Tackling speckle and coherent noise with Seismic Time-Frequency Masking: insights from a case study

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Summary

This study examines the effectiveness of Seismic Time-Frequency Masking (STFM) in handling speckle and coherent noise in land seismic data from complex scattering environments. It demonstrates STFM's ability to significantly reduce noise and enhance signal clarity through local stacking and amplitude masking. Despite not being specifically designed for coherent noise, STFM shows excellent performance in attenuating crossing noise events, particularly benefiting from accurate signal selection via local stacking and the amplitude masking component of STFM. These findings are confirmed in controlled synthetic examples and further verified in a 3D case study from a challenging desert environment. The study underscores STFM's potential in improving signal-to-noise ratios and geological interpretations in scattering-prone areas, offering valuable insights for its application in challenging seismic settings.

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Introduction

Near-surface scattering is recognized as a primary challenge complicating land seismic processing and quantitative interpretation, often making these tasks difficult or compromised (Stork, 2020; Bakulin et al., 2020). Seismic time-frequency masking (STFM) was recently proposed as an efficient data-driven method for the removal of scattering speckle noise (Bakulin et al., 2023). This noise is particularly challenging to remove due to its multiplicative nature, caused by small-scale scattering in the near-surface that leads to reflection distortion in the form of variability in both phase and amplitudes (Bakulin et al., 2022a). Firstly, Seismic Time-Frequency Masking (STFM) employs locally stacked pilots derived from prestack data to reconstruct an undistorted phase. It then attenuates amplitude noise through a time-frequency masking procedure, guided by the locally stacked data. This technique relies on local stacking to approximate the reflection signal, strategically using this model as a guide to preserve high-frequency content while mitigating phase and amplitude variations introduced by scattering. In practice, speckle noise is often accompanied by other coherent noises from the near surface, which are superimposed on the reflected signal. This case study evaluates STFM's effectiveness in addressing such additional coherent noises, including residual groundroll.

Method

We consider the general seismic trace model with both multiplicative and additive noise, which can be represented window-wise at i^{th} channel as:

$$x_i(t) = r_i(t) * s(t) + n_i(t), \tag{1}$$

where $s(t)$ represents the clean signal, $r_i(t)$ denotes the random multiplicative noise term describing signal distortions due to near-surface scattering caused by small-scale heterogeneities, $n_i(t)$ represents additive random noise, and '*' means convolution. Upon applying discrete Short-Time Fourier Transform to $x_i(t)$, we obtain a 2D complex-valued time-frequency spectrum $X(k,l)$ of the recorded trace with $k,\ l$ representing the discrete frequency bin and time frame indices, respectively. According to the STFM method (Bakulin et al., 2023), a time-frequency mask (or filter) $M(k,l)$ is applied to noisy trace to get the estimate $\hat{S}(k,l)$ of the clean signal as follows:

$$\hat{S}(k,l) = M(k,l) \cdot X(k,l)\ . \tag{2}$$

The complex-valued mask $M(k,l)$ comprises phase and amplitude masks. The phase mask is derived based on the locally stacked or beamformed data. One such mask is the "phase substitution" mask (PSM), defined as follows:

$$PSM(k,l) = \exp\left[i\{\varphi_S(k,l) - \varphi_X(k,l)\}\right], \tag{3}$$

where φ_X and φ_S are time-frequency phase spectra of original and beamformed trace respectively. The amplitude mask is calculated using the Ideal Rationale Mask technique:

$$IRM(k,l) = \sqrt{\frac{|S_{est}(k,l)|^2}{|S_{est}(k,l)|^2 + |N_{est}(k,l)|^2}}$$

where $|S_{est}(k,l)|^2$ and $|N_{est}(k,l)|^2$ are local estimates of desired signal and noise power spectra, calculated using the minimal statistic approach adopted from speech processing (Martin, 2001).

Synthetic data example

Figure 1a displays a synthetic simulation of both a horizontal signal event and crossing coherent noise event, both influenced by speckle noise and overlaid with white Gaussian noise. The events are of similar magnitude, underscoring that reflections are very weak, while even residual groundroll might be comparable to them. Local stacking, implemented as nonlinear beamforming or NLBF (Bakulin et al., 2020), primarily enhances the signal event (Figure 1b), utilizing a priori dip information. Phase substitution, as an initial stage of STFM, plays a crucial role in stabilizing the signal phase and significantly reducing the impact of scattering speckle noise (Bakulin et al., 2023). This step is instrumental in enhancing the overall signal quality and improving the clarity of seismic data in the presence of noise (Figure 1c). However, it leaves residuals of noise events due to preserving the original amplitude spectrum (Figure 1a) and minor phase inaccuracies in the stacked pilot (Figure 1b). Amplitude masking in STFM is crucial for significantly suppressing the effects of speckle noise on amplitude, as seen when comparing the signal event in Figures 1c and 1d.

It's evident that amplitude masking also plays a crucial role in diminishing noise residuals, as demonstrated by comparing noise events between Figures 1c and 1d. The amplitude mask operates as a local filter on the raw amplitude spectrum from Figure 1a, directed by a signal amplitude model from the pilot in Figure 1b. Since the pilot indicates minimal signal energy away from the horizontal event, the amplitude mask effectively suppresses crossing noise event. This example concludes that despite the presence of residual linear noise, STFM's performance in removing speckle noise remains robust, with the added benefit of weakening crossing events due to its data-driven amplitude masking.

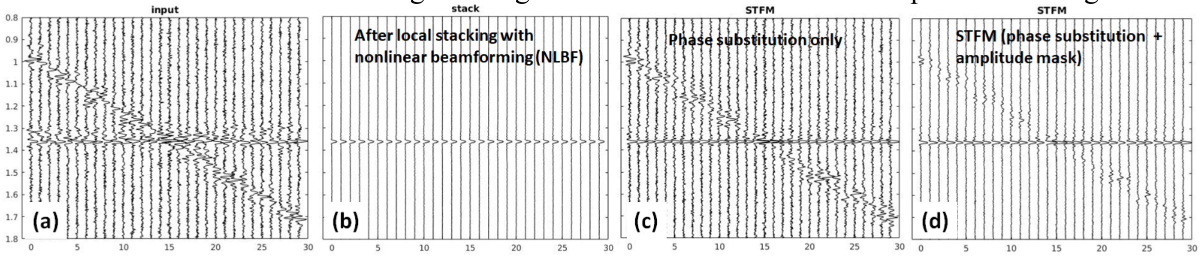

Figure 1 *STFM application to synthetic data with crossing events representing a flat reflection signal and a dipping residual groundroll energy: (a) raw gather; (b) pilot from local stacking with NLBF; (c) raw gather after phase substitution from (b) visualizes the initial stage of STFM; (d) raw gather after complete STFM, which includes both phase substitution and amplitude masking. Notice the residual noise in (c) that is more efficiently suppressed after the amplitude masking in STFM, as evident in (d).*

Real data example

Let's evaluate STFM's effectiveness on complex real data from a desert environment plagued by significant coherent noise from near-surface arrivals and speckle scattering noise disrupting the reflection events. Figure 2 shows common-midpoint gathers after different processing stages. While linear noise removal decreases groundroll amplitudes, considerable residual energy persists due to weak reflection energy (compare Figures 2a and 2b) and gaps in the acquisition preventing from more efficient suppression. Nonlinear beamforming is a data-driven method that identifies and enhances the single strongest coherent signal within a small window, performing local stacking along these trajectories to boost the signal (Bakulin et al., 2020). This approach deliberately uses a narrow dip range to avoid amplifying groundroll noise. Consequently, after applying NLBF, we see a notable reduction in groundroll amplitude (Figure 2c).

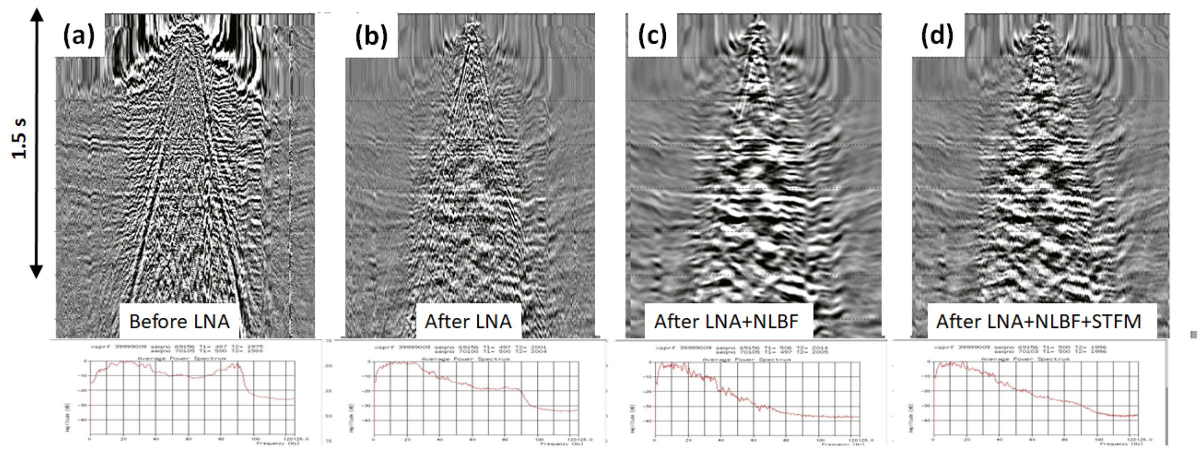

Figure 2 *Prestack CMP gathers and associated amplitude spectra: (a) and (b) before linear noise removal respectively;(c) after nonlinear beamforming applied to (b); (d) after STFM application to (b). STFM demonstrates better preservation of higher frequencies in (d) compared to local stacking in (c).*

While NLBF enhances the signal-to-noise ratio impressively, the local stacking it employs attenuates higher frequencies due to phase perturbations from speckle noise. Comparing the amplitude spectra at the bottom of Figure 2b and 2c clearly reveals the impact of NLBF on higher frequencies. Consequently, forwarding NLBF-processed data to subsequent stages may compromise the preservation of higher-frequency content in processing. As previously mentioned, STFM utilizes the phase determined by NLBF but reverts to the original raw amplitude from Figure 2b for further targeted speckle noise removal. While STFM effectively mitigates speckle noise, it isn't specifically designed to suppress coherent noise. Nevertheless, similar to synthetic examples, we observe that window-based amplitude masking also suppresses groundroll events, as evidenced by comparing Figures 2b and 2d. Thus, STFM effectively suppresses speckle noise and further weakens coherent noise events intersecting the signal.
The conclusions are supported by the stacked data in Figure 3. The improvements observed in the prestack data, as shown in Figure 2d with reduced noise, contribute to a more geologically accurate stacked image (Figure 3c). These enhancements are particularly significant in areas strongly influenced by scattering, despite being less pronounced in the stacked data compared to the prestack data.

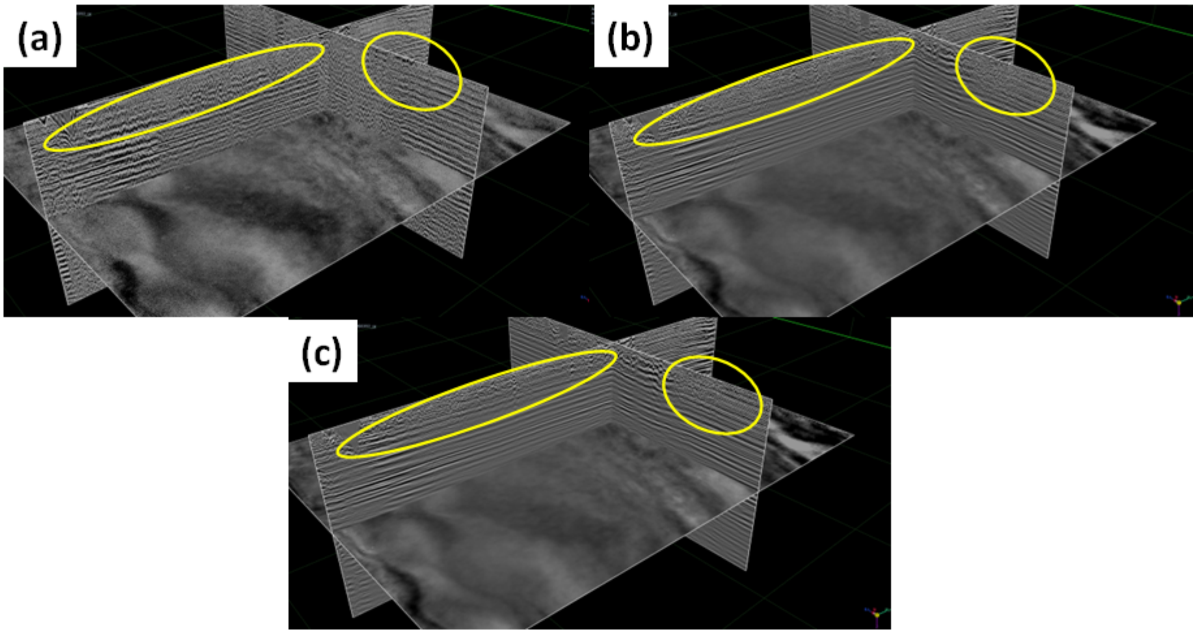

Figure 3 *3D stacked volumes at different processing stages: (a) before linear noise removal; (b) after linear noise removal; (c) after STFM. Observe consistent coherency improvements across the stages, particularly in image (c), within complex areas highlighted following speckle noise and groundroll suppression.*

To quantify these improvements, computing Signal-to-Noise Ratio (SNR) volumes is essential, as outlined by Bakulin et al. (2022b) and shown in Figure 4. There's a noticeable reduction in groundroll contamination post-linear noise removal (Figures 4a and 4b), with significant SNR enhancements throughout. However, speckle noise persists in certain areas, unmitigated by traditional processing (Figure 4b). Applying Seismic Time-Frequency Masking notably increases SNR in these areas, demonstrating STFM's capability in handling scattering noise. The remaining distortion in the stacked data (Figure 3) also includes residual groundroll, as previously discussed. STFM effectively reduces this noise, thus facilitating more accurate data interpretation. These improvements in noise reduction and signal enhancement are achieved while preserving higher frequencies, which are typically attenuated in traditional local stacking methods.

Conclusions

Speckle noise presents a significant challenge in scattering geological environments. Recognizing it as a reflection signal distortion has led to the development of Seismic Time-Frequency Masking. This method reduces phase and amplitude variability from small-scale scattering by combining local stacking for pilot generation with amplitude masking techniques derived from speech processing. Both local stacking and seismic time-frequency masking operate within specific windows and are susceptible to various noise types, including coherent crossing events. This study validates the stability of the STFM method even when additional coherent noise, like crossing events, is present. Our study demonstrates that STFM not only tackles speckle noise but also reduces the amplitude of coherent noise. The case study in a desert environment underscores STFM's ability to sharpen images and quantifies the reduction of speckle and coherent noise through signal-to-noise ratio volumes, which show marked improvement in highly scattered areas.

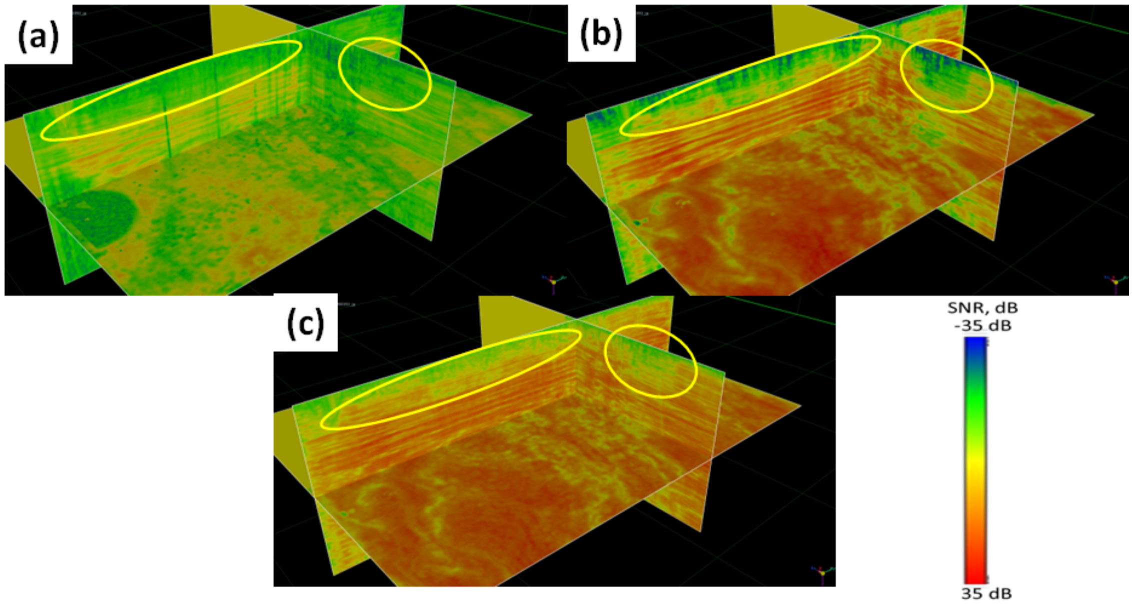

Figure 4 *Signal-to-noise ratios volumes at different processing stages: (a) before linear noise removal; (b) after linear noise removal; (c) after STFM. Notice the uniform SNR improvements throughout the stages, especially in image (c), where complex areas are distinctly enhanced following the removal of speckle noise and groundroll.*

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