Removing artifacts and overburden reflections from virtual source data

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Introduction

Virtual source (VS) method (Bakulin and Calvert, 2006) is a technique to image and monitor below complex overburden without knowledge of overburden velocities and near surface changes. VS method is related to seismic interferometry (Snieder, 2004; Wapenaar, et al., 2005); both are based on correlating the recorded wave-fields at a given pair of receivers to estimate the response between them. The simplest approach to generate VS gather is to correlate total wave-fields at VS and receivers (Mehta, et al., 2006). The resultant VS gather includes all the responses between VS and receiver, some of which may not be useful for geophysical applications. The current best practice is to correlate the gated direct arrival in total wave-field at VS with total wave-field at receivers (Bakulin and Calvert, 2006). Neither approach gives the true subsurface response because of the limitation of not having sources all around the receivers. This leads to spurious events. Other unwanted reflections come from overburden and free surface. We attempt to suppress these unwanted events using wave-field separation.

Synthetic modeling

Fig.1(A) shows P- and S-wave velocity profile used for synthetic simulation. 161 sources are placed, every 10 m, on the surface and 41 receivers are placed, every 10 m, in a horizontal well 250 m deep. We choose receiver 21 as VS. This VS gather should be equivalent to the response due to a physical source at receiver 21, i.e. ground truth response (Fig.1(B)). Ground truth response shows four P-P reflections and an S-P conversion. We concentrate on P-waves only. Fig.2(A) shows in red (plotted on top of ground truth in black) VS gather generated by correlating total wave-fields at VS and receivers. Apart from the reflections present in both cases, VS gather shows other events. Some of them are physical (overburden-related) and some are unphysical (limited source aperture). Bakulin and Calvert (2006) showed how gating before correlation eliminates some of the overburden reflections by making VS radiate predominantly downwards. However their approach can not suppress free surface and overburden-related multiples. Fig.2(B) shows the VS gather (in red) generated by gating before correlation. The reflections are preserved and many spurious events are suppressed. Gating, thus, improves the VS gather, although a better approach is to separate up and down going waves.

Wave-field separation

Fig.3(A) shows cartoons for a three-layer model to illustrate the effect of incomplete source aperture and reflections from overburden and free surface. Fig.3(A-1) shows the source location that gives the stationary phase contribution (Snieder, et al., 2006) for a physical arrival between VS (red) and receiver (yellow) as shown by black arrows. If, however, a source is placed as shown in Fig.3(A-2), VS and receiver will record waves propagating along the red arrows. Even though the source gives a stationary phase contribution, correlation of the two wave-fields does not correspond to any physical arrival between them. Such arrivals contribute to spurious events in VS gather. They cancel if a source is present below the receivers, as shown in Fig.3(A-3). For geophysical applications we cannot place a source in the subsurface. We can, however, suppress these spurious events by restricting waves at VS to be down going. Even though waves at VS are down going, we get reflections from overburden and free surface as shown by red arrows in Fig.3(A-4). We can suppress these arrivals by restricting waves at the receivers to be up going. Hence, we get the subsurface response by correlating down going energy at VS with up going energy at receivers. This represents an improvement over the current best practice of gating the direct arrival before correlation (Bakulin and Calvert, 2006). Fig.3(B) shows the VS gather (in red) generated by correlating down going waves at VS with up going waves at receivers. The spurious events are suppressed and VS gather is practically on top of ground truth response. Hence, wave-field separation indeed generates VS gather containing true subsurface response. Up-down separation and gating can be combined to generate VS gather as shown in Fig.3(C).

Field example : Mars OBC example

We demonstrate improvement in VS method, due to wave-field separation, using data recorded for seismic monitoring in the Mars field. The geometry consists of 364 air guns fired (spaced every 25 m) on the sea-surface with 120 4-C sensors (spaced every 50 m) permanently placed on the sea-floor 1 km deep. VS method allows us to redatum OBC data to sea-bed without the knowledge of water level, water temperature and source location. For Mars field data, we use the dual-sensor summation technique for up-down separation. We choose receiver 60 as the VS. Fig.4(A-1) shows VS gather, for hydrophone, generated by correlating total wave-fields at VS and receivers. The most prominent reflection is coming from free surface, labeled FSM. Hence, even for simplest overburden, correlating the total wave-fields gives a VS gather dominated by reflection from overburden. If instead, we correlate down going waves at VS with up going waves at receivers, the resulting VS gather is shown in Fig.4(A-2) and the FSM is suppressed. Reflections from subsurface are visible and strongest one is highlighted by an arrow and labeled as ``res''. Fig.4(B-1) shows VS gather obtained by current best practice. Correlating the gated direct arrival makes VS gather cleaner but strongest reflection is still FSM. To further improve VS gather quality, we combine up-down separation and gating. As shown in Fig.4(B-2), if we correlate direct arrival gated in down going waves at VS with up going waves at receivers, the VS gather is cleaner and we do see true subsurface response. Dual-sensor summation is strictly valid for zero offset data over layered media. In many practical instances where it might fail, an alternative approach would be to generate two VS gathers using the hydrophone and vertical component geophone separately, and then extract the up going waves using dual-sensor summation. Fig.4(C-2), generated by such an approach, reveals a gather very similar in quality to our best response shown in Fig.4(C-1) [same as Fig.4(B-2)]. There are, however, distortions in early times and near direct arrival because of gating in total wave-field instead of gating in down going waves.

Conclusions

VS method can be improved to get the reflection response from the subsurface using wave-field separation combined with gating. Instead of correlating total wave-fields, in practical cases it is beneficial to correlate down going waves at VS with up going waves at receivers. In addition, gating in down going waves improves signal-to-noise ratio.

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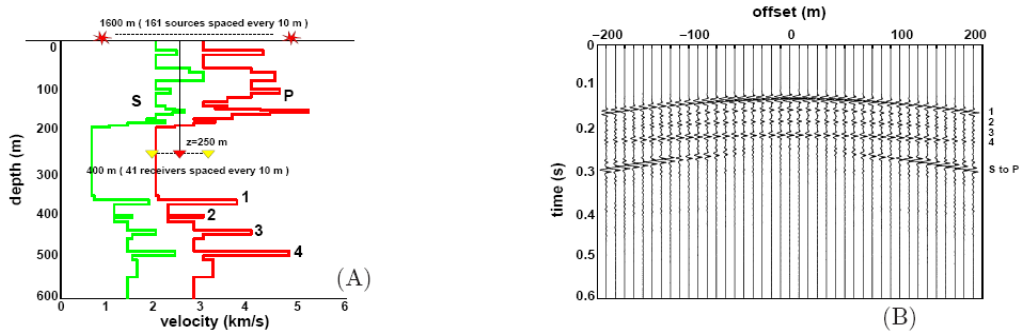

Figure 1: (A) P- and S-wave velocity profiles and acquisition geometry for synthetic model. (B) Ground truth response due to a physical source at receiver 21 (VS).

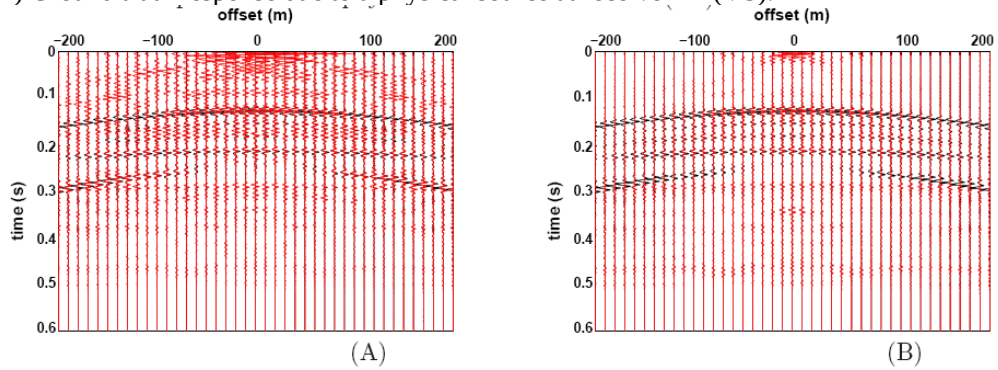

Figure 2: Ground truth response in black. VS gather (in red) generated by correlating: (A) total wave-fields at VS and receivers, (B) direct arrival at VS with total wave-field at receivers.

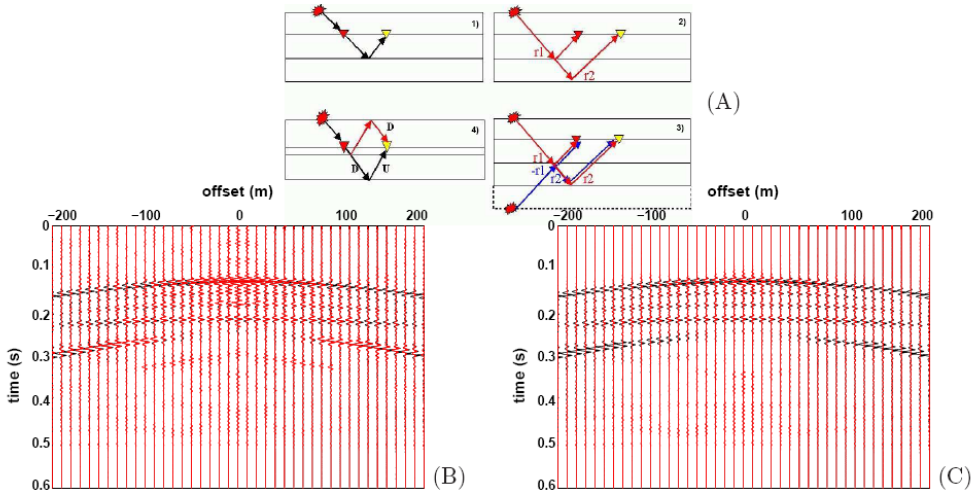

Figure 3: (A) Cartoon explaining the need for wave-field separation. (B) VS gather (in red) generated by correlating the down going waves at the virtual source with the up going waves at the receivers. (C) VS gather (in red) generated by correlating the direct arrival windowed in the down going waves at the virtual source with the up going waves at the receivers.

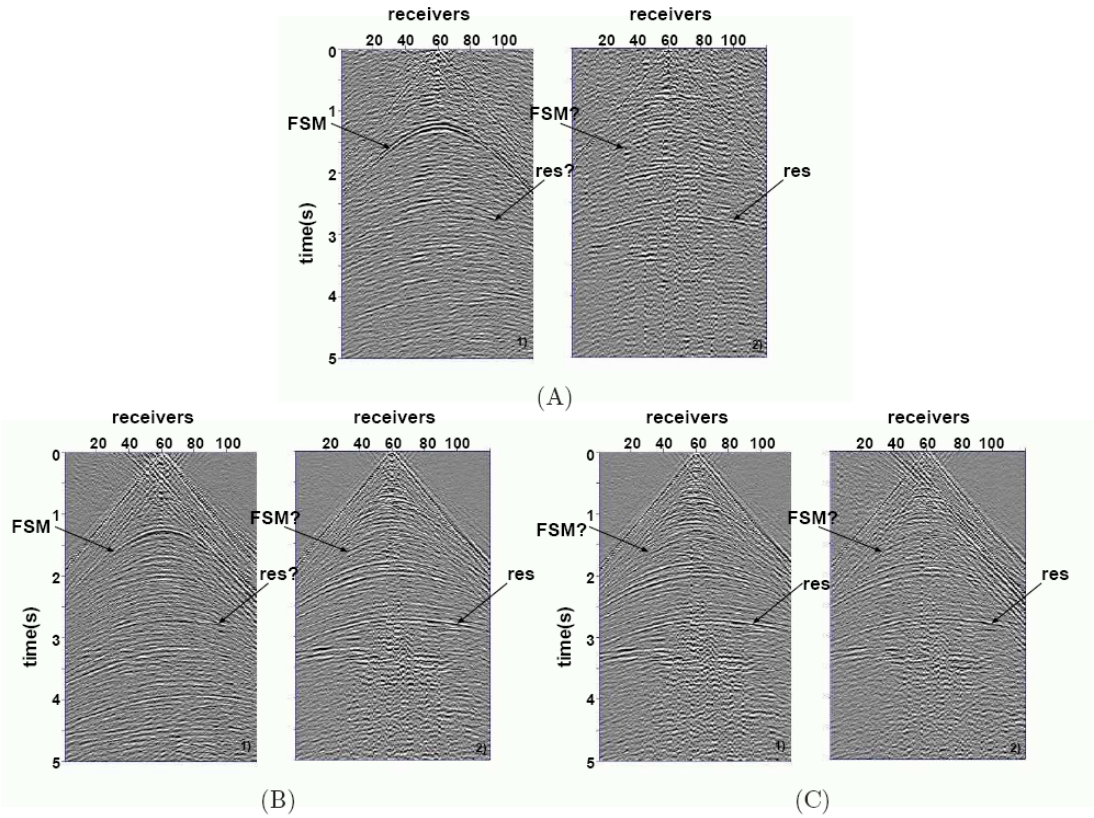

Figure 4: (A) VS gather generated by correlating the total wave-fields at both the virtual source and receivers and by correlating the down going waves at the virtual source with the up going waves at the receivers. (B) VS gather generated by correlating the direct arrival windowed in the total wave-field at the virtual source with the total wave-field at the receivers and by correlating the direct arrival windowed in the down going waves at the virtual source with the up going waves at the receivers. (C) VS gather generated by correlating the direct arrival windowed in the down going waves at the virtual source with the up going waves at the receivers and by summing the VS gathers generated for hydrophone and vertical component geophone: each of which is generated separately by the current best practice (correlate the gated direct arrival in total wave-field at VS with total wave-field at receivers).