Seismic-while-drilling with a pilot signal from a downhole memory-based vibration sensor

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Summary

When a drillbit is used as a source, processing seismic-while-drilling (SWD) data requires a recorded pilot signal as the source signature. We present initial results from a field trial where a memory-based near-bit vibration sensor is used together with a more conventional top-drive sensor. Drift in downhole clock time is resolved by a novel automated time-alignment procedure using the GPS-synchronized top-drive sensor as a reference. The downhole sensor records a pilot of better fidelity in shallow sections of the well subject to intense vibrational noise and deep sections drilled with polycrystalline diamond compact (PDC) bits. We demonstrate that better quality seismic data is achieved using a downhole pilot compared to a more traditional surface pilot from the top-drive sensor.

Introduction

A common practice in seismic-while-drilling (SWD) with drillbit as a source is to correlate seismic data with a pilot signal representing source signature (Poletto and Miranda, 2004). This allows compressing the signal and transforming continuous recordings to conventional impulse-like seismograms similar to what is done in the vibroseis technique. A conventional approach to obtaining the pilot is to record it at the top of the drillstring by an accelerometer mounted on a top drive of a drilling rig. This provides an acceptable estimation of the source signature, although affected by the drillstring filtering effects and contaminated by various abundant noises of surface origin. An alternative approach is to record the pilot signal near the bit by downhole vibrational sensors. Previous studies show that such recordings can provide a more accurate and stable representation of the pilot signal, leading to increasing the data's signal level (Poletto and Miranda, 2004; Naville et al., 2004; Poletto et al., 2014; Poletto et al., 2020). Fast telemetry can transfer the data to the surface or synchronize the downhole clock with the surface seismic time. However, it remains costly and not readily available. An alternative, more cost-effective solution is to use memory-based vibration tools. In this case, the main issue is the downhole clock's accuracy, which often experiences a significant drift exceeding the precision required for seismic applications.

Recently, SWD data were acquired during pilot testing of a prototype DrillCAM system at one of the onshore wells down to the depth of 10,000 ft (Bakulin et al., 2020). The system comprises wireless surface receivers accompanied by top-drive and downhole vibration sensors. The results obtained using the top-drive accelerometer show good quality data in the middle sections of the well and reduced signal-to-noise ratio for shallow and deep sections. In this work, we present the initial processing results obtained using the near-bit pilot signal that could address these issues.

Downhole time correction

The downhole sensor used in this study is a three-component accelerometer recording radial, axial, and tangential vibrations with a sampling rate of 1,500 Hz. The sensor's dynamic characteristics satisfies main SWD requirements as outlined by Poletto and Miranda (2004). In addition to this high-frequency data, the sensor records downhole revolutions per minute (RPM), temperature and low-amplitude vibrations with a lower sampling rate. Battery capacity allows recording the data continuously for around 100 hours. Combining several sensors in a bottomhole assembly (BHA) sub and initializing some of them with delays, provides ability to record continuous near-bit data even longer. Data can be downloaded either after each drilling run or after several runs for ease of operations, providing that the battery has been replaced. In total, seven drilling runs were recorded, providing continuous data from 590 ft to 10,419 ft with some unplanned pauses in the deeper sections.

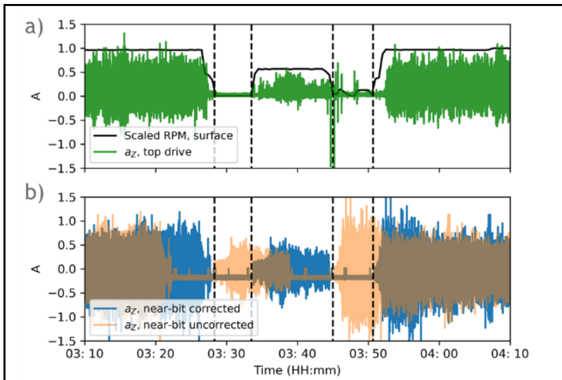

Figure 1. Top-drive accelerometer shows accurate alignment with RPM data from the electronic drilling recorder at the surface (a). Near-bit data (b) before time correction (orange line) is delayed by about 6 minutes. After time correction, the near-bit data (blue line) matches perfectly the top-drive recordings.

The comparison of raw downhole data with surface drilling parameter such as RPM shows a significant inaccuracy of time caused by initial time delay and subsequent drift of the clock. The observed drift values reach 30-40 minutes over some of the drilling runs. A typical interpretation-based correction applied by drillers uses time alignment of downhole and surface RPM data and achieves an accuracy of several seconds. It is not sufficient for SWD applications, which demand an accuracy of a few milliseconds. To reach the required precision, we use a GPS-synchronized sensor mounted on a top-drive as a reference for correlation. Figure 1a shows the top-drive accelerometer's vibrations and scaled surface RPM. Observe a good match of nondrilling intervals characterized by a low-level of vibrations and near-zero RPM values. The near-bit data have a delay of about six minutes, as shown in Figure 1b. An automated data-driven time correction algorithm (Egorov et al., 2020) has been applied to this data providing a perfect match with the top-drive recordings. The correction is done in two steps. During the first step, an energy-based misfit between the top-drive and the downhole pilots is minimized to find optimal time-delay and value of a linear drift. That provides an alignment accuracy of several seconds. An additional time-variant correlation-based correction is applied, similar to Naville et al. (2004), to reach the required few milliseconds precision.

Pilot signals comparison

Figure 2 shows a comparison of the downhole and top-drive pilot signals recorded in the shallow part within depth interval from 1,157 ft to 1,575 ft after time alignment. The continuous data are spliced into 30 s long seismic traces. Root-mean-squared (RMS) amplitudes of each trace show the vibrations' energy distribution recorded by both pilots. The low-energy amplitudes correspond to pauses in drilling, as shown by comparing the drilling indicator from the surface electronic drilling recorder. Observe a generally good match of alternation between the drilling and non-drilling intervals in both pilots. Simultaneously, the downhole recordings show more stable energy distribution within drilling intervals, as can be seen by less variable RMS curves and more uniform amplitudes within the traces. That might be attributed to a strong rig's vibrations at the surface when drilling shallow sections, which manifested as additional noise in the top-drive pilot. In contrast, the downhole tool records the vibrations right near the bit and provides more consistent data. The pilots' amplitude spectrums confirm this observation (Figure 3). The top-drive signal has strong variability of the spectrum with several peak frequencies over the entire seismic frequency range. In contrast, the downhole pilot shows more stable behavior with a steady decrease of amplitudes from 15 Hz to 80 Hz.

A standard practice to evaluate the pilot signal's quality is to analyze its autocorrelations (Poletto and Miranda, 2004). Figure 4 shows pilot autocorrelations after stacking along 30 ft depth intervals and pilot deconvolution following a standard processing practice (Poletto et al., 2014). The

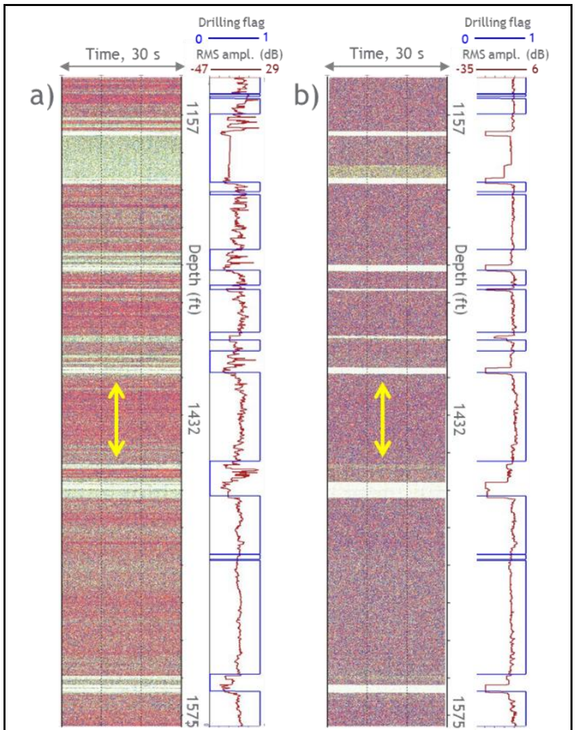

Figure 2. A comparison of the top-drive (a) and downhole (b) pilot signals at a shallow depth. Each horizontal line is a 30-s-long trace. A similar amplitude normalization with respect to a maximum value for all traces within a gather is applied. The blue curve is an indicator from a rig recorder equal to 1 during drilling periods. The red curve shows RMS amplitudes per trace vs. depth. As can be seen, low amplitudes correspond to nondrilling intervals. Note the more stable distribution of energy in the downhole pilot within drilling intervals. Yellow arrows show windows used for spectra calculation in Figure 3 and seismic gathers shown in Figure 6.

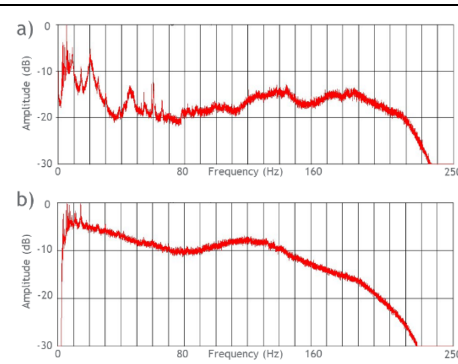

Figure 3. Average power spectra of the top-drive (a) and downhole (b) pilot signals during drilling interval marked by arrows in Figure 2. Note more uniform frequency content of downhole data with fewer peak frequencies. A low-frequency amplitude drop in the downhole data is caused by the filtering required for the time-alignment step.

strong dipping events are the long-period multiples propagating along the drillstring and bouncing between its ends. These multiples allow assessing the overall signal-to-noise ratio of the recorded pilot signals. The signal level is strong in both pilots in the middle sections between 2,000 ft and 6,200 ft. In the shallow part, above 2,000 ft, the top-drive pilot is dominated by a strong noise level similar to Figure 2. The multiple events visible in the downhole pilot are more coherent and can be tracked up to the shallowest recorded depth of 590 ft. In the deeper part below 6,200 ft, the top-drive pilot does not reveal any signal. These sections were drilled with a 16" polycrystalline diamond compact (PDC) bit, showing a known challenge of the SWD technique with such kind of bits. In contrast, the downhole pilot autocorrelations contain coherent multiple events for PDC bit between 6,200 and 7,300 ft. The weaker but still coherent signal is visible at deeper depths between 7,800 and 8,500 ft. This demonstrated that the downhole vibration sensor successfully provides the pilot signal of better quality and a higher signal-to-noise ratio.

Seismic data

As discussed in Bakulin et al. (2020), the seismic data in the considered field trial were recorded with a 3D spread of wireless single-sensor geophones. A standard SWD processing technique (Poletto and Miranda, 2004) using both recorded pilots was applied to this data. That includes correlation of the geophone recordings with the pilot signals and stacking of the correlated data over a drilling interval corresponding to a single drill-pipe (30 ft). Stacked autocorrelated pilot traces were used to derive deconvolution operators for removing anticausal components in the correlated data. A cross-line stacking of several adjacent receiver lines was also applied to enhance single-sensor recordings' signal level. Figure 5 shows processed common-shot gathers recorded at a depth of 3,182 ft. Both pilots succeed in providing reasonable seismic data at this depth level. Direct arrivals are visible and match perfectly with synthetic traveltimes calculated using a legacy velocity model from nearby wells. Note that the result obtained using the top-drive data is still noisier, especially in the near offsets, as seen in the area preceding the direct wave. The data in the shallow part at a depth of 1,412 ft produced using the top-drive and downhole signals exhibit more significant differences (Figure 6). The top-drive pilot fails to provide reasonable seismic gather in this case. The downhole pilot, in contrast, gives good quality data with a coherent first-arrival event at near-offsets. For larger offsets, refracted arrivals are also clearly visible. This is in line with our previous observations from Figure 2 and Figure 4, where the two pilots were compared for this depth level. The top-drive recordings are noisier in the shallow part and hence fail to provide an accurate estimation of the drillbit source signature.

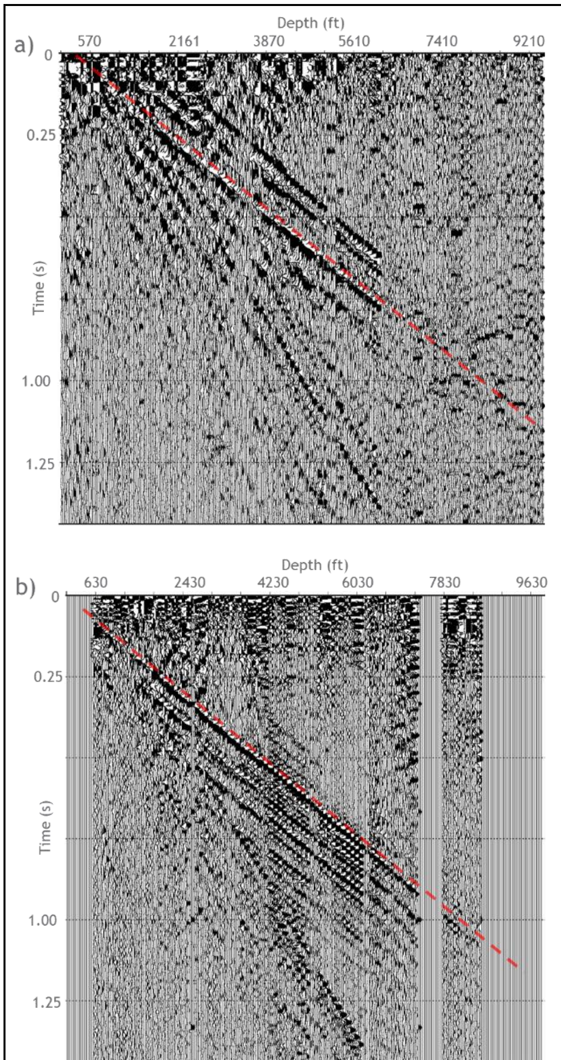

Figure 4. Autocorrelated top-drive (a) and downhole (b) pilots after stacking over 30 ft depth interval, pilot deconvolution, median filtering, and band-pass filtering. Each trace is normalized individually with respect to its maximum value. Note strong and coherent long-period drillstring multiples (right below red lines) in the shallow and deep parts, clearly visible in the downhole and not visible in the top-drive pilot.

Conclusions

We presented the first results from a field SWD trial when a memory-based near-bit vibration sensor was used to record a pilot signal for processing surface geophone data. One of the main challenges in using such a pilot is a substantial drift of the downhole clock. The accuracy required for seismic

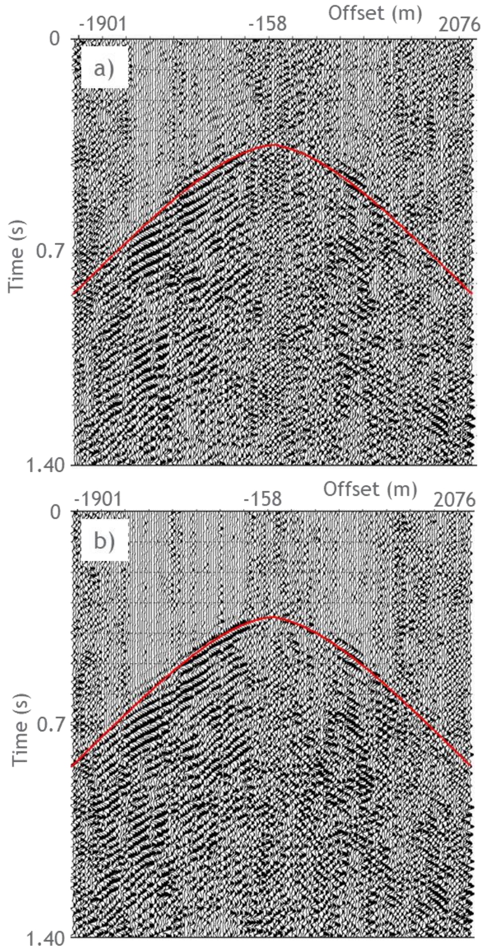

Figure 5. Common-shot gathers from SWD surface data after processing using a top-drive (a) and a downhole (b) vibration sensor. Drillbit is at 3,182 ft depth. The red line shows synthetic first-arrival traveltimes calculated using a legacy velocity model from nearby wells. Note the reasonable quality of data from both pilots. However, the top-drive-based result is noisier, especially at the near offsets.

data processing is several milliseconds or less. It is significantly more stringent than the requirements of more conventional applications of near-bit sensors such as analysis of drilling dysfunctions for drilling optimization. The automated data-driven alignment procedure has been successfully applied to this data using a GPS-synchronized top-drive vibration sensor as a reference. After the alignment, the downhole pilot shows more stable and less noisy behavior than the top-drive counterpart, especially in shallow sections. At deeper depths, where PDC bits were used, the near-bit sensor recorded long-period drillstring multiples that are completely invisible in the top-drive sensor. The near-bit pilot was successfully applied for

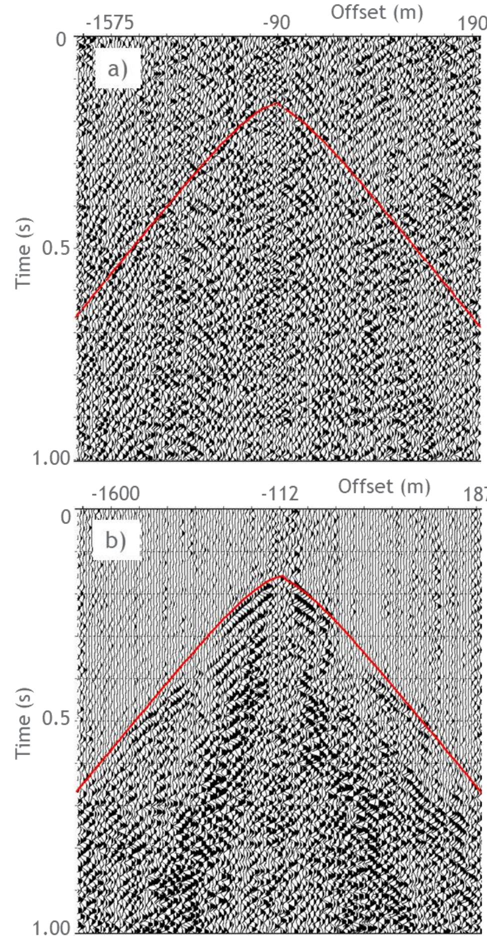

Figure 6. Same as Figure 5 but with the drillbit at 1,412 ft depth. Note how the downhole pilot provides data of reasonable quality in the shallow section, while data with the top-drive pilot is too noisy to see any signals.

correlation and deconvolution of surface geophone data. The seismic gathers confirm its more accurate recording of the drillbit source signature. This pilot provides high-quality data in the shallow part, which was not attainable using the top-drive pilot due to strong noise contamination. We conclude that such near-bit sensors can accurately record the drillbit source signature required to process SWD data.

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