Dual-sensor summation of noisy ocean-bottom data

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Summary

We present simple and robust methods for processing bottom-referenced dual-sensor data which is contaminated with noise and/or imperfect receiver coupling. These techniques facilitate the quantitative assessment of how well the field data conform to the model assumed in dual- sensor summation and provide straightforward preprocessing steps to improve the suppression of receiver ghosts and receiver-side reverberations. Examples from a recent 3D survey conducted offshore NW Java are used to illustrate the efficacy of our procedures.

Introduction

When ocean bottom cable (OBC) data are recorded in water depths exceeding 10 m, the ghost and reverberation problem is so severe that substantial alterations in the way data are acquired and processed are employed. One method for coping with the ghosts is the use of dual- sensor bottom cables which consist of receiver stations containing both hydrophones and vertically oriented geophones (see, e.g. Barr and Sanders, 1989a, 1989b). By summing pressure (hydrophone) and velocity (geophone) at optimal ratios, it is possible to reduce the deleterious effects of the ghosts and water layer reverberations. Methods for estimating these optimal ratios include specialized acquisition techniques (Barr and Sanders, 1989b) and a variety of seismic analysis schemes (see, e.g., Dragoset and Barr, 1994).

Many existing techniques for processing dual-sensor data assume that the recorded data are composed of noise-free signals recorded by ideal hydrophones and geophones well coupled to the sea floor. Real seismic data are contaminated by source-side reverberations as well as both random and coherent noises. Geophones are particularly susceptible to recording noises such as converted shear modes and cable noise. These noises may represent a significant portion of the total recorded geophone energy and can deleteriously affect the computation of summing ratios. Ocean-floor coupling of the geophone may also vary significantly due to local conditions, causing wide variation in the amplitude of the recorded signal and noise. Direct implementation of summing theory is difficult unless these noises are correctly accounted for.

The method we describe below provide a means for analyzing dual-sensor data in the presence of source-side reverberations and noises differentially recorded on the geophone and hydrophone. These methods are especially useful because they do not require explicit removal of the noise prior to analysis and are insensitive to the detailed nature of the noise. Furthermore, these methods are robust in the face of large variations in the level of recorded signal and noise from one receiver to the next.

The model and its limitations

If dual sensors are well coupled to the sea floor and both sensors have identical instrument responses over the seismic bandwidth, then for compressional waves traveling near the vertical, theory predicts that in the frequency domain, the hydrophone (H) and geophone (G) responses will be modulated by receiver-side ghost + reverberation operators:

$$H = \frac{(1-z)}{(1+rz)}A \qquad (1)$$

and

$$G = \frac{(1+z)}{(1+rz)}A \qquad (2)$$

Here r is the reflection coefficient at the sea floor, z represents the two way propagation of sound in the water column $(z = e^{-i\omega\tau})$ and A is the subsurface response of interest.

While these equations have been known since the pioneering work of Haggerty (1956) and the recent work of Barr and Sanders (1989a, 1989b), little attention seems to have been paid to assessing quantitatively how well they describe recorded dual-sensor data. Most of the previous work has been devoted to estimating the sea floor reflectivity (r) given the validity of these equations.

Extensive experience with dual-sensor field data suggests that significant aspects of the recorded seismic wavefield cannot be described by this simple model. Often high levels of coherent noise contaminate the geophone data and the equality of H/G coupling implied by this model may not be realized in practice.

Seeing through the geophone noise

The practical implementation of the dual-sensor processing procedures described below requires a robust estimate of the geophone and hydrophone auto-power (Φ_{gg} and Φ_{hh}) and the geophone-hydrophone cross-power $(\Phi\ _{h})$. These estimates may be difficult to obtain from field date because of noise. Figure 1 is a receiver gather of data recorded offshore NW Java (ONWJ) for which the water depth is approximately 40m. The hydrophone data shows good quality reflections, but spectral analysis demonstrates a high degree of contamination with the receiver ghost. The reflections present on the geophone data are also of good quality, but .this component contains a high level of coherent noise which is absent on the hydrophone data.

For hydrophone data of the quality recorded in ONWJ, the auto-power can be reliably estimated by simple stacking of autocorrelations in an appropriate near-trace annulus of the receiver gather. Similarly, the H-G cross-power can be obtained using crosscorrelations in the same annulus. In contrast, estimates of the geophone auto-power are very difficult to obtain due to high coherent noise levels. To 'see through' this noise, we estimate the geophone auto-power (Φ_{gg}) indirectly using the relation:

$$\hat{\Phi}_{gg}\Phi_{hh} = \Phi_{gh}\Phi_{hg} \qquad (3)$$

This derived $\hat{\Phi}_{gg}$ may be compared with the directly computed auto-power to obtain an estimate of the geophone noise as a percent of the total energy. The resulting estimate of geophone noise for the ONWJ 3D survey is plotted as a histogram in Figure 2. While the mode of this distribution is 35%, a large number of the receivers show noise levels greater than 50%. These receivers are primarily located in areas containing shallow gas which causes a serious reduction in signal-to-noise ratio.

Relative coupling of H and G

We now describe simple procedures that may be used to test the degree to which the field data satisfy the assumptions of equations (1) and (2) and propose a more general model that can be used to more robustly describe recorded dual-sensor data. Such a model seems to be required due to unintended differences in the hydrophone and geophone instrument responses and/or the failure of current bottom cable technology to assure that both sensors are well coupled to the sea floor.

Our generalized model keeps the equation (1) for H, but assumes that the corresponding measurement of G may differ from the ideal by a simple (complex) scale factor:

$$G = ue^{i\gamma}\frac{(1+z)}{(1+rz)}A \qquad (4)$$

Here γ and u are, respectively, the relative phase and sensitivity of G and H.

Based on this model, we subject the field data to two simple tests which facilitate the estimation of u and γ . As for most dual-sensor processing procedures, these tests are carried out independently for each receiver station, usually restricting the analysis to a subset of the shotpoints for which the assumed model (of vertically traveling waves) is reasonable.

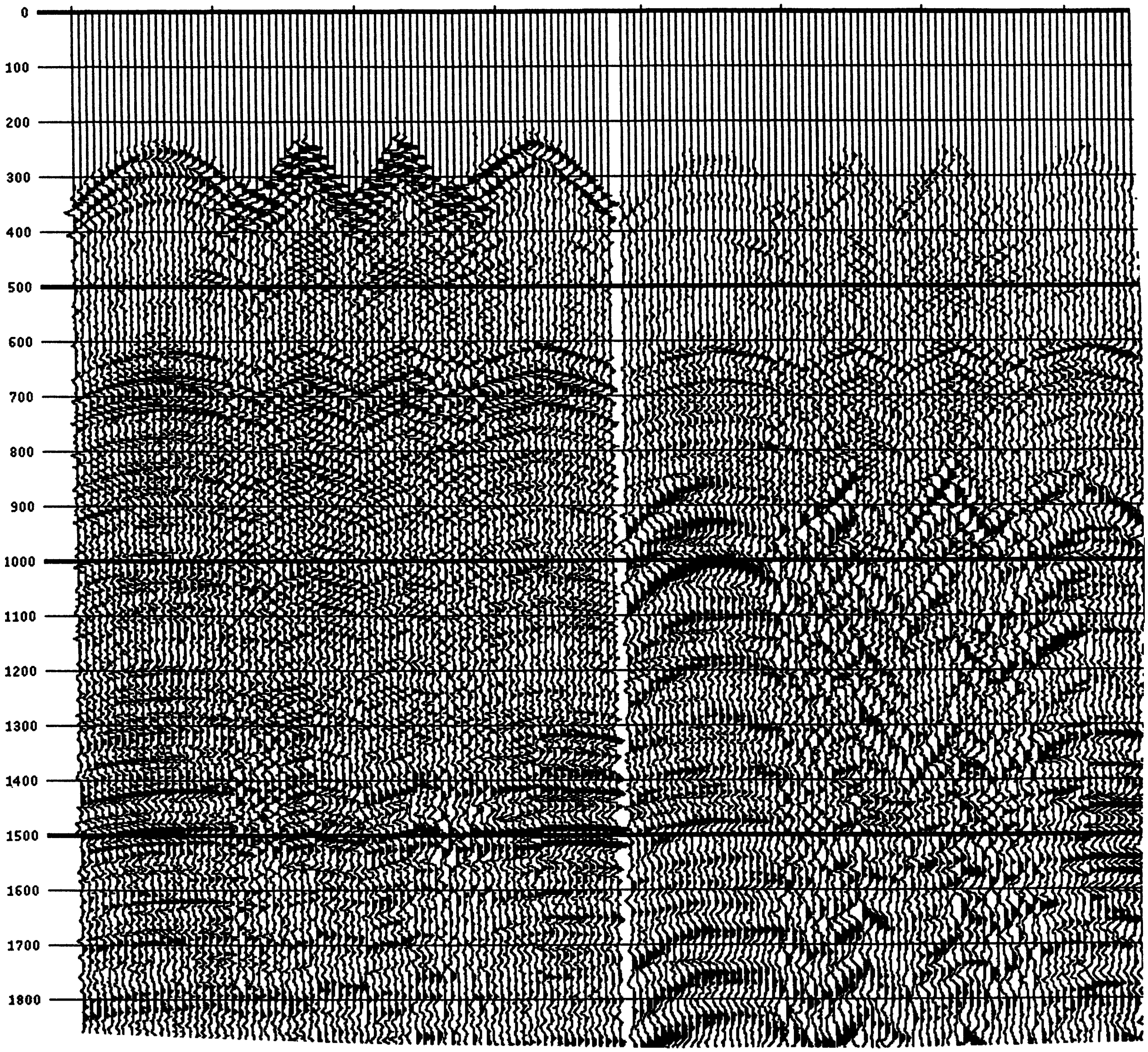

Figure 1. Hydrophone and geophone recordings (maximum offset 550m)

The first test provides a direct estimate of γ and involves forming the 'folded' cross&elation function:

$$X(t) = \sum_{\omega} (\Phi_{gh} + \Phi_{hg}) e^{i\omega t} \qquad (5)$$

It is an easy matter to establish that X $\sim$ siny , i.e., X will be small only if the relative phase of H and G is close to zero. Conversely, the minimization of X with respect to γ allows the estimation of this relative phase directly from the recorded data. Figure 3 shows the folded crosscorrelation function for the data of Figure 1 as the geophone phase is varied from -90 to + 90 deg. This nicely exhibits a pronounced minimum in the vicinity of the inferred 30 deg. phase difference.

Once γ has been determined in this fashion, we can correct the geophone data for this phase difference via: $G' = e^{-i\gamma}G$. To determine u, we observe that this generalized model should satisfy the 'cross-ghosting' relation:

$$u(1+z)H = (1-z)G' \qquad (6)$$

and the relative sensitivity u may be estimated by minimizing the difference:

$$\sum_{\omega,\,shots} |u(1+z)H - (1-z)G'|^2 \qquad (7)$$

In computing this relative coupling, the geophone auto-power may be determined using the less noise-sensitive estimate of equation (3).

In the presence of high noise levels documented in Figure 2, it is reasonable to ask how reliable is equation (3) in estimating Φ ? This question is answered by comparing geophone noise levels with correlation coefficients obtained in the solution of equation (7). When noise levels are less than 35%, the average correlation coefficient is .85; at 50% noise, the correlation coefficient has only dropped to .8. In the ONWJ 3D survey, correlation Coeffcients do not show significant decay until noise levels exceed 70%.

The estimate of u from equation (7) is used to make a further correction to G: $G'' = e^{-i\gamma}G/u$. This corrected data should now more closely satisfy the assumed form for the geophone measurement and, hence, should be a better basis for the application of any one of the numerous proposed methods for dual-sensor summation including the one described below.

Reflection coefficient estimation

To estimate r, we include in our model both source- and receiver-side reverberations (see also, Paffenholz and Barr, 1995). Then (assuming the relative coupling differences have been removed), we have:

$$H = \frac{(1-z)}{(1+rz)^2}B \qquad (8)$$

and,

$$G = \frac{(1+z)}{(1+rz)^2}B \qquad (9)$$

Given an estimate of r, Barr and Sanders have shown that the combination of H and G which optimally cancels the receiver ghost and receiver-side reverberations is:

$$\left(\frac{1-r}{2}\right)H + \left(\frac{1+r}{2}\right)G \qquad (10)$$

Using the model specified by equations (8) and (9), we estimate r by forming:

$$L = \left(\frac{1+2r}{2}\right)G + \left(\frac{1-2r}{2}\right)H + \frac{r^2 z}{2}(G-H) \qquad (11)$$

and minimizing the cumulative autocorrelation energy of L using a simple global minimization technique.

The resulting r may be substituted into equation (10) to eliminate the receiver reverberation. If instead we choose r-0, the resulting summation will eliminate the receiver-side ghost, but not the reverberation. In areas of high geophone noise this may be the best course of action.

Conclusions

Prior to summation, the geophone and hydrophone must be properly matched in amplitude and phase. Phase differences can be estimated using the folded crosscorrelation and amplitude differences by balancing the cross- ghosted geophone and hydrophone data. The detrimental effects of noise on this analysis can be minimized by stacking of correlations and using an indirect estimate of the geophone auto-power. The water bottom reflection coefficient can be estimated by construction of a function having the property that it is unbiased by the effects of source-side reverberations. The resulting reflection coefficient may be used to optimally weight the geophone and hydrophone so that receiver-side reverberations are attenuated.

Acknowledgments

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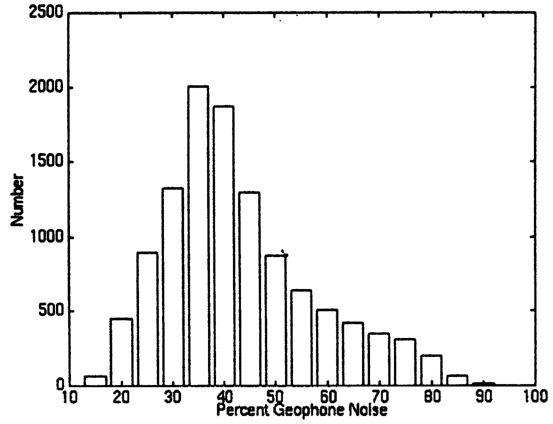

Figure 2. Percent geophone noise for ONWJ 3D survey

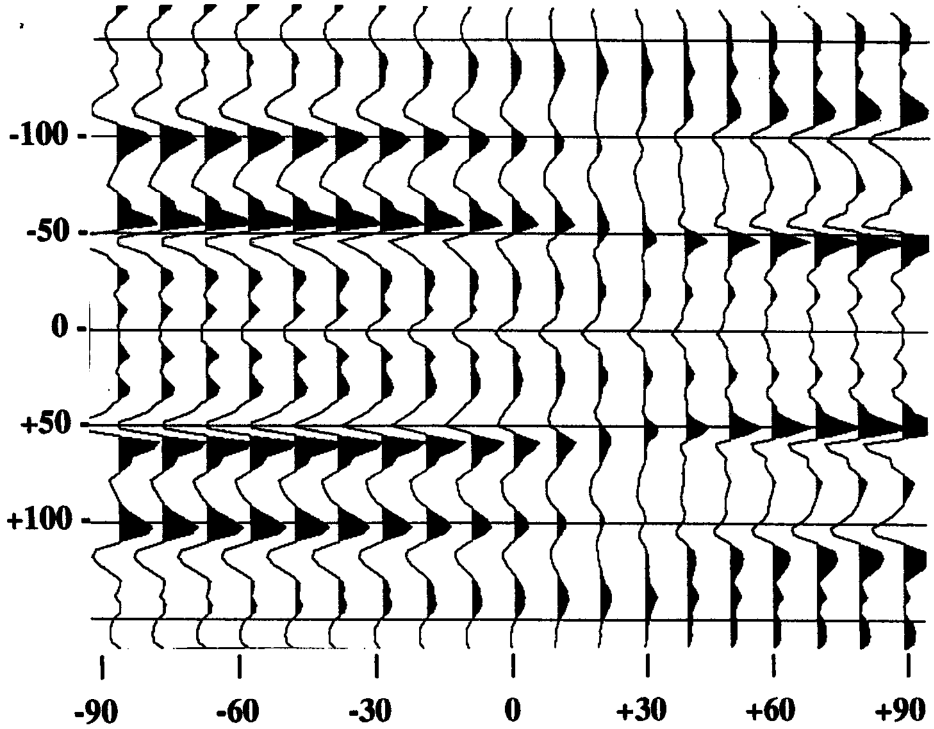

Figure 3. Folded crosscorrelation for geophone phases (-90,+90)