

High-quality signal recording down to 0.001 Hz with standard MEMS accelerometers

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Summary

Recording very low-frequency signal below 1 hertz is a major concern for seismology, in particular passive noise tomography, and is now also considered for some oil and gas applications. The seismic sensors commonly in use for hydrocarbon deposit surveys (geophones and previous generation of MEMS accelerometers) previously had performance limitations in such applications due to their technological design with very low-frequency signal being concealed by instrument noise. Tests on a recent generation of MEMS (Micro Electro-Mechanical System) sensor with an ultra-low noise floor were performed in our lab, and showed outstanding very low-frequency performance in terms of instrument noise and full scale. A teleseism that occurred during our tests was also duly detected.

Introduction

The seismic oil and gas industry demand for broadband datasets has shown an ever-increasing growth over the last decade. This demand is seen particularly for low frequencies due to their low attenuation and ease of generation, and their benefits to field data have been underlined by numerous authors: signal penetration, vertical resolution and velocity analysis are improved, interpretation is faster, and reservoir characterization more accurate. Combined with long offsets, they are mandatory to perform efficient Full Wave Inversion.

Meanwhile, seismic equipment has evolved to accompany this new paradigm. Non-linear sweeps enable the generation of powerful signal below the vibrator full-drive start frequency (Bagaini 2008, Sallas 2010), while improvements in vibrator hydraulics (Tellier 2015) have lowered the full-drive start frequency, and consequently, the time required to generate low-frequency signal.

On the receiver side, the sensitivity of a geophone decreases by 12 dB/octave below its natural frequency. Sensor design enables the attenuated low-frequency signal to be boosted, but also increases associated noise, in particular the instrument noise. When the signal level falls below the latter, there is no way to recover it, even with the highest trace density and the best processing (Maxwell, 2011).

If conventional 10 Hz geophones have sometimes proved enough to record satisfactory LF signal down to 1.5 Hz (Mahrooqi, 2012), the recovery of deep or weak low-frequency events with 10 Hz geophones can be speculative. Geophones with natural frequencies around 5 Hz have been developed in recent years for the oil & gas seismic

industry. They offer a viable alternative to their predecessors that used to be bulkier, costly and not deemed industrial. Their use in the field is steadily increasing, and, especially when the low natural frequency is combined with high sensitivity, they are well suited to single geophone applications.

Although their low natural frequency largely addresses the instrument noise issue previously mentioned, their phase rotation in the seismic frequency band, combined with manufacturing tolerances, aging and varying environmental conditions, induce amplitude and phase distortions that are detrimental to the fidelity of the signal recorded.

MEMS seismic sensors do not have the drawbacks inherited from geophone design, and have a flat amplitude and phase acceleration response from DC (0 Hz) to 800 Hz, making them the perfect candidate for very low-frequency applications. However, despite successful low-frequency field applications (Tellier, 2017), the previous generations of MEMS sensors (noise floor 40-45 ng/ $\sqrt{\text{Hz}}$) suffered from an increase in instrument noise towards low frequencies that can compromise signal proper recording below around 2 Hz (Margrave, 2012).

The noise floor of the latest generation of MEMS seismic sensors is significantly lower (around 15 ng/ $\sqrt{\text{Hz}}$), but has been qualified so far only to address the standard bandwidth of interest to the oil & gas seismic industry, that is, above 1 Hz (Lainé, 2014). Increasing concerns for even lower frequencies, for both seismology and oil & gas applications, has led to evaluations of the performance of this sensor below one hertz. The results exceeded expectations with instrument noise in the range of NHHM (New High Noise Model, Peterson 1993) down to 0.1 Hz while showing only a slight increase down to 0.001 Hz. Additionally, the sensor full scale is not compromised, and the occurrence of a teleseism during our test was detected.

Noise test setup and results

To evaluate the MEMS performance at very low frequencies, we tested the sensor in a noise-isolated acoustic chamber, located in the basement of an office building. An additional filtering structure was installed in the acoustic chamber for the optimum attenuation of environmental noise (figure 1). Data was acquired at night over several months in passive mode (no source).

Towards millihertz recording with standard MEMS accelerometers

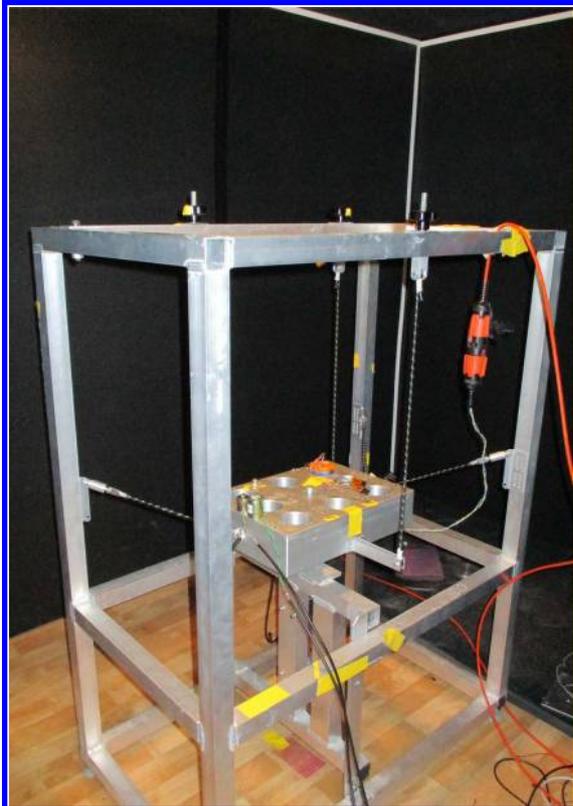


Figure 1: Test bench: view of the acoustic chamber equipped with a filtering structure. The stiff metallic framework holds a heavy plate maintained by several bungee cords. The first resonant mode of this vibration isolation table is at 2.7Hz which allows a good mechanical filtering of higher frequencies. Such isolation system has already been used to demonstrate noise performance as low as $12\text{ng}/\sqrt{\text{Hz}}$ for higher frequencies with this MEMS (see Laine, 2014)

Noise measurements were performed with small 37×56 mm boards (figure 2), fitted with the Quietseis technology (also used in DSU-508XT seismic sensors). The two boards (used for vertical and horizontal recording) were fixed on a heavy metallic support in order to lower the effect of acoustic perturbations and avoid any low frequency resonant mode of the board. Each board comprises two ASICs (Application-Specific Integrated Circuits): one for communication and data transmission, the other for closed-loop control system and calibration of the MEMS. Connectors are used for a 5 Volts power supply, PPS (Pulse Per Second) from a GPS for synchronization, and serial data transmission, thus allowing a simple recording setup for end-users. The MEMS accelerometer is soldered on the opposite side of the board (not shown on figure 2).

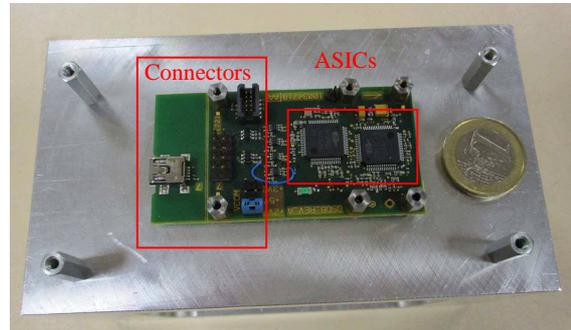


Figure 2: For noise evaluation, the stand alone board “QSDB” is fixed on an heavy metallic frame to lower acoustic perturbations. Such board can be easily integrated in any custom device.

The passive data acquired at night for several months on horizontal and vertical axes were compared with New Low Noise Model (NLNM) and New High Noise Model (NHNM) (Peterson, 1993), using USGS Matlab script “ANSS_noise_rms_rev4.m” (figure 3). For the horizontal component, noise down to $40\text{ng}/\sqrt{\text{Hz}}$ at 1 Hz, $100\text{ng}/\sqrt{\text{Hz}}$ at 0.1 Hz and $400\text{ng}/\sqrt{\text{Hz}}$ at 0.01 Hz were recorded without compromising the sensor full scale of 5m/s^2 . We demonstrated a dynamic range of 133 dB for the horizontal axis and 125.4 dB for the vertical axis in the bandwidth 0.02 Hz to 2 Hz with a fullscale of 5m/s^2 peak.

For specific application, like near-source seism monitoring, the fullscale can be increased up to 13m/s^2 peak. For vertical axis with increased fullscale, noise integrated in bandwidth 0.02 Hz to 2 Hz is equal to $2.55\text{ }\mu\text{m/s}^2$. The dynamic range is improved up to:

$$20 * \log_{10} \left(\frac{13/\sqrt{2}}{2.55e-6} \right) = 131\text{dB}$$

MEMS accelerometer data was also compared to two velocimeters (5 Hz and 10 Hz geophones) and connected to a very low-noise 24-bits Analog to Digital Converter (ADC) (figure 4, see Tellier 2017 for comparison of MEMS and analog sensor specifications). We demonstrated with this test that MEMS accelerometer noise degradation is much lower toward low frequencies than for geophones, even when connected to a high performance ADC.

Towards millihertz recording with standard MEMS accelerometers

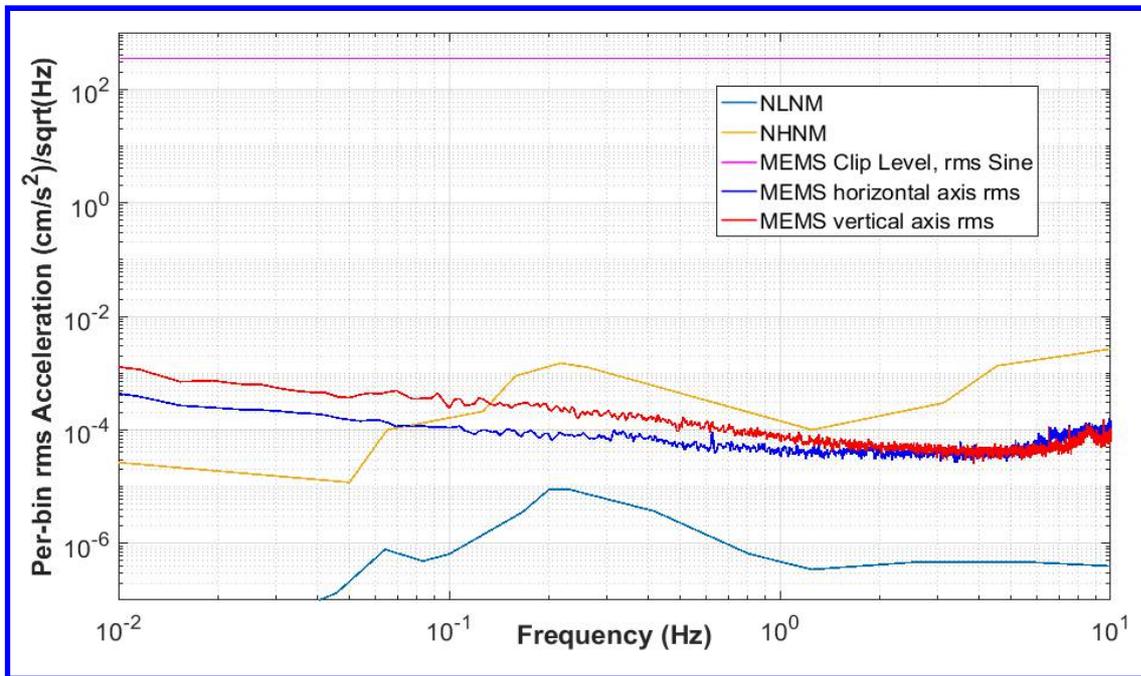


Figure 3: Noise measurement of MEMS in vertical axis and horizontal axis.

Noise integrated in bandwidth 0.02 Hz to 2 Hz is equal to $0.79 \mu\text{m/s}^2$ rms for horizontal axis and $1.9 \mu\text{m/s}^2$ rms for vertical axis.

Fullscale is 5 m/s^2 peak (3.5 m/s^2 rms). Dynamic range is $20 * \log_{10}(3.5 / (0.79e-6)) = 133\text{dB}$ for horizontal axis and $20 * \log_{10}(3.5 / (1.9e-6)) = 125.4\text{dB}$ for vertical axis

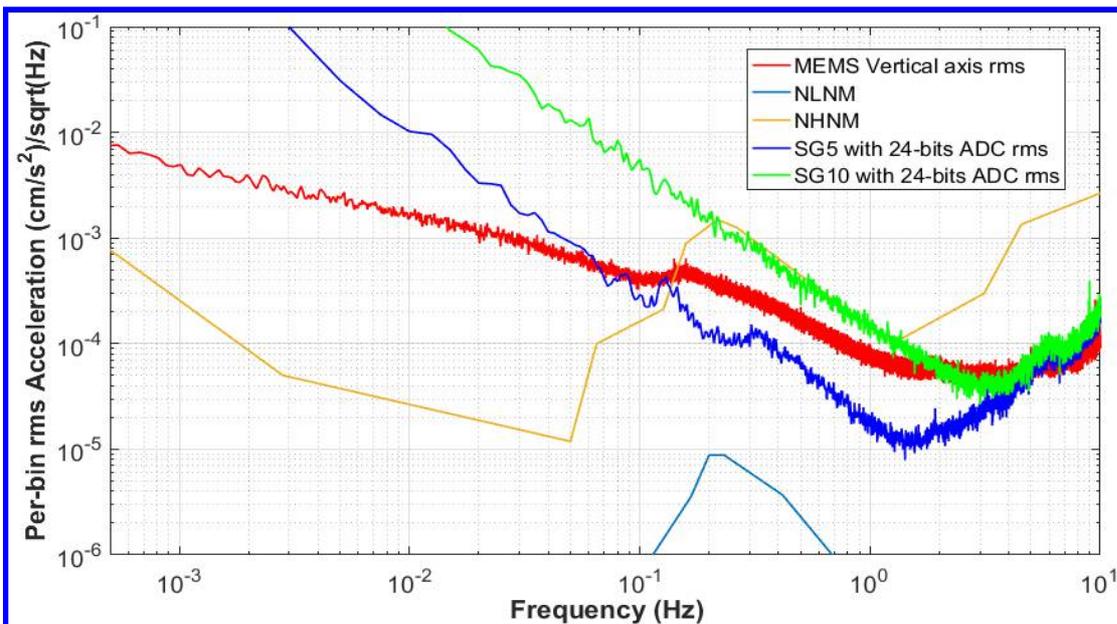


Figure 4: Comparison of MEMS accelerometer versus 5 Hz Geophone (SG5) and 10 Hz Geophone (SG10) connected to a 24-bit ADC.

Geophones measurements are differentiated to get an acceleration and scaled with theoretical response of geophones. Measurements are impacted by ambient noise at higher frequencies.

Towards millihertz recording with standard MEMS accelerometers

Earthquake in Iran-Iraq border region

The MEMS accelerometers described above were in acquisition during a teleseism of magnitude 7.4 that occurred November 12th, 2017, UTC 18:18:19. The seismic event epicenter was located in the Iran-Iraq border region, about 4,100 km from our test bench located in Nantes, France (figure 5). Both horizontal and vertical accelerations were recorded.

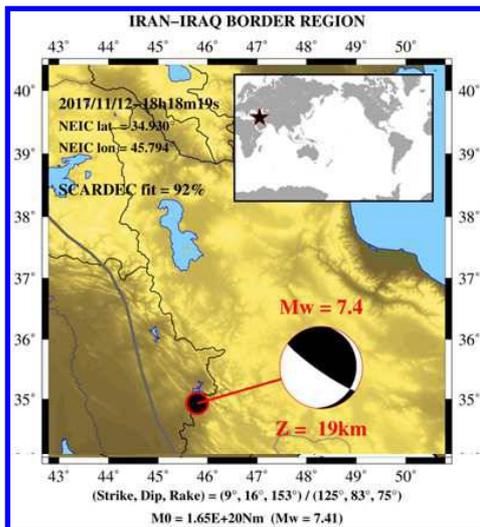


Figure 5: Magnitude 7.4 teleseism location (Source: Observatoire Geoscope, 2017)

Magnitude 7 teleseism signal is above the MEMS noise floor between 0.02 Hz and 5 Hz, with a peak around 0.1 Hz (Clinton, 2002). In order to avoid the resonance frequency of the isolation table at 2.7 Hz, the data is filtered with a pass-band zero-phase filter between 0.07 Hz and 0.45 Hz with a filter order of 20,000.

Time data for vertical axis is shown on figure 6. The first high acceleration peak at $t=180$ s was recorded in Nantes at 18:25:09 UTC. The P-wave of the seismic event was detected at 18:25:06 UTC by the closest seismic station at Chambon La Foret, France (Observatoire Geoscope, 2017, station "CLF").

Time data for horizontal axis is shown in figure 7. The high acceleration peak recorded at $t=515$ s in Nantes (18:30:24 UTC) is also very close to the S-wave arrival time at Chambon La Foret, France (18:30:35 UTC).

Those two observations proved the capability of our sensing device to record weak, very low-frequency seismic signal arising from a 4,100 km distant seismic event and their potential suitability for such applications.

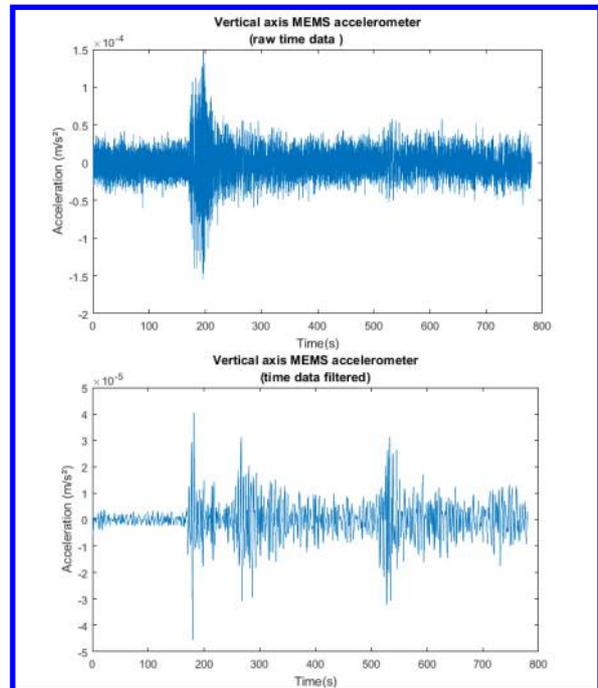


Figure 6: (a) Raw data from vertical axis MEMS accelerometer enables detecting the teleseism, but also includes excitation at 2.7 Hz of our vibration isolation table, (b) Same data filtered with a pass-band zero-phase filter between 0.07 Hz and 0.45 Hz.

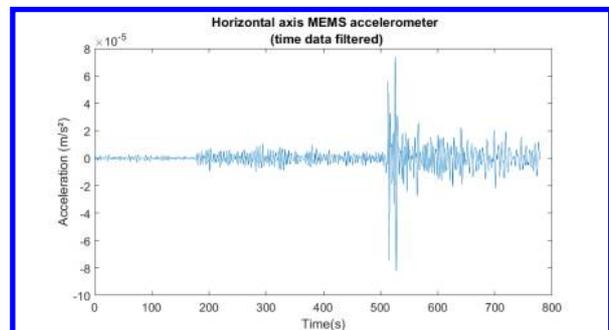


Figure 7: Time data from horizontal axis MEMS accelerometer are filtered with same pass-band zero-phase filter as above. Small signal measured after $t=180$ seconds are due to P-wave arrival.

Conclusions

A new MEMS accelerometer with improved noise floor and reduced $1/f$ noise contribution has been evaluated for very weak signals and very low frequency measurements. A noise floor below NHHM down to 0.1 Hz and showing only a slight increase down to 0.001 Hz has been demonstrated. This result opens up new possibilities for below hertz signal recording, for seismological or O&G applications.

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