Digital accelerometers: how they have impacted the seismic industry in 10 years?

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Summary

With the dawn of this century came a new generation of seismic sensors. These are 1C or 3C MEMS based accelerometers integrated with electronics to deliver a well calibrated digital signal. Contrary to arrays of geophones, they must be recorded individually as point receivers. Since noise is only filtered during processing, the interval between receivers must be reduced to avoid spatial aliasing of the noise and to increase fold coverage. The benefits provided by digital sensors are both operational (weight, power consumption, integration with the line…) and geophysical (amplitude & phase response, vector fidelity, tilt detection…). Early 2D-3C tests as well as 3D production surveys, including those performed by the highest channel count crews (35,000+), confirm the benefits of these new sensors: immunity to pick-up noise due to full digital transmission; increase of the frequency bandwidth of the signal and of the associated vertical resolution; well calibrated amplitude suitable for AVO and inversion. Case histories are proposed to illustrate the improved seismic imaging and reservoir characterization provided by digital accelerometers.

Introduction: from strings of geophones to 3C digital accelerometers

The conventional way of sensing seismic waves is by using receiver arrays and by performing the electric summation of the output voltage of each geophone. This approach is aimed at improving signal-to-noise ratio (S/N), at preserving a statistical good coupling and at increasing sensitivity to weak reflections. Drawbacks are well known: some mixing between signal & noise related to aliasing; variable filtering depending on the azimuth of the source; attenuation of the high frequencies in case of intra array statics. These explain why a step change was required.

- <u>Towards single sensors:</u> with the capability of recorders to handle more and more channels, the industry is adopting smaller arrays or even single sensors in order to preserve not only signal but also noise. S/N is improved at a later stage by data processing. A single sensor may be a single geophone connected to a digitiser or the bunch of all geophones of a string. Single sensor recording, often called point receiver, should be complemented by point source.
- <u>Towards digital sensors:</u> geophones produce a continuous voltage generated by a magnet moving with respect to a stationary coil. After transmission by the sensor cable, this analogue signal reaches the digitizer that performs its conversion into discontinuous digits to be recorded by the central unit. The idea that comes up with a single sensor is to bring together the sensor and the digitizer into a single package. Because there is no more cable and connector this improves both compactness and reliability. At the same time all perturbations (pick-up noise, cross-talk) related to the analog transmission are avoided. Because the output of such package is digits the sensor is called digital, even if the sensing part is still analog. In essence all digital sensors are single sensors that should be recorded independently.
- <u>Towards accelerometers:</u> The sensing part of a digital sensor may be a velocimeter or an accelerometer depending if its response in the seismic bandwidth is proportional to the ground velocity or to its acceleration. A coil geophone is typically a velocimeter since its voltage is proportional to the ground velocity above its resonant frequency (usually 10Hz). However, some coil geophones function as an accelerometer due to an over-damping configuration (Kamata, M., et al., 2008) around their resonant frequency (typically 25Hz). These Geophone ACcelerometers (GAC) are insensitive to tilt and they provide a lower frequency linear amplitude response (down to 2Hz in the acceleration domain) than the conventional ones. However, their phase response is still variable. The advantage of the accelerometers based on Micro-Electro-Mechanical-Systems (MEMS acting like a capacitor) is that both the amplitude and the phase responses are flat over a wide frequency range from 0Hz (DC) to up to 800Hz. Being able to sense DC is not for recording seismic energy, but to detect the gravity vector used as a reference for calibration and tilt corrections.
- <u>Towards 3 Components:</u> all 3C accelerometers are based on MEMS to benefit of the performances and of the compactness of these sensing units for the component assembly. At the beginning, their main interest was seen as the ability to ease the recording of the full-wave field (PP + PS + possibly SS) while improving their quality. Later on, the interest of 3C digital sensors focused also on their capability to improve the signal-to-noise ratio of P wave data by polarization filtering of the ground roll and by tilt correction.

Thus, “digital sensors” are not only single sensors integrated with digitizers; most of the time they are 3C MEMS accelerometers and they will be considered as such hereafter.

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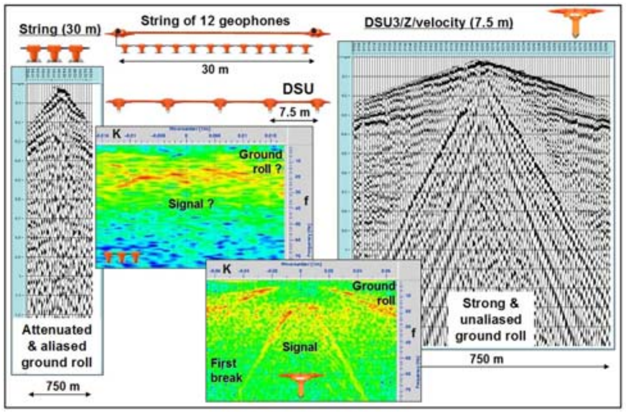

Figure 1: Shot points over the same offset range from strings of geophones (left) and digital sensors (right). FK diagram shows that the prominent ground roll from single sensor data will be easily removed contrary to the aliased geophone data.

The testing phase: the capabilities of digital sensors unravelled

The purpose of the early tests with service & oil Co's was to demonstrate that digital sensors were at least as good as conventional geophones or even better. Digital sensors were often laid-out side-by-side with geophones (Figure 1), but the comparison was seldom one-to-one. Everything was mixed: point vs. array, analog vs. digital, velocimeter vs. accelerometer, MEMS vs. coil and 3C vs. 1C making it difficult to assess the origin of the improvement. Thus, these tests were more an evaluation of a new way of doing acquisition vs. the usual one. They provided good surprises as well as a few disappointments.

- The immunity to pick-up noise: one of the obvious advantages of these new receivers is the full digital transmission of the signal from the sensor to the recorder. This provides a good immunity against electromagnetic contaminations like those occurring at proximity of power lines. Such benefit was easily evidenced from early comparisons showing that all the 50-60Hz pick-up noise on the geophone data does not exist with digital sensors (Mougenot, D. and Thorburn, N., 2004). Perturbations of the same frequencies may still occur, but only if generated by acoustic sources (pumps, motors…).
- The low frequency content: expectations were high with digital sensors to be able to move towards more low frequency signal (5Hz) highly recommended for improving seismic imaging as well as reservoir characterization (Mougenot, D., 2005). Most of the time results were disappointing, particularly with explosive sources. At the low end of the spectrum, no significant differences were found between geophones and digital sensors. In fact, the limitation was on the source side, explosive being prone in producing very low frequency ground roll (2-4Hz), but often unable to generate elastic waves with sufficient energy below 10Hz. Recently, surveys based on low frequency sweeps (Stotter, Ch. et al. 2008) or more carefully designed shot holes have provided examples where the capability of digital sensors to record these low frequencies (LF) without attenuation has been confirmed at least down to 5Hz.
- The high frequency content: the display of a Shot Point (SP) coming from digital sensors is often rewarding when it is compared with the same record coming from strings of geophones (Figure 2). The lack of high frequencies (HF) in geophone data is often explained by the effect of intra-array statics that attenuate the high end of the frequency spectrum. In fact, most of the difference occurs because comparison is done between velocity and acceleration data the latter being boosted by +6dB per octave. After integration of the digital sensor records most of this advantage vanishes. Such bias does not exist when comparison is done between stack sections after deconvolution. From the phase spectrum, this operator is able to detect that data are coming from accelerometers, and then to perform integration into velocity. On the final sections, the vertical resolution of digital sensor data is often better down to 1.5-2s twt than the one coming from large array of geophones, particularly if the interval between digital sensors was reduced. Below 2s twt this advantage may disappear due to an increase of the noise and to the lower sensitivity of the digital sensors to the weak reflections.

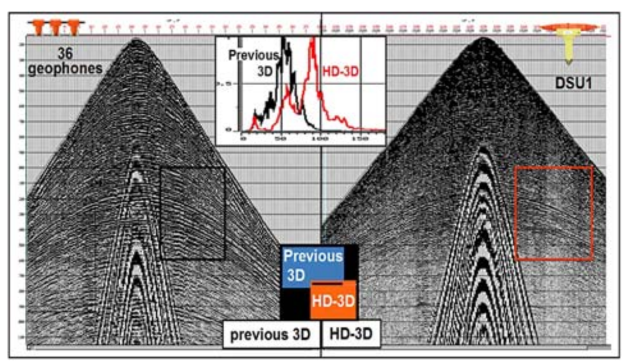

Figure 2: Comparison of SP's between strings of geophones (left) and digital sensors (right), and the corresponding amplitude spectra (Li, J. et al., 2009). The main difference in HF content comes from the comparison of velocity with acceleration data. Ground Roll is attenuated by the array.

- The signal to ambient noise ratio: large arrays of geophones are efficient in attenuating ambient noise by a factor that is the square root of the number of sensor summed electrically (e.g. 6 times for a string of 36). The same formula applied to a single sensor shows there is no attenuation at all. This translates into a degradation of the S/N and to a limited penetration of the digital sensor section if their spacing is not significantly reduced compared to the string of geophones. Only a higher fold of the stack or an increase of the trace density for the pre-stack migration will be able in this case to attenuate the ambient noise.

- The signal to organised noise ratio: Ground Roll (GR) may be particularly prominent on SP's recorded by digital sensors (no array and no LF attenuations; Figures 1-2). Thus, to prevent GR from aliasing, it is recommended that the interval between digital sensors is set below the spatial Nyquist L = Va/2Fa (Va & Fa apparent velocity & frequency of the GR) or at least below an adequate spacing that prevents interference of GR with signal (Beaten, G.J.M. et al., 2000). This may requires a large number of channels in case of very low velocity/ steep GR that gets spatially aliased at 5m receiver interval or less. Another approach does not rely on the trace interval to remove organized noise. This is the polarization filter that assumes that a radial and elliptical GR propagates from the source to the receiver. Thanks to 3C recording as performed by most of the digital sensors, this noise is recorded identically (with 90° phase shift) on the vertical and radial components. GR can therefore be isolated by correlation and then adaptively subtracted on a station-by-station basis (De Meersman, K., 2008). When this works, the receiver interval is not any more constrained by the spatial sampling of the noise. This is a good example of how full-wave recording may be helpful in improving P wave data.

To summarise we may state that digital sensors will record more noise as well as more signal. Frequency content should be enhanced compared with arrays of geophones. Assuming that the receiver point interval has been reduced in order to improve trace density and to prevent from noise aliasing, data processing should be able to produce better seismic images. One important lesson we got from these tests is that, in noisy areas or for deep targets, a single accelerometer is unable to replace a large array of geophones. It should be at least a few digital sensors over the same interval, but fortunately not as many as the number of geophones. Compared with a linear array (e.g. 6 geophones every 30m), we suggest as a rule of thumb that digital sensors should be separated by a distance between half of the station interval (e.g. 30m / 2 = 15m) and two times the distance between successive geophones (e.g. 5m x 2 = 10m).

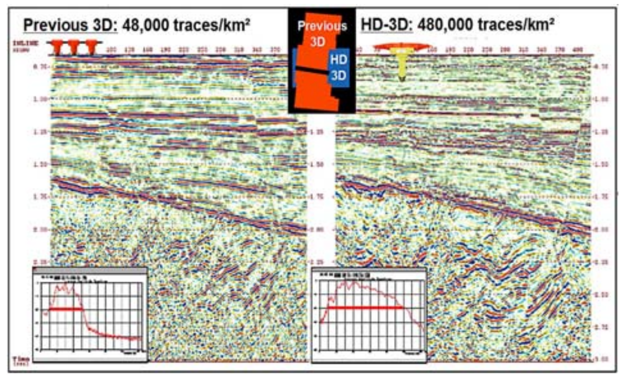

Figure 3: Comparison between two overlapping 3D surveys (Li, J. et al., 2009): one low density recorded by strings of geophones (left section) and a new high density one (HD-3D) recorded from digital sensors (right section). Both vertical resolution and signal-to-noise were improved down 3s twt by HD-3D.

The production phase: towards high density, high resolution, full wave recording

After the early test phase, as digital sensors gained acceptance and were used in production jobs, additional benefits showed up that confirm the added value of this technology.

From an operational point of view, their low power consumption, lightness and integration (fewer cables and connectors) are highly appreciated, particularly for heliportable operations. Digital sensors are fully compatible with the main acquisition systems like 408UL or 428XL that do not require any specific adaptation. They are even able to handle composite spreads made of conventional digitizer (FDU) connected to geophones and of 1C or 3C Digital Sensor Units (DSU). Automated real time QC's are available to compare displays of geophones with the vertical component of digital sensors integrated into velocity (Mougenot, D. and Thorburn, N., 2004). Large 3D seismic surveys were performed for which up to 15,000 3C digital sensors were mobilized. At the forefront of land acquisition technology, these very high channel count point receiver 3D-3C were for high resolution (down 5m x 5m bins), high density (up to 3.5 million traces /km²) and full wave surveys.

From a geophysical point of view, digital sensors 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 characterization as illustrated by these three successful case histories (Liu, J. and Mougenot, D., 2007):

- Oil water contact from high density 3D: the limited vertical resolution of seismic data is a major issue to identify thin heterogeneous reservoirs and to calibrate reflections at the well location. With the availability of high channel count recording systems and digital sensors it gets possible to preserve the HF content of the data and to improve S/N at the same time. At the NW margin of the Junggar basin (XinJiang), PetroChina did a comparison (Figure 3) between conventional low density 3D surveys based on receiver arrays (36 geophones @50m) and a point acquisition high density 3D of 100 km² using digital sensors (4,608 DSU1 @20m). The resulting trace density (480,000 traces /km²) is ten times the previous one. As benefits they observed both improved vertical resolution above an unconformity and better S/N below it. At the reservoir level (1.2 s twt) this helped to define the exact extension of the bright spots related to the oil water contact controlled by small faults (Li, J. et al., 2009).

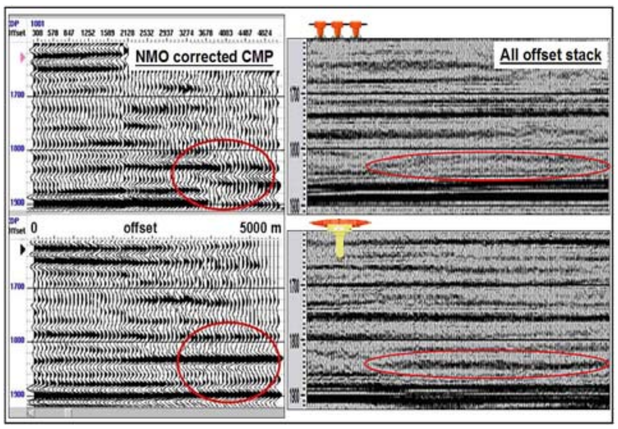

Figure 4: Comparison of NMO corrected CMP gathers and of the corresponding stacks between geophone arrays (top) and digital sensors (bottom). AVO at far offsets and corresponding amplitude anomaly on the stack are only preserved by single sensors (Shi, S. et al., 2008 & 2009).

- Thin gas reservoirs from preserved AVO: it happens that digital sensors provide a more consistent AVO over the whole offset range than arrays of geophones. In case of amplitude increase towards far offsets (class III AVO) this produces bright spots on the stack sections and helps in identifying gas reservoirs. Sulige gas field in the Ordos basin (Inner Mongolia) is the largest low sulphur gas field in China. The reservoir is a heterogeneous stack of thin fluviatile sand bodies unresolved by conventional seismic. Due to the limited amount of gas in each layer and to their depth (3300m) the success rate of the wells was not high enough (62%) to ensure an economical development of the field. Using a direct gas detection methodology was required. By using DSU's at 10m interval, instead of the conventional array of 36 geophones, prestack data were recorded that were able to preserve the large increase of amplitude at the reservoir up to 5000m offset (Figure 4). This was not possible from conventional data. After suitable processing, this AVO effect, the far offset stack or the elastic impedances inversion made it possible direct gas detection (Shi, S. et al., 2008 & 2009). This approach was performed on thousands of kilometres of point receiver high density 2D lines. As a result, the success ratio of the development wells was increased by more than 50% (up to 94.4%). This made it possible for PetroChina to triple the production of the field in 2007 from 1.3 to 4 billion cubic meters.

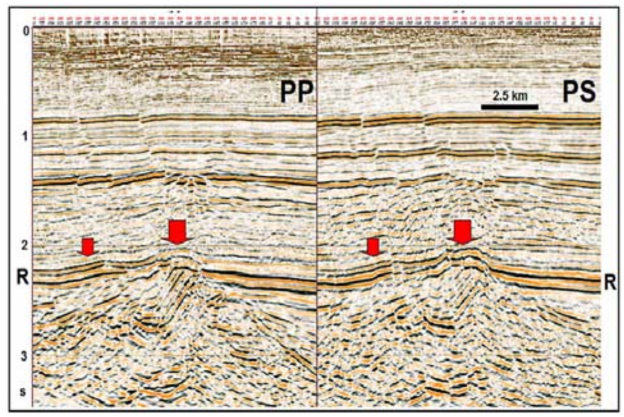

Figure 5: The PS migrated sections scaled to PP time is of sufficient quality to be compared with the PP one. Differences of amplitude at the top reservoir are evidenced on the two highs (Liang, S. et al., 2008).

- Thin gas reservoirs from dual PP-PS inversion: the quality of PS data has significantly improved by the use of 3C digital sensor instead of string of triphones while the cost of acquisition decreased. The comparison of PS with PP data is now made easier and combined pre-stack inversion can be performed to discriminate fluid and lithology variations. Nearby the giant Daqing oil field, the Qingshen gas field was discovered in 2002. Its deep reservoir (3500m) lies within heterogeneous volcano-clastic formations. The contribution of 3C data was to detect the three gas layers (each 20-50m thick) encountered by the Xushen-1 & 6 exploration wells and to define their relationships (Liang, S. et al., 2008). On the migrated sections (Figure 5), gas is only detectable by the difference of amplitude at the top of the formation between PP (weak) and PS (stronger). Prestack dual inversion made it possible to differentiate up to six layers with the corresponding elastic parameters (Vp, Vs & ρ). High gamma ratio (Vp/Vs = 1.8) was used to map the continuous shale layers that compartmentalize the volcano-clastics sediments. Within the clastics, positive values of the fluid factor were able to delineate the three gas layers and to identify their complex relationships between the two wells (Figure 6). These results were confirmed by two production wells not used in the inversion.

In addition to the many case stories already published (e.g. Roche, S.L. et al. 2006), these examples confirm the capability of digital sensors to enhance vertical resolution by widening the frequency spectrum, to better preserve amplitude, and to provide superior converted wave data, thus improving seismic imaging and reservoir characterisation.

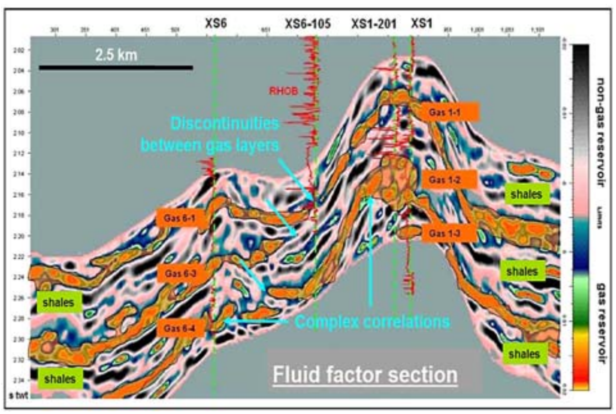

Figure 6: Fluid factor section from the PP-PS dual inversion (Liang, S. et al., 2008). The three gas layers as identified at XS-1 & 6 are also evidenced by the positives value of the fluid factor. Thanks to 3C seismic the complex relationships between the two wells are established.

Conclusion: the importance of digital sensors today

Digital sensors have found their market share (~5% in Receiver Points sold during the decade) even if they still correspond to a high-tech niche. They set the standard for 3C surveys and point receiver acquisition, and hold the greatest promise for improved imaging and better reservoir characterization. Except for 3C surveys, digital sensors 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. Today, the highest channel count surveys (35,000 channels and above) are 3D crews equipped with 3C digital accelerometers. In the meantime, these sensors have diversified: compatible with cable & cableless systems, their use is now established from land to transition zone and to the deep offshore (OBC).

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Acknowledgements

The author acknowledges Sercel for having offered him the unique opportunity to contribute to the development of the digital sensors. He is grateful to PetroChina for their confidence in the value of this technology and for their authorization to publish some of the results.