Profile Domain Timing

- The future of pulsar timing? -

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What is profile domain timing?

Traditional pulsar timing (e.g. Tempo2, TempoNest, Enterprise):

- Generate times of arrival (TOA) from time/frequency averaged data and a single (1- or 2-D) template.
- Evaluate updated timing model by refitting the TOAs.
- Susceptible to systematic errors if corrections for pulse shape variations not included.

Profile domain timing:

- Timing analysis is performed on the pulsar data itself, not the TOAs.
- Avoids systematic errors arising from profile evolution or incorrectly folded data.

Toy example based on Messenger et al. (2011):
https://github.com/mlower/project_J0437/blob/master/Alternative_method.ipynb

Past efforts

Messenger, et al. (2011):

- Proposed two methods for TOA generation: one uses search mode (single-pulse) data, the other uses folded data.
- Generates posterior distributions on pulsar signal parameters + the TOA.

Lentati, Alexander & Hobson (2015):

- Used on folded profile data.
- Profiles modelled as “shapelets (set of dimensionless basis functions).
- Accounts for variations due to additional white noise, red spin noise & DM variations.
- Easily extended to include effects from profile-modifying processes.

Lentati & Shannon (2015):

- Built upon Lentati, Alexander & Hobson (2015).
- Adds models to account for stochastic profile variations & pulse jitter.
- Uses POLYCHORD for sampling.

Lentati et al. (2017):

- Builds upon Lentati & Shannon (2015).
- Expands profiles to the frequency domain (huge parameter space).
- Likelihood evaluation sped up by interpolating over a grid of pre-computed shaplet basis vectors.
- Extremely large parameter spaces (> 1000).
- Uses either POLYCHORD or custom Hamiltonian MCMC sampling.

TempoNest2: wideband, profile-domain timing

Culmination of work presented in Lentati, Alexander & Hobson (2015), Lentati & Shannon (2015) and Lentati et al. (2017).

Key features:

- Written in Python.
- Models both temporal and frequency variations in pulse profiles (scattering, DM variations, profile evolution, jitter, etc...)
- Very large parameter spaces (~30 shapelet components, up to 1000 parameters) which require GPUs.
- Iteratively updates the timing model at each subsequent observation by fitting the Barycentred profile directly (no TOAs).

Not very well documented. Not actively being developed or maintained... (last commit Jan 18 2017)*

*github.com/LindleyLentati/TempoNest2

The future of profile timing

- What is the optimum path for performing profile domain timing?
  - Re-start development of TempoNest2?
  - Start from scratch? (follow concepts from pre-existing codes?)
  - Something else?

- Things to consider:
  - Timing on search mode data is infeasible -> huge data files, insufficient temporal resolution, low S/N per pulse, difficult to extract accelerated pulsars.
  - High dimensional parameter space -> Parallelisation? GPUs? Both?
  - Needs to still be efficient to run on non-supercomputers if it is to be widely adopted.

Hierarchical pulsar inference

- TOAs are an interface between pulse-profile analysis and timing model analysis
- What if we extended this to model all aspects of the pulse, e.g. jitter etc?

- Hierarchical inference (aka multilevel-modelling)
    - Bayesian inference extended to problems which contain a natural hierarchy
    - E.g., SATs scores (Gelman, Bayesian Data Analysis), or LIGO/Virgo Binary black-hole population properties

- **Hierarchical pulsar inference:**
    a. Analyse individual (or integrated) pulses using a shapelet formalism [Lentati et al. (2015)
    b. Treat individual pulses as a "population" about which we want to make inferences, e.g. timing-model, shape-models (as a function of time/frequency etc)
    c. Treat individual pulsars as a "population" about which we want to make inferences, e.g. gravitational-wave signals, glitches, etc

Hierarchical pulsar inference: Level a

Shapelet-based model:

$$\phi_\ell(x) = \frac{H_\ell(x) e^{-x^2/2}}{\sqrt{2^\ell \sqrt{\pi} \ell!}},$$

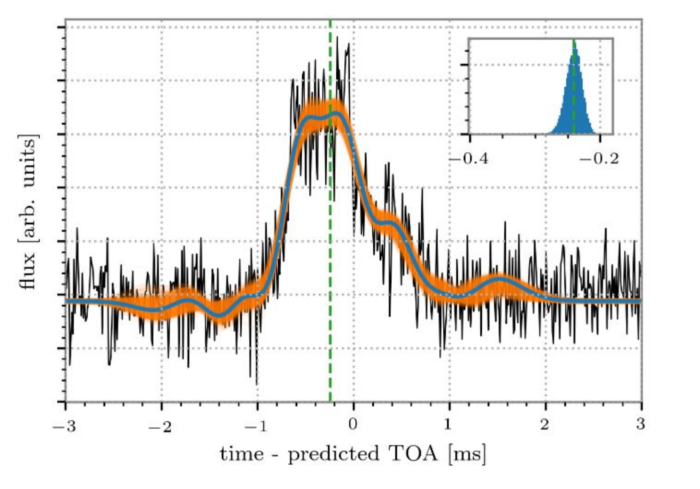
$$S(t, \mathbf{c}_i, \beta_i, \tau_i) = \sum_{\ell=0}^{n} c_i^{(\ell)} \beta_i^{-\frac{1}{2}} \phi^{(\ell)} \left(\frac{t - \tau_i}{\beta} \right)$$

Use sampling to infer the shapelet parameters

Runs in ~ 5 mins for each pulse

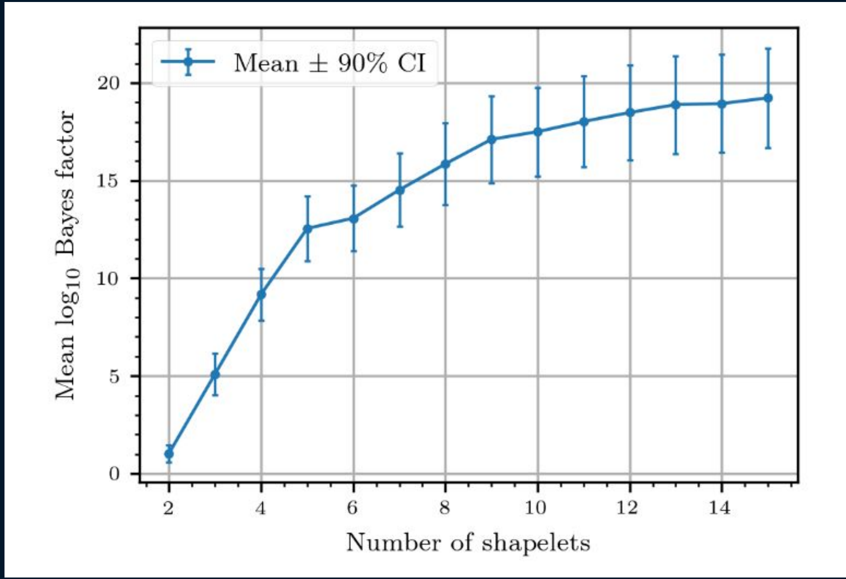
Trivially parallelizable

Results in posteriors for TOA/shape parameters which contain all the correlations between the parameters



Hierarchical pulsar inference: level a (cont)

How many shapelets?



Can apply RJMCMC/nested-sampling to estimate N, or just pick a number which is sufficiently large

Hierarchical pulsar inference: level b

At the next step, we ask questions about the first-level hyperparameters.

For example,

- A timing model is a prediction for the arrival time of the i^{th} pulse dependent on time "timing parameters"
- Given N pulses, and posteriors for their arrival times, we can infer the "timing parameters"
- Can use normal-approximations for speed or incorporate the full posterior from level a
- Can show this is formally just a generalization of the method used by Tempo2, with non-Gaussian errors allowed for the timing model

Can extend this to ask "what is the posterior on the timing parameters, including some complicated model for the pulse-profile evolution?"

Can then play the same game with level c.