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Finding (or not) New Gamma-ray Pulsars with GLAST

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Abstract. Young energetic pulsars will likely be the largest class of Galactic sources observed by GLAST, with many hundreds detected. Many will be unknown as radio pulsars, making pulsation detection dependent on radio and/or x-ray observations or on blind periodicity searches of the gamma-rays. Estimates for the number of pulsars GLAST will detect in blind searches have ranged from tens to many hundreds. I argue that the number will be near the low end of this range, partly due to observations being made in a scanning as opposed to a pointing mode. This paper briefly reviews how blind pulsar searches will be conducted using GLAST, what limits these searches, and how the computations and statistics scale with various parameters.

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INTRODUCTION

Pulsar emission mechanism(s) from radio to gamma-rays are poorly understood after 40 yrs of work. Yet despite this fact, pulsars are high-precision tools that probe a variety of topics in both fundamental physics and astrophysics. EGRET detected pulsed emission from at least 6, and probably $7-9$, young pulsars at energies $\gtrsim 100$ MeV [1]. In addition, several tens of the (primarily Galactic) unidentified EGRET sources are likely pulsars [e.g. 2, 3, 4]. With its much larger effective area and improved angular resolution, GLAST will almost certainly detect hundreds of pulsars. The majority of those pulsars will remain unidentified though (and useless as physics tools), unless pulsations are detected through 1) “folding” of the events using timing ephemerides for known radio pulsars; 2) searches of associated x-ray sources to find radio-quiet Geminga-like pulsars [5], or very faint radio pulsars [6, 7]; or 3) “blind” searches of the gamma-ray events [8]. This paper discusses the latter, and perhaps most difficult, option.

The known gamma-ray pulsars have similar characteristics [for a review, see 1]. They are mostly non-variable sources with fairly flat energy spectra in the gamma-ray regime, but with spectral cutoffs around or just above 1 GeV. The flat energy spectra imply that most of the *photons* detected by the Large Area Telescope (LAT) will be in the $\sim$100-300 MeV range, where the point spread function has a width $\gtrsim 1^\circ$. The gamma-ray pulse shapes are complex with two relatively sharp pulses which provide higher harmonic content in searches and make their detection easier.

Most of the GLAST mission will be spent in sky survey mode, where the whole sky is scanned every $\sim$3 hours[1]. On average, a point in the sky will be within the LAT field of view $\sim 1/6$ of the time. Pointed observations would increase this fraction to $\sim 1/2$ (with Earth occultations preventing higher on-source efficiency). This loss in efficiency due to scanning (more specifically, the resulting decrease in the number of source events N_s during a particular viewing period $T_{\rm view}$) will make coherent pulsation searches considerably more difficult and less sensitive.

BLIND SEARCHES FOR GAMMA-RAY PULSARS

Blind searches of low count rate event data are typically conducted using either Fourier techniques (i.e. binning events into a time series, computing one or more FFTs, and analyzing the resulting amplitude and possibly phase spectra; [e.g. 9, 8]) or via brute-force epoch folding (i.e. assembling a pulse profile by determining the pulse phase of each event from a trial ephemeris and then computing a probability of non-uniformity for the profile; [e.g. 10, 11]). Optimal sensitivity to pulsations comes from searches that treat all of the data in a “coherent” fashion, meaning that the pulsar’s rotational phase is accurately tracked over the full observation or analysis duration $T_{\rm view}$, from first event to last.

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[1] For details, see the GLAST mission website: `http://glast.gsfc.nasa.gov`

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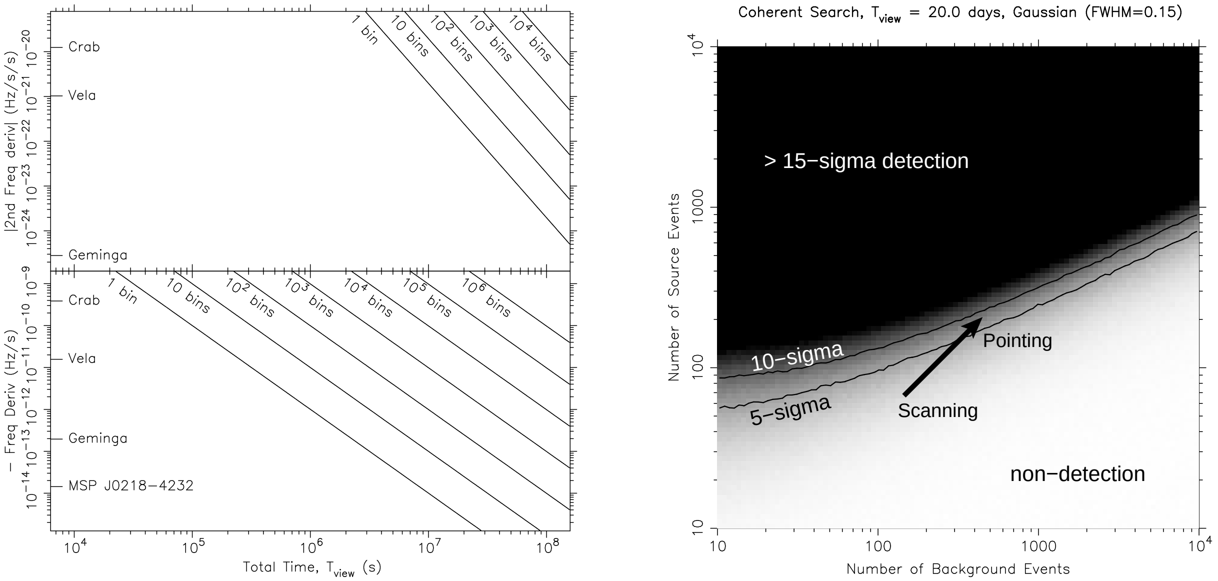

FIGURE 1. **Left)** The number of independent Fourier "bins" (i.e. $1/T_{\text{view}}$ in Hz) a signal with frequency derivative $\dot{f}$ (bottom) and frequency 2^{nd} derivative $\ddot{f}$ (top) would drift in an observation of duration T_{view}. To preserve sharp features in pulse profiles, search codes need to account for signal drift to a small fraction (1−10%) of a Fourier bin. **Right)** The 95% confidence-level detectability of a blind event-folding search with T_{view}=20 days for a pulsar with a Gaussian pulse profile with FWHM=15% in pulse phase. The "sigmas" represent Gaussian significance in standard deviations after accounting for the number of trials searched. The arrow (representing a factor of ∼3 increase in accumulated events during T_{view} and which can be translated anywhere on the plot) shows how the significance improves for pointed observations (which are still affected by Earth occultations) as opposed to scanning observations. In this case, a 20-day pointing results in an ∼8-σ detection, whereas 20-days of scanning gives a non-detection.

The real problem with gamma-ray pulsation searches comes from the fact that the sources have very low count rates of 10^{-7}–10^{-8} photons(>100 MeV) $\text{cm}^{-2}\,\text{s}^{-1}$, which for the LAT corresponds to roughly 0.2−2 events per hour. Therefore, very long observations lasting from weeks to years are required to make significant detections. And unfortunately, young pulsars are notoriously badly behaved over such timescales.

Ideally, we would only need to search over the unknown spin frequency f of a pulsar. However, young pulsars rapidly spin-down (i.e. have large frequency derivatives $\dot{f}$), they exhibit timing noise which manifests itself in searches as significant frequency 2^{nd} derivatives $\ddot{f}$ (and for the noisiest pulsars, many higher order derivatives as well), and they occasionally, on month or year timescales, "glitch" and instantaneously change their observed f and $\dot{f}$. Figure 1 shows the number of independent frequency bins of width $1/T_{\text{view}}$ in Hz, corresponding to an accumulated phase error of one rotation, over which a pulsar signal will "drift" during a coherent search for a variety of realistic values of $\dot{f}$ and $\ddot{f}$. Pulsar spin-down becomes important for energetic young pulsars in a day or two, and so all gamma-ray searches must account for an unknown $\dot{f}$. Timing noise can become important after a few weeks or months. Since gamma-ray pulse profiles contain sharp features, and therefore their pulsed signals contain many harmonics, search codes must significantly oversample the $\sim 1/T_{\text{view}}$ or $\sim 1/T_{\text{view}}^2$ spacings in f and $\dot{f}$ to maintain optimal sensitivity.

A potentially bigger problem, as shown by Chandler et al. [8], are positional errors or uncertainties ε, which cause *apparent* changes in the observed spin frequency $\delta f \sim 10^{-6}\varepsilon_{\text{mrad}} f_{10}\sin\theta$ Hz, frequency derivative $\delta\dot{f} \sim 2\times 10^{-13}\varepsilon_{\text{mrad}} f_{10}\cos\theta\,\text{Hz}\,\text{s}^{-1}$, and frequency 2^{nd} derivative $\delta\ddot{f} \sim 4\times 10^{-20}\varepsilon_{\text{mrad}} f_{10}\sin\theta\,\text{Hz}\,\text{s}^{-2}$, where $\varepsilon_{\text{mrad}}$ is the position error in milliradians, f_{10} is the spin frequency in tens of Hz, and θ is the time varying angle between the Earth's velocity vector and the line of sight to the pulsar. For candidate GLAST pulsar sources, ε will be milliradians (arcminutes) in size, making the blind detection of even stable Geminga-like pulsars much more difficult.

The intrinsic $\dot{f}$*, timing noise, glitch frequency, and position error effects place upper limits on the useful* T_{view} *for coherent pulsation searches to durations as short as ∼10 days for the most energetic and active pulsars, or a few months for older, slower, and more stable pulsars.* Because of the scanning nature of the GLAST mission, there will be fewer counts accumulated for a particular source over the specified T_{view} by a factor of ∼3 as compared to a pointed observation. This decrease in accumulated counts per unit time greatly impacts coherent search sensitivity and is the reason why scanning is not the optimal observing mode for pulsar studies.

Pulsation Detection and Computational Considerations

The power P in a periodic gamma-ray signal is $P \sim 1 + \alpha N_s^2/N_t$, where α is a pulse-shape dependent factor (0.4−0.9 for the known gamma-ray pulsars)[e.g. 12]. The total number of events N_t is the sum of the source (pulsed) events N_s and background (unpulsed) events N_b. The *probability* that noise fluctuations produce a certain search power P_o is *exponentially* related to the power: $\mathrm{Prob}(P \geq P_o) \propto \exp(-P_o) N_{\mathrm{trials}}$, where N_{trials} is the number of independent trials searched. N_{trials} is proportional to the range of f and $\dot{f}$ searched, but more importantly, to T_{view}^3.

In general then, to optimize search sensitivity, we want large N_s to maximize P, yet a relatively short T_{view} (appropriate for the limits discussed in the last section) to reduce N_{trials} and the computational complexity. This rule exposes another problem for scanning-mode observations of pulsars: if T_{view} is increased by a factor of ∼3 to recover the events "lost" compared to a pointed observation (assuming the pulsations remain well-behaved over the longer T_{view}), a detected signal will have the same power as from the shorter pointed observation, yet the probability that the signal is significant will decrease by a factor of $\sim 3^3 = 27$ due to the larger N_{trials} searched.

Computationally, the complexity of epoch-folding searches scales roughly as T_{view}^4 (i.e. $N_t \times N_{\mathrm{trials}}$), while FFT-based techniques fare slightly better and scale as $T_{\mathrm{view}}^3 \log T_{\mathrm{view}}$. Moderate sized computer clusters can currently handle epoch-folding searches of hundreds to thousands of events for viewing periods of up to several weeks (see Figure 1). For longer T_{view} or more limited computing resources, one can use evolutionary [14] and/or heirarchical [13] techniques to greatly reduce the computational burden of coherent searches without greatly impacting the overall sensitivity, *if* the average pulsation flux is time invariant. Coherent searches with GLAST with $T_{\mathrm{view}} \lesssim 1-2$ months should be sensitive to pulsars with photon fluxes (>100 MeV) of a few times 10^{-8} to a few times 10^{-7} photons cm^{-2} s^{-1} for scanning-mode observations, or as low as $\sim 2\times10^{-8}$ photons cm^{-2} s^{-1} for pointed observations.

Finally, incoherent searches are possible where the absolute phase of pulsations is *not* tracked over the full T_{view}, but only over much shorter "windows" T_{win}. Incoherent searches are less sensitive than coherent ones for the same T_{view}, but they use many fewer computing resources and enable searches with much longer T_{view} [9, 15]. The basic idea limits the duration of the coherently processed intervals T_{win} such that a signal with any reasonable $\dot{f}$ or $\ddot{f}$ stays within a single independent frequency bin (of width $1/T_{\mathrm{win}}$ Hz) or fraction thereof. These windowed analyses are then combined without phase information, but with corrections for $\dot{f}$ and/or $\ddot{f}$ effects occurring between the intervals, and analyzed. Initial simulations show that one might detect *relatively stable pulsars* with photon fluxes (>100 MeV) as low as $1-2\times10^{-8}$ photons cm^{-2} s^{-1} with $T_{\mathrm{view}} \sim 1$ yr and $T_{\mathrm{win}} \sim 1$ day. Without phase information, however, the folding of all events over such long durations to accumulate high-quality pulse profiles may be difficult or even impossible.

In summary, instabilities of young pulsars, source positional uncertainties, and the default survey/scanning mode for the mission will make blind pulsation searches with GLAST much more difficult than early estimates had predicted. It is therefore likely that GLAST will blindly discover only tens of new pulsars rather than hundreds.

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