Wide-band Timing of GMRT-discovered Millisecond Pulsars

Shyam S. Sharma1, Jayanta Roy1, Bhaswati Bhattacharya1, Lina Levin2, Ben W. Stappers2, Timothy T. Pennucci3, Levi Schult4, Shubham Singh1, and Aswathy Kaniuha1,2

1 National Centre for Radio Astrophysics, Tata Institute of Fundamental Research, Pune 411007, India; ssunder@ncra.tifr.res.in
2 Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, The University of Manchester, Manchester M13 9PL, UK
3 Institute of Physics, Eötvös Loránd University, Pázmány P. s. 1/A, 1117 Budapest, Hungary
4 Department of Physics and Astronomy, Vanderbilt University, 2301 Vanderbilt Place, Nashville, TN 37235, USA
5 Leibniz Universität Hannover, Germany

Received 2022 January 12; revised 2022 August 2; accepted 2022 August 2; published 2022 September 5

Abstract

Modeling of frequency-dependent effects, contributed by the turbulence in the free electron density of interstellar plasma, is required to enable the detection of the expected imprints from the stochastic gravitational-wave (GW) background in pulsar timing data. In this work, we present an investigation of temporal variations of interstellar medium for a set of millisecond pulsars (MSPs) with the upgraded Giant Metrewave Radio Telescope (GMRT) aided by large fractional bandwidth at lower observing frequencies. Contrary to the conventional narrowband analysis using a frequency-invariant template profile, we applied PulsePortraiture-based wide-band timing analysis while correcting for the evolution of the pulsar profile with frequency. Implementation of the PulsePortraiture-based wide-band timing method for the GMRT-discovered MSPs to probe the dispersion measure (DM) variations resulted in a DM precision of $10^{-4}$ pc cm$^{-3}$. In general, we achieve similar DM and timing precision from wide-band timing compared to the narrowband timing with matching temporal variations of DMs. This wide-band timing study of newly discovered MSPs over a wide frequency range highlights the effectiveness of profile modeling at low frequencies and probes the potential of using them in a pulsar timing array.

Unified Astronomy Thesaurus concepts: Pulsars (1306); Millisecond pulsars (1062); Astronomical techniques (1684); Pulsar timing method (1305)

1. Introduction

Millisecond pulsars (MSPs) are fast-rotating neutron stars with exceptional rotational stability, enabling the precise determination of their rotational and orbital (for systems in binary) properties, as well as using them to probe the interstellar medium (ISM; e.g., Foster & Cordes 1990). Such exceptional stability of MSPs also allows them to be used as a probe to search for gravitational waves (GWs).

The stochastic GW background manifests as an unmodeled effect in the timing residuals (known as timing noise) whose detectability depends on the timing span and precision of the measurements (Siemens et al. 2013). The Pulsar Timing Array (PTA) experiment (e.g., Detweiler 1979) uses a set of MSPs with different angular separations in the sky to search for the angular correlation between the residuals of the arrival times of pairs of pulsars (Hellings & Downs 1983). Such correlation reveals the signature of the low-frequency stochastic GW background in the timing data, where the largest contribution is thought to be coming from an ensemble of merging supermassive black hole binaries (Burke-Spolaor et al. 2019).

One of the crucial challenges for PTAs is to disentangle and mitigate the timing noise contributed by variations in the free electron density of the interstellar plasma. Time-varying ISM effects (i.e., changes in the dispersion measure (DM), the influence of scattering) on pulse arrival time need to be precisely determined to improve the timing precision. The emission from the pulsar undergoes frequency-dependent effects as it propagates through the ISM. A signal of frequency $\nu$ arrives at Earth at a delayed time $\Delta t_{\nu}$ with respect to infinite frequency, which is given by

$$\Delta t_{\nu} = K \times DM \nu^{-2},$$

where $K$ is the dispersion constant, with a value of 4.148808(3) GHz$^{-2}$ pc$^{-1}$ ms, and DM is the free electron column density integrated along the line of sight (LOS) from the observer to the source, i.e.,

$$DM \equiv \int_{\text{LOS}} n_e dl.$$

Equation (1) shows that a typical DM variation of $10^{-3}$–$10^{-4}$ pc cm$^{-3}$, seen in pulsar observations (e.g., Donner et al. 2020), introduces a change in pulse time arrival (ToA) of more than 1 µs at $\nu \sim 1$ GHz (with respect to the infinite frequency), whereas to achieve a timing precision better than 100 ns at an observing frequency of 1400 MHz, the DM variation needs to be modeled at a precision of $\sim 10^{-4}$ pc cm$^{-3}$ (You et al. 2007). Scattering of radio signals by inhomogeneities in the ISM causes frequency-dependent delays in the ToAs. For a basic model of the ISM, assuming a thin screen of plasma located between the pulsar and the observer (Scheuer 1968), scattering delays can be measured using a scintillation pattern on the dynamic spectra. The scattering delay $\tau_{\text{scat}}$ is proportional to $\nu^4$. So at lower frequencies, the DM effect ($\nu^{-2}$) can be more distinguishable from the scattering ($\nu^{-4}$) to reduce the covariance between scattering and DM effects while fitting for DM. Timing experiments at higher frequency usually find the scattering delay to be smaller than the ToA uncertainties, implying that the variations of such a delay are not having much of an adverse effect on the timing precision (e.g., Levin et al. 2016; Tumer et al. 2021). Data collected by the International Pulsar Timing Array (IPTA) consist of several MSPs (~65; Perera et al. 2019)
observed over a wide range of frequencies (0.3–3.1 GHz) with various telescopes. It aims to improve the PTA sensitivity to GW signals by combining data from the three individual PTAs (North American Nanohertz Observatory for Gravitational Waves (NANOGrav), Jenet et al. 2009; European Pulsar Timing Array (EPTA), Stappers et al. 2006; Parkes Pulsar Timing Array (PPTA), Manchester 2006). Due to the greater severity of ISM effects at low frequencies, frequencies greater than 1 GHz are preferred for high-precision timing analysis. However, low frequencies (i.e., <1 GHz) can provide a sensitive probe for measuring DM and its temporal evolution to mitigate adverse effects in the arrival times (Hassall et al. 2012), which are embedded in the high-frequency measurements.

The Giant Metrewave Radio Telescope (GMRT) is one of the most sensitive radio telescopes at low radio frequencies, covering a frequency range from 120 to 1460 MHz. The GMRT, being an IPTA telescope, can provide sensitive low-frequency timing measurements, which are already demonstrated by Jones et al. (2021) with the legacy GMRT (Roy et al. 2010) and by Krishnakumar et al. (2021) and Nobleson et al. (2022) with the upgraded GMRT (uGMRT; Reddy et al. 2017; Gupta et al. 2017). The current observing setup for the observations presented in this paper aims to utilize the maximum possible sensitivity at the low frequencies with the GMRT, and it is different from the regular Indian PTA (InPTA) monitoring program. Band-3 of the uGMRT (i.e., 300–500 MHz), with its large fractional bandwidth, provides a facility for very accurate intraband DM estimates. Precise DM measurements obtained from this band can be used to correct for dispersive delays in simultaneous high-frequency timing data. However, due to multipath scattering of pulsar signals, the DM can be different at lower and higher frequencies as shown by Cordes et al. (2016). According to the radiometer equation (Lorimer & Kramer 2004), a larger observing bandwidth results in a higher signal-to-noise ratio (S/N) pulse profile, promising better ToA and DM precision. However, the intrinsic pulse profile can evolve significantly with frequency within an observing band. In addition, at the lower frequency band of uGMRT with a larger fractional bandwidth, radio frequency interference (RFI), scintillation, and scattering can contaminate the pulse detection significance.

The standard narrowband (NB) timing technique (Alam et al. 2021a) uses a single frequency-averaged template to generate ToAs for different subbands within the observing bandwidth. The NB technique does not account for any frequency-dependent effects. It works adequately at high frequencies with smaller fractional bandwidth, where the frequency-dependent effects within the band are less compared to lower frequencies with larger fractional bandwidth. Pennucci et al. (2014) and Liu et al. (2014) describe the simultaneous wide-band (WB) ToA and DM measurement technique using a frequency-dependent template. Pennucci (2019) developed a principal-component-decomposition-based modeling of pulse profiles as a function of frequency, which is an input to the WB ToA and DM measurement technique. All of these are implemented in a package called “PulsePor-traiture” (Pennucci et al. 2016). Using PulsePortraiture (see footnote 6), we can estimate the ToA and DM simultaneously at a high precision with a frequency-dependent template.

Alam et al. (2021b) reported WB timing results for 47 NANOGrav MSPs with a range of frequency coverage: 1.4 GHz (with a bandwidth of ∼600 MHz), 800 MHz (with a

### Table 1

| PSR     | Period (ms) | Dispersion Measure (pc cm⁻³) | 400 MHz Flux Density (mJy) | 650 MHz Flux Density (mJy) | 1260 MHz Flux Density (mJy) |
|---------|-------------|-----------------------------|---------------------------|---------------------------|-----------------------------|
| J1120−3618 | 5.56        | 45.13                       | 0.6                       | ...                       | ...                         |
| J1646−2142 | 5.85        | 29.74                       | 2.2                       | 1.1                       | ...                         |
| J1828+0625 | 3.63        | 22.42                       | 1.3                       | ...                       | ...                         |
| J2144−5237 | 5.04        | 19.55                       | 1.2                       | 0.6                       | 0.8                         |
| J1640+2224 | 3.16        | 18.43                       | 21.2                      | ...                       | ...                         |
| J1713+0747 | 4.57        | 15.98                       | 6.4                       | 10.0                      | ...                         |
| J1909−3744 | 2.95        | 10.39                       | 3.8                       | 0.5                       | 0.5                         |
| J2145−0750 | 16.05       | 9.00                        | 23.8                      | ...                       | 7.5                         |

Note. The flux density values for the non-PTA pulsars (first four) are from Bhattacharyya et al. (2019) and Bhattacharyya et al. (2022). We measured the flux density values of the PTA pulsars (last four) from our observations. We also estimated the flux value of J2144–5237 at 650 MHz (not available earlier) from the current data.

bandwidth of ∼186 MHz), and 430 MHz (with a bandwidth 25–50 MHz). The detailed comparisons with NB timing results for these MSPs establish the potential of WB timing in achieving higher timing and DM precision.

In this work, we present the results of applying WB timing analysis for four GMRT-discovered MSPs with the uGMRT in band-3 (300–500 MHz) and band-4 (550–750 MHz). We validate the WB analysis pipeline with a few bright PTA MSPs observed with the uGMRT in band-3 and band-5 (1060–1460 MHz). Since the frequency-dependent effects are much more prominent at low frequencies, the observing bands of uGMRT, especially band-3 with 0.5 fractional bandwidth, demonstrate effectiveness of pulse profile modeling with frequency. Observation and data processing details are provided in Section 2. Section 3 contains the details of the NB and WB timing techniques. Section 4 contains the measurements obtained from two timing analyses and comparisons with some of the existing results (Krishnakumar et al. 2021; Alam et al. 2021b and Nobleson et al. 2022). In Section 5 we summarize the improvements seen with the WB timing analysis.

### 2. Observations and Data Processing

We observed four GMRT-discovered pulsars (from now on we will refer to them as “non-PTA pulsars”), J1120–3618, J1646–2142, J1828+0625, and J2144–5237 (Bhattacharyya et al. 2019, 2022). These pulsars were observed in band-3 and band-4. PTA pulsars J1640+2224, J1713+0747, J1909–3744, and J2145–0750 (Alam et al. 2021a, 2021b) were observed in band-3 and band-5. Table 1 lists the period, DM, and flux densities of these eight MSPs. Figures 1 and 2 show the pulse profiles of PTA and non-PTA pulsars, respectively, for the lowest- and highest-frequency subbands of the observing bands.

The four PTA pulsars are some of the best-timed MSPs and were chosen based on their high detection significance at 322/607 MHz with legacy GMRT as reported by Jones et al. (2021). Along with band-3, PTA pulsars were also observed in band-5 with uGMRT with maximum possible sensitivity to compare the ToA and DM precision with the values reported by Alam et al. (2021b) at 1.4 GHz.

The non-PTA pulsars were selected from the set of GMRT-discovered MSPs that have good S/N (>30 in 40–55 minutes for most of them) in band-3. Table 2 shows the S/N of the
observed MSPs in different frequency bands of the uGMRT. Among the non-PTA pulsars, J1646–2142 and J2144–5237 are also bright in band-4. J1120–3618 and J1828+0625 have relatively lower detection significance in band-4; thus, their band-4 observations are excluded from this work. Since the aim was to observe with the maximum time-domain sensitivity of the uGMRT, we have taken single subarray observations, where 70% and 80% of the GMRT array was phased and combined to form a single dish with an equivalent gain of 7 and 8 K Jy$^{-1}$ in band-3 and band-4, respectively. In band-5, we observed with 90% of the array providing a phased array beam with a gain of 5.9 K Jy$^{-1}$. The observational setup in all frequency bands/modes with time resolution, bandwidth, and number of antennas used in phased array is provided in Table 3. The phased array beam of the uGMRT was recorded after online coherent dedispersion (where each subband voltage sample is corrected for dispersive delays due to the ISM) for band-3 and band-4, respectively. In parallel, Stokes-I filterbank data were also acquired for offline incoherent dedispersion (where the intrachannel dispersion smearing is not corrected). In band-3, we mask the 360–380 MHz frequency band affected by the persistent Mobile User Objective System emission. In band-5, Stokes-I filterbank data were acquired for offline incoherent dedispersion. The online coherent dedispersion mode is currently not available for 400 MHz observational bandwidth.

The intrachannel dispersion smearing of the incoherently dedispersed data is decided by 4096 spectral channels over a bandwidth of 200 MHz in band-3. For example, in the case of the J1120–3618 pulsar having the highest DM in our sample, the intrachannel smearing is 0.28 ms. The uGMRT observations (both coherently dedispersed and raw filterbank) were incoherently dedispersed with known DM value to remove the interchannel dispersive delays. We performed the incoherent dedispersion and folding of the filterbank file using the PREPFOLD command available in PRESTO (Ransom 2011). For the purpose of data reduction, we used the ephemeris from legacy GMRT timing studies (Bhattacharyya et al. 2019, 2022) for the non-PTA pulsars and the NANOGrav ephemeris7 (the latest from 2020/2021 is the NANOGrav 12.5 yr data set, version 4; Alam et al. 2021a, 2021b) for the PTA pulsars. We converted PREPFOLD folded data cubes to FITS format for further analysis using the PAM command available in PSRCHIVE (van Straten et al. 2012).

---

7 https://data.nanograv.org/
For timing analysis, we divided band-3 into 128 frequency subbands for the PTA pulsars and 16 subbands for non-PTA pulsars. Band-4 and band-5 were divided into 16 subbands for non-PTA and PTA pulsars, respectively.

The four PTA pulsars were observed once a month and covered a span of ∼9 months, while more than 2 yr of data were available for all non-PTA pulsars. Figure 3 shows the cadence for all observed pulsars in the different frequency bands. We also included incoherently dedispersed data available for MSPs J1120−3618, J1646−2142, and J2144−5237 in band-3 and band-4 taken before the online coherent dedispersion mode was established.

Table 2

| MSP               | Mean Observation Time (minutes) | Median S/N Band 3/Band 4/Band 5 | No. of Epochs | Timing Baseline (yr) |
|-------------------|---------------------------------|----------------------------------|---------------|----------------------|
| J1120−3618        | 50                              | 70/80/...                        | 13            | 3.25                 |
| J1646−2142        | 40                              | 80/40/...                        | 36            | 4.08                 |
| J1828+0625        | 40                              | 30/...                           | 15            | 2.08                 |
| J2144−5237        | 55                              | 50/80/...                        | 32            | 4.00                 |
| J1640+2224        | 25                              | 400/.../60                      | 12            | 0.75                 |
| J1713+0747        | 25                              | 160/.../250                     | 12            | 0.75                 |
| J1909−3744        | 20                              | 120/.../20                      | 7             | 0.75                 |
| J2145−0750        | 30                              | 2600/.../200                    | 15            | 0.75                 |

Note. The fourth column lists the number of observations taken for each pulsar. In this counting, an incoherently dedispersed observation was ignored whenever simultaneous coherently dedispersed data were available in the same band.

For timing analysis, we divided band-3 into 128 frequency subbands for the PTA pulsars and 16 subbands for non-PTA pulsars. Band-4 and band-5 were divided into 16 subbands for non-PTA and PTA pulsars, respectively.

The Astrophysical Journal, 936:86 (17pp), 2022 September 1 Sharma et al.

Figure 2. Pulse profiles for non-PTA pulsars in band-3 (B3) and band-4 (B4) of the uGMRT. The profiles in band-3 are normalized by their peak intensity values. In band-4, the normalized profiles are scaled by the ratio of S/N in band-4 to that in band-3. The figure style and color schemes are the same as in Figure 1. The central frequencies of the lowest- and highest-frequency subbands of B4 are 575 and 725 MHz, respectively.

3. Timing Techniques

3.1. Narrowband Timing

Template generation procedure: In NB timing analysis, all the coherently dedispersed FITS files in a given uGMRT band, with significant pulse detection, are aligned using frequency-invariant phase offsets. A similar procedure is applied for incoherently dedispersed files of the same band independently. The aligned FITS are added for a particular frequency band and then averaged in frequency, separately for coherently and incoherently dedispersed FITS, to create a reference template profile for the same band. We used different templates for different frequency bands of the uGMRT; in addition, independent templates are used for coherently and incoherently dedispersed FITS. Gaussians are fitted, using the PAAS command in PSRCHIVE (van Straten et al. 2012), to
these frequency- and time-averaged profiles to create analytic noise-free templates.

NB ToA and DM estimations: For each individual uGMRT frequency band we keep the intraband frequency resolution in FITS files (16/128 subbands; Section 2) and extracted 16/128 ToAs for each epoch FITS in band-3, band-4, or band-5. Coherently and incoherently dedispersed FITS are dealt with separately using the same procedure.

Taylor (1992) prescribes a Fourier frequency domain technique for measuring the phase shifts between data profile and template by applying a cross-correlation between them in the Fourier domain. The estimation of phase shifts in the Fourier domain ensures that the ToA precision is not limited by phase bin resolution. All NB ToAs are estimated using this technique as described in Appendix A of Taylor (1992). DM is fitted individually for each epoch, keeping other parameters fixed in TEMPO2 (Hobbs et al. 2006) to measure the temporal variation of DM.

### 3.2. Wide-band Timing

For WB analysis, we select FITS files having high S/N, with the same central frequency to create the profile templates. Different WB templates are used for separate frequency bands and observing modes. We have flagged a few start and end channels plus the channels with a bad RFI condition in each band. Here we provide a brief description of the ToA and template creation procedure in WB timing, and we refer to Pennucci et al. (2014) and Pennucci (2019) for further details.

Template generation procedure: Considering the observations with one dedispersion mode, in one frequency band, the FITS data having the highest S/N are used as the initial phase alignment reference. The FITS for each epoch are then aligned relative to that initial alignment reference by determining a constant offset between them and an offset proportional to \( \nu^{-2} \) fitted over 16/128 subbands, where the \( \nu^{-2} \) factor accounts for DM variability from one observation to another. The aligned FITS of all epochs are averaged together while keeping the 16/128 subband frequency resolution. Upon iteration, it uses that result as the new reference for alignment, and the process is repeated multiple times to create an “average portrait.” Then, the average portrait is decomposed by principal component analysis (PCA) to find a set of basis eigenvectors such that their linear combination (including mean profile) can result in a frequency-dependent profile template. The mean profile (\( \bar{\rho}_{\text{mean}} \)) and the basis eigenvectors (\( \hat{e}_i \)) are smoothed in the process.

#### Table 3

Details of the Observational Setup in Different Modes

| uGMRT Band | Mode | Frequency Range (MHz) | Usable Bandwidth (MHz) | Time Resolution (\( \mu s \)) | No. of Antennas |
|------------|------|------------------------|------------------------|-------------------------------|----------------|
| Band-3     | I    | 300–500                | 135                    | 81.92                         | 22             |
| Band-4     | I    | 550–750                | 152                    | 81.92                         | 25             |
| Band-5     | I    | 1060–1460              | 300                    | 81.92                         | 27             |
| Band-3     | C    | 300–500                | 135                    | 10.24/20.48/40.96\(^a\)       | 22             |
| Band-4     | C    | 550–750                | 152                    | 10.24/20.48/40.96\(^a\)       | 25             |

*Notes. C and I represent coherent and incoherent dispersion modes, respectively. In I mode, filterbank files have 4096 channels in all the bands. 

\(^a\) In C mode, filterbank files have 512/1024/2048 channels in our observations. The table shows that the time resolution corresponds to the filterbank with different numbers of channels.

**Figure 3.** The cadence and length of the observing campaign for each pulsar in different uGMRT bands (marked by separate colors) for different observing modes, where C stands for observations with online coherent dedispersion and I for offline incoherent dedispersion. Note that Table 2 lists simultaneous C and I observations, presented in different color points here, as a single-epoch observation.
template $P(\nu)$ at a particular frequency $\nu$ can be created using the equation
\[
P(\nu) = \sum_{i=1}^{n_{\text{ev}}} \sum_{j=1}^{n_{\nu}} c_{ij} B_{i,j}(\nu) \hat{e}_i + \bar{p}_{\text{mean}},
\]
where the first sum runs over the number of basis eigenvectors $n_{\text{ev}}$ and the second over $n_{\nu}$, the number of basis splines used in the fit. $\sum_{j=1}^{n_{\nu}} c_{ij} B_{i,j}(\nu)$ are the coefficients of the eigenvectors, which can evolve with frequency to capture the profile evolution. The default constraint in the software, to limit the number of eigenvectors, is to set a threshold value for $S$.

The WB technique is enabled to simultaneously measure the ToA and DM by inclusion of the constraint in the following equation:
\[
\phi_n(\nu_n) = \phi_n + \frac{K \times \text{DM}}{P_s}(\nu_n^2 - \nu_n^2),
\]
where $\phi_n$ is the phase offset estimated at reference frequency $\nu_n$. $P_s$ is the period of the pulsar, $K$ is the dispersion constant, and $\nu_n$ is a choice of parameterization. The PulsePortraiture tool gives freedom to select the value of $\nu_n$. However, we have used the default feature of the package, which estimates the value of $\nu_n$ for zero covariance between $\phi_n$ (WB ToA) and DM. WB results in a single ToA and DM for each epoch. Individual frequency bands and modes (coherently and incoherently dedispersed) FITS files were analyzed separately for ToA and DM estimations using different templates.

A sample of WB timing analysis “jupyter notebooks” developed for the uGMRT band-3, band-4, and band-5 is available in the github. It needs a folded data cube in PSRFITS format. The WB ToAs and DM values for PTA MSPs from these GMRT observations are also provided there.

Over the uGMRT frequency bands, the pulse profiles show a clear difference in profile shape from one band to another. Thus, the absolute DM values are expected to be different for the two nonsimultaneous bands. In addition, the $\nu^{-2}$ fitting for DM estimation in NB analysis captures part of the profile evolution with the frequency that could result in different absolute DM values in the NB and WB analysis. To account for the DM variability, we have subtracted the weighted mean of absolute DM values in the NB and WB analysis. To account for the DM variability, we have subtracted the weighted mean of absolute DM values in the NB and WB analysis. To account for the DM variability, we have subtracted the weighted mean of absolute DM values in the NB and WB analysis. To account for the DM variability, we have subtracted the weighted mean of absolute DM values in the NB and WB analysis.

4. Results

With the aim of validating the WB timing pipeline, we have carried out a comparative study of NB and WB timing for the PTA pulsars, and then the validated pipeline is applied to the non-PTA pulsars.

4.1. Validation of the WB Timing Pipeline by PTA Pulsars

We have created 1024 bins for the band-3 profile of J2145$-0750$, and the rest of the PTA pulsars have 256 profile bins in band-3. In Band-5, we have created profiles with 64-bin resolution. For the PTA pulsars, we have not fitted for the long-term timing model (except DM for individual epochs), due to the availability of a shorter time span (<1 yr) with sparse sampling. The ephemerides for the PTA pulsars are obtained from the NANOGrav archive (see footnote 7).

(See footnote 7)
4.1. DM Variation for PTA Pulsars

4.1.1. DM Variation for PTA Pulsars

4.1.1.1. J1640+2224

Figures 1(a) and (e) show folded pulse profiles for J1640+2224 in band-3 and band-5, respectively. The steep spectral nature of this pulsar makes it much brighter in band-3 as compared to band-5. Figure 4 shows the DM variation with time for this pulsar in band-3.

4.1.1.2. J1713+0747

J1713+0747 has a lower flux density in band-3 compared to band-5 (Table 1). The pulse profiles in both bands have a single component with significant pulse broadening due to scattering seen in band-3 (Figure 1(b)) compared to band-5 (Figure 1(f)). The pulse profile within band-3 also evolves considerably with frequency. For J1713+0747, we measured a scintillation bandwidth of 0.85 ± 0.22 MHz at 334 MHz and 1.24 ± 0.23 MHz at 425 MHz. We find $\Delta \nu \propto \nu^{1.56}$, where $\Delta \nu$ is the scintillation bandwidth at frequency $\nu$. The estimated scaling is much shallower than the Kolmogorov spectrum. The coefficients of eigenvectors, created in PCA analysis, capture the profile evolution (including scattering) with frequency. Figure 5 shows the DM variation with time for this pulsar in band-3.

4.1.1.3. J1909–3744

J1909–3744 has a single-component pulse profile in both band-3 (Figure 1(c)) and band-5 (Figure 1(g)) and has higher detection significance in band-3 compared to band-5. Due to fewer observations (only four) in band-3 for J1909–3744, the temporal variation of the DM plot is not added. However, the median precision obtained for the available epochs is listed in Table 4.

4.1.1.4. J2145–0750

The pulse profile of J2145–0750 has two main components, and the peak amplitude ratio evolves with frequency (as seen in Figures 1(d) and (h)). The pulsar is bright in band-3, making it one of the best PTA MSPs to follow up at low frequencies. Figure 6 presents the temporal variations of DM for J2145–0750, obtained with NB and WB analysis, in band-3 of the uGMRT.

4.1.2. Comparison between NB and WB Timing for PTA Pulsars

The PTA pulsars show similar temporal DM variations for NB and WB analysis for most of the epochs. Significant temporal variation of DM ($>\pm 3\sigma_{DM}$) is seen for the PTA pulsars.

Table 4 presents a comparison of our results from NB and WB timing analysis, which lists raw (not scaled by observing bandwidth and duration) ToA and DM uncertainties. Figure 7 shows median ToA and DM precision along with the range of uncertainties (plotted as error bars) in NB and WB analysis, respectively. In general, ToAs are more precisely estimated in WB than NB timing. The median improvements in ToA uncertainty from NB to WB analysis are 2.4 and 2.7 times in band-3 and band-5, respectively. The ToAs in WB analysis are measured at the zero-covariance frequency ($\nu_0$). The ToA uncertainty has its minimum value at the estimated frequency since at other frequencies there will be some covariance between DM and ToA, which will lead to a higher ToA uncertainty. For PTA pulsars, we get median ToA uncertainty $\sim 100$ ns in WB analysis of band-3 observations except J1713+0747 (having $\sigma_{ToA} \sim 0.8 \mu$s). In band-5, the median ToA uncertainty is $<500$ ns in WB analysis for all PTA pulsars except J2145–0750 (having $\sigma_{ToA} \sim 3 \mu$s). Band-3 ToAs are at least 2 times more precise than band-5 ToAs except for J1713+0747, as its detection significance is higher in band-5 as compared to band-3.

DM precision from WB and NB analysis is almost the same for all of the observations in both band-3 and band-5. In band-3, we find the median DM precision of $(1-2) \times 10^{-5}$ pc cm$^{-3}$.
for all the PTA pulsars except J1713+0747 (having $\sigma_{\text{DM}} \sim 2 \times 10^{-4} \text{ pc cm}^{-3}$). In band-5, the median DM precision ranges from $10^{-4}$ to $10^{-3} \text{ pc cm}^{-3}$. We find a minimum of 5 times improvement in DM precision from band-5 to band-3. In the case of NB analysis, we have used the “norescale” option while fitting for DM using TEMPO2. It disables the scaling of output raw DM uncertainties by minimized $\chi^2$. We used this feature to compare the NB uncertainties directly with raw WB uncertainties.

We see a gradual improvement in ToA and DM precision with the increase of number of profile bins for PTA pulsars in both NB and WB analyses. For example, the ToA and DM uncertainties for J2145−0750 improve by a factor of $\sim 3$ in band-3 by increasing the number of bins from 128 to 1024 in WB analysis.

Table 5 contains the median DM values obtained from NB and WB analysis. In addition, it shows the number of eigenvectors used for each observed pulsar to model its profile. In the case of zero eigenvector, WB analysis will be the same as NB analysis. However, the WB ToA is calculated at zero-covariance frequency. In addition, the NB templates are created outside of PulsePortraiture by Gaussian fitting, which makes the templates different in the case of NB and WB analyses. We used one to two eigenvectors to model the WB template in band-3. In band-5, we have not used any eigenvector for all PTA pulsars except J1713+0747 (requiring one eigenvector). The difference in median DM values from NB and WB analyses lies within $\pm 1 \sigma_{\text{DM}}$ for all PTA pulsars except J1640+2224 (having DM difference of $4 \times 10^{-4}$ pc cm$^{-3}$ in band-3 and $3 \times 10^{-3}$ pc cm$^{-3}$ in band-5).
4.1.3. Comparison with Other High-precision Timing Studies

We have scaled the ToA uncertainties by a factor of \( \sqrt{\text{bandwidth} \times \frac{\text{duration}}{30\text{ min}}} \) (following scaling similar to that of Nobleson et al. 2022; Alam et al. 2021b) to compare the ToA precision obtained in our work with the values from other high-precision timing studies. We have also scaled the raw ToA uncertainties reported in Krishnakumar et al. (2021). Table 6 shows a comparison of scaled ToA and raw DM precision obtained from Krishnakumar et al. (2021; InPTA), Nobleson et al. (2022; InPTA), Alam et al. (2021b; NANOGrav), and this work.

Krishnakumar et al. (2021) reported ToA and DM precision for five PTA pulsars, including J1713+0747, J1909−3744, and J2145−0750, from simultaneous 400–500 MHz (with five antennas of the uGMRT array) and 1360–1460 MHz (with 12 antennas of the uGMRT array) observations using the multiple-subarray mode of the uGMRT. Recently, Nobleson et al. (2022) reported DM and ToA precision from WB analysis for the same three pulsars using 10 antennas of the uGMRT array at 300–500 MHz.

The use of 22 antennas of the GMRT in the current band-3 observations allowed us to achieve better ToA and DM precision for J2145−0750 than Nobleson et al. (2022). For J1909−3744, the DM precisions achieved from both the observing setups are similar, while the ToAs are more precise in our work. For J1713+0747, we notice that the DM uncertainty obtained from the current work is 2 times less

![Figure 6](image1.png)

Figure 6. DM variation with time for the PTA pulsar J2145−0750 in band-3 of the uGMRT. The color schemes are the same as in Figure 4.

![Figure 7](image2.png)

Figure 7. Median ToA (top panel) and DM (bottom panel) uncertainties obtained in the two (NB and WB) analyses for eight pulsars. Error bars represent the range of precision obtained for the individual pulsar data sets. Pulsars are arranged on the x-axis in increasing order of their band-3 DM uncertainty. We used green, blue, and black colors to represent the values obtained from WB analysis in band-3, 4, and 5, respectively. Similarly, light-green, sky-blue, and dark-gray colors are used for NB analysis values in band-3, band-4, and band-5, respectively.
Table 5

| PSR         | No. of Eigenvectors(WB) | Median DM (pc cm\(^{-3}\)) | Band-3 | Band-4 | Band-3 | Band-4 |
|-------------|-------------------------|----------------------------|--------|--------|--------|--------|
|             |                         |                            | NB     | WB     | NB     | WB     |
| J1200−3618  | 1                       | 45.1289(7)                 | 45.1289(8) | ...  | ...  |
| J1646−2142  | 1                       | 29.7568(4)                 | 29.7568(4) | 29.727(3) | 29.729(3) |
| J1828+0625  | 0                       | 22.4162(6)                 | 22.4165(6) | ...  | ...  |
| J2144−5237  | 1                       | 19.5502(4)                 | 19.5501(4) | 19.553(2) | 19.551(2) |

Note. The table also presents the median DM values obtained in NB and WB analyses for each pulsar in the subsequent columns.

Table 6

| PSR         | Scaled ToA (μs) | Scaled DM (× 10\(^{-4}\) pc cm\(^{-3}\)) |
|-------------|-----------------|------------------------------------------|
|              | N21             | S22                                      | NANOGrav |
|              | 1360–1460 MHz (GMRT) | 1060–1460 MHz (GMRT) | 1147–1765/1151–1885 MHz (AO/GBT) |
| J1640+2224  | 300–500 MHz (uGMRT) | G ∼ 3.2 K Jy\(^{-1}\) | G ∼ 7.0 K Jy\(^{-1}\) | G ∼ 2.6 K Jy\(^{-1}\) | G ∼ 5.9 K Jy\(^{-1}\) | G ∼ 9–11 K Jy\(^{-1}\) (AO) | G ∼ 2.0 K Jy\(^{-1}\) (GBT) |
| J1713+0747  | 0.81            | 0.98                                     | 1.04               | 0.79               | 0.04               | 0.09               | 0.45               | 0.99               | 0.48               |
| J1909−3744  | 0.46            | 0.12                                     | 1.92              | 0.45              | 0.09              | 0.45              | 0.99              | 0.45              |
| J2145−0750  | 1.22            | 0.12                                     | 2.83              | 5.99              | 0.48              | 5.99              | 0.48              | 5.99              |

Notes. The third and fourth rows contain the frequency range, telescope, and gain (uGMRT, AO, and GBT gain information is available at http://gmrtnrao.tifr.res.in/~astrosupp/obs_setup/sensitivity.html, http://www.naic.edu/~astro/RXstatus/Lwide/Lwide.shtml#gain, and https://science.nrao.edu/facilities/GBT/proposing/GBTpp.pdf, respectively).

precise than that of Nobleson et al. (2022). It could be attributed to the loss of gain during the current observations due to temporal dephasing in longer-baseline antennas. Due to such a possible loss of sensitivity, the scaled ToA precision for this pulsar was not improved. The best median ToA and DM precision obtained from our study in band-3 are around 100 ns and 1 × 10\(^{-5}\) pc cm\(^{-3}\), which are ~2 and ~4 times better, respectively, than the earlier GMRT results.

For all four PTA pulsars presented in this work, Alam et al. (2021b) reported ToA and DM uncertainties at 1.4 GHz from WB analysis using data from Arecibo (AO) and Green Bank Telescope (GBT). We compare our band-5 results with Krishnakumar et al. (2021) and Alam et al. (2021b). With the use of 27 antennas at band-5 of the uGMRT, we could achieve submicrosecond ToA uncertainties for most of the PTA pulsars (except J2145−0750). These values are 3–20 times less precise than the NANOGrav measurements. However, with the use of lower bandwidth and fewer antennas, the achieved ToA precision in Krishnakumar et al. (2021) is greater than 1 μs for the three common PTA pulsars. The full band-5 coverage allowed us to achieve DM precision at the level of 10\(^{-5}\) pc cm\(^{-3}\) or better, which is at least an order of magnitude more precise than the 100 MHz bandwidth observations reported in Krishnakumar et al. (2021). Moreover, the low-frequency intraband DM measurements reported in this paper are significantly more precise than the interband DM estimates reported in Krishnakumar et al. (2021). The DM precision from NANOGrav observations is 3–50 times better than that of our measurements. The DM and ToA precision achieved in band-3 of uGMRT are better than (or at least on par with) the L-band observations of NANOGrav for all of the PTA pulsars except J1713+0747.

Note: The fourth row contains the frequency range, telescope, and gain (uGMRT, AO, and GBT gain information is available at http://gmrtnrao.tifr.res.in/~astrosupp/obs_setup/sensitivity.html, http://www.naic.edu/~astro/RXstatus/Lwide/Lwide.shtml#gain, and https://science.nrao.edu/facilities/GBT/proposing/GBTpp.pdf, respectively).

9 Interband DM precision reported in K21.
The pulsar; F1

We have used only band-3 coherently dedispersed data in the timing model A1 (\(\text{PB}^{(\text{residuals J1828 timing J1646})} - \text{Post-}\text{PB}^{(\text{J1828 timing J1646})}\))

In TEMPO2 timing software. For all the non-PTA pulsars we obtained from Bhattacharyya et al. (2022). We have fitted model parameters using the TEMPO2 timing software. For all the non-PTA pulsars the band-3 coherently dedispersed data set gives the best ToA precision, so we have used only this set of ToAs for the timing model fit.

### 4.2. Results for Non-PTA Pulsars

For all the non-PTA pulsars, coherently and incoherently dedispersed profiles are created with 128 and 64 bins, respectively, in both band-3 and band-4. Their ephemerides are obtained from Bhattacharyya et al. (2019) and Bhattacharyya et al. (2022). We have fitted model parameters using the TEMPO2 timing software. For all the non-PTA pulsars we achieve phase coherent timing over a baseline of 2–4 yr. Table 7 shows the fitted model parameters and timing precision achieved for the non-PTA pulsars. For the timing fit, we have regenerated NB ToAs using frequency- and time-averaged profiles resulting in a single ToA per epoch. We have not fitted the global DM (while fitting other parameters) using the parameter file in TEMPO2. However, for a pulsar showing a larger than \(\pm 3\sigma\) DM variation, we corrected each epoch NB ToA by its DM value by adding the \(-\text{dm}\) flag in the timing file. For a smaller than \(\pm 3\sigma\) DM variation, ToAs are corrected for a fixed DM value available in the parameter file. For all the non-PTA pulsars, the band-3 coherently dedispersed data set gives the best ToA precision, so we have used only this set of ToAs for the timing model fit.

#### 4.2.1. DM Variation and Post-fit Timing Residuals for Non-PTA Pulsars

**J1120–3618**

J1120–3618 is a 5.56 ms pulsar in a binary system with 5.7 days of the orbital period. For this pulsar, we see a single broad component with an unresolved feature near its peak in band-3 (Figure 2(a)). The W50 (width at the half of intensity peak) corresponding to its broad pulse component is 1.56 ± 0.04 ms.
Figures 8 and 9 show its DM variation with time and post-fit timing residual from NB and WB analyses.

**4.2.1.2. J1646−2142**

J1646−2142 is an isolated MSP spinning with a period of 5.85 ms. Out of four non-PTA pulsars, this MSP has an interesting profile evolution with frequency (Figures 2(b) and (e)). The W50 corresponding to its strongest pulse component in band-3 is 0.91 ± 0.05 ms. In band-4, the same component has a W50 of 0.69 ± 0.05 ms. In band-3, the peak amplitude’s ratio of the second to the first component changes from 0.29 to 0.55 from the lowest- to the highest-frequency subband. In addition, the separation between two components increases from 1.69(5) ms to 1.87(5) ms from the lowest- to the highest-frequency subband, which is opposite to the radius-to-frequency mapping seen for some pulsars (Lorimer & Kramer 2004). Similarly, the peak amplitude ratio of the two components increases from 0.96 to 1.32 from the lowest- to the highest-frequency subband in band-4. However, the evolution of separation between the two peaks within band-4 is not significant and lies within ±1 phase bin error. Figures 10 and 11 show DM variation with time and post-fit timing residual from NB and WB analyses for this pulsar.

**4.2.1.3. J1828+0625**

J1828+0625 is a 3.63 ms pulsar in a binary system with an orbital period of 77.9 days. It exhibits a single narrow component pulse profile in band-3 (Figure 2(c)). The W50
corresponding to its narrow pulse component is $0.57 \pm 0.03$ ms. The temporal variation of DM and post-fit timing residual of this pulsar from NB and WB analyses are shown in Figures 12 and 13, respectively.

### 4.2.1.4. J2144$-5237$

J2144$-5237$ is a 5.04 ms pulsar present in a binary system with an orbital period of 10.6 days. The W50 corresponding to its strongest pulse component (having two subcomponents near its peak) in band-3 is $1.10 \pm 0.04$ ms. In band-4, the same component has a W50 of $1.02 \pm 0.04$ ms. In band-3, the central component of J2144$-5237$ has two resolved peaks (Figure 2(d)).

In contrast to J1646$-2142$, the ratio of the second peak’s amplitude to the first one decreases from 1.02 to 0.56 from the lowest- to the highest-frequency subband. Unlike J1646$-2142$, J2144$-5237$ does not evolve much with frequency in band-4 (Figure 2(f)). Figures 14 and 15 show its DM variation with time and post-fit timing residual from NB and WB analyses.

### 4.2.2. Comparison between NB and WB Timing for Non-PTA Pulsars

The non-PTA pulsars show similar temporal DM variations for NB and WB analyses. No significant temporal variation in DM ($< \pm 3 \sigma_{\text{DM}}$) is seen for the non-PTA pulsars except J1120$-3618$ (having $> \pm 4 \sigma_{\text{DM}}$ variation of DM). Post-fit timing...
residual variations with MJD are also similar for NB and WB analysis for all the pulsars.

ToAs are more precisely estimated in WB than NB timing in all the cases. The median improvement in ToA uncertainty from NB to WB analysis is $\sim 1.4$ times in both band-3 and band-4, respectively. In WB analysis, the median ToA uncertainty for non-PTA pulsars lies in the range of $2–5 \mu s$ in both band-3 and band-4. The ToA uncertainties for J1646–2142 and J2144–5237 are almost the same in band-3 and band-4.

The median DM uncertainties are almost the same for NB and WB analyses in both band-3 and band-4. We achieve median DM uncertainties on the order of $10^{-4}$ and $10^{-3}$ pc cm$^{-3}$ in band-3 and band-4, respectively, using the WB timing. We find $\sim 8$ and $\sim 4$ times improvements in DM precision for J1646–2142 and J2144–5237, respectively, from band-4 to band-3.

The number of eigenvectors ranges from 0 to 1 for non-PTA pulsars. The difference in median DM values from NB and WB analyses lies within $\pm 1 \sigma_{DM}$. Thus, median DM offsets between NB timing and WB timing are insignificant. We see negligible difference in ToA and DM uncertainties from coherently and incoherently dedispersed data sets of non-PTA pulsars. The increase of the number of bins in coherently dedispersed profiles of non-PTA pulsars (requiring higher time resolution data) can possibly improve the DM and ToA precision.

From the timing fit, we achieve post-fit residual rms of $<10 \mu s$ for all the non-PTA pulsars from NB and WB analyses. The rms of timing residuals is similar in NB and WB analyses. The number of eigenvectors ranges from 0 to 1 for non-PTA pulsars. The difference in median DM values from NB and WB analyses lies within $\pm 1 \sigma_{DM}$. Thus, median DM offsets between NB timing and WB timing are insignificant. We see negligible difference in ToA and DM uncertainties from coherently and incoherently dedispersed data sets of non-PTA pulsars. The increase of the number of bins in coherently dedispersed profiles of non-PTA pulsars (requiring higher time resolution data) can possibly improve the DM and ToA precision.
and WB timing. In Figure 16 we compare the precision of fitted parameters of the timing models of the four non-PTA pulsars between NB and WB analyses. We plot the differences of the fitted parameter values normalized by the uncertainties from the NB timing model (\(\sigma_{\text{NB}}\)). The error bars have a length of \(\sigma_{\text{WB}}/\sigma_{\text{NB}}\). We find that the model difference of these two timing methods is well within \(\pm 3\sigma_{\text{NB}}\), confirming the generation of similar long-term timing models from both the techniques (i.e., NB or WB).

5. Conclusions

We provide a comparative study of the WB timing analysis with the conventional NB timing analysis at low frequency using the uGMRT for a set of non-PTA GMRT MSPs and for some well-studied PTA MSPs. ToAs are, in general, more precise in WB analysis than in NB analysis. However, NB timing and WB timing provide similar DM precision for a given band. ToA precision is, in general, better in band-3 compared to band-5 for the PTA pulsars. For non-PTA pulsars, the ToA precision is similar in band-3 and band-4. In addition, band-3 of the GMRT provides much higher DM precision for all eight MSPs compared to the other observing bands.

For PTA pulsars, we typically achieve submicrosecond ToA precision from WB analysis, for individual epochs in both band-3 and band-5. For J1640+2224, J1909−3744, and J2145−0750 the DM precisions obtained, in band-3, are on the order of \(10^{-5}\) pc cm\(^{-3}\). For J1713+0747, similar DM precision can
be achieved (following Equation (3) of Jones et al. 2021) by combining near-simultaneous band-3 and band-5 observations. In band-5, the DM precision is of the order of $\sim 10^{-3}$ pc cm$^{-3}$ for the PTA pulsars. The median DM values obtained from NB and WB timing for PTA pulsars are within the median DM uncertainties except J1640+2224. Significant temporal variations of DM ($> \pm 3\sigma_{DM}$) are observed for PTA pulsars. From WB analysis the best ToA and DM precisions we find in band-3 are 87 ns and $1 \times 10^{-5}$ pc cm$^{-3}$ for J2145−0750 and in band-5 are 278 ns and $8 \times 10^{-7}$ pc cm$^{-3}$ for J1909−3744. We have compared the ToA and DM precision for the commonly observed PTA pulsars with the earlier GMRT results in band-3 (Nobleson et al. 2022) and in band-5 (Krishnakumar et al. 2021), as well as with the interband DM measurements combining band-3 and band-5 (Krishnakumar et al. 2021). The best median DM precision reported in this work is 3 times better in band-3 (for J2145−0750) and $\sim 10^2$ times better in band-5 (for J1909−3744) compared to earlier results. In addition, low-frequency intraband DM estimates with the full GMRT array are more precise than the interband measurements using the multiple-subarray mode. Thus, the current work illustrates the maximum possible DM and ToA precision achievable for some of the best-timed PTA pulsars with the WB system using the full timing sensitivity of the uGMRT.

For non-PTA pulsars, the WB timing provides microsecond ToA precision in both band-3 and band-4. The DM precisions obtained are of the order of $\sim 10^{-4}$ and $\sim 10^{-3}$ pc cm$^{-3}$ in band-3 and band-4, respectively. The non-PTA pulsars (having flux densities around 1–2 mJy at 400 MHz) have timing precision $< 10 \mu$s in NB and WB analyses at band-3. The fitted model parameters from NB and WB analyses for the non-PTA pulsars in the 2–4 yr timing baseline agree well within $\pm 3\sigma$ uncertainties, confirming the applicability of WB analysis for long-term timing. In band-3, the timing precision is similar between NB and WB analyses for all four non-PTA pulsars. This work shows the typical DM, ToA, and timing precision

![Figure 16. Comparison of our fitted timing models of four non-PTA MSPs, in band-3, from NB and WB timing analyses. Pulsar order (y-axis) for each parameter is maintained the same as in Table 5. The x-axis shows the differences of the fitted parameter (astrometric, spin, and binary) values normalized by the uncertainties from the NB timing model, i.e., $(X_{WB} - X_{NB})/\sigma_{X}^{NB}$, where X is the pulsar’s model parameter. The error bars have a length equal to the ratio of parameter uncertainties from WB and NB models, i.e., $\sigma_{X}^{WB}/\sigma_{X}^{NB}$. Model parameters for all MSPs lie within $\pm 3\sigma_{NB}$ for the two analyses.

The Astrophysical Journal, 936:86 (17pp), 2022 September 1 Sharma et al.
that can be achieved for newly discovered GMRT pulsars from low-frequency follow-up studies. For non-PTA pulsars, the difference in median DM values from NB and WB analysis is less than the DM errors in both band-3 and band-4. No significant temporal variations of DM ($\pm 3 \sigma_{DM}$) are observed for the GMRT pulsars, except J1120–3618.

In the case of the non-PTA pulsars, even with order of magnitude lower flux densities than the PTA MSPs, the achieved DM precision (Table 4) is comparable with the higher-frequency measurements for PTA MSPs (Alam et al. 2021b), making them potential candidates to include in the IPTA experiment in the search for a GW background aided by the more sensitive upcoming telescopes providing better ToA precision. Since, at the intermediate signal regime of the stochastic background of GWs, the detection significance strongly depends on the number of pulsars included in the array (Siemens et al. 2013), such low-frequency follow-up aided with WB timing can play an important role. Following the work by Nobleson et al. (2022) for PTA MSPs and the current work for newly discovered MSPs, the prospect of using a low-frequency observing facility at a sensitive telescope like the uGMRT for high-precision timing studies to aid the global PTA efforts is clearly evident.

Moreover, the timing with the full GMRT array (70%) in band-3 (with a gain of $7 \text{ K Jy}^{-1}$), presented here, is complementary to the currently existing WB timing facilities like MeerKAT and CHIME, providing lowest-frequency coverage of 580–1670 MHz (Bailes et al. 2020) and 400–800 MHz (CHIME/Pulsar Collaboration et al. 2021), respectively.

We acknowledge the support of the Department of Atomic Energy, Government of India, under project no. 12-R&D-TFR-5.02-0700. The GMRT is run by the institute National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research, India. We thank the anonymous referee for comments that improved the quality of the paper. We acknowledge the support of GMRT telescope operators for observations.

**ORCID iDs**

Jayanta Roy @ https://orcid.org/0000-0002-2892-8025
Bhaswati Bhattacharyya @ https://orcid.org/0000-0002-6287-6900

Timothy T. Pennucci @ https://orcid.org/0000-0001-5465-2889
Aswathy Kaninghat @ https://orcid.org/0000-0002-9029-318X

**References**

Alam, M. F., Arzoumanian, Z., Baker, P. T., et al. 2021a, ApJS, 252, 4
Alam, M. F., Arzoumanian, Z., Baker, P. T., et al. 2021b, ApJS, 252, 5
Bailes, M., Jameson, A., Abbate, F., et al. 2020, PASA, 37, e028
Bhattacharyya, B., Roy, J., Freire, P. C. C., et al. 2022, ApJ, 933, 159
Bhattacharyya, B., Roy, J., Stappers, B. W., et al. 2019, ApJ, 881, 59
Burke-Spolaor, S., Taylor, S. R., Charisi, M., et al. 2019, A&ARv, 27, 5
CHIME/Pulsar Collaboration, Amuri, M., Bandura, K. M., et al. 2021, ApJS, 255, 5
Cordes, J. M., Shannon, R. M., & Stinebring, D. R. 2016, ApJ, 817, 16
Donner, J. Y., Verbiest, J. P. W., Tiburzi, C., et al. 2020, A&A, 644, A153
Dettweiler, S. 1979, ApJ, 234, 1100
Foster, R. S., & Cordes, J. M. 1990, ApJ, 364, 123
Gupta, Y., Ajithkumar, B., Kale, H. S., et al. 2017, CSci, 113, 707
Hassall, T. E., Stappers, B. W., Hessels, J. W. T., et al. 2012, A&A, 543, A66
Helling, R. W., & Downs, G. S. 1983, ApJL, 265, L39
Hobbs, G., Edwards, R., & Manchester, R. N. 2006, MNRAS, 369, 655
Jenet, F., Finn, L. S., Lazio, J., et al. 2009, arXiv:0909.1058
Jones, M. L., McLaughlin, M. A., Roy, J., et al. 2021, ApJ, 915, 15
Krishnakumar, M. A., Manoharan, P. K., Joshi, B. C., et al. 2021, A&A, 651, A5
Levin, L., McLaughlin, M. A., Jones, G., et al. 2016, ApJ, 818, 166
Liu, K., Desvignes, G., Cognard, I., et al. 2014, MNRAS, 443, 3752
Lorimer, D. R., & Kramer, M. 2004, Handbook of Pulsar Astronomy (Cambridge: Cambridge Univ. Press)
Manchester, R. N. 2006, ChJAS, 6, 139
Nobleson, K., Agarwal, N., Girgaonkar, R., et al. 2022, MNRAS, 512, 1234
Pennucci, T. T. 2019, ApJ, 871, 34
Pennucci, T. T., Demorest, P. B., & Ransom, S. M. 2014, ApJ, 790, 93
Pennucci, T. T., Demorest, P. B., & Ransom, S. M. 2016, Pulse Portraiture: Pulsar timing, Astrophysics Source Code Library, ascl:1606.013
Perera, B. B. P., DeCesar, M. E., Demorest, P. B., et al. 2019, MNRAS, 490, 4666
Ransom, S. 2011, PRESTO: Pulsar Exploration and Search Toolkit, Astrophysics Source Code Library, ascl:1107.017
Reddy, S. H., Kudale, S., Gokhale, U., et al. 2017, JAI, 6, 1641011
Roy, J., Gupta, Y., Pen, U.-L., et al. 2010, ExA, 28, 25
Scheuer, P. A. G. 1968, Natur, 218, 192
Siemens, X., Ellis, J., Jenet, F. et al. 2013, CQGra, 30, 224015
Stappers, B. W., Kramer, M., Lyne, A. G., D’Amico, N., & Jessner, A. 2006, ChJAS, 6, 298
Taylor, J. H. 1992, RSPTA, 341, 117
Turner, J. E., McLaughlin, M. A., Cordes, J. M., et al. 2021, ApJ, 917, 10
van Straten, W., Demorest, P., & Osłowski, S. 2012, AR&T, 9, 237
You, X. P., Hobbs, G., Coles, W. A., et al. 2007, MNRAS, 378, 493