Field and Numerical investigation of filtered m-sequence pilots for Vibroseis acquisition

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Summary

We conducted a field test that indicated filtered m-sequences potentially to be just as effective as linear sweeps for controlling land vibrators in non-simultaneous operation. In another test, we evaluated the effectiveness of m-sequences modified by a time-domain filter as pilots driving land vibrators in simultaneous multi-sourcing. Results from the multi-sourcing survey indicated that the time-domain filtered pilots produced deblended seismograms somewhat degraded by an unsatisfactory level of crosstalk interference. The crosstalk originates from large-amplitude arrivals generated by adjacent and nearby vibrators. Numerical simulations showed that, by filtering pure m-sequences in frequency domain instead of in time domain, we can obtain an improved set of quasi–orthogonal pilots for which crosstalk interference is much reduced. The improvement comes from retaining as much as possible the spectral energy that exists in pure m-sequences at frequencies between 5 and 20 Hz.

Introduction

In Vibroseis-based land surveys, deblending of raw field data acquired with multiple simultaneous vibrators can be done at the crosscorrelation step if the vibrators are driven by a set of quasi-orthogonal pilot signals. In the context of Vibroseis acquisition, a quasi-orthogonal set has the following properties: (1) within a restricted window of time lags, the autocorrelation of any single member in the set closely approximates the delta function; (2) within the same time window, the crosscorrelation between any two different members in the set is very nearly zero. The deblending of seismograms using quasi-orthogonal pilots does not depend on differential time moveouts. Among the pilot signals that have been used in this way are variphase sweeps (Krohn et al., 2010), modified Gold codes (Sallas et al., 2011), and Galois codes (Thomas et al., 2010; 2012). Dean (2014) reviewed a variety of pseudorandom signals and their potential suitability as pilots for simultaneous multi-sourcing. Wong (2014; 2013) has shown how maximal-length sequences (m-sequences), a type of pseudorandom binary signal (PRBS) with values only of -1 and +1, can be modified to create effective quasi-orthogonal Vibroseis pilots. This paper describes the continued experimental and numerical evaluation of filtered m-sequences as pilots for Vibroseis-based simultaneous multi-sourcing.

Field testing of m-sequence pilots

Figure 1 is a schematic diagram showing the acquisition geometry for the field tests. We first acquired data with four vibrators separated by 400m in non-simultaneous operation to compare the performance of m-sequence pilots (filtered in time domain) to that of a linear sweep pilot. The linear sweep covered frequencies 4 to 140 Hz with a duration of 16 seconds and end tapers of 300ms. The m-sequence pilot was 16.378 seconds long; its spectrum is shown on Figure 5. We limited the drive levels of all pilots to 70% of the maximum allowable levels of the vibrators. We set the digital sampling interval at 2ms, and recoded raw uncorrelated data for 22 seconds with all receivers live.

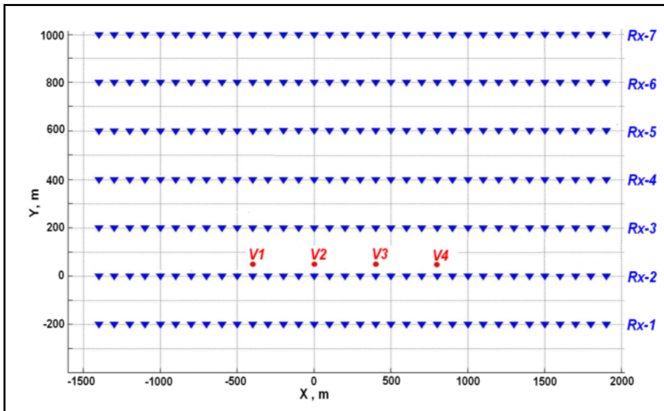

Figure 1: Field configuration for testing four simultaneous vibrators. The spacing between receiver lines is 200m. The receiver interval along each receiver line is 50m (only every second receiver is shown). The vibrators V1 to V4 are separated by about 5m from receiver line Rx-2.

Figure 2 is a comparison of the common source gathers for all seven receiver lines recorded with vibrator V4 driven first by an m-sequence pilot and then by the linear sweep pilot. This plot and other plots of the seismograms on expanded scales indicate that the filtered m-sequence pilots are potentially just as effective as linear sweep for controlling land vibrators in non-simultaneous operation.

Results for four simultaneous vibrators

We also recorded blended raw field data with the four vibrators, V1, V2, V3, and V4, in simultaneous operation and controlled by quasi-orthogonal pilots mSeq-T1, mSeq-T2, mSeq-T3, and mSeq-T4. The raw data for the near-offset line Rx-2 are shown on Figure 3. We see that the uncorrelated field signals

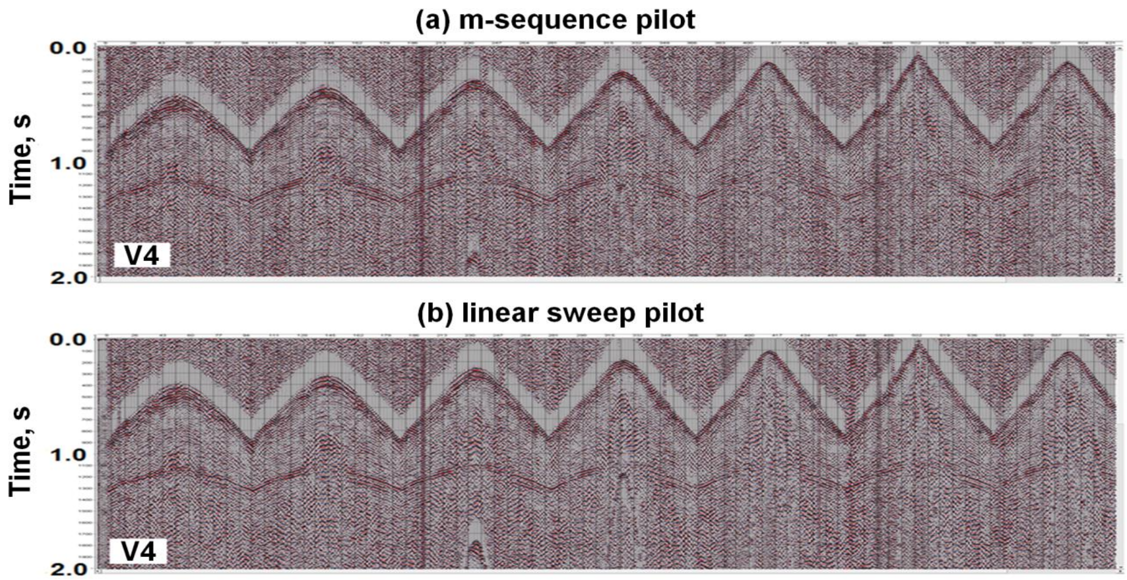

Figure 2: Comparison of field seismograms for seven receiver lines acquired with vibrator V4 in single operation: (a) driven by afiltered n m-sequence pilot, and (b) driven by a linear sweep.

from vibrators V1 and V2 are significantly weaker than the raw signals from vibrators V3 and V4**.** The large disparity in signal amplitudes creates a significant challenge to effective deblending.

We extracted deblended common-source seismograms associated with vibrators V1 to V4 by crosscorrelating the blended raw data with the appropriate filtered m-sequence pilots (note: we also could have extracted the seismograms by crosscorrelating with the recorded ground force signals instead). To emphasize the reflections, we have reduced the low-frequency surface-wave amplitudes with an Ormsby bandpass filter (15Hz-30Hz-100Hz-200Hz). The resulting common-source gathers are plotted with an AGC window of 200ms on Figure 4.

The deblended common-source seismograms for the near-offset line exhibit significant crosstalk interference due to the high-amplitude first-arrivals and surface waves produced by adjacent and nearby vibrators. The crosstalk obscures portions of the first-arrival event as well as portions of the reflection event at about 1200ms,

On the near-offset receiver line, some receivers are extremely close to the vibrator sources. The deblending technique using these particular filtered m-sequences appears unable to adequately separate comparatively very weak signals associated with the source of interest from the very strong signals from adjacent sources. The crosstalk interference is apparently much reduced on the deblended gathers for the far-offset receiver line because the differences in amplitudes due to the different vibrators are much less drastic.

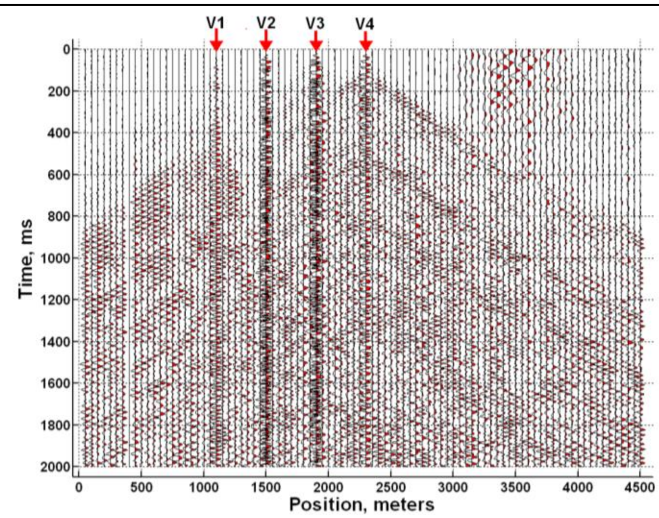

Figure 3: Uncorrelated field data recorded with four vibrators running simultaneously.

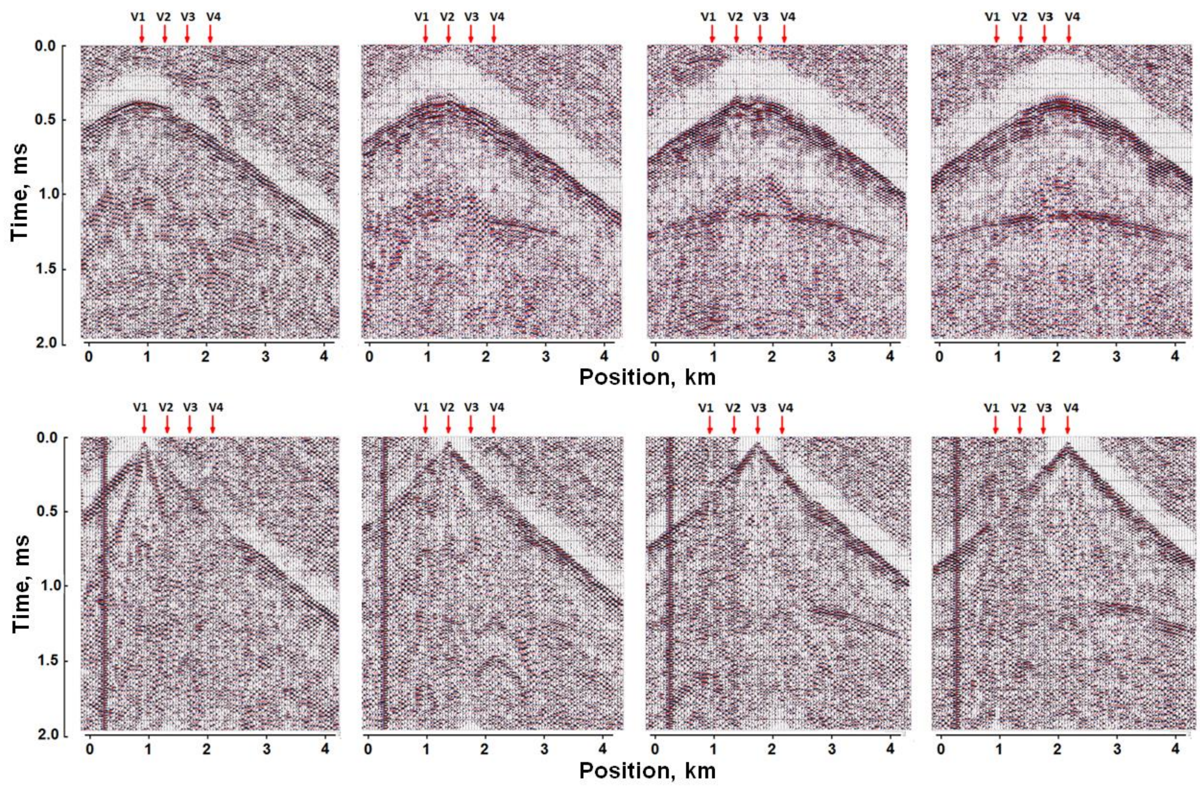

Figure 4: Common source gathers of seismograms deblended from the field data on Figure 3 by crosscorrelation with the appropriate pilots mSeq-T1 to mSeq-T4. Top: gathers associated with receiver line Rx-6 (800m from the sources). Bottom: gathers associated with receiver line Rx-2 (about 5m from the sources). Red arrows indicate the positions of the four vibrators.

The spectrum of the time-domain filtered pilots used in the field test is displayed on the left side of Figure 5. In the important frequency range of 0 to 250Hz, the time-domain filter has eliminated much of the spectral energy in the original pure m-sequence. The reduction in spectral content changes the mathematical properties of the pure m-sequences that enable them to approximate a perfectly orthogonal set so well. As a result, the time-domain-filtered m-sequences are much less effective for separating very weak signals from very strong signals.

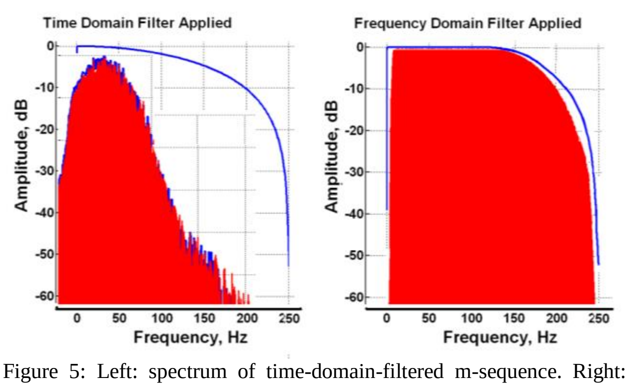

Figure 5: Left: spectrum of time-domain-filtered m-sequence. Right: spectrum of frequency-domain-filtered m-sequence. The blue line represents the spectrum of an unfiltered m-sequence in the seismically important range 0 to 250 Hz. For these frequencies, the frequency-domain-filtered m-sequence has almost exactly the same spectral content as the original unfiltered m-sequence.

Numerical simulations

A numerical simulation of simultaneous multi-sourcing with the same time-domain filtered m-sequences used in the field test resulted in the seismograms plotted at the top of Figure 6. The figure shows these particular filtered m-sequences produced synthetic gathers seriously degraded by crosstalk from nearby vibrators. Just as in the field test, the pilots have failed in the numerical simulation to reduce very strong amplitudes of first arrivals and ground roll coming from adjacent and nearby vibrators to adequate level. As a remedy to this shortcoming in the time- domain-filtered pilots, we created a new, improved set of pilots by bandpass filtering the pure m-sequences in frequency domain. The resulting spectrum is shown on the right side of Figure 6. Frequency bandpass filtering enables us to have more control on the final spectral content of the filtered m-sequence pilots. Most importantly for the quasi-orthogonality property, a set of filtered m-sequences must retain as much spectral energy as possible for frequencies below 20 Hz. Synthetic seismogram gathers produced by simulated multi-sourcing with the improved filtered m-sequence pilots are displayed on the bottom of Figure 5. Note that the much reduced crosstalk interference.

Conclusions

Field tests have verified that shifted m-sequences modified by a time-domain filter can be just as effective as linear sweep pilots for controlling land vibrators successfully in single vibrator operation. However, in a test of simultaneous multi-sourcing, a set quasi-orthogonal pilots consisting of time-domain filtered m-sequences yielded deblended seismograms with serious crosstalk interference for receive lines less than 200m from the sources.. This crosstalk originates from very strong first arrivals and surface waves generated by nearby and adjacent vibrators. For receiver lines far away from the vibrator locations, first-arrival and surface–wave amplitudes generated from nearby vibrators are not overwhelmingly stronger than the arrivals from the vibrator of particular interest. Therefore, the crosstalk interference after crosscorrelation for these lines is much less.

Numerical simulations of simultaneous multi-sourcing with filtered m-sequences as pilots for vibrators indicate that very weak signals (i.e., those associated with reflections) can be separated cleanly from very strong signals (i.e., those associated with direct arrivals and surface waves) provided that the filtering process retains a high percentage of the spectral energy of pure m-sequences at frequencies below 20 Hz. We have produced new quasi-orthogonal pilots with improved spectral content by bandpass filtering the pure m-sequences in frequency domain. In the near future, we will conduct field tests to evaluate the effectiveness of these new, improved pilots when applied to simultaneous multi-sourcing.

Acknowledgments

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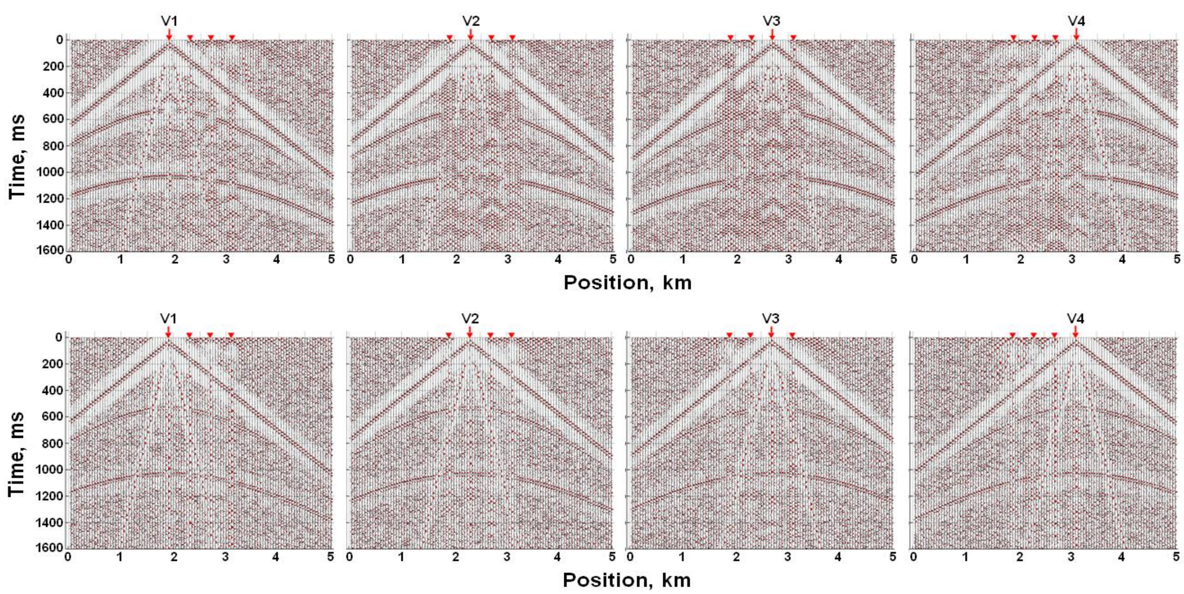

Figure 6: Common source gathers generated by numerical simulations of simultaneous multi-sourcing. The top gathers were produced with the time-domain filtered m-sequence pilots used to conduct the field testing. The bottom gathers were produced by using m-sequence pilots filtered in frequency domain to retain more spectral energy (see Figure 6).