Optimal deghosting robust to nonstationary noise from multimeasurement streamer data
Yousif I. Kamil and Philippe Caprioli, Schlumberger

Summary

The optimal deghosting (ODG) method is used to combine pressure and vertical velocity in a way to optimally minimize the impact of noise on the deghosted data. This is done by estimating the noise power spectrum of the pressure and vertical gradient to weight the contribution of each measurement. In general, the pressure and vertical velocity noise spectrums are estimated from noise-dominant data windows assuming that the noise is space-time stationary in the wide sense. If the noise statistics change with time or space, then the ODG solution is not optimal with respect to the signal to noise ratio (S/N). We propose a robust way to minimize the impact of nonstationary noise in ODG without estimating the noise power.

Introduction

The ghost reflection is a delayed replica of the seismic wavefield that gets reflected at the sea surface. When it reaches the seismic receivers, the ghost reflection (downgoing wavefield) interferes with the subsurface-reflected wavefield (upgoing wave), and this generates notches in the spectrum of the measured total wavefield. These notches reduce the usable bandwidth of the measured signal and affect the resolution of the seismic data. Several deghosting techniques are applied to overcome the receiver ghost problem. Some deghosting methods rely on additional measurements to fill the ghost notch. Examples include over/under towed streamers (Hill et al., 2006), over/sparse-under 3D streamers (Kragh et al., 2009) and the PZ summation (PZSUM) approach. The PZSUM technique is a multimeasurement approach that relies on the combination of the vertical particle velocity and the pressure to achieve deghosting (i.e., ocean bottom cables, multi-sensor streamers) (Amundsen, 1993). This approach must, however, handle the typically high levels of flow and vibration noise in towed streamer velocity measurements.

The ODG approach provides the optimal weights to the pressure and vertical velocity to minimize the noise leakage. It provides the optimal weights to the pressure and vertical velocity to minimize the noise leakage; therefore, it is optimal (in a least square sense) with respect to the S/N (Caprioli et al., 2012). The ODG approach in its current formulation requires a prior estimation of the pressure and the vertical velocity measurement noise spectrum in order to compute the optimal weights. The noise estimation stage is difficult in practice, a bit subjective and an automatic noise estimation step is welcome. Moreover, for practical reasons, in ODG, we assume that the noise is white in space and colored in time (i.e., function of frequency not frequency wavenumber) which may not be the case. In addition, the noise spectrum is commonly estimated from noise dominated windows and then used in the shot, implicitly, assuming that the noise is space-time stationary. For all these reasons, in some scenarios, while the ODG solution will estimate the upgoing wavefield correctly, it may be suboptimal with respect to S/N. In this work, we propose to modify the estimation of ODG weights to minimize the noise leakage without the need for a separate estimation-stage of the noise spectrum.

ODG

Let $P_n$ and $V_{zn}$ represent the frequency-(inline and crossline) wavenumber $(\omega, k_x, k_y)$ transformed noisy data of pressure and vertical particle velocity recorded at a depth $z$ below the sea surface. $V_{zn}$ is scaled by the acoustic impedance in water ($\rho c$) where $\rho$ is the water density and $c$ is the acoustic propagation velocity in water. Assuming that the direct arrival has been removed from the measured data, $P_n$ and $V_{zn}$ can be modelled as

$$\begin{bmatrix} P_n \\ V_{zn} \end{bmatrix} = \begin{bmatrix} G_P \\ G_z \end{bmatrix} \frac{U}{\bar{U}} + \begin{bmatrix} n_P \\ n_z \end{bmatrix}$$

(1)

where $\bar{U}$ is the measurement vector, $U$ is the upgoing wave, $n$ is the noise vector with elements $n_p$, $n_z$, denoting the noise in the pressure and vertical velocity data, respectively. $H$ is the ghost operator vector with elements $G_P$ and $G_z$ denoting the ghost models for the pressure and vertical velocity data and are given by

$$H = \begin{bmatrix} G_P \\ G_z \end{bmatrix} = \begin{bmatrix} (1 - e^{-j2\pi k_x}) \\ \frac{e^{j2\pi k_x}}{\sin \theta} (1 + e^{-j2\pi k_x}) \end{bmatrix},$$

(2)

where $\epsilon$ is the sea surface reflection coefficient, $k_z$ is the vertical wavenumber defined as

$$k_z = \frac{2\pi f}{c} \cos \theta = \sqrt{k_x^2 - k_y^2 - \frac{k_z^2}{\epsilon^2}}$$

(3)

where $\theta$ is the incidence angle. In practice, due to the coarse sampling in the crossline direction, the vertical wavenumber cannot be estimated accurately and 2D wavefield approximation is adopted. Other methods are proposed in the literature to overcome this (Özbek et al., 2010). In this work, we are going to limit our study to 2D only and focus on the optimality of the deghosting methods with respect to S/N only.
Optimal Deghosting robust to nonstationary noise

The well-known PZSUM estimates the upgoing wavefield as the average of the noisy $P_n$ and the modified $V_{en}$ measurements as

$$\tilde{U}_{PZSUM} = \frac{1}{2} (P_n + \frac{2\pi f}{c_k} V_{en})$$

(4)

The drawback of PZSUM is that it ignores the noise statistics on pressure and particle motion measurements and can result in a noisy upgoing wavefield. This is usually unfavorable, particularly at the lower end of the frequency spectrum where particle velocity measurements are often noisy.

The ODG method uses the ghost model in addition to the noise statistics estimated from pressure and vertical particle velocity measurements to minimize the leakage of noise on the final deghosted data (Özdemir and Özbek, 2008). This is achieved by formulating the deghosting as a weighted least squares minimization problem as follows:

$$\min_{\tilde{U}} W_{\text{ODG}} \tilde{U} W_{\text{ODG}} s.t. \tilde{U}^H \tilde{U} = 1$$

(5)

where the superscript $H$ is the complex conjugate transpose operator. $W$ is used to weight the pressure and vertical velocity measurement to obtain the upgoing wave. The input noise covariance matrix $R_{nn}$ is defined as

$$R_{nn} = \begin{bmatrix} \sigma_{Pn}^2 & \sigma_{PnVn} \\ \sigma_{PnVn} & \sigma_{Vn}^2 \end{bmatrix}$$

(6)

The solution is given as:

$$\tilde{U}_{\text{ODG}} = \frac{E[V_n]}{\sigma_{Vn}^2} \approx \frac{E[P_n]}{\sigma_{Pn}^2} \approx \frac{E[V_n]}{\sigma_{Vn}^2}$$

(7)

In the special case of uncorrelated pressure and velocity noises ($R_{nn}$ is a diagonal matrix), the ODG solution can be obtained by:

$$\tilde{U}_{\text{ODG}} = \frac{\sigma_{Pn}^2}{\sigma_{Vn}^2} \frac{c_k}{2\pi f} P_n + \frac{\sigma_{Vn}^2}{\sigma_{Pn}^2} \frac{2\pi f}{c_k} V_{en}$$

(8)

This solution minimizes the noise leakage and is optimal if the noise statistics are estimated correctly.

Robust Optimal Deghosting (RODG)

Here, we propose weights that do not require estimation of the noise covariance matrix $R_{nn}$. If we denote the data covariance matrix as $R_{dd}$:

$$R_{dd} = E \begin{bmatrix} P_n \\ V_{en} \end{bmatrix} \begin{bmatrix} P_n \\ V_{en} \end{bmatrix}^H = \sigma_u^2 HH^H + R_{nn}$$

(9)

where $E[.]$ is the expectation operator, $\sigma_u^2$ is the spectrum of the upgoing wave in the $(\omega, k_x)$ domain. If we use the matrix inversion lemma:

$$(A + BCD)^{-1} = A^{-1} - A^{-1}B(AD^{-1}B + C^{-1}CD^{-1})A^{-1},$$

then, it is straightforward to prove that

$$W_{\text{RODG}} = (R_{ll}^H R_{ll})^{-1} W_{\text{ODG}}$$

(10)

From equation (11), we see that replacement of $R_{nn}$ by $R_{dd}$ will result in the same weight and hence the same solution as with ODG. The main difference is that the covariance matrix used does not need an explicit estimation of the noise covariance matrix. In addition, this formulation handles any correlation between the noise in pressure and the noise in the vertical particle velocity. Moreover, because the RODG uses the data covariance matrix, it can be implemented in space time windows handling nonstationary noise and effectively mitigating the noise within each window.

From a practical point of view, we can ignore the correlation between the measurements in the data covariance matrix and reduce $R_{dd}$ to a diagonal matrix:

$$R_{dd} = \begin{bmatrix} E[P_n^2] & 0 \\ 0 & E[V_n^2] \end{bmatrix}$$

$$\approx \begin{bmatrix} \sigma_{Pn}^2 + \sigma_{PnVn}^2 & 0 \\ 0 & \sigma_{Vn}^2 + \sigma_{VnVn}^2 \end{bmatrix}$$

(12)

where $\sigma_{Pn}^2, \sigma_{Vn}^2$ denote the pressure and vertical velocity signal power, respectively. This approximation greatly simplifies the formulation and yields further insight in RODG. Substituting the simplified expression of $R_{dd}$ in (11), we see that the ghost operator vector is normalized by the data power compared to ODG which uses the estimated noise power for normalization. Therefore, the approximation has the advantage that the contribution of each component is dependent on its S/N. That is for marine data, if the S/N is high (shallow events), the RODG gives the same weight to pressure and vertical gradient. This is equivalent to the dephase, sum and spectral whitening (DPS) method (Posthumus, 1993). In contrast, in low S/N, the normalizing covariance matrix becomes equivalent to the noise covariance matrix and $W_{\text{RODG}} \approx W_{\text{ODG}}$.

Synthetic Example

A simple 2D synthetic data set is used to show the performance of RODG. The data consists of 4 events and their receiver ghosts shown in Figure 1a. The streamer depth is chosen to be 50 m so that the ghost effect can be clearly shown and the notches lie within the bandwidth of the wavelet. A white Gaussian noise (WGN) is added at a level of 6% of the maximum signal amplitude $A_{max}$. Similarly, WGN at 115% of $A_{max}$ is added to the far offset data.

Figure 1 shows 1.5 seconds of the data. The ODG weights are applied from the estimation of the noise variances in the far-offset data, assuming that the noise is stationary. The robust weights are applied to the same data without estimating the noise. It is clear that the RODG method can outperform the ODG method in the presence of nonstationary noise. Figure 2 shows one trace from near- and far-offset data to see the difference in the noise attenuation performance.
Optimal Deghosting robust to nonstationary noise

Figure 1: Simple 2D synthetic data with 4 events showing total pressure (a), scaled vertical velocity (b), and results from ODG (c) and RODG (d).

Figure 2: Traces from the ODG (a, c) and RODG (b, d) near-offset (200 m) and far-offset (2000 m) data compared with the true upgoing wave (red line). Note the noise leakage difference between ODG and RODG results.

Real Data Example

The PZSUM, ODG and RODG methods are now compared on a single shot gather from a 3D survey acquired in the North Sea (see Figure 3). The data were acquired using 3-km long multimeasurement streamers towed at 17 m depth. This leads to notch frequencies at multiples of 41.6 Hz starting at 0 Hz for pressure and 20.8 Hz for vertical particle velocity at normal incidence angle. A standard real-time preprocessing sequence was applied to the pressure and vertical velocity data including coherent noise attenuation. Figure 3 shows the data where good signal strength can be observed on both P and Z components. The low frequency noise on Z is visible and stronger than on the P data, but deep continuous reflections can be seen ‘through’ the noise. Deep and complementary notches can be seen in the f-k plots in Figure 3 (bottom) in the pressure and vertical velocity plots. The notches occur where expected (see white and orange arrows in Figure 3f and Figure 3g). Figure 4 shows the noise second-order statistics in the frequency domain which are estimated by averaging the spectra of the noise-only data window in the far-offset range (shown by the blue rectangle in Figure 3a).

This is the noise statistics used as input to ODG which for practical reason is assumed frequency only dependent. Since this noise is estimated from the shallow, far-offset data, this inherently assumes that the noise is stationary in time and offset. As mentioned before, the RODG method does not require an explicit estimation of the noise spectrum. After application of the PZSUM, ODG, and RODG methods to the combination of pressure and vertical velocity data, the results and their f-k spectra are shown in Figures 3c, 3d, 3h, 3i. As expected, the results from both ODG and RODG are quieter at low frequency compared to PZSUM results. Ghost events have been attenuated and notches are filled in by all three combinations.

Figure 5 shows the S/N spectrum of the three methods computed from two windows: A signal-dominated window from 0.5 to 1.5 sec and the first 900 m (red window) and a noise-only window computed between 0 and 1 sec (blue window) and 900 m from the far offset. The differences between the ODG (and RODG) and the PZSUM spectrum in the low frequency are mainly due to the noise handling feature of ODG and RODG compared to PZSUM which does not handle the noise. The RODG S/N is consistently higher than the ODG S/N. This can be attributed to the fact that the RODG formulation conveniently takes into account the frequency wavenumber variation of the noise.

Conclusions

The ODG method in its current formulation requires a prior estimation of the pressure and the vertical velocity measurement noise spectrum to compute the optimal weights. The noise estimation stage is not easy in practice. Moreover, for practical reasons, we assume that the noise is white in space and colored in time (i.e., function of f only not f-k) which may not be the case. In addition, the noise spectrum is commonly estimated from noise dominated windows and then used in the whole shot, implicitly, assuming that the noise is space-time stationary. The new robust solution RODG proposed here, similar to ODG, can attenuate the noise leakage into the estimated upgoing wavefield. In addition, this new solution does not require a preliminary estimation of the noise statistics; hence, unlike ODG, the new technique can handle the presence of nonstationary noise, adding advantage.

Acknowledgment

We would like to thank Schlumberger for permission to publish this work.
Optimal Deghosting robust to nonstationary noise

Figure 3: Average amplitude noise spectrum of pressure (blue) and vertical particle velocity (green) estimated from the blue window in Figure 4, as used in the ODG combination.

Figure 5: The SNR spectrum of PZSUM, ODG and RODG computed from two windows: a signal dominated window (Red window in Figure 4a) and a noise-only window computed (Blue window in Figure 4a).

Figure 4 (top) P, Z, PZSUM, ODG and RODG combined shot gather (A t^2 gain was applied to all traces) and (bottom) their FK amplitude spectra. Note the ghost notches are filled by all methods. The noise attenuation capability of ODG and RODG is demonstrated in the disappearance of low frequency amplitude from PZSUM. Note the notches indicated by the arrows in pressure (f) and vertical velocity (g).
EDITED REFERENCES
Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2014 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES


Hill, D., L. Combee, and J. Bacon, 2006, Over/under acquisition and data processing: The next quantum leap in seismic technology?: First Break, 24, no. 6, 81–96.


