frequencies.

One of the earliest observations at decametric wavelengths, is due to Bash et.al. (1970) [74] at 38 MHz. They reported their observations on PSR 1919+21 and determined its average energy per pulse, pulse shape and the dispersion measure along the line-of-sight. These observations were made with the MIT solar radar antenna at El Campo, Texas, having an effective aperture of 19,000 square .meters. Two frequency channels were used and the average profiles were obtained using cyclic integrators.

Successful detection of a few more pulsars by Bruck and Ustimenko (1973) [61,62], in the frequency range 10 to 25 MHz, confirmed the possibility of receiving pulsed signals from some pulsars at decametric wavelengths. Understandably, these pulsars had longer periods and lesser dispersion effects. These observations by Bruck and Ustimenko were made using the N-S arm of a T-shaped radio-telescope [75], having a physical area of about 10^5 square meters and with a continuous tracking facility. The receiver consisted of 16 frequency channels with independent frequency control and independently regulated predetection bandwidths (variable from 1.5 to 14 KHz). A 256-element analogue storage device was used to average many pulses. A great variety was observed in the mean amplitude and shape of the pulses, with rapid transitions from one shape to another, occurring over time scales of 2 to 5 minutes. In a few pulsars, two or even three components were noticed instead of one. A time-resolution of 20 millisecond was attained in some cases.

Through detailed studies of the extensive data on a few pulsars at decametric wavelengths, Bruck and Ustimenko reported in a series of papers [76,77,78], the detection of interpulse emission not seen at higher frequencies. The observations, particularly on PSR 1919+21, have been discussed by these authors in great detail. They find that the interpulse radiation increases at lower frequencies and shows a marked sporadic nature. Algo in the case of some other pulsars observed by them, they find evidence for emission away from the main pulse. This emission is not necessarily located exactly half way between two main pulses, and can have one or more peaks.

The radio sepctra down to 53 MHz for about a dozen pulsars were first studied by Comella (1972) [52]. The spectra in many cases were found to have low frequency turnovers. Simultaneous flux density measurements were made in the range 60 to 1420 MHz on nine pulsars by Kuzmin et al. (1978) [51]. This study revealed large variations in spectra from day to day. The measurements of the spectra of five pulsars in the 17-1420 MHz range have been reported by Bruck et.al. (1978) [53]. These observations were made at the radio-astronomical observatories at Grakov (Ukrainian SSR), Pushchino (PIAS) and and Jodrell Bank (England). This study revealed a 'turnover' in the spectra at low frequencies for all five pulsars, and that the maximum in the emission intensity lies at a frequency of 120±60 MHz on the average.

Measurements of the arrival times of the integrated pulses of PSR 0809+74 at five frequencies over the wide interval, from 400 to 39 MHz, by Davies et.al. (1984) C793 have shown that the lower frequency signals arrive with delays longer than those expected from tne known amount of dispersion. The 'superdispersion' delays in the arrival times of the signals from the same pulsar were found to be more prominent at 30 MHz (Shitov and Malofeev, 1985) [80], reaching about 150 milliseconds. The effect is interpreted as a manifestation of possible bending of the pulsar's effective radiation cone. It is argued that this bending is most likely due to twisting of the magnetic field lines that causes the electromagnetic braking of the rotation.

Measurements of the polarization characteristics of pulsar signals at decametric wavelengths are very limited. The linear polarization of the average pulses of two nearby pulsars has been studied at 39 MHz by Suleimanova et al. (1983) [81]. The results indicate, that the monotonic rotation of the position angle of the plane of polarization can be disrupted by abrupt changes by about 90° at the leading edge of the average pulse for these pulsars. A high degree of linear polarization was found in the two cases.

The decametric observations described above have yielded very valuable information about the properties of the emission from pulsars. All of the five known decametric spectra indicate 'turnovers'. Therefore, the extension of the spectra towards lower radio-frequencies for other pulsars is naturally of great interest. This is especially so for those pulsars whose intensity is still growing with decreasing frequency in the known part of their spectra. The possibility of interpulse emission appearing at lower frequencies also needs to be investigated in the case of more pulsars to establish general pulsar properties relating to shape and size of the emission cones. The pulse profiles of many pulsars, have been observed to change with frequency in the high frequency range [28,82,83]. The extension of these observations to low frequencies would be extremely valuable. Moreover, the amount of interstellar scattering can be estimated at these wavelengths to test the present understanding about the dependance of the amount of scattering on the dispersion measure and the wavelength of observation.

We note, that all the pulsars studied at decametric wavelengths so far, have dispersion measures less than 13 $cm^{-3} pc$. More pulsars, therefore, may possibly be detected at decametric wavelengths, if sufficiently sensitive observations can be made and if suitable schemes are employed to enable observation of highly dispersed pulsar signals with good time-resolution,

In this thesis, we report on our attempts to obtain observations of pulsars with high sensitivity and high time-resolution at a low radio-frequency. The Decameter-wave Radio Telescope at Gauribidnnur, India (Longitude: 77° 27′ 07" ,Latitude: 13° 36′ 12"), designed and used for continuum observations at 34.5 MHz [84,85,86] was used for this purpose. In order to enable pulsar observations with reasonable sensitivity a new tracking facility wan designed, fabricated and installed. A detailed description of the tracking system is presented in the first part of the thesis.

In the second part, a scheme for observations of strong but not highly dispersed pulsar signals is presented. Suitable procedures developed for observation, data acquisition, data processing, detection and calibration are discussed in detail. A data acquisition system was designed and built for this purpose. Our successful detections of 8 pulsars out of 20 attempted candidates are reported. A new detection criterion is used for increasing the reliability of such detections. Possiblities to study fluctuation spectra and low freqeuncy variability of pulsar signals are considered and a few relevant observations are presented.

In the third part of the thesis, a scheme devised to enable high. time-resolution observations of highly dispersed pulsar signals is described. This scheme employs a basic swept-frequency dedispersion procedure. A reliable programmable sweeping local oscillator system was designed and built to suit the requirements. The design aspects of this system are discussed in detail. This system was used with the existing multichannel autocorrelation receiver to obtain intensity patterns with high resolution in the frequency domain. A new method was used to avoid the need for gain calibration of individual frequency channels and the need for absolute synchronisation of the sweep. It is shown, that with this method, higher time-resolution can be obtained for strong pulsar signals. The details of the data processing are discussed. Using this scheme we have successfully demonstrated its ability to observe pulsars with dispersion measures as high as 35 $cm^{-3}pc$. In the end, we present a brief discussion on the results obtained using both the observing schemes.