Extending the event-weighted pulsation search to very faint gamma-ray sources

P. Bruel (LLR-CNRS/IN2P3-Ecole Polytechnique) on behalf of the Fermi-LAT collaboration
Introduction

• Following Bickel+2008, Kerr2011 demonstrated that weighting each event by the probability that it originates from the pulsar when computing \( H_{\text{test}} \) improves the pulsation search sensitivity \( (\text{gtlike}+\text{gtsrcprob}) \).

• Limitation: the spectrum of very faint pulsars can not be measured
  • \( \rightarrow \) it is not possible to compute the weights

• This talk presents 2 methods that overcome this limitation by exploring efficiently the pulsar spectral parameter space:
  • simple weights (without prior information)
  • model weights (full spatial and spectral information)

• The methods are tested on a sample of 144 LAT pulsars:
  • 117 (2PC) + 27 detected after 2PC (Hou+2014, Laffon+2014, Smith+2017)
  • Ephemerides provided by the Pulsar Timing Consortium
Simple weights: definition

2 assumptions:
- faint pulsar
- uniform background

Scan over $\mu_w$ to explore the pulsar spectral parameter phase space

Galactic diffuse spectrum + pulsar PLEC spectrum → $f(E)$ is gaussian-like (width~0.5)
Simple weights: scan

- Pulsation search = find the maximum of $P_w = -\log_{10} P(x>H_{test})$ when varying $\mu_w$, with the minimum number of trials

- $P_w(\mu_w)$ is gaussian-like around its maximum: $2<\mu<4.5$ and $0.3<\sigma<1$

6-trial algorithm:
- try 3 test values: 2, 3, 4
- try 2 test values: max $\pm$ 0.5
- try gaussian peak position defined by the 3 previous tests
- correct for the number of trials

144 psr sample

$P_s = \max_{\mu_w \text{ scan}} P_w - \log_{10} 6$
Model weights: method

- Standard binned spectral fit of the RoI centered on the pulsar (gtlike)
  - $N_{\text{pulsar}}$ and $N_{\text{total}}$ maps to derive the weights
  - one set of weight maps for each PSF event type
- Explore the pulsar spectral parameter phase space
  - $(a, \gamma)$ scan: fix $a$ and $\gamma \rightarrow$ spectral fit $\rightarrow$ find normalization
  - $\rightarrow$ compute the weights $\rightarrow$ compute the pulsation significance $P_w$

$P_w$ 90% contour looks like an ellipse:

In order to cross the 90% region, one can scan along $\gamma = -1 + 133.33 a$
Model weights: scan

- Pulsation search:
  - find the maximum of $P_w$ when varying $a$ along the “minor axis”
  - around the maximum, $P_w(a)$ is gaussian-like $\rightarrow$ 6-trial algorithm
- scan along the major axis:
  - at least two additional trials for an average gain $<5\% \rightarrow$ not useful

\[
\begin{align*}
P_m &= \max_{L_m \text{ scan}} P_w - \log_{10} 6
\end{align*}
\]

Model weights: “minor-axis” scan with 6-trial algorithm
Model weights: results

- Pulsation is detected for all 144 pulsars, including 12 with TS<25
- Compared to original Kerr2011
  - same performance on average
  - >20% gain for 8 pulsars
    - likely due to off-pulse emission
- Compared to unweighted approach:
  - >2 gain for low TS pulsars
Simple weights: results

- Pulsation is detected for all 144 pulsars, including 12 with TS<25
- Less powerful than model weights
  - -15% for the bulk of pulsars, larger loss at low TS
- Compared to unweighted approach: >~1.5 gain for low TS pulsars
Conclusions

- The simple and model weight methods are both able to detect pulsation from all pulsars, including the TS<25 ones
- The model weight method has the same sensitivity as Kerr2011
  - it can do even better when off-pulse emission is present
- The simple weight method is a little less sensitive but the loss of performance is relatively small compared to the simplicity of its implementation and its rapidity of execution (no gtlike required)
Major-axis scan

- Scanning along the major axis of the 90% ellipse:
  - compared to the a-position found in the previous step, the optimal a can be either lower or higher → at least 2 additional trials
  - relative gain is modest (<10% if the first scan crosses the 90% ellipse)
  - → for ~4-sigma pulsars, the major axis scan is not useful on average

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first scan: 6-trial algorithm
second scan: not useful
Soft-and-flat estimator

- For some TS>60 pulsars, the model weight method finds better weights than the ones obtained with the result of gtlike
- It could be explained by a significant off-pulse emission, which can have a rather soft and flat spectrum

- find a soft-and-flat estimator:
  - curvature significance ? : no, it doesn't measure the curvature itself
  - we build a simple estimator:
    \[ S = \gamma + \log_{10} E_c \quad \rightarrow \quad S_f = 0.576(\gamma + \delta\gamma) + 0.817 \log_{10}(E_c + \delta E_c) \]
unweighted Htest calib

- de Jager+1989,2010, Kerr2011 provided the asymptotic behavior $P(H>x) \sim \exp(-0.4x)$
- We ran $10^9$ MC realizations to calibrate $P(H>x)$ for small data size $N$
- $x>30$ slope parameterization
- $P(H>x)$ approximated by a double broken linear polynomial
weighted Htest calibration

- When going from unweighted to weighted Htest: \( N \rightarrow \text{sum of weights} \)
- Weighted Htest is invariant under weight global scaling \( \rightarrow \) compute \( W=\text{sum of weights under the prescription that max } w = 1 \)
- \( x>30 \) slope almost follows unweighted parameterization
- \( W \rightarrow W+5 \) works fine
Htest calibrations

Unweighted Htest:

\[
\lambda_0 = -0.398405 / \log(10) = -0.173025 \\
\lambda_1(N) = \lambda_0 + 0.0525796e^{-N/215.170} + 0.086406e^{-N/35.5709}
\]

\[
\log_{10} P(H_{20} > x) \sim \begin{cases} \\
\lambda_0 x & \text{if } x < 15, \\
15\lambda_0 + \frac{\lambda_0 + \lambda_1(N)}{2}(x - 15) & \text{if } 15 < x < 29, \\
22\lambda_0 + \lambda_1(N)(x - 22) & \text{if } x > 29. \\
\end{cases}
\]

Unweighted Htest (same as unweighted case except N \to W+5):

\[
\log_{10} P(H_{20w} > x) \sim \begin{cases} \\
\lambda_0 x & \text{if } x < 15, \\
15\lambda_0 + \frac{\lambda_0 + \lambda_1(W+5)}{2}(x - 15) & \text{if } 15 < x < 29, \\
22\lambda_0 + \lambda_1(W + 5)(x - 22) & \text{if } x > 29. \\
\end{cases}
\]