

# **General Application of MEMS Sensors for Land Seismic Acquisition – Is it Time?**

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## **ABSTRACT**

Coil based geophones are a proven technology that has been used for a long time by the industry. Recent advances in micromachined sensors now provide adequate sensitivity, low noise, and dynamic range to be applicable to seismic acquisition. MEMS have the potential to provide broader bandwidth, more accurate amplitude, and less sensitivity to planting tilt. Together with the renewed interest for 3C recording, triggered by the success of OBC surveys, these trends have incited manufacturers to develop and market new digital sensors based on MEMS accelerometers.

Several recent papers and articles 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 ten years ago. Has this technology really advanced to the point that it can, or should, be used for general-purpose land seismic acquisition? This paper will address the advantages and disadvantages for the general application of single 3C digital sensors.

## **Why accelerometers for digital sensors?**

Ground motion can be measured as displacement, velocity or acceleration. The mass/spring assembly is the model 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. In case of a stiff spring, the mass does move 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 (Micro Electro Mechanical System) is analog, while are digital. Such “digital” sensor is small (residual displacement is in the order of a few nanometers) but it is costly due to the A/D converter. Therefore only one sensor per channel will be used, a configuration which

presents pros (no intra-array statics, isotropic recording) and cons (no ambient & organized noise filtering, good coupling mandatory).

### **How it compares with single geophones?**

A MEMS accelerometer is a tiny silicon chip which size (~1 cm) and weight (< 1 gr) is much less than the ones of a coil based sensor (3 cm long & 76 gr cartridge). Would you consider some crews in the Middle East that handle daily 55 tons of geophone strings, this difference may be of importance!

From the specification point of view the main advantage of MEMS accelerometers is their broadband linear phase & amplitude response that may extend from 0 (DC) to 800 Hz within 1 dB. With MEMS, low frequencies recording (< 10 Hz) are not prevented by the resonant frequency (Figure 1) that is far above the seismic band pass (1 kHz). This makes it possible to record the Direct Current (DC) related to the gravity acceleration that provides a useful reference for sensitivity calibration and tilt measurement. Since acceleration increases with frequency (at constant velocity), accelerometers fit well with high frequency measurements. In this domain (> 40 Hz) also the electric noise of the MEMS is less than the one of the coiled geophone (Figure 2).

These broadband capabilities offer potential for a dramatic improvement in the vertical resolution of seismic data, which depends on the ratio  $2^n$  between the minimum and maximum frequencies ( $F_{max}/F_{min} = 2^n$ , n being the number of octave). It is also particularly suited for recording low frequency signal (4-5 Hz) that is reflected at the main lithological contrasts between geological formations (interest for seismic inversion without log based initial model).

While the distortion in the acceleration domain is less with a MEMS (-90 dB) than with a geophone (-70 dB), the total dynamic range of a 24 bits recording system using MEMS (120 dB) is less than the one of the same system using single geophones (135 dB, assuming weak distortion in absence of strong noise).

Finally, if we consider the amplitude calibration of a point receiver and its stability over aging and temperature variations, the overall performance of a digital sensor, where MEM's are integrated with the station electronic in a single housing, is better than the one of a geophone that is connected to different station units during a survey.

### **How it compares with arrays of geophones?**

Arrays of geophones may tremendously improve the dynamic of a receiver point by reducing the ambient/uncorrelated noise. Whatever the mounting in series or in parallel of N geophones, the dynamic range is improved by  $10 \times \log N$  dB, as the signal-to-ambient noise is reduced by the square root of N. For organised noise attenuation, geophones are laid out to provide array filtering. The size of this array and the number of wired geophones should be large enough to sample properly the maximum wavelength of the ground roll.

Despite these advantages field geophysicists would like to get rid of these large and heavy geophones arrays that slow crew productivity, require expansive logistic,

deteriorate first breaks and lower signal band pass. At a first glance, the use of single digital sensors would have many operational and geophysical advantages over geophone arrays. Layout and positioning are easiest compared to geophone strings, and this is even more relevant for 3C receiver points. Recording is isotropic (no azimuth dependant array filtering), and the high frequency content of the signal is not attenuated by intra-array static's. 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.

Practically, the spacing of single sensor point receivers should be decreased with respect to geophone arrays. This short spacing will not attenuate noise while recording. It will provide enough multiplicity (fold coverage) to decrease the ambient noise while stacking. Denser spatial sampling will also prevent the organized noise from aliasing for efficient application of FK filtering. Therefore do not expect to get better looking shot point displays while using single digital sensor. The benefits (better static's, larger frequency content, and accurate calibration) will only appear at a later stage, after data processing.

### **Acquisition geometry:**

How many of these single digital 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.

If we consider only the ground roll GR, often the strongest noise, the spacing D should be such that the noise wavelength  $L = V_a / F_a$  ( $V_a$ , apparent velocity;  $F_a$ , apparent frequency) will be sampled at least two times, i.e.  $D = V_a / 2F_a$ . This provides often values in the range of 5 to 15 m. Figures 3 & 4 are comparison of FK diagrams on two SP's recorded at the same location with different spatial sampling. At 10 m, the very low velocity ground roll (330 m/s) is aliased and interferes with signal. At 3.33 m, GR is still aliased but it vanishes at high frequencies (70 Hz) before to intersect signal. Considering this maximum frequency limitation of the noise it is possible to use a spacing (adequate sampling) a little more than half of the GR wavelet (Nyquist sampling) as suggested by G.J. M. Baeten et al. (SEG, 2000)

Up to now, we have considered that all propagations were 2D. In case of 3D acquisition or complex near surface generating backscattered noise, it would be necessary to sample the noise properly both in the inline and cross line directions. Since single digital sensors are connected by telemetry cable this would require for a single receiver line to lay out several parallel cables to form a corridor of single digital sensors. A quick calculation of the channel requirement for a 3D swath of  $4 \times 4 \text{ Km}^2$  with 100 m between receiver corridors, each one made of 5 individual lines of digital sensors with 10 m spacing provides a figure of 80,000 active channels which is still above the real-time capability of all recording systems.

Today this type of single sensor arrangement would be only compatible with 2D acquisition. Thanks to its continuous spatial sampling, this arrangement is interesting to consider. It provides a sort of universal acquisition design which is not committed to any particular type of noise since different single sensor combinations, often

referred as digital group forming (Figure 5), may be used to attenuated noise after recording. Another approach would be to replace these very channel demanding corridors of single sensors by dedicated digital arrays. In this case, the 1C or 3C single sensor arrangement will be committed to a particular type of noise, and is not necessary spatially continuous between receiver points (Figure 6).

A less complex approach may be used more commonly, as illustrated in Figure 7. Showing 2D, 3C acquisition with single digital sensors spaced with an interval of 10 meters to 25 meters.

### **Real time quality control:**

With the very high channel count required to record dense line of single digital sensors, real time quality control of the spread and of the seismic data is mandatory. In the 408UL recording system, many graphical and numerical QC's have been implemented to secure the quality of the huge amount of data recorded. Among others (like tilt & noise measurements) are the dynamic QC's provided by a built-in accelerometer that is part of each MEMS. These QC's include distortion, gain, phase & cross talk and correspond to a unique feature compared with all other recording systems.

At the end of the acquisition flow is the display of seismic data to control what is recorded on the tapes and to visually check the overall process. Of course, automatic sorting and display of each of the components of a digital sensor have been implemented, and data evaluation is supported by seismic attributes computation (energy & frequency content of the signal, ambient noise, signal-to-noise ratio, faulty traces ...). Since MEMS based digital sensors record acceleration and not velocity, as for conventional geophones, real time integration from one domain to the other has been made available. To makes it possible a one-to-one comparison between analog & digital sensors, MEMS broadband seismic data may be, in addition, filtered as a geophone does (10 Hz low cut filtering & damping, Figures 8 and 9).

### **3C recording:**

Connecting strings of triphones to a telemetry cable is an extra task involving heavy equipment, lots of wire and many connectors. Also planting, levelling and orienting properly all these triphones was mandatory since the final output is mixed and any correction will be impossible at a later stage. Having sensors and station electronics integrated in the same housing, as it is for the 408UL digital sensor unit (DSU3), will reduce overall weight and wiring errors, and should make all multi-component field operations faster, better and cheaper.

Of course, planting a 3C digital sensor would need some attention in order to get the proper coupling, but insuring its exact verticality is not anymore a concern. This is related to a unique feature of the MEMS based 3C digital sensor units: their ability to measure the continuous effect of the gravity vector. This vector is used as a reference to automatically measure the tilt ( $\pm 0.5^\circ$  accuracy). The tilt value is stored in the trace extensions, and data may be even corrected for in real time by the central unit. In the same way the sensor orientation, if not the proper one, may be

corrected during processing by assuming a radial propagation between the source and the single sensor.

Tilt measurement is only one aspect of the advantages provided, in term of vector fidelity, by the MEMS based 3C digital sensors. In addition to their broadband capabilities (0-800 Hz linear response) is the very precise orthogonality of the sensors ( $\pm 0.25^\circ$  accuracy), their accurate and stable amplitude calibration ( $\pm 0.25\%$  accuracy), and their stability with temperature variations and aging. Even the fact that MEMS would require some power while geophone does not is not a disadvantage for 3C recording since the overall consumption of a 408UL digital sensor unit (400 mW for all of the three components) is less the equivalent consumption of triphones connected to 3 station units (420 mW for 3 FDU's). This obviously will have an impact on battery management by the crews.

This 3C digital sensor technology is already field proven and many surveys have already been performed. Data from Figure 10 are from a 2D acquisition with explosive recorded with 408UL in North America. These data evidence the broadband capabilities of the MEMS based 3C digital sensor units (DSU3). High frequency preservation while stacking is not an easy task and requires careful static definition and efficient deconvolution after noise attenuation. The frequency spectrum of the signal in a large window is clearly above 200 Hz, and signal above 300 Hz is evidenced down to 0.2 seconds twt.

### **Crew Productivity**

Seismic data acquisition with high-density, three component, single point sensors will require recording large number of channels. Three components instead of one will triple the number of channels. Short receiver point spacing to get adequate noise sampling may double (or more) the number of channels. For 3D's this may mean 12 – 15,000 + channels. If the acquisition system uptime degrades significantly with this large number of channels the cost for the survey could be prohibitive.

To be productive with large numbers of channels the acquisition system must: be *low power* and use the *smallest number of batteries*. Since the beginning of the use of telemetry acquisition systems, batteries have been one of the weak links in the field.

The ground equipment must also be *lightweight* for large channel counts. The ground equipment must be extremely lightweight, but it also must remain rugged during typical field use.

*Reliability* of the ground equipment is also critical as the number of channel increases. If remote units or cables must be replaced frequently, then crew productivity will degrade quickly as the number of channels increases.

*Telemetry redundancy* is another critical tool for productive operation with large numbers of channels.

*Built-in automated Quality Control* is also critical as the number of channels increases. It becomes impossible for the instrument engineer to manually or visually check all of the system and data quality for 10,000+ channels.

**Conclusion: is it time?**

Yes, it is time to consider the use of 3C for some general 2D or 3D acquisition. Even if the shear wave data will not be used immediately, it is worth weighing the potential long-term benefit compared to the incremental cost.

The significant improvements in productivity of the new MEMS systems (such as the 408 DSU) compared to early MEMS and 3C analog systems have the potential to reduce the cost differential compared to previous 1C acquisition.

The single sensor per receiver point nature of digital sensor systems provide some strong benefits:

- Isotropic recording,
- Less attenuation caused by intra-array statics
- Potential for multicomponent noise filtering;

plus the inherent advantages of digital sensors:

- Broader bandwidth,
- More accurate amplitude response,
- Less susceptibility to tilt errors.

But there are also some potential disadvantages:

- Less suppression of random and source generated noise,
- Closer receiver point spacing may be required to adequately sample signal and noise

Should all 2D and 3D surveys be conducted with 3C digital sensor systems? No, there are serious trade-offs that must be considered. In some cases the cost and complexity to get adequate noise sampling with single sensor systems may not be worth the potential value of the shear data. But, the tremendous improvements in acquisition systems make it worth considering for more surveys.

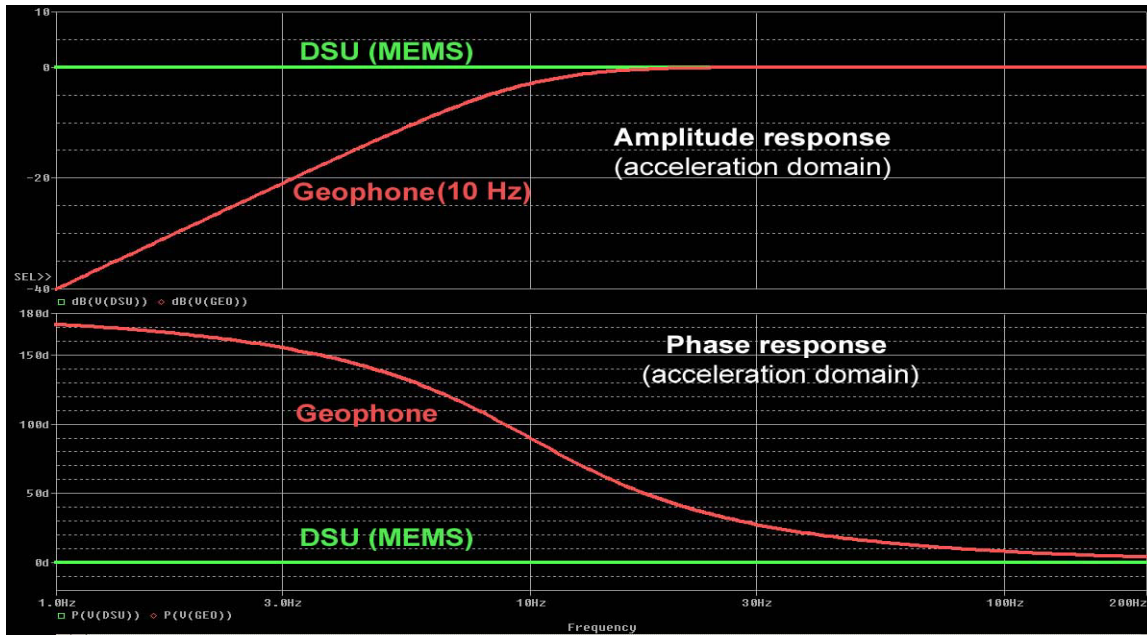


Fig. 1: Linear phase and amplitude response of a Digital Sensor Unit with MEMS compared with a 10 Hz geophone.

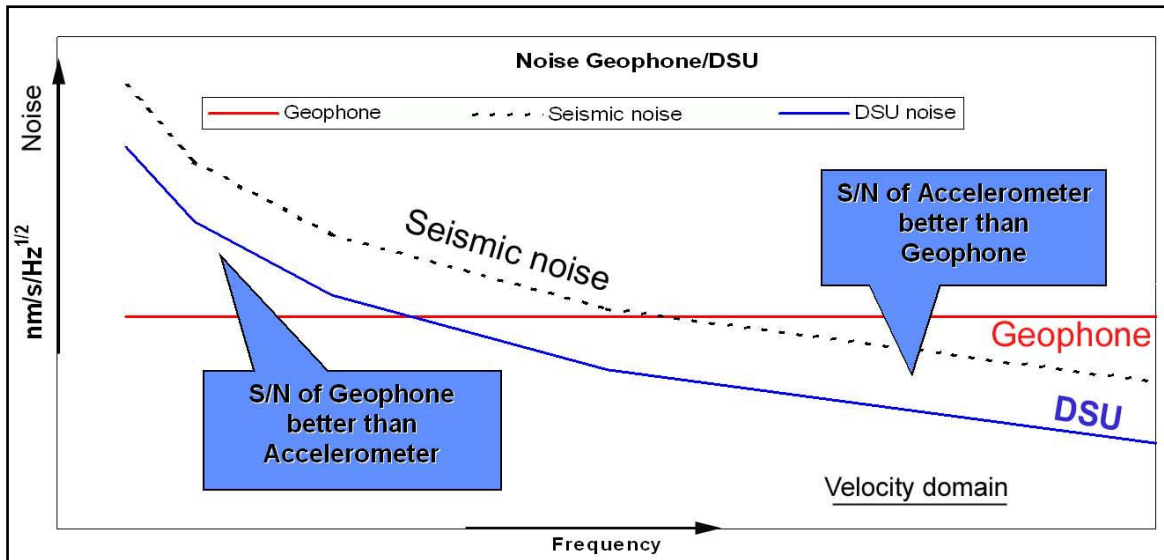


Fig. 2: Comparison in the velocity domain of the electric noise of a geophone with the one of a Digital Sensor Unit with MEMS. A typical natural seismic noise is also represented. The two sensor curves cross at about 40 Hz.



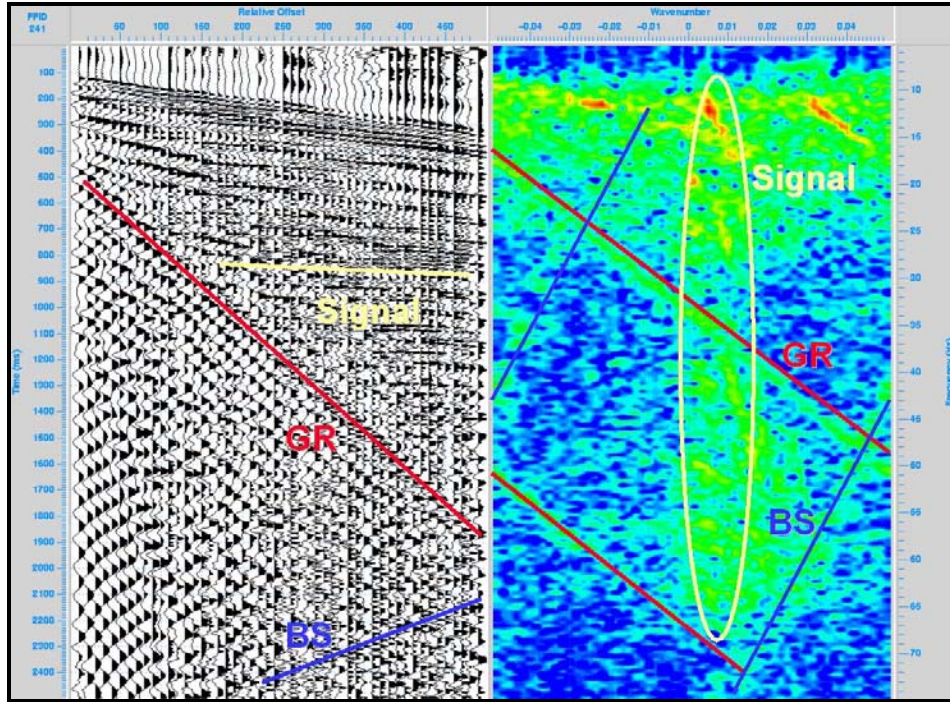


Fig. 3: Shot point (GR, ground roll, BS, back scattering) with 10 m spacing between single digital sensors. On FK, GR is aliased and interfere with signal.

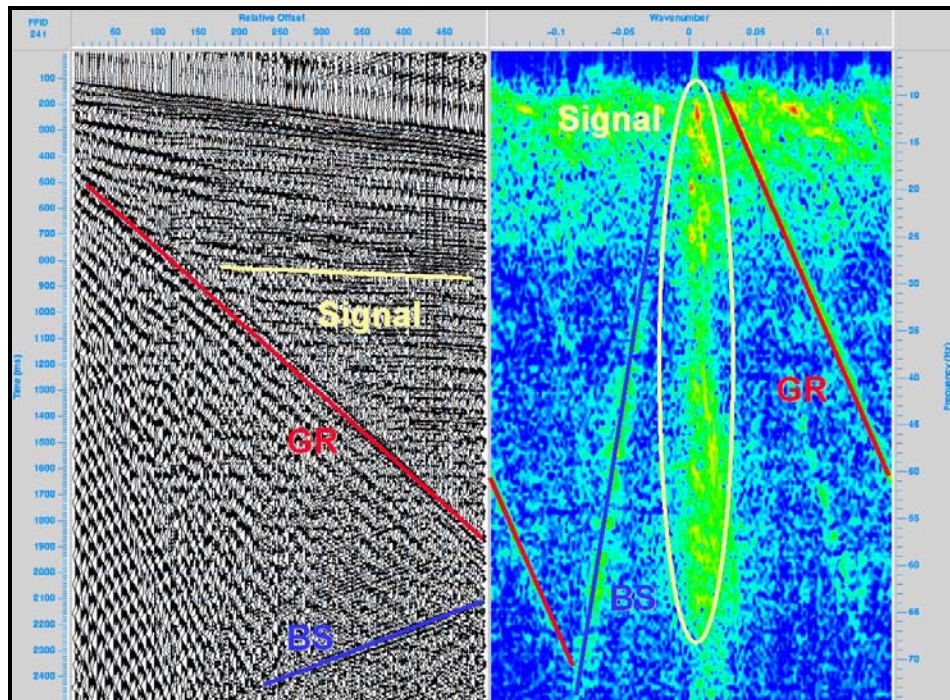


Fig. 4: Shot point with 3.3 m spacing between single digital sensors. On FK, GR is still aliased but do not interfere with signal.



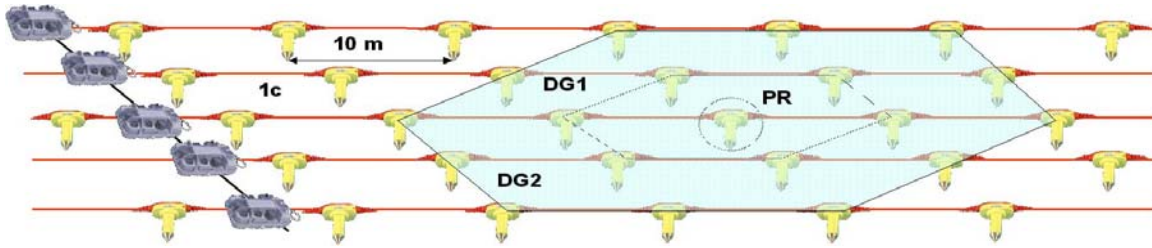


Fig. 5: Uncommitted 2D acquisition design made of a corridor of 1C single digital sensor units connected along parallel telemetric cables. At a given point receiver (PR) different types of digital group (DG1, DG2) may be considered to reduce ambient noise and filter the ground roll.

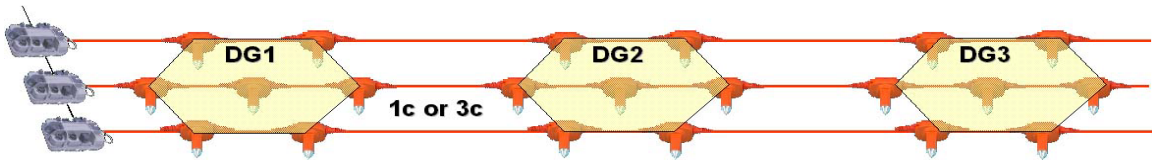


Fig. 6: Committed 2D acquisition design made of a corridor of 1C or 3C single digital sensor units connected along parallel telemetric cables. The discontinuous digital groups (DG1 ...) are dedicated to the attenuation of a given type of noise like it is for the conventional geophone strings.

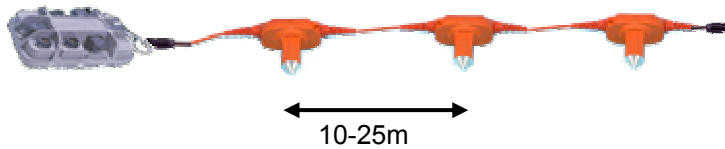


Fig. 7: Single sensor 2D, 3C Acquisition. Improved statics, broader bandwidth, less source noise filtering.

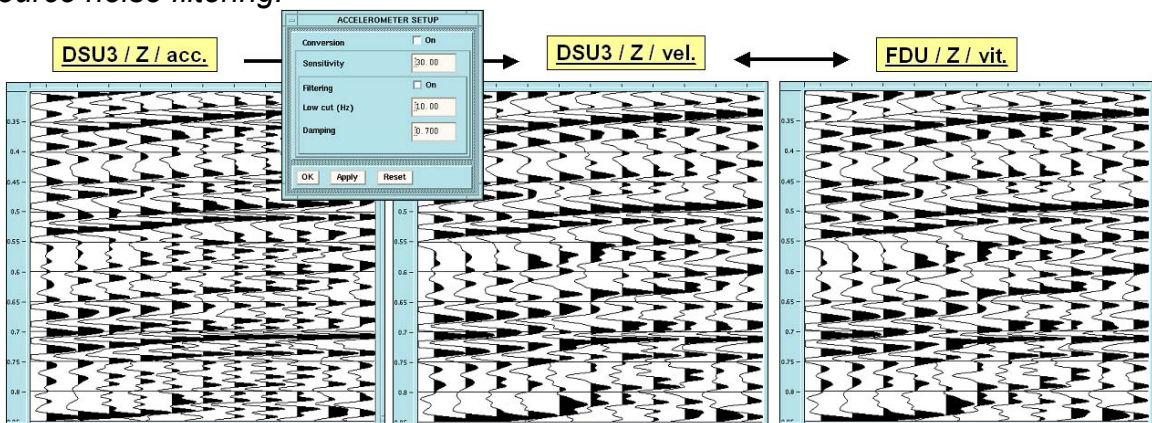


Fig. 8: Real time QC of shot points (Z component) coming from digital sensor units (DSU3) and conventional geophone strings (FDU) laid out at the same location and recorded by the same 408UL central unit.



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 the geophone.

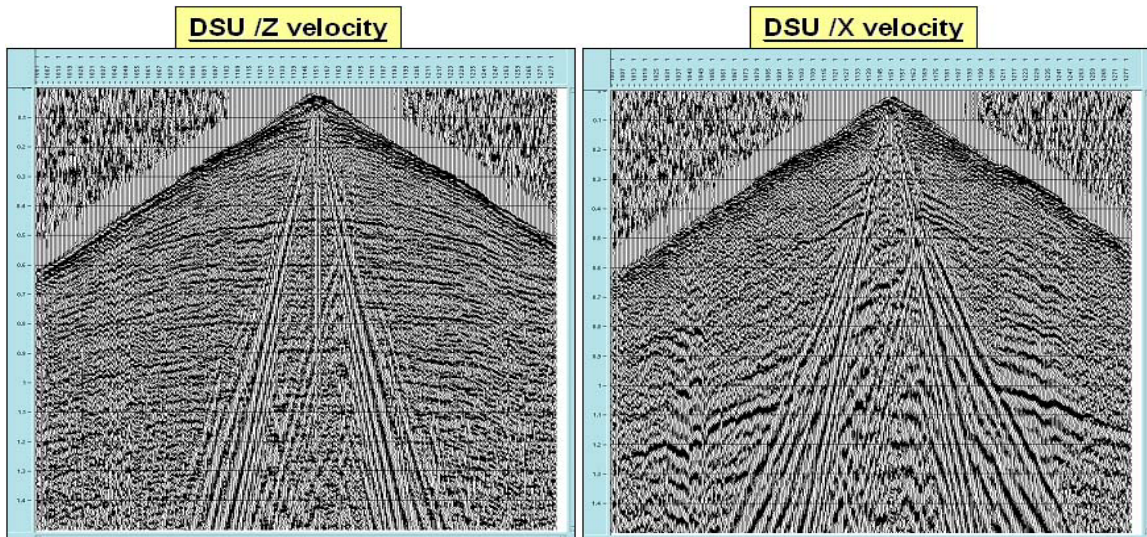


Fig. 9: Real time display of shot points (Z & X components) in the doghouse after velocity conversion and low cut filtering (10 Hz).

It is also possible, in real time, to compute on each of the 3 components seismic attributes (signal, noise, frequency content ...) to better evaluate data.

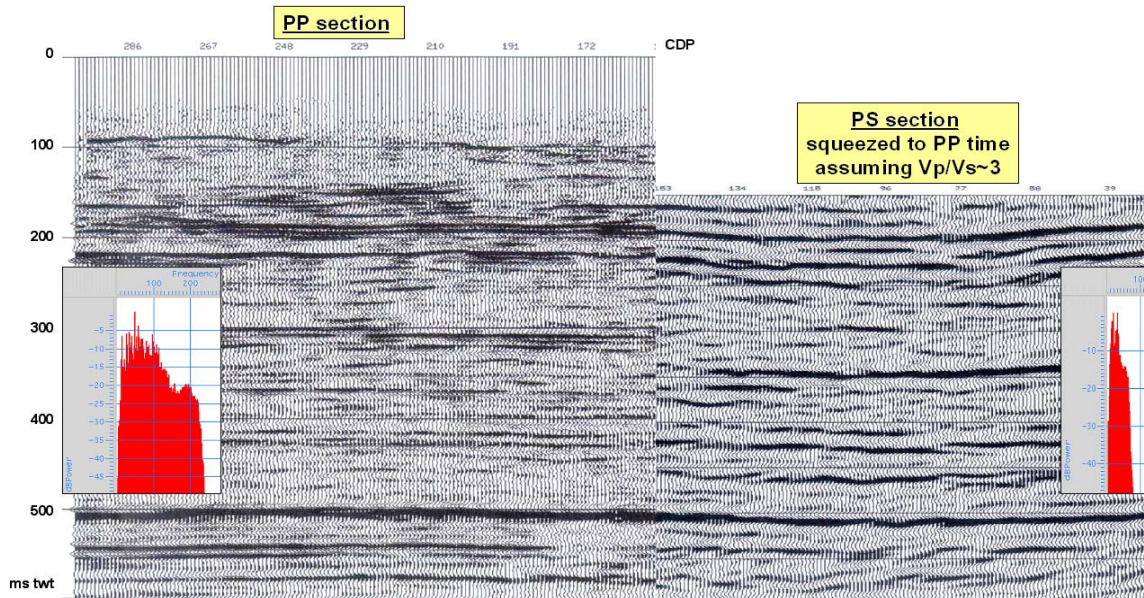


Fig. 10: comparison of PP and PS final sections corresponding to the previous SP's (Figure 7) recorded with 3C digital sensor units.

The frequency content of the PP section (0.2–1 s twt) is above 200 Hz, while in the PS section most of the HF above 70 Hz has been attenuated. The reflectivity of the two sections recorded in sand/shale formations is quite different.