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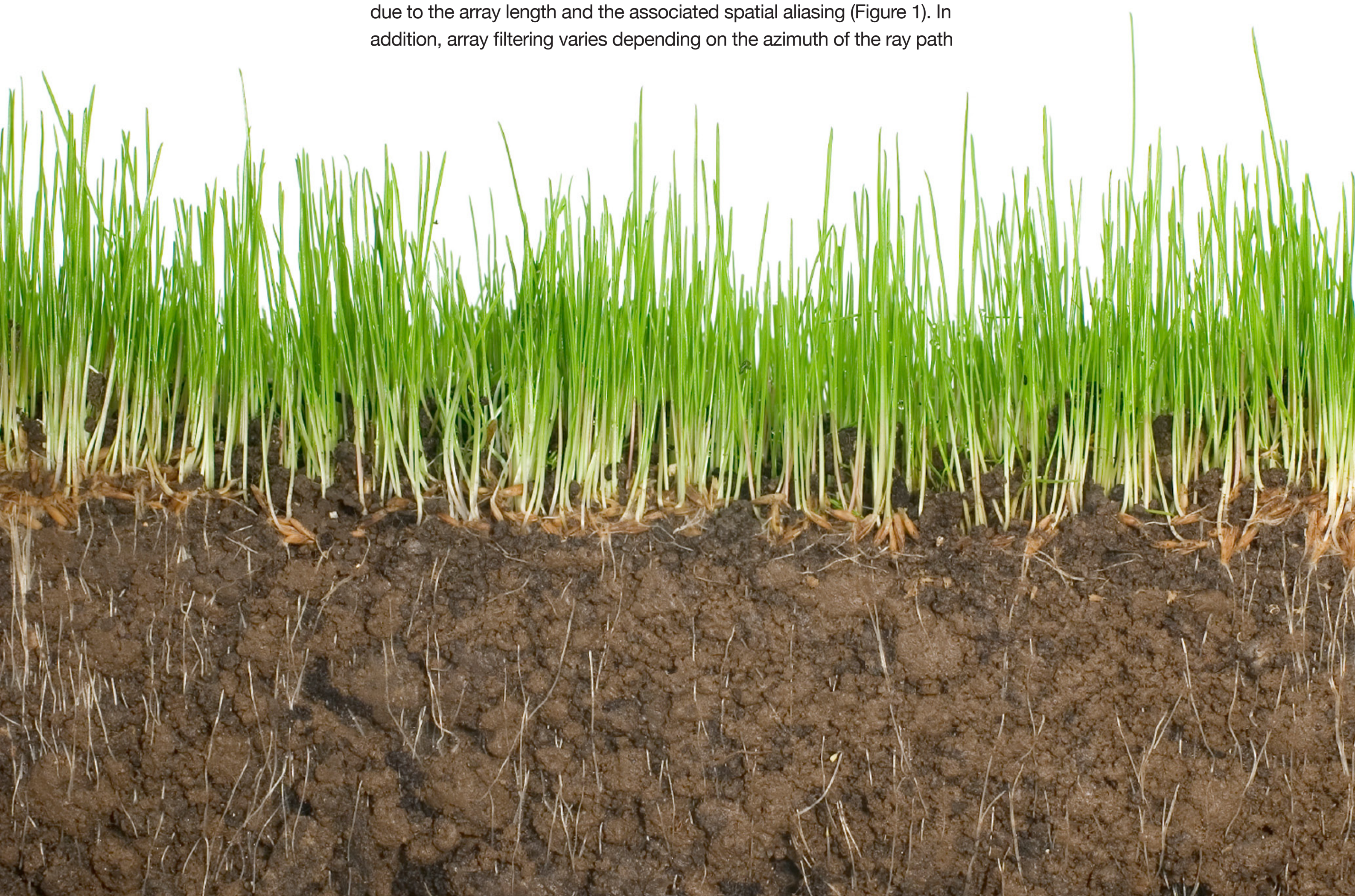
examines the advantages provided by advanced digital sensor units.

SENSORS THAT MAKE SENSE

Onshore, the conventional method of sensing weak reflected waves is by planting thousands of sensors on the surface of the ground to isolate the usable signal from the strong background noise. Since the early days of seismic exploration, these sensors have been geophones that deliver a voltage proportional to the ground velocity. More often than not, these geophones were connected into receiver groups and laid out as arrays to attenuate the source noise by simple electric summation of the individual voltages. Such arrays of geophones improve the quality and stability of the receiver coupling along the lines and increase their sensitivity. However, from an operational point of view, these arrays are heavy (7 kg for a string of 12 geophones) and they require significant manpower for transportation, planting and control. From a geophysical point of view, mixing between signal and noise often occurs due to the array length and the associated spatial aliasing (Figure 1). In addition, array filtering varies depending on the azimuth of the ray path



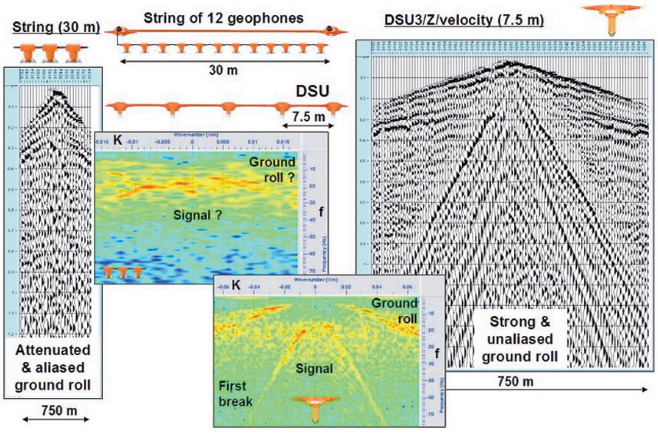


Figure 1. *Shot points over the same offset range from strings of geophones (left) and digital sensor units (DSU, right). The FK diagram shows that the prominent ground roll from the DSU data can be easily isolated and removed unlike the aliased geophone data.*

and high frequencies are attenuated due to differential time shifts between sensors (intra-array statics). Obviously a step change was needed to improve operational efficiency as well as seismic imaging.

Towards 3C digital accelerometers

With the capability of recording systems to handle an increasing number of channels, the industry is now able to adopt smaller arrays or even single sensors to preserve not only signal but also noise. With well preserved noise being easier to remove the signal-to-noise ratio is improved at a later stage by data processing.

The most basic single sensor is a geophone connected to a digitiser. The idea arose of bringing them together in a single package. Because there is no longer a cable and connector this reduces weight, and improves compactness and reliability. At the same time all perturbations (pick-up noise, cross-talk) related to the analog transmission between the sensor and the digitiser are avoided. Because the output of such a package is digits, the sensor is referred to as digital. In essence, all digital sensors are single sensors that should be recorded independently.

The sensing part of a digital sensor may be a velocimeter or an accelerometer depending on whether its response in the seismic bandwidth is proportional to the ground velocity or to its acceleration. A geophone is typically a velocimeter, the output voltage of which is proportional to the ground velocity above a specific resonant frequency (usually 10 Hz). However, its phase response is variable (90° rotation above 10 Hz). The advantage of accelerometers based on micro-electro-mechanical-systems (MEMS acting as a capacitor) is that both their amplitude and their phase responses are flat over a wide frequency range from 0 Hz (DC) up to 800 Hz. Thus, low as well as high frequencies can be recorded without any attenuation or phase variation that enables the delivery of broader band data to improve vertical resolution. Being able to sense DC, a MEMS-based accelerometer can detect the gravity vector used as a reference for sensor calibration and automated tilt corrections.

Three-component (3C) sensors are used to record the full-wave field (PP, PS and

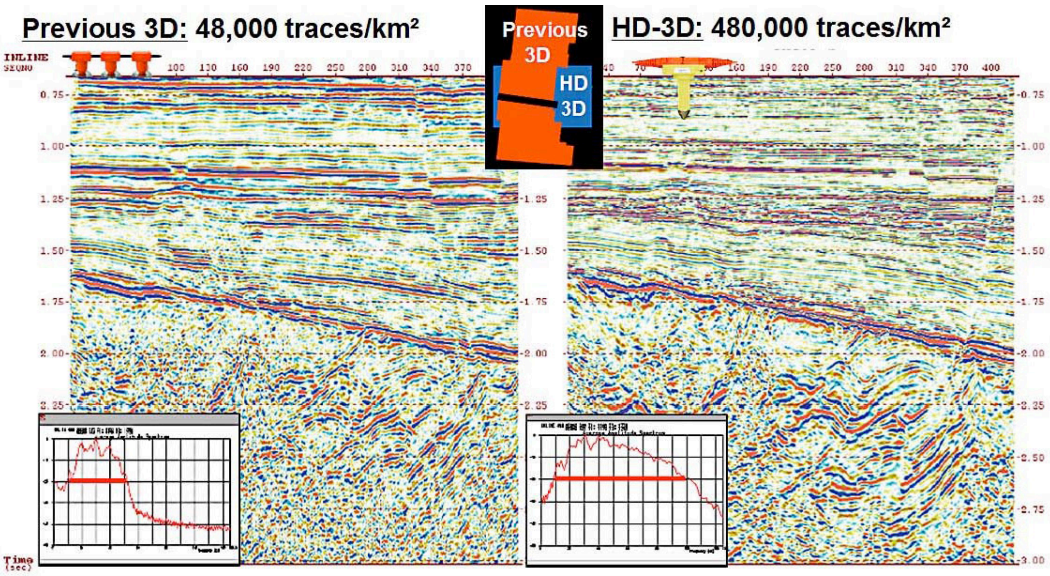


Figure 2. *Comparison between two overlapping 3D surveys[2]: one low-density survey recorded by strings of geophones (left section) and a new high density survey (HD-3D) recorded from digital accelerometers (right section). Both vertical resolution and signal-to-noise ratio were improved down to 3 sec. twt by HD-3D.*

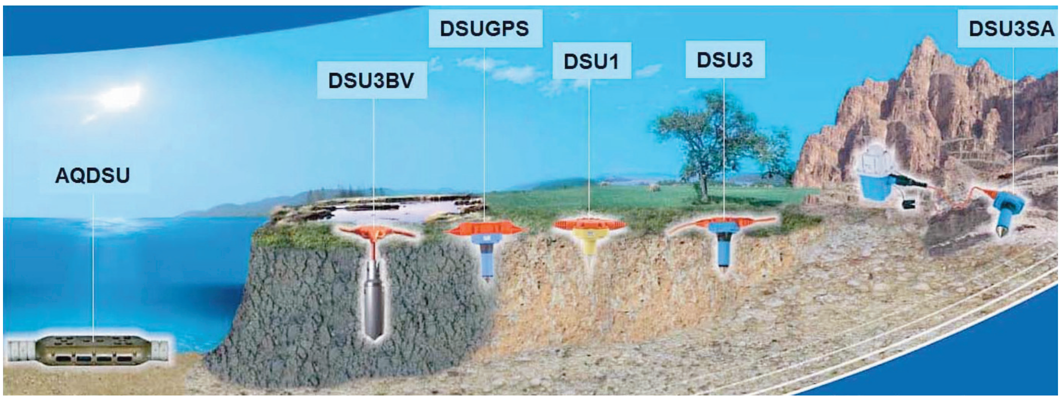


Figure 3. *A range of DSUs developed for the 428XL recording system to meet all operational requirements ranging from areas that are difficult to access to land, transition zone (TZ) and seabed (SeaRay cable) environments.*

possibly SS) to extract more elastic parameters from the subsurface and improve reservoir characterisation. The performance and compactness of MEMS made 3C accelerometers a new standard for acquisition, not only replacing previous 3C geophones for multi-component acquisition but also for any type of survey on land, transition zones and the seabed due to their light weight and high vector fidelity. Today this type of receiver represents more than 10% of the total amount of channels in operation.

Digital accelerometers for high-resolution, high-density 3D-3C recording

As digital accelerometers gained acceptance and were used in various survey conditions, additional benefits were demonstrated that confirmed the added value of this technology.

From an operational point of view, their low power consumption, lightness and integration (fewer cables and connectors) are an advantage, particularly for heliportable operations. Digital sensors are fully compatible with the corresponding main acquisition systems such as Sercel's 408UL or 428XL that do not require any specific adaptation. These recorders are even able to handle composite spreads made of conventional digitisers connected to geophones and of 1C or 3C Digital Sensor Units (DSU1 - DSU3). Automated real time QCs are available to compare displays of geophones with the vertical component of digital sensors integrated into velocity. Large composite 3D seismic surveys were performed for which up to 30 000 DSU3 were mobilised[1]. At the forefront of land acquisition technology, these very high-channel-count point receiver 3D - 3C surveys were for high-resolution (5 m x 5 m bins), high-density (above 3.5 million traces/km^2) and multi-component acquisition.

From a geophysical point of view, digital accelerometers provide superior vector fidelity, including tilt correction and amplitude calibration with respect to the gravity vector. They are the sensor of choice to improve both seismic imaging and reservoir characterisation as shown by this successful detection of an oil-water contact from a high-density 3D based on DSU1[2]. At the NW margin of the Junggar basin (XinJiang), PetroChina did a comparison (Figure 2) between a previous conventional 3D survey based on receiver arrays (36 geophones at 50 m) and a high-density 3D of 100 km^2 using digital accelerometers (4608 DSU1 at 20 m). Thanks to the reduced receiver interval and to the increased line number, trace density (480 000 traces km^2) is 10 times that of the previous survey. As a benefit of the higher fold coverage and of the single sensor acquisition, both improved vertical resolution and better signal-to-noise ratio were achieved. At the reservoir level (1.2 sec. twt) this helped to define the exact extension of the amplitude anomalies controlled by small faults that are related to the oil-water contact (OWC). As a result, the success ratio in the development drilling was improved.

In addition to the many case stories already published[3, 4, 5], these examples confirm the capability of digital accelerometers to enhance vertical resolution by widening the frequency spectrum, to better preserve amplitude and to provide superior converted wave data.

A full range of seismic receivers

Today, digital accelerometers are setting the standard for 3C surveys and single-sensor acquisition. The highest channel count surveys (90 000+ channels) conducted so far have been acquired by 3D crews equipped with digital sensors. In the meantime, MEMS-based accelerometers have diversified: compatible with cable and cableless systems, their use is now established from land to transition zone (TZ) and to seabed (OBC) environments. With respect to the Sercel 428XL system, different versions of the DSU have been developed to optimally meet all operational requirements (Figure 3).

DSU1 is a 1C version with the same specifications as the vertical component (Z) of the DSU3. Its shorter pod is completed by a longer spike to aid planting and improve coupling in soft ground. It has been used in difficult conditions such as those of the Loess Plateau in China.

DSU3BV is a version of the DSU3 that can be buried and is waterproof to a depth of 15 m. Its straight aluminium case aligned with the cable makes for easy deployment not only in transition zones but also in frozen ground from which it can be extracted without damaging the sensor thanks to a steel cable. DSU3BV has been successfully used to complement DSU3 lines in the rice pads where it provides better coupling. Its use for micro-seismic recording of frac jobs has also been very effective.

DSUGPS is an advanced receiver system: it can be placed in any position in any area without any adjustment. Thanks to two GPS antennas, each receiver calculates its own location (DGPS accuracy) and orientation (±3°) during acquisition. Deployment is quicker and more reliable: pre-survey staking operations are eliminated as well as human errors related to sensor orientation.

DSU3SA is an autonomous 3C accelerometer that has to be connected to a remote autonomous unit (RAU-D) of the UNITE cableless system. As for the DSU3BV it can be used to complement (infill) DSU3 lines in areas that are difficult to access where laying a telemetry cable may be challenging or even prohibited.

AQDSU is part of the 4C flatpack of the SeaRay cable designed for redeployable seabed operations down to 500 m water depths. It has been selected instead of the conventional omni-tilt 3C geophones for its compactness and ability to provide tilt corrected data. PP arrivals on the vertical component (Z) may be compared in real time with those on the hydrophone (P) and PS data (X, Y) are free of any cross-contamination.

Although they have diversified and represent a growing market share, digital accelerometers are not expected to replace all other receivers. Geophone arrays still offer the best compromise between cost and quality in very noisy areas or to capture the weak reflections from deeply buried strata. In the same way as explosives and vibrators on the source side, analogue and digital sensors are expected to coexist for a long time to provide an optimal solution for the different operational and geophysical constraints faced. OT

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Note

Sercel is the equipment manufacturing division of CGGVeritas.