Source and receiver amplitude equalization using reciprocity – Application to land seismic data

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Summary

Source and receiver amplitude equalization is necessary when their behavior changes with location within a given survey. Preferably, these corrections are performed in the early stages of processing. However, existing techniques which account for these effects, such as surface-consistent deconvolution, are applicable to primary reflection data only. Therefore, these techniques require prior processing. We developed an alternative method to compensate for source and receiver perturbations which has the advantage of being purely a preprocessing step. It is applicable to the whole seismic trace, and no assumptions are imposed on the subsurface. The method is based on reciprocity of the medium response. As a result of reciprocity, differences between normal and reciprocal recordings can be attributed to the source and receiver perturbations. We applied this technique to single-sensor data acquired in Manistee County, Michigan. At this site, near-surface conditions vary, and this significantly affects the data quality. The application of the equalization procedure led to a significant improvement in signal-to-noise ratio, on both prestack and poststack data.

Introduction

The variability of recordings obtained in land seismics settings cannot be fully explained with linear wave propagation models, since it is also a result of changes in source and receiver behavior within a given survey: the actual acquisition of the wavefield. For example, the source strength and signature are mainly determined by nonlinear deformation of the near-source region. As a consequence, changing near-surface conditions deteriorate the so-called repeatability of the source (Karrenbach, 1994; Aritman, 2001). Problems are also encountered at the receiver side. There, discrepancies between signals recorded by geophones which are only a few meters apart are also commonly observed in the field.

Detection and compensation for these perturbations is necessary in the early stages of processing, since the performance of multichannel filter operations rapidly deteriorates in the presence of amplitude or phase perturbations. This was already recognized by Newman and Mahoney (1973), who demonstrated that the performance of the source and receiver arrays is sensitive to source and receiver perturbations. These arrays, or more generally multichannel or frequency-wavenumber filters, are commonly used for ground roll and multiple attenuation. Despite that compensation for acquisition effects should be done in the early stages of processing, pre-existing surface-consistent deconvolution techniques require pre-processing to isolate primary reflections (Taner and Koehler, 1981; Cambois and Stoffa, 1992).

In contrast, we use an alternative approach to compensate for source and receiver perturbations, which require few or no preprocessing steps. In principle, it can be directly applied to the recorded wavefield, because it uses the whole seismic trace instead of primary reflection data only. Furthermore, it does not require midpoint binning, and no assumptions are imposed on the subsurface. The approach uses reciprocity of the medium response for evaluating lateral source and receiver amplitude variations. As a result of reciprocity, differences between normal and reciprocal traces can be attributed to differences in source strength and receiver coupling. Karrenbach (1994) and Luo and Li (1998) applied this technique to determine the seismic source wavelet, assuming that the receiver perturbations can be neglected. Van Vossen et al. (2004) demonstrated that the latter constraint can be relaxed, adapting the procedure such that both source and receiver amplitude perturbations can be estimated.

Method

We discuss the equalization procedure for single component data, and denote the vertical component of the recorded particle velocity with $v(t, \mathbf{x}_s, \mathbf{x}_r)$, with $\mathbf{x}_s$ and $\mathbf{x}_r$ the source and receiver positions, respectively.

Considering the earth as a linear system for the propagation of seismic waves, the recorded traces satisfy the convolutional model,

$$v(t, \mathbf{x}_s, \mathbf{x}_r) = R(t, \mathbf{x}_r) * G(t, \mathbf{x}_s, \mathbf{x}_r) * S(t, \mathbf{x}_s) \qquad (1)$$

where $R(t, \mathbf{x}_r)$ is the receiver response for the vertical component recordings at surface location $\mathbf{x}_r$, $S(t, \mathbf{x}_s)$ is the source signature at surface position $\mathbf{x}_s$, and $G(t, \mathbf{x}_s, \mathbf{x}_r)$ is the corresponding medium response. The asterisk ($*$) denotes convolution in the time domain.

Application of reciprocity requires symmetric data acquisition. This includes identical source and receiver positions and shot/receiver patterns, and identical source and receiver components. A field study performed by Fenati and Rocca (1984) indicated that in practice, these reciprocal conditions do not have to be met exactly. They observed that the fit between normal and reciprocal traces was not influenced by the choice of a vibratory or explosive source, except at short offsets. Furthermore, in case of a regular acquisition geometry with non-identical source and receiver positions, e.g. when a source is located between two adjacent receivers, interpolation can be used before determining the corrections.

The reciprocity theorem states that the medium response (or Green function) is invariant when the source and receiver positions are interchanged. Reciprocity of the medium response is expressed as:

$$G(t, \mathbf{x}_s, \mathbf{x}_r) = G(t, \mathbf{x}_r, \mathbf{x}_s). \qquad (2)$$

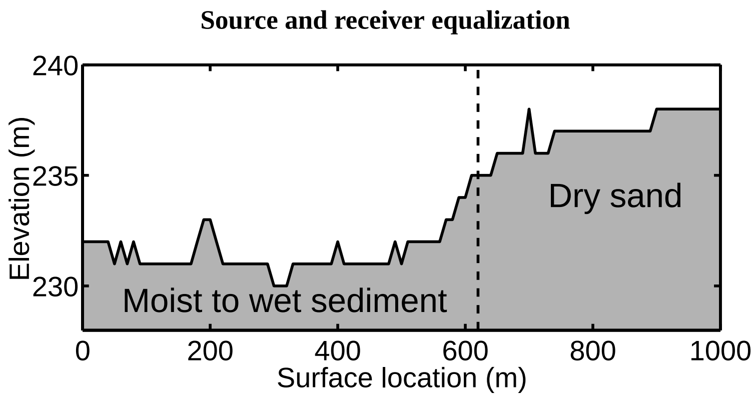

Fig. 1: Surface topography and indication of near-surface material properties along the acquisition line.

This identity requires that the source orientation is similar to the recorded particle velocity component.

We assume that $R(t, \mathbf{x}_r)$ and $S(t, \mathbf{x}_s)$ are surface consistent. This means that effects associated with a particular source or receiver remain constant throughout the recording time, and affect all wave types similarly, regardless of the direction of propagation. The time dependence in $R(t, \mathbf{x}_r)$ and $S(t, \mathbf{x}_s)$ denotes the length of the finite-impulse response filters. Then, the convolutional model and reciprocity result in a system of equations which constrain the individual terms in the convolutional model. Additional information is required to obtain a unique solution to the inverse problem. We use a criterion which minimizes variation in common-offset sections of the medium response (Van Vossen et al. 2004) .

Data description

We illustrate the method on single-sensor data acquired in Manistee County, Michigan. The site is characterized by changing near-surface conditions along the acquisition line. As indicated in Figure 1, these change from moist-to-wet sediments between 0 and 600 m to dry sands beyond that point. The location of the dry sands coincides with the more elevated sections along the acquisition line. Both source and receiver spacing is 10 m. The wavefield is emitted by an array of explosive sources which are located at approximately 5 ft depth.

The conditions for application of the source and receiver equalization method are not exactly met. There are small differences between source and receiver locations (order of a few meters), and the radiation pattern of the shot pattern will differ from the response of a vertical component source positioned at the surface. We assume that we can still treat reciprocity as an exact relationship for determining the source and receiver corrections. Furthermore, an important aspect of the acquisition is that each geophone was deployed at only one surface location, i.e. the location of a geophone was fixed during the whole survey.

In principle, the equalization procedure can be directly applied to recorded data. We only performed trace editing to remove void records, and we muted acausal noise in a few traces. In case of non-identical source-receiver positions, data interpolation is required. We did not have to apply data interpolation before the equalization procedure in this application.

Results on prestack data

The effect of the equalization procedure on prestack data is illustrated in Figures 2 and 3, which show a common shot (CS) and a common receiver (CR) gather with the CS and CR located at $x = 100$ m. For visualization purposes, we applied offset-scaling with the following function:

$$f(\mathbf{x}_o) = 1 + \eta \mathbf{x}_o \qquad (3)$$

with $\eta = 0.10/\Delta x$, where Δx is the source spacing (10 m). In the accompanying paper (Van Vossen et al., 2005), we discuss the characteristics of the source and receiver corrections and investigate the correlation with near-surface material conditions.

The traces in the CS and CR gather have identical and uniform scaling. The differences between the traces in the CR and CS gather are evident. In the CR gather (Figure 3a), the traces generated by sources positioned beyond $x = 600$ m, those are the sources positioned in the dry sand (see Figure 1), are strongly attenuated. The corresponding reciprocal traces in the CS gather (Figure 2a) do not show such a signature of changing near-surface conditions. Another difference between the traces in the CR and CS gather is that correlated events are more pronounced in the near-offset section of the CR domain.

Figures 2b and 3b show the data after the source and receiver equalization. The CR gather shows that reflectivity is measured beyond $x = 600$ m, indicating that we successfully corrected for the source attenuation effect. Furthermore, in both the corrected CR and CS gather, the correlated events are enhanced.

Results on poststack data

We also evaluated the consequences of the applied source and receiver equalization procedure on poststack data. The basic processing sequence comprises the following steps: (i) trace editing, (ii) mute ground roll, air blast and refractions (performed in common receiver domain), (iii) spherical divergence correction, (iv) normal moveout correction, and finally (v) CDP stack. The poststack data are shown in Figure 4a, and the data which has

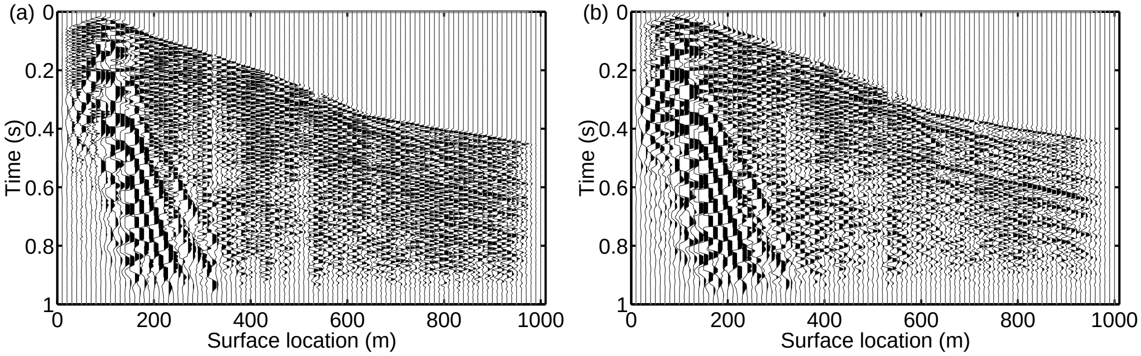

Fig. 2: Effect of source and receiver amplitude correction on a common shot gather (source located at $x = 100$ m): (a) shows the input data, and (b) shows the filtered data. Both plots are scaled with respect to their maximum value (plotted with a similar relative amplitude scaling).

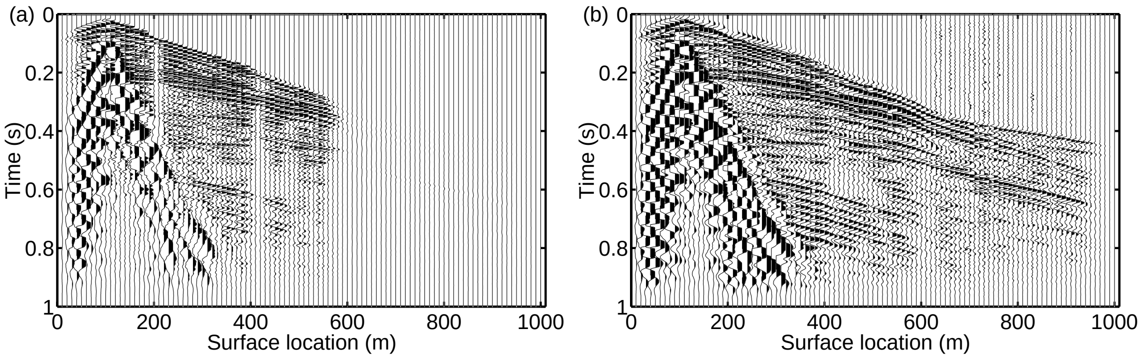

Fig. 3: Effect of source and receiver amplitude correction on a common receiver gather (receiver located at $x = 100$ m): (a) shows the input data, and (b) shows the filtered data. The plots are scaled similar to the common shot gathers in Figure 2.

been compensated for lateral source and receiver differences are shown in Figure 4b. The right part of the sections is dominated by low frequency events, guided waves. A comparison between the poststack data shows that the source and receiver equalization clearly improves the signal-to-noise ratio. Subsurface structure can be easier identified after the equalization procedure and reflectors are more continuous.

Conclusions

We successfully applied a preprocessing technique based on reciprocity to compensate for source and receiver perturbations on field data acquired in Manistee County, Michigan. Both prestack and poststack data show a significant improvement in the signal-to-noise ratio after the source and receiver equalization procedure. We observed significant improvements in both the CR and CS gathers, indicating that both source and receiver perturbations have to be taken into account to properly compensate for acquisition effects.

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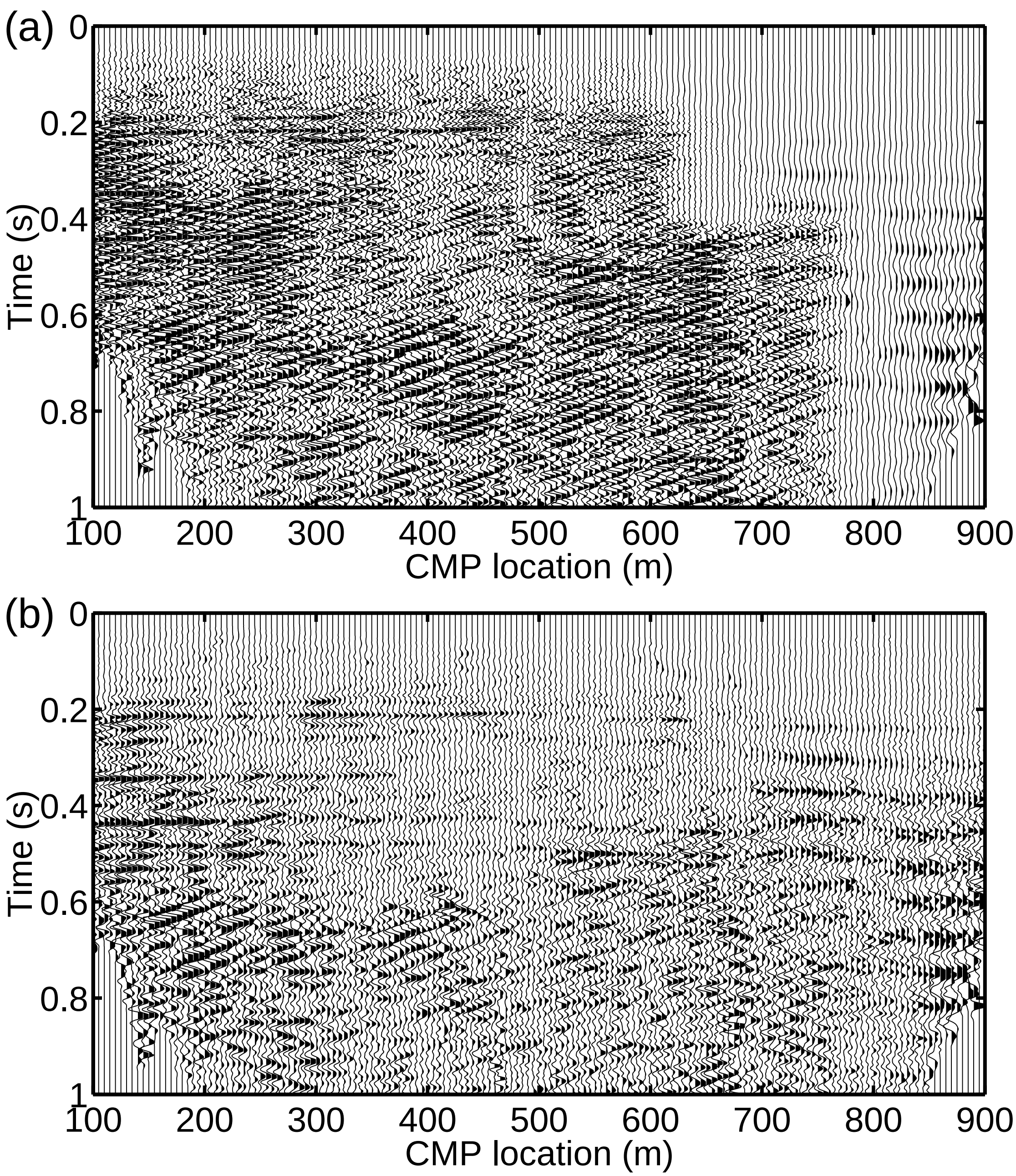

Fig. 4: The effect of source and receiver equalization on CDP stacked data. (a) shows the uncorrected data, and (b) the corrected data.