Research Paper

Refining Linear Noise Suppression in 2D Marine Seismic Data Through Frequency-Wavenumber Domain Optimization

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ABSTRACT

Linear noise is one of the most persistent challenges in marine seismic acquisition, often masking shallow reflectors and degrading subsurface imaging quality. Conventional filtering approaches may suppress linear noise but frequently compromise primary reflection energy, particularly in 2D datasets with complex acquisition geometries. This study refines linear noise suppression by optimizing frequency–wavenumber (F-K) domain filtering parameters, including dip discrimination, directional cone design, and adaptive tapering. The proposed workflow enhances event separation by analyzing the noise signature in the F-K spectrum and implementing a time–offset variant F-K windowing strategy tailored to marine streamer characteristics. Results obtained from real 2D marine seismic data demonstrate significant improvements in signal-to-noise ratio, continuity of primary reflections, and preservation of steep dips. Comparative analyses against conventional F-K filtering show that the optimized approach reduces linear noise more effectively while maintaining signal fidelity. The optimized F-K strategy provides a practical and robust solution for improving the quality of 2D marine seismic data, offering insights into noise behavior and filter parameterization for future seismic processing applications.

Keywords: F-K Optimization, Linear Noise, Noise Suppression, Quality Improvement, Reflection Enhancement

INTRODUCTION

The fidelity of marine seismic imaging critically depends on effective suppression of coherent noise, which otherwise obscures reflection events and reduces interpretability of subsurface structure. Among the most persistent noise types in 2D marine streamer data is linear noise, generated by direct arrivals, refractions, sourceghosts, and other acquisition related disturbances. These noise events are characterized by strong amplitude, linear moveout, and high apparent velocity, often masking early-time reflections and degrading shallow imaging quality (Hlebnikov, 2021).

Conventional processing approaches such as simple muting, band-pass filtering, or prediction error filters are frequently inadequate for such noise because they lack the dip and velocity selectivity required to distinguish linear noise from primary reflection energy (Irshadibima et al., 2017). In contrast, the frequency–wavenumber (F-K) domain offers a more effective wavefield separation framework, as different seismic event types map to distinct regions in the F-

K domain based on their dip and apparent velocity (Huang et al., 2017). Thereby, F-K filtering enables selective attenuation of undesired linear events while preserving reflection coherency.

Nonetheless, the practical application of F-K filtering often faces limitations. In many cases, fixed filter parameters (reject cones, velocity/dip thresholds) do not account for time variant noise behavior, offset dependency, or acquisition geometry asymmetries typical of marine streamer surveys. This may result in residual linear noise or, worse, partial suppression of genuine reflections particularly steep dips or shallow events (Mu et al., 2025). Recent advances in seismic denoising further suggest that adaptive and optimized filter designs possibly integrating anti-aliasing, spectral leakage control, and dip-space tuning provide superior results compared to conventional, static F-K filters (Mu et al., 2025).

In this context, the present study proposes an optimized F-K domain filtering workflow specifically tailored for 2D marine seismic data afflicted by linear noise. The method combines comprehensive F-K spectral diagnostics, adaptive dip discrimination, directional cone definition, and time offset variant windowing to maximize separation between linear noise and primary reflections. Application to real marine datasets reveals improved signal to noise ratio (SNR), enhanced reflector continuity, and bandwidth preservation compared to standard F-K filtering highlighting the importance of parameter optimization in modern seismic processing workflows.

LITERATURE REVIEW
Linear Noise in Marine 2D Seismic Data
Marine towed-streamer data are affected by a broad range of coherent and incoherent noise types, including swell noise, source and receiver ghosts, cable noise, propeller noise, and various forms of interference. A recent tutorial by Hlebnikov et al. (2021) provides a systematic classification of such noise in towed marine surveys and emphasizes that many of these events appear as coherent linear moveout in the time–offset domain. Linear noise is typically associated with direct and refracted arrivals, environmental effects, and acquisition-related artefacts, and is characterized by strong amplitude, nearly linear traveltime curves, and relatively high apparent velocity. These properties allow linear noise to dominate early-time records and mask shallow reflections, particularly in high-resolution surveys.

Frequency-wavenumber (F-K) domain and wavefield separation
The frequency–wavenumber (F-K) domain provides a natural framework for separating seismic wavefields based on their moveout characteristics. For a 2D marine gather $s(t,x)$ in time t and offset x, the 2D Fourier transform is defined as

$$S(f, k_x) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} s(t,x) e^{-i2\pi(ft - k_x x)} \, dt \, dx \quad (1)$$

where f is temporal frequency and k_x is the horizontal wavenumber. In this representation, events with different apparent velocities v_{app} occupy distinct regions because, for a linear event $t(x) = t_0 + x/v_{app}$, energy tends to concentrate along the dispersion relation

$$v_{app} \approx \frac{2\pi f}{k_x} \quad (2)$$

Thus, primary reflections and linear noise with different dips and apparent velocities are mapped into separable zones of the F-K spectrum, enabling dip-based wavefield separation. Yilmaz (2001) describes F-K filtering as a standard tool for noise attenuation and wavefield separation in reflection seismic processing, particularly for

coherent ground roll and linear events. In marine settings, F-K transforms have been widely used to distinguish between signal and coherent noise based on apparent dip and to design reject cones that attenuate unwanted linear energy while preserving reflections. In these applications, the filter is typically implemented as a multiplicative mask $M(f,k_x)$ in the F-K domain, where

$$S_{filtered}(f, k_x) = M(f, k_x)\, S(f, k_x) \quad (3)$$

with $M(f,k_x)$ designed to be close to zero inside the noise cone and close to one in the pass region, often smoothed by a cosine taper to reduce edge artefacts.

MATERIALS & METHODS
Dataset
The seismic dataset analyzed in this study was acquired using a single streamer marine configuration. The survey employed a 25 m shot spacing and an equivalent 25 m receiver spacing, resulting in 96 recording channels sampled at 4 ms. The acquisition line extends approximately 2.68 km, and each shot record was recorded with a maximum length of 5 seconds. The data were collected in a water depth of about 200 m. The source wavefield was generated by a conventional airgun array, producing a dominant frequency near 40 Hz and a usable bandwidth between 3 and 125 Hz. This acquisition layout follows established marine survey standards and provides sufficient spatial and temporal resolution for effective multiple attenuation and subsequent seismic processing.

Preprocessing Workflow
Preprocessing was applied to ensure that the noise characteristics remained unchanged prior to the F-K filtering stage. The initial preprocessing sequence included:

- Geometry assignment and navigation quality control: validating the accuracy of source and receiver positions along the survey line.
- Trace editing and despiking: removing dead traces and high-amplitude spikes to prevent contamination of the spectral domain.

- Amplitude recovery: applying spherical divergence correction only when required for visualization; this correction was intentionally omitted before filtering to preserve the true amplitude relationship between noise and signal.

No deconvolution, statics, or normal moveout (NMO) corrections were applied before the F-K analysis to maintain the integrity of the original wavefield.

Noise Characterization in the F-K domain
Characterizing noise in the frequency–wavenumber (F-K) domain is essential for designing effective linear noise attenuation. Because seismic events occupy distinct frequency–wavenumber regions based on dip and apparent velocity, F-K analysis enables clear separation of coherent linear noise from primary reflections through diagnostic evaluation of energy distribution and propagation characteristics.

Shot gathers are transformed into the F-K domain, where coherent linear noise appears as high-energy ridges with nearly constant apparent velocity. These narrow features represent direct waves, refractions, and acquisition noise. Primary reflections, however, form broader, diffuse spectral zones due to their hyperbolic moveout and wider dip distribution.

To quantify these differences, spectral energy analysis is performed across both positive and negative wavenumber axes. This analysis identifies zones where noise energy is concentrated, enabling initial estimates of the apparent velocity ranges associated with undesired wavefields. Apparent velocity v_{app} is assessed using the relation:

$$v_{app} = \frac{2\pi f}{k_x} \qquad (4)$$

which links frequency and wavenumber for events exhibiting linear moveout. Noise events typically cluster within restricted v_{app}, whereas reflections span a broader velocity spectrum. These distinctions provide the foundation for dip-based separation.

The next phase involves directional propagation assessment. Because certain noise types such as direct waves or streamer related noise often propagate preferentially in one horizontal direction, asymmetric energy distributions may appear between positive and negative k_x values. Detecting such asymmetries is essential for determining whether directional F-K filtering should be applied, ensuring that only noise traveling in a specific direction is attenuated while opposite dip reflection energy remains intact.

Overall, the noise characterization process provides a detailed mapping of energy distributions, propagation directions, and apparent velocities for both noise and signal components. This information forms the basis for designing optimized F-K filters that selectively suppress undesired linear noise while preserving the fidelity of primary reflections throughout the seismic section.

F-K filter design and optimization
A reject polygon was designed to attenuate the noise components in the F-K domain. The filter mask $M(f,k_x)$ is defined as:

$$M(f, k_x) = \begin{cases} 0 \; if \; (f, k_x) \in noise \; zone, \\ 1 \; if \; (f, k_x) \in signal \; zone. \end{cases} \qquad (5)$$

To avoid spectral leakage and edge effects, a cosine taper was applied:

$$M_{taper} = \frac{1}{2}\left[1 + cos\left(\pi \frac{|k_x| - k_1}{k_2 - k_1}\right)\right] \qquad (6)$$

where k_1 and k_2 define the transition boundary.

When noise propagation is asymmetric common in towing direction or feathered streamer surveys directional filtering is applied:

$$M(f, k_x) = \begin{cases} 0 \; k_x > k_{noise}, \\ 1 \; k_x \leq k_{noise} \end{cases} \qquad (7)$$

This selectively removes noise travelling in a predominant direction while preserving opposite-dip reflections.

RESULT
F-K spectrum analysis
The initial F-K spectrum of the unfiltered shot gathers clearly reveal strong linear noise occupying narrow, high-energy ridges aligned along specific dip directions. These ridges correspond to direct arrivals, refracted waves, and streamer-related disturbances, exhibiting apparent velocities distinct from those of the primary reflections. In contrast, reflection energy appears as broader, diffuse regions indicative of hyperbolic moveout. The clear separation of noise and signal in the F-K domain confirms the suitability of dip-based filtering for this dataset.
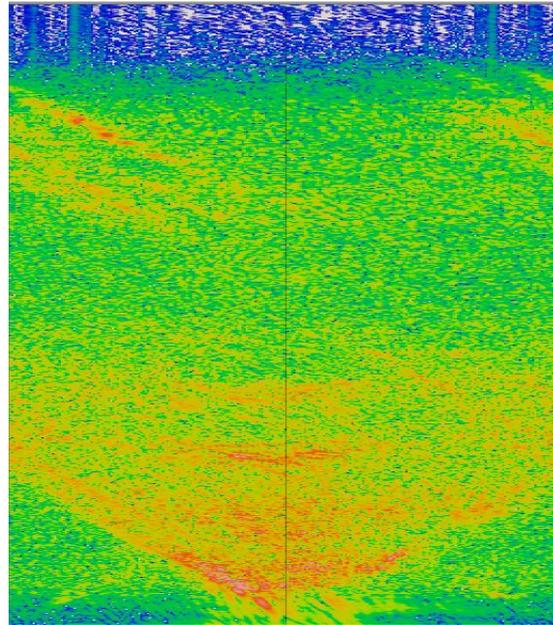
Figure 1. Initial F-K spectrum of the unfiltered shot gathers

Performance of Optimized F-K Filtering on shot gathers

Application of the optimized F-K filter results in a substantial reduction of linear noise along the near- and mid-offsets. The reject zone constructed using adaptive dip discrimination and time offset variant windowing effectively removes coherent linear noise without introducing visible spectral leakage. Post filtering gathers show improved continuity of reflection events, with noise ridges significantly attenuated while maintaining the integrity of higher dip reflections.

Compared with conventional FK filtering, the optimized approach preserves a larger portion of primary reflection energy, particularly in early time windows where noise and signal dips overlap. No visible artefacts, such as ringing or aliasing, were observed in the filtered gathers.
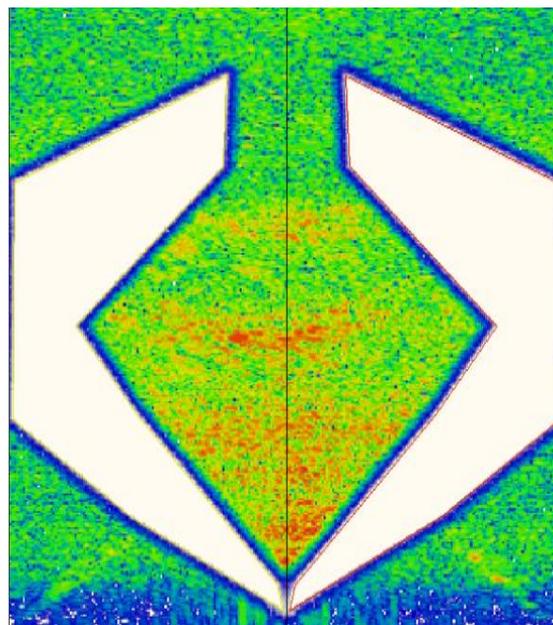

Figure 2. Rejection zone in the F-K spectrum

Amplitude Spectrum and Bandwidth Preservation

Spectral analysis shows that the optimized filter removes energy primarily within the low-frequency range (5–15 Hz) associated with linear noise. The useful bandwidth of the reflections, extending approximately from 15 to 85 Hz, remains largely unchanged. This indicates that the filtering strategy successfully avoids unnecessary suppression of signal frequencies.

The amplitude spectra also reveal reduced low-frequency dominance, which improves the vertical resolution of subsequent imaging steps. The minimal distortion of mid- and high-frequency components demonstrates the filter's ability to maintain reflection fidelity.
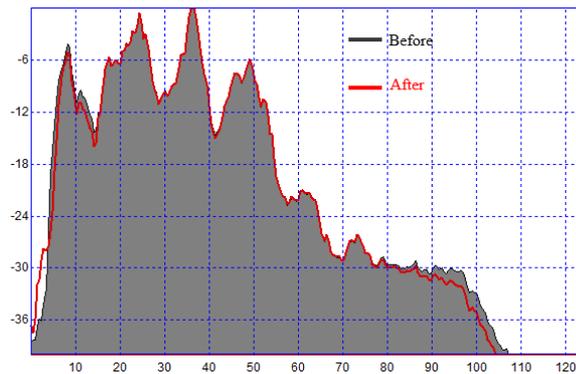

Figure 3. Comparison amplitude spectrum analysis before and after F-K filtering

Effect on stack section

Stacked sections produced from the filtered gathers show notable improvements in reflector continuity and lateral coherency. Target reflectors that were previously masked by linear noise now appear clearly, revealing geological features that were indistinguishable in the unfiltered stack. Deeper reflectors also show increased continuity due to improved pre-stack conditioning.

(a)
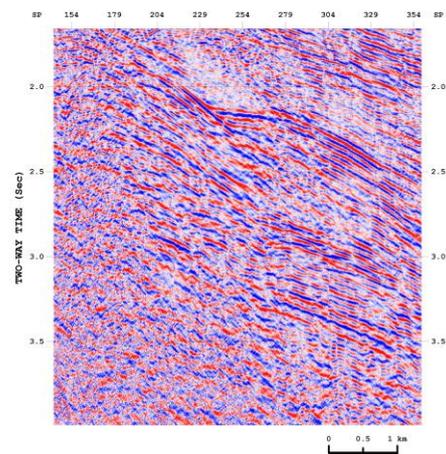
(b)

Figure 4. Comparison stack section (a) before and (b) after F-K filtering
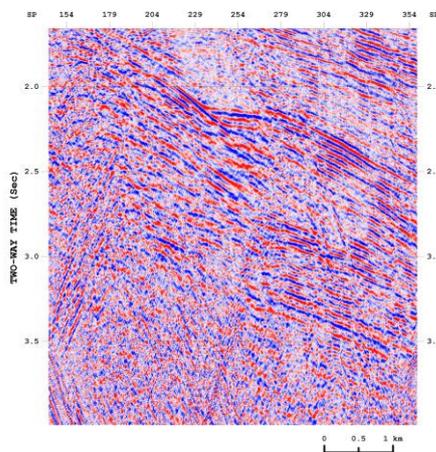
No evidence of reflection truncation or dip-dependent artefacts is observed, indicating that directional FK filtering did not remove meaningful signal energy. The stack exhibits a smoother amplitude distribution and reduced clutter in the early-time zone.

DISCUSSION

The improvements obtained through the optimized F-K workflow primarily stem from its ability to intelligently discriminate signal from noise based on wavefield

propagation characteristics. By analyzing apparent velocity and spectral energy distribution, the filter successfully excludes coherent linear noise without excessively broad muting zones. This is particularly important in shallow marine settings, where primary reflections often exhibit dips that overlap with noise.

The observed enhancement in reflector visibility especially in the below 2 seconds suggests that linear noise had previously been obscuring crucial geological information. The clearer delineation of these reflectors supports more reliable structural interpretation and better constraint during velocity model building. It also indicates that the noise belonged to a wavefield distinct from the target signal rather than forming part of scattered or converted energy that might otherwise require different treatment.

Directional analysis also proves essential for preventing unnecessary removal of dipping geological structures. By reducing filtering to only the noise propagation direction, seismic continuity is preserved along the geologically relevant dip direction. This demonstrates that directional F-K filtering can be advantageous over conventional when streamer geometry or environmental factors generate spatial asymmetry in noise patterns. The moderate SNR improvements (4–8 dB) across multiple offset gates imply that the filter is efficient not merely in early time windows but across a broad time range. This suggests that the spatial coherence of the noise extends beyond the direct arrival zone, reinforcing the need for prestack noise attenuation rather than relying solely on stacking to suppress coherent interference.

Finally, improvements measured in stacked sections confirm the cumulative benefit of the filtering reduced clutter, improved event continuity, and enhanced reflector amplitude balance all contribute to a more geologically interpretable seismic image. This strengthened imaging performance highlights the significance of optimized pre-stack conditioning rather than relying exclusively on downstream processes such as migration or attribute analysis.

CONCLUSION
This study confirms that optimized F–K domain filtering offers a significant improvement in suppressing coherent linear noise in 2D marine seismic data. By characterizing noise through apparent velocity and dip behaviour, and implementing time–offset adaptive cones, the method effectively attenuates unwanted energy while preserving primary reflections. Results show measurable gains in signal-to-noise ratio, clearer reflector continuity, and improved stack quality compared to conventional F–K filtering. These outcomes demonstrate that F–K optimization is a valuable enhancement to early pre-stack processing and provides a strong foundation for subsequent imaging and interpretation workflows.

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