Which sensor for land nodal seismic: recording acceleration or velocity?

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Summary

Land seismic is evolving towards denser surveys, single sensor recording, and lower frequencies. A number of new nodal systems have been introduced to facilitate this evolution: some use moving coil geophones, while others use new sensors, based on MEMS or piezoelectricity, which record acceleration instead of velocity as for geophones.

We show, in this paper, that the domain in which you record the data, acceleration or velocity, does not really matter, as you can always convert the data into the domain of your choice for processing. The type of sensor used will however have an impact on the quality of the data. Moving coil geophones, especially when used as a single sensor and at low frequency, introduce perturbations in the signal.

We conclude that accelerometers are the better choice for single sensor broadband surveys.

Introduction

Acceleration and velocity sensor have both been successfully used in land seismic. Moving coil geophones measuring velocity have long been the standard seismic sensors. MEMS accelerometers were introduced twenty years ago (Tessman et al., 2001). The motivations were higher recording fidelity extending to the low frequencies, with the objective to bring the perturbations due to the sensor at least 40 dB below the signal, and a potential for miniaturization.

The take-up of this new technology has been slow, a choice between recording acceleration or velocity being first of all a choice between a single sensor accelerometer and an analog array of geophones. It took time for the industry to learn how to deal with and process the large volume of data coming with single sensor recording.

It is only in recent years and with the introduction and growth of another technology, nodal recording, that single sensor recording has become more common. It is now possible to record seismic with fully cable-free systems, with all the operational benefits it provides. Point receiver nodal systems are now available with a variety of sensors: MEMS accelerometers (Tellier et al., 2017), piezoelectric accelerometers (Manning et al., 2018), but also standard and high sensitivity geophones measuring velocity.

In this paper, we will look at different types of acceleration and velocity sensors, and study how their design and specifications impact their performance. We will then analyze and compare field data recorded in velocity and acceleration.

Review of sensor characteristics

The current land seismic sensors measuring particle motion (acceleration or velocity) are based on a mass/spring system, which are governed by the damped harmonic oscillator equation.

In a moving coil geophone, a voltage is generated in the coil which is proportional to ground velocity above the resonant or natural frequency of the system (figure 1). In an accelerometer, the sensor output is proportional to ground acceleration below its resonant frequency. Accelerometers have therefore a higher resonant frequency than moving coil geophones, and a flat response down to low frequency.

It is difficult to directly compare the sensitivity of an accelerometer and a moving coil geophone, as they do not record in the same domain. We can however calculate the frequency dependent sensitivity of an accelerometer in the velocity domain and reciprocally, then make a direct sensitivity comparison frequency by frequency:

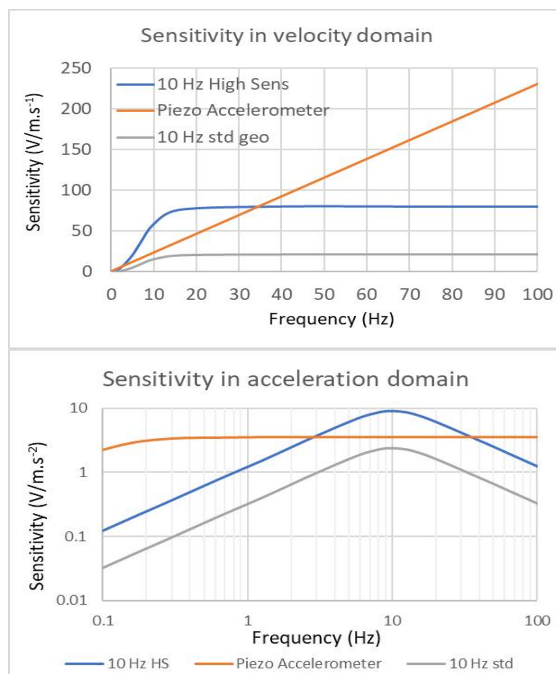

Figure 1: Sensitivity vs frequency for a standard geophone (21 V/m/s, grey), a high sensitivity geophone (80 V/m/s, blue) and a piezoelectric accelerometer (3.6 V/g, orange); top velocity domain linear scale, bottom acceleration domain in logarithmic scale

As expected, accelerometers are more sensitive at high frequency. We can see from figure 1 that moving coil geophones are more sensitive than accelerometers around their resonant frequency. This advantage however disappears at very low frequency, where the accelerometer again becomes the more sensitive sensor. This has been already demonstrated for a MEMS accelerometer in Fougerat et al. (2018).

Although the moving coil geophones have a sensitivity advantage around their resonant frequency, their response is not optimal in this frequency band. As in any damped resonant harmonic system, the phase shifts by 180 degrees across the resonance.

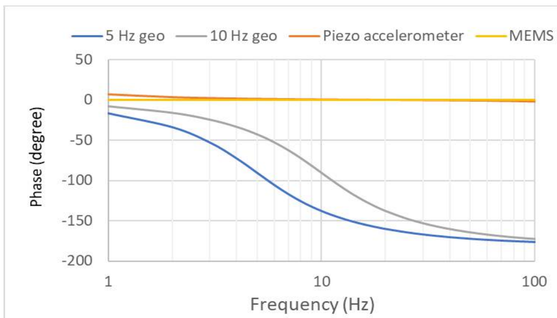

Figure 2: phase response of four land sensors: 5 Hz geophone (blue), 10 Hz geophone (grey), piezoelectric accelerometer (orange) and MEMS accelerometer (yellow)

Because of manufacturing tolerances, but also because of ageing and temperature variations, every geophone will have a slightly different resonant frequency and damping, what will respectively shift the phase response in frequency and change its slope across the resonance. As long as you are in a frequency area where the phase response is flat, it has no consequence. It is however different in the frequency band around the resonance, where the phase changes rapidly with frequency. Phase response variations are introduced. These phase differences between different geophone will result in time shifts between recorded signals at these frequencies. This has been demonstrated and illustrated in Tellier et al. (2021), who gave it the name of “data jitter”.

These perturbations in the data are usually significantly higher than the stated objective of - 40 dB for signal fidelity. To achieve this, the phase error should be lower than 0.57 degree, while Tellier et al. (2021) showed than it can be several degrees around the resonant frequency

Analog arrays, by summing the output of several geophones, used to average out and mask these errors. They are now becoming apparent as we move to single sensor recording and focus more on the low end of the frequency spectrum.

Accelerometers, who essentially have a zero phase response in the seismic frequency band, do not suffer from this issue. They have a flat amplitude and phase response down to low frequencies, all commercial seismic accelerometers have a bandwidth specified down to 1.5 Hz or lower.

It has long been considered adequate to use moving coil geophones with a resonant frequency of 10 Hz. In recent years however, with the push to extend the frequency bandwidth of seismic data, notably towards the low frequencies for Full Wave Inversion, it has become more common to use geophones with a lower resonant frequency, down to 5 Hz. This has some impact on the performance of the geophone. The data jitter issue is still present, it is only shifted down, as you can see from figure 2.

Another issue associated with the low resonance frequency of a moving coil geophone is the gravity sag of the mass. The gravity sag z of the moving mass in a mass spring system, corresponds to the shift in equilibrium position of the mass between horizontal and vertical position and is fully determined by the resonant frequency of the system ($z = g / (2*\pi*f_0)^2$). It is 2.5 mm for a 10 Hz geophone, going to 10 mm for a 5 Hz geophone. This is dealt with by using asymmetric top and bottom spring, and by measuring around the equilibrium position in vertical position. This introduces performance degradation with tilt, as the moving mass will move from its nominal position, and makes it very difficult to lower the resonant frequency without increasing the size of the sensor.

Although MEMS and piezoelectric accelerometers have similar response characteristics in the seismic frequency band, their designs are very different, starting with their moving mass. In the piezoelectric accelerometer introduced by Manning et al. (2018), the battery cell powering the node is used as reaction mass for the sensor, it weighs in the tens of gram. With this large moving mass generating the seismic signal, low power electronics can be used. This single battery cell used as reaction mass is sufficient to power the node.

On the other end, the moving mass of a MEMS accelerometer can be in the order of milligrams. Because of this very small moving mass, the Brownian motion of air molecules surrounding would be sufficient to create high level of noise in the acceleration measurement. It is therefore necessary to package the MEMS sensors under vacuum. The sensor then becomes mechanically underdamped, and a feedback loop system is usually introduced to control the resonance (Paulson et al., 2015).

This feedback loop system has advantages and disadvantages. As it controls the resonance, it makes it possible to extend the bandwidth of the sensor towards high frequencies, often up to 1 kHz. The feedback loop also limits the movement of the mass, which usually is the main source of measurement distortion in a particle motion sensor. Some seismic MEMS accelerometers have an impressive distortion specification of -90 dB below the signal. This is however more a theoretical than a practical advantage: other particle motion sensors such as moving coil geophones or piezoelectric accelerometers generally are around -60 dB. This is still an order of magnitude better than the stated objective of -40 dB for signal perturbation and will have no impact on data quality.

A drawback of the feedback loop system is its power consumption. While passive sensors like moving coil geophones or piezoelectric accelerometers only use traditional preamplifier and digitizer, MEMS accelerometers require much more complex electronics providing power to the feedback circuitry keeping the sensor mass stationary.

As long as a MEMS sensor is in a cabled system, this power can be provided through the cable, making it possible to take benefit of the small size of the sensor. In a nodal system however, the size of a node is not driven by the size of the sensor, but by the size of the battery. Paradoxically, the small size of the MEMS sensor is a contributing factor to its relatively high power consumption, which in turn dictates the number of battery cells needed and the size and weight of the node.

Field data examples

Comparative studies where geophones and accelerometers are placed in the same location do offer a great opportunity to study the conversion from one unit to another and compare it to the natively measured signal.

Figure 3 shows a shot gather on collocated STRYDE nodes with piezoelectric accelerometers and geophone nodes.

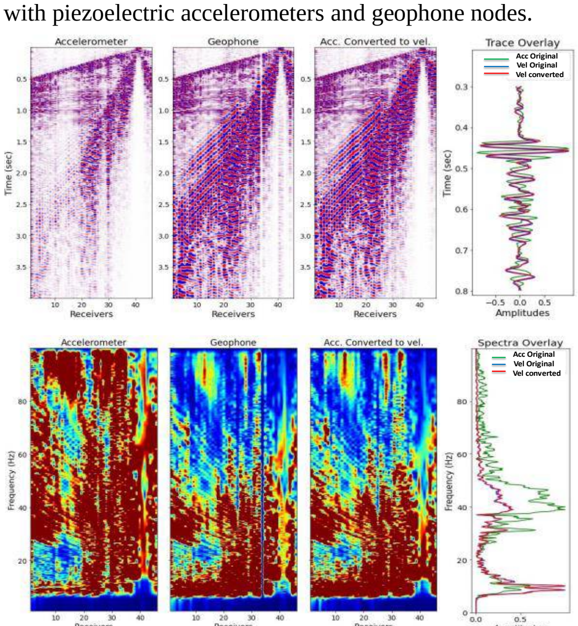

Figure 3: shot gathers; top: time, bottom: frequency; left to right: acceleration from piezo accelerometer, velocity from geophone node, acceleration converted to velocity, middle trace

The acceleration data from the piezoelectric nodes have been converted to velocity. As can be seen on both time and frequency domain, the converted dataset looks identical to the natively measured velocity data. The geophone data in this case has not been corrected for the sensor response as the sweep started at 8Hz which is already above the resonance frequency of the 5Hz geophone used in this experiment.

Similar comparisons have been done before with similar results, as in Hauer et al. (2008). This confirms that, independently of the domain used for recording, you can always convert the data in another domain of your choice for processing. This is routinely done in marine seismic, in streamers or at the seabed, where accelerometer data is converted to velocity before being combined with the pressure data for deghosting by PZ summation.

Continuing on the analogy with marine seismic, it has been shown that at the seabed, where the high frequency first break signal can travel unattenuated over long distances, recording in acceleration increases the risk of clipping (Goujon et al., 2007). Is it the same in land seismic?

A first indication is given by the seismic trace spectra in figure 3. We can see that, in velocity (red and blue lines), the maximal spectrum content is around 10 Hz, corresponding to ground roll energy, while it is around 40 Hz in acceleration (green line).

We can examine in more details some short offset traces from an explosive source:

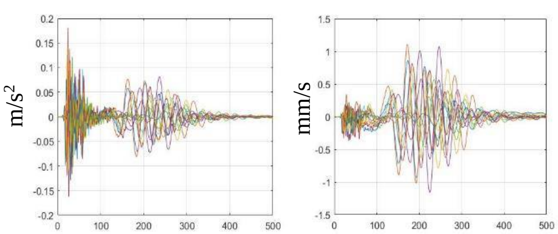

Figure 4: Short offset traces in acceleration (left) and velocity (right), explosive source

We observe that in this case, the largest amplitude in the acceleration domain is the direct arrival at the start of the trace (left), while the later arriving ground roll is clearly the strongest event in the velocity domain (right). This can be explained by the frequency content of these events: as we have seen in the sensitivity plots (figure 1), high frequencies will have higher amplitudes in acceleration, while ground roll frequencies around 10 Hz will have higher amplitudes in velocity.

We can now look at vibroseis traces. To study possible clipping, we need to look at the raw uncorrelated data.

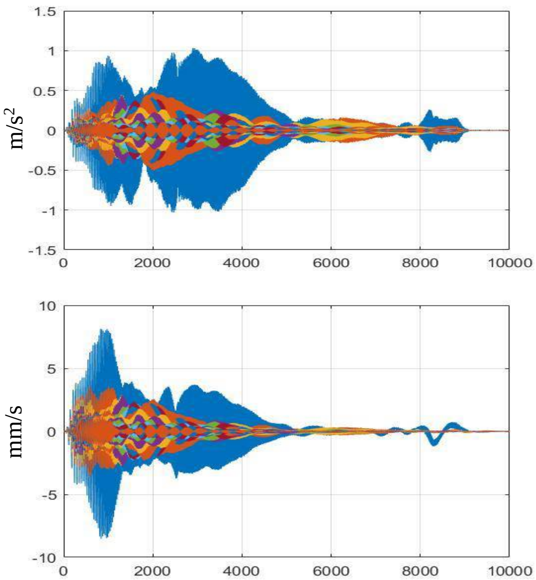

Figure 5: Short offset traces in acceleration (top) and velocity (bottom), vibroseis source, raw uncorrelated data

The plot shows 15 traces on top of each other spaced every 2 m with an offset from the vibrator ranging from 10 to 40m. The velocity data has been obtained by integrating the acceleration data.

As we look at raw data, low frequencies from the sweep are mainly at the start of the traces, while higher frequencies are towards the end. We can observe that the acceleration data has a more balanced frequency content, while amplitudes in velocity are significantly higher on the low frequencies at the start of the trace.

The blue curve in the background, at 10 m from the vibrator, has the highest amplitude: 1 m/s^2 in acceleration and 8 mm/s in velocity

A gain of 16 dB was used when recording with the piezoelectric accelerometer. The full scale is then 1.1 m/s^2.

We can see that the blue curve did not clip, but was right below the full scale. The full scale of a node with a high sensitivity geophone (80 V/m/s) when using a gain of 18 dB, is 4 mm/s: it would have clipped.

At shorter offsets, both sensors would have clipped using these gain settings, which are generally considered optimum for noise performance away from the source.

Both point receiver accelerometers and moving coil geophones risk clipping at very short offset. It can happen for both explosives and vibroseis surveys. It will be very dependent on local signal propagation conditions. This is not a big issue as long as the node recovers quickly and can record faithfully the rest of the trace.

There is however a difference between the two types of sensors: the time in the trace when the clipping could occur. As we have seen, accelerometers have their stronger amplitude on first arrivals, while the largest amplitude on moving coil geophone corresponds to the ground roll.

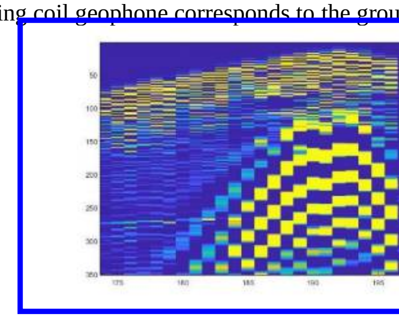

Figure 6: Shallow reflection arriving at same time as maximum ground roll amplitude at short offset

There is a high risk that it will correspond to the arrival time of shallow reflections.

The industry has so far not experienced issues with clipping on geophones. On reason might be that it was much less likely to happen on geophone strings, as the amplitude of the ground roll is attenuated by the analog sum of the signal in the array. The use of a single sensor using a high sensitivity geophone increases the risk, especially if high electronic gain is chosen.

Conclusion

We have shown that seismic data recorded by an accelerometer can be converted to velocity and made equivalent to the data recorded by a moving coil geophone, allowing you to chose in which domain to process the data independently of the acquisition domain.

Although this could mean that you are free to choose any domain for the acquisition, we have also shown that the existing sensors measuring velocity and the sensors measuring acceleration have significantly different measurement characteristics.

The response of the moving coil geophone presents significant limitations, especially at low frequency. They are becoming more apparent without the array averaging effect.

With the increased focus on low frequency, we conclude that accelerometers are the better choice for broadband single sensor land seismic.

10.1190/segam2021-3583516.1

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