GBT Memo 294

Consequences of replacing the GBT and/or Arecibo with the Jansky VLA forNANOGrav

Scott Ransom on behalf of
The North American NanoHertz Observatory for GravitationalWaves (NANOGrav)

September 13, 2016

To: Anthony Beasley, NRAO Director

From: Scott Ransom (NRAO) on behalf of the North American NanoHertz Observatory for Gravitational Waves (NANOGrav)

Subject: Consequences of replacing the GBT and/or Arecibo with the Jansky VLA for NANOGrav

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1 Summary

While the Jansky VLA (JVLA) is optimally designed to address a wide variety of critical topics in astrophysics, it is highly inefficient and drastically over-designed for radio pulsar timing observations compared to the two world-class NSF-funded single-dish radio telescopes. The JVLA's reduced sensitivity compared to the GBT, and especially compared to Arecibo, would require thousands of hours of precious JVLA time per year to match the world-leading timing results currently being generated by the GBT and Arecibo. Dedicating thousands of hours at the JVLA annually to pulsar timing would substantially reduce its hours available for the imaging science projects for which it was designed and for which it is the best instrument in the world. The lack of sensitive sub-GHz receiving systems would require that NANOGrav acquires long-term access to non-US telescopes such as the GMRT and CHIME in order to correct for interstellar medium (ISM) effects. Finally, pulsar surveys to provide additional millisecond pulsars (MSPs), which greatly enhance pulsar timing array (PTA) sensitivity, will be impossible with the JVLA for computational reasons for many years to come. A loss of access to both the GBT and Arecibo would dramatically decrease the discovery space for North American GW science and would signal an effective abdication of US leadership in pulsar science.

2 Observational Requirements of NANOGrav

NANOGrav is pursuing the detection and study of GWs via pulsar timing, one of the avenues to open GW astronomy, a "science discovery frontier area" identified in the last Astronomy Decadal Survey. The number of pulsars required to form an effective pulsar timing array is estimated to be at least 20 under optimistic scenarios, and more realistically 50–100. NANOGrav currently conducts coordinated and optimized observations of about 45 pulsars, about half each using Arecibo and the GBT. Timing observations require wide-band (capable of covering 600–800 MHz of bandwidth at 1–2 GHz frequencies) coherent dedispersion instrumentation, which is now available at the JVLA as well as at GBT and Arecibo.

Observations of duration ∼20–40 minutes (required to partially overcome timing limitations due to pulse jitter) are made at two different observing frequencies every 3–4 weeks for each pulsar. The observing cadence is set to over-sample timing variations due to astrometric, orbital, and spin-down effects as well as our expected nanoHertz (nHz, i.e. several year periods) GW signals. Time-of-arrival (TOA) precision is inversely proportional to signal-to-noise, and therefore telescope sensitivity.

The paired high- (1–2 GHz) and low-frequency (typically 430 MHz at Arecibo and 820 MHz at the GBT) observations are required to remove the time variable dispersive effects of the ISM, which can be orders-of-magnitude larger than our expected GW signals. Currently these observations are taken within 1–2 days of each other, although future simultaneous ultra-wideband observations from $\sim$0.5–3 GHz would be preferred.

NANOGrav's GW sensitivity improves in direct proportion to the number of MSPs being timed (Siemens et al., 2013). We currently add additional MSPs primarily from ongoing sensitive wide-area GBT and Arecibo pulsar surveys (e.g. PALFA and GBNCC). Our predicted GW sensitivity assumes the continued addition of $\sim$4 MSPs per year to our timing array. Figure 1 shows predictions for the likely amplitude of the nHz stochastic GW background as well as NANOGrav's future sensitivity to such a background.

NANOGrav timing observations currently require over 400 hours per year at both Arecibo and the GBT, while the search observations use $\sim$500 hours per year at both telescopes. An additional $10-20$ hours of telescope time per year will be required at both telescopes as we continue to find high-precision MSPs. Demorest et al. (2013) reported the first five years of NANOGrav work and presented limits competitive with those of the other PTAs with much longer timing data sets. McLaughlin (2013) summarizes NANOGrav's current work, and recently, preliminary analyses of our 9-year data set (presented at the 2014 IPTA meeting in Banff) suggest that NANOGrav results are beginning to set the international standard, based in significant part on the high sensitivity provided by the GBT and AO. For additional background information on high-precision pulsar timing see Lommen & Demorest (2013).

3 Using the JVLA for Pulsar Observations

Currently the JVLA performs *no* regular pulsar timing or search observations in its regular observational program, whereas those observations use $\sim$25–30% of the GBT's available time. However, within the last year, the JVLA's Cluster Back End (CBE) has been configured to allow high-precision pulsar timing observations if the array is operated in "phased-array" mode (i.e. with the signals from each antenna coherently summed towards a particular position on the sky).

3.1 Sensitivity

Since pulsars are steep-spectrum radio sources, any high-precision timing at the JVLA would predominately use the L-band receivers (1–2 GHz). Unfortunately, the inefficient illumination of the JVLA dishes at L-band, poorer system temperatures by 5K or more compared to the GBT, and similar available total bandwidths, mean that the GBT is 30-40% more sensitive than the JVLA (see Appendix A for a summary of telescope sensitivities). If we wanted to compensate for this sensitivity loss with observing time, our observation durations would need to increase by almost a factor of two compared to the GBT. Given the JVLA's current oversubscription rates and the fact that it does no pulsar work means that we would likely get *less* observing time than at the GBT and our TOAs would have 40–50% larger errors. Recent simultaneous exploratory GBT and JVLA observations of two NANOGrav pulsars are shown in Figure 3.

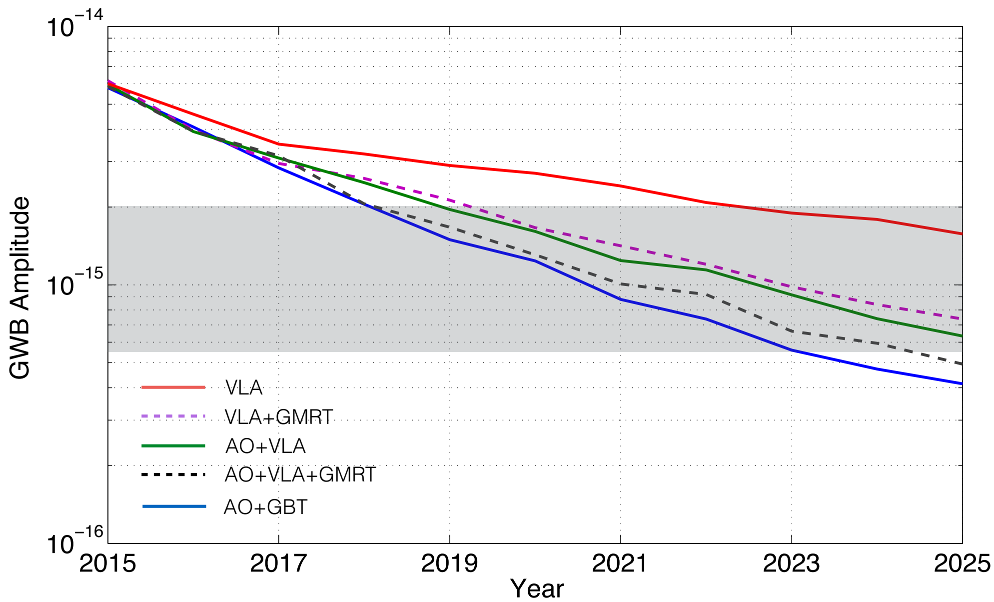

Figure 1: Predictions for NANOGrav's sensitivity to a stochastic GW background assuming a switch from the GBT, and possibly also Arecibo, to the JVLA starting in 2015. The curves represent a 3-σ detection in 90% of the simulations, while the gray band shows the expected range of the true stochastic GW background. The solid lines show timing observations only using US facilities, while the dashed lines show the results of supplementing the US observations with hundreds of hours of lower-frequency time on international telescopes like the GMRT or CHIME. The delays in detection and follow-on GW science, or equivalently GW sensitivity losses, come from a combination of reduced telescope sensitivity, poorer dispersive corrections (especially when other telescopes like CHIME or the GMRT are not available), fewer MSP additions to the array due to the cessation of GBT and Arecibo pulsar surveys, and less observing time. The effects would be much worse without our nine year baseline of GBT timing data. These simulations assume that we will acquire ∼200–250 hours per year of JVLA time with a loss of the GBT, or 450–500 hours per year of JVLA time with the loss of both the GBT and Arecibo.

3.2 Sub-GHz Observations for ISM Corrections

The lack of a sensitive sub-GHz observing system at the JVLA is a substantial weakness which would have to be addressed. Without sensitive low-frequency timing observations, the time-varying dispersive effects of the ISM would dominate our error budget. Figure 1 shows that if we simply replace the GBT with the JVLA, within a few years it will take an *additional* couple of years to detect GWs. A larger loss of sensitivity is apparent for individual continuous wave GW signals as shown in Figure 2. If we can secure substantial time on non-US telescopes with a 0.4–1 GHz capability, such as the GMRT in India and CHIME in Canada (available in 2016), we could make the ISM corrections necessary to recover most of the lost GBT capability. However, securing that non-US telescope time, especially year after year for 5–10 years in the future, adds substantial risk to the project and detracts from US leadership in this enterprise.

3.3 Pulsar Surveys

NANOGrav depends on continued pulsar surveys to discover additional MSPs to improve our GW sensitivity. Most of the MSPs added over the previous five years have been from GBT surveys, several of which are ongoing and continuing to discover bright, high-precision MSPs. If we lost access to the GBT, these critical surveys would end. Pulsar surveys with radio arrays are incredibly difficult due to the massive data rates generated — tens of thousands of spectra per second for each resolved pixel in the field-of-view. For the JVLA, the data rate would be 10–20 GB/s, and that would have to be stored and then shipped elsewhere for processing. To make the processing even remotely feasible, we would need E-array, which would decrease the processing costs with respect to a D-array survey by a factor of $\sim$100. Simply put, a JVLA-based MSP survey is practically impossible in the next decade. Similarly, MeerKAT will not conduct wide-area pulsar surveys within the next decade for these same reasons. SKA pulsar search processing remains one of the most technically challenging parts of that project.

3.4 Imaging vs non-Imaging

Finally, the capabilities that make the JVLA the premier imaging radio telescope in the world, such as excellent image fidelity and dynamic range at four configurable spatial resolutions, are completely unused by pulsar timing observations. Pulsar timing requires only a phased-array data stream from a single point on the sky. However, just generating and using that stream has its own risks:

- Phasing requires telescope time that is not needed at a single-dish telescope, resulting in loss of observing efficiency.
- Phasing of the array is more difficult in the extended configurations of the JVLA.
- Radio Frequency Interference (RFI) can cause loss of phasing efficiency (see Figure 3).
- The stability of polarization properties, an important aspect of high-precision pulsar timing, has not been investigated in detail with phased-array data.
- Absolute time and time transfer at the JVLA has not been investigated as it has not been required at the nanosecond level before.

In general, an array like the JVLA is heavily over-designed for pulsar observations, resulting in costs per hour approximately a factor of three higher than for the GBT. In fact, the GBT is itself even heavily over-designed for pulsar observations (we do not need frequencies >10 GHz, in general). The main requirements for pulsar observations are excellent sensitivity in the 0.3–3 GHz band and full sky coverage. The reason that the next generation "pulsar" telescopes are being built as arrays (e.g. MeerKAT and SKA) is purely because large numbers of small dishes is a cost-effective way to provide that sensitivity and sky coverage.

4 A loss of both the GBT and Arecibo

For the MSPs visible from Arecibo, no other telescope can approach its achievable timing precision due to its unparalleled sensitivity. NANOGrav would require *several thousands of hours of JVLA time* to only partly replicate the $\sim$400 hours of Arecibo time we currently use annually. If we assume that we could get 200–250 hours per year of JVLA time to compensate for the loss

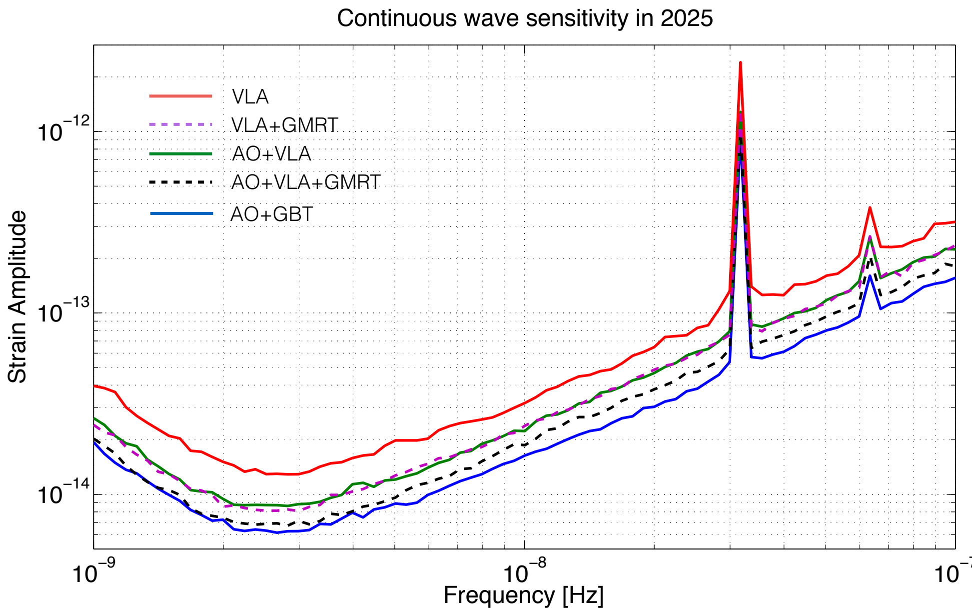

Figure 2: Predictions for NANOGrav's sensitivity to continuous wave GWs in 2025, showing the long-term effects of switching away from the GBT and possibly Arecibo. The line colors and types are the same as in Figure 1. The ∼50% loss of sensitivity when using Arecibo + JVLA (compared to Arecibo + GBT) is due to reduced TOA precision from the Southern pulsar J1909−3744 and from additional systematics caused by inadequate ISM corrections. The latter can be mostly mitigated by using non-US low-frequency telescopes such as the GMRT and CHIME, but with substantial additional risk. If the JVLA alone is used, the sensitivity is a full factor of two less than would be achieved with Arecibo + GBT, corresponding to a detection volume an order-of-magnitude smaller, thereby making a detection much less likely. As in Figure 1, these simulations assume that we will acquire ∼200–250 hours per year of JVLA time with a loss of the GBT, or 450–500 hours per year of JVLA time with the loss of both the GBT and Arecibo.

of Arecibo 1–2 GHz observations, our arrival time precision would decrease by a factor of ∼12, making almost half of the current Arecibo NANOGrav MSPs useless for GW work.

Without the GBT and Arecibo, the three most sensitive ongoing large-area pulsar surveys for MSPs in the world would cease. Without these and related surveys, such as targeted searches of *Fermi* gamma-ray unassociated sources, the most effective way to improve future PTA sensitivity (i.e. adding more high-precision MSPs) would be hugely impaired.

The loss of these telescopes would also heavily impact related educational and outreach programs. A key aspect of the Arecibo Remote Command Center (ARCC) is conducting pulsar observations with Arecibo and the GBT. The queue-based operational mode of the JVLA would not allow such activities. The Pulsar Search Collaboratory (PSC) has involved nearly 2,000 middle- and high-school students in analysis of pulsar search data taken taken with the GBT. The ARCC students also analyze the search output from GBT and Arecibo pulsar surveys for both scientific and educational purposes. These valuable activities, which are building a diverse STEM pipeline in the US, would cease when the corresponding pulsar searches end.

Finally, without a large and scientifically-viable single-dish radio telescope, development of new hardware capabilities for pulsar science would be significantly more difficult. For example, we cannot easily test or conduct early science operations of cutting-edge observing systems like the ultra-wideband system (∼0.5–3 GHz) proposed for the GBT using the JVLA. The already devastated university radio groups need such small-scale yet high-impact developmental access.

5 Conclusions

If the JVLA were to replace the GBT and/or Arecibo for NANOGrav observations, NANOGrav could still, in principle, achieve its goal of directly detecting and characterizing low-frequency GWs, albeit with substantial additional risk. The detection would likely take at least 2–3 additional years during this critical time for GW science, and would require the use of non-US telescopes for the sub-GHz observations to correct for ISM effects, using methods that are not yet demonstrated. These predictions are optimistic in that they assume that some as yet unseen noise process (e.g. pulsar spin noise) will not limit our detection first, and exacerbate the loss of the GBT and/or Arecibo.

NANOGrav JVLA 1–2 GHz observations would require at a minimum 200–250 hours per year to compensate for GBT timing and a similar or even larger amount of time to compensate for Arecibo, decreasing the time available for other science projects that better utilize the JVLA's unique high-fidelity imaging and multiple spatial resolution capabilities. Searches for new MSPs to increase our GW sensitivity are currently impossible with the JVLA. If the JVLA were required to replace both the GBT and Arecibo, NANOGrav would experience dramatically reduced sensitivity and probability for GW detection, and would provide much less effective basic physics tests. To better, but still only partially, recuperate the lost 1–2 GHz timing precision from both the GBT and Arecibo would require more than 1000 hours per year of JVLA time.

References

Demorest, P. B., et al. 2013, ApJ, 762, 94

Lommen, A. N., & Demorest, P. 2013, Classical and Quantum Gravity, 30, 224001

McLaughlin, M. A. 2013, Classical and Quantum Gravity, 30, 224008

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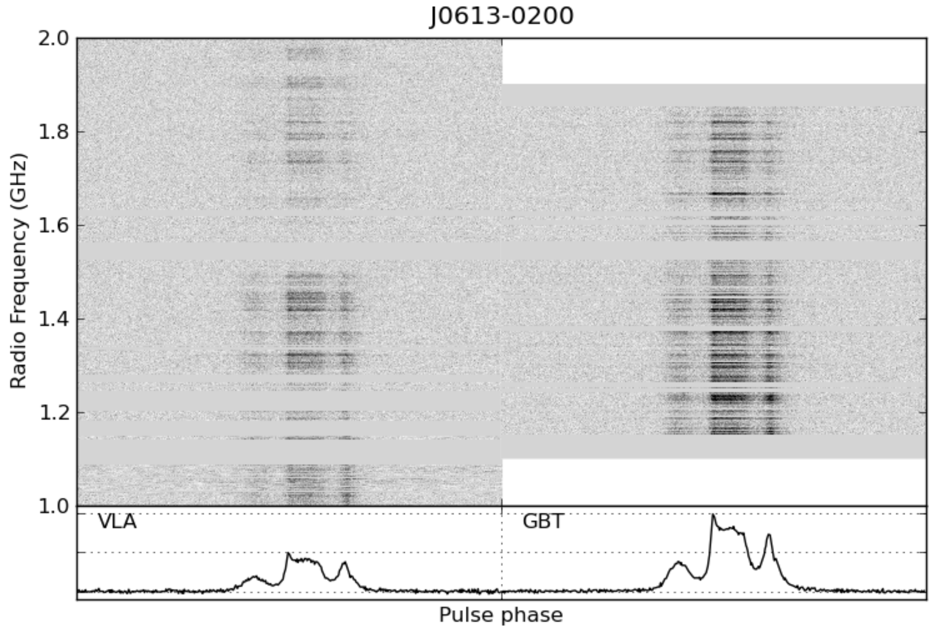
Appendix A: Observational Capabilities

	JVLA	GBT	Arecibo
High-freq Timing System	L-band	L-band	L-wide
Usable Bandwidth (MHz)	800	650	600
SEFD (Jy)	14.4[a]	9.5	3.0
Sensitivity[b]	0.73	1.0	3.0
Low-freq Timing System	P-band	820 MHz	430 MHz
Usable Bandwidth (MHz)	70(?)	190	20
SEFD (Jy)	∼150	14	10
Low-freq Survey System	P-band	350 MHz	327 MHz
Usable Bandwidth (MHz)	70(?)	90	70
SEFD (Jy)	∼150	30	16

[a]From EVLA Memo 152 assuming 26 antennas
[b]$\sqrt{\mathrm{BW}}$/SEFD scaled so GBT≡1. Higher is better.



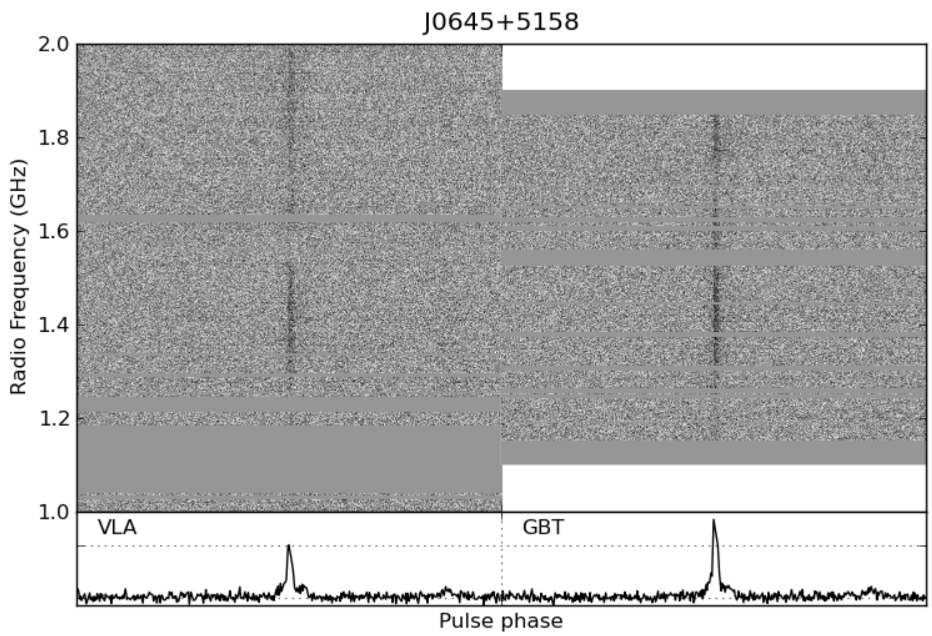


Figure 3: Simultaneous observations of two NANOGrav pulsars taken with the JVLA and the GBT. Each observation was approximately 50 minutes in duration. The data have been normalized such that the off-pulse noise levels are the same for each telescope. The nominal band passes of the L-band receivers are shown in gray, and gray bands without noise indicate where interference (RFI) was excised. For the observation of PSR J0613−0200 (top), the S/N of the GBT detection is a factor of two larger than for the JVLA. This was due to a loss of phasing efficiency caused by strong RFI for the Southern source. The observation of PSR J0645+5158 (bottom), a significantly weaker Northern source, shows a ∼50% improvement in S/N for the GBT, much closer to the ∼30–40% improvement that we expect from simple radiometer calculations.