Continuous gravitational wave searches with pulsar timing arrays: Maximization versus marginalization over pulsar phase parameters

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Continuous gravitational wave searches with pulsar timing arrays: Maximization versus marginalization over pulsar phase parameters

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Abstract. Resolvable Supermassive Black Hole Binaries are promising sources for Pulsar Timing Array based gravitational wave searches. Search algorithms for such targets must contend with the large number of so-called pulsar phase parameters in the joint log-likelihood function of the data. We compare the localization accuracy for two approaches: Maximization over the pulsar phase parameters (MaxPhase) against marginalization over them (AvPhase). Using simulated data from a pulsar timing array with 17 pulsars, we find that for weak and moderately strong signals, AvPhase outperforms MaxPhase significantly, while they perform comparably for strong signals.

1. Introduction

Pulsar timing arrays (PTAs) aim to detect gravitational waves (GWs) in the $10^{-9} - 10^{-6}$ Hz range. Among the most promising sources in this frequency band are Supermassive Black Hole Binaries (SMBHBs). (See [1] for a review of the current status of PTA based SMBHB searches.)

The pulsar timing residual induced by GWs from a non-evolving SMBHB crossing an Earth-pulsar line of sight depends on the so-called pulsar phase parameter. This parameter arises from the time-of-flight of a radio pulse crossing the perturbed space-time between a pulsar and Earth. For a PTA consisting of N pulsars, this leads to at least N unknown parameters in the joint log-likelihood function of all the timing residuals.

Following the Maximum Likelihood (ML) prescription for parameter estimation, the joint log-likelihood function must be maximized over all signal parameters, including the N pulsar phases. Direct numerical maximization over pulsar phases [2] is not scalable when N becomes large. A scalable algorithm (MaxPhase), where the pulsar phases are maximized semi-analytically, was proposed in [3]. (The code is available from `https://github.com/yanwang2012/RAAPTR`). This algorithm was applied to a prospective PTA in the Square Kilometer Array (SKA) era in [4]. While the above algorithms follow the Frequentist canon of maximum likelihood, an alternative approach, which is natural in Bayesian statistics, is to treat pulsar phases as nuisance parameters and marginalize over them. Maximizing the marginalized likelihood over the remaining parameters provides an *ad hoc* Frequentist estimator, which we call AvPhase. In this paper, we present a brief comparison of MaxPhase and AvPhase.

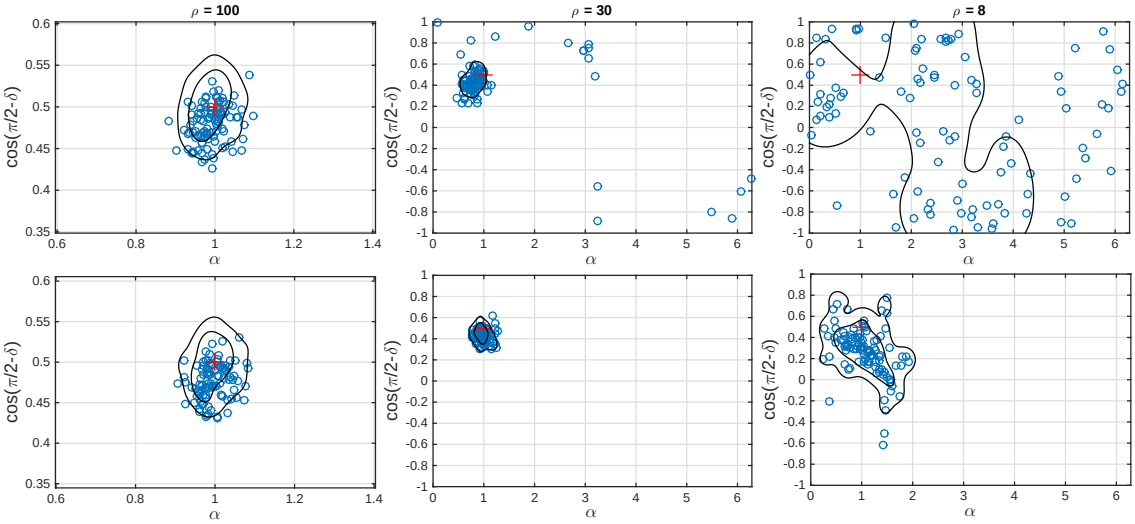

Figure 1. Estimated sky locations (circles) obtained from MaxPhase (top row) and avPhase (bottom row). A red plus sign marks the true location of the source, with 100 independent data realizations used for each location. The Right Ascension and Declination of the source are denoted by α and δ respectively. The 68% and 95% confidence contours are overlaid.

2. Results and discussion

We simulated a PTA data set with 17 pulsars which are observed for 5 years with biweekly cadence. The timing precision for each pulsar is set to be 100 ns. The strength of the GW signal is characterized by the network signal-noise-ratio ρ, which is chosen to be 100, 30 and 8 corresponding to strong, moderate and weak signal scenarios.

Fig. 1 shows the estimated sky locations of the GW source for the three scenarios. In order of decreasing ρ, the 68% (95%) confidence contours for MaxPhase cover 18 deg^2 (49 deg^2), 354 deg^2 (all sky), and 14785 deg^2 (all sky) respectively; while the corresponding ones for avPhase cover 18 deg^2 (46 deg^2), 111 deg^2 (369 deg^2), and 1162 deg^2 (3535 deg^2) respectively.

Our results show that the localization of avPhase performs significantly better than MaxPhase in the weak and moderate signal scenario, and its performance is comparable to MaxPhase in the strong signal scenario.

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References

[1] Lommen A N 2015 *Reports on Progress in Physics* **78** 124901

[2] Wang Y, Mohanty S D and Jenet F A 2014 *Astrophysical Journal* **795** 96 (*Preprint* 1406.5496)

[3] Wang Y, Mohanty S D and Jenet F A 2015 *Astrophysical Journal* **815** 125 (*Preprint* 1506.01526)

[4] Wang Y and Mohanty S D 2016 *ArXiv e-prints* (*Preprint* 1611.09440)