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Building Blocks – Considerations for high-fidelity broadband land seismic data acquisition

Author information – Howard Watt, Nicolas Tellier, Stéphane Laroche, Phillippe Herrmann & Gilles Ollivrin
Affiliation – Sercel Houston TX USA, Sercel Nantes France, Sercel Massy France

Introduction

Developments in land acquisition methods and equipment have greatly reduced the cost of vibroseis source points. These savings can be reinvested into denser spatial sampling improving data quality (Wams, 1998). In addition to improved spatial sampling, the industry has recently focused on acquiring data with the broadest possible bandwidth. The potential benefits of broadband acquisition are well documented (Denis et al., 2013):

- Improvements in AVO and inversion
- Deep imaging in areas of complex overburden
- Sharpening the seismic wavelet by removing interference from side lobes
- Highlighting subtle and gradual variations in acoustic impedance

The process of acquiring a seismic project is analogous to constructing a building. Compromises on design, materials, or methods can seriously impact the end product. Acquisition geophysicists need to understand how decisions regarding the equipment and methods used can impact the final product. If the recording parameters of the sources and receivers are akin to a blueprint, the acquisition equipment would be the materials used for the construction. We will discuss important considerations regarding today's seismic recording systems and how they can affect our ability to record high-fidelity broadband seismic data.

Vibroseis – Broadband Source

As we want to maximize our recorded bandwidth in an efficient and cost-effective manner, careful considerations must be taken when evaluating both vibrator models and sweep methods. The past decade has seen several improvements in our ability to extend the seismic signal frequency toward the lows. A vibrator's performance is a combination of the unit's force and its broadband capabilities. Low-Dwell or "Custom Sweep" methods such as EmphaSeis (Sallas, 2010) and MD-Sweep (Bagaini, 2008) have been widely accepted by the industry. These methods reduce the vibrator's drive level to match its mechanical and/or hydraulic limitations while decreasing the sweep rate to maintain a flat energy spectrum. A variety of alternate approaches, Long Linear Start Tapers, Logarithmic, and Low-Frequency Linear have also been proposed to extend the signal bandwidth below the vibrator's "full-drive start frequency" capabilities. On paper, these sweeps appear to meet our expectations for low-frequency output, but in practice, offer no control over the level of energy generated and subsequent energy spectrum (figure 1) (Tellier et al., 2019).

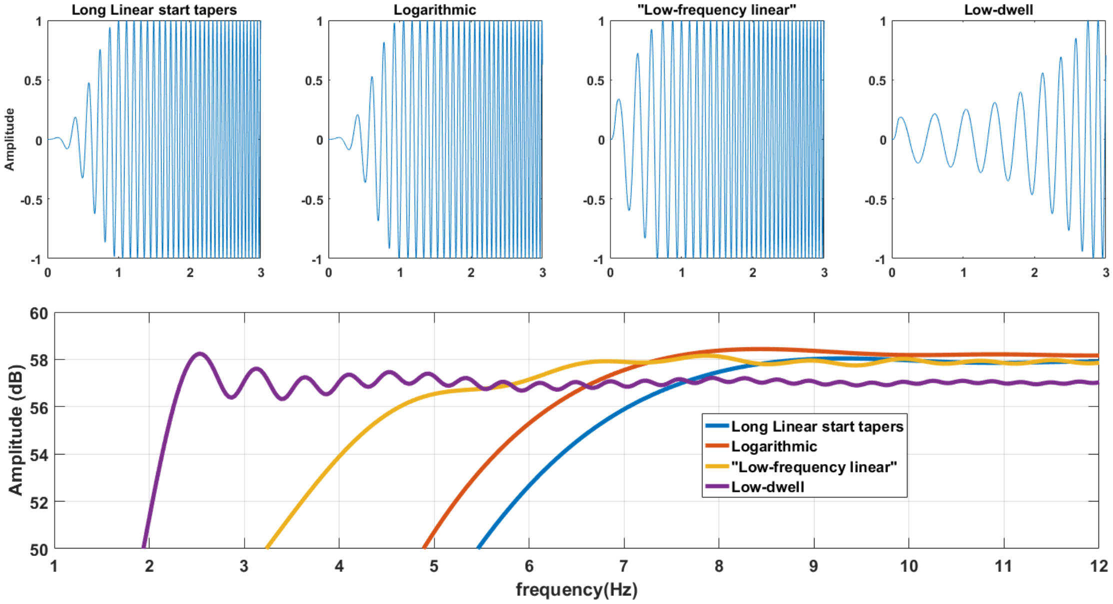

Figure 1: *Sweep envelopes at low frequencies (top) and low-frequency amplitude spectrum (bottom) of a low-swell sweep with various alternative low-frequency sweeps (example with a 2-80 Hz, 12 s, 80%, Nomad 65 Neo). Full signal amplitude is reached at 2.5 Hz for the low-dwell sweep, but at 5 Hz for the 'Linear Low Frequency', 7.2 for the logarithmic sweep (-0.2 dB/oct) and 8.4 Hz for the sweep using a 1 s linear taper.*

In the early 2010s manufacturers proposed new vibrator models or modifications to their existing vibrator designs to decrease their full-drive start frequencies. Significant low-frequency gains require the utilization of a heavier reaction mass and considerably longer reaction mass stroke. To control these lower frequencies, heavier more complex hydraulic systems are required. Careful consideration should be given to the performance of these vibrator designs and their utilization. A design that excessively boosts its low-frequency output may compromise its effectiveness at generating higher frequencies. Furthermore, depending on the vibrator type and sweep, one side effect of the increased emission of low frequencies (typically below 5 to 10 Hz) tends to be higher levels of distortion as compared to a conventional sweep.

During the past 10 years, several methods have been introduced to address the distortion associated with the generation of these low frequencies. However due to performance issues, complexity of implementation, and the proprietary nature of some of the methods, their widespread implementation has been limited (Ollivrin, 2019). Recently, a novel approach has been introduced that avoids the generation of harmonics associated with low-frequency sweeps. Integrated into the vibrator electronics, SmartLF predicts the low-frequency distortion and modifies the servo value input signal accordingly, resulting in a much-improved ground force signal (Figure 2).

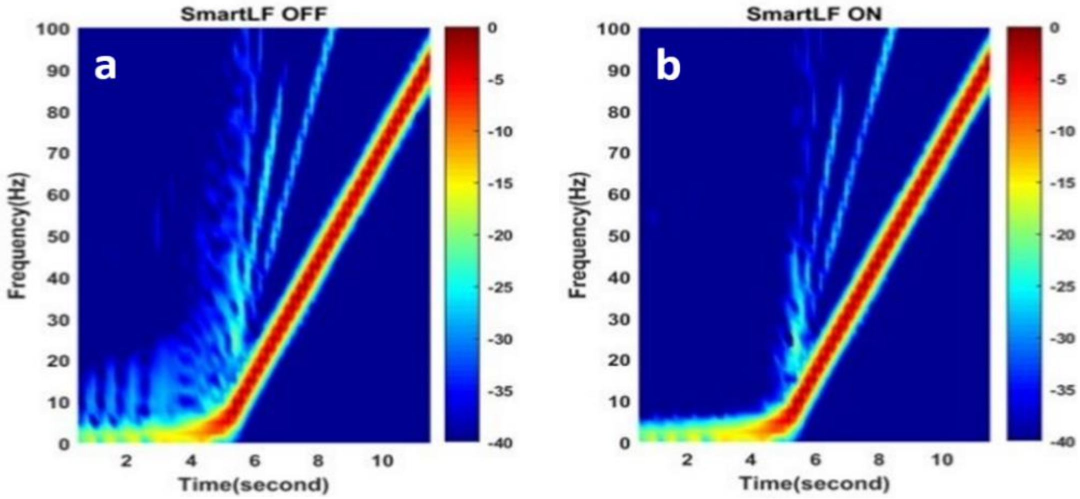

Figure 2*: Low-frequency distortion results for a low-dwell sweep 2-96 Hz, 80% 12s, Nomad 65 NEO, ploughed field: Left (a) – SmartLF turned OFF, Right (b) – SmartLF turned ON.*

Receivers

The electromagnetic “moving coil” geophone has undoubtedly been the most widely used sensor in the past 100 years. Since the late 1960s, the most notable improvements have been related to increases in reliability, similarity, and sensitivity (Meunier, 2011). In the past, arrays of 12 or more sensors were used, this was reduced to arrays of 6 and in recent years, the use of a single sensor per station has become quite common. Although conventional geophones have a “natural” frequency within the seismic band they do have an inherent limitation; accurately recording low frequencies. In general, their phase response varies between 0 and 180 degrees with the shift occurring around their natural frequency (90° lag). Below their natural frequency geophones have a 12 dB/octave analog low-cut. To some extent data processing can correct for both the phase and amplitude however, this depends on accurate knowledge of its instrument response. Unfortunately, due to the nature of a geophone’s construction, its response can vary with both time and temperature. As the industry continues to improve its ability to generate lower-frequency signals, companies are moving from the more common 10 Hz geophone to 5 Hz geophones in an effort to record these lower frequencies. Reducing the natural frequency of a geophone has a few drawbacks, it is more sensitive to tilt and has increased size and weight. We could look at Piezo-electric sensors which may have a better low-frequency response as compared with conventional geophones however, they have the drawback of higher levels of instrument noise, poor distortion performance and sensitivity to non-vertical polarized signal.

Broadband Receivers - MEMS

An alternative to the moving coil geophone was introduced in the early 2000s. Based on MEMS (Micro-Electro-Mechanical Systems) technology, these digital sensors offered a number of significant improvements over their conventional analog predecessors; insensitivity to environmental electromagnetic noise, a flat amplitude and phase response across the entire seismic bandwidth of interest from DC (0 Hz) upwards, significantly improved performance at upper frequency limits (absence of spurious modes), negligible manufacturing tolerances (figure 3) and insensitivity to variations in temperature and aging. The first two generations of MEMS sensors were primarily used in a 3-component form factor that offered additional benefits over conventional 3C geophones; insensitivity to tilt, excellent vector fidelity, and the ability to perform accurate automatic vertical-orientation-rotation. Additionally, they were less prone to errors during deployment. As the industry transitioned to broadband recording, the relatively elevated noise floor (below 10 Hz) of the early-generation MEMS sensors was perceived as a limiting factor when recording weak signals below a few hertz. Furthermore, they were typically benchmarked against conventional geophone arrays, thus requiring an increased station count. This coupled with the increased power consumption of these first and second-generation MEMS sensors resulted in a more costly solution.

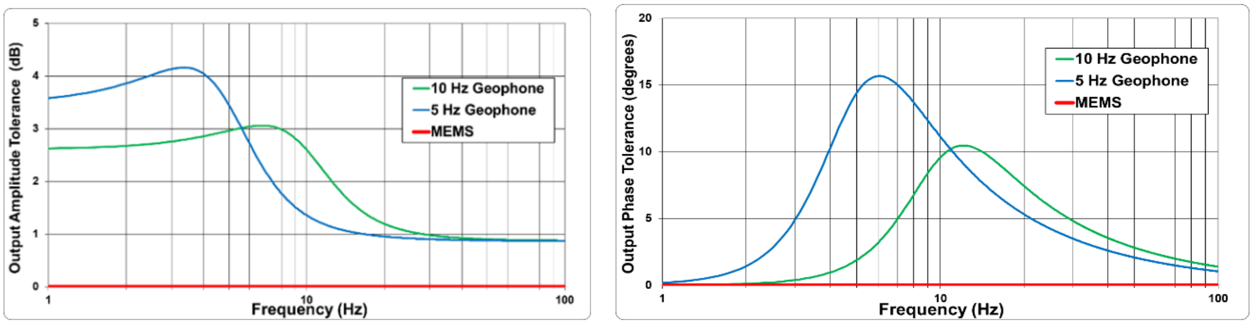

Figure 3: *Illustration of the manufacturing tolerances for three types of sensors; MEMS, 5 & 10 Hz geophones (worst case, aging and temperature not included). Left – Maximum deviation in amplitude response. Right – Maximum deviation in phase response (Tellier 2020).*

As MEMS sensing technology continued to develop, the introduction of a third-generation of sensors addressed concerns associated with previous versions. With more projects transitioning to high-density point-source blended acquisition, the improved sensor distortion (-90 dB) becomes more attractive when compared to conventional geophones (-62 dB). Additionally, the much-improved noise floor (table 1) shows outstanding very low-frequency performance in terms of instrument noise and full scale (Fougerat 2018). The industry's move to single-sensor recording has also highlighted a shortcoming in conventional geophones. Sensor-to-sensor variations, inherent to the manufacturing process, can manifest as amplitude and phase perturbations (figure 4) (Tellier, 2021). Even with advanced processing, it is difficult to compensate for these errors.

MEMS - Generation	1 – 10 Hz	10 – 200 Hz
1st & 2nd	~120 ng/√Hz	40 – 45 ng/√Hz
3rd	30 ng/√Hz	15 ng/√Hz

Table 1: *Comparison of the noise floor values by frequency range for the 3 generations of MEMS sensors. Note: Below 10 Hz, the noise floor of the 3rd generation MEMS sensor is approximately 1/4th its previous level.*

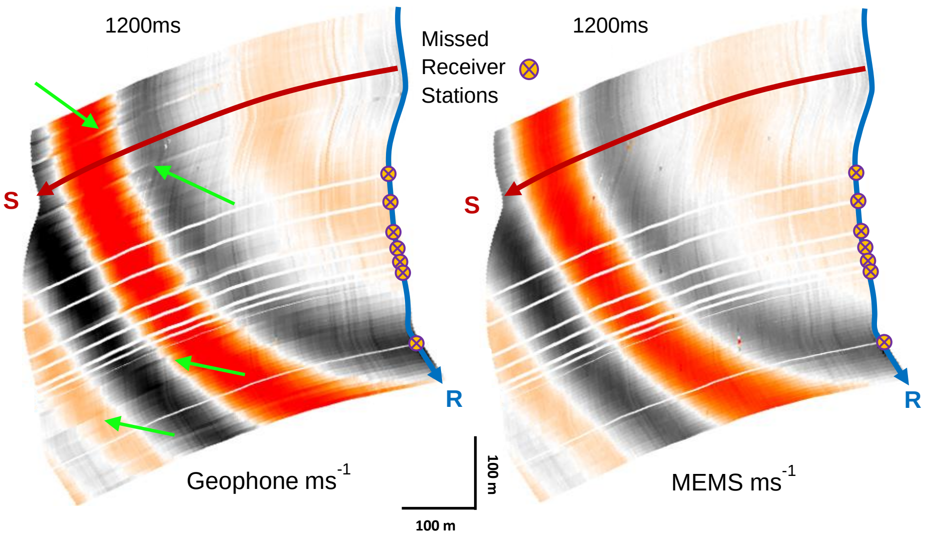

Figure 4: Side-by-side geophone and MEMS time slice comparison after sensor response correction (2 – 4 Hz Octave). Data jitter" (green arrows) highlight the octave-dependent amplitude (horizontal) and phase (blurred wavefront) errors. The seven white lines perpendicular to the receiver line are skipped sensor positions. (gold/purple ⊗)

Conclusion

The needs of today's interpreter continue to challenge both the acquisition and processing geophysicist. Choices made during the planning phase of an acquisition project are critical to supplying a data set that meets the requirements for FWI, imaging deep reservoirs under complex overburden or shallow high-resolution targets. Acquisition geometries continue to move towards higher-density point-source point-receiver solutions. On the source side, we need to provide a broadband signal that is rich in both low and high frequencies while mitigating the increased distortion often associated with low-frequency sweeps. We also must be mindful that single-source operations provide a weaker signal than arrays of vibrators. On the recording side, we need receivers that are capable of accurately recording the incoming signal bandwidth while providing the processor with a data set free of sensor artifacts. This paper will discuss important considerations for the sources and receivers we choose as the "building blocks" of better broadband data acquisition.

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