A Search for High-Impact MSPs for the NANOGrav PTA

Introduction and Scientific Motivation

The direct detection of gravitational waves (GWs) has already opened a new window on the universe (Abbott et al. 2016). Even this single detection has revealed unexpected astrophysical sources, and the field will expand to probe astrophysical phenomena for which electromagnetic observations are insufficient or impossible. Unlike the kHz GWs recently observed, pulsar timing arrays (PTAs) are sensitive to GWs of nanohertz frequencies, where the most promising sources are a stochastic gravitational wave background (GWB) from supermassive black hole binary (SMBHB) coalescences in the early universe, nearby SMBHBs that emit continuous waves (CW), and bursts with memory (BWM). As a GW passes through the Earth and surrounding spacetime, pulsars' pulse arrival times will be delayed or advanced in a characteristic pattern. For an isotropic GWB, the correlations between pulse arrival times for a given pulsar pair depends on the angular separation of those pulsars in accordance with the so-called 'Hellings & Downs curve' (Hellings & Downs 1983; Figure 1); the magnitude of the correlations will also depend on the amplitude of the GWB.

Siemens et al. (2013) and Taylor et al. (2015) showed that, in addition to high timing precision (with a target residual rms $\lesssim 100\,\mathrm{ns}$), significantly increasing the number of MSPs (N_{MSP}) in PTAs is essential to detect the GWB on a reasonable timescale, because the power of the background signal increases linearly with N_{MSP}. In particular, starting with the current NANOGrav array and the most stringent limit on the GWB amplitude (Shannon et al. 2015), Taylor et al. (2016) showed that **adding $\sim$4 MSPs with $\approx$250 ns long-term RMS timing residuals to NANOGrav each year will likely yield a detection of the GWB within the next decade.** One of the primary goals of current pulsar searches is therefore to find MSPs that can be added to PTAs.

In addition to increasing N_{MSP}, it is also clear from the Hellings and Downs curve that MSP pairs with angular separations $\zeta < 30^\circ$, $\sim 80^\circ$, and $> 160^\circ$ would enhance our ability to distinguish a GWB signal from background noise. It is especially beneficial to add MSPs with these separations from the best-timed PTA MSPs, as they provide comparatively smaller errors on individual correlations. Siemens et al. (2013) shows $\rho \propto \sqrt{\sum_{N_{\mathrm{pair}}} \Gamma^2(\zeta)}$, where ρ is the signal-to-noise ratio of the GWB in a PTA, Γ is the correlation term from Hellings & Downs (1983), the sum is over all pulsar pairs in the array, and ζ is the angular separation of an individual pair. As new pulsars are added to the array, there is an improvement in the signal-to-noise ratio of the GWB given by the angular position of this new MSP. Figure 1 shows the relative increase in ρ from adding an MSP at any position on the sky compared to the ρ given by the ten best-timed NANOGrav MSPs, as described in NANOGrav Collaboration (2015). Just **one additional MSP discovered in the highlighted 20° region of the sky would increase ρ by** $\sim 20\%$.

There has been a thus-far successful push to find new MSPs that can be added to NANOGrav and other PTAs, in particular through deep all-sky pulsar surveys (e.g., Stovall et al. 2014) and through searches for radio pulsations in the error ellipses of gamma-ray sources that lack confirmed associations with known multiwavelength objects (e.g., Ransom et al. 2011, Hessels et al. 2011, Cromartie et al. 2016). As of June 2014, 6.5% of the unassociated gamma-ray sources detected by the *Fermi* Large Area Telescope (LAT) that were searched with radio telescopes were found to be new MSPs with $P < 30\,\mathrm{ms}$. Of these new MSPs, 22% (11 MSPs) are now being timed by NANOGrav and other PTAs, and up to 25% are still under consideration for inclusion. Depending on the specific comparison, LAT-guided targeted searches are between one and several orders of magnitude more efficient in finding PTA-quality MSPs than are current pulsar surveys.

Proposed Observations and Target Selection

We propose to search for new MSPs in the 20°-radius cone of Figure 1, with the goal of opti-

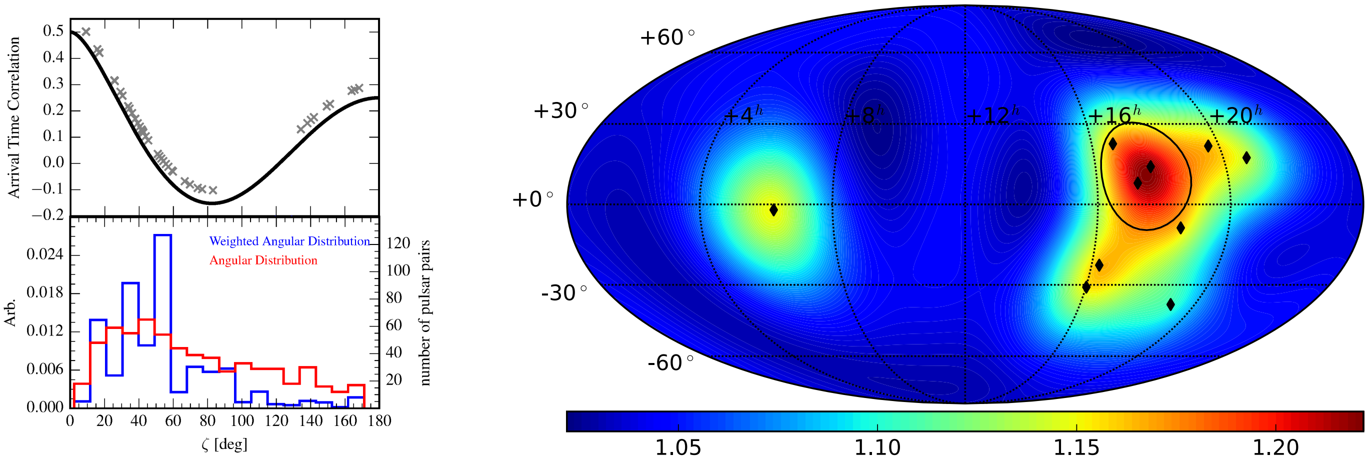


Figure 1: *Left:* The correlation curve from Hellings & Downs (1983) is plotted in the top panel. Green marks denote pairs between the ten best-timed MSPs. The bottom plot is taken from Figure 1 of Arzoumanian et al. (2015) and shows the unweighted (red) and cross-correlation-weighted (blue) angular distributions of NANOGrav MSPs from the nine-year dataset. There is a clear deficit in pulsar pairs with $\zeta < 20°$. *Right:* The improvement in the signal-to-noise ratio of a GWB from adding a pulsar at a given sky position. This is calculated with only the ten NANOGrav pulsars with lowest white noise RMS values, both pre- and post-whitening. Black diamonds mark pulsar positions, and the circle denotes the region on the sky that has been identified for specific targeting. An MSP in this location would give a much larger boost to the SNR of a GWB in the NANOGrav dataset when compared to an identical pulsar in a different part of the sky.

mizing our sensitivity to the shape of the Hellings and Downs curve. Rather than surveying the full region, we propose to target *Fermi* LAT unassociated sources in this region of the sky. Within this region, we have identified $\sim$70 gamma-ray sources from the 3FGL LAT catalog that (a) have no multi-wavelength association, (b) are associated with a multi-wavelength object of unknown nature, or (c) have an unconfirmed association with a multi-wavelength object. Because these associations are positional, sources with unconfirmed non-pulsar associations can (and sometimes do) turn out to be pulsars, so we do not immediately exclude them from our source list.

As has been widely recognized (e.g., Ackermann et al. 2012), pulsars typically display low variability in gamma-ray flux and high gamma-ray spectral curvature. Gamma-ray flux is not an indicator of radio brightness (bright radio MSPs have been found in faint gamma-ray sources), so we have not excluded faint gamma-ray sources from our list. From the 3FGL point source catalog, we find that the ratio of curvature significance to detection significance, $\sigma_{\rm curve}/\sigma_{\rm det}$, has typical values of 0.32 ± 0.13 for known gamma-ray pulsars and for the subset of MSPs found through *Fermi*-guided searches, with little or no dependence on $\sigma_{\rm det}$ (Figure 2), and that known pulsars and MSPs have variability indices $20 < V < 80$ (excluding exceptional cases like the Crab and PSR J2021). Examining the left panel of Figure 2, we exclude from our target list sources with $V > 65$ and $\sigma_{\rm curve}/\sigma_{\rm det} < 0.15$. This resulted in the list of 25 sources that we propose to search (Table 1).

We note that there are already 15 fully-recycled MSPs aside from J1713 in this "hot spot," three of which are being timed by NANOGrav (J1600, J1738, and J1741) and one more which will be added in the coming year (J1745, which was discovered in a similar *Fermi*-guided search). The rest have been excluded because they are too weak, have too broad a pulse, or have timing residual RMS values that are too large for inclusion. Given that $\sim 6.5\%$ of the *Fermi* sources searched have led to MSP discoveries, we expect that we will find 1–2 MSPs in this region of the sky. Additionally, because we expect ~ 100 detectable MSPs to be located in this part of the sky (discussed below), it is possible our search will have a yield significantly greater than 6.5%.

We request 23 hr of time to observe a total of 25 Fermi sources in the 20-degree radius hotspot region. We will observe at 1374 MHz with the ALFA receiver and the Mock Spectrometer backend with 300 MHz bandwidth, which has been successfully employed for pulsar searches by the PALFA survey (Lazarus et al. 2015). This time will be split into 2 observations per source, where each observation consists of one or three 10-minute integrations (three if the LAT error circle is larger than the $3.8' \times 3.5'$ beam of one of the seven ALFA receivers), and allows for 25% overhead per observation for setup and slewing. Details of the observation strategy are given in the Technical Justification below.

Technical Justification and Expected Results

We propose to observe each of the 25 *Fermi* sources twice, with 600 s integrations per pointing. This dual-pass observing strategy will improve our chances of detecting scintillated or highly accelerated binary pulsars, and will reduce the adverse effects of transient RFI. Our targets are taken from the 3FGL LAT catalog, in which point sources have typical 95% positional uncertainties between $\sim 5'$–$20'$. Before these observations occur, co-I E. Ferrara will obtain significantly improved positional error ellipses from the 4FGL catalog (currently still internal to the LAT collaboration). We expect that up to half of our sources will have positional error ellipses that fit inside a single Arecibo L-band beam at the 95% uncertainty level, so that for these sources we will only require one L-Wide pointing per observation. For the remaining sources, we will use three 600 s ALFA pointings in order to search the complete position error ellipse. Assuming that 15 sources will require three pointings per observation and 10 sources will require one pointing, and including 25% overhead time for setup and slewing, we require a total of 23 hr observing time.

Radio sensitivity limits in our region of interest (see Figure 2) are determined by PALFA and AO-Drift coverage as well as planned coverage by HTRU-North, providing a combined, median sensitivity limit of $S_{1400} = 0.16$ mJy. The median sky temperature in the region is a factor of ~ 40 times higher at 327 MHz than it is at 1374 MHz (center frequencies of AO-Drift and PALFA surveys respectively), while the boost in flux at low frequency (due to pulsars' steep spectral indices $\alpha \sim -1.4$; Bates 2013) is only a factor of ~ 10. Combining the effects of sky temperature and pulsar spectral indices with other differences between AO-Drift and PALFA observing set-ups (e.g. bandwidth, receiver temperature, channel bandwidth, etc.) implies that high-frequency observations are more sensitive in our region of interest by a factor of ~ 4.

Simulating a millisecond pulsar population, using parameters suggested in e.g. Swiggum et al. (2014), we find that ~ 650 MSPs lie inside the region shown in Figure 2, although we expect that most of these are intrinsically dim and/or too distant to be detectable. There are 16 simulated MSPs with fluxes above the current median sensitivity limit in the 20°-radius conical region, which agrees nicely with the number of known MSPs there (15). Considering a PALFA-like observing set-up with increased integration time (600 s), we find a median sensitivity limit of $S_{1400} = 0.015$ mJy, more than a factor of 10 better than the current median value. There are 100 simulated MSPs above this sensitivity limit.

Comparing the sensitivities of proposed observations with those of previous surveys in our region of interest, we show that the proposed observations could easily detect sources that were previously missed. Careful analysis of a simulated MSP population indicates a good chance of overlap between previously-missed MSPs (detectable with our proposed observing set-up) and *Fermi* LAT unassociated sources noted in Table 1. Combining the predicted MSP density in this region with the 6.5% rate of MSP discoveries in *Fermi* sources, we expect to find 2–3 new PTA MSPs.

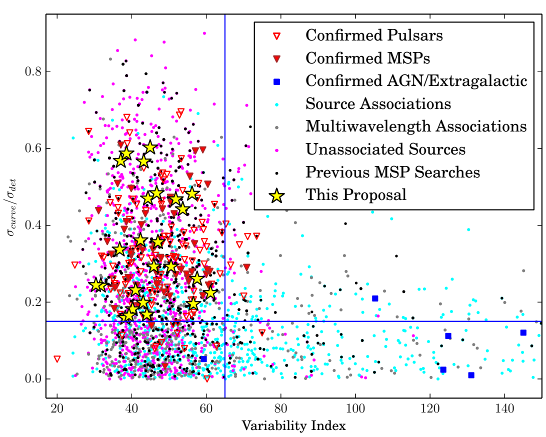
Proposal Team and Productivity

The PI has not led an Arecibo proposal before, but all co-investigators are active members of the NANOGrav collaboration, the *Fermi* Pulsar Search Consortium, and/or the ongoing PALFA (at

Arecibo) or GBNCC (at Green Bank) pulsar sky surveys. Our team already has processing scripts from these other searches, and will use computer clusters at West Virginia University, the University of Wisconsin-Milwaukee, and the National Radio Astronomy Headquarters in Charlottesville, VA that are already used for pulsar searching. This proposal is part of the larger NANOGrav effort to detect GWs; two of the co-Is (J. Simon and D. Madison) are experts in GW detection. NANOGrav has produced a number of important results recently using Arecibo data from NANOGrav proposals (e.g., Arzoumanian et al. 2015).

For NSF-defined broader impacts, these observations will provide *Direct Research Experiences and Training for Undergraduates*. Some of the search observations will be conducted by undergraduates in the Arecibo Remote Command Center (ARCC) program at UWM and F&M (two of the national ARCC sites). ARCC has been successful in giving real research opportunities to undergraduates and introducing them to pulsar research. ARCC students may also help reduce the data and search for pulsar candidates.

References: Abbott, B. P. et al. 2016, Phys. Rev. Lett. 116, 061102 • Arzoumanian et al. 2015, ApJ, 813, 65 • Bates, S. D. 2013, MNRAS, 431, 1352 • Chamberlin, S. J. et al. 2015, Phys Rev D, 91, 044048 • Cromartie, T. et al. 2016, arXiv:1601.05343 • Hellings, R. W., & Downs, G. S. 1983, ApJL, 265, L39 • Hessels, J. W. T. et al. 2011, AIPC, 1357, 40 • Lazarus, P. et al. 2015, ApJ, 812, 81 • Ransom, S. M. et al. 2011, ApJ, 727, 16 • Shannon, R. M. et al. 2015, Science 349, 1522 • Siemens et al. 2013 • Stovall, K. et al. 2014, ApJ, 791, 67 • Swiggum, J. K. et al. 2014, ApJ, 787, 137 • Taylor et al. 2015, arXiv:1511.05564



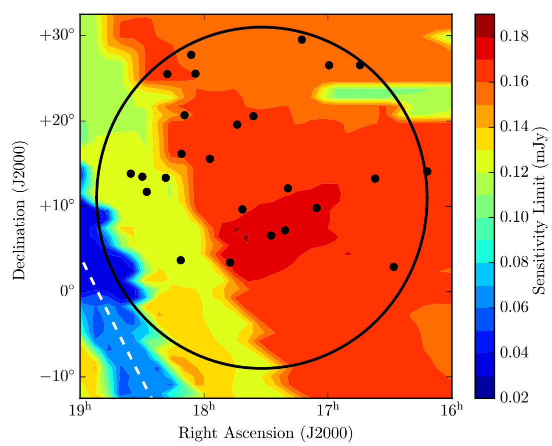


Figure 2: *Left:* The ratio of curvature to detection significance plotted against variability index for 3FGL point sources, whose source types are given in the legend. Blue lines show variability and spectral cuts. Black points are LAT sources that have been or will be searched through other proposals. The yellow stars show the LAT sources targeted in this proposal. *Right:* Colored contours show the lowest current sensitivity limits reached by recent pulsar surveys as a function of sky position; surveys contributing to the coverage shown here include the High Time Resolution Universe North (HTRU-N) survey, Pulsar Arecibo L-band Feed Array (PALFA) survey, and the Arecibo 327 MHz drift scan survey. Sensitivity limits from surveys with different center frequencies have been normalized to 1400 MHz by assuming a typical pulsar spectral index, $\alpha = -1.4$. The solid black line indicates the boundary of the “hotspot” shown in Figure 1. The Galactic plane is indicated here with a white, dashed line and black circles show positions of the 25 *Fermi* LAT unassociated sources we plan to target. Note that many of these targets lie in regions surveyed to a sensitivity limit of $S_{1400} > 0.15$ mJy, while our estimated sensitivity is 2–10× deeper.