A Fourier Domain “Jerk” Search for Binary Pulsars

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A Fourier Domain "Jerk" Search for Binary Pulsars

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ABSTRACT

While binary pulsar systems are fantastic laboratories for a wide array of astrophysics, they are particularly difficult to detect. The orbital motion of the pulsar changes its apparent spin frequency over the course of an observation, essentially "smearing" the response of the time series in the Fourier domain. We review the Fourier domain acceleration search (FDAS), which uses a matched filtering algorithm to correct for this smearing by assuming constant acceleration for a small enough portion of the orbit. We discuss the theory and implementation of a Fourier domain "jerk" search, developed as part of the PRESTO software package, which extends the FDAS to account for a constant orbital jerk of the pulsar. We test the performance of our algorithm on archival Green Bank Telescope observations of the globular cluster Terzan 5, and show that while the jerk search has a significantly longer runtime, it improves search sensitivity to binaries when the observation duration is 5 to 15% of the orbital period. Finally, we present the detection of Ter5am (aka PSR J1748−2446am), a new highly-accelerated pulsar in a compact, eccentric, and relativistic orbit, found using our jerk search, with a likely pulsar mass of $1.649^{+0.037}_{-0.11}\,M_\odot$.

Keywords: binaries: general – pulsars: general – pulsars: individual (J1748−2446am) – stars: neutron

1. INTRODUCTION

The first observed binary pulsar was located in a double neutron star system discovered by Hulse and Taylor in 1974 (Hulse & Taylor 1975). Precise timing of the pulsar revealed orbital decay consistent with predictions from general relativity, providing the first experimental demonstration of the existence of gravitational waves and earning Hulse and Taylor a Nobel Prize in physics in 1993. In the 44 years since this original discovery, binary systems have continued to serve as fantastic laboratories for surveying a wide array of astrophysics, allowing us to further probe relativity and gravity in the strong-field limit, neutron star equations of state, neutron star atmospheres, and the end stages of stellar evolution. For a more comprehensive overview of binary pulsar discoveries and properties, see Phinney & Kulkarni (1994) and Stairs (2004).

While these systems can be used to conduct valuable science, the process of detecting binary pulsars is a particularly difficult challenge. A solitary pulsar can be detected relatively simply by taking the fast Fourier transform (FFT) of an observational time series and searching through the resulting Fourier powers in frequency space. Pulsars generally have narrow pulse profiles which manifest as a series of peaks at harmonics of the spin frequency in the Fourier domain. In a typical search, the power contained in these harmonics is summed to increase the significance of the final detection (e.g. Lorimer & Kramer 2012).

However, in the case of binary pulsars, the detection process becomes complicated by the orbital motion of the pulsar around its companion. If the observation duration T is longer than even a small fraction of the orbital period P_{orb}, Doppler shifting causes the apparent pulsar spin frequency to change appreciably as the orbiting pulsar moves away from or toward the observer. As a result, the Fourier power of the signal is "smeared" across neighboring frequency bins, leading to a decrease in the significance of the detection in the Fourier domain. Higher harmonics of the pulsar signal are impacted more than the fundamental, as Doppler smearing increases proportionally with harmonic number.

Acceleration searches are a class of algorithms that account for this Doppler smearing by assuming that,

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over a small enough fraction of the orbit ($T \lesssim P_{orb}/10$), the pulsar's acceleration is approximately constant, and therefore its measured spin frequency drifts linearly in time (e.g. Johnston & Kulkarni 1991). Blind acceleration searches iterate over many constant acceleration values and complete data manipulations in the time or Fourier domain to recover the original signal power that the orbital motion has spread over several frequency bins.

Iterating over acceleration increases the dimensionality of the search and therefore the search complexity. Because of the computational limitations associated with this increased complexity, the acceleration search has not been used for wide pulsar surveys until just this past decade. However, for high priority targeted searches, such as those towards supernova remnants (e.g. Middleditch & Kristian 1984), globular clusters (e.g. Camilo et al. 2000), and *Fermi* unassociated sources (e.g. Ray et al. 2012), these searches have uncovered more than 100 binary pulsars. The vast majority of these pulsars were found using a Fourier domain implementation of an acceleration search (Ransom et al. 2001, 2002), which has recently become known as the Fourier Domain Acceleration Search (FDAS; Dimoudi et al. 2018)[1].

While the FDAS is effective when $T \lesssim P_{orb}/10$, search sensitivity to fainter pulsars improves with longer observing duration as $\sqrt{T}$. Thus, as a practical matter, acceleration searches are largely limited to discovering only the brightest weakly accelerated binary pulsars. To enable the detection of fainter and more highly accelerated systems, we can add another level of approximation to the acceleration search by instead assuming that the next derivative of orbital motion, the "jerk", is constant. Under this assumption, the measured spin frequency changes quadratically with time.

A search over jerk allows us to increase the observation duration to encompass a larger portion of the pulsar orbit than is possible in an acceleration search, while still retaining significant power in the Fourier domain (Bagchi et al. 2013). Therefore, although adding the jerk dimension substantially increases the runtime of the search, it also allows us to probe for systems previously missed in acceleration searches due to residual Doppler smearing. This capability will be especially useful in targeted searches for more exotic systems like Galactic Center pulsars, pulsar-black hole binaries, and the most compact and relativistic double neutron star systems.

We have developed and tested a Fourier domain jerk search as part of the PRESTO[2] software package (Ransom 2001). This paper briefly describes the details and performance of our implementation, and presents the detection of a new pulsar in the globular cluster Terzan 5 found using our jerk search.

2. JERK SEARCH THEORY AND IMPLEMENTATION

Our jerk search functions as a fairly straightforward extension to the original FDAS implemented in PRESTO's `accelsearch` program. The mathematics and methodology of this FDAS are described in detail in Ransom et al. (2002) and Dimoudi et al. (2018). In the following section, we provide just a brief summary.

2.1. *Acceleration Search Review*

In short, the FDAS is a matched filtering algorithm that corrects for Doppler smearing by assuming that the pulsar's acceleration, α, is roughly constant over the course of the observation. Under this assumption, each harmonic of the pulsar signal would experience a constant frequency derivative, $\dot{f}$, according to the relation $\alpha = \dot{f}c/f$, where c is the speed of light and f is the frequency of the harmonic. Using the Convolution Theorem, the algorithm correlates template Fourier domain amplitude and phase responses for a number of trial accelerations with the complex Fourier amplitudes from an FFT of the original input time series. The correlations are completed as a series of short FFTs following a computationally efficient "overlap-and-save" technique (see section 3 of Dimoudi et al. 2018).

When stacked according to the trial $\dot{f}$ value, the resulting power spectra from these correlations form a 2D plane in Fourier frequency vs frequency derivative space. Figure 1 shows examples of such f-$\dot{f}$ planes for both simulated and actual pulsar signals. Once the f-$\dot{f}$ plane is constructed, the algorithm searches through it and identifies candidate pulsar signatures according to a pre-calculated power threshold. The search also incoherently sums the powers from a number of harmonics onto the fundamental to increase the probability of detecting narrow pulse profiles.

For an acceleration search, the template responses can be calculated analytically (see section 4.2.2 of Ransom et al. 2002, for a complete mathematical derivation). With a constant acceleration, we can approximate a harmonic of the pulsar signal as a sinusoid with a quadrat-

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[1] Other algorithms have been developed to detect binary pulsars under different observational conditions, including the Dynamic Power Spectrum when $T \sim P_{orb}$ (Chandler 2003) and phase modulation searches when $T \gtrsim 2P_{orb}$ (Ransom et al. 2003).

[2] https://github.com/scottransom/presto

ically varying phase. Taking the Fourier transform of this signal yields an analytic expression for the template, composed of Fresnel integrals. The simulated signals in the bottom left panel of Figure 1, which show the response of an accelerated (but jerk-corrected) pulsar across three harmonics, also effectively demonstrate the distinctive "X" shape that these templates form when displayed in the f-$\dot{f}$ plane. In bottom right panels, the $z = 0$ lines show the powers of the initial FFT of the time series, without any sort of acceleration or jerk correction.

2.2. *Jerk Search*

Just as the acceleration search is rooted in the approximation of constant acceleration via a linearly varying spin frequency, our jerk search approximates a constant jerk with linearly varying acceleration, or a quadratically varying spin frequency. A constant jerk corresponds to a constant second time-derivative of the frequency,

$$\dot{\alpha} = \frac{\ddot{f}}{f} c = \frac{wc}{fT^3}, \tag{1}$$

where $\dot{\alpha}$ is the jerk and $\ddot{f}$ is the second time-derivative of the frequency. In this equation we also introduce the w parameter, which corresponds to the Fourier jerk in the context of a time-normalized coordinate system where the observation duration is set to $T = 1$ and u represents the fraction of the observation complete at any given instant (such that $0 \leq u \leq 1$). Then, instead of considering frequency f, we define $r = fT$, which represents the wavenumber, or FFT bin (i.e. frequency) number. From this definition, $z = \dot{r} = \dot{f}T^2$ corresponds to the Fourier acceleration or the number of frequency bins that the signal drifts through over the course of the observation. Similarly, $w = \dot{z} = \ddot{f}T^3$ is the number of frequency derivative bins that the signal drifts through over the course of the observation. We use this r, z, w coordinate system throughout our jerk search code, as it is computationally and intuitively convenient when dealing with the properties of discrete Fourier transforms.

The actual mechanics of the jerk search are very similar to what we have just described for the acceleration search. We use the same overall process of overlap-and-save matched filtering, threshold searching, and harmonic summing, except instead of generating an f-$\dot{f}$ plane of powers, we arrange the correlation results in an f-$\dot{f}$-$\ddot{f}$ (or r-z-w) volume which we then search for candidates.

Generating this r-z-w volume requires us to calculate different template responses for correlation. Under the assumption of constant jerk, we approximate a harmonic of the pulsar signal $n(u)$ as a sinusoid with a cubically varying phase

$$n(u) = a \cos \left[2\pi \left(r_0 u + \frac{1}{2} z_0 u^2 + \frac{1}{6} w u^3 \right) + \phi \right] \tag{2}$$

where a is the amplitude of the signal, r_0 and z_0 are the Fourier frequency and frequency derivative at the start of the observation, and ϕ is a starting phase. In the interest of making our jerk search ultimately easier to implement, we want to produce templates that are symmetric in the r and z dimensions. To accomplish this, we can define our initial Fourier frequency and frequency derivative values, r_0 and z_0, in terms of offsets in w from the average frequency and frequency derivative over the course of the observation, $\bar{r}$ and $\bar{z}$,

$$r_0 = \bar{r} - \frac{\bar{z}}{2} + \frac{w}{12} \text{ and } z_0 = \bar{z} - \frac{w}{2}.$$

These relations come from averaging $r(u) = d\Phi/du$ and $z(u) = d^2\Phi/du^2$ from $u = 0$ to $u = 1$, where Φ is the phase of the cosine in eqn. 2.

Expanding eqn. 2 into complex exponentials gives

$$\begin{aligned} n(u) = \frac{a}{2} \Big\{ & e^{2\pi i \left[(\bar{r} - \frac{\bar{z}}{2} + \frac{w}{12}) u + \frac{1}{2} (\bar{z} - \frac{w}{2}) u^2 + \frac{1}{6} w u^3 \right]} e^{i\phi} \\ & + e^{-2\pi i \left[(\bar{r} - \frac{\bar{z}}{2} + \frac{w}{12}) u + \frac{1}{2} (\bar{z} - \frac{w}{2}) u^2 + \frac{1}{6} w u^3 \right]} e^{-i\phi} \Big\}. \end{aligned} \tag{3}$$

The Fourier transform of $n(u)$ is the response of the jerked signal,

$$\begin{aligned} A_{\bar{r}} &= N \int_0^1 n(u) e^{-2\pi i \bar{r} u} du \\ &= \frac{aN}{2} e^{i\phi} \int_0^1 e^{2\pi i \left[(-\frac{\bar{z}}{2} + \frac{w}{12}) u + \frac{1}{2} (\bar{z} - \frac{w}{2}) u^2 + \frac{1}{6} w u^3 \right]} du \end{aligned} \tag{4}$$

where N is the number of samples in our original time series and the second term in eqn. 3 averages to zero. The correlation templates for the search are simply the complex conjugates of eqn. 4.

Unlike the template integral for an acceleration search, eqn. 4 has no analytic solution. However, as in the acceleration case, the template shape is independent of the absolute value of r_0 or $\bar{r}$. This independence allows us to simulate the portion of the binary orbit described by eqn. 2 efficiently in a time series of only a few hundred or a few thousand points, depending on z and w, that we can then FFT and thereby compute the Fourier integral numerically. The simulated signals in the bottom right panel of Fig. 1 show the uncorrected response of the first three harmonics of a jerked pulsar when displayed in the f-$\dot{f}$ plane (located at $w = 0$ in the f-$\dot{f}$-$\ddot{f}$ volume).

Once portions of the f-$\dot{f}$-$\ddot{f}$ volume are computed, they are typically converted to normalized powers, and then either incoherently added to other portions of the f-$\dot{f}$-$\ddot{f}$

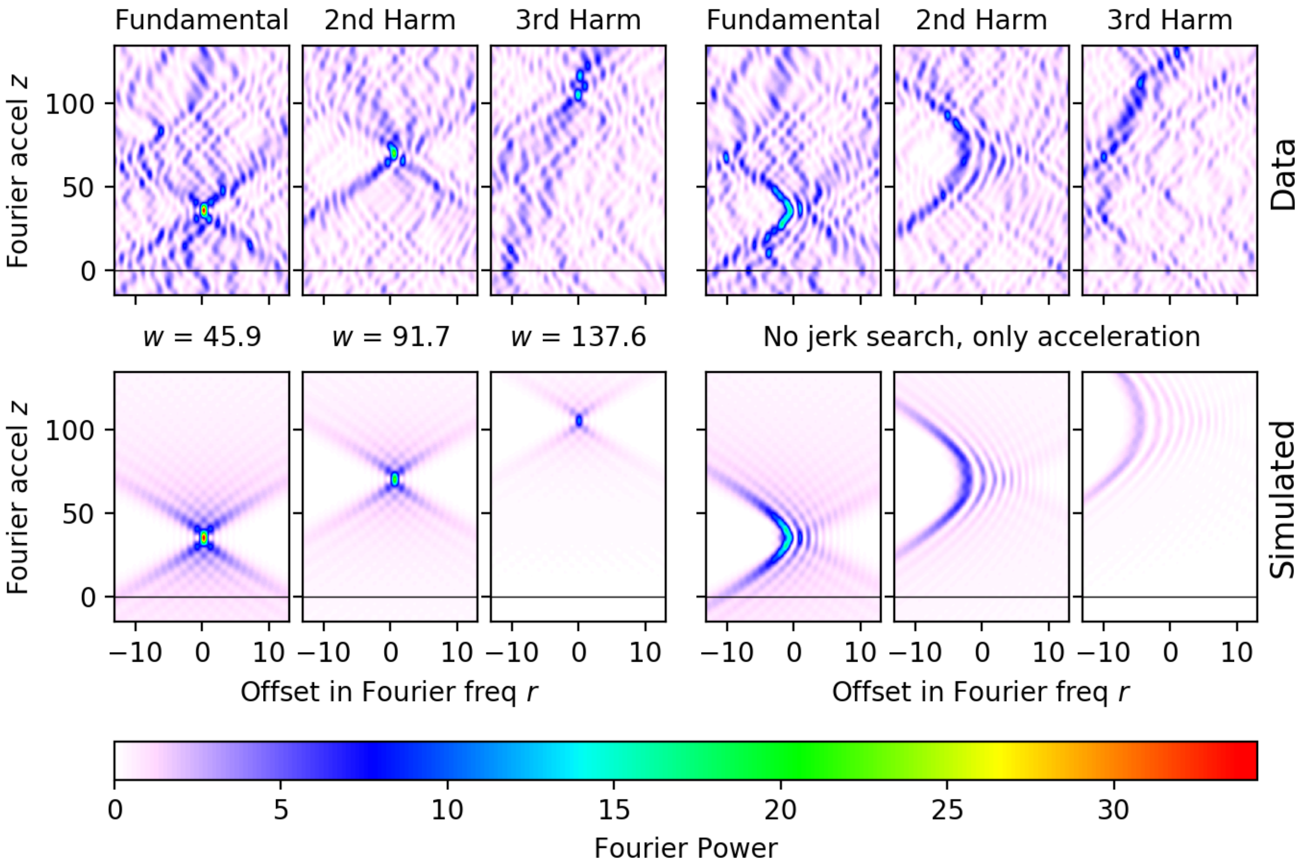

Figure 1. Detection of the first three harmonics of the pulsar J1748−2446M (aka Ter5M) from the exact same portion of the GBT observation where we found the new pulsar, J1748−2446am. Each image shows powers from slices in the f-$\dot{f}$ plane (i.e. Fourier r vs Fourier z) at specific values of the Fourier jerk w. The top and bottom rows show the data or a simulated noiseless response after properly correcting for the jerk of the pulsar during the observation (left three columns) or using only an acceleration search (i.e. with no correction for jerk, right three columns). The detection significance is much higher using the jerk search as more harmonics are detected and each of those harmonics has more power. A completely un-accelerated search would correspond to searching the $z = 0$ line in the acceleration-only search. The simulated signals also effectively show the shapes of some of the Fourier domain search templates for acceleration (left) or jerk searches (right).

volume at signal harmonics, or searched directly for significant signals (see e.g. Ransom et al. 2002). As per a normal Fourier search, the power-normalized incoherent harmonic sums are χ^2-distributed with $2m$ degrees of freedom, where m is the number of summed harmonics. Determining the overall significance of a signal is beyond this paper, however, for well-behaved data (i.e. a relatively uniformly sampled and white-noise dominated input time series), the approximate number of independent Fourier bins searched must be accounted for (i.e. a search trials factor). For a jerk search, the approximate number of independent trials for a single choice of the number of harmonics to sum m, is

$$N_{\rm trials} \sim \frac{N_r}{m}\left(\frac{N_z}{6.95}\right)\left(\frac{N_w}{44.2}\right), \qquad (5)$$

where N_r, N_z, and N_w are the numbers of Fourier frequency bins, z bins, and w bins searched for the highest harmonic summed. The numerical values 6.95 and 44.2 are the Fourier widths at half-power of the Fourier response in the z and w directions, respectively.

When conducting searches, in order to help prevent "scalloping" of a signal's power due to the finite grid of computed r, z, and w points, `accelsearch` oversamples the volume in each of those directions. The grid spacing used is 0.5 (i.e. interbinning or Fourier interpolation), 2, and 20, for r, z, and w, respectively. To determine what range of z and w values to search, we simulated thousands of realistic pulsar binaries and "observed" them with integrations of tens of minutes to hours. Most sys-

Table 1. PSR J1748−2446am

Timing Parameters	
Right Ascension (RA, J2000)	$17^{\mathrm{h}}\ 48^{\mathrm{m}}\ 04\overset{\mathrm{s}}{.}8235(2)$
Declination (DEC, J2000)	$-24^\circ\ 46'\ 47\overset{''}{.}21(9)$
Pulsar Period (ms)	2.933819877244(2)
Pulsar Frequency (Hz)	340.8525546358(2)
Frequency Derivative ($\mathrm{Hz\,s^{-1}}$)	$1.5893(4)\times10^{-14}$
Reference Epoch (MJD)	53700
Dispersion Measure (pc $\mathrm{cm^{-3}}$)	238.193(3)
Orbital Period (days)	0.80010926(2)
Projected Semi-Major Axis (lt-s) .	0.937815(5)
Orbital Eccentricity	0.204736(9)
Epoch of Periastron (MJD)	53700.440278(6)
Longitude of Periastron, ω (deg) . .	337.365(2)
Time Derivative of ω, $\dot\omega$ ($\mathrm{deg\,yr^{-1}}$)	0.454(4)
Span of Timing Data (MJD)	53193−54195
Number of TOAs	217
RMS TOA Residual (μs)	38.5
Derived Parameters	
Mass Function ($M_\odot$)	0.00138336(2)
Total System Mass ($M_\odot$)	1.85(2)
Min Companion Mass ($M_\odot$)	≥ 0.15
Companion Mass ($M_\odot$)	0.194 (+0.11, −0.023)
Pulsar Mass ($M_\odot$)	1.649 (+0.037, −0.11)
Flux Density at 2 GHz (mJy)	$\sim$0.06

NOTE—Numbers in parentheses represent 1-σ uncertainties in the last digit. The timing solution was determined using `TEMPO` with the DE436 Solar System Ephemeris and the DD binary model. The time system used is Barycentric Dynamical Time (TDB). The minimum companion mass was calculated assuming a pulsar mass of $1.4\,M_\odot$. The total system mass and 68% central confidence ranges on the masses of the pulsar and its companion were determined assuming that $\dot\omega$ is due completely to general relativity, and a random orbital inclination (i.e. probability density is uniform in $\cos i$).

tems are detected with $|z| < 200$ and $|w| < 600$. Using larger search ranges with realistic orbits simply results in loss of sensitivity due to a breakdown in the constant acceleration or constant jerk assumptions.

The slices through the jerk volume displayed in Figure 1 illuminate other salient properties of the jerk search that are worth noting. First off, we can see that when the jerk volume is sliced through at the w of the pulsar signal (in this case 45.9), the response of the signal in the resulting f-$\dot f$ plane is the characteristic "X" shape that we expect from a standard acceleration search (see Ransom et al. 2002), indicating that the smearing due to jerk has been mitigated.[3] Another important feature to note is that the higher harmonics of the signal are essentially "jerked" out of significance in the acceleration search. This is just as predicted by eqn. 1, which shows that as the harmonic number (and therefore frequency, f) increases and the jerk remains constant, the Fourier w of the signal must increase proportionally. Thus, higher harmonics are more heavily affected by jerk. This effect is clearly illustrated in the left panel of Figure 1. As the frequency doubles from the fundamental to the second harmonic, the Fourier w also doubles from 45.9 to 91.7. As a result, the detection significance is much higher using the jerk search as each of the harmonics has more power to contribute during harmonic summing.

3. PERFORMANCE

While developing and testing the algorithm and its implementation in `accelsearch`, we repeatedly searched two archival Robert C. Byrd Green Bank Telescope (GBT) observations of the globular cluster Terzan 5 taken 2005 May 15 and 2008 September 12. These data, similar to those described in Ransom et al. (2005), and dedispersed at dispersion measures (DMs) of 238.00 and $238.72\,\mathrm{pc\,cm^{-3}}$, respectively, contain numerous binary MSPs with relatively short orbital periods ($P_b \lesssim 1\,\mathrm{day}$) that are detectable with significant accelerations and jerks over integrations between 10 min to the $\sim$7 hr durations of the observations.

As an example of how detection significances can vary on real pulsars, we describe how five different Terzan 5 MSPs were detected in a single search of a 4096-s segment of the 2005 data, using `accelsearch -numharm 4 -zmax 300` and with and without `-wmax 900`. Each of the reported detection significances are in σ (i.e. equivalent gaussian significance) after correcting for the approximate number of independent trials searched (see §2.2), which is $\sim$41 times larger for the jerk searches than the acceleration searches, using these parameters.

For the isolated MSP Ter5L, the acceleration-only search detected the pulsar with a significance of $7.4\,\sigma$, compared to $6.6\,\sigma$ for the jerk search. Similarly, the weakly accelerating long-period binary Ter5E was detected at 8.9 and $8.2\,\sigma$, respectively, although the total summed power was larger in the jerk search. These results show, as expected, that you pay a penalty with a jerk search for weakly- or un-accelerated pulsars due to the larger phase space searched. The situation was different for the compact binaries Ter5I, M, and N. Ter5I and Ter5M were detected with 1.2 and 3.0 extra sigma in

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[3] For an animated projection through the r-z-w volume for a sinusoid, see http://www.cv.nrao.edu/~sransom/ffdot_wrange.gif

the jerk searches, although Ter5N lost $0.9\,\sigma$ since $w \sim 0$ during that portion of the pulsar's orbit.

These test searches, as well as the thorough analysis performed by Bagchi et al. (2013), show that jerk searches can improve the sensitivity to highly accelerating pulsars with $T \sim 0.05 - 0.15 P_{orb}$ by a significant amount. The penalty is a slightly reduced sensitivity, due to the additional independent trials searched, to weakly or un-accelerated pulsars, and a substantially longer run time, in this case, by a factor of almost 80.

4. DETECTION OF A NEW PULSAR: TER5AM

While searching eleven overlapping segments of duration 4096 s from the 2008 observation, with `-zmax 100` and `-wmax 500`, we detected a highly accelerating new pulsar with a spin period of 2.93 ms, $z = -21$, and $w = -15$ in one segment, using a four-harmonic sum[4]. A similar search, using acceleration but no jerk, did not detect the pulsar, mostly because the higher harmonics had been "jerked" out of significance.

After determining a better DM for the pulsar, we searched other archival observations and detected it several additional times, allowing us to solve the compact and eccentric orbit, and eventually determine a fully-coherent timing solution. Here we present the timing from the first ~1000 days of Terzan 5 observations made with the GBT Pulsar Spigot (Kaplan et al. 2005). Most of the observations were taken at 2 GHz with a usable bandwidth of ~600 MHz (out of 800 MHz total), a sample time of $81.92\,\mu$s, and 2048 frequency channels (see Ransom et al. 2005; Hessels et al. 2006, for details).

The timing solution for PSR J1748−2446am includes a strong detection of the advance of periastron (i.e. $\dot{\omega}$). If entirely relativistic, which is likely given a white dwarf companion, the total mass of the system is $1.85 \pm 0.02\,M_{\odot}$, and the component masses can be constrained with the mass function by assuming random inclinations (see Table 1). A longer-duration timing solution, comprising ~14 yrs of Spigot and coherently-dedispersed GUPPI data will be presented elsewhere (Ransom et al., in prep.).

5. CONCLUSIONS

In this paper we have presented the implementation and performance of a new Fourier domain jerk search, which extends the PRESTO FDAS to account for linearly varying acceleration (i.e. constant jerk). Consistent with the analysis conducted by Bagchi et al. (2013), we find that our algorithm can significantly improve search sensitivity to pulsar binaries where $T \sim 0.05 - 0.15 P_{orb}$. Trade-offs of the algorithm include a significantly longer runtime and decreased sensitivity to un-accelerated systems due to the increased independent trials factor. While testing our algorithm on GBT observations of the globular cluster Terzan 5, we discovered Ter5am, an interesting compact eccentric binary that already shows relativistic periastron advance. Other relativistic effects (such as relativistic γ) will likely become detectable in coming years, allowing us to obtain precise mass measurements for both objects in the system.

Looking to the future, this jerk search technique will be especially useful in high profile targeted searches for exotic systems such as Galactic Center and globular cluster pulsars, pulsar-black hole binaries, and the most compact and relativistic double neutron star systems. Since each of the template correlations in the r-z-w volume are independent of each other, this technique also has parallelization potential. While the current implementation makes use of OpenMP, a straightforward extension of the Dimoudi et al. (2018) methodology would allow us to implement the jerk search on GPUs. This could significantly reduce the runtime cost of the algorithm, opening it up to wider use and less focused searches.

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Software: PRESTO (Ransom 2001)

Facility: GBT

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[4] We also detected 9 other known binary pulsars showing accelerations and jerks: Ter5A, E, I, J, M, N, V, ae, and ai. For a full list of pulsars in the cluster, see: http://www.naic.edu/~pfreire/GCpsr.html

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