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# Permanent Buried Receiver Monitoring of a Carbonate Reservoir in a Desert Environment

A. Bakulin (Saudi Aramco, EXPEC Advanced Research Center), R. Smith* (Saudi Aramco, EXPEC Advanced Research Center), M. Jervis (Saudi Aramco, EXPEC Advanced Research Center)

## Summary

Onshore time-lapse seismic is a major challenge, particularly in the harsh desert environments encountered in Saudi Arabia. Injection of CO2 into a stiff carbonate reservoir results in weak 4D signal, which can easily be contaminated by noise generated by changing near surface conditions. Using a hybrid acquisition system, consisting of permanent buried receivers and surface vibroseis sources, the seasonal variations in data repeatability are clearly identified. Data acquired under the same conditions (e.g., both surveys during the dry season) provide the best data quality, with significant waveform variations observed when comparing surveys from different seasons (i.e., dry-wet). Buried receiver acquisition and specialized processing has resulted in outstanding final stack repeatability. For surveys acquired under dry conditions, mean NRMS values in the range of 3-5 % have been reported for surveys separated by up to two years. This level of repeatability has allowed small signals due to CO2 injection to be detected, which grow with increasing injection volume and are consistent with engineering data.

## Introduction

Time-lapse seismic was selected to monitor $CO_2$ injection in the first of its kind pilot project for Saudi Arabia. Seismic monitoring is a major challenge, with injection into a rigid carbonate reservoir expected to result in a weak 4D response. In addition, challenging near-surface conditions consisting of varying sand thickness, highly variable near-surface velocities, and underlying karsted limestone severely inhibiting seismic imaging and monitoring in the region. Dune migration and seasonal variations in the near surface can potentially lead to high levels of non-repeatability between time-lapse surveys. As a result, a highly repeatable acquisition system was required to enable small 4D changes caused by $CO_2$ injection to be observed.

A hybrid scheme, comprising surface vibroseis sources and buried receivers, was selected as the best solution to minimize 4D noise under these conditions (Bakulin et al., 2012). The final deployment (Figure 1) is composed of 1003 receivers buried at a depth of 50-80 meters arranged on a 50x50 meter grid. A dense 10x10 meter shot carpet is utilized to ensure sufficient sampling for noise attenuation and to achieve high-fold coverage. Continuous acquisition results in one complete survey every four weeks. These frequent surveys provide greater confidence when interpreting small features detected in the final difference volumes. The downhole nature of recording also allows key insights into the repeatability trends. In this paper, we show seasonal variations observed in the data along with initial qualitative results of successful $CO_2$ monitoring in a harsh desert environment.

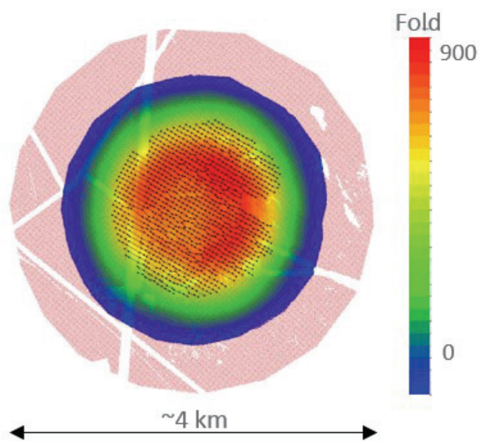


***Figure 1*** *The final survey design includes 1003 buried sensors at a depth of 70-80 m (black dots) and dense vibroseis source grid (pink shaded area). Here high fold data (denoted by color scale) is acquired on 5x5 m bins to improve signal-to-noise ratio.*

## Seasonal repeatability

Using buried receivers enables the direct, downgoing wavefield to be recorded. Bakulin et al. (2014) found that these early arrivals contain useful information about the data quality, with a clear correlation to the final stack repeatability observed. In theory, if the early arrivals show changes over time due to surface or source variations, the repeatability of the wavefield illuminating the reservoir will also be affected. Acquiring monthly surveys allows us to assess how seasonal trends impact the data repeatability.

To determine early arrival repeatability, the nearest offset trace for each shot point from the baseline survey is selected. Next, the corresponding trace for each of the monitor surveys is found. A 50 ms window about the first break pick time is then used to calculate repeatability attributes for all survey combinations. The NRMS is a common metric used to measure the level of 4D noise between two surveys and is sensitive to all variations, including amplitude changes and time-shifts (static and dynamic). Figure 2a shows the mean shot-point NRMS of each survey compared to a baseline from the dry (red) and wet (blue) seasons. Here, we clearly observe that comparing surveys acquired in the same season (i.e., dry-dry or wet-wet) produces the best data repeatability. For instance, we see a sharp increase in NRMS (i.e., decreasing repeatability) with the onset of the first wet season when using the dry season survey as a baseline.

Predictability is another commonly used repeatability attribute. Unlike the NRMS, predictability is not sensitive to amplitude scaling or small time shifts. When used in conjunction with the NRMS, it can help to better understand 4D differences. The equivalent mean predictability return time plot is shown in Figure 2b, with values closer to one indicating higher similarity. A comparable trend to that observed with NRMS is found, with an abrupt and prolonged decrease in data repeatability when comparing data acquired in different seasons. The fact that both NRMS and predictability show the same trend indicates that seasonal variations in repeatability are caused by waveform changes rather than a simple time-shift or amplitude scaling. This has implications for data processing as these types of changes will be more difficult to correct.

The differences between data acquired during the dry and wet seasons are visualized in Figure 2c. Here the waveforms are stable during dry season surveys (surveys 1 and 4). Significantly larger differences can be seen after the start of the wet season (surveys 6 and 8). Although the changes appear small, they are the same magnitude as the expected changes due to $CO_2$ injection.

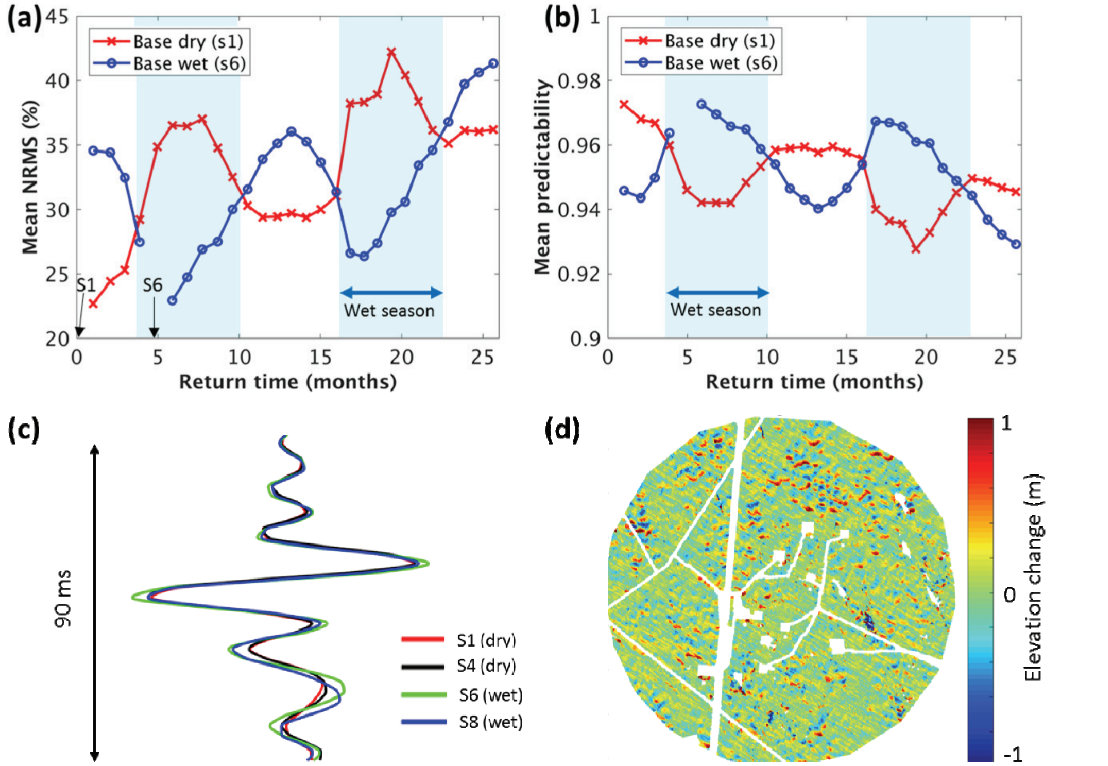


***Figure 2*** *Seasonal repeatability trends indicated by early arrival analysis including (a) mean NRMS using a baseline from the dry (red) and wet (blue) seasons, (b) mean predictability, (c) early arrival waveforms changes for a single shot-receiver pair during dry and wet conditions, and (d) changes in elevation over a two year period resulting from sand dune migration.*

Despite repeatability improving once we return to dry conditions (red line, Figure 2a), we do not record the same level of repeatability as for the first few surveys. In general, we observe decreasing repeatability with increasing return time (elapsed time between baseline and current survey). A major part of this 4D noise is likely the result of migrating sand dunes that are a common feature of desert environments. Figure 2d shows the change in elevation over a 24 month period, which reveals shifts of up to one meter and is constantly increasing over time.

The final stack NRMS, computed in a window about the reservoir of interest (but excluding the production zone) is shown in Figure 3. Here, the baseline survey from the first dry season is used for reference. The results show outstanding data repeatability for data acquired during the dry season, with mean NRMS values in the range of 3-5 % (Figure 3a) for surveys separated by around one year. A slight deterioration in repeatability is still observed when comparing data from different seasons, with a clear increase in the average and standard deviation, making the results more difficult to interpret.

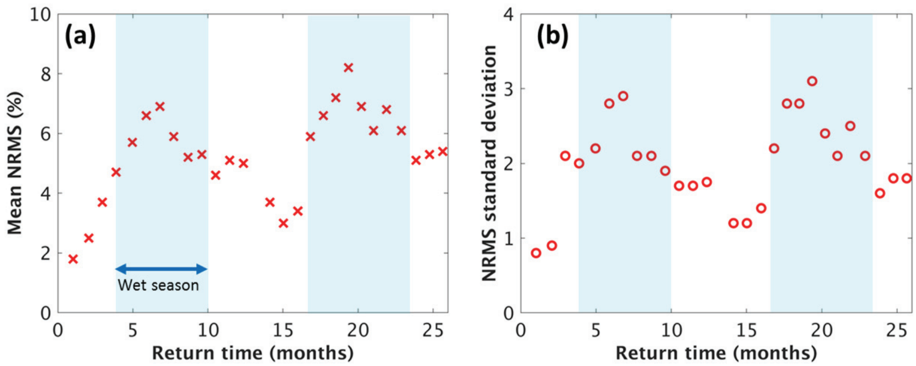


***Figure 3*** *NRMS statistics for the final migrated data (computed in the reservoir window, excluding production zone) showing (a) mean NRMS and (b) standard deviation return curves for each monitor survey compared to the first survey (acquired under dry conditions).*

**Initial qualitative interpretation**

Excellent data repeatability has enabled small 4D signal related to $CO_2$ injection to be identified. Here, we focus on initial qualitative results from two injector-producer pairs. Comparing data acquired in the dry season, we detect a plume that clearly stands above the background noise between the northern two injectors after a period of 14 months (Figure 4a). As was observed in the early arrival analysis, comparing two surveys acquired during the wet season can also produces highly repeatable data. Figure 4b shows the NRMS computed between two surveys acquired in the wet season and also separated by 14 months. We see similar features as the dry season maps, with the strongest signal (indicating largest volume of $CO_2$) moving towards producer two (P2). The details are not expected to be exactly the same as the dry season map (Figure 4a), since the two maps cover different time periods with different injection schedules.

The following year, a much larger plume is identified that includes important differences (Figure 4c). During the first year, more $CO_2$ was measured in P2 than in producer one (P1). This is supported by the 4D seismic results which suggest a large volume of $CO_2$ moving towards P2 (Figures 4a and 4b). During the second year, a larger volume of $CO_2$ was observed in producer one (P1), which is consistent with the observations made from 4D seismic, with a clear connection now made between injector one (I1) and P1.

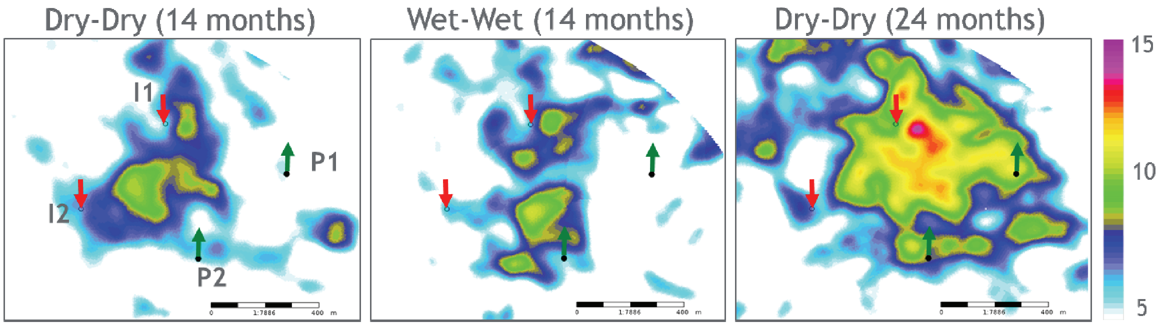


***Figure 4*** *NRMS maps computed about the reservoir of interest at different stages during the acquisition including (a) baseline and monitor surveys acquired under dry conditions 14 months apart, (b) both surveys acquired under wet season conditions and separated by 14 month, and (c) dry conditions after two years. Arrows I1 and I2 represent injectors one and two while P1 and P2 are producers one and two, respectively.*

## Conclusions

Successful seismic monitoring of $CO_2$ injection has been demonstrated under the most challenging of conditions, a stiff onshore carbonate reservoir in the presence of a complex near surface. Specialized acquisition using buried sensors has resulted in excellent data repeatability, which has allowed small time-lapse signals related to injection and production activities to be detected. A clear $CO_2$ plume that grows with increasing injection volume is observed and is consistent with production data. Frequently acquired surveys show clear seasonal trends in data repeatability. While comparing surveys acquired under similar conditions (i.e., dry-dry or wet-wet season) results in excellent repeatability, the 4D noise is significantly higher when comparing surveys acquired in different seasons (i.e., dry-wet). Resolving non-repeatability resulting from different seasons and the uncertainty it introduces remains a challenge.

## Acknowledgments

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## References

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