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## Radio Pulsar Timing for Fermi: The Second Half-decade

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### 1. Introduction

The *Fermi* Pulsar Timing Consortium (PTC) can be proud: we achieved both of the goals that we established before launch, which were 1) to not mess up the “obvious, guaranteed” science foreseen for CGRO-like pulsars, and 2) to remain as open as possible to the discovery potential of the LAT’s high-sensitivity all-sky survey (Smith & Thompson 2008a,b; Smith et al. 2008). The good working relation established between PTC and the LAT team smoothed the way for the successes of the Pulsar Search Consortium (PSC), including discovery of some of the faintest-ever radio signals from some blind-search pulsars (e.g. Pletsch et al. 2012), and use of the LAT’s “treasure map” of unidentified, steady sources to significantly increase the number and variety of known millisecond pulsars (Ray et al. 2012).

Now, after five years on orbit, with the Second *Fermi* Pulsar Catalog behind us (2PC, Abdo et al. 2013), and with 148 gamma-ray pulsars in the bag, it’s time to update our timing strategy. This document will mostly discuss target lists, but will also briefly address author lists. The 15 December 2013 Parkes proposal deadline is our goal, with the 5 November 2013 Nançay deadline being good preparation.

### 2. What we’ve been looking at so far

The PTC agreement was to time all possible pulsars with spindown power  $\dot{E} > 10^{34}$  erg s<sup>−1</sup>. The ones that ultimately got timed are shown as green, red, and black symbols in Figure 1. The number of gray dots (ones we haven’t gamma phase-folded) above  $10^{34}$  is small. For most, some good reason explains why we ‘missed’ it. “All\_gt1E34unfolded” lists them<sup>1</sup>. Table 1 summarizes the different lists of pulsars.

PTC later agreed to share as many non-MoU ephemerides as possible with the LAT team:

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<sup>1</sup>The longer lists of pulsars discussed in this memo will be files attached to <https://confluence.slac.stanford.edu/display/GLAMCOG/Year+6+Pulsar+Timing>. If you can’t get them, ask one of the authors to send you a .tar file. Links there to “Timing” and “Year 2 Timing” are worth reading.

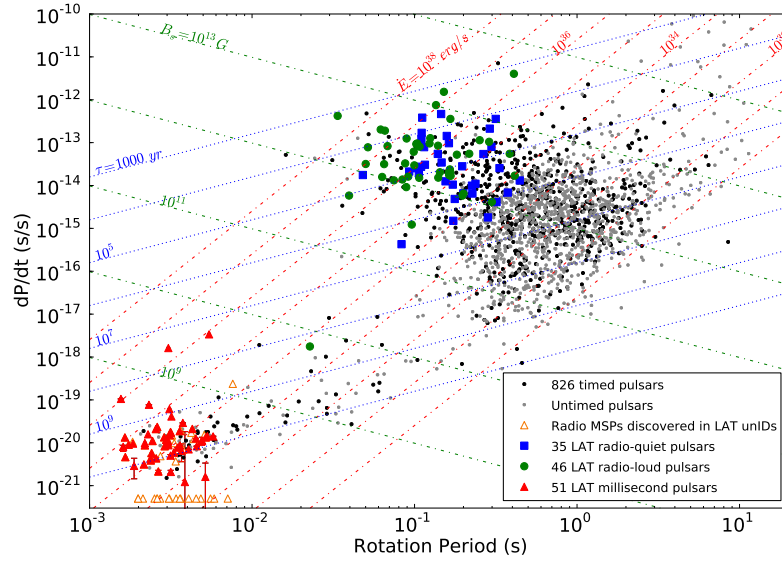


Fig. 1.— The rate of period increase  $\dot{P}$  vs. rotation period  $P$  for pulsars outside of globular clusters. Large colored markers show the 132 publically announced gamma-ray pulsars, of the 148 detected, including over half of the 59 pulsars discovered by the PSC, as of Oct 2013. “Timed” means that we phase-folded the gamma-rays using a radio or X-ray rotation ephemeris, but gamma pulsations were not seen. The  $\dot{P}$  uncertainties visible for some MSPs come from the Shklovskii correction. New MSPs for which the spindown rate is unavailable are plotted at  $\dot{P} = 5 \times 10^{-22}$ .

these appear as the six hundred or so black dots with  $\dot{E} < 10^{34}$  erg s<sup>-1</sup> in Figure 1. Thus, we have discovered that the gamma-ray deathline for young pulsars is about 10x lower than what we thought from EGRET ; and apparently another 10x lower for MSPs (Guillemot & Tauris 2014). We have also, alas, been able to confirm the prejudice that if any old, low-power pulsars emit gamma rays, that they are not bright, or not common, or neither. The spreadsheet file “results\_wSearchPulsation.xls” contains the results of Lucas’ phase-folding for most of the > 800 black, green, and red dots.

“As many as possible” is highly latitude-dependent, as illustrated in Figure 2, right-hand panel. In the northern sky, roughly half of the  $\dot{E} < 10^{34}$  erg s<sup>-1</sup> pulsars have been folded. LAT does not have ephemerides for the other half<sup>2</sup>. Nançay. Westerbork and Urumqi round out the TOA samples for some pulsars. (Nothing from Effelsberg?) In the Parkes’ sky, nearly none of the  $\dot{E} < 10^{34}$  erg s<sup>-1</sup> pulsars have been gamma phase-folded.

GBT and Arecibo provided timing for some key, interesting, radio weak pulsars earlier in the mission, no longer necessary on a routine basis: either they are now timed by the LAT, or remain undetected by the LAT. Similarly, a few PTC members were devoted to providing Xray ephemerides to the LAT team. Except for Geminga, none of these were detected, and in the future can probably be studied on a case-by-case basis.

### 3. What to look at in the future

MSP minimum observed  $\dot{E}$  for gamma emission keeps going down. We should phase-fold them *all*, regardless of prejudice: science arguments abound. “UnfoldedMSPs” lists the millisecond gray dots. Umpteen are visible only from Parkes.

There are far too many young “boring” pulsars to time them all, especially in the South. We now list a series of guidelines that can help us pick which to time.

- “HighEdotNeverSeen” lists the  $\dot{E} > 10^{34}$  erg s<sup>-1</sup> for which, after 5 years of devoted phase-folding, no hint of pulsations or DC emission has been seen. From the LAT’s point of view, we could stop timing these, to free up radio telescope time. Parkes may wish to continue monitoring them for other Science goals.
- “ParkesTimesNorth” lists pulsars that Parkes times, that are accessible by the Northern telescopes. In 2009, Simon suggested dropping these. It doesn’t seem to have happened, possibly due to those ‘other Science goals’. Well?

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<sup>2</sup>We believed that Andrew Lyne at JBO tries to time all northern pulsars, and intended to share the timing solutions for all that he times with the LAT team. A quick look at the 400 or so ‘missing’ northern pulsars in ATNF suggests that they have  $S_{1400} < 0.5$  or so, so perhaps many are too weak for routine timing at JBO.

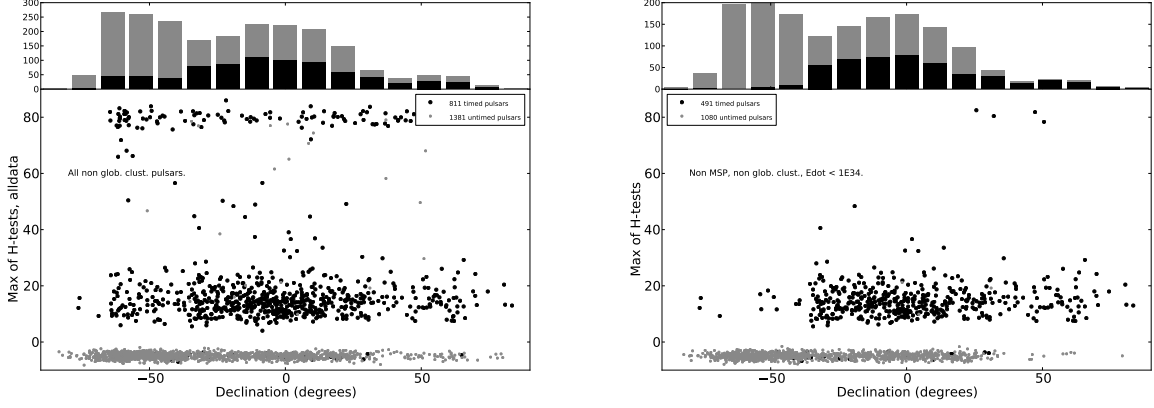


Fig. 2.— Maximum of  $\leq 4$  H-test values versus pulsar declination. For clarity, large maxima are smeared to  $80 \pm 2$ , and unfolded pulsars are smeared at  $-5 \pm 1$ . The four values use either 5 years of LAT data ; or only the ephemeris validity interval ; and either the value at the end of the interval; or the peak during the interval. H-test is not corrected for the 855 trials over the “cookie-cutter” energy and angular radius cuts. Left: All field pulsars. Right: Only low power, non-recycled pulsars. Is it true that *half* of the northern pulsars aren’t folded after all?!

Table 1: Summary of the pulsar lists. The files are attached to <https://confluence.slac.stanford.edu/display/GLAMCOG/Year+6+Pulsar+Timing>.

File name	Purpose	$\dot{E}$ cut	Decl cut	How many
All_gt1E34unfolded.txt	99.7	1180.		
results_wSearchPulsation.xls	299.0	6.11		
NorthNotFolded.txt	163.2	160.		
SouthNotFolded.txt				
MSPsNotFolded.txt				
HighEdotNeverSeen.txt				
DeathlineProbe.txt				
WeakCloseHiLat.txt				

- “DeathlineProbe” focusses on the  $10^{33} < \dot{E} < 10^{34}$  erg s<sup>-1</sup> range, in order to study whether the gamma-ray deathline is gradual or sharp. Figure 1 shows many (NNN) gray dots in the zone.
- “WeakCloseHiLat” aims to increase the number of black dots amongst the overall population. Latitude and distance cuts favor reasonable gamma signal-to-noise even for low luminosity. Gamma-ray detection of the low spindown power pulsars is a worthwhile longshot (Hou & Smith 2013). If we favor high S1400 pulsars to make life easier for the radioastronomers, will that introduce an unwanted beaming bias? Matthew started listing archival Parkes observations of some of these, and was starting to think about sky temperature.
- “Interpulsars” lists the handful of young radio interpulse pulsars. Fermi currently detects three. Since their geometry is particularly well-studied using RVM-like approaches, we may want to explore more of them. There’s so few, maybe a table instead of a file. The ones we haven’t seen are low edot, low b, far, uninspiring.
- “CatalogCoincidences” lists pulsars that fall within the error ellipse of weak (TS> 10) 4-year LAT sources. We could time all or some of these (e.g. the ones with the highest  $\sqrt{\dot{E}/d^2}$ , or ones with not-too-small latitude  $|b|$ , et cetera).

Dave, review the plots and lists and text you made for Matthew. Integrate Matthew’s search of the Parkes observation archives, along with his comments about S1400 (and sky temperature).

Review also the old Timing confluence pages – they’re actually really good and worth reading.

Blabla about faint PC emission, where you favor low beta (the Hou & Smith (2013) is probably good enough, not that I expect this note’s busy readers to then go look that up). Could narrow radio beam be an FoM? Unless you mean wide! Probably not solid enough to merit cuts.

Why would you cite “unmodulated” in *this* document? List the coincidences with DC sources.

When you’re done, need an ‘OR’ of your lists, as a proposition.

Add figure of HTS vs FoM here.

#### 4. Author lists

The MoU lists observatory PI’s as the ‘responsible person’ for each pulsar, and Patrick Weltevrede as the overall coordinator. We thank Patrick for leading this effort during the early years. More recently, Lucas Guillemot has taken over. We propose to make that Official.

We further propose significant pruning of the PTC list that the LAT team uses to generate the emailings leading to sign-in on the author lists for PTC papers. The GBT, Arecibo, and Xray efforts that were so important in 2009 are essentially over. Studies of specific pulsars not in the list

we propose should be organized outside of the PTC. The updated author list will favor the people at the key radiotelescopes who actively participate in the observations and data reduction.

Perhaps we’ll end up writing that list of names down in this space at some later time? Or not?

As stated in the introduction, PTC has been working great and we certainly don’t want to spoil that! We will circulate this memo to the PTC *and* the PSC, so as not to leave out anyone willing and able to contribute timing solutions for large numbers of pulsars. We hope that the new, improved PTC will be people involved in the timing of many putatively boring pulsars. The LAT team encourages and welcomes cooperation with people working on specific projects, so if you’re not a part of this specific timing campaign you can still write great papers with us.

Thus, we suspect that consensus will mainly be with the PI’s from the large radio telescopes, who will speak for their groups.

## REFERENCES

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Table 2: Proposed new target lists.

Category name	Purpose	Cuts	N pulsars
South (= Parkes)			
$\dot{E} > 10^{34}$ erg s $^{-1}$			
Interpulse			
Deathline			
Fermi co-location			
Other $\dot{E} < 10^{34}$ erg s $^{-1}$			
North			
$\dot{E} > 10^{34}$ erg s $^{-1}$			
Interpulse			
Deathline			
Fermi co-location			
Other $\dot{E} < 10^{34}$ erg s $^{-1}$			