The practicability of reservoir monitoring with true 4D surface seismic data

Adeyemi Arogunmati and Jerry M. Harris, Stanford University, California, USA*

Summary

Harris et al., (2007) proposed a strategy, called true 4-D, for quasi-continuous reservoir monitoring with sparse data. True 4-D introduced two concepts for processing sparse but continuously recorded datasets: (1) dynamic imaging and inversion, and (2) data evolution. Arogunmati and Harris (2009, 2010) presented an approach to data evolution, i.e., inversion or imaging using estimated data from sparse data. In this paper, we examine the practicability of their approach, and present its application to full trace synthetic and field surface seismic data. The true 4-D approach is implemented by acquiring data as little as 5% of conventional 3-D survey data volume at small time intervals. Unrecorded data at each interval are then estimated using recorded data at all intervals to produce an image with good spatial resolution of the subsurface. The high temporal resolution obtained using the true 4-D approach is its main benefit.

Introduction

The temporal frequency of time-lapse surveys is a key factor in designing a continuous monitoring project; therefore the ability to vary the data acquisition frequency is of utmost importance. Attempts have been previously made to establish continuous and quasi-continuous seismic monitoring scenarios. These scenarios have been primarily designed around quick turn-around of acquired conventional 3-D survey sized seismic data volumes, .i.e., a short period of time from the time the data are acquired and the time the final image is delivered (e.g., Clarke et al., 2005; Lumley, 2001). With this strategy, equipment and manpower availability often puts a limit on how frequently the reservoir can be imaged (Houston et al., 2003).

Time-lapse monitoring using dedicated ocean bottom cables (OBCs) have gotten some traction in recent years, e.g. at the Valhall field (Barkved et al., 2005), Clair field (Foster et al., 2008), and the Chirag-Azeri fields (Foster et al., 2008). The ability to use embedded receivers makes our true 4-D approach even more appealing by eliminating repeated receiver deployment costs. Using synthetic and field data, we show how our continuous true 4-D monitoring strategy can be implemented in the field. We also show synthetic and field data results from quasi true 4-D surveys.

Method

Standard 3-D surveys over hydrocarbon reservoirs could take anywhere from a few weeks to a few months to complete (e.g., MacLeod et al.,1999). Depending on what kind of changes occur in the reservoir, a lot may vary between the time the first shot is recorded and the time the last shot is recorded. Our approach is focused on reservoir monitoring projects where an early detection of abnormality in the reservoir is very important. Reservoirs with structural stability problems and sequestered CO_2 reservoirs fall within this category. Figure 1 shows a possible source deployment scenario for continuous imaging in a monitoring project over a period of three months. We have assumed the receivers are dedicated

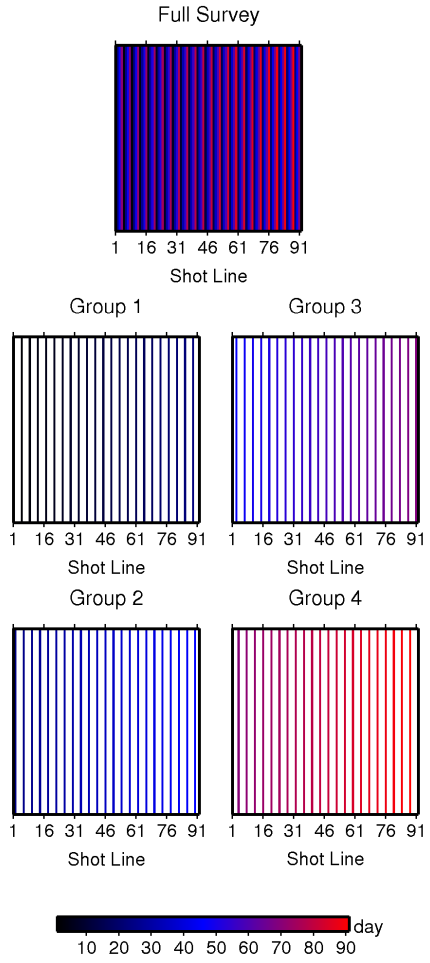


Figure 1: An idealized illustration of shot lines from a standard full survey (top) split into four groups (bottom 4) based on seismic shot time for true 4-D imaging.

OBCs and the airgun sources are towed by a source boat. With the conventional approach, one image will be produced from this survey. However, if a temporal resolution of 3 weeks for the reservoir changes is good enough, the deployed shots could be split into four groups as shown in Figure 1.

Because each group is acquired within 3 weeks, the temporal resolution period of interest, four images of the reservoir over the course of three months can be produced. This concept/ideology can be extrapolated to any time frame. Figure 2 shows an acquisition map from an OBC survey at the Valhall field (Van Gestel et al., 2008) with a similar time scale diagrammed in Figure 1. Even though the project was not designed for the approach presented, it is obvious that a field implementation of the approach described in Arogunmati and Harris (2009, 2010) is possible using this dataset.

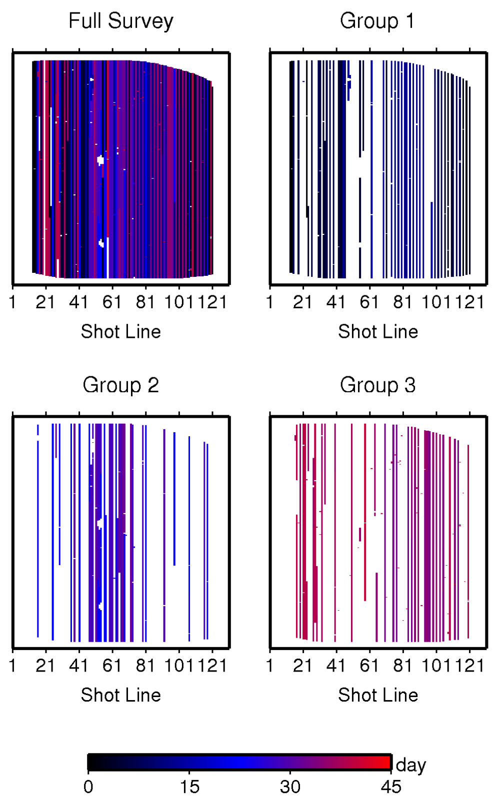


Figure 2: Shot lines from a standard full field survey (top left) split into three groups based on seismic shot times.

Although we have made our argument using marine seismic examples, the same argument can also be made using land seismic examples.

An entirely different acquisition strategy is to plan seismic acquisition surveys on multiple fields such that data are acquired simultaneously. This is more practical with offshore fields. This strategy involves shooting selected lines on one field, then moving to the second field and so on, and then coming back to the first field to acquire a second group of selected lines. This is continued until the entire area of interest has been covered. The advantage of this strategy is that the source boat does not have to move slowly so as to acquire a complete survey over a prolonged period of time. The limitation, however, is that the fields being surveyed have to be close enough to make this strategy economical.

Synthetic Example

We use a 2-D synthetic reservoir model to illustrate the practicability of the true 4-D approach. The reservoir is a CO_2 sequestration reservoir injected with CO_2 over a period of twenty months. Each month is represented by an updated velocity model. We assume that a temporal resolution of

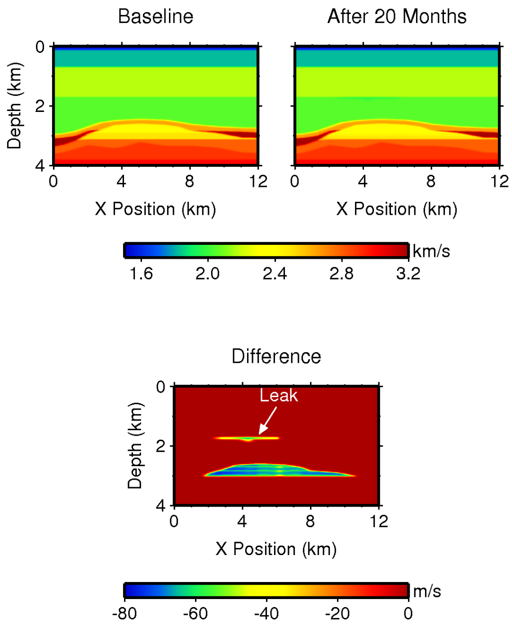


Figure 3: Selected synthetic velocity models, and the difference between them.

one month. The injected CO_2 causes a maximum change of 3% velocity in the reservoir. The pre-injection synthetic velocity model, the 20th velocity and the difference model, are shown in Figure 3.

A leak was synthesized in the reservoir in the 12th month. The addition of the leak was intended to test the ability of our approach to early detect the leak, despite using sparse data, which is one of the main reasons for a continuous monitoring program at a CO_2 sequestration site. Dense synthetic data were computed for each model using an elastic wave equation algorithm. OBC cables were assumed and shots were placed at the water surface. Spacing between shots and between receivers was based on conventional survey spacing. The synthetic data were then sub-sampled to 10%, 20%, and 50% of the original size. With this sub-sampling scenario, a complete survey cycle is achieved after ten, five, and two months respectively. Sample receiver gathers are shown in Figure 4.

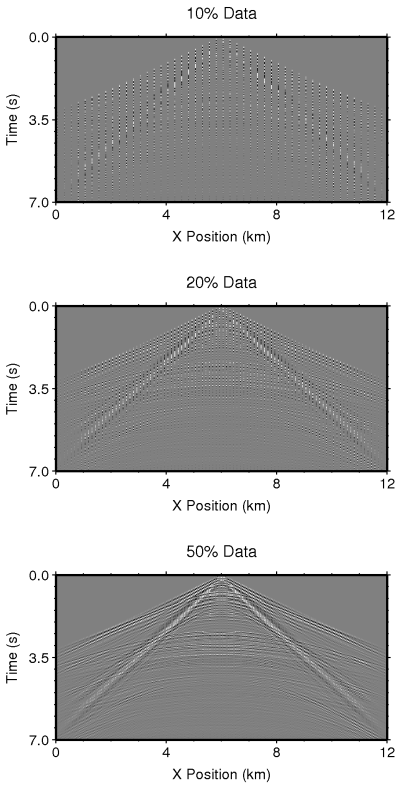


Figure 4: Selected sub-sampled synthetic shot gathers.

After sub-sampling the synthetic datasets, we estimated discarded traces using the minimum weighted norm interpolation algorithm (Liu and Sacchi, 2001), and reconstructed the velocity models using reflection tomography (Clapp, 2001). The tomography scheme is implemented in the post-migrated domain. Tomography in the post-migrated domain is efficient because it ensures that consistent reflectors are picked and picking is easier (Stork, 1992).

As noted in Arogunmati and Harris (2009), the approach requires that data estimation is done each time new data are available until there is no further improvement on estimation error. Figure 5 shows results of traveltime tomography after data estimation from 20% data. The results shown are reconstructions done after the synthetic seismic data from the 18th velocity model has been made available.

From our results, the leak starts being delineated in the 13th month; one month after it actually occurred, and the image of the leak improves in clarity as more data becomes available and missing data are re-estimated.

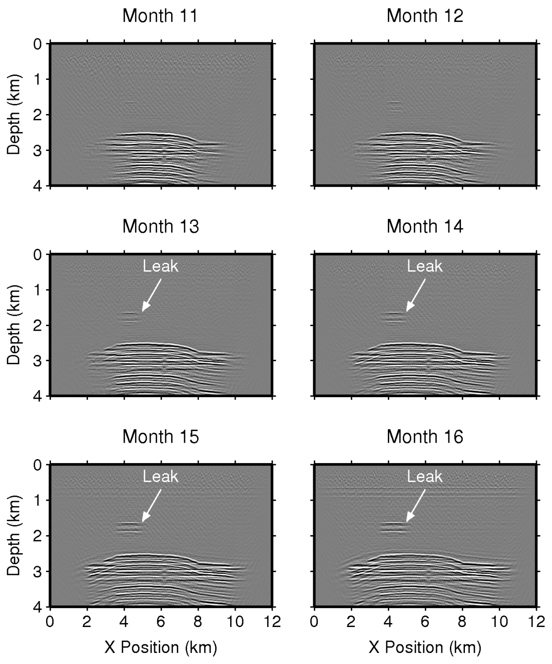


Figure 5: Reconstructed velocity model diferences using data estimated from 20% true data after 18 months. Notice how the leak in the reservoir is delineated in month 13, the month after it occurred.

Application to Field Data

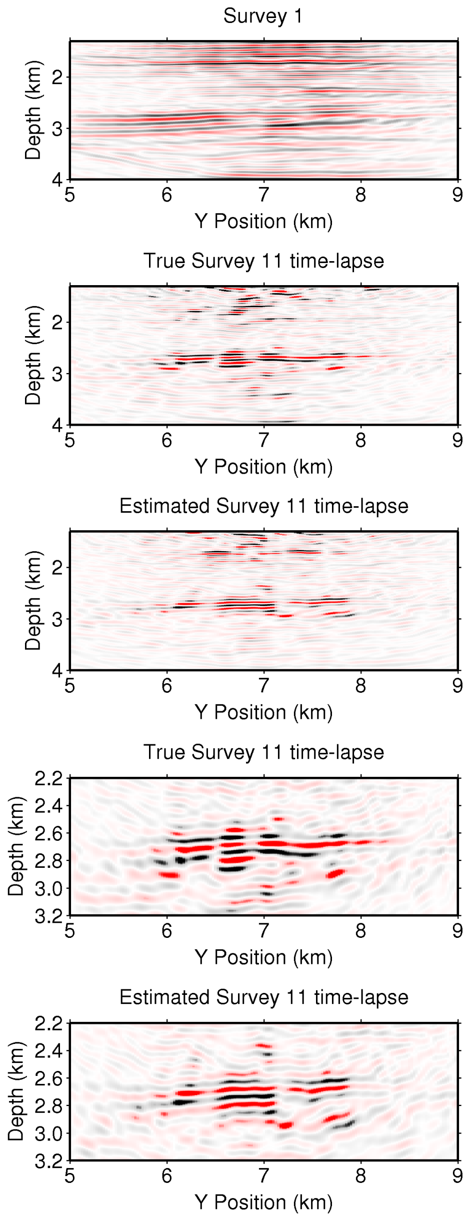
After successfully testing the practicability of the approach on synthetic data, we began testing it on the Valhall field time-lapse dataset. Our interest in the Valhall field is the injected water used in secondary recovery (Van Gestel et al., 2008). Injection started in early 2006, after the 6th seismic survey. We will track the injected water using data from the 7th to 11th survey. Figure 6 shows inline and crossline migrated sections from the baseline survey (Survey 1) and the time-lapse responses of the 11th survey. For reference, the baseline survey was completed in November 2003 (Van Gestel et al., 2008), and the 11th survey was completed in November 2008. We clearly see the amplitude changes in the time-lapse images. The Valhall data has been used to observe time-lapse changes resulting from water injection as water migrates away from the injector well towards the producer well (Van Gestel et al., 2008). Figure 6 also shows time-lapse sections from estimated Valhall datasets resulting from an application of the true 4-D approach described in this paper. We subsampled the Valhall datasets from surveys 7 to 11 to 30% of their original sizes to simulate a true 4-D dataset and then applied the data evolution approach. The plots show that despite the large reduction in the size of individual survey datasets, the time-lapse signal was recovered.

Conclusions

The quasi-continuous monitoring approach also known as true 4-D has been shown to be effective for reservoir monitoring where temporal resolution of the reservoir changes is more important than spatial resolution. This paper examines the practicability of the true 4-D approach using both synthetic and field data. We used synthetic and field survey data to show how a conventional 3-D survey could be expanded into a true 4-D survey simply by scheduling the source line patterns appropriately. The synthetic seismic data examined were computed from 20 synthetic velocity models showing the state of a CO_2 sequestration reservoir over a period of 20 months at one month intervals. A leak in the reservoir was used to test the ability of the true 4-D approach to delineate such features. Results show that the true 4-D approach described favors early leak detection in CO_2 sequestration reservoirs. We have applied the true 4-D approach to the seismic time-lapse data from the Valhall field and the results are good. Future work will include amplitude correction on the estimated datasets, and we will continue to test our approach on available field data.

Acknowledgements

We would like to thank the Global Climate and Energy Project (GCEP) and the Smart Fields Consortium at Stanford for supporting this research; and Ray Abma, Richard Clarke, Jean-Paul Van Gestel, Olav Barkved and Robert Clapp for suggestions at various points during this research. We would also like to thank BP and the Valhall partnership (BP Norge AS, Amerada Hess Norge, Total E&P Norge AS and A/S Norske Shell) for permission to publish this paper.


Survey 1

True Survey 11 time-lapse

Estimated Survey 11 time-lapse

True Survey 11 time-lapse

Estimated Survey 11 time-lapse

Figure 6: Inline migrated section for the baseline survey (Survey 1) and the corresponding time-lapse section for the true and estimated 11th survey data.

REFERENCES

Arogunmati, A. and M. J., Harris, 2009, An approach for quasi-continuous time-lapse seismic monitoring with sparse data: 79th Annual Meeting and International Exposition, SEG, Expanded Abstracts.

Arogunmati, A. and M. J., Harris, 2010, A data-estimation based approach for quasi-continuous reservoir monitoring using sparse surface seismic data: 72nd EAGE Conference & Exhibition, Extended Abstracts.

Barkved, O. I, Buer, K., Kristiansen, T. G., Kjelstadli, R. M., Kommedal, J. H., 2005, Permanent seismic monitoring at the Valhall field, Norway: paper IPTC 10902, 2005.

Clapp, R., 2001, Geologically constrained migration velocity analysis: PhD thesis, Stanford University.

Clarke, R., Askim, O. J., Pursley, K., Vu, P., Askim, O. J., 2005, 4D rapid turnaround for permanent 4C installation: 75th Annual Meeting and International Exposition, SEG, Expanded Abstracts.

Foster D., Fowler, S., McGarrity, J., Riviere, M., Robinson, N., Seaborne, R., and Watson, P., 2008, Building on BP's large-scale OBC monitoring experience – The Clair and Chirag-Azeri projects: The Leading Edge, **27**, 1632-1637.

Harris, J. M., Zoback, M. D., Kovscek, A. R., Orr, F. M. Jr, 2007, Geologic Storage of CO_2, *in* Global Climate and Energy Project 2007 Technical Report. (http://gcep.stanford.edu/research/technical_report.html).

Houston, M., Grumman, 2003, Requirements, constraints and advantages of fiber optic sensor arrays for permanent offshore applications: paper OTC 15072, 2003.

Lumley, D., 2001, Time-lapse seismic reservoir monitoring: Geophysics, **66**, 50-53.

MacLeod, M. K., Hanson, R. A., Bell, C. R., McHugo, S., 1999, The Alba field ocean bottom cable seismic survey: Impact on Development: paper SPE 56977, 1999.

Stork, C., 1992, Reflection tomography in the postmigrated domain: Geophysics, **66**, 50-53.

Van Gestel, J., Kommedal, J. H., Barkved, O. I., Mundal, I., Bakke, R., Best, K. D., 2008, Continuous seismic surveillance of Valhall Field: The Leading Edge, **27**, 1616-1621.