Use of early arrivals for 4D analysis and processing of buried receiver data on land

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Summary

For 4D acquisition with buried receivers we propose a simple and robust 4D binning scheme based on direct early arrivals. With buried receivers, the near-field downgoing energy can be recorded. Shots with poorly repeatable early arrivals are rejected to exclude gathers with the most unrepeatable reflections. The method has been applied to a field 4D dataset from Saudi Arabia with 11 repeat vintages. We confirm that both image quality and repeatability can be improved.

Introduction

For marine acquisition, seismic repeatability is often tied to reproducing geometry of the shots and/or receivers (Calvert, 2005). On land, there are other significant sources of non-repeatability (in addition to geometry) that are not present in marine environments (Jervis et al., 2012). In this study, we focus on buried receiver acquisition with surface vibroseis sources (Bakulin et al., 2012). While there are some geometry errors associated with repositioning surface vibrators, the tolerances are much smaller than in marine surveys (typically around 1-2 m). Attempts to see if geometry-based rejection may improve repeatability were not very successful. It turns out that the benefit of data rejection was quickly outweighed by reduction in fold, leading to deteriorating signal to noise ratio (SNR) and thus repeatability. Nevertheless, other factors related to variable source coupling and near-surface variations still remain significant sources of non-repeatability on land data despite well repeated shot geometry. Unlike acquisition geometry, these factors are hard to quantify based on simple metrics as generally they require assessment of the pre-stack traces, which have notoriously poor SNR in the Arabian Peninsula. For buried receiver data we have the luxury to record the downgoing arrivals that are used to illuminate the reservoir. The correlation between repeatability of these early arrivals and deep reflection data were reported in a previous study (Bakulin et al., 2014). Here we make use of this relationship and design a rejection scheme based purely on the pre-stack direct arrival NRMS and demonstrate that it can improve repeatability of the imaged reflection data.

Field data

To demonstrate the concept we use 11 repeat 2D surveys acquired over the course of 19 months. Each survey consists of a dense carpet of nine source lines (7.5 m x 7.5 m inline and crossline sampling) recorded into 80 buried geophones at 30 m depth. The first six surveys (1 to 6) were collected within year one over a three month period. Then, after a 17-month break, an additional five surveys (7 to 11) were acquired in year two over the period of a week.

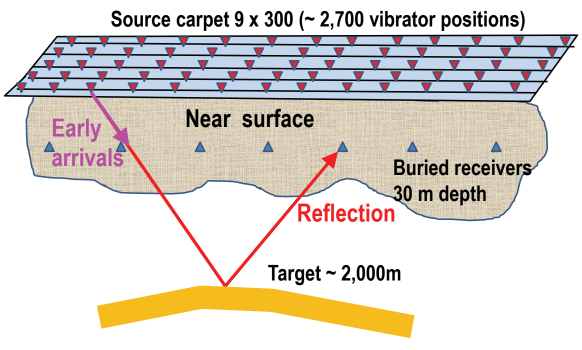

Figure 1. Acquisition geometry used for repeatability tests.

Early arrivals

In a previous study (Bakulin et al., 2014) we have shown a clear correlation between average repeatability of early arrivals and repeatability of stack reflection data. Here we intend to make a next step and utilize this relationship in the pre-stack domain. Figure 2 shows the normalized root-mean square (NRMS) differences between early arrivals from near-zero-offset traces of two pairs of surveys. NRMS is computed for each shot using early arrivals from a single trace recorded by the nearest receiver (0-30 m offset). One can see that early arrivals are well reproduced between surveys 1 and 2, whereas they are less repeatable between 1 and 5.

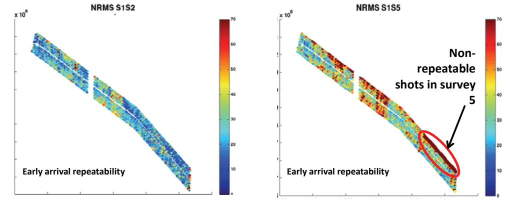

Figure 2. NRMS of near-zero-offset traces from each shot between: (a) surveys 1 and 2, (b) surveys 1 and 5.

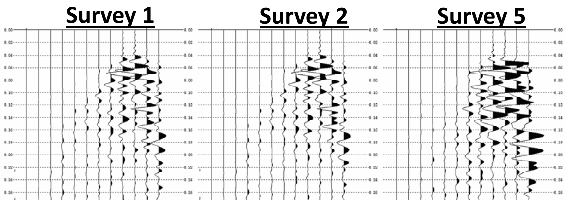

Figure 3. Early arrivals for single shot from three surveys (highlighted area in Figure 2). Note similarity between 1 and 2 and differences with survey 5.

It is clear that there is significant shot-to-shot variability: some groups of shots repeat well, whereas others look clearly different. Picking a shot from an area of high

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NRMS, we can see significant differences manifested in direct arrivals from survey 5 at this location (Figure 3). The exact nature of these differences is not always clear and may be due to variable source coupling, vibrator or near surface changes. Studying them is beyond the scope of this study and is discussed elsewhere (Jervis et al., 2012). Our goal is to design a simple 4D binning scheme that rejects shots with poor repeatability to improve overall repeatability. This rejection is based on simple physical consideration of wave propagation: the early direct arrival represents mostly downgoing P-wave energy that will illuminate the reservoir and give rise to reflected events (Figure 1). We deliberately focus on very small offsets (0-30 m) representing small propagation angles (0-45 deg. for receivers at 30 m depth) that are used for reflection imaging and therefore try to exclude horizontally propagating refracted or surface-wave arrivals. If this direct arrival is significantly non-repeatable for whatever reason, then a different wavefield illuminates the reservoir and reflected signals would also be altered. By rejecting traces with significantly different early arrivals, we expect to exclude non-repeatable pre-stack signals and thus improve the repeatability of the seismic image. While this sounds plausible, it is difficult to verify this concept directly using pre-stack gathers because of their poor SNR. Typical pre-stack common-receiver gathers from the area (Figure 4) show nice and clean direct arrivals, but little sign of reflections despite dense shot sampling (7.5 m). While reflections can be uncovered after heavy noise removal, this process is invariably multi-trace and as such spreads a lot of noise around, thus making it very challenging to estimate repeatability of the pre-stack reflections at the level of accuracy achievable with direct early arrivals that require no pre-processing. Nevertheless, we can evaluate the concept by processing binned and unbinned data to a final stack and evaluate the impact on the overall post-stack repeatability. We evaluate the proposed 4D binning scheme using this criteria below.

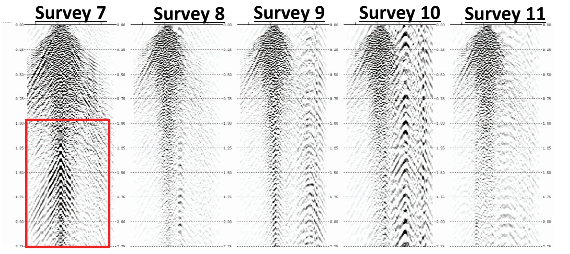

Figure 4. Example of pre-stack shot gathers from a fixed location. Red box shows linear events attacked by additional noise removal.

4D binning scheme based on early arrivals

Guided by this simple logic, we design a simple 4D binning scheme based on multiple surveys (Figure 5). Here we use only a single trace with the smallest offset for each shot. Again the logic here is that if one of the near-vertically propagating direct arrivals has changed for this particular shot, it likely means that the vibrator coupling or near surface has changed at this location and other traces from that same shot are similarly affected. First, NRMS values for all pairs of surveys are computed forming a matrix. Then, the mean NRMS for each survey is calculated by averaging along the rows of the matrix. Shots with NRMS above a certain threshold are rejected, but only from the anomalous survey. In a land multi-survey case it makes sense to reject shots only from an anomalous survey, while leaving it in the other surveys. In an ideal case, one might reject a shot from all surveys, thus keeping a fixed acquisition geometry across all vintages. For noisy land data with many vintages we did not find such an approach productive, as we may lose fold and degrade repeatability.

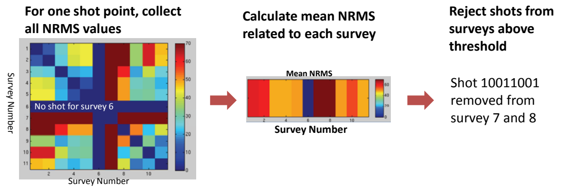

Figure 5. Shot rejection method with threshold of 70% NRMS.

Additional linear noise on second year surveys

Surveys from the second year have a large number of shots affected by deep linear noise appearing at later times (Figure 4). Such noise is not present during the first year and it appears associated with one of the vibrators used. It often overlaps with the target reservoir. If we were to attempt rejecting affected shots (30 to 40%), the reduction in fold outweighs the benefit of binning. Therefore an additional linear noise removal step (LFK) was applied only to surveys 7 to 11 to specifically target this noise for year two data. We shall analyze repeatability with and without this additional noise removal step.

Repeatability of binned data

One way to evaluate the repeatability of multiple vintages is to examine so called return curves relating NRMS to survey interval (Bakulin et al. 2014). They describe repeatability between all pairs of surveys displayed as a function of acquisition or survey return time. It has been observed that repeatability in a desert environment seems to progressively degrade with increasing survey interval time, from days to months to years (Figure 6). Here we use a window around the reservoir to evaluate NRMS since there was no production; hence no changes are expected during the study period. A very prominent NRMS jump occurred between the surveys in year 1 and year 2. Nevertheless, we analyze all 11 surveys at once to maintain a consistent multi-survey approach.

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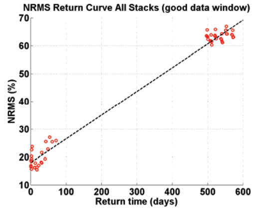

Figure 6. Return curve for all 11 surveys. Observe big jump between year 1 and year 2 as well as increase over time.

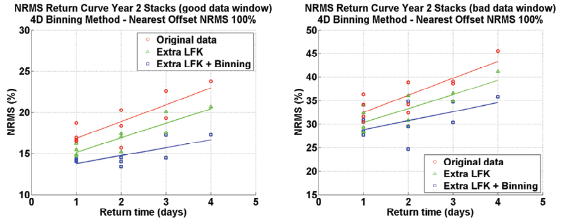

Figure 7. Return curve for surveys 7 to 11 before and after binning and additional linear noise removal filter (LFK) for window in a good (a) and bad (b) data area shown in Figure 10.

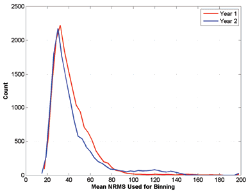

Figure 8. Mean NRMS distribution for year one and year two surveys. While generally the second year has a sharper peak, it also has a significant volume of outliers (NRMS>80%).

NRMS computed from pre-stack data is much higher than for stacked sections. If we utilize a threshold of 100% NRMS for shot rejection based on early arrivals, we observe an improvement in post-stack repeatability for surveys 7 to 11 both in good and bad data areas (Figure 7). We observe almost no improvement on the year 1 surveys (not shown). If we review percentages of rejected shot records (Table 1), we observe that surveys 7-11 experience average rejection of 5% of the data, whereas for year 1 we have rejected less than 1%. Shot records from year 1 (surveys 1 to 6) have low ambient noise and no issues with additional linear noise described above. There is a general gradual trend of increasing NRMS with time for the early arrivals as well as stacked NRMS (Figure 6), but those cannot be rectified by shot rejection. Surveys from year 2 (surveys 7 to 11) have linear noise issues and much higher ambient noise. This is supported by comparing the distribution of NRMS used for binning shown in Figure 8. While the main peak appears sharper for second year surveys (which seems to be reflected in lower stack NRMS between year 2 surveys), we observe significantly larger tail (NRMS > 80%). We conclude that 4D binning using early arrivals seems most effective to deal with the outliers or the tail of the distribution.

How much data to reject and what threshold to use?

An important practical question is how much data one can reject or, alternatively, what NRMS threshold to use. Before analyzing binning effects, note that additional linear noise removal did help to improve repeatability of all surveys from year 2 (Figure 9). As for the binning effects, when too little data is rejected (for mean NRMS > 150%), then repeatability is only affected to a small degree. Nevertheless, it is worth mentioning that rejecting just 60 to 80 (0.2%) of the worst shots may improve NRMS by about 1%. At the other extreme, when too much data is rejected (mean NRMS < 50%), then the drop in the fold outweighs the benefit of rejecting less repeatable data, thus reducing overall stack repeatability. For year 2 data (surveys 7 to 11), it is between 60 and 140% NRMS where we observe a sweet spot with repeatability improving by about 2%. In terms of data rejection, this window represents a range between 0 and 25% of the total number of gathers. In contrast, data from year 1 (surveys 1 to 6, Figure 10) seems fairly repeatable so that 4D binning has almost no impact. Indeed, for year 1 there is a rather small tail on Figure 8 so that any binning with NRMS higher than 80% results in

	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	s11
# Shots removed	11	2	13	2	143	13	109	113	172	205	137
Approx. % removed	0.4	0.1	0.5	0.1	5.2	0.5	3.8	4.0	6.1	7.3	4.9

Table 1. Statistics of shots rejected and approximate percentage of data removed from each survey for a threshold of 100% NRMS.

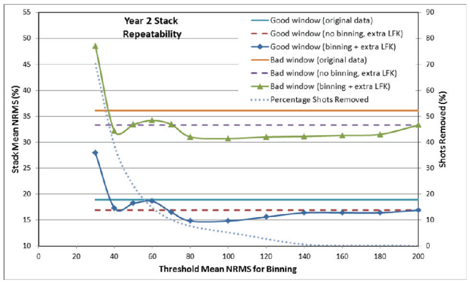

Figure 9. Average stack repeatability for surveys 7 to 11 (year 2) as a function of rejection threshold based on NRMS of early arrivals.

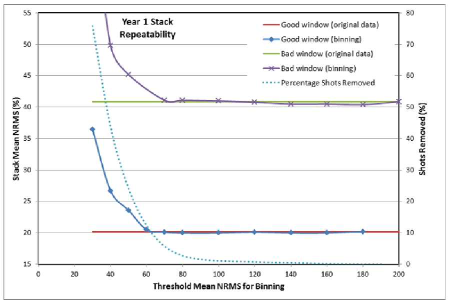

Figure 10. Same as Figure 8 but for surveys 1 to 6 (year 1).

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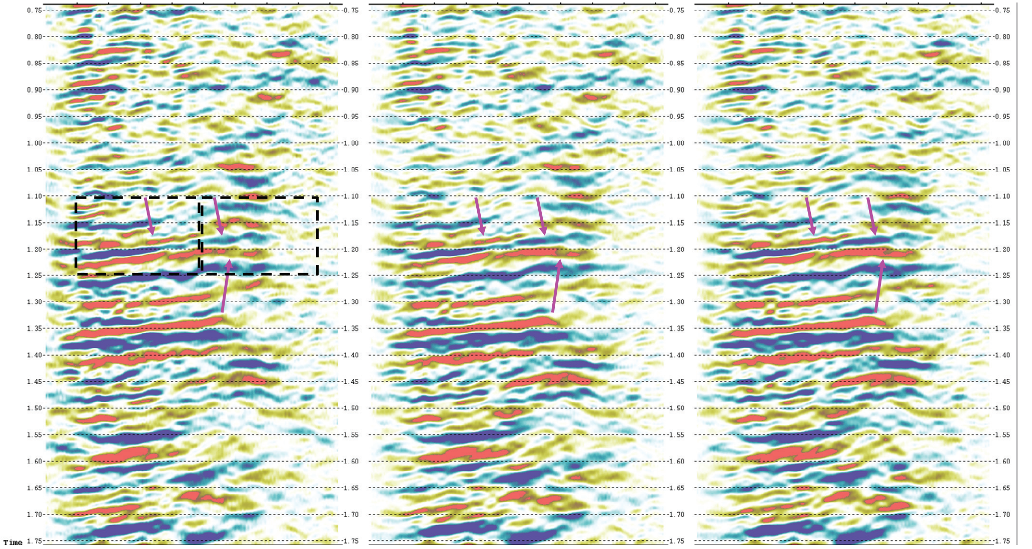

Figure 11. Effect of 4D binning and additional linear noise removal on the image quality for survey 9 (year 2). Left panel shows the stack with no 4D binning or filtering, the middle panel shows the stack with no binning but LFK noise filtering and the right panel shows the stack after binning and LFK noise filtering. The dashed boxes in the left panel represent the windows used for the good data area (left box) and bad data (right box).

very small data rejection rate (Figure 10). Rejecting data from inside the main lobe of the distribution (Figure 8, 20-80% NRMS) seems to have little or no effect, while at 60% cut-off (8% data rejected) repeatability starts to degrade due to reduced fold. 4D binning alone is unable to fix the fundamental repeatability problem existing between surveys from year 1 to year 2, manifested in consistently changed character and spectra of early arrivals and reflections (see Figure 6). This problem is likely associated with near-surface changes and as such requires a more fundamental solution that can correct for these changed source signatures, such as virtual source redatuming with multidimensional deconvolution (Alexandrov et al., 2015). Finally, we examine the effect of 4D binning and additional noise removal on the image (Figure 11). We observe improved definition and continuity of the target reflections, thus validating that 4D binning improves both image quality and repeatability.

Discussion and conclusions

We have proposed a simple multi-vintage 4D binning procedure tested on 11 onshore surveys acquired over the course of two years. Despite the use of receivers buried at 30 m depth, this land data from Saudi Arabia is quite noisy and represents a challenge for imaging and monitoring. Since shot geometry was repeated with less than 1 to 2 m of accuracy, we have not been able to identify any binning strategies based on pure geometry that is successful in improving repeatability as is normally done for marine data. Instead, we focused on identifying and rejecting shots with high ambient noise and different source signatures. Such shots were identified based on early arrivals recorded by buried receivers at small propagation angles not exceeding 30 degrees. These early arrivals represent a very stable part of the records with good signal-to-noise ratio. Inspection and analysis of early arrivals requires no signal processing. This is in contrast to the analysis of reflections, that is generally very difficult on pre-stack gathers and often requires considerable pre-processing to reveal the underlying signal. When early arrivals show significant changes over time, either from near-surface changes or from additive noise, it implies that the reservoir is illuminated by a different or contaminated wavefield and as a consequence the target reflections would also be altered. In a previous study we reported a clear correlation between repeatability measurements using pre-stack early arrivals and those using post-stack reflections. In this study we used the repeatability of early arrivals as a 4D binning criterion. For data from surveys in year 2 with ambient noise and vibrator issues, we have observed that rejection of up to 25% of the most non-repeatable data may improve stack NRMS by about 2%. Such a gain is important for noisy land data where 4D signal is expected to be small. For less noisy surveys from year 1 (surveys 1 to 6), 4D binning shows benefit and the stack becomes less repeatable after rejecting more than 8% of the data. For more noisy year 2 surveys, 4D binning shows improvement in repeatability using an upper limit of 60% pre-stack NRMS with most repeatability improvement when the noisiest gathers are rejected representing the upper tail of the NRMS distribution that may represent up to 25% of the data for noisy surveys. These thresholds give us important insights on allowable amount of skips and rejections for different types of data quality.

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EDITED REFERENCES

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