Evaluating new designs of land hydrophones and geophones for permanent monitoring

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Summary

We present a novel and efficient methodology to assess the performance of new permanent sensor designs intended for land reservoir monitoring. This is essential to pave the way for permanent installation of 1000 4C sensors over a CO2 injection site. This methodology focuses on evaluating the performance of geophones and hydrophones deployed above and below the water table. It allows us to obtain what we think is a reliable estimate of signal-to-noise and short-term repeatability using pre-stack data obtained with both individual sensors (hydrophones and geophones) as well with so-called dual sensor (summed geophone and hydrophone). We present several field case studies using various configurations and sensor types from different manufacturers.

Introduction

Permanent monitoring with shallow buried sensors on land is becoming more popular. Although there is no reported installation in desert environments, initial feasibility studies (Bakulin et al, 2012) provided valuable insight and revealed that hydrophone and geophone summation can significantly improve imaging with buried sensors (Burnstad et al., 2012a). However there are a number of challenges related to repeatability of hydrophones cemented above the water table (Burnstad et al., 2012b). To address these challenges we develop novel methodologies to quickly evaluate pre-stack repeatability of new sensor designs deployed above and below the water table. We describe the methodologies and demonstrate usage on real data examples.

Methodology

We design two acquisition layouts based on concepts presented by Burnstad et al (2012b). The first is a common offset walk-around VSP geometry that requires only a small amount of data to quickly deliver estimates of repeatability based on first breaks. The second is a multi-offset walk-away VSP geometry to allow 2D processing such as noise removal and dual sensor summation. From the walk-away we derive estimates of pre-stack repeatability and signal-to-noise ratio (SNR) at the target reflection. Figure 1 outlines the two procedures designed to analyze both layouts. Multiple sites are repeatedly collected, usually up to five times over five days. Figure 2 shows a field data example of walk-around hydrophone and geophone traces used to confirm polarity and timing at one of the sites.

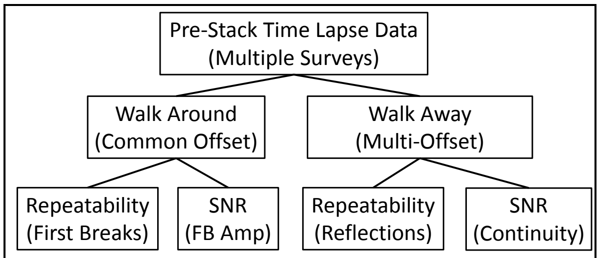

Figure 1. Diagram showing the time-lapse evaluation methodology for permanent sensors.

To derive repeatability metrics we use the standard deviation of semblance values extracted from cross-correlations where individual traces are cross-correlated with a mean trace. For the walk-around geometry, a mean trace is formed within each common azimuth bin that includes all repeat surveys. For the walk-away geometry, a mean trace is formed within each common offset bin for all repeat surveys. Each extracted semblance value (the maximum absolute amplitude on a correlation function) is normalized by average semblance within the bin. Finally, an estimate of repeatability is formed by standard deviation analysis across all normalized bins.

As a complement to repeatability we estimate SNR for both geometries. For the walk-around data we use amplitude decay below the first arrival as a proxy for SNR. For the walk-away data we calculate a frequency-dependent continuity estimate stacked across all offsets.

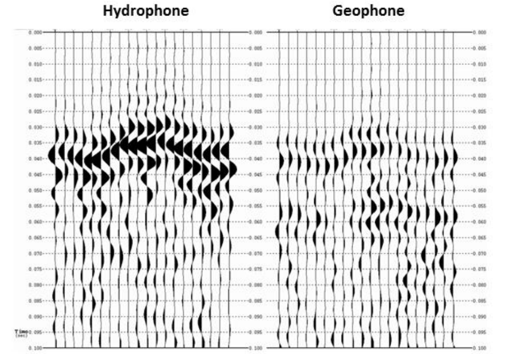

Figure 2. Hydrophone traces (left) and geophone traces (right) at one of the walk-around sites. As expected first arrival polarity is opposite and timing is consistent between the two sensors.

Walk-Around Data Analysis

In a previous study permanent sensors were cemented above the water table (Bakulin et al., 2012). Further, the hydrophones were packaged in special fluid-filled vessels. Despite these efforts average hydrophone repeatability was consistently less than for geophones (Table 1). In addition

DOI http://dx.doi.org/10.1190/segam2013-1020.1

hydrophone coupling was extremely variable from station to station, requiring special corrections in processing. To overcome these challenges, we decided to test sensors deployed below the water table at an average depth of 71 meters. Performing walk-around analysis using five repeated surveys at several sites we find that hydrophones are as repeatable as geophones (Table 1). Though variations from site to site do exist, being below the water table generally lowered the difference between hydrophone and geophone repeatability. Also, hydrophone sensors below the water table should require no special fluid packaging which could simplify deployment. Thus we show that an advantage is gained by placing the sensors below the water table and focus on sensor type and deployment method below the water table.

Survey	Water table	Geophone repeatability	Hydrophone repeatability
Previous	Above	3.8%	6.6%
New 7A	Below	3.4%	4.3%
New 7B	Below	3.7%	3.1%
New 7C	Below	4.7%	4.7%

Table 1. Comparison of repeatability obtained with sensors cemented above and below the water table at different sites throughout the survey area. In all cases, placing the sensors below the water table leads to smaller differences between hydrophone and geophone repeatability.

Sensor Comparison

We considered two different sensor packages deployed in both cement and sand gravel pack below the water table. Sensor A included a sensitive hydrophone plus geophone, while sensor B comprised a less sensitive (stiffer) hydrophone plus geophone.

Walk-around analysis for sensor A in sand and cement produced results shown in Figure 3. For the sensors deployed in sand the repeatability and SNR characteristics are consistent between hydrophone and co-located geophone. Cementing the sensor results in high variations in repeatability up to 14%. Thus we concluded that for sensor A, sand is the preferred deployment option for permanent monitoring. Note that sensors in cement are slightly different from the ones deployed later in sand. The reason being that significant 60 Hz noise contamination was observed on the initial sensor data and a modification was made to subsequent hydrophones to better attenuate 60 Hz noise which changed the impulse response of the sensor.

Sensor B hydrophones are consistent in repeatability with the geophones in either sand or cement deployment. However offset-dependent frequency analysis (Figure 4) indicates that sensor B hydrophones in sand reaches a noise floor over a moderate offset range (800 m to 1200 m). We emphasize that this offset range is critical for 4D monitoring since target reflections in this range are outside the noise cone where non-repeatable backscattered and surface noise dominates. Therefore deployment of sensor B hydrophones should be in cement to improve the impedance match with the formation. Using the best medium for each sensor we summarize the comparison in Table 2. Both hydrophone types exhibit repeatability comparable to collocated geophones, but results suggest B hydrophones have slightly better repeatability using a less sensitive (stiffer) sensor in cement.

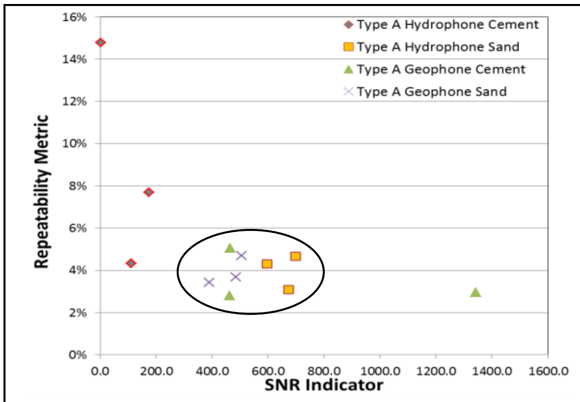

Figure 3. Repeatability vs. SNR for dual sensor type A in sand and cement below the water table. Note that in sand hydrophone and geophone perform in a similar fashion (ellipse). This clearly indicates that sand is an optimum medium for this sensor type.

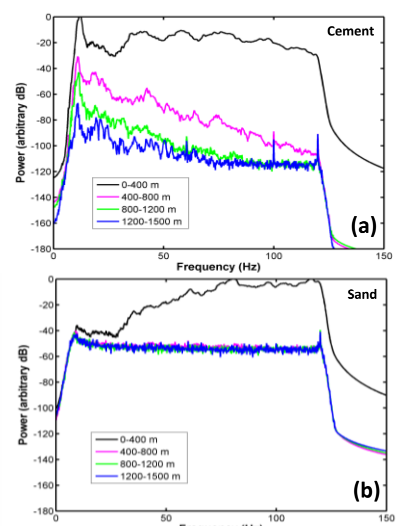

Figure 4. Frequency decay versus offset for sensor B hydrophones in cement (a) and sand (b). Entire traces (0-6 s) are used for computation of the spectra. Both sensors are located below the water table. Note that in sand the hydrophone is recording only noise on all but the nearest offsets.

DOI http://dx.doi.org/10.1190/segam2013-1020.1

Sensor	Medium	Geophone Repeatability	Hydrophone Repeatability
Type A	Sand	3.1%	3.7%
Type B	Cement	2.3%	2.3%

Table 2. Repeatability from walk-around analysis for two different sensor types.

Although the walk-around analysis proved to be quick and efficient it is felt repeatability and SNR should ultimately be evaluated on target reflections as opposed to first arrivals. To this end we collect multi-offset data using a walk-away geometry to allow preprocessing stages such as noise reduction by multi-channel filtering and dual sensor summation to be applied prior to data analysis.

Figure 5 shows that after noise removal, both hydrophone and geophone gathers show clear reflections. The hydrophone-geophone summation result in Figure 5e is used to compare repeatability and SNR for different sensor types. Using a dual sensor result for analysis is better than either the hydrophone or geophone alone (Burnstad et al., 2012a) and will ultimately be used to measure reservoir changes during permanent seismic monitoring of the CO2 injection.

We first compare the pre-stack SNR of sensors A and B. The metric is calculated by normalizing a summed trace-to-trace crosscorrelation by a summed autocorrelation of each trace. Normalization is done in the frequency domain. Offsets from 500 to 1500 m are used in the analysis. The result is shown in Figure 6 where we also plot average amplitude spectra of the windowed input data. The SNR of both sensors appears quite similar and decreasing toward higher frequencies as expected. The bandwidth of sensor A appears significantly wider than B.

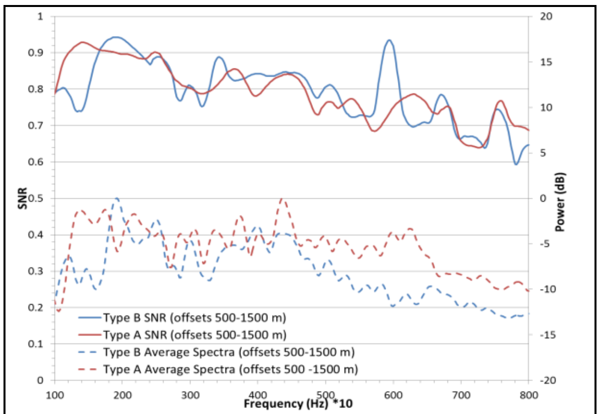

Figure 6. Signal-to-noise ratio (solid line) and average amplitude spectrum (dashed line) estimated on dual sensor gathers for sensor A (red) and sensor B (blue). Horizontal scale is frequency time 10. While SNR is similar, the bandwidth of dual sensor A appears wider than that of dual sensor B.

We then compare pre-stack repeatability using dual summation estimates from sensors A and B extracted at the reservoir level. Using the method described earlier, raw semblance values (Figure 7) are used to estimate the repeatability using the standard deviation of the semblance. The plots for either dual sensor clearly show a lot of scatter caused by residual surface and backscattered noise even after filtering and summation. This plot shows how the scatter is highest at near offsets and highlights the importance of medium offsets outside the noise cone. Hence our earlier reference to critical offsets when analyzing frequency decay versus offset. Also annotated on Figure 7 are repeatability estimates for two offset ranges. The previously mentioned critical offset range and the entire offset range. We summarize our sensor comparison below the water table in Table 3.

	Med	SNR	Bandwidth	Decay	Repeat
A	Sand	Similar	Excellent	Less	8.0%
B	Cement	Similar	Good	More	7.8%

Table 3. Summary of comparison based on walkaway data analysis from sensors A and B (summed hydrophone and geophone) deployed below the water table.

Summary and Discussion

In this study we addressed several issues raised by a previous time lapse feasibility study, that proved time-lapse seismic could be successfully collected using buried multi-component sensors in an arid desert environment with a complex near surface (Berron et al.,2012; Jervis et al., 2012). A key issue identified here is hydrophone performance and repeatability. In this follow-up study we evaluated new hydrophone designs deployed above and below the water table in both sand and cement. We used two acquisition geometries and repeated the study at several locations in our planned CO2 pilot survey area. We then derived new repeatability and SNR metrics to efficiently tabulate and compare results.

It is obvious from multi-site analysis that field conditions or conveyance operations can influence the final results. As such it also presents additional challenges to be addressed before and during installation of the final sensor array.

Conclusions

Given sufficient redundancy in our observations we conclude the following: (1) deployment below water table results in similar hydrophone and geophone repeatability, a key improvement compared to previous survey where hydrophones have low repeatability, (2) the optimum deployment medium is dependent on sensor design and type, (3) signal processing tends to decrease repeatability and SNR differences regardless of sensor design or deployment media, (4) differences in bandwidth and

DOI http://dx.doi.org/10.1190/segam2013-1020.1

frequency decay versus offset should be taken into account for the final design, and (5) offset-dependent repeatability highlights the need for careful survey design over critical offset ranges.

Acknowledgements
We would like to thank Saudi Aramco for allowing us to publish this work. We thank our partners CGG/ARGAS (Arabian Geophysical and Surveying Company), Geospace Engineering and Saudi Makamin Oil and Gas Services for their effort in executing equipment, lab and field trials.

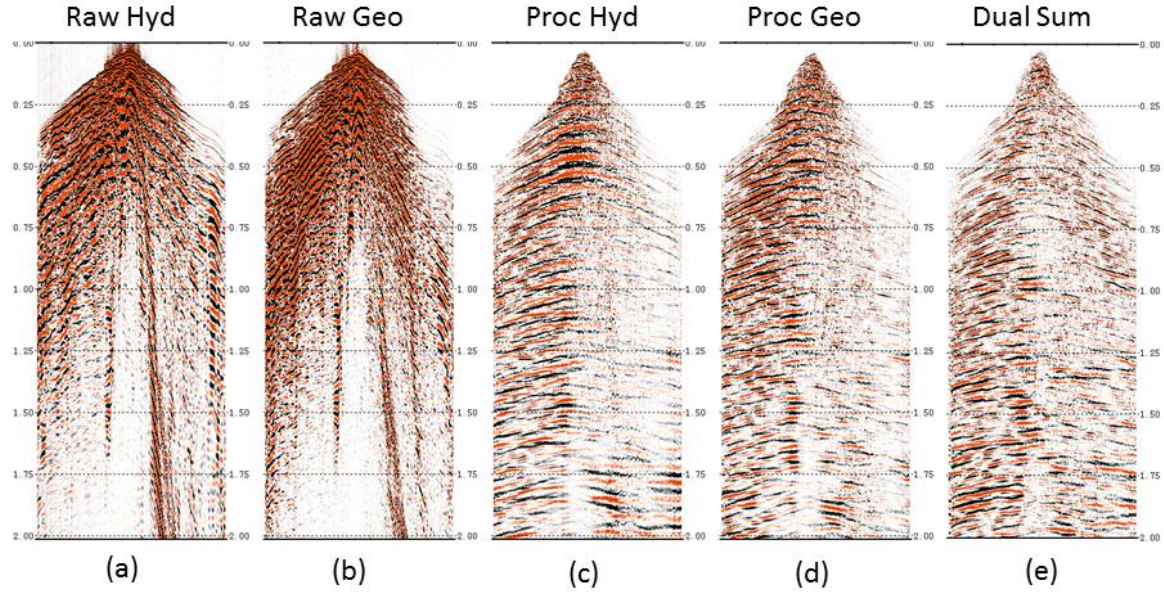

Figure 5. Walk-away data processing example for one day of collection applied to sensor A (deployed in sand below the water table). Raw hydrophone and geophone records (a and b) are input to noise removal (c and d) and then summed (e). Repeatability and signal-to-noise ratio analysis are run on the dual sensor summation output (e).

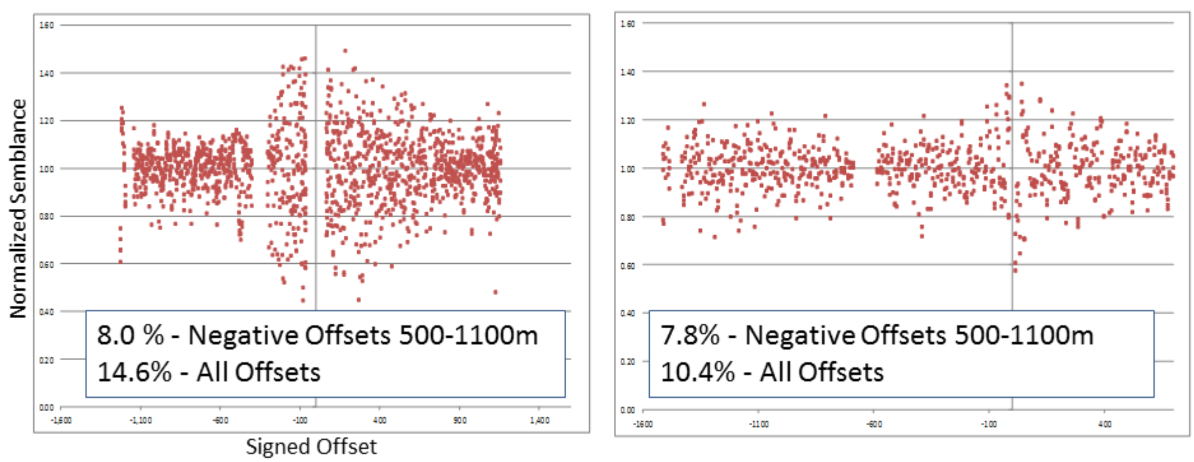

Figure 7. Pre-stack time lapse semblance versus source to receiver offset for walk away geometry. Sensor A (left) is compared to sensor B (right). Horizontal scale is signed offset and vertical scale is normalized semblance. Repeatability metrics for two offset ranges are annotated. For offsets less than 500m semblance values increase substantially, possibly indicating presence of time lapse residual noise after ground roll arrivals. Within an optimum offset range of 500-1100m repeatability is similar between both sensors.

DOI http://dx.doi.org/10.1190/segam2013-1020.1

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EDITED REFERENCES

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