DISCOVERY OF NINE GAMMA-RAY PULSARS IN FERMI LARGE AREA TELESCOPE DATA USING A NEW BLIND SEARCH METHOD

H. J. Pletsch1,3, L. Guillemond4, B. Allen1,2,3, M. Kramer1,5, C. Aulbert1,3, H. Fehrmann1,3, P. S. Ray6, E. D. Barr4, A. Belfiore7,8,9, F. Camilo10, P. A. Caraveo9, Ö. Çelik11,12,13, D. J. Champion4, M. Dormody7, R. P. Eatough14, E. C. Ferrara15, P. C. C. Freire4, J. W. T. Hessels14,15, M. Keith16, M. Kerr17, A. de Luca18,19, A. G. Lyne15, M. Marelli19, M. A. McLaughlin19, D. Parent20,23, S. M. Ransom21, M. Razzano17,22, W. Reich4, F. M. Szarkinson2, B. W. Stappers5, and M. T. Wolff6

1 Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany
2 Institut für Geowissenschaften, Universität Hannover, Hannover, Germany
3 Institut für Geowissenschaften, Universität Hannover, Hannover, Germany
4 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
5 Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, The University of Manchester, Manchester M13 9PL, UK
6 Space Science Division, Naval Research Laboratory, Washington, DC 20375-5352, USA
7 Santa Cruz Institute for Particle Physics, University of California at Santa Cruz, Santa Cruz, CA 95064, USA
8 Dipartimento di Fisica Nucleare e Teorica, Università degli Studi di Pavia, I-27100 Pavia, Italy
9 INAF-Istituto di Astrofisica Spaziale e Fisica Cosmica, I-20133 Milano, Italy
10 Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA
11 NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
12 Center for Research and Exploration in Space Science and Technology (CRESST) and NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
13 Department of Physics and Center for Space Sciences and Technology, University of Maryland Baltimore County, Baltimore, MD 21250, USA
14 Astronomical Institute “Anton Pannekoek,” University of Amsterdam, Postbus 94249, 1090 GE Amsterdam, The Netherlands
15 Netherlands Institute for Radio Astronomy (ASTRON), Postbus 2, 7990 AA Dwingeloo, The Netherlands
16 CSIRO Astronomy and Space Science, Australia Telescope National Facility, Epping NSW 1710, Australia
17 W. W. Hansen Experimental Physics Laboratory, Kavli Institute for Particle Astrophysics and Cosmology, Department of Physics and
SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94305, USA
18 Istituto Universitario di Studi Superiori (IUS), I-27100 Pavia, Italy
19 Department of Physics, West Virginia University, Morgantown, WV 26506, USA
20 Center for Earth Observing and Space Research, College of Science, George Mason University, Fairfax, VA 22030, USA.
21 National Radio Astronomy Observatory (NRAO), Charlottesville, VA 22903, USA
22 Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, I-56127 Pisa, Italy

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ABSTRACT

We report the discovery of nine previously unknown gamma-ray pulsars in a blind search of data from the Fermi Large Area Telescope (LAT). The pulsars were found with a novel hierarchical search method originally developed for detecting continuous gravitational waves from rapidly rotating neutron stars. Designed to find isolated pulsars spinning at up to kHz frequencies, the new method is computationally efficient and incorporates several advances, including a metric-based gridding of the search parameter space (frequency, frequency derivative, and sky location) and the use of photon probability weights. The nine pulsars have spin frequencies between 3 and 12 Hz, and including a metric-based gridding of the search parameter space (frequency, frequency derivative, and sky location) and the use of photon probability weights. The nine pulsars have spin frequencies between 3 and 12 Hz, and including a metric-based gridding of the search parameter space (frequency, frequency derivative, and sky location). The new method is computationally efficient and incorporates several advances, including a metric-based gridding of the search parameter space (frequency, frequency derivative, and sky location) and the use of photon probability weights.

Key words: gamma rays: stars – pulsars: general – pulsars: individual (PSR J0106+4855, PSR J0622+3749, PSR J1620–4927, PSR J1746−3239, PSR J1803–2149, PSR J2028+3332, PSR J2030+4415, PSR J2111+4606, PSR J2139+4716)

1. INTRODUCTION

The Fermi Gamma-ray Space Telescope has been operating since its launch in 2008 June. The Large Area Telescope (LAT) on board the Fermi satellite has an effective area of ~0.8 m² (on-axis, above 1 GeV) and is sensitive to photons with energies from 20 MeV to more than 300 GeV (Atwood et al. 2009). Post-processing assigns an arrival time, energy E, and direction to the photons; we call these “events.” The arrival times are accurate to better than 1 µs, and the energies are accurate to within 15% between 0.1 and 10 GeV on-axis. The directional precision is energy dependent: 68% of photons have angular offset less than ~0.8° (E/GeV)−0.8 from the true direction (Abdo et al. 2009c).

Gamma-ray pulsars are among the most interesting sources observed by the Fermi LAT. These are rapidly spinning neutron stars whose regular beam of gamma-ray emissions passes by the detector with each rotation. The Fermi LAT has detected gamma-ray pulsations from more than 50 normal and millisecond pulsars (MSPs) previously discovered in radio-
frequency searches (see, e.g.; Abdo et al. 2010c; Ransom et al. 2011; Keith et al. 2011; Cognard et al. 2011; Theureau et al. 2011).

In contrast, the so-called blind searches for gamma-ray pulsars are not guided by any prior knowledge (e.g., from radio or X-ray observations) of the pulsars’ parameters. Previous blind searches of the data recorded by the Fermi-LAT have been spectacularly successful; they have discovered 26 gamma-ray pulsars (Abdo et al. 2009a; Saz Parkinson et al. 2010; P. M. Saz Parkinson et al. 2011, in preparation). This paper describes the “blind” discovery of nine additional pulsars using a new method.

The blind search problem is computationally demanding because the relevant pulsar parameters (typically sky position, frequency \( f \), and spin-down rate \( \dot{f} \)) are not known a priori and must be explicitly searched (Chandler et al. 2001). So far, blind searches of LAT data have used a clever “time-differencing technique” as described in Atwood et al. (2006) and Ziegler et al. (2008). One powerful motivation for seeking even better methods is the application to MSPs, of which previous blind searches have not found any. The blind search for MSPs is more computationally challenging due to the higher frequency range that must be covered. Moreover, most MSPs are in binary systems, where the orbital modulation parameters must also be searched, adding orders-of-magnitude to the computational complexity and challenge.

This paper presents results from a new effort to find isolated gamma-ray pulsars (including MSPs), using a novel method inspired by computationally efficient techniques recently developed to search gravitational-wave detector data for weak continuous-wave signals from rapidly spinning isolated neutron stars (Pletsch & Allen 2009; Pletsch 2010). In particular, the search method uses a recently developed optimal incoherent-combination method first described in Pletsch & Allen (2009) together with a “sliding coherence window technique” (Pletsch 2011).

The method was originally intended to find isolated MSPs up to 1.4 kHz spin frequency with spin-down rates in the range \(-5 \times 10^{-13} \text{ Hz s}^{-1} \leq f \leq 0\), with a corresponding range of characteristic ages \( \tau = -f/2\dot{f} \). However, the search technique is also sensitive to normal (non-MSP) isolated pulsars, and several normal pulsars were discovered soon after we began. This prompted us to extend the spin-down-rate search range, in order to include younger objects (having smaller \( \tau \)), down to ages (\( \sim \) kyr) comparable to the Crab pulsar. Here we report on the discovery of nine pulsars from this ongoing effort in which a total of 109 sources selected from the Fermi-LAT Second Source Catalog (Abdo et al. 2011b) are being searched for new gamma-ray pulsars.

The outline of this paper is as follows. Section 2 describes the LAT data preparation and the selection of unidentified sources to search for previously unknown gamma-ray pulsars. The new hierarchical search method is explained in Section 3 and illustrated in Section 4 with a detailed example: our first discovery, PSR J1620–4927. Section 5 presents the results for all the new gamma-ray pulsars. The search for counterparts in other regions of the electromagnetic spectrum is discussed in Section 6. This is followed by a brief conclusion.

2. SOURCE SELECTION AND DATA PREPARATION

The Fermi-LAT Second Source Catalog (2FGL; Abdo et al. 2011b) lists 1873 sources, described by fits to elliptically shaped 95% confidence sky regions. Among these sources 576 are not associated with counterparts observed at other wavelengths and thus might contain unknown gamma-ray pulsars.

In searching for new gamma-ray pulsars, it is important to identify and exclude sources that are blazars. Previously observed Fermi-LAT gamma-ray pulsars (see, e.g., Abdo et al. 2010c) have sharp cutoffs in their emission spectra at a few GeV, and stable gamma-ray fluxes. In contrast, blazars emit above 10 GeV, and their fluxes vary with time. An illustration of the different spectral properties and variability behavior can be seen in Figure 17 of Abdo et al. (2011b). Gamma-ray pulsars tend to have large curvature significances (“Signif_Curve” in the 2FGL catalog, which gives the improvement in the quality of the spectral fit when changing from a power law to a curved spectral model) and small variability indices (“Variability_Index” in the 2FGL catalog, a measure of flux instability over time). In contrast, blazars tend to have small curvature significances and large variability indices.

For the search for gamma-ray pulsations we select 2FGL sources with curvature-significance values greater than \( 4\sigma \) (here and throughout the manuscript, \( \sigma \) denotes the standard deviation for a Gaussian distribution) and variability indices smaller than 41.6. We further select bright objects by choosing sources with detection significances (“Signif_Avg”) greater than 10\( \sigma \). Finally, we restrict the list to sources with no known associations (“unassociated sources”) or associated with known supernova remnants (SNRs). By applying the above selection criteria to a preliminary version of the 2FGL catalog, we obtained a list of 109 2FGL sources to search for gamma-ray pulsations. (One source, 2FGL J0621.9+3750, was associated with an active galactic nucleus (AGN) in the final 2FGL catalog.)

The Fermi Science Tools (ST)24 v9r23p1 are employed to select the Fermi-LAT events for our search. Using gtselect, we take events from 2008 August 4 to 2011 April 6, with reconstructed directions within 8\( ^\circ \) of the gamma-ray sources, energies above 100 MeV, and zenith angles \( <100^\circ \). Only events belonging to the Pass 6 “Diffuse” class are retained, as those events have the highest probability of being photons (Atwood et al. 2009). For the event probability weighting described below we use the P6_V11 Instrument Response Functions (IRFs). Using the gmkttime tool, times when the rocking angle of the satellite exceeded 52\( ^\circ \) are excluded. We also require that DATA_QUAL and LAT_CONFIG are unity and that Earth’s limb does not impinge upon the region of interest (ROI).

As demonstrated in previous work (Bickel et al. 2008; Kerr 2011a), the sensitivity of gamma-ray pulsation searches can be improved by weighting the \( j \)th event with a probability \( w_j \in [0, 1] \) that it originated from a putative pulsar. The photon weights \( w_j \) are calculated by using a full spectral model of the region around the gamma-ray source, and by exploiting the IRFs to provide background rejection which is superior to simple angular and energy data-selection cuts. For the first time in this paper such a photon-weighting scheme has been applied in a blind search; further details are given in Section 3.

To calculate the weights \( w_j \) for each event from a given source, we perform likelihood spectral analyses using the pointlike tool (see Kerr 2011b, for a description). For each selected source, we construct a spectral model for the region by including all sources of the 2FGL catalog found within 8\( ^\circ \) of the selected source, using the spectral forms given in the catalog. The spectra of the selected sources are modeled as

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24 See http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/overview.html and http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/ for details and tutorials.
exponentially cutoff power laws, typical of known gamma-ray pulsars, of the form \( N_0 (E / \text{GeV})^{-3} \exp \left( -E / E_c \right) \), where \( N_0 \) is a normalization factor, \( \Gamma \) is the photon index, and \( E_c \) is the cutoff energy. The Galactic and extragalactic diffuse emission and residual instrument background also enter the calculation of the weights. The Galactic diffuse emission is modeled using the \textit{gll\_iem\_v02\_P6\_V11\_DIFFUSE} map cube, while the extragalactic diffuse and residual instrument backgrounds are modeled using the \textit{isotropic\_iem\_v02\_P6\_V11\_DIFFUSE} template (a detailed description of these background models can be found in Section 3 of Abdo et al. 2010a). These models are available for download at the Fermi Science Support Center.25

The tool \textit{gtsrcprob} is then used to calculate the event weights \( w_j \) based on the best-fit spectral models obtained from the maximum likelihood analyses.

3. THE NEW SEARCH METHOD

In a year, the LAT detects of order 10\(^3\) photons from a typical gamma-ray pulsar; in the same year, a typical pulsar rotates at least 10\(^9\) times around its axis. The blind-search problem is to find a rotational-phase model \( \Phi(t) = 2\pi (ft + t^2/2) \) and a sky position that match the solar system barycenter (SSB) arrival times \( t \) of the different photons, where \( \Phi \) denotes the rotation angle of the star about its axis, in radians, measured from its starting position at \( t = 0 \), and observed at the SSB. The signal hypothesis is that the photons’ arrival times are “clustered” near specific “orientations” of the star (i.e., \( \Phi(t) \mod 2\pi \)) deviates from uniformity on the interval \([0, 2\pi]\)). The null hypothesis is that the arrival times of the photons are a random Poisson process. In this paper, we do not explicitly indicate the dependence of \( \Phi \) on \( f \), \( t \), and sky position, but this dependence is important and implicit in many formulae below.

To find a matching phase model, a grid of “templates” in the four-dimensional parameter space of sky position and \( (f, t) \) is constructed. Note that the 2FGL catalog sky positions of the targeted unassociated sources based on the spatial distribution of events are typically not precise enough for pulsar searches. A search grid of sky points around this catalog position is needed to reduce signal loss arising from imperfect correction of the Doppler shifts caused by Earth’s orbital motion around the SSB. The need for sky gridding is particularly acute for MSP spin frequencies. Therefore, in contrast to previously published blind searches,26 we grid a circular sky region centered on the 2FGL catalog source location using a radius which is 20% larger than the semi-major axis of the 95% confidence elliptical error region (given by the “Conf\textunderscore 95\textunderscore SemiMajor” parameter).

Unfortunately the number of templates (grid points) required to discretely cover the entire four-dimensional search parameter space increases as a high power of the coherent integration time. Hence a fully coherent approach for several years of data is computationally impossible. Therefore, we employ a search strategy which is designed to achieve maximum overall sensitivity at fixed computing cost.27

To efficiently scan through years of Fermi-LAT data for previously unknown gamma-ray pulsars, we use a so-called hierarchical search approach. This is analogous to hierarchical methods used in searches for gravitational-wave pulsars (Schutz & Papa 1999; Papa et al. 2000; Brady & Creighton 2000; Abbott et al. 2009a, 2009b; Cutler et al. 2005). In a first semi-coherent stage, we here adopt the optimal metric-based gridding methods described in Pletsch & Allen (2009) along with the sliding coherence window technique (Pletsch 2011). In a second stage, significant semi-coherent candidates are automatically followed up in a fully coherent analysis. Finally, a third stage further refines coherent pulsar candidates by using higher harmonics. Full details of the complete search scheme will be presented in forthcoming work (H. J. Pletsch & L. Guillelmet 2011, in preparation).

Here we first describe the principle of the method, to firmly establish the analogy with the existing gravitational-wave literature. Then we describe what is done in practice, which is mathematically equivalent (up to justifiable approximations) but computationally more efficient.

In the first stage, a semi-coherent detection statistic \( S \) is computed for each template. We refer to \( S \) as “semi-coherent” because it is effectively the incoherent sum over several years, of terms which are coherent over several days. The coherent terms are the power in Fourier bins, calculated by treating each photon arrival as a delta function in time. Denoting the arrival time of the \( j \)th event (photon) at the SSB by \( t_j \), the coherent power \( P_t \) in a (Gaussian) window centered at time \( \tau \) is defined by

\[
P_t = \sum_{j=1}^{N} w_j e^{\Phi(t_j)} e^{-2\pi(t_j - \tau)^2 / T^2}.
\]

The sum is taken over all photons (here, \( N = 8000 \)) in the data set; the effective window duration is \( \int e^{-2\pi t^2 / T^2} dt = T / \sqrt{\pi} \). As described in Section 2, the weights \( w_j \) estimate the probability that the photon comes from the selected source. To form the semi-coherent detection statistic \( S \), the values of \( P_t \) are summed (“incoherently combined”)

\[
S = \frac{2}{T} \int d\tau P_t - \sum_{j=1}^{N} w_j^2.
\]

Note that in this definition we have subtracted a constant (phase model independent) term. Because it contains a Gaussian window, the integrand in Equation (2) falls off exponentially at early and late time (large values of \( |\tau| \)). Thus, the limits of integration can be taken as the entire real line \( \tau \in (-\infty, \infty) \); to good approximation this gives the same value as integrating only over the total observation interval (about 975 days in this search).

The semi-coherent detection statistic \( S \) is an incoherent sum of powers, which discards the phase information over time periods longer than of order \( T \). This uniform overlap maximizes the search sensitivity for fixed \( T \) and for fixed computational resources (Pletsch 2011). For computational efficiency, in this search we choose the \( N = 8000 \) photons with the highest probabilities (largest values of \( w_j \)).

To understand how to compute \( S \) efficiently, one can explicitly evaluate Equation (2). Completing the squares in the product of the Gaussians and carrying out the integration over \( \tau \), one obtains

\[
S = \sum_{j=1}^{N} \sum_{k=1}^{N} w_j w_k e^{\Phi(t_j) - \Phi(t_k)} e^{-\pi(t_j - t_k)^2 / T^2} - \sum_{j=1}^{N} w_j^2.
\]
Here the effective duration of the Gaussian window is \( e^{-\pi^2T^2} \). In practice, to compute the semi-coherent power efficiently, we replace the Gaussian window in Equation (3) with a rectangular window of the same duration \( T \), as given below in Equation (5). In this search, the width of the rectangular window is \( T = 2^{19} \approx 6 \) days.

The template grid in parameter space is the Cartesian product of a rectangular two-dimensional grid in \((f, \delta f)\) and a sky grid which has constant density when orthogonally projected onto the ecliptic plane. The problem of constructing efficient search grids has been intensively studied in the context of gravitational wave searches (see, e.g., Brady et al. 1998; Brady & Creighton 2000; Prix 2007; Pletsch & Allen 2009; Pletsch 2010) and we employ these concepts here. The values of frequency are equally spaced, separated by the fast Fourier transform (FFT) frequency-bin width \( \Delta f = 1/T \). In practice, to reduce the fractional loss in \( S \) for frequencies not coinciding with Fourier frequencies, we use a computationally efficient interpolation, referred to as “interbinning” (Ransom et al. 2002). The spacing in the other three dimensions is determined by a metric which measures the fractional loss in the expected value of \( S \) that arises if the signal is not located exactly at a grid point (Balasubramanian et al. 1996; Owen 1996; Prix 2007). In spin-down \( f \), we use a uniform grid spacing \( \Delta f = \sqrt{720m/\pi\gamma T^2} \). In this search \( m = 0.3 \) is the maximum tolerable fractional loss in \( S \), and from Pletsch & Allen (2009),

\[
y^2 = 1 + \frac{60}{N} \sum_{j=1}^{N} \frac{(t_j - \bar{t})^2}{T^2},
\]

where \( \bar{t} = \sum_{j=1}^{N} t_j/N \) is the mean photon arrival time. The description of this grid can be found in Pletsch & Allen (2009) with a detailed derivation in Pletsch (2010). The grid in the sky is determined by the same metric, permitting a maximum fractional loss \( m \) in the value of \( S \). The spacing of the sky grid is determined by the Doppler shift arising from Earth’s (more precisely, the Fermi satellite’s) motion around the Sun. At the north Ecliptic pole the angular spacing is \( \Delta \theta = \sqrt{2m \ c/\pi f D} \), where \( c \) is the speed of light and \( D \) is a baseline distance (defined below). When the entire sky grid is projected into the plane of the ecliptic, the grid points are uniformly spaced on the plane (Astone et al. 2002; Abbott et al. 2009a, 2009b). This angular spacing is similar to the angular spacing in the diffraction pattern of a two-slit system, where the wavelength is \( c/f \) and the separation of the two slits is the straight-line distance \( D \) between two points on Earth’s orbit about the Sun. If the coherent integration time \( T \) is less than half a year, then \( D = (998 \ s) \ c / (\pi T/1 \ yr) \). If the coherent integration time \( T \) is greater than half a year, then \( D = (998 \ s) \ c / (\pi T/1 \ yr) \) is the diameter of Earth’s orbit about the Sun.

To compute \( S \) efficiently, a time series is constructed and subsequently Fourier-transformed into the frequency domain. The time series contains \( T \Delta f_{\text{BW}} \) bins, where \( \Delta f_{\text{BW}} \) is the total frequency bandwidth being searched at a time using complex heterodyning at the center of \( \Delta f_{\text{BW}} \) (see, e.g., Patel et al. 2010). The time series is initialized to zero, then the values of \[ w_j w_k e^{-i2\pi f / (f_j - f_k)} \] are added into the bins determined by the time differences \( \Delta t_{jk} = t_j - t_k \), for all pairs of photons \( j, k \) for which \( 0 < |\Delta t_{jk}| \leq T \); the bin index is obtained by rounding the absolute value of the product \( \Delta f_{\text{BW}} \Delta t_{jk} \) to its nearest integer value.

Then the array is Fourier-transformed into the frequency domain (exploiting the FFT) to obtain \( S \) over the entire \( f \) grid. Up to an overall window-dependent normalization, one can write for given values of \( f, \delta f \), and sky position,

\[
S = \sum_{j,k=1}^{N} Q(|\Delta t_{jk}| / T) \ w_j w_k e^{-2\pi i f / \Delta t_{jk}} (f_j - f_k)^i,
\]

where the rectangular function \( Q(x) \) is unity if \( 0 < x \leq 1 \) and vanishes otherwise.\(^{29}\)

Although other aspects are different, the use of an FFT applied to time differences is very similar to techniques previously used in blind searches of Fermi-LAT data (Atwood et al. 2006, Equation (3) therein has a typo which is corrected in Equation (2) of Ziegler et al. 2008). The method used in Atwood et al. (2006) was the first application of this classic method (e.g., Blackman & Tukey 1958) to gamma-ray astronomy (in estimating the power spectrum an approximate autocovariance function is calculated using a maximum lag, and then Fourier-transformed).

In contrast to previous searches, our method uses an optimal gridding of the parameter space for both the semi-coherent and coherent stages, as well as an automated follow-up, and incorporates the spin-down corrections in a way that permits heterodyning and highly efficient code.

The search was done on the 1680-node Atlas Computing Cluster (Aulbert & Fahrmann 2008) built around four-core processors with 8 GB of random-access memory; for these we used a heterodyning bandwidth \( \Delta f_{\text{BW}} = 256 \) Hz. Breaking the full frequency range of the search into frequency bands allows the computation to fit into memory and also allows the use of different sky grids in each band. This further reduced the computational cost, since the number of required sky grid points increases with the square of frequency.

After computing \( S \) on the four-dimensional grid in parameter space, points with statistically significant values of \( S \) are candidates for possible pulsar signals, and are followed up in a second stage. This is done by “refining the grid” and increasing the coherent integration time. This is a hierarchical scheme which is analogous to “zooming”: successively swapping microscope objectives for ones of higher magnification, then recentering the interesting point on the slide (see, e.g., Cutler et al. 2005; Krishnan et al. 2004). In our case, this is done by constructing the fully coherent detection statistic \( P \) over the entire data set (or equivalently taking the Gaussian window-size \( T \to \infty \) in Equation (1)) obtaining

\[
P = \frac{1}{\kappa^2} \left| \sum_{j=1}^{N} w_j e^{-\Pi(t_j)} \right|^2,
\]

where for convenience we have normalized by the positive constant \( \kappa \) given by

\[
\kappa^2 = \frac{1}{2} \sum_{j=1}^{N} w_j^2.
\]

\(^{28}\) Complex heterodyning is a procedure which shifts frequencies in time-series data by a fixed offset \( f_0 \). This is accomplished by multiplying the time series by \( e^{-i2\pi f_0 t} \), shifting all frequencies by \( f_0 \).

\(^{29}\) Note that by symmetry \( S \) is real, because interchanging indices \( j \) and \( k \) is equivalent to complex conjugating the exponential factor.
The computing cost to coherently follow up a single candidate is negligible in comparison to the cost of the previous semi-coherent search. In selecting statistically significant semi-coherent candidates which are automatically followed up in the second stage using a fully coherent analysis, we do not use a fixed threshold to define “statistical significance.” In the semi-coherent stage, the search code keeps an internal list of the strongest signal candidates. Each member of this list is coherently followed up and corresponds to the largest value of $S$ detected in eight adjacent spin-down values for the entire heterodyning frequency bandwidth and a single sky point.

The refined grid of the fully coherent follow-up covers a region of parameter space of size $(4\Delta f) \times (4\Delta f) \times (4\Delta \theta) \times (4\Delta \theta)$ when projected into the ecliptic plane. In other words, it covers a region whose volume is 256 times larger than the volume of a fundamental cell in the original grid: its extent in each dimension of parameter space is four grid intervals. The refined grid has a spacing given by the previous formulae for $\Delta f$, $\Delta \dot{f}$, and $\Delta \theta$, except that the coherence time $T$ is set equal to the length of the entire data set, and $y = 1$. Since in this case only a small parameter-space region around the candidate is explored, it is computationally efficient to compute $P$ directly in the time domain (FFTs are not used), exploiting the sparsity of the photon data.

If the value of $P$, which measures the fully coherent power (in a single harmonic), is statistically significant, then in a third stage further refinement is carried out by higher harmonics (Fourier components). We adopt the so-called $H$-test, which has been widely used in X-ray and gamma-ray pulsar detection (de Jager et al. 1989; de Jager & Büsching 2010). This test measures the statistical significance of the energy in the first 20 (non-DC) Fourier components of the pulse profile as a function of phase. As in Equation (1), the $H$-test can also be modified to include the photon probability weights $w_j$ (see Kerr 2011a). Note that Equation (5) in Kerr (2011a) contains an error; corrected formulae used in this work are given below.

The weighted $H$-test statistic is defined as follows. For each photon arrival time $t_j$, the pulse phase $x_j$ (between zero and one) is calculated as $x_j = [\Phi(t_j) \mod 2\pi] / 2\pi$. The pulse profile (for $0 \leq x < 1$) is a sum over the photons

$$p(x) = \sum_{j=1}^{N} w_j \delta(x - x_j),$$

where $x_j$ is the pulse phase of the $j$th photon and $\delta(x)$ is a one-dimensional Dirac delta function. It can be expressed as a Fourier series

$$p(x) = \kappa \sum_{\ell=-\infty}^{\infty} \alpha_\ell e^{2\pi i \ell x},$$

which implies that the (complex) Fourier coefficients $\alpha_\ell$ are given by

$$\alpha_\ell = \frac{1}{\kappa} \sum_{j=1}^{N} w_j e^{-2\pi i \ell x_j},$$

where the definition of $\kappa$ is identical to Equation (7). The normalization of the Fourier coefficients has been chosen so that if the photon arrival times are uniformly distributed, independent random variables, then in the limit of the large numbers of photons, for $\ell > 0$, $\Re(\alpha_\ell)$ and $\Im(\alpha_\ell)$ are independent Gaussian random variables with zero mean and unit variance. Finally, the weighted $H$-test statistic is defined as

$$H = \max_{1 \leq \ell \leq 20} \left[ \sum_{\ell=1}^{L} |\alpha_\ell|^2 - 4(L-1) \right].$$

The quantity which is subtracted, $4(L-1)$, is motivated by an empirical numerical study (de Jager et al. 1989), providing the best omnibus test for unknown pulse profiles.
Maximizing $H$ over sky position, frequency $f$, and spin-down rate $\dot{f}$ selects the “narrowest and sharpest” overall pulse profile. In contrast, maximizing the statistic $P = |\alpha|^2$ of Equation (6) favors putting more power into the lowest harmonics.

Using $H$ as the test statistic, a further stage of parameter-space refinement is done in the same way as before: in the frequency, spin-down, and sky parameters, we cover regions that include four grid steps (in each dimension) of the previous grid. The chosen refinement factor (ratio of the number of grid points after and before refinement, in each dimension) is about an order of magnitude. At each grid point, the weighted $H$-statistic of Equation (11) is found. The parameter-space point with the largest statistic is selected as our best estimate of the pulsars’ parameters which are then further refined through the timing-analysis procedure (Ray et al. 2011) described in Section 5.2.

The hierarchical search pipeline has been validated by successfully recovering previously known gamma-ray pulsars, including some of the brightest gamma-ray MSPs (Abdo et al. 2010c; H. J. Pletsch & L. Guillemot 2011, in preparation). In the next section, the complete search scheme is illustrated with a detailed example.

4. EXAMPLE: RESULTS FOR PSR J1620–4927

Before giving the results for all of the pulsars that have been discovered with this new search method, we first go through a single example in detail. This illustration uses PSR J1620–4927, the first new pulsar found in this work.

Figure 1(a) shows the first stage of the analysis. For each $f$ and $\dot{f}$ value, the largest value of $S$ found in the sky grid is displayed as an intensity. The point of highest intensity corresponds to PSR J1620–4927’s $f$ and $\dot{f}$ parameters.

The second analysis stage is the automated follow-up of all candidates shown in Figure 1(a). As explained in Section 3, this is accomplished by carrying out a fully coherent search over a small region of parameter space around each candidate which has been identified as statistically significant in the previous semi-coherent stage. If the candidate found in the semi-coherent step was simply a statistical outlier, then the fully coherent statistic $P$ will not be significant. Figure 1(b) presents the results of the fully coherent statistic $P$ for PSR J1620–4927. Again the point of highest intensity compared to the background, indicating the presence of a coherent signal in the data set, is due to the new pulsar.

The importance of the photon probability weights $w_j$ can be illustrated by repeating the analysis using the same 8000 photons with the weights set to unity. (Note that the weights were used in selecting the 8000 photons, so this is not a complete comparison.) The result is that Figure 1(a) still shows a statistically significant outlier in the semi-coherent search step, which is followed up automatically and gives a statistically significant outlier in the fully coherent output of Figure 1(b). In both steps the signal and its statistical significance are reduced, but the pulsar is still found. However for some of the other new pulsars, this is not the case: if the weights are set to unity, then the pulsar is not detected. Overall the weights play a larger role for sources in crowded regions of the sky, for example, near the Galactic plane.

At the third stage, further refinement is carried out by maximizing the weighted $H$-test statistic over a small region of parameter space around the most significant candidate from the previous step. As described in Section 3, the parameter-space grid used at this stage is yet another order-of-magnitude finer than the one of the previous stage. Figure 2 shows the corresponding results for PSR J1620–4927.

The parameter-space point with the largest $H$-test statistic is selected as our best estimate of the pulsar parameters at this stage. The uncertainties in these estimated parameters can be obtained by using the fact that a 1σ deviation for a Gaussian distribution has a value $\approx 0.6$ of the maximum. In the current example, as shown in Figure 2, the value of the maximum weighted $H$-test statistic is 566.

Figure 2(c) illustrates the way the weighted $H$-test statistic accumulates over the total observation time. The linearity of this plot indicates that the properties of the source, and of the data, were time stationary; it shows that the pulsar’s emission is not changing with time. In this way it also gives additional confidence that the pulsar is real and not a statistical noise outlier. (We have not provided analogous plots for the other eight pulsars reported in this paper, but they are similar.)

As shown in de Jager & Büsching (2010) and Kerr (2011a), the weighted $H$-test has a false alarm probability approximately
The inferred rotational parameters of the new pulsars are presented in Table 2. In addition, further derived parameters are given, including the spin-down power $P_{\text{sd}} = 4\pi^2 I \dot{f} f$, where $I = 10^{45}$ g cm$^2$ is the assumed neutron star moment of inertia, and the magnetic field strength at the neutron star surface $B_S \approx 3.2 \times 10^{19} (f/f_0^2 s^{-1})^{1/2}$ G and at the light cylinder $B_{\text{LC}} \approx 2.94 \times 10^8 (f/f_0^2 s^{-1})^{1/2}$ G, respectively.

Figure 3 plots the newly discovered pulsars on an $f$–$\dot{f}$ diagram, where they can be compared with the known pulsar population. One can see that the new pulsars lie in a similar region (and hence belong at large to the same population) as the previously found blind-search Fermi-LAT gamma-ray pulsars.

Two of the nine new systems, PSRs J1803–2149 and J2111+4606, are young energetic pulsars ($E \gtrsim 6 \times 10^{53}$ erg s$^{-1}$ and $\tau \lesssim 100$ kyr), located near the Galactic plane. Among the seven remaining less-energetic and older pulsars, five are also located near the Galactic plane ($|b| < 5^\circ$) and two are found at higher Galactic latitudes ($|b| > 10^\circ$). One of these, PSR J0106+4855, has the largest characteristic age $\tau = 3$ Myr.

Table 1

| Pulsar Name | Source Association | R.A.$^a$ (hh:mm:ss.s) | Decl.$^a$ (dd:mm:ss.s) | $\dot{f}$ (deg) | $\dot{f}$ (deg) |
|-------------|--------------------|-----------------------|------------------------|----------------|----------------|
| J0106+4855  | 2FGL J0106.5+4854 | 01:06:25.06(1)        | +48:55:51.8(2)         | 125.5          | -13.9          |
| J0622+3749  | 2FGL J0622.9+3750 | 06:22:10.51(2)        | +37:49:13.6(9)         | 175.9          | 11.0           |
| J1620–4927  | 2FGL J1620.8–4928 | 16:20:41.52(1)        | -49:27:37.1(3)         | 333.9          | 0.4            |
| J1746–3239  | 2FGL J1746.5–3238 | 17:46:54.947(8)       | -32:39:55.8(7)         | 357.0          | -2.2           |
| J1803–2149  | 2FGL J1803.3–2148 | 18:03:09.632(9)       | -21:49:13(4)           | 8.1            | 0.2            |
| J2028+3332  | 2FGL J2028.3+3332 | 20:28:19.860(5)       | +33:32:04.5(6)         | 73.4           | -3.0           |
| J2030+4415  | 2FGL J2030.7+4417 | 20:30:51.35(4)        | +44:14:38.1(4)         | 82.3           | 2.9            |
| J2111+4606  | 2FGL J2111.3+4605 | 21:11:24.13(3)        | +46:06:31.3(3)         | 88.3           | -1.4           |
| J2139+4716  | 2FGL J2139.8+4714 | 21:39:55.95(9)        | +47:16:13(1)           | 92.6           | -4.0           |

Notes. A list of the nine new pulsars reported in this work, showing their sky locations and associations cataloged gamma-ray sources. The associations listed include sources from the Fermi-LAT Second Source Catalog (2FGL; Abdo et al. 2011b), the Fermi-LAT First Source Catalog (1FGL; Abdo et al. 2010a), the Fermi-LAT Bright Source List (0FGL; Abdo et al. 2009b), the AGILE Catalog (1AGL; Pittori et al. 2009), and the Third EGRET Catalog (3EG; Hartman et al. 1999).

$^a$ Right ascension (J2000.0) and declination (J2000.0) obtained from the timing model, where the numbers in parentheses are the statistical 1σ errors in the last digits.

$^b$ Galactic longitude ($l$) and latitude ($b$), rounded to the nearest tenth of a degree.

5. RESULTS FOR ALL NEW PULSARS

Table 1 shows the names and sky positions of the nine discovered pulsars, and also lists known source associations. The inferred rotational parameters of the new pulsars are presented in Table 2. In addition, further derived parameters are given, including the spin-down power $P_{\text{sd}} = 4\pi^2 I \dot{f} f$, where $I = 10^{45}$ g cm$^2$ is the assumed neutron star moment of inertia, and the magnetic field strength at the neutron star surface $B_S \approx 3.2 \times 10^{19} (f/f_0^2 s^{-1})^{1/2}$ G and at the light cylinder $B_{\text{LC}} \approx 2.94 \times 10^8 (f/f_0^2 s^{-1})^{1/2}$ G, respectively.

Figure 3 plots the newly discovered pulsars on an $f$–$\dot{f}$ diagram, where they can be compared with the known pulsar population. One can see that the new pulsars lie in a similar region (and hence belong at large to the same population) as the previously found blind-search Fermi-LAT gamma-ray pulsars.

Two of the nine new systems, PSRs J1803–2149 and J2111+4606, are young energetic pulsars ($E \gtrsim 6 \times 10^{53}$ erg s$^{-1}$ and $\tau \lesssim 100$ kyr), located near the Galactic plane. Among the seven remaining less-energetic and older pulsars, five are also located near the Galactic plane ($|b| < 5^\circ$) and two are found at higher Galactic latitudes ($|b| > 10^\circ$). One of these, PSR J0106+4855, has the largest characteristic age $\tau = 3$ Myr.
Figure 4. Phase–time diagram and pulse profile for PSR J0106+4855. The left panel shows the pulse phase at the arrival time of each photon, where the gray-scale intensity represents the photon probability weight. The upper right plot shows the summed probability weights: the integrated pulse profile using a resolution of 32 bins per rotation. The error bars represent the 1σ statistical uncertainties. The four plots below resolve the integrated pulse profile according to separate energy ranges. For clarity, the horizontal axis shows two pulsar rotations in each diagram. In obtaining these plots the 8000 events with the highest probability weights have been used (as in the blind search).

Table 2

| Pulsar Name | f (Hz) | \(\dot{f}\) \((-10^{-12}\text{ Hz s}^{-1})\) | Weighted H-test | \(\tau\) (k yr) | \(\dot{E}\) \((10^{34}\text{ erg s}^{-1})\) | \(B_S\) \((10^{12}\text{ G})\) | \(B_{L,C}\) (kG) |
|-------------|--------|-----------------|-----------------|----------------|-----------------|-----------------|-----------------|
| J0106+4855  | 12.02540173638(8) | 0.61881(7) | 843.1 | 3081.1 | 2.9 | 0.2 | 3.0 |
| J0622+3749  | 3.00112633651(5) | 2.28985(4) | 288.8 | 207.8 | 2.7 | 2.9 | 0.7 |
| J1620–4927  | 5.8161320951(5) | 3.54782(4) | 566.4 | 259.9 | 8.1 | 1.4 | 2.4 |
| J1746–3239  | 5.01149235750(3) | 1.64778(3) | 249.8 | 482.3 | 3.3 | 1.2 | 1.3 |
| J1803–2149  | 9.404983174(2) | 17.25984(6) | 451.9 | 86.4 | 64.1 | 1.5 | 11.0 |
| J2028+3332  | 5.65907208453(2) | 1.55563(2) | 1108.3 | 576.8 | 3.5 | 0.9 | 1.5 |
| J2030+4415  | 4.40392486537(5) | 1.2576(2) | 584.8 | 555.2 | 2.2 | 1.2 | 1.0 |
| J2111+4606  | 6.35593408654(4) | 57.4218(3) | 554.3 | 143.6 | 4.8 | 11.1 |
| J2139+4716  | 3.5354059962(2) | 0.2232(2) | 351.1 | 2511.5 | 0.3 | 0.7 | 0.3 |

Notes. The reference epoch for all measured rotational parameters is MJD 55225 and the time range for all timing models is MJD 54682–55719. The derived quantities in Columns 5–8 are based on the \(f\) and \(\dot{f}\) values obtained from the timing model and are rounded to the nearest significant digit. To model the timing noise present in PSR J1803–2149, a second frequency derivative is necessary: \(\ddot{f} = 7.3(8) \times 10^{-24}\text{ Hz s}^{-2}\). To model the timing noise present in PSR J2030+4415, higher frequency derivatives up to third order are necessary: \(\dddot{f} = -1.5(3) \times 10^{-23}\text{ Hz s}^{-2}\) and \(\ddot{f} = -6(2) \times 10^{-31}\text{ Hz s}^{-3}\). To model the timing noise present in PSR J2111+4606, higher frequency derivatives up to fourth order are necessary: \(\dddot{f} = 2.30(5) \times 10^{-22}\text{ Hz s}^{-2}\), \(\dddot{f} = -7.9(2) \times 10^{-30}\text{ Hz s}^{-3}\), and \(\dddot{f} = 3.2(4) \times 10^{-37}\text{ Hz s}^{-4}\). The numbers in parentheses are the statistical 1σ errors in the last digits.
Figure 5. Phase–time diagram and pulse profile for PSR J0622+3749. The plots have identical form as those shown in Figure 4.

Table 3
Pulse-Profile Parameters of the Discovered Gamma-Ray Pulsars

| Pulsar Name   | Peak Multiplicity | FWHM$_1$   | FWHM$_2$   | $\Delta$ |
|---------------|-------------------|------------|------------|----------|
| J0106+4855    | 2                 | 0.02 ± 0.01| 0.05 ± 0.01| 0.50 ± 0.01|
| J0622+3749    | 2                 | 0.21 ± 0.04| 0.03 ± 0.03| 0.47 ± 0.03|
| J1620–4927    | 2                 | 0.13 ± 0.04| 0.15 ± 0.05| 0.21 ± 0.03|
| J1746–3239    | 2                 | 0.32 ± 0.07| 0.11 ± 0.11| 0.63 ± 0.06|
| J1803–2149    | 2                 | 0.04 ± 0.02| 0.05 ± 0.03| 0.40 ± 0.02|
| J2028+3332    | 2                 | 0.10 ± 0.02| 0.04 ± 0.01| 0.38 ± 0.02|
| J2030+4415    | 2                 | 0.09 ± 0.03| 0.04 ± 0.01| 0.49 ± 0.02|
| J2111+4606    | 2                 | 0.08 ± 0.02| 0.07 ± 0.02| 0.31 ± 0.02|
| J2139+4716    | 1                 | 0.13 ± 0.03| ...         | ...          |

Notes. For each of the nine pulsars, we give the parameters describing the shape of the pulse profile, including the peak multiplicity, the full widths at half maxima (FWHM) of the peaks, and the separation $\Delta$ between the gamma-ray peaks for pulsars with more than one peak.

and the lowest surface magnetic field strength ($B_S \approx 2 \times 10^{11}$ G) of all LAT blind-search pulsars found to date. Also standing out, PSR J2139+4716 has the smallest spin-down power ($\dot{E} = 3 \times 10^{33}$ erg s$^{-1}$) among all non-recycled gamma-ray pulsars ever detected (see De Luca et al. 2011).

5.1. Source Associations

As listed in Table 1, all but one of the new pulsars have gamma-ray counterparts from the Fermi-LAT First Source Catalog (1FGL; Abdo et al. 2010a). The exception is PSR J2028+3332, which first appeared in the 2FGL catalog. In addition, these eight 1FGL unassociated sources have been classified as likely pulsar candidates based strictly on a comparison of their gamma-ray properties with previously detected LAT pulsars (Abdo et al. 2011a).

PSR J2111+4606 is associated with the source 0FGL J2110.8+4606 from the Fermi Bright Source List (Abdo et al. 2009b). Only 10 objects from this catalog still remain to be identified.

The new system PSR J1620–4927 is associated with the unidentified AGILE source 1AGL J1624–4946 (Pittori et al. 2009).
Figure 6. Phase–time diagram and pulse profile for PSR J1620–4927. The plots have identical form as those shown in Figure 4. Note that for this particular pulsar, based on the photon probability weights, no selected events (among the 8000) have energies in the 0.1–0.3 GeV range.

Table 4

Spectral Parameters of the Discovered Gamma-Ray Pulsars

| Pulsar Name       | $\Gamma$  | $E_c$ (GeV) | $F_{100}^a$ (10$^{-8}$ photons cm$^{-2}$ s$^{-1}$) | $G_{100}^b$ (10$^{-11}$ erg cm$^{-2}$ s$^{-1}$) | $L_{ps}$ (10$^{33}$ erg s$^{-1}$) | $d_{ps}$ (kpc) |
|-------------------|-----------|-------------|---------------------------------|---------------------------------|-------------------------------|----------------|
| J0106+4855        | 1.47 ± 0.23 | 3.31 ± 0.92 | 2.56 ± 0.77 ± 0.32 | 2.40 ± 0.31 ± 0.04 | 5.5 | 1.4$^c$ |
| J0622+3749        | 0.59 ± 0.34 | 0.60 ± 0.13 | 2.21 ± 0.35 ± 0.08 | 1.69 ± 0.15 ± 0.05 | 5.3 | 1.6 |
| J1620–4927        | 1.01 ± 0.18 | 2.44 ± 0.82 | 9.61 ± 1.01 ± 0.94 | 13.5 ± 10 ± 1.7 | 9.1 | 0.7 |
| J1746–3239        | 1.33 ± 0.08 | 1.65 ± 0.12 | 9.97 ± 0.94 ± 1.85 | 7.86 ± 0.41 ± 0.77 | 5.8 | 0.8 |
| J1803–2149        | 1.96 ± 0.11 | 5.73 ± 1.72 | 20.7 ± 3.1 ± 0.5 | 13.1 ± 1.1 ± 2.1 | 25.6 | 1.3 |
| J2028+3332        | 0.86 ± 0.21 | 1.53 ± 0.24 | 5.12 ± 0.87 ± 0.44 | 6.09 ± 0.41 ± 0.13 | 6.0 | 0.9 |
| J2030+4415        | 1.89 ± 0.14 | 2.16 ± 0.65 | 13.3 ± 1.4 ± 0.2 | 7.06 ± 0.48 ± 0.66 | 4.8 | 0.7 |
| J2111+4606        | 1.63 ± 0.14 | 5.43 ± 1.80 | 4.39 ± 0.69 ± 0.02 | 4.13 ± 0.34 ± 0.30 | 38.4 | 2.7 |
| J2139+4716        | 0.80 ± 0.27 | 1.02 ± 0.21 | 2.65 ± 0.44 ± 0.19 | 2.51 ± 0.21 ± 0.01 | 1.8 | 0.8 |

Notes. This table describes the spectral properties of each of the nine pulsars, modeling each spectrum as an exponentially cutoff power law with photon indices $\Gamma$ and cutoff energies $E_c$. The spectral parameters listed here for each pulsar are obtained from maximum likelihood fits. The first quoted uncertainties are statistical, while the second are systematic and correspond to the differences in the best-fit parameters observed when doing the spectral analyses with the P6_V3 IRFs and associated diffuse emission models (namely, the $gll_{iem}_{v02}$ map cube and $isotropic_{iem}_{v02}$ template). For each object, the pseudo-gamma-ray luminosity $L_{ps}$ and the pseudo-distance $d_{ps}$ are inferred from the apparent spin-down power $\dot{E}$ and the energy flux $G_{100}$ above 100 MeV. Note that these estimated gamma-ray luminosities and distances are subject to a number of caveats, detailed in Saz Parkinson et al. (2010), and could differ significantly from the actual values.

$^a$ Photon flux measured above 100 MeV.

$^b$ Energy flux measured above 100 MeV.

$^c$ The actual distance is 3.0 kpc, as inferred from the dispersion of the radio pulse measuring the free electron column density; see Section 6.1.

2009). This AGILE source is however about 10 times brighter, with a flux of $(67 \pm 13) \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$. In addition, it has an error radius of 0:58 and encloses other 2FGL sources. The new gamma-ray pulsar could therefore only explain a fraction of the total flux detected by AGILE from 1AGL J1624–4946.
While not formally associated in the 2FGL catalog (Abdo et al. 2011b), PSR J2028+3332 lies within the 99% error contours for the EGRET source 3EG J2027+3429. However, the pulsar accounts for only about a fifth of the flux for the EGRET source. Another nearby LAT source, 2FGL J2025.1+3341, is associated with an AGN and has a peak LAT flux that can account for the remainder of the measured EGRET flux.

We have searched the TeVCat online catalog of TeV sources for very high energy counterparts to the newly discovered pulsars, but found no associations. This is not surprising, considering that most of the new gamma-ray pulsars have moderate spin-down power ($\sim 10^{34}$ erg s$^{-1}$) and relatively large characteristic ages ($\gtrsim 100$ kyr), while pulsars associated with TeV pulsar wind nebulae (PWNe) tend to be young and energetic. PSRs J1803–2149 and J2111+4606 have properties that make associations with TeV PWNe plausible; however, no detections of TeV emission from these directions have been reported.

5.2. Timing Analysis

For each new gamma-ray pulsar, the definitive parameters as given in Tables 1 and 2 are determined via precise measurements of pulse times of arrival (TOAs) and by fitting the parameters of a timing model to these measurements using methods described in Ray et al. (2011).

To obtain a set of TOAs, photons are extracted for each source using a radius and minimum energy cut to optimize the signal-to-noise ratio for each pulsar. Then these data are subdivided into segments of about equal length. The set of best-guess pulsar parameters from the search (maximizing $H$) is used as a preliminary ephemeris to fold the photon arrival times, producing a set of pulse profiles. The TOAs are then measured by cross-correlating each pulse profile with a multi-Gaussian or kernel-density template derived from fitting the entire data set. This is done using the unbinned maximum likelihood method described in Ray et al. (2011). Then Tempo2 (Hobbs et al. 2006) is used to fit the TOAs to a timing model including sky position, frequency, and frequency derivative.

As often is the case, the youngest object found in this work (PSR J2111+4606, $\tau = 17$ kyr) exhibits particularly large timing noise. In turn, this requires including higher-order frequency-derivative terms to make a good timing model fit; in this case up to the fourth derivative of the frequency as shown in Table 2. For the same reason, the timing models in Table 2 for PSRs J2030+4415 and J1803–2149 include terms up to the third and the second frequency derivative, respectively.

Based on these timing solutions, Figures 4–12 show the resulting phase–time diagrams and pulse profiles for each of the newly discovered pulsars. These plots are obtained from calculating the phase for each of the 8000 photons selected for the blind search and using the parameters listed in Tables 1 and 2.
and weighting each event by its probability of originating from the pulsar $w_j$. The integrated pulse profiles (weighted pulse phase histograms) are constructed with a resolution of 32 bins in phase per rotation. The $1\sigma$ error bars in the integrated pulse profiles are statistical only and are given by $(\sum_j w_j^2)^{1/2}$, where $j$ runs over all events falling into the same phase bin. (Note that the formula for the fractional error has the opposite sign of the exponential: $-1/2$.)

As seen in Figures 4–12, eight of the nine pulsars have pulse profiles with two peaks. For pulsars where the two peaks are separated by nearly one-half of a rotation, it is possible to detect or discover the pulsar at the second harmonic (i.e., at twice the actual spin frequency of the pulsar). For pulsar candidates which were discovered with (apparently) single-peaked profiles, we tested for the true fundamental spin frequency by folding at the subharmonic of the discovery frequency. If the subharmonic is the correct frequency, the two resulting peaks may satisfy one or more of the following conditions: offsets that are measurably different than 0.5 in phase, significant differences in the integrated weighted counts under each peak, or significant differences in the shape of the peaks in different energy bands. With modest signal-to-noise ratios, such determinations are not always conclusive. For PSR J0106+4855, our identification of the true period was subsequently confirmed by the detection of radio pulsations with a single-peaked profile. For the one apparently single-peaked pulsar in our sample, PSR J1239+4716, none of the above tests yield strong evidence for the profile being double peaked at half the frequency. Additional data will be required to strengthen this conclusion.

In order to further characterize each pulse profile, we fit the pulsars’ weighted gamma-ray peaks to Lorentzian lines. The derived pulse shape parameters are listed in Table 3. Note that PSRs J0622+3749 and J1746–3239 show indications of substructures in their main gamma-ray peak. For these pulsars a single Lorentzian line function is used for fitting the main component. Apart from PSR J0106+4855, which is detected at radio wavelengths (see Figure 13), there is no particular reference for absolute phase of these pulsars. For the other eight pulsars we have arbitrarily assigned the absolute phase reference such that the first peak occurs at a value of 0.1 in phase. The gamma-ray pulse profiles shown in Figures 4–12 along with the pulse-profile parameters listed in Table 3 are very similar to those of the previously discovered gamma-ray pulsars in blind searches (Abdo et al. 2009a; Saz Parkinson et al. 2010; Abdo et al. 2010c), further supporting the theory that the gamma-ray emission consists of fan beams produced in the outer magnetosphere.

5.3. Spectral Parameters

The spectral parameters for the new pulsars are obtained by fitting each phase-averaged spectrum with an exponentially cutoff power law with a photon index $\Gamma$ and a cutoff energy $E_c$. The results for each pulsar are listed in Table 4. In addition to $\Gamma$ and $E_c$, which are explicit parameters of the fit, Table 4 also gives the important derived physical quantities of photon flux $F_{100}$.
Analogous to the pulse-profile properties, $\Gamma$ and $E_c$ measured for the new pulsars are also similar to those observed for previously detected gamma-ray pulsars (Abdo et al. 2010c). This is not surprising, because (as described in Section 2) target sources for our search have been selected based on similarity of their spectral properties to known gamma-ray pulsars.

The distance (3 kpc) for one of the new pulsars (PSR J0106+4855) can be inferred based on the dispersion of the radio pulse measuring the free electron column density (see Section 6.1 for details). As the remaining eight pulsars are radio-quiet, this method cannot be used to estimate their distance. Furthermore, none of the pulsars are associated with a known SNR, preventing us from deriving distance estimates from such source associations.

However, it is still possible to obtain a crude estimate of the distance to the new pulsars, by exploiting the observed correlation between the gamma-ray luminosity $L_\gamma$ and the spin-down power $\dot{E}$ for other gamma-ray pulsars with distance measures (see Abdo et al. 2010c). Based on this correlation “pseudo-gamma-ray luminosities” $L_{ps}$ are derived as

$$L_{ps} \sim 3.2 \times 10^{33} (\dot{E}/10^{34} \text{ erg s}^{-1})^{1/2} \text{ erg s}^{-1},$$

where the $\dot{E}$ values are obtained from Table 2. Assuming a geometrical correction factor $f_\Omega = 1$ for the emission cone (Watters et al. 2009) for all gamma-ray pulsars, the relation $L_\gamma = 4\pi f_\Omega G_{100} d^2$ is used to convert the energy flux and pseudo-gamma-ray luminosity into a “pseudo-distance” $d_{ps}$, following Equation (2) of Saz Parkinson et al. (2010):

$$d_{ps} \sim 1.6 \frac{(\dot{E}/10^{34} \text{ erg s}^{-1})^{1/4}}{(G_{100}/10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1})^{1/2}} \text{kpc.}$$

For each of the new pulsars the resulting values for $L_{ps}$ and $d_{ps}$ are shown in Table 4. Note that these estimated gamma-ray luminosities and distances are subject to a number of caveats, detailed in Saz Parkinson et al. (2010), and could differ significantly from the actual values.

5.4. Why Were the New Pulsars not Found in Previous Blind Searches?

To examine whether the nine pulsars found with this new method could be detected with previous methods, we apply the same search method (Atwood et al. 2006; Ziegler et al. 2008) used to successfully discover the 26 previously found blind-search LAT gamma-ray pulsars (Abdo et al. 2009a; Saz Parkinson et al. 2010; P. M. Saz Parkinson et al. 2011, in preparation). We select input data as done in previous searches; events are selected based on a fixed ROI and minimum-energy cut as described in Saz Parkinson et al. (2010). We use the same coherence window size ($T = 2^{18}$s) as in the previous (and in the first stage of this paper’s search) search. No photon weights

![Figure 9. Phase–time diagram and pulse profile for PSR J2028+3332. The plots have identical form as those shown in Figure 4.](image-url)
are computed or used. No sky gridding is done in the first stage of the search; only the 2FGL catalog sky position is used.

The previous blind search code recovers three of the nine pulsars (PSRs J1620−4927, J2028+3332, and J2111+4716) when the 2FGL sky locations are searched. Two of the remaining six pulsars are detected only if the correct known sky position is used (as opposed to the 2FGL catalog position). If in addition the ROI and energy cuts are optimized (scanning different values) then three of the remaining four pulsars are detected. Finally, if the coherence window size is doubled (which dramatically raises the computational burden in a full blind search) then the last pulsar is found.

As compared to the previously published blind-pulsar searches of LAT data, the methods used for this work incorporate several significant improvements in sensitivity and computational efficiency, as well as a longer data set, that explain why these new discoveries are made. First, the use of efficient parameter space gridding over both sky position and frequency derivative allows pulsars to be found that are much farther from the LAT catalog position than is possible with previous searches. In addition, using photon weights for both event selection and for the search computations ensures that the detection significance is near optimal with only a single trial over event selections. A key factor is that while weighting the photons provides only a modest sensitivity improvement over optimal cookie cutter selections, the improvement can be large when compared to non-optimal cuts.

One might think that the additional systems found in this paper come about purely from the significantly increased computer power that was available. This is not the case: the improved methods deserve almost all of the credit. The improved methods are so computationally efficient that had we searched only up to 64 Hz as was done in previous searches, we could have searched all 109 selected 2FGL sources over the initial spin-down range ($|\dot{f}| \leq 5 \times 10^{-13}$ Hz s$^{-1}$) and would have found seven of the nine new pulsars using less than 5000 CPU hr. These are modest resources in comparison with those used in previous blind searches. The remaining two pulsars would only have been found if the spin-down range were increased by a factor of 20 to $|\dot{f}| \leq 10^{-11}$ Hz s$^{-1}$, increasing the required CPU time to about 100,000 hr.

6. RADIO AND X-RAY COUNTERPART SEARCHES

6.1. Pulsed Radio Emission

These discoveries represent a substantial increase in the number of gamma-ray pulsars detected in blind searches of

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31 The UCSC group has about 30,000 CPU hr month$^{-1}$ available; their previous search of 2 years of Fermi-LAT data used 65,000 CPU hr.
Fermi-LAT data. Of the 26 previously discovered LAT blind-search pulsars, only 3 have been found to pulse in the radio band (Camilo et al. 2009; Abdo et al. 2010b; Saz Parkinson et al. 2010; P. M. Saz Parkinson et al. 2011, in preparation) and there are tight upper limits on the others (Ray et al. 2011; Keith et al. 2011). In order to exploit these new discoveries in population studies of the relative beaming fraction and geometry of the radio and gamma-ray emission, it is essential to determine if they are also visible as radio pulsars.

Because the source list was chosen from Fermi-LAT pulsar-like unassociated sources, all of these sources had been previously searched for radio pulsations by the Fermi Pulsar Search Consortium (Ransom et al. 2011; Hessels et al. 2011). We have re-analyzed all of these archival observations, with increased sensitivity because we can now do a single frequency trial folding the radio data with the gamma-ray ephemeris, and search only in a single parameter, the dispersion measure (DM). This greatly reduces the number of points searched in parameter space (the “trial factor”) and implies that much smaller pulsed signal amplitudes are statistically significant. Where we saw an opportunity to go significantly deeper, we also made a number of new radio observations.

The telescopes and observing configurations used are described in Table 5, and the characteristics of the individual radio observations are shown in Table 6. We compute the sensitivities using the modified radiometer equation given in Equation (A1.22) of Lorimer & Kramer (2005):

$$S_{\text{min}} = \beta \frac{5}{G} \frac{T_{\text{sys}}}{n_p t_{\text{int}} A F} \sqrt{\frac{W}{1/f - W}},$$  

(14)

where $\beta$ is the instrument-dependent factor due to digitization and other effects (when unknown, we assume $\beta = 1.25$), a value of 5 has been assumed for the threshold signal-to-noise ratio for a confident pulsar detection, $T_{\text{sys}} = T_{\text{rec}} + T_{\text{sky}}$, $G$ is the telescope gain, $n_p$ is the number of polarizations used (2 in all cases), $t_{\text{int}}$ is the integration time, $A F$ is the observation bandwidth, $f$ is the pulsar spin frequency, and $W$ is the pulse width (for uniformity, we assume $W = 0.1/f$). Note that conventionally the 3 K background temperature is included in the receiver temperature $T_{\text{rec}}$, which is measured on cold sky, and so $T_{\text{sky}}$ represents the excess temperature from the Galactic synchrotron component, which we estimate by scaling the 408 MHz map of Haslam et al. (1982) to the observing frequency $\nu$ with a spectral index $\alpha = -2.6$ (defined as $S_{\nu} \propto \nu^\alpha$).

We use a simple approximation of a telescope beam response to adjust the flux sensitivity in cases where the pointing direction was offset from the true direction to the pulsar. This factor is given by $q = e^{-(\theta/HWHM)^2/2}$, where $\theta$ is the offset from the beam center and HWHM is the beam half-width at half-maximum. A computed flux density limit of $S_{\text{min}}$ at the beam
center is thus corrected via division by $q$ for targets offset from the pointing direction.

For eight of the nine pulsars, we have established that they are indeed radio-quiet (or extremely radio-faint), as viewed from Earth.

For PSR J0106+4855 our observations and analysis have revealed very faint radio pulsations. In two of our archival 45 minute Green Bank Telescope (GBT) observations at 820 MHz, we detect the pulsar at a DM of $70.87 \pm 0.2$ pc cm$^{-3}$ with a single-trial significance of $4\sigma - 5\sigma$ in each observation. Although the detections are not individually very strong, we gain additional confidence in their veracity from the fact that the peak phases are consistent to 0.01 pulse periods when each observation is folded using the ephemeris determined from our gamma-ray timing. The summed radio profile shows a narrow peak with a duty cycle of $\sim 2\%$, as shown in Figure 13.
We estimate a flux density of $\sim 20 \mu$Jy in both observations, using the standard radiometer equation and a measurement of the off-pulse noise level. These radio pulsations are detected at a flux density below the nominal detection limit of 30 $\mu$Jy because the duty cycle is a factor of five smaller than the 10% duty cycle used in the sensitivity calculation for unknown pulse shapes. This corresponds to an equivalent flux density of 8 $\mu$Jy at 1400 MHz using a typical pulsar spectral index $\alpha = -1.7$. As seen in Table 6, we have made two other observations of this source, one at 350 MHz with the GBT and one at 1.4 GHz with Effelsberg. Neither of these observations detect the radio pulsations. Accounting for this narrow duty cycle of the pulse, the minimum detectable flux density for the Effelsberg observation at 1.4 GHz was about 15 $\mu$Jy, so the non-detection in that observation is not surprising. This constrains the spectral index to be $\alpha \leq -0.5$. On the other hand, a spectral index of $-1.7$ would imply a flux density at 350 MHz of 85 $\mu$Jy, which is above the nominal sensitivity of our 350 MHz observation. This implies that either $\alpha > -1.3$ or the sensitivity of that observation was affected by scatter or DM broadening or higher than expected sky background. Using the NE2001 model (Cordes & Lazio 2002), the measured DM corresponds to an estimated distance of 3.0 kpc, over a factor of two larger than the pseudo-distance. Given the radio detection, we can measure the so-called phase lag $\delta = 0.073 \pm 0.003$ between the gamma-ray and radio emission.

6.2. Continuum Radio Emission

Pulsars and SNRs have the same origin, although the comparatively short lifetimes of SNRs mean that the number of...
pulsar–SNR associations is quite small. However the rare associations are of high interest, as they constrain a number of pulsar and SNR parameters. A recent text-book example is the association of the gamma-ray pulsar J0007+7303 with the shell-type SNR CTA 1 (Abdo et al. 2008; Sun et al. 2011).

For the nine new gamma-ray pulsars no association with a known SNR listed in the most recent SNR catalog (Green 2009) is found. However, SNRs are difficult to identify in case they are faint, confused, or distorted by interaction with dense clouds. We have used large-scale and Galactic-plane radio continuum surveys to search for structures in the vicinity of the new pulsars, which may indicate an association.

For the two pulsars PSRs J0106+4855 and J0622+3749 located above 10° of Galactic latitude, we used the MPIfR-survey sampler32 to extract maps from the 408 MHz and 1420 MHz surveys (Haslam et al. 1982; Reich 1982), which show faint sources and extended smooth diffuse emission, but no discrete object. The high-resolution interferometric NVSS maps (Condon et al. 1998) show numerous compact sources, but no extended features.

The remaining pulsars are located within 4° of Galactic latitude covered by Galactic-plane surveys. The southern-sky pulsar PSR J1620–4927 is located toward the gradient of an extended emission complex as seen in southern-sky surveys (Reich et al. 2001; Jonas et al. 1998). The Southern Galactic Plane Survey (Haverkorn et al. 2006) is insensitive to large-scale emission, but shows no small-scale structures within 0.5° of the pulsar. PSR J1746–3239 is located at b = −2:2 close to an emission ridge sticking out from the plane. The shell-type SNR G356.6–1.5 with a size of 20° has a flat spectrum 6 Jy thermal source visible in all Galactic-plane surveys. Quiroga et al. (2006) list details for the H I region with a deconvolved Gaussian size of 2.7′ and a distance of 3.4 kpc. Also CO emission was observed (Soviljevic et al. 1987). The pulsar is located at the periphery of this emission complex, but further studies are needed to investigate this region. PSR J2028+3332 is located at the southern boundary of the thermal Cygnus-X complex. The 11 cm survey (Reich et al. 1984) shows patchy structures in the field and an extragalactic 1.8 Jy source 40′ distant from the pulsar. PSR J2030+4415 is seen toward the northern periphery of strong complex emission from the Cygnus-X region. Dedicated studies are needed to find any emission associated with the pulsar. PSRs J2111+4606 and J2139+4716 are both located in low emission areas, where the 21 cm and 11 cm Effelsberg Galactic-plane surveys show faint structures close to the noise level.

6.3. X-Ray

Subsequent to the pulsar discoveries, we searched for archival X-ray observations covering the new pulsars’ sky locations. As listed in Table 7, we have found short Swift observations (3–10 ks exposure) for five of the pulsars. In addition there is a 6 ks long XMM-Newton observation for PSR J1620–4927 and a 23 ks long Suzaku observation for PSR J0106+4855. For the two remaining pulsars, PSRs J1746–3239 and J2028+3332, 10 ks long Swift observations were carried out following the discoveries.

These X-ray data were analyzed, and no X-ray counterparts were found for any of the new gamma-ray pulsars.

In order to estimate upper limits on the X-ray flux for each new pulsar, a power-law spectrum with a photon index of 2

### Table 7

| Pulsar Name | Instrument | Exposure Time (ks) | Absorbing Column (10^22 cm⁻²) | Flux Upper Limit (10⁻¹³ erg cm⁻² s⁻¹) | Lγ /Lₓ |
|-------------|------------|-------------------|-----------------------------|---------------------------------|--------|
| J0106+4855  | Suzaku     | 23.0              | 1.0                         | 0.843                           | >285   |
| J0622+3749  | Swift XRT  | 4.4               | 4.0                         | 2.58                            | >65    |
| J1620–4927  | XMM-Newton | 6.0               | 4.0                         | 0.674                           | >1988  |
| J1746–3239  | Swift XRT  | 8.7               | 1.0                         | 1.74                            | >451   |
| J1803–2149  | Swift XRT  | 7.7               | 5.0                         | 3.26                            | >34    |
| J2028+3332  | Swift XRT  | 10.3              | 1.0                         | 1.57                            | >387   |
| J2030+4415  | Swift XRT  | 10.2              | 4.0                         | 2.53                            | >279   |
| J2111+4606  | Swift XRT  | 10.1              | 3.0                         | 2.25                            | >183   |
| J2139+4716  | Swift XRT  | 3.2               | 1.0                         | 3.20                            | >78    |

Notes. The sky locations of all nine pulsars have been searched for (non-pulsating) X-rays, using both archival and new data. No X-ray sources were found at the new pulsar locations, so flux upper limits and lower limits on the gamma-ray to X-ray luminosity ratio are reported.

32 http://www.mpifr.de/survey.html
and a signal-to-noise of 3 is used. The values for the absorbing columns are estimated analogously to Marelli et al. (2011). In the 0.3–10 keV energy range, the derived upper limits on the X-ray flux of the pulsars are between 1 and $3 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, except for PSR J1620–4927, where an upper-limit X-ray flux of $6 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ is obtained, and PSR J0106+4855, with an upper-limit X-ray flux of $2.3 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$. These results, listed in Table 7, are consistent with the gamma-to-X-ray flux ratios for previously found Fermi-LAT pulsars (Marelli et al. 2011).

7. CONCLUSION

This work reports on the discovery of nine gamma-ray pulsars through the application of a new blind-search method to about 975 days of Fermi-LAT data. The new pulsars were found by searching unassociated sources with typical pulsar-like properties selected from the Fermi-LAT Second Source Catalog (Abdo et al. 2011b).

The sensitivity of blind searches for previously unknown gamma-ray pulsars is limited by finite computational resources. Thus, efficient search strategies are necessary maximizing the overall search sensitivity at fixed computing cost. We have developed a novel hierarchical search method, adapted from an optimal semi-coherent method (Pletsch & Allen 2009) together with a sliding coherence window technique (Pletsch 2011) originally developed for detection of continuous gravitational-wave signals from rapidly spinning isolated neutron stars. The first stage of the method is semi-coherent, because coherent power computed using a window of six days is incoherently combined by sliding the window over the entire data set. In a subsequent stage, significant semi-coherent candidates are automatically followed up via a more sensitive fully coherent analysis. The method extends the pioneering methods first described in Atwood et al. (2006).

The new method is designed to find isolated pulsars up to kHz spin frequencies, by scanning a template grid in the four-dimensional parameter space of frequency, frequency derivative, and sky location. The optimal and adaptive sky gridding (not done in previously published blind searches) is necessary, particularly at the higher search frequencies, because the source-catalog sky positions are not precise enough to retain most of the signal-to-noise ratio in year-long data sets. A fundamental new element of the method is the exploitation of a parameter-space metric (well studied in the continuous gravitational-wave context; see, e.g., Brady & Creighton 2000; Prix 2007) to build an efficient template grid, as well as a metric approach to construct an optimal semi-coherent combination step (Pletsch & Allen 2009; Pletsch 2010). A further enhancement over previous searches is the sub-division of the total search frequency range into bands via complex heterodyning. This accommodates memory limitations, parallelizes the computational work, and permits the use of efficient sky grids adapted to the highest frequency searched in each band. A photon probability weighting scheme (Kerr 2011a) is also used for the first time in a published blind search, further improving the search sensitivity.

The nine newly discovered pulsars increase the previously known Fermi-LAT blind-search pulsar population (Abdo et al. 2009a; Saz Parkinson et al. 2010; P. M. Saz Parkinson et al. 2011, in preparation) by more than one-third and bring the total number to 35. The inferred parameters of the new pulsars suggest that they belong to the same general population as the previously found blind-search gamma-ray pulsars. Deep follow-up observations with radio telescopes have been conducted for all of the new pulsars, but significant radio pulsations have only been found for PSR J0106+4855. The null results for the other eight pulsars indicate that they belong to the growing population of radio-quiet gamma-ray pulsars, which can only be detected via their gamma-ray pulsations.

The computational work of the search has been done on the 6720-CPU-core Atlas Computing Cluster (Aulbert & Fehrmann 2008) at the Albert Einstein Institute in Hannover. Recently, in 2011 August, we have moved the computational burden of the search onto the volunteer distributed computing system Einstein@Home33 (Abbott et al. 2009a, 2009b; Knispel et al. 2010). This will provide significantly more computing power and will allow a complete search of the parameter space up to kHz pulsar spin frequencies. We also hope that in the future an improved version of these methods can be used to carry out blind searches for gamma-ray pulsars in binary systems.

The combination of improved search techniques and much more powerful computational resources leaves us optimistic that we can find still more gamma-ray pulsars in the Fermi-LAT data. These advances should also greatly increase the chance of finding the first radio-quiet gamma-ray MSP with the Fermi-LAT. We hope that further discoveries, and further study of these systems, will eventually provide important advances in our understanding of pulsars, and of their emission mechanisms and geometry.

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33 Einstein@Home is available at http://einstein.phys.uwm.edu/.
