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Simultaneous Multiple Source Acquisition using m-Sequences

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Summary

High-resolution 3D seismic imaging of producing reservoirs, for which there is increasing demand, require very high volumes of field data. Efficiency in the acquisition of such high data volumes can be maximized by deploying as many receivers as possible, and examples of surveys involving 100,000 receivers are not uncommon. For land surveys, acquisition efficiency can also be increased by operating multiple vibrator sources simultaneously. Simultaneous sourcing results in recorded signals which are blends or sums of the signals produced by the individual sources, and a method is required to extract the individual signals. This article presents a set of quasi-orthogonal pilot signals that can be used to drive multiple vibrators simultaneously. These pilots are shifted m-sequences, and their special properties enable the recovery of seismograms (each uniquely associated with a single vibrator) from the combined received signals.

Introduction

Effective simultaneous operation of multiple seismic sources depends on a method of extracting individual traces (each uniquely tied to a separate vibrator) from a single received signal equal to the sum of the signals from all the sources. When the multiple sources are vibrators, extraction with zero cross-talk can be achieved if a set of perfectly orthogonal pilot signals is used to drive the vibrators. Each member of such an ideal set has an autocorrelation which is a delta function, while cross-correlations between different members are exactly zero. Sets of real pilot signals will never be perfectly orthogonal: autocorrelations will only approximate delta functions, and cross-correlations will not be exactly zero. Realistic quasi-orthogonal sets can be constructed using special mathematical entities such as maximal length sequences (m-sequences) and Gold codes. When used as pilot signals to drive several vibrators simultaneously, the special properties of these entities (especially the m-sequences) make possible the de-blending of the total signal at a receiver. The de-blending is achieved by circular cross-correlation of the total signal with each of the quasi-orthogonal pilots,, a procedure that extracts the seismograms associated with the individual sources.

Recently, Pecholcs et al. (2010) reported on a case study in which 24 vibrators operating simultaneously were used to acquire data for a 3D land seismic survey. The use of 24 simultaneous sources resulted in more than 40,000 shot points per 24-hour period and an impressive increase in acquisition productivity. The multiple vibrators were controlled by a set of modified Gold codes (Sallas et al., 2011; Sallas and Gibson, 2008). The field results reported by Pecholcs et al. (2010) indicated that modified Gold codes appeared to serve adequately as pilots for simultaneous sourcing.

Gold codes are derived from simpler and more fundamental mathematical entities known as maximal length sequences, or m-sequences. Gold codes and m-sequences are pseudorandom binary sequences (PRBS). They are periodic and have values only of -1 and +1, and they are pseudorandom in the sense that their autocorrelations approximate the delta function. Both m-sequences and Gold codes are used in diverse fields of science and engineering. Examples of applications are the estimation of impulse responses of linear systems, wireless communication, data encryption, and

GPS/GNSS technology (Holmes, 2005). Gold codes are popular for wireless communications because thousands or even millions of weakly-correlated forms can be easily produced from different preferred (or optimal) pairs of m-sequences. In seismic acquisition, m-sequences have been used successfully in crosswell applications to drive piezoelectric vibrators (Hurley, 1983; Wong et al. 1983, 1987; Yamamoto, 1994; Wong, 2000). It can be shown that modified m-sequences are better than modified Gold codes as pilot signals for simultaneous multi-sourcing because m-sequences have much lower correlation noise, and are therefore closer to being perfectly orthogonal.

Shifted m-sequences

Mathematically, an m-sequence is characterized by its degree *m*, its fundamental length L, and its base period t_b. The fundamental length L is related to the degree *m* by Equation 1:

$$L = 2^m - 1 \,, \qquad (1)$$

where *m* is an integer. The exponential form of Equation 1 means that the fundamental length grows very quickly with the degree. For practical applications, *m* is limited to values of 10 to 20. If *m* = 11, then L = 2047; when *m* = 15, L = 8191.

In terms of real time, the m-sequence is periodic with period equal to

$$T_m = L \cdot t_b \,. \qquad (2)$$

The m-sequence can be up-sampled with sample time t_s, where

$$r = t_b / t_s \,, \qquad (3)$$

is the up-sample ratio, typically equal to an integer value of 1, 2, 4, 8, or 16.

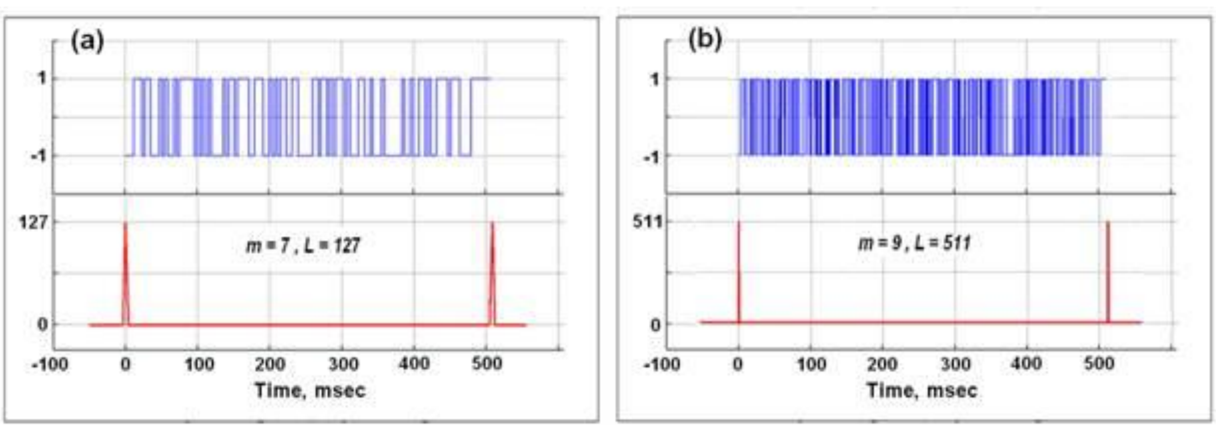

Figure 1: Two examples of m-sequences (blue), and their autocorrelations (red): (a) m = 7, L = 127, t_b = 4ms, t_s =1ms, T_m = 504ms; (b) m = 9, L = 127, t_b = 1ms, t_s =1ms, T_m = 511ms. The periods T_m have been deliberately set to be short to emphasize the periodicity of the autocorrelations.

The autocorrelation of an up-sampled m-sequence, after scaling by 1/*r*, consists of narrow triangles with scaled peak values equal to *L* resting on a scaled constant level of -1. It is important to note that the scaled constant level of -1 is independent of the degree *m*. Each triangular peak approximates a delta function. Figure 1 shows two examples of m-sequences and their autocorrelations. These and all other m-sequences can be generated by linear feedback shift registers or by logic statements in software (Golomb and Gong, 2005). From Figure 1, we see that the scaled triangular peaks are increasingly better approximations to the delta function as *m* increase.

After constructing an initial m-sequence S_1, multiple shifted versions are obtained by systematically applying a shift time t_{shift}. If we want a set of N shifted m-sequences, we define t_{shift} by

$$t_{shift} \leq T_m/N \,. \qquad (4)$$

The autocorrelations of the shifted m-sequences S_1 to S_N also are periodic and have the appearance of a series of triangular peaks. The base width of each triangular peak is equal to $2t_b$. Compared to t_{shift} and the period T_m, the base width is very narrow when the degree *m* is greater than 10. Each triangle of the autocorrelations therefore is a very good approximation to the delta function. Within a window of lag times less than t_{shift}, the scaled values of cross-correlations between different S_i are all equal to -1; they are nearly zero compared to the scaled peak value *L* of the autocorrelations. The set

$$\{ S_j \,,\ j = 1, 2, \dots N \}$$

of shifted m-sequences is almost perfectly orthogonal in this window, and is suitable as pilots for controlling multiple vibrators operating simultaneously as long as arrivals outside the window are considered to be unimportant.

For example, if T_m = 8188ms and N = 4, then t_{shift} can be given a value of 2040ms. The set $\{S_1, S_2, S_3, S_4\}$ is obtained by applying time shifts of 0ms, 2040ms, 4080ms, and 6120ms. Since the sequences are periodic, the shifts result in wrap-around of values. Figure 2(a) displays the first 2040ms of four shifted m-sequences constructed in this way. Figure 2(b) displays the auto- and cross-correlations of this set restricted to lag times of 0ms to 2000ms. The figure indicates that this set is almost perfectly orthogonal within the window of restricted lags.

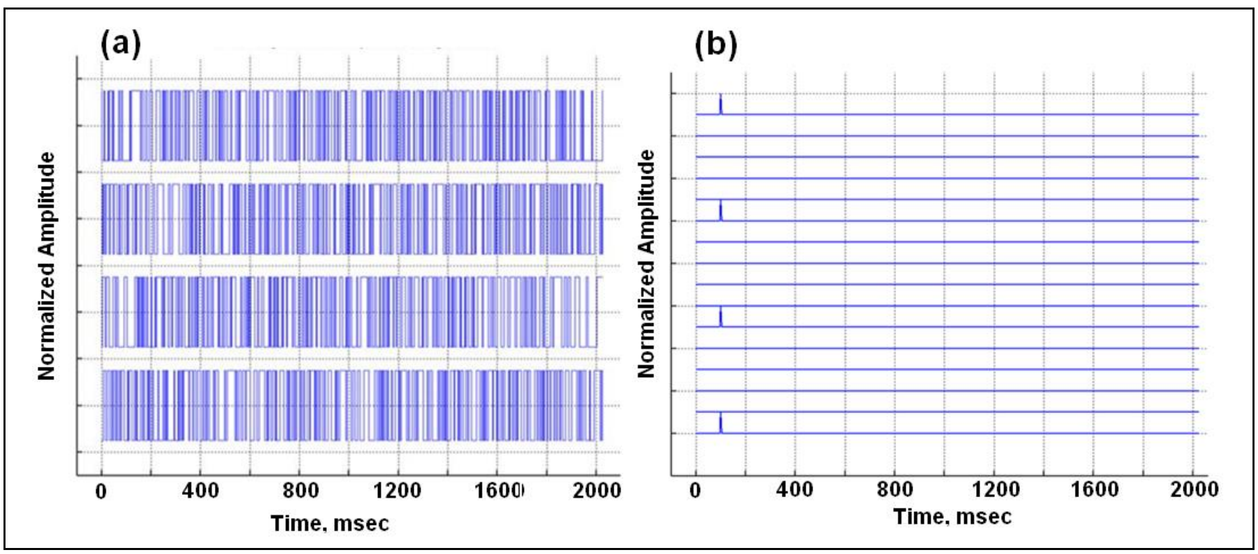

Figure 2: (a) Four shifted m-sequences, with *m* = 11, *L* = 2047, t_b = 4ms, t_s =1ms, T_m = 8188ms, t_{shift} = 2040ms. (b) The auto- and cross-correlations, with scaled peak values of 2047 and scaled off-peak values of -1.

Driving multiple vibrators with quasi-orthogonal shifted m-sequences

During acquisition, vibrator sources are driven by two complete cycles of the shifted m-sequences, and the recording or listen time is also two complete cycles. Figure 3(a) shows plots of two wavelets used to represent seismic arrivals in the impulse response of the earth to a seismic source. The second event is much weaker, and is visible only with AGC. Figure 3(b) displays the convolutions of the wavelets with two cycles of each of the shifted m-sequences of Figure 2(a). The convolutions represent received signals R_1 to R_4 and are filtered versions of the original m-sequences S_1 to S_4. The received signal have been systematically delayed by 100ms to represent the increasing arrival times due to increasing separations between the four sources and a single receiver. The initial times of the R_j have zero values because the receiver sees no energy until vibrations have travelled the distance between the sources and the receiver. At the single receiver, the detected signal will be the sum R_T since the four sources are operating simultaneously. Individual seismograms, each associated uniquely with a different source, are recovered from the second half of the recorded signal R_T by circular cross-correlation with each of the pilot signals S_1 to S_4. These traces are plotted with AGC on Figure 3(c), and they clearly show both the strong and the weak arrivals with no visible cross-talk.

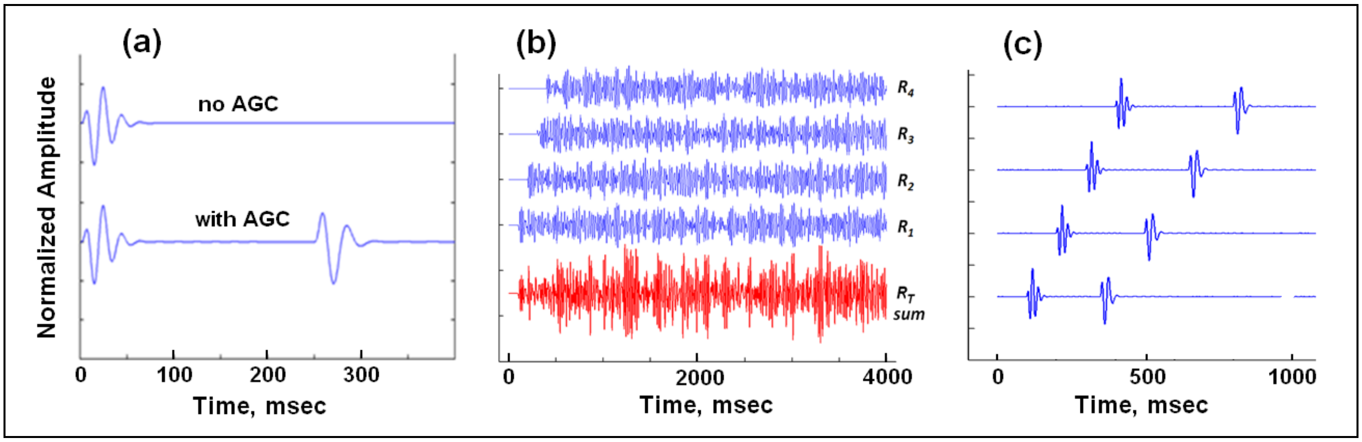

Figure 3: (a) A source function with a strong event and a second event 10,000 times weaker (the second event is visible only with AGC). (b) Blue: convolutions of the source function with two cycles of each of the pilots on Figure 2(a). Red: sum of the four delayed convolutions. Only the first 4000ms of the convolutions are plotted. (c) Cross-correlation of the summed convolution with each of the pilots on Figure 2(a), plotted with AGC.

Conclusions

Operating multiple vibrator sources greatly increases the efficiency of seismic acquisition for 3D surveys. The numerical simulation in this study has shown that using shifted m-sequences as pilots to drive multiple sources simultaneously results in the extraction of high-quality seismograms with minimal cross-talk from the combined signal recorded at a single receiver.

Acknowledgements

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References

Gold, R., 1967. Optimal binary sequences for spread spectrum multiplexing: IEEE Trans. Inform. Theory, **13**(4), 619-621.

Golomb, S.W., and Gong, G., 2005. Signal design for good correlation: for wireless communication, cryptography, and radar: ISBN-0-521-82104-5.

Holmes, J.K., 2007. Spread spectrum systems for GNSS and Wireless Communications, Artech House, Norwood, ISBN-9787-59693-083-4.

Pecholcs, P., Lafon, S. K., Al-Ghamdi, T., Al-Shammery, H., Kelamis, P. G., Huo, S. X., Winter, O., Kerboul, J.B., and Klein, T., 2010. Over 40,000 vibrator points per day with real-time quality control: opportunities and challenge: SEG Exp. Abstracts, **29**, 111-115.

Sallas, J., Gibson, J., Maxwell, P., and Lin, F., 2011 . Pseudorandom sweeps for simultaneous sourcing acquisition and low-frequency generation, The Leading Edge, **30**, 1162-1172.

Sallas, J., and Gibson, J.B., 2008. Efficient seismic data acquisition with source separation, U.S. Patent No. 7,859,945.

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

Wong, J., Hurley, P., and West, G.F., 1987. Crosshole seismic scanning and tomography: The Leading Edge, **6**, 31-34.

Wong, J., Hurley, P., and West, G.F., 1983. Crosshole seismology in crystalline rocks: Geophys. Res. Lett., **10**, 686-689.