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Simultaneous Source Designature and Receiver Deghosting in the Joint Shot-receiver Domain

G. Poole* (CGG), S. King (CGG) & J. Cooper (CGG)

SUMMARY

The success of any broadband survey is dependent upon the accuracy with which acquisition and environmental factors are compensated for in processing. Such compensation ideally involves directional source designature and deghosting along with receiver deghosting. Traditionally, receiver deghosting is applied in the shot domain, and directional designature in the receiver domain. We introduce an algorithm working in the joint shot-receiver domain that simultaneously corrects for source and receiver side effects in a single process. The algorithm is shown to produce broadband results with improved spatial consistency compared with sequential directional designature and receiver deghosting on a North Sea dataset.

Introduction

Direct recording of the broadband Earth response is not possible due to acquisition and environmental factors. Source and receiver array effects impose directional variations in the seismic recordings which may impact the integrity of AVO. Free surface ghosts introduce notches in the spectrum, thus limiting the usable bandwidth of the recorded data. A variable free surface datum (e.g. relating to swell/waves) at the time of acquisition creates additional complications (King and Poole, 2015). In order to reveal the broadband Earth response, these factors should be accurately compensated for during processing.

Traditionally, source designature was designed to debubble and zero phase the input data, but for broadband processing it has become necessary to further compensate for the ghost notches in order to widen the available bandwidth. This is only possible when precise knowledge of the farfield signature is available. Poole et al. (2013) showed how farfield signatures derived from nearfield hydrophone data can better attenuate residual bubble compared with those obtained from traditional modelling software. More recently, broadband sources have become available, which use airguns at more than one depth to diversify the source ghost (Hegna and Parkes, 2012).

On the receiver side numerous techniques have been developed to remove the free surface ghost. Some examples include the use of over-under streamers (Sønneland et al., 1986), variable-depth streamers (Soubaras, 2010; Poole, 2013; Wang et al., 2014a), and streamers incorporating geophones as well as hydrophones (Carlson et al., 2007).

This paper combines directional source designature (including the source ghost) and receiver deghosting into a single solution.

Method

Working in the receiver domain, Poole et al. (2013) described a modification to the linear Radon equations to model source array and free surface ghost directivity effects. The resulting τ-p model represented an isotropic point source, and enabled accurate shot-to-shot directional designature. Considering a frequency slice, the formulation was given by:

$$d_r(n_r) = L_r(n_r, m_r)p_r(m_r) \qquad (1)$$

The elements of the $n_r \times m_r$ matrix L_r were defined by:

$$L_r(n_r, m_r) = e^{-2\pi i f x(n_r) s_x(m_r)} g(n_r, m_r) \qquad (2)$$

d_r was the input receiver gather, p_r was the unknown τ-p model to be found by inversion, farfield resignature operators were given by g for the m_r^{th} source-side slowness and the n_r^{th} shot in the receiver gather, and the complex exponential related to the reverse slant stack operator for inline position x and slowness s_x at frequency f. The source resignature operators had the flexibility to vary from shot to shot, and could accommodate source datum corrections.

Using a similar theory but this time working in the shot domain, the linear Radon equations have also been modified to model the receiver-side free surface ghost (Poole, 2013). This approach derived a τ-p model representing up-going energy at sea surface datum that simultaneously satisfied both up-going and down-going arrivals in the input data. The model was used to derive an estimate of down-going energy that was subsequently subtracted from the input data, resulting in receiver deghosting. Using sparse inversion, Wang et al. (2014a) described a similar approach, but in 3D, and demonstrated its effectiveness on complex wide azimuth data.

Following notation similar to Wang et al. (2014a) the receiver deghosting linear equations may be given by:

$$d_s(n_s) = L_s(n_s, m_s)p_s(m_s) \qquad (3)$$

where the elements of the $n_s \times m_s$ matrix L_s are:

$$L_s(n_s, m_s) = e^{-2\pi i f \tau_{\mathrm{up}}(n_s, m_s)} + Re^{-2\pi i f \tau_{\mathrm{dw}}(n_s, m_s)} \qquad (4)$$

$$\tau_{\mathrm{up}}(n_s, m_s) = x(n_s)s_x(m_s) - z(n_s)s_z(m_s) \quad (5)$$
$$\tau_{\mathrm{dw}}(n_s, m_s) = x(n_s)s_x(m_s) + z(n_s)s_z(m_s) \quad (6)$$
$$\frac{1}{v_w^2} = s_x^2(m_s) + s_z^2(m_s) \quad (7)$$

d_s is the input shot gather, p_s is the unknown *τ-p* model to be found by inversion, and $L_s(n_s, m_s)$ is the combined reverse slant stack and receiver reghost operator for the m_s^{th} receiver-side slowness and the n_s^{th} receiver in the shot gather. L_s encodes up-going and down-going arrivals with timing τ_{up} and τ_{dw} respectively. The free surface reflectivity *R* is usually taken to be equal to -1. τ_{up} and τ_{dw} are defined by the receiver position (x, z) of each trace multiplied by slowness (s_x, s_z). The slowness in the *x*- and *z*-directions is linked to the water velocity v_w as in equation 7.

Instead of applying source designature in the receiver *τ-p* domain and receiver deghosting in the shot *τ-p* domain separately, we define a single linear problem to correct both source and receiver sides simultaneously in the joint shot-receiver domain. The joint shot-receiver domain can be defined by a group of shots within a spatially consistent shot window, recorded by receivers within a spatially consistent receiver window, as shown in figure 1.

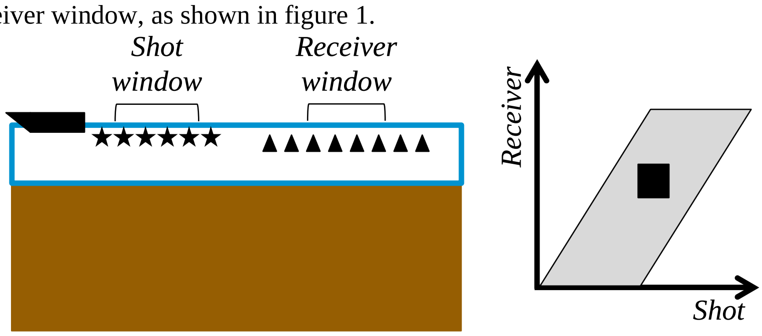

Figure 1 *Illustration of the shot-receiver domain, defined by a group of traces relating to shots firing within a spatially consistent shot window, recorded by receivers within a spatially consistent receiver window. This relates to a rectangular area in the shot-receiver stacking chart, right.*

Combining equations 1 and 3 gives:

$$d_{sr}(n_s, n_r) = L_{sr}(n_s, n_r, m_s, m_r)p_{sr}(m_s, m_r) \quad (8)$$
$$L_{sr}(n_s, n_r, m_s, m_r) = e^{-2\pi i f x(n_r)s_x(m_r)} g(n_r, m_r)\left[e^{-2\pi i f \tau_{\mathrm{up}}(n_s,m_s)} + Re^{-2\pi i f \tau_{\mathrm{dw}}(n_s,m_s)}\right] \quad (9)$$

where data in the shot-receiver domain is given by d_{sr}. The operator L_{sr} encodes both the source directivity (including source array effects and ghost) and the receiver ghost. Found by inversion, the resulting shot-receiver domain *τ*-p_s-p_r model p_{sr} represents an isotropic point source recorded by a receiver without free surface ghost. While the above formulation does not compensate for the receiver array effect, it is possible to modify further the equations to correct for this. The model may be reverse slant stacked with a conventional algorithm to create output data free of source directivity and source/receiver ghosts. The *τ-p* model may relate to 2D or 3D sampling. This may include the case of *τ*-p_{sx}-p_{rx}-p_{ry}. In practice it may be advantageous to use sparse inversion to find the *τ-p* model. Use of the low frequencies to dealias high frequencies following the approach of Herrmann et al. (2003) is generally necessary due to aliasing in the receiver domain relating to the shotpoint spacing.

While the current strategy allows simultaneous corrections at the source and receiver sides, it may also be used to correct for source or receiver sides separately, respectively by setting the sea surface reflectivity to zero or setting the resignature operators to unity. Additional ghost time delays relating to a variable free surface datum may be implemented following King and Poole (2015). Receiver deghosting a contiguous group of shots simultaneously may take advantage of notch diversity occurring due to variations in wave height between shots. The approach is compatible with multi-level sources and variable-depth streamers with single or multi-sensor receivers (for example, Poole, 2014 or Wang et al., 2014b). In addition, the equations may be further modified to model multiples following Poole et al. (2015).

Real data example

The data example comes from a multi-level source acquisition using variable-depth streamers acquired in the central North Sea. Figure 2 compares input data with data after directional source designature, directional source designature followed by receiver deghosting, and joint directional designature and receiver deghosting. The approach used angle-dependent farfield signatures calculated using notional sources that were derived from nearfield hydrophone data. The directional designature application included debubbling and multi-level source deghosting to broaden the bandwidth as much as possible. Figure 2 makes the comparison for a shot (a,b,c,d), common channel at 150 m offset and 8 m receiver depth (e,f,g,h), channel zoom below 8 Hz (i,j,k,l) and above 80 Hz (m,n,o,p), respectively. The designature and deghosting process is shown to reduce wavelet complexity, resulting in a broadband dataset. The joint designature and deghosting approach results in broadband data with reduced cable tug and improved spatial consistency at both low and high frequencies as highlighted.

Conclusions

We have introduced a combined source designature and receiver deghosting approach working in the joint shot-receiver domain. The method derives a τ-p_s-p_r model of the input data representing a point source without free surface ghosts. This is achieved by encoding the source directivity and free surface ghosts as part of a sparse inversion problem. The strategy handles source take-off angles for designature and receiver incoming angles for receiver deghosting simultaneously. The real data example shows that working on shot and receiver sides at the same time can result in more spatially consistent broadband data compared with sequential applications of designature and deghosting.

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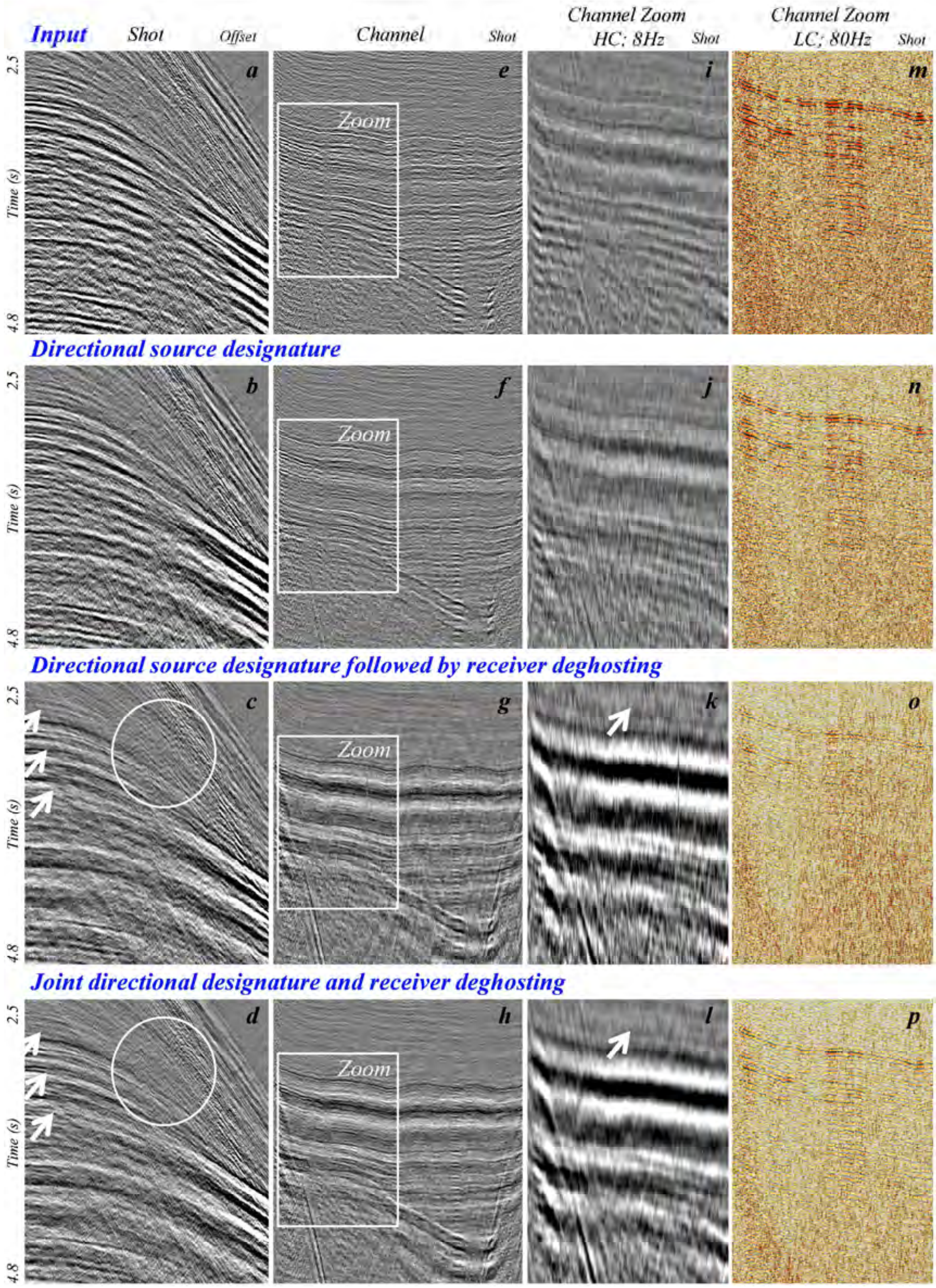

***Figure 2** Real data example comparing input, designature, sequential designature and receiver deghosting, and the proposed joint directional designature and receiver deghosting. Displays are given for shots (a,b,c,d), common channel (e,f,g,h), low frequency channel zoom (i,j,k,l), and high frequency channel zoom (m,n,o,p).*