A novel technique for estimating pulsar dispersion measures

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1. Introduction

The radio signals from a pulsar suffer dispersion as they travel through the ionized interstellar medium (ISM), resulting in a frequency dependent arrival time of the pulses. The effect is quantified by the pulsar's dispersion measure (DM), defined as the integral of the electron column density along the line of sight of the pulsar. The relative time delay between the pulse arrival time at two frequencies, Δt, can be expressed as,

$$\Delta t \quad = \quad K \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) DM \quad , \tag{1}$$

where $K = \frac{1}{2.410331 \times 10^{-4}}$ MHz^2 cm^3 s/pc [2]. Here Δt is in units of second for f_1 and f_2 in MHz and DM in the units of pc/cm^3. The DM of a pulsar is a basic parameter, and its value needs to be known with sufficient accuracy for proper dispersion correction to be carried out on the received signal, to probe the pulsar emission geometry [6], for probing the spectrum of electron density fluctuations in the ISM [2], etc.

Here we describe a novel technique for accurate estimation of pulsar DMs, using the Giant Metre-wave Radio Telescope (GMRT) in a simultaneous multi-frequency pulsar observation mode. The DM is estimated by measuring the relative time delay in arrival of signals at simultaneous dual frequencies using Equation 1. The subsequent sections describe the details of the observation strategy, data reduction, DM estimation technique, main results, and simulations carried out.

2. Observation Strategy

The accuracy of the DM estimate depends on the precision of the estimation of the relative time delay, Δt, between the pulse profiles at two frequencies. For a given value of RMS of time delay (limited by the S/N of the data, and the coarseness of the sampling interval), greater the Δt, the more accurate is the DM estimate. This would favour large separations between the two observing radio bands. The pulsar profile evolution with frequency favours a smaller separation between the two radio wave-bands. Also, according to Equation 1, for a given separation between a pair of radio bands, smaller values of frequencies give a larger value of estimated Δt, and in turn, more accurate DM estimation. The final two frequency bands of operations were decided by these considerations.

The GMRT is comprised of 30 antennas, distributed over a region of 25 km diameter [7], which can be configured as a "single dish" in the incoherent or coherent array mode [4]. The GMRT operates at radio frequency bands – 150, 235, 325, 610 and 1400 MHz. The antennas can be grouped into several sub-arrays and each sub-array can independently be operated at a radio band of interest. Because of these unique feature of the GMRT, this novel novel of DM estimation was carried out. To avoid the overlapping of on-pulses at two simultaneous frequency bands of observations, we selected the suitable frequency bands mostly out of 235, 325 and 610 MHz. Signals from different observing frequency bands and antennas are down-converted to baseband signals of 16 MHz band-width, which is splitted into 256 channels, at the back-end. The relative delay – geometrical as well as instrumental – between different antenna signals is compensated to an accuracy of 32 nanosec before they reach the pulsar receiver. For this experiment, the signals from antennas in all sub-arrays were added incoherently in the same pulsar receiver, to produce a single stream of output data, recorded at a sampling rate of 0.516 ms. In off-line, the streams of single pulses at each frequency band are extracted separately from the single stream of recorded data.

We selected a sample of 12 pulsars having sufficiently large fluxes ($S_{400} > 100$ mJy), a range of DM values ($\sim 10 - 40$ pc/cm^3), and sampling different directions in the Galaxy. At every epoch of observation, each pulsar from our sample was observed for a few thousand pulses at a pair of frequency bands of the GMRT. The epochs were separated by intervals of about two weeks, and the whole experiment was carried out over a duration of about one and half years.

3. Data reduction and DM estimation

The recorded data were pre-processed off-line to convert from raw time-frequency format to a single pulse time series and folded profiles. The pre-processing involved de-dispersion of the data in two frequency bands, folding and interference rejection. Here we describe this technique in a very brief, for more details see [1]

For each pulsar, to recover the pulse trains at the two radio bands, the acquired data were de-dispersed within the 16 MHz band-width of each band by using the catalog DM values. Where needed, bad data points were rejected from the de-dispersed data.

The de-dispersed, interference free data trains were folded at the Doppler-corrected pulsar periods to obtain the average pulse profiles at the two radio frequency bands. The pulse profile data at each observation band were demarcated with three windows $-$ two off-pulse and one on-pulse window. The on-pulse window contained the properly de-dispersed average pulse profile, while the off-pulse windows (one on each side of the on-pulse) were off-pulse regions which were free of contamination from the wrongly de-dispersed pulse profile of the other frequency band. Data only from these window regions were used in the subsequent analysis described below.

From the reduced data, the dispersion delay between the two frequency bands, $\Delta t_m \, (= \Delta t_p + \Delta t_i + \Delta t_f)$, was estimated. Here, Δt_p is the integral number of pulsar periods delay, Δt_i is the number of time sample bins delay within a pulsar period and Δt_f is the fraction of a time sample bin delay. We have carried out estimation of Δt_m by two different methods: (i) by estimating the delay between the average pulse profiles (hereafter AP), and (ii) by measuring the mean delay between the single pulse data trains (hereafter SP). To overcome the effect of the radial velocity of the observer with respect to the pulsar, predominantly due to the orbital motion of the earth around the Sun, the observation frequencies and the time delay, Δt, were Doppler corrected to the solar system barycenter.

As the first step of analysis, in the AP method, the mean from the off-pulse data windows was estimated and subtracted from the whole pulse profile data. In the SP method, the mean computation and baseline subtraction was carried out individually for each pulse, while using the same off-pulse windows. In the AP method, because of the folding process, the value of Δt_p was estimated from the catalog DM value. To estimate Δt_i, pulse profiles at the two frequency bands were cross-correlated, and where the cross-correlation (hereafter CC) peaked, was Δt_i. The lower frequency pulse profile was rotated left circularly by this amount to align it with the higher frequency pulse profile. In the SP method, the two time series were cross-correlated. Individual pulses show

Table 1: DM results from average profile analysis

Pulsar	Frequency combination (MHz)	Catalog DM Old/new (pc/cm^3)	$\langle DM \rangle$ ($\sigma_{DM_{(noise)}}$) (pc/cm^3)	$\sigma_{DM_{(total)}}$ (pc/cm^3)	$\frac{\Delta DM}{\sigma_{DM_{(total)}}}$
B0329+54	243 + 610	26.776/26.833	26.77870 (3)	0.00103	+ 2.64
B0818−13	243 + 325	40.99/40.938	40.9222 (13)	0.0043	− 15.71
B0823+26	243 + 325	19.4751/19.454	19.4545 (4)	0.0016	− 12.85
B0834+06	243 + 325	12.8579/12.889	12.8671 (4)	0.0017	+ 5.38
B0950+08	325 + 610	2.9702/2.958	2.9597 (8)	0.0050	− 2.1
B1133+16	325 + 610	4.8471/4.864	4.8288 (6)	0.0071	− 2.57
B1642−03	325 + 610	35.665/35.727	35.75760 (14)	0.00072	+128.20
B1642−03	243 + 325	35.665/35.727	35.72270 (7)	0.00090	+ 64.00
B1919+21	243 + 325	12.4309/12.455	12.4445 (11)	0.0054	+ 2.50
B1929+10	243 + 325	3.176/3.180	3.1755 (4)	0.0015	− 0.31
B1929+10	325 + 610	3.176/3.180	3.1750 (4)	0.0020	− 0.51
B2016+28	243 + 320	14.176/14.172	14.1611 (7)	0.0025	− 6.07
B2016+28	325 + 610	14.176/14.172	14.1664 (8)	0.0051	− 1.90
B2045−16	243 + 320	11.51/11.456	11.5094 (12)	0.0114	− 0.05
B2217+47	325 + 610	43.54/43.519	43.5196 (7)	0.0061	− 3.38

significant pulse to pulse jitter in the longitude of occurrence, the average profile is usually significantly broader than the individual pulses, and hence the CC function obtained in the AP analysis is broader in comparison to that from the SP analysis.

The CC as described above gives an accuracy of the order of an integral time sample bin. To estimate the delay with an accuracy of a fraction of a time sample bin, the cross-spectrum (CS) of two aligned pulse profiles was computed, and a linear gradient to the phase of the CS was best fitted by least-square method, which gives the information of fractional bin delay. Using Equation 1, the corresponding DM value was obtained. The noise in the folded profiles, estimated from the off-pulse windows, was properly propagated to the CS to estimate the error in final DM result. The above steps were carried out at each epoch to obtain a time series of DM values for each pulsar.

4. Results and discussions

The results obtained for the average profile method are summarised in Table 1. Column 2 and 3 give the observing frequency bands and catalog DM value for each pulsar from [8, 5] respectively. For each pulsar, we obtained the mean DM, $\langle DM \rangle$, and the quadrature average of RMS noise, $\sigma_{DM_{(noise)}}$, over the period of observations (columns 4 of Table 1). The We also estimated the total fluctuation of the DM time series, $\sigma_{DM_{(total)}}$ (column 5 of Table 1), which is composed of an estimation error on the DM, and the other processes likely to play a role in the time variability of DM (a prime candidate for which is DM fluctuation due to large scale electron density irregularities in the ISM). The mean DM, $\langle DM \rangle$, for each pulsar is estimated with a fairly good accuracy – ~ 1 part in 10^3 or better (DM accuracy at each epoch is ~ 1 part in 10^4 or better). Column 6 of Table 1 shows the difference between our $\langle DM \rangle$ value and the catalog DM value [8], in units of

$\sigma_{DM_{(total)}}$. For most of our sample pulsars, results agree with the catalog values within 3 $\sigma_{DM_{(total)}}$, there are some pulsars, e.g., B0818−13, B0823+26, B0834+06, B1642−03 and B2016+28, showing a significant difference. The mean value of DM for PSR B1642−03 shows the largest discrepancy with the old catalog value. The new pulsar catalog value is very close to the lower of our two results.

Most of our observed pulsar DMs (except PSR B2217+47) show the fluctuations over a constant mean DM, indicating that the observed changes are due to electron density fluctuations in the ISM. PSR B2217+47 shows a monotonic increase of its DM. The amplitude of this change ($\simeq 0.02$ pc/cm^3/year) is such that it would require a very high electron density gradient in the ISM, which can be produced by the line of sight to the pulsar crossing through a blob of enhanced plasma density [3].

For some of our pulsars, we carried out the observations at two pairs of frequency bands. Our results for PSR B1642−03 show a significant difference in DM obtained from two pairs of frequencies. To understand the frequency dependency of pulsar DM, we carried out the simulations. In simulations, for generating the pulse profiles, we modeled pulse components as Gaussian functions with different widths, amplitudes and locations. The middle component of the higher frequency profile was taken as the fiducial point. From this point the shift of fiducial point of the lower frequency profile was estimated from the input DM. The uniformly distributed random numbers were added through out the pulse period as a noise. The profiles were either generated by using some evolution index or by fitting with real data of sample pulsars. The simulation results show that for simple core component dominated profiles, the DM variation with frequency can be due to emission geometry of pulsar polar cap, but in case of complex, cone component dominated profiles, it can be due to evolution of pulse profile with frequency.

As described above, the DM estimates were obtained from two independent methods (AP and SP) – For some pulsars, the difference in DM from the two methods is negligible, e.g. PSR B1642−03, but for PSR B0329+54, the $\langle DM \rangle$ value obtained from the SP analysis is 26.7751(7) pc/cm^3 significantly lower than the catalog value, which is lower than the $\langle DM \rangle$ value from the AP analysis. This is yet to be interpreted properly.

References

[1] Ahuja, A. L., Gupta, Y., Mitra, D., Kembhavi, A., 2005, *MNRAS* **357**, 1013.

[2] Backer, D. C., Hama, S., Hook, S. V., and Foster, R. S., 1993, *ApJ* **404**, 636.

[3] Bhat, N.D.R., Gupta, Y., Rao, P, 1999, *ApJ* **514**, 249.

[4] Gupta, Y., et al, 2000, in IAU Colloq. 177, Pulsar Astronomy, ed. M. Kramer, N. Wex, And R. Wielebinski (ASP Conf. Ser. 202; San Francisco: ASP), 277.

[5] Hobbs, G., Lyne, A.G., Kramer, M., Martin, C.E. and Jordan, C.A., 2004, *MNRAS* **353**, 1311.

[6] Kardashev, N. S., et al, 1982, *A& A*, **109** 340.

[7] Swarup, G., et al, 1997, in High Sensitivity Radio Astronomy, ed. N. Jackson and R. J. Davis (Cambridge: Cambridge University Press).

[8] Taylor, J. H., Manchester, R. N., and Lyne, A. G., 1993, *ApJS* **88**, 529.