The virtual source method applied to Mars field OBC data for time-lapse monitoring

Kurang Mehta[1], *Jonathan Sheiman*[2], *Roel Snieder*[1] *& Rodney Calvert*[2]
[1] *Center for Wave Phenomena, Department of Geophysics, Colorado School of Mines, Golden, CO 80401*
[2] *Shell International Exploration and Production Inc., 3737 Bellaire Blvd. Houston, TX 77001*

Summary

Virtual source (VS) method, a technique to image and monitor below complex overburden, requires surface shooting recorded by receivers placed below the overburden. Ability to redatum the recorded data to the receiver locations without of the knowledge of overburden velocities makes VS method a valuable tool for time-lapse monitoring. We incorporate a combination of wavefield separation and deconvolution of the correlation gather by the source power spectrum in VS method, applied to Mars field OBC data to suppress non-repeatability in the overburden, hence demonstrating an improvement for time-lapse monitoring.

Introduction

VS method (Bakulin and Calvert, 2006) is a technique to image and monitor below a complex overburden without the knowledge of overburden velocities and near-surface changes. It is a form of seismic interferometry (Derode, et al., 2003; Schuster, et al., 2004; Snieder, 2004; Wapenaar, et al., 2005; Curtis, et al., 2006; Korneev and Bakulin, 2006) which states that correlating the waves recorded by a given pair of receivers when summed over the physical sources gives the impulse response between the two receivers.

Time-lapse monitoring is a powerful tool for tracking changes in the sub-surface. Conventionally, the changes can be tracked by observing the difference between two seismic surveys obtained over the surveillance period. The difference in the two seismic surveys also include changes in the overburden and acquisition discrepancies, which are both prominent and undesirable.

We apply VS method to Mars field OBC data acquired in the years 2004 and 2005 (Mehta, et al., 2006). The data is acquired by 120 4-C sensors (spaced every 50 m) permanently placed on the seafloor 1 km deep and 364 air guns (at an interval of 25 m) shooting from the sea surface (Fig. 1). VS method is advantageous over the conventional seismic method in time-lapse monitoring at the Mars field because one can generate VS at each permanently placed receiver location, hence becoming independent of the variation in the overburden as well as acquisition discrepancies. The variations in the overburden (sea water) include changes in sea water level, sea surface roughness, sea water temperature and salinity. Acquisition discrepancies include variations in the source location and the source power spectrum. In order to remove the effect of varying source power spectrum, we deconvolve the prestack correlated data (correlation gather) by auto-correlation of source-time function.

Conventional seismic imaging

Mars field OBC data for the baseline survey was acquired October-November 2004. The repeat survey was carried out in June 2005. Conventional seismic data refers to wavefield recorded by the sensors on the seafloor due to sources on the sea surface. To allow comparison with VS seismic images, conventional seismic data is refocused down to the seafloor using water velocity. We migrate the refocused conventional seismic data using Kirchhoff depth migration. The depth images are then converted to time images (Figs. 2(a) and 2(b)) with time t=0 denoting the seafloor level. Fig. 2(c) is the difference of the two images obtained after locally time-aligning these images. There were no production-related sub-surface changes over the surveillance period. The differences are, hence, mainly due to variations in the overburden and acquisition discrepancies. After being refocused at the seafloor, the waves propagate, not only through the sub-surface (solid rays in Fig. 3(a)), but also through the time-varying overburden (dashed rays in Fig. 3(a)). The variations in the overburden and acquisition contribute to the prominent undesirable differences observed in Fig. 2(c).

We quantify the repeatability using normalized root mean square (NRMS) of the difference of the images for the years 2004 and 2005. The NRMS of the difference is defined as

$$NRMS = \sqrt{\frac{<(M-B)^2>}{<(M^2+B^2)/2>}},$$

where 'B' represents the base survey (2004) and 'M' represents the monitor survey (2005). The symbols '<>' represents the average value over the seismic image. Decrease in the value of NRMS indicates improvement in the repeatability. For the refocused conventional seismic data, the NRMS value is 0.2892.

Virtual source method

We generate VS data with every receiver as VS, and then migrate using Kirchhoff depth migration. The simplest approach to generate VS gather is to correlate the total wavefields at VS and receivers (Mehta, et al., 2007). The images for the years 2004 and 2005 obtained by migrating VS data, generated using simplest approach, are shown in Figs. 4(a) and 4(b). Fig. 4(c) is the difference of the two images after local time-alignment. In order to highlight the features, we show the difference image amplified by 10 (Fig. 4(d)). These differences can be attributed to the waves propagating through the time-varying overburden (dashed rays in Fig. 3(a)). The variation in the source location is removed. The NRMS of the difference for VS data generated by the simplest approach (0.3493) is higher than the NRMS for the conventional seismic image because the pre-processing of conventional seismic data included suppression of the free-surface multiples. VS data generated by simplest approach, however, include the free-surface multiples.

Wavefield separation

The free-surface multiple is the response from the overburden and mainly contain downgoing waves. If instead of correlating the total wavefields, the downgoing waves at VS are correlated with the upgoing waves at the receivers, the free-surface multiple and other overburden reflections can be suppressed (Mehta, et al., 2007).

The current practice to generate VS gather involves correlating the direct arrival windowed in the total wavefield at VS with the total wavefield at the receivers (Bakulin and Calvert, 2006). The images for the years 2004 and 2005 obtained by migrating VS data, generated by the current practice, are shown in Figs. 5(a) and 5(b). The free-surface multiple still dominates because the total wavefield is used for correlation at the receivers. Fig. 5(c) is the difference of the images for the years 2004 and 2005. Fig. 5(d) is the difference image amplified by 10. For VS data generated by the current practice, the waves still propagate through the overburden after reflecting from the near-seafloor (dashed rays in Fig. 3(b)) and hence, the NRMS of the difference for VS data generated by the current practice (0.3346) is higher than for the conventional seismic data.

In order to make VS data independent of the overburden, we generate VS gather by correlating the downgoing waves at VS with the upgoing waves at the receivers. For OBC data, up-down separation of the wavefield is possible by dual-sensor summation (e.g., Robinson, 1999). Figs. 6(a) and 6(b) are the images for the years 2004 and 2005, obtained by migrating VS data generated after wavefield separation. Correlation of downgoing waves at VS with the upgoing waves at the receivers suppresses the free surface multiple and highlights the reservoirs at around 3.5 seconds. Fig. 6(c) is the difference of the images for the years 2004 and 2005. The difference image amplified by 10 (Fig. 6(d)) shows that the NRMS of the difference image is 0.2676. The decrease in the value of NRMS compared to the simplest approach and current practice supports the improvement in repeatability after wavefield separation. This improvement is due to waves propagating predominantly through the sub-surface (solid rays in Fig. 3(c)). Wavefield separation applied to VS method suppressed the first-order multiples propagating through the overburden, hence making VS image less sensitive to the overburden related changes. The difference image has some low-amplitude coherent events which could be the multiples depicted by the dashed rays in Fig. 3(d). These multiples cannot be suppressed even by applying wavefield separation. Improvement in VS method by wavefield separation applied to the Mars field accounts for the variation in the overburden and source location. The variation in the source power spectrum, however, still exist.

Source power spectrum variation

The correlation of the wavefields recorded by a given pair of receivers contains auto-correlation of source-time function, hence the correlation gather must be deconvolved by the auto-correlation (Schuster, et al., 2004; Snieder, 2004; Wapenaar, et al., 2005). Since we use air guns as sources, variation in the source pulse is mainly due to changes in the air bubble, assuming that pre-processing of the two data sets attempted to equalize the source pulses. The variation of the auto-correlation of the source pulse (for receiver 90) as a function of source location for the years 2004 and 2005 is shown in Figs. 7(a) and 7(b), respectively. The two figures show auto-correlation of the direct arrival at receiver 90. The event close to ±0.35 s is the residual bubble. Fig. 7(c) is the difference in the auto-correlation of the source pulse for the years 2004 and 2005. The residual bubble variation is pronounced and consistent for every source location. Deconvolving each trace of the correlation gather by auto-correlation of source-time function is equivalent to applying a filter that is inverse of the auto-correlation. Difference of *self-decons* (convolution of inverse and auto-correlation) for the years 2004 and 2005 (Fig. 7(d)) shows that systematic residual bubble variation is suppressed. Hence, deconvolving the correlation gather by the source power spectrum suppresses the source signature variations. Migrated images, for the years 2004 and 2005, generated after applying both wavefield separation and deconvolution are shown in Figs. 8(a) and 8(b). Fig. 8(c) is the difference of the images. Fig. 8(d) is the difference image amplified by 10. The improvement in the repeatability by combining wavefield separation and deconvolution is evident by the decrease in the NRMS to 0.1624.

The repeatability can be further improved by windowing the direct arrival in the downgoing waves at VS. By windowing the direct arrival in the downgoing waves, we are imposing a P-wave VS, hence suppressing the non-repeatability in the shear waves. The images in Figs. 9(a) and 9(b) are obtained by migrating VS data generated by combining wavefield separation, windowing and deconvolution. Fig. 9(c) is the difference of the images and Fig. 9(d) difference amplified by 10. The corresponding NRMS reduces to 0.1414. Combination of wavefield separation, windowing and deconvolution, hence improves the repeatability of the images created with VS data making VS method a useful tool for time-lapse monitoring.

Acknowledgments

We thank Shell for permission to show the Mars OBC data and for the financial support through the GameChanger Program.

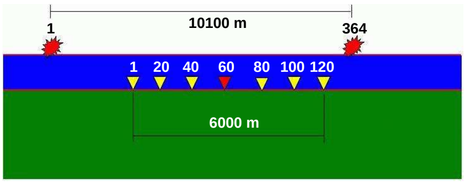

Fig. 1: Cartoon of the acquisition geometry for the Mars field OBC data.

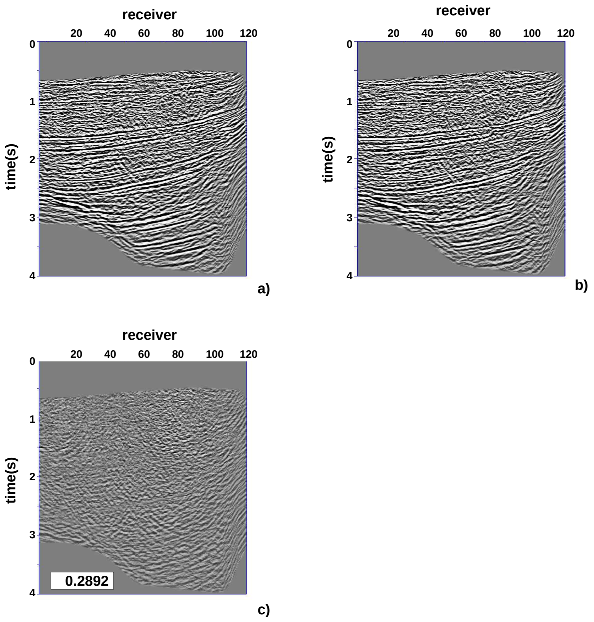

Fig. 2: Images generated by migrating the conventional seismic data. Panels (a) and (b) are the images for the years 2004 and 2005. Panel (c) is the difference of the two images.

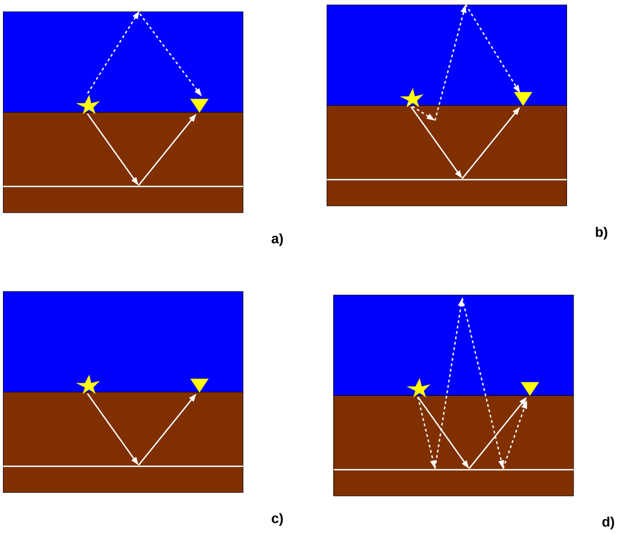

Fig. 3: Cartoons of the possible ray paths demonstrating the wave propagation possible for different approaches to generate the VS data.

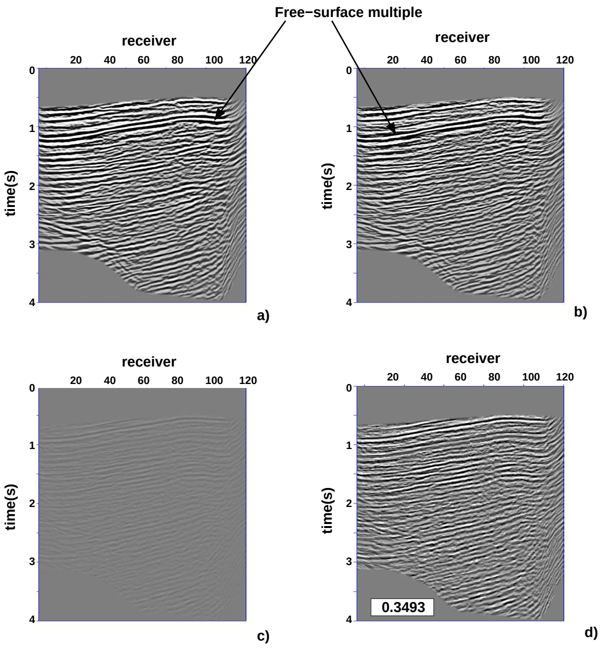

Fig. 4: Migration of the VS data generated by correlating the total wavefields. Panels (a) and (b) are the images for the years 2004 and 2005. Panels (c) is the difference of the two images. Panel (d) is the difference amplified by 10.

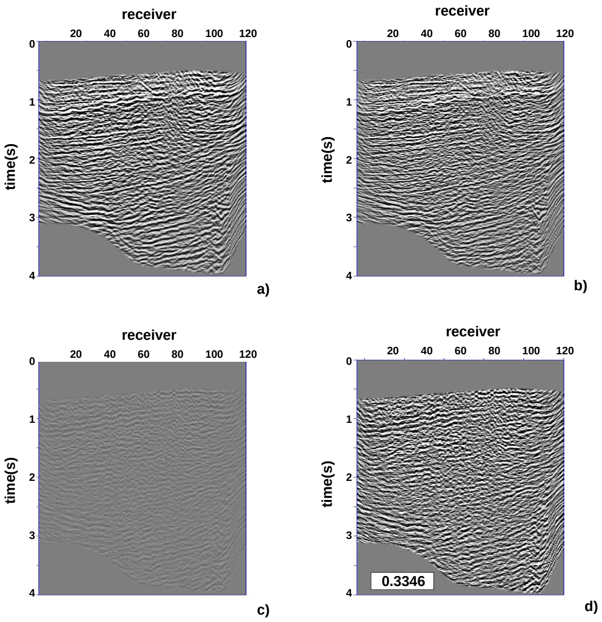

Fig. 5: Migration of the VS data generated by the current practice. Panels (a) and (b) are the images for the years 2004 and 2005. Panel (c) is the difference of the two images. Panel (d) is the difference amplified by 10.

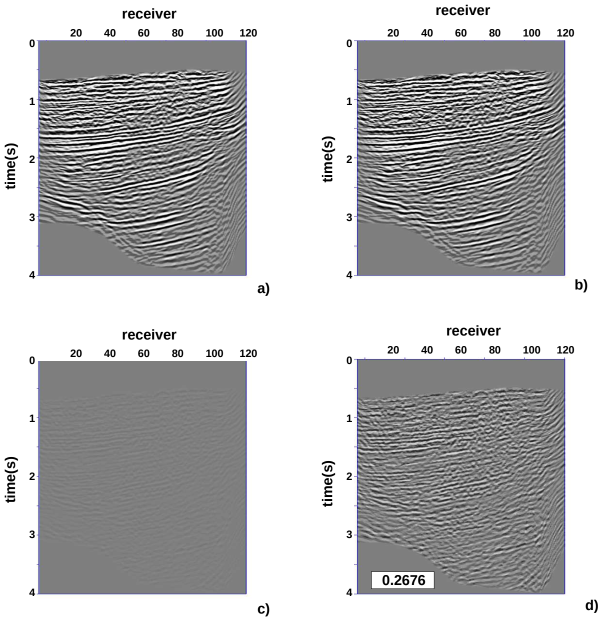

Fig. 6: Migration of the VS data generated after wavefield separation. Panels (a) and (b) are the images for the years 2004 and 2005. Panel (c) is the difference of the two images. Panel (d) is the difference amplified by 10.

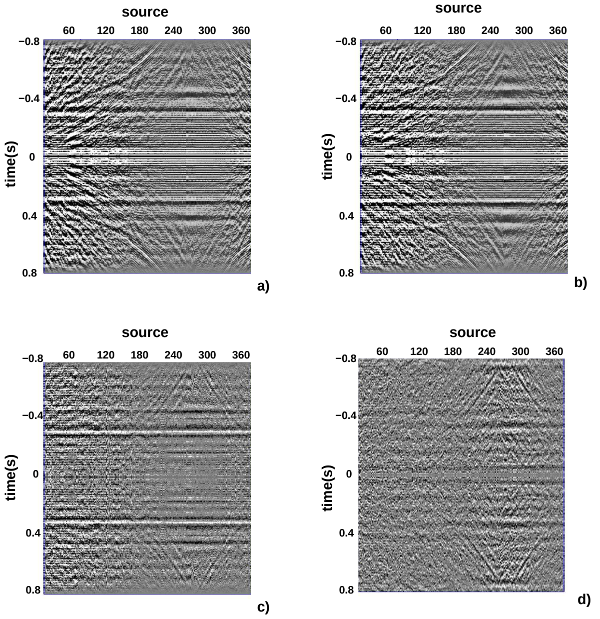

Fig. 7: Variation of the auto-correlation of the source wavelet corresponding to receiver 90 as a function of source location for (a) 2004 and (b) 2005. Panel (c) is the difference of the gathers in (a) and (b). Panel (d) is the difference of the self-decons for the years 2004 and 2005.

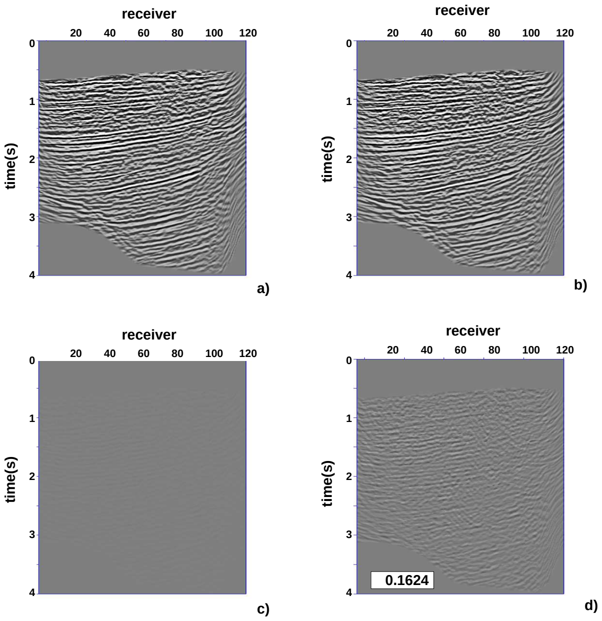

Fig. 8: Migration of the VS data generated by combining wavefield separation and deconvolution. Panels (a) and (b) are the images for the years 2004 and 2005. Panel (c) is the difference of the two images. Panel (d) is the difference amplified by 10.

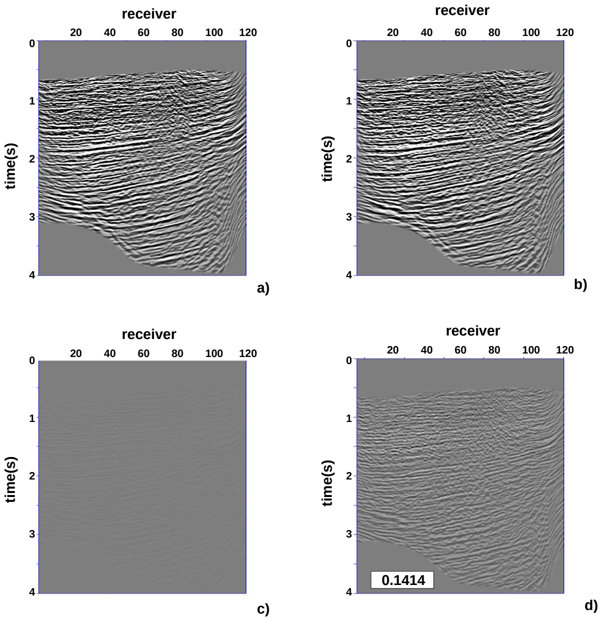

Fig. 9: Migration of the VS data generated by combining wavefield separation, windowing and deconvolution. Panels (a) and (b) are the images for the years 2004 and 2005. Panel (c) is the difference of the two images. Panel (d) is the difference amplified by 10.