A method to suppress spurious multiples in virtual-source gathers retrieved using seismic interferometry with reflection data

Boris Boullenger, Kees Wapenaar and Deyan Draganov, Delft University of Technology*

Summary

Seismic interferometry applied to surface reflection data (with source and receivers at the surface) allows to retrieve virtual-source gathers at the position of receivers, where no source was shot. As a result of the crosscorrelation of all primary and multiple reflections, the virtual-source gathers contain retrieved physical reflections as well as non-physical (ghost) reflections also called spurious multiples. We show that a significant part of the ghost reflections can be suppressed by using surface-related multiple elimination on the active data advantageously. The method that we propose consists in retrieving the strong ghost reflections mainly from the crosscorrelation of primaries only and in subtracting this result from the virtual-source gather retrieved from all the data. The resulting new virtual-source gathers provide a better estimate of the reflection response since it is now less polluted by undesired non-physical events that may bring ambiguity in the interpretation. This is better to make a more effective use of the virtual-source gathers, for example for imaging.

Introduction

Seismic interferometry by crosscorrelation is the process that retrieves the seismic response between a pair of receivers as if from a source at the position of one of the receivers (Schuster 2004; Wapenaar and Fokkema, 2006). Applied to surface exploration data (i.e., with sources and receivers at or very near the surface), seismic interferometry allows to retrieve virtual-source gathers at the position of receivers where no sources were present during the acquisition. Having these extra source gathers may be useful for example for reconstruction of missing data and during imaging. For such a surface configuration, the retrieved virtual responses contain the physical reflections (as if from a source at the position of a receiver) but also non-physical (ghost) reflections (Snieder et al., 2006; Draganov et al., 2012; King and Curtis, 2012). The physical reflections are retrieved through the correlation of primary reflections with their induced surface-related multiples (van Wijk, 2006; Schuster, 2009) whereas the ghost reflections are the result of other cross-terms. These ghost events can be as strong as the target physical reflections and may further overlay them. More dramatic is that they could be misinterpreted as physical reflections. Therefore it is our objective to suppress the ghost reflections efficiently in the virtual-source gathers. This would allow the use of the extra reflection information from the virtual-source gathers with more confidence. The proposed method is done, here, by using surface-related multiple elimination advantageously for seismic-interferometry purposes.

Method

The theory of retrieving the Green's function between a pair of receivers located at the Earth's (free) surface requires a two-step process: crosscorrelating the responses from a subsurface boundary of sources enclosing the receivers and summing over the sources. In seismic exploration, sources are only present at the surface. This will result in incomplete destructive interference for several correlated events that can be interpreted in the virtual response as ghost reflections (spurious multiples). The virtual-source response from a receiver position x_A to a receiver position x_B is obtained by crosscorrelating the response at x_A with the one at x_B for each source and by summing the result over the sources. In the frequency-domain, this translates into:

$$C\left(x_B,x_A,\omega\right)=\sum_x R^*(x_B,x,\omega)R\left(x_A,x,\omega\right), \quad (1)$$

where x is the position of sources, R is the recorded reflection-response and * denotes complex conjugation. The crosscorrelation result C has both a causal and anti-causal part in the time domain. The causal part is taken as the estimated reflection response between x_A and x_B. Repeating this operation for other receivers will result in a virtual-source gather for a virtual source at x_A.

The operations described above involve the crosscorrelation of many different events, leading either to physical or ghost reflections. It is important to be able to discriminate between them. In Figure 1, we illustrate schematically the creation of physical and ghost events in the virtual-source response. The retrieval of physical reflections (green rays in Figure 1b) between x_A and x_B is enabled by the crosscorrelation of a primary at x_A with a connected surface-related multiple at x_B (Figure 1a) .The crosscorrelation of two primary reflections, one recorded at x_A and the other at x_B (Figure 1a), produces an unwanted ghost reflection event (red ray in Figure 1b) that will pollute the virtual-source trace. The ghost reflections come mainly from the correlation of primary reflections with primary reflections as these are the strongest arrivals in the recorded data. Physical reflections are retrieved by the correlation of primaries with connected surface-related multiples. Correlation of surface-related multiples with other surface-related multiples would contribute to the retrieval of both physical and ghost reflections. As these retrieved ghost reflections would be kinematically the same as the ones retrieved from the correlation of primaries only, but would be weaker, here we do not investigate them further.

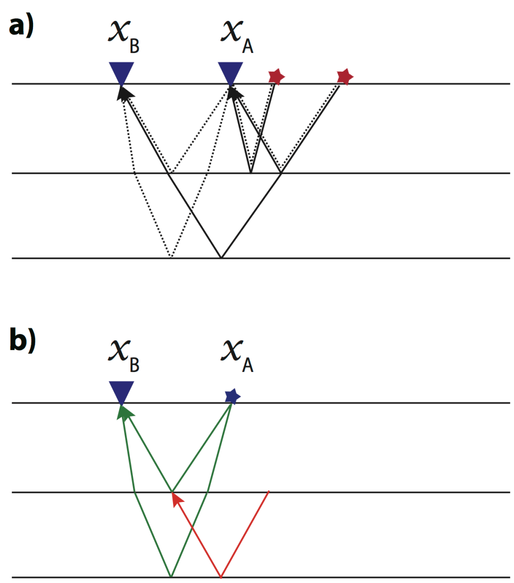

Figure 1: Schematic representation of several correlation terms involved in seismic interferometry. The red stars denote active sources and the blue triangles denote two receivers at x_A and x_B. a) The reflection data contain primaries (black solide lines) and surface-related multiples (black dashed line). b) The retrieved virtual-source response contain physical reflections (green rays) but also non-physical events (red ray).

The above means, that if no surface-related multiples are present in the input reflection data, none of the physical reflections can be retrieved by crosscorrelation interferometry. This means that applying seismic interferometry on reflection data that is free from surface-related multiples will result in only having ghost reflections. Therefore, this process can be used to predict the ghost-reflection energy in order then to subtract it from the virtual responses retrieved with the complete data. This assumes that most of the energy connected to the surface-related multiples can be removed in the active data. Several techniques, e.g. SRME, can be applied to this goal. In practice, it would be sufficient to eliminate the strongest surface-related multiples in the data, namely the first-order multiples.

Numerical example

We consider a simple five-layer acoustic subsurface model as shown in Figure 2a. Sources are placed every 20 m at the free surface from 0 m to 4000 m and receivers between 0 m and 4000 m every 10 m. The full reflection response contains four primaries as well as internal multiples and surface-related multiples (see Figure 2b). The surface-related multiples are then removed to obtain only the primaries together with the much weaker internal multiples. The surface-related-multiple-free reflection response is shown in Figure 2c for a source at x=2000 m. The new dataset can be seen as a result of performing conventional multiple-removal techniques.

First, we use the dataset that contains all multiple reflections to retrieve a virtual-source gather for a virtual source at x=2010 m. This is done by applying equation 1 and by taking the causal part of the correlation result. The virtual-source reflection response is shown in Figure 3a. It contains relatively strong ghost reflections (indicated by the red arrows that relate to the red ray in Figure 1b), but also the desired physical reflections (indicated by the green arrows that relate to the green rays in Figure 1b). For our simple subsurface, we can identify the ghost reflections by comparison of the virtual common-source gather with a neighboring active common-source gather (compare Figure 3a and Figure 2b). For convenience, we also show in Figure 3c the directly modeled reflection response for a source at x=2010 m for comparison. For a complex subsurface, where actually virtual-source gathers might be required for improved imaging, unambiguous interpretation of the ghost reflections might not be possible only by comparison with a neighboring active-source gather. For such cases, we propose the method below.

Second, we apply seismic interferometry to the active reflection data without the surface-related multiples. The corresponding virtual-source reflection response is shown in Figure 3b. The six ghost reflections indicated by red arrows are all kinematically reproduced. However, because no surface-related multiples are present in the input data, the gather does not contain any of the physical reflections. Note also that the prediction includes the linear events already present in Figure 3a. These are caused by the correlation of primaries with themselves.

In the next step, we subtract the virtual-source gather obtained using the data free from surface multiples from the virtual-source gather obtained using the full reflection data. The result is shown in Figure 4a. The strong spurious multiples present in the original virtual-source gather are now significantly attenuated as compared with the initial gather in Figure 3a. Note also that the linear correlation noise is completely removed. However, the ghost reflections are not completely removed because not only crosscorrelation of primaries with primaries contribute to their retrieval but also crosscorrelation of surface-related multiples with other surface-related multiples. The latter crosscorrelated energy is not retrieved by seismic interferometry when applied to the surface-multiple-free data and so cannot be directly subtracted from the original gather.

A solution to cope with this, is to perform adaptive subtraction of the gathers in Figure 3a and 3b. We observed that the ghost reflections in Figure 3b are kinematically correctly predicted. Adaptive subtraction of the gathers can then effectively cancel completely the spurious multiples. This step should be performed with care as the adaptive filter must cancel the predicted ghost reflections while preserving the retrieved physical reflections. In Figure 4b, we show the result of adaptively subtracting the gathers in Figure 3a and 3b. This allows the complete suppression of the predicted ghost reflections (compare with Figure 3a and with Figure 3c). Although the adaptive subtraction is not free of some artifacts and may be improved in the future, we believe that this final virtual-source gather is a much better estimate of the reflection response as if from a source at x=2010 m.

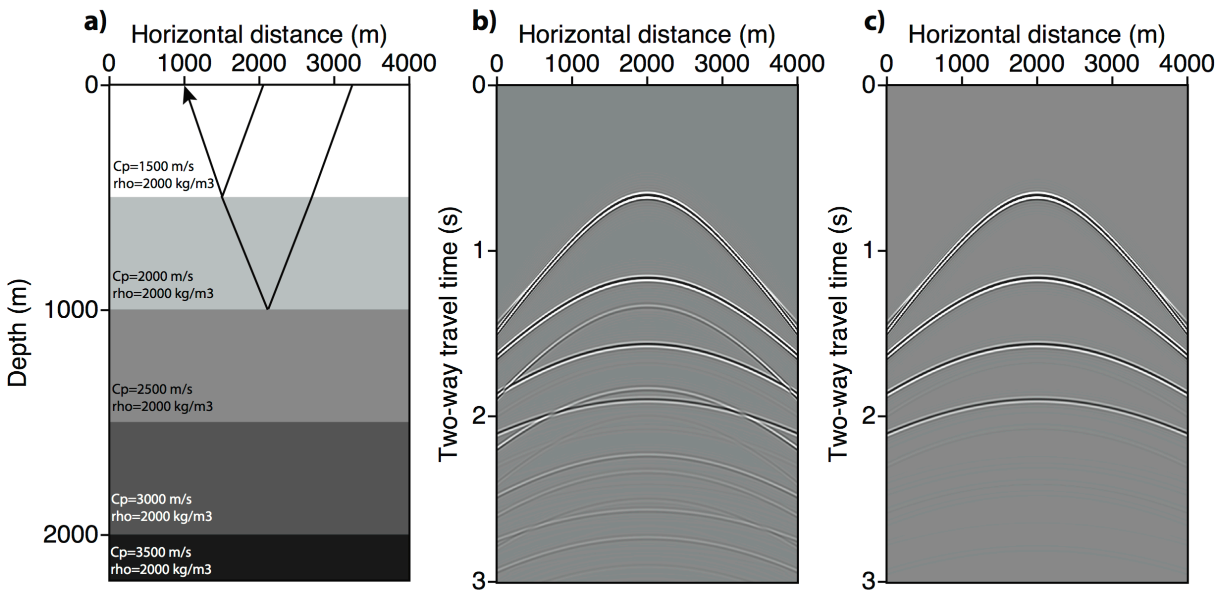

Figure 2: a) The acoustic subsurface model used in the numerical example. b) Full reflection response for a source at x=2000 m, including surface-related multiples. c) Reflection response for a source at x=2000 m with surface-related multiples removed.

Conclusions

We propose a method that allows the suppression of non-physical reflections in virtual-source gathers retrieved using seismic interferometry by crosscorrelation on surface exploration data. The major part of the ghost reflections is produced by the crosscorrelation of the primary reflections, whereas the desired physical reflections are obtained from the crosscorrelation of primaries with connected surface-related multiples. We show that application of seismic interferometry to the reflection data after suppression of the surface-related multiples, can predict the ghost reflections kinematically correctly. The predicted ghost events can be then subtracted from the original virtual-source gather in order to suppress these unwanted retrieved signals. The subtraction could be done adaptively to optimize their cancellation. This will lead to a better estimate of the reflection response in virtual-source gathers. The ghost-free virtual-source gathers could then be combined with more confidence with the original active data for example to add extra signal for imaging.

Acknowledgements

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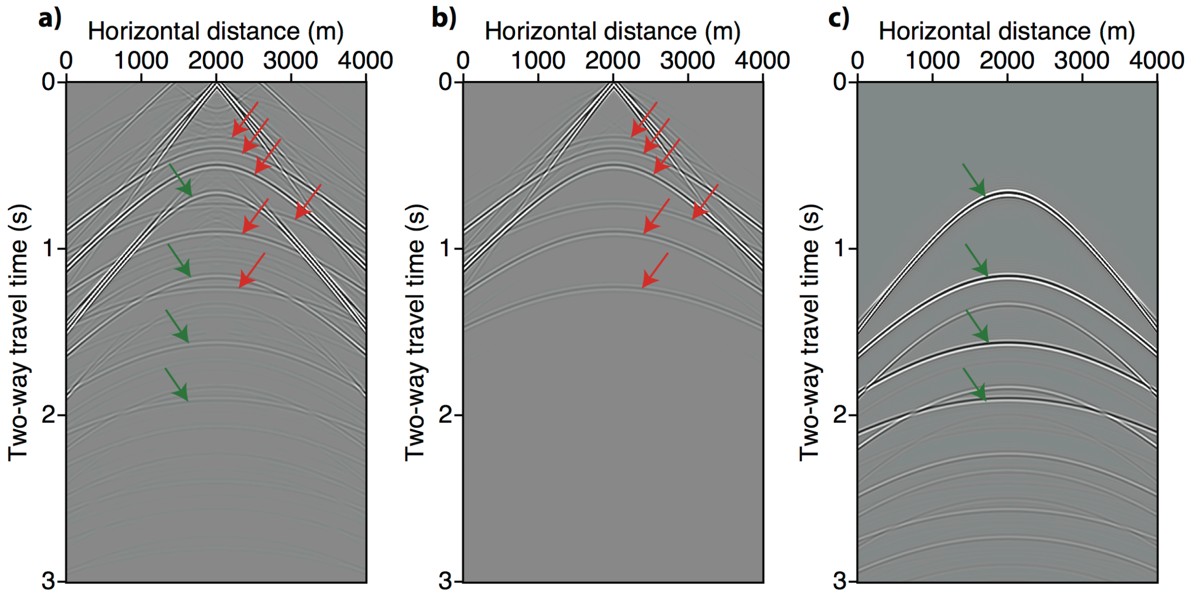

Figure 3: a) Virtual-source gather for a virtual-source at x=2010 m using the full reflection data. The green arrows indicate primary (physical) reflections. The red arrows indicate ghost (non-physical) reflections. b) Virtual-source gather at x=2010 m using the reflection data without surface-related multiples. c) Direclty modelled reference reflection response for a source at x=2010 m.

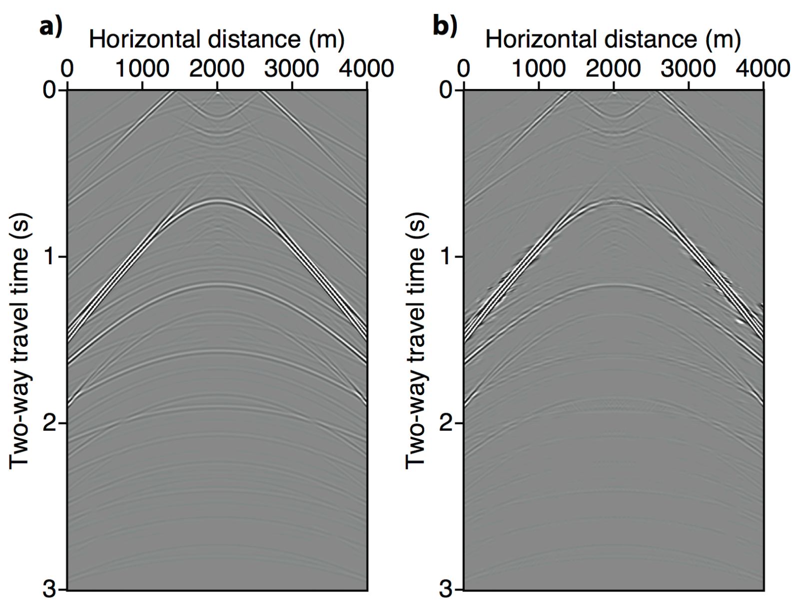

Figure 4: Results of subtraction of the predicted ghost reflections. a) Virtual-source gather at x=2010 m obtained by directly subtracting the result in Figure 3b from the result in Figure 3a. b) As in a), but using adaptive subtraction.

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