Upper Limits on High-Frequency Single-Source Gravitational Waves

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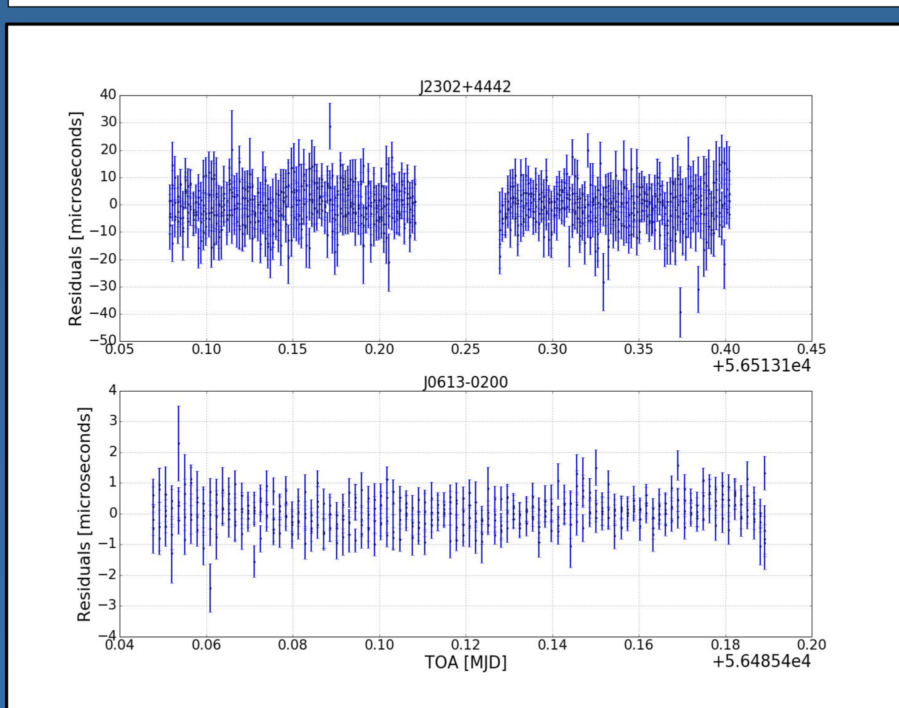
ABSTRACT

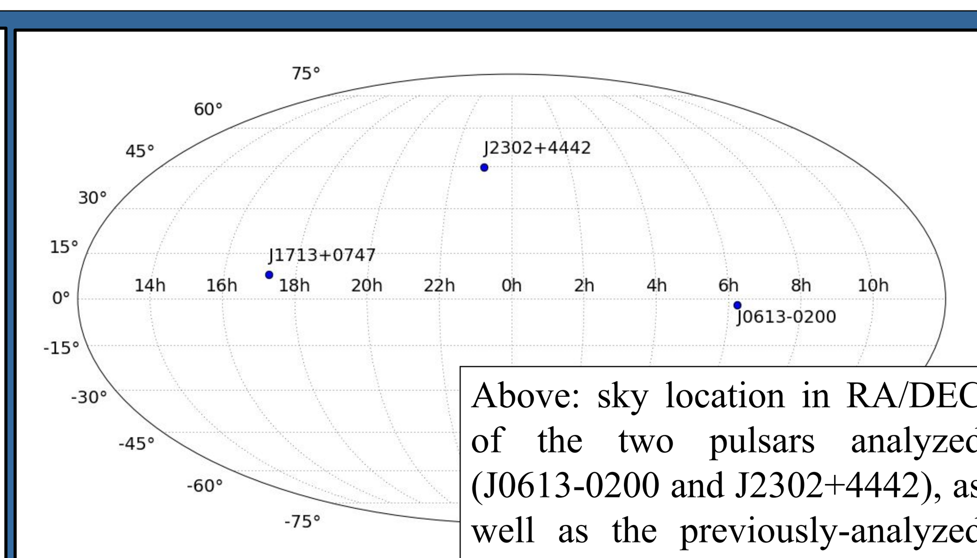
Multiple-hour long observations of single pulsars allow us to probe high-frequency regions of the gravitational wave (GW) spectrum typically outside the sensitivity of pulsar timing arrays. Using single-pulsar Shapiro delay measurements from the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) taken by the NRAO Green Bank Telescope (GBT), we apply known techniques for detecting continuous wave (CW) sources. By analyzing simulated data with an injected source, we verify the accuracy of the CW search method for hours-long data sets. Furthermore, by applying an identical analysis to the true data, we find that the data places new upper limits on high-frequency CW strains. Specifically, due to the positions of the pulsars analyzed, stronger directional limits can be placed on CW sources in the high GW frequency regime.

DATA

In 2013, eight pulsars were observed at the GBT for extended periods of time for the initial purpose of observing NANOGrav pulsars with significant Shapiro delays in order to better measure the delays and therefore improve timing models (Pennucci et al. 2015, Fonseca et al. 2016). Of the eight data sets, two were chosen for our analysis. Both J2302+4442 and J0613-0200 had small rms residual values and long continuous timing tracks. Each pulsar was observed three times over the course of the full observation period. For each pulsar, the longest single observation track was selected for observation. J2302 was observed continuously for over eight hours, and J0613 was observed continuously for over three hours. The residuals were generated using the tempo2 software (Hobbs et al. 2006), drawing its parameters from NANOGrav's 9-year data release. The binary orbit periods of each pulsar are of particular interest, as a binary period naturally weakens the sensitivity of the pulsar to continuous wave sources of a similar frequency. The binary period for pulsar J2302 is given as about 126 days, and the binary period for pulsar J0613 is given as about 1.2 days.



Above: residual plot for the three hour observation of J0613-0200 (bottom) and the eight hour observation of J2302+4442 (top). Integration time is 120s, and error bars are at the 1-sigma level. Data from four separate sub-bands in the 820MHz band are plotted.



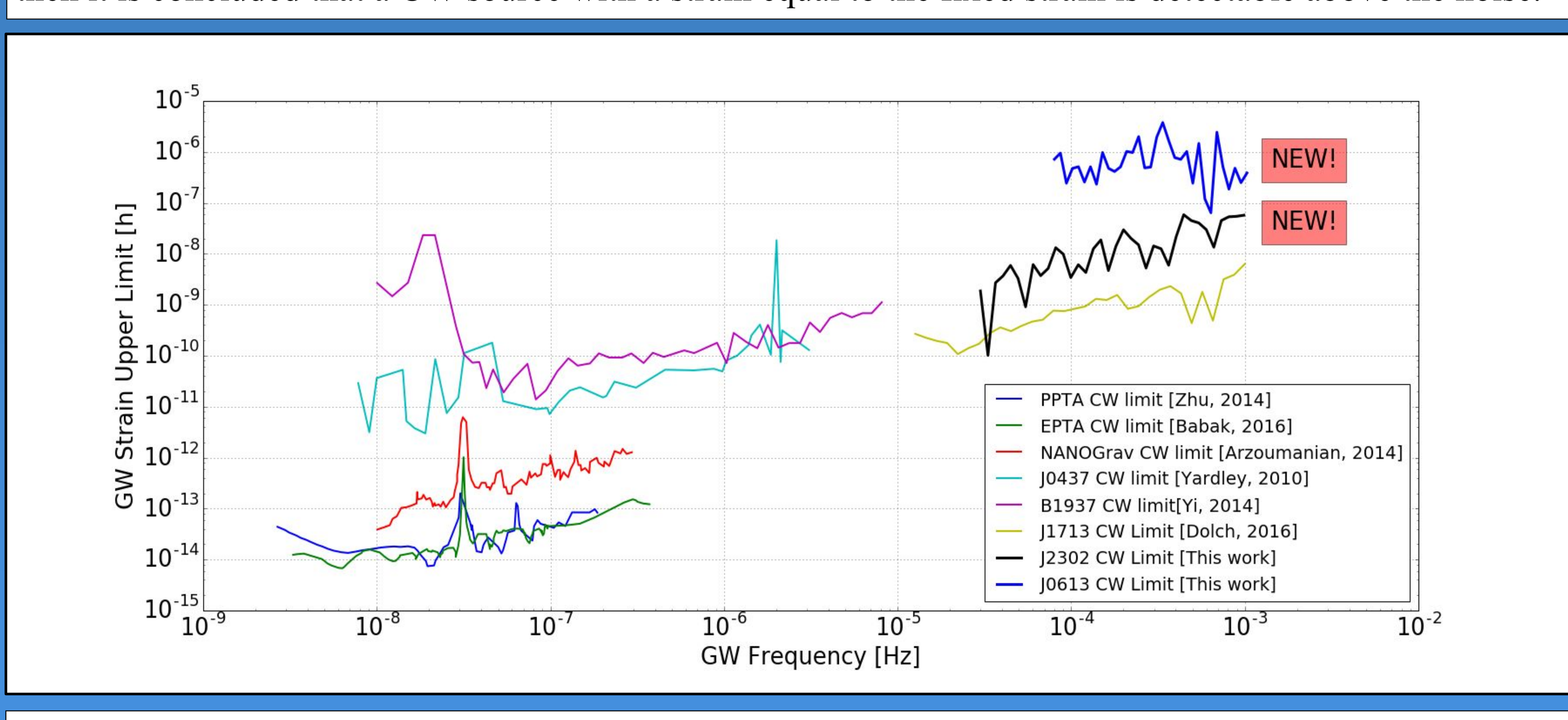
Above: sky location in RA/DEC of the two pulsars analyzed (J0613-0200 and J2302+4442), as well as the previously-analyzed J1713+0747. Further analysis will put stronger limits on continuous wave strain amplitudes in the directions of J0613-0200 and J2302+4442.

Left: the 100m Robert C. Byrd Green Bank Telescope in Green Bank, WV, USA. Image courtesy of NRAO/AUI.

GENERATING A GRAVITATIONAL WAVE LIMIT

Even without a detection, upper limits on GW strain amplitude can still be determined. This is done by simulating fixed-strain CW sources with a random sky location and inclination, and seeing if they can be detected with the given noise model. By ramping up the injected source's strain amplitude until a detection is made, we obtain the lowest detectable strain—the strain limit—for that GW frequency. Running this analysis across a range of frequencies determines the upper limit curve.

For this analysis, 5,000 sources were sequentially simulated, and using the fixed noise model, simulated residuals are generated. From these generated residuals, the Fp statistic for the simulated data is calculated. A source is labelled "detectable" if the simulated data's Fp statistic is higher than the corresponding Fp statistic in the actual data. If more than 95% of the simulated sources are detectable, then it is concluded that a CW source with a strain equal to the fixed strain is detectable above the noise.



Recent single-source omnidirectional GW limits from the PPTA, EPTA, and NANOGrav, as well as single-pulsar limits from J0437-0745 and B1937+21. Also plotted is the high frequency limits obtained in this analysis from J0613-0200 and J2302+4442, and the previously published limit from J1713+0747. Of the two new results, J0613-0200 has lower rms residual values but is less limiting, probably due to Shapiro delay harmonics given its 1.6 day binary period.

BACKGROUND

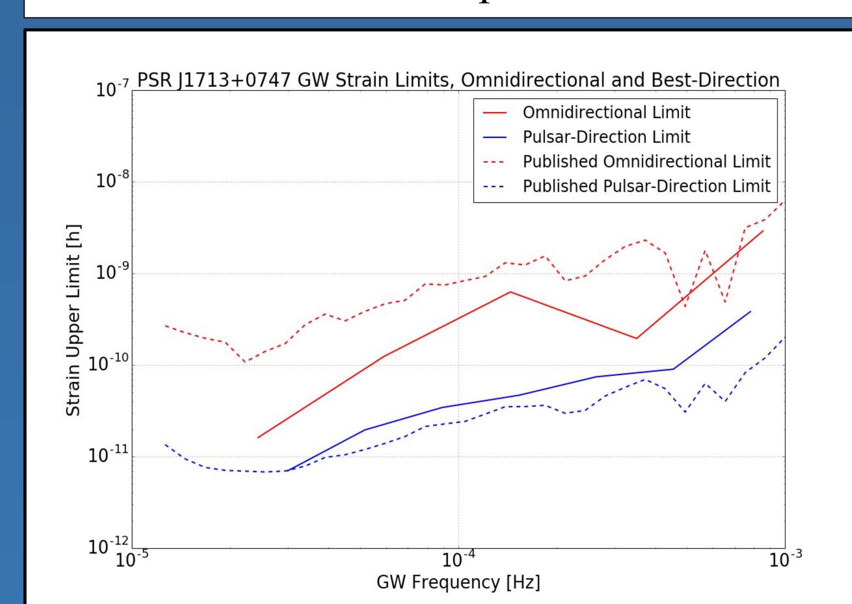
The International Pulsar Timing Array (IPTA) is tuned to probe GW frequencies on the months-to-years timescale. Observations of individual pulsars are carried out on a weekly-to-monthly basis, due to the large amount of pulsars needed to be observed. With such infrequent observations, however, GW periods on the order of hours remain unexplored. This is due to the intrinsic limit on detection set by the Nyquist frequency. Beyond this frequency, the sampling rate is not enough to properly detect a CW, and any such CW signal would appear as white noise in the data (Yi & Zhang 2016).

Recently, a 24 hour global observation was carried out on J1713+0747 (Dolch et. al. 2014), which resulted in a new set of limits on CW strain in the days-to-hours frequency range due to the average sampling rate of about 0.5 samples/min. Limits were set for both CW sources in the direction of J1713 and for random-direction CW sources. However, J1713 is not the only pulsar that has been observed for long, continuous observations. The pulsars J2302-0200 and J0613+4442 were each observed for multiple hours at a time, originally for the purpose of measuring the Shapiro delay of each pulsar. Such data sets allow for analysis similar to that done on the J1713 24-hr campaign. These pulsars allow for better directional limits to be placed in the 10^{-5} to 10^{-3}Hz frequency range.

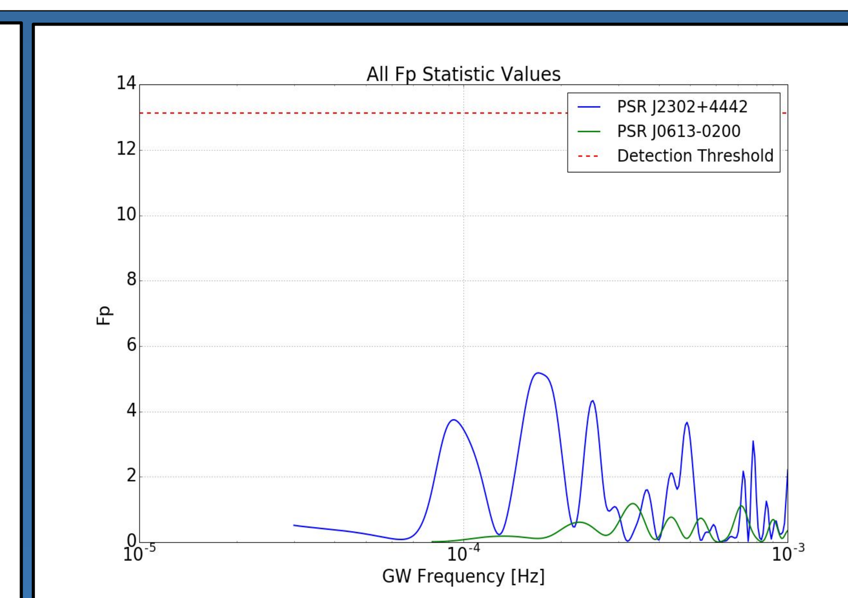
METHODS

For each pulsar, we developed a noise model that included both white and red noise estimations. Five parameters were varied: EFAC, two EQUAD, Jitter-EQUAD, RNAMP, and RNIND. The five parameters were chosen for a noise model that has been used in previous analysis schemes. The EFAC parameter acts as a constant multiplier on the TOA uncertainties. The EQUAD and Jitter-EQUAD parameters represent additional Gaussian white noise added to the EFAC noise. The RNAMP and RNIND parameters describe the amplitude and spectral index of a red noise variance. Using the Markov Chain Monte Carlo method for exploring parameter spaces, we found the maximum a posteriori values for each parameter, and used them to construct the noise covariance matrix.

Our main tool for analyzing the sensitivity of a pulsar to continuous wave sources is the Fp statistic (Arzoumanian et. al. 2014). The Fp statistic is a frequentist detection statistic that can be thought of as a measure of how much a particular frequency dominates the data. A high Fp statistic is indicative of a potential CW source at that frequency.



Upper limit on GW strain for CW sources from PSR J1713+0747, both omnidirectional and pulsar-direction. Also plotted is the published upper limit curve (Dolch et. al. 2016) from the same data set. The coincidence of our results with the published results gives confidence for our pipeline.



The Fp statistic calculated from the residuals. The dashed line shows the minimum Fp value needed to claim a detection with a false alarm probability of 10^{-4}.

CONCLUSIONS

Using our pipeline, we were able to recreate the omnidirectional and directional limits from the J1713+0747 24 hour global campaign, which verified the integrity of our analysis algorithm. Using observations from the GBT on PSR J0613-0200 and PSR J2302+4442, we are able to place omnidirectional limits consistent with limits already placed in that GW frequency range. Further analysis will be able to place more strict directional limits on CW strain amplitude in directions that have not been probed before in this frequency range.

NEXT STEPS

Further analysis will attempt to remove statistical fluctuations in the data through using a greater number of simulations. Directional limits can be placed in the direction of both J2302 and J0613. Also, similar analyses can be carried out on each of the other six pulsars observed by the GBT in the Shapiro delay project. For each pulsar, strict directional limits on CW strain amplitude can be placed for GW frequencies in the 10^{-4} to 10^{-3}Hz range.

ACKNOWLEDGMENTS

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References: Arzoumanian et al. (2014), Babak et al. (2016), Dolch et al. (2014), Dolch et al. (2016), Hobbs et al. (2006), Pennucci et al. (2015) [PhD thesis], Fonseca et al. (2016), Yardley et al. (2010), Yi et al. (2014), Yi & Zhang (2016), Zhu et al. (2014)