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DrillCAM Seismic System to Aid Geosteering and Drilling Optimization

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Abstract

As the number of new exploration and development wells continues to increase, guiding the bit while drilling in real time is becoming one of the most requested technologies. Seismic-while-drilling may enable accurate prediction of high-pressure zones, fractures and cavities, coring points, target depths, and geosteering in high-quality reservoir zones to optimize drilling decisions and reduce costs. A fully integrated real-time system to map and predict ahead of the bit and geosteer in high-quality reservoir zones is presented, showing application of seismic while drilling (SWD). We call this technology DrillCAM.

Recent enabling technological advances were made in wireless high-channel recording, signal enhancement and imaging algorithms, as well as high-performance computational resources that are easily deployable to the field. Such technological advances open a completely new set of possibilities for real-time drill bit guidance and navigation. One key enabler for DrillCAM is the use of wireless seismic receiver stations. Compared to conventional cabled geophones and cableless nodal systems, wireless receivers can provide real-time recording and transmission without the need for extra equipment for data retrieval, flexible receiver spacing and areal coverage. This, in turn, results in a flexible lightweight system for easy mobilization and ultralow power consumption for extended battery life.

We show a carefully designed field data acquisition experiment using the drill bit as a downhole seismic source and a large number of seismic receivers at the surface. The wireless receivers are arranged in flexible geometries that adapt to target bit depths. Using dedicated sensors, the bit signature (pilot signal) is recorded using high-frequency surface and downhole accelerometers. The system integrates surface seismic recordings and surface noise recordings with pilot signal recordings. The initial field experiment is conducted on a nearly vertical onshore well. This experiment demonstrates the feasibility of an integrated DrillCAM SWD system.

The paper presents the motivation, objectives, numerical studies, and first field test of a novel integrated real-time SWD system. Not only does such a system detect bit signals while drilling, it also validates these signals against other measured data and drilling activities.

Introduction

Seismic while drilling (SWD) technology encompasses techniques that record while drilling, maneuvers, or connecting drill pipes (Poletto and Miranda, 2004; Naville et al., 2004). Two main SWD technologies have been used in the industry; drill-bit SWD and vertical seismic profiling while drilling (VSP-WD). Drill-bit SWD records seismic signals generated by the drill bit using surface seismic receivers and VSP-WD records seismic signals generated by a surface seismic source using downhole receivers.

A key step of the drill-bit SWD approach is extracting the drill-bit vibrations signature (or pilot signal) from responses recorded on dedicated reference receivers at the top of the drilling string (near the swivel), in the stand pipe, near or on the top-drive motor, or other locations (Poletto et al., 2000). These dedicated receivers record the drill-bit pilot signal travelling through the drillstring. Ideally, the drill-bit pilot signal is best recorded downhole at the bit itself or right above it where recorded signals encounter minimal transmission effects. The ideal option limits real-time access to the recorded data downhole. A sequence of seismic traces is then generated by continuously correlating the pilot signal with data recorded by the surface receivers. After further data processing, conventional surface-based seismic imaging methods are applied to obtain an image of the subsurface structure around and ahead of the drill bit (Rector III and Marion, 1991; Hardage, 1992).

The VSP-WD approach uses wireline downhole receivers paired with a surface seismic source. Therefore, drilling operations must cease to acquire the data at each depth level, which, in turn, requires more rig time and therefore extra costs. Nevertheless, this requirement ensures recording a high signal-to-noise ratio (SNR) signal that is generated by an active strong surface source and recorded by downhole receivers. Several different types of telemetry systems are used to transmit the information from downhole receivers to the surface, such as wireline cables, mud pulse telemetry (Peng et al., 2013; Esmersoy et al., 2013), downhole memory (Mathiszik et al., 2011) and wired-pipe telemetry (Poletto et al., 2015).

Both drill-bit SWD and VSP-WD methods have been successfully applied to locate the drill-bit on surface seismic image data, predict overpressured zones ahead of the drill-bit, and convert time-to-depth in real time. Drill-bit SWD technology is not used widely today, due to the extensive use of polycrystalline diamond compact (PDC) bits that are quieter and, therefore, generate weaker seismic energy as compared to roller cone bits. VSP-WD technology uses an active strong surface source, but with the drawback of slowing drilling operations. Previous attempts to develop downhole sources achieved limited success. This is mainly due to the energy generated by downhole sources being trapped inside the borehole, which often manifests itself as tube waves, resulting in insufficient remaining energy to penetrate into the formation (Radtke et al., 2013). As a result of these shortfalls, imaging ahead and around the bit during drilling operations is not commonly used.

Recent advances in seismic sensing with high-channel count systems, signal enhancement and imaging algorithms, and proliferation of near-bit sensors continuously recording downhole vibrations while drilling, open a whole new set of possibilities for real-time drill-bit guidance and navigation. A key enabler is the use of cableless receivers, which can provide flexible receiver spacing and areal coverage, and real-time recording and transmission without the need for extra data retrieval equipment. In this paper, we present DrillCAM: a fully integrated SWD real-time system to image ahead and around the bit, and show examples using simulated data as well as an initial field experiment (Al-Muhaidib et al., 2018). The system consists of three main components including surface seismic sensors, top-drive and downhole vibration measurement sensors (Figure 1), which will be presented and discussed.

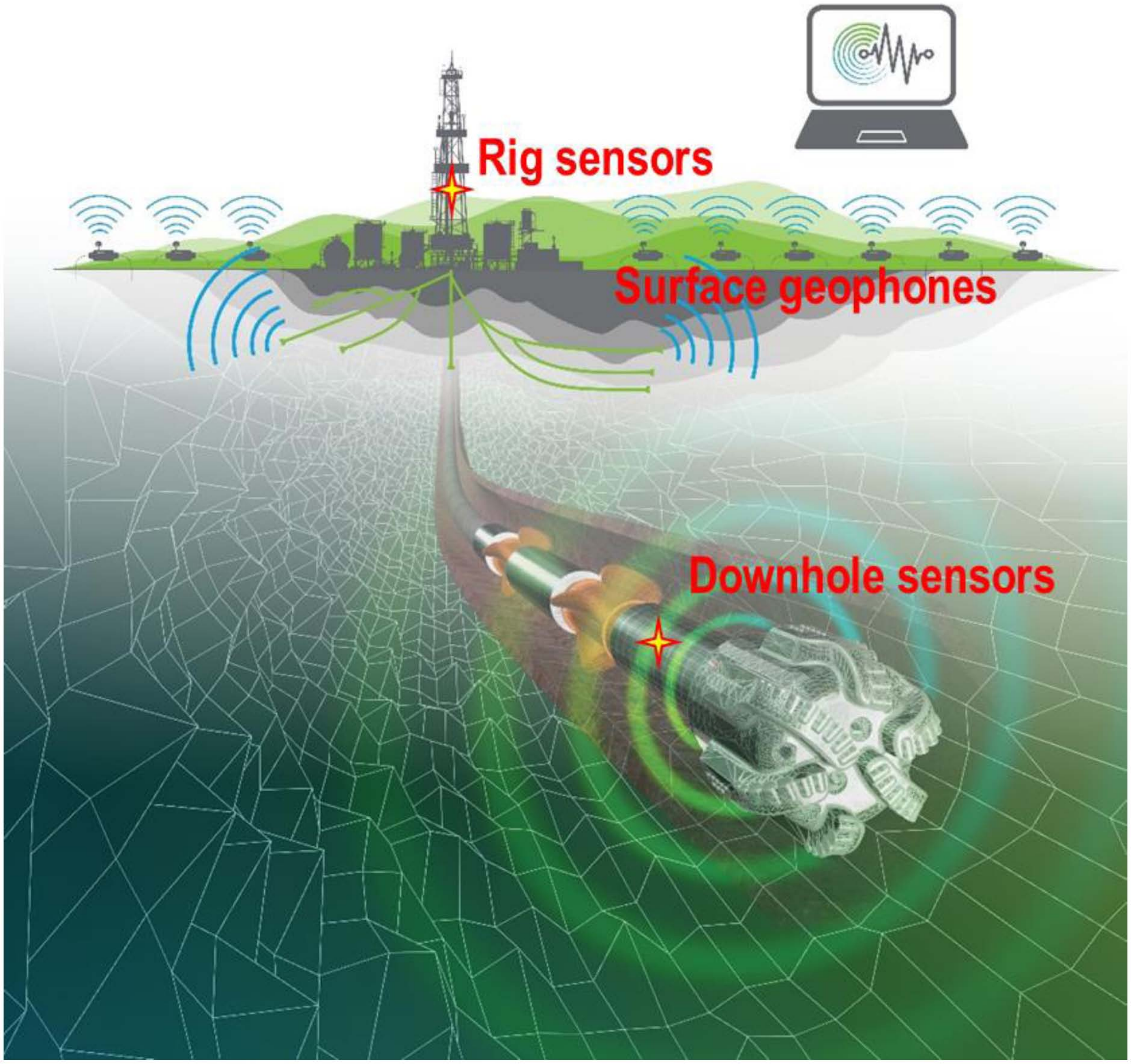

Figure 1—Cartoon illustrating the main components of DrillCAM integrated SWD system.

Motivation and Objectives

Motivation

Guiding the bit while drilling in real time is a key technology required to enable accurate prediction of high-pressure zones, cavities and fractures, casing and coring depths, and geosteering to enhance oil and gas recovery and optimize drilling decisions, which translates into reduced risk and cost reduction. Previous attempts were limited due to various factors including insufficient receiver density and aperture coverage (i.e., equipment limitations), lack of robust near-bit pilot recordings, and shortage of computational resources in the field, to deliver real-time images that are required for immediate decision making.

Making an analogy with self-driving cars, we observe that big advances were made due to significant improvements in real-time sensing capabilities. Likewise, to make serious advances in drilling optimization and automation, we need to upgrade real-time sensing capabilities while drilling. Seismic while drilling holds significant promise to deliver many such capabilities if we can harvest the new acquisition and processing technologies in an efficient DrillCAM system.

Objectives

In addition to the goal for DrillCAM to image ahead and around of the drill bit in real-time, it is also set to provide valuable information to explorationists and drillers. By getting closer to the target with the drill bit as a seismic source, a real-time system is expected to improve the accuracy of formation top identification by accurate locating the bit within seismic volumes. Better accuracy also would allow for better prediction of geologic boundaries, fractured or loss circulation zones ahead of the bit from a distance of 1,000 feet with reduced depth uncertainty from +/-200 feet to +/- 50 feet. Other possible predictions enabled by SWD are the prediction of properties ahead of the bit such as seismic velocities, which can be translated to pore pressure, geomechanical and fracture properties. Lower predicted velocities usually correspond to an increase in pore pressure or an increase in fracturing.

Other applications of SWD that are geared toward drilling operations are the real-time monitoring of drill-string health and vibrations (Figure 2) allowing for detection of the strongest vibrations and taking measures to prevent drill-string failures. Excessive vibration while drilling through harder rocks can increase risk of drillstring failure, which can lead to drilling delays, well side-tracking or well abandonment in extreme cases.

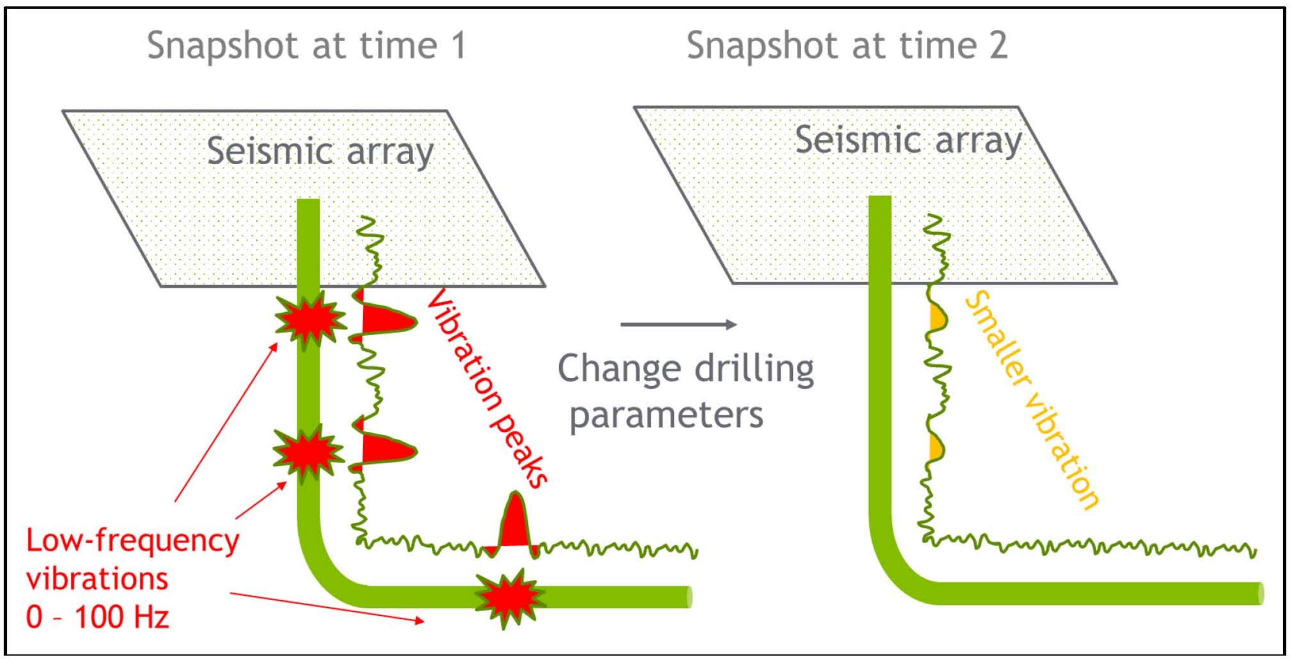

Figure 2—Vibration along the drillsting at two different time snapshots

Logging while drilling (LWD) is another area where SWD can contribute. For example, real-time generation of acoustic and pseudo logs from drillstring vibrations, real-time earth model updates and correlations with pre-drill seismic data where "on-the-fly" targeting decisions may be made for geosteering. Synthetic logs may be generated using only readily available drilling dynamics data including vibration data, rate-of-penetration, torque, weight-on-bit, etc. Another application that usually consumes a lot of the rig time after drilling is vertical seismic profiling (VSP), particularly multi-offset VSP. A real-time SWD system would allow for seismic velocity measurements and VSP imaging while drilling saving rig time during subsequent wireline operations.

Numerical Study

Numerical studies to optimize acquisition geometries for the field tests are addressed in this section. Validation and optimization of acquisition geometries to locate the drill bit on seismic and perform imaging around and ahead of the drill bit is one of the key factors of the DrillCAM technology. 3D numerical simulation tests using the drill bit as a downhole source and dense surface receivers show good imaging results ahead of the bit and around the well (Figure 3 and Figure 4). In addition to specialized seismic data acquisition design, new imaging algorithms ought to be developed to process and image the data efficiently in real time.

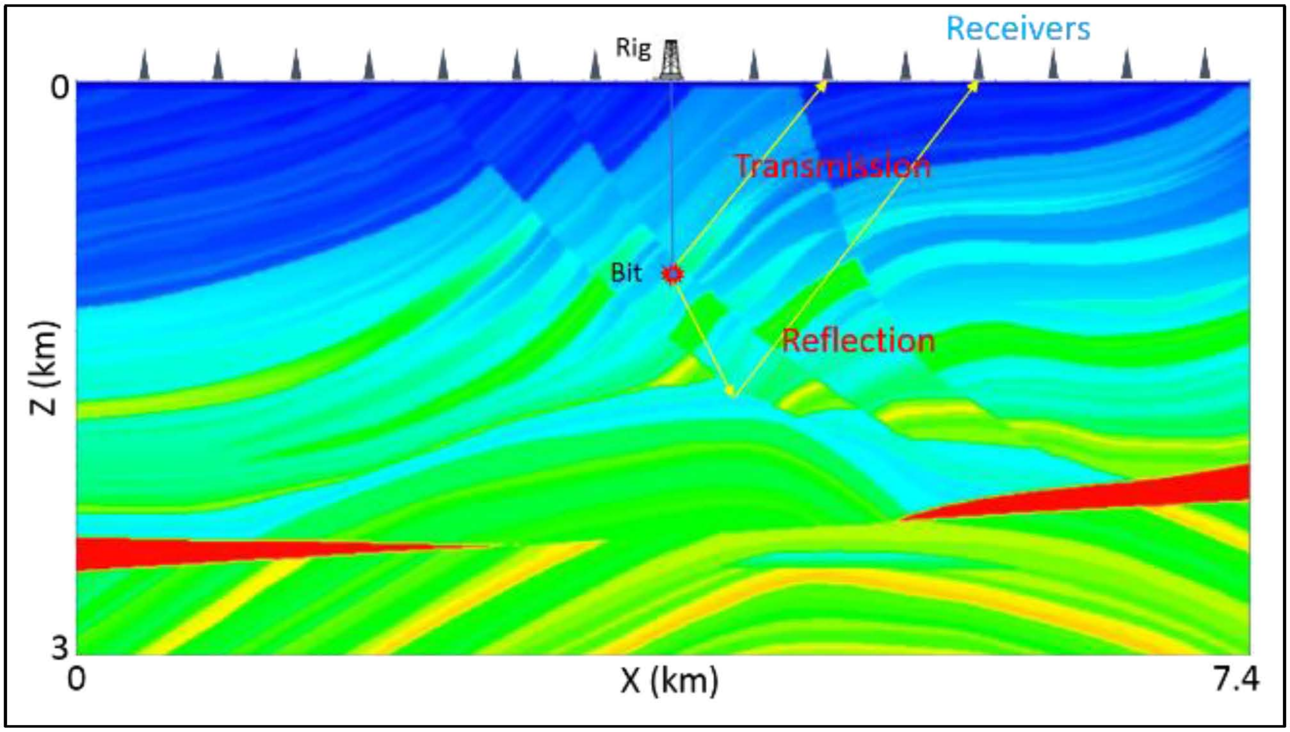

Figure 3—Marmousi synthetic model with complex geology used to validate imaging ahead of the bit, illustrating transmitted and reflected waves generated by the drill bit and recorded by surface receivers.

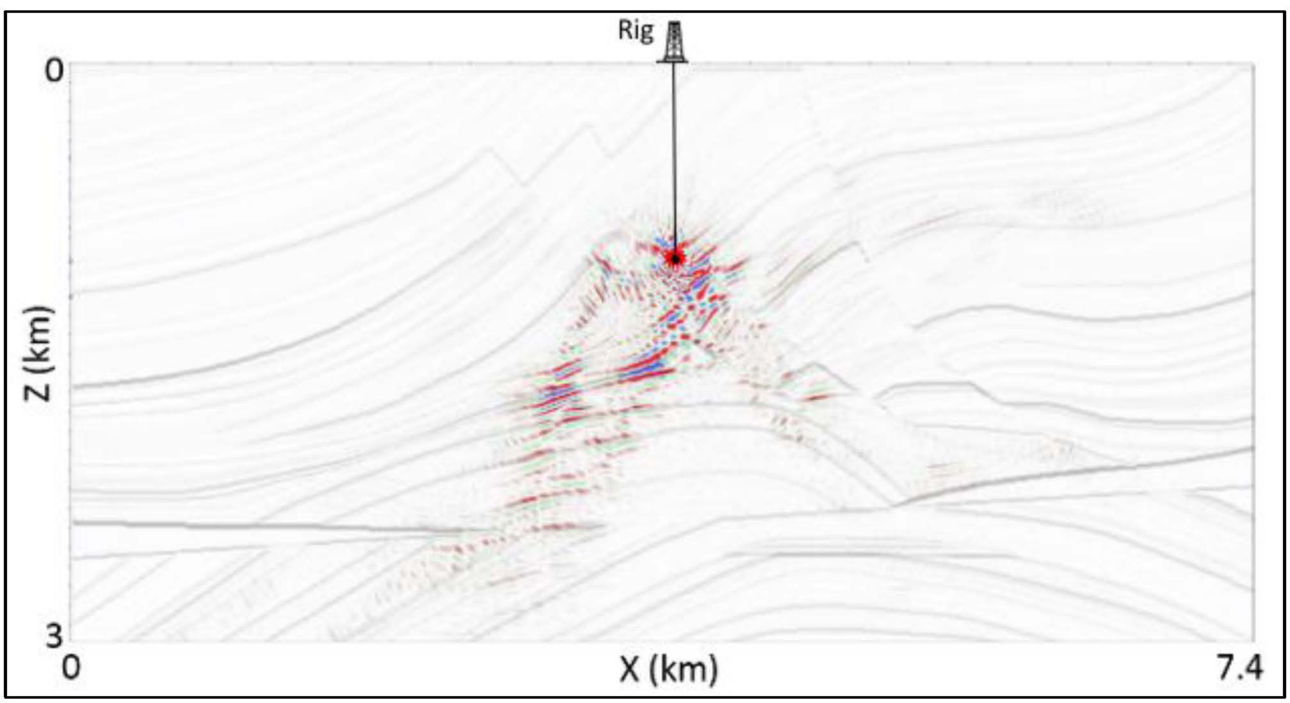

Figure 4—Numerical results of imaging ahead of the bit overlaid on the true reflectivity model.

Adequate design of adaptive seismic acquisition geometries is key for effective and efficient SWD recording as the source location is continuously changing. Numerical studies of imaging the location of the bit using different receiver network apertures (e.g., 500 m and 2000 m) and sampling intervals (e.g., 100 m and 400 m) are shown in (Figure 5). These results indicate that the receiver aperture is more important than the spatial sampling intervals for a fixed source depth. As the source depth continues to increase, a wider aperture receiver is required to record the seismic energy arriving at far offsets. In the meanwhile, receiver spatial sampling still plays an important role in focusing the image and sampling the noise more adequately.

Therefore, to optimize cost and efficiency while recording well sampled and focused data, an adaptive acquisition geometry is proposed where receiver layouts change as the drill-bit depth continues to increase, providing optimal angle coverage and resolution at all times. This approach is operationally feasible with the recent advances in real-time cableless and lightweight seismic recording systems.

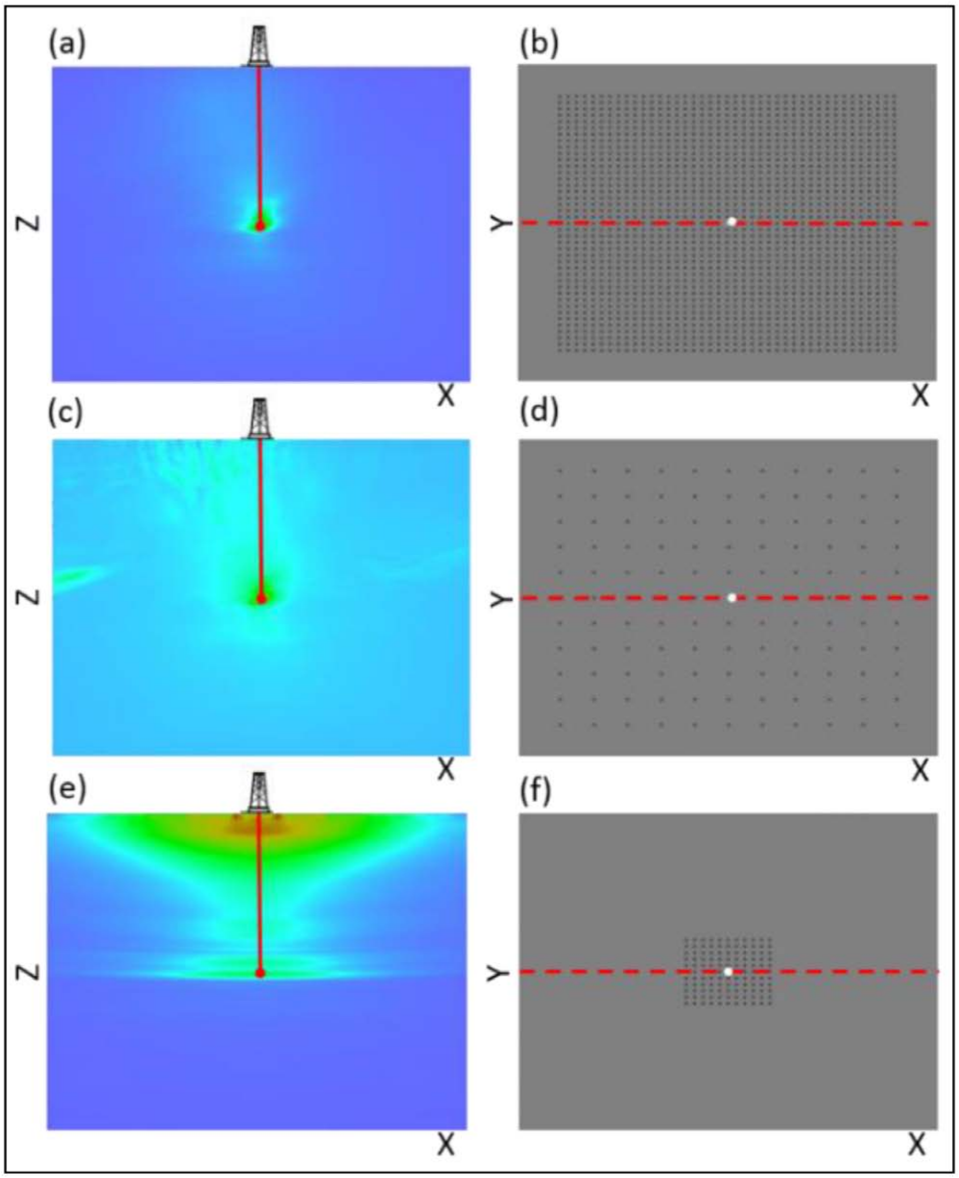

Figure 5—Effect of receiver network aperture and spatial sampling on the seismic image quality. Depth image slices to the left and receiver geometry map views to the right; (a) and (b) 2000 m aperture with 100 m spatial sampling, (c) and (d) 2000 m aperture with 400 m spatial sampling, and (e) and (f) 500 m aperture with 100 m spatial sampling. The source depth is at 1 km, with the lateral position in the middle of the receiver spread (white dot).

Field Test

The first field trial of the DrillCAM SWD system is being conducted on an onshore field. The objective of this test is to evaluate the system and the data quality and to validate integration of all the components involved. Here we discuss these components in more detail focusing on installation and acquisition procedures. Some initial real data examples will also be presented and discussed.

Wireless Surface Seismic Data Acquisition

More than 2,600 wireless surface seismic stations comprise the first key component of the integrated system. These surface receiver stations record seismic signals that are emitted by the drill bit during drilling operations. Wireless receivers allow flexible acquisition geometries that can be adapted to different drilling depths. Examples of such acquisition geometries that are used for the current field test are shown in (Figure 6). At shallow drilling depths the layout of receivers has a square shape with 1100 m edge size, where the rig is lying at the center (Figure 6a). This provides good angular coverage and illumination of shallow targets from all directions/azimuths. A dense grid of receivers with a spatial interval of 25 m in inline and crossline directions is used to best sample strong noise and signal arriving with low apparent velocities. Two additional orthogonal lines with the length of 6 km provide additional offset coverage. Larger offsets are required for deeper depths, and a cross-like acquisition with fat orthogonal lines of receivers is utilized (Figure 6b). Wireless transmission of seismic data reduces operational overhead and downtime typical of cable-based systems. Moving from one acquisition geometry to another is performed during non-drilling operations such as casing or cementing and does not affect either the drilling or data recording. Examples of wireless seismic recording units located around the rig site are shown in (Figure 7). Each unit is connected to a standard seismic geophone coupled to the ground. The units are equipped with lightweight batteries that are changed on a regular basis by a small mobile seismic crew. The data from all units is transferred by radio in real time to a recording cabin located on the rig site, which allows to control functionality of the system and to monitor status of each of the recording channels separately.

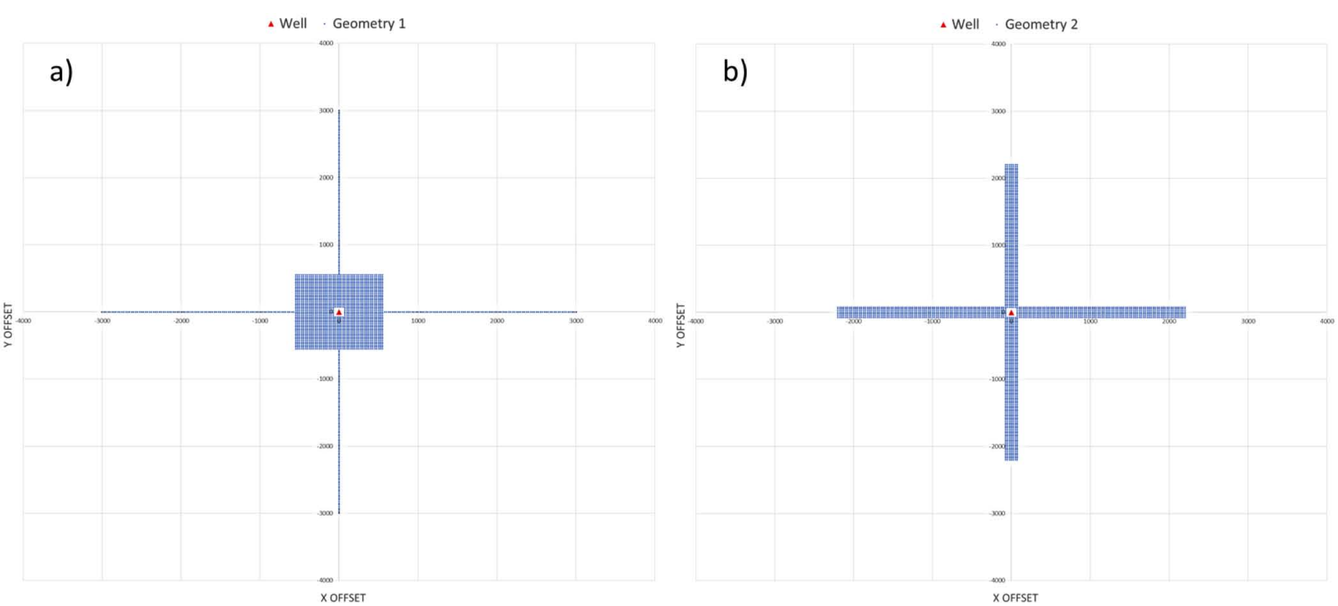

Figure 6—Shallow-oriented (a) and deeper-oriented (b) acquisition geometries used in the DrillCAM SWD field test.

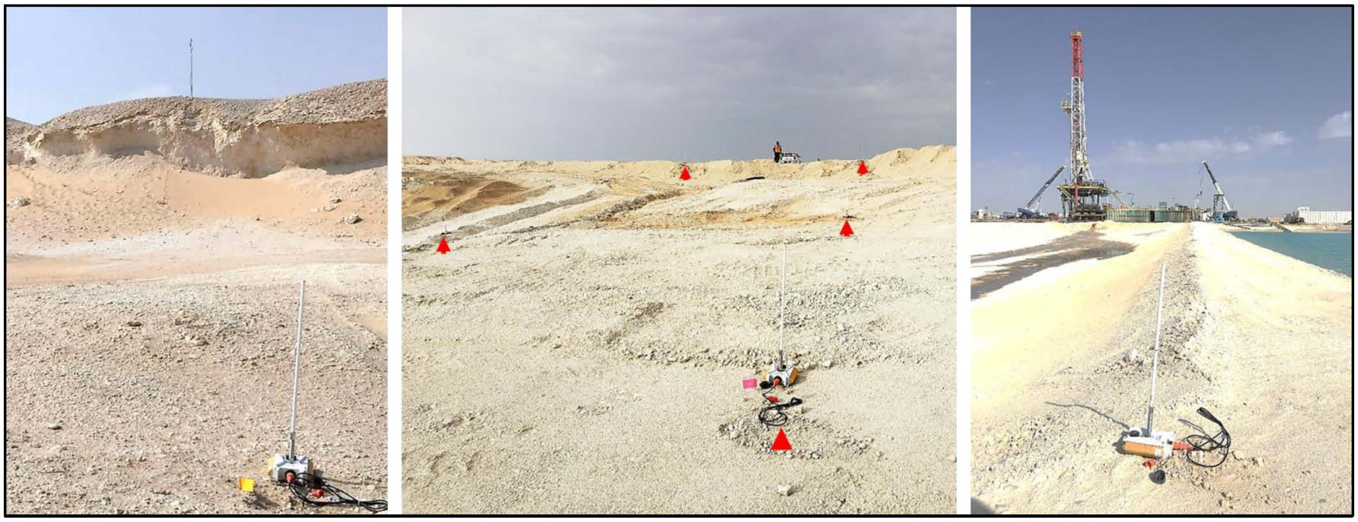

Figure 7—Wireless receiver stations deployed around the rig site recording seismic data while drilling.

In addition to the receivers around the rig, the surface receiver stations are also placed at various locations at the rig site (Figure 8). They record both the drill bit signal in the proximity of the rig and also noise generated by different types of surface equipment such as generators, shakers, pumps, etc. These recordings are of great importance to interpret and to attenuate different kinds of noise observed in seismic data at farther offsets.

Figure 8—Wireless receiver stations at the rig site.

Top-drive Pilot Recording

A second key component of the integrated system is a sensor that records drill string vibrations at the surface. This is a three-component accelerometer that is attached to the top-drive and transfers the recordings by a cable running through the mud service loop to the same recording cabin as the wireless units (Figure 9). These drillstring vibration signals are used as a pilot source signature needed to decode the surface seismic data from a random drill-bit source. The use of cable-based top-drive sensors enables real-time data retrieval from a hazardous area.

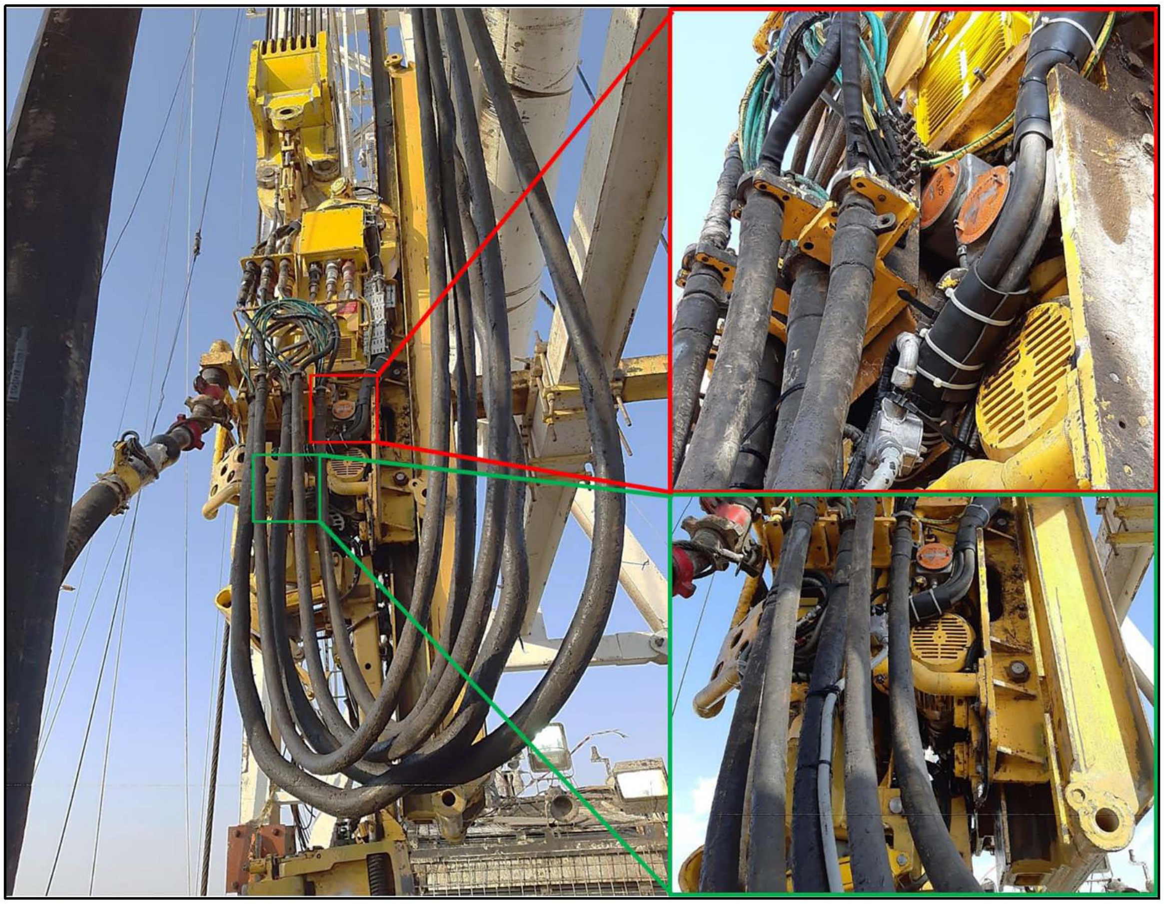

Figure 9—The top-drive vibration sensor used for pilot traces recording. (a) In red, two top-drive sensors for redundancy. (b) In green, cables running along the mud service loop to the recorder unit.

Downhole Pilot Recording

The third integrated system component is a tool that continuously records vibration data downhole. This is a three-component accelerometer located inside the sub directly behind the drill bit (Figure 10). It allows to record the signals with high-frequency sampling similar to surface seismic. Since the tool is located very close to the source of the seismic waves, the recordings are not affected by factors such as propagation along the drillstring, and so represent very accurate source pilot signals. Similar to the surface pilot signal from the top-drive, these recordings can be used to decode seismic signals recorded at the surface and to provide seismic data similar to conventional seismic. At the moment, these downhole vibrations are recorded into internal memory and are retrieved after completion of each drilled section, however propagation of these signals to the surface in real time is also under consideration.

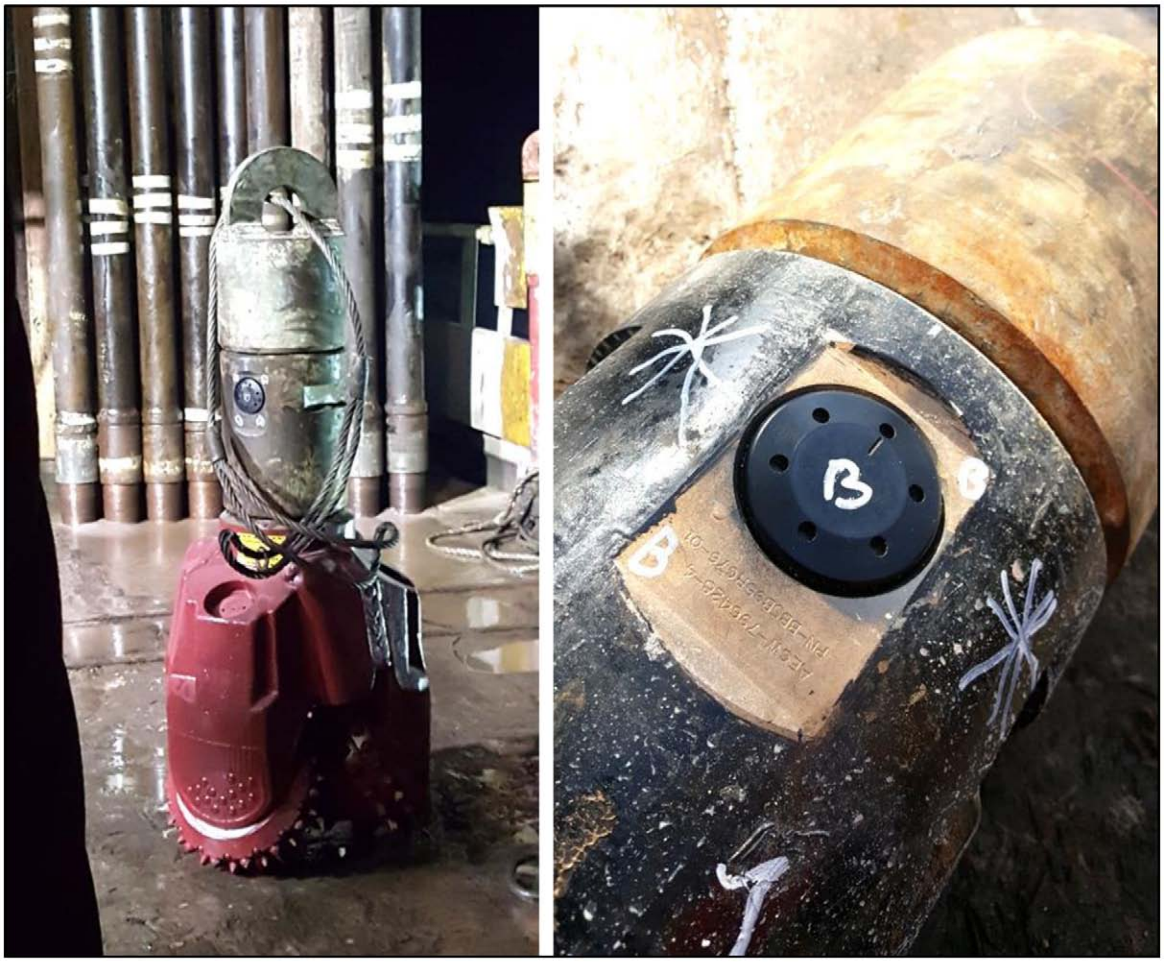

Figure 10—Drill bit with a bit-sub hosting the downhole vibration recording tool, Left. On the right, a closer look into the downhole vibration tool used for pilot signal recording.

Field Tests Initial Results

Seismic data recordings are done when the rig is performing drilling operations. An example of a seismic trace recorded by the top-drive sensor is shown in (Figure 11). This trace represents vibrations of the drillstring when the bit is penetrating through rock. Correlation of this trace with the seismic data from surface wireless recording units provides seismic data for analysis and interpretation. An example of such a record obtained after correlation with the pilot trace is shown in (Figure 12). The seismogram represents a 2D line, going through the drilling pad, extracted from raw correlated seismic data at a shallow drilling depth. The horizontal axis represents distance and the vertical axis represents recording time. Seismic events are clearly seen on this gather and overall, the data look very promising. Since this is a raw gather, most of the events correspond to surface-related noise coming with low apparent velocity. Additional processing is required to extract useful seismic signals propagating from, and below, the drill bit.

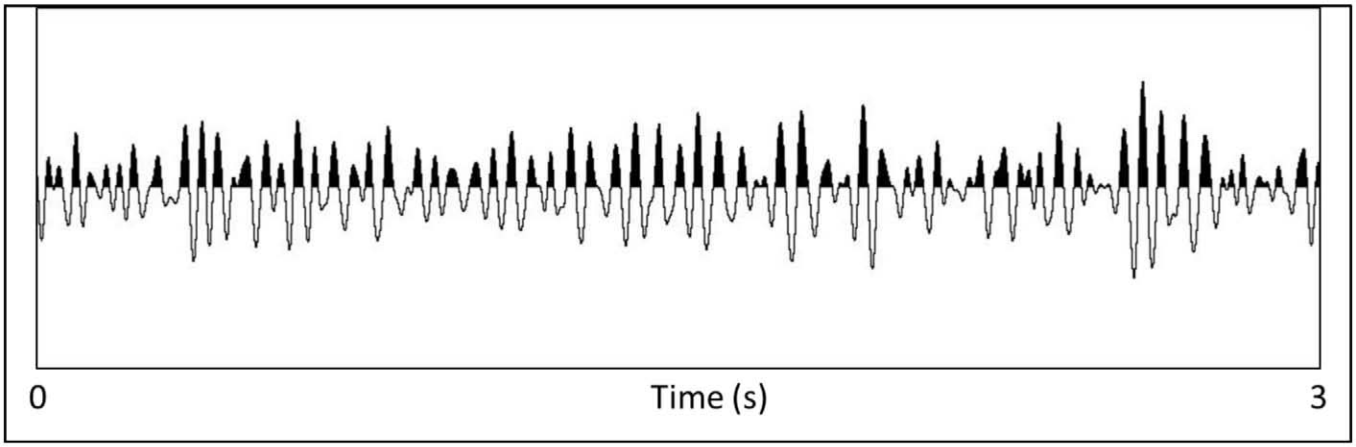

Figure 11—An example of pilot trace from top-drive sensor after some preprocessing.

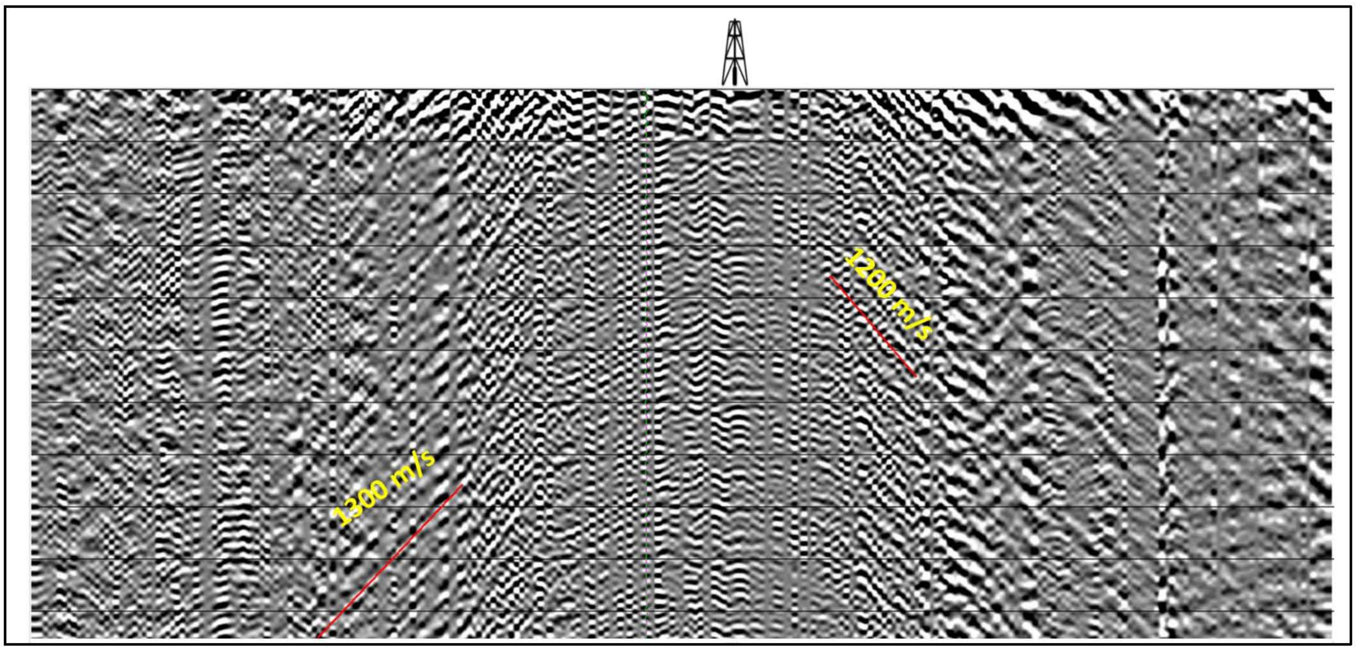

Figure 12—Raw correlated seismic data using pilot trace from the top-drive sensor for a 2D line running through the rig pad.

Conclusions

We present DrillCAM: An integrated real-time SWD acquisition system. The motivation and objectives of this work are driven by pressing drilling challenges and continuing technological advances in seismic recorded. Key aspects of the DrillCAM system include the use of dense 3D adaptive survey geometries with wireless seismic receivers and accurate recordings of drill-bit and drillstring vibrations downhole and at the surface. Additional advantages are expected from advanced data-enhancement and processing algorithms and large high performance computational resources deployed directly in the field. These factors should enable to successfully record, image and interpret drill-bit seismic data in real time.

The initial ongoing field trial of the system shows promising results. A good level of integration of all the involved components was achieved, which allowed seismic data to be acquired with a reasonable quality. Initial decoding of the recorded seismograms using the surface pilot traces reveals seismic signals typical of conventional seismic surveys. Additional processing and interpretation of the recorded data is ongoing.

DrillCAM aspires to provide accurate prediction of high-pressure zones, cavities and fractures, coring points, and target depths, leading to significant cost and risk reduction. Further future work will improve the system integration, incorporate the use of not only seismic data, but also various data types, including mud logging, drill cuttings, drilling data and LWD data, and integrate them using big-data analytics and artificial intelligence techniques.

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