Topological Data Analysis for Gravitational Wave Detection under Low Signal-to-Noise Ratios

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Abstract

The reliable detection of gravitational waves (GWs) in noisy time-series data remains a central challenge in data-driven astrophysics. In this work, we explore Topological Data Analysis (TDA) as a feature-extraction framework for GW-like chirp signals embedded in Gaussian noise. We reconstruct time-delay embeddings of simulated waveforms, construct Vietoris–Rips filtrations, and extract persistence diagrams up to the first homology group. These diagrams are transformed into vectorized summaries, including persistence images, landscapes, and Betti curves, which are then used as input features for standard machine learning classifiers. We systematically evaluate detection performance across a range of signal-to-noise ratios (SNR $\in$ [2,10]) and compare TDA-based methods against classical baselines (time-domain and spectral features) and shallow neural models. Our results show that persistence-based descriptors achieve competitive detection accuracy, maintain robustness under decreasing SNR, and provide interpretable insights into the topological structure of GW signals. These findings highlight TDA as a promising tool for enhancing the interpretability and reliability of gravitational-wave data analysis.

Keywords: Topological Data Analysis, Gravitational Waves, Sinal-to-Noise Rations