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QTAM: Qtransform from visualization to physics

The increasing data volume from gravitational-wave observatories presents both an opportunity for new discoveries and a significant challenge for existing analysis methods. While deep learning models, particularly those designed for image processing, are powerful tools for analyzing 2D time-frequency representations of transient signals, their application has been limited by a fundamental conflict. The large data footprint of high-resolution spectrograms makes them computationally expensive for large-scale ML analysis, forcing a reliance on lossy compression techniques that discard physical information and break invertibility. This limitation has preserved a methodological gap between precise, but less scalable, 1D time-domain analysis and efficient, but often non-invertible, 2D machine learning approaches.

We address this challenge by introducing a GPU-accelerated, fully invertible Q-Transform (QT) implemented in PyTorch. Our primary contribution is a novel, anti-aliased resampling algorithm that operates directly in the Fourier domain. This technique facilitates aggressive, yet lossless, temporal downsampling of the CQT, producing a compact data representation suitable for large-scale ML pipelines without sacrificing the ability to exactly reconstruct the original, band-passed time-series. By enabling full invertibility post-resampling, our method eliminates the need for lossy pre-processing and empowers hybrid 1D-2D analysis strategies. The introduction of this CQT is the first step in bridging the gap between the current data analysis methods used in the Virgo collaboration and the future machine-learning powered ones which will be crucial for the analysis of ET data.

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