

Th N103 11 Deghosting by Echo-deblending

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SUMMARY

Because of the strong sea surface reflectivity, a marine source generates both a direct wavefield and a ghost wavefield. This corresponds to a blended source array, the blending process being natural. Consequently, deghosting becomes deblending ('echo-deblending'). We discuss source deghosting by an iterative deblending algorithm that properly includes the angle-dependence of the ghost: it represents a full-wavefield solution.

The method is independent of the complexity of the subsurface: only what happens at and near the surface is relevant. This means that the actual sea state causes the reflection coefficient to become frequency dependent and the water velocity may not be constant due to temporal and spatial variations in the pressure, temperature and salinity. As a consequence, we propose that estimation of the actual ghost model should be part of the echo-deblending algorithm. This is particularly true for source deghosting, where interaction of the source wavefield with the surface may be far from linear.

The proposed echo-deblending algorithm is also applied to the detector deghosting problem. The detector cable may be slanted and shot records may be generated by blended source arrays, the blending being man-made.

Finally, we demonstrate that the proposed echo-deblending algorithm is robust for background noise.



Introduction

The source and detector ghost effects in marine acquisition cause angle-dependent notches in the spectrum and severe attenuation of the low frequencies. Today, there is a renewed interest in ghost suppression because it removes the large sidelobes of the wavelet, improving the resolution significantly. Some recent examples at the detector side are Soubaras (2010), Ferber et al. (2013), Beasley et al. (2013) and Ferber and Beasley (2014), and at the source side Mayhan and Weglein (2013) and Amundsen and Zhou (2013). In this paper, we describe source deghosting as a special case of deblending ('echo-deblending'), based on Berkhout and Blacquière (2014), leading to a non-causal, full-wavefield algorithm. Its output are *two* ghost-free records: one due to the real source below the water level and one due to the ghost source at the mirrored location above the water level. The method is independent of the complex subsurface: only what happens at and near the surface matters. Examples of carpet shooting (Walker et al., 2014) and interpolation of multi-sensor data at the detector side (Letki and Spjuth, 2014) allow practical application of source deghosting without any approximations. The echo-deblending algorithm can also be applied at the detector side. The detector cable may be slanted and the shot record may be blended, the blending being man-made.

Source deghosting in terms of deblending

In marine acquisition, the sources are towed at some spatially varying depth $+z_s(x, y)$. Due to the strong surface reflectivity two wavefields are generated: one travelling down and one going up, reflecting at the surface and then travelling down. Hence, a recording can be considered as the sum of the responses of the real sources at $+z_s$ and the ghost sources at $-z_s$. It is a *natural* blending process:

$$\mathbf{P}(z_0; \pm z_s) = \mathbf{P}^-(z_0; +z_s) + \mathbf{P}^-(z_0; -z_s),$$
(1)

where the \pm sign indicates that the real sources and the ghost sources are included. Column \vec{P}_j of data matrix **P** is one frequency component of shot record *j*. The detectors are located at the surface: $z_d(x,y) = z_0$ (for now assumed to be ghost-free). The responses due to sources at $+z_s$ and $-z_s$ can be expressed as extrapolations of the response due to sources at the reflection-free surface z_0 :

$$\mathbf{P}^{-}(z_{0};+z_{s}) = \mathbf{P}^{-}(z_{0};z_{0})\mathbf{F}^{+}(z_{0},+z_{s}),$$
(2a)

$$\mathbf{P}^{-}(z_{0};-z_{s}) = \mathbf{P}^{-}(z_{0};z_{0})\mathbf{R}^{\cap}(z_{0},z_{0})\mathbf{W}^{-}(z_{0},-z_{s}).$$
(2b)

Here matrices \mathbf{F}^+ and \mathbf{W}^- represent reverse and forward extrapolation in the near-surface water column, superscripts + and - indicating down and up, and a column of \mathbf{R}^{\cap} represents a frequency component of the angle-dependent water-surface reflectivity at one surface gridpoint. In the following we replace $\mathbf{R}^{\cap}(z_0, z_0)$ by $-\mathbf{R}$, making the polarity-reversal effect of \mathbf{R}^{\cap} explicit and simplifying the notation.

Closed-loop source deghosting by deblending

Since the ghost generation is a blending process, deghosting is a deblending process. We use the iterative closed-loop approach of Figure 1 (Berkhout and Blacquière, 2014), which we briefly summarize here. In the first iteration, the adaptive subtraction module is skipped: there are no simulated records at $+z_s$ and $-z_s$ yet. It means that in iteration one, the measured data $\mathbf{P}(z_0; \pm z_s)$ are considered to be the deblended estimates at both $+z_s$ and $-z_s$. They are input to module 'wavefield extrapolation to level z_0 ' that brings the sources to z_0 . For the real sources this means *forward* extrapolation with \mathbf{W}^- and for the ghost sources *reverse* extrapolation with \mathbf{F}^+ and application of $-\mathbf{R}^{-1}$. This results in two different response estimates related to virtual sources at z_0 :

$$[\mathbf{P}^{-}(z_0;z_0)]^{(i)} = [\mathbf{P}^{-}(z_0;+z_s)]^{(i)}\mathbf{W}^{-}(+z_s,z_0),$$
(3a)

$$[\mathbf{P}^{-}(z_{0};z_{0})]^{(i)} = -[\mathbf{P}^{-}(z_{0};-z_{s})]^{(i)}\mathbf{F}^{+}(-z_{s},z_{0})\mathbf{R}^{-1},$$
(3b)



Figure 1 Echo-deblending is a closed-loop process: ouput and input are connected via a feedback loop.

where the brackets [,] indicate an estimate and superscript (*i*) indicates the iteration counter (*i*=1,2,...). In module 'nonlinear filtering at z_0 ' we take the average of equations 3a and 3b. Using that $[\mathbf{P}^-(z_0; +z_s)]^{(1)} = [\mathbf{P}^-(z_0; -z_s)]^{(1)} = \mathbf{P}(z_0; \pm z_s)$, in iteration one this leads to:

$$[\mathbf{P}^{-}(z_{0};z_{0})]^{(1)} = \mathbf{P}^{-}(z_{0};z_{0}) \left[\mathbf{I} - \frac{1}{2} \mathbf{R} \mathbf{W}^{-}(z_{0},-2z_{s}) - \frac{1}{2} \mathbf{F}^{+}(z_{0},+2z_{s}) \mathbf{R}^{-1} \right].$$
 (4)

Here the amplitude of the data at z_0 is correct whereas the two wavefields at $\pm 2z_s$ are scaled by 1/2. The average is then thresholded in the time domain: $[\mathbf{P}^-(z_0;z_0)]^{(i)} \Rightarrow [\mathbf{P}^-(z_0;z_0)]^{(i)}$, such that the two responses at $\pm 2z_s$ are suppressed and parts of the response at z_0 are passed. In the next module the thresholded result is extrapolated reverse and forward to compute preliminary estimates related to sources at $+z_s$ and $-z_s$. In the last module the final estimates are computed by adaptively subtracting the preliminary estimates from the measured data. The sum of the two final estimates is compared to the measured data. If the difference is sufficiently small the procedure ends. If not, the next roundtrip is carried out, while the threshold is lowered to zero in the last iteration. Figure 2 shows the result for a complex receiver gather. The sources are towed at a depth of 30 m. After the echo-deblending process, the notch around 25 Hz has been removed for all angles. This is also clear in the deblended x, t-domain, showing the deghosted results at +30 m and -30 m. The deblending error is below -20 dB for 30 iterations.

Model estimation prior to source deghosting

In many methods for deghosting, the propagation velocity is taken constant and the surface reflectivity is considered to be -1. However, in practice this model is too simple. The actual surface reflectivity is related to the sea state in a frequency-dependent way (Orji et al., 2013). Also, the speed of sound is a function of temperature, depth, and salinity. We therefore propose to use all available information to obtain accurate estimates of \mathbf{F}^+ , \mathbf{W}^- and \mathbf{R} . The remaining refinements should be estimated from the data. We propose to use the autocorrelation of the data for this purpose. Figure 3 shows examples for the case of one horizontal reflector and different source-depth levels: 25 m, 50 m, 100 m, and 200 m, respectively. The ghost model is clearly visible, showing the real operators \mathbf{F}^+ , \mathbf{W}^- and \mathbf{R} .

Transformation to a new source depth

The autocorrelation in Figure 3 shows that for increasing source depth the ghost model can be easier identified. We therefore propose to realize larger source depths numerically. It can be verified that:

$$\mathbf{P}(z_{0};\pm 3z_{s}^{'}) = \mathbf{P}(z_{0};\pm z_{s}^{'})\mathbf{R}\left[\mathbf{I}+\mathbf{RW}^{-}(+z_{s}^{'},-z_{s}^{'})+\mathbf{R}^{-1}\mathbf{F}^{+}(-z_{s}^{'},+z_{s}^{'})\right]$$
(5a)

equals:

$$\mathbf{P}(z_{0};\pm 3z_{s}') = \mathbf{P}^{-}(z_{0};z_{0})\mathbf{F}^{+}(z_{0},+3z_{s}') - \mathbf{P}^{-}(z_{0};z_{0})\mathbf{\hat{R}}\mathbf{W}^{-}(z_{0},-3z_{s}'),$$
(5b)

where $z'_{s} = 3^{n-1}z_{s}$ and $\hat{\mathbf{R}} = \mathbf{R}^{3^{n}}$ for n = 1, 2,



A special case related to the above source depth transformation is that the real source is kept at the same depth (Ferber and Beasley, 2014). Alternatively, the ghost source can be kept at the same depth. The iterative application of methods like these causes the responses of the real sources and ghost sources to become more and more separated in time. The disadvantage of these methods is that they are sensitive to background noise. On the other hand, our echo-deblending algorithm is rather insensitive to background noise. This is not surprising as the blending concept is favourable to background noise (Berkhout and Blacquière, 2013) It is interesting to realize that the source depth transformation can be applied prior to our closed-loop deghosting process as a preprocessing step. If we apply this step N times and we stack the results during echo-deblending algorithm a modest role of the thresholding. Our current focus is on the combination of echo-deblending with source depth transformation where we apply only a few ghost-shifting steps. The combination allows low blending ánd background noise levels in the output.

Echo-deblending at the detector side

The echo-deblending concept can also be used at the detector side. In that case the method works on shot records. Such shot records may be blended, the blending being man-made. Figure 4 shows a simulated blended shot record (blending factor three), including -6 dB background noise, recorded by a slanted cable. Note the excellent performance of the echo-deblending algorithm and its robustness to the noise.

Concluding remarks

A marine shot record is a *blended* recording, with source(array)s at $+z_s$ and $-z_s$, the blending codes being +1 and $-\mathbf{R}$ respectively. Hence, source deghosting is a deblending process. This view leads to an iterative, full-wavefield algorithm ('echo deblending') that takes the angle- and frequency-dependent properties of the near surface into account, while it does not depend on the complex subsurface.

Optionally, the performance of echo-deblending can be improved by transforming the sources to larger depth levels, increasing the time separation between responses of the real and the ghost sources.

The method is robust for background noise, which is characteristic for deblending algorithms. The



Figure 2 Input (a,d), deghosted result at $+z_s$ (b,e) and at $-z_s$ (c,f) with $z_s = 30$ m. The echo-deblending process resolved the notch (k_x , f) and recovered the deghosted signals for all angles (x,t).



Figure 3 The autocorrelation of the data-with-source-ghost for $z_s = 25$ m, 50 m, 100 m, and 200 m, respectively. The autocorrelation contains information on the actual **R**, **W**⁻ and **F**⁺.



Figure 4 Echo-deblending at the detector side for a man-made blended shot record, blending fold 3, recorded by a slanted streamer, $z_d(x, y)$ ranging from 10 m to 60 m. Input (left) containing -6dB back-ground noise and echo-deblended result (right). The deghosted wavefields have been recovered for all angles and the method appears robust for background noise, being typical for deblending processes.

method can also be applied at the detector side, where man-made blending and recordings by slanted cables can be handled.

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