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Local zeta coherence in pulsar timing residuals: Normalization, cadence effects, and significance for PSR J1909−3744

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ABSTRACT

We present a windowed "zeta-coherence" analysis of pulsar timing residuals and study how cadence and time-of-arrival (TOA) weights inflate the aggregate coherence statistic. Using PSR J1909−3744 as a stability benchmark, we compare the raw zeta sum to L1 and L2 normalizations and evaluate significance with permutation-based nulls. We find that late-time excursions apparent in the raw statistic are substantially mitigated by L1 and persist—though attenuated—under L2, indicating a non-trivial contribution beyond sampling density. The method is lightweight, compatible with TEMPO2/PINT outputs, and readily extensible to PTA datasets.

Keywords: pulsars: general — pulsars: individual (PSR J1909−3744) — methods: data analysis

1. INTRODUCTION

Millisecond pulsars (MSPs) offer exceptional rotational stability and have become key probes for gravitational-wave backgrounds and fundamental physics. However, apparent phase coherence in timing residuals can be artificially amplified by heterogeneous cadence and by the distribution of TOA weights. To disentangle genuine coherence from sampling artifacts, we introduce a local, windowed zeta-coherence analysis and apply it to PSR J1909−3744, a canonical high-stability MSP used by multiple PTAs.

2. DATA AND PREPROCESSING

We analyzed public timing solutions (`.par`/`.tim`) for PSR J1909−3744 from PTA releases (NANOGrav/EPTA/IPTA). Residuals were computed with `PINT` using the DE440 solar-system ephemerides. We use a sliding window of width W days, advanced by a step Δt, and inside each window we aggregate a zeta-coherence statistic over trial periods $p \le p_{\max}$.

Denote by w_i the TOA weights in a window centered at t_0, and by $Z(t_0)$ the absolute zeta sum. We also record the weight budget

$$W_{\mathrm{sum}}(t_0) = \sum_i w_i, \tag{1}$$

$$W_2(t_0) = \sum_i w_i^2, \tag{2}$$

$$N_{\mathrm{win}}(t_0) = \text{number of TOAs in the window.} \tag{3}$$

Unless otherwise noted we set $p_{\max} = 10^4$ in the same time units as the code, with $W \in [30, 45]$ days and $\Delta t \in [10, 30]$ days (typical of our runs).

3. ZETA COHERENCE AND NORMALIZATIONS

The raw aggregate $|Z|$ scales with both TOA count and weights. To suppress trivial scaling we report two normalized variants:

$$\mathrm{L1}(t_0) = \frac{|Z(t_0)|}{W_{\mathrm{sum}}(t_0)}, \qquad \mathrm{L2}(t_0) = \frac{|Z(t_0)|}{\sqrt{W_2(t_0)}}. \tag{4}$$

L1 penalizes weight-heavy windows linearly, while L2 matches the natural ℓ_2 concentration and is less sensitive to a few very large w_i.

4. RESULTS FOR PSR J1909−3744

Figure 1 summarizes the evolution of the statistic across the dataset: the raw sum, and the L1 and L2 normalizations. Large late-time features in the raw curve are strongly reduced under L1 and persist (attenuated) under L2, consistent with cadence-driven inflation plus a residual coherent component.

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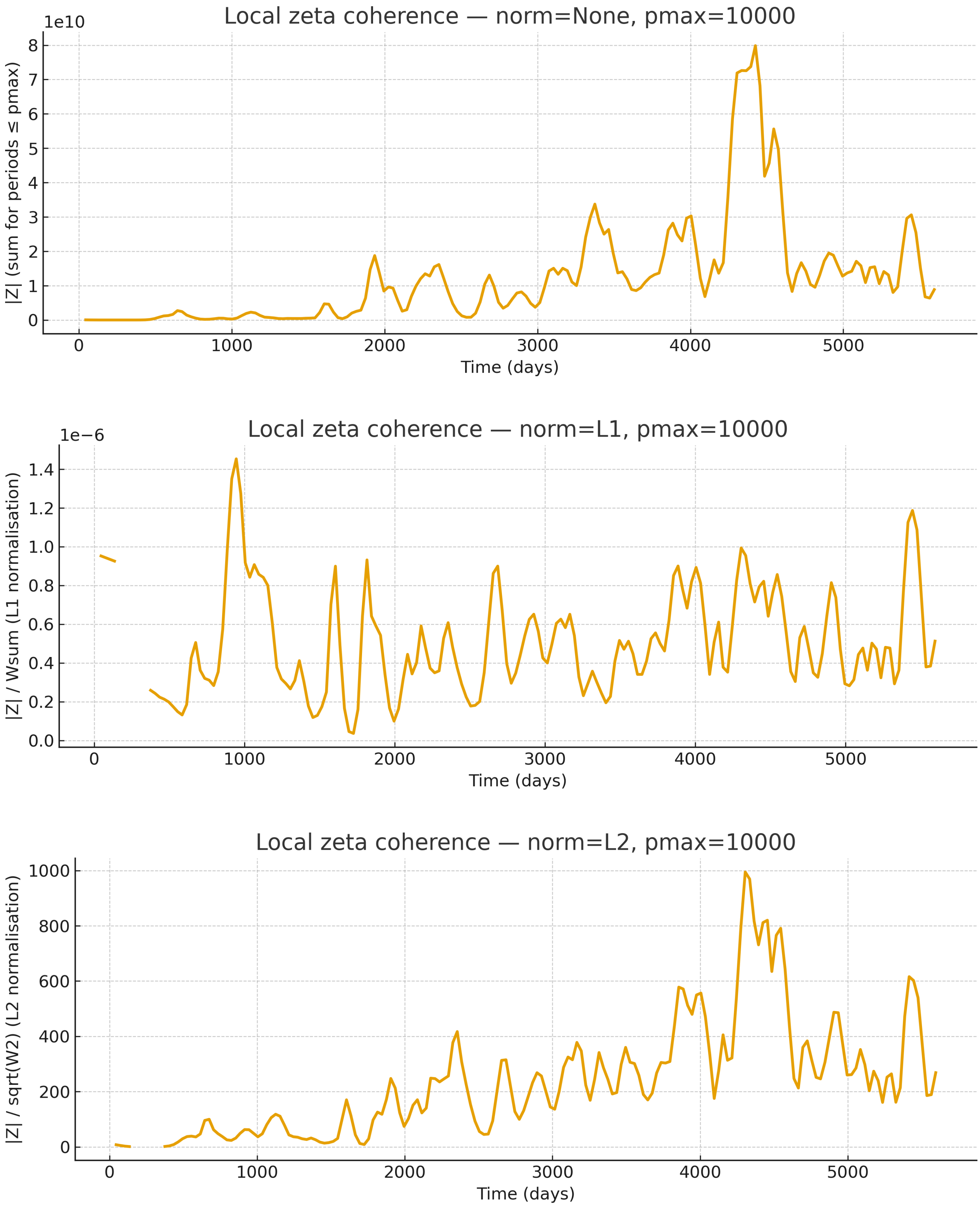

Figure 1. Windowed zeta-coherence for PSR J1909−3744. *Top:* raw $|Z|$ (sum over $p \leq p_{\max}$, here $p_{\max} = 10^4$). *Middle:* L1 normalization $|Z|/W_{\text{sum}}$. *Bottom:* L2 normalization $|Z|/\sqrt{W_2}$. All panels share the same time axis (window center t_0 in days).

Table 1. Top-5 strict local peaks by normalization (window center t_0 in days).

Normalization	t_0 (days)	Peak value
L2	4305	994.789
L2	4455	820.113
L2	4545	791.072
L2	5415	615.957
L2	3855	578.021
L1	945	1.4533×10^{-6}
L1	5445	1.1870×10^{-6}
L1	4305	9.9360×10^{-7}
L1	1815	9.3166×10^{-7}
L1	3885	9.0025×10^{-7}
Raw $\|Z\|$	4425	7.9855×10^{10}
Raw $\|Z\|$	4545	5.5613×10^{10}
Raw $\|Z\|$	3375	3.3724×10^{10}
Raw $\|Z\|$	5445	3.0606×10^{10}
Raw $\|Z\|$	4005	3.0273×10^{10}

4.1. *Peak locations*

To characterize localized episodes we extract strict local maxima from each curve. Table 1 lists the top five peaks for L2, L1, and the raw sum (values for the dataset processed in this work).

5. SIGNIFICANCE VIA PERMUTATIONS

To evaluate whether peaks can be explained by cadence/weights alone, we build a permutation-based null. For each window we randomly permute the residuals (times and weights held fixed), recompute $|Z|$, and repeat to obtain the 95th-percentile envelope $q_{95}(t_0)$. Where available, we overlay q_{95} on the L2 curve and flag sustained excursions above the envelope as unlikely under the null.

6. DISCUSSION

The contrast between L1 and L2 demonstrates that raw coherence is inflated by observing density and weight concentration. Peaks that remain strong under L2—and exceed q_{95} when available—are more plausibly tied to intrinsic or instrument-specific behavior. Applying the identical pipeline to another stable MSP (e.g., PSR J1744−1134) provides a control for network-wide or processing changes.

7. CONCLUSIONS

Local zeta coherence, particularly under L2 normalization, provides a robust, low-cost summary of evolving coherence in pulsar timing residuals. The method integrates seamlessly with TEMPO2/PINT workflows and scales to PTA datasets for comparative studies.

REPRODUCIBILITY AND DATA

Timing files are sourced from public PTA releases. Residuals are computed with `PINT` (DE440). Our post-processing script converts the `pulsar_zeta_pint.py` CSV outputs into the figures used here.

We thank XYZ for valuable discussions. This work used open PTA datasets and community software.

REFERENCES