A Time Differencing Technique for Detecting Radio-Quiet Gamma-ray Pulsars

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Difficulties with Blind γ-Ray Pulsar Searches

- Very low photon flux: many pulsation periods generally separate successive photons
- Long observation time *T:*
  - Large FFT of $f_{max} \times T$ frequency bins required.
  - Unknown frequency derivatives (and even second derivatives) have a large impact on the analysis.
  - Timing noise, prevalent in young pulsars, can compound or render impossible such analyses.
  - Glitches in the pulsar rotation may occur during the viewing period.

- See Scott Ransom's talk on Tuesday (Session 4.3).

Published Analysis Used for EGRET

- Chandler, et al., ApJ 2001, 556, 59.
- Correct photon arrival times for frequency drift:

$$t_i = \tilde{t}_i + \frac{1}{2}\frac{\dot{f}}{f_0}\tilde{t}_i^{\,2}$$

Step over successive guesses for the ratio $\frac{\dot{f}}{f_0}$

- Calculate the power spectrum from a DFT (using FFT algorithm):

$$F_\ell = \sqrt{2/N_\gamma}\sum_{j=0}^{N-1} a_j e^{-i2\pi\ell j/N}$$

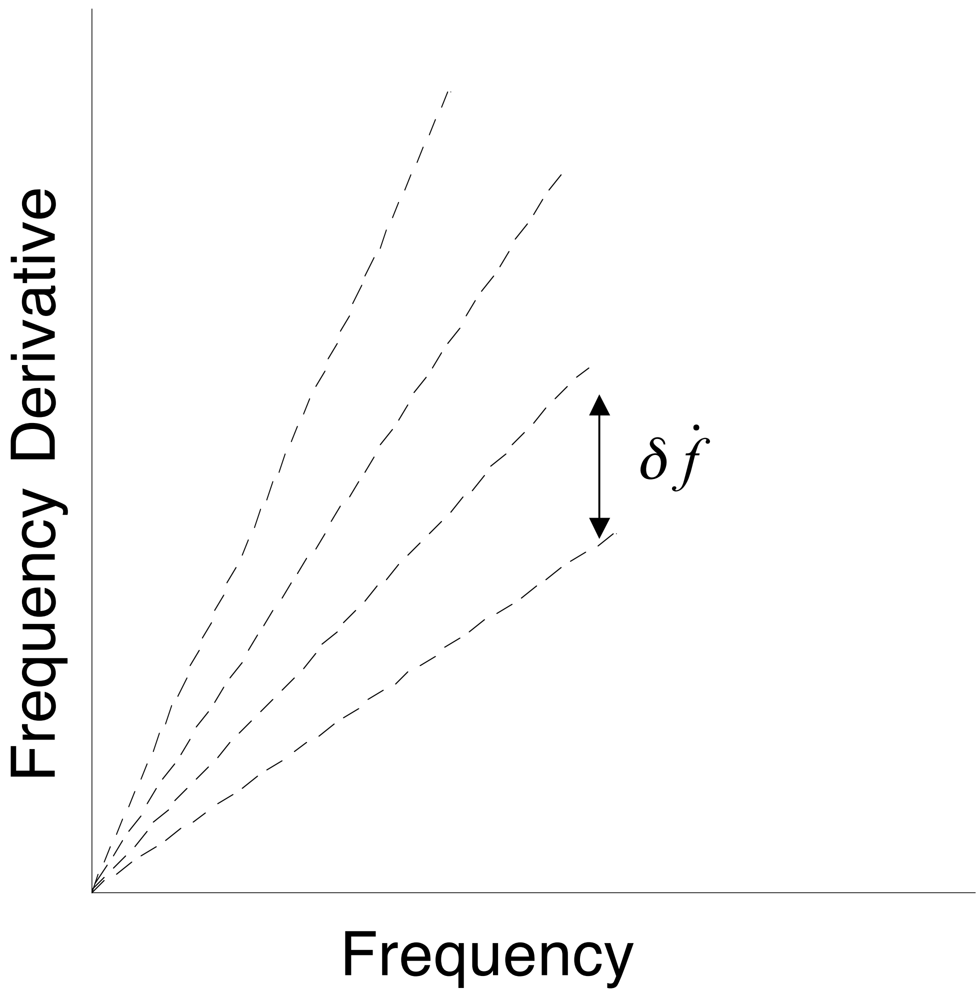
a_j is the # of photons in the jth bin

(Billion-point FFTs executed on a supercomputer.)

- Look for candidate peaks in the power spectra. $|F_\ell|^2$
- Refine the candidates by searching more finely in the surrounding f, f-dot space.
  - (The initial search, using FFTs, dominates the computing requirements)

(Throughout, all times are assumed to be already barycenter corrected.)

Scanning the f, $\dot{f}$-dot space.



Step over successive guesses for the ratio $\dfrac{\dot{f}}{f_0}$

Each frequency derivative trial samples a line passing through the origin.

The step size needed for the frequency derivative gets very small for a long viewing period T:

$$\delta\dot{f} = \frac{1}{T^2}$$

And the FFT time scales as T, so the total CPU time scales as T^3.

The CPU time and memory requirements become prohibitive for long viewing periods!

Stacked FFT Method

- Divide the viewing period T into N_W equal intervals.
- Do an FFT and calculate the power spectrum in each interval.
- Add ("stack") the power spectra incoherently.
- Search for, and refine, peaks as before.
- Advantages:
  - Core memory requirement reduced by $1/N_W$.
  - Only a very modest reduction in calculation for a given f-dot, since the FFT scales as $n \cdot \log(n)$.
  - But the requirement on frequency derivative steps is relaxed to

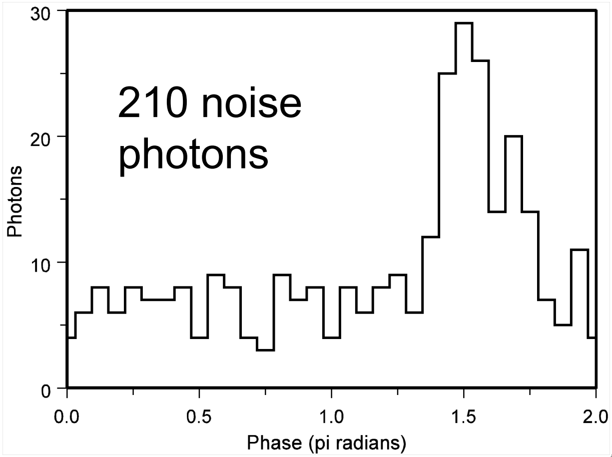
$$\delta \dot{f} = \frac{N_W}{T^2}$$

- Disadvantage: some loss of sensitivity from not taking advantage of coherence over the full time period, but
  - This is mitigated by the reduced number of f-dot trials.
  - The coherence may not be there anyway, due to timing noise and glitches.

Time Difference Method

- Choose a time window equal to T/N_W (similar to stacking).
- For each photon, calculate the differences between its time-of-arrival and those of all succeeding photons, up to a maximum time difference equal to $T/N_{W.}$
- Bin the time differences and calculate their FFT.
  - Note that for N_W=1 the real part of this FFT is equivalent to the power spectrum of the Chandler et al. analysis.
  - The imaginary part also tends to contribute to a periodic signal in case the f-dot correction is inexact.
- Advantages:
  - Only 1 FFT of length $f_{\max}\times T/N_W$ is done, instead of N_W FFTs of the same length (stacking) or 1 FFT of length $f_{\max}\times T$.
  - The same advantages as the stacking method with respect to memory requirements and f-dot step size.
  - No loss of sensitivity compared with the stacking method (next slide).
- Disadvantages: the same comments as for the stacking method.

MC Test of the Time-Difference Method



Generate Poisson noise plus signal photons from a single peak in a phase plot (at left), including a frequency first derivative.

Find for each method the number of signal photons needed to make a 95% C.L. detection

TABLE 1

COMPARISON OF FOUR METHODS

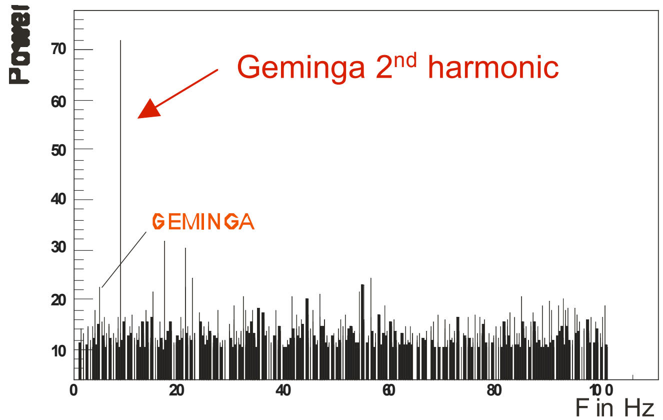
Parameter	M1 Full FFT	M2 Stacked	M3[a] T. Diff. Re	M4[b] T. Diff. Re and Im
No. of FFT bins	4,194,304	262,144	262,144	262,144
95% C.L. power	36.4	90.0	127	100
Min. signal γ, $\dot{f}$ exact	81.8 ± 0.3	111 ± 3	98 ± 2	100 ± 2
Min. signal γ, $\dot{f}$ high	88.6 ± 0.7	114 ± 4	112 ± 4	108 ± 3
Assumed error in $\dot{f}$ (%)	0.3	4.5	4.5	4.5
Relative CPU time	19.2	14.8	1	1

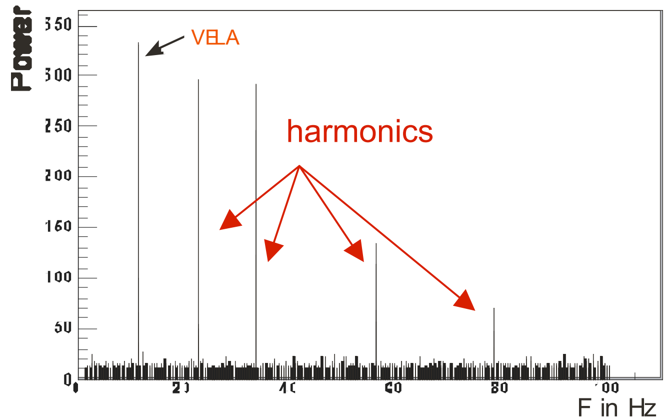
The sensitivity of the time-difference method beats the stacking method and is only slightly less than for the full FFT (*not* yet accounting for f-dot trial factors.)

W.B. Atwood, M. Ziegler, R.P. Johnson, B. Baughman, ApJ Lett. 2006, 652, 49.

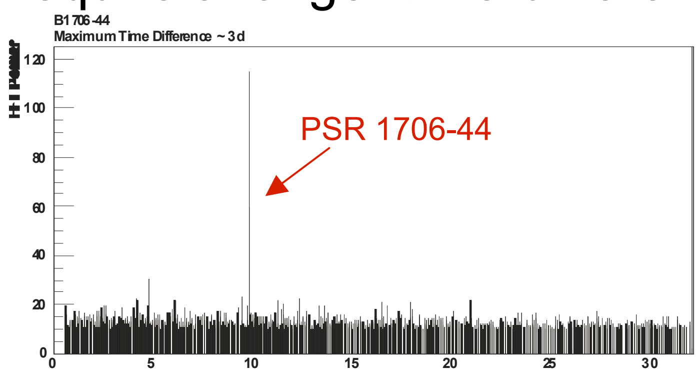
Blind Searches in EGRET Data

The bright pulsars Vela and Geminga can be found using a time-difference window of only 3 hours. No scan in the frequency derivative is needed. The time to calculate the FFT is only about 1s.





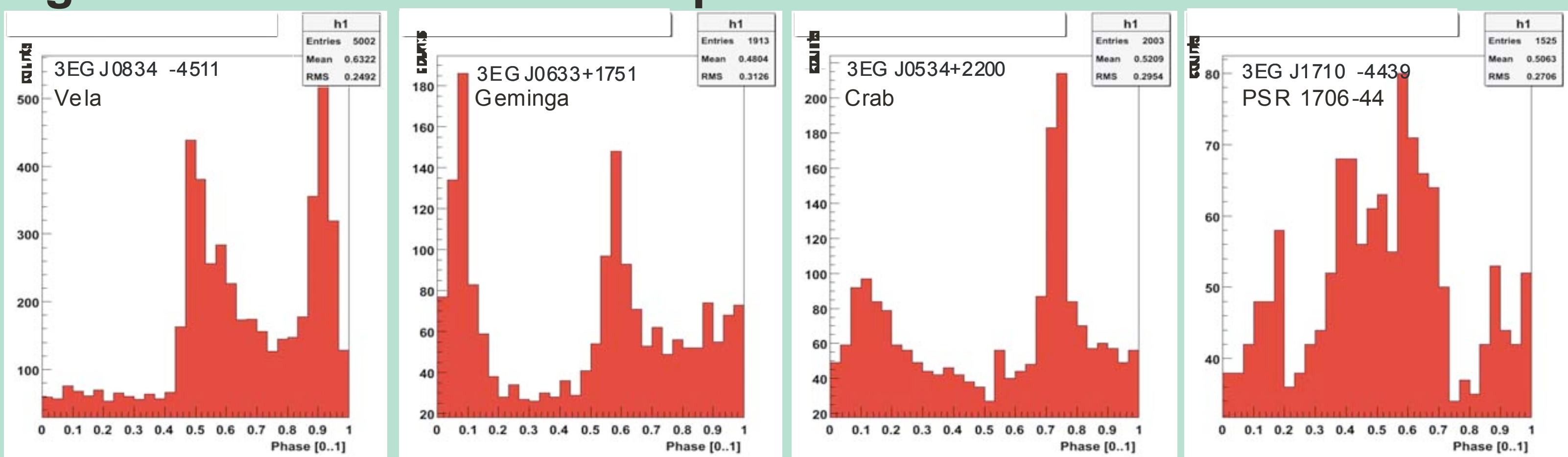
Pulsars with a large spin down rate like the Crab pulsar require a scan in the frequency derivative. Faint pulsars like PSR 1706-44 require a longer time-differencing window (e.g. 3 days).



See poster P14.33. M. Ziegler et al., Searching for Radio Quiet Gamma-ray Pulsars.

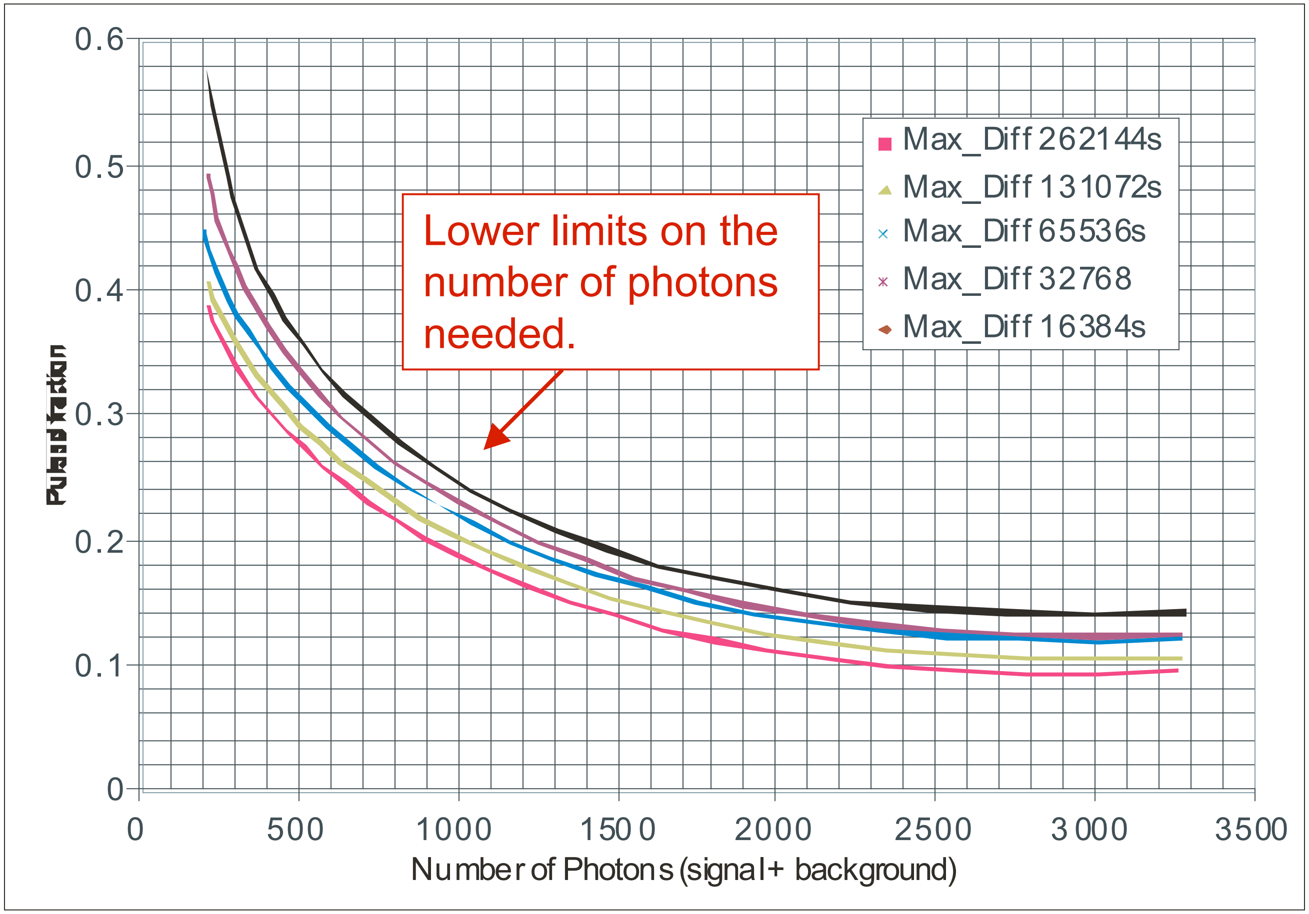
Below are the light curves of four EGRET pulsars found in the blind-search scan. The scan was performed on the positions given in the 3EG catalog (3° radius). In each case, the photon arrival times were folded into phase plots according to the frequency and *f*-dot found in the scan.

Lightcurves of known EGRET pulsars found in the scan

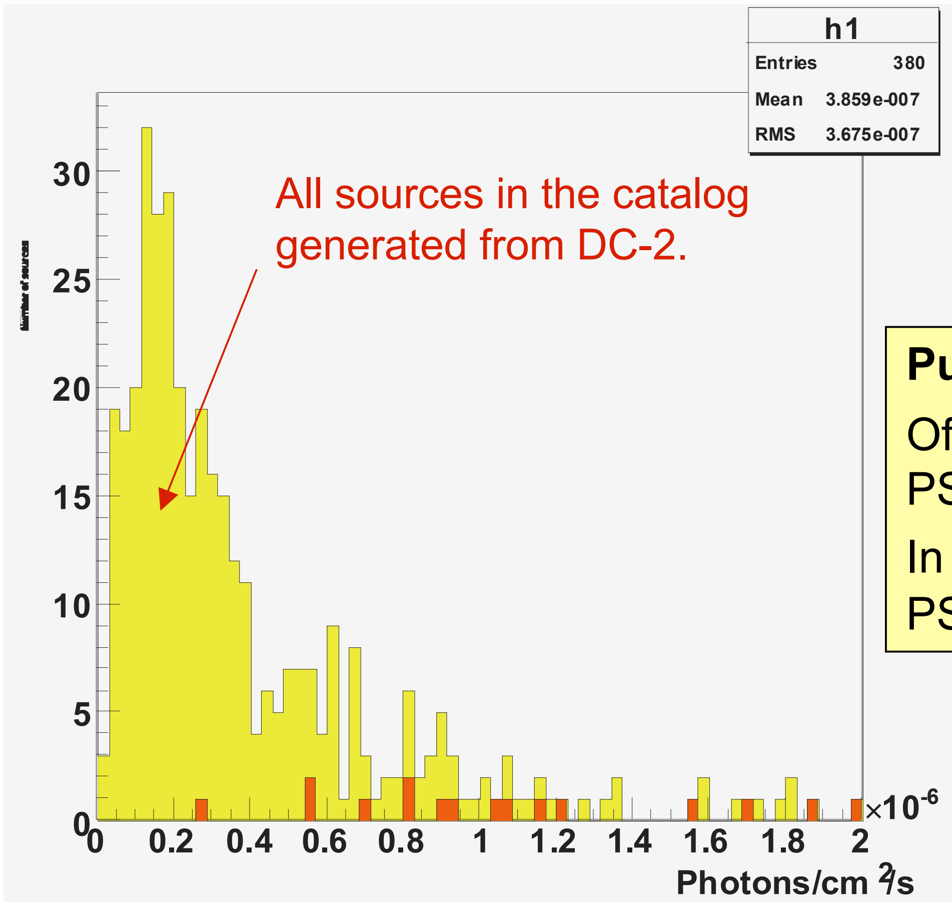


Several additional pulsar candidates with fairly good significance were found. The evaluation of those pulsars is still in progress. We probably need to wait for GLAST to determine whether they are real.

- Lower limits on detection at 95% C.L. for a 14-day viewing period, using 5 different time-difference windows.
- The trial factor is taken into account when calculating the significance.



Search through simulated GLAST data (DC-2)



Pulsar with lowest flux:

Off plane (b=11.9):
PSR_J1852m2610 **flux 3×10^{-7} Ph/cm^2/s**

In plane (b= –0.9):
PSR_J1856p0113 **flux 7×10^{-7} Ph/cm^2/s**

16 radio-loud and 3 radio-quiet pulsars were found.

Conclusions

- The time-differencing method shows excellent promise for blind pulsar searches with GLAST data.
- The method provides an economical way to study very long viewing periods (e.g. a year) while minimizing sensitivity to frequency derivatives and timing noise.
- The method has been tested on EGRET data and GLAST DC-2 simulated data and has performed well, detecting known EGRET sources plus some interesting new candidates.