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

Theoretical analyses and numerical simulations predict that shifted m-sequences are suitable pilot signals for driving multiple simultaneous land vibrators. We have carried out a field test to confirm this experimentally. Filtered m-sequences were used successfully to control hydraulically-powered land vibrators. Raw field data recorded with two vibrators driven simultaneously by two quasi-orthogonal m-sequences were easily separated by crosscorrelation into individual source gathers with little crosstalk. Comparison of deblended seismograms acquired using m-sequence pilots with seismograms acquired using a linear sweep pilot showed little difference in data quality.

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).

When controlled sources such as land vibrators are used, simultaneous sourcing can be done effectively with minimal crosstalk if the vibrators are driven by a set of quasi-orthogonal pilot signals. A quasi-orthogonal set in this context 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 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). 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.

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 spikes that approximate delta functions.

Wong (2013) 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 1](image1.png)
**Figure 1**: First 2040ms of four shifted m-sequences, with \( m = 11, L = 2047, t_b = 4\)ms. The time \( \Delta t \) between sequences is 2040ms. The full lengths of the sequences are 8188ms.

![Figure 2](image2.png)
**Figure 2**: Correlations \( C_{ij} \) for the set of four shifted m-sequences on Figure 1. \( C_{ii} \) is the autocorrelation of the i-th sequence; \( C_{ij} \) is the crosscorrelation between two different sequences i and j.
Field testing of m-sequence pilots

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

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

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 they 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 100 Hz.

Figure 3 displays the first 1000ms of two 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, although their autocorrelation peaks are no longer simple triangles. Vibrators driven by the filtered m-sequences behaved smoothly. The power spectra of the modified sequences can be adjusted by using different time-domain filters.

In our field test, we employed two vibrators in non-simultaneous single operation driven separately by the mSeq1-F and mSeq2-F signals shown on Figure 3, and in simultaneous operation driven by the same two signals. We recorded raw field data with a linear array of 138 geophones spaced at 50m intervals. We also recorded data using a conventional linear sweep pilot (4Hz to 140Hz, sweep time of 16 seconds, end tapers of 300ms).

Seismograms were extracted from the raw data post-survey by crosscorrelating them with the pure m-sequences or with the linear sweep pilot.

Single vibrator results

Figure 4 compares common-source gathers acquired using the three different pilots driving a single vibrator in non-simultaneous operation. In all three sets of seismograms, the same reflections appear clearly. For the traces 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. Possibly these artifacts are related to small harmonic distortions and/or nonlinearities in the mechanical responses of the vibrators. We need to
Field testing of m-sequence pilots for land vibrators

determine definitively the cause of the artifacts, and eliminate them if possible. 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. A constant time delay exists between the 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. Figure 4 is strong experimental evidence supporting the claim that (filtered) m-sequences can be used successfully to control land vibrators.

Simultaneous vibrator results

We positioned two vibrators 200m apart close to the line of geophones. We specified mSeq1-F as the pilot for one vibrator and mSeq2-F as the pilot for the other. We then recorded raw data while running both vibrators simultaneously. The raw data are shown on Figure 5.

From the raw data, we extracted deblended seismograms associated with vibrators 1 and 2 by crosscorrelating with the pure m-sequences mSeq1 and mSeq2, 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 6(a) and 6(b). For comparison, we have included on Figure 6(c) a gather recorded using the linear sweep pilot.

On Figures 6, 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 4).

We reduced interference from the weak artifacts using simple processing steps that included NMO/DMO alignment, trim statics, signal enhancement, and trace interpolation. Figure 7 displays the results. 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.
Field testing of m-sequence pilots for land vibrators

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 8. 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.

Conclusion

Our field test has proven that shifted m-sequences modified by a time-domain filter can control land vibrators successfully. The quality of seismograms acquired with m-sequence pilots compares favorably 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 non-linearities in the mechanical behavior of the vibrators. The artifacts have predictable time moveouts that are parallel to the first arrivals. For this reason, they can be reduced fairly easily by processing to a level where their interference with the weaker reflections is minimal.

We have also shown that raw data recorded with two vibrators in simultaneous operation and controlled by shifted m-sequences can be separated by crosscorrelation, producing seismograms with little crosstalk between the two simultaneous sources. This result is experimental confirmation of numerical simulations by Wong (2013) demonstrating the quasi-orthogonal property of shifted m-sequences. Future field tests, involving four or more vibrators, will be done to further confirm the suitability of shifted m-sequences for controlling multiple vibrator sources operating simultaneously.

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References


