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PREDICTIVE DECONVOLUTION BASED ON SEISMIC WAVEFORM DIAGNOSTICS FOR ENHANCED MARINE IMAGING RESOLUTION

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Abstract. Short-period multiples are a persistent problem in marine seismic processing, particularly in shallow-water environments where near-surface reverberations interfere with primary reflections and decrease temporal resolution. Predictive deconvolution remains a widely used method for attenuating such coherent noise. However, conventional implementations often apply fixed operator parameters, limiting their adaptability to waveform variations across time and offset. This study introduces a predictive deconvolution framework guided by seismic waveform diagnostics, in which operator parameters specifically prediction lag and filter length are selected based on trace characteristics such as waveform periodicity and spectral energy distribution. The approach is designed to improve multiple suppression while preserving the fidelity of primary reflections on a 2D marine pre-stack seismic dataset acquired in a shallow offshore setting characterized by strong short-period multiples and limited bandwidth. The results demonstrate around 25% increase in frequency bandwidth, improved reflector continuity, and reduced coherent noise in pre-stack gathers. Compared to conventional deconvolution, the waveform informed design achieves a more effective balance between attenuation and resolution. The proposed approach is applicable to modern marine datasets where high-resolution imaging is limited by near-surface interference.

Keywords: *Multiple Attenuation, Predictive Deconvolution, Spectral Enhancement, Seismic Imaging, Seismic Waveform.*
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INTRODUCTION

Short-period multiples especially in shallow marine environments pose a significant barrier to high resolution seismic imaging. Reverberations from water layers and near-surface reflectors often overlap primary events, reducing temporal resolution and obscuring subtle stratigraphic features critical for accurate subsurface interpretation [1]. Predictive deconvolution remains one of the primary tools for multiple attenuation in 2D marine seismic data. However, its performance hinges on appropriately selected operator parameters prediction lag and operator length anchored in assumptions of stationarity and minimum-phase wavelets. Intelligent parameter choice is crucial, but existing fixed parameter workflows often underperform in heterogeneous seismic environments, resulting in either inadequate multiple suppression or distortion of primary signals [2].

Recent advances emphasize data adaptive filter design demonstrated improved predictive deconvolution via non-Gaussian optimization across offsets, while deep learning approaches have emerged for semi-supervised multiple attenuation, particularly in shallow marine environments where high-resolution imaging is required [3]. Although promising, many adaptive techniques introduce computational complexity or require large training datasets, limiting practicality in typical offshore processing. The convolutional model presumes that the seismic wavelet remains constant over time and maintains a consistent phase. Every seismic trace is produced by convolving the wavelet with the reflectivity of the subsurface [4]. Seismic wavefields in both the depth and time domains share a close relationship and are described using comparable mathematical formulations [5].

In this work, we propose a waveform diagnostic guided predictive deconvolution framework. Operator parameters are derived directly from waveform periodicity, spectral signatures, and Autocorrelation side-lobe structure, on a trace-by-trace basis. This approach locally optimizes filter design to enhance multiple suppression while preserving primary event fidelity.

The method is validated on a real 2D prestack marine seismic dataset, acquired in a shallow-water setting characterized by strong multiple interference. Our evaluation focuses on spectral bandwidth increasing, multiple suppression, and reflector continuity improvements in stacked sections. We demonstrate that waveform diagnostics can effectively balance attenuation and resolution delivering a practical, scalable enhancement to standard marine seismic processing.

METHODS

Data

This study utilizes a 2D marine prestack seismic dataset acquired in a shallow-water offshore environment with an average water depth of less than 50 meters. The acquisition geometry consisted of a single towed streamer with 96 hydrophone channels spaced at 25 meters, yielding a maximum offset of 2,400 meters. The source was air gun with a shot interval of 12.5 meters and a sampling interval of 4 milliseconds. The recording system captured data in the nominal bandwidth of 0–125 Hz.

The seismic line traverses relatively flat bathymetry with minimal lateral structural variation, but is strongly influenced by near-surface and soft sediment layers that generate short-period water bottom and interbed multiples. These characteristics make the dataset ideal for testing adaptive deconvolution approaches aimed at coherent multiple suppression and resolution recovery.

Preprocessing and Data Conditioning

Before applying predictive deconvolution, the seismic dataset underwent several preprocessing workflow to prepare the seismic traces for the stable operator design across all offsets and time windows. The following conditioning sequence was applied using Vista seismic data processing environment:

- **Geometry Assignment**
  First, geometry information assigned and QC using navigation file data (SPS file) and SEG-Y headers to specify coordinate for all sources and receiver position, trace labelling and assign unique numbers. Data must be updated with correct geometry [6]. The processing can not be continued to the next step if the geometry is not correctly updated.
- **Trace Editing**
  Trace editing eliminated dead or noisy channels. This step can be done manual editing or automatic trace editing using a combination of amplitude variance thresholding and median filtering to maintain signal to noise ratio.
- **Amplitude Recovery**
  To compensate for geometric spreading losses and time-dependent attenuation, a spherical divergence correction was applied using a time-power gain function of the form

$$g(t) = \left[\frac{v(t)}{v(0)}\right]^2 \frac{t}{t(0)} \quad (1)$$

  where t is two-way travel time, v(t) is RMS velocity and v(0) is velocity at specified time t(0). This gain curve was carefully chosen to restore deeper reflectors while avoiding over-amplification of noise in the later time windows. Following divergence correction, trace-wise RMS normalization was performed within 1-second overlapping windows to equalize energy across offsets and shots. This step ensures that all traces contribute evenly to the predictive deconvolution operator estimation, particularly when parameters are computed using envelope and autocorrelation metrics. Failure to balance amplitude can lead to biased operator design and uneven multiple suppression performance [7].
- **Noise Attenuation**
  A zero phase bandpass filter (3-125 Hz) was applied to remove low frequency swell noise, FK filter to remove linear noise while preserving lateral coherence. This noise attenuation was applied to each shot gather and improved lateral continuity of events and reduced random phase fluctuations that could obscure side lobe structures in the autocorrelation function.

Predictive Deconvolution

Predictive deconvolution is a model driven filtering method that operates under the assumption that multiples are temporally predictable, while primary reflections behave as an uncorrelated spike train. In its conventional form, the filter is designed using the Wiener-Levinson algorithm, which computes an operator that minimizes the least-squares error between a predicted future signal and the actual recorded trace. The filter depends on two key parameters: the prediction lag L, representing the delay at which coherent multiples appear, and the operator length N, determining how many samples are used to estimate that prediction. While this technique is theoretically effective, its performance in real datasets is highly sensitive to the choice of L and N, and conventional implementations often apply fixed values across an entire line or volume. Such global parameter choices are inadequate for datasets exhibiting significant waveform variation due to near-surface heterogeneity, depth dependent attenuation, or offset induced phase shifts.

An adaptive predictive deconvolution approach is introduced, allowing the automatic adjustment of prediction lag and filter length based on the periodicity and characteristics of various multiple reflections. Comparative modeling demonstrates that this technique performs notably better when handling high-energy interlayer multiples with complex and unclear wave patterns, as confirmed by real seismic data. Several important resulting sections are examined and contrasted, highlighting the strong potential of the method [8]. To take full advantage of the spatial characteristics of seismic data and suppress noise, several authors developed multichannel predictive deconvolution [9][10].

Seismic Waveform Diagnostics

Instead of using fixed values for the prediction lag L and operator length N across the entire dataset, we introduce a more flexible, diagnostic-based approach. For each seismic trace, a set of waveform attributes is computed to guide the selection of these parameters in a way that responds to the local signal behavior. This diagnostic analyzes each trace individually, capturing variations in waveform periodicity, spectral shape, and coherent energy patterns. By tailoring the deconvolution operator to these features, the method adapts to changing subsurface conditions while preserving signal fidelity. The key diagnostics used in this process are described in the following steps:

- **Autocorrelation envelope**
  Identify the presence of multiples, we examine the autocorrelation function of each seismic trace and compute its Hilbert envelope, which captures the instantaneous amplitude of the autocorrelation signal over time. This envelope helps highlight where side lobes secondary peaks associated with repeating patterns occur in the trace. These side lobes typically represent short period multiples, such as water bottom reverberations or interbed echoes, and are seen at lag times corresponding to their two-way travel paths. By focusing on the first prominent side lobes following the main peak, we can estimate the dominant periodicity of the multiples, which is essential for determining the prediction lag L in the deconvolution filter. One of the key advantages of using the envelope is its ability to smooth out random noise and phase inconsistencies, allowing for more reliable detection of true periodic energy. This makes the process more robust than simply relying on raw autocorrelation peaks[12]. Ultimately, this step ensures that the filter targets coherent, high-energy multiples while minimizing the risk of mistaking noise or weak signals for true periodicity.
- **Dominant period detection**

Estimate the prediction lag L, we analyze the autocorrelation envelope of each seismic trace and identify the first prominent side lobes that follows the main peak, which typically corresponds to the period of short-period multiples. The time interval between the central peak and this side lobes is interpreted as the dominant multiple period and is assigned as L. To avoid errors from noise or weak reflectivity, only side lobes with amplitudes greater than 15% of the main peak are considered valid[13]. This threshold ensures that only physically meaningful, coherent periodicities are used in the operator design, reducing the risk of applying filters based on random signal fluctuations.

- **Energy decay curve**
  Determine the appropriate operator length N, we examine how much energy remains in the autocorrelation function beyond the predicted lag L. Specifically, we look for the duration over which this energy stays above 5% of the total normalized trace energy. This approach ensures that the filter is long enough to capture and suppress the predictable multiple energy, but not so long that it affects unrelated parts of the signal or diminishes primary reflections.
- **Spectral kurtosis**
  Prevent the operator length N from becoming excessively long and unintentionally distorting the primary reflection spectrum, we use spectral kurtosis as a control metric. This parameter helps detect whether the resulting filter causes the spectrum to become too flat, which would indicate oversuppression of meaningful high frequency content. If the spectral kurtosis after filtering was reduced by more than 15% compared to its original value, the operator length was automatically shortened. This adjustment ensures that the filter remains effective in suppressing multiples without compromising the resolution of primary seismic events [9].

Integration with Conventional Processing Workflow

The waveform guided predictive deconvolution was applied directly after the data conditioning phase and prior to normal moveout (NMO) correction, ensuring that the filter operated on unaltered offset dependent waveform features. Once deconvolution was complete, standard velocity analysis and NMO correction were performed to generate Common Midpoint (CMP) gathers. To assess how the deconvolution affected velocity estimation, we compared the coherency and sharpness of semblance panels before and after filtering.

RESULT AND DISCUSSION

Spectral Bandwidth Enhancement

The frequency spectra from near offset prestack gathers reveal a clear improvement in usable bandwidth after applying the waveform guided predictive deconvolution. Figure 1 shows before a filtering, most of the spectral energy was concentrated in the 18 to 30 Hz range, with noticeable attenuation above 42 Hz. Following the application of the diagnostic based filter, the post deconvolution spectrum in Figure 1 shows broader energy distribution, with significant amplitude preserved up to approximately 90 Hz, particularly within the 45–90 Hz range. The –3 dB bandwidth increased by roughly 24 to 27%, varying across CMP locations.

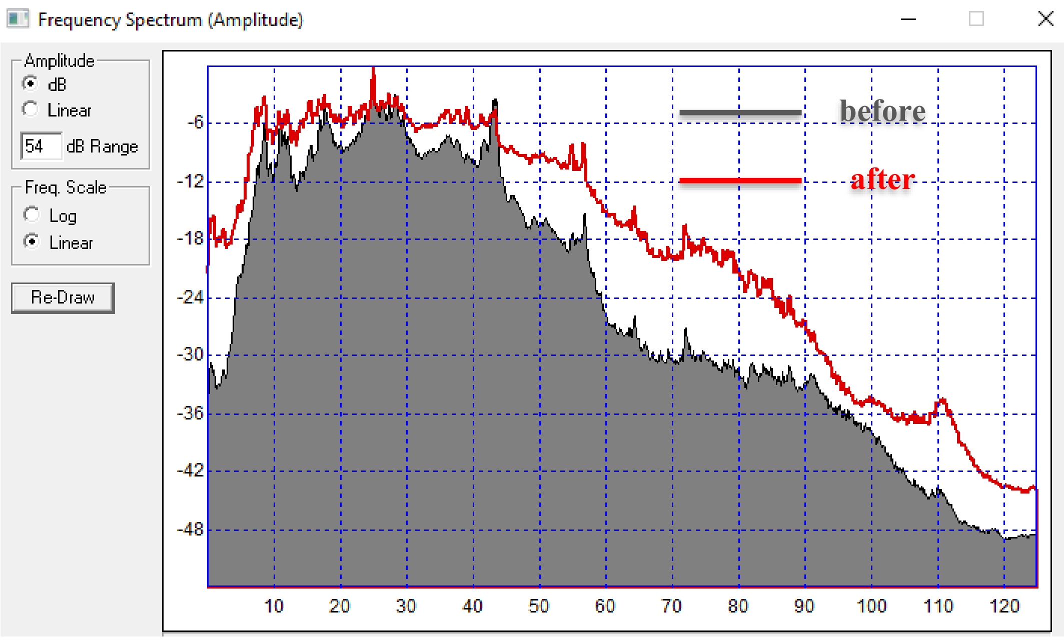


Figure. 1 Frequency spectra before (grey) and after (red) waveform guided predictive deconvolution

This enhancement can be attributed to the selective removal of short-period multiples, which often obscure high frequency primary reflections. By tuning the deconvolution operator based on waveform periodicity and spectral shape, the filter was able to retain meaningful high frequency components while eliminating redundant, low-lag energy. These outcomes are consistent with improvements reported in recent adaptive deconvolution studies, including those involving spectral decomposition and waveform curvature analysis for improved multiple suppression [14].

Autocorrelation

The autocorrelation functions computed from representative prestack traces clearly demonstrate the effectiveness of the proposed method in suppressing short-period multiples. In the unfiltered data as shows in Figure 2, strong side-lobes appear at lag intervals of approximately 24 to 30 milliseconds, which is consistent with shallow water bottom reverberations commonly observed in marine environments. After applying the waveform guided predictive deconvolution, these side lobes in Figure 3 were significantly reduced by an average of 45 to 50%, while the amplitude of the central peak remained stable. This suggests that the filter successfully removed coherent, predictable energy associated with multiples without compromising the integrity of the primary reflections. Additionally, the autocorrelation envelope decays more rapidly after filtering, further indicating that unwanted periodic energy has been effectively attenuated. These improvements highlight the advantage of trace specific parameter estimation particularly the dynamic selection of prediction lag L and operator length N compared to traditional fixed operator approaches.

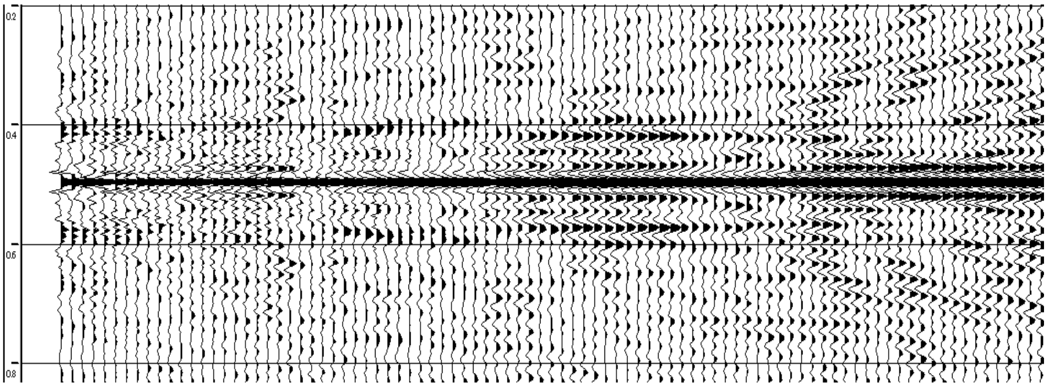


Figure. 2 Autocorrelation before waveform guided predictive deconvolution

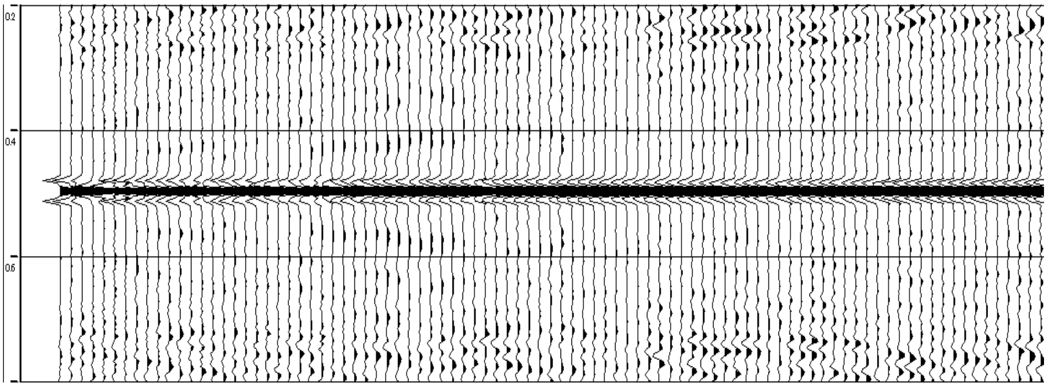
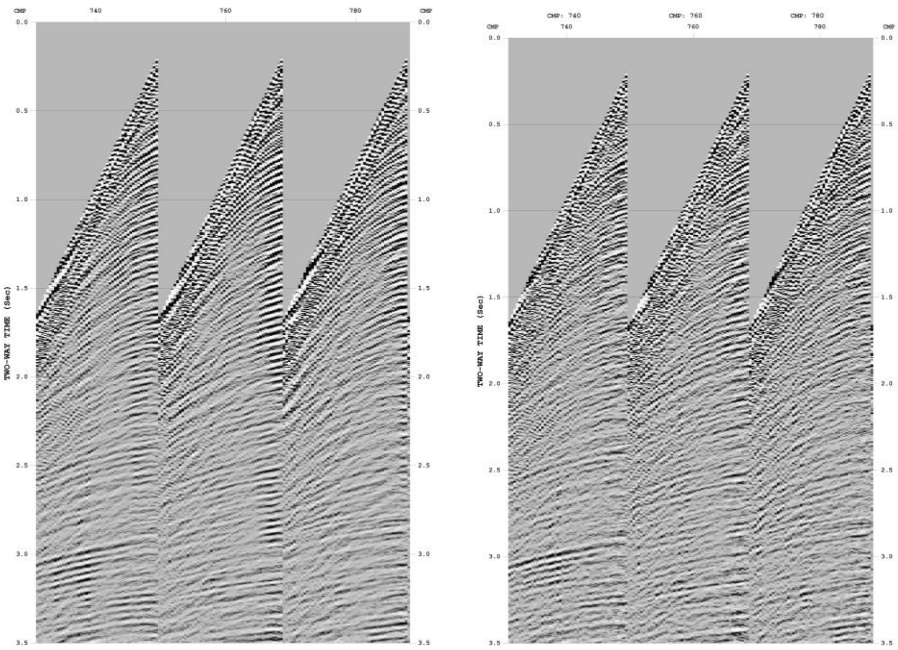


Figure. 3 Autocorrelation after waveform guided predictive deconvolution

Improvement in Pre-Stack and Stack Domain

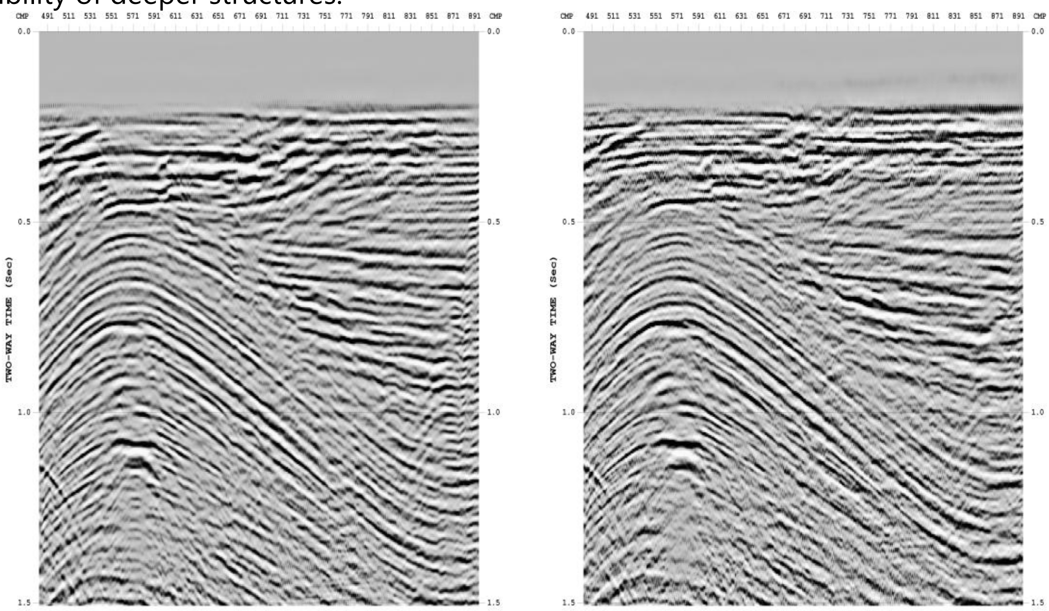
In the prestack domain, the improvement in trace by trace coherence is particularly evident shows in Figure 4, especially at mid to far offsets where reverberations had previously covered continuous reflection patterns. After applying the adaptive predictive deconvolution, the normalized cross-correlation between neighboring traces increased by approximately 12 to 15% across several representative CMPs. This enhancement confirms that the method successfully restored lateral continuity by suppressing short-period multiples that interfere with true reflectivity. The resulting increase in coherency also contributed to more reliable velocity analysis. This is supported by the semblance panels, which display sharper, more distinct velocity peaks and improved event focusing after filtering.



(a) (b)

Figure. 4 CMP gather (a) before and (b) after waveform guided predictive deconvolution

In the stacked domain, the benefits of waveform guided deconvolution become even more apparent in Figure 5. The initial stacked section prior to deconvolution shows smeared and discontinuous reflectors just beneath the water bottom, along with poor visibility of deeper structures.



(a) (b)

Figure. 5 Stack section (a) before and (b) after waveform guided predictive deconvolution

Following deconvolution, the final stacked image reveals much clearer and more continuous reflectors, particularly within the central portion of the profile where an anticline structure is present. The flanks of this anticline, which were previously obscured by reverberation noise and waveform distortion, now appear more sharply delineated and structurally coherent. Horizon tracking through deeper reflectors show better alignment with the expected geological stratigraphy, suggesting improved imaging fidelity across the section.

CONCLUSION

This study presented a waveform guided predictive deconvolution approach aimed at improving temporal resolution and imaging clarity in 2D marine prestack seismic data. Unlike conventional methods that rely on fixed filter parameters, our technique adapts to the unique characteristics of each seismic trace. By analyzing waveform attributes such as the autocorrelation envelope, spectral distribution, and signal periodicity the method dynamically determines the optimal prediction lag and operator length. This filter design more effective suppression of short-period multiples without reduce primary reflections.

We applied the method to a real shallow water marine dataset known for strong reverberations and limited high-frequency content. The results demonstrated clear improvements on frequency bandwidth expanded by 24–27%, and side lobe energy in the autocorrelation function was reduced by nearly half. These enhancements translated into better lateral coherence, more reliable velocity analysis, and cleaner, more continuous reflectors in both prestack and stacked domains. The imaging of a central anticline structure, in particular, showed significant improvement in clarity and structural definition.

In summary, this waveform driven approach offers a practical and adaptable upgrade to traditional predictive deconvolution workflows. It is especially useful in challenging marine environments where waveform variability and reverberation noise limit conventional techniques. Looking ahead, this method could be extended to 3D datasets or integrated with machine learning tools to further automate and refine seismic data enhancement [15].

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