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Source Deghosting and Demultiple for Calm and Rough Weather Conditions

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Summary

Source deghosting and demultiple algorithms have been extensively studied but mostly in the case of a flat sea-surface. In this work, we consider time-varying sea-surfaces in different types of weather conditions and derive an inversion approach for removal of sea-surface effects. Starting from Rayleigh's reciprocity theorem, we model seismic data including time-dependent wavefields scattered at the sea-surface, and highlight the temporal variation of these wavefields through simple synthetic examples, comparing two different weather conditions (calm and rough). We also reveal a limitation of source deghosting in the context of time-dependent wavefields: source deghosting affects the sea-surface multiples and can compromise the success of demultiple processing, which is applied in a later step. Results shows that this limitation is also important under calm weather conditions. To overcome this limitation, we propose simultaneously source deghosting and demultiple, therefore, removing all sea-surface effects in one-step. Synthetic data examples are shown using the Sigsbee2B geological model.

Introduction

The flat sea-surface assumption, which is commonly used in marine seismic processing, neglects the spatial and temporal variations of the sea-surface that occurs during acquisition. However, only a few studies on dynamic rough sea-surfaces have shown the impact of the sea-surface roughness and its temporal variation on the seismic data through synthetic modeling, raising a potential concern for time-lapse seismic. Laws and Kragh (2002) highlight the possible risk for time-lapse seismic due to a non-negligible Root-Mean-Square (RMS) error on the stacked data introduced by the sea roughness. Blacquiere et al. (2018) introduce a method using a statistical sea-surface to model the time-varying effects of the sea on the seismic data and emphasise the consequences of a dynamic sea-surface for the different order of surface related multiples. Cecconello et al. (2018) and Konuk and Shragge (2018) model the interaction with a time-varying rough sea-surface using a time-domain derivation of the Rayleigh reciprocity theorem and mimetic finite difference algorithm respectively. They both show significant amplitude errors compared to a stationary case.
After modeling the effects of time-varying sea-surfaces, the next logical step is to investigate the removal of sea-surface effects by source deghosting and demultiple. This is an important pre-migration step as it should correct for any notches in the frequency spectra and removes all the sea-surface related multiples. In Cecconello et al. (2018b), we presented the theoretical background behind source deghosting and demultiple by inversion and their limitations in the context of rough weather conditions. Here, we show the result of a comparative study between two different sea states (calm and rough weather) where we apply source deghosting and demultiple steps on a data set modeled using the complex geological model Sigsbee2B.

Modeling seismic wavefields interacting with a time-varying sea-surface

We model seismic wavefields interacting with a time-varying sea-surface using a time-domain version of the Rayleigh reciprocity theorem. It consists in splitting the ray path into two states A and B (see Figure 1 where the dotted lines correspond to the wavefields in state A and the solid lines to the wavefields in state B), combining them using the Gauss theorem, and applying wavefield separation and source-receiver reciprocity. The time synchronization of this combination is a crucial element, as it will assure the correct interaction with the sea-surface for each time step.

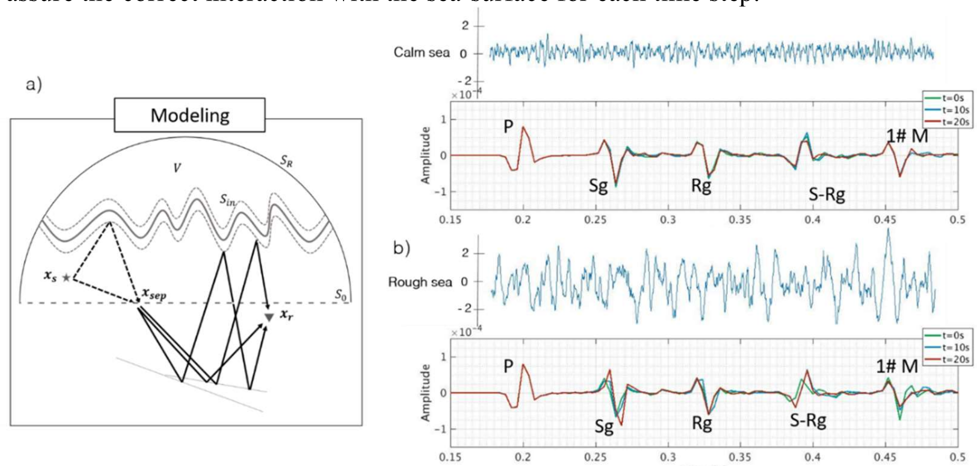

***Figure 1** a) Wavefield decomposition for the Rayleigh reciprocity theorem in a general case where both up- and down-going wavefields are present at the receivers. b) Result of the modeled pressure wavefields for a simple flat subsurface and time-varying rough and calm sea-surfaces at three different firing times, following equation 1. Modeled wavefields are primaries (P), source ghost (Sg), receiver ghost (Rg), source-receiver ghost (S-Rg) and first order sea-surface multiple (1# M).*

Finally, we invite the reader to read Cecconello et al. (2018) for an extensive derivation of the following equation:

$$s^A(t-t_s) * p_t^B(\boldsymbol{x_r}, t-t_s; \boldsymbol{x_s}, 0) = -2\int_{-\infty}^{\infty}\int_{S_0}\left[p_t^{B^{\cdot,+}}(\boldsymbol{x_r}, t-\tau; \boldsymbol{x_{sep}}, 0)\nabla p_t^{A^+}(\boldsymbol{x_{sep}}, \tau; \boldsymbol{x_s}, t_s)\right]\cdot \boldsymbol{n_0} dS_0 d\tau\,, \quad (1)$$

where $\boldsymbol{x_s}$, $\boldsymbol{x_r}$, and $\boldsymbol{x_{sep}}$ represent the positions of the source, the receiver and the separation level points (located on S_0) respectively, t is the global time and t_s the emission time of the source, s^A is the source signature and $\boldsymbol{n_0}$ the unit normal downward pointing vector to the separation surface S_0 (see Fig. 1a). Equation 1 models the time-varying source ghosting operation of the total pressure wavefield $s^A(t-t_s) * p_t^B(\boldsymbol{x_r}, t-t_s; \boldsymbol{x_s}, 0)$ by combining the down-going pressure gradient of the source wavefield $\nabla p_t^{A^+}(\boldsymbol{x_{sep}}, \tau; \boldsymbol{x_s}, t_s)$ with the time-varying impulse response $p_t^{B^{\cdot,+}}(\boldsymbol{x_r}, t-\tau; \boldsymbol{x_{sep}}, 0)$. Both combined wavefields interact with the sea-surface, they are thus time-dependent wavefields (denoted by the subscript *t*). With this formulation, we can model any type of sea-surface scattered wavefields. An example of the sea-surface influence through ghosts and multiples is shown in Figure 1b, where the amplitude differences for different firing times are put in relation to the weather conditions.

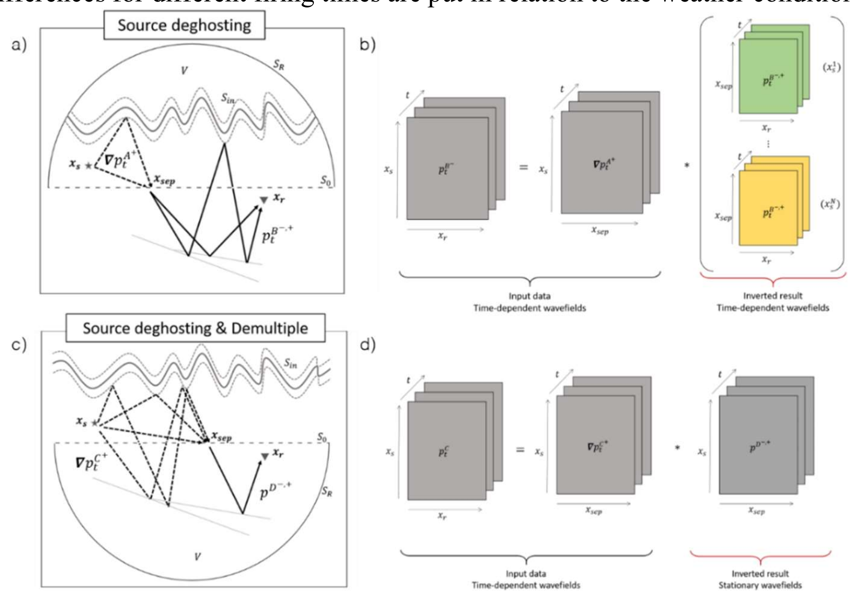

Figure 2 *First column: Wavefield decomposition for the Rayleigh reciprocity theorem with only up-going wavefields and the wavefields are separated to perform a) source deghosting c) source deghosting and demultiple simultaneously. Second column: Inverse problem represented in terms of matrix multiplications for b) source deghosting (eq 1) d) source deghosting and demultiple (eq 2).*

Removal of sea-surface effects and impact of the sea-state

Source deghosting: We apply source deghosting by inversion provided that the up-going pressure and source wavefields are known (see Figure 2a). However, due to the time-dependency of the inverted wavefield $p_t^{B^{-,+}}(\boldsymbol{x_r}, t-\tau; \boldsymbol{x_{sep}}, 0)$, we are confronted by an underdetermined system of equations. As explained in Cecconello et al. (2018b), to obtain a solvable system of equations, we need to expand the up-going part of equation 1 by adding more sources. The wavefields that need to be inverted contain wavefields interacting with the sea-surface (such as sea-surface multiples), and these wavefields will be different for each new source. Thus, each new equation creates a new set of unknown parameters, making the problem ill-posed (see Figure 2b). This restriction can be relaxed if the weather conditions are calm and the sea-surface shape gets reasonably close to a flat surface.

Source deghosting and Demultiple: The source deghosting restrictions can be overcome by removing all sea-surface effects simultaneously. To do so, we create two new states C and D and derive a new version of the time domain Rayleigh reciprocity theorem following the configuration of Figure 2c. Keeping only the up-going part of the wavefield, we obtain:

$$p_t^{C^-}(\boldsymbol{x_r}, t; \boldsymbol{x_s}, t_s) = -2 \int_{-\infty}^{\infty} \int_{S_0} \left[p^{D^{-,+}}(\boldsymbol{x_r}, t-\tau; \boldsymbol{x_{sep}}, 0) \boldsymbol{\nabla} p_t^{C^+}(\boldsymbol{x_{sep}}, \tau; \boldsymbol{x_s}, t_s) \right] \cdot \boldsymbol{n_0} dS_0 d\tau \, . \quad (2)$$

Equation 2 models the total up-going pressure wavefield $p_t^{C^-}(\boldsymbol{x_r}, t; \boldsymbol{x_s}, t_s)$ by combining the total down-going time-varying sea-surface reflectivity pressure gradient wavefield $\boldsymbol{\nabla} p_t^{C^+}(\boldsymbol{x_{sep}}, \tau; \boldsymbol{x_s}, t_s)$ with the unknown subsurface reflectivity free of any sea-surface effects $p^{D^{-,+}}(\boldsymbol{x_r}, t-\tau; \boldsymbol{x_{sep}}, 0)$. Inverting equation 2 is equivalent to applying source deghosting and demultiple in one-step. In the new problem configuration, all the time-dependent wavefields are contained in the input data, leaving the inverted wavefield, $p^{D^{-,+}}(\boldsymbol{x_r}, t-\tau; \boldsymbol{x_{sep}}, 0)$, stationary (see Figure 2d). Therefore, we can create a solvable system of equations by adding a sufficient number of sources.

Synthetic data examples

Using a modified version of the Sigsbee2B geological model (shallower sea floor, see Figure 3a), we illustrate the restrictions on source deghosting and demultiple as explained in the previous section. We model an up-going pressure wavefield composed of primary reflections, source ghost and the first-order sea-surface multiple and its corresponding source ghost. We consider 100 stationary receivers separated laterally by 6 m at 30 m depth and the sources are at 15 m depth. The source fires above each receiver location at a regular time interval of 2 s. Both calm and rough sea states are considered. The total up-going pressure wavefields are displayed in Figure 3b (calm sea) and c (rough sea). The same scaling is applied for all the plots in this abstract.

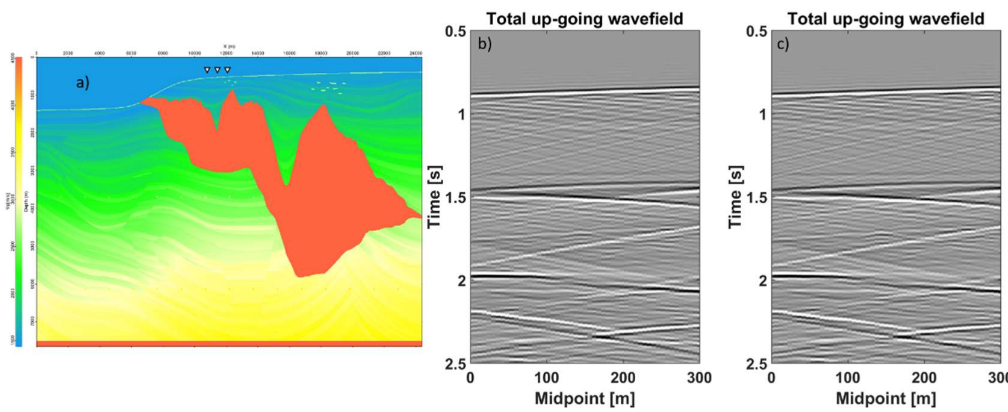

Figure 3 *a) Modified Sigsbee2B model with receiver location marked by the white triangles. The colour legend correspond to* $\boldsymbol{V_P}$ *(m/s). Total up-going pressure wavefield for (b) calm sea and (c) rough sea.*

<u>Source deghosting:</u> We apply source deghosting on the modeled up-going pressure wavefield data set (see Figure 2b), using the modeled pressure gradient of the down-going wavefield (i.e., the source wavefield). In a field data acquisition, both input wavefields to the inversion can be obtained by wavefield separation (i.e., up-going pressure) and from near-field recordings (i.e., the source wavefield). The result of the inversion and the difference to the modeled solution are shown in Figures 4a and b for the calm sea and Figures 4c and d for the rough sea. In both cases, we can observe errors from 1.7 s, which corresponds to the first appearances of the multiples. However, the amplitude error is much bigger in rough weather. The error in the calm sea state could be, in certain case, considered as negligible. These results highlight the importance of the time-dependency of the scattered seismic waves in rough sea states.

<u>Source deghosting and demultiple:</u> As a second case, we remove all sea-surface related effects by source deghosting and demultiple in one-step. Here, the input down-going pressure gradient wavefield is obtained in a real acquisition by wavefield separation. The result of the inversion and the difference to the modeled solution is shown in Figures 5a and b for the calm sea and Figures 5c and d for the rough sea. Both cases are equally successful (see Figures 5b and d).

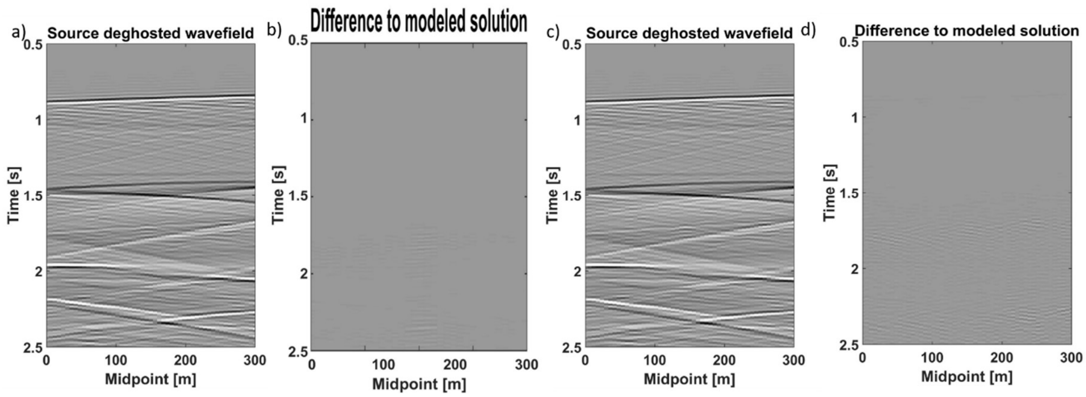

Figure 4 *Source deghosting result in the case of a calm sea-surface (a) and a rough sea-surface (c). The difference to the modeled solution is shown respectively in (b - calm) and (d - rough).*

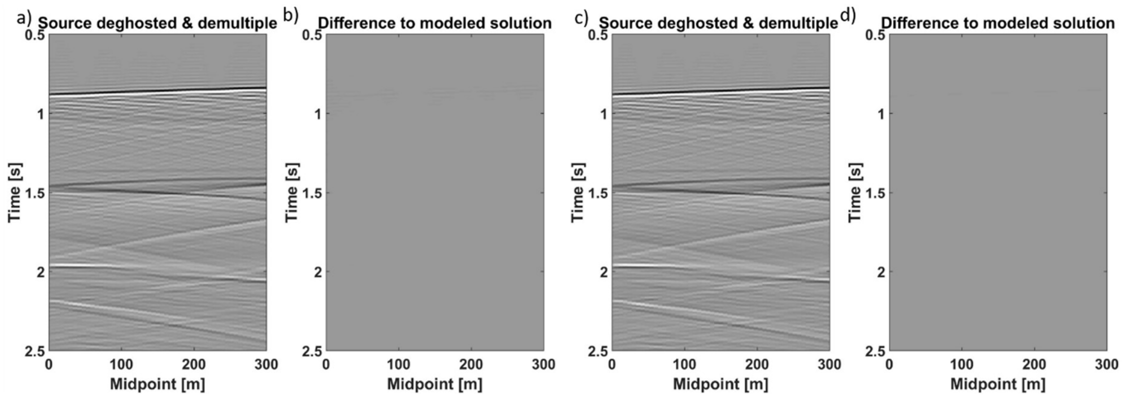

Figure 5 *Source deghosting and demultiple result in the case of a calm sea-surface (a) and a rough sea-surface (c). The differences to the modeled solutions are shown respectively in (b - calm) and (d - rough).*

Conclusions

In this work, we have compared the effects of two different sea-surface cases: a rough and a calm weather condition. Following the equations derived for modeling seismic wave scattering from time-varying sea-surfaces, we have revealed shortcomings of the source deghosting. The synthetic results for source deghosting show a significant error in the rough case and a possibly negligible one in the calm case. This raises a concern for subsequent processing steps, which are relying on source deghosted data, when weather conditions are rough. In a second approach, we have shown the successful application of source deghosting and demultiple on an up-going pressure wavefield for all sea state.

Acknowledgment

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