Resolving Galactic Binaries Using a Network of Space-Borne Gravitational Wave Detectors

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Abstract

Extracting gravitational wave (GW) signals from individual Galactic binaries (GBs) against their self-generated confusion noise is a key data analysis challenge for space-borne detectors operating in the $\approx [0.1, 10]$ mHz range. To investigate this, we use realistic simulated LISA and Taiji data containing the set of 30×10^6 GBs used in the first LISA data challenge (Radler), and an iterative source extraction method called GBSIEVER introduced in an earlier work. We find that a coherent network analysis of LISA-Taiji data boosts the number of confirmed sources by $\approx 75\%$ over that from a single detector.

Keywords: gravitational wave, data analysis, Galactic binaries, LISA-Taiji network.

GBSIEVER

GBSIEVER (Galactic Binary Separation by Iterative Extraction and Validation using Extended Range) implements an iterative scheme as follows:

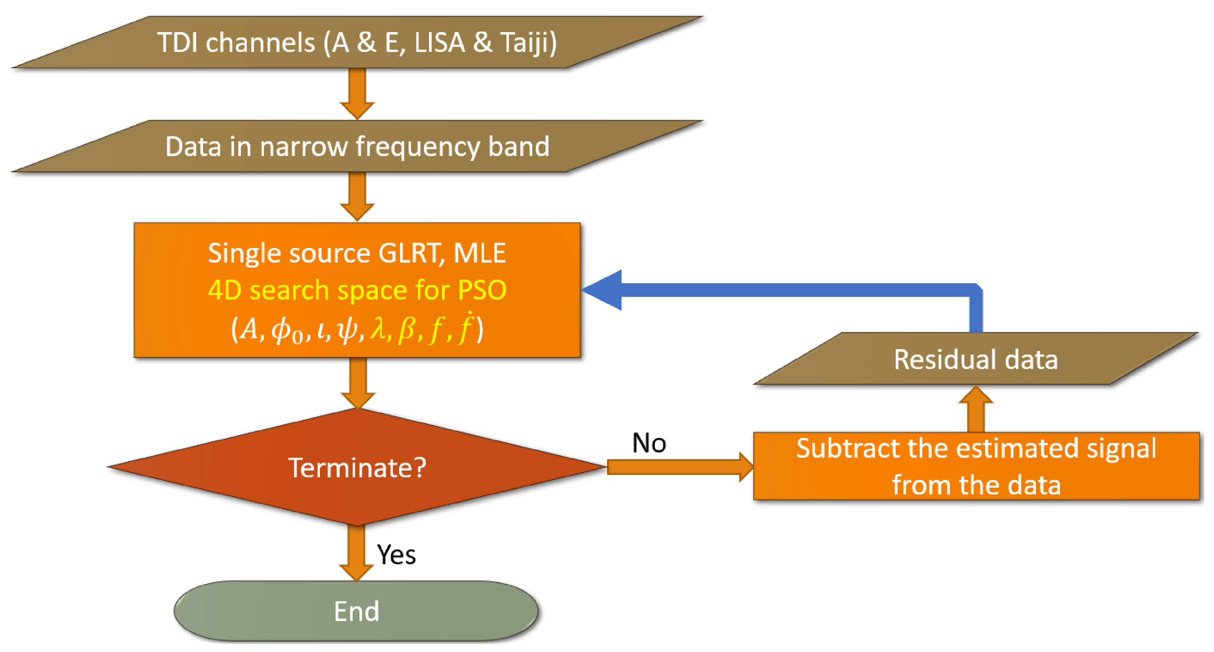

Figure 1: Flow chart

The following techniques have been implemented to complete the research:

- $\mathcal{F}$-statistic reduces the dimension of the search space.
- White noise approximation & undersampling reduces the data length without loss.
- Particle Swarm Optimization (PSO) performs parameter estimation effectively.
- Edge effect handling eliminates on-edge spurious sources.
- Cross-validation improves parameter estimation performance.

Source Resolution

GBSIEVER imposes different SNR and cross-validation cutoffs in different blocks in SNR-frequency plane, here we show the numbers for the cutoff combinations called *Main* to obtain our principal results:

Treatments	Rpt.	Cfm.	Det. rate
LISA alone	12251	10388	84.79%
LISA-Taiji	21993	18151	82.53%

Table 1: Source resolution performance

- **Reported**: the final list of estimated sources returned by GBSIEVER
- **Confirmed**: the reported sources that match true sources as determined by a prescribed metric for association
- **Detection rate**: the fraction of confirmed sources in the set of reported ones

The number of confirmed GBs is boosted from $10,388$ for LISA to $18,151$ for the LISA-Taiji network, a remarkable increase of 74.73%!

If the first frequency range ($[0, 3]$ mHz), which has the lowest detection rate is ignored, the detection rate for the LISA-Taiji network becomes 93.08% while that for LISA becomes smaller at 90.89%.

Residuals

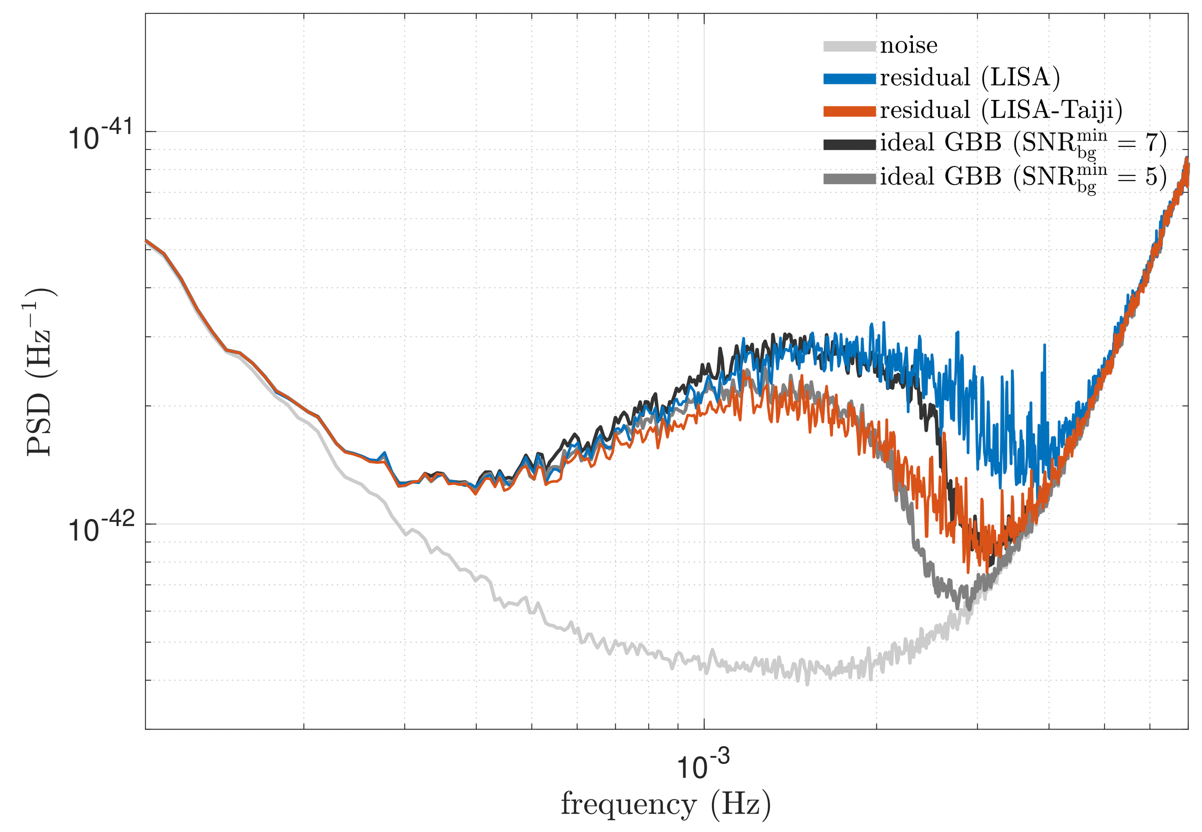

Figure 2: Residuals obtained with the single-detector (blue) and network analysis (red) compared with the single-detector ideal GB background (GBB) for $\mathrm{SNR}_{\mathrm{bg}}^{\mathrm{min}} = 5.0$ (dark gray) and 7.0 (black). The GBB curves are from an ideal but infeasible method [3] that perfectly removes all sources above $\mathrm{SNR}_{\mathrm{bg}}^{\mathrm{min}}$, The $\mathrm{SNR}_{\mathrm{gb}}$ here is defined relative to the floor of the PSD of the data.

We find that a network of space-based detectors will allow the GB background to be reduced substantially below the lowest level possible with a single detector. Thus one expects the non-GB search performance to be significantly improved.

Parameter Estimation Performance

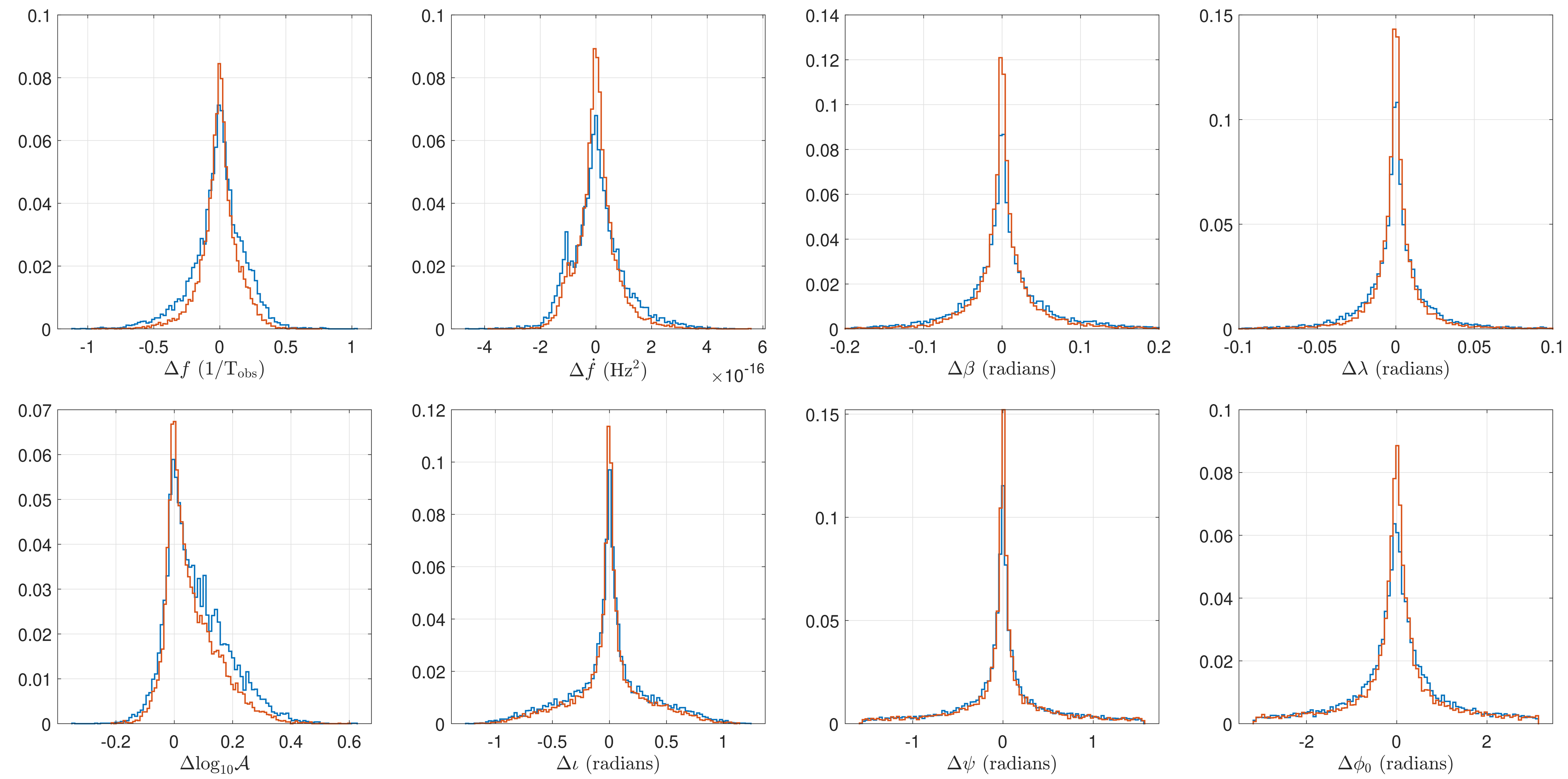

Figure 3: Estimated PDF of differences in the parameters of confirmed and associated true sources for the subset of sources that were common to LISA (blue) and the LISA-Taiji network (red) analyses. $\sqrt{2} \times \Sigma_{\mathrm{net}}/\Sigma_{\mathrm{sngl}}$ for the parameters are: f: 1.0218, $\dot{f}$: 1.0471, β: 1.0388, λ: 1.0697, $\log_{10}\mathcal{A}$: 1.2003, ι: 1.2429, ψ: 1.3649, ϕ_0: 1.3440 ($\Sigma_{\mathrm{net}}/\Sigma_{\mathrm{sngl}}$: standard deviation of the PDF for the network/single-detector). Deviations from unity suggest that a Fisher information based error analysis of single sources may not be adequate in the GB resolution problem.

References

[1] X.-H. Zhang et al. *Phys. Rev. D*, 104:024023, 2021.
[2] X.-H. Zhang et al. *arXiv preprint arXiv:2206.**, 2022.
[3] N. Karnesis et al. *Phys. Rev. D*, 104:043019, 2021.

Future Research

- More realistic mock data, e.g. TDI 2.0, non-Gaussian non-stationary noise, unknown PSD of noise, non-GB signals in the data, etc.
- Probe sky distributions, formations, evolutions and interactions of GBs from outcomes of GBSIEVER.

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