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AN ALFA PULSAR SURVEY OF THE GALACTIC PLANE

October 1, 2004

THE PALFA CONSORTIUM[1]

ABSTRACT

We propose the first year of a large-scale survey of the Galactic plane using ALFA. Primary emphasis will be on the inner Galaxy but we also propose a search of the Galactic anticenter region. Arecibo's high gain and wide-band spectrometers allow surveys of much greater volumes (per unit solid angle) than the eminently successful Parkes Multibeam Survey, particularly for short-period pulsars. The survey will thus find not only a large sample of pulsars, but also rare objects that are especially useful for probing fundamental aspects of neutron stars, testing theories of gravity, and detecting gravitational backgrounds, among other enterprises. We estimate that with our eventual software processing, we will discover a pulsar about every 1.5 hr of on-sky observing time. In addition, our analysis also will detect transient signals from pulsars that are intermittent or from other kinds of objects. Preliminary observations in 2004 Aug-Sep have yielded discovery of eight new pulsars in a quick-look analysis, including one from detection of its single pulses. Many more are expected in the data we already have. Given the pace of observations so far, our ability to glean from them new pulsar discoveries, and our expectation that full resolution code will complete the processing of precursor-survey data by the end of 2005 January, a comprehensive pulsar survey using existing WAPP spectrometers can be initiated on or after 2005 Feb 1.

Subject headings: neutron stars; black holes; magnetars; General Relativity; gravitational waves; stellar evolution; relativistic plasma physics; interstellar medium;

I. INTRODUCTION

This proposal is for the first year of a long-term pulsar survey of the Galactic plane using the Arecibo L-band Feed Array. A companion proposal requests telescope time for follow-up timing observations of the pulsars we discover. In what follows, we describe the scientific motivation for the survey and compare its expected outcome to that of the recent Parkes Multibeam Survey (PMB). We then describe the results of test observations with ALFA made under a precursor survey, the technical aspects of the proposed survey, and the resulting request for telescope time.

Why more pulsars? Radio pulsars continue to provide unique opportunities for testing theories of gravity and probing states of matter otherwise inaccessible to experimental science. In large samples, they also allow detailed modeling of the magnetoionic components of the interstellar medium (ISM). For these and other reasons, we propose initiation of a large-scale pulsar survey that aims to discover rare objects especially suitable for their physical and astrophysical payoffs. Of particular importance are pulsars in short-period orbits with relativistic companions, ultrafast millisecond pulsars (MSPs) with periods $P < 1.5$ ms that provide important constraints on the nuclear equation of state and MSPs with stable spin rates that can be used as detectors of long-period ($\gtrsim$ years) gravitational waves. Long period pulsars ($\gtrsim 5$s) are of interest for understanding their connection, if any, with magnetars. Additionally, any objects with especially large space velocities, as revealed through subsequent astrometry, will help constrain aspects of the formation of neutron stars (NS) in core-collapse supernovae. While particular, rare objects will be the initial focus of survey follow up observations, long-term payoff will occur from the totality of pulsar detections, which

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can be used to map the electron density and its fluctuations and the Galactic magnetic field. Finally, multiwavelength analyses (including infrared, optical and high energy observations) of selected objects will provide further information on how NS interact with the ISM, on supernovae-pulsar statistics, and on the relationship of radio pulsars to unidentified sources found in surveys at high energies.

We have summarized the science case for PALFA surveys in several documents, including the whitepaper for the PALFA Consortium that can be found at http://alfa.naic.edu and in a memo "Preliminary Paper on Pulsar Search" that can be found at http://alfa.naic.edu/memos/alfa_memos.html. Here we reiterate the primary reasons for why PALFA pulsar surveys will provide enormous scientific return.

As the world's largest single aperture, the Arecibo telescope will provide the most sensitive surveys of the pulsar sky for at least 10 years. Only when the Square Kilometer Array comes on line ($\gtrsim$ 2015) will more sensitive surveys of the microwave pulsar sky become possible. It is notable that one of the five key projects identified for the SKA is the usage of pulsars for strong-field tests of gravity and gravitational wave detection (Kramer et al. 2004 and references therein). Such tests can provide answers to one of the questions posed in *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*[2]: "Was Einstein right about gravity?" To do so requires timing of pulsars like the extraordinary double-pulsar binary J0737-3039 (Lyne et al. 2004), which comprises a recycled pulsar with 23ms spin period and a canonical pulsar with 2.8s period in a 2.4-hr orbit. Additional such binaries remain to be discovered, some with even smaller orbital periods, allowing correspondingly stronger tests of gravity.

A Galactic Census: We envision a Galactic census of radio pulsars that aims to detect at least half of the active radio pulsars that are beamed at us. Arecibo surveys represent the next major step toward the census, which the SKA will complete (Cordes et al. 2004 and references therein). Taking beaming and the radio lifetimes of pulsars into account, the fiducial NS birth rate of 10^{-2} yr^{-1} implies $\sim 2 \times 10^4$ detectable pulsars in the Galaxy. About 1/4 of these are within the Arecibo sky[3] so there are roughly 5000 pulsars accessible to Arecibo, about half of which are at low Galactic latitudes.

The first reason for proposing a complete Galactic census is obvious: the larger the number of pulsar detections, the more likely it is to find rare objects that provide the greatest opportunities for use as physical laboratories. These include binary pulsars as described above and also those with black hole companions; MSPs that can be used as detectors of cosmological gravitational waves; MSPs spinning faster than 1.5 ms, possibly as fast as 0.5 ms, that probe the equation-of-state under extreme conditions; hypervelocity pulsars with translational speeds in excess of 10^3 km s^{-1}, which constrain both core-collapse physics and the gravitational potential of the Milky Way; and objects with unusual spin properties, such as those showing discontinuities ("glitches") and apparent precessional motions (including 'free" precession in isolated pulsars and binary pulsars showing geodetic precession).

The second reason for a full Galactic census is that the large number of pulsars can be used to delineate the advanced stages of stellar evolution that lead to supernovae and compact objects. In particular, with a large sample we can determine the branching ratios for the formation of canonical pulsars and magnetars. We can also estimate the effective birth rates for MSPs and for those binary pulsars that are likely to coalesce on time scales short enough to be of interest as sources of periodic, chirped gravitational waves (e.g. Burgay et al. 2003).

The third reason is that a maximal pulsar sample can be used to probe and map the ISM at an unprecedented level of detail. Measurable propagation effects include dispersion, scattering, Faraday rotation, and HI absorption that provide, respectively, line-of-sight integrals of the free-electron density n_e, of the fluctuating electron density, δn_e, of the product $B_{\parallel} n_e$, where $B_{\parallel}$ is the LOS component of the interstellar magnetic field, and of the neutral hydrogen density. The resulting dispersion measures (DM), scattering measures (SM), rotation measures (RM) and atomic hydrogen column densities ($N_{\rm HI}$) obtained for a large number of directions will enable us to construct a much more detailed map of the Galaxy's gaseous and magnetic components, including their fluctuations.

PALFA surveys will detect pulsars from the following distinct subclasses:

1. *Canonical pulsars:* These pulsars have spin periods ranging from tens of milliseconds to 8 s and surface magnetic field strengths $B \sim 10^{12\pm1}$ G. Some are born with periods $\sim$ 10 ms, though evidence suggests that others are born with periods longer than 0.1 s. In the standard picture of NS formation,

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[2] National Academies Press, 2003, ISBN 0-309-07406-1

[3] The current ANTF pulsar catalog indicates that 22% of the known pulsars are in the Arecibo sky: 2% Galactic anticenter and 20% inner Galaxy. Arecibo can observe 1/4 of all Galactic longitudes, but much of this range contains lower-than-average pulsar space density. We note that these numbers include pulsars that are well out of the Galactic plane because they have high space velocities.

all pulsars start as canonical pulsars. *Young pulsars* are especially important members of this class because they are associated with supernova remnants and often show copious numbers of glitches. A few will be found around main-sequence companions.

2. *Millisecond pulsars:* objects in binaries that survive the SN explosion and the companion object evolves into a white dwarf. The long, preceding accretion phase spins the pulsar up to millisecond periods while attenuating the (assumed) dipolar field component to $10^8 - 10^9$ G. The consequent small spin-down rates seem to underly the high timing precision of these objects and imply spin-down time scales that exceed a Hubble time in some cases. The high timing precision makes some of these objects suitable for use as detectors of gravitational waves. MSPs typically have $P \sim 3 - 5$ ms and $\dot{P} \sim 10^{-20}$.

3. *Modestly recycled pulsars:* are objects in binaries that survive a first SN explosion and subsequently accrete matter that spins-up the pulsar and reduces the effective dipolar component of the magnetic field. Accretion is terminated in these objects by a second supernova explosion that may or may not disrupt the binary. Those that survive are seen today as relativistic NS-NS binaries. Evolutionarily, it is possible that some surviving binaries include black-hole companions. These pulsars typically have $P \sim 30$ ms and $\dot{P} \sim 10^{-18}$.

4. *Strong-magnetic-field pulsars:* Recently discovered radio pulsars have fields $\gtrsim 10^{14}$ G rivalling those inferred for "magnetar" objects identified through their X-and-γ radiation, which seems to derive from non-rotational sources of energy. The relationship between magnetars and high-field radio emitting pulsars, whose radiation derives solely from spin energy, is not yet known. High field radio pulsars typically have $P \sim 5$s and $\dot{P} \sim 10^{-13}$.

Canonical pulsars and MSPs account for $\sim 90\%$ and $\sim 10\%$ of all pulsars, respectively, with relativistic binaries and high-field pulsars comprising $\lesssim 1\%$. It would not be surprising to find additional classes of pulsars in a high-yield survey.

Comparison of PALFA Surveys with the Parkes Multibeam Survey: The ALFA system was conceived in large part to exploit the wide bandwidth and high sensitivity of the Arecibo telescope for pulsar surveys.[4] To demonstrate its expected yield, we compare it with the very successful Parkes multibeam survey (PMB), which has discovered ~ 700 new pulsars using a 13-beam system (e.g., Manchester et al. 2001). Table 1 compares the specifications of the PALFA and PMB surveys. For ALFA, we give values for the spectrometers currently available (WAPPs = Wideband Arecibo Pulsar Processors) and for the new 300-MHz 'PALFA' spectrometer expected to become available in mid-2005.[5] ALFA+WAPPs provide the same sensitivity in 60s as did the 2100s pointings of the PMB. With precursor observations we have used 67s and 134s pointings (to obtain data lengths compatible with 2^n-length FFTs) and to allow coverage of sufficient solid angle to assess the efficacy of our search strategies. Here we propose a total dwell time per direction ~ 268 (for the inner Galaxy) that provides at least a two-fold increase in the maximum detectable distance $D_{\rm max}$ over the PMB and hence a survey volume that is at least 8 times larger. These numbers follow from the requirement that we survey much deeper than the PMB and thus reach the nominal boundaries of the Galactic disk for a good fraction of the 1.4 GHz pulsar luminosity function. About 95% of pulsars have L-band luminosities $L_p > 1$ mJy kpc^2, which (Table 1) can be seen to 4.6 kpc for $P \gtrsim 1$s, and 65% have $L_p > 10$ mJy kpc^2, which can be seen to 15 kpc at long periods, as may be seen in Figure 1 (left panel).

Figure 1 shows $D_{\rm max}$ vs P for four different pulsar luminosities for the PMB and PALFA surveys. For PALFA, $D_{\rm max}$ is significantly larger than for PMB for short-period pulsars in particular because the PMB spectrometer's dump time is 4 times longer and its channel bandwidth is 10 times larger than the PALFA II spectrometer, thus causing significantly more dispersion smearing, $\Delta t_{\rm DM}$, that broadens the pulses and reduces their detectability. The PMB also employed high-pass filtering to mitigate total-power changes that limited the sensitivity to pulsars longer than 3s. In round numbers, PALFA II surveys will reach ~ 1.8 and 4 times further in $D_{\rm max}$ for long-period pulsars and MSPs, respectively. These correspond to much larger search volumes ($\propto D^3_{\rm max}$): a factor of 6 for long-period pulsars and a factor of 50 for MSPs. Thus, even in directions searched in the PMB, PALFA surveys will probe pulsar-occupied but unexplored search volumes. The right panel of Figure 1 shows the comparison in terms of minimum detectable flux density.

Survey Plans and Data Flow: Our long term goal is to survey the entire Galactic plane visible with the Arecibo telescope (at latitudes $\lesssim 5^\circ$) and also to survey out of the plane to intermediate Galactic latitudes

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[4] The original science case for an NSF pre-proposal may be found at http://alfa.naic.edu/memos.

[5] The new spectrometer will employ a polyphase filter-bank architecture with less spectral leakage between channels and will thus be more immune to RFI. However, there will be more interfering signals in the wider 300 MHz passband.

TABLE 1
Comparing PALFA and Parkes Multibeam Surveys

Item	ALFA + WAPPs	ALFA II	PMB
System Parameters:			
SEFD[a] (Jy)	3.6 (4.6)	3.6 (4.6)	36
FWHM/beam (arcmin)	3.6	3.6	14
No. of beams	7	7	13
Total Bandwidth (MHz)	100	300	288
Spectral channels	256	1024	96
Bandwidth/channel (MHz)	0.39	0.29	3.0
Dump time (μs)	64	64	250
Dwell time/position (s)	67, 134, 268	134, 268	2100
Sky coverage rate[b] (deg^2 hr^{-1}	1.2	3.6	0.95
$S_{\rm min_1}$[c] in 1 min (μJy)	330 (420)	190 (241)	1900
$\Delta t_{\rm DM}$ (DM = 50) (μs)	59	44	453
Survey Parameters:			
$S_{\rm min}$[*] (μJy)			
(1 s, DM = 0 pc cm^{-3})	119	48	150
(1 ms, DM = 50 pc cm^{-3})	700	460	6,600
$D_{\rm max}$[†] (kpc)			
(1 s, 1 mJy kpc^2)	2.9	4.6	2.6
(1 ms, 1 mJy kpc^2)	1.2	1.5	0.4
$V_{\rm max}$[♯] (kpc^3 sr^{-1})			
(1 s, 1 mJy kpc^2)	8.1	32	5.8
(1 ms, 1 mJy kpc^2)	0.6	1.1	0.02

[a] SEFD = system equivalent flux density; the two values for ALFA are for the central and outer beams, respectively.

[b] Sky coverage rate is calculated for dwell times such that the sensitivity $S_{\rm min_1}$ is the same for all cases (i.e. 60s, 20s and 2100s for ALFA+WAPPs, ALFA II, and PMB, respectively).

[c] $S_{\rm min_1}$ = minimum detectable flux density in a single harmonic of the Fourier analysis with 10σ threshold with two polarizations summed. Note: Sensitivity values do not account for quantization errors in the WAPPs or in the PMB spectrometer. Nor do they account for the effects of RFI.

[*] Calculated for T=134s for WAPPS+PALFA 268s for ALFA II, and 2100s for PMB. Numbers are shown only for beam 0

[†] $D_{\rm max} = \sqrt{L_p/S_{\rm min}}$ where L_p is the "luminosity" (mJy kpc^2) and $S_{\rm min}$ is from the previous rows. The pulsar luminosity function is very broad, extending from $\ll 1$ to 10^3 mJy kpc^2 at 1.4 GHz.

[♯] $V_{\rm max} = D^3_{\rm max}/3$ is the volume searched per unit solid angle.

$\lesssim 30°$. Under the precursor survey period (2004 Aug 1 - Oct 7, with expected extension through 2005 Jan 31), we have surveyed only latitudes $|b| \lesssim 1°$ in both the inner Galaxy and anticenter directions. Here we propose to do the first year of a full-Galactic plane survey at much greater sensitivity than both the precursor survey and the PMB.

Survey data are voluminous using the WAPPs: ~ 0.3 Tbyte hr^{-1} if taking data at full efficiency. The rate will increase by a factor of 4 when the new PALFA spectrometer becomes available (see below). A quick-look analysis is done in near-real time using the Arecibo Signal Processor (ASP) provided by groups at UC Berkeley, U. British Columbia, and Princeton (see more below). This analysis performs both standard periodicity and single-pulse searches of the data after reducing the time-and-frequency resolutions (to increase processing speed) and performing one level of RFI excision. Full off-line analysis will take place at several of our home institutions, and the data products and raw data will be transferred for final storage and analysis at the Cornell Theory Center (CTC). The CTC will acquire storage resources and accompanying high-performance computers over a 5-yr period commencing this month (2004 Sep) until ~ 1 petabyte (1 PB = 10^3 TB) of storage is acquired. This time period matches, by design, the data accumulation period for PALFA surveys.

The analysis produces a variety of intermediate as well as final data products. These amount to $\sim 0.1\%$ of the original data volume and are thus trivial to store. Our plan is to provide web-based tools for accessing data products so that intelligent classification of candidate signals can be made, whether they are celestial

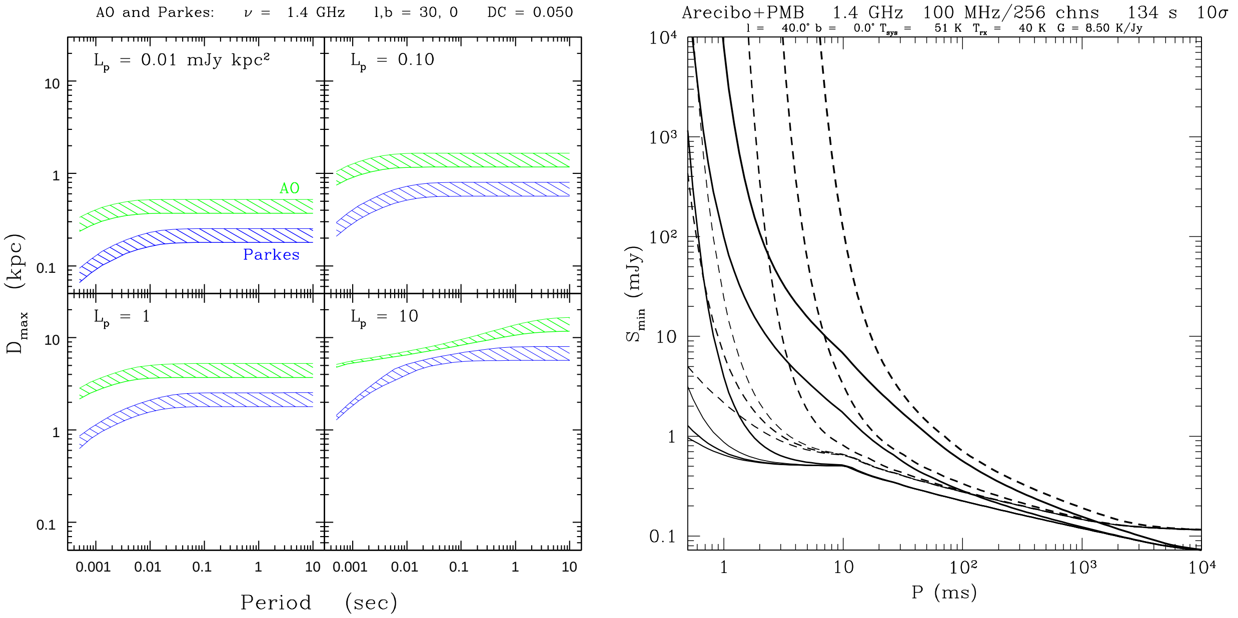

Fig. 1.— *Left:* Maximum detection distance, $D_{\max}$, vs. spin period for the direction $\ell, b = 30^\circ, 0^\circ$ (at the edge of the declination limit for Arecibo) and for a fixed pulse duty cycle of 0.05. The four frames correspond to different values of the 'pseudo-luminosity' $L_{\rm p}$, which is the period-averaged flux density $\times D^2$. The distribution of $L_{\rm p}$ for pulsars is broad, covering several orders of magnitude, because the emission is beamed. The top and bottom boundaries of each shaded region are for full- and half-gain, respectively. The telescope parameters are as in Table 1 using ALFA II parameters for Arecibo. Propagation effects, which limit $D_{\max}$ at large distances, are calculated using the electron density model NE2001 (Cordes & Lazio 2002). For distances > 5 kpc, $D_{\max}$ is affected by pulse broadening from scattering. *Right:* Minimum detectable flux density vs. P for different values of DM. Solid lines: for full-resolution PALFA data using the WAPP systems and dwell time of 134s, as described in the text. Dashed lines: for the Parkes multibeam survey, which used 96 channels across 288 MHz and 250 μs sampling for a dwell time of 2100 s. For each set of curves, DM values from the lowest to the highest curve are 1, 10, 50, 200, 500 and 1000 pc cm^{-3}. The breakpoint at $P \sim 10$ ms for the solid curves occurs because we assume that the intrinsic pulse duty cycle scales as $P^{-1/2}$ with a maximum of 0.3, which occurs at this period. Above 10 ms, the number of harmonics contributing to detections increases from 1 to 32 (the maximum searched) as the duty cycle gets smaller.

in nature or interference. The classified signals will be made publicly available in a manner consistent with "virtual observatory" concepts, with the CTC as the host node for the data. Other information deposited there will include a catalog of new pulsars with parameters determined from a related timing program and astrometric observations with the VLA and other instruments.

Who will do the work? Pulsar surveys with ALFA require the collective resources of the PALFA Consortium. The precursor survey period has allowed the Consortium to develop observing procedures, logging methods, data analysis software, database tools, and confirmation and follow-up observational criteria that are needed for the long term survey. Of the 33 current members listed on the first page, more than half have visited Arecibo during the observations in the first two months of the precursor survey and additional members have worked on other necessary aspects of the project. Analysis of WAPP data at full resolution will take about 20 times longer than the quick-look analysis and will increase by another factor of 4 when the new spectrometer becomes available. For the precursor data, this computational load can be handled at Arecibo with available resources. But for the survey proposed here using the WAPPs and the new spectrometer, analysis of data with the new spectrometer must occur off-island at Consortium member institutions (about 7 in number). We are developing those resources now and will ramp up on full-resolution processing over the next few months. We have the resources to keep up with the data rate at the anticipated duty cycle of observations.

Results of the Precursor Survey: One goal of the precursor survey has been to commission the ALFA system by acquiring data in pulsar-search mode using the WAPP spectrometers to characterize the data quality, including an assessment of radio frequency interference (RFI). In addition, we have developed observing methodologies, continued with survey simulations, and developed end-to-end resources for data acquisition bookkeeping, analyzing data, archiving results, and organizing follow-up observations.

TABLE 2
New Pulsars Discovered in the PALFA Precursor Survey

Pulsar	P (ms)	$\widehat{\mathrm{DM}}$ (pc cm^{-3})	$\langle S/N\rangle$	Comments
J0540+32	524	120	36	Strong, sporadic single pulses
J0628+09	207	88	13	Discovered as S/N=40 single pulses; (periodicity not yet confirmed)
J1904+07	209	275	15	Strong, sporadic
J1906+07	144	217	11	
J1928+1746	69	174	19	First ALFA pulsar; also detected at C,X bands (flat spectrum)
J2009+33	1438	254	13	sporadic; confirmed using single pulses
J2010+32	1442	350	23	distinct from J2009 and J2010+33
J2010+33	932	300	30	distinct from J2010+32, sporadic

$\widehat{\mathrm{DM}}$ is the DM value at which the search algorithm identified the pulsar.
$\langle S/N\rangle$ = signal to noise ratio of the average pulse shape (peak/rms).

By Oct 1, we have obtained 24 hr of on-source time for the inner Galaxy and 17 hr for the Galactic anticenter. (Other telescope time has been used for testing operational aspects of pulsar surveying and other tasks related to commissioning ALFA.) The *quick-look* analysis of precursor data has led to:

1. Discovery of a new pulsar in the first hour of observing! See J1928+1746 in Table 2.
2. Discovery of seven additional pulsars, including one through detection of its strong, occasional pulses and not through its periodicity.
3. Redetection of 19 known pulsars (Table 3). We have not missed any known pulsars that were within the half-power contours of any of the ALFA beams.

We expect that analysis of full-resolution data, now ongoing, will yield additional discoveries because it will reach $D_{\max}$ values a factor of 2 to 4 larger (for long-period pulsars and MSPs, respectively) than the quick-look analysis.

Table 3 includes the offset of the pulsar position from the nearest ALFA beam center. In some cases, pulsars were detected even though this offset was significantly larger than the beam width (FWHM $\sim$ 3.6 arcmin). Such wide field detections are a consequence of the high coma lobes of the six off-axis beams (-8.7 dB down), which make mapping projects difficult but which have a silver lining for pulsar surveys: the coma lobes have gains comparable to about 70% of the Green Bank Telescope's peak gain and about 170% of the Parkes peak gain! These facts, bolstered by simulations discussed below, indicate that the high sidelobes can be exploited in the pointing strategy we will use for the initial stages of our surveys, which we discuss in the next section.

II. Proposed Survey

Regions to Survey: We propose to survey the entire Galactic plane visible from Arecibo: the longitude range from 32°–77° in the inner Galaxy and 168°–214° in the anticenter region for latitudes $|b| \lesssim 5°$. This will take 5 yr or longer, depending on how high in Galactic latitude we search (see below) and if we are scheduled at a rate $\sim$ 140 hr/4 months, the approximate rate we are scheduled in the precursor survey. Simulations (Figure 2, left) indicate that about 1000 new pulsars will be detected, though we caution that simulations depend on poorly known aspects of the pulsar population, such as its radial distribution.

Figure 2 (right) delineates regions of the Galaxy that we propose to survey. The pulsar *population* has no definitive latitude range owing to its wide range of velocities. However, the PMB has found a falloff in the number of pulsar *detections* at a characteristic latitude of a few degrees. Given the two-component velocity distribution of pulsars (Arzoumanian et al. 2001), we can understand this low-latitude subset of pulsars as comprising bright, young objects combined with somewhat older, low-velocity pulsars. Older pulsars, especially those from the higher velocity component, easily extend the population's latitude range to 5° and beyond, but with lower space density. Our Arecibo detections are likely to show a different latitude distribution than the PMB. Therefore, our plan is somewhat open ended as to how high we will search in latitude with the specified survey parameters. We will start our observations at the lowest latitudes and work our way to higher $|b|$. Additionally, we will use simulations and interpretation of the PMB survey to

TABLE 3
Known Pulsars Redetected in the PALFA Precursor Survey

Pulsar	P (ms)	$\widehat{\mathrm{DM}}$ (pc cm^{-3})	DM (pc cm^{-3})	S_{1400} (mJy)	⟨S/N⟩	$\Delta\theta$ (arc min)
J0631+1036	287	125	148	0.8	76	6.7
J1901+0716	644	252	282	0.9	42	2.2
B1903+07	648	245	226	1.8	161	—
J1905+0616	990	258	283	0.5	41	—
J1907+0740	557	332	353	0.41	20	—
J1908+0734	212	11	46	0.54	13	—
J1908+0909	336	468	438	0.22	13	5.5
J1910+0714	2712	124	106	0.36	14	—
B1913+10	404	240	240	1.3	30	6.7
J1913+1000	837	422	452	0.53	26	1.7
J1913+1011	35	179	170	0.50	10	2.8
B1914+13	282	237	219	1.2	150	1.8
B1915+13	195	95	103	1.9	74	2.3
B1919+14	618	92	74	0.7	41	0.4
B1925+188	298	99	166	—	19	4.5
B1937+21	1.6	71	71	16	30	—
B1957+2831	308	139	163	1.0	54	—
J2002+30	422	196	184	—	24	—
B2002+31	2111	234	197	1.8	88	6.7

Pulsar parameters are from http://www.atnf.csiro.au/research/pulsar/psrcat/, the ATNF pulsar database.

$\widehat{\mathrm{DM}}$ is the DM value at which the search algorithm identified the pulsar.

$\langle S/N \rangle$ = signal to noise ratio of the average pulse shape (peak/rms).

$\Delta\theta$ = angular distance from the nearest beam centroid the pulsar was discovered in; for some pointings we do not have this information.

understand better the population distribution in b. No matter what $|b|$ we ultimately search to, it will take much longer than the one year we are now requesting time for.

In the future, we will also request ALFA time to survey out of the Galactic plane for the purpose of identifying millisecond pulsars, relativistic binary pulsars, and high-velocity canonical pulsars, all of which will be found preferentially at $|b| > 5^\circ$.

Survey Parameters: Table 1 summarizes the parameters for the proposed Galactic Plane survey. We will use the WAPP spectrometers until the new PALFA spectrometer, with triple the overall bandwidth, becomes available some time in the second half of 2005. For the inner Galaxy we will use 268s total dwell time per sky position and half that (134s) for the anticenter region. These numbers are double what we are now using in the precursor survey and follow from our goal of at least doubling the distance reachable for a pulsar of given period compared to the PMB survey.

Pointing Strategies: During the precursor survey period, we have investigated the merits of different pointing strategies. The alternatives consist of *single or multiple passes* on each sky position and also *sparse or dense-sampling* approaches:

> *Sparse vs. Dense Sampling:* Figure 3 (left panel) shows the ALFA beam pattern for three pointings that tile most of the sky with at least half-gain of one of the outer six beams This dense-sampling scheme may be compared to a sparsely-sampled scheme where only the first of the three pointings is done before moving to a non-contiguous region of the sky. Eventually, we aim to cover the Galactic plane with dense sampling. However, by sampling sparsely first, the *rate* of new pulsar discoveries can be front-ended to the earlier stages of the survey. The sidelobes have lower gain but provide a significant amount of solid angle, as shown in the right-hand panel of Figure 3. Simulations indicate that in a fixed amount of observing time, sparse sampling detects 50% more pulsars than dense sampling, all other factors being the same. Eventually, of course, a sparse survey will run out of sky to cover (in this case, the Galactic plane, where the density of pulsars is greatest). To find weaker objects that have been missed, to increase the level of completeness of the survey, and — most importantly — to detect extremely rare objects that may provide the greatest astrophysical return, the full target region then can be densely sampled.

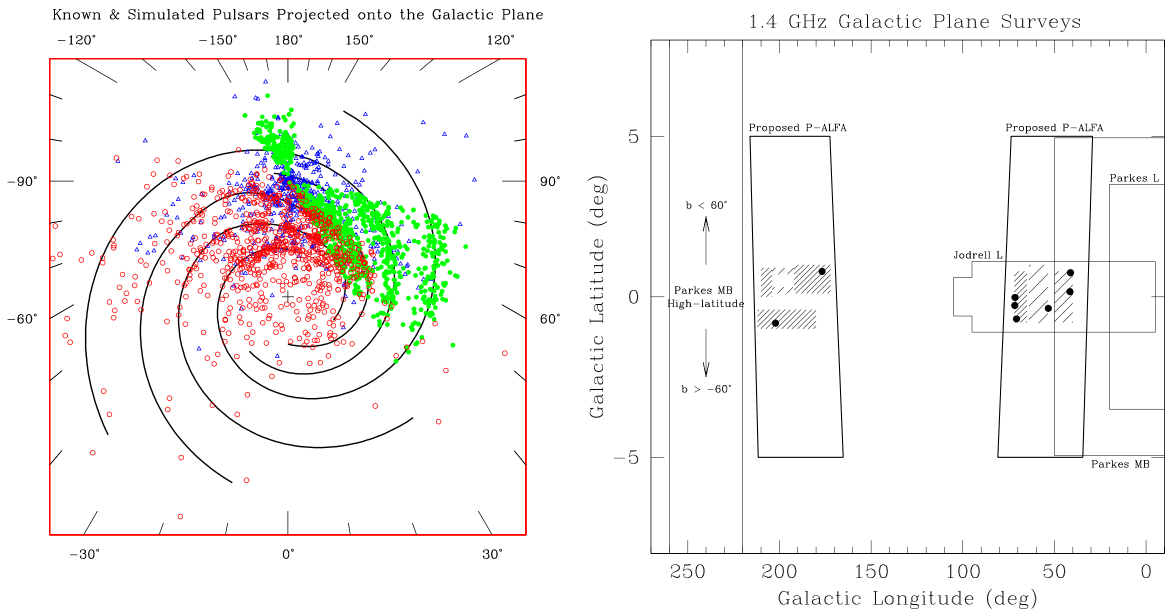

FIG. 2.— *Left:* Projection of simulated and real pulsars onto the Galactic plane. Curved lines represent spiral arms. The simulation is a realistic model of the population and of specific surveys, producing the correct number of detections for the PMB. Blue triangles: known pulsars from surveys other than the PMB survey. Open red circles: PMB-discovered pulsars. Green points: 1100 simulated pulsars detected in ALFA surveys of the Galactic plane. *Right:* Regions of the Galactic plane proposed for PALFA surveys, taking into account declination limits and restricted to $|b| \leq 5°$. Hash marks show approximate boundaries of regions covered in the precursor survey and dots show new pulsars we have discovered. We also show boundaries of other prominent L-band surveys that have been made in or near these regions, including the PMB survey and single-pixel surveys with Parkes and Jodrell Bank. A shallower PMB survey for millisecond pulsars extended to Galactic longitude 220°. Arecibo surveys at 0.43 GHz have covered some of our proposed search areas, but to distances $D_{\max}$ much smaller than we can reach owing to the limiting effects of interstellar dispersion and scattering.

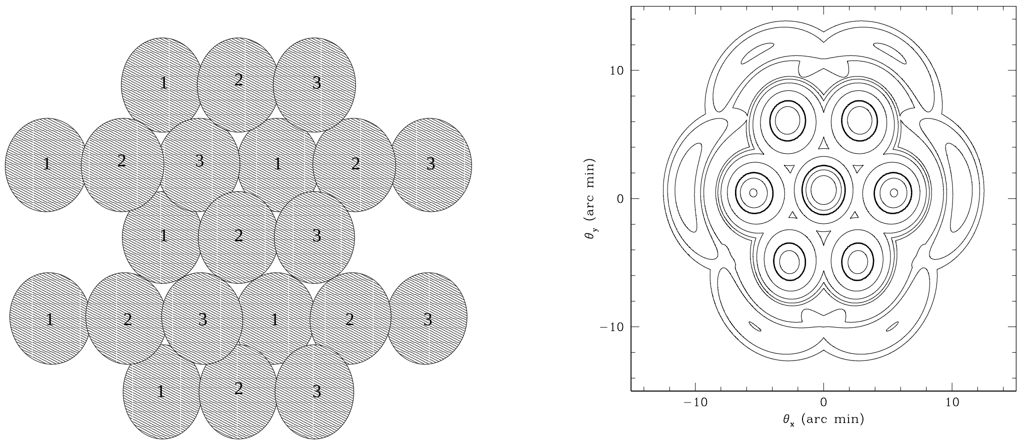

FIG. 3.— *Left:* ALFA beam locations on the plane of the sky for three pointings, labeled 1–3, in a dense sampling grid that covers nearly all of the solid angle with at least half the gain of the relevant beam. Sparse sampling consists of making only one of these pointings. Note the ellipticity of the beams and of their pattern for a given pointing. *Right:* Contours of telescope gain with the ALFA system. The gain is the maximum gain for a given direction from any of the 7 beams. We have used a representative analytical description using elliptical Airy functions combined with first-order coma lobes (C. Cortés, private communication). The contours are at $-1, -2, -3, -6, -10, -13$ and -16 dB from the central peak. At small zenith angles the peak gain ~ 10.4 K Jy^{-1} and the maximum sidelobe level is approximately 1.5 K Jy^{-1}.

> *Single vs. Multiple Passes:* If pulsar signals were intrinsically steady (apart from the basic pulsation) and if there were no extrinsic modulations (eclipses, scintillations, etc.) nor RFI, the optimal detection strategy would allocate the designated time per sky position (T) in a single contiguous block. For this case, detections would be limited solely by radiometer noise. However, pulsars display several kinds of strong intrinsic modulations and they are well known to scintillate. Rare — but most interesting — are objects eclipsed by their orbital companions. For modulated objects, a multiple-pass strategy may optimize the chances for discovery of new objects even if the total time per sky position, T, is held fixed. The additional yield of a multi-pass approach over a single-pass approach so far can be assessed only through simulations, because the two approaches have not been compared in any real survey. (Some of our precursor survey time is being devoted to the two approaches.) Simulations indicate that a dual-pass approach can find 5–15% more pulsars than a single-pass approach for the same total T by mitigating scintillations and pulse nulling. However, this increase must be weighed against other issues, such as reduced telescope efficiency and assumptions about the intrinsic variability. Another advantage of a dual-pass approach is that either pass can serve as the confirmation pass for its counterpart. For each of our new discoveries, we require at least one confirmation pass that could be accomplished as part of a dual pass approach. We will determine the best strategy through continued simulations combined with results of the precursor survey and apply it to the survey proposed here.

To summarize, for the survey proposed here, our provisional plan is to adopt a sparse, dual-pass pointing strategy. This plan may change according to the results of further simulations, the outcome of further observations and data analysis, and other considerations by the Consortium.

Real-time Quicklook Processing: We will continue to use the ASP quick-look processing pipeline over the duration of this project because (a) it provides timely assessment of data quality and (b) apparent pulsar detections can be identified immediately as previously known pulsars or as new pulsars through a prompt confirmation observation. The processing pipeline includes the following steps:

1. Forming data streams (correlation functions vs. time) for each ALFA beam.
2. Unpacking and Fourier transforming to obtain intensity vs. time and frequency. For the quick-look analysis, the data are smoothed and decimated (currently by a factor of 16 in time and 8 in frequency) to speed up the processing.
3. Dedispersion (summing over frequency while compensating for interstellar dispersion delays) to produce a time series for each of N_{DM} trial values of dispersion measure.
4. Identification of single dispersed pulses by smoothing each time series by varied amounts and identifying 'events' that are above threshold (5σ).
5. RFI excision by defining a mask array based on the FFT of the DM = 0 time series, which is most affected by RFI.
6. Fourier transforming each time series and identifying harmonics and sums of harmonics above a predefined threshold (typically 7σ) to define candidate pulsars.
7. Signal averaging appropriate time series at candidate pulse periods to form an average profile, including subaverages in subbands of the total passband and subaverages vs. time.
8. Creating diagnostic plots for the single-pulse and periodicity analyses.

The real-time pipeline organizes diagnostic plots into pages that can be looked over during and after the observations. Candidate signals are included in the MySQL database at Arecibo that consolidates information about all pointings and processing results (see below).

An example of the quick-look output for the periodicity analysis leading to our first pulsar discovery is shown in Figure 4. Single-pulse analysis leading to another pulsar discovery is shown in Figure 5, which demonstrates the inferential power of the 7 simultaneous beams in assessing whether RFI or celestial signals are detected.

Off-line Processing: Processing of full-resolution ALFA data using the WAPP spectrometers currently requires about 20 times real time on a 16-node Linux cluster. The analysis steps are identical to those outlined above for the quick-look processing, but include more trial values of DM, more sophisticated RFI excision, and implementation of acceleration searches. For the precursor survey, computer resources at Arecibo can accommodate much of the processing load and keep up with the average data rate[6] for the

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[6] The Galactic plane is visible for about 6 hr/day and we have been observing roughly one out of three days, on average.

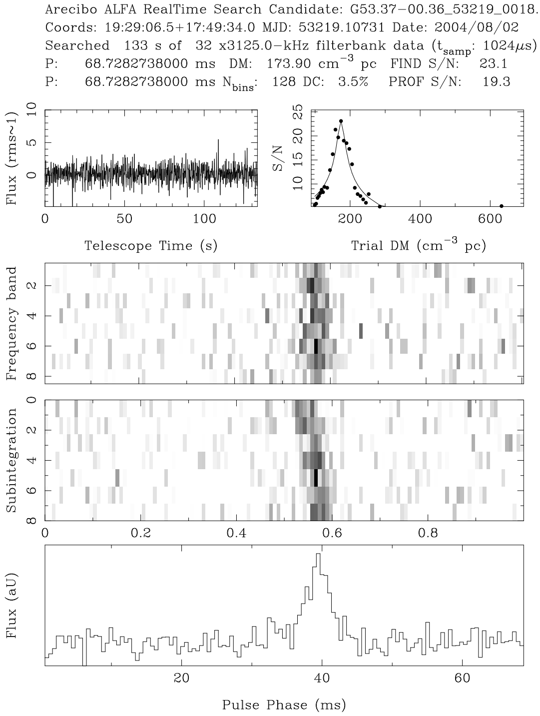

FIG. 4.— Summary page that shows the first discovery from the precursor survey. A page like this is produced for each candidate signal that emerges from the periodicity analysis. Top left: dedispersed time series. Top right: amplitude of identified signal vs. DM. Second from top: grey-scale plot of signal-averaged flux density vs. frequency band, showing that the signal is broadband. Second from bottom: grey scale plot of signal-averaged flux density vs. subintegration (i.e. time) showing that the signal is peristent. Bottom: pulse profile using all the data.

simplest level of processing. In addition, there will be adequate storage on site (50 TB) to allow us to access all data taken during the precursor survey while we refine both our search algorithms and our processing pipeline. However, full processing requires use of the resources we have at our home institutions for several reasons:

1. We will continue to develop our end-to-end processing pipeline, including improvement of pulsar-specific detection algorithms and also refinement of our RFI mitigation techniques. We thus expect to reprocess search data multiple times, as has been the case with other pulsar surveys.
2. The computational requirements increase dramatically if we compensate for orbital acceleration as a means for finding binary pulsars in short-period orbits ($\lesssim$ hours). How we deal with orbital acceleration is contingent on the dwell time per pointing of our survey and thus ties into our decision on multiple vs. single pass strategies. However, even with the shortest contemplated dwell time, there is a region of spin-period and orbital-period search space that requires compensation for acceleration. The processing load scales linearly with the number of accelerations searched, which can be in the hundreds for long dwell times.
3. Accumulated data will soon exhaust the storage capacity at Arecibo and will be moved to a long-term archive at the Cornell Theory Center. Computer resources at the CTC will be used by some of us for data processing. For others, the CTC can make data available over the network (for small data volumes) or it can supply data on a portable, high-capacity disk.
4. The data rate of the new PALFA spectrometer will be 4 times greater than at present and will require greater computational capacity. Computer resources at Consortium member institutions can handle this increased processing load. These resources include several large Linux and WindowsNT clusters.
5. Access to data and computational resources for algorithm development is an integral component to the training of students.

Processing sites in addition to Arecibo will include Cornell, Haystack Observatory, Jodrell Bank Observatory, McGill, NRAO, UBC, and UC Berkeley.

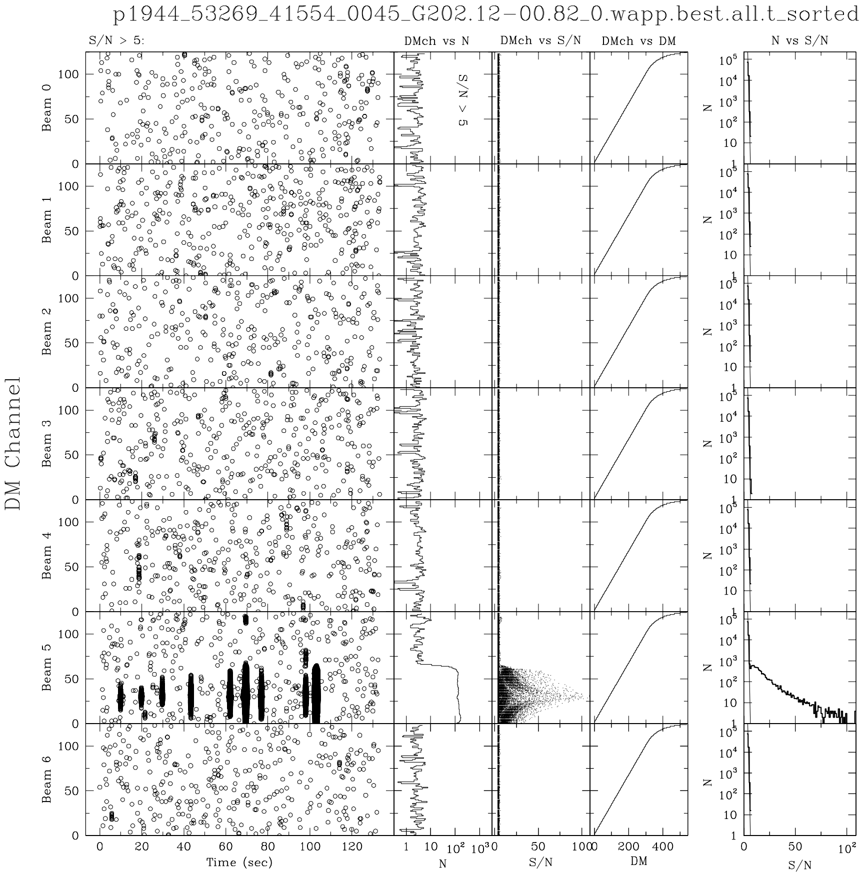

Fig. 5.— Results of single pulse analysis that led to the discovery of J0628+09. The raw data are dedispersed with 124 trial values of DM, producing a time series for each such DM channel. Each row is for one of the seven ALFA beams and shows, from left to right: events vs. DM channel and time, using a threshold S/N $> 5\sigma$ and different amounts of smoothing (up to 32 time samples); number of events per DM channel; scatter plot of DM channel vs. S/N; the nonlinear mapping from DM channel to DM value; and histogram of S/N. In the right-most plots, the plotted line at low S/N is the theoretically expected histogram of S/N for noise only (see, e.g., Cordes & McLaughlin 2003 for a description of this method). Beam 5 shows excess events in all the diagnostic quantities, corresponding to very sporadic emission with DM = 88 pc cm^{-3}. The event "bleeds" into neighboring DM channels because the pulses have finite width.

Software: The current software package is an amalgam of pulsar search codes that have been developed at several Consortium institutions over the last 10 yr. The quick-look processing, for example is based on 'sigproc' code (D. Lorimer) and single-pulse detection code from Cornell and Jodrell. Codes for full-resolution processing include those from Cornell, UCB (Ramachandran, Backer et al.), McGill/NRAO (Ransom) and Jodrell (Lorimer). For off-line processing, we wish to develop a new package that uses the best algorithms for the various stages of the processing. To decide what those best approaches are, our current plan is to process full-resolution data from the precursor survey with multiple codes and report results in a uniform format that will be included in the MySQL database, with a flag for which code yielded a given candidate signal. By building up this aspect of the database, we can assess which algorithms are best. In parallel with this empirical approach, we began a process in 2004 May to identify the overall structure of the new software package. Such a comprehensive and well-tested pulsar search package will be an important legacy of the PALFA Consortium and will prove invaluable to other search efforts.

PALFA Survey Databases: The PALFA consortium has developed an extensive, easy-to-use database for managing sky maps, observation records, search code output, and other project-related data. The database is accessed via MySQL, a freely available database software package and is served on the Arecibo network. It is used both interactively, using a MySQL command line interface, and via scripts, written in Python. The system is under continuous development. Information presently stored in the database includes:

- Lists of potential telescope pointings, forming a grid on the sky, from which a day's observing schedule is constructed.
- A record of telescope observations, including telescope position, integration time, etc. This database table is updated after each observing session by a script which harvests the relevant information from the log of the CIMA telescope control system.
- A list of candidate pulsar signals. This table is dynamically updated by the quick-look pipeline as each data file is analyzed.
- A list of known pulsars derived from the on-line ATNF database (http://www.atnf.csiro.au/research/pulsar/psrcat/).

The PALFA database has been used for such tasks as monitoring and mapping observation progress, checking telescope schedules to protect against duplicate observations, and comparing observation records against lists of known sources. Database tasks presently under development include scripts for automated generation of observing schedules and scripts for displaying and filtering candidate signals, so that true pulsar detections can be more easily culled from the morass of radio frequency interference and other false signals (e.g. instrumentation generated artifacts).

Data Archive: Long-term archival of the raw data, processing output, and survey results will be done at the Cornell Theory Center. The CTC's mission is to support research at Cornell, including that of research centers, including NAIC. Over the last two years we have developed a pilot database system at the CTC that catalogs processing output and provides web-based tools for their analysis.[7] This system was based on a 1 deg^2 pilot survey using a single-pixel system at Arecibo. It is the foundation for a similar system for the PALFA data. The PALFA database system will include catalogs and access to raw data as well as processing products. It also will incorporate information contained in the MySQL database on Arecibo computers. With help from the CTC, we are developing scripts that automatically will transfer results from the MySQL database to the CTC ServerSQL database.

PALFA surveys will generate $\sim$ 1 PB of raw data. A plan is now in place for storing the raw data at the CTC and providing web-services access to the database. This plan was proposed to the NSF/CISE Research Infrastructure Program as a combined Astronomy/Computer Science/CTC proposal that was successful in gaining funding for a 5-yr development program.[8] By the end of CY2004, two Unisys 16-Itanium processor machines and 100 TB of data storage will be available as part of this project. Over the next five years, storage capacity will grow to 1 PB. Network bandwidth from Puerto Rico will be too low to transport data to the CTC. However, it is viable today to ship data to the CTC on portable disk packs having 0.5 to 1.6 TB capacities and USB2.0 and Firewire interfaces. PALFA Consortium members have invested in 20 TB of such portable disks, which will cycle between Arecibo, member institutions, and the CTC.

The CTC system is based on MSWindows/NT and ServerSQL. This mostly should be transparent to the Linux/MySQL based users of the PALFA Consortium owing to the use of web-services as the interface.

We envision long-term utility of the CTC database and archival system by the broader astrophysical community. The raw PALFA data will be available for analysis by researchers interested in applying new algorithms for finding pulsars and transient signals. They will also be useful in cross-wavelength studies, such as looking for radio counterparts to sources identified at high energies. The next-generation gamma-ray telescope (GLAST), for example, will discover pulsars on its own, such as objects similar to the Geminga pulsar, for which PALFA data can be searched for corresponding radio emission. In this way, we and others can leverage the PALFA data by making use of prior information derived from high-energy observations.

III. Spectrometers

Currently we are using the four Wideband Arecibo Pulsar Processor (WAPP) systems for data acquisition. For each ALFA beam we obtain a data stream of correlation functions with 256 lags every 64 μs. The correlation functions are computed with 3-level sampling and are recorded to disk as 16-bit integers after summing them for the two polarization channels. The resultant time and frequency resolutions are listed in the 'ALFA+WAPPs' column of Table 1. With the WAPPs, we process the cleanest 100 MHz passband that can be found within the overall 300 MHz bandwidth of the front end system. So far, RFI has not been a major problem, though about 10% of the data is unsuitable for pulsar detection with our current RFI rejection algorithms (which are preliminary and will be improved).

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[7] http://arecibo.tc.cornell.edu

[8] 14 Sept 2004 announcement: https://www.fastlane.nsf.gov/servlet/showaward?award=0403340

In 2003, we communicated to NAIC the desired specifications for a new PALFA spectrometer, which are in accord with the development plan expressed by NAIC engineers. The new spectrometer will use a polyphase filterbank approach based on FPGAs and will provide the same overall capabilities as the WAPPs. Improvements will consist of (a) 300 MHz total bandwidth with selectable number of channels, up to 2048; (b) $\geq$ 8-bit sampling at the spectrometer input; (c) selectable number of output bits; (d) subbanding of the 300 MHz total bandwidth in 100 MHz chunks, with possible overlap, in order to avoid the most RFI intense portions of the spectrum; (e) greater rejection of narrowband RFI from spectral leakage owing to the sharp passbands of the polyphase filters.

The advantages of the new spectrometer thus include better sensitivity from the larger total bandwidth and greater immunity from RFI. We recognize that the actual improvements we see over the WAPPs depend on how much of the 300 MHz passband actually will be usable and how well we can reject RFI in software. With the wider bandpass, dedispersion will provide greater rejection of short-duration bursts of interference.

IV. Telescope Time request

We request 140 hr per 4-month cycle (420 hr total from 2005 Feb 1 through 31 Jan 2006) to (a) acquire survey data; (b) conduct immediate confirmation observations of identified candidate objects; and (c) conduct ancillary observations on small numbers of particular objects that warrant follow-up observations at other frequencies or initial timing observations to assess whether an object is isolated or in a binary system. The PALFA Consortium is submitting a companion, long-term timing proposal that requests time for continued timing of newly discovered objects. The timing observations mentioned here are only very preliminary ones and include the discovery observations. The precursor observations to date have mostly used the sparse-sampling approach discussed in §II, which requires an explicit confirmation observation for a pulsar candidate. So far, we have made confirmation observations on only about 10 candidates, though a few of these have required more than one attempt. If we choose the dual-pass strategy, the confirmations will mostly be absorbed into item (a).

We request that our telescope time be split into the inner Galaxy and anticenter regions (c.f. Figure 2) roughly in a 4:1 ratio because we expect to discover more pulsars in the inner Galaxy region. To do so requires longer integrations to search the relevant Galactic volume than in the anticenter. Our current discoveries (Table 2) show 1/4 anticenter objects, a fraction we consider unrepresentative because the quick-look analysis favors low-DM pulsars and also possibly because of small numbers; the full analysis will yield a larger fraction of inner-Galaxy discoveries. Since the anticenter observations do not need to search to the same $D_{\max}$ as the inner Galaxy, we will continue to use anticenter integration times that are half those for the inner Galaxy. With 268s total-integration time (perhaps split into two passes), we will cover about 0.22 deg^2 hr^{-1} in the inner Galaxy and twice that in the anticenter direction (assuming 80% observational efficiency due to slewing overhead, etc).

Our net request is then:

Inner Galaxy: 112 hr per four-month cycle = 336 hr total.

Anticenter Directions: 28 hr per four-month cycle = 84 hr total.

We note also that, should there be gaps in the schedule for anticenter time (roughly 4.5 to 7.5 hr LST), the PALFA survey would be able to make use of additional time.

Proprietary Data Period: We suggest a proprietary period of 12 months starting from the time when the PALFA Consortium has developed its processing pipeline so that data are routinely processed at full resolution and with suitable RFI excision algorithms applied.

Commensal Observing: PALFA surveys are compatible with commensal observations in several ways. First, groups in the EALFA and GALFA Consortia are welcome to observe simultaneously with pulsar-search-defined pointings as long as there is no excessive use of pulsed calibration signals during the observations. Second, we are interested in making use of EALFA-defined pointings at high Galactic latitudes for the purpose of finding millisecond pulsars, other pulsar sub-populations, and transient signals of any type. Such commensal observations must await the availability of the PALFA spectrometer because EALFA surveys will use the WAPP spectrometers. Thus no commensal observations can begin before about mid-2005. In the meantime, we have communicated to an EALFA group led by R. Giovanelli that we will make use of their data, obtained in multiple-pass, drift-scan mode with 1-sec integrations, to search for transient signals that may or may not originate from pulsars. The processing of such data using a subset of PALFA software is straightforward and does not tax our computing resources. Moreover, it will also help us quantify the RFI environment at Arecibo more comprehensively.

V. Survey status reports and Data products

We will provide status reports of all aspects of our survey at 4-month intervals. We will keep current the web sites that already exist and will evolve over the course of the survey. These include the PALFA web pages at Arecibo (http://alfa.naic.edu/pulsars and http://www.naic.edu/∼palfa) and the CTC web page (http://arecibo.tc.cornell.edu).

Publications are expected to be of the following types and time scales:

1. *Description of the precursor survey and announcement of the first discoveries.* Now being prepared for submission to ApJ.
2. *Results on individual objects of particular interest.* As appropriate, we anticipate reporting the results of follow-up timing, polarization, and multifrequency observations (including high energies) on objects that prove of particular interest. These will include binary pulsars in especially compact orbits and in eclipsing systems; unusual millisecond pulsars (e.g. faster than the current fastest MSP); pulsars with magnetar-strength magnetic fields; sources with unusual transient behavior; counterparts to high-energy sources; and any other objects where a publication would stimulate ancillary multiwavelength observations or observations with non-electromagnetic instruments (e.g. LIGO).
3. *Periodic reports on large samples of pulsars.* On time scales of a year and longer, we will have accumulated sufficient timing data, polarization results, etc. to publish results as a sub-catalog of the overall survey. At least one year of timing data is required to obtain the astrometric and spin parameters of a pulsar.
4. *Population analyses of the complete survey.* On a ∼5-yr time scale, it would be appropriate to analyze the sample (along with the complete sample of pulsars from other surveys) to characterize the Galactic population of pulsars, including binary and MSP subpopulations. In addition, as other follow-up observations (scattering and Faraday rotation measures) accumulate, modeling of the Galactic electron density and magnetic field will be reported.

In addition to formal publications in refereed journals, we will produce technical reports that are relevant to Observatory operations. For example, our data are suitable for characterizing RFI on a variety of frequency and time scales. As a routine part of our processing, we will assess and quantify RFI and summarize its properties on a periodic basis. We will use statistical analysis of dynamic spectra to characterize RFI, including its temporal and spectral occupancy.

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