Submission code: 6NG475VQPB

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Spectrally Penalized Dynamic Time-Warping for Improved Trace Alignment in Time-Lapse Seismic Data

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Abstract Summary

Time-lapse (4D) seismic studies often face challenges due to non-repeatability and temporal misalignments in seismic traces, mainly resulting from changes in subsurface physical properties over time. To tackle this issue, we investigate and compare two dynamic time-warping (DTW) trace correction techniques: the conventional DTW method and a novel variant that incorporates spectral penalization. The proposed approach utilizes spectral information to constrain the alignment process, penalizing frequency-domain inconsistencies and promoting trace alignment that better preserves both amplitude and frequency content. This spectral regularization bolsters the robustness of the time-warping operation, particularly in scenarios with subtle or frequency-dependent changes. A comparative analysis reveals that the proposed method yields a more accurate correction of temporal shifts, resulting in enhanced characterization of reflectivity differences between the baseline and monitor datasets. These findings suggest that incorporating spectral constraints into time-warping algorithms can substantially improve the reliability of seismic repeatability assessments and time-lapse interpretation.

Introduction

Seismic prospecting is crucial for mapping subsurface structures and identifying hydrocarbon reservoirs. In 4D seismic surveys, repeated measurements track reservoir changes over time by comparing baseline and monitor datasets. However, time shifts resulting from subsurface changes can misalign seismic events, and conventional correction methods, such as cross-correlation, often fail to handle complex or nonlinear variations effectively. To address these challenges, we propose a dynamic spectral penalization time warping (SPDTW) method, which preserves frequency domain characteristics while enhancing the physical fidelity of seismic signals. This approach is an adaptation of the traditional time warping technique proposed by Sakoe and Chiba (1978).

Methods

We provide brief comments on key time series alignment methods, focusing on classical DTW and its enhanced variant, SPDTW, which applies frequency-domain penalization via the Fourier transform.

Dynamic Time Warping

DTW is a widely adopted algorithm for aligning time series that exhibit temporal variations, such as local stretching or compression. Unlike conventional techniques that assume linear temporal correspondence, DTW performs non-linear alignment by adaptively warping the time axis to minimize the cumulative dissimilarity between two sequences. In seismological applications – particularly in time-lapse (4D) studies – DTW has shown notable effectiveness in compensating for temporal shifts induced by subsurface changes. Hale (2013) demonstrated that DTW outperforms standard cross-correlation methods in aligning structural features in seismic images, especially under complex, non-stationary conditions.

The algorithm begins by constructing a cost matrix that quantifies local discrepancies between all time-sample pairs from the input signals. A dynamic programming scheme then computes the optimal warping path that minimizes the global alignment cost, subject to boundary, monotonicity, and continuity constraints. The results are smooth, non-linear mapping synchronizing corresponding events, even when temporally displaced. However, classical DTW operates exclusively in the time domain and does not preserve spectral characteristics, which may lead to distortions in amplitude and frequency content. Such a limitation has motivated the development of spectral-regularized variants that yield more physically consistent alignments in seismic processing contexts.

Spectral Penalization Dynamic Time Warping

In seismic analysis, amplitude and spectral content are crucial for interpreting subsurface properties, particularly in time-lapse (4D) studies, where subtle temporal and frequency-domain variations indicate fluid movement or geomechanical changes. To address the limitations of classical DTW – especially its tendency to distort spectral characteristics – we introduce a modified alignment strategy that incorporates spectral penalization into the warping process.

Unlike traditional DTW, which operates solely in the time domain, SPDTW introduces a frequency-domain regularization term based on the Discrete Fourier Transform (DFT). For each candidate alignment path, the method incrementally evaluates subsamples of the signal and compares their spectral magnitudes to that of the original trace. Specifically, the penalty term quantifies the cumulative spectral deviation between the DFT of the full signal and that of each subsequence. This is formulated as a logarithmic energy difference, which emphasizes discrepancies in dominant frequency components.

The spectral penalty is then added to the time-domain misfit, yielding a modified local cost function. A weighting parameter α controls the influence of the spectral constraint: as α approaches zero, SPDTW converges to standard DTW; higher values enforce stricter spectral fidelity. Parseval's theorem is applied to normalize spectral energy to avoid over-penalization, ensuring a balanced trade-off between alignment flexibility and physical signal consistency.

Results

We validated the SPDTW technique using a convolutional model in a controlled setting, which allowed for precise control over wavelet behavior. Although tested synthetically, the method remains applicable to real data, both in the prestack domain and seismic imaging.

Convolutional Model

To evaluate DTW and the proposed SPDTW for seismic alignment, we designed a controlled test using three synthetic reflectivity events, shown in Figure 1(a). The black curve denotes the baseline reflectivity from the initial acquisition, while the blue dashed curve represents the monitor, simulating time-lapse changes due to reservoir dynamics.

Reflectivity sequences were convolved with a zero-phase Ricker wavelet (25 Hz peak frequency), commonly used in seismic processing. To emulate acquisition imperfections, white noise at 1% of

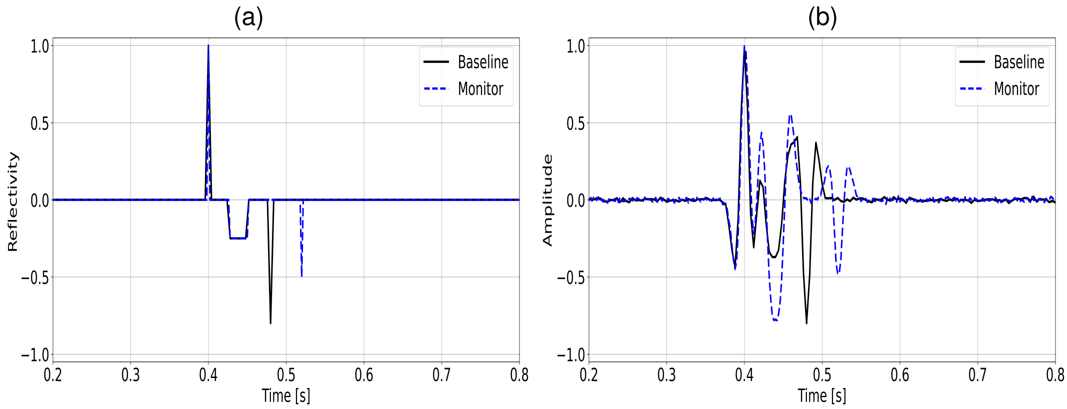

Figure 1: (a) Reflectivity: Black curve (baseline), blue dashed curve (monitor). (b) Seismic trace: Baseline and monitor data reflecting subsurface variations.

the maximum amplitude was added. This setup replicates realistic 4D seismic scenarios where subsurface changes introduce observable time shifts.

Figure 1(b) shows the resulting seismic traces. While DTW aligns shifted events (Figure 2(a)), it often distorts the waveform due to its sole reliance on time-domain similarity. In contrast, SPDTW (Figure 2(b)) incorporates spectral penalization, preserving both amplitude and frequency content during alignment.

Comparisons of the alignment results and associated cost matrices (Figure 3) confirm that SPDTW achieves better spectral fidelity and physical consistency. These improvements enhance the interpretability of time-lapse differences, making SPDTW more suitable for reservoir monitoring and seismic repeatability analysis.

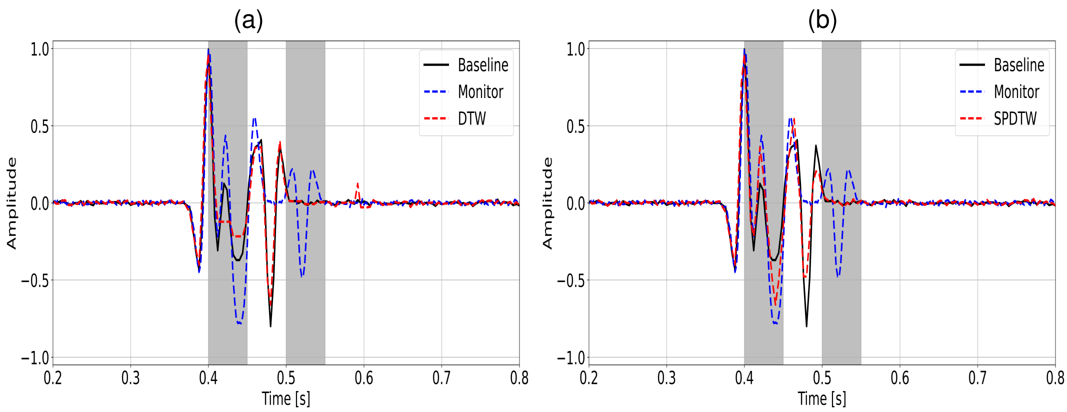

Figure 2: (a) DTW alignment: Baseline (black) and monitor (blue) with waveform distortion. (b) SPDTW alignment: Baseline (black) and monitor (blue) with preserved spectral integrity.

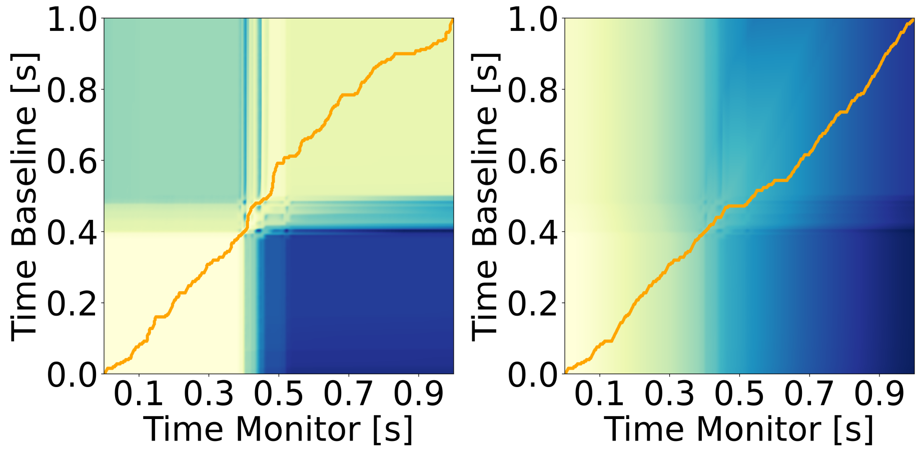

Figure 3: Cost matrix for alignment using: (Left) DTW distance. (Right) SPDTW distance.

Conclusions

In this work, we introduced a spectral penalty to preserve the fundamental characteristics of the input signal during the alignment process. This penalty ensures that the correction does not compromise key frequency components, striking a balance between alignment accuracy and spectral fidelity. By combining the DTW algorithm with spectral penalization, we present an innovative solution to common challenges in 4D seismic studies, where subtle changes in signal characteristics are crucial for accurate interpretation. The spectral penalty enhances the robustness of the alignment, particularly in scenarios involving complex or non-stationary subsurface changes, such as fluid displacement or compaction. Our method improves both time-domain alignment and frequency-domain consistency, which is essential for reliable time-lapse seismic interpretation. This approach offers a significant advancement in seismic repeatability analysis, enabling more accurate monitoring of reservoir dynamics over time. Future research could further refine the spectral regularization and explore its applicability to other types of seismic data, such as prestack and imaging datasets, expanding its potential in various geophysical contexts.

Acknowledgments

The authors gratefully acknowledge the support provided by the following organizations: Petrobras (Petróleo Brasileiro S.A.) for financing this research; The High-Performance Geophysics Laboratory (HPG Lab) members and the Centro de Estudos de Energia e Petróleo (CEPETRO) at the Universidade Estadual de Campinas (UNICAMP) for their ongoing assistance throughout this research.

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