Processing and analysis of seismic-while drilling data acquired with wireless geophones and instrumented top drive in the desert environment

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Summary

Advanced geophysical sensing while drilling is getting renewed interest due to accelerating trend to automate and optimize drilling as well as drive to better characterize complex near surface and overburden in a desert environment. We present processing and initial applications results from the first field trial of DrillCAM system on an onshore well in a desert environment. DrillCAM combines a set of geophysical techniques from seismic-while-drilling to imaging ahead and around the bit to drillstring vibration health monitoring to the estimation of formation properties at the bit. In this study, we focus on seismic-while-drilling applications. Using a top-drive sensor as a pilot, we successfully retrieve a checkshot-while-drilling, make a kinematic look-ahead prediction, and obtain a VSP corridor stack that ties with the surface seismic. Robust near-offset checkshot signals were obtained from both rollercone and PDC bits above 7,200 ft after limited pre-processing of challenging single-sensor data with supergrouping. The real-time capabilities of the system make the data available for continuous data processing and interpretation, which in turn facilitates drilling automation and improve real-time decision-making.

Introduction

With the increasing complexity of exploration targets and escalating accuracy requirements, seismic-while-drilling (SWD) is getting renewed interest (Poletto and Miranda, 2004; Naville et al., 2004; Al-Muhaidib et al., 2018). Specifically, in a desert environment, exploring for low-relief structures requires very accurate knowledge of near surface and overburden, not achievable with current borehole geophysics in the presence of multiple casing strings. Another impetus is drilling optimization demanding accurate information about drillbit positioning, formation properties around the bit, and vibration regime of the bottom-hole assembly (BHA). Also, traditional SWD applications such as real-time checkshot, imaging ahead of the bit, and well-seismic tie, always remain in demand, especially when no rig time is required to achieve them.

Bakulin et al. (2019a) described acquisition details of the field trial of the DrillCAM system with wireless geophones, instrumented top drive, and downhole near-bit tool. Here we focus on processing and analysis of SWD data and describe initial applications.

A field experiment on onshore well

Figure 1 shows the schematics of adaptable surface acquisition geometry with wireless geophones. Details of the top drive sensor and downhole tool are described by Bakulin et al. (2019a). Using a complete dataset of multiple continuous measurements from the surface down to 10,000 ft, we focus on processing and analysis of surface geophone and the top-drive sensor data for seismic-while-drilling applications of DrillCAM.

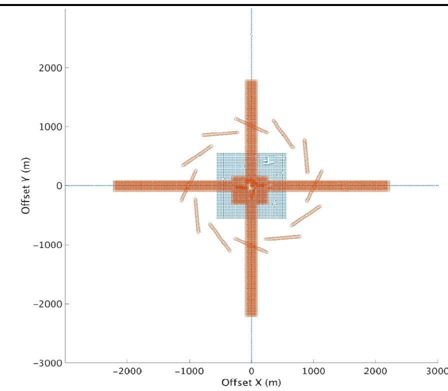

Figure 1. Wireless geophone layout of DrillCAM field trial showing adaptable acquisition geometry with aperture increasing with bit depth: blue dots show receiver positions used for drilling from the surface to 2600 ft, whereas red dots show the receiver pattern for deeper drilling below 2,600 fts.

Pre-processing of SWD data

Seismic gathers recorded during the drilling activity clearly shows the presence of strong seismic events. The main target signals of the SWD technique are direct arrivals and reflected waves induced by the drillbit and recorded at the surface. Since strong surface vibrations accompany the drilling process, the data are inevitably contaminated by the noise manifested as surface waves induced and radiated by the rig structure itself, pumps, mud shakers, engines, generators, etc. A high level of noise requires specialized techniques and workflows for processing and interpretation of SWD data.

The first step is a transformation of the continuous bit noise records to correlated impulsive data. To perform such transformation, conventional SWD makes use of a pilot signal similar to the vibroseis technique. The drillbit source signature is a priori unknown, random, and complex, and not readily extractable from the geophone data itself. In the current trial, we use the vertical component of a top-drive sensor as an estimate of the pilot signal. Autocorrelation and deconvolution of the top-drive traces and stacking over drilling one drill-pipe length (32 ft) provides evidence of vibrations propagating along the drillstring. Strong and reliable signals are seen down to 6,200 ft depth (Figure 2a). Above this depth, mostly rollercone bits were used with a single occurrence of polycrystalline diamond compact (PDC) bit marked in Figure 2. Below 6,200 ft, only PDC bits were utilized that seem to produce weaker vibrations of the drill-string column limited in propagation distance. Dipping events in Figure 2 correspond to multiples bouncing between the borehole assembly and the top drive. These multiple arrivals are typically used to estimate drill-string propagation velocity and time delays required to 'redatum' the pilot time from the top drive to the subsurface bit location. Using the actual BHA and drill pipe configurations, synthetic modeling of the extensional waves in the drill-string is performed for the top drive location (Figure 2b). We observe a good match between the real and synthetic data, verifying the reliable quality of the recorded pilot and overall functionality of the top-drive recording system.

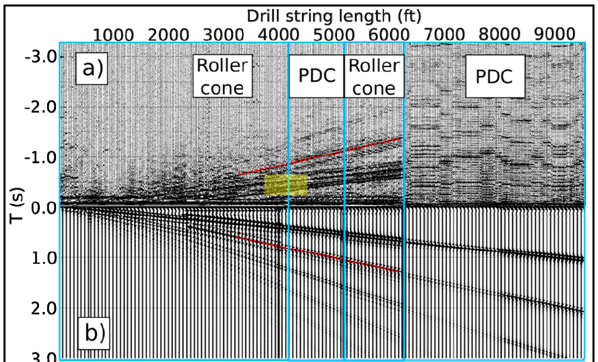

Figure 2. Top drive pilot traces after autocorrelation and deconvolution: (a) real data, (b) synthetic modeling of wave propagation in the drillstring using the actual BHA details.

Surface geophone data correlated and deconvolved with pilot trace (Poletto et al. 2001) can be further vertically stacked over 32 ft depth intervals to provide conventional common-shot seismograms with a source position corresponding to the current drillbit depth. These gathers contain noise typical for SWD surveys caused by rig noise itself or by drillbit vibrations propagating along the drill-string and inducing refracted and surface waves that propagate away from the rig acting as a conversion point. The dominant frequency of this noise is typically low compared to primary events, so high-pass filtering is useful for reducing it to some extent. Additional stacking of several receiver lines in the cross-line direction enhances the signal and provides common-shot seismograms (Figure 3) typical for SWD land surveys. Direct arrivals are clearly identified and can be used for velocity estimation between the bit location and the surface, while observed deeper reflections can be used for imaging purposes and look-ahead prediction. After resorting all common-shot gathers

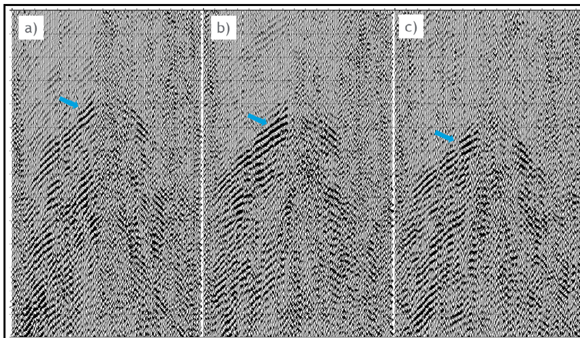

Figure 3. After stacking of several receiver lines and high-pass filtering, common-shot gathers after pre-processing show clear direct arrivals marked by arrows: (a) bit depth of 3,690 ft, (b) bit depth of 4,590 ft, (b) bit depth of 5,640 ft.

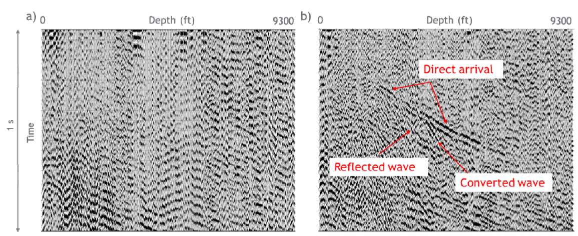

Figure 4. Single-sensor reverse VSP gather at an offset of 475m before (a) and after (b) pre-processing using supegrouping of 25 adjacent traces. Observe clear VSP direct arrivals on (b), but not on (a) due to intense scattered noise in the near surface.

into the common-receiver domain, we extract a reverse VSP gather shown in Figure 4a. We note the poor signal-to-noise ratio typical for single-sensor measurements in a desert environment with complex near surface that usually requires aggressive enhancement (Bakulin et al., 2019b). Future surveys may benefit from large receiver arrays of several tens of meters (Poletto and Miranda, 2004) typical for conventional SWD surveys, even in a more uncomplicated near-surface condition. The application of supergrouping (Bakulin et al., 2018) with a group size of 100 x 100 m provides dramatic signal enhancement uncovering a drillbit signal from the carpet of scattered noise. The final reverse VSP gather with the offset of 475 m from the well (Figure 4b) resembles conventional VSP gather and contains major seismic events such as direct wave, reflected, and converted arrivals.

Seismic-while-drilling applications

Since wireless geophones transmit seismic data from the entire sensor spread to a central recorder at the rig close to real time, automating land processing flow on a rig computer instantly delivers seismic gathers ready for various SWD applications. We illustrate and discuss several potential applications of the system using the recorded DrillCAM data. Some of the applications are intended to provide real-time information to improve drilling decisions making, while others allow obtaining additional valuable information for exploration, not available now.
Checkshot while drilling. As the first application of the SWD system, we describe retrieving a time-depth curve or a so-called checkshot while drilling. The conventional checkshot survey is performed by excitation at the surface and recording down the hole using seismic sensors clamped to the borehole wall. Wireline checkshot survey consumes rig time, requires well intervention, as well as mobilization of a VSP crew to the rig. Besides, such a survey is only available after drilling. With a checkshot obtained while drilling, a time-depth relation can be calibrated in real time, whereas the bit can be continuously tracked on the seismic image even in the presence of significant errors in the depth or time velocity model. Real-time checkshot helps to reduce pre-drilling depth uncertainty for key formations and enables a more accurate selection of casing points for drilling. Conventional VSP in cased holes often struggles to deliver reliable checkshot in the shallow sections of the well. From an exploration perspective, this prevents us from addressing substantial uncertainty associated with velocity variations in the complex near surface and shallow overburden typical to arid environments. The SWD checkshot can provide the required time-depth information along the whole depth interval starting from the surface, thus allowing to fill this gap in the overburden characterization.

After the pre-processing stage, we obtain reverse VSP gather at an offset of 475 m and pick first arrivals (Figure 5) following a conventional VSP analysis. The data quality allows us to obtain reliable picks in the depth interval of 1,830-7,290 ft. It is interesting to note that while intervals of 4,200-5,200 ft and 6,200-7,300 ft were drilled with PDC bits, they possess good data quality similar to other intervals drilled with rollercone bits. However, below 7,300 ft (PDC bits only) arrivals become hard to pick using conventional methods. Since no wireline VSP was available in the DrillCAM well, to validate the obtained checkshot, we construct a composite synthetic model using surveys from three nearby wells. Modeled VSP gather shows good correspondence with the real one in terms of direct arrivals (Figure 5a,b). The picked travel-times after verticalization (transforming picked times from offset to zero-offset measurements) show a good match with the synthetic traveltimes (Figure 5c). The variation is mainly due to the first-break jittering effect noted on the noisy field gathers. Validation confirms the ability of the DrillCAM to deliver a reliable time-depth curve along the extended depth interval similar to conventional VSP surveys. We note that the shallow time-depth information is not readily available from the considered reverse VSP gather due to its finite offset. Data with smaller offsets has more substantial contamination by rig noise requiring more advanced techniques and utilizing multiple neighboring receivers to address. We conclude that the presented example clearly illustrates the availability of reliable time-depth information in the SWD data recorded in real time and without consuming additional rig time.

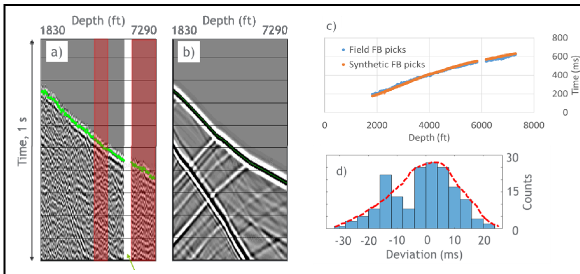

Figure 5. A comparison between real (a) and synthetic (b) reverse VSP gather at an offset of 475 m from the rig shows a good match between direct arrivals. The red rectangles denote sections drilled with PDC bits. Green dots show picked first-arrival traveltimes. After verticalization, traveltimes provide a time-depth curve matching composite model built using three nearby wells (c). The average deviation between the two curves is about 1-3 time samples (4-12 ms) (d).

Ahead of the bit prediction. While checkshot relies on direct arrivals only and allows the instant location of bit on seismic, a more advanced SWD application is to use reflected arrivals to look ahead of the bit, specifically to predict key upcoming formations. In flat geology, a typical drilling program relies on the estimated formation depths derived from adjacent wells or from seismic. In the presence of complex near surface, uncertainties in these estimations can reach hundreds of feet, adding additional risk and cost to the drilling operations. The SWD provides effective means to refine the estimate of the formation depths ahead of the bit. Besides, SWD accuracy improves with decreasing distance to the target, making it a perfect method to tackle uncertainty in overburden horizons.
To illustrate this process, we further process zero-offset synthetic and real finite-offset VSP datasets to enhance the upgoing reflections. Figure 6 shows both of them after two-way-time (TWT) flattening and median filtering that enhances upgoing waves. Reflection events associated with

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already drilled and ahead of the bit formations are clearly observable both in the field and synthetic data. The field gather after un-flattening is plotted in Figure 7. The marked reflector is an interface that is associated with an expected over-pressured zone known from offset wells in the area. Its accurate depth prediction is critical for mitigating drilling hazards and for the accurate setting of the casing point. The pre-drilling formation depth estimate was 10,047 ft. Using DrillCAM reverse VSP gather, we show how more precise look-ahead prediction can be achieved. Kinematic extrapolation of the reflector in time and depth is performed below the current drillbit depth location. Similar to this, the picked checkshot traveltime curve is extrapolated using the existing velocity trend from nearby wells. The intersection of these two lines provides an improved look-ahead estimation of 9,930 ft with some

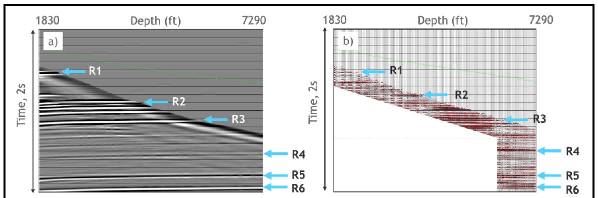

Figure 6. Zero-offset VSP synthetic (a) and DrillCAM reverse VSP gather (b) after enhancing upgoing reflections and two-way time flattening. Observe the excellent correlation between the key reflectors marked by arrows above and below the bit at a depth of 7,290 ft .

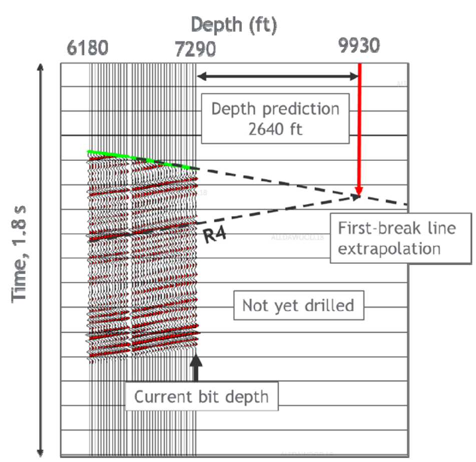

Figure 7. Look-ahead kinematic prediction. The un-flattened field gather from Figure 10 is kinematically extrapolated to predict the depth of key R4 reflector accurately. Depth is estimated at 2,640 ft ahead of bit or 9,930 ft total depth. This estimate compares well with post-drill formation top picked at 9,920 ft.

uncertainty caused by extrapolation and picking errors. The actual formation top was penetrated at 9,920 ft, confirming the accuracy of kinematic prediction when the bit was still 2,640 ft away from the formation. The prediction accuracy improves as the bit gets closer to the formation. Kinematic prediction illustrates the value and the potential of the SWD data for the accurate location of key formation tops ahead of the bit in real time.

Conclusions

We have conducted the first successful trial of DrillCAM at an onshore well delivering a complete dataset of multiple continuous measurements from the surface down to 10,000 ft. Three main acquisition components consisting of surface geophones, top drive sensors, and downhole accelerometers were integrated for the first time using both existing and novel elements. The use of wireless stations allowed sensor placement within the rig pad in areas crowded with equipment where cabled systems would not have been viable.

Using specialized land processing, including supergrouping, we successfully transformed the drillbit recordings into reliable seismic signals perfect for various SWD applications. We specifically demonstrated real-time while drilling checkshot and validated obtained results using nearby wells. We showcased successful look-ahead prediction using VPS reflections, significantly reducing pre-drill uncertainty. Finally, we have achieved good ties between the SWD corridor stack and surface seismic (not shown). Most processing steps can be easily automated, allowing continuous data processing and interpretation that will facilitate drilling automation and improve real-time decision-making. Future studies will focus on extending the checkshot curve to the shallower and deeper intervals using more advanced 3D processing and imaging ahead of the bit using extended multi-offset SWD VSP dataset.

A continuously recording 3C downhole accelerometer was successfully tested and delivered reliable data with sub-millisecond sampling. This data was utilized for estimating formation properties and identifying drilling dysfunctions that would be subject to future publications. Continuous recording of all data and completeness of the dataset (0-10,000 ft) makes it a perfect candidate for various analysis techniques based on Artificial Intelligence.

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