Processing and repeatability of 4D buried receiver data in a desert environment

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Summary

We present results from a first of its kind permanent seismic monitoring system in a desert environment. This new system consists of sensors buried at 70 m depth and surface vibroseis sources. We describe processing challenges associated with this single-sensor and single-source dataset and present initial solutions that allowed us to obtain robust 3D reservoir images. The system has achieved a remarkable repeatability with mean NRMS of 4-5 % across high fold area between closely spaced repeat surveys.

Introduction

Monitoring onshore fields in a desert environment represents an extreme geophysical challenge. Surface 4D seismic is generally too noisy, whereas fully buried source-receiver systems are generally only successful for shallow targets and benign near surface (Berron et al., 2015). We have installed a new type of hybrid 4D system using deeply buried receivers and surface vibroseis sources (Bakulin et al. 2012, 2013, 2015). Here we describe initial processing results as well as short-term repeatability observations from several monitor surveys.

Permanent monitoring system

The layout of the permanent 3D installation is shown in Figure 1. Over 1000 receivers are permanently installed at a depth of about 70 m occupying a roughly circular patch shown in black (Figure 1). The source locations cover a larger circular patch shown in pink (Figure 1) giving relatively good azimuthal and offset coverage. Receiver holes are positioned on a 50 by 50 m grid, whereas sources are on a 10 by 10 m grid. Single vibrators are used in flip-flop mode to acquire the data resulting in a single-source and single-buried sensor high-fold data.

Pre-stack data

Figures 2a and 3a show typical shot gathers recorded on vertical geophones. While no surface waves are expected to reach the receiver depth, we observe plenty of arrivals with low apparent velocities. These likely represent shear waves, their multiples and trapped modes associated with highly contrasting near-surface layers. On this single-sensor data we observe some reflections at larger offsets (Figure 3a) whereas they are hard to see at smaller offsets. This suggests that near-surface complexity with karsts and high-contrast vertical and lateral velocity variations leads to extreme elastic scattering.

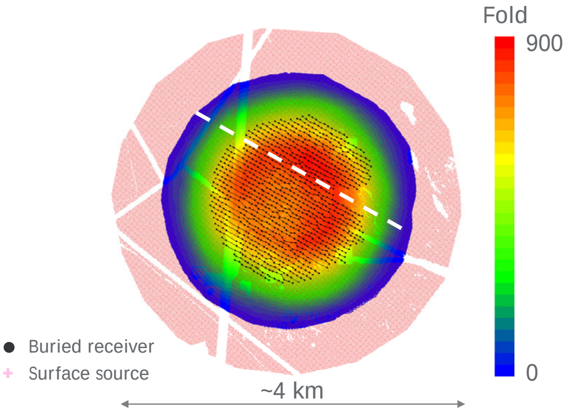


Figure 1. Source/receiver geometry of permanent buried-receiver (black dots) installation and associated fold obtained using surface vibroseis sources (pink dots).

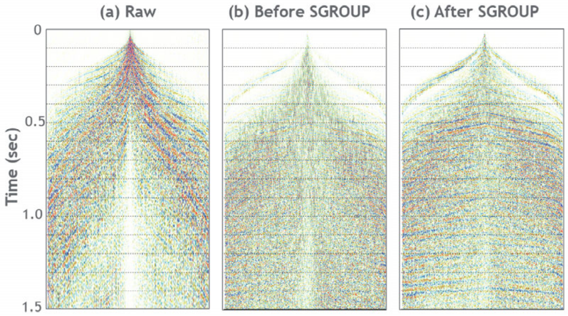


Figure 2. Near-offset (<1km) pre-stack common-shot gather and associated repeatability before (a), after processing without (b) and with supergrouping (c).

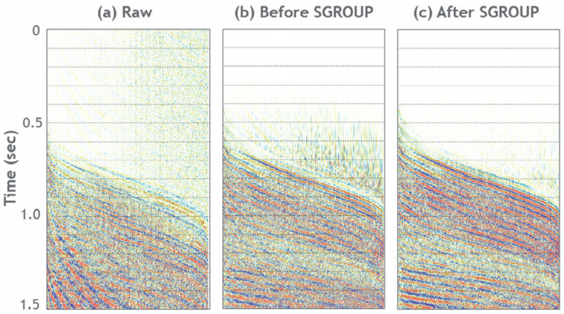


Figure 3. Same as Figure 2 for a far-offset shot (>1.2 km).

Buried receiver processing

We process the data as surface seismic capitalizing on the dense source carpet to remove all shear-wave related and unwanted arrivals. Figures 2c and 3c show the same shot gathers after processing before stack. Clearly processing did an excellent job in cleaning up the noise and revealing reflections. Refraction and residual statics helped to line up the reflections. Localized noise removal cleaned up noise with low apparent velocities. Surface-consistent scaling corrected for variable coupling of source and receivers. Figures 2b and 3b show gathers after all single-sensor processing steps. One can see that while reflection energy is more evident, it remains relatively weak. To enhance the data we performed supergrouping of the single-sensor data (Neklyudov et al., 2015) and chose to do it at the end of the processing sequence so that individual scalars and statics can be evaluated before summation. We summed 7x7 shot groups after NMO to ensure that higher frequencies are not attenuated. Clearly, supergrouping helped to boost signal-to-noise ratio by stacking reflection energy while further knocking down coherent and random noise (Figure 2c and 3c). This suggests that source strength and character still remain important considerations for data acquired in such an extreme scattering near surface extending dozens and perhaps hundreds of meters deep. This may explain unsuccessful trials with weak piezoelectric sources buried in a desert environment (Berron et al., 2012). A CDP stacked image along one of the lines of the 3D volume is shown in Figure 6a. Clearly the target horizon is well imaged. Discontinuous events in the shallow part suggest additional overburden and/or near-surface imaging issues that need to be addressed.

Field efforts to achieve and monitor repeatability

One of the main acquisition requirements was to repeat source geometry to within 0.75 m for 90% of the data for monitor surveys. To achieve it, we have designed acquisition in such a way that vibrators follow the same source path in each repeat survey. This target was exceeded during actual field acquisition with mean value of source geometry repeatability between surveys around 0.35 m with 97% of the vibration points repeated with an accuracy of better than 0.75 m. Since reporting on a direct relationship between repeatability of stacked data and pre-stack direct arrivals (Bakulin et al., 2015), we used the latter for in-field real-time quality control (Figure 4). This served multiple goals: identify bad receivers, detect acquisition issues and allowed immediate assessment of repeatability between surveys to take correction action if needed.

Pre-stack repeatability

A 4D compliant processing sequence was adapted for land data. Certain steps required application of multi-survey processing. For instance, surface-consistent scaling allowed for different shot and receiver scalars for each survey aiming to simultaneously balance data within each survey as well as between surveys. This is necessary to correct for variable shot/receiver scalars over calendar time. We observed that variation in receiver scalars is small compared to shot scalars as would be expected for this configuration.

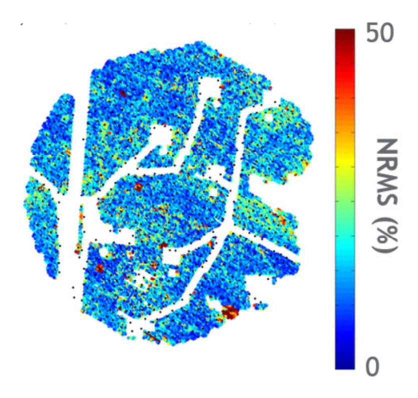


Figure 4. NRMS of early arrivals between two surveys. Areas of high NRMS identify problematic receivers or acquisition issues.

First, let us examine pre-stack repeatability of the buried receiver data. Figure 5 shows that field acquisition efforts in repositioning the source paid off quite well. Raw pre-stack data have reasonable repeatability outside of a near-offset noise cone. Pre-stack 4D processing improves the repeatability and leads to much better NRMS especially at medium and longer offsets.

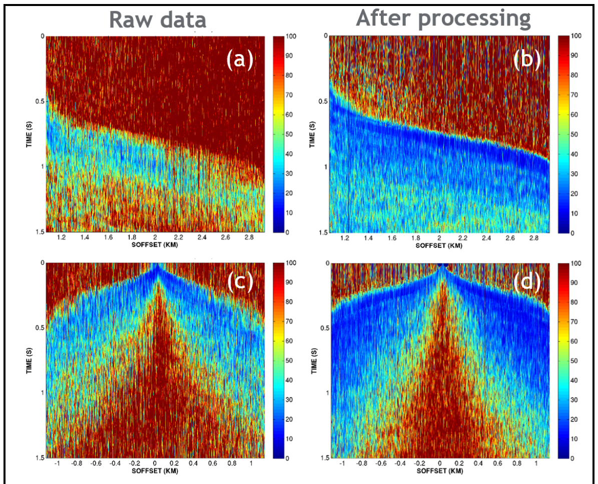


Figure 5. Repeatability (NRMS) of same long and short-offset gathers as on Figure 1 and 2 for raw data (a,c) and after processing and before stack (b,d).

Stack repeatability

Figure 6a shows one line through the 3D volume oriented as shown in Figure 1. Since the data repeats wiggle for wiggle both in the reservoir zone as well as outside, we show only preliminary time-lapse difference magnified by a factor of five (Figure 6b). There is a very small amount of coherent residuals in the overburden suggesting that multi-survey processing can be further optimized. However, the reservoir zone is repeated very well. No reservoir signal is expected between these two baseline surveys and the time-lapse image confirms that. To quantify repeatability, we evaluate NRMS in a 50 ms window following a picked target horizon. Figure 7 shows a histogram of the resulting NRMS distribution over the entire imaged area with single-sensor processing prior to supergrouping. Likewise Figure 8 shows the same charts but for data with shot supergrouping applied prior to stacking. We observe that supergrouping has approximately halved all the NRMS estimates. Since lower NRMS is tightly related to better signal-to-noise ratio, we first conclude that arrays can deliver additional suppression of coherent and random noise that is not included in a simple single-sensor imaging process. Second, we clearly see significant impact of the fold when comparing NRMS of the entire imaged area (that includes lower-fold areas) with that of only high-fold area (>325). In particular, NRMS standard deviation is greatly reduced by about a factor of three in the high fold area. Finally, we highlight that achieving a 4 to 5 % NRMS using an onshore seismic monitoring system with surface vibrators is a remarkable achievement, particularly in an area with a complex near surface. Receiver decimation tests may shed additional light on possible dependencies between repeatability and fold. It is clear that high-density source acquisition such as the one presented here may be a required price to pay for achieving single-digit NRMS in desert environments.

Each step of the processing sequence was assessed based on its impact on image quality and repeatability. Histograms of repeatability and event continuity were used to evaluate processing effects and select processing steps that generally improve both image quality and repeatability. We have used NRMS between two consecutive traces in inline and crossline direction as a simple measure of image quality and continuity. We have called it NRMSc. We observed good spatial correlation between NRMS (derived from a pair of surveys) and NRMSc (derived from a single survey). This gave us the ability to predict/anticipate trouble spots with higher NRMS based on zones with increased NRMSc. Many of them are associated with areas of unresolved imaging challenges related to shallow or deeper overburden or lower acquisition fold.

Figure 9 shows the progression of mean NRMS (measured on the histograms as shown in Figure 7 and 8) through the main steps of the processing flow. Steps that lead to deterioration of

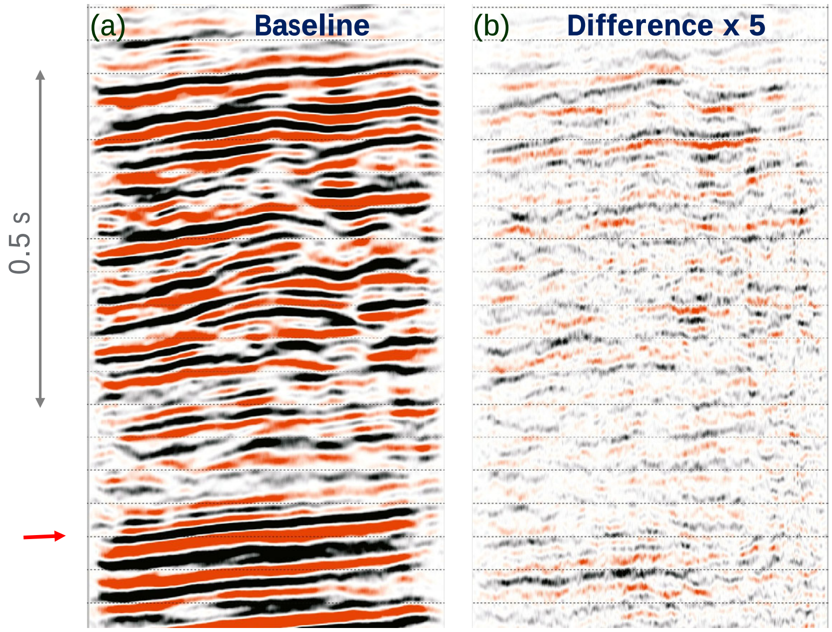
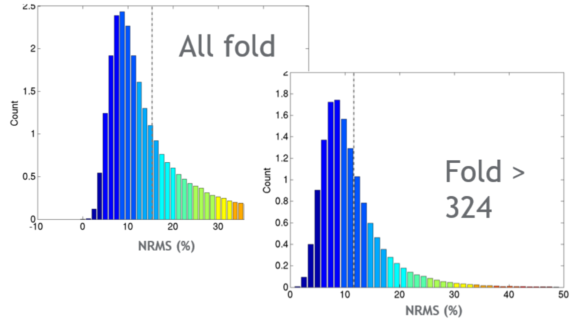
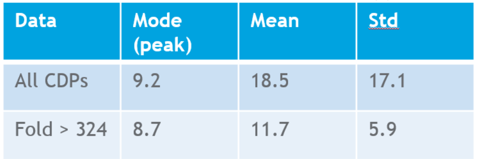


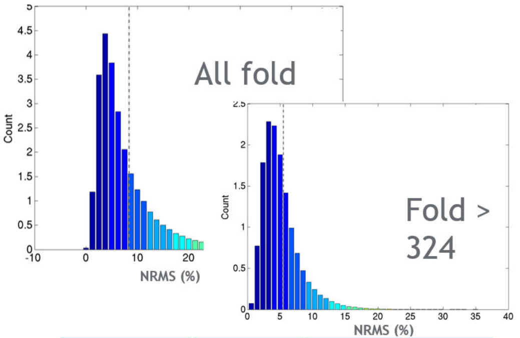
Figure 6. CDP stack of the first survey (a) and time-lapse difference (b) after one month. Location of the line in 3D volume is shown on the Figure 1.

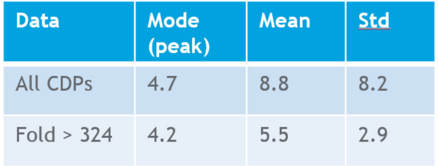




Data	Mode (peak)	Mean	Std
All CDPs	9.2	18.5	17.1
Fold > 324	8.7	11.7	5.9

Figure 7. Stack NRMS between two repeat surveys measured along 50-ms window around target horizon without application of supergrouping.





Data	Mode (peak)	Mean	Std
All CDPs	4.7	8.8	8.2
Fold > 324	4.2	5.5	2.9

Figure 8. Same as Figure 8 but with application of supergrouping.

repeatability were scrutinized and often dropped. Observe the particularly strong reduction of NRMS during denoising and supergrouping which is expected for single-sensor data land data acquired over areas with very complex near surface.

Conclusions

We have presented data from an onshore buried receiver system in a desert environment. Despite deep placement of the receivers around 70 m, single-sensor data remains challenging for imaging due to many shear-related and trapped modes recorded on the vertical geophones. Dense carpet shooting with a single vibroseis source allows us to overcome single-sensor processing challenges by effectively applying noise attenuation in the common receiver domain and obtain reliable images. An important role is played by supergrouping after NMO. Several repeat surveys have been acquired allowing us to evaluate the repeatability of the buried-sensor surface-source system. Tight tolerance on source repositioning and repeating the acquisition path has led to quite repeatable pre-stack data as measured using early arrivals. A simultaneous multi-survey land processing sequence ensures that repeatability improves through the processing sequence and culminates in stacked volumes with a mean NRMS of around 5 % for the window of interest. Frequent surveys may provide additional opportunities to discriminate between seasonal variations and actual 4D signal. Buried receiver data also provides opportunities for virtual source redatuming that may additionally improve imaging and repeatability (Alexandrov et al., 2015).

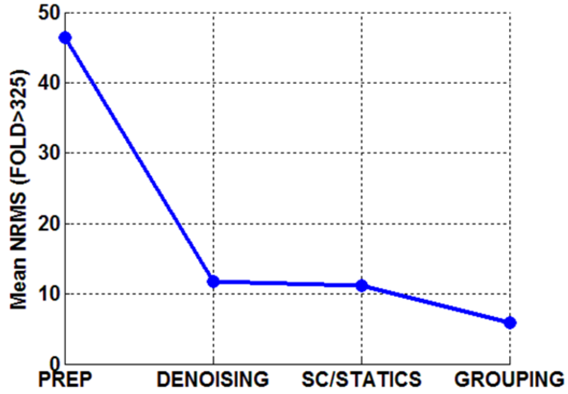


Figure 9. Progression of stack repeatability (mean value measured over high-fold areas) throughout the processing sequences: noise removal, multi-survey surface consistent processing and residual statics, and supergrouping.

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EDITED REFERENCES

Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2016 SEG Technical Program Expanded Abstracts have been copyedited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Alexandrov, D., A. Bakulin, J. van der Neut, and B. Kashtan, 2015, Correcting for non-repeatable source signatures in 4D seismic with buried receivers: Virtual source case study from Saudi Arabia: 86th Annual International Meeting, SEG, Expanded Abstracts, 5343–5347, http://dx.doi.org/10.1190/segam2015-5890959.1.

Bakulin, A., R. Burnstad, M. Jervis, and P. Kelamis, 2012, Evaluating permanent seismic monitoring with shallow buried sensors in a desert environment: 82nd Annual International Meeting, SEG, Expanded Abstracts, http://dx.doi.org/10.1190/segam2012-0951.1.

Bakulin, A., M. Jervis, R. Burnstad, and R. Smith, 2013, Making seismic monitoring work in a desert environment with complex near surface: 83rd Annual International Meeting, SEG, Expanded Abstracts, 4900–4904, http://dx.doi.org/10.1190/segam2013-0886.1.

Bakulin, A., R. Smith, M. Jervis, and R. Burnstad, 2015, Use of early arrivals for 4D analysis and processing of buried receiver data on land: 85th Annual International Meeting, SEG, Expanded Abstracts, 5493–5497, http://dx.doi.org/10.1190/segam2015-5749603.1.

Berron, C., E. Forgues, A. Bakulin, M. Jervis, and R. Burnstad, 2012, Effects of complex near surface on 4D acquisition with buried source and receiver: 82nd Annual International Meeting, SEG, Expanded Abstracts, http://dx.doi.org/10.1190/segam2012-0937.1.

Berron, C., L. Michou, B. De Cacqueray, F. Duret, J. Cotton, and E. Forgues, 2015, Permanent, continuous and unmanned 4D seismic monitoring: Peace River case study: 85th Annual International Meeting, SEG, Expanded Abstracts, 5419–5423, http://dx.doi.org/10.1190/segam2015-5813292.1.

Neklyudov, D., A. Bakulin, M. Dmitriev, and P. Golikov, 2015, Enhancement 3D broadband land seismic data with smart super groups for processing and FWI: 77th Annual International Conference and Exhibition, EAGE, P7 06.