MEMS-based 3C accelerometers for land seismic acquisition: Is it time?

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Recent advances have allowed development of micro electro mechanical system (MEMS) sensors with the sensitivity, low noise, and dynamic range needed in seismic acquisition. This is a possible "breakthrough" because MEMS accelerometers have the potential to provide broader bandwidth, more accurate amplitude, and less sensitivity to planting tilt than the coil-based geophones that have long been used in the industry.

Several papers have presented the advantages of three-component acquisition with single digital sensors based on MEMS, and the advent of these sensors has been promoted as the next big advance in land seismic acquisition—much like the shift to 24-bits recording systems 10 years ago. So, this is a good time to ask an obvious question: Has this technology really advanced to the point that it can, or should, be used for general-purpose land seismic acquisition? This paper will attempt to answer that question by addressing the advantages and disadvantages for the general application of single 3C digital sensors.

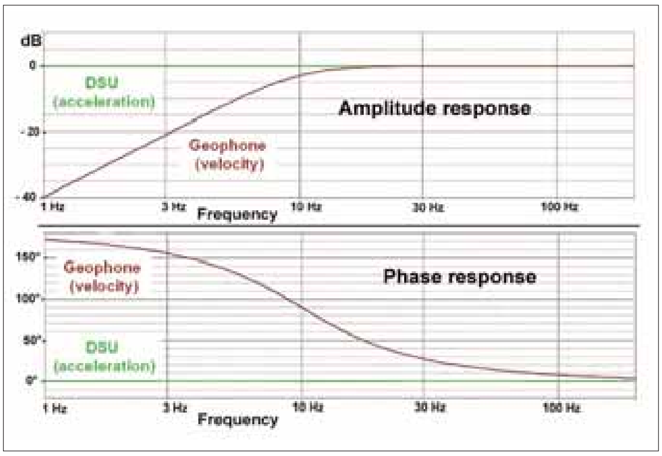

Figure 1. Linear phase and amplitude response of a digital sensor unit (DSU) with MEMS compared with that of a 10-Hz geophone. The response is in the velocity domain for the geophone and in the acceleration domain for the DSU.

Why accelerometers for digital sensors? Ground motion can be measured as displacement, velocity, or acceleration. A mass/spring assembly is used for all these measurements. With a soft spring, the mass (the coil in the geophone) does not move and represents the reference for displacement or velocity measurements. With a stiff spring, the mass moves with the case, but with a small residual displacement related to the acceleration. This acceleration can be measured either by the strain on the spring (e.g., low cost, low power, high distortion air bags) or by a feedback force applied to the mass to cancel the displacement (e.g., high performance digital sensors requiring power supply).

In this last implementation the sensor based on MEMS is still analog, while the control loop and the output provided by an application specific integrated chip (ASIC) are digital. Such a "digital" sensor is much smaller than the current standard. A MEMS accelerometer is a tiny silicon chip with a length of ~1 cm and weighing less than 1 g. A coil-based sensor is a cartridge with a length of 3 cm and weight of 76 g. Within the chip, the residual displacement between the inertial mass and the frame is on the order of a few nanometers, while the motion of a geophone coil may reach 2 mm.

However, manufacturing such a "digital" sensor is expensive due to the cost of MEMS + ASIC. Therefore, actual recording in the field will use a single-sensor configuration (i.e., only one sensor per active channel).

Comparison of MEMS-based sensors and coiled geophones. From the specification point of view, the essential benefit of MEMS accelerometers is a broadband linear amplitude and phase response that may extend from 0 (dc) to 800 Hz within 1% in amplitude and 20 ms in time (Figure 1) . MEMS resonant frequency is far above the seismic band pass (1 kHz). This makes it possible to record frequencies below 10 Hz without attenuation, including the direct current (dc) related to the gravity acceleration. The gravity vector provides a useful reference for sensitivity calibration and tilt measurement of 3C MEMS-based sensors that has no equivalent for geophones. Because acceleration increases with frequency (at constant velocity), MEMS accelerometers also are excellent for high-frequency measurements. In this domain (> 50 Hz) the floor/electric noise of the MEMS is lower than that of the equivalent geophone/station electronics.

These broadband capabilities offer possible dramatic improvement in the vertical resolution of seismic data, which depends on the ratio between the maximum and minimum frequencies of the signal ($F_{max}/F_{min} = 2^n$, n being the number of octaves). A MEMS accelerometer is particularly suited for recording low frequency signals (< 5 Hz) like reflections at the main boundaries between lithological formations (or even earthquakes). In this frequency range, the limitation is more on the source side because such LF signals cannot be emitted with a sufficient S/N ratio. Recording of high frequencies is limited by their strong attenuation during propagation. However, MEMS sensors should be able, if close enough, to listen to microseismic events (~500 Hz) as fluids move in the reservoir during oil and gas production.

The total dynamic range of a 24-bit recording system using MEMS can be up to 120 dB (ratio between the floor noise at 4 ms sampling rate—4.5 $\mu m/s^2$—and the maximum signal—4.5 m/s^2—that can be recorded with less than -90 dB distortion). It is lower than the total dynamic range of the same system using single geophones that should be up to 140 dB (this is also the total dynamic range of the latest 24 bits recording systems). In practical situations (including the distortion generated by a strong signal or noise), the instantaneous dynamic range of a MEMS accelerometer (95 dB) is much better than the one of a single geophone (no more than 70 dB, but this may be improved by using groups of geophones). These differences in total and instantaneous dynamic ranges explain why a MEMS-based sensor is more suited to record a weak signal in presence of strong noise (near offsets) while a geophone (and even more a string of geophones) is more effective in recording a weak/deep reflection in presence of low noise (far offsets).

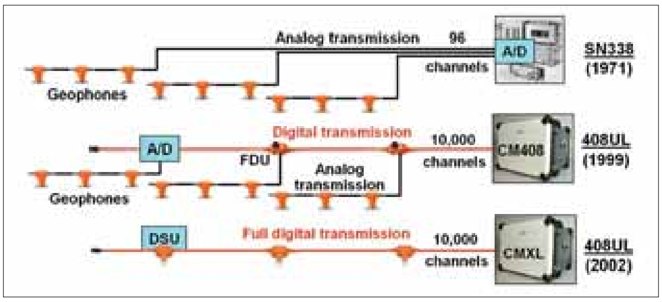

Figure 2. *In the first digital recording system (top), all transmissions between geophone groups and central unit, including the A/D converter, were analog. About 30 years later (center), only transmission between geophone groups and the field digitizing unit (FDU) was analog. Today (bottom), the digital sensor unit (DSU) makes possible full digital transmission.*

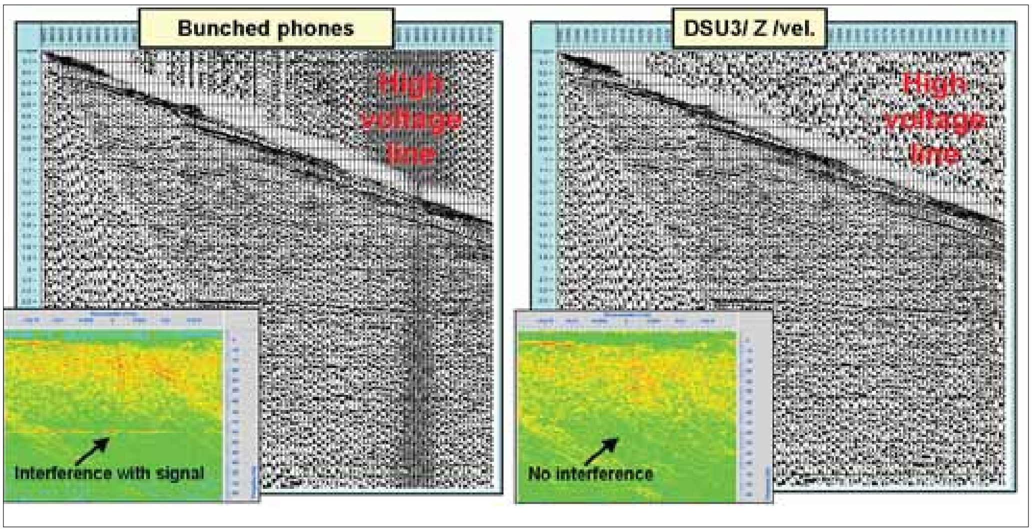

Figure 3. *Shotpoint comparison between the vertical component of a digital sensor unit (DSU3) and bunched phones planted at the same location (photo). Strong pick up of a high voltage line is due to analog transmission up to the station electronics. The f-k diagram shows this 50-Hz noise interfere with signal. DSU data are not contaminated. (Data courtesy of BatchNeftGeofisika)*

Amplitude calibration of a MEMS sensor and its stability over aging and temperature variations are better than that of traditional geophones. Overall, the performance of a digital sensor, in which MEMS are integrated with the station electronics in a single housing, is better than conventional station electronics that is connected during the same survey to different strings of geophones of variable characteristics.

The full digital transmission. In the early 1970s, the A/D converter of the first digital recording system was implemented in the central unit. One analog pair of wires for each channel was used for transmission between strings of geophones and the recording truck (Figure 2). Noise from electromagnetic interference, signal cross-talk, and sensitivity to leakage were common. About 30 years later, the electronics distributed in the seismic network provided digitization close to the geophone groups. Only two pairs of wires are necessary for telemetric transmission of 10 000 or more channels in real time. Sensitivity to leakage is reduced and the digital data are controlled by each node of the seismic network (and, thus, may be retransmitted if necessary). However, noise pick may still contaminate the analog signals transmitted through the strings of geophones. This should disappear with the integration of the sensor with the station electronics as it is done with the MEMS accelerometers.

The advantages for the full digital transmission have already been checked. During field tests, records by bunched geophones were compared to MEMS sensors at the same location (Figure 3). 50 Hz (picked up below a high voltage line) is obvious on the shotpoint recorded by bunched phones. On the corresponding *f-k* diagram, the electromagnetic noise interferes strongly with signal. This noise does not occur on any of the three components of the MEMS sensors due to the full digital transmission.

Digital sensors to replace arrays of geophones? Arrays of geophones may tremendously improve the dynamic range of a receiver point by reducing ambient and coherent noise. Compared to a single geophone, an array of N geophones, whether connected in series or in parallel, improves the dynamic range by 10 × logN dB, as the ambient noise is reduced by the square root of N. For attenuation of coherent noise, geophones are laid out in a spatial pattern that provides array filtering. The size of the array and the number of wired geophones should be large enough to properly sample the maximum wavelength of the ground roll.

Despite these advantages, field geophysicists would like to get rid of arrays because they are large and heavy and, as a result, slow crew productivity and require expensive logistics. At first glance, the use of single digital sensors would have many operational and geophysical advantages over geophone arrays. Layout and positioning are easier than with geophone strings, and this is even more relevant for 3C receiver points. Recording is isotropic (no azimuth-dependent array filtering), and the high frequency content of the signal is not attenuated by intra-array statics (particularly in S-wave recording). However, these benefits are only true in an ideal world where reflected signal is not contaminated by noise—i.e., in a situation where a single coiled geophone would have been sufficient.

In the field, the spacing of single sensors should decrease with respect to the length of a geophone array. This shorter spacing will not attenuate noise while recording, but it will provide enough multiplicity (fold coverage) to decrease the ambient noise while stacking data. Denser spatial sampling also prevents the coherent noise from aliasing. Therefore, we cannot expect to get better looking shotpoint displays while recording with single digital sensors. The benefits (larger frequency content, more accurate amplitude) will only show up with the final sections, after data processing.

New requirements for acquisition geometry. In practice, how many MEMS sensors would be necessary to replace a string of N geophones? It is unlikely that anyone will record as many single digital sensors as hard-wired geophones, and it is probably not necessary, even though that would provide excellent noise attenuation.

Let us consider ground roll (GR), often the strongest noise. In this case, the digital sensor spacing D should be

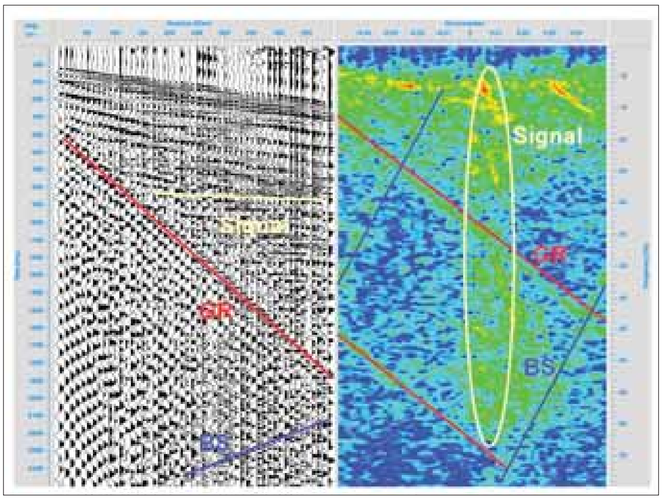

Figure 4. *Shotpoint (GR = ground roll, BS = backscattering) with 10-m spacing between single digital sensors. On the f-k diagram, GR is aliased and interferes with signal. (Data courtesy of CGG)*

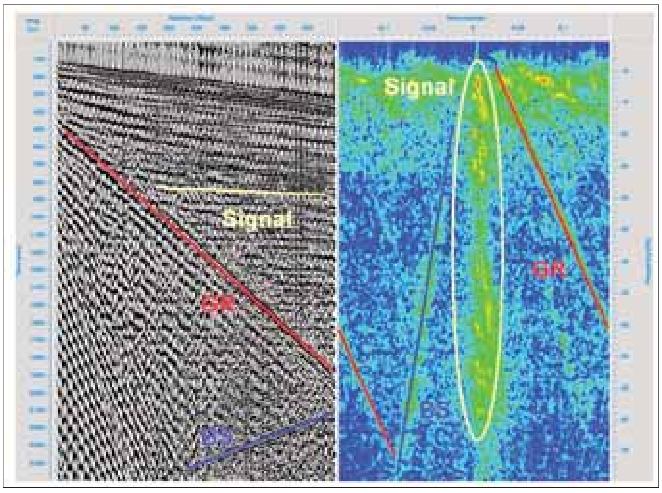

Figure 5. *Shotpoint with 3.3 m spacing between single digital sensors. On the f-k diagram, GR is still aliased but does not interfere with signal. (Data courtesy of CGG)*

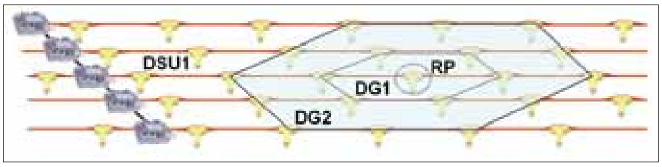

Figure 6. *2D acquisition design that uses a corridor of 1C single digital sensor units connected along parallel telemetric cables. At a given receiver point (RP) different types of digital groups (DG1, DG2) may be considered to reduce ambient noise and filter the ground roll.*

such that the GR wavelength L = Va/Fa (Va = apparent velocity, Fa = apparent frequency) will be sampled at least two times (i.e., D = Va/2Fa). This often provides values in the range of 3 to 30 m. Figures 4 and 5 compare *f-k* diagrams of two SPs recorded at the same location with different spatial sampling. At 10-m spacing, the very low velocity ground roll (330 m/s which is as low as the air blast) is aliased and interferes with signal. At 3.33-m spacing, GR is still aliased but it vanishes at high frequencies (70 Hz) before intersecting the signal. Considering this maximum frequency limitation of the noise it is possible to adequately sample with a spacing a little more than half of the GR wavelet, as suggested by Baeten et al. (2000).

Up to now, we have considered only 2D propagation.

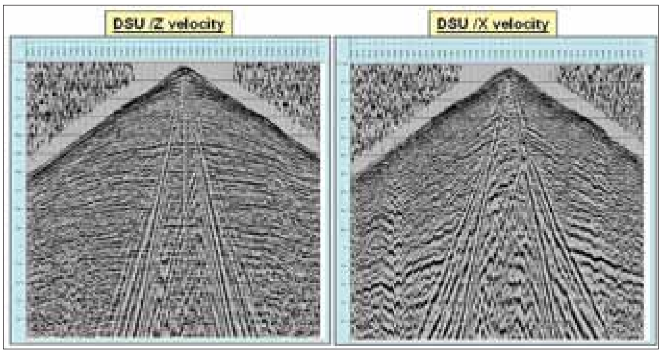

Figure 7. *Real time display of three-component digital sensor shot points (Z and X components) in the doghouse after velocity conversion and low-cut (10 Hz) filtering. (Data courtesy of Veritas DGC and Devon)*

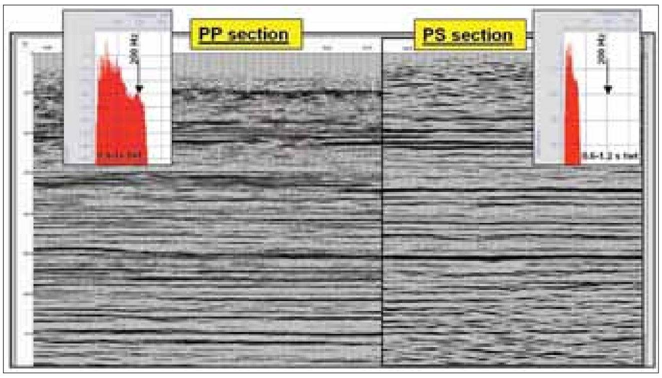

Figure 8. *Comparison of PP and PS final sections corresponding to the previous SPs. The PS section is squeezed to PP time by assuming constant $V_P/V_S = 3$. The frequency content of the PP section is above 200 Hz; in the PS section, frequencies above 70 Hz have been attenuated. The reflectivity of the two sections recorded in sand/shale formations is quite different. (Data courtesy of Veritas DGC and Devon)*

With 3D acquisition or complex near-surface-generated backscattered noise, it would be necessary to sample the noise properly both in the inline and crossline directions. Such areal sampling would require a corridor of single digital sensors equivalent to the patches of hard-wired geophones. Since digital sensors are directly connected to a telemetry cable, deployment of such receiver line would require several parallel cables (Figure 6) instead of only one telemetry cable for all geophones. A quick calculation of the channel requirement for a 3D swath of 4 × 4 km^2 with 100 m between receiver lines (each having five individual cables with single digital sensors at 10-m spacing) produces a figure of 80 000 active channels. This amount is still beyond the real-time capability of all recording systems at 2 ms sampling. Today, this type of single sensor arrangement is only compatible with a 2D acquisition.

Due to the continuous spatial sampling, this corridor of single sensors provides a sort of 2D universal acquisition design. Different single sensor combinations, often referred as digital group forming, may be used to attenuate noise after recording by all single digital sensors. Since groups overlap from point-to-point, each single sensor may be used in different digital groups. At a given receiver point, this "group forming" may even involve time-dependent digital arrays since S/N ratio decreases as traveltime increases.

A new era for 3C recording. Connecting strings of three-component geophones (triphones) to a telemetry cable involves heavy equipment, lots of wire, and many connectors. With standard equipment, planting, leveling, and properly orienting these triphones is painful but

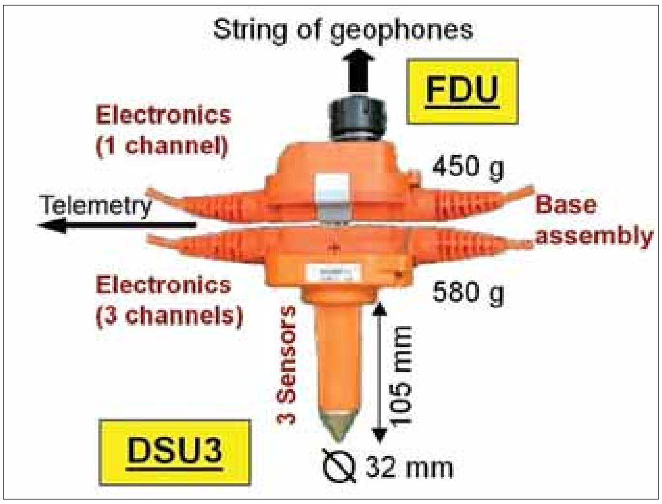

Figure 9. Back-to-back comparison of a 408UL station electronics (FDU) that should be connected to a string of geophones with a 408UL 3C digital sensor unit (DSU3) that includes three sensors with the corresponding electronics. Base assembly to the telemetry line is the same to switch easily from analog to digital sensors.

mandatory. The final output is the electric sum of all triphones connected to the same station electronics and any correction is impossible at a later stage. Having sensors and station electronics integrated in the same housing will reduce overall weight and wiring errors, and should make all multicomponent surveys faster, better, and cheaper.

Of course, planting a 3C digital sensor would need some attention to get the proper coupling, but ensuring its exact verticality is not mandatory. This is because of a unique feature of the MEMS-based 3C digital sensor—its ability to measure the continuous effect of the gravity vector. This vector is used as a reference to automatically compute with high accuracy (±0.5°) the tilt of each horizontal sensor. These tilt values are stored in the trace header extensions, and data may be even corrected for tilt in real time by the central unit. Sensor orientation may be corrected, if necessary, during processing by assuming a radial propagation between the source and the single sensor (3D surveys only).

Tilt measurement is only one aspect of the advantages provided, in terms of vector fidelity, by the MEMS-based 3C digital sensors. Their broadband capabilities (0-800 Hz linear response), the very precise orthogonality of the sensors (±0.25° accuracy) and the accurate and stable amplitude calibration (±0.25% accuracy) will improve overall quality of 3C seismic data.

Many surveys have already field proven this 3C digital sensor technology. Data in Figures 7 and 8, from a 2D acquisition recorded with explosives in North America, demonstrate the broadband capabilities of the MEMS 3C digital sensor. High frequency preservation while stacking has required careful static definition and efficient deconvolution after noise attenuation. On the final PP section, the frequency spectrum of the signal in a 0.4-1.0 s window is above 200 Hz, and signal beyond 300 Hz is evident down to 0.2 s.

Crew productivity with single 3C digital sensors. Seismic data acquisition with high-density single digital sensors will require recording a large number of channels. Short receiver point spacing to get adequate noise sampling may double (or more) the number of channels. Three components instead of one will triple the number of channels. For 3D surveys, this may mean tens of thousands of channels. To maintain productivity with a such high channel count, the

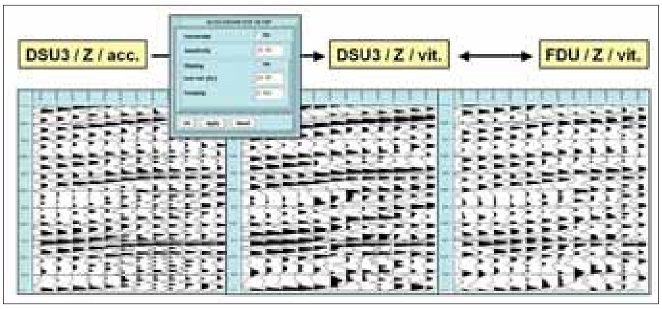

Figure 10. Real time QC of a shotpoint (Z component) coming from digital sensor units and conventional geophone strings (FDU) laid out at the same location and recorded by the same central unit. For visual comparison it is possible in real time to integrate acceleration data into the velocity domain, and to apply low cut filtering to mimic geophone data.

ground equipment must be light, and the acquisition system low power. Transmission redundancy should be available thanks to multipath telemetry, and real-time quality control of the spread and of the seismic data should be available for quick quality control.

As implemented in the 408UL recording system (Figure 9), the 580 g of a 3C digital sensor unit (including the base assembly with the telemetry cable, all station electronics for the three channels and the three MEMS sensors) compares favorably with the 450 g of the 1C field digitizing unit (including the same base assembly and the electronics for only one channel to be connected to a string of geophones). This comparison illustrates the high level of sensor/electronics integration that MEMS accelerometers makes it possible.

Considering costs associated with manpower and health/safety/environmental issues related to the use of vehicles, a seismic crew should use the smallest number of batteries and use each to its maximum duration (i.e., the recording system must be low power). Even the fact that MEMS require some power while the geophone does not is not a disadvantage for digital sensor recording. At least with the 408UL recording system, the overall consumption of a three-component digital sensor (400 mW) is less than the equivalent consumption of three field digitizing units connected to triphones (420 mW).

Distributed electronics with computing and buffering capabilities as implemented in the most advanced telemetry cable systems makes it possible to secure data transmission. In case of a cable failure, the use of multiple transverses between the receiver lines and the central units will permit the seismic network to reroute data through a different path.

As the number of channels increases up to 10 000 and beyond, manual or visual checking of the entire system and data quality becomes impossible. This explains the importance of automated real-time quality control as already implemented for single digital sensor recording. For example, the tilt measured from the residual dc on the horizontal components can be checked continuously. The result is stored numerically and also displayed graphically with a warning color if tilt is above a predefined threshold. In addition each MEMS sensor includes a built-in reference accelerometer that provides a continuous tracking of such factors as distortion, gain, phase, and cross-talk. During the recording, the data may be visualized component by component (Figure 7); several attributes (e.g., signal, noise, frequency content, faulty trace) are available on a trace-by-trace or shot-by-shot basis which allows continuous monitoring of the acquisition process.

Since MEMS sensors record acceleration and not velocity, real time integration from one domain to the other has been made available. To provide a one-to-one comparison between analog and digital sensors, MEMS broadband seismic data may be filtered to resemble geophone data (10 Hz low cut filtering and damping, Figure 10).

Conclusion. Is it time to use digital sensors? MEMS-based single digital sensors offer new capabilities compared with conventional arrays of geophones. The sensor itself (MEMS + ASIC) should provide better vector fidelity thanks to its accurate and stable calibration (amplitude and orthogonality), and its broadband linear response (from dc to 800 Hz). Tight integration of the sensor with the station electronics allows size/weight reduction and lower power consumption.

Such a sensor will provide, for the first time, complete digital transmission, from the sensor to the central unit, which is less sensitive to electromagnetic pick-up, cross-talk, and leakage. Overall MEMS technology offers the potential to reduce costs while improving data quality. However, there are two limitations to the use of MEMS sensors: one is geophysical (digital sensors are recorded as single sensors) and the other is economic (manufacturing costs of MEMS compared to coiled geophones).

If single-sensor recording provides obvious advantages for deployment and signal preservation, these benefits are strongly balanced by the inability of single sensors to attenuate any ambient or shot-related noise. Records by single digital sensors will be dominated by noise, and this domination will be even worse if point receivers are used in conjunction with point source (i.e., without any source array filtering). In noisy areas with strong, dispersive, and backscattered ground roll and with high ambient noise this may prevent recording any usable signal.

To be able to recover signal, all this noise should be attenuated during processing. For ambient noise reduction, the fold coverage should increase. This is possible by decreasing the spacing and increasing the number of single digital sensors. For coherent noise attenuation, the point receiver spacing should also decrease, perhaps not down to the geophone spacing, but at least down to the Nyquist distance necessary to keep the corresponding ground-roll unaliased. For both ambient and coherent noise, this implies increasing the number of point receivers and channel capabilities (which will increase the cost of acquiring data). Thus a question arises: Does it make sense to invest and operate single digital sensors instead of conventional geophone arrays?

Is it time? In all realms of seismic recording, single sensor acquisition, done properly, has the potential to increase data resolution to the levels required for the definition of subtle targets and detection of small changes. When 120 dB recording became a reality there was a lot of talk about the geophysical benefits of this new range of seismic data. There is also a lot of discussion that up to now we have really not ever used this breakthrough in the actual processing and interpretation of the data. In the single sensor world, we will now require dynamic ranges every bit as wide as these new systems allow.

We have discussed sampling for single sensor acquisition and know that better sampling with higher channel counts will be required. When we consider the different wavelengths associated with P-wave data and S-wave data, the sampling requirements of the recording layout become more complicated than when we strictly consider a P-wave survey. At this time there are crews in the field using single sensor MEMS-based systems to record 3D-3C with improved but still practical spatial sampling. These crews are recording both good PP-wave data as well as good PS-wave data.

In some surveys, crews are deploying lines of 3C MEMS-based sensors strategically within a 3D layout of analog phones (1C) recorded on the same system at the same time. In this way P-wave sampling and S-wave sampling can be different on the same survey, moving closer to optimum spacing for specific wavefields. This is only one example of the creativity of system manufacturers, their customers, and their customer's clients when new technology offers new solutions to pressing exploration and production problems.

So, is it time for MEMS-based sensors? Why not! In this industry we have always had exploration or production problems that we couldn't solve with existing technology. So we look for the next technology with which we can push the envelope. Successful and efficient use of MEMS-based sensors is a reality. TLE

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