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Pulsar Observations at 34.5 MHz using the Gauribidanur Telescope: I

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Abstract. The behaviour of pulsars at low radio-frequencies (below ~50 MHz) remains poorly understood mainly due to very limited observational data on pulsars at these frequencies. We report here our measurements of pulse profiles at 34.5 MHz of 8 pulsars using the Gauribidanur Radio Telescope. None of the 8 pulsars show any significant interpulse emission at this frequency which conflicts with an earlier claim from 25 MHz observations. With the exception of one pulsar (PSR 0943 + 10) all the observed pulsars show turnovers at frequencies above 35 MHz in their spectra. We also report our attempts to study the short and long term variations in the pulsar signals at this low frequency.

Key words: pulsars—interstellar scattering—dispersion

1. Introduction

The mean pulse profile and the radiant flux density of a pulsar depend on frequency and therefore, these quantities need to be investigated over as wide a frequency range as possible. Most of the available data on pulsars, numbering now about 500, are from observations at high radio-frequencies. There is a considerable lack of observations towards lower radio-frequencies (below 50 MHz). This is due to various difficulties in observing pulsars at decametric wavelengths arising mainly from the effects of the propagation of pulsar signals through the interstellar medium. Two important effects in the interstellar medium, namely dispersion and scattering, cause considerable reduction in the apparent peak (pulsing) intensity of pulsars at low radio-frequencies. These propagation effects also cause smearing of the details in the pulse profile. As the sky background becomes brighter at lower frequencies, additional difficulties arise if the pulse energy decreases instead of increasing towards lower frequencies.

Some of the earliest observations at decametric wavelengths are due to Bash *et al.* (1970) at 38 MHz and Craft (1970) at 40 MHz. Successful detection of a few more pulsars by Bruck & Ustimenko (1973), in the frequency range of 10 to 25 MHz, confirmed the possibility of receiving pulsed signals from some pulsars at decametric wavelengths. Understandably, these were the pulsars with longer periods and lower dispersion. Through detailed studies of extensive data on a few pulsars at decametric wavelengths, Bruck and Ustimenko reported in a series of papers (1976, 1977, 1979), the

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detection of interpulse emission not seen at higher frequencies. They also found evidence for emission away from the main pulse in some cases. The radio spectra down to 53 MHz for about a dozen pulsars were first studied by Comella (1972). The spectra in many cases were found to have low frequency turnovers. Observations at 80 and 160 MHz (Slee *et al.* 1986) of a larger sample of pulsars have shown that in general the spectra become less steep towards lower frequencies. Measurements of the spectra of five pulsars in the 17–1420 MHz range have been reported by Bruck *et al.* (1978). This study revealed turnovers 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 over a wide frequency range (Davies *et al.* 1984; Shitov & Malofeev 1985), have shown that the lower frequency signals arrive with delays longer than those expected from the known amount of dispersion.

The decametric observations described above have yielded very valuable information about the properties of the emission from pulsars (Bruck 1987). 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 increasing 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 properties relating to the shape and size of the pulsar emission cones. The pulse profiles of many pulsars have been observed to change with frequency in the high frequency range (*e.g.* Manchester 1971; Kuzmin *et al.* 1986; Kardashev *et al.* 1986; Slee *et al.* 1987). The extension of these observations to low frequencies is extremely valuable. Moreover, the amount of interstellar scattering can be estimated at these wavelengths to test the present understanding (see Alurkar *et al.* 1986 and references therein) about the dependence 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 and are confined to the Northern hemisphere. 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.

Here, we report on our attempts to observe pulsar signals with high sensitivity and high time-resolution at a low radio-frequency. The Decameterwave Radio Telescope at Gauribidanur (GEETEE)*, India (Longitude: 77° 27′ 07″, Latitude: 13° 36′ 12″ N), operating at 34.5 MHz (Deshpande, Shevgaonkar and Sastry 1989, DSS) was used for these observations. The observations and data processing procedure is described in detail. Our successful detections of 8 pulsars are reported. The results are discussed in the end.

2. Observations

The present observations made with the GEETEE used the new tracking facility to obtain more observing time per day. A detailed description of the tracking system is

*This telescope is jointly operated by the Indian Institute of Astrophysics, Bangalore and the Raman Research Institute, Bangalore.

given by DSS. The sensitivity improvement due to the new tracking facility made it feasible to attempt observations of a few strong pulsars having low dispersion measures (DM) with this telescope. As the signals from even the strongest of the pulsars will be well buried in the Galactic background noise it is impossible to detect individual pulses in our observations. However, with the use of the tracking facility a source can be observed over an interval of $42 \times \sec\delta$ minutes. Thus, it is possible in one observing session to receive a large number of pulses, $N(= 2520 \sec\delta/P)$, from a pulsar at declination δ and with a period P seconds. These pulses were averaged, using standard averaging techniques, to obtain $\sqrt{N}$ improvement in the signal-to-noise ratio.

The present observations were made by using the existing single frequency channel correlation receiver, to correlate the outputs of the EW and S arms of the T array where we obtain both the in-phase (COS) and the quadrature (SIN) correlation outputs (see DSS for more details). A predetection bandwidth of 30 kHz (optimum for low DM pulsars) was used. Post-detection time-constants in the range 10–30 milliseconds were employed. The EW arm was used in the tracking mode. In an ideal situation, the SIN correlation for a point source can be discarded as it does not contain the source contribution. However, in practice, due to beam pointing error and ionospheric refraction, the source contribution in the SIN correlation is generally non-zero. This also causes a corresponding reduction in the source contribution and consequent worsening of the signal-to-noise ratio in the COS correlation. In the Appendix we describe a procedure using both the correlations to partially recover such a loss in the signal-to-noise ratio. Both the correlations were recorded using a data logging system on to magnetic tapes at a rate of 3 milliseconds per sample. Thus, each of the two correlations is sampled at intervals of 6 milliseconds. The data recording is stopped for a short interval ($\sim$ 500msec) every time the EW beam is switched to next position during the tracking to allow ample time for the settling of the tracking phase shifters.

The GEETEE accepts only a single linear polarization. The observed output therefore depends on the source polarization, the observing frequency and the Faraday rotation in the intervening medium. Such a dependence can be ignored if the differential Faraday rotation across the pre-detection bandwidth is sufficiently large. However, with 30 kHz bandwidth the limited polarization sensitivity of the GEETEE may significantly affect observations of strong linearly polarized sources with rotation measures less than about $20\,\mathrm{rad\,m^{-2}}$. To help reduce this effect to a large extent, different centre frequencies (in the range 34.4 to 34.6 MHz) were used during different observing sessions (4 to 10).

Using the above-mentioned procedure, observations were attempted on 20 known pulsars. These observations were made mostly at night to minimize possible interference due to terrestrial signals in the observing band. Most of these observations were made during 1984 (November)–1985 (March).

3. Data processing

The data processing procedure used here basically employs the standard 'signal averaging technique'. Knowing the apparent period P, the number of output bins (N_B) is chosen, such that the bin-width (Δt_{bin}) is approximately the same as the sampling interval (Δt_s), and that $\Delta t_{bin}.N_B = N_p.P$, where N_p = no. of periods over which averaging is performed. In this kind of processing, the data averaging is customarily performed only over a single period stretch i.e. $N_p = 1$. However, here we use $N_p = 2$, i.e. perform averaging over a two-period stretch, for reasons that will be discussed a little later.

The data for the COS and SIN channels are processed separately using the following procedure. First, for each data block (obtained in one beam position during tracking; i.e. of duration $40 \times \sec\delta$ seconds) a mean value is computed and subtracted from the corresponding samples. The standard deviation (σ_i) in each block is also estimated. Because of the asynchronous sampling (i.e. $\Delta t_{\text{bin}} = t_s$), the resultant profile would be smeared additionally by an amount equal to the bin-width if the samples are added to the nearest bin while averaging. Such smearing is avoided by using linear interpolation to add the sample value with suitable weights in both the bins which are on either side of the sample. We also keep an account of the effective number of samples added in each bin. The final average samples are obtained after appropriate normalization for the system gain. The estimate of the noise in such average profiles is computed using the standard deviations due to noise (σ_i) obtained for each data block.

In the course of this averaging process, if any absolute sample value is found to be greater than 5 times the standard deviation estimated for the data in the respective record, then that sample is rejected as possibly due to interference. However, the bin numbers corresponding to such samples are noted, so that the possibility of these high sample values being due to very strong pulses from the pulsar could still be considered, if the bins are found to be confined only to the pulse window in the average profiles. In this manner, the average profiles are obtained for both the SIN and COS channels separately.

As the data is averaged over a two-period stretch, each half of the stretch corresponds to the average of alternate pulses. These halves can be considered to be two independent sets of data obtained under the same observing conditions and to have, in general, the same average contribution from the pulsar signal. With this understanding, the data over two-period stretches are tested for a significant detection of two similar looking pulses separated exactly by the apparent period of the pulsar. The threshold for the significant detection is chosen to be three times the value of the standard deviation due to noise. This procedure increases the reliability of such detections as it can discriminate against any spurious detections due to interference. However, the signal-to-noise ratio in the two-period stretch is reduced by a factor of $\sqrt{2}$, compared to that in the case of averaging over a one-period stretch, making the detections difficult in the marginal cases. This disadvantage can be overcome by choosing a larger bin-width. It is required that at least one of the two correlation channels satisfies the detection criterion. It should be noted that, in any further processing, only the data with the original bin-size have been used. In the initial stages, as an additional check for the validity of our detections, the corresponding raw data were folded with wrong periodicities and were confirmed to fail in the detection test.

Using the above mentioned procedure, it has been possible to successfully detect signals from 8 pulsars. Their average profiles were obtained by combining the two halves of the two-period stretch for each channel. One such output obtained using the data in the direction of PSR 0834 + 06, is shown in Fig. 1

In the case of each successful detection, the average profiles over a one-period stretch were available for both of the COS and SIN channels. We have employed a new scheme (see Appendix) to combine the COS and SIN correlation channel outputs in an optimum way. We show that with this scheme the resulting average profile, in general,

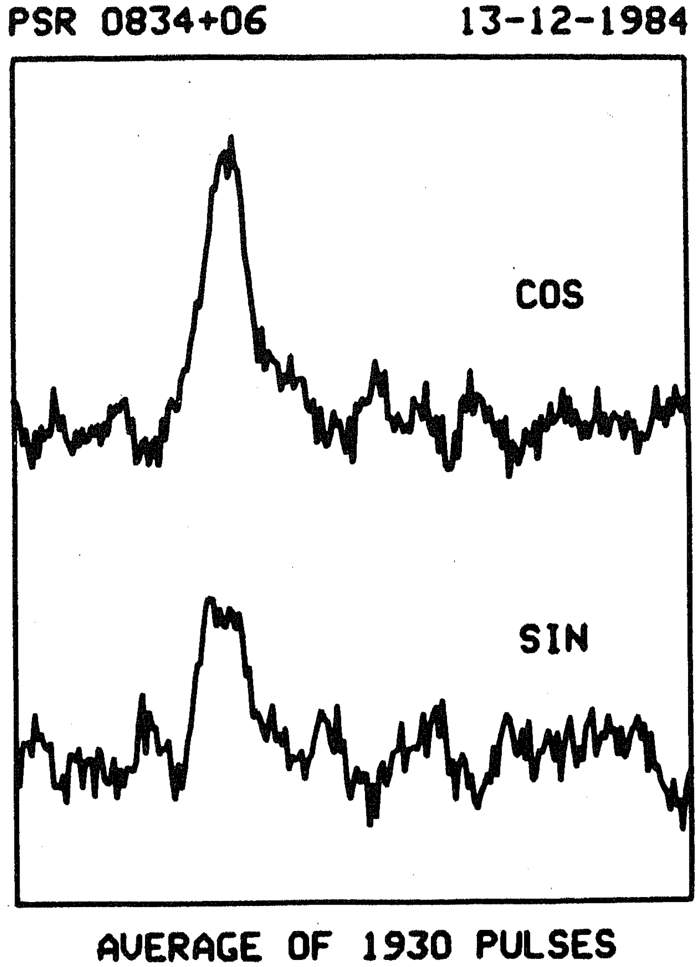

Figure 1. Typical average profiles obtained from data of the COS and SIN channels.

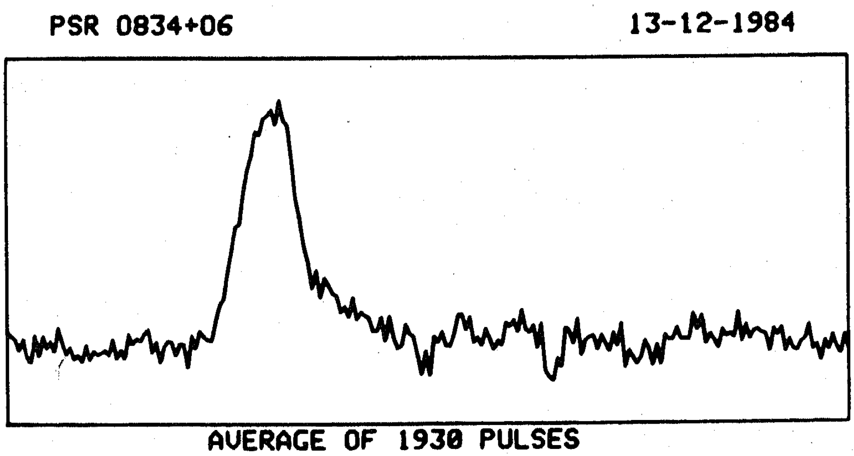

Figure 2. An average profile obtained after combining the COS and SIN channel outputs (shown in Fig. 1) in an optimum way.

will have better signal-to-noise ratio than that available in the individual channels. Fig. 2 shows one such average profile obtained for PSR 0834 + 06.

3.1 *Flux Calibration*

To obtain appropriate flux calibrations, observations were made on suitable continuum point sources during every session of the pulsar observations. Sources with declinations close to those of the pulsars observed were selected for calibration. The assumed flux densities at 34.5 MHz for most of these calibrators were obtained by extrapolating from the 38 MHz values (Kellermann, Pauliny-Toth and Williams 1969). These values were used after applying the correction suggested by Baars *et al.* (1977). If such data were not available, the values at 80 and 160 MHz (Slee 1977) were used.

The recorded data during each calibration observation were used to obtain average deflections, D_c and D_s in the COS and SIN channels respectively. The deflection, D_0, corrected for collimation error was obtained as

$$D_0 = \frac{(D_c^2 + D_s^2)^{\frac{1}{2}}}{\mathrm{sinc}\left[\frac{1}{\pi}\tan^{-1}(D_s/D_c)\right]} \quad (1)$$

If S is the source strength in Janskys, then the calibration factor R_{cal}, in Janskys per count of deflection, is computed as $R_{\mathrm{cal}} = S/(D_0 K)$; where K is the system gain normalization factor. Such values of R_{cal} obtained from observation of 5–7 calibrators on each day, were used to obtain an average daily calibration $\langle R_{\mathrm{cal}} \rangle$ (in Janskys per count), which was used in turn to obtain a calibrated profile, $a(t)$, as $a(t) = A_0(t) \, . \, \langle R_{\mathrm{cal}} \rangle$ (Janskys).

3.2 *Estimation of the Average Pulse Energy and the Amount of Interstellar Scattering*

The calibrated average pulse profiles were used to estimate the average pulse energy and the amount of pulse broadening due to interstellar scattering. The calibrated profiles obtained on different days were combined together to improve the signal-to-noise ratios. For the purpose of estimating the average pulse energy, the data from different days were averaged with equal weights. The same input data were averaged

Table 1. Estimates of the Average Pulse Energy and the Scatter Broadening of the pulse at 34·5 MHz.

Pulsar	Average pulse energy‡ (10^{-29} Jm^{-2} Hz^{-1})	Scatter broadening§ (msec)
PSR 0628 − 28†	1750 ± 480	45 ± 15
PSR 0809 + 74	710 ± 320	3 ± 2
PSR 0834 + 06	2100 ± 100	16 ± 3
PSR 0942 − 13†	110 ± 60	—
PSR 0943 + 10†	960 ± 120	8 ± 3
PSR 0950 + 08	420 ± 60	9 ± 4
PSR 1133 + 16	900 ± 90	9 ± 3
PSR 1919 + 21	2560 ± 400	—

†New detections at decametric wavelengths
‡Errors quoted are 5σ values
§Errors quoted are 1σ values.

also with suitable weights (inverse noise power) to maximise the signal-to-noise ratio. This latter output was used to obtain the estimates of the amount of (interstellar) scatter broadening (τ_s). For this purpose, a best fit profile was obtained in each case. The nature of the function used to fit the observed profile is given by Equation A.5 (see Appendix). The estimate of the average pulse energy was obtained by integrating the observed pulse profile within the pulse window inferred from the best fit profile. The estimates obtained for 8 pulsars are listed in Table 1. Our estimates of τ_s may have larger errors than those quoted here, if our assumptions about the intrinsic pulse profiles ($i(t)$ in equation A.5) at 34.5 MHz do not hold good.

4. Results and discussion

a) Pulse profiles and energy spectra

Three pulsars, namely PSR 0628 − 28, PSR 0942 − 13 and PSR 0943 + 10, have been detected for the first time at decametre wavelengths. The average pulse profiles (Fig. 3) and the energy spectra (Fig. 4) are presented here for seven of the detected pulsars. The error bars correspond to five times the standard deviation due to noise.

i) PSR 0628 − 28 The profile shown in Fig. 3a is seriously affected by the dispersion smearing across 30 kHz. The spectrum of the pulse energy of this pulsar is found to be straight in the frequency range 61 to 1420 MHz (Kuzmin *et al.*, 1978). However, an extension of the spectrum to frequencies below 60 MHz, using our estimate for the pulse energy, shows a turnover in the spectrum (Fig. 4a). The emission intensity appears to peak at frequencies close to 60 MHz.

ii) PSR 0809 + 74 This is the only pulsar that has been observed extensively down to a very low frequency of 10 MHz (Bruck & Ustimenko, 1973). Although this is one of the strongest pulsars at the frequency of our observation, the signal-to-noise ratio is rather poor. The telescope sensitivity in the direction of this pulsar is very much reduced due to its large zenith angle. However, the increased tracking time for this pulsar, by virtue of its high declination, has made integration of more number of pulses possible leading to a partial compensation in the signal-to-noise ratio. The pulse profile obtained by us is shown in Fig. 3g. The average pulse energy estimated using this profile is consistent with the turnover in the spectrum of Bruck *et al.* (1978). However, our estimate may have large calibration errors due to the lack of suitable calibration sources at nearby declinations. Fig. 4b shows the spectrum of the average pulse energy using our estimate along with other observations (Bruck *et al.* 1978).

iii) PSR 0834 + 06 Observations on this pulsar were made on 11 days. After combining the data on all days, we are able to obtain a high signal-to-noise ratio for its average profile (Fig. 3b). Our estimate of the average energy per pulse in this case is in good agreement with the estimates at other frequencies (see Fig. 4c). The average profile (Fig. 3b) does not show any significant interpulse emission contrary to that reported at 25 MHz.

iv) PSR 0942 − 13 Observations of this pulsar were made on two days. The final average profile is shown in Fig. 3c. Using our estimate for the pulse energy along with the value for the average flux at 400 MHz (Manchester & Taylor 1981), we estimate a spectral index of -0.76 ± 0.28. Due to the large gap in the measured points on the

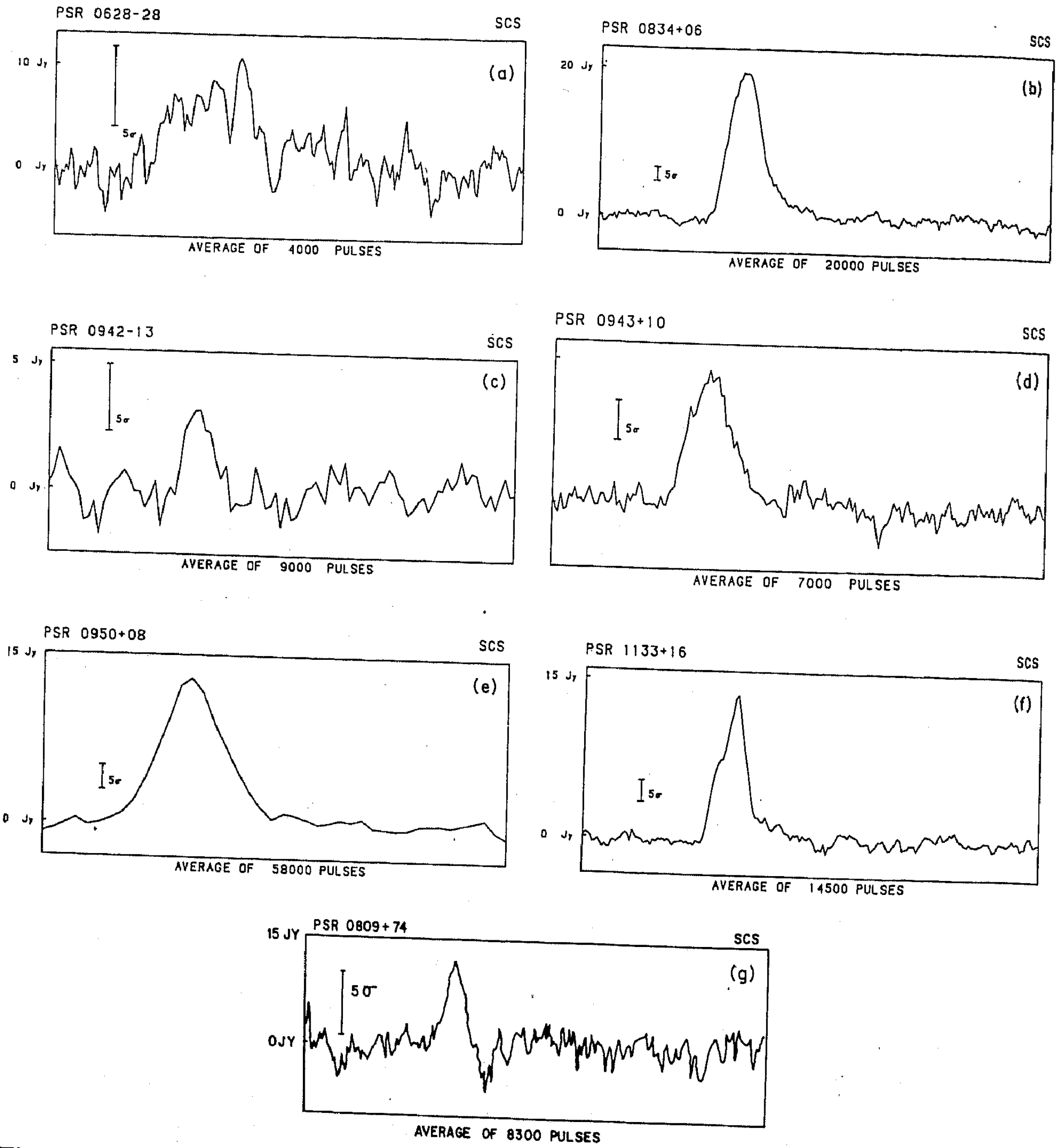

Figure 3. The average pulse profiles for (a): PSR 0628 − 28; (b): PSR 0834 + 06; (c): PSR 0942 − 13; (d): PSR 0943 + 10; (e): PSR 0950 + 08; (f): PSR 1133 + 16 and (g): PSR 0809 + 74 observed at 34.5 MHz. The error bars correspond to five times the r.m.s. noise deviation.

spectrum, it is difficult to comment about the existence of a turnover in the spectrum in the frequency range of 35 to 400 MHz.

v) **PSR 0943 + 10** Suleimanova and Izvekova (1984) have reported mode changing for this pulsar at 62 and 102 MHz. The time-resolution in the profile obtained here (Fig. 3d) is not adequate to see any details in the pulse profile. Our estimate for the average pulse energy, when combined with similar estimates in the range 53 to 606 MHz by Comella (1972) and Slee *et al.* (1986), suggests that the spectrum is still rising even upto 34.5 MHz. This happens to be the first case to the best of our knowledge where the spectrum for a long period pulsar does not have a turnover above 34.5 MHz. Investigation of the spectrum at frequencies below 34.5 MHz would be important. The spectral index computed using our estimate with that at 400 MHz (Manchester & Taylor 1981) is about − 1.65.

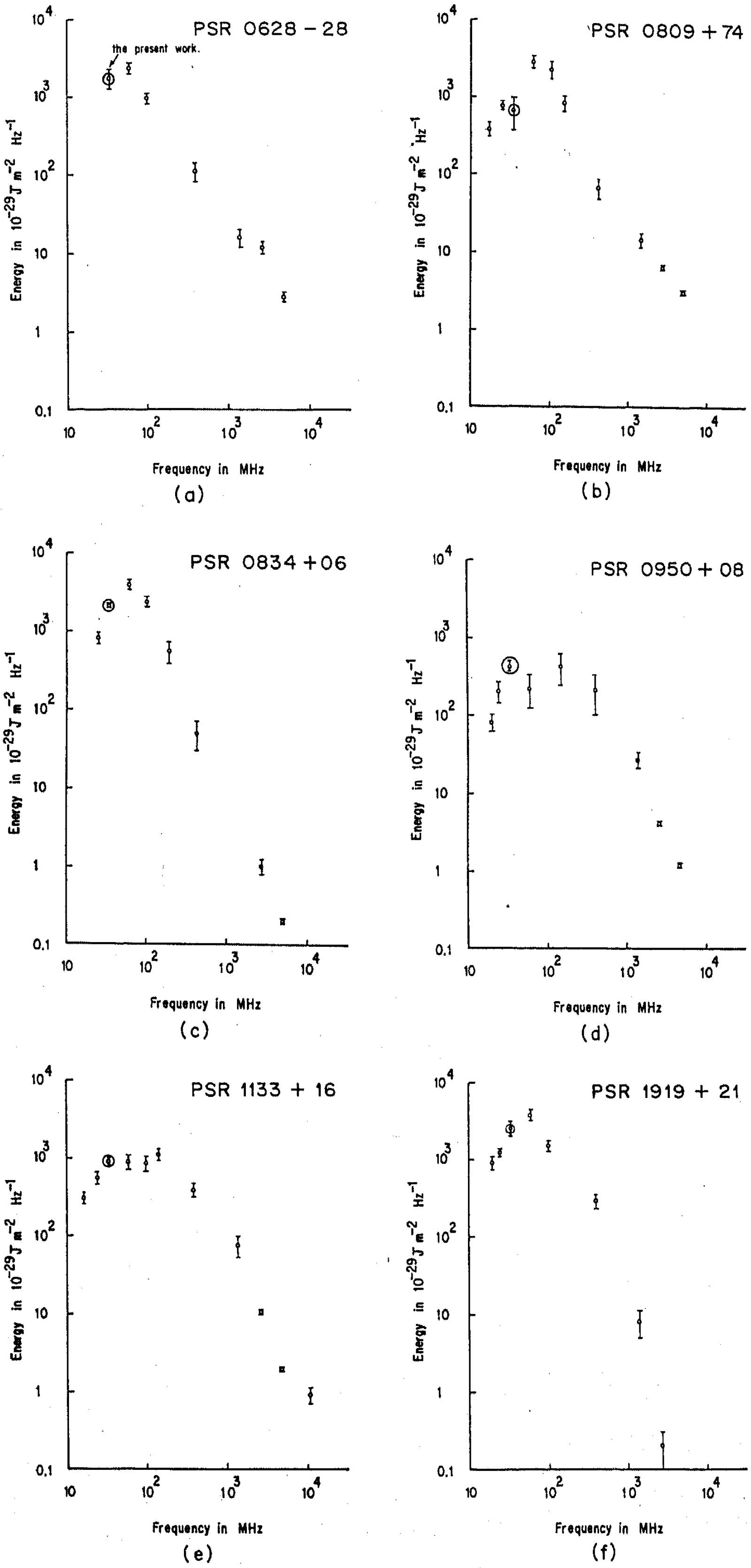

Figure 4. The average pulse energy spectra of (a): PSR 0628 − 28; (b): PSR 0809 + 74; (c): PSR 0834 + 06; (d): PSR 0950 + 08; (e): PSR 1133 + 16 and (f): PSR 1919 + 21 over the radio-frequency range. The points indicated by an extra circle correspond to the present measurements.

vi) PSR 0950 + 08 This has the smallest dispersion measure among known pulsars. Due to its short period, it was possible to average a large number of pulses leading to better sensitivity. Fig. 3e shows a profile averaged over 54000 pulses using the data obtained on six days. The longitude resolution in this case is not adequate to see finer details in the pulse. Our estimate of the average energy per pulse when compared with other observations (Bruck *et al.* 1978) appears to suggest that the estimate at 61 MHz (Kuzmin *et al.* 1978) may be in considerable error (see Fig. 4d).

vii) PSR 1133 + 16 Fig. 3f shows an average profile for PSR 1133 + 16 at 34.5 MHz. The observations were made on 8 days. The two components which have been observed at and above 61 MHz (e.g. Taylor and Huguenin 1971; Izvekova *et al.* 1979; Slee *et al.* 1986) are just distinguishable in this profile. However, a predicted profile (see equation A.5) assuming a single component in the intrinsic pulse could not give a good fit to the observed profile for the estimation of the scattering width. Therefore, the intrinsic pulse is assumed to have two components of width 12 msec each with a separation of 45 msec. The widths and the separation of the components at 61 MHz are used after $(\text{wavelength})^{0.25}$ scaling. With this assumption, it is possible to obtain a very good fit to the observed profile, provided a component intensity ratio of 0.6:1 is used. It should be pointed out that in the frequency range 80 to 102 MHz (Slee *et al.* 1987; Izvekova *et al.* 1979) this intensity ratio is about unity, and is greater than unity at 400 MHz (Manchester 1971). The energy spectrum is shown in Fig. 4e.

viii) PSR 1919 + 21 We estimate the average pulse energy to be $(2560 \pm 400) \times 10^{-29}\,\text{Jm}^{-2}\text{Hz}^{-1}$. This estimate is obtained from observations made using a 16 frequency channel analog receiver (Deshpande, Sastry & Radhakrishnan 1984). Fig. 4f shows our estimate with those at other frequencies (Bruck *et al.* 1978) on an energy vs. frequency plot.

b) Decametric emission outside the main pulse window

One of the main motivations for the present observations was to look for low-frequency interpulse emission as reported by Bruck & Ustimenko (1976, 1977, 1979). None of the 8 pulsars show any significant interpulse emission at our frequency. Owing to the high signal-to-noise ratio in the case of 4 pulsars, we can obtain useful upper-limits for the emission, if any, outside the main-pulse window. The 3σ limits obtained are: 2% of the main pulse energy for PSR 0834 + 06, 6% for PSR 0950 + 08, 3.5% for PSR 1133 + 16 and 6% for PSR 0943 + 10 (Deshpande & Radhakrishnan 1990). Here we have assumed the width of any such feature outside the main-pulse window to be the same as that of the main pulse. Unless the spectrum of such emission is much steeper than that of the main pulse, these observations conflict with the results reported by Bruck and Ustimenko. Recent 25 MHz observations at Arecibo (Phillips & Wolszczan 1989) have also not detected any significant interpulse emission.

c) Short and long term variations

The prime objective of this work was to study average profiles for as many pulsars as possible and to estimate the above mentioned average parameters. However, it was also thought useful to study the fluctuation spectra and low-frequency variability of pulsar signals using the data obtained during these observations.

4.1 *Fluctuation Spectra*

The time-resolution obtainable in our case is adequate to attempt to study intrinsic subpulse and average profile fluctuations by obtaining suitable power spectra of the modulation function. Such fluctuation spectra can reveal the drifting nature of the subpulses and fluctuations of the pulse energy including the effects of pulse nulling (Drake & Craft 1968; Backer 1970). In general, the observed power spectra have contributions due to the fluctuations caused by the intervening medium. The observed spectrum is a convolution of the spectrum of the intensity modulations due to the invervening medium with the intrinsic modulation spectrum of the pulsar. Thus, any narrow spectral features due to the intrinsic modulation will in general be smeared due to the scintillation in the intervening medium. However, as the scintillations due to the interstellar medium have a very small decorrelation bandwidth at our frequency compared to the observing bandwidth, they will be effectively smoothed out. The interplanetary and the ionospheric scintillations, however, may affect the spectrum significantly.

The data obtained on some strong pulsars from the observations reported here were analysed using 'the longitude-resolved Fourier analysis' method first applied to the study of drifting subpulses by Backer (1970). In this method, the observed intensities as a function of time at each fixed longitude are Fourier transformed separately. We have chosen the width of the longitude bins, within which the data are averaged, to be about 2 per cent of the period. A sequence of samples for a fixed longitude is Fourier transformed in blocks of 256 samples and the amplitude spectra for many blocks are averaged. Such spectra suffer heavily from aliasing effects because at a given longitude only one sample per period can be available.

Fig. 5 shows the fluctuation spectra at different longitudes obtained for PSR 0834 + 06. The values at zero frequency as a function of longitude correspond to the average pulse profile. Such analyses were repeated for this pulsar on different days. At high radio frequencies, the fluctuation spectra for this pulsar show a narrow line feature indicating strong periodic modulation at about 0.46 cycles/period (Taylor & Huguenin 1971). However, our spectra for longitudes within the pulse window do not show any significant deviation from those for longitudes outside the pulse window. Our observations suggest that any periodic modulation which can result in a narrow line feature must be weak at 34.5 MHz and that the depth of modulation does not exceed 6 per cent, when it would have been seen above the noise. It is possible that there is strong

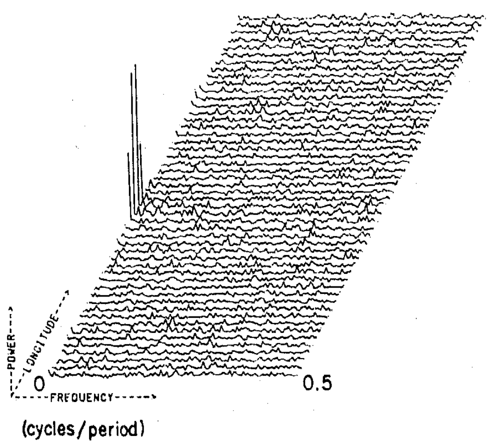

Figure 5. The fluctuation spectra at different longitudes for PSR 0834 + 06 at 34.5 MHz.

modulation, but then its contribution must be spread over a broad region in the spectrum

4.2 *Slow Variability*

Slow variability of the apparent intensity of pulsars has been extensively studied at high radio-frequencies (e.g. Huguenin, Taylor & Helfand 1973). These variations have time scales in a wide range. The slow variability is generally attributed to the refractive scintillations produced by large scale irregularities in the electron density in the interstellar medium (Goodman & Narayan 1985). No measurement of such variability at decametric wavelengths has been reported so far in the literature.

We have made some attempts to make such measurements using the observations discussed above. We have selected three strong pulsars (PSRs 0834 + 06, 0950 + 08 and 1133 + 16) and have made observations over a span of about 80 days. The calibrated pulse energies obtained from these observations have been used to compute a modulation index, *m*, defined as

$$m = \frac{\left[\frac{1}{N_{\text{obs}}} \sum^{N_{\text{obs}}} (S_i - \bar{S})^2\right]^{\frac{1}{2}}}{\bar{S}} \quad (2)$$

where $\bar{S}$ = average of S_i, S_i = the pulsar intensity in *i*th measurement, and N_{obs} = the total number of such measurements (about 10 in the present case). The computed modulation indices in two of the three cases did not indicate any modulation significantly above the standard deviations in calibration. Only in the case of PSR 0950 + 08 do we find significant modulation. The estimated value of *m*, in this case, is 0.34 ± 0.15. This value is in good agreement with similar estimates by Slee *et al.* (1986) at 80 and 160 MHz. The large error in the above estimate is mainly attributable to the calibration errors. The apparent non-detection of any significant variability in the other two cases may be understood as an effect of the short observing time (81 days) compared to the characteristic time scales of such intensity variations at our frequency (Deshpande & Nityananda 1990). Further observations over longer time spans can be undertaken for detailed investigation.

d) Scatter broadening

As can be seen from Table 1, our estimates of the scatter broadening at 34.5 MHz have large error bars. However, these estimates (within their errors) are in general agreement with similar estimates at higher frequencies (Alurkar *et al.* 1986). A more quantitative comparison of these estimates suggests that the wavelength dependence of the scatter broadening is steeper than (wavelength)^4.

5. Summary

We have reported here our observations of 8 pulsars at a low frequency by employing the method described in this paper. The profiles obtained from the present observations are affected mainly by dispersion smearing over the 30 kHz band and fail to show the pulse structure in detail. Subsequently, to obtain high resolution pulse profiles we have made observations employing the swept-frequency dedispersion method (Deshpande 1987; Deshpande & Radhakrishnan 1990). Details of these latter observations will be reported separately. Our estimates of the pulse energies in 5 cases do confirm the low frequency turnovers already known from other observations. Out of the 3 new detections by us at 34.5 MHz, only in one case (PSR 0943 + 10) does the spectrum not appear to have a turnover down to 34.5 MHz. Such a spectrum can be of great interest if this trend continues at even lower frequencies.

Regarding the interpulse emission, we notice no significant emission beyond the main pulse window in those cases where significant interpulse emission was reported at 25 MHz.

Our attempts to study fluctuation spectra and slow variability of pulsars have shown that such studies at decametric wavelengths are feasible and can be very valuable if pursued in future.

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APPENDIX

The procedure used for optimal combination of the pulse profiles from COS and the SIN correlation outputs.

In the present case, the COS and the SIN channel outputs ($A_c(t)$ and $A_s(t)$) can be written as

$$A_c(t) = gA_o(t)\cos\left(\frac{\pi\Delta\theta}{\theta_0}\right) \qquad \text{(A.1a)}$$

$$A_s(t) = gA_o(t)\sin\left(\frac{\pi\Delta\theta}{\theta_0}\right) \qquad \text{(A.1b)}$$

where $g =$ the gain factor due to collimation error $= \text{sinc}(\Delta\theta/\theta_0)$; $\theta_0 =$ separation between the peak and the first null of the S arm beam in N–S direction; $\Delta\theta =$ effective collimation error in N–S direction; and $A_o(t) =$ the COS channel output when $\Delta\theta = 0$.

$A_o(t)$, the main function of interest, can be obtained from $A_c(t)$ and $A_s(t)$ by using the equations (1a, b) as

$$A_o(t) = \frac{1}{g}[A_c^2(t) + A_s^2(t)]^{\frac{1}{2}} \qquad \text{(A.2)}$$

The factor g can be estimated using the value of $\Delta\theta$ obtainable as

$$\Delta\theta = \frac{1}{\pi}\tan^{-1}\left[\frac{A_s(t)}{A_c(t)}\right]\cdot\theta_0 \quad \text{for } A_o(t) \neq 0 \qquad \text{(A.3)}$$

However, in a practical situation, i.e. in the presence of noise, the signal-to-noise ratio obtainable for $A_o(t)$ is worsened further, if the above procedure is used (Deshpande 1987). Hence, we have employed a new scheme to estimate $A_o(t)$ from the COS and SIN channel outputs in an optimum way.

In this scheme, the channel with better signal-to-noise ratio is selected first. As most of the times such a channel corresponds to the COS correlation, for further discussion, we will assume this channel to be the COS channel ($A_c(t)$ such that $0 \leqslant t < P$ where P is the pulsar period). A best fit pulse profile is obtained for this channel data. The best fit profile ($F_1(t)$) takes into account the intrinsic pulse width, dispersion smearing, the receiver time-constant and gives estimates for the pulse amplitude (Amp_1) and the amount of the interstellar scatter broadening (τ_s). The best fit profile can be written as

$$F_1(t) = \mathrm{Amp}_1 \cdot G(t) \quad \text{(A.4)}$$

and

$$G(t) = i(t) * s(t) * d(t) * r(t) \quad \text{(A.5)}$$

where $i(t)$ = a Gaussian to represent the intrinsic pulse profile; $s(t)$ = a truncated exponential, with τ_s as the characteristic width representing the scattering in the interstellar medium; $d(t)$ = the receiver bandpass converted into time function by the dispersion law; $r(t)$ = the impulse response of the post-detection filter; and $*$ denotes convolution.

The equivalent width of the Gaussian pulse in $i(t)$ is obtained using the pulse width at 400 MHz (Manchester & Taylor 1981) and assuming that the pulse width is $\propto$ (frequency)$^{-0.25}$. The best fit function, $G(t)$, is then used to estimate the best-fit-pulse-amplitude (Amp_2) for the other channel output $A_s(t)$ as,

$$\mathrm{Amp}_2 = \frac{\int A_s(t)\,\mathrm{d}t}{\int A_s(t) \cdot G(t)\,\mathrm{d}t} \quad \text{(A.6)}$$

The effective collimation error $\Delta\theta$ is then estimated as

$$\Delta\theta = [\tan^{-1}(\mathrm{Amp}_2/\mathrm{Amp}_1)] \cdot \theta_0/\pi \quad \text{(A.7)}$$

Now, it is possible to obtain two independent estimates (say $A_{o1}(t)$ and $A_{o2}(t)$) of $A_o(t)$, as follows

$$A_{o1}(t) = Y \cdot A_c(t)/\mathrm{Amp}_1 \quad \text{(A.8a)}$$

and

$$A_{o2}(t) = Y \cdot A_s(t)/\mathrm{Amp}_2 \quad \text{(A.8b)}$$

where

$$Y = (\mathrm{Amp}_1^2 + \mathrm{Amp}_2^2)^{\frac{1}{2}}/g \quad \text{(A.9)}$$

The r.m.s. noise deviations (σ_1, σ_2) in the profiles $A_{o1}(t)$ and $A_{o2}(t)$ respectively are given by

$$\sigma_1 = \sigma Y/\mathrm{Amp}_1 \quad \text{(A.10a)}$$

$$\sigma_2 = \sigma Y/\mathrm{Amp}_2 \quad \text{(A.10b)}$$

where σ = r.m.s. noise deviation in the profile $A_c(t)$, $A_s(t)$.

It should be noted that the errors in the determination of Amp_1 and Amp_2 are much smaller than σ and are therefore ignored here. The two independent estimates, $A_{o1}(t)$ and $A_{o2}(t)$, are combined with suitable weights, to obtain the best possible estimate of $A_o(t)$. The optimum weight is proportional to the inverse of the noise power in the estimate.

It can be shown that, the r.m.s. of the noise, σ_o, for the profile $A_o(t)$ is given by $\sigma_o = \sigma/g$ and the corresponding signal-to-noise ratio is given by

$$(S/N)_{A_o} = (S/N)_{A_c}[1 + (\text{Amp}_2/\text{Amp}_1)^2]^{\frac{1}{2}}$$
$$= (S/N)_{A_s}[1 + (\text{Amp}_1/\text{Amp}_2)^2]^{\frac{1}{2}} \quad \text{(A.11)}$$

where $(S/N)_i$ refers to the signal-to-noise ratio for the profile $A_i(t)$.

Thus, by using the above procedure, it is possible to partially recover the loss in signal-to-noise ratio in the COS channel due to collimation errors.

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