

Chapter 5 Multi-Messenger Astronomy: Pulsar Timing

Summary: Pulsar Timing

Authors: Thankful Cromartie (on behalf of the SAC)

In the 55 years since their discovery, pulsars have gained recognition as indispensable probes of a wide range of astrophysics, including low-frequency gravitational waves, the interstellar medium, and the neutron star interior equation of state. The DSA-2000 will provide the superior sensitivity and frequent observing cadence required for high-precision millisecond pulsar (MSP) timing (Section 4.4), and is therefore positioned to become a world-class instrument for work in the three aforementioned scientific areas.

Low-frequency gravitational waves from supermassive black hole binaries: Pulsar timing array experiments conduct frequent observations of a network of precisely-timed MSPs in order to search for correlated deviations in their pulse arrival times characteristic of a stochastic background of low-frequency (nHz) gravitational waves. The North American Nanohertz Observatory for Gravitational Waves (NANOGrav) collaboration is one such experiment. Along with partner members of the International Pulsar Timing Array, NANOGrav has detected a common red noise process in its pulsars that may signal the presence of such a gravitational wave background, and is expected to imminently announce evidence for the “smoking gun” spatial correlations that such a background would induce.

NANOGrav is slated to be one of several key DSA-2000 projects (Sections 4.1, 4.2). Notably, the DSA-2000 will enable NANOGrav to time ~ 200 MSPs at better-than-monthly cadence, which more than doubles the number of MSPs currently in the array. Because the number of MSPs timed is the largest contributor to gravitational wave background sensitivity, DSA-2000 will enable much improved characterization of the nHz gravitational wave background spectrum. What’s more, the DSA-2000 will come online in time to help NANOGrav more quickly gain sensitivity to single (continuous) binary black hole mergers with the flexibility to facilitate weekly observations as needed (Section 4.5). Excitingly, this also introduces the prospect of pursuing truly multi-messenger astrophysics by following up EM events from surveys such as the Rubin LSST and searching for individual sources in pulsar timing array data (Section 4.3).

Probing the interstellar medium: Observations of radio pulsars provide a novel method for probing the ionized interstellar medium (ISM). As emission from the pulsar traverses its path to the Earth, it undergoes dispersive delays ($\propto \nu^{-2}$), refraction, scattering, and scintillation. The DSA-2000 will enable monitoring of ISM variability on a wide range of spatial scales using both observations of the ~ 200 MSPs timed by NANOGrav, as well as countless Galactic and extragalactic transients (Sections 4.8, 4.9). Sophisticated algorithms designed to recover intrinsic pulse profiles broadened by ISM scattering require high S/N data such as those that result from DSA-2000 observations.

Neutron star mass measurements and more: Precise measurements of the masses of neutron stars $> 2M_{\odot}$ place straightforward and important constraints on the equation of state describing the behavior of the supranuclear-density matter inside these objects’ cores. A subset of the pulsars timed by DSA-2000 will show evidence of the relativistic Shapiro delay, which helps constrain the masses of pulsars and their companions. Through both NANOGrav’s regular monitoring of ~ 200 MSPs, as well as orbital phase-targeted observations of promising systems, DSA-2000 will be a significant contributor to a growing collection of highly precise neutron star mass measurements (Section 4.6).

The DSA-2000 will facilitate advances in areas of pulsar astrophysics outside of the relatively narrow selection of pulsar timing array sources. By searching for circularly polarized sources in the Galactic plane at high frequencies, the DSA-2000 could help uncover energetic young pulsars that were too highly scattered to be discovered by other searches of the plane (Section 4.7).

5.1 Gravitational Wave Astrophysics with Pulsar Timing Arrays

Authors: M. E. DeCesar

Summary

Pulsar timing arrays are sensitive to nanohertz-frequency gravitational waves, with binary supermassive black holes being the primary expected source. A gravitational wave background is expected to be the first source detected by these arrays, followed by one or more individual binaries in the foreground; NANOGrav and other arrays have begun to see hints of such a background signal. The DSA-2000 will be the primary facility used by NANOGrav. Its high sensitivity and sky coverage will greatly increase NANOGrav's sensitivity, allowing improved characterization of the gravitational wave background and highly increased sensitivity to individual sources.

State of the Field

The gravitational-wave (GW) spectrum spans many orders of magnitude in frequency. Thus far, GWs have only been detected at high frequencies ($\gtrsim 10$ kHz) by the LIGO-Virgo ground-based interferometers. Pulsar timing arrays (PTAs) are poised to make the first detection of GWs at much lower, nanohertz (nHz), frequencies ($\sim$ light-year wavelengths). The most likely expected sources of nHz GWs are supermassive black hole binary (SMBHB) systems, formed in the aftermath of galaxy mergers and brought to < 0.01 pc separations through dynamical and environmental interactions. Some other potential sources include cosmic strings, inflation-era relics, dark matter, and primordial black holes. The first detection expected from PTAs is that of a stochastic GW background (GWB) produced by a population of inspiraling SMBHBs, followed by continuous-wave (CW) detections of one or more individual SMBHB systems (for a review of nHz GWs and PTA science, see, e.g.: Burke-Spolaor et al. 2019; Verbiest, Osłowski, and Burke-Spolaor 2021; Taylor 2021).

PTAs are composed of many millisecond pulsars (MSPs) that are highly stable in their spin properties and are timed with high precision for years to decades (the best-timed MSPs to date have timing precision ~ 100 ns over more than a decade). GWs passing through spacetime local to the Earth alter the light travel time to the pulsars, causing very small (~ 10 – 100 ns) and slowly-varying deviations in their pulse arrival times. GW-induced timing residuals are correlated between pulsars, with a stochastic GWB inducing quadrupolar spatial correlations between pulsar pairs, the Hellings-Downs correlation curve (Fig. 1a; Hellings and Downs 1983).

There are several PTAs carrying out MSP timing campaigns around the world. Four of them—the European, Indian, and Parkes PTAs (EPTA, InPTA, and PPTA), and the North American Nanohertz Observatory for GWs (NANOGrav)—together constitute the International PTA (IPTA), which combines the constituent PTAs' data into a single, more sensitive data set. The NANOGrav 12.5-yr data set, as well as the most recent EPTA and IPTA data sets, showed the first strong evidence for a low-frequency spectral process common to the MSPs in the array (e.g., Fig. 1b; Arzoumanian et al. 2020; Chen et al. 2021; Antoniadis et al. 2022), the first hint of a GWB expected before detecting Hellings-Downs spatial correlations. The NANOGrav 15-yr data set, the EPTA and PPTA data sets, and the next IPTA data set are all in progress and may find further evidence for a GWB.

DSA-2000's impact

The DSA-2000 will be the primary telescope used by NANOGrav for the detection and characterization of nHz GWs. It is expected that NANOGrav, and likely other PTAs, will have detected the GWB by the

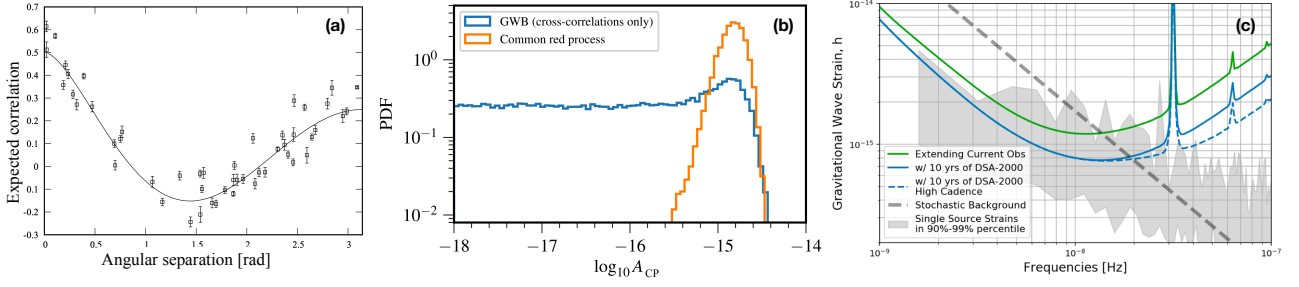


Figure 5.1: (a) The solid line shows the Hellings-Downs correlation curve; the scattered points show simulated data from an optimistically sensitive PTA (Verbiest, Osłowski, and Burke-Spolaor 2021). (b) Posterior probability densities for the presence of Hellings-Downs correlations (blue; not measured) and a common low-frequency spectral process (orange; measured) in the NANOGrav 12.5-yr data set (Arzoumanian et al. 2020). (c) Single-source sensitivity projections for NANOGrav in 2036 (credit: J. Hazboun; see chapter by J. Hazboun for details). Green shows extending current observations to 2036; solid blue, ten years of DSA-2000 observations; and dashed blue, ten years of $\sim$ weekly observations.

time the DSA-2000 begins operations (e.g., Pol et al. 2021). However, the DSA-2000 will be crucial for characterizing the GWB spectrum and for detecting one or more individual, foreground SMBHBs. The DSA-2000 will time ~ 200 MSPs with at least a monthly cadence; this large number of MSPs will provide excellent coverage of MSP pair separations and will therefore significantly increase NANOGrav’s sensitivity to the GWB (the GWB S/N grows linearly with the number of MSPs, e.g. Siemens et al. 2013). Furthermore, as shown in Fig. 1c, ten years of DSA-2000 observations will bring NANOGrav’s sensitivity firmly into the range of predicted strains for foreground single sources, increasing the range of GW frequencies at which NANOGrav will be sensitive to individual SMBHBs and increasing the likelihood of detecting one or more of these sources. Employing a higher cadence, e.g. weekly on the best-timed MSPs, will further increase NANOGrav’s sensitivity at high GW frequencies (see chapter by J. Hazboun).

System requirements / desired additions to baseline design (see table below)

NANOGrav will use the full bandwidth of the DSA-2000, providing a lever arm for measuring the dispersion measure at each epoch. Multiple phased beams will be used to time several pulsars at once.

Table 5.1: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	Match to project/NANOGrav requirements
Pointing	all-sky	beams targeting NANOGrav pulsars
polarization	IQUV for 2 MHz channels, I only for all other channels	IQUV for all channels
continuum channels	605 channels, 0.7–2.0 GHz, 2.15 MHz resolution	605 coherently-dedispersed channels, 0.7–2.0 GHz, 2.15 MHz resolution
Cadence	1 every 4 months	at least one 20- to 30-minute pointing per pulsar month
need for additional modes	N/A	coherent dedispersion (fold-mode)

5.2 Tuning PTAs for Single-Source Detections

Authors: Jeffrey S. Hazboun

Summary

Pulsar timing arrays (PTAs) have been focused on the recent detection of a stochastic gravitational wave background (GWB) Agazie et al. 2023b, but attention is turning to the detection of a single, resolvable supermassive black hole binary system. New techniques (Hazboun, Romano, and Smith 2019) for calculating the sensitivity of PTAs have allowed in-depth studies of various configurations in order to tune their observing strategies. These will allow the optimization of both the continued characterization of the GWB and the detection of the first continuous gravitational wave.

State of the Field

Pulsar timing arrays (PTAs) are decades long observing campaigns of millisecond pulsars with the purpose of detecting and observing nanohertz gravitational waves. Recent work by the North American Nanohertz Observatory for Gravitational Waves (Agazie et al. 2023b) and other PTAs around the world (Reardon et al. 2023a; Antoniadis et al. 2023a) has revealed evidence for the GWB produced by supermassive binary black holes. NANOGrav is preparing for the post-GWB detection era by studying the optimal observing strategies for individual pulsars, and the entire PTA, specifically in terms of searches for individual GW sources. The first detection of single sources are expected within 5-10 years of a definitive GWB detection Kelley et al. 2018.

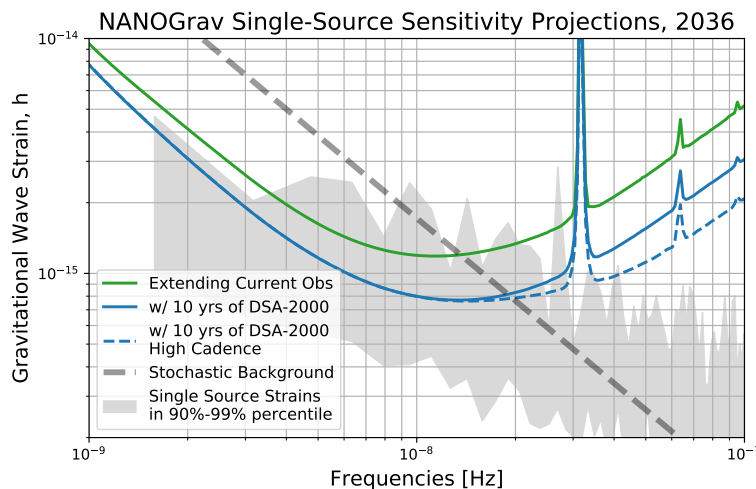


Figure 5.2: Single-source sensitivity curves showing the increased sensitivity of NANOGrav with the DSA-2000, as compared to extending NANOGrav’s current observing campaign with current telescopes. The gravitational wave background will be a strong foreground, hampering the detection of sources in the lowest frequencies. Tuning DSA-2000 observations for more optimal detections of single-sources is shown in the dashed blue curve.

DSA-2000’s impact

The DSA-2000 array will allow NANOGrav a substantial amount of observing time with fantastic sensitivity. This time allocation will allow a full budgeting and reconfiguring of the current pulsar timing campaign which has been focused on the detection of the stochastic GWB. Flexibility in the scheduling of pulsar observations within the NANOGrav time allocation will be used to tune our galactic-scale GW

detector to search for single-sources detections, while continuing to characterize the GWB.

System requirements / desired additions to baseline design (see table below)

The system requirements below are mostly reasonable for NANOGrav observations, however higher bandwidth (at the lower range) would further the science objectives by adding frequencies where pulsars often have higher flux. The lower frequency range particularly benefits the best pulsars, which are the most important for single, resolvable source detections.

Table 5.2: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	Match to project/NANOGrav requirements
Frequency band	0.7–2.0 GHz	0.5–2.0 GHz
Pointing	all-sky	beams targeting NANOGrav pulsars
polarization	IQUV for 2 MHz channels, I only for all other channels	IQUV for all channels
continuum channels	605 channels, 0.7–2.0 GHz, 2.15 MHz resolution	605 coherently-dedispersed channels, 0.5–2.0 GHz, 2.15 MHz resolution
Cadence	1 every 4 months	at least one 20- to 30-minute pointing per pulsar month
need for additional modes	N/A	coherent dedispersion (fold-mode)

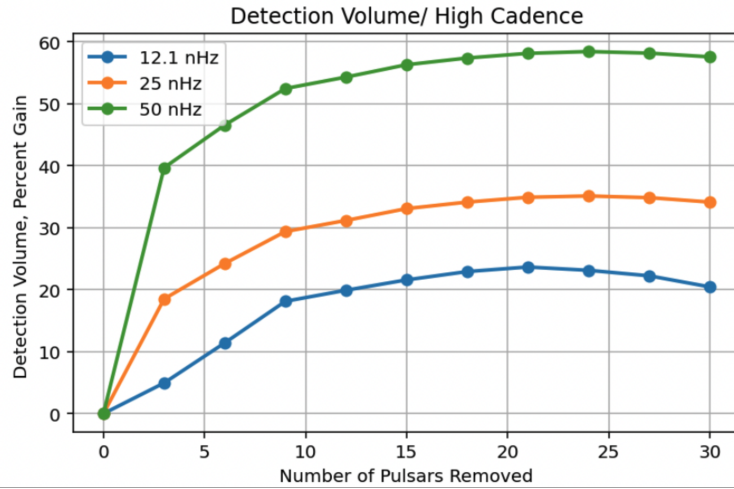


Figure 5.3: Curves showing the increases in detection volume (normalized to the NANOGrav 11-year single-source analysis in Aggarwal et al. 2019) made by removing sub-optimal pulsars and reallocating observing time to the best pulsars. A minimum number of pulsars is necessary to mitigate the GWB, as can be seen by the diminishing returns at 12.1 nHz when we remove more than ~ 20 pulsars..

5.3 Multi-messenger Observations of Supermassive Black Hole Binaries

Author: Tingting Liu (West Virginia University)

Summary

Through the precision timing of a large number of millisecond pulsars (MSPs), the next-generation pulsar timing array (PTA) experiment with the DSA-2000 will significantly boost the detection prospects of individual supermassive black hole binaries (SMBHBs) and enable multi-messenger science in the nanohertz gravitational-wave (GW) frequency regime, with significant synergies with EM observatories such as the Rubin LSST.

State of the Field

SMBHBs are expected to form as the result of hierarchical structure formation and are important for addressing questions such as the role of mergers in the growth of SMBHs. Yet, convincing evidence for their existence has been scarce. This can be largely attributed to the observational challenges of searching for, and confirming, sub-pc SMBHBs which cannot be spatially resolved with current (or perhaps even future) observatories. Therefore, the most direct evidence for their presence will be provided by GW detections. Through the precision timing of an array of MSPs, PTAs are increasingly sensitive to GWs in the $\sim 10^{-9}$ – 10^{-7} Hz range. In fact, the major PTA collaborations have recently announced the evidence for a stochastic background of GWs (Agazie et al. 2023b; Reardon et al. 2023b; Antoniadis et al. 2023b; Xu et al. 2023), and detections of individual sources are possible by ~ 2030 .

Additionally, SMBHBs are thought to be able to accrete from their gaseous environments and radiate at AGN luminosities; hence, they are also promising multi-messenger sources. Numerical simulations of accreting SMBHBs suggest that their unique structural features, together with the orbital motion of the binary, could imprint themselves on the EM emission of the AGN, making it possible to search for SMBHBs via *indirect* observations. In particular, the search for periodic or quasi-periodic variability in AGN has attracted significant interest in recent years as a possible approach to searching for sub-pc SMBHBs. More than 100 candidates have been proposed as the result of systematic searches in current time-domain surveys, and it has been predicted that there may be hundreds of periodically varying SMBHBs detectable in the Rubin LSST volume (Kelley et al. 2019; Kelley, D’Orazio, and Di Stefano 2021).

What is more exciting for GW and multi-messenger astronomy is the prospect of performing targeted searches in PTA GW data following the identifications of EM candidates by observatories such as Rubin. Recent work has shown that by using the EM information of the source as priors, targeted searches can yield higher signal-to-noise ratios (SNRs) and more precise parameter measurements (Liu and Vigeland 2021). Thus, multi-messenger searches could uncover sources that are otherwise undetectable in unguided, all-sky GW searches. Furthermore, the resulting parameter measurement precision will allow us to extract detailed astrophysical information from the observations, test theoretical predictions, and study these sources as rare and fascinating laboratories for binary accretion in AGN.

DSA-2000’s impact

The DSA-2000 will significantly boost the single-source detection capabilities of the PTA, by timing a large number of MSPs with high timing precision. A monthly pulsar timing campaign of MSPs with the lowest timing noise (`all_sky_best`) would achieve approximately the same results as a monthly `all_sky`

campaign in terms of detection SNR and parameter estimation, but with less total observing time (first two filled circles in the lower panels in Figure 5.4). For an intermediate-SNR source (represented by S2 in the figures), the PTA can measure the GW amplitude (α) at the $\sim 20\%$ level and the GW frequency (ω) at the $\sim 0.5\%$ level. Further, by timing the best pulsars at a higher (e.g., weekly) cadence, both SNR and parameter measurement uncertainties can be significantly improved (solid circles versus empty circles in the *all_sky_best* case in the lower panels).

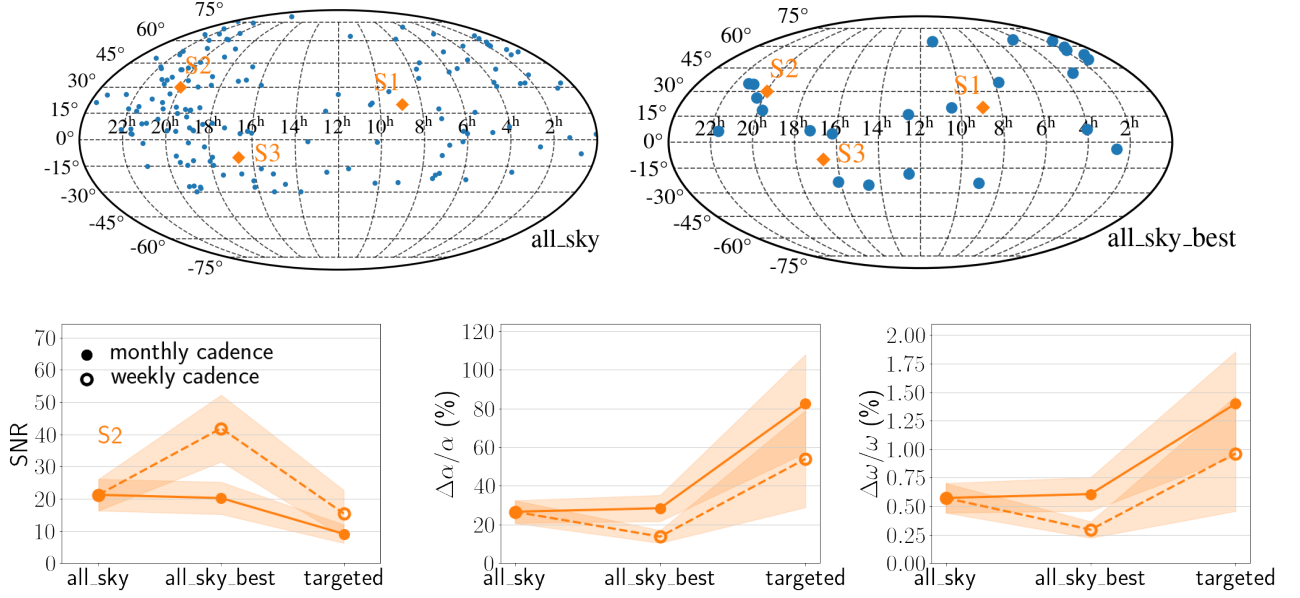


Figure 5.4: The DSA-2000 will be able to observe ~ 150 MSPs with $< 1\mu s$ timing noise (assuming 60 min integration time); the simulated pulsars are shown as small blue circles in the top left panel. Among those, ~ 20 would have < 100 ns timing noise (large blue circles in the top right panel). (Figures from Liu et al. 2023)

System requirements / desired additions to baseline design (see table below)

To optimize the PTA for single source observations, a high cadence campaign of pulsars with the lowest timing noise is preferred.

Table 5.3: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Pointing	all-sky	pulsar timing fields
Cadence	1 every 4 months	monthly or weekly

5.4 High-precision pulsar timing with DSA-2000

Authors: Sophia Sosa (RIT, NANOGrav)

Summary

DSA-2000 is expected to play a central role in pulsar searching and monitoring campaigns, both of which constitute the centerpieces of NANOGrav's efforts to detect long-period gravitational waves (GWs). In particular, DSA-2000 will represent a substantial improvement over currently-existing observatories twofold: by implementing broadband radio-receivers, which will allow for high-timing precision observations, and by significantly improving the cadence of current monitoring campaigns, which in turn will enable the detection of GW single sources.

State of the Field

In the current era of multi-messenger astrophysics, the next natural step is to expand our search to long-period gravitational waves (GWs). Such GWs are beyond the scope of Earth-based detectors, and observing them involves using pulsars through the technique of pulsar timing. Since 2004, NANOGrav has been consistently searching, observing, and analysing pulsar data in order to achieve the timing precision (Alam, M.F., et al. 2021a, 2021b) and time baselines (Siemens et al., 2013) necessary for detecting these long-period signals. These efforts are strongly dependent on the available observing infrastructure. As of 2023, NANOGrav has been awarded roughly 5% of the total observing time of the Green Bank Telescope (GBT) and monthly observations at the Very Large Array, while working towards integrating data from the CHIME telescope. The decommissioning of the Arecibo Telescope, which was the primary instruments in pulsar searching, severely hindered NANOGrav's observational capabilities. In this scenario, DSA-2000 emerges as a natural successor of Arecibo's trajectory.

DSA-2000's impact

DSA-2000 has the potential to significantly expedite NANOGrav's first detection of long-period gravitational waves due to its following characteristics:

1. **Broadband receivers:** *Using narrowband observations to model frequency-dependent effects, such as interstellar dispersion, can introduce parameter mis-estimations in the timing model, which in turn introduce offsets in the timing residuals, limiting the GW sensitivity (See Fig. 5.5). By introducing broadband receivers, DSA-2000 will be able to mitigate such mis-estimations, thereby providing better timing solutions. As a byproduct, we will also gain better models of frequency-dependent effects and an invaluable understanding of the interstellar medium.*
2. **Improved timing precision:** *It has been reportedly proven (Alam, M.F., et al. 2020) that broadband receivers wide bandwidth (BW) with multiple polarization channels (n_p), such as those proposed for DSA-2000, can significantly decrease the systematic error of timing residuals, as theorized by the radiometer equation (Lorimer and Kramer, 2012):*

$$\sigma_{\text{sys}} = \frac{T_{\text{sys}}}{\sqrt{n_p \text{BW}}} \quad (5.1)$$

Sosa Fiscella et al (2021) quantified the effects of both variables on the RMS of timing residuals, and found that using $n_p = 2$ and increasing the BW by a factor of 2 can decrease the RMS by a factor of $\sim 1/3$ (see Fig. 5.6). We expect similar improvements using DSA-2000's receivers.

3. **High observation cadence:** *the observing time allocated at DSA-2000 for NANOGrav's observing*

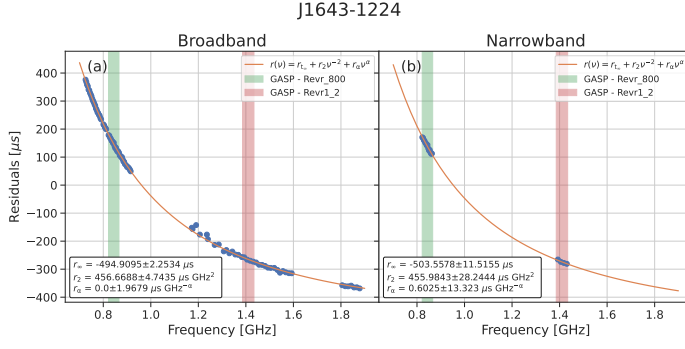


Figure 5.5: Example of fitting a dispersion model using residuals (blue dots) that are obtained using either the broadband (left panel) or narrowband (right panel) observations J1643–1224 with the GBT. The frequency ranges corresponding to the two GBT narrowband receivers, Revr_800 and Revr1_2, are shaded in green and red, respectively. The best-fit curve is presented in orange. Since the broadband observation cover a wider range of frequencies, the resulting fit of PSR J0437+4715 with at the Argentina will provide a more accurate modeling of dispersion. Source: Institute of Radioastronomy, showing a decrease in RMS with increasing BW and n_p .

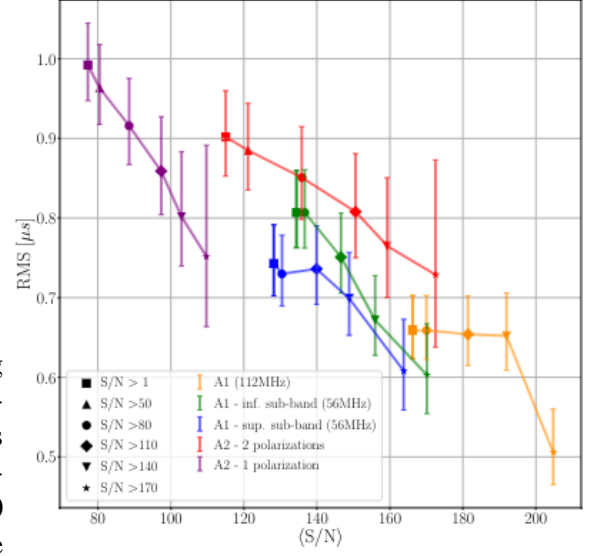


Figure 5.6: Timing residual RMS using observations at the Argentina, showing a decrease in RMS with increasing BW and n_p .

campaigns will improve upon the weekly to monthly cadence of other observatories in the International Pulsar Timing Array (Perera et al. 2019; Lam & Hazboun 2020). This is of particular importance for resolving GW single-sources, such as SMBHBs (Arzoumanian et al. 2020).

System requirements / desired additions to baseline design (see table below)

Extending the frequency band up to 4 GHz would allow us to match GBT's backends. A higher observation cadence is of utmost importance for resolving GW single sources.

Table 5.4: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Frequency band	0.7–2.0 GHz	Desirable: 0.7–4.0 GHz
Declinations	$\delta > -31^\circ$	Some pulsars at lower DEC, but OK
Cadence	1 every 4 months	Higher cadence for single source detection

5.5 Pulsar Timing with the DSA-2000 (and Some Lessons from CHIME/Pulsar)

Authors: Deborah C. Good

Summary

DSA-2000 will be a valuable instrument for pulsar timing, especially high precision millisecond pulsar (MSP) timing, which is used for tests of general relativity and gravitational wave searching. Commissioning a new pulsar timing instrument like DSA-2000 and integrating it into pulsar timing array (PTA) data sets is non-trivial, but rewarding. Recent work commissioning CHIME/Pulsar and integrating CHIME/Pulsar data into the NANOGrav dataset provides a road map for the DSA-2000 pulsar timing backend.

State of the Field

Pulsars are rapidly rotating, highly magnetized neutron stars, observed primarily at radio frequencies and increasingly at high frequencies (X-ray and γ -ray). Though the neutron star emits light continuously, its spin creates the appearance of pulsation, with the pulse period equal to the spin period of the pulsar. Radio pulsars were first discovered in 1967 (Hewish et al. 1968), and their value as tests of gravity was quickly realized (for a review see Stairs 2003). Later, the discovery of millisecond pulsars (MSPs; Backer et al. 1982), which have very high timing precision, opened the possibility of detecting a stochastic background of low-frequency gravitational waves with a pulsar timing array (PTA). PTAs are discussed in more detail in “Gravitational Wave Astrophysics with Pulsar Timing Arrays” elsewhere in this volume.

We observe pulsars by recording their pulses, particularly the pulse profile and the time of arrival (TOA). Before recording pulse information, we mitigate dispersion effects from the ionized interstellar medium. In modern pulsar instruments like DSA-2000, we use coherent de-dispersion to remove these effects; see Hankins and Rickett 1975. It is possible to record individual pulses, but most pulsars (especially MSPs) are too dim to observe in this manner. Instead, we “fold” data at the pulsar’s spin period, stacking many sections of raw data, each one period long, to increase our signal-to-noise ratio.

From each folded observation, we extract the time of the pulse’s arrival using a template for the pulse (Taylor 1992). These TOAs become the primary data product used in pulsar timing analyses. We fit a timing model to these TOAs including spin parameters, astrometric parameters, binary parameters, time-dependent dispersion measure variations, and additional white & red noise parameters. Precision timing models must be refit each time more data is added to the data set. For more thorough discussions of pulsar timing techniques, see Lommen and Demorest 2013 and Lorimer and Kramer 2005; for a NANOGrav specific discussion, see Alam et al. 2021. PTAs like NANOGrav are then able to leverage these timing solutions for gravitational wave searches.

To observe pulsars, DSA-2000 will employ a digital beamforming, enabling the simultaneous observation of several pulsars by forming linear combinations of the voltages from each antenna, “phasing up” the array to several points simultaneously. After beamforming, DSA-2000 will include a digital backend to conduct de-dispersion and folding, generating `psrfits` format files (Hotan, van Straten, and Manchester 2004). NANOGrav and other pulsar timing users will then extract TOAs and update timing models.

DSA-2000’s pulsar observation system is a unique and exciting project, but one following a well-trod path. In particular, DSA-2000 bears certain similarities to CHIME (the Canadian Hydrogen Intensity Mapping Ex-

periment), especially CHIME/Pulsar. The CHIME/Pulsar project is described in CHIME/Pulsar Collaboration et al. 2021 and early integrations with the NANOGrav dataset are presented in Good 2021.

In preparation for the 2023 DSA-2000 Science Meeting, the CHIME/Pulsar team prepared a list of lessons learned to share with the DSA-2000 team. Our primary message is **“Timing is the easy part.”** We also had five specific recommendations. First, everything takes more time and more people than you expect. Second, it is very valuable to involve science personnel in system work. Third, distribute your knowledge base, avoiding single points of failure amongst personnel. Fourth, diversify the science you generate with each data product, being open to new projects. Fifth and finally, don’t reinvent the wheel: use existing tools wherever possible.

DSA-2000’s impact

The DSA-2000 will time ~ 200 MSPs on a monthly basis, which will significantly improve NANOGrav’s ability to detect and characterize low-frequency gravitational waves. (See “Gravitational Wave Astrophysics with Pulsar Timing Arrays.”) It will also improve our ability to determine the physical parameters of neutron stars and determine the neutron star equation of state. (See “The Equation of State of Dense Nuclear Matter with the DSA-2000.”)

System requirements / desired additions to baseline design (see table below)

DSA-2000 is well-suited to pulsar timing, but there are certain important system requirements. Pulsar timing requires a beamforming system, able to digitally point the array at individual pulsars and a digital backend capable of coherently de-dispersing and folding beamformed data. The proposed 0.7-2.0 GHz frequency range is suitable for pulsar timing, but lowering the minimum observing frequency to 0.5 GHz would be advantageous, allowing improved understanding of dispersion measure variations and other interstellar medium effects.

Table 5.5: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	Match to project/NANOGrav requirements
Pointing	all-sky	beams targeting NANOGrav pulsars
polarization	IQUV for 2 MHz channels, I only for all other channels	IQUV for all channels
continuum channels	605 channels, 0.7–2.0 GHz, 2.15 MHz resolution	605 coherently-dedispersed channels, 0.7–2.0 GHz, 2.15 MHz resolution
Cadence	1 every 4 months	at least one 20- to 30-minute pointing per pulsar month

5.6 Massive Neutron Stars with the DSA-2000

Authors: Scott M. Ransom (NRAO Charlottesville / University of Virginia)

Summary

Measurements of the masses of the highest mass neutron stars provide extremely strong constraints on the dense matter equation of state, and therefore crucial (and high impact) input into high density nuclear physics. The DSA-2000 should make many such measurements, if it can find new millisecond pulsars and make occasional multi-hour timing tracks of the most promising systems.

State of the Field

The cores of neutron stars contain some of the most exotic and unknown physics in the Universe. The densities are so high, and the nuclear physics so uncertain, that we know neither the particle makeup of the cores, nor all the ways that those particles interact. That uncertainty means that measurements of the physical properties of neutron stars, such as their mass and radius, especially those with extreme values, will strongly impact multiple areas of physics. High-precision pulsar timing observations can provide precise measurements of interesting neutron star masses for a small subset of pulsar binaries.

The most constraining pulsar masses are the highest ones, which we expect from millisecond pulsars (MSPs) that have been “recycled” via mass accretion during an x-ray binary phase. Mass measurements require two “post-Keplerian” timing parameters, and the most robust of those come from two sub-classes of systems:

1. Highly-inclined (i.e. nearly edge-on) systems with $\lesssim 1 \mu\text{s}$ timing precision (i.e. the same precision needed for NANOGrav timing for gravitational waves) where the Shapiro Delay can be measured.
2. Rare eccentric systems, as found in globular clusters or occasionally in the Galactic disk, where precession of periastron and one other parameter can be measured over short (i.e. 1–2 yr) timescales.

DSA-2000’s impact

The DSA-2000 will provide world-leading (or near world-leading, given FAST and SKA-Mid) pulsar timing observations of MSPs over a large fraction of the sky. That timing precision is a crucial requirement for well-determined pulsar masses via Shapiro Delay, and it greatly improves masses for pulsars in eccentric systems, as well. Since NANOGrav will effectively time all high-precision MSPs visible by the DSA-2000, basic Shapiro Delay measurements will happen as a matter of course since monitoring will randomly sample the orbital phases of the binaries.

However, those Shapiro delay measurements will improve substantially if promising systems are targeted at key orbital phases (e.g. superior conjunction) for 1–2 long tracks of 4–8 hrs each. Such requests would be rare but likely high-payoff.

In addition, the currently planned pulsar search capability of the DSA-2000 means that it should uncover thousands of new pulsars, dozens of which will be in binaries suitable for NS mass measurements. Many additional exotic binaries, especially eccentric systems, could be found by the DSA-2000 if deep searches of globular clusters (i.e. 1–8 hr tracks) can be made before SKA-Mid comes fully online.

System requirements / desired additions to baseline design (see table below)

Besides the baseline requirements for high-precision timing of MSPs, in general, to best measure high-mass neutron stars, we will need to search for and find MSPs over the whole sky. The searches will

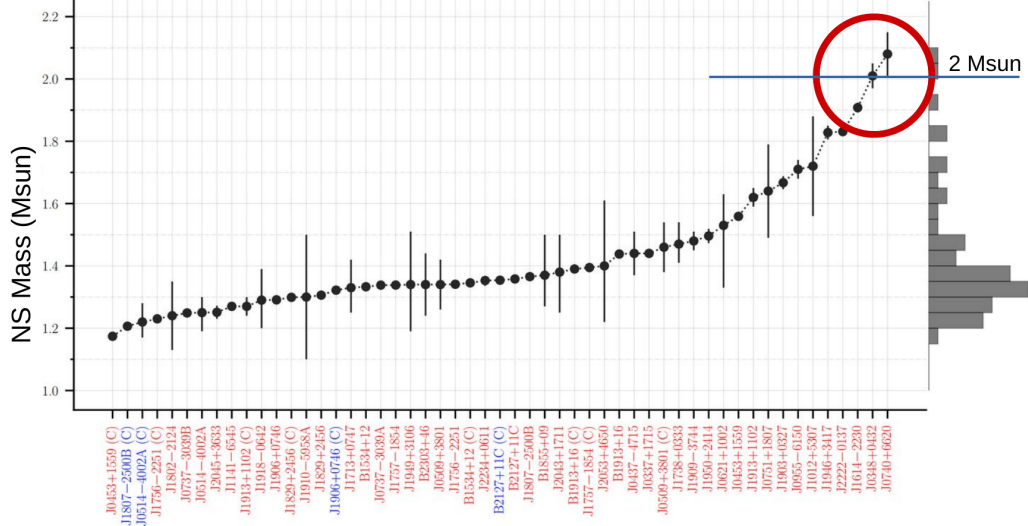


Figure 5.7: Neutron star mass measurements as curated by Paulo Freire and Vivek Krishnan. The figure is slightly modified from that shown on their [webpage](#). The papers announcing the three circled high-mass neutron stars (Demorest et al., 2010; Antoniadis et al., 2013; and Cromartie et al., 2020) currently have $\sim 7,000$ citations combined, and include the two most highly cited papers about pulsars *ever*.

require finer frequency resolution and a substantially different and more complex backend than the timing observations. We will then need to carefully time the small subset (i.e. $\sim 1\%$) of pulsar binaries in the two subsets listed above. This will include both new pulsars and older systems where the DSA-2000's timing precision is "world-best". For Shapiro delay observations, 1–2 long tracks (i.e. 4–8 hrs) for each system would greatly improve parameter estimates. Deep search capabilities (i.e. 1–8 hrs in duration) of globular clusters not searched by FAST or SKA-Mid, where eccentric MSP binaries are much more common, would be highly desired.

Table 5.6: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
need for additional modes	N/A	Occasional 4–8 hr timing tracks
need for additional modes	N/A	MSP search capabilities, in general
need for additional modes	N/A	Pulsar search 1–8 hr observations(?)

5.7 Identifying highly scattered young pulsar candidates through circular polarization continuum observations

Authors: Frank Schinzel

Summary

With more than 300 γ -ray pulsars detected by the Fermi γ -ray satellite and an unabated pace of pulsar discoveries, it has long been assumed that there are few new radio-loud pulsars to be found in the Galactic plane (GP). The 4FGL-DR3 catalog however presents a doubling in the number of pulsar-like γ -ray sources with no plausible multi-wavelength counterpart, so called unassociated γ -ray sources (UAS), to about one quarter of all detected GP sources. It is the hypothesis that the growing population of UAS in the GP are in fact missing radio-loud young, energetic pulsars that are hidden from standard pulse searches by interstellar scattering. To overcome this limitation, an all-sky search of circularly polarized GP sources has the potential to uncover highly scattered pulsar candidates, missed by traditional pulsar searches. This would allow a concentrated follow-up of identified pulsar candidates with limited resources at higher frequencies to overcome interstellar scattering. This has the potential to extent the young pulsar population to objects beyond the Galactic center and provide a better census of birth-rates and kick-velocities for this class of pulsars.

State of the Field

In the past, radio imaging techniques were successfully applied to identify large numbers of AGN among the Fermi UAS e.g. Schinzel et al. 2017. More recently imaging methods were used for pulsar identifications of UAS, exploiting their steep radio spectral indices to help discover at least seven MSPs (Bhakta et al. 2017; Frail et al. 2018), a pulsar wind nebula (Bhakta et al. 2017), and a score of candidate pulsars (Hyman et al. 2019; Bruzewski et al. 2021).

All non-thermal radio sources are polarized at a low level. Pulsars are unusual in having time-resolved (circular and linear) polarized emission as much as 100%, or time-averaged values of 10-15%. Most interestingly is that Weltevrede and Johnston 2008 note that the young, energetic pulsars have much higher polarization than normal. Low-mass flare stars and RS CVns are known to produce bursty, highly-polarized emission Villadsen and Hallinan 2019b. Nonetheless, pulsars dominate polarized sources in large-scale surveys e.g. Lenc et al. 2018b, while the false positive rate of flare stars is small ($<1/250 \text{ deg}^2$; Callingham et al. 2021) and they are easily identified via their X-ray and optical/NIR emission. Linear polarization can suffer from bandwidth depolarization if radio waves pass through a strong magneto-ionized medium along the line of sight, also commonly referred to as Faraday rotation. The same electrons that scatter-broaden pulsar pulses can reduce or even cancel out any linear polarization. However, circular polarization (V Stokes) is immune from Faraday rotation and is thus preserved.

The perhaps first, independent discovery of a pulsar using circular polarization was that of PSR J1431-6328 (Kaplan et al. 2019), followed by identification of two pulsar candidates near the Galactic center where confirmation is still pending (Hyman et al. 2021). In those instances, fractional circular polarization (Stokes V/I) is found at levels of 13–20%. To summarize, circular polarization serves as a strong tracer for pulsars, is immune to scattering from the interstellar medium, and does not suffer from depolarization due to bandwidth depolarization.

DSA-2000's impact

DSA-2000 will be able to contribute to this search in three ways. 1) It's sensitivity will be at least one order of magnitude greater than what can easily be achieved with today's point and shoot telescopes. 2) Its widefield, all-sky survey capabilities will essentially provide a large list of potential pulsar-like circularly polarized candidates for follow-up in search of radio pulsations at >2.0 GHz. This will beat interstellar scattering, while employing limited follow-up telescope resources. 3) Its survey cadence will allow for variability as factor to distinguish circularly polarized source classes.

System requirements / desired additions to baseline design

N/A

5.8 The Dynamic Ionized Interstellar Medium in the DSA-2000 Era

Authors: Michael T. Lam

Summary

The DSA-2000 will provide an unprecedented view of the dynamic ionized interstellar medium through radio pulsar and transient observations. Utilizing the information encoded in a number of propagation effects on the radio emission, and with high-cadence, wideband observations of up to 200 pulsars, DSA-2000 will provide an unprecedented view of the physics of turbulence in the interstellar medium across many spatial scales.

State of the Field

Radio pulsar emission travels through free electrons in the ionized interstellar medium (ISM), causing the emission to undergo numerous propagation effects. The dominant effect for radio waves is *dispersion*, in which the light is dispersed so that longer wavelengths are delayed and arrive later at the observatory than shorter wavelengths. The time delay is inversely proportional to the electromagnetic frequency squared (ν^{-2}) and directly proportional to the *dispersion measure* (DM), which is the integrated electron density along the line of sight from the pulsar to the Earth, $DM = \int_0^D n_e(l) dl$.

Time variations of DM are well known in the literature and there have been many methods of modeling them, including piecewise constants (“DMX”), trend analyses, and Gaussian-process regression. Physical mechanisms for the time-variability include the line of sight passing through the turbulent ISM, solar wind, filaments, compact plasma lenses, and more. Therefore, long-term, high-cadence monitoring of DM is important for uncovering the physics of the ionized ISM.

In addition to dispersion, radio emission undergoes refraction, scattering, and scintillation. These propagation effects cause observable changes in pulse shapes and delays, as well as *dynamic spectra*, allowing us to infer what impacts the geometry and physics of the intervening media have on the radio emission. The turbulence in the ISM is described by the electron-density wavenumber spectrum, which has a power-law form across many orders of magnitude. The exact physics of turbulence in the interstellar medium is encoded in this spectrum. Different observables probe different spatial scales of this spectrum, and so tracking these observables along many lines of sight allows us to build a complete picture of turbulent structures in the ISM.

DSA-2000’s impact

The DSA-2000 will provide high-sensitivity access to the electron-density wavenumber spectrum covering many orders of magnitude, from Earth-radius to kiloparsec scales. It will observe DM variations in up to 200 pulsars and scintillation/scattering variations in many of them. Galactic and extragalactic transients will provide additional spatial and temporal constraints.

System requirements / desired additions to baseline design (see table below)

The current baseline design would allow for probes of the electron-density wavenumber spectrum between $\approx R_{\text{Earth}}$ and kpc scales. Sub-arraying capabilities will allow for a greater tracking of pulsars while optimizing cadences and integration lengths for these types of studies. A pipeline for Galactic and extragalactic transients will assist in coverage across the sky.

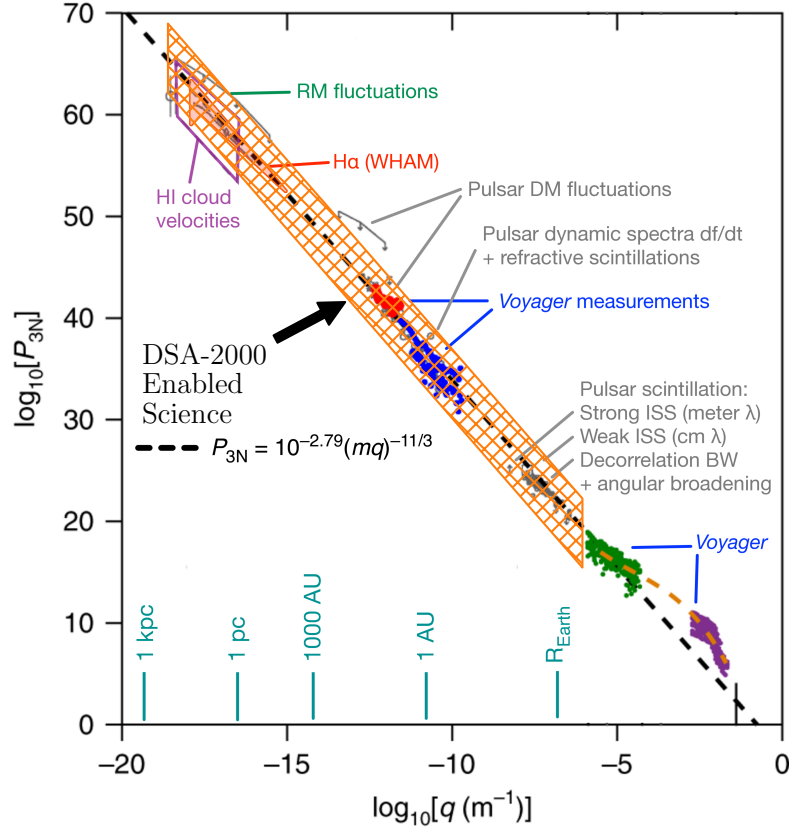


Figure 5.8: Electron-density wavenumber spectrum, modified from Lee and Lee (2019, NatAs, 3, 154) and Stinebring et al. (2019, BAAS, 51, 492). The highlighted region shows science enabled by the DSA-2000 using various pulsar and transient observables.

Table 5.7: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Cadence	1 every 4 months	200 pulsars observed monthly
need for additional modes	N/A	Sub-arrays optimize for pulsar sensitivity/cadence/integration considerations

5.9 Probing Turbulent Magnetized Plasma in the Galactic Interstellar Medium with Pulsars and other Tracers

Authors: James M. Cordes, Stella Ocker, and Shami Chatterjee

Summary

Understanding the cycling of energy in the interstellar medium (ISM) requires a much better characterization of ionized gas including densities, magnetic fields, and temperatures on a wide range of scales (e.g. Stinebring et al. 2019, Twelve Decades: Probing the Interstellar Medium from kiloparsec to sub-AU scales, <https://ui.adsabs.harvard.edu/abs/2019BAAS...51c.492S>). Density and magnetic fluctuations occur from ~ 100 km to pc (or larger scales), suggestive of a turbulence process. The ISM also strongly influences the outcomes of surveys for pulsars and fast radio bursts (FRBs), which themselves yield the objects and signals that uniquely diagnose the medium. Survey design and interpretation therefore requires detailed modeling of the Milky Way's ISM.

Next-generation Galactic models for the ionized ISM (i.e. electron density and magnetic fields and their multiscale fluctuations) will have utility across many subfields. They require large samples of the standard four measures [dispersion (DM), Faraday rotation (RM), scattering (SM), and emission measure (EM)], which can be provided by DSA-2000 in concert with multifrequency continuum maps (for EM). Current models suffer from poor sampling of clumps and voids (e.g. HII regions and hot-phase bubbles) in the ISM.

DSA-2000 can provide a transformational increase in the number of lines of sight for Galactic tomography: another ~ 5000 pulsar lines of sight, $\sim 10^4$ or more FRB lines of sight, and millions of AGNs, many of which will pass through intervening galaxies and clusters. The ~ 8000 HII regions in the MW require a comparable number of pulsars to have at least one pulsar sample each HII region. Multiwavelength follow up of AGNs (e.g. optical absorption and VLBI angular broadening measurements) can yield characterization of the ISM in other galaxies for comparison with that of the Milky Way.

State of the Field

In broad brush, the Galaxy is well characterized in terms of large scale features, gas phases, and overall energetics but a holistic, multiscale model that accounts for the dynamics of structure and turbulent flows remains to be developed. Also from a purely astronomical viewpoint, Galactic models are only coarsely predictive. For example, the inventory of DMs on FRB (fast radio burst) lines of sight relies on suitable modeling of the foreground Galactic electron density (ditto for RM). It is already known that the foreground DM is overpredicted for some FRBs, yielding large uncertainties in redshifts based on DM and even in whether some FRBs are extragalactic.

Multiple subfields can benefit from vastly improved interstellar diagnostics and modeling that will result from large samples. In addition to FRBs, these include the distance scale for pulsars and magnetars; predictions of interstellar signal distortions on spectra from stellar flares (e.g. features in dynamic spectra) and on any signals detected in SETI; and multiscale modeling of the Galactic magnetic field, relevant to cosmic ray propagation. Also, characterization of lines of sight is beneficial to pulsar timing arrays for disentangling ISM-induced fluctuations from long-wavelength gravitational waves.

Work over the last decade has refined methods for exploiting the high information content contained in dynamic spectra of pulsars (especially ‘scintillation arcs’). These reveal the presence of poorly understood thin

screens that likely are associated with shocks or interfaces between larger scale features. Parallel developments have led to estimates for the ‘inner scale’ of (most likely) turbulent density fluctuations $\sim 100\text{-}1000$ km based on analysis of scattering broadening of pulsar pulses. A uniform set of wideband measurements of dynamic spectra and pulse shapes will allow mapping of thin screens over the solar neighborhood of the MW and a picture for variations in inner scale over a good fraction of the MW.

DSA-2000’s impact

DSA-2000 has the potential for sampling many thousands of lines of sight (and more AGNs) and providing data products (dynamic spectra and chromatic pulse shapes in all Stokes parameters) that are needed for the program outlined above. The sensitivity of DSA-2000 is key to providing these data products in the context of pulsar and FRB detections in observations conducted commensally with the sky survey. Multiple passes in the sky survey are important for this as well. The outcome will be a sea change in our ability to model structure in the ISM on small as well as large scales.

System requirements / desired additions to baseline design (see table below)

Pulsar dynamic spectra require sub-MHz frequency resolutions in the lower part of the RF band and time resolution for dedispersed pulse shapes with pulsar periods from ~ 1.4 to 20 s needs to be as short as $10\text{ }\mu\text{s}$ for millisecond pulsars. The dwell time needed for dynamic spectra depends on the DM of the pulsar. More distant pulsars have finer scale scintillations so the 15m dwells of the sky survey over multiple epochs are adequate for those. More nearby pulsars need longer dwells in the upper part of the DSA-2000 band but may be sampled adequately in the lower part of the band if RFI is not prohibitive. Faraday rotation measures require channelization that satisfies $\Delta\nu = 0.56\text{ MHz} \times \nu^3 (\Delta\phi/0.1\text{ rad})(10^3\text{ rad m}^{-2}/\text{RM})$ with ν in GHz and where $\Delta\phi$ is the allowed polarization position angle rotation across a channel.

Table 5.8: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Frequency band	0.7–2.0 GHz	✓
Pointing	all-sky	✓
Declinations	$\delta > -31^\circ$	✓
Spatial resolution	3.5"	✓
polarization	IQUV for 2 MHz channels, I only for all other channels	✓
continuum channels	605 channels, 0.7–2.0 GHz, 2.15 MHz resolution	higher $t - \nu$ resolution needed
low-resolution HI channels	5600 channels from 0.7–1.45 GHz, 134 kHz (28 km s^{-1} at $z=0$, 56 km s^{-1} at $z=1$)	
tuneable zoom band A	4096 channels, 8 kHz (1.8 km s^{-1})	
tuneable zoom band B	2048 channels, 1.05 kHz (0.22 km s^{-1})	
need for short-baseline array	N/A	
Cadence	1 every 4 months	✓
need for additional modes	N/A	

5.10 Probing the Interstellar Medium using CLEAN Deconvolution on Radio Pulsar Profiles

Authors: Olivia Young and Michael T. Lam

Summary

Pulsar radio waves are distorted and delayed as they propagate toward the Earth due to interactions with the free electrons that comprise the interstellar medium. Multipath propagation results in later times of arrival for the lower frequencies and causes the observed pulse to arrive with a broadened tail described by the pulse broadening function. We employ CLEAN deconvolution to recover the intrinsic pulse shape and pulse broadening function. Our work expands upon previous efforts and parameterizes the efficacy of the method on simulated data, leading to an automatic and consistent determination of the scattering timescale and its uncertainty.

State of the Field

Radio emission from pulsars is distorted as it moves through the ISM. Irregularities in the ISM cause multipath propagation, resulting in the pulse of light arriving at the Earth with a broadened tail. A common model of the ISM assumes turbulent *Kolmogorov* fluctuations, leading to an exponential tail, which we know is not accurate along many lines of sight.

CLEAN deconvolution is an iterative method used to determine the pulse broadening timescale of radio pulsar profiles and rebuild the intrinsic profile. CLEAN iteratively subtracts small copies of a simplified, broadened pulse from the observed pulse. We are then able to rebuild the intrinsic pulse and choose the “correct” broadening timescale using a set of figures of merit.

CLEAN’s performance is predominantly dependent on two factors: the pulse broadening timescale and the S/N of the observation, with recall accuracy increasing as both factors increase. The current success of CLEAN is limited by the need for high signal-to-noise ratio (S/N) profiles, which often require summing observations over long timespans or large bandwidths to achieve these high S/N values. With the DSA-2000’s sensitivity, high cadence, and wide bandwidth, CLEAN will be usable on a larger array of pulsars, and enable short-timescale measurements of ISM variations.

DSA-2000’s impact

As current applications are impeded by a lack of access to high S/N data, the DSA-2000 will greatly increase both the numbers of pulsars with high enough S/N for CLEAN to be able to accurately recover the pulse broadening, and will therefore also allow for better sampling in time of the changing ISM.

System requirements / desired additions to baseline design (see table below)

The current baseline design would allow for wideband observations of up to 200 pulsars at high cadences, allowing us to deploy CLEAN on many pulsars with high time resolution to measure rapid (~monthly) changes in the ISM. A pipeline for Galactic and extragalactic transients will assist in coverage across the sky.

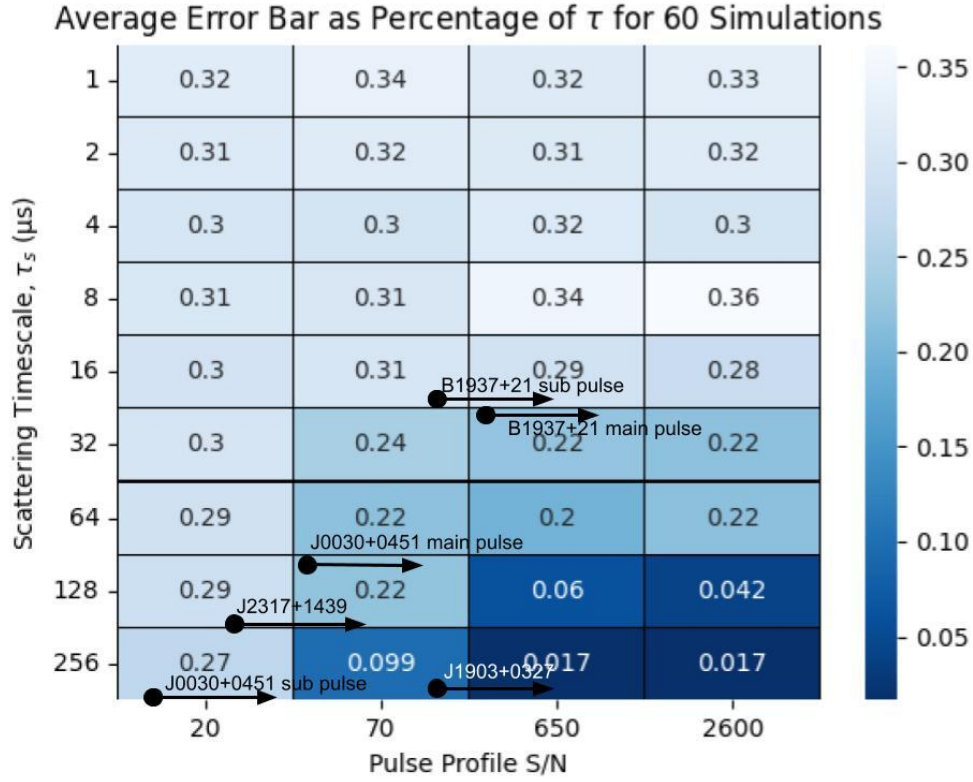


Figure 5.9: Parameterization results for our CLEAN algorithm on simulated data, overlaid with results of running CLEAN on one year’s worth of pulse profiles for select NANOGrav 12.5-year pulsars centered at 1200 MHz with a 10 MHz bandwidth. Darker colors indicate smaller uncertainties, showing improved recall at high S/N and large scattering timescales. The increased S/N promised by the high-cadence pulsar observing with the DSA-2000 would increase the sensitivity of our measurements. Modified from Young and Lam (in prep.).

Table 5.9: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Cadence	1 every 4 months	200 pulsars observed monthly
need for additional modes	N/A	Sub-arrays optimize for pulsar sensitivity/cadence/integration considerations

5.11 Constraining black-hole formation in the early universe: the case for 100 yr of pulsar timing

Joseph Simon (University of Colorado) and James Cordes (Cornell University)

Summary

Pulsar timing arrays (PTAs) have revealed a stochastic gravitational wave background (GWB), most likely produced by a population of supermassive black hole binaries (SMBHBs). Detection of individual binaries, particularly at $z > 1$, is needed to probe formation and evolution of SMBHBs. Remarkably, for fixed observed GW frequency the GW strain increases for $z \gtrsim 2.6$ because of its strong dependence on orbital period, which is shorter in the rest frame than in the observer's frame by a factor $(1+z)^{-1}$. Current data sets ~ 20 yr in length need to be extended substantially in order to probe redshifts $z > 1$ because coalescence times are much shorter for fixed period in the observer's frame. Other benefits of long data sets include (1) better characterization of the GWB and SMBHB evolution astrophysics; (2) increased chances of detecting gravitational memory bursts; (3) greater likelihood of detecting gravitational lensing from Galactic objects, including dark matter clumps; detecting flyby events from substellar objects; and detecting plasma lensing events, whose astrophysics is also not well understood.

State of the Field

The co-evolution of galaxies and their SMBHBs remains one of the great puzzles in astrophysics. Recently, there is increasing evidence that SMBHBs were more massive in the early Universe than previously thought, which is leading to a shift in our understanding of SMBHB formation and evolution. JWST observations revealed a $\sim 10^8 M_\odot$ SMBHB at $z \sim 10$ (Bogdán et al. 2023), and a re-examination of HST galaxies highlighted the potential for $> 10^{10} M_\odot$ SMBHBs at $z > 3$ (Matt, Gültekin, and Simon 2023). Even the stochastic GWB measured by PTAs hints at a more massive and more numerous population of SMBHBs (Agazie et al. 2023a), with the potential for individually detectable binaries at much higher redshifts than previously thought (Simon 2023).

Now that a stochastic GWB has been measured at nanohertz frequencies, the next milestone is to identify some of the individual SMBHBs that comprise it. Each will appear as a continuous wave [CW] signal in timing residuals at twice the redshifted orbital frequency, $f_{\text{gw}} = 2f_{\text{orb}}^{(\text{rest})}/(1+z)$. Requiring several GW cycles for detection, a time series of length $T(z) > \text{few} \times f_{\text{gw}}^{-1}$ is needed.

Data sets substantially longer than those currently available ($T \sim 20$ yr) are required because the greatest sensitivity is for observation frame periods $\gtrsim T$, corresponding to rest-frame periods $P_{\text{orb}}^{(\text{rest})} \gtrsim T/(1+z)$, which can have much shorter coalescence times $\propto P_{\text{orb}}^{(\text{rest})8/3}$ than binaries at low redshifts (see Figure 1). This reduces the likelihood for a signal existing in the PTA band. The greater cosmological volume sampled at high redshifts can compensate, but only up to redshifts where the formation rate of SMBHBs is substantial. A reduced formation rate at high z therefore requires longer data sets to maximize the odds of detection and also increase the detection sensitivity. Also helpful is the scaling of the dimensionless strain $h \propto (1+z)^{5/3}/D_L(z)$ (where D_L is the luminosity distance), which first decreases with z and then increases for $z \gtrsim 2.63$ for fixed observed GW frequency (Rosado et al. 2016). This implies that the primary factor for constraining the high- z population of SMBHBs is the availability of sustained pulsar timing data. As outlined in the summary, long spans of PTA data also have other, unique astrophysical benefits.

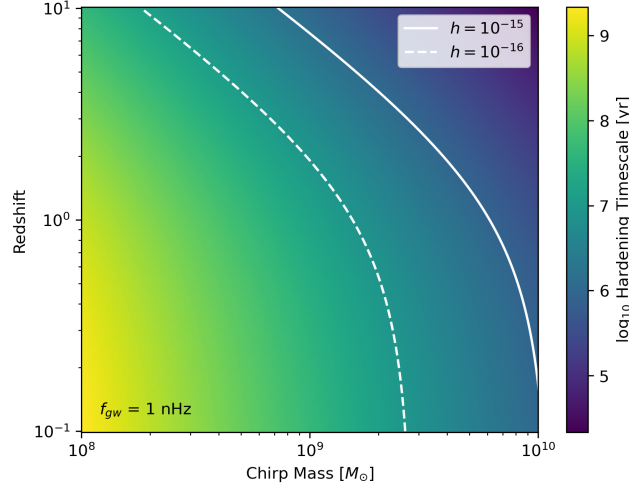


Figure 5.10: The binary hardening timescale is the rest-frame duration that a binary spends at a given observable gravitational wave frequency (f_{gw}). Above this quantity is plotted as a function of binary chirp mass and redshift for $f_{\text{gw}} = 1 \text{ nHz}$, which corresponds to $T \sim 30 \text{ yr}$ of data. At higher redshifts, binaries of the same rest-frame chirp mass are further along in their inspiral and thus will spend less time at this observational frequency. For a given rest-frame chirp mass, binaries at higher redshift also have larger strain values, as seen from the constant lines of strain plotted in white showing two separate strain values, $h = 10^{-15}$ (solid line) and $h = 10^{-16}$ (dashed line). To capture the most massive SMBHBs at high redshift, PTAs must continue to extend their timespans.

DSA-2000's impact

PTA observations are continuing globally but without coordination and long-term planning, so a lapse in observations is possible. DSA-2000 is therefore highly important because it provides dedicated time for PTA observations with the best sensitivity to pulsar observations that yield highly precise arrival times.

System requirements / desired additions to baseline design (see table below)

System requirements already include those needed for precision pulsar timing. The explicit requirement for probing high redshift GW sources is sustained timing with $< \text{monthly}$ cadence into the indefinite future.