# Controlling a land vibrator with m-sequences: a field test

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## ABSTRACT

We conducted initial field measurements to test the idea of driving a land vibrator with maximal length sequence (m-sequence) pilots. Seismograms were recorded with the CREWES IVI EnviroVibe vibrator controlled by m-sequence pilots. The m-sequence seismograms were compared to seismograms acquired with the vibrator controlled by a conventional frequency sweep, and with data acquired with an accelerated weight-drop source. The comparison indicated significant issues regarding how hydraulically-powered vibrators respond to pilot signals that try to force very sharp accelerations on the reaction mass. Nevertheless, the m-sequence seismograms from this initial field test show promise, and point to possible modifications to the m-sequence pilots to make them more compatible with the particular mechanical characteristics of a land vibrator.

## INTRODUCTION

Frequency upsweeps are the standard pilot signals for controlling hydraulically-driven land vibrators. Numerical simulations suggest that pilot signals based on maximal-length sequences, or m-sequences, have noise reduction advantages over frequency sweeps (Wong, 2012). Although m-sequences have been used successfully to drive piezoelectric vibrators in crosswell applications (Wong 2000) and sonar sources in oceanography (Behhringer et al., 1982; Dushaw et al., 1999), no attempts seem to have been made to apply them for driving land vibrators. We have conducted preliminary field evaluation of the concept of using m-sequences (m-sequences) pilot signals to control land vibrators.

## FIELD PROCEDURE

Seismograms were recorded with the CREWES IVI EnviroVibe vibrator source and an accelerated weight drop source powered by compressed air. As pilots for the small vibrator, we used two different m-sequences at three different amplitude levels and a single 10-250Hz linear frequency upsweep. Pilots named mseq11, mseq12, and mseq13 are all the same signal, but with amplitudes set to 9%, 18% and 35% of maximum drive level. Pilots named mseq14, mseq15, and mseq16 are time-shifted (by about 2.04 seconds) versions of mseq11, meq12, and mseq13, respectively. More details about m-sequences can be found in Wong (2012). The amplitude of the frequency-sweep pilot was set to about 90% of maximum drive level.

Sweep times were 16.376 seconds for the m-sequences, and 20 seconds for the frequency sweep. Listen times were 22 seconds. All seismograms were recorded with same set of receivers: 45 three-component downhole geophones cemented in a well at depths of 0m to 135m at 3m intervals, and two short surface lines of 16 three-component geophones each, oriented in perpendicular East-West and North-South directions. The surface lines were centred on the well, and the geophones on each line were separated by 10m. Because of time limitations, only two source locations were occupied: one within 2 metres of the well, and the second at the end of the East-West line 80m from the well.

The location of the weight-drop source was close, but not identical, to the vibrator location near the well.

For the vibrator measurements, we recorded both correlated and uncorrelated data for all the geophones. We also recorded the signals from accelerometers mounted on the base plate and reaction mass of the vibrator. It was hoped that these signals would provide clues as to how the hydraulically-powered vibrator reacts to the sharp transitions that are characteristic of pure m-sequences.

## RESULTS

### Comparing m-sequence seismograms with weight-drop seismograms

Figures 1 is a comparison of the vertical-component seismograms from the downhole geophones. For times between 0ms and 250ms, the weight-drop traces and the m-sequence traces are quite similar, and any difference between the two sets of seismograms might be explained by the fact that the weight-drop source and the vibrator source were located at positions differing by several meters.

However, when we display the seismograms for the surface geophones for times up to 1000ms on Figure 2, we see significant differences between the seismograms obtained by the two sources. Spurious arrivals exist on the m-sequence seismograms that do not appear on the weight-drop seismograms.

### Comparing m-sequence seismograms with frequency-sweep seismograms

Figure 3 compares seismograms for the E-W and N-S surface lines acquired with the mseq14 pilot with those acquired with the frequency sweep. The vibrator was located near geophone at the western end of the E-W line. Although the m-sequence seismograms have the general appearance of seismic data, detailed comparison with the frequency-sweep seismograms reveal that they have serious shortcomings. The m-sequence seismograms are plagued by artifacts that are not present for the swept-frequency seismograms. For the both the E-W and N-S lines, the weak first-arrival direct P events seen clearly near 100ms on vertical-component traces for the swept-frequency data are almost completely masked on the equivalent m-sequence traces.

## MORE PROBLEMS IDENTIFIED

### Poor quality seismograms

In the above examples, we see that there are many spurious artifacts present on the seismograms acquired with m-sequence pilots. These artifacts are not present on the seismograms from the weight drop source and the swept-frequency vibrator. The existence of these artifacts is a serious problem, since they mask the presence of any weak reflections from deep subsurface structures.

### Lack of repeatability

Seismograms recorded repeatedly with the vibrator at the same location and driven by the same m-sequence pilot are not identical. The four sets of seismograms on Figure 4 were recorded with the vibrator near the centres of the E-W and N-S lines. The same mseq11 pilot was used to control the vibrator for all four sets. Each plotted traces was normalized to its maximum value. We see high amplitude events at late times when none should exist. The presence of these late events suggests that the vibrator responds unevenly in time to the m-sequence pilots, generating arrivals that look like multiples.

### Erratic and rough vibrations

During testing, it was observed that, while the vibrator ran smoothly with frequency-sweep pilots, using m-sequence pilots caused erratic and rough operation. This observation is confirmed by recordings of uncorrelated data. Figure 5 shows uncorrelated signals from the vertical components of two geophones at the west end of the East-West line nearest the vibrator position.

We see the full duration of the frequency sweep (20 seconds) and the m-sequence (16.376 seconds) pilot within the listen time of 22 seconds. The strongest traces on the plots (labeled $V_1$) are from the geophone only a meter or two from the vibration point, and they should be a good representation of the source waveforms imparted into the ground by the vibrator. We see the spiky bursts of energy in the source waveform when the vibrator is driven by an m-sequence, whereas the source waveform produced by the swept-frequency pilot is smooth-looking.

The erratic and spiky source waveforms seem to be independent of the drive amplitude of the m-sequence pilots. On Figure 6, maximum amplitudes of the source waveforms do not change very much as the drive amplitudes of the m-sequence pilots increase from 9% to 18% to and 35% of maximum level. This suggests that the reaction mass in trying to follow the motion dictate by the m-sequence becomes pinned at various times and cannot move beyond certain designed mechanical limits. The net effect is an unpredictable jerky motion of the reaction mass when it becomes unpinned.

This observation is supported by the plots on Figure 7, which shows that the vibrations sensed by accelerometers on the base plate and reaction mass. We speculate that Trace 4 in the diagram is a phase-corrected drive signal $S_{PC}$ given by

$$S_{pc} = (2 * S_{RM} - S_{BP})/2 \ ,$$

where $S_{BP}$ is the base plate signal and $S_{RM}$ is the reaction mass signal.

The accelerometer signals on the base plate and reaction mass for the m-sequence pilot have a very spiky appearance, as opposed to the much smoother appearance of the same signals for a frequency-sweep pilot.

## SUMMARY AND DISCUSSION

The extremely fast transitions between -1 and 1 that exist on a pure m-sequence pilot forces the reaction mass to try to respond with very high accelerations. This perhaps causes unpredictable nonlinear behaviour in the hydraulic valves that control the forces moving the reaction mass. If this is the case, then decreasing the sharpness of the transitions (i.e., increasing the rise and fall times) should solve the problems of erratic operation and non-repeatability caused by m-sequence pilots.

Figure 8a shows the first 2 seconds of the normalized mseq11 pilot. Figure 8b shows the same signal after time domain filtering by convolving with a short time series equal to (1 4 6 4 1)/16. Applying this filter creates a running-average version of the original m-sequence, so that the very sharp transitions in the pure m-sequence have been changed to more moderate ramps. If the m-sequence (d) is used for controlling the vibrator, the acceleration levels being forced upon the reaction mass would be much decreased, perhaps solve the erratic and non-repeatable behaviour of the vibrator.

From past experience, we believe that the IVI EnviroVibe with sweep amplitudes at 90% of full drive level operates best at frequencies below 150Hz to 200Hz. This gives us a clue as to what the minimum rise and fall times on the filtered m-sequence should be. Different filtered m-sequence pilots could be tried in field testing to try to find one that limits the acceleration of the reaction mass motion and so enable the vibrator to operate smoothly. We intend to experiment with driving the IVI EnviroVibe with various filtered m-sequence to document their effects on field seismograms.

There are compelling reasons for attempting to make m-sequences possible for driving land vibrators. For one thing, cross-correlation with m-sequences promises to lead to large gains in signal-to-noise ratios (Wong, 2012). For another, shifted m-sequences might prove to be useful in practice as quasi-orthogonal pilot signals for multiple simultaneous source acquisition (Wong, 2013).

## ACKNOWLEDGEMENT

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## REFERENCES

Behringer, D., Birdsall, T., Brown, M., Cornuelle, B., Heinmiller, R., Knox, R., Metzger, K., Munk, W., Speisberger, J., Spindel, R., Webb, D., Worcester, P., Wunsch, C., 1982, A demonstration of ocean acoustic tomography: Nature, **299**, 121-125.

Dushaw, B.D., Howe, B.M., Mercer, J.A., and Spindel, R.G., 1999, Multimegameter-range acoustic data obtained by bottom-mounted hydrophone arrays for measurement of ocean temperature: IEEE Journal of Ocean Engineering, **24,** no. 2, 202-214.

Wong, J., 2000, Crosshole seismic imaging for sulfide orebody delineation near Sudbury, Ontario, Canada: Geophysics, **65**, 1900-1907.

Wong, J., 2012, Spread spectrum techniques for seismic data acquisition: CREWES Research Reports, **24**, 82.1-82.20.

Wong, J., 2013, Multiple simultaneous vibrators controlled by m-sequences: 83rd Annual International Meeting, SEG, Expanded Abstracts, 109-113.

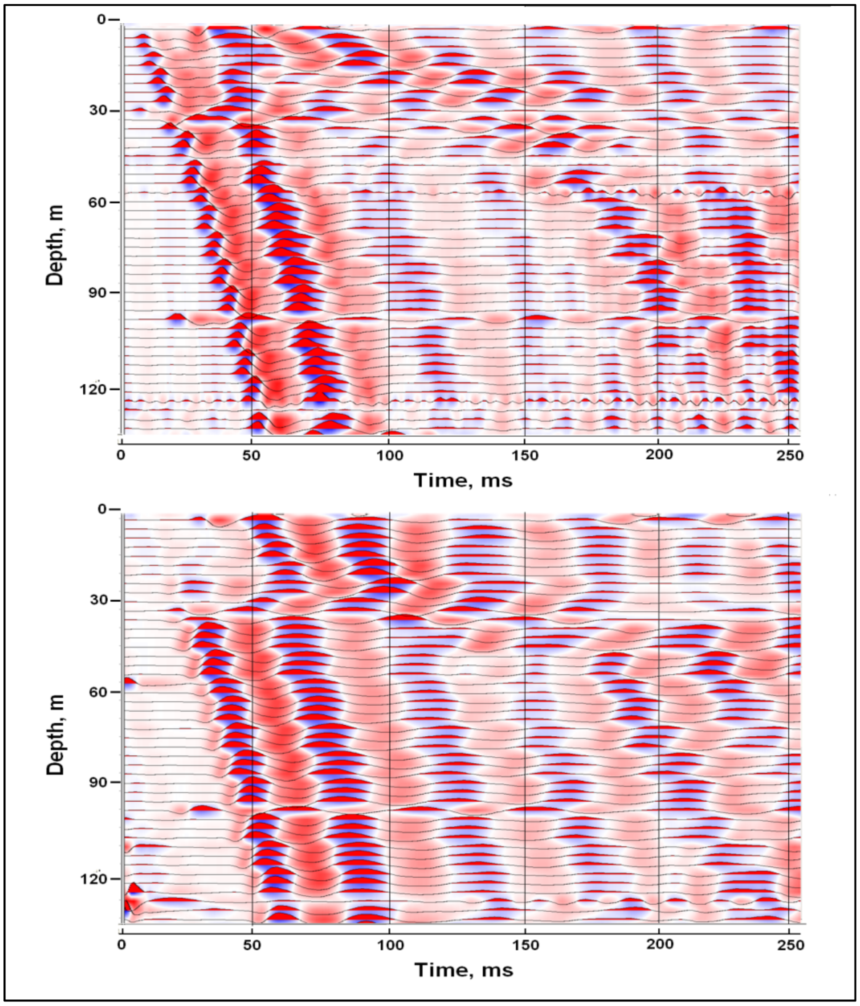

FIG. 1. Vertical-component seismograms from geophones cemented in a well, recorded with two different sources located at slightly different positions. Top: acquired with accelerated weight drop source. Bottom: acquired with EnviroVibe vibrator driven by an m-sequence pilot.

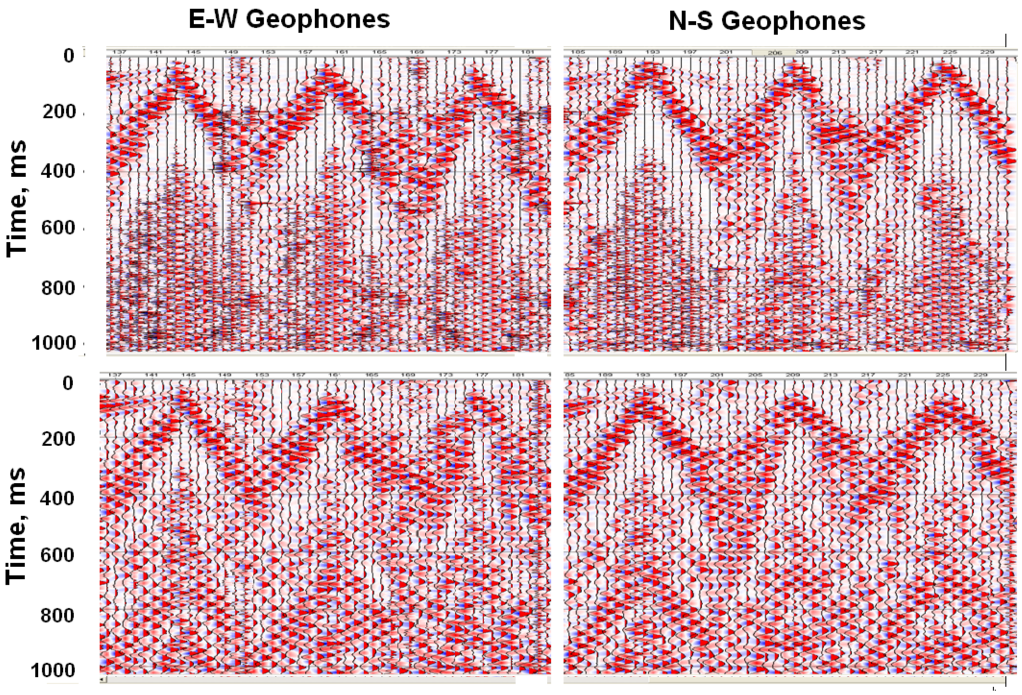

FIG. 2. 3C seismograms from surface geophones, plotted with 200ms AGC. For each display panel, vertical-component traces are the in left-most gather. Top: acquired with accelerated weight drop source. Bottom: acquired with EnviroVibe vibrator driven by mseq11.

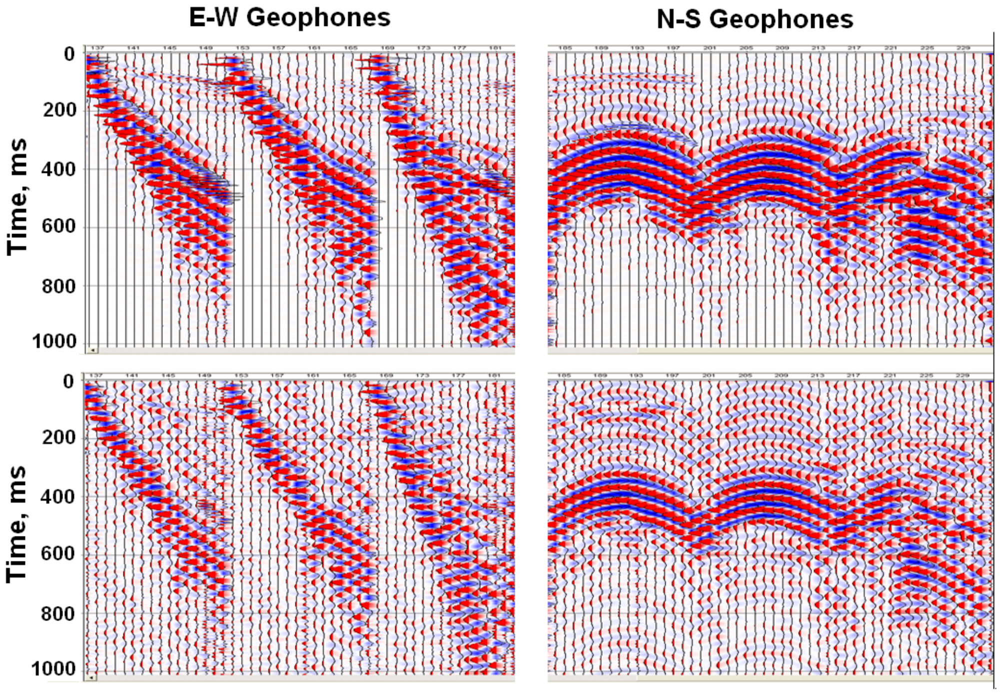

FIG. 3. Three–component seismograms from surface geophones, plotted with 200ms AGC. Within each display panel, the vertical-component traces are the in left-most gather. Traces were recorded with EnviroVibe source controlled by frequency sweep (top), and by mseq14 (bottom).

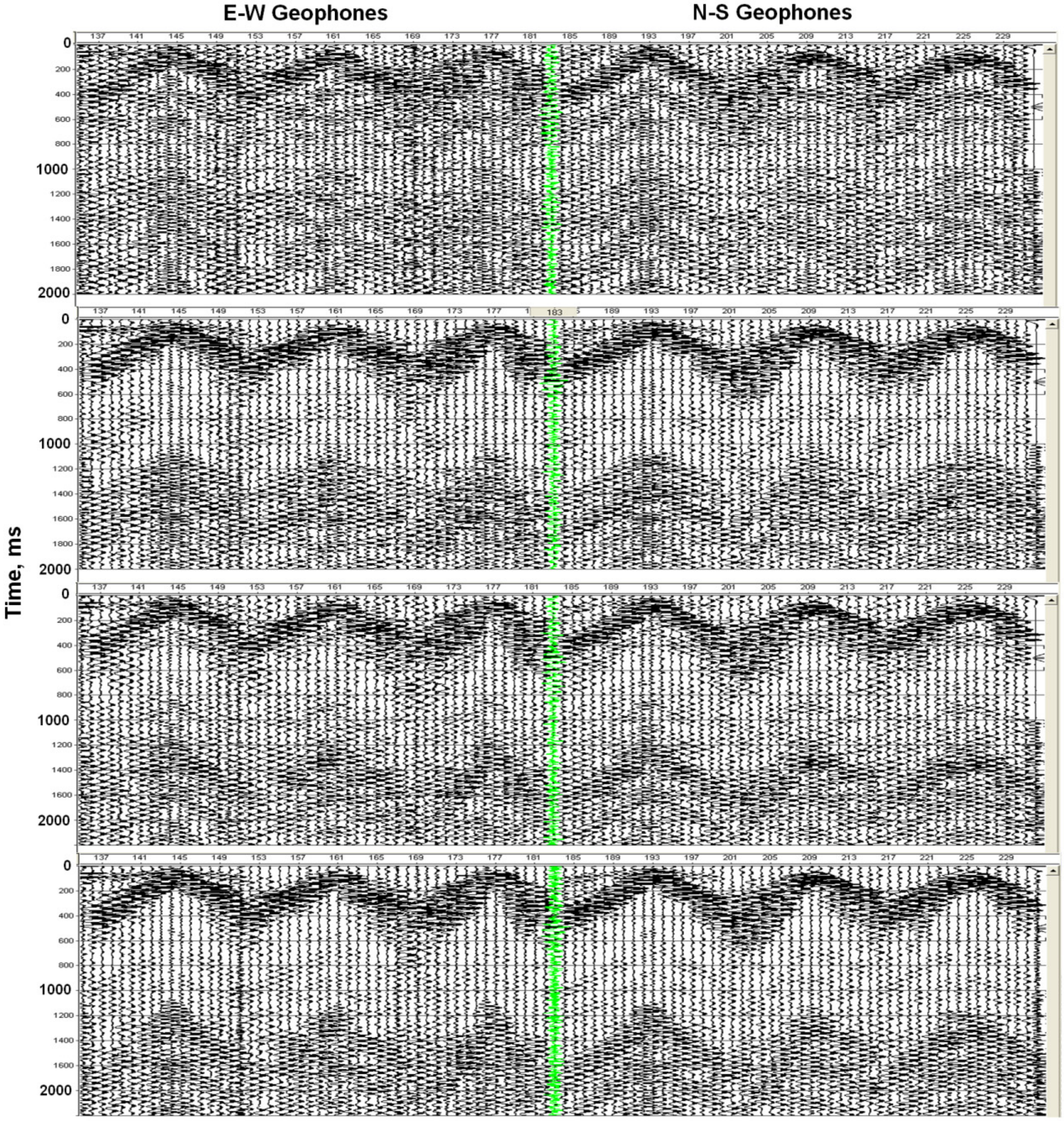

FIG. 4. Four repetitions of seismograms recorded with the same mseq11 pilot on surface 3C geophones. Each trace on this plot has been normalized by its maximum value. Left-most gathers for both E-W and N-S lines are the vertical component traces.

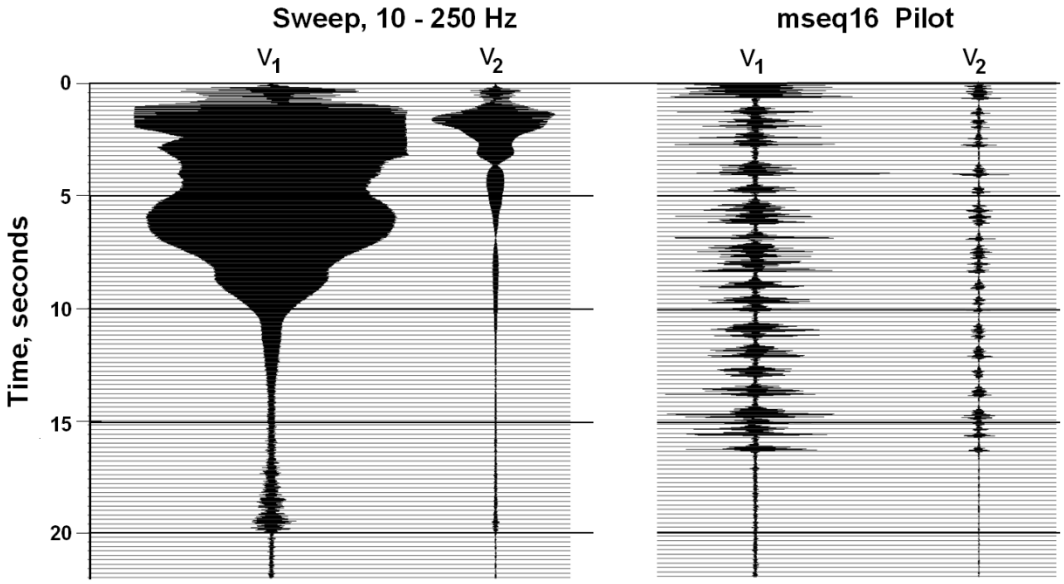

FIG. 5. Uncorrelated vertical-component signals from two geophones at the west end of the E-W line, recorded for the frequency sweep pilot and for the m-sequence pilot. The V1 geophone is within a meter or two from the vibrator, while the V2 geophone is 10m away. Amplitude plotting scales are identical, so visual comparison of relative signal strengths is valid.

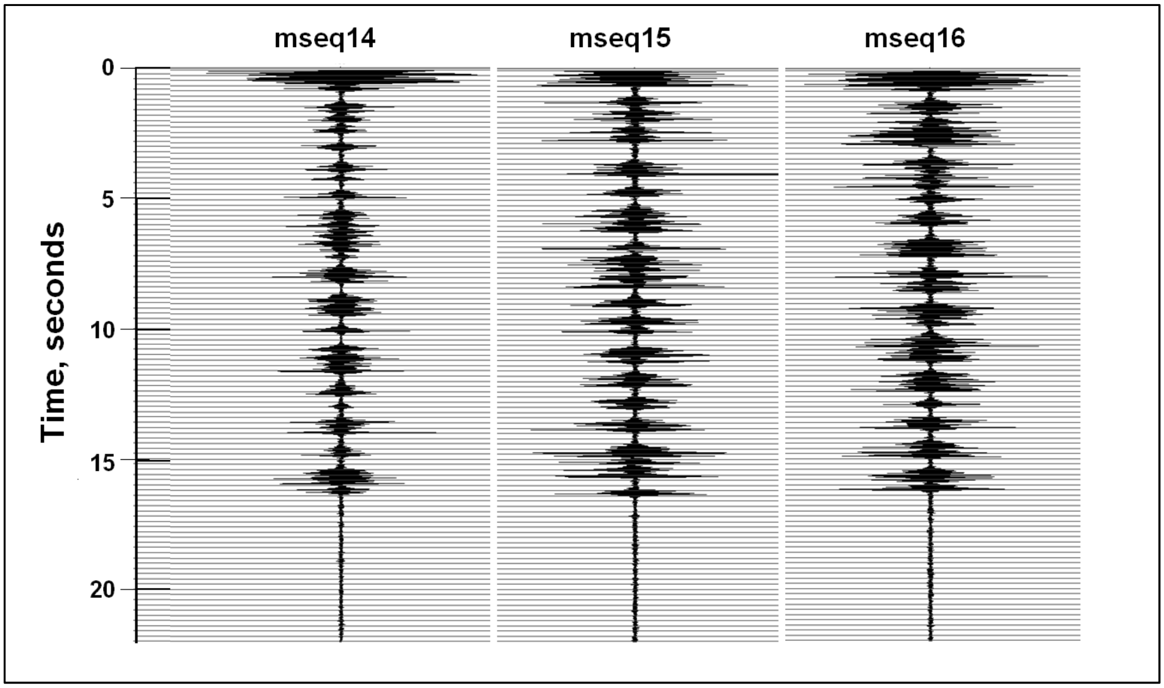

Fig. 6. Uncorrelated $V_1$ signals of the nearest geophone to the vibrator at the west end of the E-W line, for pilots with drive levels equal to 9%, 18% and 35% of maximum. The $V_1$ signals, representative of the source waveform, are erratic in time and are not repeatable in detail.

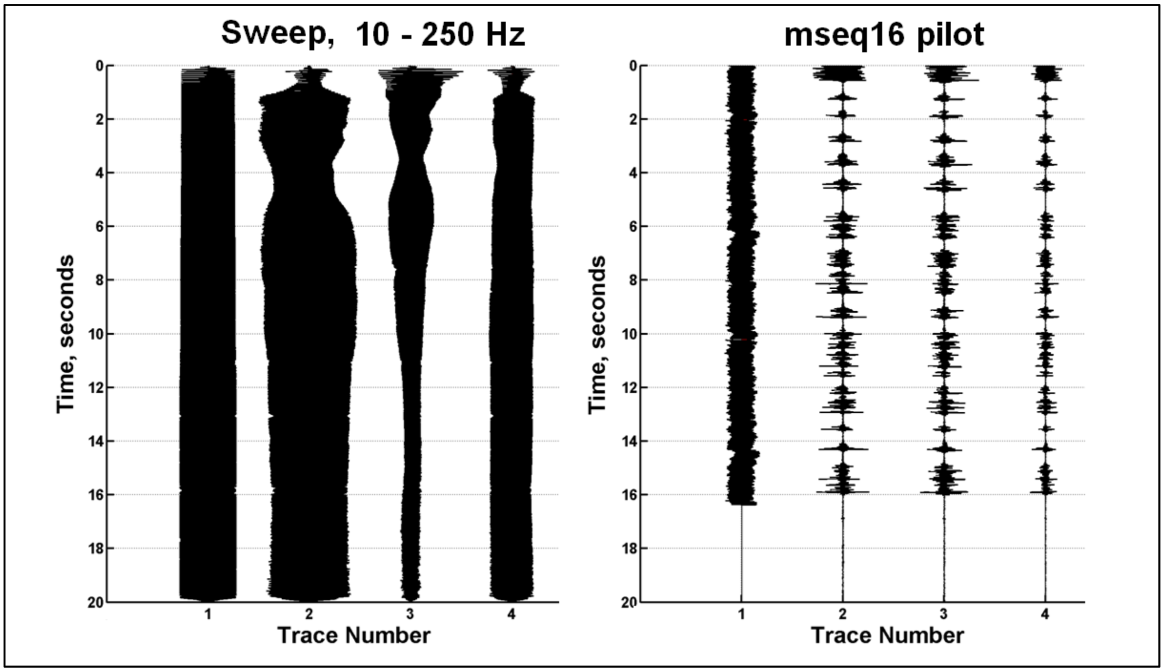

Fig. 7. Uncorrelated signals recorded on the vibrator using a Geometrics Geode. Trace 1 is the pilot signal. Trace 2 is from an accelerometer on the reaction mass. Trace 3 is from an accelerometer on the base plate. Trace 4 is a "phase-corrected drive signal" that is a linear combination of Traces 2 and 3.

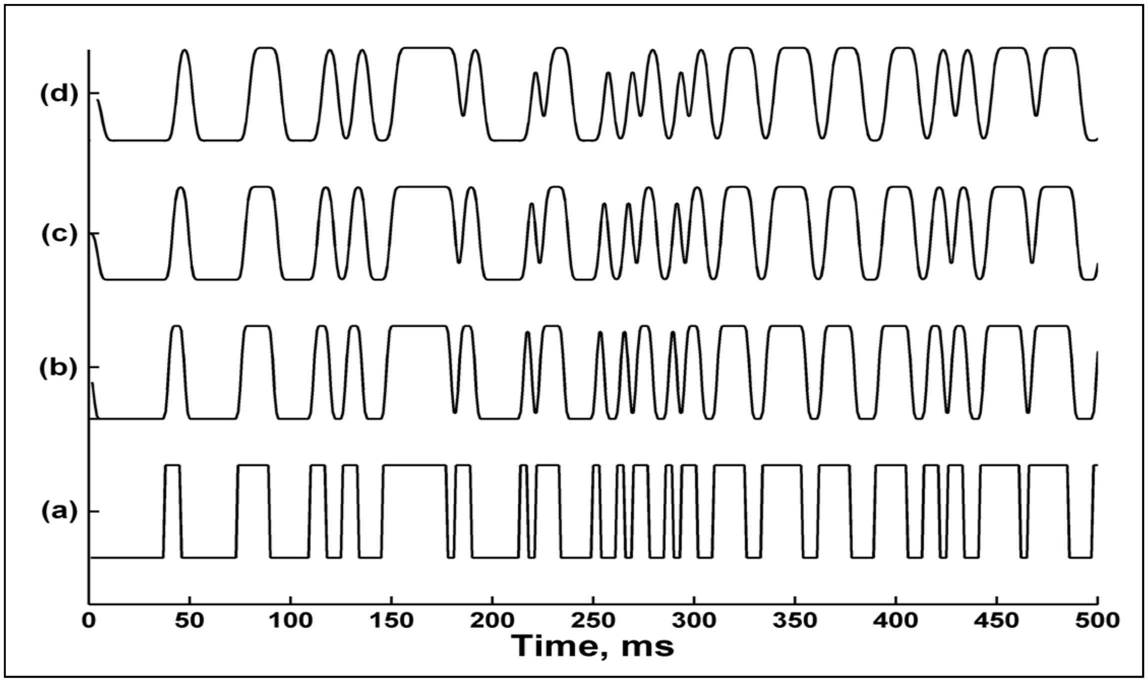

FIG. 8. Filtered m-sequences. (a) Original m-sequence; (b) filtered once; (c) filtered twice; (d) filtered 3 times. With each application of the filter, the rise and fall times at the transitions between -1 and 1 increase.