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Adaptive Deghosting Including the Rough and Time Variant Sea Surface

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Summary

A rough and time-variant sea surface can cause uncertainties of the source and detector locations with respect to the sea surface. Deghosting of pressure data that ignores the rough and time-variant character of the sea surface will result in noise and ringing.
The effect of a rough and time-variant sea surface at the source is different from the detector side. At the source side an effective rough and time-invariant sea surface is considered, where at the detector side a rough and time-variant sea surface is considered. For both sides a deghosting method is proposed that on-the-fly will optimize the actual detector and/or source locations. The method uses wavefield propagation to take into account a rough and time-variant sea surface. In order to account for the time-variant effects the method is applied for specific windows of the data. An extreme case with a rough and time-invariant sea surface will show that the adaptive source deghosting method is able to improve the SNR after deghosting compared to a non-adaptive deghosting method. The next extreme case will show that at the detector side the window-based adaptive deghosting method will further improve the perfomance in the case of a time-variant surface.

Introduction

Deghosting of pressure data requires a ghost model. An inexact ghost model will introduce noise and ringing in the data after deghosting. A rough and time-variant sea surface can cause inexact source and detector locations with respect to the sea surface in the ghost model. Therefore, ghost model estimation has to be part of the closed-loop deghosting algorithm (Vrolijk and Blacquière, 2017). At the detector side Rickett et al. (2014) and King and Poole (2015) introduce adaptive deghosting algorithms in the τp-domain that take into account small deviations in the delay times of the ghost operator. That approach is not exact in the presence of a rough sea surface where the angles of the incoming wavefield are different from the angles of the reflected wavefield.

A deghosting method is proposed that on-the-fly will optimize the actual dectector and/or source locations. The method uses wavefield propagation to take into account a rough and time-variant sea surface.

Theory

In marine acquisition, detectors are towed at some depth z_d, which is a spatially dependent variable, i.e., $z_d = z_d(x,y)$. The reflectivity at the sea surface located at depth z_0 is very strong which means that two pressure wavefields are measured at a detector: the first is directly travelling up, the second is going up, getting reflected at the water surface and then travelling down. The latter generates the so-called ghost response at the detector side. We now formulate the forward model. The measured wavefield at the detector side is the sum of the two wavefields mentioned: the direct one and the one reflected at the sea surface. Using the matrix notation (Berkhout, 1985), the process can be formulated as follows for each frequency component in the space domain for a single shot record:

$$\vec{P}(z_d;z_0) = \mathbf{D}_0(z_d)\mathbf{G}(z_d,z_d)\mathbf{X}(z_d,z_0)\vec{S}_0(z_0), \tag{1}$$

where the source is located at z_0, $\vec{S}_0$ is the source pressure field, $\mathbf{X}^{\cup}$ is the Earth transfer function, $\mathbf{D}_0$ is the detector matrix and $\vec{P}$ is a monochromatic shot record. The ghost operator at the detector side is given by:

$$\mathbf{G}(z_d,z_d) = [-\mathbf{W}^{+}(z_d,z_0)\mathbf{W}^{-}(z_0,z_d) + \mathbf{I}(z_d,z_d)]. \tag{2}$$

The $\mathbf{W}^{-}(z_0,z_d)$ matrix represents propagation from the dectector level to the sea surface and the $\mathbf{W}^{+}(z_d,z_0)$ matrix represents propagation from the sea surface to the detector level, the minus sign is the result of a strong sea surface reflectivity of -1. Finally, the model can be extended to include the ghost response related to sources at level $z_s(x,y)$ as well:

$$\vec{P}(z_d;z_s) = \mathbf{D}_0(z_d)\mathbf{G}(z_d,z_d)\mathbf{X}(z_d,z_s)\mathbf{G}(z_s,z_s)\vec{S}_0(z_s), \tag{3}$$

where $\mathbf{G}(z_s,z_s)$ is the ghost operator at the source side.

In practise, the shape of the sea surface is time-variant, meaning that $z_0 = z_0(x,y,t)$. This time-variant effect needs to be included in the forward model. However, the time-variant effect on the ghost wavefield

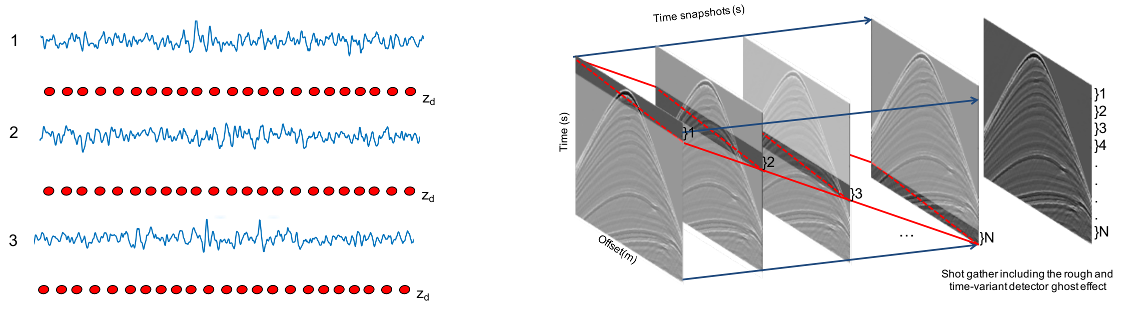

***Figure 1** The rough detector ghost effect is calculated for multiple time instances. In order to create a shot gather with a rough and time-variant detector ghost effect the result of these snapshots is combined.*

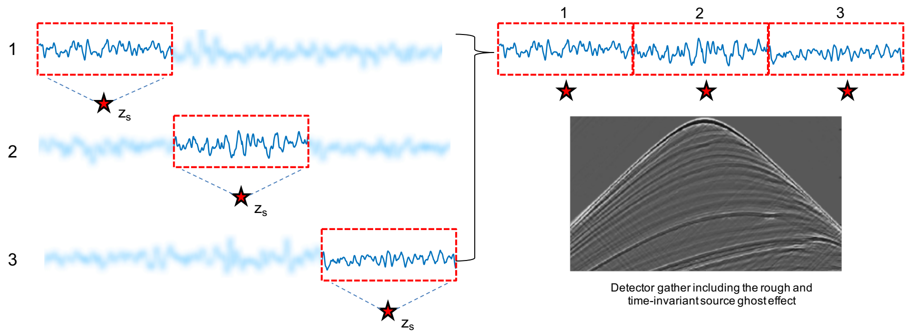

Figure 2 *A dectector gather with a rough and time-invariant source ghost effect is the result of an effective time-invariant sea surface, which is the combination of different time instances of the actual sea-surface.*

at the source side differs from that at the detector side. The upgoing wavefield at the detector side is reflected from the sea surface during the full recording. This needs to be included by calculating positions of dectectors with respect to an actual time-variant sea surface and the corresponding ghost model for each time instance (see Figure 1). At the source side however, the upgoing wavefield is reflected only at one specific time and sea surface location. Therefore, when modeling the source ghost wavefield, the time-variant sea surface can be replaced by an effective time-invariant sea surface. Obviously, each shot is emitted at a different time, meaning that the actual sea surface is different from shot to shot (see Figure 2).

Method

The adaptive closed-loop detector deghosting method is based on solving the following constrained minimization:

$$min|\vec{P}(z_d;z_s) - \mathbf{D}_0(z_d)\mathbf{G}^{\cap}(z_d,z_d)\mathbf{X}(z_d,z_0)\vec{S}_0(z_0)|_2 \quad \text{subject to} \quad |\mathbf{x}_0(z_d;z_s)\vec{s}_0(z_0)|_1 < \tau \;\text{ and }\; z_{min} < \Delta z(x,y) < z_{max}. \tag{4}$$

In this underdetermined system there are two unknowns, being the ghost-free shot record $\mathbf{X}(z_d,z_0)\vec{S}_0(z_0)$ in the frequency domain and the depth of detectors with respect to the sea surface, with $\Delta z(x,y) = |z_d(x,y) - z_0(x,y)|$. The sparsity constraint, set by a user defined constant τ, is applied to $\mathbf{x}_0(z_d;z_s)\vec{s}_0(z_0)$, the ghost free data in the time domain. A box constraint is added to limit the solution space of parameter $\Delta z(x)$. The set of equations is solved with the projected quasi-Newton method (Schmidt et al., 2009) to determine $\mathbf{X}(z_d,z_0)\vec{S}_0(z_0)$ and $\Delta z(x,y)$ without explicitly calculating the inverse ghost matrix $[\mathbf{G}(z_d,z_d)]^{-1}$. In every iteration the gradient with respect to both variables is calculated. The gradient for parameter $\Delta z(x,y)$ is hidden in $\mathbf{G}(z_d,z_d)$ and calculated with a first order approximation. A similiar approach can be applied to a receiver gather for source deghosting with a rough and time-invariant sea-surface. We can take into account a rough and time-variant sea-surface similiar to Grion and Telling (2017) by solving the set of equations for multiple time windows in a consecutive manner.

Examples

Case I: Source deghosting for a time-invariant, rough sea surface

The time-invariant and rough effective sea surface and its ghost effect at the source side, corresponding to sources around 20 m and sea state 9, is modelled with a standard Kirchoff method (Laws and Kragh, 2002; Pierson and Moskowitz, 1964). This extreme case has been chosen for illustration purposes. A detector gather including the primaries, internal multiples and the source ghost effect is given in Figure 3a. The small time deviations in the ghost wavefield (see Figure 3a) indicate that the actual depth with respect to the sea surface used in our ghost model is different depending on the wave height and lateral position. As a reference we show in Figure 3b the result after non-adaptive deghosting (Vrolijk and Blacquière, 2017) assuming an inaccurate ghost model for a flat sea and fixed source locations at 20 m. Note that the sparsity constraint is able to suppress some of the noise. However, Figures 3b and e indicate

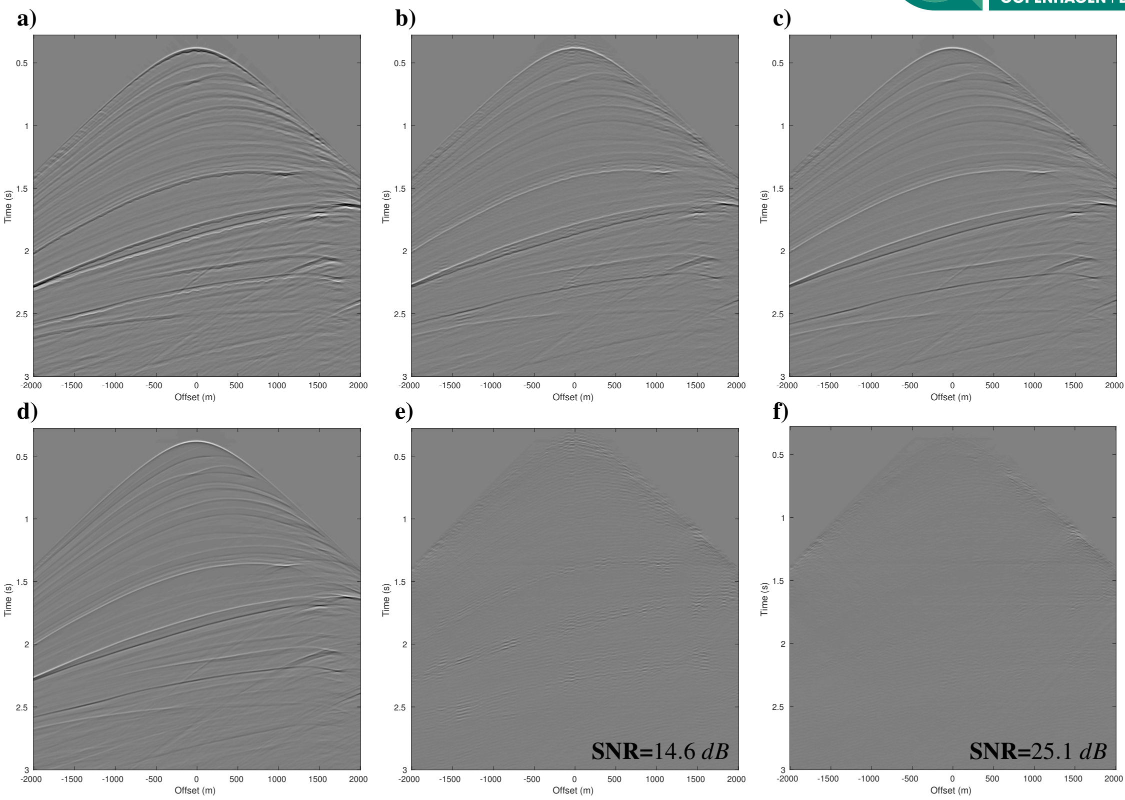

Figure 3 *In a) sources are at $z_s = 20$ m, b) output after source deghosting, c) output after adaptive source deghosting, d) modelled ghost-free data, d) residual after deghosting and e) the residual energy after adaptive source deghosting.*

that ignoring the rough character of the sea-surface will introduce noise and ringing. The residual and corresponding SNR in Figure 3e are given with respect to the modelled data that are shown in Figure 3d. In Figures 3c and f we see that a more accurate deghosting result is obtained after the adaptive deghosting method. The SNR after the adapative method is improved with more than 10 dB with respect to the SNR after the non-adaptive method.

Case II: Detector deghosting for a time-variant, rough sea surface

The time-variant sea surface and its ghost effect at the detector side is modelled, corresponding to detectors around 30 m and the extreme sea state 9, according to Figure 1. The shot gather including the primaries, internal multiples and the time-variant detector ghost effect is given in Figure 4a. Thus, in this case the actual depth of detectors with respect to the sea surface is depending on the wave height, lateral position and time. Now, we show as a reference in Figure 4b the result after adaptive deghosting. The residual and corresponding SNR in Figure 4e are given with respect to the modelled data that are shown in Figure 4d. The ghost model that comes out of this adaptive deghosting corresponds to a rough and time-invariant sea surface. Therefore, the artefacts in Figures 4b and e are mostly related to a time-variant sea surface. In Figures 4c and f we see that a more accurate deghosting result is obtained after the window-based adaptive deghosting method. The SNR after the window-based adaptive deghosting method is improved more than 3 dB with respect to the SNR after the adaptive method.

Conclusion and discussion

In this paper an adaptive deghosting method is discussed that is able to correct uncertainties in the depth of sources and detectors with respect to the sea surface and accurately deghost the data. It is shown that after adaptive deghosting, in the presence of a time-invariant, rough sea surface noise is suppressed. A window-based approach in the time-domain is able to further improve the performance in the case of a time-variant sea surface.

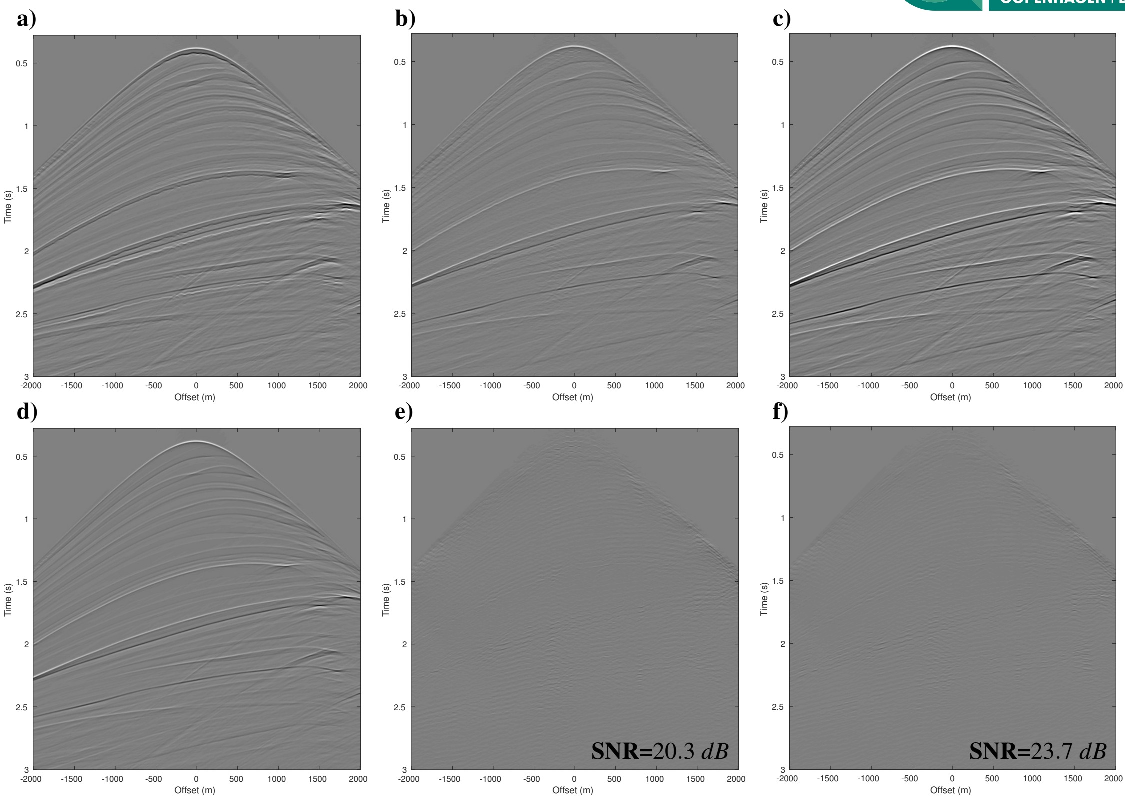

Figure 4 *In a) detectors are at* $z_d = 30$ *m, b) output after adaptive detector deghosting, c) output after window-based adaptive detector deghosting, d) modelled ghost-free data, d) residual after adaptive detector deghosting and e) the residual energy after window-based adaptive detector deghosting.*

The examples in this abstract are modelled and deghosted in 2D. Full 3D wavefield deghosting requires a dense sampling in both the inline and crossline direction. Sun and Verschuur (2017) propose a 3D deghosting method for pressure data at the detector side that implicitly handles sparse data. A similiar approach can be followed to extend the adaptive deghosting method of this paper. Practical 3D source side deghosting is an even bigger challenge, due to coarse sampling in both the inline and crossline direction. Finally, we remark that carpet shooting (Walker et al., 2014) allows practical application of 3D source deghosting without any approximations if non-linear effects of source wavefields are neglected.

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