Understanding MEMS-based digital seismic sensors

Nicolas Tellier[1*] and Jérôme Lainé[1] explain how to understand operating characteristics of Digital Sensor Units (DSU) and discuss the quality and cost issues in the light of experience gained after more than a decade of field operations.

Introduction

Over the last few decades almost all the electronic devices we use in our daily lives have switched from analog to digital owing to the numerous benefits they offer, such as miniaturization, enhanced functionalities or reduced power consumption, etc. This revolution also reached the seismic industry, primarily when fully digital recorders and telemetries became available in the late 1970s. However, measurement of the Earth's displacement by sensors remained analog. The last step towards full digital recording was made in the early 2000s with the launch of digital seismic sensors based on MEMS (Micro Electro Mechanical Systems) accelerometers that had the potential to replace analog geophones that had been used since the early days of seismic dating back to the 1930s.

However, although digital sensors have established a foothold and indeed even become a reference for a number of different applications, the anticipated revolution has however not lived up to the expectations of the seismic industry, the current situation being perhaps analogous to using audio cassette tapes alongside MP3 music files. More than a decade after the release of the first digital seismic sensors, several explanations for such a situation have become clear:

- the operating principles of digital sensors are somehow perceived to be more complicated than those of geophones, and trickier to understand;
- the quality of data acquired with digital sensors is sometimes judged to be no better than equivalent to data acquired with geophones (more often than not, this is owing to a comparison of single digital sensors with strings of geophones at the same trace interval);
- the cost of digital sensors is often seen to be higher (at least for one-component – 1C – acquisition) than the cost of a conventional Field Digitizing Unit (FDU) connected to a string of geophones.

This article aims firstly to review the main operating characteristics of MEMS-based Digital Sensor Units (DSU), especially when compared to geophones, and then discuss the quality and cost issues in the light of experience gained after more than a decade of field operations. We conclude that their use with an adapted high-density geometry makes it possible to achieve much better imaging than with geophone arrays, for an equivalent cost.

Operating characteristics of digital seismic sensors

What do we measure with MEMS digital sensors?

Both geophones and MEMS technology-based accelerometers operate on the principle of a damped mass-spring system (Figure 1).

For geophones, the resonant frequency [$F_{resonance} = \sqrt{(\text{spring stiffness / mass})}$] is low: this is due to the fact that the spring stiffness is weak (when compared to the 'heavy' mass of the coil driven by the spring). This means that for any signal of interest (above resonant frequency) the proof mass (i.e., the coil) is

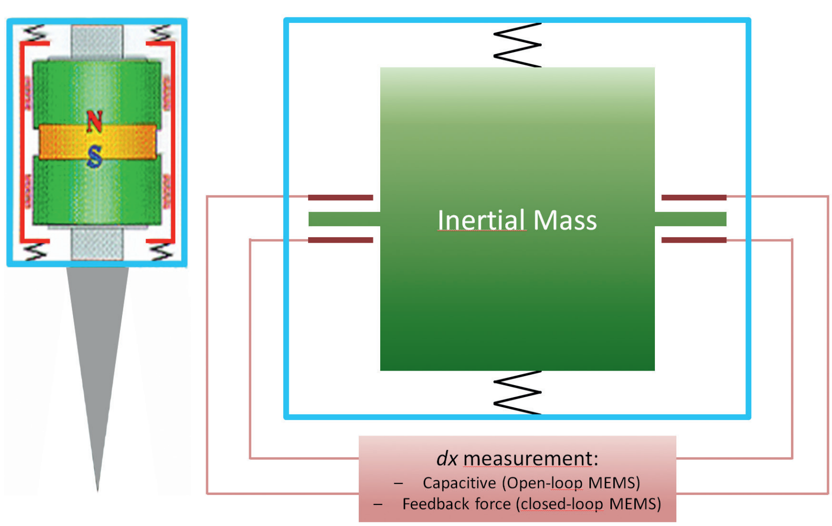

Figure 1 Geophone (left): the sensor casing (blue) is attached to a spike (grey) and to the magnet (yellow). All these components move with ground motion, while the coil (red) connected to the casing by a soft spring (black), remains motionless. Digital sensors (right): the principle is the same as for geophones on a microscopic scale, with a MEMS casing (blue) attached to a sensor casing (not represented). The inertial mass (green) is maintained by stiff springs (black) and then moves with casing/ground motions. When subjected to an acceleration, the small displacements of the inertial mass are measured by electrodes (red).

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the reference point. When the ground shakes, the coil remains motionless while the geophone casing and the magnet moves relatively to the coil. As a geophone is an electromagnetic device, the output voltage signal produced by the coil is proportional to the relative displacement rate (velocity) of the magnet attached to the casing. Geophones act then as velocimeters above their resonant frequency (commonly 10 Hz) and deliver an analog voltage proportional to ground velocity.

For MEMS accelerometers, it is even simpler: resonant frequency is high because the spring stiffness is strong (compared with the associated 'light' mass). This resonant frequency is higher than the frequency bandwidth of interest for seismic imaging. As a result, when subjected to a seismic wave, the proof mass (i.e. the inertial silicon mass) moves in phase with the casing. Consequently, when the velocity is constant, there is no relative force applied to the mass (as is the case for a passenger inside a car on a freeway). When the sensor casing is subjected to a variation in speed, i.e., an acceleration, then a force is applied to the mass that moves from its resting position by a value *dx* given by Equation (1):

$$dx = \frac{Force}{Spring\ stiffness} = \frac{Mass * Acceleration}{Spring\ stiffness} \qquad (1)$$

Digital sensors act then as accelerometers below their resonant frequency (around 1 kHz) and deliver digits proportionally to ground acceleration.

Computation of the MEMS acceleration output depends on the way in which the MEMS is controlled. Two ways can be distinguished:

1. Open-loop MEMS accelerometers (no control of the inertial mass oscillation): *dx* is measured by a capacitive position sensing interface. The ground acceleration is obtained from the measured displacement and the known spring stiffness and mass:

$$Acceleration = \frac{dx * Spring\ stiffness}{Mass} \qquad (2)$$

2. Closed-loop MEMS accelerometers (a feedback force is applied so that the mass displacement remains close to null): the ground acceleration is obtained by measuring the force applied to the inertial mass to maintain it at its resting position, this force being produced by applying a voltage on the electrodes (Figure 1).

$$Acceleration = \frac{Force}{Mass} \qquad (3)$$

The feedback force can be generated by an analog controller (as for the first generations of digital sensors); on modern sensors it is now digitally controlled.

Understanding the specifications of MEMS digital sensors

Several concepts are reviewed here with relevant examples. These concepts can usually be found in the specifications of digital sensors, and allow a comparison of their performances:

Noise Floor is the output of the sensor in the absence of any external perturbations (i.e., if we consider the sensor to be ideally isolated from its environment). This non-null output corresponds to the noise produced by the sensor itself, mainly as a result of:

- The collision of gas molecules in the sensing cell (i.e., the MEMS depicted, right, in Figure 1). This noise, called Brownian noise, is mitigated by a high vacuum maintained by a device called 'getter' that traps any residual gas molecules.
- The noise produced by electronic components when operating. Electronic noise has various origins, the main one being the agitation of the charge carriers in electrical conductors, known as thermal noise.

There are two ways to express a noise floor (Figure 2):

- For temporal analysis, RMS (Root value of the Mean of the Squared values) is preferred. The noise floor is then expressed in the same unit as the signal (for example Volt, m/s or m/s²). The RMS noise value is the sum of all the noise sources

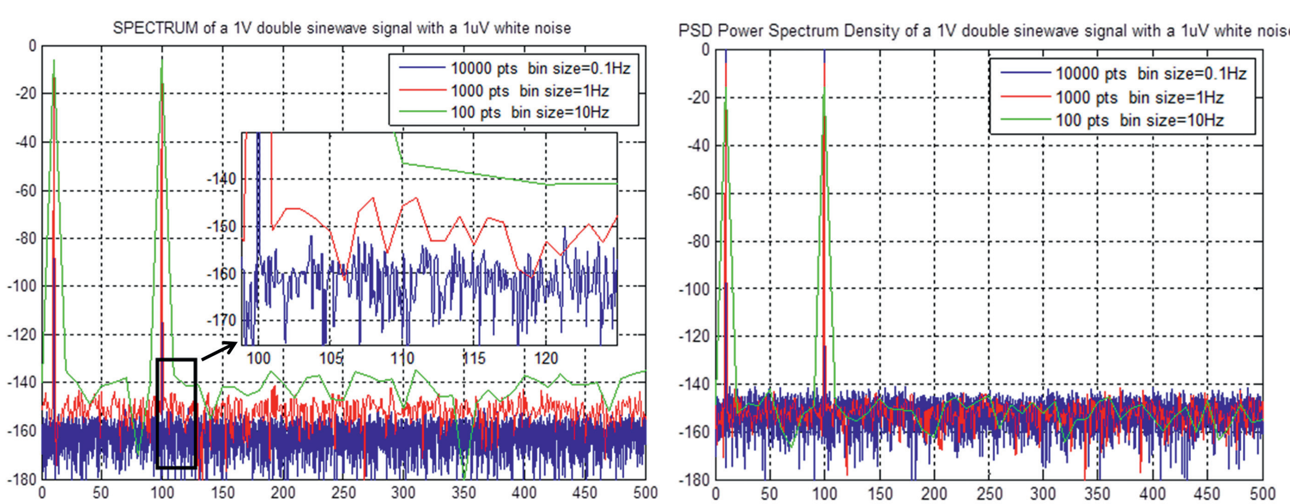


Figure 2 Spectra of a 1 V signal having two rays at 10 and 100 Hz, with white noise of 1 mV. (Left): spectrum is expressed in amplitude: the noise floor is dependent on the frequency resolution. Increasing the number of computation points 'spreads' the noise: each point represents a smaller bandwidth (bin size) that consequently has lower amplitude. In this example, the noise floor seems to be divided by 10 when the number of points is multiplied by 10. (Right): Expressing noise in power density avoids this artifact: comparing the noise floor performance of different systems should then be done in power density.

within the Nyquist bandwidth, i.e., from 0 Hz up to $F_s/2$, with F_s being the sampling frequency.

Example 1: for a 6-180 Hz seismic signal of interest, 2 ms sampling rate is used (F_s = 500 Hz to record data without aliasing up to 250 Hz), then the noise RMS will be expressed on the 0-250 Hz bandwidth.

Example 2: if the noise floor is 'flat', the noise floor RMS of an acquisition system increases by a factor of ~√2 (+3 dB) when the frequency bandwidth considered is doubled.

- For spectral analysis, Noise Density is preferred. The unit is x/√Hz with x being the unit of the signal. Only one value is then sufficient to fully specify noise performance, irrespective of the sampling rate, the length of acquisition and the frequency resolution of the spectral analysis. Moreover, when comparing the noise spectra between two systems, it is mandatory to display spectra in noise density (in V/√Hz) or in PSD (Power Spectral Density, in V^2/Hz) as the noise density value does not depend on the frequency resolution.

Note that noise RMS can be computed from Noise Density by multiplying the latter by the square root of the bandwidth that is defined by the sampling frequency, the digital antialiasing filter and the low-cut filter, if any.

Example: with a sampling rate = 2 ms, a 0.8 Nyquist digital filter and a 3 Hz low-cut filter, the bandwidth is [3 200 Hz]. With this configuration, the RMS noise of a digital accelerometer having a noise density of 15ng/√Hz is:

Noise rms =

$$\text{Noise density}*\sqrt{\text{bandwidth}} = 15*10^{-9}*\sqrt{197} = 210.5\ \text{ng}.$$

The noise floor level depends on the MEMS construction (Moreau et al., 2014). As an example, the noise floor of the latest generation of digital sensors (< 15 ng/√Hz) is divided by ~3 compared to the previous generation (< 40 ng/√Hz). This is of particular importance when recording very low frequencies (< 5 Hz) for which MEMS noise floor increases.

Full scale is the maximum signal amplitude that can be measured. For an FDU, this limitation is due to the maximum input voltage of the Analog-to-Digital Converter (ADC) that is allowed (that is dependent on the selected gain). For a DSU operating in closed-loop, this limitation is owing to the maximum feedback force that can be applied to the seismic mass. It can be expressed either in peak value, or RMS value (assuming the signal is a sine wave, the latter is equal to the full scale (peak) divided by √2).

Example: an FDU having a peak full scale at 2.26 V / 0.565 V (low/high gain) has a RMS full scale at 1.6 V / 400 mV. These values can be converted into velocities by applying the geophone string sensitivity. For digital sensors, a typical full scale value is 5 m/s² peak.

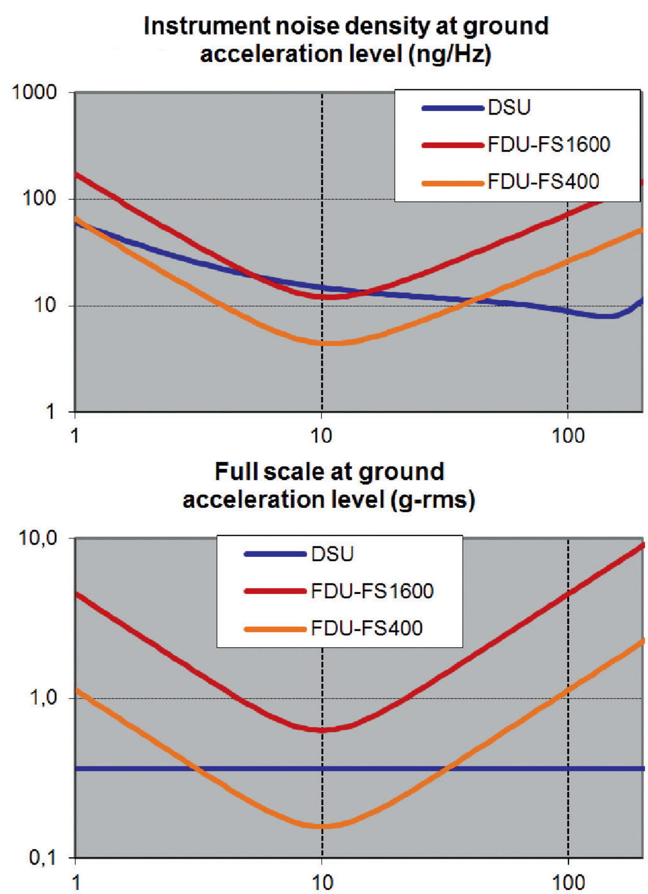


Figure 3 (top) compared instrument noise and (bottom) full scale of a DSU and FDU with two different gains. The FDU full scale is derived to enable comparison.

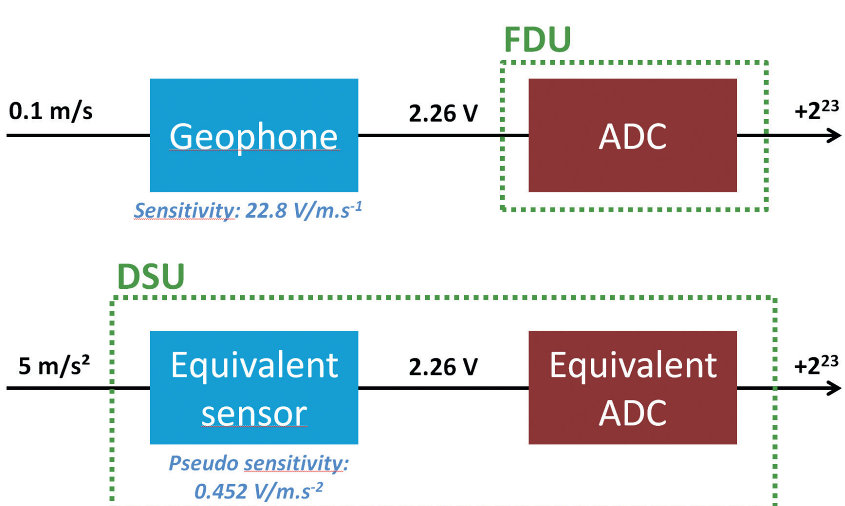


Figure 4 Comparison of DSU and FDU sensitivity: (top) With an FDU having a full scale of 2.26V (digital output $+2^{23}$), the maximum recordable signal when using a 22.8 V/m/s geophone will be 2.26/22.8=0.1 m/s; (bottom) to enable comparison, the DSU can be split into an ADC and a virtual sensor with a pseudo sensitivity of 2.26 V / 5 m.s^{-2} = 0.452 V/m/s².

Dynamic range is the ratio of the full scale over the RMS noise, expressed in decibels. It is the most important signal specification of a sensing unit as it describes its capability to record simultaneously large and very weak signal amplitudes.

Example: for a system having a full scale of 1.6 V RMS (±2.26 V peak) and a noise of 450 nV RMS at a 2 ms sample rate,

$$\text{dynamic range} = 20*\log 10 \frac{1.6}{450*10^{-9}} = 131 \text{ dB}$$

Sensitivity is the factor used to convert the analog or digital signal produced by the sensor into the physical quantity we wish to measure. Such a conversion is mandatory to compare seismic data recorded by analog and digital sensors. The output of a geophone is a voltage. This is then expressed as a velocity by dividing by the geophone sensitivity (in V/m/s). The issue is different for digital sensors, as a digital output ranges from -2^{23} to $+2^{23}$ (for a 24-bit system). The DSU's maximum recordable signal of 5 m/s² corresponds then to $+2^{23}$. DSUs can be compared with FDUs by introducing a pseudo sensitivity to convert input acceleration into voltage: the pseudo sensitivity is the ratio between the full scale of an FDU of reference with the full scale of the DSU (Figure 4).

Note that the FDU ADC noise RMS, when converted in velocity, will appear lower when using high-sensitivity geophones.

Comparing acceleration data sets with velocity data sets

The motion shown by both geophone and digital sensors is the ground particle motion at the location of measurement. However, velocity (output from the geophone above its resonant frequency) and acceleration (output from the MEMS digital sensor below its resonant frequency) are 90 degrees apart. In addition, the amplitude response of both types of sensor displays a difference of +6 dB/octave (high frequencies are boosted by digital sensors). As a result, seismic data recorded by digital sensors seem to have a higher frequency/vertical resolution, but this is mainly because we are in a different domain. If we had derived geophone data in the acceleration domain, we would also have boosted the high frequencies.

It is therefore mandatory to apply a conversion to compare both data sets. This conversion is always performed from acceleration to velocity which is the reference domain for interpreters to pick reflectors at their exact time location: zero-phase wavelets are aligned with the contrasts in acoustic impedance only in the velocity domain. This conversion is often performed by applying an integration operator that boosts the low frequencies but also boosts the associated noise. To avoid introducing noisy data into data processing, zero-phase deconvolution may be applied directly to acceleration data. It is often stated that the output is in the velocity domain irrespective of the type of sensor.

Geophysical benefits and operational advantages of MEMS digital sensors

Digital sensors must be used as single sensors since they must be recorded individually. This means that the benefits for operations have to be found when comparing digital sensors with digitizers, each connected to a single geophone (or to bunched phones if single ones are not available). For 3C (three-component) recording, a single 3C digital sensor must be compared to three digitizers connected to a triphone.

The original technology behind digital seismic sensors provides a wide range of geophysical benefits that ultimately ensure the higher fidelity and stability of seismic measurements:

- Geophone specifications are given with tolerances (e.g., for sensitivity or natural frequency) and for a given operating temperature. As a consequence, the geophone output will be dependent on the temperature, the unit manufactured, but also on the ageing of the miscellaneous components. This is not the case for digital sensors, the output of which is insensitive to ageing and temperature. As a result, seismic amplitudes are better preserved, which makes such sensors highly suitable for miscellaneous applications (e.g., AVO) (Mougenot, 2013); and wavelet phase is also more stable, particularly in low frequencies.
- Electromagnetic noise is not picked up owing to the fact that there is no coil; the full digital transmission avoids picking up other external noise through the line.
- The digital sensor's amplitude and phase response remains linear and flat from 0 to around 1 kHz in the acceleration domain. Moving to the velocity domain, digital sensor amplitudes increase by 6 dB per octave compared with the geophone's flat response above its natural frequency – this makes digital sensors particularly suitable for high-frequency recording. At low frequencies, below the geophone's natural frequency, the digital sensors are only attenuated by 6 dB/octave compared with the 12 dB/octave attenuation of geophones, while the latest generation of MEMS significantly reduced the low-frequency instrument noise (Moreau et al., 2014).
- MEMS noise fits better with field noise, i.e., with noise decreasing towards the high frequencies.
- Finally, the 3C digital sensors enable high vector fidelity since they are capable of detecting the gravity field and then measuring the tilt angle and correcting it.

Field operations are also simplified when operating with digital seismic sensors. Firstly, one digital channel is smaller and lighter (~30%) than an FDU with its string of geophones, and uses less power (~20%). Secondly, the sensor's tight integration with the telemetry makes the line more robust (less connectors) and easier to manage, particularly for cable lay-out, pick-up and repairs. As a result, operations are significantly facilitated by the deployment of less field equipment, and less staff and technical resources to manage this equipment.

Data quality

The second, but surely most important question, concerns the quality of data acquired with digital sensors. The literature abounds with examples of successful deployment of digital sensors for mining (e.g., Meisheng et al., 2008), 3C applications (e.g., Stotter, 2011), thin gas reservoir identification from preserved far offset AVO (e.g., Shi et al., 2008, 2009), or tight oil exploration (Xuming et al., 2014), and they are widely used for any application in regions such as China or North and South America.

Two new tests acquired with digital sensors were conducted in 2016 to assess the benefits of digital sensors for broadband recording, particularly on the low-frequency side. The first test (Figure 5) was commissioned by Ritek, the technology division of Lukoil, and acquired in February 2016 by Geotech SeismoRazvedka in the Samara region (South Russia). The initial purpose of the test was to compare low-frequency sweeps starting from 2 Hz with linear sweeps starting from 7 Hz, but digital sensors available at the time of the tests enabled the comparison with 10 Hz geophones.

As digital sensor evaluation was not the main purpose of these tests, the parameters chosen were actually quite unfavourable for this type of sensor: one digital sensor was indeed compared to a string of 12 geophones, with the latter offering important source-generated noise attenuation directly in the field. The theoretical benefit on the raw shot's signal-to-ambient-noise ratio is then of √12 for the geophone array, which can be more realistically reduced to √6 if considering a minimum decorrelation distance between receivers of 5 m. The datasets were nonetheless processed identically to allow unbiased comparisons, apart from a mandatory integration for the DSU data. The digital sensors showed a data quality that outstripped the data quality obtained with the geophone strings, particularly in terms of data bandwidth. This produced an imaging that was richer in low frequencies that are particularly visible at great depths (Figure 6). Even better results could have been expected from digital sensors if used with a suitable geometry and a dedicated processing flow.

The second test was acquired in December 2015 in Manitoba, Canada, with the purpose of comparing three types of sensors laid out side-by-side on three 2900 m parallel lines (290 RPs with 10-m group intervals each):

- Line 1 = Single 5 Hz geophone in marsh casing.
- Line 2 = 3x2 10 Hz geophones in land casing podded in a 4 ft diameter circle.
- Line 3 = Single DSU QuietSeis.

The DSU QuietSeis sensor is the latest generation of digital sensors, designed to enhance even further the capability to record low frequencies, particularly as a result of an ultra-low sensor noise floor, lower than the noise floor of a geophone connected to a digitizer (Moreau 2014) thus enabling the characterization of even deeper and weaker events. The three receiver lines were acquired by a single 40,000 lbs Mertz 18 vibrator, using a single low-dwell sweep of 2-90 Hz, 30 s length, on a 20 m VP grid. Here again, a clear deeper penetration of the low frequencies is visible on the stack after amplitude compensation and denoising, and these results are confirmed on the corresponding spectra with an advantage in terms of signal amplitude around 5 dB below 6 Hz when compared to geophones (Figure 7).

The cost issue

Designing an ideal survey that would provide at a reasonable cost all the required information to understand the subsurface and all its features (from large-scale structures to the most subtle fault) without any compromises has long been the dream of land seismic designers and interpreters. Current thinking revolves around the concept of obtaining dramatically more field data (of individually lower quality) that fits the Big Data motto of 'more

	Conventional sweep	Low-dwell sweep
Bandwidth	7-90 Hz	2-90 Hz
Length	10 s	13.5 s
Start taper	linear, 500 ms	low-dwell, 4 s
end taper	500 ms	500 ms
Vibrator	62,000 lbf	62,000 lbf
Drive level	50%	50%
Vertical stack	4	4

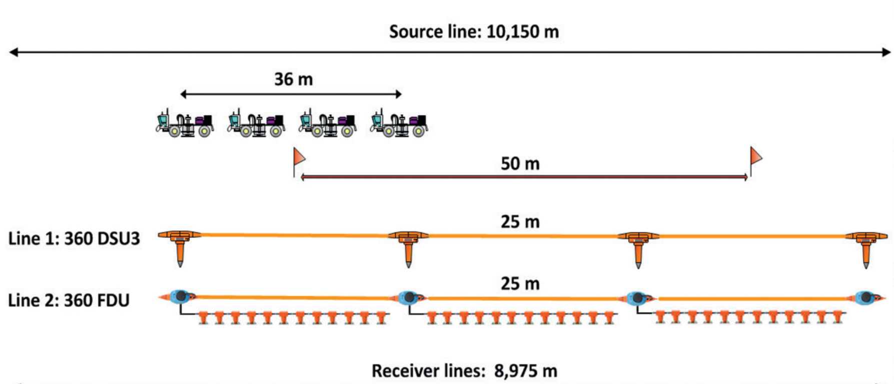


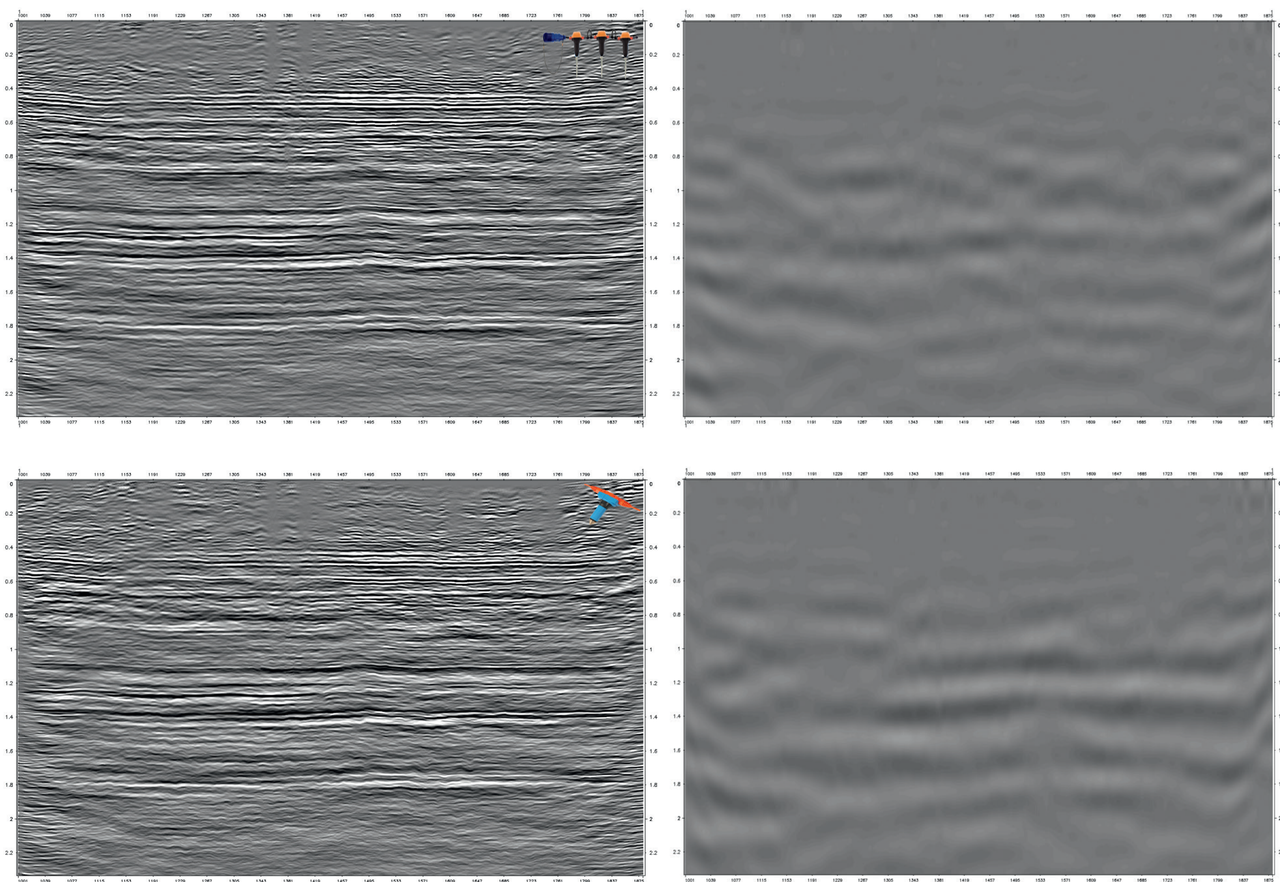
Figure 5 Test overview: sweep parameters (top left), geometry (bottom left), sources (top right), DSU-428 digital accelerometers (middle right) and the test area (bottom right).

data is better data', the information acquired on such projects being rich enough to perform adequately any analysis, ranging from accurate velocity models to seismic attribute analysis, and make the interpretation less subjective.

Land project designs have therefore gradually evolved in this direction, principally with:

- Adapted 3D geometries (dense and wide-azimuth, and also enabling the long offset recording), with high-channel-count spreads and reduced source and receiver arrays;
- High-productivity shooting methodologies, such as slip-sweep, DS3, DS4 or Free Vibrator, producing more than 10,000 VPs per day;
- Processing resources and technologies able to cope with enormous quantities of noisy data.

This logic remains true provided the field data is not affected by acquisition artifacts that cannot be addressed at the processing stage, such as the use of source or receiver arrays: they have proven to be an effective way of attenuating powerful surface waves directly in the field, but at the cost of high-frequency attenuation because of the intra-array filtering. While source fleets have significantly decreased in recent years, commonly down to a single or dual vibrator in the Middle East, the still widespread use of strings of geophones (even with a clear tendency to reduce the quantity of geophones per channel)



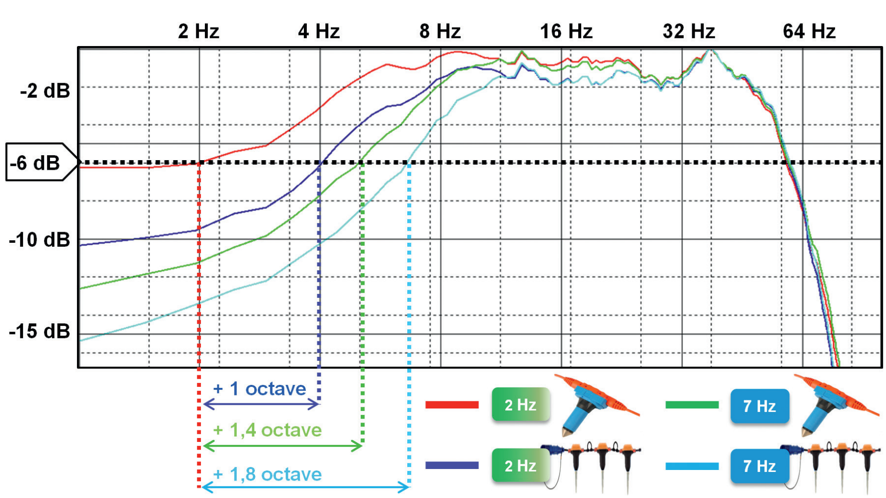


Figure 6 PSTM of the 2-Hz geophone data (top left) and 2-Hz DSU data (middle left), with their respective band-pass filter 1-2-4-6 (right). Bottom: spectra in logarithmic scale of PSTM for the four sets of data. On the 2 Hz dataset at a -6 dB level, the DSU data offer one extra octave of signal when compared to geophones.

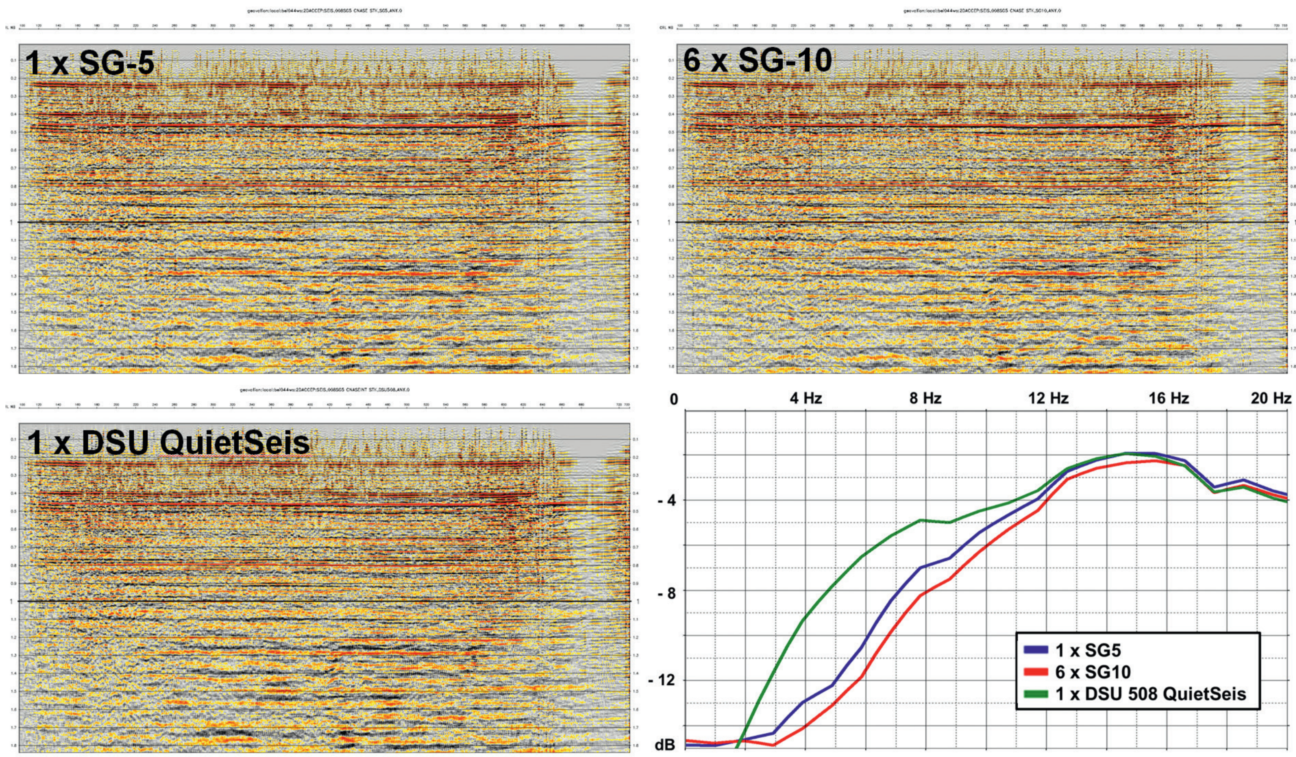


Figure 7 Stacks after amplitude compensation and denoising on a 150-1000 ms time window, and corresponding spectra. The same processing flow was applied, apart from the integration for DSU data.

remains by far the less mature approach towards performing a high-quality acquisition without compromise. This is confirmed by the fact that the number of crews using single sensors represents only a very small percentage of the total active crews worldwide, and among these crews, analog single sensors are used as often as digital MEMS. Therefore, whereas the technical and geophysical advantages of MEMS have been largely demonstrated, how can we explain the limited commercial success of this technology?

The last obstacle appears to be chiefly economic (Postel, 2016), mainly owing to the fact that when compared to a FDU with a string of geophones, a DSU configuration remains more expensive as a result of the higher density required. The usual 'rule of thumb' when substituting DSU's for geophones (Mougenot, 2011) is to use a DSU spacing that is:

- Larger than twice the geophone interval
- Smaller than half the channel interval

However, when analysing the cost of seismic sensors it is necessary to take a holistic approach and distinguish between capital expenditure for equipment (Capex) and operational expenditure (Opex) to operate this equipment. For Opex, the comparison is clearly unfavourable for geophone strings, if we take into account the effort needed to transport, deploy, retrieve, maintain and repair large quantities of equipment – in addition to the staff required for these tasks and the subsequent logistics (accommodation, catering, laundry, transportation etc.). HSE exposure is also correspondingly increased.

Reducing the cost of DSU deployment in terms of Capex and Opex is currently an ongoing process:

- The cost of manufacturing this equipment is steadily declining with mass production.
- The cost of deployment logistics is also declining as the field process is streamlined.

As for marine seismic acquisition, another major step forward concerning Capex and Opex would come with a standardization of the group interval. This will drastically simplify manufacturers' stocks and contractors' inventories and accelerate the global worldwide deployment of this type of equipment.

Conclusion

After more than a decade of existence in the market, digital seismic sensors have proven their technical and geophysical effectiveness for a wide range of applications, and their performance continues to improve at a regular pace. Their acceptance remains limited, however, as they represent only ~10% of the market in terms of channels (300,000 digital RPs compared with 3 million analog ones) and much less in terms of sensors (compared with about 50 million geophones). In low SNR areas subject to strong low-velocity source-generated noise, noise filtering with receiver arrays remains the preferred option for survey operators who rely only on shot displays for quality control.

We can expect digital sensors to replace these arrays once they can be deployed with a trace interval (both inline and crossline) that is small enough to record the full wavefield without aliasing and thus manage efficiently any type of noise at the processing stage. The key factor will then be the cost, especially in an industry facing a seemingly endless troubled period. That notwithstanding, the significant reduction in operational expenses offered by downsized seismic crews when operating with single sensors – a downsizing that will be probably driven even further by the mechanization of sensor layout and pick-up – and the constant progress being made in denoising algorithms will most likely be the primary factors that will convince operators to finally make the leap. This will make it possible to achieve much better imaging than with arrays, for an equivalent cost.

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