A method for deghosting of data recorded with a streamer of arbitrary shape in rough sea conditions

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ABSTRACT
Deghosting of pressure-only data has become a routine in marine seismic processing. Most existing techniques suffer from noise susceptibility or excessive simplification of the used ghost model, which leads to difficulties in removing the ghost waves. The algorithm presented in this paper is based on the wavefield extrapolation theory, and is capable of taking into account arbitrary streamer shapes and rough sea surfaces. The computations are performed in the frequency domain and come down to solving systems of linear equations. Regularization and data-adaptive statistical optimization of the parameters prevent noise amplification. We describe the theory of the method and test it against synthetic and field datasets with different streamer shapes for both rough and flat sea surfaces.

Key words: Seismic, Signal processing, Rough seas.

INTRODUCTION
Seismic data acquired in marine conditions contain ghosts. They are generally considered as noise during seismic processing, as the presence of ghost waves deteriorates the resolution of the seismic data, altering the shape of the amplitude spectrum and introducing notches in it (Hatton, Worthington and Makin 1986). It is known that ghost elimination (or deghosting) allows one to get a broadband image of the subsurface, which, in turn, improves the results of structural (Duval 2012) and amplitude (Schakel and Mesdag 2014) interpretation.

The problem of eliminating ghost waves from seismic gathers has been discussed in the literature since the beginning of marine seismic surveying. A number of techniques aimed at attenuating the ghost arrivals have been created. Some of them require sophisticated acquisition technologies, such as variable-depth streamers (Soubaras and Dowle 2010), multi-level sources and receivers (Posthumus 1993; Siliqi et al. 2013) and multicomponent recording (Barr and Sanders 1989). There are also processing-based solutions to the deghosting problem, the algorithms that do not require any changes in the standard acquisition configuration and can be used to process single-component data. This is justified by the fact that the majority of seismic surveys are performed using single-component streamers. Moreover, there are enormous amounts of legacy data to be re-processed to acquire better images of the subsurface.

Most processing-based deghosting solutions imply some assumptions about the streamer geometry. In most cases, the constant-depth streamer assumption is used. On the basis of this assumption, some researchers use one-dimensional operators in the Radon domain (Yilmaz and Baysal 2015), others apply two-dimensional filters in the \( \omega - p \) domain (Perz and Masoomzadeh 2014). The latter technique may also be used for data acquired with a slanted streamer assumption (Masoomzadeh, Woodburn and Hardwick 2013). The term ‘slanted’ here means variable-depth streamers with strictly linear shape. Rickett et al. (2014) have presented an algorithm for flat and slanted streamer acquisition. It is based on local plane-wave decomposition, and the upgoing wavefield is
estimated together with the ghost delay in the local plane-wave domain.

Some existing deghosting techniques are designed to process data acquired with variable-depth streamers. For example, Poole (2013) presented a pre-migration deghosting technology for variable-depth streamer data. A modified Radon transform (plane-wave decomposition) is used to simultaneously deghost and redatum the data.

In recent years, a number of new methods have been developed. These methods are based on the wavefield extrapolation theory, and can naturally handle smooth variations in the streamer shape. For example, Beasley, Coates and Ji (2013) apply Kirchhoff extrapolators to create the model of the ghost wavefield, and Robertsson and Amundsen (2014) use finite-difference operators for the same purpose. These algorithms have a number of advantages: they are applied before migration and can be easily modified to take into account the roughness of the sea surface, given an estimate of the sea surface shape. These wavefield extrapolation-based techniques are at early stages of development with respect to potential applications to real data.

As it is clearly stated by Beasley et al. (2013), deghosting techniques based on the wavefield extrapolation theory can naturally handle the sea surface variations. Some other existing deghosting methods are also able to take the roughness of the sea surface into account (Grion, Telling and Holland 2016). It is known that rough sea effects may introduce significant variations in the wavelet (Laws and Kragh 2002; Kragh and Laws 2006; Egorov et al. 2018), so accounting for them may potentially improve the quality of processed data. Still, that is possible only if an estimate of the sea surface shape is provided. In order to acquire the shape of the sea surface, many techniques may be used. Kragh, Laws and Combee (2002) showed that the shape of the sea surface may be derived from the low-frequency noise common for marine seismic. Orji, Söllner and Gelius (2012) imaged it using separated upgoing and downgoing wavefields and dual-sensor data. King and Poole (2015) proposed an iterative method based on cross-correlating the ghost and primary wavefields. It should be noted that not all of these methods may be used for arbitrary streamer geometry and single-component recording. For example, an algorithm proposed by Orji et al. (2012) utilizes separated downgoing and upgoing wavefields, which are obtained from dual-sensor measurements.

Here, we present a deghosting algorithm that can be used to process single-component marine seismic data acquired with a streamer of known arbitrary shape. ‘Arbitrary’ means that data acquired with any streamer shape can be processed: flat, slanted or variable-depth, with no constraints on the streamer shape. The algorithm is based on the wavefield extrapolation theory, and the deghosted solution is obtained by solving a number of regularized systems of linear equations. This regularization, along with the statistical optimization of the deghosting parameters, prevents noise amplification and helps to acquire better processing results. We demonstrate the robustness of our algorithm using field and synthetic datasets.

Our method can naturally handle rough sea surfaces. We discuss how the rough sea surface can be taken into account in a separate section of this paper. We also propose a simple approach to the estimation of rough sea surfaces from seismic data that are based on calculating and analysing autocorrelations of traces and does not require wavefield separation. We apply our method to a synthetic seismic gather calculated using the Kirchhoff approximation to prove its capabilities.

In case of a horizontal streamer and a flat sea surface, our ghost prediction operator based on the Kirchhoff integral theory will act similarly to the common regularized deghosting techniques implemented in the frequency-slowness or frequency-wavenumber domains. However, its advantages become obvious when the data acquired with a streamer of complex shape and rough sea surface is being processed.

In this paper, only two-dimensional examples are considered. Application of the described algorithm to three-dimensional (3D) data is also possible, however it might require extra processing steps to deal with the coarse receiver sampling in the crossline direction to avoid possible aliasing. A number of studies were related to crossline data interpolation for the purpose of deghosting. Deghosting and crossline interpolation are often carried out in a joint manner. Özbeke et al. (2010) presented an algorithm for joint deghosting and interpolation for multicomponent streamer data using matching pursuit. Rickett (2014), in turn, applied a sparsity-constrained inversion using local plane waves for true 3D deghosting and interpolation of single-component marine seismic data. As such a joint technique was not developed for our deghosting technology, 3D modification of our deghosting algorithm may be used after crossline interpolation by one of the existing methods (Gülinay 2003; Zwartjes and Sacchi 2007). We feel that aspects of data interpolation are out of scope of this paper and might be a subject of a separate study. In this sense, our algorithm faces the challenges similar to many other multichannel deghosting techniques.
**BEHAVIOUR OF THE GHOST WAVES**

Ghost waves are the reflections from the free surface (air/water boundary) that follow either the downgoing waves emanated by the source (in this case, they are called source-side ghosts) or the upgoing waves recorded by the receiver (receiver-side ghosts).

Immediately after source excitation, the downgoing wavefield generated by the source (an airgun array wavelet is given as an example in Fig. 1a) interferes with the wavefield reflected downward from the sea surface – the source-side ghost. The amplitude of the source-side ghost depends on the sea surface reflection coefficient (which is approximated by \(-1\) in case of a flat sea surface), and its delay depends on the source depth. The result of this interference (Fig. 1b) propagates through the medium, where it is reflected from depth interfaces. The reflected signal comes back to the streamer, where it is recorded by the receiver. This signal further propagates through the water to be reflected from the sea surface and recorded again as a receiver-side ghost. The signal on the seismic gather has a lot more complicated waveform (Fig. 1c) when compared to the initial wavelet.

Ghosts introduce minima in the amplitude spectrum of the recorded wavelet at certain frequencies. For pressure recordings in marine seismic, the first minimum is always at 0 Hz, which causes attenuation of low frequencies in Fig. 1(b,c). The positions of other minima depend on the source and receiver depths. Here, the minima at frequencies of 83 and 63 Hz (Fig. 1b,c) are caused by source and receiver depths of 9 and 12 m, respectively. Amplitude characteristics of the ghost operator were explained in detail by Hatton et al. (1986).

The algorithm proposed here is aimed at receiver-side deghosting, but it may also be applied for source-side deghosting using the reciprocity principle. This possibility will be discussed after the theory of the technique is outlined.

**ALGORITHM**

Like many other deghosting algorithms, our method is sensitive to the noise events that do not have ghosts or do not fit the ghost model. Before applying the algorithm, all these noise events, such as the direct wave, need to be removed. After direct wave elimination, a common source gather \( d(x, t) \) may be expressed as a sum of two wavefields:

\[
d(x, t) = w(x, t) + g(x, t),
\]

where \( w(x, t) \) is the upgoing wavefield at the receiver, which contains both the primary and the multiple waves. It can be considered the ideal result of the receiver-side dehosting procedure. \( g(x, t) \) is the downgoing (ghost) wavefield, which should be eliminated.

After Fourier transform over \( t \), we obtain:

\[
\tilde{d}(x, \omega) = \tilde{w}(x, \omega) + \tilde{g}(x, \omega),
\]

where \( \omega \) is the angular frequency, and \( \tilde{d}(x, \omega) \), \( \tilde{w}(x, \omega) \) and \( \tilde{g}(x, \omega) \) are the Fourier transforms of wavefields \( d(x, t) \), \( w(x, t) \) and \( g(x, t) \), respectively.

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As \( \hat{m} \) is a reflected wave in a homogeneous layer, it can be viewed upon as a direct wave in a homogeneous medium recorded by ‘mirror’ receivers in case of a flat sea surface. This also requires \( a \approx -1 \) (Brehkovskikh 1980). In case of rough sea, this assumption is violated, so the field of the reflected wave has to be calculated directly (e.g. using raytracing or wave propagation techniques). It is important to note that, even for a rough sea surface, we use constant \( a \) that does not depend on frequency. In our algorithm, the sea surface shape is determined explicitly, and the effects introduced by roughness are incorporated in \( \hat{m} \). Special aspects of taking into account rough sea surfaces will be discussed in a separate section of this paper.

For the horizontal free surface, \( \hat{m} \) may be expressed as:

\[
\hat{m}(b, x, \omega) = \frac{1}{r(b, x)} e^{j\phi(b, x)},
\]

(4)

where \( r(b, x) \) is the distance travelled by the wave from \( b \) to \( x \), \( v \) is the acoustic wave velocity in the water, \( j = \sqrt{-1} \).

The normal derivative of \( \hat{m}(b, x, \omega) \) is calculated as follows:

\[
\frac{\partial}{\partial n_1} \left( \frac{1}{r(b, x)} e^{j\phi(b, x)} \right) = \left( \frac{j\omega}{r(b, x)} - \frac{v}{r^2(b, x)} \right) e^{j\phi(b, x)}
\times e^{j\phi(b, x)} \frac{\partial}{\partial n_1} r(b, x),
\]

(5)

where \( r(b, x) = \frac{r(b, x) v}{v} \) is the traveltime curve of the reflected wave. According to Červený (2001):

\[
\frac{\partial}{\partial n_1} r(b, x) = \cos \varphi(b, x) \frac{\varphi(b, x)}{v},
\]

(6)

where \( \varphi(b, x) \) is the angle between the normal to the surface \( \Sigma_1 \) and the ray connecting \( b, c \) and \( x \) (see Fig. 3).

Substituting expressions (5) and (6) into the integral (3) leads to:

\[
\hat{g}(x, \omega) = a \int_{b \in \Sigma_1} \hat{w}(b, \omega) \cos \varphi(b, x) \left( \frac{j\omega}{r(b, x)v} - \frac{1}{r^2(b, x)} \right)
\times e^{j\phi(b, x)} db.
\]

(7)

The expression in equation (7) contains both the far-field (proportional to \( r^{-1} \)) and the near-field (proportional to \( r^{-2} \)) terms.

In equation (7), the integration is performed over the surface \( \Sigma_1 \). In order to make a transition from integration to summation, we make an assumption of constant receiver interval on the streamer \( \Delta b_1 \) and constant distance between the streamers \( \Delta b_2 \). In other cases, data need to be mapped to a regular grid.

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Vector coordinate of the $k$th receiver on the $k$th streamer is defined as $b = (k\Delta b_1, l\Delta b_2)$. Using this representation, we can transform the integral (7) into:

$$
\tilde{g}(x, \omega) = a \sum_{bc \in \Sigma_1} \tilde{w}(b, \omega) \cos\phi(b, x) 
\times \Delta b_1 \Delta b_2 \left( \frac{j \omega}{r(b, x)v} - \frac{1}{r^2(b, x)} \right) e^{i \tau(b, x)},
$$

where $\sum_a b$ is a short form of $\sum_b \Delta b$.

We introduce the following notations: $h^{3D}(x, \omega)$ is the weighting coefficients, $\tau$ is the summation trajectory, with

$$
h^{3D}(b, x) = \cos\phi(b, x) \Delta b_1 \Delta b_2 
\times \left( \frac{j \omega}{r(b, x)v} - \frac{1}{r^2(b, x)} \right) \cdot \tau(b, x) = r(b, x)v.
$$

Superscript (3D) is put here to lay emphasis on the fact that the transformation is applied to three-dimensional (3D) gathers.

Using these notations, we can transform equation (2) into:

$$
\tilde{d}(x, \omega) = \tilde{w}(x, \omega) + a \sum_{bc \in \Sigma_1} \tilde{w}(b, \omega)e^{i\tau(b, x)}h^{3D}(b, x).
$$

A similar expression may also be acquired for two-dimensional (2D) case by replacing 3D weighting coefficients with their 2D equivalents. The 2D expression of the weighting coefficients with included near-field term is as follows (Margrave and Daley 2001):

$$
h^{2D}(b, x) \approx \cos\phi(b, x) \Delta b_1 \sqrt{\frac{\omega}{2\pi r(b, x)v}} e^{i\tau(b, x)}
\times \left( 1 + \frac{3jv}{8or(b, x)} \right) e^{-j\tau}. \tag{11}
$$

It is important to note that strict computation of the weighting coefficients in 2D requires the calculation of the Hankel function. In the derivation of the analytic form used in expression (11), the Hankel function is approximated by a series. So, in contrast to $h^{3D}(\cdot, \cdot)$, the $h^{2D}(\cdot, \cdot)$ coefficients are approximate. Still, the 2D numerical examples below show that this approximation is valid.

At a constant frequency $\omega$, expression (10) is a system of linear equations with complex coefficients:

$$
S\hat{\omega} = \hat{d}.
$$

$S$ is the matrix of the linear system, $\hat{\omega}$ and $\hat{d}$ are the vectors composed of the elements of $\tilde{w}(x, \omega)$ and $\tilde{g}(x, \omega)$ for a constant $\omega$. The unknown vector here is represented by the deghosted wavefield $\hat{\omega}$, which may be obtained by solving this system for each frequency in the signal frequency range $\omega \in (\omega_1, \omega_2)$. Direct solution of the system implies calculating an inverse of the ghosts operator, which may express unstable behaviour. In order to achieve a more stable solution and deal with the noise amplification, the least squares regularized approach should be applied as (Seber 1977):

$$
\hat{\omega} = (S^H S + \gamma E)^{-1}S^H \hat{d},
$$

where $E$ is the identity matrix, $\gamma$ is the regularization coefficient and superscript $H$ denotes conjugate transpose. The regularization coefficient $\gamma$ is defined as a percentage of the maximum diagonal element of $S^H S$.

After this system is solved for all the frequencies, $\hat{w}(x, \omega)$ is acquired. Its inverse Fourier transform is calculated to obtain the deghosted wavefield in time domain $w(x, t)$.

**OPTIMIZATION**

In the previous section, the reflection coefficient of the sea surface $a$ and the acoustic wave velocity in the water $v$ were assumed to be known. However, it may be useful to vary these parameters in order to improve the deghosting results, as it is known that the acoustic wave velocity in the water depends on temperature and salinity, and the value of the reflection coefficient $a$ may differ from $-1$ in case of a rough sea surface (Hatton et al. 1986).

Denisov and Firsov (2016) use the minimum-energy criterion to estimate the sea surface reflection coefficient and to determine the receiver depth in the process of deghosting. The same principle will be used in the current study.

Let us denote the deghosting result obtained using the reflection coefficient $a^*$ and the velocity $v^*$ by $w(x, t^*)$. Using these notations, it is possible to form an objective function that characterizes the energy of the deghosting result:

$$
J(a^*, v^*) = \sum_{t} \sum_s (g(x, t))^2.
$$

Then the optimization problem to be solved to obtain the optimal values $a$ and $v$ is written as:

$$
\hat{a}, \hat{v} = \arg\min_{a^*, v^*} J(a^*, v^*). \tag{15}
$$

Although it is also possible to use the minimum-energy criterion to refine the streamer shape, this is a separate problem and is out of scope of this research.

During the optimization, deghosting trials are done many times to compute the objective function. As a result of testing, we found out that one trial optimization step (one deghosting with a given set of $a^*$ and $v^*$) takes approximately 20% more
time when compared to common deghosting techniques in \( \omega - p \) or \( \omega - k \) domains. Extra 35\% of processing time is needed in case the rough sea surface is taken into account.

Our least-squares optimization approach is based on the assumption that the wavelet with the ghost included has higher energy than the wavelet without the ghost. We expect this criterion to be correct for a broadband source wavelet and a deeply towed streamer, which means relatively large lag between the primary and the ghost. In that case, the energy of the two interfering events should exceed the energy of a single primary wave. In case of a narrow-band wavelet, a preliminary spectrum whitening of the source wavelet by means of source signature deconvolution, a standard tool in a modern marine data processing flow, may be required to satisfy the minimum-energy assumption. Still, we never experienced a situation where preliminary signature deconvolution was necessary.

It is important to note that the statistical optimization is not the essence of our theory, but only its optional element. In case the source wavelet is narrow-band or the tow is not deep enough for minimum-energy criterion to work, the values of \( \hat{a} \) and \( \hat{v} \) may be constrained using \textit{a priori} information. If that still deteriorates the result of deghosting, our approach can be used similarly to the known deterministic methods: given the streamer geometry, one can manually set the acoustic wave velocity, assume the reflection coefficient to be –1 and apply the deterministic inversion by solving the system of linear equations.

SYNTHETIC DATA EXAMPLE

The proposed algorithm was tested on both the synthetic and real data. A synthetic gather was calculated for a simple model with one deep flat boundary (seabottom) and a flat sea surface. Under such conditions, the ray-theoretical computations used to calculate this gather are accurate. Complex streamer geometry was used intentionally to show the capabilities of the algorithm. The acquisition geometry was two-dimensional, with 6.25-m receiver interval. The wavelet from Fig. 1 was used for modelling. The reflection angle at the maximum offset is around 25\°. The maximum displayed offset was chosen to be 750 m for the visualization purposes. To demonstrate the stability in the presence of noise, white noise was added to the gather. Signal-to-noise ratio of the input gather was equal to 8.0. It was computed as a ratio of maximum absolute amplitude of the trace and the root mean square amplitude of noise.

The streamer geometry and the seismic gathers before and after deghosting are shown in Fig. 4. The streamer geometry is complex, with strong variations in depth from 7 m to 13 m. Source ghost was included in the modelling. As it can be seen from Fig. 4(b), the variations in streamer depth cause variations in the receiver ghost arrival time. At far offsets, the ghost is separated from the primary due to deep tow. Application of unregularized deghosting leads to the amplification of noise (Fig. 4c). As a result of regularized deghosting, all of the variations have been well accounted for, and the ghosts have been successfully eliminated in the whole offset range, with streamer depths varying from 7 m to 13 m (Fig. 4d). Regularization allows the geophysicist to control the noise amplification. The difference between the original gather and the regularized deghosting result is shown in Fig. 4(e). For
this gather, the regularization parameter $\gamma$ was equal to 5%. When choosing $\gamma$, we pick the smallest value that provides acceptable signal-to-noise ratio of the output, which is similar to the way regularization coefficient is chosen in spiking deconvolution. The signal-to-noise ratio of the output gather in Fig. 4(d) is equal to 7. We believe that this drop in signal-to-noise ratio is not only related to the amplification of noise, but also to the drop in the maximum absolute amplitude of the signal after deghosting (e.g. compare Fig. 1c and b). As the scaling of all the gathers in Fig. 4 is the same, it can be seen that the level of ambient noise in the output data is similar to the level of noise in the input, which shows that the described algorithm is robust in the presence of noise.

As it can be seen from the results shown, the method has successfully eliminated the ghost on the data recorded with a curved streamer. Besides, in spite of a relatively shallow tow at short offsets, the energy of the primary interfering with a ghost is larger than that of the primary wave. This effect justifies the application of the least squares objective to refine the parameters of the ghost reflection.

**REAL DATA EXAMPLE**

As the variable-depth streamer shooting configurations are still not as widely used as the conventional flat streamers, we were only able to test the algorithm on a real two-dimensional dataset acquired with a horizontal streamer. The source and streamer tow depths were equal to 14 m and 15 m respectively, which leads to minima in the amplitude spectrum at frequencies of approximately 54 Hz and 50 Hz (for normal incidence). The sampling rate equals 4 ms. Consequently, the Nyquist frequency is 125 Hz. The source interval is 25 m and the receiver interval is 12.5 m.

Figure 5(a) shows an input common-shot gather. The estimate of the signal amplitude spectrum is characterized by very low energy in the frequency range from 0 to 10 Hz and a

![Figure 5](image_url)
minimum around 50–55 Hz. The same gather after receiver-side deghosting (Fig. 5b) has wider frequency band, which is mainly caused by the amplification of low frequencies.

As the streamer was flat, the source-side ghosts could be suppressed with the same technique, just for the display purposes. Rigorous application of source-side deghosting would involve sorting the data into common-receiver point gathers and applying the algorithm to those gathers using the reciprocity principle. Note that the construction of a common-receiver point gather requires a flat streamer geometry, implying that receiver-side redatuming to a flat-streamer geometry should be applied for data acquired with variable-depth streamers.

Here, we assume that on a half-spread distance the Earth is locally one-dimensional, i.e. the dip of the reflectors is relatively small. Then our scheme can be applied directly to the common-shot gathers as if they were common-receiver point gathers. For source-side deghosting, the depth of the receiver should just be replaced by the depth of the source. As a result of the source-side deghosting (Fig. 5c), the frequency content around the minimum was recovered and the energy of the low frequencies was restored. The amplitude spectrum is reminiscent of the theoretical airgun array signal spectrum in Fig. 1(a). The wavelet shape has become much simpler and is represented by a single pulse, which can be seen on the seabottom reflection.

Both for source-side and receiver-side deghosting, a regularization coefficient equal to 5% was used. Acoustic wave velocity was equal to 1450 m/s, constrained optimization for the sea surface reflection coefficient $a$ was carried out. Due to good weather conditions, the optimized reflection coefficients were in the range between –1 and –0.95.

To achieve maximum resolution, minimum-phase spiking deconvolution was applied (Fig. 5d). It helps to deal with the overamplification of low frequencies with respect to the desired flat amplitude spectrum, which is caused by the strong low-frequency output of the original unghosted airgun array signal. If we apply spiking deconvolution directly to the input data, we will flatten the amplitude spectrum, but we will not achieve the desired deghosting result, since the wavelet shape will be significantly different. The ideal output of deghosting is shown in Fig. 1, and its amplitude spectrum is far from being flat. Hence, successful wavelet sharpening implies deghosting followed by deconvolution.

The same characteristics of the wavefields may be observed on the stacked data before and after the source- and the receiver-side deghosting followed by deconvolution (Fig. 6).

Of course, spiking deconvolution could influence the results of amplitude-versus-offset (AVO) inversion and other dynamic interpretation techniques. When true-amplitude processing is needed, statistical spiking deconvolution may be replaced with signature deconvolution at this stage, if a good estimate of airgun array signal is available. Moreover, the deterministic signature deconvolution might account for a possible non-minimum-phase nature of the wavelet. When trying the spiking deconvolution algorithm here, we intended to demonstrate how the procedure, which is an industry

![Figure 6](image-url)
standard for achieving better data resolution, is capable of eliminating the overamplification of low frequencies and adding high frequencies to the output of deghosting. Clearly, broadband processing implies the transformation of the recorded wavelet into a pulse with a flat amplitude spectrum within the signal frequency band. After deghosting, the resulting wavelet in the data will be the unghosted source function of the airgun array. One can estimate the source air-gun array wavelet (or model it) and perform the deterministic signature deconvolution. At this processing step, the residual bubble pulses are removed and the wavelet is finally transformed into the desired function with a flat amplitude spectrum.

Our algorithm involves wave propagation, hence it is susceptible to aliasing. Aliased events are not processed correctly. In case of the used 12.5 m interval between the traces, the events with apparent velocity of 1500 m/s become aliased at the frequency of \( \frac{c}{2} \) Hz. The aliasing noise is weak in the displayed figures due to the fact that it might touch only the high frequencies. This high-frequency noise gets amplified at the deconvolution step, although it still does not contribute much to the displayed stacked data. However, if stronger alias protection is required, the data need to be interpolated before dehosting. The marine data processing result demonstrated is the only real data example we had a permission to show. Since the data were acquired with a flat streamer and in still water conditions, the improvement over the known processing schemes is related to the mentioned above computational stability due to the statistical optimization and regularization. The main advantage of our algorithm, which lies in its ability to process the data acquired with complex streamer shapes and in rough sea conditions, is illustrated here with the synthetic examples.

ROUGH SEA CASE

Data acquired in bad weather conditions require special treatment to get high-quality dehosting results. Due to the recursive nature of the dehosting operator, perturbations introduced by the rough sea surface may cause unwanted oscillations in the processing output. That may be accounted for using a known shape of the sea surface.

We will demonstrate the capabilities of our algorithm for determining the water surface geometry using a synthetic seismic gather with a single reflection and its ghost generated by a three-dimensional Pierson–Moskowitz rough sea surface with 4 m significant wave height (a slice of that surface along the streamer direction can be seen in Fig. 7c). The gather (Fig. 7a) was modelled using the Kirchhoff approximation, which includes both the far-field and the near-field terms (Laws and Kragh 2002). A flat streamer towed at the depth of 8 m was assumed, the source depth was 5 m. In our example, we considered the sea surface in a ‘frozen’ state. The variation of the sea surface in time may be taken into account using multiwindow processing. Kragh and Laws (2006) showed how multiwindow processing could be used to improve statistical deconvolution results in case of rough sea. Dehosting may be applied in a similar manner, however a careful study on understanding the limitations of this approach and choosing a proper window size for the procedure still needs to be carried out.

For each trace in the seismic gather, an autocorrelation is calculated (a set of autocorrelations is displayed in Fig. 7b). Since the reflection coefficient of the sea surface is close to \(-1\), the autocorrelation has a strong minimum corresponding to the ghost wave time lag, and this minimum can be picked
Method for deghosting automatically (minima of the autocorrelation functions are shown in red in Fig. 7b). Obviously, the output curve has a trend for decreasing with offset (red curve in Fig. 7c). This is caused by the fact that the ghost wave time lag decreases with angle/offset. We suggest detrending that curve to get the ‘pure’ (or ‘angle independent’) ghost delays that can be approximately attributed to the two-way vertical traveltime. Then the delays picked are transformed into the wave height above each receiver. In this case, to demonstrate the capabilities of our algorithm, we used linear trend removal, which may be a simplification. We believe that different trend functions may need to be considered when processing long-offset field data. Certainly, such an approximation is true for a small ray emergence angle and a deep tow of the seismic streamer. This algorithm is applicable to the data acquired with a constant-depth streamer, finding an alternative method for different streamer shapes remains a subject of our future research.

The sea surface geometry estimate obtained after trend removal is marked with blue in Fig. 7(c). This curve agrees well with the shape of the sea surface used for modelling, which is marked with black in the same figure. Clearly, the amplitudes of the sea waves at long offsets are underestimated, but the synthetic data tests show that this accuracy is enough to significantly improve the deghosting results.

The acquired surface after trend removal will now be utilized to calculate \( \tilde{m}(b, x, \omega) \) needed for the deghosting scheme. Instead of using mirror positions of the receivers (Fig. 3) to evaluate \( r(b, x) \) and \( \cos \varphi(b, x) \) in expression (9), proper ray-tracing has to be performed (Fig. 8). This is the only change needed to incorporate the rough sea effects into the processing scheme. Of course, this will only result in an approximate solution, as this method of calculating the ghost is based on the Kirchhoff approximation (Ogilvy 1991). However, tests on synthetic data show that even this approximation helps to improve the processing output. Deghosting results for the synthetic seismic gather from Fig. 7 are shown in Fig. 9. It can be seen that ignoring the rough sea surface introduces noise into the output, also severe variations in the waveform of the deghosted signal are noticeable. It is clear that taking the shape of the sea surface into account helps to eliminate those variations and weaken the roughness-related artefacts (Fig. 9b). Note that, although the streamer is relatively shallow, our autocorrelation-based method of rough sea surface estimation works well, indicating that the range of applicability of this algorithm is wider than could be expected.

CONCLUSIONS AND DISCUSSION

In this paper, we describe the process of ghost wave generation in terms of wavefield extrapolation. This allows us to create a deghosting algorithm that is based on the inversion of the integral expression for the ghost wave model. In the process of inversion, the values of the sea surface reflection coefficient and the acoustic wave velocity in the water are refined via statistical optimization with the minimum-energy objective.

The majority of the existing deghosting schemes is based on simpler models of wave propagation. However, due to the general character of our model, the proposed scheme is capable of handling arbitrary streamer geometry and rough sea surfaces assuming known streamer shape. The described scheme obtains the deghosted wavefield by solving a number of systems of linear equations, which enables application of regularization in order to deal with the noise amplification.

We derive the algorithm for both two-dimensional (2D) and 3D cases, however provide only 2D synthetic and field
data examples. In the examples shown, as well as in the derivation of the 2D algorithm, we assume that the streamer does not deviate from the seismic line. Synthetic and real data tests prove that the algorithm is capable of successfully attenuating ghosts for different types of streamer geometry. Even rough sea surface can be taken into account. It is shown on a flat-streamer synthetic dataset that autocorrelations of the data may be used to obtain an estimate of the rough surface, and that this estimate is enough to significantly improve processing quality for the data acquired in rough sea conditions. Determining the shape of the rough sea surface and taking it into account during deghosting in case of non-flat streamer geometry remains the subject of our future work. Further testing on real data is needed to prove the applicability and robustness of our algorithm.

We apply optimization to obtain the estimates of the sea surface reflection coefficient and the acoustic wave velocity in the water. Probably, it is also possible to refine the shape of the sea surface and the streamer geometry using the same minimum-energy objective. This may be the subject of our future research.

Here we focus on the deeply towed streamer case because it clearly reveals the advantages of our scheme that allows the computation of the optimized solutions. Shallow data recording, in case of a narrow-band airgun array signal, might violate the minimum energy assumption involved in the optimization. Still, this does not mean that the algorithm becomes useless. Clearly, the scheme can be used in a more conventional deterministic manner, i.e. without the search for the reflection coefficient or the water velocity. To do this, the user is only expected to specify a zero width of the permissible range of the sought-for values without introducing any changes into the algorithm.

We were able to successfully remove the ghost waves on the synthetic gathers, which were computed with the streamer as shallow as 7–8 m. Such streamer depth is comparable to the streamer depth used for the acquisition of numerous legacy datasets that may need broadband re-processing.

Finally, we strongly emphasize that we had no intention of proposing a universal deghosting method and we are far from the idea of recommending to replace all other well-proven methods by our algorithm. As in seismic deconvolution, migration, demultiple, etc., a geophysicist can have a variety of approaches to choose from. The main advantages of our dehosting tool (besides the developed optimization and regularization aspects) become evident in case of a rough sea surface and curved streamer shape.

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