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True phase and amplitude broadband seismic signal sensing with the 3rd generation of MEMS sensors

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Abstract

The signature of the source and the transfer function of the recording system and of the sensing elements have to be known in order to convert native seismic data into true amplitude and phase ground seismic motion, e.g. for FWI modelling purposes. Source signatures are nowadays recorded for each shot and the transfer function of the recording system is known and stable in time. The less accurately known responses are those related to the analog sensing elements which are subject to manufacturing tolerances and sensitive to temperature and ageing variations. This uncertainty is no longer a concern when using a MEMS technology which is a native digital sensing solution with an exact and invariant response to ground motions. Field test data illustrates how geophone data converted into ground particle velocity exhibits jitter, a consequence of the varying responses of the individual sensors, jitter which is not observed when using MEMS sensors, a consequence of their invariant response. The use of MEMS therefore allows for an exact conversion of the native seismic data into any ground motion units (acceleration, velocity, displacement). These features are to be observed soon in India: after a valued use of MEMS sensors of 1st generations in the country in the 2000's, the 3rd generation is currently being introduced in the country by several seismic players, in order to support nodal (single sensor) acquisitions, that as a matter of fact require more than ever high-fidelity response for each individual sensor.

Introduction

Seismic sensors are key components of the acquisition chain. While geophones have been in use since the early ages of seismic exploration, the way they are used has evolved: large geophone arrays now belong to the past, as operators now favour higher-trace densities with reduced arrays or single sensors. In the early 2000's, MEMS (Micro Electro Mechanical Systems) started challenging the geophone monopoly, and began to replace the last analogue component in the acquisition chain, whereas recording systems had made the leap more than 20 years previously. Geophones are pure analogue devices since their sensing principle relies on an induced voltage, generated by a coil (acting as a proof mass) moving relatively to a magnet. While MEMS sensors operate upon the same mass-spring principle, the way they sense ground movement is completely different (Tellier 2017). With closed-loop MEMS sensors, we do not want the (light) proof mass to move. Instead, to counteract the inertial force on the mass due to ground acceleration, an electrostatic feedback force is applied to the mass by an electronic ASIC (Application Specific Integrated Circuit) switching a voltage signal on its electrodes to keep the proof mass stationary. As a result, a precise measurement of ground acceleration is made possible by the accurate monitoring of this voltage by the high-performance electronics in the ASIC: the acceleration measurement is then wholly digital. In terms of performance MEMS exhibit lower distortion than geophones (-90 dB vs. -62 dB), are insensitive to electromagnetic contamination and are not affected by the spurious frequency phenomenon (Tellier 2020). In addition, the latest, third generation, MEMS sensors have among other improvements overcome the low-frequency limitations associated with previous generations (Lainé 2014, Fougerat 2018). Their main benefit however lies in their ability to record seismic data without jitter. This paper presents data-supported

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comparisons between the two sensor types and discusses the impact on final imaging, in a context of reintroduction of MEMS sensors in India by several national seismic players.

From sensor output to ground particle motion

Recovering the genuine ground motion requires the removal of the imprints of all components of the seismic acquisition chain. This process, called equipment de-signature, applies to vibrators (through ground force deconvolution), recording systems (through correction of their impulse response) and also to seismic sensors. However, the way to convert sensor native output into ground motion differs according to sensing technology. The geophone response is dependent on three parameters (sensitivity, damping and natural frequency) each of which affect the amplitude and phase of the raw recorded signal. The conversion of the raw geophone signal (a voltage) into ground motion (generally, a velocity) requires an accurate knowledge of these three parameters, in order to design a fit-for-purpose second order de-signature operator. This however is not the case in practice, as geophone specifications are provided with manufacturing tolerances (typically in the 5% – 7.5% range), furthermore variation due to temperature and ageing is not taken into account. With geophones, we therefore have an approximate estimate of the ground particle velocity (Figure 1, left): this causes a jitter on the data recorded, i.e., an amplitude and phase perturbation induced solely by sensor-to-sensor variations in the sensor response.
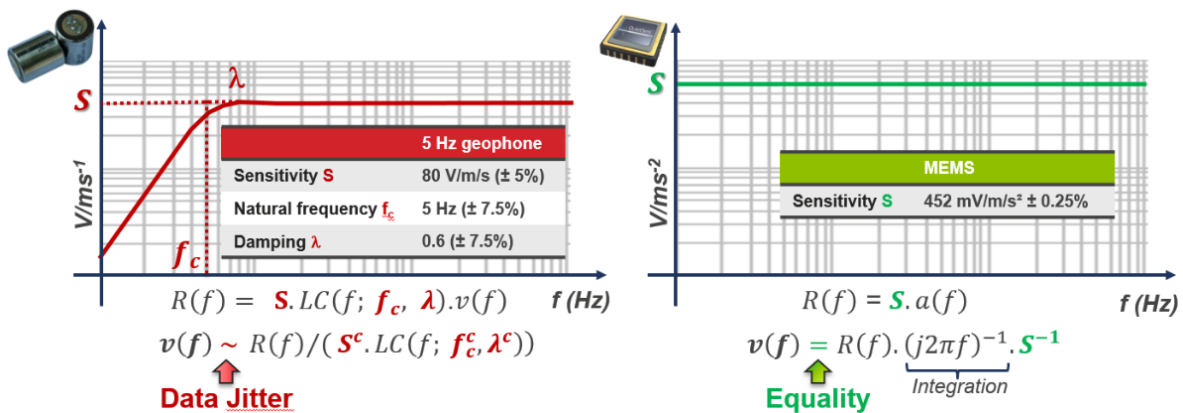

Figure 1 Geophone (left) and MEMS (right) inherent responses. R(f) refers to sensors raw responses, and v(f) to ground particle velocity after sensor signature correction. For geophones, LC () refers to a 2nd order de-signature operator, the exponent "C" indicates catalogue nominal values and its absence factual values of individual sensors (with account of tolerances).

The issue is different for MEMS, since they exhibit a flat and linear output in the acceleration domain. Their response is then related to the ground acceleration only by a frequency-independent sensitivity scalar, that displays extremely low tolerance (± 0.25%). This effectively allows for an accurate true phase and true amplitude conversion of the MEMS' inherent measurement into ground particle acceleration (Figure 1, right), that can be further converted into velocity or displacement through a simple integration process supported by any basic data processing software.

Field validation

A specific test was designed to illustrate, assess and compare the level of sensor-related data jitter for different sensor technologies. Along a 500-m long receiver line, 100 receiver positions consisted of co-located third-generation MEMS sensors and 5 Hz high-sensitivity geophones. 200 source

positions were shot along the 500-m long cross-spread source line, using a single 80,000 lbf vibrator and a broadband 1.5 - 150 Hz SmartLF sweep. This test makes it possible to measure the impact of a sensor's manufacturing tolerances on seismic data. Sorting the cross-spread data into in-line and cross-line offsets, the propagating seismic wave fronts appear circular while source-to-source variations will manifest themselves as a striping perpendicular to the source lines and sensor-related data jitter with a striping perpendicular to the receiver line. To enable a relevant comparison of geophone and MEMS records, both were corrected for sensor response and displayed in the ground particle velocity domain, as described in figure 1. Figure 2 compares 700 ms time slices for the [2-4] Hz octaves: the geophone time slice exhibits an octave-dependent data jitter, with sensor-to-sensor phase variations (blurred borders between wave front maximums and minimums) and amplitude variations (striping perpendicular to the receiver line). MEMS-related time slices do not exhibit sensor-related data jitter: only a minimal source-to-source striping can be observed.
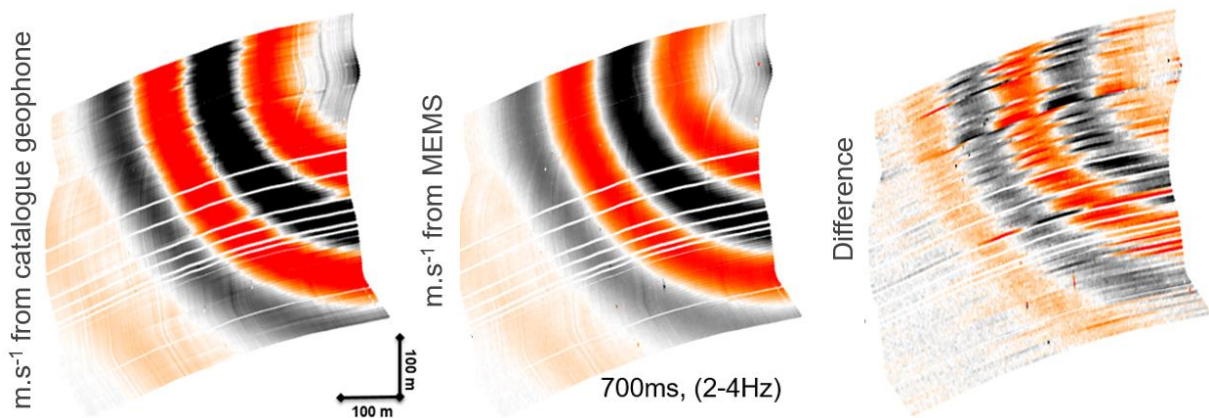

Figure 2 [2-4] Hz time slices at 700 ms: (left) 5 Hz geophones, (middle) MEMS, (right) difference.

Due to the homogeneity of the seismic signal recorded with MEMS sensors, we used the MEMS data as a reference to invert for geophone parameters, and access their actual true damping, sensitivity and natural frequency (which can be retrieved otherwise only in laboratory conditions). A histogram of these 100 inverted geophone parameters (Figure 3, top) clearly shows biased distributions, not centered on the manufacturer's published specifications and out of tolerance. For each of the 100 deployed geophones, the amplitude ratio (dB) can be displayed as well as the phase error (rad/2π) between the geophones' inverted result and the manufacturer's specifications, as a function of frequency (Figure 3, bottom).
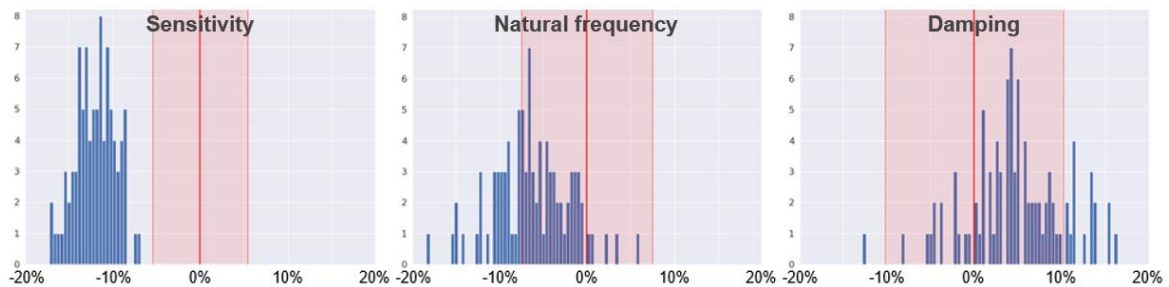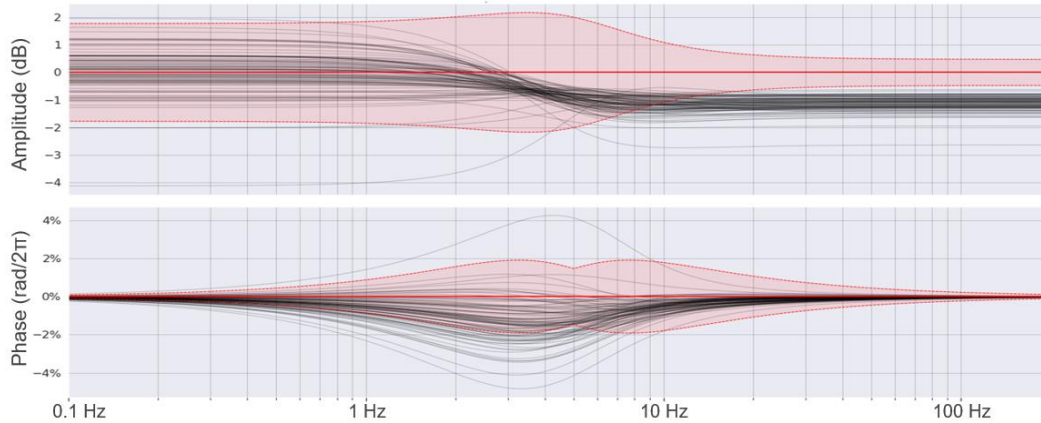
Figure 3 (top) Histogram of the deviation of the 100 inverted geophone closed-circuit parameters from their catalogue values, expressed as a percentage; and (bottom) corresponding amplitude and phase errors (black lines). For both graphs, catalogue nominal values are indicated in plain red lines, the pink shaded areas represent values that are within the manufacturer's tolerance specification.

To check the ability of inverted geophone parameters to correct for data jitter, we can compare the differences in time slices when using catalogue values (figure 2, left) and inverted values (figure 4, left). By doing so, we can observe a significant reduction in the difference between geophone inverted and MEMS time slices: this confirms that the observed differences are mainly due to the deviation of geophone parameters from the catalogue nominal values.
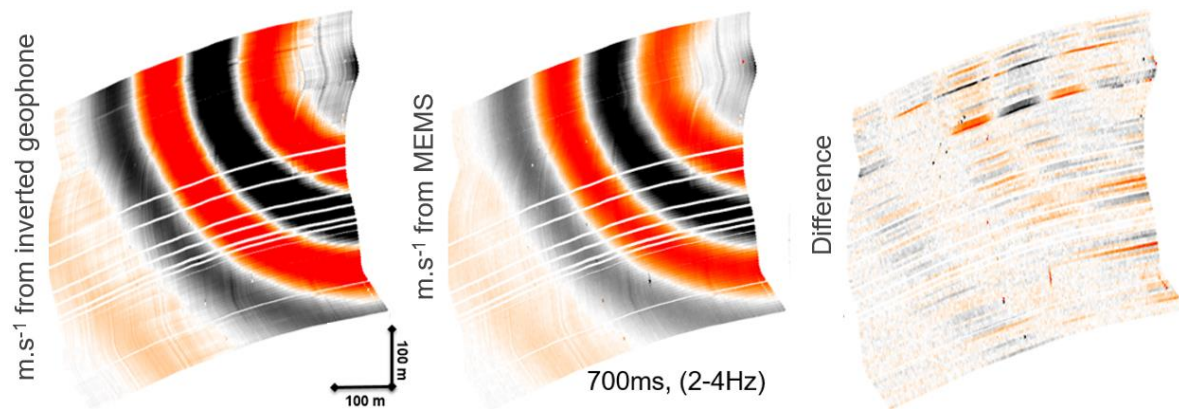

Figure 4 Time slices computed with geophone inverted values. Refer to figure 2 for a comparison with the same time slices computed from catalogue values.

Impact on imaging

The sensor-related jitter has a detrimental impact on signal preservation, starting with the very early stages of processing, when velocity filters are applied for surface-wave removal before any surface-consistent corrections can be derived. Figure 5a represents the temporal response of the 100 consecutive MEMS receivers, sensing a synthetic horizontal plane wave with a flat amplitude spectrum beyond 1 Hz. Figure 5b, right, represents its (log(f),k) spectrum, with all the energy concentrated around k=0 as a consequence of the lateral invariance of both the plane wave and the MEMS response. This spectral focalization ensures an excellent preservation of the reflection signal after velocity filtering. The situation is quite different with geophones (Figures 5c and 5d): the sensor-to-sensor variations introduce a spreading of the signal in the (log(f),k) spectra, with, as a consequence, a damaged signal after application of a velocity filter, especially at low frequencies.

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This spreading in the (log(f),k) also makes it less effective to remove the surface waves leaking into the signal cone.

One can question the ability of surface-consistent corrections to correct for sensor data jitter. The necessary conditions for success are:
- A signal-to-noise ratio that is high enough for proper phase estimation ;
- No multi-channel de-noise across geophones to retrieve individual geophone parameters ;
- Introducing an additional three term parametric form to the receiver operator. Doing so makes it possible to deal with long operators without inversion overfitting ;
- No amplitude spectral replacement at low frequencies based on catalogue values for receiver geophone operators.

These four conditions are however difficult to meet: insufficient surface-consistent correction will then leave a systematic geophone bias, which will survive the stack whatever the trace density. Contrary to the case with geophones, MEMS sensors have the advantage of not requiring any compensation for sensor-induced data jitter.
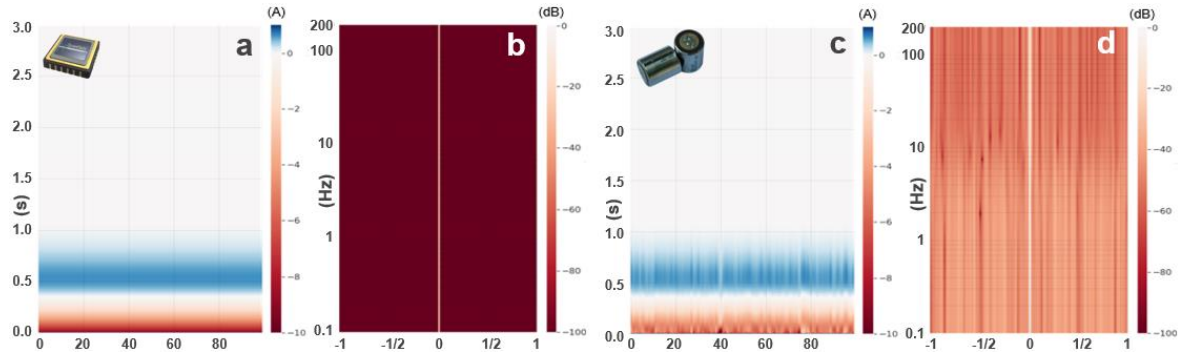

Figure 5 Response of the 100 MEMS sensors and geophones (in m/s), corrected for sensor response, to a synthetic horizontal plane wave: time response (a, c), and temporal frequency response (in log scale) versus wave number normalized by Nyquist (b,d).

Conclusion

The industry trend is to move towards nodal systems, with single-sensor broadband signal recording. Although project trace densities keep increasing for such acquisitions, we often observe a decrease in sensor densities actually planted into the ground compared to previous acquisitions. The individual response of each sensor has therefore become as important as our knowledge of the source signature. In order to exactly transform the recorded data into ground particle motions over a large range of frequencies and avoid sensor-related jitter on the recorded data, it is necessary to operate with sensors having an exactly known and invariant response. As illustrated with a field test, this is the case for MEMS sensors, but not for geophones. This data jitter concept has not been identified until now for several reasons:
- Use of arrays that mix individual sensor performance;
- Signal variations from sensor to sensor erroneously attributed to coupling or variations in terrain;
- Lack of reference sensors on commercial surveys;
- Lack of dedicated experiments using low-frequency equipment and finely sampled cross spreads designed to ease the identification of the phenomenon.

Given the exactly known and invariant response of MEMS sensors, they are without doubt the technology of choice to avoid introducing jitter into recorded data, to preserve amplitudes and phase

and to remove noise. This, added to the excellent low-frequency performance of the third generation MEMS, make these sensors the perfect solution for FWI applications.

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