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## Identification and Elimination of Surface-related Multiples Using Seismic Interferometry with Active Sources

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### SUMMARY

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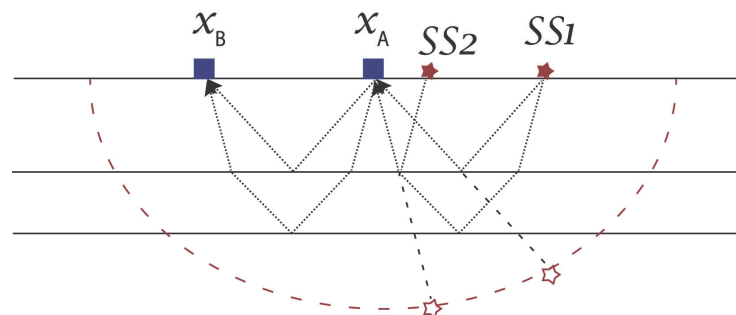
With sources and receivers at the Earth's surface, the Green's function retrieved by seismic interferometry by cross-correlation will contain non-physical reflections. The physical reflections will be retrieved only if surface-related multiples are present in the original active seismic data. We show how the retrieved physical reflections can be used to identify and eliminate associated surface-related multiples from the active data. The procedure may be used to quality control the effectiveness of conventional surface-related multiple elimination. We apply this idea on numerically modeled active data and show the procedure to follow.

## Introduction

Seismic interferometry (SI) by cross-correlation retrieves the Green's function between receivers using recordings from enclosing boundary sources. Applied to receivers at the Earth's (free) surface, SI will retrieve the reflection response between the receivers, as if from a virtual source at the position of one of the receivers (Wapenaar and Fokkema, 2006). In this case, the exact retrieval of the reflection response requires, among others, that the boundary sources be only in the subsurface. In exploration configurations, i.e. with receivers and sources at the Earth's surface, many non-physical (ghost) reflections will be retrieved together with the physical reflections (Snieder et al., 2006; Draganov et al., 2012; King and Curtis, 2012). In this case, the physical reflections in the virtual response are retrieved from the cross-correlation of primary reflections with connected surface-related multiples (SRMs) (Schuster et al., 2004). In the following, we show how the physical reflections retrieved by SI by cross-correlation can be used to detect and identify SRMs in the original active reflection data. Once identified, a SRM can be eliminated. Also, quality control of the elimination of SRMs can be performed when conventional multiple-elimination techniques are used.

## Concept

Consider an exploration configuration with receivers and active sources placed at the Earth's surface (see Figure 1). Applying SI to retrieve the reflection response between two receivers at  $x_A$  and  $x_B$  requires cross-correlating the recorded responses at these receivers from the active sources and summing over the sources (Wapenaar and Fokkema, 2006). According to the theory, the retrieval of the reflection response requires subsurface sources effectively enclosing the receivers (dashed red line in Figure 1), while no sources at the free surface are required. The main contribution to the physical reflections in the retrieved response comes from the sources in the stationary-phase regions (Schuster et al., 2004; Snieder 2004). In Figure 1, the positions of the relevant stationary points for the physical reflections between  $x_A$  and  $x_B$  are depicted by red empty stars along the subsurface-source boundary (for illustrative purposes straight rays are drawn).



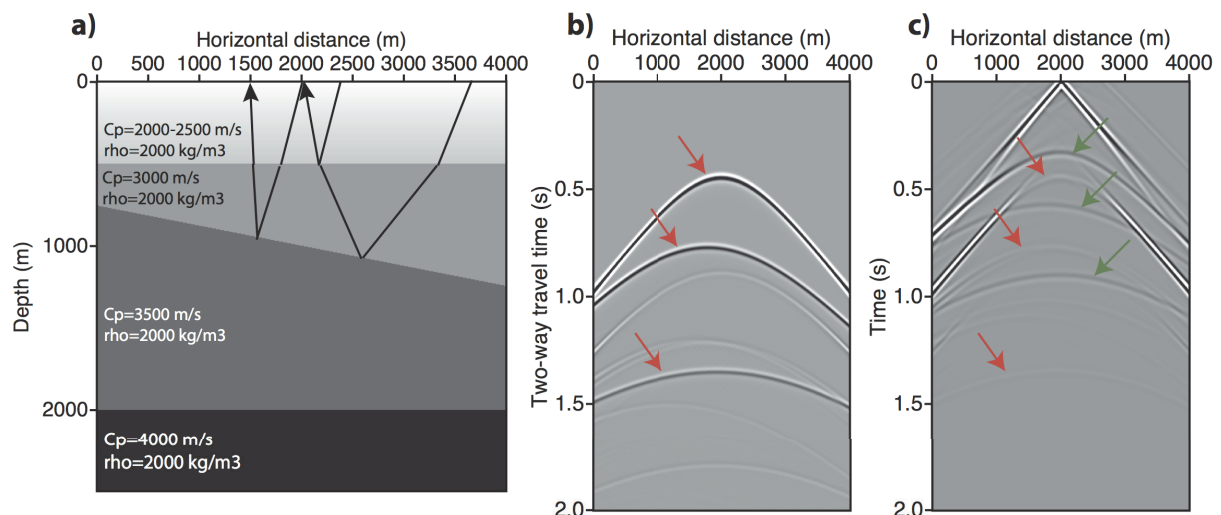
**Figure 1** Schematic representation of stationary-phase points for the retrieval of physical reflections in SI by cross-correlation. The blue boxes denote receivers at positions  $x_A$  and  $x_B$ . The red dashed line represents a source boundary. The white stars indicate sources at stationary points. The red stars denote active sources at stationary points SS1 and SS2.

Having sources only at the surface does not fulfill the theoretical conditions for applying SI. Nevertheless, applying SI with this type of active data can also retrieve physical reflections. As schematically shown in Figure 1, the contribution from the stationary points on the subsurface boundary could be substituted by sources at the surface by projecting the subsurface rays to the surface. The surface sources are denoted as SS1 and SS2. In this case, the retrieval of the physical reflections requires the presence of SRMs in the seismic data. If this latter condition is true, SS1 and SS2 are stationary because their radiated wavefields are recorded as primaries at  $x_A$  and as SRMs at  $x_B$ . The application of SI between  $x_A$  and  $x_B$  will remove the common travel paths SS1- $x_A$  and SS2- $x_A$  and will turn the SRMs into retrieved primaries at  $x_B$ . Hence the retrieval of a physical reflection relies on the presence of corresponding SRMs in the active data. If the SRMs were correctly and completely suppressed, physical reflections would not be retrieved at all. This means that retrieving and

identifying a physical reflection in the SI result is a reliable quality control that SRMs are present in the input active dataset. Next, we can use the retrieved results to identify and remove the SRMs in the active data. If a physical reflection is retrieved, one can identify the stationary-phase region contributing to its retrieval at the corresponding two-way travel time (TWT) with the use of a correlogram (panel containing the correlated traces for all sources). This allows us to determine the position of the sources for which a primary reflection is recorded at the virtual source position ( $x_A$ ) and a connected SRM is recorded at the position  $x_B$ . We then predict the TWT of the SRM in the active data at  $x_B$  by adding the TWT of the primary at  $x_A$  to the TWT of the correlated event in the stationary-phase region. This procedure allows us to pinpoint unambiguously SRM energy in the original active data (for example, as residuals after applying conventional removal techniques).

### Numerical example

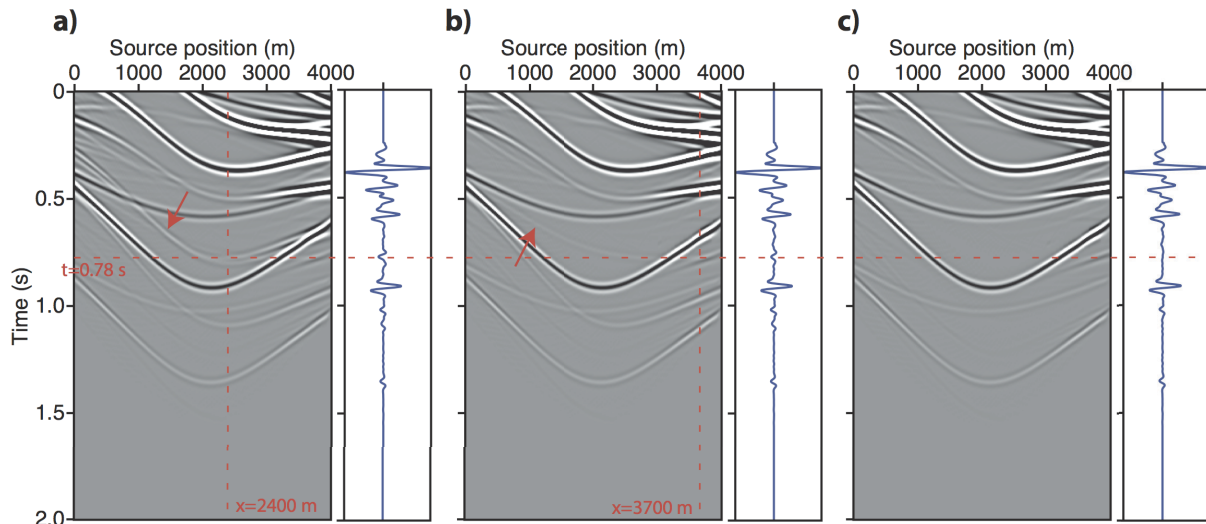
We consider a simple four-layer acoustic subsurface model with one dipping reflector and gradient in the upper layer (see Figure 2(a)). We place sources every 20 m at the free surface from 0 m to 4000 m and record the reflection response at receivers between 0 m and 4000 m every 10 m. The responses contain the three primary reflections as well as first-order surface-related multiples (see Figure 2(b)). Discriminating correctly between primaries and multiples is important to perform further processing and interpretation accurately.



**Figure 2** (a) The acoustic subsurface model used in the numerical example with indicated velocities ( $C_p$ ) and densities ( $\rho$ ). Down to a depth of 500 m, the velocity gradually increases from 2000 m/s to 2500 m/s. The black arrows indicate ray paths. (b) Reflection response for a source at  $x=2000$  m. The red arrows indicate primary reflections. (c) Reflection response as if from a virtual source at  $x=2010$  m, retrieved using SI by cross-correlation. The green arrows indicate non-physical (ghost) reflections.

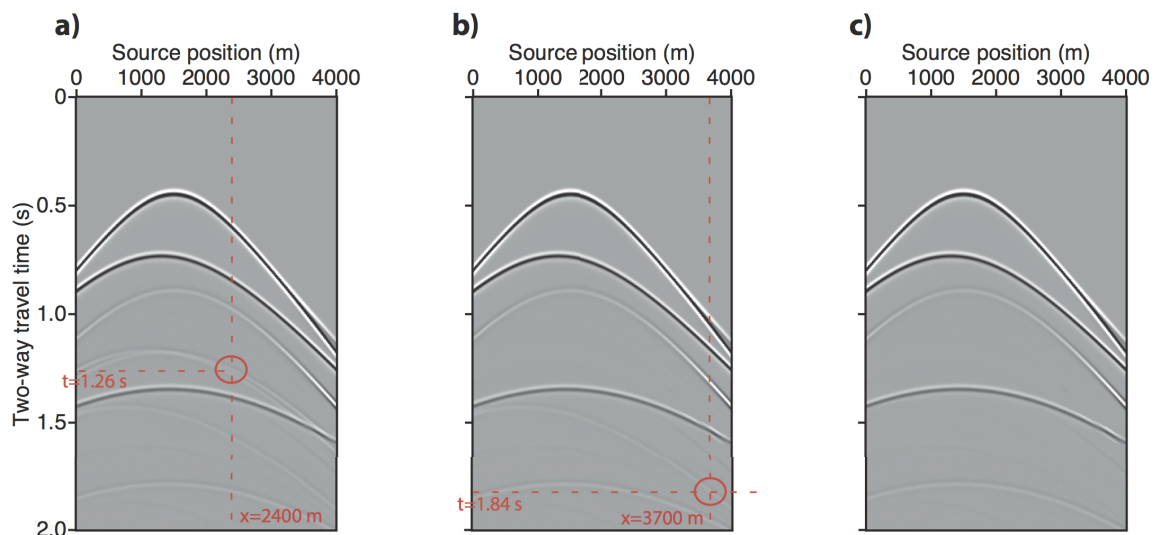
We apply SI to retrieve the reflection response from a virtual source at  $x=2010$  m. Note that the direct arrival has been removed. The virtual-source response is shown in Figure 2(c). It contains relatively strong ghost reflections, but also the physical reflections, which we can identify by comparison with neighbouring active common-source gathers (compare Figure 2(b) and 2(c)). The latter is a clear indication that SRMs are present in the original input reflection data.

We now focus on the retrieved primary reflection from the dipping reflector (second red arrow from top in Figure 2(c)). We choose to look at the retrieved response for the receiver at  $x=1500$  m. This retrieved trace is shown in blue in Figure 3(a). For this trace, the physical reflection is well identified at 0.78 s. This event is the result of summation of the individual cross-correlated responses, from sources in the stationary-phase regions. We visualize the individual contributions in the correlogram corresponding to the receiver at  $x=1500$  m (see Figure 3(a)). Note that, for the summation, we applied a taper at the two ends of the source array to suppress limited-aperture artefacts after summation.



**Figure 3** Correlogram for the receiver at  $x=1500$  m (and virtual source at  $x=2010$  m) and the resulting summed (retrieved) trace (in blue). For convenience, the first 0.25 s are muted in the summed trace. The horizontal red dashed line indicates the time at which the physical reflection on the dipping reflector is retrieved. The red arrows indicate correlated-events functions. **(a)** All primaries and first-order multiples are present in the active data. **(b)** A SRM associated with the reflection from the dipping reflector is muted before cross-correlation. **(c)** Both SRMs associated with the reflection from the dipping reflector are muted before cross-correlation.

Looking at times around  $t=0.78$  s allows for the interpretation of stationary-phase regions for the retrieval of the primary from the dipping reflector. In this case, a clear stationary-phase region lies in the vicinity of  $x=2400$  m, as the correlated-events function reaches a maximum there. This means that for sources in this region, a specular ray exists, recorded as a primary at  $x=2010$  m and a SRM at  $x=1500$  m. For the source at  $x=2400$  m, we pick the arrival time of the first primary reflection at  $x=2010$  m (not shown). This TWT is  $t=0.48$  s. Therefore, we predict that a SRM must be present around  $t=0.48+0.78=1.26$  s in the active data for a receiver at  $x=1500$  m and a source at  $x=2400$  m. As shown in Figure 4(a), this indeed corresponds to an event that we now can interpret as SRM. For the next step, we mute this event in the entire common-receiver gather.



**Figure 4** Common-receiver gather from the active data for a receiver at  $x=1500$  m. **(a)** The event at  $x=2400$  m and  $t=1.26$  s is identified as a SRM associated with the reflection from the dipping reflector. **(b)** The multiple identified in (a) is muted. The event at  $x=3700$  m and  $t=1.84$  s is also identified as a SRM associated with the reflection from the dipping reflector. **(c)** The two SRMs are muted.

Applying SI after muting the multiple, we see that, a weaker, but still visible physical reflection is retrieved (compare Figures 3(a) and 3(b)). This means that SRMs associated with the reflection from the dipping reflector are still present in the active data. The correlogram in Figure 3(b) indicates the presence of an additional correlated-events function for which the stationary-phase region is at  $t=0.78$  s. This region lies in the vicinity of  $x=3700$  m. For the source at  $x=3700$  m, we pick the TWT  $t=1.06$  s for the second primary reflection at  $x=2010$  m (not shown). A SRM is therefore expected at  $t=1.06+0.78=1.84$  s for a source at  $x=3700$  m. As shown in Figure 4(b), this corresponds to a specific arrival that we interpret as SRM. When this latter arrival is muted in the entire receiver gather, the SI result does not contain a physical reflection from the dipping layer anymore (Figure 4(c)). This means that all SRMs associated with the reflection from the dipping reflector are now removed from the active data. These correspond to the specular rays drawn in Figure 2(a). The presence of a retrieved physical reflection from the shallowest reflector in the SI data indicates that the active data contains SRMs associated with the reflection from that reflector. The SRM identification and elimination process can be repeated to remove its multiples. In such a way, all SMRs in the data would be eliminated.

If we now apply SI to SRM-free active data, the retrieved results would contain only ghost reflections. This new result could be adaptively subtracted from the original SI results retrieved using the active data with the SRMs present. In such a way, ghost reflections in the original SI results would be suppressed, which would make then suitable for possible merging with the active data when having extra sources at receiver positions is desired.

## Conclusion

We propose to use seismic interferometry by cross-correlation with active sources at the surface to identify and eliminate surface-related multiples (SRM). We also propose to use this as a quality control of the removal of SRMs by conventional techniques. The procedure is data-driven. With sources and receivers at the Earth's surface, the retrieval of physical reflections from seismic interferometry requires the presence of corresponding SRMs in the active data. This is because a given primary reflection is retrieved from the cross-correlation of a primary with connected SRM. For this reason, applying SI with this type of active data gives a direct indication whether SRMs are still present in the data. We show how to use stationary-phase regions that retrieve the physical reflections in order to pinpoint the SRMs in the active data. Once identified, they can then be eliminated from it.

## Acknowledgements

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