MULTI RADIO FREQUENCY OBSERVATIONS OF PULSARS

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1. INTRODUCTION

An investigation of the frequency dependence of the radio emission of pulsars promises to contribute considerably to the understanding of such outstanding questions as:

1. Is the emission mechanism narrowband or broadband?
2. What is the coherence time of the radiation?
3. Does a radius-to-frequency mapping exist?
4. Is pulsed radiation absorbed in the magnetosphere?

The 100-m telescope in Effelsberg is satisfactorily sensitive in the GHz frequency range so that we could observe averaged pulses up to 22.7 GHz (Bartel et al., 1977; Bartel et al., 1978) and single pulses at 8.8 GHz (Bartel et al., 1980a), which are the highest radio frequencies respectively at which pulsars have been detected. Therefore quite naturally the analysis of the frequency dependent pulsar emission became one of the focal points of interest in pulsar research at the MPIfR.

It is the purpose of this paper to present results, which we obtained partly in collaboration with other institutes, and to indicate their influence on the solution of the above mentioned questions.

2. SINGLE PULSE SPECTRA AND THE CORRELATION BETWEEN ENERGIES AT DIFFERENT FREQUENCIES

Simultaneous triple-frequency single pulse observations have been performed at Arecibo (111.5, 430 MHz), Jodrell Bank (408, 1420 MHz) and Effelsberg (2695 MHz) between 1976 and 1977 (Hankins et al., 1981). In all cases the Stokes parameter I was recorded. Figure 1 shows an example of single pulse spectra between 0.43, 1.42 and 2.7 GHz for PSR 0823+26.

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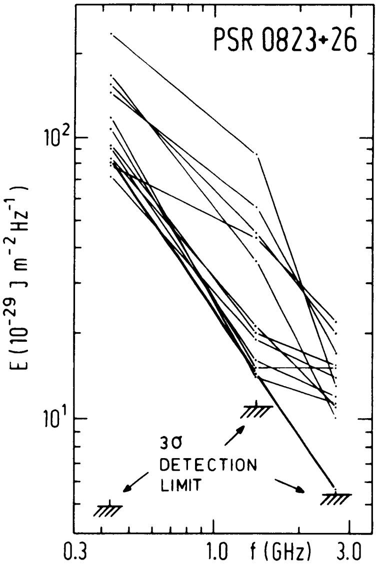

Figure 1:
Single pulse spectra for PSR 0823+26. Energies of 12 out of 28 adjacent single pulses are plotted, which exceed the 3σ detection limit at all three frequencies. The average spectrum of 443 single pulses is given as a thicker line.

Single pulse spectra are moderately scattered around the mean and roughly resemble average spectra over time intervals of days in the degree of variation (Kuzmin et al., 1978). This indicates that mean single pulse energies are correlated over wide frequency ranges. To investigate this behaviour in more detail we calculated crosscorrelation functions between ∿ 100 or more mean single pulse energies at two frequencies. The functions always peak at zero-period lag after the pulse arrival times have been corrected for the dispersion delay due to the interstellar medium. Hence movements of the radiating sources along the line of sight with a velocity v_g over a distance d, which might lead to a time delay of the onset of the intensity outburst between the two frequencies, were always smaller than the time resolution of the crosscorrelation function, which is the pulsar period P_1, so that

$$d\,\frac{(1-\beta)}{v_g} < P_1 \;, \quad \beta = \frac{v_g}{c}$$

The zero-lag crosscorrelation coefficients are given for a number of pulsars in dependence of the frequency ratio f_1/f_2 in Figure 2. All these pulsars exhibit significantly correlated energy variations over the indicated frequency range. An especially interesting example is PSR 0823+26 which was observed three times at three different frequencies simultaneously (Hankins et al., 1981). An only marginal loss in correlation could be detected for frequency ratios up to 6:1. For PSR 1133+16 we even find the same correlation over a 275-415 MHz range and a 327-2695 MHz range, however these two data points were not obtained simultaneously. For even wider frequency intervals the correlation however decreases significantly.

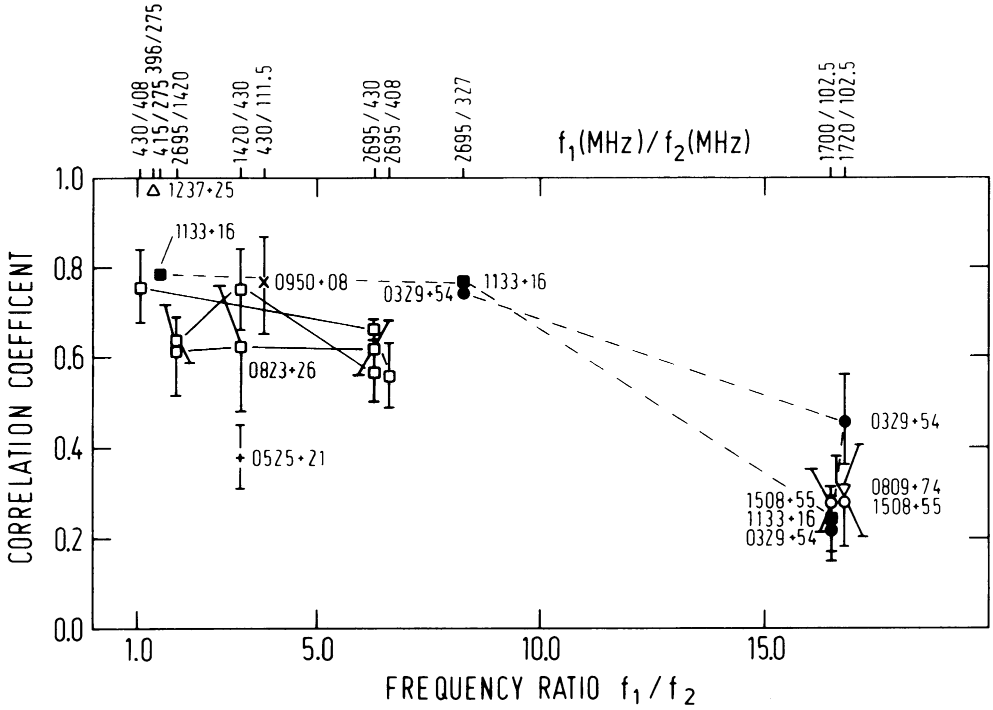

Figure 2: Correlation coefficients between mean single pulse energies at frequencies f_1, f_2. Data for frequency ratios f_1(MHz)/f_2(MHz) are referenced to: (275/396, 275/415) (Taylor et al., 1975); (430/408, 2695/1420, 1420/430, 430/111.5, 2695/430, 2695/408) (Hankins et al., 1981); (2695/327) (Bartel and Sieber, 1978); (1700/102.5) (Popov et al., 1981); (1720/102.5) (Bartel et al., 1980c). The simultaneous triple-frequency observation data are connected by solid lines. All data with the possible exception of those at 275/396 and 275/415 are noise corrected. Linear polarization only was recorded at 102.5 and 327 MHz. $\pm 1\sigma$ error bars are indicated.

This analysis reveals that pulsars in general fluctuate in mean single pulse energies correlatedly over a large portion of the whole radio spectrum. This result favours a broadband emission mechanism but can also be explained by narrowband emitters if they retain their identity long enough when they travel from low to high altitudes and radiate at increasingly lower frequencies (Buschauer and Benford, 1980).

3. A COMPARATIVE ANALYSIS OF AVERAGE PULSE AND SINGLE PULSE FREQUENCY BEHAVIOUR

Frequency dependent properties of average pulses have been extensively studied (Sieber, 1973; Sieber et al., 1975; Backer, 1976; Izvekova et al., 1979; Bartel et al., 1980a). Pulsars have in general steep spectra from ∿ 0.1 GHz onwards and exhibit in some cases (∿ 25%) a break after which the spectrum steepens even more (Sieber, 1973). This critical frequency appears around 1 GHz and correlates with the discontinuity found for the pulse component separation (Sieber et al., 1975). In general the separation of components ΔS in an average profile becomes narrower with frequency approximately according to $\Delta S \propto f^{-0.25}$, at least up to ∿ 1 GHz from where onwards the separation stays constant or even increases (Sieber et al., 1975). The behaviour at $f < 1$ GHz is in agreement with models in which radiation at different frequencies is emitted at different radii from the star (Komesaroff, 1970; Tademaru, 1971; Ruderman and Sutherland, 1975; Cheng and Ruderman, 1980). The widths of individual components also follow the general trend to narrow with increasing frequency, and even exhibit in some cases a break in their frequency behaviour (Sieber et al., 1975; Backer, 1976; Bartel, 1978; Bartel et al., 1980a).

Typical subpulse widths of single pulses, calculated from autocorrelation functions, strongly correlate (97%) with the width of components in the average pulse profile (Bartel et al., 1980a), so that they are expected to exhibit a very similar frequency behaviour. In the cases analyzed this has been confirmed (Bartel et al., 1980a). A pronounced frequency dependence was also found for the degree of pulse to pulse fluctuation. This is measured by the modulation index m defined as the standard deviation σ of a number of single pulse energies around the total mean $<E>$ in its noise corrected form

$$m = \frac{(\sigma_{on}^2 - \sigma_{off}^2)^{1/2}}{<E_{on}> - <E_{off}>} ,$$

where the indices on, off denote the parameters measured in the on-pulse and the off-pulse window, respectively. In general single pulse energies are extensively modulated at low frequencies (Taylor and Huguenin, 1971; Bartel et al., 1980b). The modulation index decreases with increasing frequency according to $m \propto f^{-0.4\pm0.3}$ and increases again according to $m \propto f^{0.6\pm0.2}$ for 5 pulsars which were observable at sufficiently high frequencies, thus establishing a break at which the pulse to pulse fluctuation behaviour changes drastically. This break occurs around 1 GHz and coincides with the critical frequencies of the pulse energy spectrum and/or the component separation within the estimated errors (Bartel et al., 1980b). As an example all the referred parameters are given for PSR 1133+16 in Figure 3.

The break in the curves may indicate the frequency from where onwards the coherent amplification mechanism is no longer dominant (Backer and Fisher, 1974; Sieber et al., 1975; Bartel et al., 1980b). In the low frequency region all the pulses are steadily coherently amplified, so that strong fluctuation is expected. Coherence, however, becomes increasingly difficult to maintain towards smaller wavelengths.

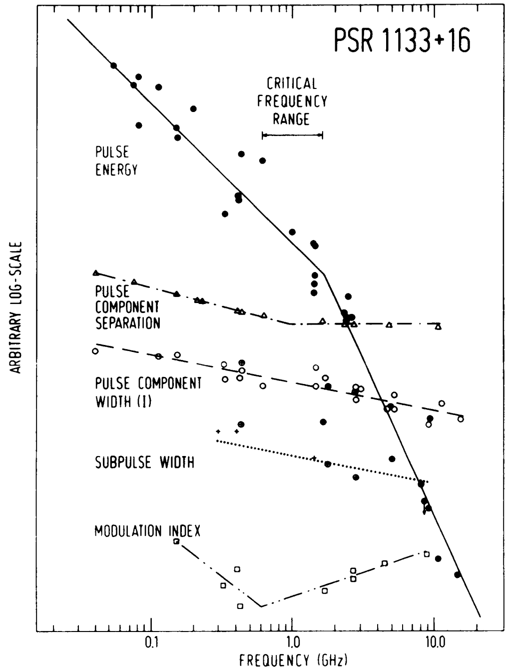

Figure 3:
The frequency behaviour of PSR 1133+16. The above 3 curves denote properties of the average pulse, whereas the 2 curves below are stationary single pulse properties. Data are from: pulse energy ● (Sieber, 1973), pulse component separation Δ (Sieber et al., 1975), pulse width of 1. component O ⊕ (Bartel et al., 1980a), subpulse width + ⊕ (Bartel et al., 1980a), modulation index (Bartel et al., 1980b). Subpulse widths ⊕ and component widths (I) ⊕ were computed for the same pulses.

Pulses at higher frequencies than ∿ 1 GHz suffer significantly from sporadic breakdowns of the coherent amplification mechanism. The pulse energy spectrum then steepens, single pulses are increasingly stronger modulated, and the component separation becomes independent of frequency, since a defined radius-to-frequency mapping may no longer exist. The critical frequency may then imply a coherence time of ∿ 1 ns for the radiation (Cordes, 1979).

4. THE FREQUENCY DEPENDENT BEHAVIOUR OF PSR 0809+74

Most intriguing results on PSR 0809+74 were previously obtained from simultaneous single pulse observations at 102.5 and 1720 MHz in Pushchino and Effelsberg respectively (Bartel et al., 1980c). The results strongly support (i) the assumption that a radius-to-frequency mapping exists and (ii) that longitudinally dependent absorption of pulsed radiation occurs within the pulsar magnetosphere.

Figure 4a,b shows 170 adjacent single pulse intensities, disposed in a grey tone plot. Nulling occurs simultaneously over many periods at both frequencies. Microstructure features with a typical timescale of 1.5 ms are present at 0.1 GHz but not observed at 1.7 GHz. Drifting subpulses exist at both frequencies, they are however much more pronounced at the low frequency. But as the repetition period of the driftbands for increasing pulse numbers is with $P_3 = 11.1\ P_1$ the same

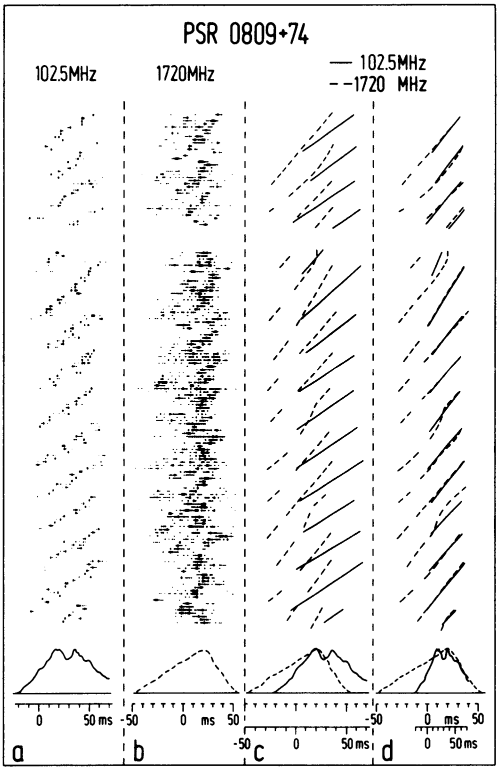

Figure 4:
170 adjacent single pulses, with pulse numbers running from top to bottom, are displayed for two frequencies in a grey tone plot. Nulling is indicated by the missing pulses in the upper half of the figure. The drifting subpulse structure in parts a and b is approximated by pencil lines in parts c and d. The integrated profiles from 467 single pulses are given at the bottom. Pulse arrival times are corrected for the interstellar dispersion delay. Please not that the scale for the 102.5 MHz data is contracted around the longitudinal point at 0 ms by a factor P_2(102.5 MHz)/P_2(1720 MHz) = 1.81 so that the driftbands run parallel and overlap. (From Bartel et al., 1980c)

over the broad frequency range (Wolszczan et al., 1981), the subpulse separation P_2 and thus also the drift velocity changes according to $\sim f^{-0.23}$ (Bartel et al., 1980a). Furthermore, the intensity variation of the drifting subpulses alone is correlated over the frequency range, implying that physically related emitters are observed at both frequencies, though they appear at differently varying longitudes. This result is strong evidence for a radius-to-frequency mapping in the pulsar magnetosphere.

Pulse arrival time measurements show that, after having been corrected for the well-known dispersion delay due to the interstellar medium (Lyne and Rickett, 1968), the profiles do not align (Fig. 4c). An analysis of the one-to-one subpulse correspondence at both frequencies indicates a fiducial point at 0 ms (in Fig. 4) which occurs approximately at the longitude where at 1.7 GHz drifting is interrupted and exhibits a phase jump (Wolszczan et al., 1981), linear polarization drops to zero, and circular polarization reaches its maximum (Morris et al., 1981). At 0.1 GHz the fiducial point occurs almost outside the pulse window, indicating that the whole leading 1.7 GHz pulse profile has no analogy at the low frequency. Only the trailing part can be properly mapped over the broad frequency range, while the leading part is "missing" at 0.1 GHz.

To investigate the frequency range over which the "missing" radiation can be expected, the subpulse separation P_2 is compared with the average pulse profile width $t_{1/2}$ (FWHM) in Figure 5 (Bartel, 1980).

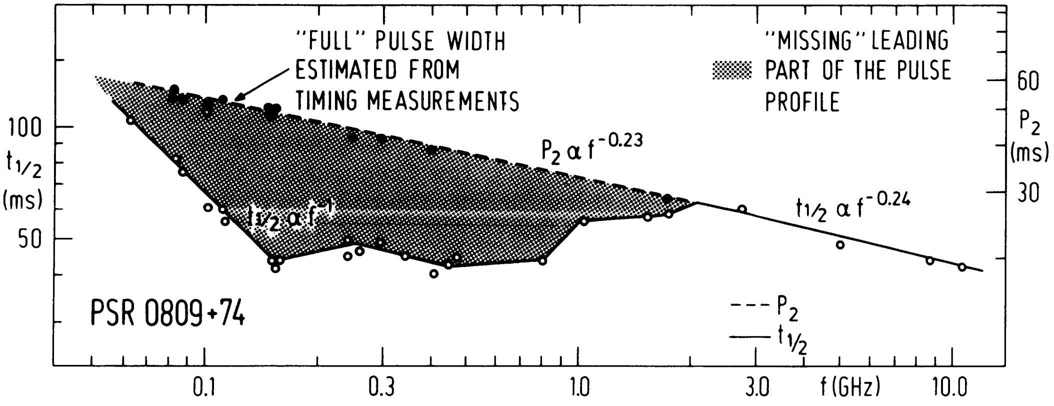

Figure 5: The average pulse profile width (FWHM) $t_{1/2}$ (o) and the longitudinally averaged subpulse separation P_2 (●) versus frequency for PSR 0809+74. Please note that P_2 refers to a different scale than $t_{1/2}$. Data are taken from Bartel (1980) and references therein.

$t_{1/2}$ obeys a $f^{-0.24}$ law at high frequencies but is smaller at lower frequencies, whereas P_2 obeys the same law from 60 to 1720 MHz. Apart from a relative scaling offset P_2 fits the 0.1 GHz "full" profile width, estimated from the differential timing measurements, quite well. This indicates that $t_{1/2}$ in the high frequency range and the shifted P_2 reflects the frequency dependence of the pulsar emission cone. Thus it can be expected that emission in the leading part of the pulse profile is "missing" not only at 0.1 GHz but from ∿ 2 GHz down to ∿ 0.05 GHz.

This phenomenon can be interpreted as being due to cyclotron absorption at a frequency $f_{9,abs}$

$$f_{9,abs} = 0.56 \, B_3 \, \gamma_3^{-1} \, \Theta_{-1}^{-2} \, [\mathrm{GHz}], \quad \gamma^{-1} << \Theta << 1$$

with B_3 as the magnetic field strength in kG, γ_3 as the Lorentz factor in units of 10^3 and Θ_{-1} as the angle between magnetic field lines and the direction of wave propagation in units of 10^{-1} rad. A magnetic field strength $B \sim 10^3$ G, at which absorption can occur at 560 MHz, is expected at a radius of only 13% of the light cylinder radius. Here a dipolar field and a field strength $B_s \sim 4.6 \; 10^{11}$ G (Taylor and Manchester, 1975) at the surface $r_s \sim 10^6$ cm of the star is assumed.

As pointed out by Blandford and Scharlemann (1976), cyclotron absorption has to be considered as a very fundamental process in pulsar magnetospheres. They concluded that within the Ruderman and Sutherland (1975) model the optical depth to cyclotron absorption τ_c is so large that it is hard to understand why pulsar radiation can be detected at all. To avoid this problem they assumed a non-uniform particle density distribution, so that $\tau_c << 1$ for particular ray paths.

The absorption profile for PSR 0809+74 (Fig. 5) can be understood by assuming a longitudinally and radially dependent density distribution of equal numbers of positrons and electrons in a distance of $r \sim 10^9$ cm from the star. Then the magnetosphere might be transparent at high frequencies $f > 2$ GHz and also at very low frequencies $f < 50$ MHz, whereas it is opaque for radiation in the leading part of the pulse profile at intermediate frequencies.

REFERENCES

Backer, D.C.: 1976, Astrophys. J. 209, p. 895.
Backer, D.C. and Fisher, J.R.: 1974, Astrophys. J. 189, p. 137.
Bartel, N.: 1978, Ph.D. Thesis, Bonn University.
Bartel, N.: 1980, Astron. Astrophys., in press.
Bartel, N. and Sieber, W.: 1978, Astron. Astrophys. 70, p. 307.
Bartel, N., Sieber, W., and Wielebinski, R.: 1977, Astron. Astrophys. 55, p. 319.
Bartel, N., Sieber, W., and Wielebinski, R.: 1978, Astron. Astrophys. 68, p. 361.
Bartel, N., Sieber, W., and Graham, D.A.: 1980a, Astron. Astrophys. 87, p. 282.
Bartel, N., Sieber, W., and Wolszczan, A.: 1980b, Astron. Astrophys., in press.
Bartel, N., Kardashev, N.S., Kuzmin, A.D., Nikolaev, N.Ya., Popov, M.V., Sieber, W., Smirnova, T.V., Soglasnov, V.A., and Wielebinski, R.: 1980c, Astron. Astrophys., in press.
Blandford, R.D. and Scharlemann, E.T.: 1976, Mon. Not. R. Astr. Soc. 174, p. 59.
Buschauer, R. and Benford, G.: 1980, Mon. Not. R. Astr. Soc. 190, p. 945.
Cheng, A.F. and Ruderman, M.A.: 1980, Astrophys. J. 235, p. 576.
Cordes, J.M.: 1979, Space Sci. Rev. 24, p. 567 (Reidel Publ. Co., Dordrecht, Holland and Boston, USA).
Hankins, T.H., Sieber, W., Bartel, N., Lyne, A.G., Ritchings, R.T., and Cooke, P.: 1981, in preparation.
Izvekova, V.A., Kuzmin, A.D., Malofeev, V.M., and Shitov, Yu.P.: 1979, Astron. Zh. 56, p. 322; transl.: Soviet Astron. 23, p. 179.
Komesaroff, M.M.: 1970, Nature 225, p. 612.
Kuzmin, A.D., Malofeev, V.M., Shitov, Yu.P., Davies, J.G., Lyne, A.G., and Rowson, B.: 1978, Mon. Not. R. Astr. Soc. 185, p. 441.
Lyne, A.G. and Rickett, B.J.: 1968, Nature 218, p. 326.
Morris, D., Graham, D.A., Sieber, W., Bartel, N., and Thomasson, P.: 1981, Astron. Astrophys. Suppl., submitted.

Popov, M.V., Bartel, N., Kardashev, N.S., Kuzmin, A.D., Nikolaev, N.Ya., Sieber, W., Smirnova, T.V., Soglasnov, V.A., and Wielebinski, R.: 1981, in preparation.
Ruderman, M.A. and Sutherland, P.G.: 1975, Astrophys. J. 196, p. 51.
Sieber, W.: 1973, Astron. Astrophys. 28, p. 237.
Sieber, W., Reinecke, R., and Wielebinski, R.: 1975, Astron. Astrophys. 38, p. 169.
Tademaru, E.: 1971, Astrophys. Space Sci. 12, p. 192.
Taylor, J.H. and Huguenin, G.R.: 1971, Astrophys. J. 167, p. 273.
Taylor, J.H. and Manchester, R.N.: 1975, Astron. J. 80, p. 794.
Taylor, J.H., Manchester, R.N., and Huguenin, G.R.: 1975, Astrophys. J. 195, p. 513.
Wolszczan, A., Bartel, N., and Sieber, W.: 1981, Astron. Astrophys., submitted.

DISCUSSION

RICKETT: How did you correct the pulse energies for the effects of interstellar scintillation — to deduce that the spectral index is varying?

BARTEL: The pulses shown were recorded within about 20 s. The fading time of interstellar scintillation is for PSR 0823+26 at 430 MHz however on the order of 15 min.

HANKINS: Could the missing part of the emission from PSR 0809+74 at 102.5 MHz be an effect of having observed with linear polarization?

BARTEL: No, PSR 0809+74 is only about 10% linearly polarized at 102.5 MHz.

MANCHESTER: What determination of dispersion measure was used to align the 1720/102.5 MHz simultaneous observations for PSR 0809+74? Is not your measurement the most accurate available?

BARTEL: We used DM = 5.77 ± 0.03 from Lyne and Rickett (1968). They measured pulse arrival times at 151, 408 and 630 MHz and did not find any deviation from the f^{-2}-cold plasma dispersion relation greater than the error quoted, which is a good reason to take their value seriously. If we determined a dispersion measure by simply taking the center of the profiles at 102.5 and 1720 MHz as fiducial points, then our value exceeds their error considerably. So we shifted the profiles according to their dispersion measure.

Independently from timing measurements the proper alignment of the pulse profiles was also obtained by correlating the driftbands at both frequencies.