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STATION-CONSISTENT DECONVOLUTION FOR MULTI-SOURCE BOREHOLE SEISMIC DATA

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ABSTRACT

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Receiver coupling variations within a downhole array can occur for a variety of reasons but the effects are most severe when there is an absence of cement behind casing. In such a setting, source-generated body waves couple to the casing and produce axial particle motion which is picked up on the vertical component as high amplitude, narrow band noise. This noise repeats for all shots and has a characteristic spectrum for each receiver. So long as there are more good receivers than bad, robust estimation procedures allow the unwanted residual receiver response to be estimated and removed. Since the vertical component is most severely affected and is also essential for compressional wave imaging it is critical to remove the receiver coupling variations within the array before further processing.

We adapt the well-known process of surface-consistent deconvolution to the multi-source VSP geometry where a multi-component downhole array remains stationary. The offset and CMP terms of surface-consistent deconvolution for surface seismic data are replaced by a distance-indexed average term, estimated using a novel re-indexing of shot-receiver pairs. Additionally, a frequency-independent scale factor is optionally included to handle the inevitable rotation of horizontal components. The source and receiver terms are estimated using a median or trimmed mean with Gauss-Seidel iteration. An amplitude-preserving minimum phase operator is then constructed and applied to the data to remove the receiver coupling variations. We illustrate the process on two data sets, one a 40 level Gulf of Mexico walkaway, the other an 8 level HFM (hydraulic fracture monitoring) 34 perforation shot data set.

KEYWORDS: borehole seismic, VSP, deconvolution, HFM, microseismic.

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INTRODUCTION

Long downhole arrays are most often deployed in casing because of the risk of getting them stuck in open hole. Consequently, the mechanical coupling between the casing and the formation is very often the most important factor determining data quality. Ideally the casing would be in direct contact with the formation but due to geomechanical stresses borehole enlargement is common. The annulus between casing and formation is usually, but not always, filled with cement. It is when cement is absent that source-generated casing arrivals and ringing are problematic, degrading vertical component data and compromising multi-channel processes such as wavefield separation. Other settings where receiver coupling variations may be present include intervals where multiple casing strings are present, irregularities of the casing, or, in the case of open hole, non-cylindrical borehole shape.

The redundancy provided by multi-source borehole seismic data acquired with a multi-receiver downhole array allows techniques developed for surface seismic surveys such as surface-consistent deconvolution (Taner and Koehler, 1981; Levin, 1989; Cambois and Stoffa, 1992; Cary and Lorentz, 1993) to be considered. While the borehole seismic geometry is different the same basic idea can be adapted and applied to multi-source multi-receiver borehole seismic data. We will describe our approach and show results on a forty level walkaway data set from the Gulf of Mexico and an eight level microseismic data set.

METHOD

Consider a seismic signal emanating from a source (indexed by i) recorded by a geophone (indexed by j) in a borehole at depth at some distance. It may be written in the frequency domain as the product of an average spectrum, $a(\omega)$, multiplied by residual source $s(\omega)$ and receiver $r(\omega)$ spectra as:

$$d_{ij}(\omega) = a_k(\omega)\cdot s_i(\omega)\cdot r_j(\omega)\cdot c_j \quad , \tag{1}$$

where k is an index defined later and c is a frequency-independent constant that will be iteratively estimated to handle any possible rotation of horizontal components. It is initialized to

$$c_j = rms_j / \overline{rms} \quad , \tag{2}$$

where rms_j signifies the root mean square for receiver j averaged over all sources and $\overline{rms}$ is the average receiver rms. The average term $a(\omega)$ has an index k because we include within it offset and depth terms through a distance indexing scheme. The distance index is defined as $k = j + |i - i_{mid}|$ where i_{mid}

is the index of the shot nearest the receiver. This is illustrated schematically in Fig. 1 for a line of sources; for an areal distribution of sources they are first indexed by distance from the top receiver. An average log spectrum is computed for all shot-receiver pairs with equal distance index. Denoting the number of sources as N_s and the number of receivers as N_r, $N_s \times N_r$ traces become $N_r + N_s/2$ averages indexed by k. By taking the logarithm of the amplitude spectra, subtracting $\ln|a_k(\omega)|$ from the data and making substitutions like $S_i(\omega) = \ln|s_i(\omega)|$, eq. (1) becomes

$$D_{ij}(\omega) = S_i(\omega) + R_j(\omega) + C_j \ . \tag{3}$$

Eq. (3) represents a system of $N_s \times N_r$ equations and $N_s + N_r$ unknowns. Following Carey and Lorentz (1993) we solve for the source and receiver terms using the Gauss-Seidel method. In this method the L2 norm is minimized my iteratively averaging over directions orthogonal to each component in turn. In our two component problem we proceed by estimating residual source and receiver terms for iteration n as:

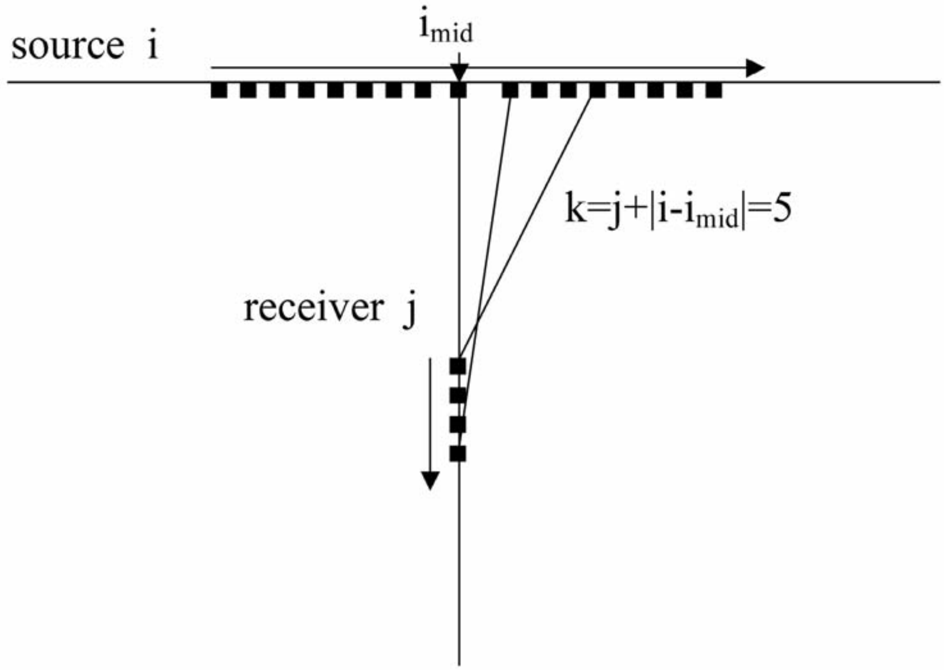

Fig. 1. The source-receiver distance indexing scheme for walkaway VSP data. The two lines connecting a source and a receiver have the same distance index.

$$\begin{aligned} S_i^n(\omega) &= (1/N_r)\sum_{j}^{N_r}\{D_{ij}(\omega) - R_j^{n-1} - C_j^n\} \ , \\ R_j^n(\omega) &= (1/N_s)\sum_{i}^{N_s}\{D_{ij}(\omega) - R_i^n - C_j^{n-1}\} \ , \end{aligned} \tag{4}$$

with the receiver term initialized to 0. In practice we have found that the median rather than the mean is a better estimator for the source and receiver terms. Having estimated the residual receiver term the optional receiver gain constant may then be updated as:

$$C_j^n = C_j^{n-1} + (1/N_\omega)\sum_{\omega} R_j(\omega) \ , \tag{5}$$

where N_ω is the number of frequencies. Iteration proceeds until source and receiver terms cease changing, usually 5-8 iterations. Having arrived at estimates of the residual source and receiver log amplitude spectrum we design a minimum phase operator to remove the unwanted variation from the data. For offshore multi-offset VSP this is done only for the receiver term as shot-to-shot variation is usually small and in any case shot variations are usually removed through common shot processing and deterministic deconvolution.

RESULTS

We demonstrate the results of our method on two types of borehole seismic data. Both data sets are absolutely raw, no processing has been applied. The first is a forty level walkaway VSP data from the Gulf of Mexico. This data set exhibited receiver coupling resonances over intervals where cement was absent behind casing and where there was a liner inside casing. Fig. 2 shows the estimated average term versus distance index. Fig. 3 shows the estimated residual receiver log amplitude spectra plotted alongside one of 313 input shot gathers. Fig. 4 shows the construction of the minimum phase operator for one receiver. A minimum phase inverse receiver response operator is computed for each receiver. Fig. 5 shows the results of applying the receiver operators to each receiver in a shot gather. Where the data are good, little is done and where the data exhibit ringing significant noise attenuation is achieved, exposing useful reflection signal. The first arrival is, however, still corrupted by the casing arrival which travels faster than the energy that travels through the formation. Moveout filters will be needed to remove this coherent noise. The data shown are a subset of a 3DVSP case study (Graves et al., 2008).

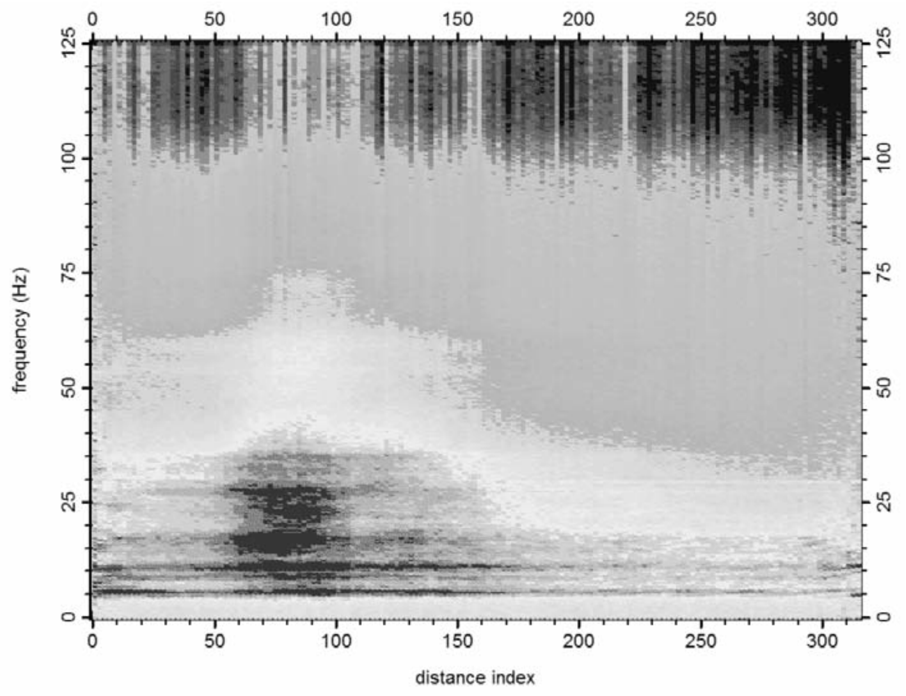

Fig. 2. Distance - indexed average log amplitude spectra.

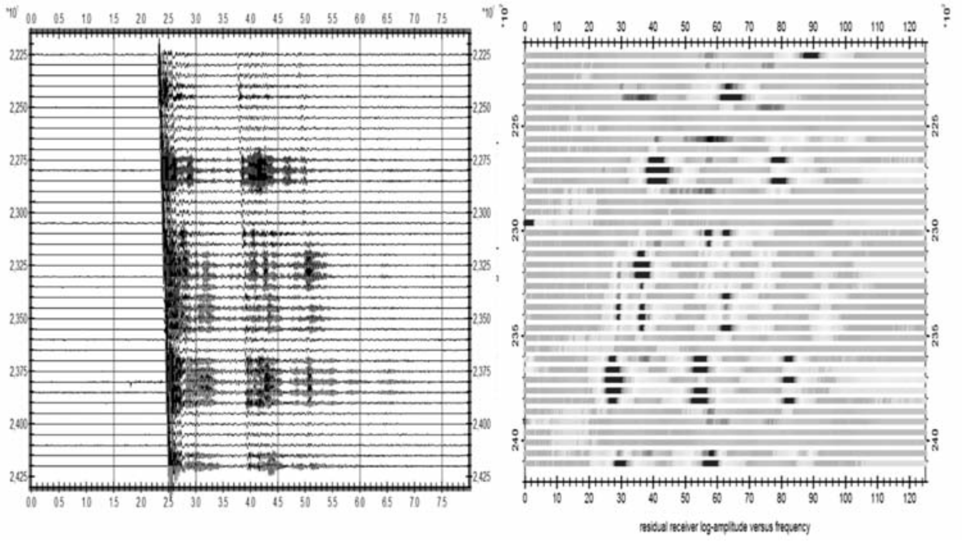

Fig. 3. A Z-axis shot gather (left) and the estimated residual log-amplitude receiver spectra (right).

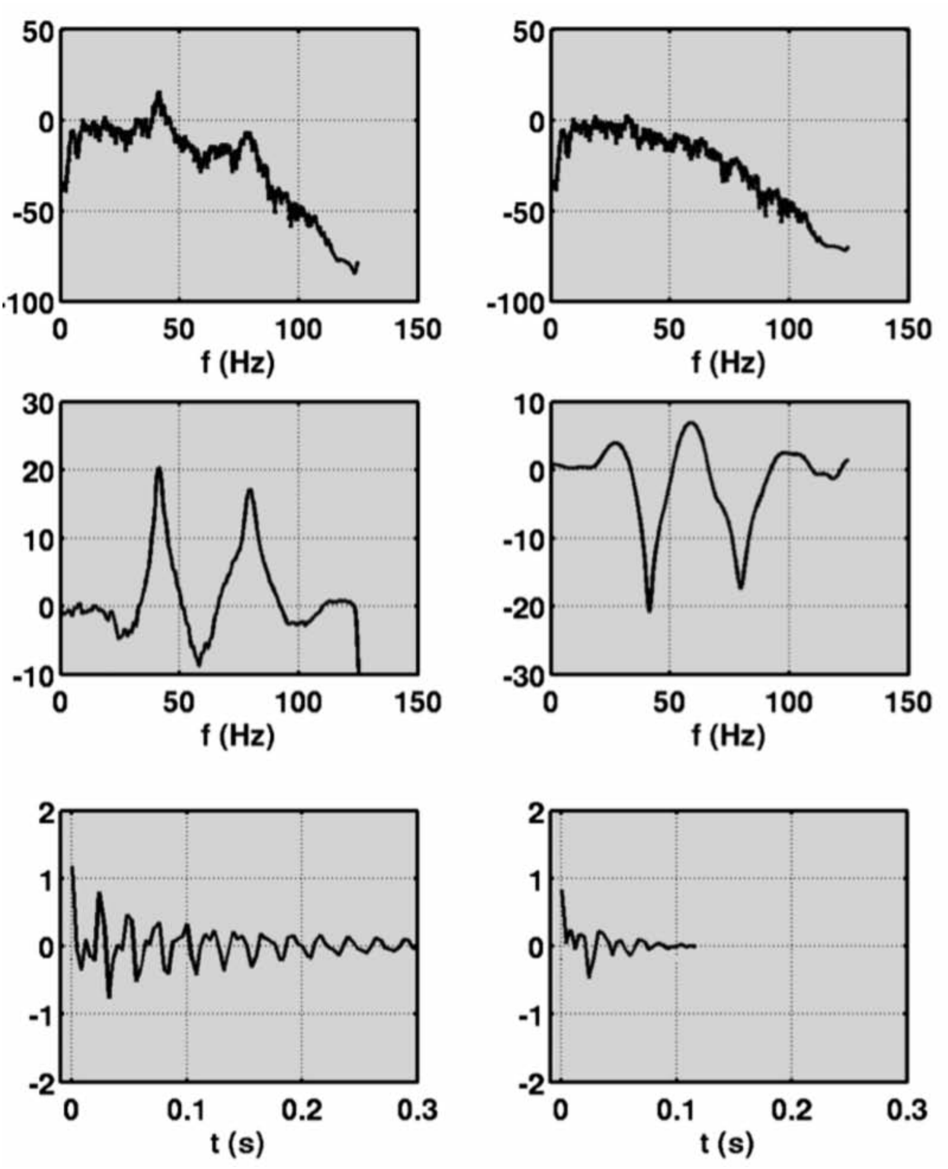

Fig. 4. Minimum phase deconvolution operator design. Upper left: input trace spectrum; middle left: estimated residual receiver log-amplitude spectrum; lower left: time domain receiver response function; upper right: trace amplitude spectrum after deconvolution; middle right: inverse receiver spectrum; bottom right: minimum phase receiver response inverse filter.

The second example comes from an eight level HFM (hydraulic fracture monitoring) data set composed of 8 (three component) receiver levels and 34 perforation shots. For a review of such surveys see Fehler et. al. (2001). For this application no distance indexing is employed in computing the average spectrum. In Fig. 6, one of 34 perforation shots is shown before and after application of the receiver term of station-consistent deconvolution. The two obviously bad levels have been significantly improved and are now usable. However, a couple of levels have actually gotten slightly worse, indicating that receivers should be selected for operator application so as not to degrade good data.

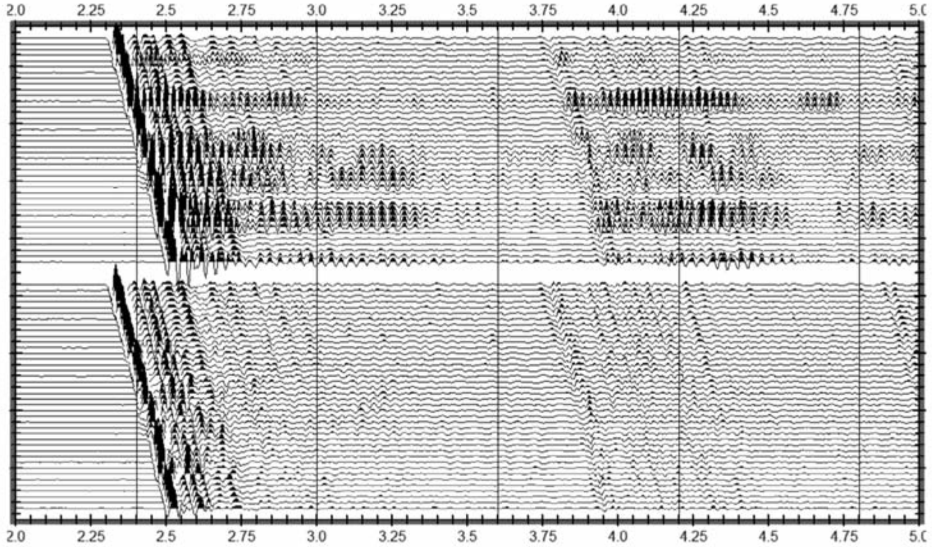

Fig. 5. The results of applying the receiver term station-consistent deconvolution operator estimated from 313 shots to data from a single shot gather. Top: before; bottom: after.

CONCLUSIONS

We have adapted surface-consistent deconvolution for multi-source borehole seismic data. Our approach amounts to a simple two component decomposition with the analogy of offset and CMP terms being bundled into a distance-indexed average term. We also include an optional receiver gain constant to handle horizontal components that may be pointing in different directions from level to level. The process is run on raw data and does not require time picking or any other preprocessing. We showed the application of the technique to two types of multi-source borehole seismic data - a walkaway VSP and an HFM perforation shot data set. We showed results of applying the receiver correction term only because the source term showed little variation. Land VSP data would benefit from application of the source correction term, however, if common shot processing and deterministic deconvolution are used, as is often the case, residual shot variations will be removed in processing. We have found that in most cases the receiver term can be applied safely to all levels but in cases where fewer levels are available to estimate receiver residuals some levels can be degraded. In this case receivers should be selected for operator application. Finally, although more sophisticated methods of solution such as conjugate gradient (CG) could be used, we have found the Gauss-Seidel method to be quite adequate for this application. And while what we describe is a simple adaptation of a well known technique, we thought the application to borehole data and the results worthy of sharing it through publication.

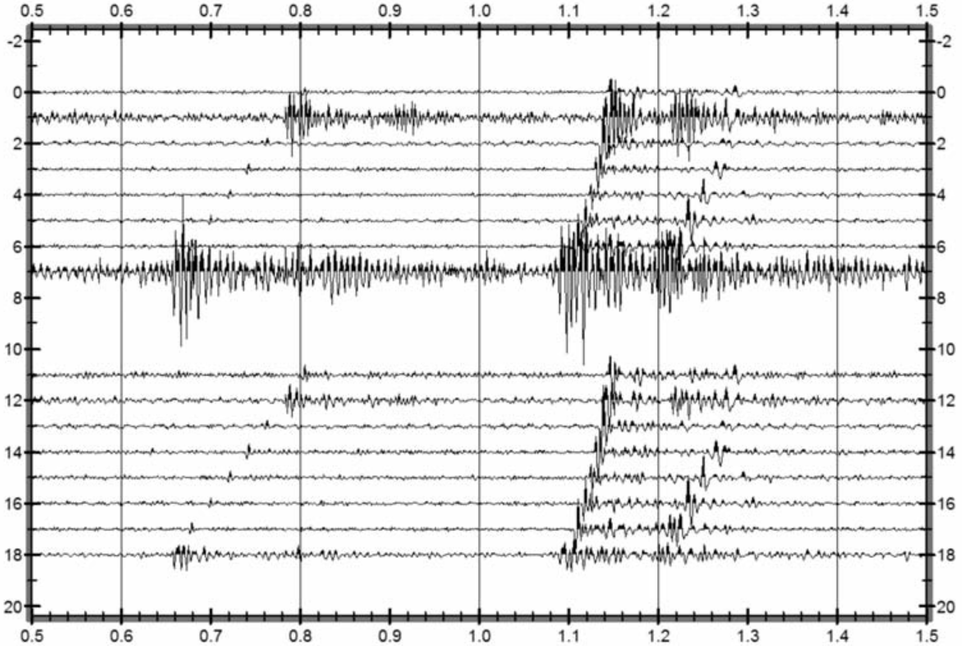

Fig. 6. The results of applying the receiver term station-consistent deconvolution operator estimated from 34 perforation shots of a HFM (hydraulic fracture monitoring) data set to one perforation shot. Top: before; bottom: after.

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