SCATTER BROADENING MEASUREMENTS OF 124 PULSARS AT 327 MHZ

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ABSTRACT

We present the measurements of scatter broadening timescales (τsc) for 124 pulsars at 327 MHz using the upgraded Ooty Radio Telescope. These pulsars lie in the dispersion measure range of 37–503 pc cm\(^{-3}\) and declination (δ) range of \(-57^\circ < \delta < 60^\circ\). New τsc estimates for 58 pulsars are presented, increasing the sample of all such measurements by about 40% at 327 MHz. Using all available τsc measurements in the literature, we investigate the dependence of τsc on dispersion measure. Our measurements, together with previously reported values for τsc, affirm that the ionized interstellar medium up to 3 kpc is consistent with the Kolmogorov spectrum, while it deviates significantly beyond this distance.

Key words: ISM: general – pulsars: general – scattering

Supporting material: figure set, machine-readable tables

1. INTRODUCTION

Free electrons in the interstellar medium (ISM) affect the pulsar signal in three different ways: cold plasma dispersion, free–free absorption, and scattering. The broadband pulsar signal is dispersed in the ISM resulting in a delay in pulse arrival time, which is a function of wavelength, λ, and its magnitude is described by the quantity known as the dispersion measure DM = ∫0^D n_e dl pc cm\(^{-3}\), where n_e is the column electron density per cm\(^3\) and D is the distance to the pulsar in parsecs. DM for a pulsar is obtained as part of its discovery and if the distance D to the pulsar is known (by parallax method, for example), then the mean electron density in the ISM can be estimated. Alternatively, if the mean n_e is known (either from observations or from the free electron density distribution model of the Galaxy such as NE2001 by Cordes & Lazio 2002), the approximate distance to the pulsar can be determined. The pulsar signals are also absorbed by free electrons in the ISM. This process is known as free–free absorption and is responsible for the turnover observed in many of the pulsar spectra at lower frequencies (Sieber 1973). Pulsar signals are also affected by the fluctuations of the electron density in the ISM. Such fluctuations give rise to random variations in the refractive index of the medium. The pulsar signal traverses such irregularities and is scattered in the process. This phenomenon, known as “interstellar scattering” of pulsar signals, was first investigated by Scheuer (1968). It essentially arises due to the multipath propagation of the pulsar signal. Williamson (1972) demonstrated that a narrow pulse with a sharp rise time, while passing through a Gaussian distribution of irregularities, will broaden in time due to scattering, giving rise to an exponential decay of the pulse with a characteristic timescale τsc known as the scatter broadening time. The multipath propagation also leads to a diffraction pattern in the observer’s plane that decorrelates over a characteristic bandwidth Δν, such that 2π τsc Δν = C1, where C1 is of the order of unity. These scattering parameters are strongly frequency (ν) dependent and scale as ν−β, where β is the power-law index. If the same volume of electrons is responsible for dispersion and scattering, then a simple scaling relation τsc ∝ ν−4DM\(^2\) can be shown to exist in the model of Scheuer (1968). In general, the scattering strength can be attributed to a power-law electron density spectrum of the form P_e(ν) = C_n\nu^{-\alpha}, where the wavenumber and α = 2β/(β − 2) (Rickett 1977). For a Kolmogorov distribution of irregularities where β = 11/3, the scaling relation is expected to be τsc ∝ C_n\nu^{-4.4}DM\(^2\) (Romani et al. 1986). Several attempts to verify these scaling relations and fathom an understanding of the ionized component of the ISM exist in the literature (Ramachandran et al. 1997; Mitra & Ramachandran 2001; Löhmer et al. 2001, 2004; Bhat et al. 2004; Lewandowski et al. 2013, 2015). These investigations show that the observed values of α are much lower (≤4.0) than the theoretical value of 4.4 for several of the high-DM pulsars. Hence, accurate τsc measurements over multiple frequencies are essential for these studies.

At meter wavelengths, the τsc values for DM > 100 pc cm\(^{-3}\) dominate over the intrinsic pulse width and it is possible to obtain reliable τsc measurements. A survey of a number of highly dispersed pulsars with a possible detectability at 327 MHz with the aim of finding τsc was carried out at Ooty Radio Telescope (ORT) by Ramachandran et al. (1997) and Mitra & Ramachandran (2001) for 47 out of 706 pulsars discovered by that time. Currently, many more (~2200) pulsars have been discovered and, further, the ORT has been upgraded for improved sensitivity. Hence, a large number of accurate τsc measurements at 327 MHz using the ORT are now possible. With this aim, we have launched a survey of τsc measurements. In this paper, we report results from the current survey, which includes several new τsc measurements and significantly improved τsc estimates for pulsars with previously measured values.

2. OBSERVATIONS AND DATA REDUCTION

Observations were conducted for 124 pulsars from 2013 January to 2014 September using ORT, situated in southern India at a latitude of 11° N. It has an offset parabolic cylindrical reflector, 530 m long in north-south direction and 30 m wide in east-west direction, placed on a hillside with a north-south slope of 11° (Swarup et al. 1971).

The feed array consists of 1056 dipoles oriented along the north-south direction. Hence, the telescope is sensitive only to
The telescope operates at a central frequency of 326.5 MHz. The front-end electronics down-convert the signal to an intermediate frequency (IF) of 30 MHz with a bandpass of 16 MHz (Selvanayagam et al. 1993). The 1056 dipoles are grouped in 22 modules with half of them each in the north and south halves of the telescope. A separate IF is obtained from each half after appropriately phasing the modules and combining their output to form 12 beams, which cover 36° in the sky.

Recently, a new Pulsar ORT New Digital Efficient Receiver, PONDER, was commissioned at ORT to process the IF outputs (Naidu et al. 2015). The two IF outputs of beam 7 (the central beam) are converted to baseband and 8 bit digitized in PONDER after processing through a 16 MHz low pass filter. The digitized signals from the two halves are added in PONDER and a 4096 point Fast Fourier Transform is carried out in real-time across the 16 MHz passband, providing 2048 channels across the passband with a spectral resolution of 7.8125 KHz. The channelized data were then incoherently dedispersed in real-time to the nominal DM taken from the ATNF pulsar catalog (http://www.atnf.csiro.au/research/pulsar/psrcat/; Manchester et al. 2005), duration of observation, and peak signal-to-noise ratio.

(This table is available in its entirety in machine-readable form.)

Note. For each pulsar, the table lists the MJD of observation, measured topocentric period, dispersion measure and rotation measure taken from the ATNF pulsar catalog (http://www.atnf.csiro.au/research/pulsar/psrcat/; Manchester et al. 2005), duration of observation, and peak signal-to-noise ratio.

| Sr. No. | Pulsar Name | MJD (days) | Period (seconds) | DM (cm⁻¹ pc) | RM (Catalog) | Duration of Observation (minutes) | SNR (peak) |
|---------|-------------|------------|-----------------|--------------|--------------|-----------------------------------|------------|
| 1       | B0447-12    | 56621.84   | 0.438011        | 37.04        | 13.00        | 32                                | 33         |
| 2       | B0450-18    | 56643.65   | 0.548955        | 39.90        | 13.80        | 29                                | 43         |
| 3       | B0458+46    | 56623.85   | 0.638556        | 42.19        | −43.00       | 168                               | 13         |
| 4       | B0523+11    | 56621.92   | 0.354428        | 79.35        | 37.00        | 31                                | 47         |
| 5       | B0531+21    | 56623.96   | 0.033689        | 56.79        | −42.30       | 10                                | 56         |

Table 1
Summary of Observations

The observed pulse profile $P(t)$ is a convolution of intrinsic pulse shape $P_s(t)$ with (1) the impulse response characterizing the scatter broadening in the ISM $s(t)$, (2) the dispersion smear across the narrow spectral channel $D(t)$, and (3) the products, which allowed for a faster observation-to-analysis turn-around time, even for 8 hr long observations. Second, it has a flexible spectral resolution which enables minimization of the dispersion smear across a channel, and consequently allows for robust estimation of scatter-broadening parameters. It also has a real-time coherent dedispersion capability eliminating this smear completely. For this project, a fixed spectral resolution of 7.8125 KHz was used. Finally, it will allow real-time measurements of dynamic spectra, which will also be useful for measurements of ISM effects on pulsed signals in the future (See Naidu et al. 2015 for more details). The above mentioned capabilities will be useful for future similar investigations of pulsar scatter-broadening.

2.1. Source Selection

We selected 124 pulsars for our study using the following method. The pulsars in our sample lie in the ORT observable declination, (δ) range of −57° < δ < 60°, and have a flux density at 400 MHz greater than 1 mJy. The flux density at 327 MHz was estimated using the available spectral index in the ATNF catalog. Where the spectral index was not available, the flux density at the frequency available in the ATNF catalog was scaled using a spectral index of −1.6 (Lorimer et al. 1995). The above criteria yielded a large number of pulsars, and the list was further pruned by removing pulsars with DMs that are not sufficiently high, given that their $\tau_\delta$ values are likely to be significantly smaller than the intrinsic pulse profile width. Pulsars with sufficiently large DM where the estimated scattered pulse width (obtained by scaling an existing $\tau_\delta$ measurement at another frequency by $\lambda^{4.4}$) exceeds the pulse period were also removed. The final list of pulsars lies in the DM range of 37–503 pc cm⁻³ and is listed in Table 1 along with the observed parameters. The observing time for each pulsar was fixed in the following manner. While for every pulsar at least 2000 pulses were acquired to obtain a stable profile, pulsars with a low signal-to-noise ratio were integrated until a minimum peak signal-to-noise ratio of 5 was obtained. Most of the observations lasted 30 minutes, whereas observations were carried out in some special cases up to 8 hr due to the low signal-to-noise ratio of the pulsar.

2.2. Analysis Procedure

The observed pulse profile $P(t)$ is a convolution of intrinsic pulse shape $P_s(t)$ with (1) the impulse response characterizing the scatter broadening in the ISM $s(t)$, (2) the dispersion smear across the narrow spectral channel $D(t)$, and (3) the

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3 http://www.atnf.csiro.au/people/pulsar/psrcat/
4 http://www.atnf.csiro.au/research/pulsar/tempo2/
instrumental impulse response, $I(t)$, defined as
\[
P(t) = P_i(t) \ast s(t) \ast D(t) \ast I(t),
\]
where $\ast$ denotes convolution. The rise times of the receivers and back end are small enough to consider the effect of $I(t)$, while $D(t)$ is a rectangular function of temporal width given by the dispersion smearing in the narrow spectral channel for incoherent dedispersion. We use the ISM transfer function $s(t) = \exp(-t/\tau_{cs})$ (Williamson 1972).

The prime difficulty in extracting $\tau_{cs}$ stems from the fact that the intrinsic unscattered pulse profile $P_i$ is unknown. In several earlier studies, various assumptions were made regarding $P_i$ with no clear advantages or disadvantages. For example, Ramachandran et al. (1997) and Mitra & Ramachandran (2001) assumed $P_i$ to have a Gaussian shape and simultaneously fitted for the pulse width and $\tau_{cs}$. Bhat et al. (2004) used a clean-based algorithm where they claim to recover the intrinsic pulse profile and simultaneously give the pulse broadened profile, while Löhmer et al. (2001) used a high frequency unscattered profile as a model for $P_i$. In this paper, we follow the method described by Löhmer et al. (2001, hereafter referred as LKML01). For every pulsar in our sample, we searched for a high-frequency profile in the EPN database,\(^5\) where the expected $\tau_{cs}$ is significantly smaller than the pulse width. In those cases where such profiles were not available, often the widths of the profile at a high frequency were found in the literature. We used this width to construct a Gaussian profile as a template for $P_i$. Finally, this model $P_i$ was used to obtain a best-fit model by minimizing the normalized $\chi^2$ value (Löhmer et al. 2001) defined by
\[
\chi^2 = \frac{1}{(N-4)} \sum_{j=1}^{N} [P_j(t) - P_{m}(a, b, c, \tau_{cs})]^2,
\]
where $\sigma_{off}^2$ is the off-pulse root mean square, $P_j(t)$ is the observed pulse profile, $P_{m}(t)$ is the model profile, and $N$ is the total number of bins in the profile. The model profile $P_{m}$ is scaled with the pulse amplitude $a$, shifted by a constant offset $b$ in phase, and fitted to a baseline $c$ to minimize $\chi^2$. For fitting purposes, we use the nonlinear fitting routine “nrmin” given in Numerical Recipes (Press et al. 2001), where the errors in $\tau_{cs}$ are obtained from the covariance matrix.

Two examples\(^6\) of the fitting procedure used to estimate $\tau_{cs}$ values are shown in Figure 1. The top panel of the left-hand figure is the fit to the profile of PSR B1900+01, and the bottom panel is the high-frequency profile obtained at 1.4 GHz, which has a single component and is used as a template $P_i(t)$. The fitting process yields an excellent fit to the data (shown in the top panel of the figure) with $\chi^2 \sim 1$ and $\tau_{cs} \sim 28.2$ ms. It is important to note that we have ignored the effect of pulse width and component evolution with observing frequency in our fitting algorithm. It is known that pulse width increases with increasing wavelength as $\lambda^{0.3}$ due to radius to frequency mapping (Thorsett 1991; Mitra & Rankin 2002), and hence the $\tau_{cs}$ value that we obtain is an upper limit. However, in several cases, particularly for high DM pulsars, the $\tau_{cs}$ evolution is significantly higher than the width evolution, and hence the measured values of $\tau_{cs}$ are robust. In the example of PSR B1900+01, the pulse width is expected to increase from a higher-frequency profile by a factor of 1.5, whereas the expected increase in $\tau_{cs}$ is a factor of 40, indicating that the $\tau_{cs}$ measurement is reliable. However, the values of $\tau_{cs}$ can be affected by the presence of an unidentified pulse component on the trailing part of the profile, as discussed by LKML01. They suggested that an increased error bar to three standard

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\(^5\) http://www.jb.man.ac.uk/research/pulsar/Resources/epn/browser.html

\(^6\) Results of the fitting procedure for all 124 pulsars and integrated profiles are available in Appendix A. All the pulsar profiles used in this study are publicly available in SIGPROC ASCII format and can be downloaded from http://rac.ncra.tifr.res.in/data/pulsar/124-ascii-profiles.tar.
For each pulsar, the table lists its position in galactic longitude, galactic latitude and dispersion measure taken from the ATNF pulsar catalog discussed in Section 2.2.

| No. | PSR       | $l$ (deg) | $b$ (deg) | DM (pc cm$^{-3}$) | $\tau_{sc}$ (ms) | $\sigma_{\tau_{sc}}$ (ms) | $W_{sc}$ (ms) | $\chi^2$ | $N_{dof}$ | $D$ (kpc) | $\tau_{sc}^{NEW}$ (ms) | $\log C_2^2$ (m$^{-20/3}$) |
|-----|-----------|-----------|-----------|------------------|-----------------|-------------------------|-------------|---------|----------|----------|----------------------|----------------------|
| 1   | B0447-12  | 211.08    | −32.63    | 37.04            | 4.0 ± 0.1       | 33.77 ± 1.0           | 1.0         | 464     | 1.9      | 0.02     | −1.38                |                      |
| 2   | B0450-18  | 217.08    | −34.09    | 39.90            | 0.75 ± 0.01     | 37.39 ± 0.8          | 0.8         | 487     | 2.4      | 0.02     | −2.16                |                      |
| 3   | B0458+46  | 160.36    | 3.08      | 42.19            | 19 ± 1.2        | 36.79 ± 1.2          | 1.2         | 483     | 1.4      | 0.05     | −0.57                |                      |
| 4   | B0523+11  | 192.70    | −13.25    | 79.34            | 1.02 ± 0.04     | 19.90 ± 1.0          | 1.0         | 478     | 3.1      | 0.21     | −2.27                |                      |
| 5   | B0531+21  | 184.56    | −5.78     | 56.79            | 1.99 ± 0.02     | 27.90 ± 1.0          | 1.0         | 124     | 1.7      | 0.28     | −1.52                |                      |

Notes. For each pulsar, the table lists its position in galactic longitude, galactic latitude and dispersion measure taken from the ATNF pulsar catalog (http://www.atnf.csiro.au/research/pulsar/psrcat/; Manchester et al. 2005), measured $\tau_{sc}$ with error, 3$\sigma$ pulse width, normalized $\chi^2$, number of degrees of freedom, distance to the pulsar and expected $\tau_{sc}$ taken from cords & Lazio (2002) model and the scattering strength $C_2^2$ from our measurements. Pulsars shown in bold characters are the ones observed with ORT by Ramachandran et al. (1997) and Mitra & Ramachandran (2001).

Denote pulsars with multicomponent profiles, where only one of the components is fitted to get an estimate of the $\tau_{sc}$ due to the effects of profile evolution as discussed in Section 2.2.

This table is available in its entirety in a machine-readable form.

Deviations are usually sufficient to account for these effects. It is noteworthy that for $\sim$70% of the pulsars in our sample, the above procedure serves as an acceptable model.

The remaining $\sim$30% of pulsars in our sample have multiple component profiles, both at higher and lower frequencies (except three cases that are discussed below). For these pulsars, applying the method of LKMLL01 is not possible. The profile evolution in pulsars is such that the location and amplitude of the high-frequency profile components change significantly at lower frequency. However, if the separation of a profile component (identified at both higher and lower frequencies) from the adjacent one is significantly larger than $\tau_{sc}$, then the LKMLL01 method can be applied to the component. The second example of PSR B0736-40 shown in the right-hand panel of Figure 1 pertains to such a case. The high-frequency template for PSR B0736-40 has two components, and as shown in the figure, we have considered only the trailing component as a model and fitted this to the trailing component of the pulse profile at 327 MHz. This has resulted in significantly better fitting, and hence better estimation of $\tau_{sc}$. We have applied this procedure to our data where possible ($\sim$30% of the pulsars presented here). To gain additional confidence in this method, we have performed extensive simulations where we created unscattered templates with two Gaussian components and convolved with the exponential transfer function to obtain the scattered profile for an input $\tau_{sc}$ value. We then used the procedure described above to extract $\tau_{sc}$ from the scattered profile. Multiple templates were obtained by varying the amplitude ratio and the separation of the Gaussian components, and for each case the corresponding $\tau_{sc}$ value was estimated. We find that for majority of the cases where components could be resolved, we are able to recover the $\tau_{sc}$ value (within three standard deviations). When the separations between the components and/or the ratio of the amplitudes are too small, we tend to overestimate $\tau_{sc}$ by about 10%, as can be seen in Figure C1.

There are three pulsars in our sample, namely, B1737-30, B1834-10, and B1859+03, which have a slow rising edge and heavily scatter-broadened trailing edge. For these pulsars, the LKMLL01 model is found to be inadequate, since the rising edge of the profiles are poorly modelled. If we assume that there is no unidentified emission component that changes the profile shape in the rising edge for these pulsars, then there exists the possibility that the transfer function of the ISM toward these pulsars is responsible for these profile changes. We have explored whether the transfer function for a uniformly distributed ISM with Gaussian density fluctuation (see Williamson 1972, 1973; Löhmer et al. 2004; Bhat et al. 2004) given by $s(t) = \left(\frac{\pi^{1/2}}{8t^{3/2}}\right) \exp\left(-\pi^{2}t_{sc}/4t\right)$ can model the data, since the rising edge of this transfer function increases much more slowly, as seen in the data. In all three cases, we found reasonable fits which yielded $\tau_{sc}$ values of 62 ± 3, 203 ± 23, and 103 ± 1, respectively (the fitted profiles are given in Appendix B). However, before we conclude that the effects seen in these pulsars are related to a different transfer function, further modeling of the evolution of pulse profiles based on high-quality multifrequency observations need to be done, which is beyond the scope of the present study.

Table 2 lists the estimated $\tau_{sc}$, the error $\delta\tau_{sc}$, and the $\chi^2$ for all 124 pulsars in our sample. The left panel of Figure 2 shows the distribution of reduced $\chi^2$ for our sample, which lie in a range of 0.5–1.5 and peak around unity. This confirms that the model profile $P_m$ is a good fit to the data for the majority of pulsars in our sample. In the right panel of Figure 2, $\tau_{sc}$ values for 31 pulsars which are common between our sample (the abscissa) and that of Ramachandran et al. (1997) and Mitra & Ramachandran (2001), the ordinate are shown for comparison. The $\tau_{sc}$ values obtained between these two methods are generally in good agreement with each other.

### 3. Results and discussions

The primary goal of this work is to provide a large database of $\tau_{sc}$ measured at 327 MHz (P band). In this paper, we have estimated $\tau_{sc}$ values for 124 pulsars, of which, as far as we know, 58 are new measurements in the P band, which thereby increases the $\tau_{sc}$ measurements at 327 MHz by almost 40%. Including our current sample and measurements available in the literature, we found 154 pulsars for which scattering measurements exist in the P band, of which 136 have $\tau_{sc}$ measurements with 124 from this paper and 12 from Ramachandran et al. (1997) and Mitra & Ramachandran (2001). Eighteen have decorrelation bandwidth $\delta\nu_d$.
measurements from Bhat et al. (1999). Additionally, we found 134 pulsars that have $\tau_{sc}$ values and 70 pulsars with $\delta \nu_d$ values measured at different frequencies. Thus, scattering measurements currently exist for 358 pulsars spanning a DM range of 2.9–1073 pc cm$^{-3}$.

Generally, scattering properties along various lines of sight to the pulsars are examined by studying the relation between $\tau_{sc}$ and DM. Figure 3 shows the $\tau_{sc}$ versus DM plot at 327 MHz for all 358 pulsars. The filled circles are direct measurements at 327 MHz. The filled triangles are $\delta \nu_d$ measurements at 327 MHz which have been converted to $\tau_{sc}$ using the relation $\tau_{sc} = C_{1}/2n \delta \nu_d$, where $C_{1}$ is assumed to be 1.16 (see Löhmer et al. 2004 for discussion). For convenience of discussion, let us define four different DM regions in the $\tau_{sc}$ versus DM plot: region R1 for DM ranges from 0 to 40 pc cm$^{-3}$; region R2 for DM ranges from 40 to 100 pc cm$^{-3}$; region R3 for DM ranges from 100 to 500 pc cm$^{-3}$; and region R4 for DM ranges above 500 pc cm$^{-3}$. It may be noted that in region R2, no reliable $\tau_{sc}$ or $\delta \nu_d$ measurements are currently available in the P band. In this range in the P band, $\tau_{sc}$ becomes unreliable since the expected $\tau_{sc}$ values are significantly smaller than the profile widths. The $\delta \nu_d$ values are also difficult to measure since they decorrelate over a significantly small bandwidth. Further $\tau_{sc}$ measurements in the P band in region R4 are not possible since the scattering time exceeds the pulsar period. However, the 327 MHz data reveal the basic feature of the $\tau_{sc}$ versus DM relation, where at low DM, i.e., region R1, the slope is flatter compared to the high DM region R3 (Sutton 1971; Rickett 1977; Cordes et al. 1985; Ramachandran et al. 1997).

In order to fill in data in the P band for the missing DM ranges R2 and R4 in Figure 3, we rely on scattering measurements at higher frequencies. In region R2, $\delta \nu_d$ measurements and in region R4, $\tau_{sc}$ measurements are available at higher frequencies. These measurements therefore need to be scaled to 327 MHz using a frequency scaling law $\tau_{sc} \propto \nu^{-\alpha}$. The properties of the Kolmogorov spectrum of electron density irregularities, which has been widely used as a reference to understand the $\tau_{sc}$ versus DM curve, predicts $\alpha = 4.4$. However, observationally there is evidence that the frequency scaling of $\alpha = 4.4$ might not be uniform across the pulsar sample (for a current view on this topic, refer to Lewandowski et al. 2015). For DMs below about 100 pc cm$^{-3}$, Cordes et al. (1985) and Johnston et al. (1998) found $\alpha$ to be consistent with 4.4, whereas for higher DM values, Löhmer et al. (2001) and Lewandowski et al. (2013) reported a much smaller value of $\alpha \sim 3.44$. The scaling relations for these pulsars were obtained on a case by case basis using detailed modeling and measurement of $\tau_{sc}$ and $\delta \nu_d$. Bhat et al. (2004) conducted an exhaustive study to obtain $\alpha$, treating it as a parameter (constant across the whole DM range) and fitted for $\alpha$ using direct estimates of $\tau_{sc}$ and $\delta \nu_d$ at the observing frequencies. It yielded a value of 3.86 $\pm$ 0.16. Currently, more accurate measurements are required to establish the frequency scaling as the function of DM. Here we use $\alpha = 4.4$, which can be referenced to the Kolmogorov spectrum, and scaled the scattering measurements to 327 MHz using the frequency dependence of $\nu^{-4.4}$ (note that the $\delta \nu_d$ measurements are converted to $\tau_{sc}$ using $C_{1} = 1.16$). The scaled $\delta \nu_d$ and $\tau_{sc}$ values are shown as open triangles and open circles, respectively, in Figure 3.

The combined $\tau_{sc}$ versus DM plot is obtained using all currently available scattering measurement data of 358 pulsars. We fitted the empirical relation $\tau_{sc} = ADM \times (1 + BD M^{\beta})$, as was suggested by Ramachandran et al. (1997). By fixing $\gamma = 2.2$, the term $(1 + BD M^{\beta})$ can provide a useful description for assessing the deviation of $\tau_{sc}$ with DM from the Kolmogorov theory. The best form of the fit (shown as a solid curve in the figure) corresponds to $\tau_{sc} (\text{ms}) = 3.6 \times 10^{-6} \text{DM}^{2.2}(1 + 1.94 \times 10^{-3} \text{DM}^{2.0})$, which is consistent with the earlier studies of Ramachandran et al. (1997) and Löhmer et al. (2004). Note that there is a large spread in $\tau_{sc}$ for a given DM and in the bottom panel of Figure 3 the fractional residual (i.e., (data-model)/model) is shown, where it appears that with increasing DM the spread in $\tau_{sc}$ increases. There are a few reasons for the spread in $\tau_{sc}$ measurements. As discussed earlier, the methods applied for estimating $\tau_{sc}$ can lead to uncertainties due to ambiguity in the intrinsic pulse shape. This mostly affects $\tau_{sc}$ values in regions R1 and R2 in the P band. However, for larger DMs, i.e., regions R3 and R4, $\tau_{sc}$ values are significantly larger than the pulse

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**Figure 2.** Plot in the left panel is the histogram of the normalized $\chi^2$ distribution defined by Equation (2) and that given in Table 2 for all 124 pulsars observed in the current study. The right panel is a comparison of the $\tau_{sc}$ observed in the current study with the previous results from ORT (Ramachandran et al. 1997; Mitra & Ramachandran 2001). The new measurements are plotted in the x axis and the old measurements in the y axis for comparison. A 45° line, drawn in black, shows that the new measurements and old measurements are comparable and are within the error bars.
Figure 3. Top panel shows the plot of $\tau_\text{sc}$ versus DM at 327 MHz. Filled circles are $\tau_\text{sc}$ measurements at 327 MHz (these include all the measurements presented in this paper and 12 measurements from Ramachandran et al. 1997 and Mitra & Ramachandran 2001). The black filled triangles correspond to the $\delta v_d$ measurements from ORT by Bhat et al. (1999) at 327 MHz. The open circles and open triangles correspond to $\tau_\text{sc}$ and $\delta v_d$ measurements, respectively, available at a different frequency (Roberts & Ables 1982; Cordes et al. 1985; Alurkar et al. 1986; Cordes 1986; Dewey et al. 1988a; Johnston 1990; Weisberg et al. 1990; Clifton et al. 1992; Bhat et al. 2004; Lewandowski et al. 2013) and scaled appropriately to 327MHz (see the text for more details). The continuous curve is a least squares fit to the whole data set. The bottom panel shows the fractional residual (i.e., data-model/model) plotted against DM. The fractional residuals are plotted for a limited y range, since there are some anomalous pulsars whose residuals are significantly high.

profile widths, and hence the ISM properties are mostly the reason for the observed spread in $\tau_\text{sc}$. Clearly our analysis reveals several anomalous lines of sight, for example PSR B1015-56 has a DM of 439 pc cm$^{-3}$ while the measured $\tau_\text{sc}$ is 13 ms, which is a factor of 10 lower than the mean $\tau_\text{sc}$ for that DM. Anomalous scattering is a commonly observed phenomenon, and is most probably related to an inhomogeneous distribution of scattering material along pulsar line of sight.

The indirect (i.e., non-P-band measured) $\tau_\text{sc}$ values in Figure 3 depend on $C_1$ and the frequency scaling. The change in $C_1$ in the lower DM range can lead to a change in the slope of the $\tau_\text{sc}$ versus DM relation. As argued by Rickett (1977) and Löhmer et al. (2004), there is very little allowance in the theory for changing $C_1$ values from close to unity. However, the frequency scaling of $\nu^{-4.4}$ used in Figure 3 has been a subject of scrutiny in recent studies by (Löhmer et al. 2001, 2004; Lewandowski et al. 2013, 2015). These careful studies of multifrequency $\tau_\text{sc}$ measurements revealed that at high DM ($\gtrsim$500 pc cm$^{-3}$), the frequency scaling is about 3.4, which is significantly smaller than the Kolmogorov value. This can result in flattening of the slope in region R4 of the $\tau_\text{sc}$ versus DM curve, and only a systematic multifrequency study to obtain scattering estimates for a large sample of pulsars can resolve some of these issues. However, there is significant overlap of pulsars with direct P-band $\tau_\text{sc}$ measurements (filled circles) and frequency scaled $\tau_\text{sc}$ measurements in DM region R3, where no differences in $\tau_\text{sc}$ values can be seen. We can hence speculate that for pulsars below DM 500 pc cm$^{-3}$, the frequency scaling of $\nu^{-4.4}$ is a good approximation (also a result supported by Löhmer et al. 2001, 2004; Lewandowski et al. 2013).

It has been also speculated that the breakdown of the homogeneity condition in the ISM (Rickett 1977) can lead to the steepening of $\tau_\text{sc}$ values. This can be checked by evaluating the scattering strength $C_2$ along pulsar lines of sight. In the top panel of Figure 4, the estimated $\log (C_2^2)$ for all 358 pulsars as a function of pulsar distance in kiloparsecs is shown. The $C_2^2$ values were obtained for a homogeneous medium with Kolmogorov spectrum using the expression given by Cordes (1986) as $C_2^2 = 0.002\nu^{11/3}D^{-11/6}\delta v_d^{-5/6}$, where $\nu$ is the observing frequency in GHz, $D$ is the distance to the pulsar in kiloparsecs, and $\delta v_d$ is the decorrelation bandwidth in MHz. The distance to the pulsars were obtained using the Cordes & Lazio (2002) model of Galactic free electron density distribution. The dashed line in the top panel of Figure 4 correspond to the case of homogeneous medium, where $\log (C_2^2) = -3.5$ (Johnston et al. 1998). Our results are consistent with all earlier studies (Cordes 1986; Johnston et al. 1998; Löhmer et al. 2004) where the lines of sight to pulsars below 3 kpc have a value closer to $-3.5$. For the distant pulsars, the deviation is significant toward larger $\log (C_2^2)$ values which indicate that a high level of inhomogeneity exists along these lines of sight. The bottom panel of Figure 4 shows the distribution of all 358 pulsars in the Galaxy where a majority of the pulsars lie toward the inner regions of the Galaxy, and hence are likely to encounter several HII regions. Note that the enhanced scattering seen
around a Galactic longitude of ~260° is due to the Gum Nebula (Mitra & Ramachandran 2001).

4. SUMMARY

In this paper, we report new observations of 124 pulsars using ORT at 327 MHz with the aim of estimating scatter broadening ($\tau_{sc}$) values. Our attempt has yielded 58 new $\tau_{sc}$ measurements at 327 MHz, which increases the sample with known $\tau_{sc}$ measurement at 327 MHz by about 40%. The major difficulty in estimating $\tau_{sc}$ lies in the uncertainty of knowing the intrinsic (unscattered) pulse shape. We have hence used the method suggested by Löhmer et al. (2001, 2004) in which the intrinsic pulse profile is obtained from higher frequencies where the profile is unscattered. This method significantly reduces the uncertainty in $\tau_{sc}$ measurements. Furthermore, we have also assimilated 234 scattering measurements from the literature and have used them to study the ISM properties. Our results are consistent with earlier works where, for low DM (or below 3 kpc), the ISM is consistent with a Kolmogorov spectrum, but it deviates significantly for high-DM pulsars. In Figure 3, the $\tau_{sc}$ values in the P band for several pulsars were obtained estimating $\tau_{sc}$ from $R_{\Delta t}$ using a frequency scaling of $\nu^{-4.4}$ from higher frequencies. The high sensitivity of the upgraded ORT and the flexibility of PONDER will be useful to enhance the sample of such observations further, particularly to weaker pulsars, which were not covered in this study. We also note that these measurements can be improved by observations of pulsars at multiple frequencies with instruments, such as GMRT, covering the low-DM sample with frequencies including and below 300 MHz and the high-DM sample at 610 or 1420 MHz and such observations are planned in the future.

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APPENDIX A

SAMPLE AND FIT RESULTS

Figure set A1 shows the plots of 124 pulsars for which $\tau_{sc}$ measurements are done by fitting Equation (1) as explained in Section 2.2 of the main paper. The transfer function used for these fits is $s(t) = \exp(-t/\tau_{sc})$. Refer the figure caption of Figure set A1 for the plot details. All the fitted plots of 124 pulsar are available in the electronic edition of the paper.

APPENDIX B

FIT RESULTS USING PULSE BROADENING FUNCTION PBF2

As noted in Section 2.2, there are three pulsars for which the transfer function $s(t) = \left(\frac{\tau_{sc}^3}{8t^5}\right)^{1/2} \exp(-\tau_{sc}^2/4t)$ (also referred to as the PBF2 function) is used to fit the data, since the exponential form proved to be inadequate. The results of the fits are given in Table B1 and the plots are presented in Figure B1.

APPENDIX C

SIMULATION FOR EXTRACTING $\tau_{sc}$ USING MULTICOMPONENT PROFILES

We present the results of simulations using the two component pulsar model as a template. In Figure Set C2, the bottom panel is the template profile created using two Gaussian components defined as $A_1 \exp(-x - x_1)^2/\sigma_{1}^2 + A_2 \exp(-x - x_2)^2/\sigma_{2}^2$, where $A_1$ and $A_2$ are the amplitudes of the Gaussians, $x_1$ and $x_2$ are the peak locations of the Gaussians, and $\sigma_{1}$ and $\sigma_{2}$ is the width which is assumed to be the same for both the Gaussians. The period of the

Figure A1. Each plot consists of two panels, and the plot title provides the pulsar name, pulse period, observing frequency, and observatory name (ORT). The top panel shows the observed profile as a solid black line and the best-fit model as a solid red line. The legend in the top right gives the DM of the pulsar and the estimated $\tau_{sc}$ with error bars. The bottom panel shows the high-frequency template profile (solid black line) that has been used to fit the scattered profile as explained in Section 2.2 of the paper. Wherever possible, we have used the high-frequency profile from the EPN database (http://www.jb.man.ac.uk/research/pulsar/Resources/epn/browser.html) as templates for the fitting purpose. For pulsars whose high-frequency profiles were not available in the EPN database, we created the template profile using the width estimates available in the literature. For some multicomponent pulsars, only part of the profile is fitted to obtain a reliable estimate of $\tau_{sc}$. In such cases, the black dashed line shows the actual EPN profile and the black solid line shows the template profile used for fitting (see Section 2.2 for more details). The details of the reference IDs indicated in each plot for the template profiles are as follows: ant94—Arzoumanian et al. (1994), bhj+12—Burke-Spolaor et al. (2012), dsb+98—D’Amico et al. (1998) gfh98—Gould and Lyne 1998, hfs+04—Hobbs et al. 2004, hhk98—von Hoensbroech et al. 1998, jhk98—Johnston et al. 1998, jobh06—http://www.atnf.csiro.au/people/jobh414/ppdata/index.html, lorr94—Lorimer 1994, ml95—Qiao et al. 1995, rb1—Rankin and Benson 1981, sgg+95—Seiradakis et al. 1995, tmm93—Taylor et al. 1993, wml93—Wu et al. 1993.

(The complete figure set (124 images) is available.)
pulsar is assumed to be 1024 ms. The resulting profile is convolved with an exponential transfer function of the form $\exp(-t/t_{sc})$ with the value of $t_{sc}$ as 30 ms. Multiple profiles were obtained by varying the amplitudes and the separation of the Gaussians. The trailing edge component of the profile thus obtained is processed to extract the value of $t_{sc}$ with the method as explained in the Section 2.2 of the paper. The plots of all our simulations are given below. Each plot gives the separation of the components used and the amplitudes (given as a ratio of the two components) of the components along with the $t_{sc}$ obtained. Figure C1 shows the relation between $t_{sc}$ and the separation between the components. As one can see, the measured $t_{sc}$ is very close to the actual value of 30 ms when the separation between the components are larger. Also, when the separation between the components and/or the ratio of the amplitudes are too small, we tend to overestimate $t_{sc}$ by about 10%. All the plots of the simulated profiles are available in the electronic edition of the paper.

REFERENCES

Alurkar, S. K., Slee, O. B., & Bobra, A. D. 1986, ApJ, 39, 433
Arzoumanian, Z., Nice, D. J., Taylor, J. H., & Thorsett, S. E. 1994, ApJ, 422, 671
Bhat, N. D. R., Cordes, J. M., Camilo, F., Nice, D. J., & Lorimer, D. R. 2004, ApJ, 605, 7591
Bhat, N. D. R., Rao, A. P., & Gupta, Y. 1999, ApJS, 121, 483
Blitz, L., Fich, M., & Stark, A. A. 1982, ApJ, 49, 183
Burke-Spolaor, S., Johnston, S., Bailes, M., et al. 2012, MNRAS, 423, 1351B
Clifton, T. R., Lyne, A. G., Jones, A. W., McKenna, J., & Ashworth, M. 1992, MNRAS, 254, 177
Cordes, J. M., & Lazio, T. J. W. 2002, arXiv:astro-ph/0207156
Cordes, J. M. 1986, ApJ, 311, 183
D'Amico, N., Stappers, B. W., Bailes, M., et al. 1998, MNRAS, 297, 28
Dewey, R. J., Cordes, J. M., Wolszczan, A., & Weisberg, J. M. 1988a, AIP Conf. Proc. 174, Interstellar scintillations of binary pulsars. Radio wave scattering in the Interstellar Medium ed. J. Cordes, B. J. Rickett, & D. C. Backer (New York: AIP), 217
Gould, D. M., & Lyne, A. G. 1998, MNRAS, 301, 235
Hobbs, G., Faulkner, A., Stairs, I. H., et al. 2004a, MNRAS, 352, 1439
Hobbs, G. B., Edwards, R. T., & Manchester, R. N. 2006, MNRAS, 369, 655
Johnston, S. 1990, PhD thesis, The University of Manchester
Johnston, S., Nicastro, L., & Koribalski, B. 1998, MNRAS, 297, 108 http://www.atnf.csiro.au/people/job414/ppdata/index.html
Lewandowski, W., Dembska, M., Kijak, J., & Kowalinska, M. 2013, MNRAS, 434, 69
Lewandowski, W., Kowalinska, M., & Kijak, J. 2015, arXiv:1502.06330v2
Lühr, O., Kramer, M., Mitra, D., Lorimer, D. R., & Lyne, A. G. 2001, ApJ, 562, 157
Lühr, O., Mitra, D., Gupta, Y., Kramer, M., & Ahuja, A. 2004, A&A, 425, 569
Lorimer, D. R. 1994, PhD thesis, The University of Manchester
Lorimer, D. R., Yates, J. A., Lyne, A. G., & Gould, D. M. 1995, MNRAS, 273, 411
Manchester, R. N., Hobbs, G. B., Teoh, A., & Hobbs, M. 1993, AJ, 129, 4
Manoharan, P. K. 2010, SoPh, 265, 137
Mitra, D., & Ramachandran, R. 2001, A&A, 370, 586
Mitra, D., & Rankin, J. M. 2002, ApJ, 577, 322
Naidu, A., Joshi, B. C., Manoharan, P. K., & Krishnakumar, M. A. 2015, ExA submitted (arXiv:1503.01405)
Press, W. H., Flannery, B. P., Teukolsky, S. A., & Vetterling, W. T. 2001, Numerical Recipes in Fortran 77: The Art of Scientific Computing (Cambridge: Cambridge Univ. Press)
Qiao, G. J., Manchester, R. N., Lyne, A. G., & Gould, D. M. 1995, MNRAS, 274, 572
Ramachandran, R., Mitra, D., Deshpande, A. A., McConnel, D. M., & Ables, J. G. 1997, MNRAS, 290, 260
Rankin, J. M., & Benson, J. M. 1981, AJ, 86, 418
Rickett, B. J. 1977, ARA&A, 15, 479
Roberts, J. A., & Ables, J. G. 1982, MNRAS, 201, 1119
Romani, R. W., Narayan, R., & Blandford, R. 1986, MNRAS, 220, 19
Scheuer, P. A. G. 1968, Natur, 218, 920
Seiradakis, J. H., Gil, J. A., Graham, D. A., et al. 1995, A&AS, 111, 205
Selvanayagam, A. J., Praveenkumar, A., Nandagopal, D., & Velusamy, T. 1993, IETE Tech. Rev., 10, 333
Sieber, W. 1973, A&A, 28, 237
Sutton, J. M. 1971, MNRAS, 155, 51
Swarup, G., Sarma, N. V. G., Joshi, M. N., et al. 1971, NPhS, 230, 185
Taylor, J. H., Manchester, R. N., & Lyne, A. G. 1993, ApJS, 88, 529
Thorsett, S. E. 1991, ApJ, 377, 263
von Hoensbroech, A., Kijak, J., & Krawczyk, A. 1998, A&A, 334, 571
Weisberg, J. M., Pildis, R., Cordes, J. M., Spangler, S. R., & Clifton, T. 1990, BAAS, 22, 1244
Williamson, I. P. 1972, MNRAS, 157, 55
Williamson, I. P. 1973, MNRAS, 163, 345
Wu, X., Manchester, R. N., Lyne, A. G., & Qiao, G. 1993, MNRAS, 261, 630