Field testing of multiple simultaneous vibrator sources controlled by filtered m-sequences

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ABSTRACT

Theoretical analyses and numerical simulations predict that shifted m-sequences are suitable quasi-orthogonal pilot signals for driving multiple land vibrators in high-efficiency simultaneous-source acquisition. We conducted field tests to provide experimental confirmation for the theoretical predictions. Shifted m-sequences modified by a realizable time-domain filter were used successfully to control hydraulically-powered land vibrators. In one field test, blended raw field data recorded with two vibrators driven simultaneously by two quasi-orthogonal filtered m-sequences were easily separated by crosscorrelation into individual source gathers with little crosstalk. However, in a second test involving four simultaneous vibrators driven by four quasi-orthogonal filtered m-sequences, the separation of blended raw data by crosscorrelation into ordinary common source gathers resulted in a high level of crosstalk interference from strong surface-wave arrivals generated by adjacent and nearby vibrators. Numerical simulations indicate that the performance of filtered m-sequence pilots used in simultaneous multi-sourcing is improved if the filtering process does not alter very much the spectra of the original pure m-sequences in the frequency range of 0 to 250Hz. For such cases, the ability to isolate very weak signals from very strong signals without crosstalk interference is retained.

INTRODUCTION

High-resolution 3D seismic imaging often requires field datasets with hundreds of millions or even billions of seismic traces. Acquiring such large datasets efficiently involves deploying as many geophones as possible. Acquisition productivity can be further enhanced by using multiple simultaneous sources. In both marine and land seismic surveys, this can be done with distance-separated seismic sourcing (DSSS). In this technique, several sources located at widely-spaced positions are activated synchronously or semi-randomly in time. The different time moveouts of events on gathers of seismograms from these sources are exploited to deblend the field data into individual common-source gathers (Beasley, 2008; Bouska, 2010; Bagaini and Yi, 2010).

In Vibroseis-based land surveys, acquisition with multiple simultaneous vibrators can be done successfully 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 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 with small or no oscillatory side lobes. The deblending of seismograms using quasi-orthogonal pilots is effected at the correlation stage, and 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). Pecholcs et al. (2010) described a test 3D survey using 24 simultaneous vibrators controlled by variphase sweeps and modified Gold codes. Dean (2014) reviewed a variety of pseudorandom signals and their suitability as pilots for simultaneous multi-sourcing.

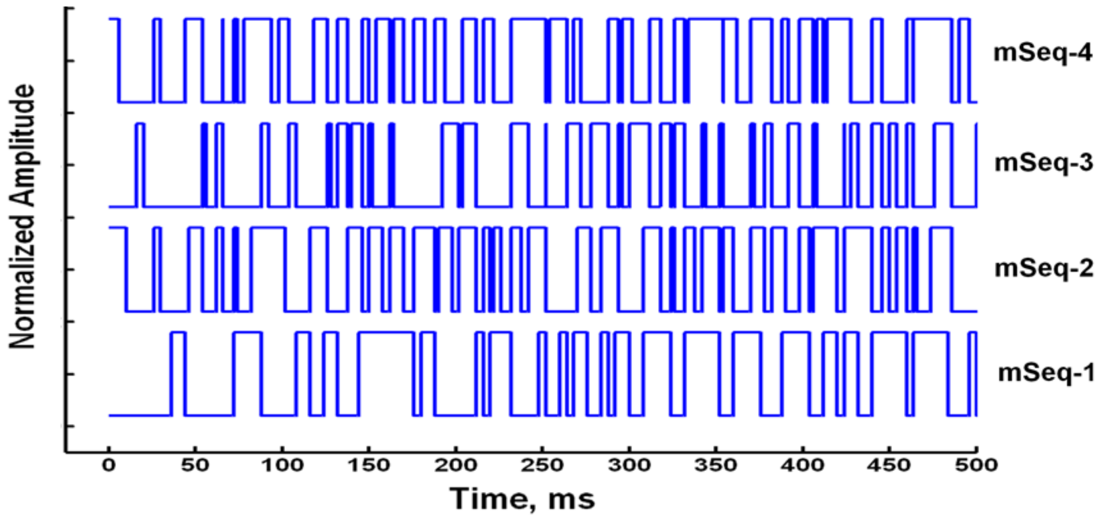

Figure 1: First 500ms of four shifted m-sequences, with m = 11, L = 2047, t_B = 4ms. The time t_{Shift} between sequences is 2040ms. The full length of one period of the sequences is 8188ms.

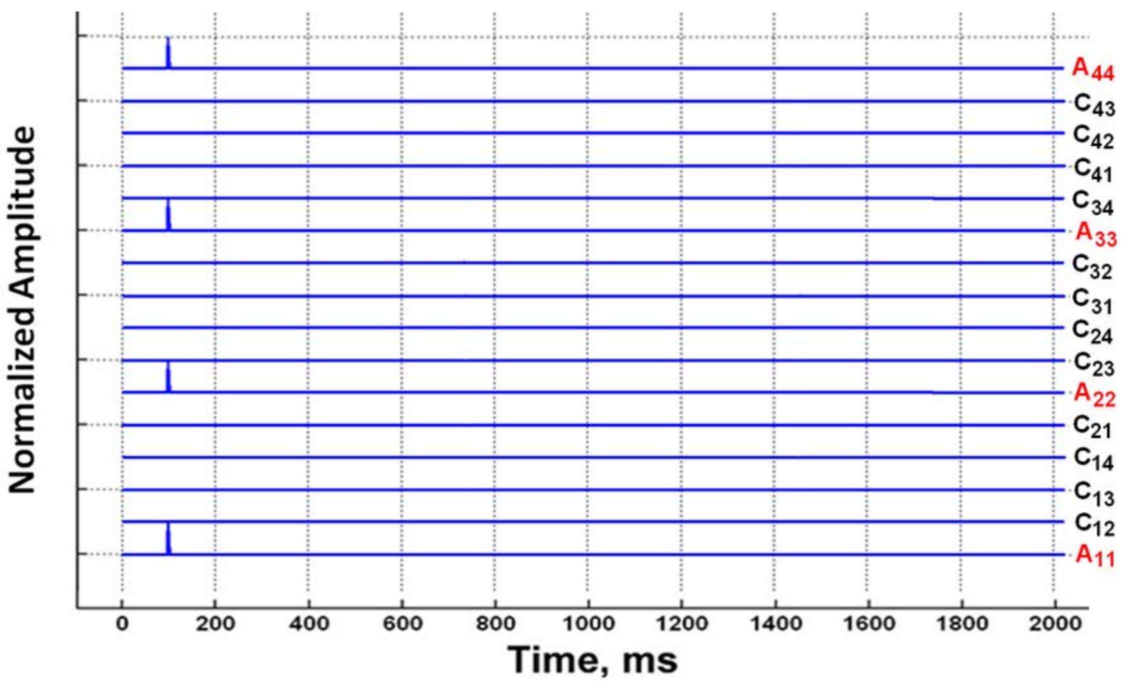

Figure 2: Auto- and crosscorrelations for the set of four shifted m-sequences on Figure 1. *Aii* is the autocorrelation of the *i*-th sequence; *Cij* is the crosscorrelation between two different sequences *i* and *j*.

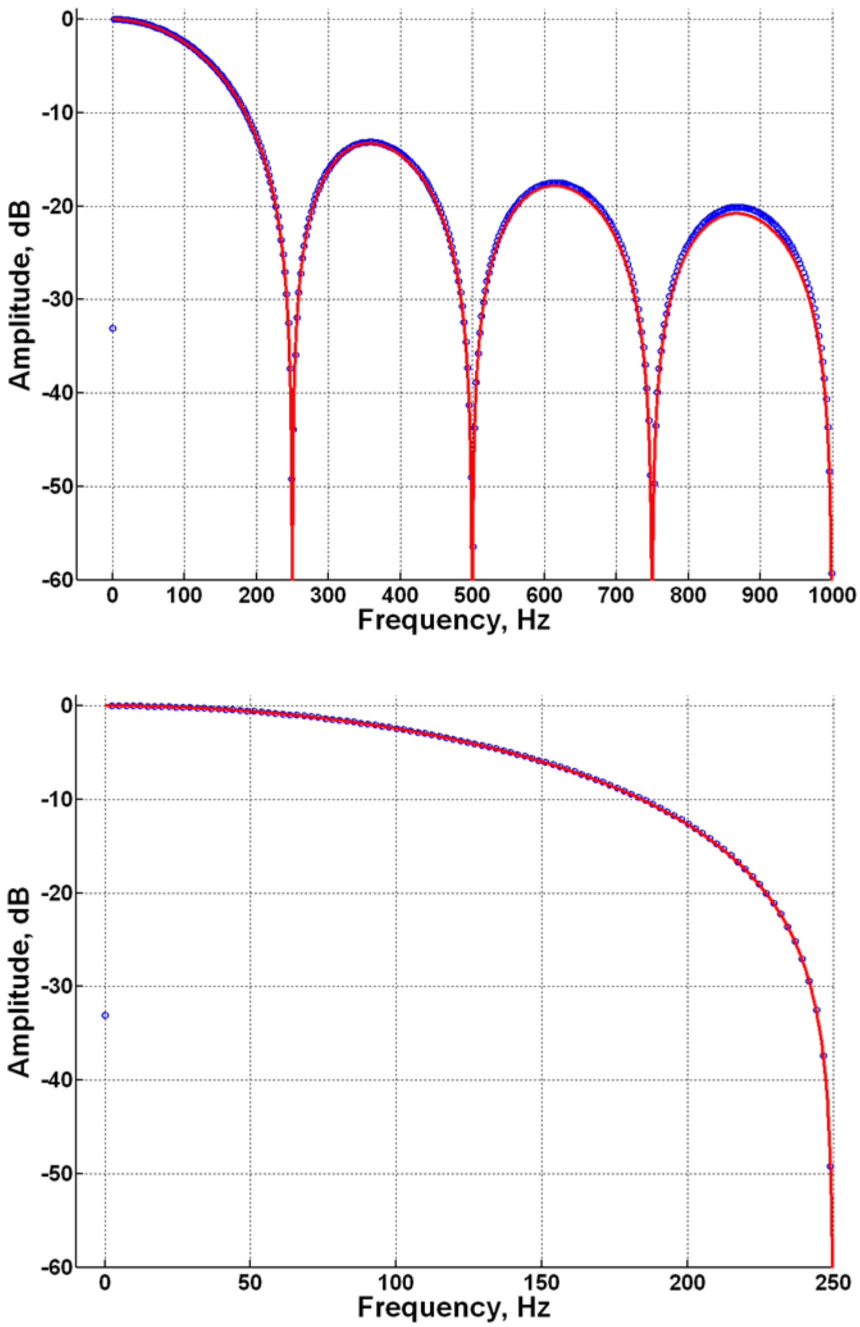

Figure 3. Amplitude spectrum for an m-sequence defined by m = 11, L = 2047, t_B = 4ms, t_S = 0.25m. Blue = pure m-sequence, red = sinc function. The bottom plot is an expanded view of the spectrum in the important frequency range 0 to 250Hz.

MAXIMAL LENGTH SEQUENCES

Maximal-length sequences, or m-sequences, are special mathematical signals that have step-function-like transitions between two values, -1 and 1. An m-sequence is characterized by its degree m, its fundamental length $L = 2^m - 1$, and its base period t_B. The sequence is periodic, repeating itself after a time equal to $L \cdot t_B$. Because the transition times are pseudorandom within each period, the autocorrelations of m-sequences are streams of triangular spikes that approximate delta functions.

Wong (2013; 2012) used numerical examples to show how multiple shifted m-sequences constructed from a single m-sequence form a set of pilot signals with the desired quasi-orthogonal properties. Such a set is displayed on Figure 1. The autocorrelations and crosscorrelations of the four signals in the set are plotted on Figure 2. The autocorrelations are narrow triangles with scaled peak values equal to 2^m-1; all scaled off-peak values are equal to a constant value of -1. Figure 2 shows that the set is almost perfectly orthogonal in the time range 0ms to 2040ms.

Figure 3 compares the amplitude spectrum of the pure m-sequences of Figure 1 to the sinc-squared function that describes the amplitude spectrum of a boxcar function with width t_B. That the two spectra are almost identical is a fundamental property of pure m-sequences, and reflects the fact that the autocorrelations on Figure 2 are actually narrow triangles.

FIELD TESTING OF FILTERED M-SEQUENCE PILOTS

We followed up on Wong's 2013 numerical study and conducted field measurements to verify two points:

1. that hydraulically-powered land vibrators can be controlled successfully by m-sequences, and
2. that quasi-orthogonal shifted m-sequences can be used for simultaneous sourcing.

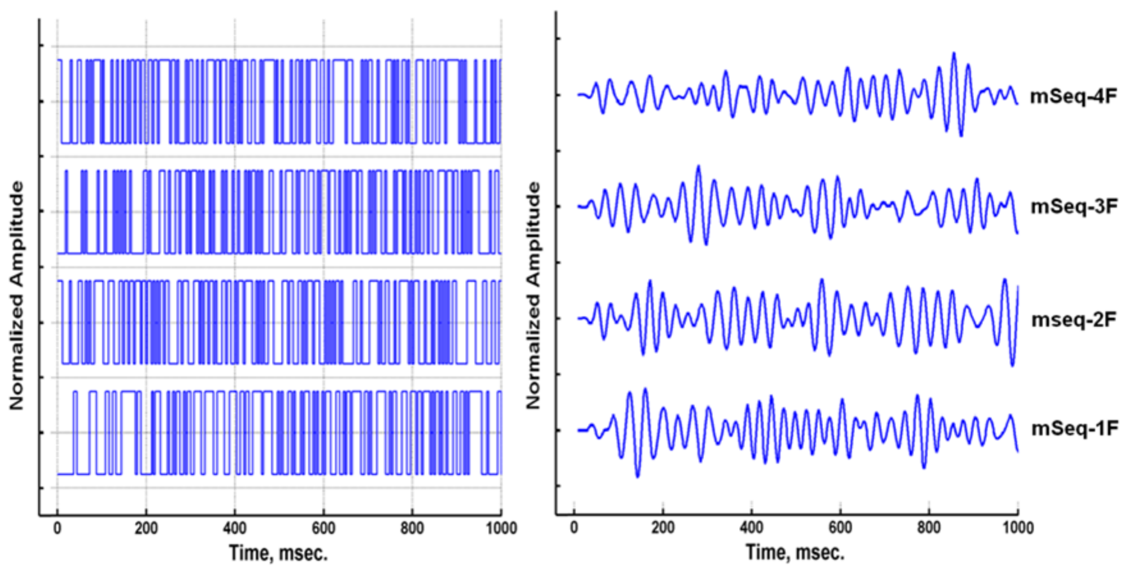

Figure 4: Left: pure m-sequences mSeq-1 to mSeq-4. Right: time-domain filtered m-sequences mSeq-1F to mSeq-4F. Only the first 1000ms of the sequences have been plotted; the full periods of the sequences are 8188ms.

Initial attempts to drive land vibrators with pure m-sequences were unsuccessful. The square-wave-like transitions in the pure m-sequences are not compatible with the mechanical characteristics of the hydraulic valves and positioning controls in land vibrators, and the sharp pseudorandom transitions cause the vibrators to operate erratically. We modified the pure m-sequences by convolving them with a realizable time-domain filter that changed the square-wave-like transitions to more moderate ramps. The filter was designed to reduce energy at frequencies below 20 Hz and above 100Hz.

Figure 4 displays the first 1000ms of four shifted m-sequences, before and after application of the time-domain filter. The filtered m-sequences are also quasi-orthogonal in the time window 0ms to 2040ms. However, their autocorrelation peaks are no longer simple triangles, and their scaled crosscorrelation values are no longer equal to a constant -1. Vibrators driven by the filtered m-sequences pilots behaved smoothly. We tested these pilots at two different sites and acquired the field results shown below.

FIRST TEST SITE

Figure 5 is a schematic representation of the survey geometry at our first test site. We employed two vibrators V1 and V2 separated by 200m and located about 5m from receiver Rx-2. The vibrators were driven respectively by the filtered m-sequence pilots mSeq-1F and mSeq-2F partly displayed on Figure 4 (total sweep time of about 16.5 seconds, listen time of 22 seconds). We recorded raw field data with a linear array of 138 geophones spaced at 50m intervals along receiver Rx-2. We also recorded data using a conventional linear sweep pilot (4Hz to 140Hz, sweep time of 16 seconds, end tapers of 300ms, listen time of 20 seconds). Seismograms were extracted from the raw data post-survey by crosscorrelating them with the pure m-sequences or with the linear sweep pilot.

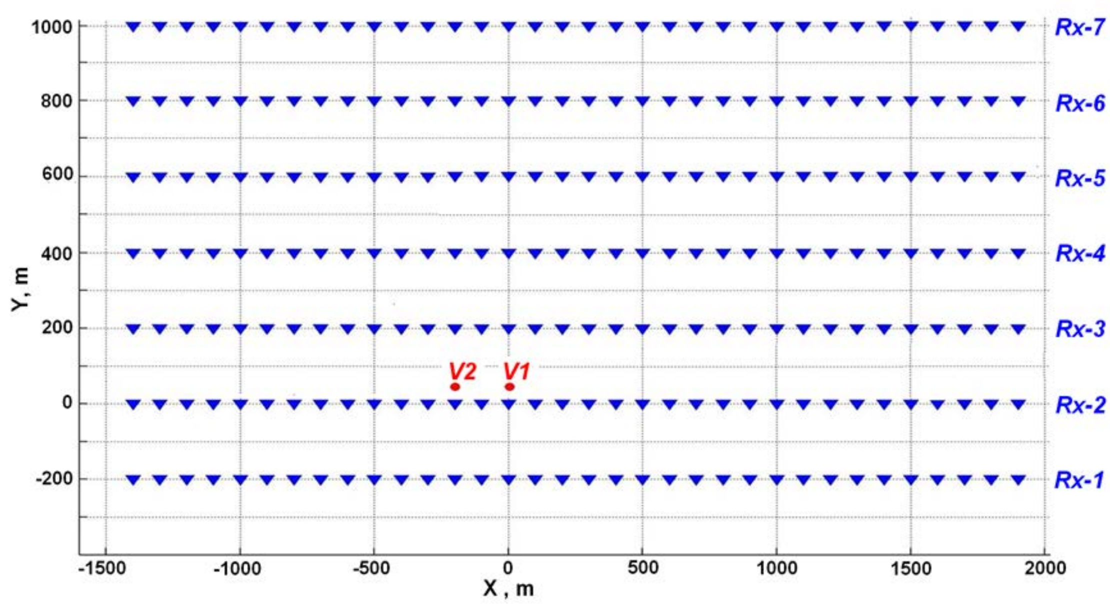

Figure 5: Field configuration for testing two simultaneous vibrators. The spacing between receiver lines is 200m. The geophone interval along each receiver line is 50m (only every second geophone is shown). The two vibrators V1 and V2 are separated by 200m.

Single vibrator results

Figure 6 compares common-source gathers acquired using the three different pilots driving a single vibrator V1 in non-simultaneous operation. Figures 6(a) and 6(b) show seismograms acquired with two different filtered m-sequence pilots. Figure 6(c) displays the seismograms recorded with the linear sweep pilots.

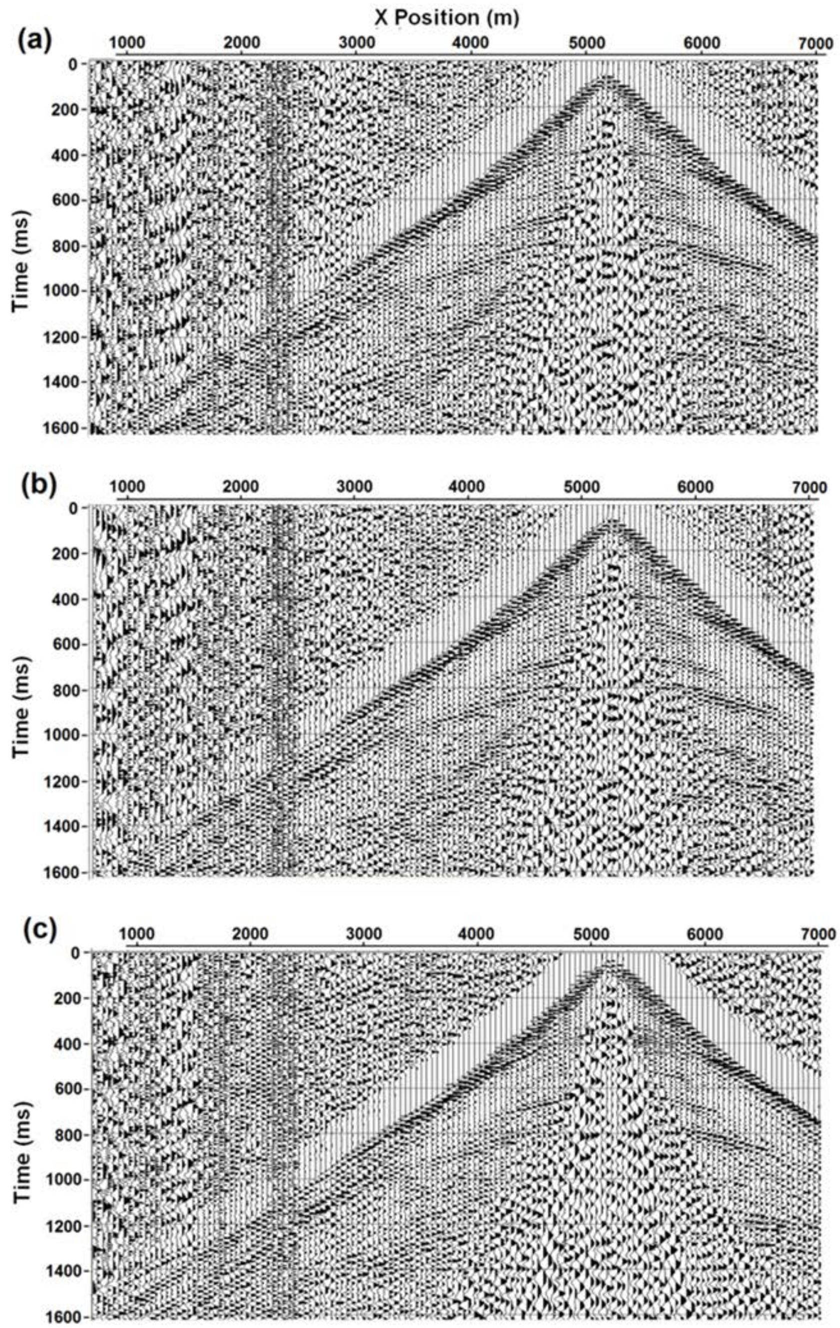

Figure 6: Seismograms for receiver line Rx-2, acquired with a single vibrator driven by three different pilots: (a) mSeq-1F pilot; (b) mseq-2Fpilot; (b) linear sweep pilot.

There is good similarity in the appearances of the seismograms acquired with the filtered m-sequence pilots, but there are small differences between those acquired with the filtered m-sequence pilots and those acquired with the linear sweep pilot. A constant time delay exists between the filtered m-sequence and the linear-sweep seismograms. This delay is related to the time duration of the time-domain filter used to modify the pure m-sequences, and occurs because the seismograms were extracted by crosscorrelation using the pure m-sequence signals. The delay disappears if the cross-correlation had been done with either the filtered m-sequences or the "ground force" signals.

On the gathers of traces on Figures 6(a) and 6(b) produced with m-sequence pilots, weak artifacts with time moveouts running parallel to the first arrivals partially obscure the weaker reflections. These artifacts also appear in the signals from the accelerometers attached to the reaction masses and base plates. They probably are related to small harmonic distortions and/or nonlinearities in the mechanical responses of the vibrators. The ground-roll noise associated with the m-sequence seismograms seems to have lower relative amplitudes than the ground-roll noise associated with the linear sweep seismograms.

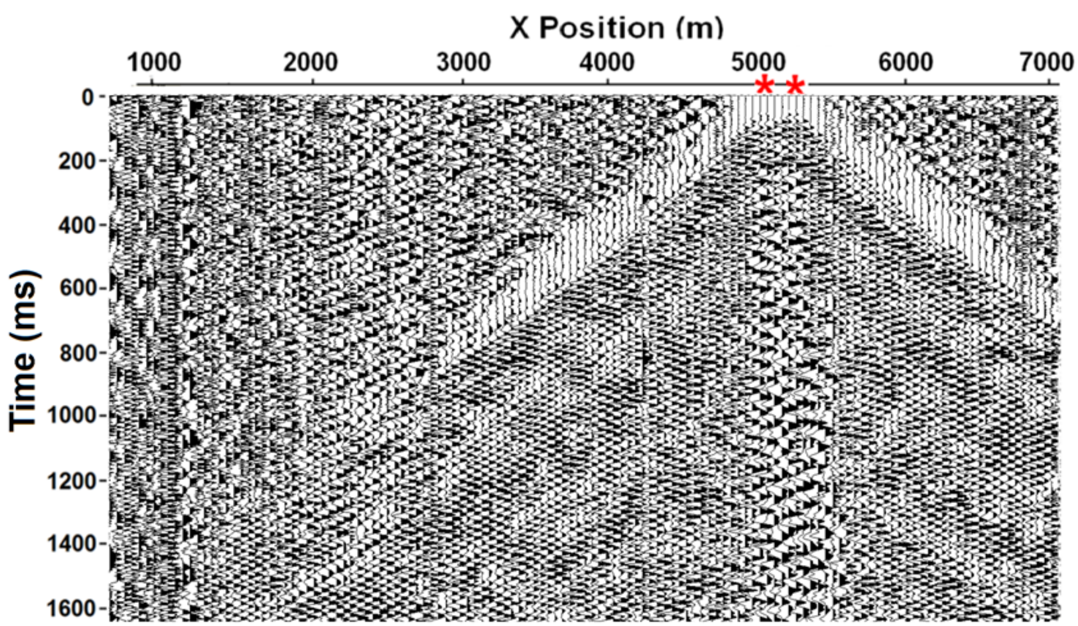

Figure 7: AGC plot of blended raw field data, recorded with two simultaneous vibrators controlled by filtered m-sequence pilots. The right and left red stars indict positions of the two vibrators V1 and V2 controlled by the filtered m-sequence pilots mSeq-1F and mSeq-2F, respectively.

Simultaneous vibrator results

Using mSeq-1F as the pilot for vibrator V1 and mSeq-2F as the pilot for vibrator V2, we recorded blended raw data by running both vibrators simultaneously. The blended raw data are shown on Figure 7. From the raw data, we extracted separate common source gathers of seismograms associated with vibrators V1 and V2 by crosscorrelating with the pure m-sequences mSeq-1 and mSeq-2, respectively. To emphasize the reflections, we removed the low-frequency surface wave arrivals with a bandpass filter (15Hz-30Hz-100Hz-200Hz). The resulting common-source gathers are plotted with an AGC window of 200ms on Figure 8(a) and 8(b). For comparison, we have included on Figure 8(c) a gather recorded using the linear sweep pilot.

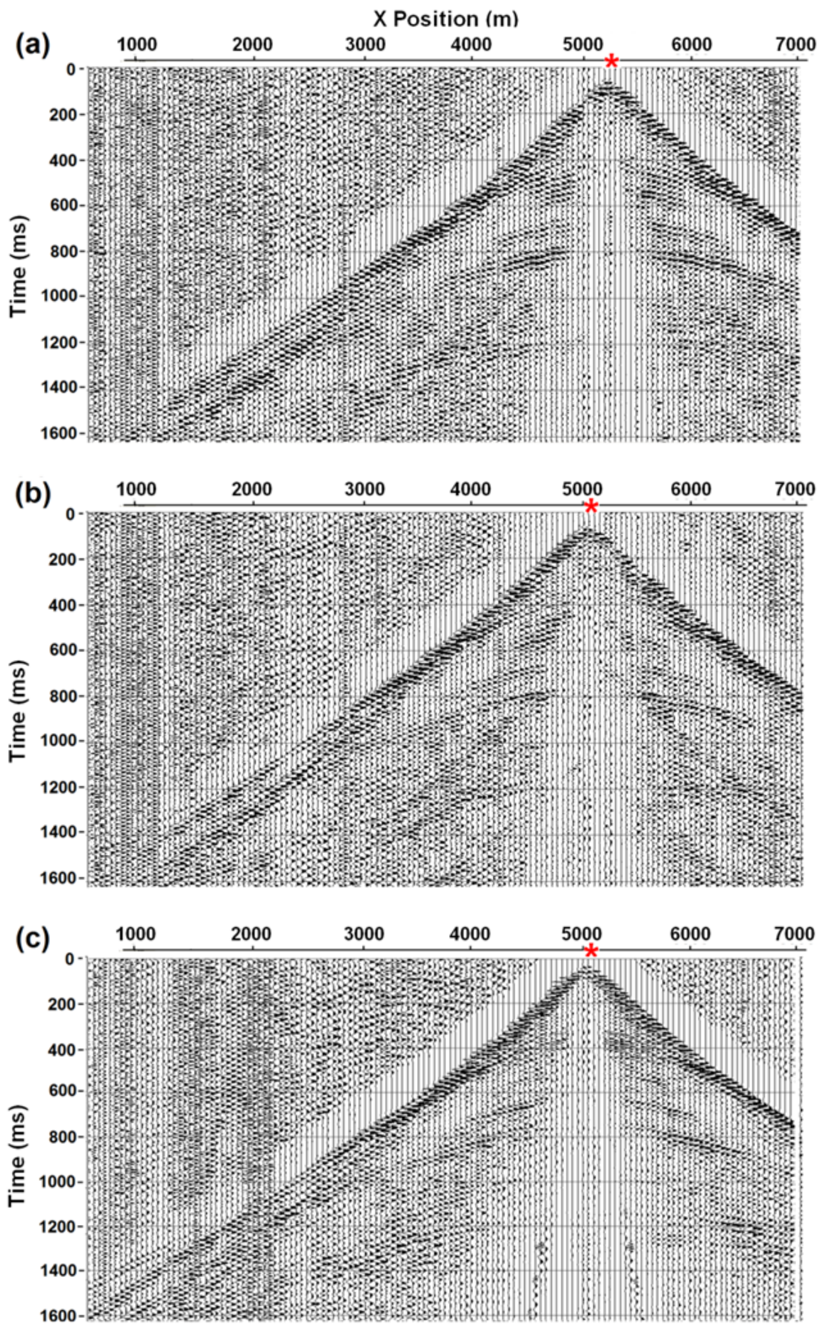

Figure 8: Common-source gathers (CSGs) extracted from the blended raw field data of Figure 7: deblended traces (a) for vibrator V1 driven by the mSeq-1F pilot; (b) for vibrator V2 driven by the mSeq-2F pilot; (c) seismograms recorded for vibrator V2 in single operation using the linear sweep pilot.

On Figure 8, all the reflections that appear on the gather acquired with the linear sweep pilot are also discernible on the gathers acquired with the filtered m-sequence pilots. However, the weaker reflections near 1000ms and 1200ms on the m-sequence gathers are degraded by weak artifacts with time moveouts that run parallel to the first arrivals. These are the same artifacts that appear on the gathers acquired with non-simultaneous operation of the vibrators (see figure 6).

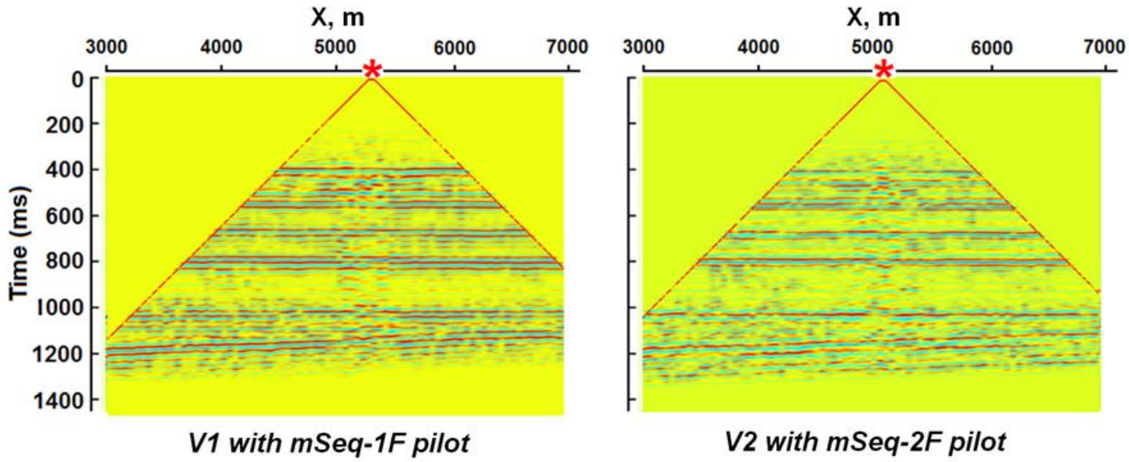

Figure 9: Common-source seismograms for V1 and V2 extracted from the blended raw data of Figure 7, after processing (bandpass filtering, AGC gain, NMO/DMO alignment, trim statics, trace interpolation, and signal enhancement).

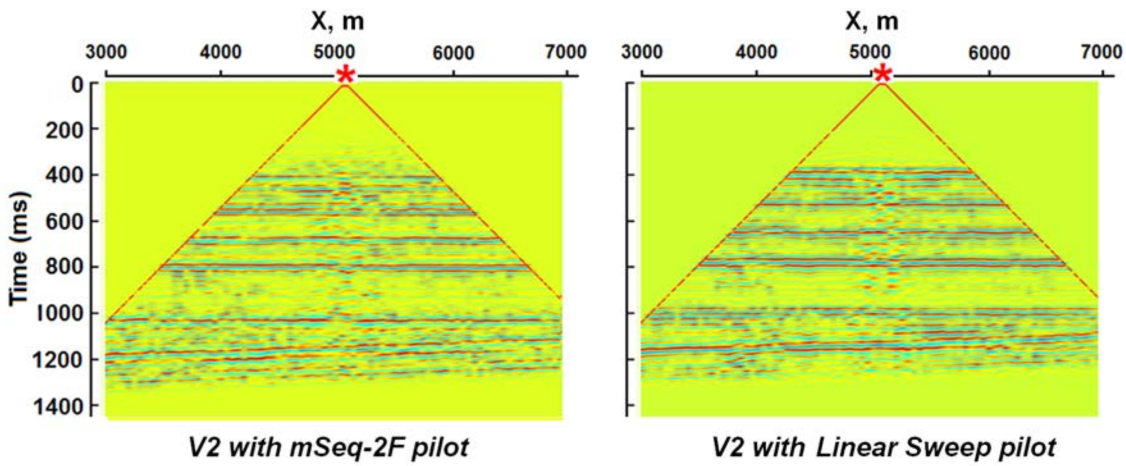

Figure 10: Common-source seismograms for V2 after processing (bandpass filtering, AGC gain, NMO/DMO alignment, trim statics, trace interpolation, and signal enhancement). Left: extracted from the blended raw data of Figure 7. Right: acquired with linear sweep pilot.

We reduced interference from the weak artifacts using simple processing steps that included NMO/DMO alignment, trim statics, signal enhancement, and trace interpolation. Figure 9 displays the processed results for the V1 and V2 gathers extracted from the blended data. Figure 10 displays the results for vibrator V2 acquired with the mSeq-2F and linear sweep pilots. After processing, reflections on data acquired simultaneously with the m-sequence pilots are similar to but not identical to reflections on data recorded with the linear sweep pilot. The details in the processing flow probably could be adjusted to improve the similarity.

The average frequency spectra of all the traces on each processed gather are shown on Figure 11; they appear to be very similar to each other. We did not apply a deconvolution process to whiten the different spectra. However, the signal enhancement technique that we did use appears to have balanced the spectra.

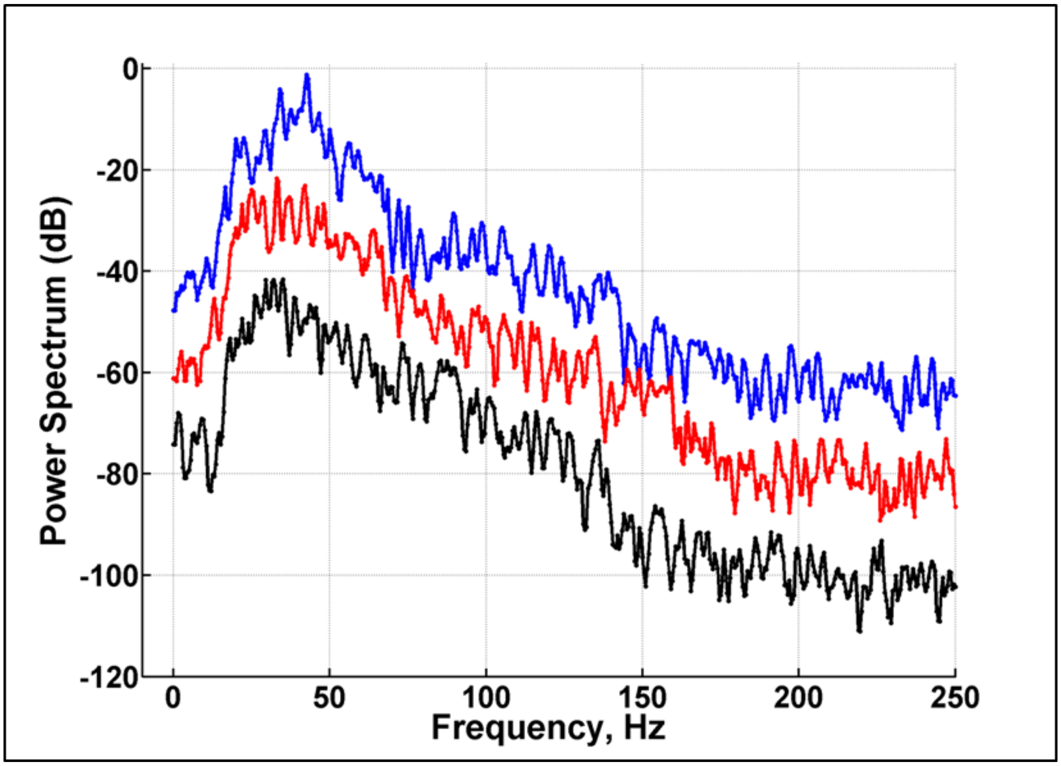

Figure 11: Average power spectra of the gathers shown on Figure 7: blue = mSeq-1F data; red = mSeq-2F data; black = linear sweep data. Spectra are displaced by 20dB for clarity of display.

SECOND TEST SITE

Figure 12 is a schematic representation of the acquisition geometry for field-testing at the second site. Seven receiver lines were laid out with 200m between adjacent lines. Along each line, geophones were deployed at 50m intervals. Four vibrators, V1, V2, V3, and V4, were placed at 400m intervals along a line parallel to and about 5m from receiver line Rx-2. We recorded raw field data for all seven receiver lines.

Single vibrator results

Figure 13 displays the seismograms acquired for all seven receiver lines using vibrator V4 in single-source operation. The top set of traces was recorded using the mSeq-4F pilot; the bottom set of traces were recorded using the linear sweep pilot. The two sets of seismograms are visually very similar, and the same single reflection at times between 1000ms and 1200ms appears clearly with similar signal-to-noise ratios. These results suggest filtered m-sequences are potentially just as effective as linear sweeps for controlling land vibrators in sequential operation.

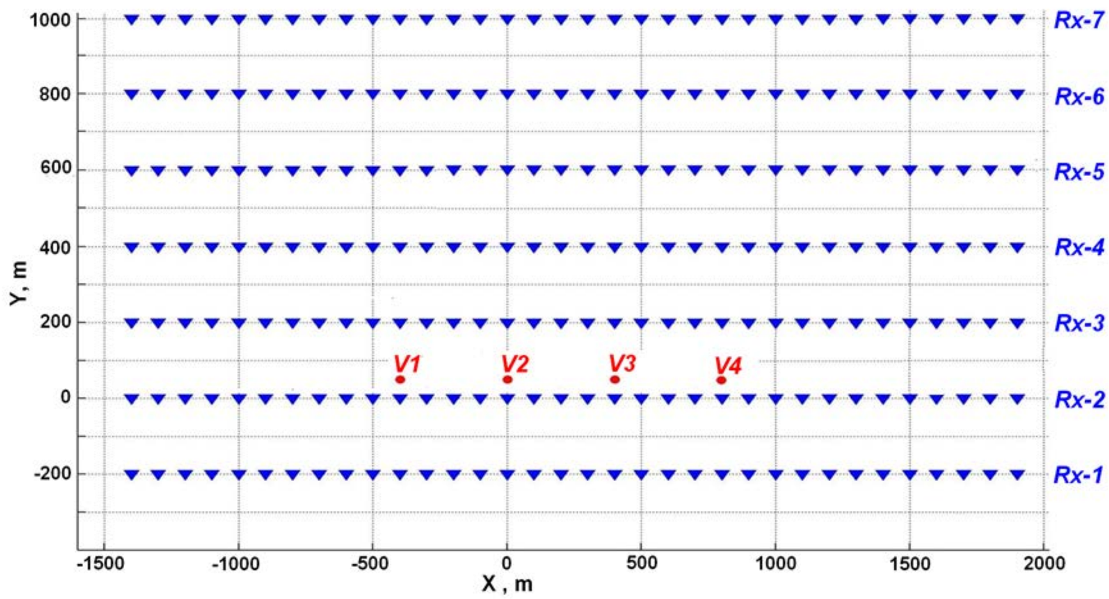

Figure 12: Field configuration for testing four simultaneous vibrators. The geophone interval along each receiver line is 50m (only every second geophone is shown).

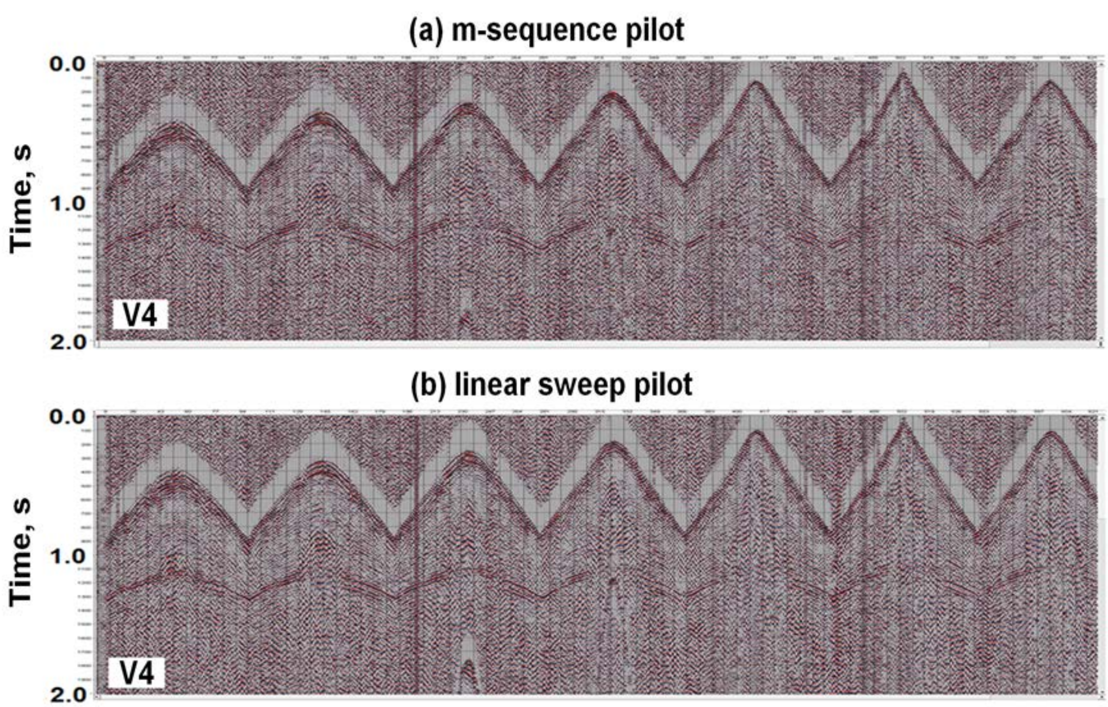

Figure 13: Comparison of seismograms for seven receiver lines acquired with vibrator V4 in single operation driven (a) by an m-sequence pilot and (b) by a linear sweep pilot.

Simultaneous vibrator results

We then recorded blended raw field data with the four vibrators, V1, V2, V3, and V4, in simultaneous operation and controlled respectively by pilots mSeq-1F, mSeq-2F, mSeq-3F, and mSeq-4F. The raw data for a far-offset receiver line (Rx-6, 800m from the source line) and the near-offset line (Rx-2, about 5m from the source line) are shown on Figure 14. On this figure, we see that the uncorrelated signals from V1 and V2 are significantly weaker than the raw signals from V3 and V4. This disparity in signal amplitude is especially true for the receiver line located only 5m from the source line, and probably is caused by different ground surface coupling conditions at the locations of the four vibrators.

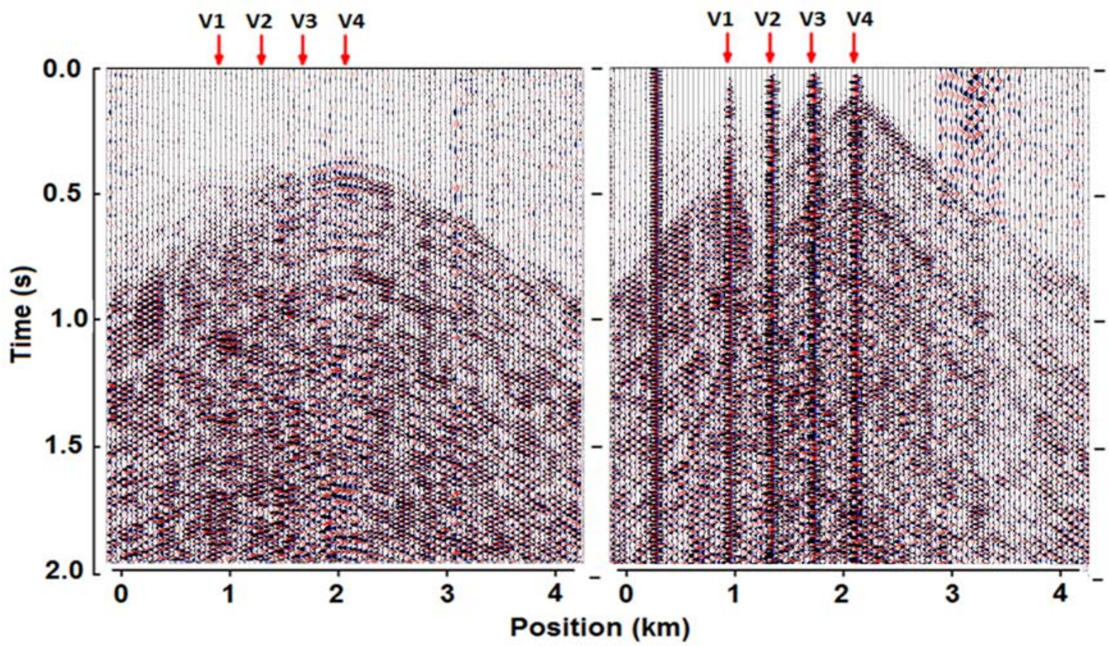

Figure 14: Blended raw field data produced by four simultaneous vibrators for far-offset receiver line (left) and near-offset receiver line (right). The far-offset receiver line Rx-6 is 800m from the source line). The near-offset line Rx-2 is about 5m from the source line.

We extracted common-source seismograms associated with vibrators V1 to V4 by crosscorrelating the blended raw data with the appropriate pure m-sequences (note: we could have extracted the seismograms by crosscorrelating with the filtered m-sequences or the recorded ground force signals instead). To emphasize the reflections, we have removed the low-frequency surface wave arrivals with an Ormsby bandpass filter (15Hz-30Hz-100Hz-200Hz). The resulting common-source gathers are plotted with an AGC window of 200ms on Figures 15 to 18.

On these figures, we see that the common-source seismograms for the near-offset line exhibit significant crosstalk interference. The crosstalk obscures portions of the first-arrival event as well as portions of the reflection event at about 1200ms, and is linked to high-amplitude surface-wave arrivals from adjacent and nearby vibrators. The deblending technique using these particular filtered m-sequences appears unable to adequately separate the very weak body-wave signals from the very strong surface-wave signals existing on the near-offset receiver line. The crosstalk interference is apparently much reduced on the deblended gathers for the far-offset receiver line, probably because the differences in surface-wave amplitudes and body-wave amplitudes in the raw field data are much smaller.

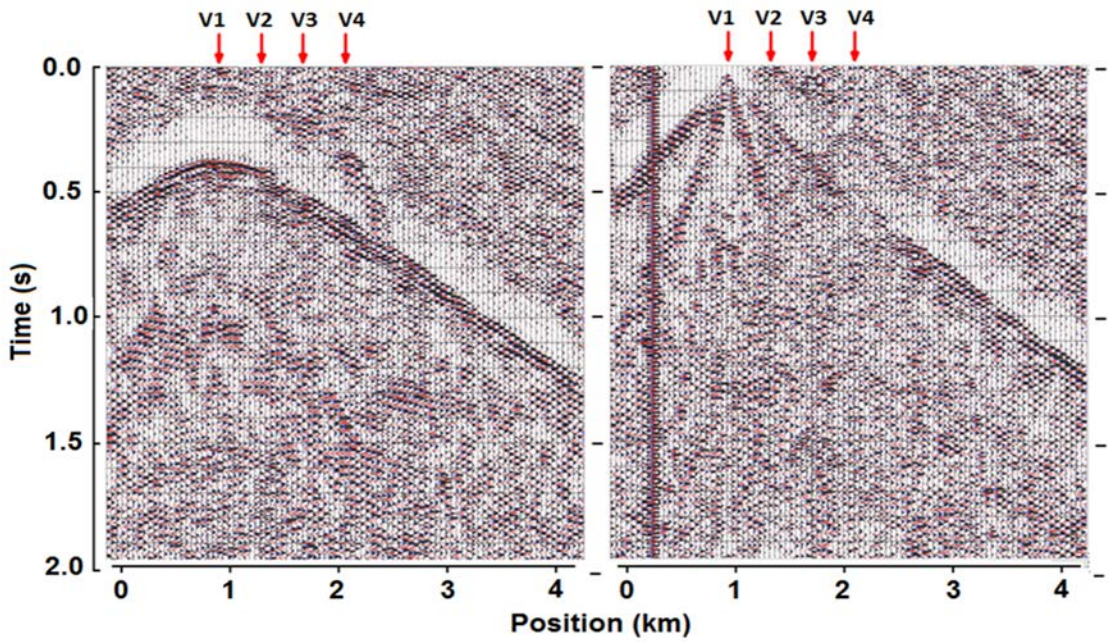

Figure 15: Common source gathers associated with far-offset and near-offset receiver lines, for vibrator V1, deblended from the raw field data shown on Figure 14.

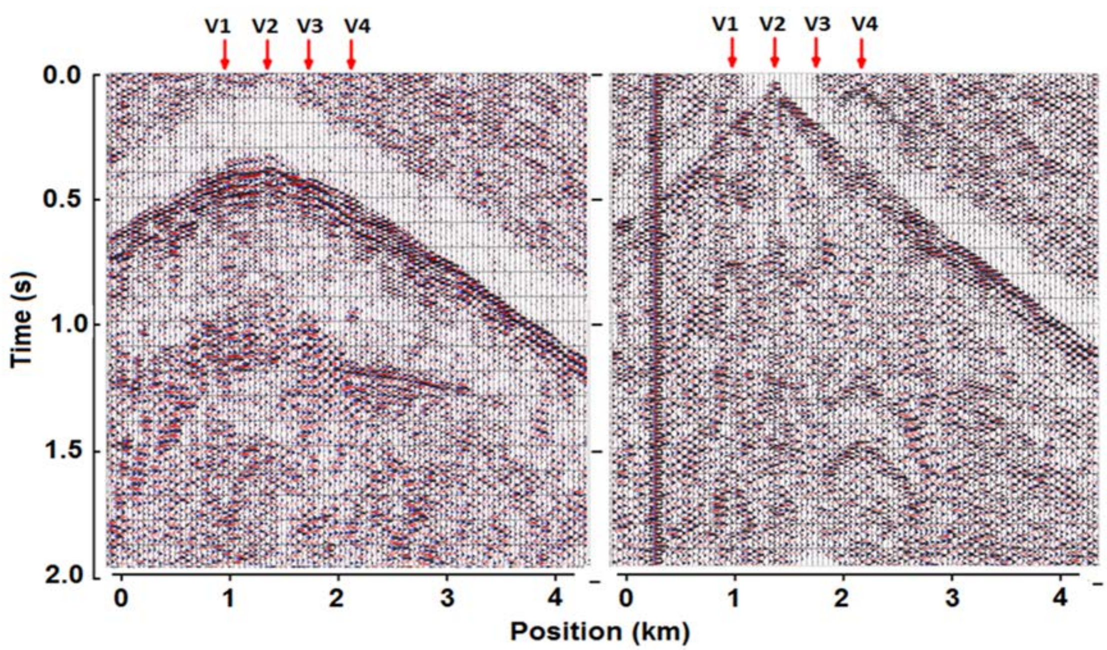

Figure 16: Common source gathers associated with far-offset and near-offset receiver lines, for vibrator V2, deblended from the raw field data shown on Figure 14.

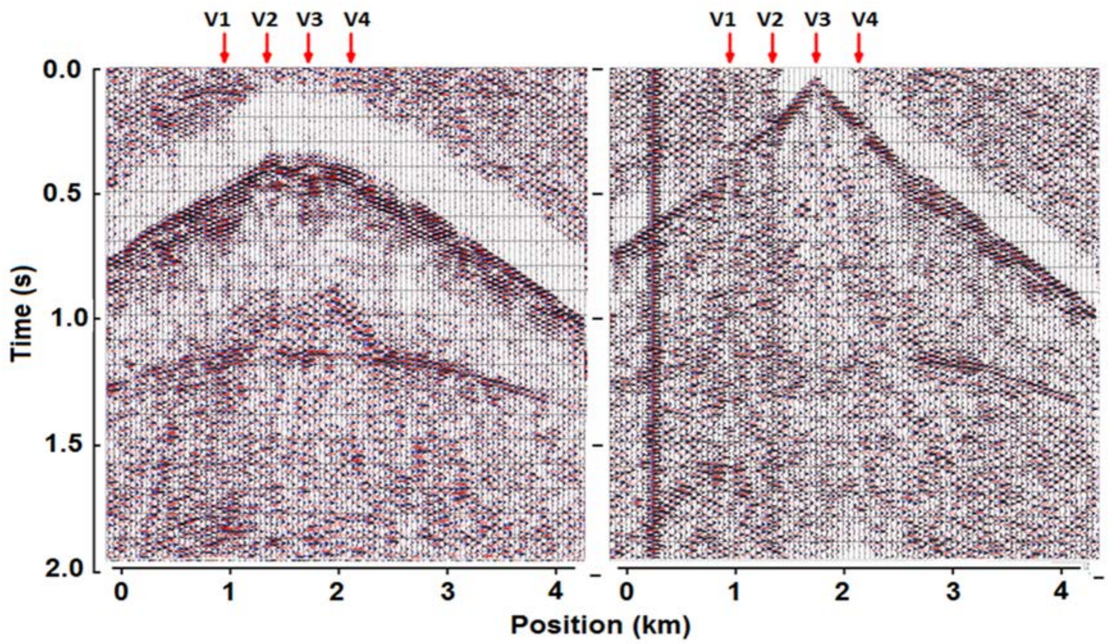

Figure 17: Common source gathers associated with far-offset and near-offset receiver lines, for vibrator V3, deblended from the raw field data shown on Figure 14.

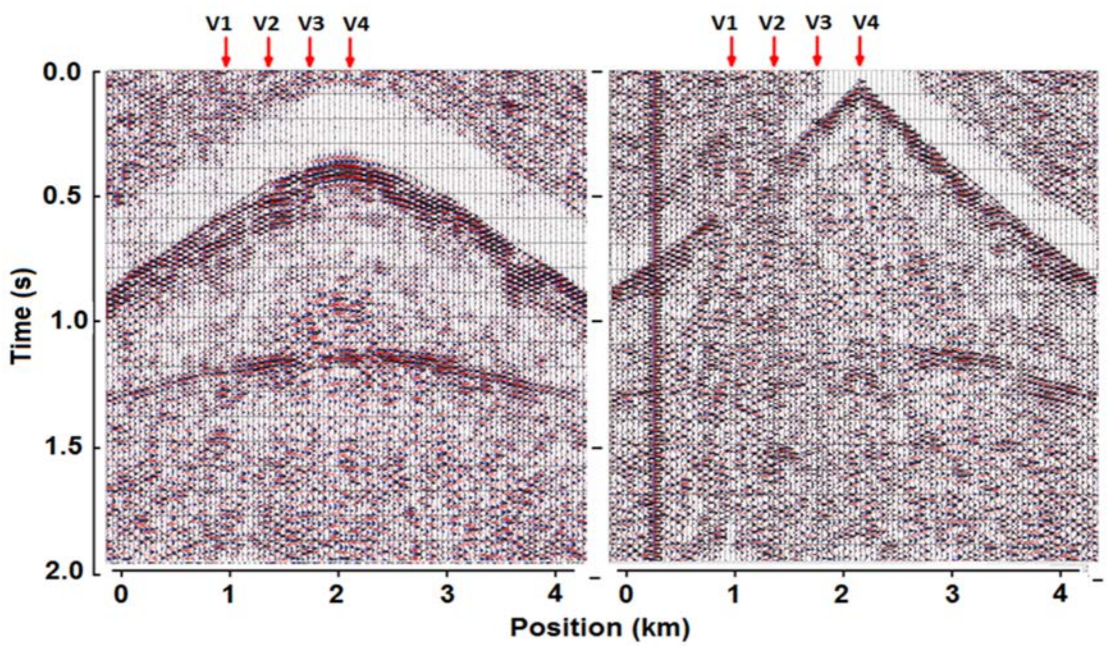

Figure 18: Common source gathers associated with far-offset and near-offset receiver lines, for vibrator V4, deblended from the raw field data shown on Figure 14.

NUMERICAL SIMULUTIONS

To examine more closely the reason why the particular time-domain filtered m-sequences used in these field tests performed so poorly in deblending weak signals from strong signals in the raw data, we performed a numerical experiment. Figure 19 shows a set of pure m-sequences pilots on the left. On the right, we see the seismograms that result from using the pure m-sequences in a multi-sourcing simulation. This is an AGC plot, but the amplitudes of the first arrivals are .001 times the amplitudes of the strong second arrival (i.e., 60dB down). The pure m-sequences perform very well in separating very weak signals from very strong signals in blended raw data.

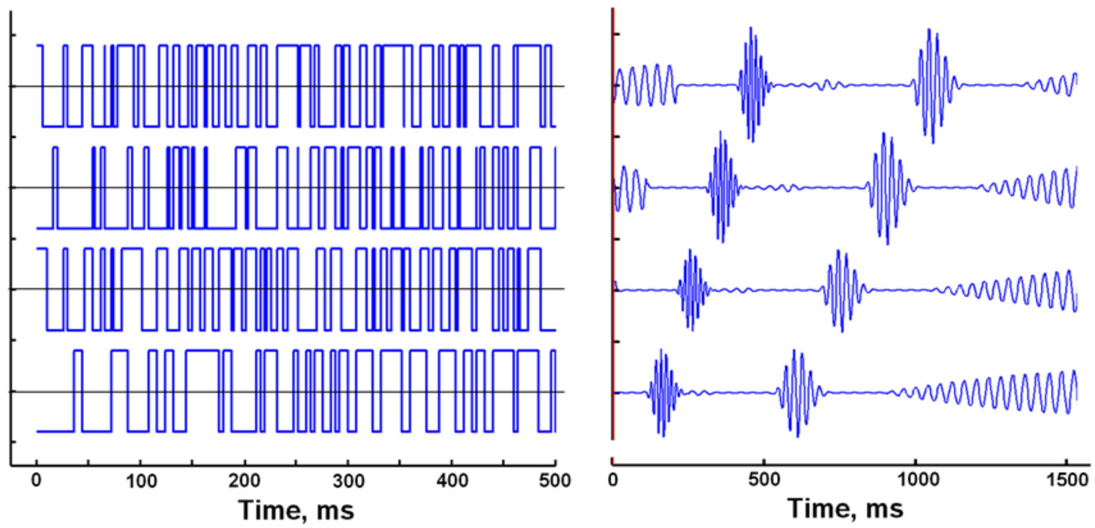

Figure 19: Left: Pure m-sequence pilots. Right: results of numerical simulation of multi-sourcing using pure m-sequence pilots.

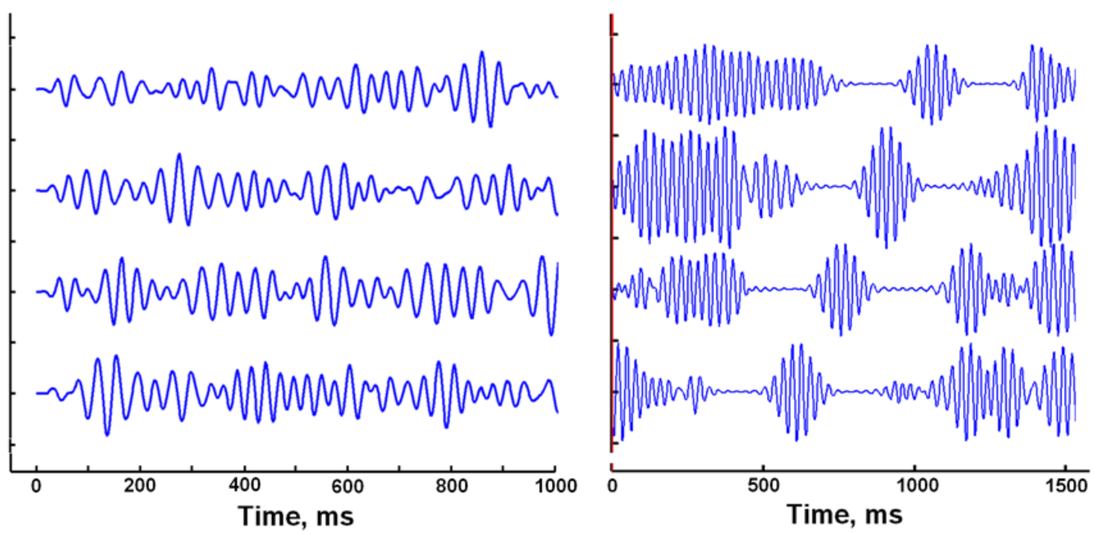

Figure 20: Left: Time-domain filtered m-sequence pilots. Right: results of numerical simulation of multi-sourcing using time-domain filtered m-sequence pilots.

We repeated the same numerical simulation using the time-domain filtered m-sequences used in the field test. The time-domain filtered pilots are displayed on the left side of Figure 20, and the seismograms resulting from the simultaneous multi-sourcing simulation are plotted on the right side. These seismograms show that the time-domain filtered m-sequences failed to separate the weak first arrival from the strong second arrival. The weak arrival is completely obscured by crosstalk and correlation noise.

On the left side of Figure 21, we have displayed the spectrum of a pure m-sequence as the blue line, and the spectrum of its time-domain filtered counterpart in solid red. 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 drastic reduction in spectral content changes the mathematical properties of the pure m-sequences that enable them to approximate a perfectly orthogonal set so well. The reduction in spectral content is so severe that the filtered m-sequences are rendered ineffective for separating very weak signals from very strong signals.

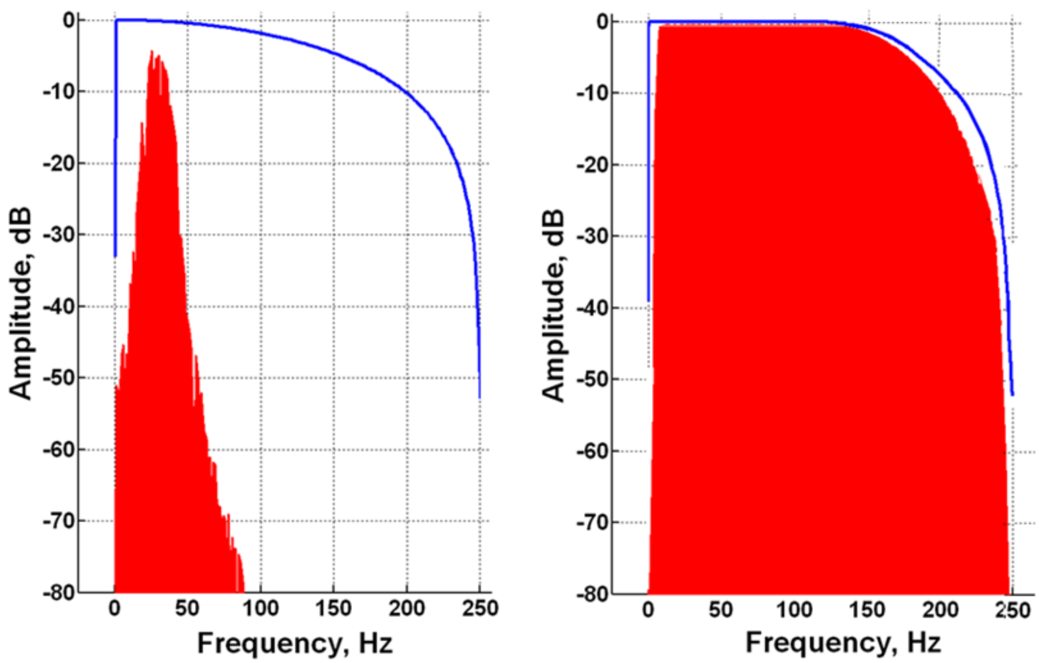

Figure 21: Pilot signal spectral energy in the frequency bans 0 to 250 Hz. Blue lines = pure m-sequences of Figure 20. Left red = spectrum of time-domain filtered m-sequences of Figure 21 (*m* =11, t_B = 4ms; dominant frequency of filter= 50 Hz). Right red = spectrum of frequency-domain filtered m-sequences (*m* =13, t_B = 2ms; bandpass filter corners = 5-10-125-250 Hz).

Instead of using a time-domain filter to moderate the square-wave transitions on pure m-sequences, we can use a bandpass filter in frequency domain to do the same thing. A bandpass filter enables us to have more control on the final spectral content of the filtered m-sequence pilots. On the right side of Figure 21, the spectrum of a pure m-sequence after bandpass filtering in frequency domain is displayed in red. For frequencies less than the high-frequency cutoff of 250Hz, the filtered pilot has almost the same spectral content as the original unfiltered m-sequence.

Figure 22 shows a set of frequency-domain filtered m-sequences on the left. The seismograms from a simulation of using them as pilots for simultaneous sourcing are shown on the right. On these seismograms, both the weak and the strong arrivals appear distinctly above the correlation noise with good separation, almost as well as in the case where pure, unfiltered m-sequence pilots were used.

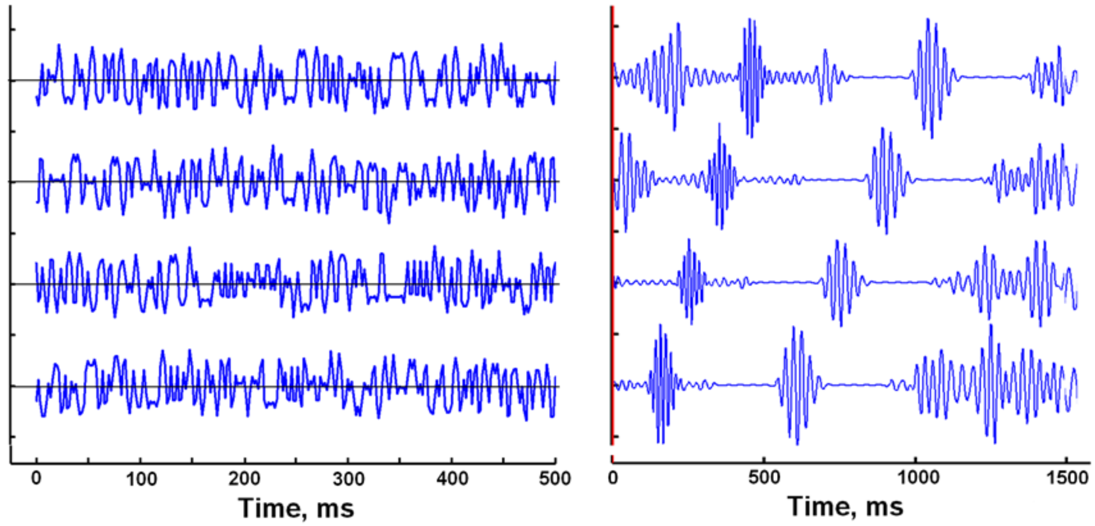

Figure 22: Left: Frequency-domain filtered m-sequence pilots. Right: results of numerical simulation of multi-sourcing using frequency-domain filtered m-sequence pilots. The amplitude spectra are identical to the one shown on the right side of Figure 20.

Plots of the auto-and cross-correlations for the three types of m-sequence pilots (pure, time-domain-filtered, and frequency-domain-filtered) reveal why their deblending performances are so different. On the relative amplitude plots of Figure 23, we see that that autocorrelations of the pure and frequency-domain filtered m-sequences are much more spiky (i.e., simulates a delta function more closely). By contrast, the autocorrelation of the time domain filtered m-sequences is much broader in time and possesses relatively large side lobes.

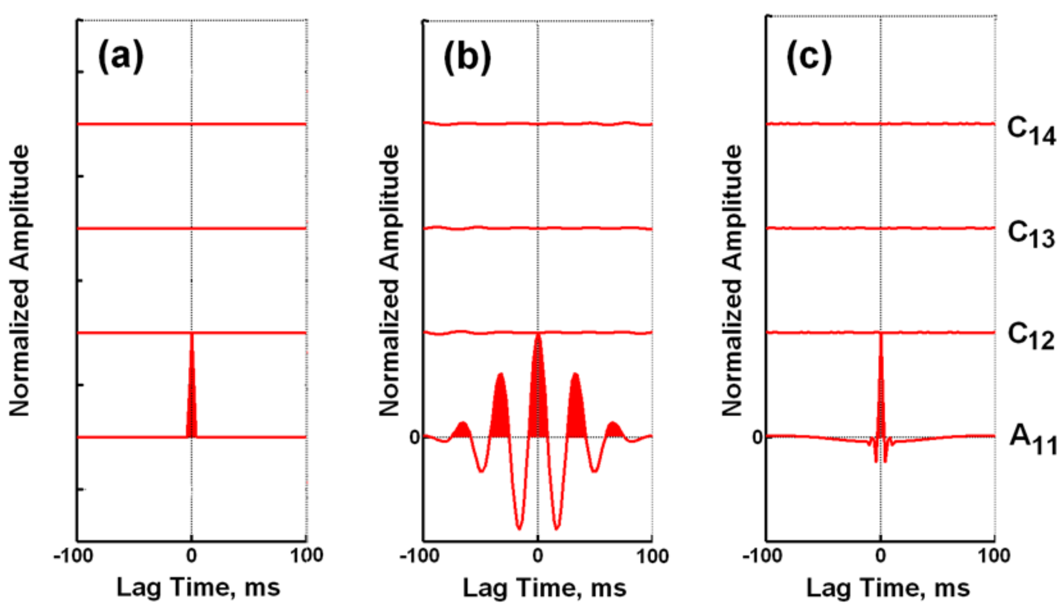

Figure 23: Auto- and crosscorrelations for: (a) pure m-sequences of Figure 19; (b) time-domain filtered m-sequences of Figure 20; (c) frequency-domain filtered m-sequences of Figure 22.

On the decibel plots of Figure 24, we see that, relative to the autocorrelation peak value, the crosscorrelation values for the time-domain filtered m-sequence are much larger and more oscillatory than those for the pure and frequency-domain filtered m-sequences. The oscillatory crosscorrelation values for a set of quasi-orthogonal pilot signals determine the amount of correlation noise and crosstalk when the set is applied in simultaneous multi-sourcing: the small the oscillatory values, the smaller the correlation noise and the better the separation of weak signals from strong signals will be. Therefore, the ratio (expressed in decibels) of the maximum absolute value of the cross-correlations to the autocorrelation peak value is a very useful figure of merit. Any quasi-orthogonal set of filtered m-sequences with a figure of merit less than -65dB would be suitable as pilots for simultaneous multi-sourcing.

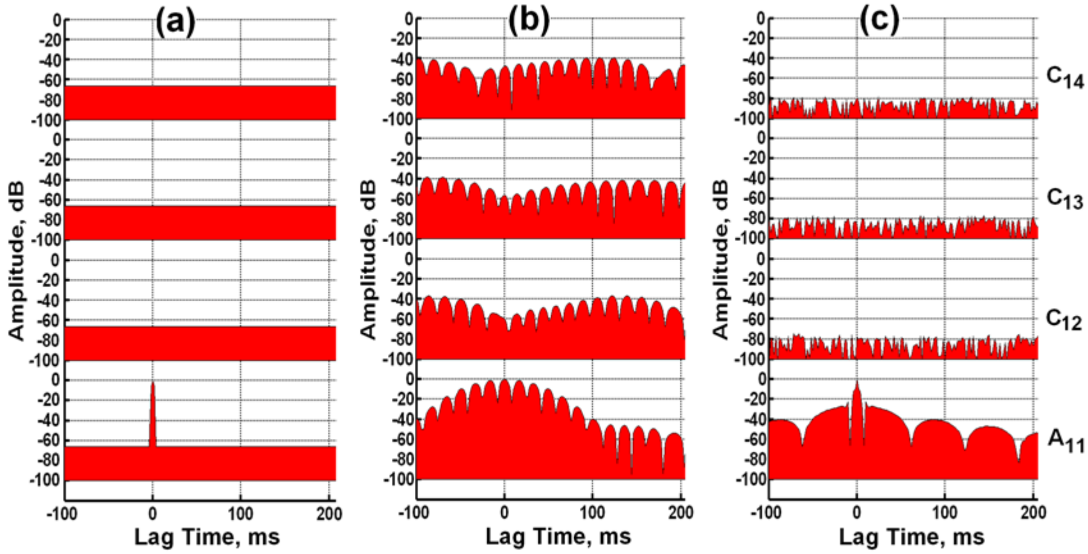

Figure 24: Decibel displays of auto- and crosscorrelations for (a) pure m-sequences of Figure 19, maximum crosscorrelation value = -66 dB; (b) time-domain filtered m-sequences of Figure 20, maximum crosscorrelation value = -36 dB; (c) frequency-domain filtered m-sequences of Figure 22, maximum crosscorrelation value = -71 dB;

CONCLUSION

Our field tests at the first test site have verified that shifted m-sequences modified by a time-domain filter can control land vibrators successfully. The quality of seismograms acquired with filtered m-sequence pilots compares favourably with the quality of seismograms acquired with linear sweep pilots. A caveat is that weak reflections on seismograms acquired using m-sequence pilots are somewhat degraded by low-amplitude artifacts likely caused by harmonic distortions and/or nonlinearities in the mechanical behavior of the vibrators. The artifacts have predictable time moveouts that are parallel to the first arrivals, and simple processing steps can reduce them to a level where their interference with the weaker reflections is minimal.

Our field tests at the first site have also shown that raw data recorded with two vibrators, separated by 200m in simultaneous operation and controlled by time-domain filtered m-sequences, can be deblended by crosscorrelation to produce separate common source gathers of seismograms with little crosstalk between the signals from the two simultaneous sources. This result is experimental confirmation of numerical simulations by Wong (2013) demonstrating the quasi-orthogonal property of shifted m-sequences.

However, additional testing at the second site involving four simultaneous vibrators driven by a set of time-domain filtered m-sequences yielded deblended seismograms with serious crosstalk interference. This crosstalk originates from the strong surface-wave arrivals associated with nearby vibrators. For raw data recorded on receiver lines far away from the vibrator locations, surface–wave amplitudes are not overwhelmingly strong compared with the body-wave amplitudes. Therefore, the crosstalk interference after crosscorrelation for these lines is much reduced.

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 surface waves) provided that the filtering process does not eliminate a high percentage of the spectral energy of pure m-sequences in the important frequency range of 0 to 250Hz. The time-domain filter used to create the pilot signals on Figure 4 eliminated too much of this energy, with the result that the pilots performed poorly for simultaneous multi-sourcing.

We have produced new quasi-orthogonal pilots with much better spectral content by bandpass filtering the pure m-sequences in frequency domain. In the near future, we will conduct field tests and record raw unblended using improved sets of filtered m-sequence pilots to control four and eight vibrators in simultaneous operation.

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