

# Acquiring low frequencies : sweeps, sensors, sampling and stories

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## Summary

The quest for extending the bandwidth of seismic data has been accelerating lately on-shore North America. Assessing the feasibility of recording useful low frequencies for a given target is a problem where the seismic hardware, source parameters, design layout and seismic processing must be considered. We aim to provide general recommendations and guidelines regarding the equipment, the survey designs and processing techniques that maximize the chances of recovering useful low frequency data, with illustrations from Alberta, Alaska and the Lower 48.

## Introduction

Low frequencies are becoming more important and relevant to on-shore seismic acquisition as waveform inversion model building and impedance inversion techniques become more advanced and common as part of the process of reservoir analysis (Baeten, 2013). Structural analysis also benefits from a broad bandwidth, with improved wavelet sharpness and denser image texture (Denis, 2013).

In order to successfully acquire and utilize this data to achieve the maximum benefit, one has to ensure that the survey design, source and sensor attributes and processing of the data are in harmony. Although we will mainly focus on the acquisition aspects in this presentation, we feel that subsequent processing applications are of the utmost importance. If the data is not acquired with the final product in mind, processing may not be able to remedy its deficiencies. We will begin with source and receiver aspects, then discuss geometry and imaging and finish with some case-studies.

## Theory and/or Method

### *The vibroseis source*

Seismic vibrators are not fully efficient at low frequencies. For example the lowest frequency, full force output for a 270,000 N vibrator is around 8 Hz. Below that frequency mechanical constraints, namely hydraulic pump flow until around 4 Hz, and reaction mass below that, prevent the vibrator from imparting full force energy into the ground. A solution to this problem is to modulate the sweep rate as a function of these constraints to make-up for the low force output and build up energy (Baeten, 2010). The output force as a function of frequency is shown down to 1.5 Hz on figure 1a. This force matches the flow and displacement constraints discussed previously. The benefit of adding octaves is illustrated on the amplitude spectra of the sweeps (figure 1b) as well as on the autocorrelation wavelets (figure 1c). The broader-band the wavelet, the more it exhibits low side-lobes and a time-focused clean peak.

The loss of energy over the bandwidth compared to an 8 Hz start is acceptable up to 4 Hz (-0.6 dB), but it results in a scalable energy loss to acquire octaves below: -1.5 dB for a 2 Hz start; and -3 dB for 1.5 Hz. It is equivalent to state that to achieve the same signal to noise ratio over the shared bandwidth, one should double the sweep length for a 1.5 Hz start versus a 8 Hz start.

The lower the start the more inefficient the vibrator, and the costlier the source parameters.

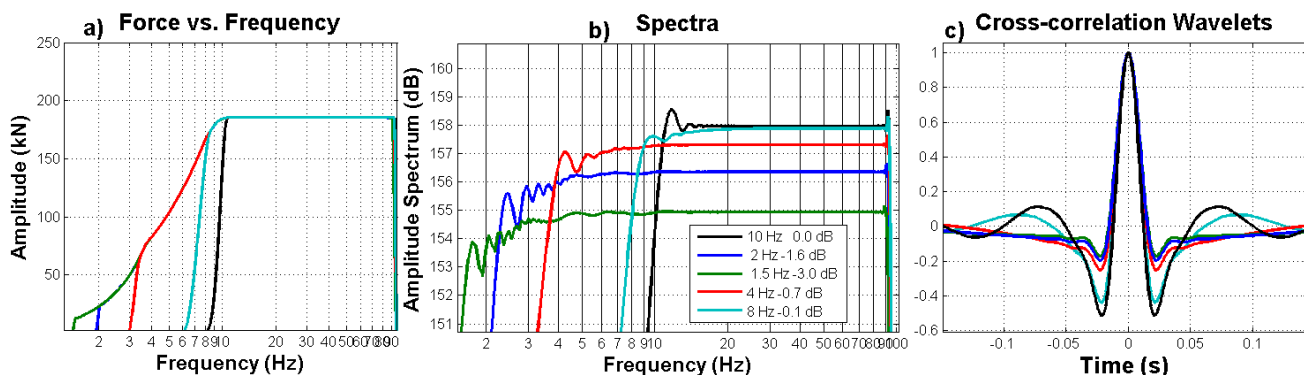


Figure 1: Vibroseismic sweep attributes for several starting frequencies : 10, 8, 4, 2 and 1.5 Hz Force (a) and amplitude (b) as a function of frequency and cross-correlation wavelets in time domain (c).

**The recorder/sensor system**

The geophone coil motion can be modeled as a simple harmonic oscillator, where its response shape is fully determined by its resonance frequency and its damping. The response is scaled according to the sensitivity of the unit (figure 2a). Connecting several units in series adds the individual sensitivities, at the expense of increased equivalent impedance which may result in induced noise pickup.

MEMS accelerometers have a flat response in the acceleration domain, which results in a 6dB/octave straight line response in velocity domain (figure 2a).

To assess the lowest particle motion that can be detected on a non-summed recording, sensitivities have to be combined with the system noise (dominantly thermal, but also quantization) (figure 2b). The optimal sensitivity is reached when the “ambient” noise, i.e. the noise recorded by the sensor, exceeds the thermal noise, as seen in (figure 2c). Figure 2d shows a case where the system noise is prevalent, which means that it would be the main adversary when seeking to retrieve the source signal. It is thus advised that the sensor sensitivity choice should be determined according to the ambient noise level for maximum efficiency; sensitive sensors for quiet areas (Maxwell, 2011).

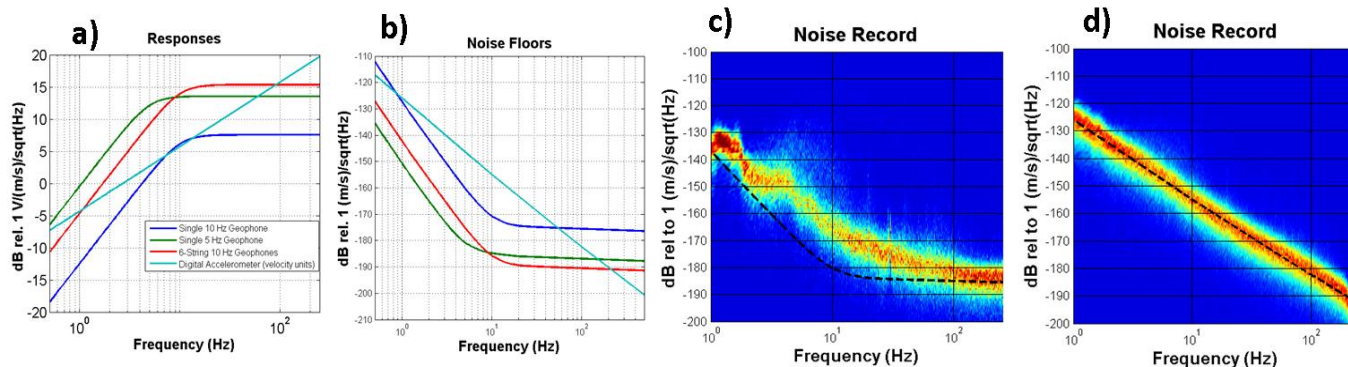


Figure 2: Sensor responses and noise floors, theoretical (a and b) and passive measurements (c and d). The theoretical noise floor is superimposed in black in (c) and (d).

**Acquisition geometries and Imaging**

Spatial sampling requirements are not as costly for low-frequencies. For example, at 5 Hz it takes 30 meters station interval to properly sample a slow 300 m/s ground roll, which helps the linear noise attenuation through velocity-filtering. Statics do not prove as destructive as they can be for higher pitched waves, since a time difference represents a small phase lag.

Another important consideration regarding the signal to noise ratio as a function of frequency is the imaging process. The Fresnel zone radius is inversely proportional to the square root of the frequency.

If the migration is considered as a summation surface, a bigger zone of influence results in a larger signal summation order. The signal-to-noise ratio after migration is thus favorable for low-frequencies.

Low-frequencies also present challenging aspects, namely the preservation of the phase throughout the processing sequence. A small phase-lag quickly results in large time-shifts which may jeopardize interpretation.

Applying an inverse sensor response prior to the deconvolution should also be considered. In the absence of noise, the statistical estimation of the wavelet in the deconvolution should contain the sensor effect. A recent on-shore example from North America proposed a match filter between measurements on standard and low-frequency phones avoiding unstable inverse filters that provided satisfactory results (Chiu, 2013). In another example from the Middle-East, the authors also advocate in favor of accounting for the sensor response as early as possible (Mahrooqi, 2011).

## Examples

### Alberta

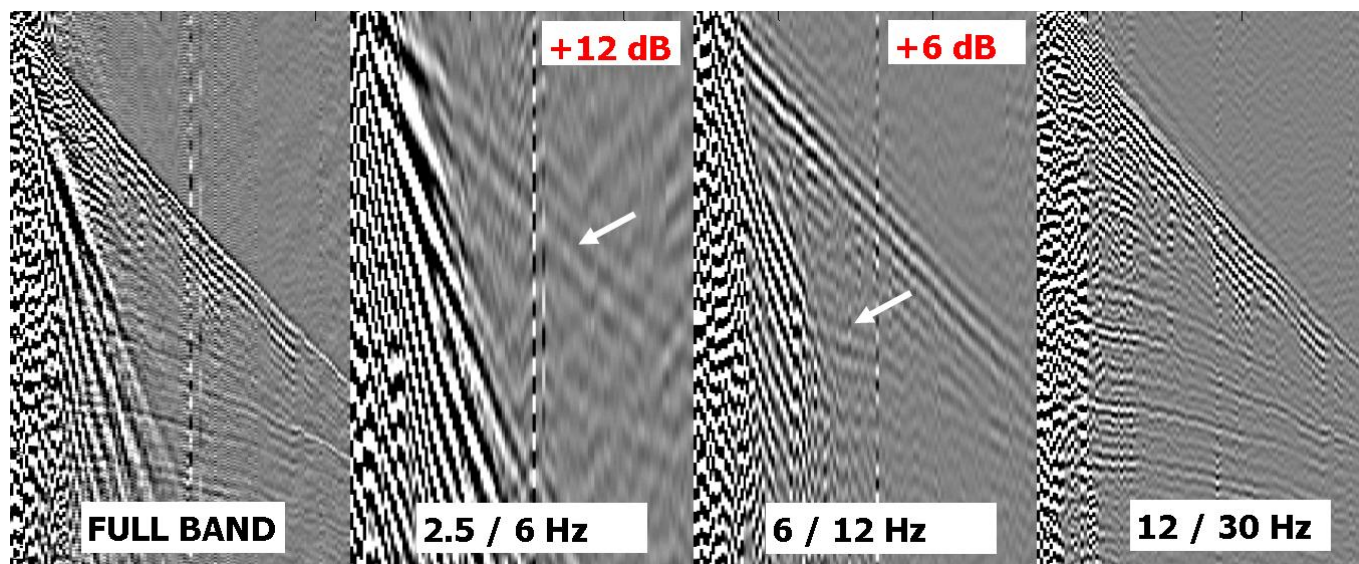


Figure 3: Near receiver line from a shot gather. Correlated, no processing. Data courtesy of Talisman Energy.

Figure 3 shows a shot gather acquired in Alberta, split in several band-pass filters. The vibrator array contained three 270,000 N peak force units. On the receiver side, strings of 6 geophones in series were laid out. The gather displayed used a sweep that began from a 3 Hz corner frequency. On the low-pass panels low-frequency source generated ground roll dominates, yet refracted and reflected body waves are visible, evidence that useful signal is there.

### Alaska

Another example is from the Alaskan North Slope, where figure 4 compares pre-stack shot gather filter panels and zero offset section of pre-stack time migrated (PSTM) image. As previously seen, the ground roll dominates the low-pass section of the shot gather, yet body waves are clearly visible on unprocessed gathers. After imaging, structural features match between low-pass and high-pass panels.

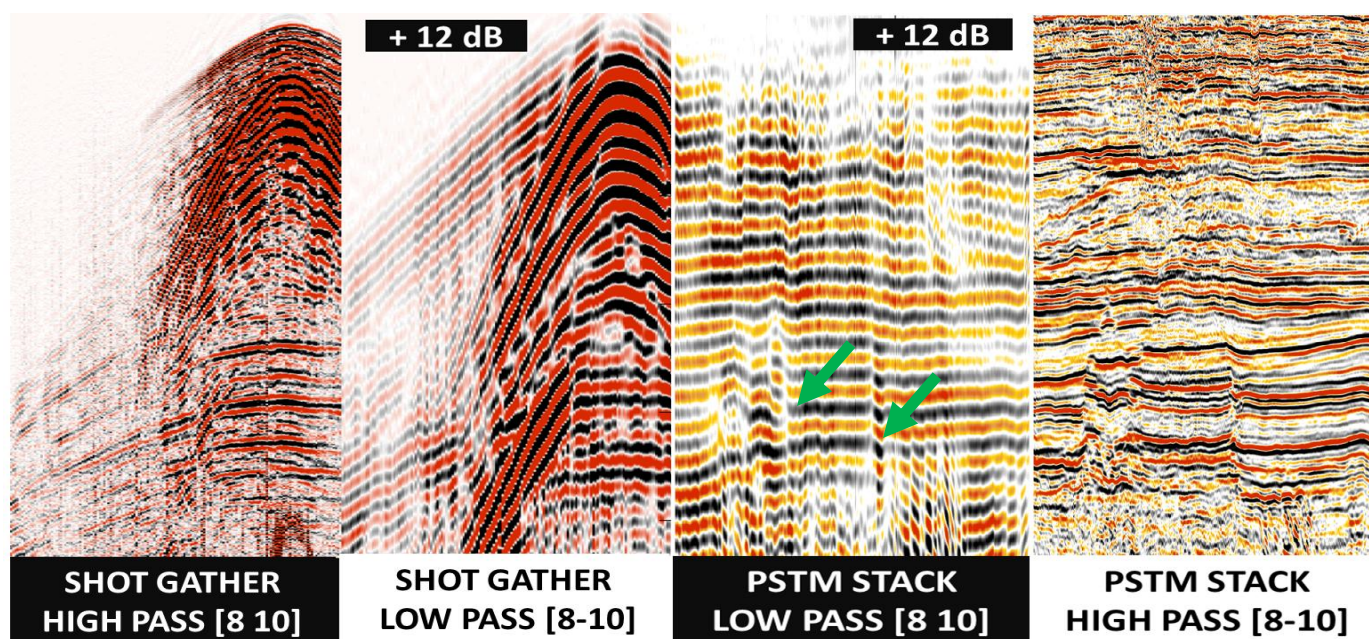


Figure 4: Pre-stack filter panels versus pre-stack migrated zeros offset section filter panel. Data courtesy of CGG multi-client and new ventures.

## Conclusions

From an acquisition hardware point of view, the outlook for low frequencies is somewhat grim at first: the standard receiver devices have low sensitivity and the standard seismic vibrators weak. On the receiver side, it is recommended to properly choose receiver sensitivity according to ambient and instrument noise levels. On the source side we can use specifically designed low-dwell sweeps.

When looking at the physical phenomena of seismic wave propagation, long wavelengths suffer less from attenuation. Velocity-filtering is efficient on non-aliased low frequencies, and the Fresnel zone dimensions increase the migration operator summation surface which enhances further signal-to-noise ratio on pre-stack time-migrated data.

For conventional seismic exploration, it is therefore argued and illustrated that low frequencies down to 2.5/3Hz do not systematically require sophisticated and specialized equipment, and may be acquired at a reasonable cost on standard crews configurations. The added benefit upstream in terms of inversion and reservoir analysis could make these low frequencies extremely beneficial at little extra-cost.

## Acknowledgements

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## References

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