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Optimizing the Next GBT Pulsar Survey

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Abstract

Large-area pulsar surveys are important tools for increasing the population of known pulsars, which are used to study various extreme physical phenomena. As the current large-scale survey on the Robert C. Bryd Green Bank Telescope (GBT), the Green Bank North Celestial Cap (GBNCC) survey approaches completion, it is important to begin planning next-generation pulsar surveys that are competitive with current and upcoming pulsar surveys conducted on other instruments. We present the results of simulated pulsar population and survey studies conducted for potential GBT pulsar surveys using the 820 MHz, L-Band, S-Band, Ultra-wide band, and the Focal L-Band Array for the GBT (FLAG) receivers. We determined that the most effective survey would be conducted at frequencies of 1.1 to 1.9 GHz using the GBT L-Band receiver at an dwell time of 180 s over a 1700 square degree region along the galactic plane. Such a survey would detect approximately 500 new pulsars, about 50 of which would be MSPs. We also compare these results to a possible survey with the FLAG receiver over the same region with a 1260 s dwell time, which is projected to discover 550 pulsars.

1. INTRODUCTION

Pulsars are rapidly spinning neutron stars with powerful magnetic fields and emit beams of radiation from each magnetic pole (Lorimer 2008). In astronomy, pulsars have been used to study extreme states of matter, general relativity, and led to the discovery of the first extra-solar planets (Cromartie et al. 2020; Kramer et al. 2006; Wolszczan & Frail 1992). Millisecond pulsars (MSPs) are used in pulsar timing arrays, where correlated fluctuations in pulse arrival times are studied with the goal of detecting stochastic background gravitational waves (Arzoumanian et al. 2018). There are currently over 2,800 known pulsars, roughly 8% of which are MSPs (ATNF Pulsar Catalogue v1.63; Manchester et al. 2005).

The current large-area survey being conducted on the GBT, the GBNCC survey, is nearing completion, which motivates making plans to determine where the next GBT survey should be focused in order to maximize the number of new pulsars, in particular MSPs (McEwen et al. 2020). In this paper we present the results of simulated pulsar surveys to show that the next GBT pulsar survey should be conducted using the L-Band receiver with an dwell time of 180s. In section 2, we present information on several current large area pulsar surveys being conducted on other telescopes. In section 3, we outline our methods of simulating pulsar populations and determining which type of survey would produce the most results for a reasonable amount of telescope time. In section 4, we show the results of our analyses, and in section 5, discuss how our results support our chosen next-generation survey.

2. CURRENT SURVEYS

2.1. *Green Bank North Celestial Cap Survey*

The GBNCC pulsar survey covers the entire sky above declination (δ) $-40°$ at 350 MHz with a 100 MHz bandwidth, and is conducted on the GBT (Stovall et al. 2014; McEwen et al. 2020). To date, the survey has discovered 161 new pulsars, including 25 MSPs and 24 rotating radio transients (RRATs) (McEwen et al. 2020). Data collection began in 2011 and is expected to be completed within the next few years.

2.2. *The Arecibo 327 MHz Drift-Scan Survey*

The Arecibo 327 MHz Drift-Scan (AODRIFT) Survey is a 327 MHz drift-scan survey conducted on the Arecibo Telescope from δ $-1°$ to $38°$ (Martinez et al. 2019). Data collection began in 2011 and to date, the survey has discovered 85 new pulsars, including 16 recycled pulsars, 10 MSPs, and 16 RRATs (Martinez et al. 2019).

2.3. *The Commensal Radio Astronomy FAST Survey*

The Commensal Radio Astronomy FAST Survey (CRAFTS) is a drift-scan survey conducted on the Five-hundred-meter Aperture Spherical radio Telescope

(FAST) using a frequency bandwidth of 270-1620 MHz at δ -14° to 60° (Qian et al. 2019). Data collection began in 2017 (Qian et al. 2019).

2.4. *The Pulsar Arecibo L-Band Feed Array Survey*

The Pulsar Arecibo L-Band Feed Array (PALFA) survey is an L-Band survey centered at 1375.5 MHz conducted on the Arecibo telescope. The survey has a low galactic longitude (ℓ) region from 32° to 77° and a high ℓ region from 168° to 214° (Cordes et al. 2006). Data collection began in 2004 and the survey has discovered 196 new pulsars, including 31 MSPs and RRATs[1].

2.5. *The High Time Resolution Universe Pulsar Survey*

The High Time Resolution Universe (HTRU) Pulsar survey is split into a northern (HTRU-N) and southern (HTRU-S) sky survey. HTRU-N. HTRU-N is conducted on the Effelsberg telescope at 1360 MHz with 240 MHz bandwidth, and HTRU-S is conducted on the Parkes telescope and centered on 1352 MHz with a 340 MHz bandwidth (Barr et al. 2013; Keith et al. 2010). Both have three survey regions, a low galactic latitude (b) region with $|b| < 3.5^\circ$ and $-80^\circ < \ell < 30^\circ$, a mid-latitude region with $|b| < 15^\circ$ and $-120^\circ < \ell < 30^\circ$, and a high-latitude region of $|b| > 15^\circ$ (Keith et al. 2010). To date, HTRU-S has discovered over 100 new pulsars, including 9 MSPs[2].

3. METHODS

Galactic pulsar populations were simulated using PsrPopPy, a python-based software package used to simulate pulsar populations and surveys (Bates et al. 2014). Models of the galactic pulsar population were generated using PsrPopPy `populate` function and normalized to match the results of the Parkes Multibeam Survey, as it is currently the largest and most successful large area pulsar survey to date (Stairs et al. 1999; Bates et al. 2014). To account for random fluctuations within a particular simulated population we averaged all results over 100 pulsar population models. For each realization of the galactic pulsar population we generated a canonical pulsar population with a mean spin period of 500 ms and an MSP population with a mean spin period of 30 ms. This accounted for limitations within PsrPopPy in generating a diverse pulsar population.

We looked at potential future surveys using the following GBT recievers: 820 MHz (0.68-0.92 GHz), L-Band (1.15-1.73 GHz), S-Band (1.73-2.6 GHz)[3], Ultra-wide band (UWB) (0.7-4 GHz)[4], and the Focal L-Band Array for the GBT (FLAG) (1.365-1.515 GHz) (Rajwade et al. 2019). For each receiver we used dwell times of 60 s, 120 s, 180 s, 300 s, 600 s, and 1800 s. Detailed survey parameters are listed in Table 1. We compared the future surveys at each dwell time to the following extisting large scale surveys: GBNCC, AODRIFT, CRAFTS, PALFA, and HTRU. We simulated each survey on the model populations using the PsrPopPy `dosurvey` function. For each galactic population we assigned each pulsar to the survey that detected it with the highest S/N and created sky maps for each survey of all the pulsars the survey detected with the highest S/N (see Figure 2). This measure of survey sensitivity helped determine which type of future survey would be the most sensitive and accounts for regions of the galaxy with the most pulsars. This allowed us to optimize each survey for regions that would yield the most pulsars. In Figure 1, we plotted the period vs DM of pulsars detected in a single pulsar model, where a 180 s integration time was used for each GBT future survey with colors indicating the survey which detected a particular pulsar with the highest S/N.

Our first step was to define the best survey regions. This was done by dividing the sky into bins and calculating which survey detected the most pulsars with the highest S/N in each sky bin. We saw three distinct regions where the GBT L-Band receiver detected the most pulsars (see Figure 3) and calculated the total survey area from which we determined the total number of observing hours needed for each dwell time. Survey duration was calculated by dividing the survey area by the angular size of the L-Band receiver and multiplying by the dwell time per pointing if we assume no overlap between pointings. If a half width half max overlap is assumed, this increases the survey duration by a factor of 2.25, and quarter width half max separation causes a 1.5 factor increase in survey duration.

The next step was to predict the total number of new pulsars within our newly defined survey region. We reran surveys over the newly defined survey regions and subtracted any pulsars within the new survey region that were detected by any of the current surveys. To account for pulsars that have already been discovered, we determined the number of known pulsars listed in the ATNF pulsar catalog within the survey region that were not discovered by any of the current surveys listed

[1] http://www.naic.edu/∼palfa/newpulsars/

[2] https://sites.google.com/site/htrusouthdeep/home/discoveries

[3] https://www.gb.nrao.edu/scienceDocs/GBTog.pdf

[4] https://greenbankobservatory.org/science/instruments-2020-2030

in Table 2, and subtracted this from the total pulsar count.

4. RESULTS

4.1. *Survey Type*

In Figure 2, we have sky maps of all the pulsars a particular survey detected with the highest S/N. In this figure we have used 180 s dwell times for the future survey, and indicated the number of pulsars in each subplot in the subplot title. Maps for all the other dwell times used to study the future surveys can be found in Appendix A. The GBT L-Band survey discovered 565 pulsars with a higher S/N than all the other current and future surveys. The majority of pulsars appear to be clustered in regions of the Galactic plane that the FAST and Arecibo telescopes cannot observe, so a survey focused on the region L-Band is sensitive to would not be competing with the FAST or Arecibo telescopes to find pulsars. These sky maps do not take into account discoveries that have already been made by the current surveys so the number of pulsars assigned to L-Band does not represent the true expected yield from an L-Band survey.

4.2. *Survey Region*

In Figure 3, we see that there are three regions in the galactic plane where the GBT L-Band receiver, labeled in pink, detects more pulsars with the highest S/N than any of the other current and future surveys. For ease of reference we have over plotted lines of constant δ of $-45°, -12°$, and $60°$. $-45°$ is the lowest δ that the GBT can observe and $12°$ is near the lowest declination observable by FAST (actual limit is $-14°$). This limit appears to be dwell time dependent, since at a high dwell time of 1800s, the L-Band survey region extends to cover most of the galactic plane (see Figure 13).

Since higher dwell times had higher sensitivity, we created maps for each dwell time and calculated the total survey area per dwell time (see Appendix B and Table 3). Due to the very small survey region at 60 s a dwell time, we excluded it from this analysis. We also excluded the 1800 s dwell time as a large-area survey with such a long dwell time would take more telescope time than a survey could reasonably be awarded. We considered a reasonable amount of telescope time to be less than the GBNCC total observing time of ~ 6000 hours.

Dwell Time (s)	Area (deg^2)	Duration (hr)
120	1191	2247
180	1712	4845
300	1954	9215
600	2397	22611

Table 3. Best survey region area and duration for the L-Band receiver for four dwell times. We have assumed no overlap between pointings.

For a 180 s dwell time L-Band survey, we would need approximately 4845 observing hours if we do not use overlapping pointings. For a half-width half max overlap, the survey would need 10,902 hours and for a quarter-width half max overlap, 7268 hours. We divided the survey area into three sub-regions which are defined in Table 4.

Region	ℓ range	b range	δ range
low ℓ	$-126°$ to $-81°$	$-9°$ to $6°$	$-45°$ to $-12°$
mid ℓ	$-57°$ to $18°$	$-20°$ to $19°$	$-45°$ to $-12°$
high ℓ	$100°$ to $137°$	$5°$ to $9°$	$> 60°$

Table 4. Survey regions defined for the GBT L-Band survey with a 180 s dwell time.

4.3. *Survey Yield*

In Table 5, we have listed the survey yield for an L-Band survey at dwell times of 120 s, 180 s, 300 s, and 600s. For a 180 s dwell time L-Band survey we would expect to discover about 500 new pulsars including roughly 50 MSPs. In comparison, the GBNCC survey has discovered 161 new pulsars, 25 of which are MSPs.

Dwell time (s)	MSP	Part. recyc.	Canonical	Total
120	33	36	273	342
180	49	53	396	498
300	73	80	589	743
600	126	131	963	1220

Table 5. The number of MSPs, partially recycled, canonical, and total pulsars detected by the L-Band receiver at four dwell times. MSPs are categorized as pulsars with spin periods less than 15 ms, partially recycled are spin periods between 15 ms and 200 ms, and canonical pulsars are those with spin periods above 200 ms. These numbers have been averaged over 100 pulsar populations and corrected for pulsars found by current surveys and known pulsars in the ATNF catalog.

5. DISCUSSION

Taking into account survey yields and duration, a 180 s L-Band survey would be an ideal candidate for the GBT large area survey.

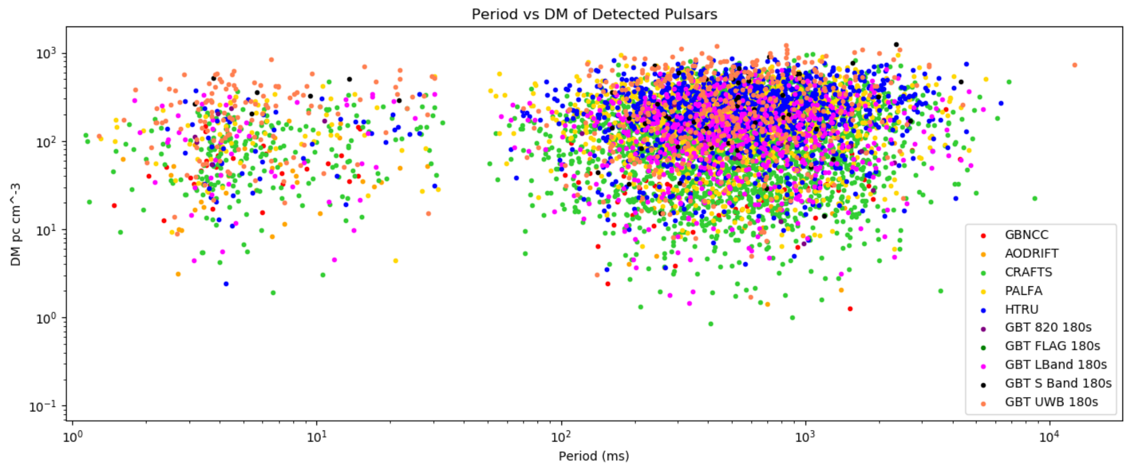

Figure 1. Spin period vs DM for all pulsars in a single galactic population detected by a current or future survey. The color represents which survey detected the pulsar with the highest S/N.

Receiver	820 MHz	L Band	FLAG	UWB	S Band
Gain (K/Jy)	2.0	2.0	2.0	2.0	2.0
Sampling time (ms)	0.08192	0.02024	0.02048	0.0109	0.02024
T_{sys} (K)	46	26	25	20	22
Central Frequency (MHz)	820	1500	1420	2350	2165
Frequency Bandwidth (MHz)	200	650	150	1500	800
Channel Bandwidth (MHz)	0.0244	0.0976	0.303	0.183	0.0488
FWHM (′)	15	9	23.81	9	5.8

Table 1. Table of survey parameters used for possible future GBT surveys in PsrPopPy to detect simulated pulsars. Each was run with dwell times of 60 s, 120 s, 180 s, 300 s, 600 s, and 1800 s.

Survey	GBNCC	AODRIFT	CRAFTS	PALFA	HTRU-N & HTRU-S
Integration Time (s)	120	60	60	268, 180	1500, 180, 90 & 4300, 540, 270
Gain (K/Jy)	2	11	10.1	8.5	1.5 & 0.6
Sampling Time (ms)	0.08192	0.082	0.2	0.064	0.05941 & 0.064
T_{sys} (K)	46	113	65	25	21 & 25
Center Frequency (MHz)	350	327	1024	1375.5	1360 & 1352
Bandwidth (MHz)	100	68.7	1350	322.6	240 & 340
Channel Bandwidth (MHz)	0.0244	0.02439	0.25	0.36604	0.5859 & 0.39
FWHM (′)	30	15	2	3.6	9.6 & 14
δ range (°)	-40–90	-1–38	-14–60	0–38	-20–90 & -90–10
ℓ range (°)	-180–180	-180–180	-180–180	32–77, 168–214	-180–180 & -80–30, -120–30, -180–180
b range (°)	-69–90	-90–90	0–90	0–5	0–3.5, 0–15, 15–90 for both N & S

Table 2. Table of existing survey parameters used in PsrPopPy to detect simulated pulsars. For the purpose of determining overall survey yield, HTRU North and South results were combined.

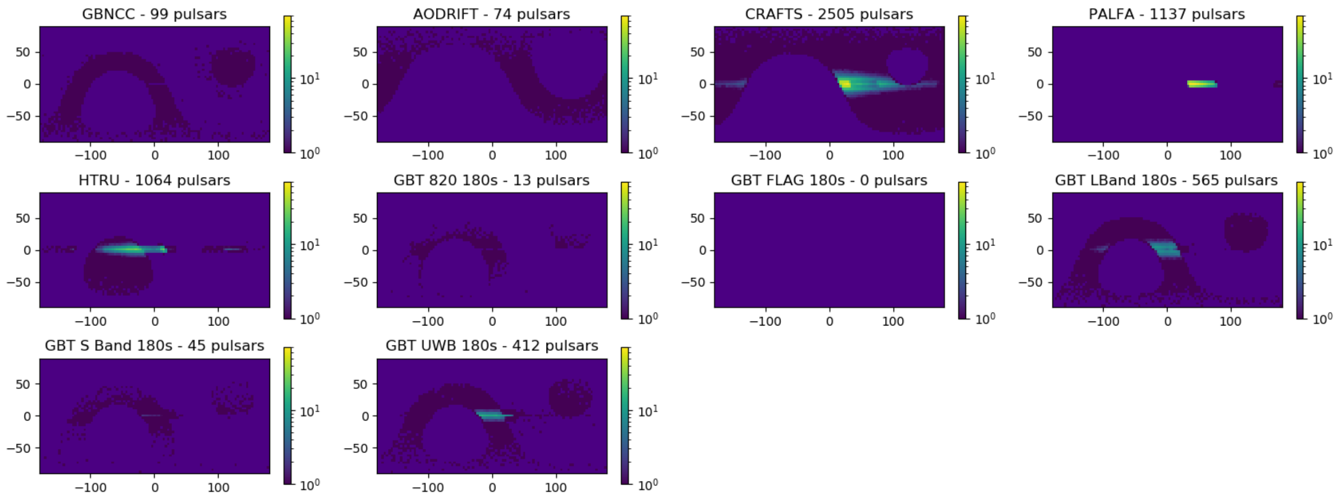

Figure 2. Skymaps of pulsars detected with the highest S/N by each current survey and each future survey using a 180s dwell time for the future surveys. Color scales indicate the number of pulsars found in a particular sky bin, and the total number of pulsars per map is indicated in each title. These maps have been averaged over 100 galactic populations.

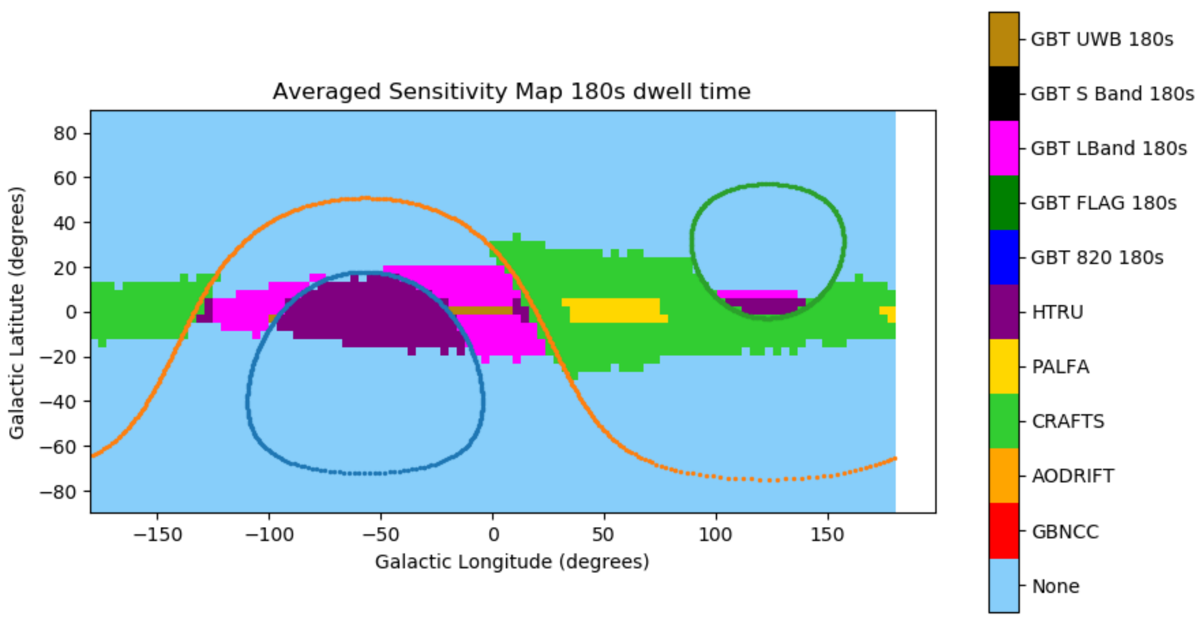

Figure 3. Skymap in which each bin color indicates the survey that detected the most pulsars averaged over 100 galactic populations. The blue, orange, and green lines indicate constant δ of $-45°$, $-12°$, and $60°$ respectively. For this map, all possible future GBT surveys use a 180 s dwell time. Regions labelled as 'None' detected less than one pulsar for any of the surveys after being averaged.

5.1. *Comparisons with GBT FLAG receiver*

The GBT FLAG receiver covers a similar frequency range to the L-Band receiver, although with a much smaller bandwidth and higher system temperature. As seen in our dwell time maps, the FLAG receiver suffers from significantly lower sensitivity, however it has a field of view (FOV) seven times larger than the L-Band receiver and thus can significantly drive down the number of pointings needed to cover the same area as the L-Band receiver. Also, the larger field of view means that there is relatively uniform sensitivity across the area of a single beam. Seven L-Band beams across the same area as a single FLAG beam would have reduced sensitivity at the edges of each beam.

If we use a longer dwell time, this can help account for the reduced sensitivity of FLAG. Looking at the 180 s L-Band survey area, if we were to use seven times the dwell time on a FLAG survey (1260 s) we would use the same amount of overall observing hours and detect about 50 more pulsars than at L-Band (Table 6). The longer dwell time would mean that we were more sensitive to nulling pulsars and RRATs, but less sensitive to short-orbital period binaries.

Dwell Time (s)	Duration (hr)	Number of Pulsars
180 L-Band	4845	498
1260 FLAG	4845	552

Table 6. Survey duration and yield for L-Band at 180 s and FLAG at 1260 s over the survey area defined for L-Band at 180 s.

5.2. *Future Studies*

Further studies into this project would include examining potential timing precision of the MSPs discovered in a single pulsar population to determine how many PTA candidates might be expected from an L-Band survey. We would also run population studies on the pulsars discovered by L-Band vs FLAG in order to study the impact of the longer FLAG dwell time on the types of pulsars discovered.

ACKNOWLEDGMENTS

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This project was conducted using the python package PsrPopPy described in Bates et al. (2014) and the version used by the authors of this paper can be found at https://github.com/NihanPol/PsrPopPy2.

REFERENCES

Arzoumanian, Z., Baker, P. T., Brazier, A., et al. 2018, ApJ, 859, 47, doi: 10.3847/1538-4357/aabd3b

Barr, E. D., Champion, D. J., Kramer, M., et al. 2013, MNRAS, 435, 2234, doi: 10.1093/mnras/stt1440

Bates, S. D., Lorimer, D. R., Rane, A., & Swiggum, J. 2014, MNRAS, 439, 2893, doi: 10.1093/mnras/stu157

Cordes, J. M., Freire, P. C. C., Lorimer, D. R., et al. 2006, ApJ, 637, 446, doi: 10.1086/498335

Cromartie, H. T., Fonseca, E., Ransom, S. M., et al. 2020, Nature Astronomy, 4, 72, doi: 10.1038/s41550-019-0880-2

Keith, M. J., Jameson, A., van Straten, W., et al. 2010, MNRAS, 409, 619, doi: 10.1111/j.1365-2966.2010.17325.x

Kramer, M., Stairs, I. H., Manchester, R. N., et al. 2006, Science, 314, 97, doi: 10.1126/science.1132305

Lorimer, D. R. 2008, Living Reviews in Relativity, 11, 8, doi: 10.12942/lrr-2008-8

Manchester, R. N., Hobbs, G. B., Teoh, A., & Hobbs, M. 2005, VizieR Online Data Catalog, VII/245

Martinez, J. G., Gentile, P., Freire, P. C. C., et al. 2019, ApJ, 881, 166, doi: 10.3847/1538-4357/ab2877

McEwen, A. E., Spiewak, R., Swiggum, J. K., et al. 2020, ApJ, 892, 76, doi: 10.3847/1538-4357/ab75e2

Qian, L., Pan, Z., Li, D., et al. 2019, Science China Physics, Mechanics, and Astronomy, 62, 959508, doi: 10.1007/s11433-018-9354-y

Rajwade, K. M., Agarwal, D., Lorimer, D. R., et al. 2019, MNRAS, 489, 1709, doi: 10.1093/mnras/stz2207

Stairs, I. H., Lyne, A. G., Camilo, F., et al. 1999, arXiv e-prints, astro. https://arxiv.org/abs/astro-ph/9903290

Stovall, K., Lynch, R. S., Ransom, S. M., et al. 2014, The Astrophysical Journal, 791, 67, doi: 10.1088/0004-637x/791/1/67

Wolszczan, A., & Frail, D. A. 1992, Nature, 355, 145, doi: 10.1038/355145a0

APPENDIX

A. DWELL TIME MAPS

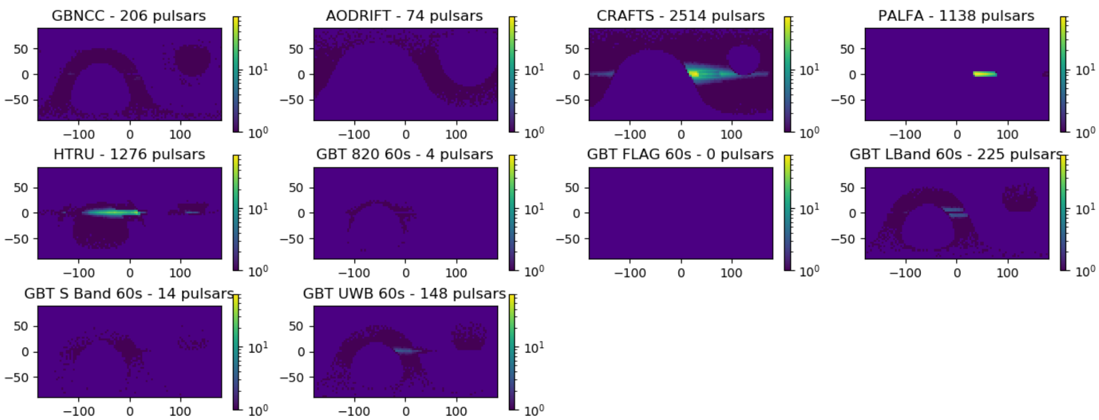

Figure 4. Skymaps of pulsars detected with the highest S/N by each current survey and each future survey using a 60s dwell time for the future surveys averaged over 100 galactic populations.

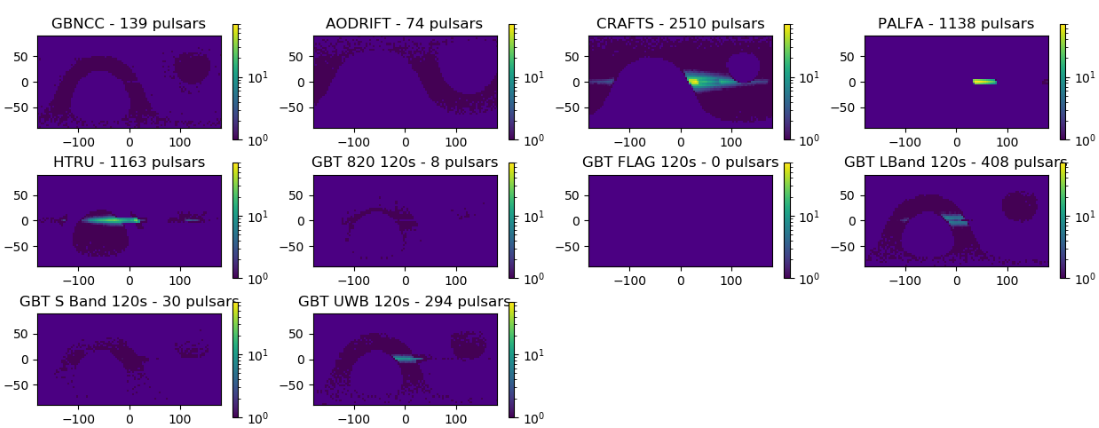

Figure 5. Skymaps of pulsars detected with the highest S/N by each current survey and each future survey using a 120s dwell time for the future surveys averaged over 100 galactic populations.

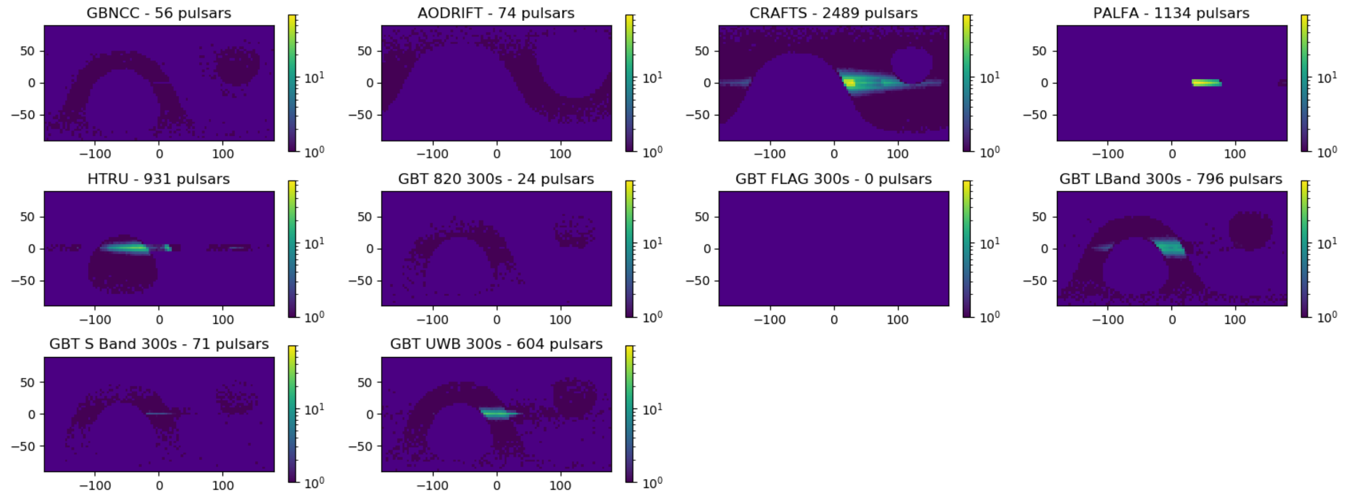

Figure 6. Skymaps of pulsars detected with the highest S/N by each current survey and each future survey using a 300s dwell time for the future surveys averaged over 100 galactic populations.

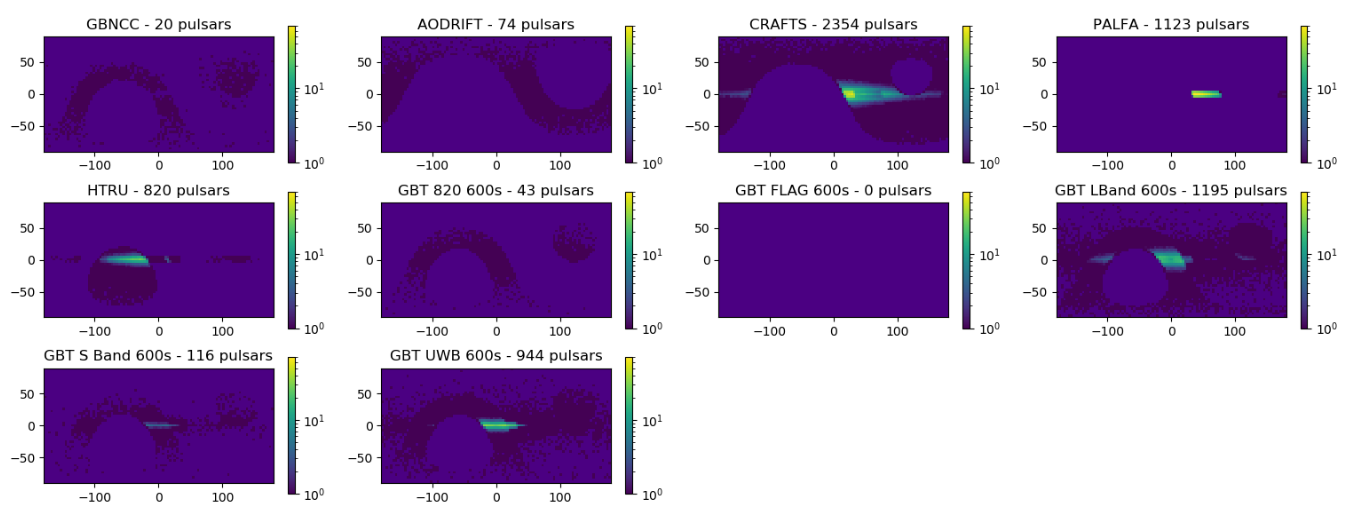

Figure 7. Skymaps of pulsars detected with the highest S/N by each current survey and each future survey using a 600s dwell time for the future surveys averaged over 100 galactic populations.

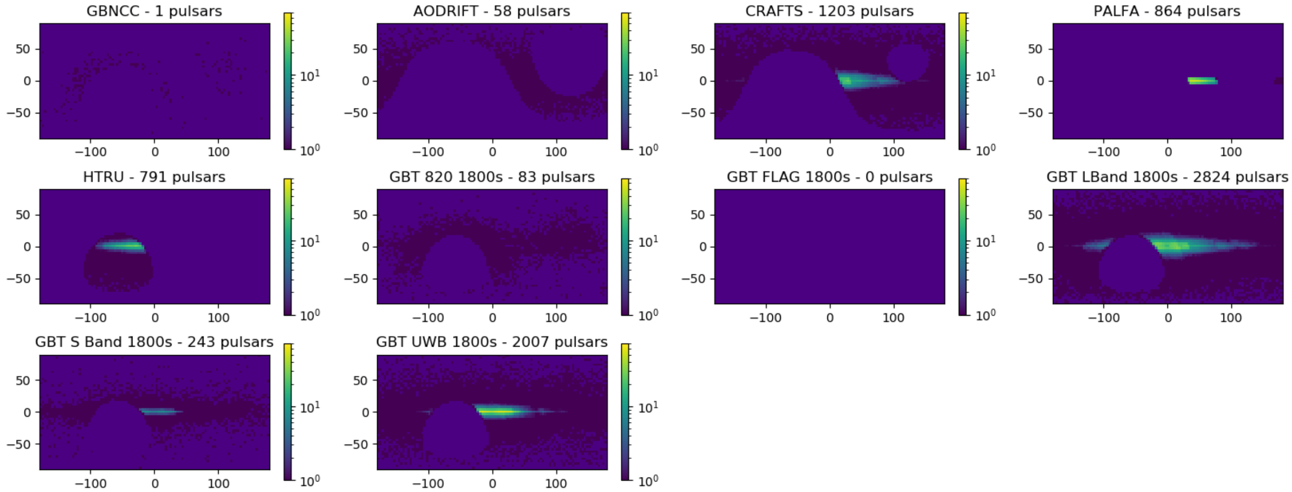

Figure 8. Skymaps of pulsars detected with the highest S/N by each current survey and each future survey using a 600s dwell time for the future surveys averaged over 100 galactic populations.

B. SENSITIVITY MAPS

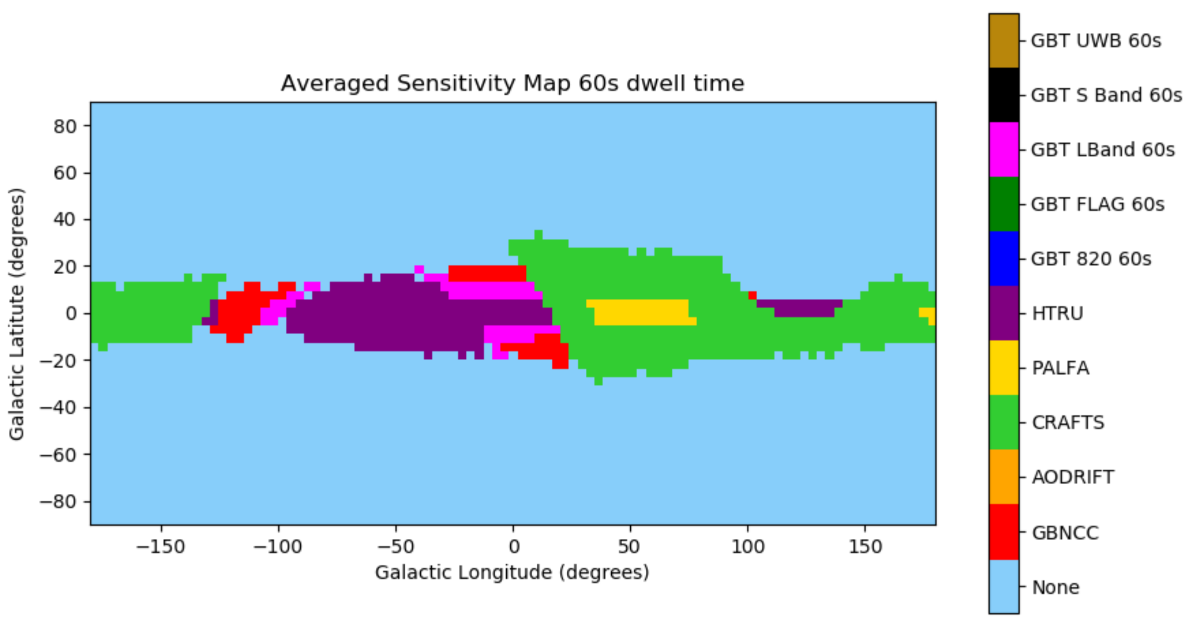

Figure 9. Skymap in which each bin color indicates the survey that detected the most pulsars averaged over 100 galactic populations. For this map, all possible future GBT surveys use a 60 s dwell time.

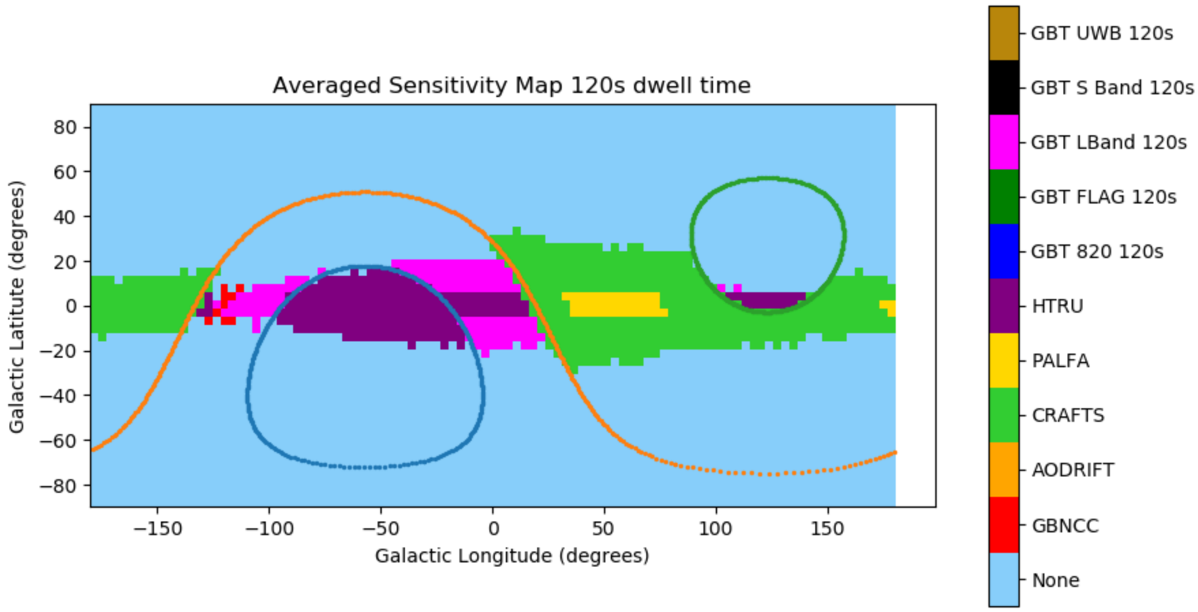

Figure 10. Skymap in which each bin color indicates the survey that detected the most pulsars averaged over 100 galactic populations. The blue, orange, and green lines indicate constant δ of -45°, -12°, and 60° respectively. For this map, all possible future GBT surveys use a 120 s dwell time.

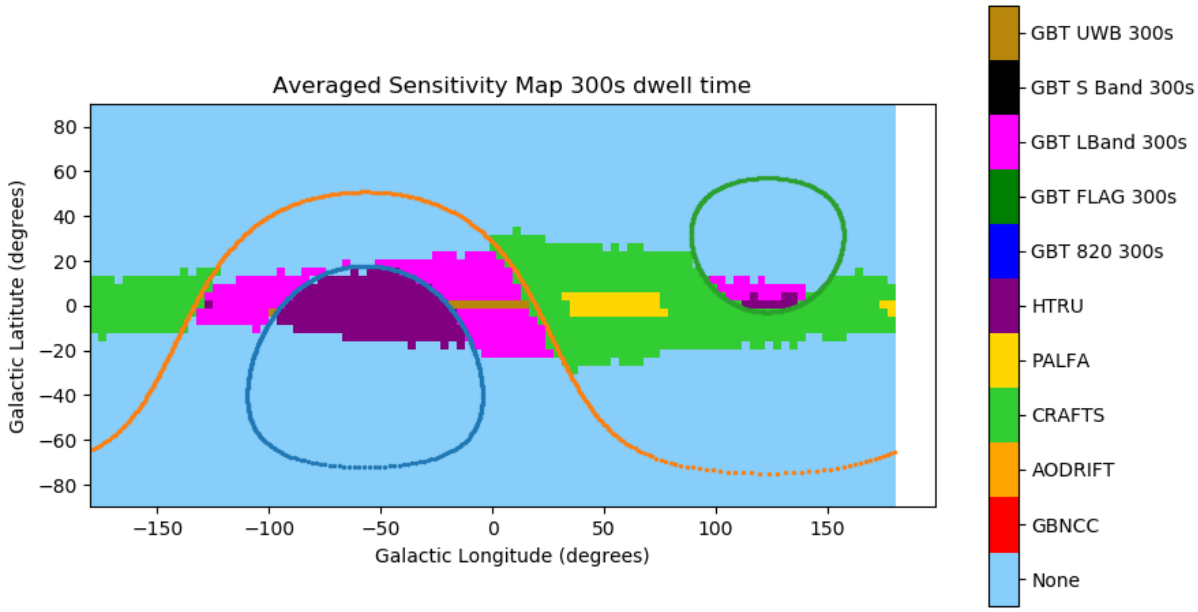

Figure 11. Skymap in which each bin color indicates the survey that detected the most pulsars averaged over 100 galactic populations. The blue, orange, and green lines indicate constant δ of -45°, -12°, and 60° respectively. For this map, all possible future GBT surveys use a 300 s dwell time.

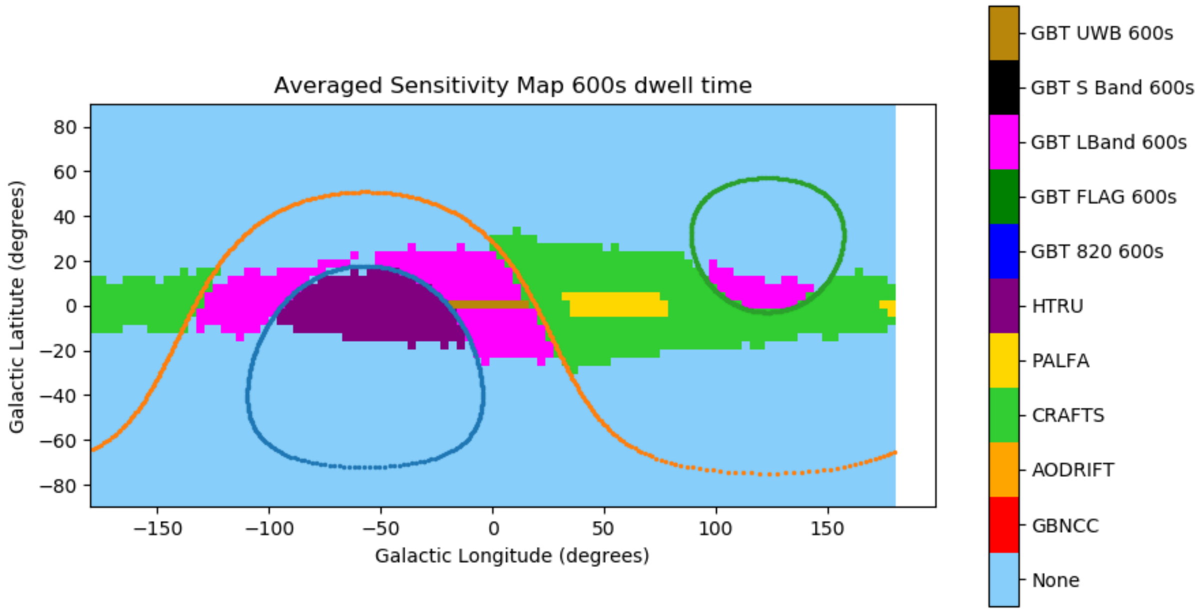

Figure 12. Skymap in which each bin color indicates the survey that detected the most pulsars averaged over 100 galactic populations. The blue, orange, and green lines indicate constant δ of -45°, -12°, and 60° respectively. For this map, all possible future GBT surveys use a 600 s dwell time.

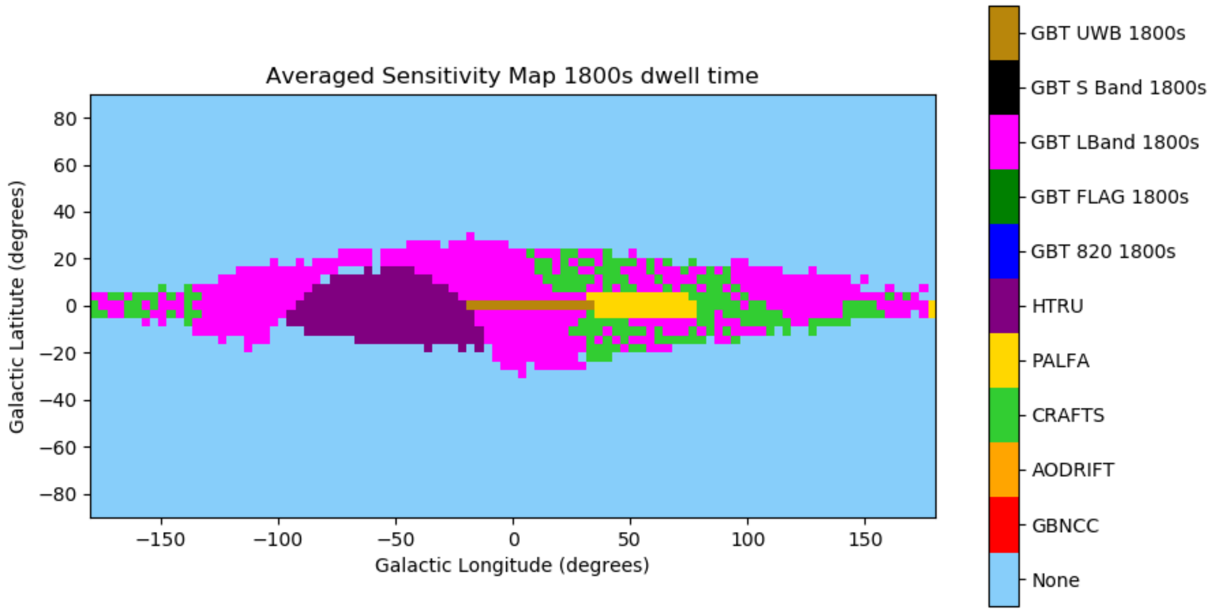

Figure 13. Skymap in which each bin color indicates the survey that detected the most pulsars averaged over 100 galactic populations. For this map, all possible future GBT surveys use a 1800 s dwell time.