Clipped amplitude reconstruction for ocean bottom node data using projection onto convex sets

T. Seher[1]

[1] TGS

Summary

Amplitudes recorded by seismic receivers are usually clipped when the signal level exceeds the maximum signal that can be safely recorded by the instrument. Clipping leads to spectral leakage of energy from the signal into the noise band causing spectral distortion. To improve the fidelity of seismic recordings, this spectral distortion should be mitigated in the seismic processing sequence. To this end, I have investigated Fourier transform based interpolation methods. These methods usually apply iterative reconstruction techniques such as the projection onto convex sets algorithm and can be readily repurposed for the reconstruction of clipped seismic amplitudes. In more detail, my proposed algorithm involves identification of clipped samples and reconstruction of the correct amplitudes by iteratively thresholding the spectrum. This proposed algorithm allows effective "declipping" of the seismic data. For a typical ocean-bottom seismometer record, clipping only affects the near-offset traces and corrupts only a few samples. However, carefully mitigating this clipping in ocean-bottom hydrophone data has allowed me to improve the signal-to-noise ratio of the clipped samples by 14 dB. The improvement of the signal fidelity early in the seismic processing sequence benefits subsequent transform-based processing steps such as up/down deconvolution.

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Introduction

Seismic sensors saturate when the signal level exceeds the dynamic range of the system (Strudley and Nash, 2009). Therefore, ocean-bottom recordings of strong events such as the direct arrivals will be clipped if the recorded voltage exceeds the instrument's maximum voltage. This clipping of strong amplitudes leads to spectral leakage and an increased noise floor in the seismic spectra. If the resulting spectral leakage is not correctly handled during processing, it may negatively affect processes such as up/down deconvolution, which rely on the accuracy of the recorded seismic amplitudes (Bagaini and Boiero, 2022).

The quality of seismic processing strongly depends on the input data quality. One common issue that detrimentally impacts seismic processing is the presence of noise (e.g., spikes or bias in the recorded data) that distorts the spectral estimates of the true signal, and a variety of techniques exist to tackle those distortions (e.g., despike or detrend). Clipped events similarly distort the true signal. In this study, I introduce a new technique for reconstructing clipped seismic amplitudes (i.e., declip) based on frequency-wavenumber domain thresholding. Fourier transform based methods are popular for the regularization and interpolation of seismic data (Duijndam et al., 1999; Xu et al., 2005; Abma and Kabir, 2006). With a few minor modifications, these methods can be repurposed for the reconstruction of clipped data. For example, the projection onto convex sets (POCS) algorithm (Abma and Kabir, 2006) has previously been applied for the reconstruction of clipped seismometer recordings in global earthquake seismology (Zhang et al., 2016). My new method extends the algorithm proposed by Zhang et al. (2016) by using a windowed 2D Fourier transform in place of the 1D solution proposed in the original paper.

In this study, I will present my new algorithm for the reconstruction of clipped seismic traces and illustrate its use with a synthetic example. I will then demonstrate that my new algorithm mitigates clipping for a single receiver from the North Sea, and finally show the impact on up/down deconvolution (Amundsen, 2020) for an entire receiver line.

Method

The POCS algorithm implemented in this study is a modified version of the algorithm described by Abma and Kabir (2006). The crucial assumption of this algorithm is that larger spectral components are less affected by spectral leakage due to gaps in a sampled function than weaker spectral components, which can be used to guide the reconstruction of those gaps. I exploit this characteristic to mitigate the effect of clipping in seismic data.

My algorithm has two main steps. In the first step, clipped samples are identified based on the absolute value of the amplitudes. In the second step, the POCS algorithm reconstructs the true amplitudes of the clipped samples in an iterative procedure. During each iteration, the data are Fourier transformed, weak spectral components are set to zero using a decreasing magnitude threshold, and the modified spectrum is inverse Fourier transformed. This has the effect of predicting the data corresponding to the reconstructed spectrum. Subsequently, the clipped samples are replaced with the predicted samples. Care is taken not to decrease positive clipped values or increase negative clipped values (i.e., the sign of the clipped amplitudes is conserved). The threshold is then lowered, and the algorithm proceeds to the next iteration. Finally, after a fixed number of iterations the algorithm terminates, and the resulting data is written to disk.

To illustrate the new algorithm, I created a simple example by convolving a series of spikes with a 30 Hz source wavelet (Figure 1a). I then clipped the seismic data at 60% of the maximum absolute amplitude, resulting in a corruption of 5% of the samples. Examining the spectra (Figure 1b), I observe spectral distortion in the signal band (< 75 Hz) and spectral leakage in the noise band (> 75 Hz). Applying my reconstruction algorithm mitigates the spectral distortion in the signal band and reduces the spectral leakage in the noise band. After application of the algorithm, the noise floor of the reconstructed data is close to the noise floor of the true data.

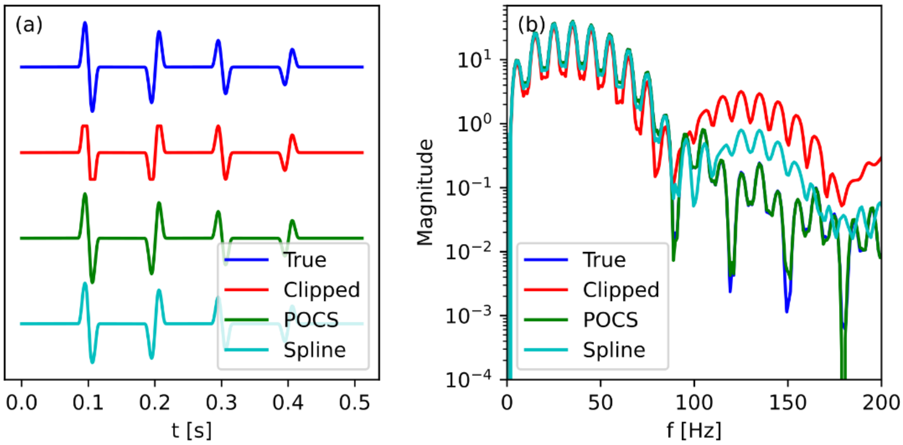

***Figure 1** Synthetic example showing the effects of clipping and clipped amplitude reconstruction in the time domain (a) and the frequency domain (b).*

To demonstrate the efficiency of the proposed method, I compare my POCS algorithm with a reconstruction method based on the cubic spline interpolation of the clipped samples (Figure 1). Both methods allow reconstruction of the clipped samples. However, the POCS algorithm outperforms the spline-based method. The signal-to-noise ratio of the input clipped samples is 11 dB, which is increased to 58 dB using my POCS reconstruction algorithm. For comparison, the spline-based reconstruction only achieves a signal-to-noise ratio of 23 dB. I note that the signal-to-noise estimate is estimated over the clipped samples only to avoid normalization problems, because the number of unclipped samples not affected by clipping is significantly larger than the number of clipped samples.

Examples

As a demonstration of the effectiveness of my new algorithm, I apply my reconstruction technique to clipped hydrophone recordings from an OBN survey in the North Sea (Figure 2). For this survey, clipping affects only one in a thousand traces. Clipping can be readily identified based on the known dynamic range of the instruments. Every value larger/smaller than a known threshold is clipped. For processing this field data example, I have selected a window size of 116 traces and 285 samples that showed clipping. Inside the reconstruction window approximately 0.2% of the samples are corrupted affecting only 7 traces. I note that most of the data are unaffected by clipping. After the application of my 2D POCS algorithm, the clipping is successfully mitigated, and the signal-to-noise ratio of the clipped samples is improved by approximately 14 dB. The reconstructed data is then used in subsequent processing steps.

Finally, I applied my clipped amplitude reconstruction algorithm to a receiver line from a seismic survey in the North Sea to demonstrate that the reduction of spectral leakage improves the performance of up/down deconvolution. I processed the dataset with and without declipping using identical processing flows until up/down deconvolution and estimated the difference between the resulting brute stacks. Figure 3a shows the brute stack of the data after up/down deconvolution with declipping. Figure 3b shows the difference between the two datasets that can be attributed to the presence of clipping. While clipping in this dataset only affected the direct arrival, the spectral division as part of up/down deconvolution leads to changes in the entire seismic trace. This effect is most obvious for the first order seafloor multiple around 0.2 s but impacts most strong multiples in the seismic section.

Discussion and Conclusion

The POCS interpolation algorithm can be modified to handle the reconstruction of clipped seismic traces. By effectively tracking clipped samples the proposed algorithm is superior to an approach removing and interpolating entire corrupted traces for two reasons. One, the algorithm conserves the unclipped amplitudes. Two, the algorithm exploits information about the sign of the clipped amplitudes. The reconstructed positive amplitudes must be larger than the clip value and vice versa for negative amplitudes.

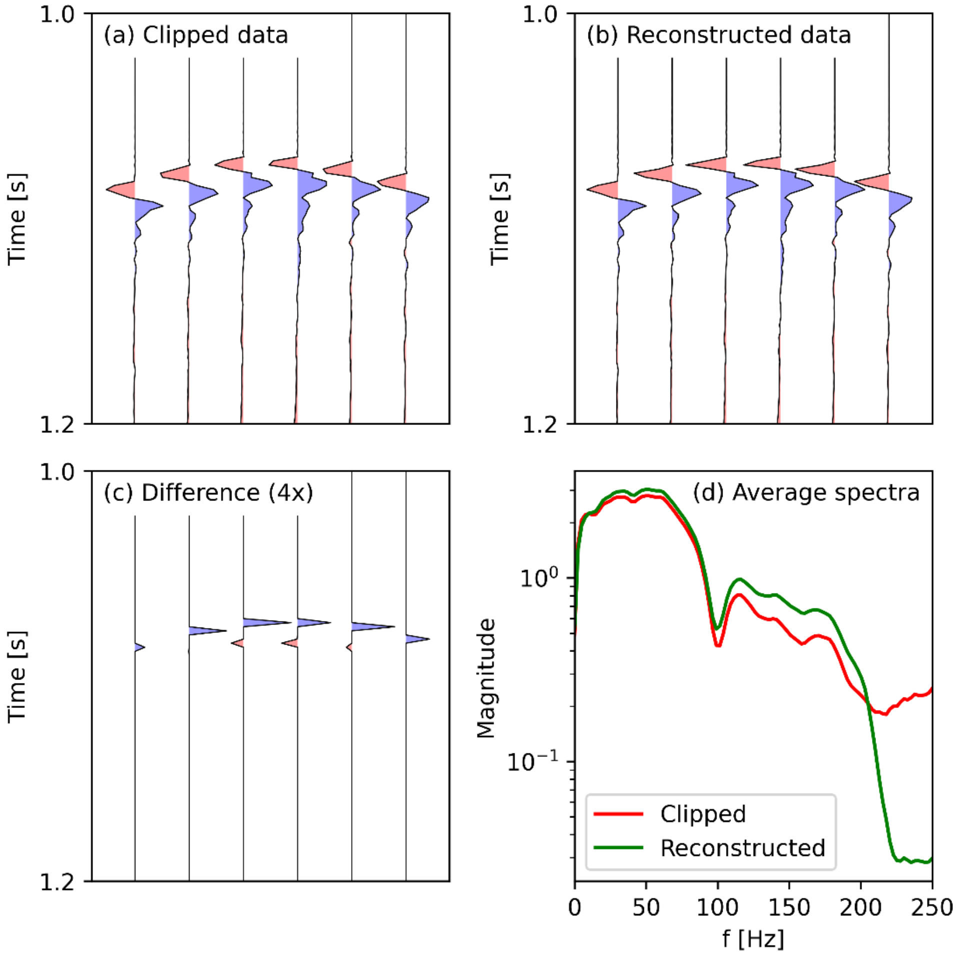

Figure 2 *Real data example showing the effect of clipped data reconstruction. Figure (a) shows the corrupted input traces and figure (b) the reconstructed traces. Figure (c) shows the difference between the clipped and reconstructed data and figure (d) the average spectrum for the input and output data.*

For OBN data the algorithm can be easily applied in common receiver gathers treating the data either as 1D traces or 2D records. The 3D extension of the method is possible but may be challenging because the algorithm is ideally applied early in the processing sequence prior to regularization. At this stage, finding adjacent shots in the inline direction along the sail line is easy, but finding adjacent shots in the crossline perpendicular to the sail line can be difficult. This difficulty can arise for example due to the presence of incomplete sail lines and repeated shots. In addition, the shot spacing along a sail line tends to be close to regular, compared to the crossline direction where the shot spacing tends to be more erratic. This regularity in the inline direction facilitates the application of a 2D fast Fourier transform.

An additional point of concern is the presence of aliasing in the data. While aliasing is not a major concern for reconstruction with the 1D POCS algorithm, spatial aliasing could be an issue for the 2D algorithm. In my opinion, spatial aliasing does not fundamentally affect the reconstruction for declipping. Unlike its use in spatial regularization, in declipping the POCS algorithm relies primarily on the coherency of the events in the frequency-wavenumber spectrum and not the physically correct location in the spectrum.

The POCS based algorithm described in this study allows reconstruction of clipped amplitudes in OBN data and mitigation of spectral leakage related to the limits of the instruments' dynamic range. While the proposed method can be applied using either 1D or 2D Fourier transforms, I found the windowed 2D Fourier transform to be the most suitable for seismic applications due to the geometry of OBN acquisitions. Addressing the problem of spectral leakage early in the processing sequence benefits up/down deconvolution. Thereby correctly handling spectral leakage should lead to superior seismic products overall.

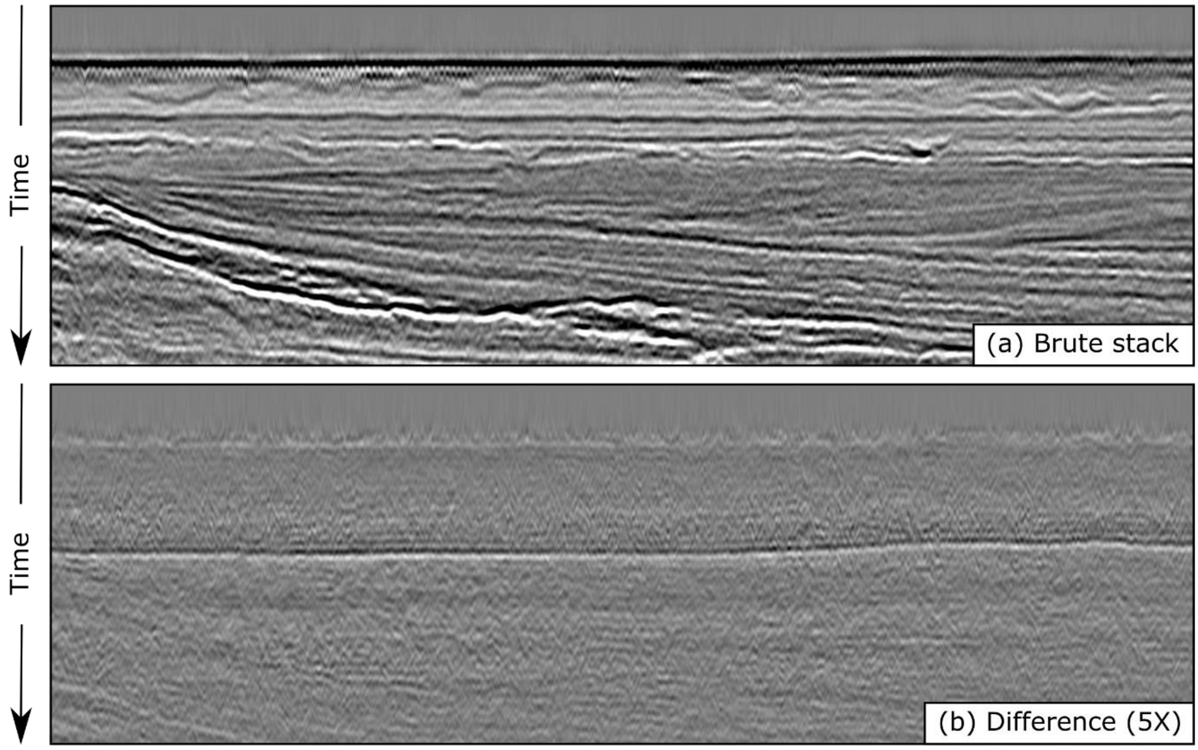

Figure 3 *Real data example showing the effect of clipping on up/down deconvolution. Figures (a) shows the brute stack for one receiver line with declipping applied. Figure (b) shows the difference between the up/down deconvolution results with/without clipped amplitude reconstruction.*

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