A high-sensitivity MEMS-based accelerometer

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Abstract

A new generation of accelerometers based on a microelectromechanical system (MEMS) can deliver broadband (0 to 800 Hz) and high-fidelity measurements of ground motion even at a low level. Such performance has been obtained by using a closed-loop configuration and a careful design which greatly mitigates all internal mechanical and electronic noise sources. To improve the signal-to-noise ratio toward the low frequencies at which instrument noise increases, a new MEMS has been developed. It provides a significantly lower noise floor (at least –10 dB) and thus a higher dynamic range (+10 dB). This performance has been tested in an underground facility where conditions approach the minimum terrestrial noise level. This new MEMS sensor will even further improve the detection of low frequencies and of weak signals such as those that come from deep targets or from microseismic events.

Introduction

In the search for oil and gas, seismic-reflection surveys are used to explore deep and complex targets. Successful imaging of these difficult targets requires an extended bandwidth and the dense sampling of the seismic wavefield across a large range of offsets and azimuths. This is achieved (Seeni et al., 2010; Mougenot and Liu, 2012) by using single-sensor single-source (S^4) high-density (HD) wide-azimuth acquisition (WAZ). In parallel, definition of an accurate velocity model using techniques such as full-waveform inversion is facilitated by preservation of an adequate signal-to-noise ratio at low frequencies (Mahrooqi et al., 2012).

Accelerometers based on a microelectromechanical system (MEMS) have been developed which are easily integrated with seismic recording systems and which fulfill all these requirements from operational and geophysical points of view (Mougenot et al., 2011). A receiver point might consist of a single device (e.g., the digital sensor unit [DSU]) whose weight is about half that of a single geophone connected to a digitizer (Figure 1). This lightweight and compact design eases the deployment of a large number of channels as required by S^4 HD WAZ 3D. While recording, MEMS sensitivity to external perturbations (e.g., temperature and electromagnetic pickup) is one order of magnitude less than that seen in geophones. MEMS delivers a digital signal within tight specifications. In particular, the MEMS response to a constant acceleration that varies in frequency is constant from DC (0 Hz) to 800 Hz, both in phase and in amplitude, which is optimal to capture a broadband signal (Mougenot and Thorburn, 2004).

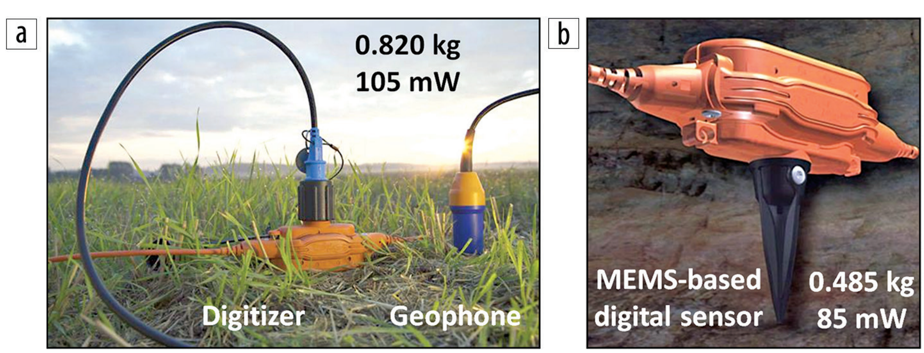

Figure 1. Compared with (a) a geophone connected to a digitizer, (b) a MEMS-based digital sensor provides many advantages. Some advantages are operational (e.g., compactness, weight, and power consumption), and others are related to geophysical performance (e.g., linear response over a large bandwidth, low distortion, and insensitivity to external perturbations).

However, the noise floor of MEMS accelerometers increases significantly toward the lowest frequencies (< 5 Hz), which might become apparent while recording in a very quiet environment (Meunier and Menard, 2004). This limitation to record a weak signal at low frequency can be compensated for by denser spatial sampling (Mougenot, 2013), but that would require using a significant number of MEMS accelerometers. A more straightforward solution is to decrease the noise floor. In this article, we describe a practical solution to this challenge with the development of a new generation of MEMS-based digital sensor.

Mechanical structure of a MEMS accelerometer

In the new capacitive MEMS, combs of electrodes (Figure 2) are distributed in different groups, each ensuring a different function. Two of them measure ground motion (seismic), another compensates for gravity, and the last is to perform active built-in tests (gain and distortion). Each group comprises at least a pair of combs for upward and downward motions. At each end of the MEMS axis, two springs enable a motion of the mass along its sensitive axis while restricting any cross-axis displacement that would induce crosstalk.

The frame–inertial mass assembly is engraved directly on a large silicon plate (wafer) from which hundreds of MEMS are manufactured simultaneously. Each one is sealed inside a ceramic package (Figure 3) under ultrahigh vacuum to reduce the Brownian-motion noise which results from the impact of air molecules against the mass. This vacuum is maintained because of an active metal compound called getter that pumps any remaining gas molecules throughout the life of the product.

Removing gas in the vicinity of the moving mass also removes any resistance to mass motion. As a result, the damping D, i.e., the energy loss resulting from air friction, is reduced. As shown by equation 1 below, Brownian noise is linked directly to the damping D (or quality factor defined as $Q = w_0M/D$), temperature T (as chaotic motion of gas molecules increases with temperature), and the proof mass:

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$$\text{Brownian noise} = \frac{\sqrt{4K_B TD}}{M} = \sqrt{\frac{4K_b T w_0}{MQ}}\ (m.s^{-2}.\text{Hz}^{-0.5}), \qquad (1)$$

where T is temperature in kelvin, D is damping, Q is quality factor, M is mass, K_B is Boltzmann constant, and w_0 is resonant pulsation. As explained further, "closing the loop" is mandatory to prevent the proof mass from ringing at the resonant frequency of the mass-spring system.

Electronic position sensor of a MEMS accelerometer

A MEMS accelerometer is based on the same principle as a coil geophone; it is a mass-spring system. When submitted to ground acceleration, the casing moves with respect to an inertial mass. In the case of a conventional geophone, an analog voltage $V(t)$ is induced by magnetic flux variation caused by coil displacement when submitted to ground velocity. The output signal is then proportional to the velocity of the coil with respect to the magnet. This explains why the geophone is a velocimeter above a resonant frequency that is inherent in the system. Indeed, the voltage output signal of an analog geophone is given by

$$V(t) = \frac{d\varnothing(x_r)}{dt} = \frac{d\varnothing(x_r)}{dx_r} \times \frac{dx_r}{dt} = S \times v(t), \qquad (2)$$

where S is sensitivity, $v(t)$ is ground velocity, $\varnothing x_r$ is magnetic flux, and x_r is coil position.

In the case of MEMS, mass displacement is measured by a companion application-specific integrated-circuit (ASIC) chip which includes a capacitive position sensor that measures capacitance C_m between the mobile electrodes attached to the inertial mass and those attached to the frame, the nominal distance (gap) between each finger of the mass and of the frame being a few micrometers. Because capacitance C_m is a function of the position of the moving mass with respect to the frame, the voltage signal at the output of the position sensor is proportional to the mass displacement $x_r(t)$ induced by ground acceleration even when constant (0 Hz):

$$V(t) = \Delta V \times \frac{C_m(t)}{C_{\text{ref}}} = \frac{\Delta V}{C_{\text{ref}}} \times \frac{2\varepsilon_0 Se}{\text{gap}^2} \times x_r(t), \qquad (3)$$

where ΔV is sensing voltage, C_m is variable capacitance, C_{ref} is position-sensor referenced capacitor, ε_0 is air permittivity, S_e is electrode surface, and $x_r(t)$ is mass position.

Benefits of a closed-loop configuration for MEMS accelerometers

Because the inertial mass M is limited in size to maximize the number of MEMS dies on a single silicon wafer, the air damping D should be as low as possible. Damping is ultralow because of the vacuum, so any small vibration would cause an open-loop MEMS to vibrate indefinitely at w_0, hiding useful seismic signals. The trade-off chosen for open-loop design to mitigate Brownian noise is to keep damping at a minimum value and increase the mass to keep noise level at a reasonable value. Moreover, w_0 has to be set far from useful bandwidth to minimize resonant frequency on the frequency-response flatness. However, this has a negative impact on sensitivity because in such an open-loop system, it is inversely proportional to w_0^2.

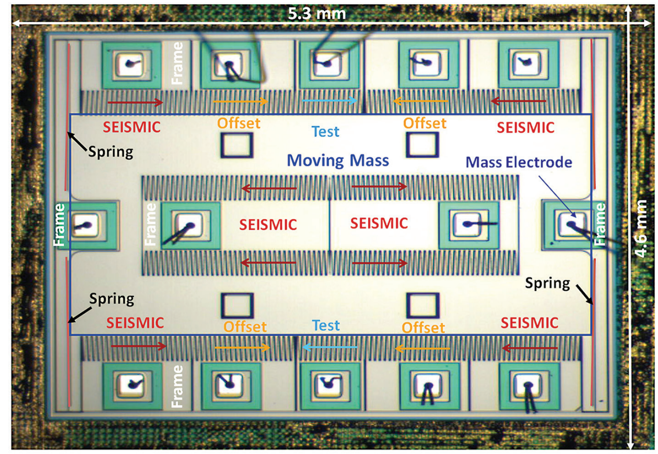


Figure 2. MEMS architecture of a single vector sensor from a digital sensor unit (DSU) as seen by microscope. This silicon mass-spring system is a purely mechanical component that behaves like a capacitor. Between the moving mass and the frame are combs of electrodes distributed in 12 areas to ensure upward and downward measurement of ground acceleration as well as compensation from offset (gravity) and tests with respect to a reference force.

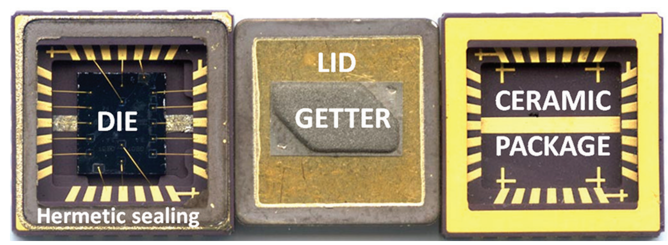


Figure 3. The MEMS is comprised of a silicon die inside a hermetically sealed ceramic package with ultrahigh vacuum that is maintained via a getter which absorbs residual air molecules.

Closing the loop (Figure 4) removes all these pitfalls and adds many benefits. Closing the loop involves starting from an open-loop MEMS and position detector, adding a high-gain loop (digital loop filter), and then using this output to steer a feedback that forces the inertial mass back to its rest position. Because of the high-gain digital filter, the closed-loop gain is constant, whatever the perturbations.

This can be expressed mathematically in terms of transfer function $H(s)$ defined as $H(s) = Y(s)/X(s)$, where $Y(s)$ is the output of a function, $X(s)$ is the input, and (s) is the Laplace variable which tells that transfer function fluctuates with frequencies. Because of this common tool in automatic systems analysis, a series of consecutive blocks in a loop can be expressed as the product of the transfer function of each block.

Therefore, the output of an open-loop accelerometer made up of a MEMS H_{MEMS} connected to a capacitive position detector H_{detect} and submitted to a ground acceleration $Acc(s)$ is

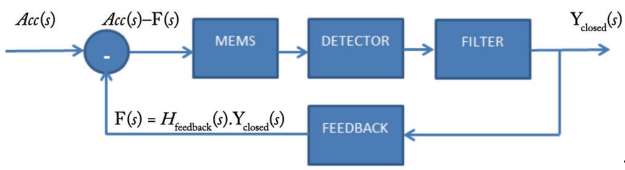
$$Y_{\text{open}}(s) = H_{\text{MEMS}}(s).H_{\text{detect}}(s).\,Acc(s). \qquad (4)$$

The output of a closed-loop accelerometer made up of the same MEMS and position detector followed by a high-gain filter H_{filter} and with a feedback loop F_{feedback} that feeds a portion of the output back to the input is

$$Y_{closed}(s) = H_{MEMS}(s).H_{detect}(s).H_{filter}(s).(Acc(s) - H_{feedback}(s).\ Y_{closed}(s))$$

$$\frac{Y_{closed}(s)}{Acc(s)} = \frac{H_{MEMS}(s).H_{detect}(s).H_{filter}(s)}{1+H_{feedback}.H_{MEMS}(s).H_{detect}(s).H_{filter}(s)} \approx$$

$$\frac{1}{H_{feedback}(s)} \text{ if } H_{filter}(s) \text{ gain is high enough.}$$



. (5)

As a result, the output of the closed-loop sensor is no longer linked to the MEMS or the capacitive position sensors' transfer function with their inherent defaults and is only a function of the feedback loop generated by the ASIC that can be designed more easily to be stable and accurate.

For example, the stiffness of the springs that has a direct impact on the sensitivity and resonant frequency of an open-loop system can vary within 10% to 20% of its nominal value because of temperature or process variations. In a closed-loop MEMS accelerometer, sensitivity is no longer a function of such mechanical parameters because it is driven mainly by the electrostatic feedback force. Because of the high reactivity of this loop, the response of the MEMS accelerometer is flat over the whole bandwidth (0 to 800 Hz). The closed loop also minimizes the mass displacement because any force on the mass induced by acceleration is counteracted immediately by an opposite electrostatic force. As a result, the actual mass displacement is negligible (a few nanometers), and no distortion is induced by any spring-stiffness nonlinearity.

MEMS noise-floor attenuation

The current generation of MEMS has a noise floor (40 ng/√Hz from 10 to 200 Hz) that is lower than the ambient noise in most of the surveyed areas. However, this noise increases toward low frequencies, particularly below 5 Hz, where it can exceed ambient noise. Below 55 Hz, it becomes higher than that of a single geophone connected to a digitizer (Figure 5a). Even if processing data recorded from closely spaced MEMS accelerometers could mitigate this gap, it became important to put the MEMS noise floor at a level similar to that of the geophone, particularly for low frequencies and weak-reflection recording. For that, significant changes in the MEMS and associated ASIC were required.

To reach the target specification (Figure 5b) of 10 to 15ng/√Hz for a new generation of MEMS accelerometers, it has been necessary to mitigate all internal electronic and mechanical noise sources without any increase in power consumption:

- The first electronic noise contribution was the noise of the position sensor. The structure has been improved, and the noise of the reference voltages it uses has been lowered.
- The other main electronic noise is the force actuator that closes the loop. Because feedback force is defined by the amplitude of the signal sent on moving electrodes and by the duration of its application, these two parameters have been

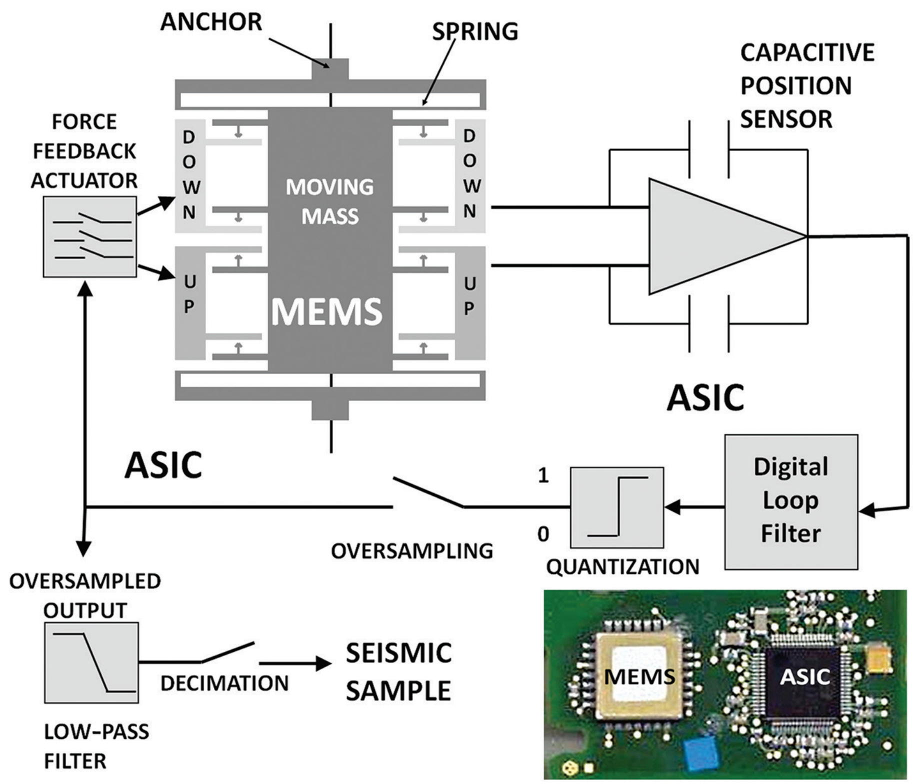


Figure 4. MEMS has a companion chip (ASIC) that performs a servoloop control by detecting the position of its moving mass. To limit the displacement to a few nanometers, a force-feedback actuator generates within microseconds a voltage that brings the electrodes back to their rest positions.

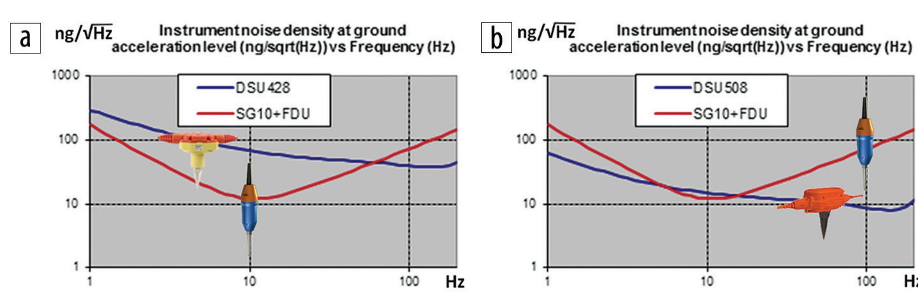


Figure 5. Comparison in acceleration of the noise floor from different sensors: (a) previous-generation MEMS sensor and (b) the new one, both shown versus a 10-Hz geophone connected to a digitizer. The new MEMS brings the noise floor to a level lower than that of the geophone.

improved by removing as much amplitude and phase noise as possible in the control signals applied on MEMS electrodes.
- On the mechanical side, the MEMS vacuum has been pushed farther to lower the Brownian noise. Moreover, a detailed analysis of all high-frequency spurious modes has been performed. Mechanical design has been modified to mitigate all spurious modes that could impact the stability and system noise performances.

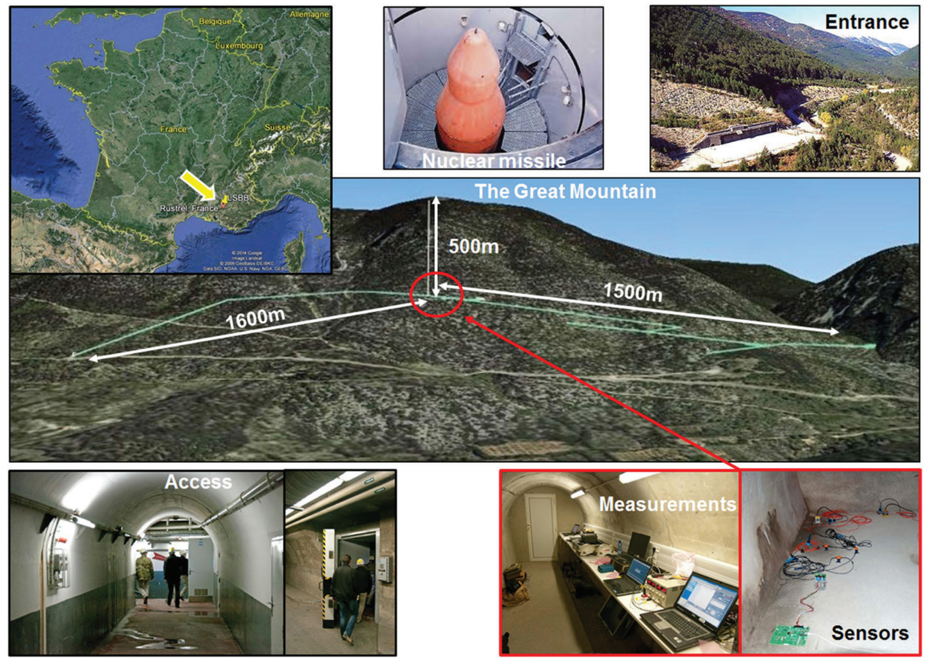


Figure 6. The LSBB is a low-noise underground facility in a rural area in the south of France that previously housed a silo for nuclear missiles. The high acoustic shielding of the laboratory, buried 500 m under the mountain, make it possible to obtain low noise measurements.

Measurement of noise floor

To verify the noise floor of the new-generation MEMS, testing necessitated the use of a quiet area to enable measurement of such low levels of noise. The facility selected is in the south of France in a missile silo that was decommissioned in 1997 to be used for scientific measurements that require great isolation (Figure 6). The core facility of the Laboratoire Souterrain à Bas Bruit (LSBB), an Interdisciplinary Underground Science and Technology (i-DUST) laboratory, is buried 500 m below a mountain in a rural area far from industrial activity, roads, and railways. The extremely weak anthropic impact and the acoustic shielding allow a threshold of noise close to the minimum terrestrial noise to be reached (0.4 ng/√Hz from 1 to 100 Hz; Peterson new low-noise model [NLNM]).

Measurements were done on vertical and horizontal MEMS accelerometers (Figure 7). From 1 Hz to 1 kHz, the measurements show a good fit between the expected noise floor and the actual one. From 60 ng/√Hz at 1 Hz, noise reaches 20 ng/√Hz at 6 Hz and is below 10 ng/√Hz at 70 Hz. The performance is even better on the horizontal component, which does not require gravity compensation. From 30 ng/√Hz at 1 Hz, noise reaches 20 ng/√Hz at 3 Hz and is below 10 ng/√Hz at 70 Hz. In both cases, the gap with the typical instrument noise of the previous-generation MEMS (DSU-428) is –10 to –12 dB. If we compare the new noise floor with that of a single geophone connected to a digitizer for most frequencies, except around 10 Hz, it is lower (Figure 5b).

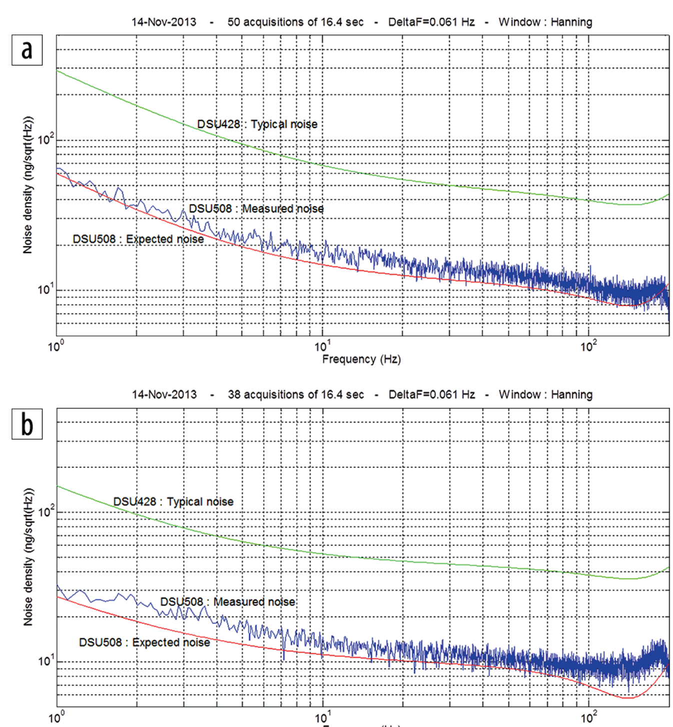


Figure 7. (a) Noise-floor density in ng/√Hz (nano-g per root hertz with g = 9.80665 m/s²) comparison of the vertical component of the new MEMS-based sensor (expected noise shown in red, measured noise in blue) compared with the previous one (typical noise shown in green). A reduction of at least 10 dB is noticed throughout the bandwidth. (b) Noise-floor density in ng/√Hz (nano-g per root hertz with g = 9.80665 m/s²) comparison of the horizontal component of the new MEMS-based sensor (expected noise shown in red, measured noise in blue) compared with the previous one (typical noise shown in green). The same reduction (–10 dB) as for the vertical component is noticed except that the general noise level is less because of the absence of gravity compensation.

Interests of low-noise-floor MEMS for seismic acquisition

Although the noise floor has been lowered significantly, the full scale of the new MEMS is still identical to the previous one (0.5 g), and it is constant in the acceleration domain. The instantaneous dynamic range of the MEMS accelerometer is the ratio of the rms values of this full scale over the noise floor. In the frequency range of 10 to 100 Hz corresponding to a sampling rate of 4 ms, the amount of noise is about 100 ng, and the dynamic range reaches 130 dB. With respect to the dynamic range of the previous MEMS generation (120 dB @ 4 ms for the DSU-428), this is a significant improvement.

In desert areas and for the lowest frequencies, the noise floor can be the limiting factor to record weak signals because it becomes higher than the ambient noise. In such conditions, a drop of –10 dB (/$\sqrt{10}$) corresponds to an improvement of the signal-to-noise ratio that would have been obtained with the previous MEMS only by using 10 times more recording channels or by increasing the vibroseis sweep length by a factor of 10 (Gibson et al., 2010).

When instrument noise is above ambient noise, the amplitude of weaker signals that can be identified is reduced significantly. Assuming that this noise has a Gaussian distribution, the vertical component of the new MEMS sensor will detect a noncoherent signal (e.g., a microseismic event) that has more than three times lower amplitude than could be detected with the previous MEMS sensor generation.

In a bandwidth of 100 Hz, the magnitude in acceleration of a noncoherent event of three times the rms noise that is detected with a probability of 99.7% would be

- for the new MEMS sensor (DSU-508): 12 ng × $\sqrt{100}$ × 3 = 360 ng
- for the previous MEMS sensor (DSU-428): 40 ng × $\sqrt{100}$ × 3 = 1200 ng

In the case of a coherent signal detection such as for that of a vibrator, we can obtain from the new MEMS the same signal-to-instrument-noise ratio as with the previous MEMS using a stack order or a sweep length 10 times lower.

Conclusions

MEMS accelerometers exhibit many favorable characteristics that make them the sensor of choice for broadband single-sensor single-source high-density 3D acquisition. The previous-generation MEMS sensors (DSU-428) provided many successful examples of projects in which vertical resolution of the sections was increased because of broader frequency bandwidth. However, at low frequency and for deeper and weaker events, the improvement was not significant unless the survey was recorded with much higher trace density.

Today, a new MEMS sensor generation has been developed that displays a significantly lower noise floor (at least –10 dB) and thus a higher dynamic range (+10 dB). Considering that MEMS sensor response is linear in the acceleration domain down to DC, there should be no attenuation and sufficient signal-to-noise ratio toward the low end of the spectrum. These are the ideal conditions to record low frequencies (down to 1 Hz) as emitted by heavy vibrators using low dwell sweeps. This should fulfill the frequency requirement for the latest inversion methodologies (e.g., FWI).

Three-component MEMS accelerometers also become suited to passive monitoring of weak microseismic events such as those generated by hydraulic fracturing. TLE

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