The effects of time-gating and radiation correction on Virtual Source data

Joost van der Neut, Delft University of Technology; Andrey Bakulin, Shell International Exploration and Production*

Summary

In the Virtual Source (VS) method we cross-correlate seismic recordings at two receiver locations to create a new data set as if one of these receivers is a Virtual Source and the other is a receiver. We evaluate the amplitude and phase spectra of VS data, generated in a laterally invariant medium, in the FK-domain. It is shown that phase information is accurately retrieved, whereas amplitudes are subject to an imprint of the overburden. This imprint, which can be interpreted as the VS amplitude radiation pattern, can be estimated by auto-correlation of the downgoing wave field that was used for VS creation. We can optimize the radiation characteristics by spatial deconvolution with the estimated radiation pattern. Another strategy is to apply time-gating to the downgoing wave field, as is commonly applied in the current best practice of the VS method. We offer an explanation why time-gating indeed enhances the amplitude radiation characteristics of VS data, while having minor influences on the phase spectrum. It can be argued that the phase is best retrieved if the correlated signals have long recording times, as multiple scattering will be most effectively exploited. We show how phase information from total field correlations can be combined with amplitude information from time-gated fields to improve the phase spectrum without deteriorating the amplitudes. Finally, we show how time-gating and amplitude radiation correction through spatial deconvolution can be combined.

Introduction

The Virtual Source (VS) method is an innovative technique to image and monitor the subsurface in cases where complex overburden prevents seismics and VSP to deliver good results (Bakulin and Calvert, 2004, 2006). Placing receivers below complex overburden allows measuring the propagation response directly and apply time-reversal logic to redatum surface shots into downhole receiver locations without any additional information about the medium between sources and receivers. Redatumed shots are called Virtual Sources. Theory suggests that a correct response can be recovered when sources are located on a closed surface surrounding the receivers, however practical applications typically involve one-sided illumination with limited aperture (Bakulin and Calvert, 2006). This creates artifacts and it generally distorts VS amplitudes. An important improvement of the VS method was suggested by Mehta et al. (2007), who reasoned that separation of the up- and downgoing wave fields before cross-correlation would eliminate spurious events, caused by the lack of illumination from below the receiver array. Time-lapse imaging of VS data produces highly repeatable data even in the presence of changing overburden (Bakulin & Calvert, 2004; Bakulin et al., 2007a). However, quantitative interpretation of 4D signals requires confidence in the recovered VS amplitudes. We show that these amplitudes are subject to the radiation characteristics of the generated VS. We make a clear distinction between the amplitude and phase spectra of VS data. For simplicity we restrict ourselves to Virtual Sources in laterally invariant media, although part of the theory can be extended to general inhomogeneous media. We show how the amplitude radiation pattern of a Virtual Source can be estimated and how VS radiation can be manipulated by either a radiation correction in the FK-domain, or by time-gating, as currently applied in the best practice of the VS method.

Virtual Source amplitude radiation correction

Purpose of the Virtual Source method is to redatum shot locations from the earth surface to a receiver level at depth, without requiring additional information about the medium between sources and receivers. We do so by cross-correlating the downgoing wave field at the VS location with the upgoing wave field at other receiver locations and integrating over the source locations (Mehta et al., 2007). The result is supposed to converge to the reflection response between the Virtual Source and the other receivers, in an equivalent medium where the half-space above the receiver array is replaced by a homogeneous medium. If the medium is laterally invariant, we can freely shift the data spatially and each shot record can be synthesized from the central shot record. If both receivers and sources have constant spacing, the retrieved reflection response can be written in the FK-domain as $R^{VS} = \left\{G^{+}\right\}^{*} G^{-}$, where G^{+} and G^{-} are the FK-transforms of the down- and upgoing wave fields of the central shot records, respectively, R^{VS} is the FK-transform of the retrieved reflection response of the medium below the receiver array and superscript $*$ denotes complex conjugation. If we write the wave fields in terms of amplitude and phase, that is $G^{\pm} = \left|G^{\pm}\right| \exp\left(i\phi^{\pm}\right)$, we can rewrite the retrieved reflection response of VS data in terms of phase $\phi^{VS} = \phi^{-} - \phi^{+}$ and amplitude $\left|R^{VS}\right| = \left|G^{+}\right|\left|G^{-}\right|$, where $R^{VS} = \left|R^{VS}\right| \exp\left(i\phi^{VS}\right)$. Alternatively, we can interpret the reflection response of the medium below the receivers as the spatial deconvolution of the upgoing wavefield with the downgoing wavefield; that is: $R^{GT} = G^{-} / G^{+}$. Superscript GT stands for Ground Truth (GT), as we assume the true reflection response to obey this relation. Note that this result is strictly speaking only valid for the acoustic case. However, we assume that this equation also holds approximately for P-waves excited by vertical force sources and registered as vertical particle velocities in an elastic medium. Note that the phase of the GT response, which we write as $R^{GT} = \left|R^{GT}\right| \exp\left(i\phi^{GT}\right)$, indeed corresponds to the phase of VS data, since $\phi^{GT} = \phi^{-} - \phi^{+} = \phi^{VS}$, but the amplitude spectrum is different: $\left|R^{GT}\right| = \left|G^{-}\right| / \left|G^{+}\right| \neq \left|R^{VS}\right|$. By comparing the representations of VS and GT data in terms of amplitude and phase, we can show that both reflection responses are related as $R^{VS} = \left|G^{+}\right|^{2} R^{GT}$. Thus the amplitude spectrum as retrieved by the VS method has an imprint of an additional factor $\left|G^{+}\right|^{2}$, which can be interpreted as the amplitude radiation pattern of the generated Virtual Source. In laterally invariant media, the VS data can be corrected by a stabilized deconvolution with $\left|G^{+}\right|^{2}$ in the FK-domain. Van der Neut et al. (2008) show applications of this procedure for various source types and discuss how similar reasoning can be applied in general inhomogeneous media by replacing the FK-transforms by more localized Wigner transforms.

Effects of time-gating

The practice of time-gating the downgoing wave field before cross-correlation was an integral part of the Virtual Source method from the very beginning (Bakulin and Calvert, 2004, 2006). In essence, the time-gate determines which part of the wavefield will be time-reversed. For *P*-wave imaging, the time gates are usually applied around the first arrivals (Bakulin and Calvert, 2006; Bakulin et al, 2007b). For *S*-wave imaging, the gates are placed around directly arriving shear waves in the receiver gathers (Bakulin et al, 2007c). In practical cases with limited aperture, limiting the time-reversed wavefield to only the strongest arrivals of a particular kind leads to better VS data than cross-correlating the entire wavefields as suggested by theory. Even if wavefield separation is applied at the pre-processing stage, time-gating proved useful in reducing artifacts and improving the signal-to-noise ratio of VS data (Mehta et al., 2007). These improvements have been explained on a physically intuitive level. Here we offer more rigorous explanation in terms of the VS radiation pattern. VS data created from time-gated fields (indicated with a subscript zero) can be written as $R_0^{VS} = \left\{G_0^{+}\right\}^{*} G^{-}$, where G_0^{+} represents the gated downgoing wave field. By writing this field as $G_0^{+} = \left|G_0^{+}\right| \exp\left(i\phi_0^{+}\right)$, it can be shown that the phase of the VS data reads $\phi_0^{VS} = \phi^{-} - \phi_0^{+}$, whereas we can write the amplitude spectrum as $\left|R_0^{VS}\right| = \left|G_0^{+}\right|\left|G^{-}\right|$. It can thus be shown that VS data from gated fields relates to the GT response as $R_0^{VS} = \left|G_0^{+}\right|\left|G^{+}\right| R^{GT}$, where $\left|G^{+}\right|\left|G_0^{+}\right|$ can be interpreted as the VS amplitude radiation pattern. Once more, amplitude radiation correction of VS data from gated fields can be implemented by a stabilized deconvolution with the estimated radiation pattern in the FK-domain. Spectrum $\left|G_0^{+}\right|$ will generally be more predictable and inhabits a more uniform spatial distribution. In contrast, spectrum $\left|G^{+}\right|$ involves later times and will be less predictable, more complex and thus less uniform. Therefore time-gating improves the amplitude radiation characteristics, as we will demonstrate in the example below. While improvement of the amplitude response is obvious, the effect of time-gating on the phase response is less understood. Wapenaar (2006) suggested that longer recording times of both down- and upgoing fields can improve the results of the VS method in terms of phase and the time-gating practice might eliminate meaningful correlations in the coda of the wave fields. However no drawbacks of time-gating have been reported in practical applications (Bakulin et al., 2007). Here we investigate whether it may be beneficial to combine phase information from total field recordings with amplitude information as retrieved with time-gated fields.

Example: 1D Elastic Model with large contrasts

We test our theory on a layered elastic model, inspired by reservoirs as they typically occur in the Middle East (Mehta et al., 2007). In this model, 321 sources are situated at 2 m depth with 5 m source spacing. The upper 200 m of the overburden consists of finely layered material. Below 200 m we find a homogeneous layer in which 161 receivers are situated at 250 m depth. Below the receivers we find four strong reflectors that we want to image. In Figure 1A we show the result of the VS method, without time-gating applied. In analogy, the Ground Truth (GT) response is created by placing an active source at the VS location, with the half-space above the receiver array replaced by a homogeneous medium. Mehta et al. (2007) showed how time-gating can improve the quality of the data (Figure 1B). Alternatively, amplitude radiation correction can be applied by spatial deconvolution in the FK-domain, resulting in significant improvements (Figure 1C). Note that radiation correction yields better results than time-gating, especially at larger offset, but the latter is easier to apply in realistic cases and can be exported to general inhomogeneous media. Note also that spurious artifacts can be induced by the radiation correction, as we see in the bottom of the gather in Figure 1C. If time-gating and radiation correction are combined these artifacts are eliminated (Figure 1D), but at large offsets the radiation correction applied to ungated fields (Figure 1C) yields better coverage.

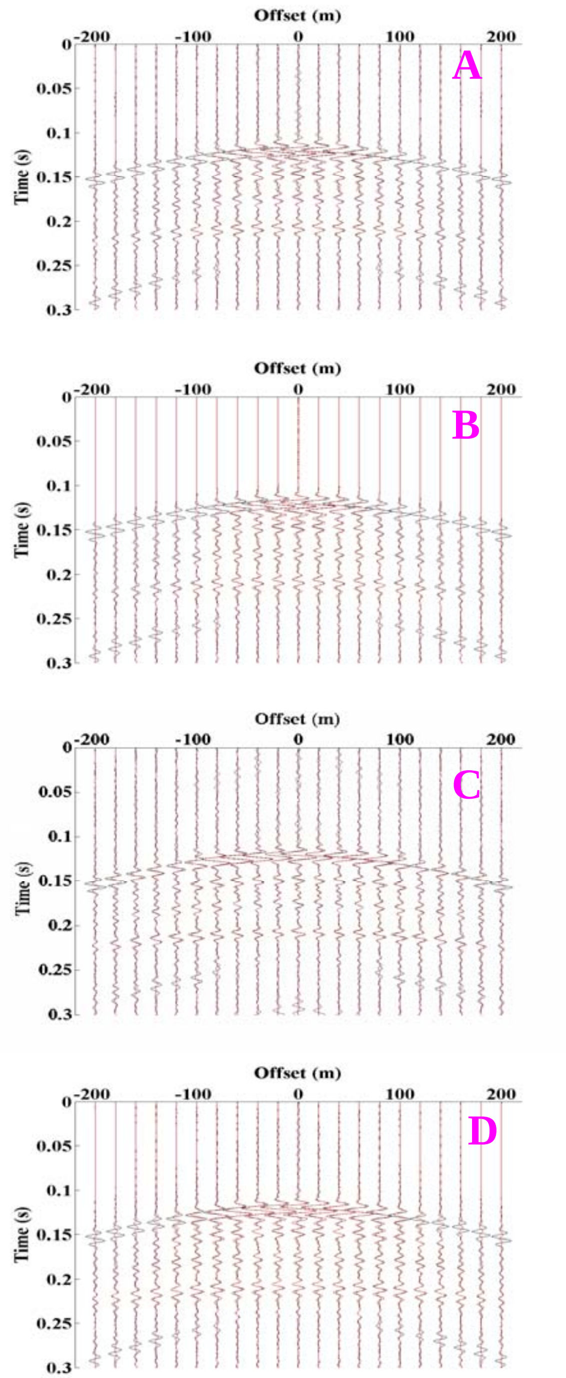

Figure 1: VS data (red) vs the GT response (black)
A) VS from ungated fields,
B) VS from gated fields,
C) VS from ungated fields after radiation correction,
D) VS from gated field after radiation correction.

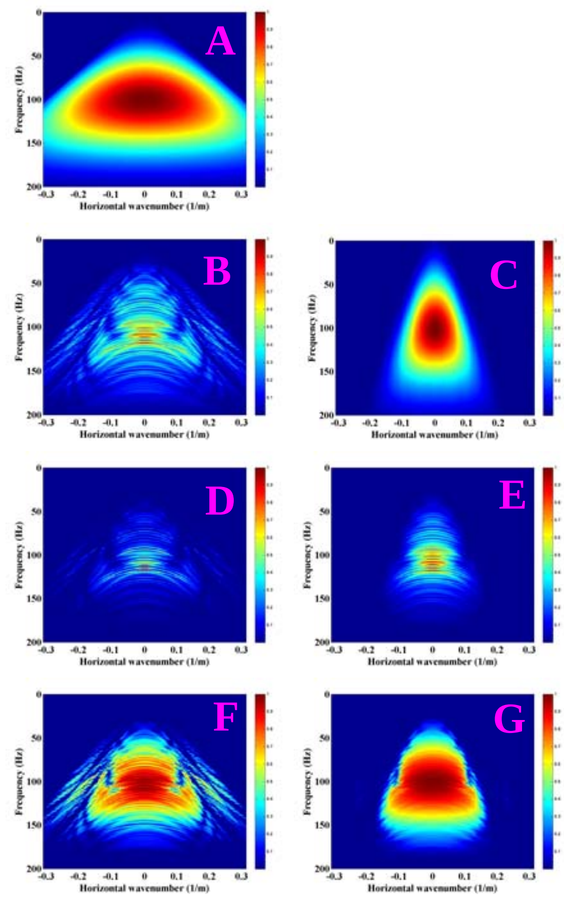

Figure 2: Amplitude FK-spectra representations:
A) radiation pattern of an actual downhole source (vertical force),
B) ungated downgoing wave field,
C) time-gated (around first arrivals) downgoing wave field,
D) radiation pattern of a VS obtained from total fields,
E) radiation pattern of a VS obtained from gated fields,
F) corrected radiation pattern of a VS from total fields,
G) corrected radiation pattern of a VS from gated fields.

To understand the improvements induced by time-gating and amplitude radiation correction, we study the VS radiation characteristics in the FK-domain. In Figure 2A we show the amplitude radiation pattern of an actual source (buried vertical force) in a homogeneous medium, obtained by recording the radiation with a receiver array at some horizontal level and transforming the data to the FK-domain. The result can be interpreted as the desired "radiation pattern" of our VS. The spectrum of the downgoing wave fields that are used for the VS creation with and without time-gating applied are shown in Figures 2B and 2C, respectively. The gated field is more uniform but also narrower than the ungated field. Virtual Sources created from gated fields thus have a narrower and more uniform radiation pattern (Figure 2E) than their counterparts from ungated fields (Figure 2D), explaining the improved robustness induced by the time-gating. After amplitude radiation correction, the VS radiation characteristics improve drastically – see Figures 2F and 2G. The narrowing effect of time-gating on the radiation pattern cannot be recovered by the radiation correction, as we see in Figure 2G, explaining the lack of coverage at large offsets that we have seen in Figure 1D. Virtual Sources from ungated fields have additional information at large incidence angles (Figure 2F), causing better amplitude retrieval at large offsets. However, due to less predictable radiation of the VS obtained with ungated fields, spurious events are easier to induce by the radiation correction, as we observed in Figure 1C. Finally, we would like to comment on the phase spectrum of the retrieved signals. In Figure 3 we show the absolute phase difference between the VS data and the GT response for both VS data generated with and without time-gating applied. We can clearly recognize the correctly reconstructed part of the spectrum, where the phase difference is small (indicated in red). Note that the VS data from total field correlations are slightly better in phase with the GT. We also note that for gated wavefields larger discrepancies in phase occur at larger wavenumbers, where amplitude spectra of VS radiation diminishes (see Figure 2E). Within the bounds of the reconstructed amplitude radiation (Figure 2D and 2E), both VS phase responses show similarly good match to the GT response. However, mathematically it poses no problem to compute the phase spectrum from the total fields, the amplitude spectrum from the gated fields and combining them. In Figure 4 we show the result of this operation, revealing only minor improvements compared to the initial results with both amplitude and phase retrieved from time-gated fields (Figure 1B) for this particular example. It remains worthwhile to test whether this conclusion remains true for inhomogneous 3D media.

Conclusion

We have applied the VS method to imaging below stack of highly contrasting layers and showed how the amplitude radiation pattern of the generated Virtual Sources can be estimated in the FK-domain. These estimates can be used for amplitude radiation correction through deconvolution in the FK-domain, which can drastically improve the quality of VS data in laterally invariant media. A different and more realistic solution that can easily be implemented, even if hampered by lateral variations, is to improve the amplitude radiation pattern by time-gating the downgoing wave field before entering the cross-correlation process, as is already common practice in current implementation of the VS method. Vizualization of the radiation patterns in the FK-domain may be helpful in selecting proper time gates, as to create a uniform and broad radiation pattern. Time-gating increases the robustness of amplitude radiation correction as it supresses spurious artifacts that arise in the deconvolution process. On the other hand, the time-gating step may limit the diversity of the illuminated wavenumbers by eliminating multiply scattered arrivals. In this case, radiation correction may not be able to recover the missing wavenumbers. We have also shown that the effects of time-gating on the phase spectrum are minor for the discussed example. As correlating longer signals can improve the convergence to the GT response in terms of phase it can be worthwhile to investigate the retrieval of the reflection response in two stages. First the amplitude spectrum can be retrieved by correlation of the gated fields. This amplitude spectrum can then be assigned to a phase spectrum as obtained from total field correlations. We have shown that this method can easily be implemented and yields desirable results. However, it remains to be investigated if this strategy yields significant improvements over the current best practise of the VS method. We anticipate that this work may have an impact on VS seismics in horizontal wells and in particular on time-lapse monitoring with Virtual Sources. For instance, even in the case of complex changing overburden and non-repeatable surface acquisition we should be able to manufacture Virtual Sources with identical radiation patterns. This could lead to repeatable time-lapse VS data free of amplitude distortions.

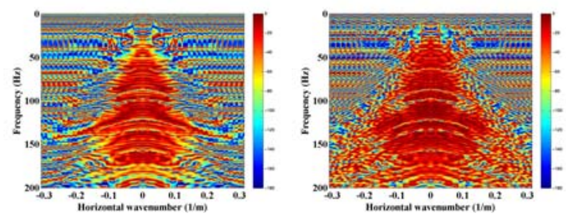

Figure 3: Absolute phase differences between VS and GT data; VS data on the left-hand side is generated from gated downgoing fields; VS data on the right-hand side is generated from total downgoing fields; red colors represent information in phase with the GT; blue colors are out of phase.

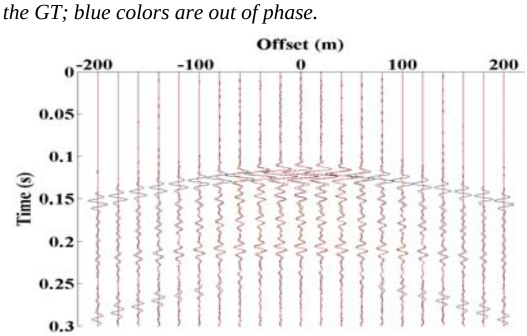

Figure 4: VS data; the amplitude spectrum is obtained from time-gated fields and the phase spectrum from total fields (red) compared with the GT response (black).

EDITED REFERENCES

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