Timing Pulsars with CHIME and the NANOGrav 15yr Dataset

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Abstract

The North American Nanohertz Observatory for Gravitational Waves (NANOGrav) conducts long-term timing campaigns on large numbers of millisecond pulsars (MSPs). Wideband (WB) timing of the NANOGrav datasets was first done in the 12.5yr dataset, and proved to be extremely helpful for measuring the time-varying dispersion measure, which can significantly limit timing precision. However, we are limited by the fact that NANOGrav only observes most pulsars once per month. In contrast, the Canadian Hydrogen Intensity Mapping Experiment (CHIME) Telescope currently observes most NANOGrav MSPs at nearly daily cadence at 600 MHz with a 400 MHz bandwidth. Using WB timing techniques, we combined one year of data taken at CHIME with data over the same time period from the NANOGrav 15yr Dataset for three MSPs.

1 Introduction

The North American Nanohertz Observatory for Gravitational Waves (NANOGrav) conducts high-precision timing over long timescales of a large number of millisecond pulsars (MSPs) with the goal of detecting the background gravitational wave signature from merging supermassive black hole binaries [1].

Pulsars are a class of rapidly spinning and highly magnetized neutron star characterized by the emission of electromagnetic radiation from both magnetic poles which is most easily observed at radio wavelengths. Measurements of pulse time of arrivals (TOAs) can be used to infer several intrinsic characteristics of pulsars such as spin period and spin period derivative via pulsar timing [2]. TOAs can also be used to infer extrinsic astrometric parameters such as sky position, parallax and proper motion which are very important for gravitational wave searches [1]. For binary pulsars we can measure Keplerian binary parameters, and relativistic post-Keplerian (PK) binary parameters. Both are extremely useful for placing limits on neutron star masses, which are an important astrophysical constraint on the poorly understood nuclear equation of state [3].

When timing pulsars, we can expect some evolution of the pulse profile shape as a function of frequency caused by intrinsic changes in the pulsar magnetosphere, and extrinsic effects caused by interstellar scattering and frequency-dependent dispersion measure (DM). When measuring TOAs, especially from MSPs, this profile evolution can significantly impact timing precision by introducing frequency dependent time delays[4]. Wideband (WB) timing is a relatively recently developed technique in which a single TOA and simultaneous DM measurement from every observation using a 2-D 'portrait' which captures the evolution of pulse profile in frequency and phase. The portrait is made by aligning and averaging all available data to compute a high S/N data template. This template is then de-noised using wavelet smoothing, and an averaged portrait is derived using principal component analysis and spline interpolation [5].

The Canadian Hydrogen Intensity Mapping Experiment (CHIME) Telescope is a drift scan radio telescope that has been observing sources in the NANOGrav pulsar timing array (PTA) for the past three years [6, 7]. In this paper, we present preliminary results of data combination of CHIME data with that from the NANOGrav 15 year dataset (NG15) for three pulsars: PSR J1012+5307, PSR J2302+4442, and PSR J0645+5158.

2 Methods

This analysis focuses on an 11 month period between April 2019 and March 2020, which is the overlap between the CHIME telescope beginning timing observations on NANOGrav sources and the cut-off date of data collection for NG15.

2.1 NANOGrav Data

Observations for all three sources were conducted on the 100-m Robert C. Byrd Green Bank Telescope (GBT) at monthly cadence using the 820 MHz and 1.4 GHz receivers. Data taken during our time period of interest was recorded using the Green Bank Ultimate Pulsar Processing Instrument (GUPPI) with 2048 phase bins and 1.56 MHz width frequency subbands for both receivers. Observation lengths vary from 15-45 minutes [8].

NG15 data was reduced using the `nanopipe` software package and WB TOAs were calculated using the `PulsePortraiture`[1] software package, with the same model portraits as in the NANOGrav 12.5-yr dataset [9].

2.2 CHIME Data

All CHIME observations were taken in fold-mode centered at 600 MHz with a 400 MHz bandwidth and 1024 frequency channels. PSR J1012+5307, PSR J0645+5158 had 2048 phase bins, whereas PSR J2302+4442 data had 1024 phase bins. Observations for each source were conducted at nearly daily cadence with an average observation length of 15 minutes.

As one of the long-term goals of this project is to fully integrate CHIME TOAs into the NANOGrav 15-yr dataset, we matched the data reduction process in `nanopipe` as closely as possible. For each pulsar, we used the `PSRCHIVE` [10] tool `pam` to scrunch each observation into a single time sub-integration and 64 frequency sub-integrations. To remove radio frequency inference (RFI), we first used `pazi` on a thirty-day sample of observations for each pulsar and determined which frequency bins were consistently corrupted and then used `paz` to remove those channels from all observations.

CHIME-specific WB portraits were made for each source using the `PulsePortraiture` software package. Data portraits were made by averaging and aligning all observations for a given source that exceeded an imposed S/N threshold (60 for PSR J1012+5307 and 20 for both PSR J2302+4442 and J0645+5158) using `ppalign.py`. The threshold was empirically determined for each source in order to prevent noisy or marginal detections being added into the data portrait. Clean and high S/N data portraits were important because noise could get artificially modeled as profile evolution [5]. Then, `ppspline.py` was used to make a spline model of profile evolution which was later used to generate WB TOAs with `pptoas.py`.

2.3 Timing Analysis

Combination of NG15 and CHIME WB TOAs was done using the `PINT` software package[2]. We started with the NG15 ephemerides and added an additional JUMP and DMJUMP for the CHIME receiver to account for phase and DM offsets from data taken at other receivers. We then iteratively added CHIME WB TOAs in small increments and re-fit for a new ephemeris. Since this analysis was done over a relatively short timescale, we froze all astrometric and relativistic parameters at the values in the NG15 timing ephemerides.

[1] https://github.com/pennucci/PulsePortraiture
[2] https://github.com/nanograv/PINT

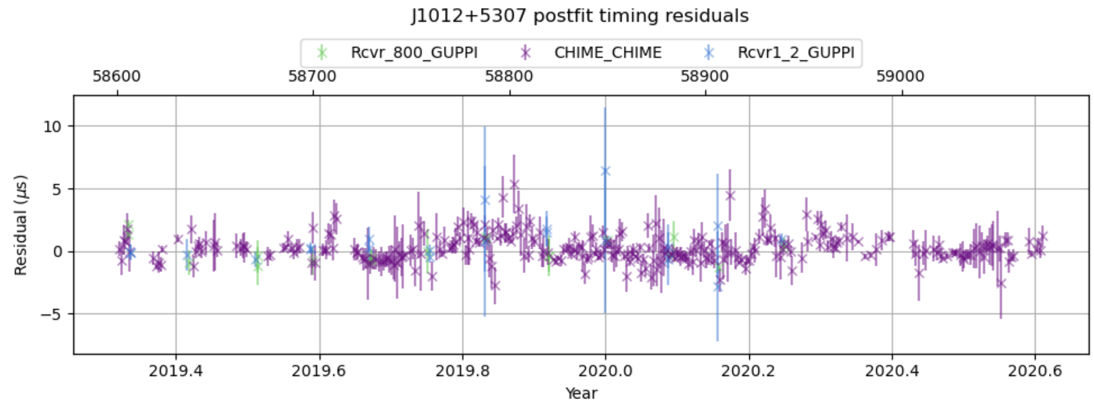

Figure 1: TOA vs Post-fit timing residuals with error bars for J1012+5307 across the NG15 and CHIME overlap period. The bottom axis represents the TOA is units of years and the top in MJD. Green and blue points are GBT data taken at 820 MHz and 1400 MHz, respectively. CHIME data is in purple.

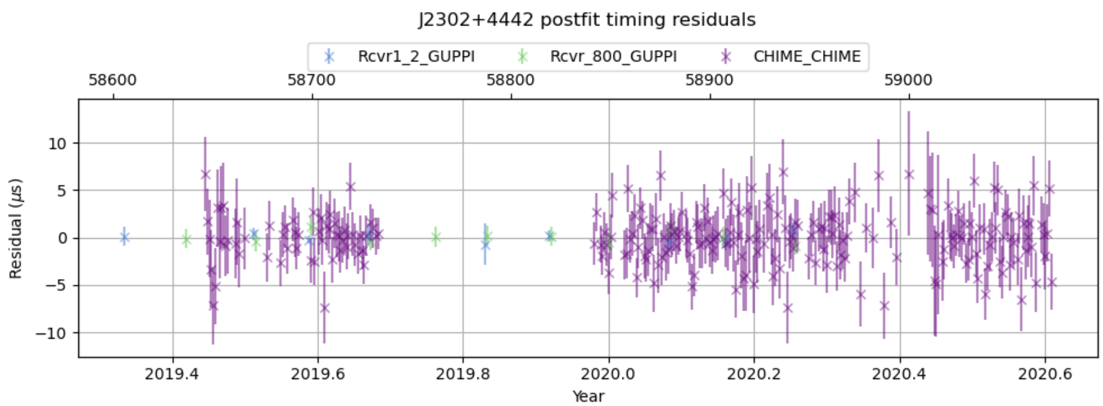

Figure 2: TOA vs Post-fit timing residuals with error bars for J2302+4442 across the NG15 and CHIME overlap period. The bottom axis represents the TOA is units of years and the top in MJD. Green and blue points are GBT data taken at 820 MHz and 1400 MHz, respectively. CHIME data is in purple.

3 Results

Spin parameters and timing statistics for all three sources can be found in Table 1. For all three sources there were roughly 10 times the amount of CHIME TOAs compared to NG15 TOAs.

PSR J1012+5307 is a 5.26-ms MSP in a 14.5-hr orbit with an ultralight $0.156 \pm 0.0015\ M_{\odot}$ white dwarf companion that was first discovered in the Jodrell Bank Millisecond Pulsar Survey [11, 12]. Timing residuals are in Figure 1. The timing ephemeris in Table 1 uses the ELL1 binary model [13]. The post-fit RMS, 0.715 μs is approximately 0.0136% of the pulsar spin period with a χ^2_{red} of 1.223.

PSR J2302+4442 is a 5.192-ms binary pulsar in a 125.9 day nearly circular orbit about a white dwarf companion. It was originally a Fermi Large Area Telescope source that confirmed to be an MSP by the Nançay Radio Telescope [14]. The timing ephemeris uses the DD binary model, and the post-fit RMS is roughly 0.035% of the spin period with a χ^2_{red} of 0.993 (Table 1) [15, 16]. Plotted timing residuals can be found in Figure 2.

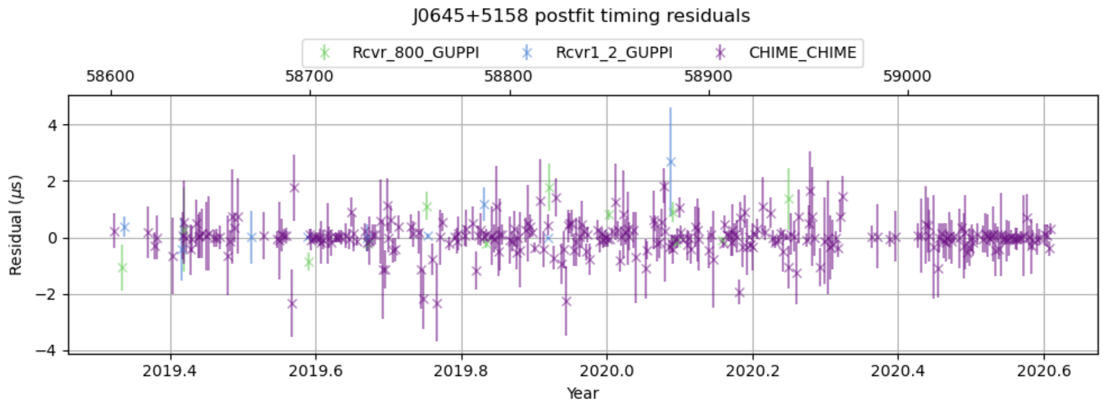

Figure 3: TOA vs Post-fit timing residuals with error bars for J0645+5158 across the NG15 and CHIME overlap period. The bottom axis represents the TOA is units of years and the top in MJD. Green and blue points are GBT data taken at 820 MHz and 1400 MHz, respectively. CHIME data is in purple.

Table 1: Pulsar parameters and timing statistics

Parameter	PSR J1012+5307	PSR J2302+4442	PSR J0645+5158
Spin Period, P (s)	0.0052557490261562(13)	0.0051923246510214(3)	0.00885349668727665(7)
Period Derivative, $\dot{P}$ (s s^{-1})	$1.7099(49) \times 10^{-20}$	$1.393(9) \times 10^{-20}$	$4.92(18) \times 10^{-21}$
Dispersion Measure (pc cm^{-3})	9.0224	13.7234	18.2485
Binary Model	ELL1	DD	N/A
Orbital Period, $\mathrm{P_b}$ (days)	0.60467271399(5)	125.9352966(7)	N/A
Eccentricity, e	$1.57(16) \times 10^{-6}$	0.00050305(2)	N/A
Projected Semi-Major Axis (lt s)	0.58181824(5)	51.4299679(6)	N/A
Longitude of Periastron, ω (deg)	91(6)	207.896(19)	N/A
Epoch of Periastron (MJD)	58837.315(11)	58821.3672(6)	N/A
Timing Data Span (MJD)	58601-59071	58605-59071	58602 - 59071
$\mathrm{N_{toa}}$ (GBT/CHIME)	39/308	20/234	21/273
RMS Residual (μs)	0.715	1.848	0.202
χ^2_{red}	1.223	0.993	1.334

In parentheses are the PINT-reported uncertainties in the last significant digit.

PSR J0645+5158 is a 8.8-ms isolated MSP discovered in the Green Bank North Celestial Cap Survey [17]. The post-fit RMS is about 0.0023 % of the spin period with a χ^2_{red} of 1.334 (Table 1). Timing residuals are plotted in Figure 3.

4 Conclusions and Future Work

For the most part, timing residuals for all three sources are flat, although for PSR J1012+5307, there is some small structure in the residuals that could be attributed to unmodeled red noise. In general, CHIME TOAs seem to have larger uncertainties than the GBT TOAs, which may be partially attributed to CHIME TOAs being measured at lower frequencies and the CHIME telescope having a lower gain than the GBT. Spin and binary parameters, where applicable, are consistent with those published in the NANOGrav 12.5yr dataset [9].

Our conservative RFI excision approach has the potential to remove a significant amount of frequency information. The CHIME telescope is in a much smaller radio quiet zone than the GBT and parts of its observing band overlap with those used for cell phones and therefore are completely unprotected for radio astronomy. This results in an extremely variable RFI environment that is particularly noticeable for low declination sources, and necessitates making an automated RFI excision algorithm.

The next steps of this analysis will be to extend it to the entire NG15 and CHIME timing baseline, and to look at measurements of astrometric and PK parameters. The timing baseline of CHIME is roughly three years and thus will be long enough to make independent measurements of some astrometic and PK parameters. This work will facilitate the eventual full integration of CHIME data into future NANOGrav datasets.

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