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.
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 non-repeatable pre-stack signals and thus improve the repeatability. This rejection is based on simple physical considerations.

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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.
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 have a lower percentage of shots rejected than the year 1 surveys. 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.

![Figure 6. Return curve for all 11 surveys. Observe big jump between year 1 and year 2 as well as increase over time.](image)

![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.](image)

![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.

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

![Figure 10. Same as Figure 8 but for surveys 1 to 6 (year 1).](image)

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


