LSPSM For Pre- and Poststack Time Lapse Studies

Abdolnaser Yousefzadeh* and John C. Bancroft, CREWES, University of Calgary, Calgary, Alberta, Canada
*ayousefzad@yahoo.com

Summary

We use synthetic data to show how different acquisition geometries between baseline and monitor surveys lead to different Kirchhoff migration artifacts for the same model. Dead receivers in permanently planted geophone surveys will also cause some artifacts in the Kirchhoff migration of monitor surveys that are different from baseline survey artifacts. Consequently, the resulting time lapse image shows the difference between artifacts which may dominate the changes of the reflectivity model. The least squares prestack Kirchhoff migration (LSPSM) is performed separately on both the baseline and monitor data, where no caveat is introduced. We show how LSPSM can attenuate these effects and provide comparable high resolution images for both pre- and poststack time lapse studies.

Introduction

A time lapse study includes recording and analyzing a secondary seismic survey after a period of time in order to detect subtle differences or changes in the physical properties of the hydrocarbon reservoirs or injection sites. The first seismic survey is called the baseline survey and subsequent ones are called monitor surveys. Assuming all acquisition parameters, instrumentation, environmental noise, near surface effects, and processing procedures are exactly equal, the comparison between two final migration images may show the effect of fluid movement in a reservoir by a small difference in the traveltime of an event, or a change in seismic attributes, such as reflectivity.

One of the first successful time lapse surveys was performed in 1987 in the Holt Fireflood reservoir to show the movement of the gas/oil contact (Greaves and Fulp, 1987). More than 100 time lapse seismic surveys were performed around the world by 2001 (Lumley, 2001). Time lapse studies are not restricted to the comparison of poststack images; for example, Vedanti and Sen (2009) performed prestack time lapse study by inversion of prestack data for elastic parameters to track the thermal front of an *in situ* combustion project.

Ignoring the effect of other differences, a key point in comparing two seismic surveys is that both, baseline and monitor surveys, have similar acquisition geometries. However, this is not always feasible. The baseline survey may be an old survey with a very limited number of sources and receivers. Monitor surveys may use more modern equipment which allow better and denser data acquisition. There may be some new surface obstacles that prevent new data acquisition from matching the baseline geometry. Changes in acquisition geometries may be reduced by placing permanent receivers under the surface. However, some receivers may not function properly after a period of time. Lost geophones will leave new artifacts in the migration image of the monitor data. In marine data acquisition, there is poor control on the positioning of the hydrophones due to streamer feathering. The ocean bottom cable (OBC) method of data acquisition can be used instead of a streamer; however, it has the same problem as permanently planted geophones. It is shown that LSPSM can be used to attenuate the effects of different acquisition geometries and improve the time lapse image resolution.

Reducing the effect of different acquisition geometries by LSPSM

Migration is always accompanied by acquisition footprint (Ji, 1997; Nemeth, et al., 1999). The pattern of acquisition footprint depends on the acquisition geometry. Different acquisition geometries between old and new surveys leave different artifacts in the migration images of the baseline and monitor surveys. Therefore, time lapse artifacts may dominate the changes in the model parameters.

Consider the baseline survey experiment as

$$d_0 = G_0\, m_0, \tag{1}$$

where d_0, G_0, and m_0 are the recorded data, forward modeling operator, and reflectivity for the baseline survey, respectively. Assume the Earth's reflectivity changes from m_0 to m_1 after a period of time as:

$$m_1 = m_0 + \Delta m, \tag{2}$$

where m_1 is the reflectivity at the time of the monitor surveying, and Δm is the difference in reflectivity between two data acquisitions. The monitor survey records data, d_1, which mathematically is expressed by

$$d_1 = G_1\, m_1, \tag{3}$$

where G_1 is the forward modeling operator of the monitor survey. Migration of the two surveys gives

$$\widehat{m_0} = G_0^T\, d_0, \tag{4}$$

for the baseline survey and

$$\widehat{m_1} = G_1^T\, d_1, \tag{5}$$

for the monitor survey, where $\widehat{m_0}$ and $\widehat{m_1}$ are migration of baseline and monitor surveys, respectively, and G^T is the migration operator. Even when the model is not changing, i.e. $m_1 = m_0$, $\widehat{m_0}$ and $\widehat{m_1}$ will be different due to different acquisition parameters between G_0 and G_1 (Yousefzadeh and Bancroft, 2012). When two acquisition geometries are similar, and change in the velocity of the modeling operators is negligible, $G_0 \sim G_1$, we may write:

$$\widehat{m_1} = G_0^T\, d_1 = G_0^T\, G_0\, m_1 = G_0^T G_0\, (m_0 + \Delta m) = \widehat{m_0} + G_0^T G_0\, \Delta m, \tag{6}$$

or,

$$\widehat{m_1} - \widehat{m_0} = G_0^T G_0\, \Delta m, \tag{7}$$

which states that the difference between the baseline and monitor migration images is proportional to the changes in the model parameters between the two surveys (Yousefzadeh and Bancroft, 2012). However, since $G_0^T G_0$ is not a unitary operator, the difference in migration images is not exactly equal to the real changes in the reflectivity.

The baseline and monitor migration images must be cross-equalized to remove the effect of non-repeatability of data acquisition and migration artifacts before generating the time lapse image. A few cross-equalization methods have been proposed. As an example, Rickett and Lumley (2001) suggested a cross-equalization flow, including two runs of a match filter application after regridding the data for amplitude, phase, and bandwidth balancing.

LSPSM is an effective method to reduce the acquisition artifacts and to make the final images comparable. Separate damped LSPSM of the baseline, m_{DSL0}, and monitor, m_{DSL1}, surveys,

$$m_{DSL0} = \left(G_0^T\, G_0 + \mu_0^2 I\right)^{-1} G_0^T\, d_0, \tag{8}$$

and

$$m_{DSL1} = \left(G_1^T\, G_1 + \mu_1^2 I\right)^{-1} G_1^T\, d_1, \tag{9}$$

where μs are the tradeoff parameters and I is an identity matrix, provides images that are less affected by the corresponding acquisition geometries. Therefore, they represent the changes in the reflectivity

model better than the migration images. This implies that, regardless of the difference between G_0 and G_1, $m_{DSL0} \sim m_{DSL1}$ when $m_1 = m_0$.

In addition to this, the ability of data reconstruction by LSPSM (Nemeth, et al., 1999) provides another reliable domain for the comparison between two surveys, the data domain. Data sets reconstructed from two surveys into a new geometry make the prestack time lapse studies more feasible and reliable.

Example 1: One model, different acquisition geometries

We compare the differences between migration and LSPSM time lapse images from the same model (Figure 1) but with different acquisition geometries for the baseline and the monitor surveys.
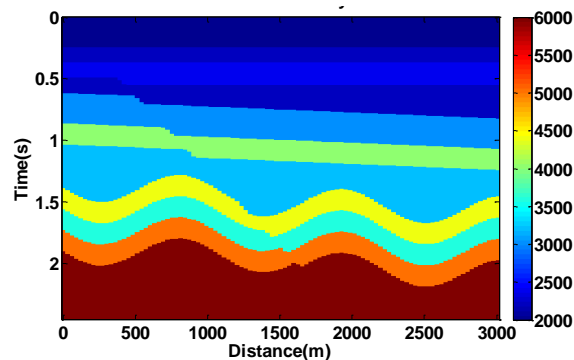

Figure 1: Velocity model for baseline and monitor survey in Example 1.

Assume the baseline survey has the acquisition geometry shown in Figure 2a. There are 32 sources and 100 receivers per source. Source spacing is 93.75 m and receiver spacing is 18.75 m. Acquisition geometry of the monitor survey is shown in Figure 2b, and includes 20 sources and 200 receivers per source. The source spacing is 150 m and receiver spacing is 15 m. Baseline and monitor synthetic data are generated with these geometries, and 1% random noise is added to both data sets. The source wavelet and the other modeling parameters are equivalent for both experiments. These geometries are significantly different; however, due to dense sampling, they produce accurate migration images. Consequently, the difference between the two migration images should be negligible. As we show, this is not necessarily true. Even dense data sampling produces a type of acquisition footprint which may be different from the acquisition footprint of a subsequent dense survey of the same area.

These two data sets Kirchhoff migrated and least squares prestack Kirchhoff migrated. Figure 3a shows the migration image difference. Due to the presence of different acquisition footprints, the difference image is not zero and shows some changes in the reflectivity model which are not due to the changes in the physical properties of the model. Figure 3b shows the difference between two LSPSM images. Comparing Figure 3a with Figure 3b shows that the LSPSM method has significantly reduced the acquisition footprint and returned images that are more compatible in a time lapse study than the conventional migration images.

Prestack time lapse studies provide very useful information about fluid flow using AVO methods. Noise and other undesired events such as multiples may get attenuated by stacking or migration, but they remain in the prestack data. In addition, prestack data are more affected by the different acquisition geometries of the baseline and monitor surveys. Therefore, prestack time lapse studies require more attention to detail when considering time lapse differences. Two surveys may have different offset spacings for the same CMP gather. Data reconstruction by LSPSM can provide two new baseline and monitor data sets for a given geometry in which CMPs have equivalent numbers of traces and offsets. Consequently, data reconstructed from two different surveys are made comparable.

For instance, consider an image point at 2000 m in the previous example. Figure 4 show the CMP gather from baseline (a) and monitor (b) surveys. Both CMP gathers have 10 traces. However, a

comparison is not feasible because of the differences in the traces' offsets. Subtracting the two CMP gathers results in panel (c) in Figure 4 in which is not a desirable difference.

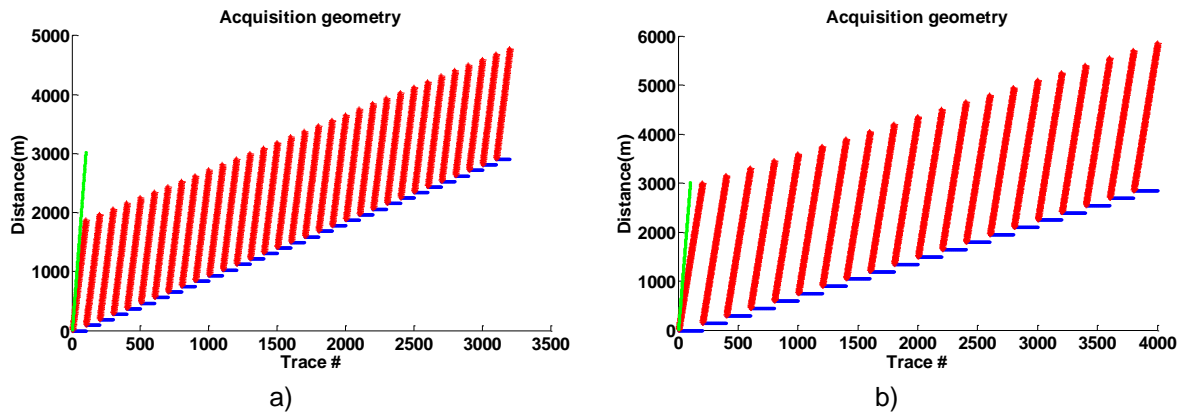a)   b)

Figure 2: Acquisition geometry for a) baseline, and b) monitor surveys Blue and red: source and receiver positions for each seismic trace, positions of the image points are shown in green.
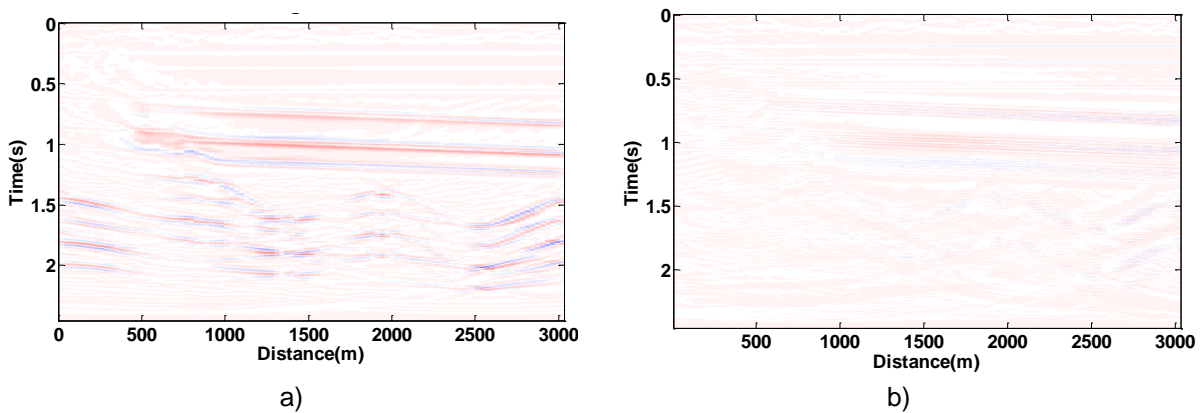

a)   b)

Figure 3: a) Kirchhoff migration and b) Kirchhoff LSPSM time lapse images

a)   b)   c)
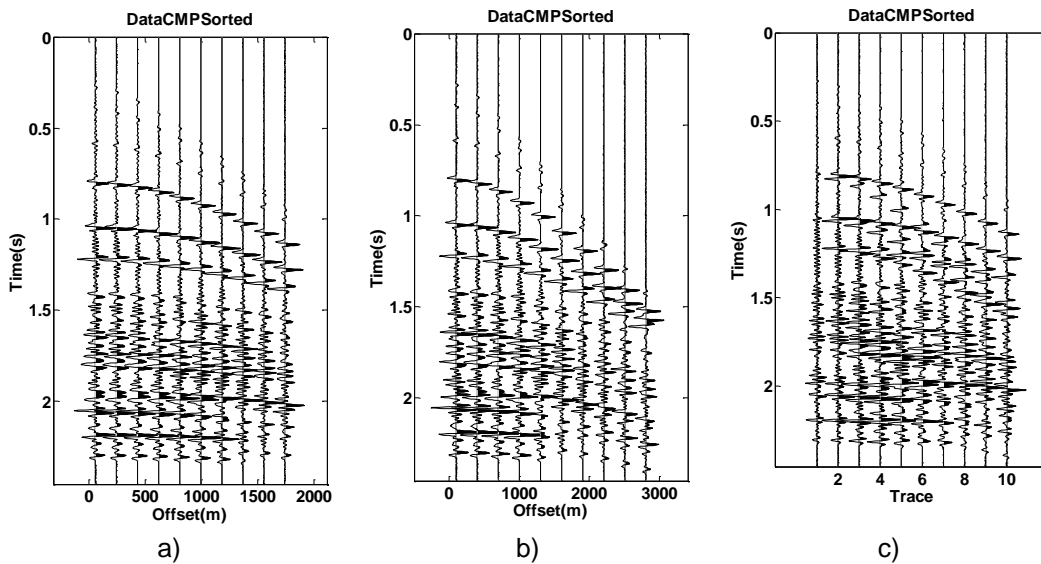
Figure 4: CMP gathers from a) baseline and b) monitor surveys and c) their difference!.

Using the LSPSM method with the geometry of the baseline survey, data from both surveys are reconstructed. Figure 5 shows the reconstructed data from baseline survey, monitor survey, and the difference for the CMP at 2000 m. Since there is no change in the model parameters, two reconstructed CMP gathers are similar and the difference panel shows very low energy residuals. Therefore, data reconstruction of both, baseline and monitor surveys, makes a prestack time lapse study feasible. This is very useful in AVO inversion studies, before and after fluid or steam injection, to track the movements of a fluid/gas boundary or changes in the reservoir temperature due to steam injection.
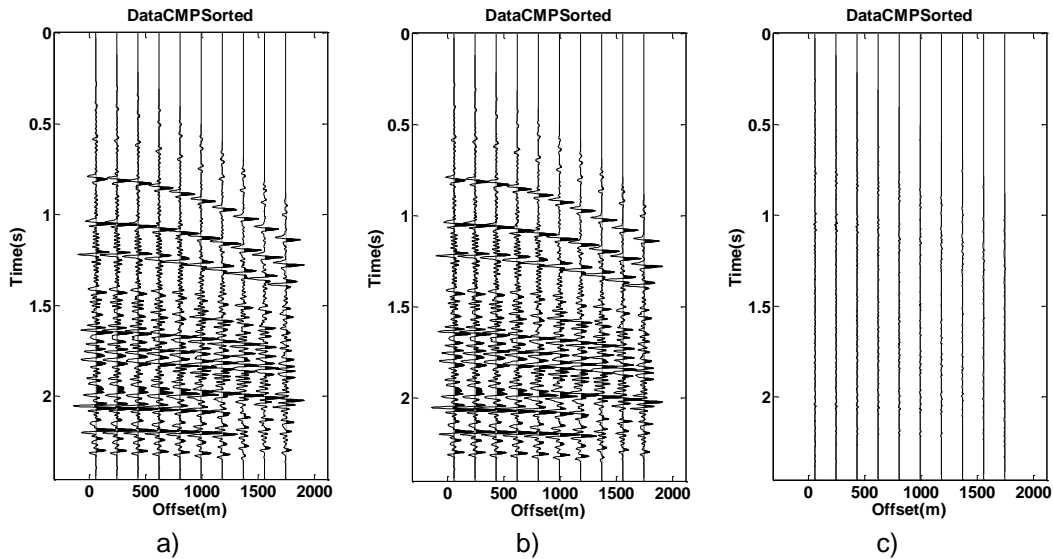

a)   b)   c)

Figure 5: Reconstructed CMP gathers from a) baseline and b) monitor surveys and c) their difference.

Example 2: Two models, same acquisition geometry

In this section we assume that the baseline and monitor surveys have similar geometries but the velocity model changes from baseline to monitor survey. Consider that the baseline geometry at Example 1 applies to the monitor surveys, too. Assume that the velocity of the dipping layer at 1 s drops by 15% from 4000 m/s to 3400 m/s before the monitor survey (Figure 6).

Data are produced for baseline and monitor surveys with the corresponding velocity models. Figure 7a shows the difference between migration images of the baseline and monitor survey. The resulting time lapse image shows the difference in reflectivity due to velocity change. Since the only change in the velocity model is the dipping layer at 1 s, all other events below 1.3 s are migration artifacts and not changes in the model parameters. Figure 7b shows the difference between LSPSM images. Comparison between the two time lapse images shows that the LSPSM time lapse image has a higher resolution than the migration time lapse image, and migration time lapse artifacts are attenuated.
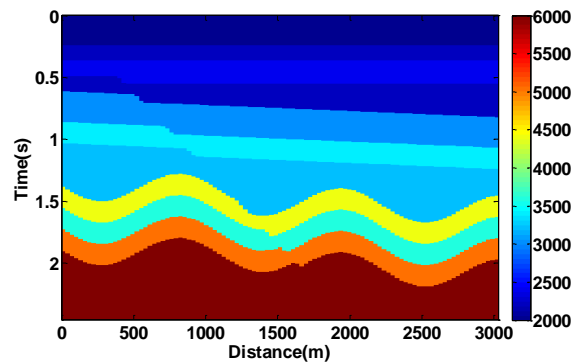

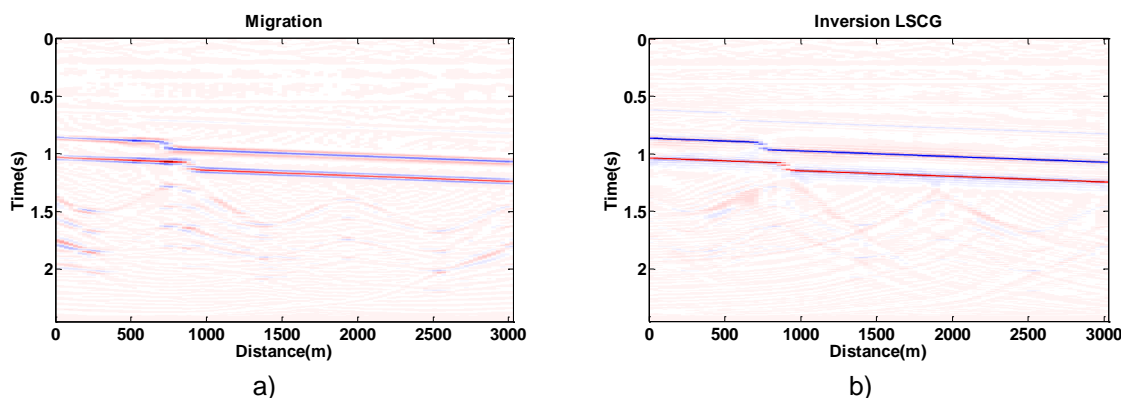Figure 6: Velocity model for monitor survey in Example 2.

Figure 7: a) Migration and b) LSPSM time lapse images resulting from subtraction of baseline and monitor images.

Conclusions

The usefulness of separate LSPSM of time lapse data has been investigated. This analysis assumed that there is no difference in the acquisition instruments, environmental noise, near surface effects, processing flows, and parameters for both baseline and monitor surveys. It is the difference in acquisition geometries that leaves different artifacts at the migration images. These artifacts may mask reflectivity changes in the time lapse image. It was shown how LSPSM of both baseline and monitor data sets can attenuate acquisition footprints and create reliable time lapse images. The reconstructed data from two surveys make the prestack time lapse studies more easily feasible. It is important to mention that other corrections such as removing the near surface effects and attenuating multiples must be performed before inverting the data.

Acknowledgements

Authors wish to acknowledge the sponsors of the CREWES project for their continuing support. They also appreciate the computer technicians of the CREWES project. Thanks to Rolf Maier in particular for his careful and attentive editing.

References

Greaves, R. J., and T. J., Fulp, 1987, Three-dimensional seismic monitoring of an enhanced oil recovery process: Geophysics, **52**, 1175-1187.

Ji, J. 1997, Least squares imaging, datuming, and interpolation using the wave equation: Stanford Exploration Project, **75**, 121-135.

Lumley, D. E., 2001, The next wave in reservoir monitoring: The instrumented oil field: The Leading Edge, **20**, 640-648.

Nemeth, T., C. Wu, and G. T. Schuster, 1999, Least-squares migration of incomplete reflection data: Geophysics, **64**, 208-221.

Rickett, J. E., and D. E. Lumley, 2001, Cross-equalization data processing for time-lapse seismic reservoir monitoring: A case study from the Gulf of Mexico: Geophysics, **66**, 1015-1025.

Vedanti, N., and M. K. Sen, 2009, Seismic inversion tracks in situ combustion: A case study from Balol oil field. India: Geophysics, **74**, 103-112.

Yousefzadeh, A., and J. C. Bancroft, 2012, LSPSM/inversion for pre- and poststack time lapse studies: CREWES Annual Research Report, Vol. **24**.