Enhancing the Pulsation Sensitivity of the Fermi LAT

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We present a new spectroscopy-based search technique offering on average 50% increased sensitivity to pulsed signals relative to current methods.

Abstract

The overlap between the populations of radio-loud and GeV-bright pulsars is one of the key observables in the effort to understand high-energy emission from pulsar magnetospheres. The Pulsar Timing Consortium is timing over 200 high-luminosity pulsars to produce ephemerides with which Fermi LAT photons may be folded to search for pulsations, and over 25 radio-loud pulsars have been detected so far. However, pulsars clustered along the Galactic plane suffer from the strong diffuse background at low Galactic latitudes and from source confusion, and the pulsed signal may be obscured. On the other hand, millisecond pulsars at high Galactic latitude are generally weak GeV sources, and it is important to maximize the pulsed signal. We propose a pulsation search utilizing spectroscopy to help discriminate between photons associated with the pulsar and the background. We outline the method, examine its validity, and assess its performance on known pulsars. We present preliminary results of a pulsation search of a few promising candidates, and we briefly discuss future applications.

Background and Motivation

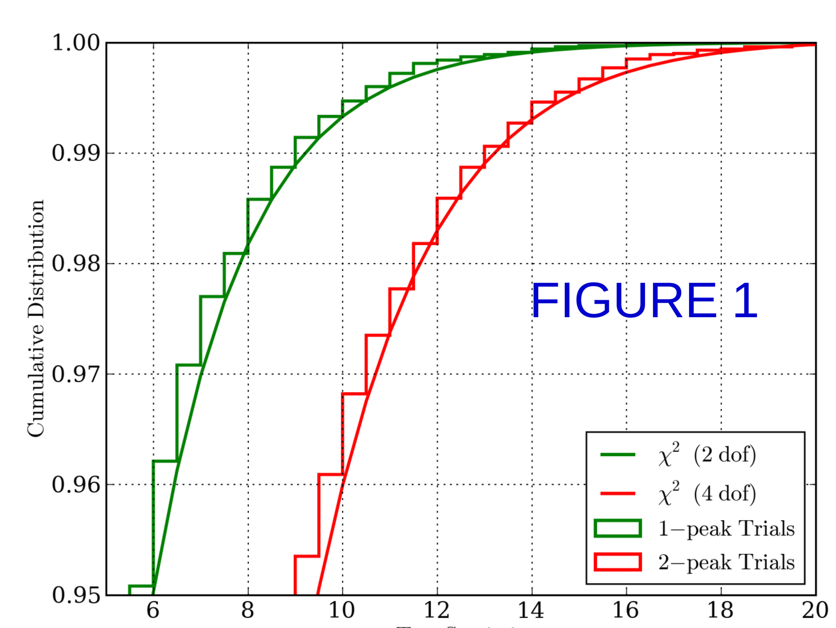
To increase signal-to-noise ratio (SNR), the pulsation searches employed by the LAT Collaboration—e.g., in the first LAT pulsar catalog [1]—apply deep cuts to the data, incurring signal loss. Tuning such cuts to maximize the significance incurs trials factors.

An alternative to cuts is to **weight** each photon with some estimate for the probability that it comes from the pulsar rather than the background, and spectroscopy provides a natural estimator. One models all emission—including the putative pulsar—in the region of interest (ROI) and folds this model through the instrument response function, finally fitting model parameters via maximum likelihood. This forward folding is precisely the procedure employed by the *gtlike* [2] and *ptlike* [3] spectral analysis tools, and generally the output of one of these tools forms the input to the pulsation search outlined below.

A New Statistic

The proposed pulsation search also follows a likelihood approach and simply incorporates the parameterized light curve f(φ) of the pulsar into the emission model for the ROI. The spectrum furnishes the weights w_i, defined as the ratio of signal to background ($0 < w_i < \infty$) for each photon. After some simplifications, the resulting test statistic (TS) is, with the sum over all photons in the ROI,

$$\mathrm{TS} = 2\sum_{i=1}^{N_\gamma} \ln \frac{1 + w_i \times f(\varphi_i)}{1 + w_i}.$$



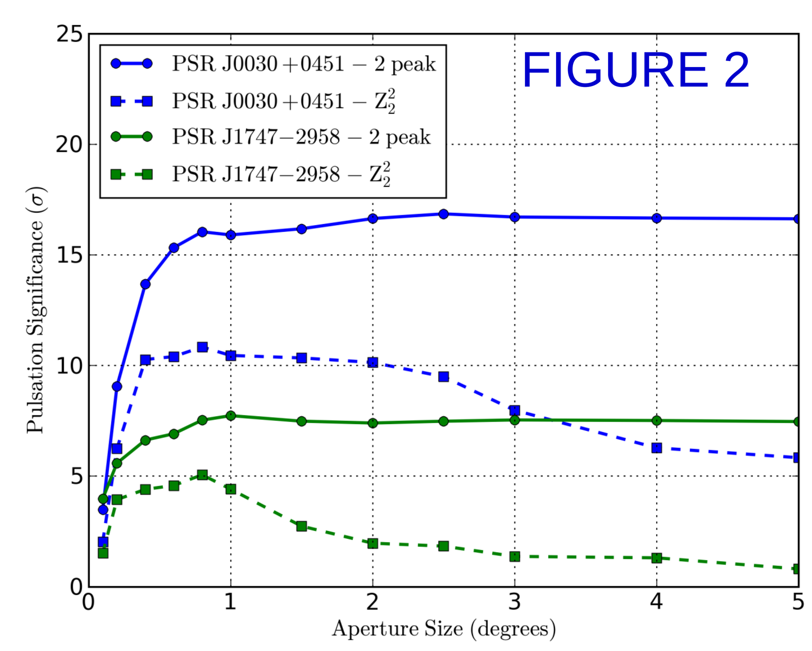
Calibration

In order to calibrate the TS, we pick profiles that allow us to apply Wilk's Theorem. An *n*-gaussian profile—that is a sum of *n* gaussians each with normalization fixed to 1/*n*—satisfies the requirements. If the TS is maximized with respect to the position and width of each of the gaussians, then with enough events the TS is distributed as χ^2 with 2*n* degrees of freedom.

To verify this expectation, we performed 10,000 Monte Carlo trials in which the phases for a collection of photons from PSR J0030+0451 were randomized and a 1- and 2-gaussian profile fit. **Figure 1** shows that the resulting TS distribution follows the expected null distribution. **In all results, we use *n*=2 profiles, which were generally superior to the *n*=1 profile** (see **Figure 5**).

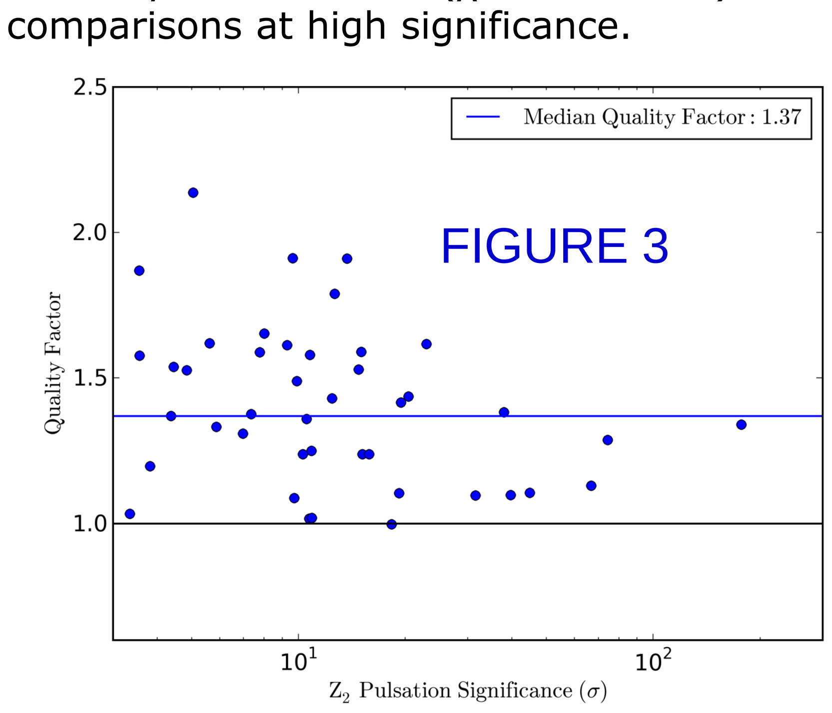
Cut Independence

A drawback of the existing method is the strong dependence on the SNR of the data selected. In the proposed method, photons inconsistent with emission from the pulsar naturally have a low weight and do not affect the TS. It is then advantageous to maximize the signal with a large ROI, limited essentially by computation. Thus, **there is no need for tuning or trials factors with the new method**. To demonstrate this, and to determine the maximum useful aperture size, we compare the new method and the Z^2 test in **Figure 2**, showing the significance as a function of aperture size for two pulsars from the pulsar catalog: PSR J0030+0451, which has a high SNR, and PSR J1747-2958, sited in the Galactic plane, with a low SNR. While the Z^2 significance peaks at a particular aperture size, the new method significance increases monotonically. Similar robustness holds for energy cuts.



Testing on Known Pulsars

We repeated the significance analysis performed for the first LAT pulsar catalog [1]. Using the data sets and timing solutions as outlined in that paper, we calculated the significance with a variety of methods. We selected the Z^2 test [4] with two harmonics as a good representative of existing methods: it is an unbinned, powerful omnibus test, and its analytic calibration (χ^2 with 4 dof) allows comparisons at high significance.



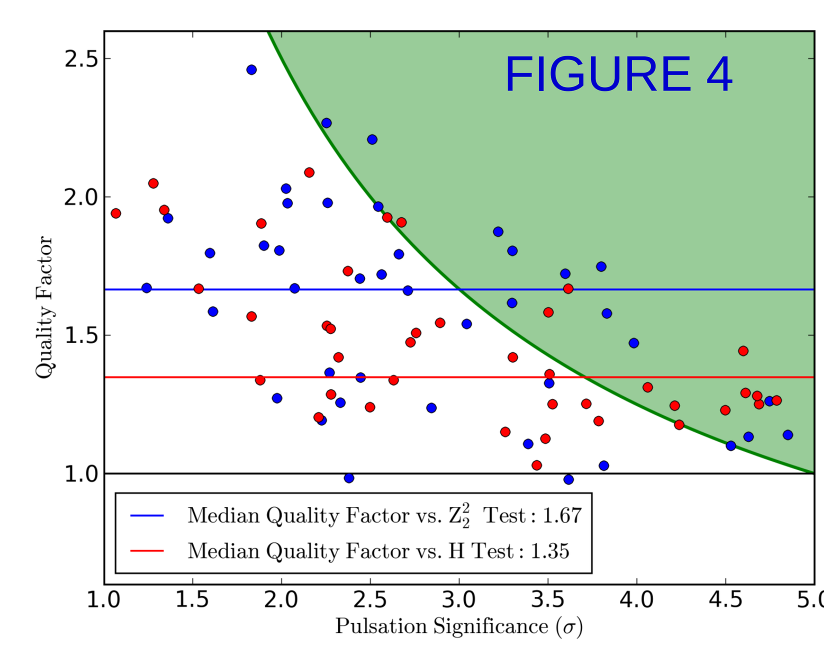
We use a 2-peak profile to fit the data and in **Figure 3** report the **quality factor, defined as the ratio of the significances**, against the Z^2 significance. It indicates the fractional increase in sensitivity, and **a value >1 indicates that new method is better**.

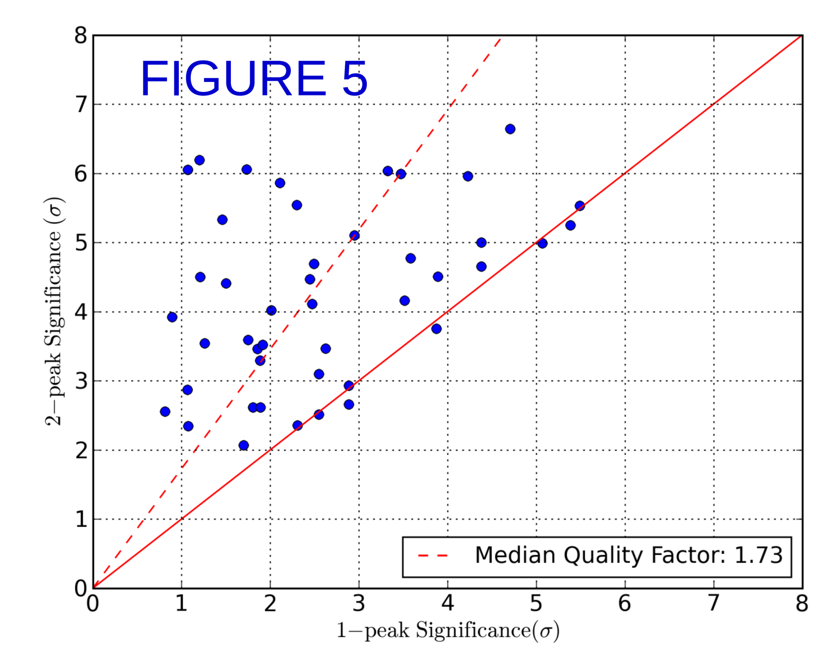
Performance at Low Significance

Although the proposed method increases the significance of the known pulsars by about 40%, real benefit comes if the new technique can generate detections that would otherwise lie below threshold. That is: **does the new technique improve low significance results?**

To dilute the significance of the known pulsars, we took random sets of photons (again using the data sets described in [1]) from a selection of 10 pulsars divided such that the expected significance for the subsets fell roughly at 1, 2, 3, and 4 sigma. Each pulsar furnished 3-10 independent sets at these significant levels, and the results from these sets were averaged. Thus, each parent pulsar provided 4 statistically independent realizations of low significance pulsars.

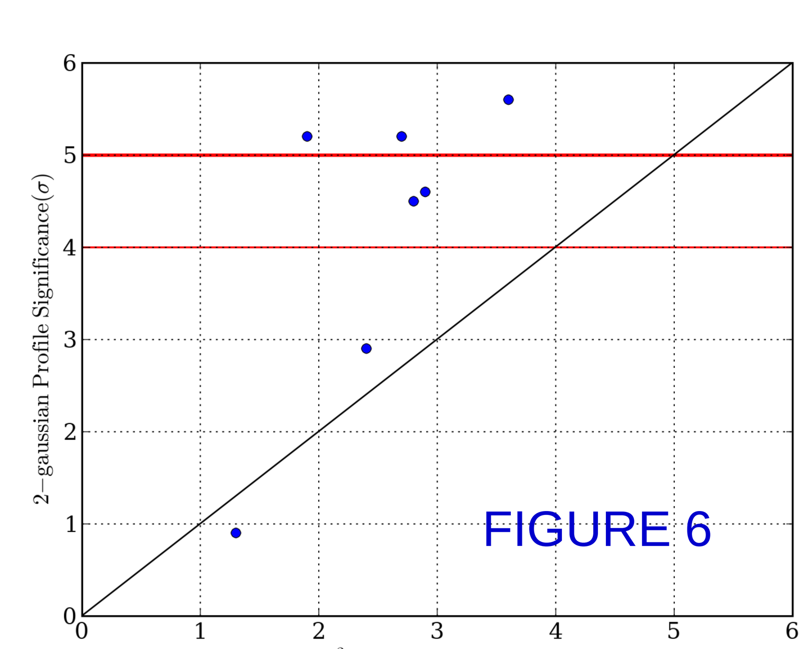
Figure 4 shows the quality factor, for the Z^2 test (blue) and the H test [4] (red) along with a green shaded "detection" region indicating that the application of the new technique yields a value of >5 sigma. **In nearly all cases, the new technique is superior, with a increase in sensitivity of 50%.**





Results from Initial Trials

Drawing from a preliminary version of the 1FGL catalog, we checked the method on a handful of sources spatially coincident with known radio pulsars. We prepared data sets with the longest possible baseline for which we had good timing solutions (details available). For comparison with existing methods (Z^2 and H-test) we used a 1-degree extraction radius and applied the energy-dependent cut outlined in [1]. We measured the spectra with *ptlike* and calculated the TS for a 2-gaussian profile using the same photons as for the Z^2 and H test. **Of the 7 pulsars tested, pulsations were detected in 5 at >4σ and in 3 at >5σ.** The Z^2 test is shown in **Figure 6**. H-test significances were lower than Z^2 for all but one pulsar. The high yield from this small trial is very promising.



Future Work

We will expand the trial outlined at left to **all** of the radio-loud pulsars for which we have valid timing solutions. We expect this study to yield many new detections and potentially new classes.

The 2-gaussian form presented here is overly restrictive and is not optimal for all pulsar light curves. We plan to explore the performance of using the spectroscopic photon weights in some of the statistical tests presented here, although such modified tests will require Monte Carlo calibration.

Finally, we are expanding the method to blind searches. We have already successfully adapted the likelihood formulation presented here to searches for X-ray binaries and are actively working on the extension to blind searches for pulsars. In each case, we hope for similar increases in sensitivity with the inclusion of spectral information.

References

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