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Improving the efficiency of seismic exploration systems based on the use of pseudo-random sweeps: Mathematical modeling

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Abstract

The study explores the potential to improve seismic imaging resolution using broadband pseudorandom sweep signals and outlines the corresponding requirements for seismic acquisition systems. We analyze the quality of the resulting seismic images of a 2D inhomogeneous velocity structure using a synthetic vibroseismic dataset modeled for a series of sweep signals constructed based on pseudorandom code sequences (PRCS) of mechanical load pulses. The study demonstrates that the detailed seismic images showing main reflecting boundaries can be recovered by means of correlation processing of the vibroseismic data. It can be seen, through their comparison with single-pulse mode seismograms, that the imaging accuracy achieved with a particular PRCS sweep signal primarily depend depends on the pulse duration.

Keywords: Seismic acquisition systems; Vibration seismic; Vibroseis; Seismic source sweep; Seismic reflection; Correlation processing; Impulse response; Pseudorandom code sequence

1. Introduction

Enhancing the efficiency of seismic exploration requires advancements in equipment, including acquisition systems and signal sources, as well as improvements in methodological techniques for field survey operations, data processing and interpretation. A distinctive feature of seismic acquisition systems with hybrid telemetry [1] is, in particular, their ability to employ molecular-electronic sensors, which offer an extended frequency range [2]. This capability enables higher resolution through the use of broadband source pulses. This study focuses on the potential use of pseudorandom sweep signals to address this challenge.

The main limitations of the widely used reflection seismic method [3] stem from the need to detect high-frequency, low-amplitude seismic signals against an interfering wave bias. The use of vibroseis systems [4], as opposed to explosive and non-explosive impulsive sources, has made it possible to increase the energy of seismic waves created in the subsurface. In such systems, sweep signals are typically quasi-harmonic frequency-modulated (FM) signals with a linear variation of instantaneous frequency over time within the range of tens Hz to 100–200 Hz. However, the quality of reflection discrimination from the correlograms computed from vibration seismic data, is not always satisfactory [5]. Consequently, it is important to evaluate the optimality of vibrational sweep signals of various types through numerical modeling.

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The conventional approach to vibroseis data processing data involves correlogram calculation by correlating the source sweep signal with the received seismic traces [4, 6]. For successful identification of distinct (non-overlapping in time) reflections from a complex-pattern recorded signal [7], the autocorrelation function (ACF) of the sweep signal must closely resemble a narrow (delta-like) pulse. Using the pseudorandom code sequences (PRCS) of mechanical load instead of the frequency-modulated sweep signals can significantly improve this characteristic due to the narrow mainlobe of the PRCS ACF and the low amplitude and rapid attenuation of its side lobes [8].

Given the known advantageous properties of pseudorandom code sequences—broadband characteristics and a narrow autocorrelation function—and their application in various geophysical methods, it is reasonable to further investigate the effectiveness of such signals in vibrational seismic exploration.

In our previous studies [9–11], the use of PRCS with quasi-rectangular pulses was analyzed in case of 1D and simple 2D velocity models, demonstrating certain advantages over conventional sweep signals with linear frequency variation. In this study, we examine a more complex multilayered 2D velocity model with smooth layer boundaries and compare vibrational seismic data for several PRCS-based quasi-harmonic sweeps, differing in overall duration and the length of individual pulses.

2. Material and methods

To simulate vibrational seismic data, a synthetic velocity model was constructed (Fig. 1a), qualitatively representing a sedimentary anticline structure above a basement uplift. The model consists of eight layers with smooth boundaries, featuring a monotonic increase in the velocities of both compressional (V_p) and shear (V_s) waves from top to bottom. This configuration corresponds to positive reflection coefficients and V_p contrasts varying within the range of 1.1 to 1.4. The layer parameters (V_p, V_s and density ρ) are provided in Fig. 1a. The modeling domain spans 1,500 m both ve PRCS rtically and horizontally.

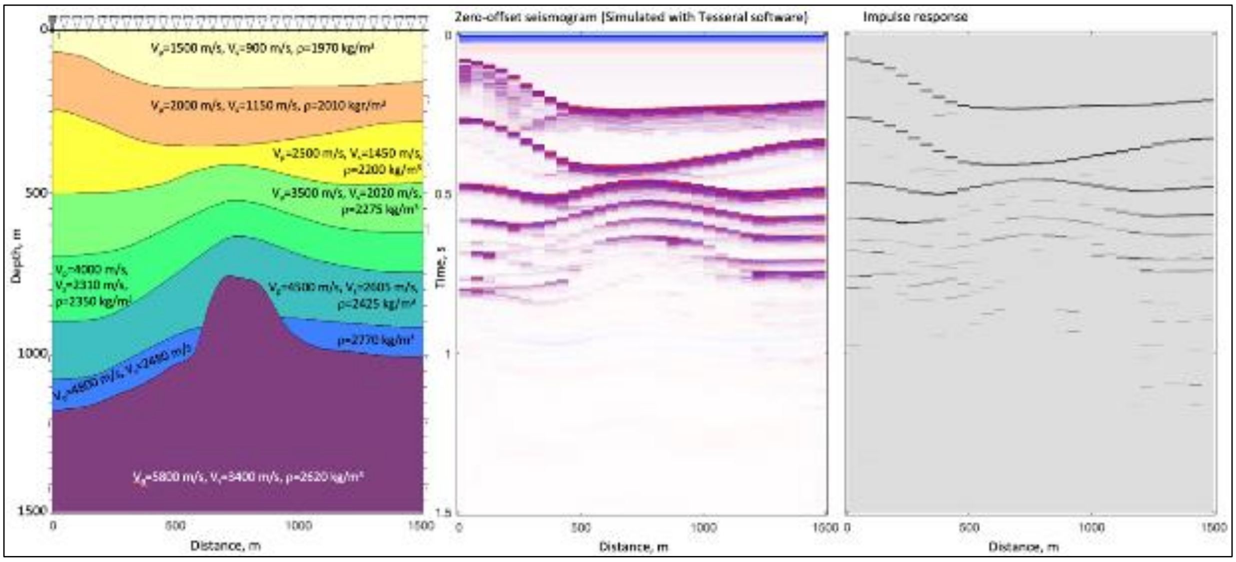

Figure 1 Left to right: the velocity model used for the full-wave simulation of the vibrational seismic data; a seismogram modeled assuming zero-offset mode (co-located sources and receivers) for a single pulse source with a central frequency of 400 Hz; impulse response amplitudes (reflection coefficients distribution).

At the first stage, full-wave finite-difference modeling was performed using Tesseral software [12] for a single wavelet-like pulse of short duration (~ 5 ms) with a central frequency of 400 Hz. This modeling provided an idealized seismic image (Fig. 1b) and an estimate of the impulse response amplitudes (Fig. 1c) assuming a zero-offset acquisition geometry (co-located sources and receivers) positioned on the surface with a horizontal spacing of 50 m. The time step and spatial mesh size were automatically selected based on the signal's frequency spectrum and the minimum wavelength values within the modeling domain.

Sweep signals were constructed using two binary pseudorandom code sequences (PRCS), containing either 63 or 127 elements, respectively, and generated according to the M-sequence computing code [13]. These sequences are referred to as PRCS No. 1 and PRCS No. 2 in the text and figures further on. Based on the generated PRCS, quasi-sinusoidal signals were created for two carrier frequencies, modulated by the respective PRCS, using the logical procedure described in [14]. Examples of the constructed PRCS and the resulting sweep signals are shown in Fig. 2.

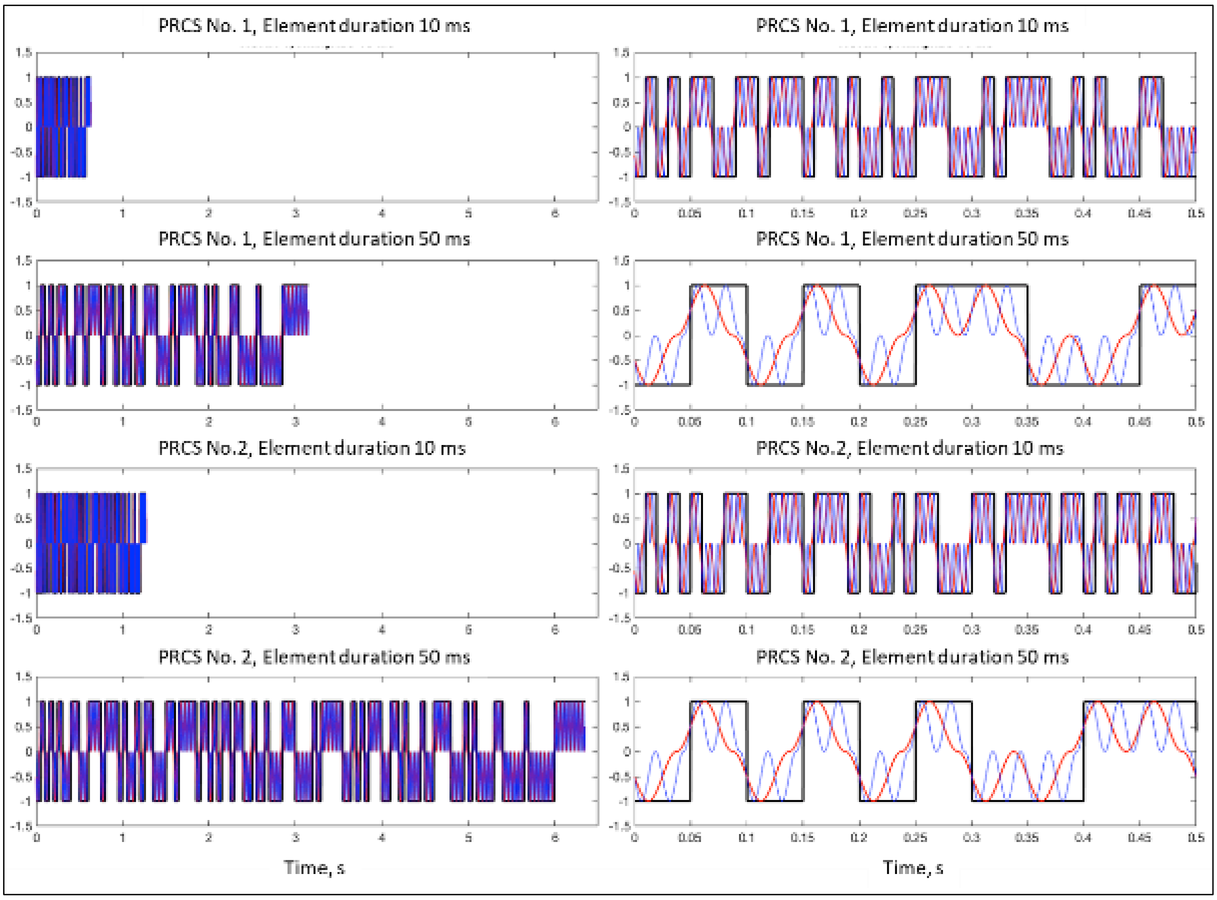

Figure 2 Seismic source sweep signals used for seismogram modeling. The left panel shows the full duration of the signals, while the right panel displays arbitrary fragments of 0.5 s duration. The corresponding PRCS are represented by black lines. The resulting sweep signals, shown in red, are constructed with a carrier period matching the duration of a single PRCS impulse. Signals shown in blue have a carrier period half the duration of a single PRCS impulse.

Fig. 3 illustrates the amplitude spectra of the constructed sweep signals. Sweep signals with the shortest PRCS impulse duration (10 ms) and a carrier period equal to the impulse duration exhibit the broadest spectrum, ranging from fractions of a Hz to 80–90 Hz. In contrast, signals with a doubled carrier frequency demonstrate an additional spectral maximum in the 100–300 Hz range, clearly separated from the main range by a pronounced minimum at 100 Hz. Subsequent lobes have significantly lower amplitudes, while the amplitude spectra of signals with longer impulses (50 ms) decline more steeply, with a noticeable drop starting at 10 Hz.

The spectral differences between sweep signals based on PRCS No. 1 and No. 2 are minor, despite the twofold difference in their total duration. Therefore, based on the spectral composition, the highest resolution can be expected with signals constructed using PRCS with 10-ms code pulses and a carrier period matching the pulse duration.

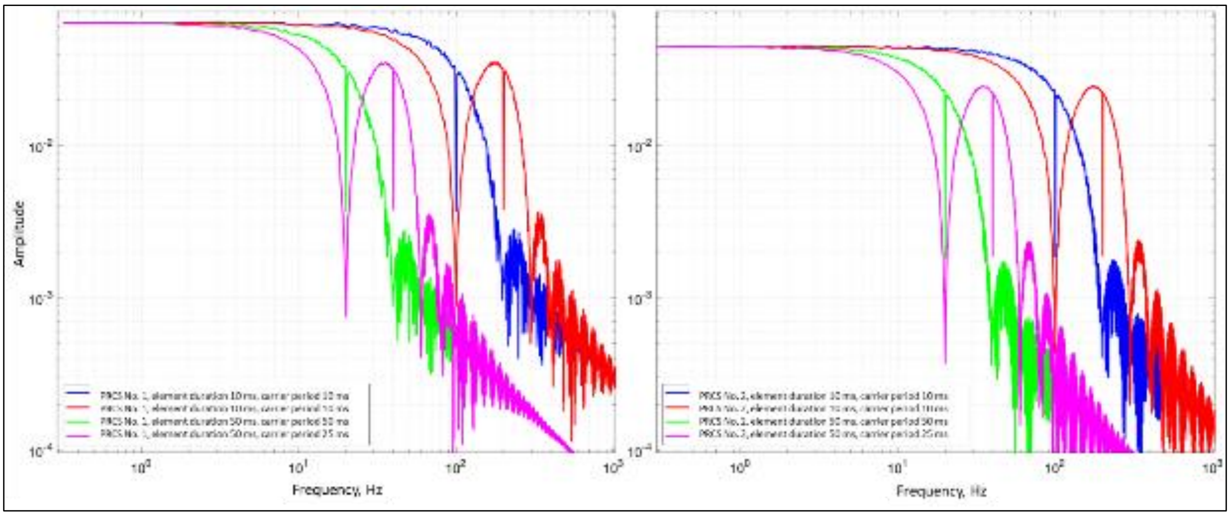

Figure 3 Amplitude spectra of sweep signals based on PRCS No. 1 (left) and PRCS No. 2 (right).

In the next stage, we subsequently calculated the convolution of all the synthesized sweep signals with the impulse response, derived from the 2D modeling. This produced vibration seismic datasets of a duration corresponding to the sweep signal length and the temporal range of the impulse response.

Following the standard approach typically used in vibrational seismic data processing, the simulated datasets were employed to calculate the cross-correlation function (CCF) between the source sweep signal *m* and the received seismic trace *s*:

$$B_{ms}(\tau) = \frac{\sum_{j=1}^{N} m_j \cdot s_{j-\tau}}{\sqrt{\sum_{i=1}^{N} m_i^2 \cdot \sum_{i=1}^{N} s_i^2}}, \qquad (1)$$

where the indices *i* and *j* denote the sample indices of the signals, and τ represents the time shift as a number of samples.

3. Results

The main results are presented as a series of correlograms in Figs. 4–5, characterized by a clear manifestation of reflections from major reflective boundaries and a close approximation to the "true" distribution of reflection coefficients for all of the analyzed sweep signal variants. Sweep signals with shorter pulses (10 ms, top row in Figs. 4–5) consistently demonstrate better temporal localization of reflections.

Correlograms calculated with the sweep signals with longer pulses (50 ms, bottom row in Figs. 4–5) exhibit higher sensitivity to weaker reflections associated with deeper horizons, enabling their identification in the resulting images. This highlights the potential trade-off between temporal resolution and sensitivity to weaker (deeper) reflections when selecting sweep signal parameters.

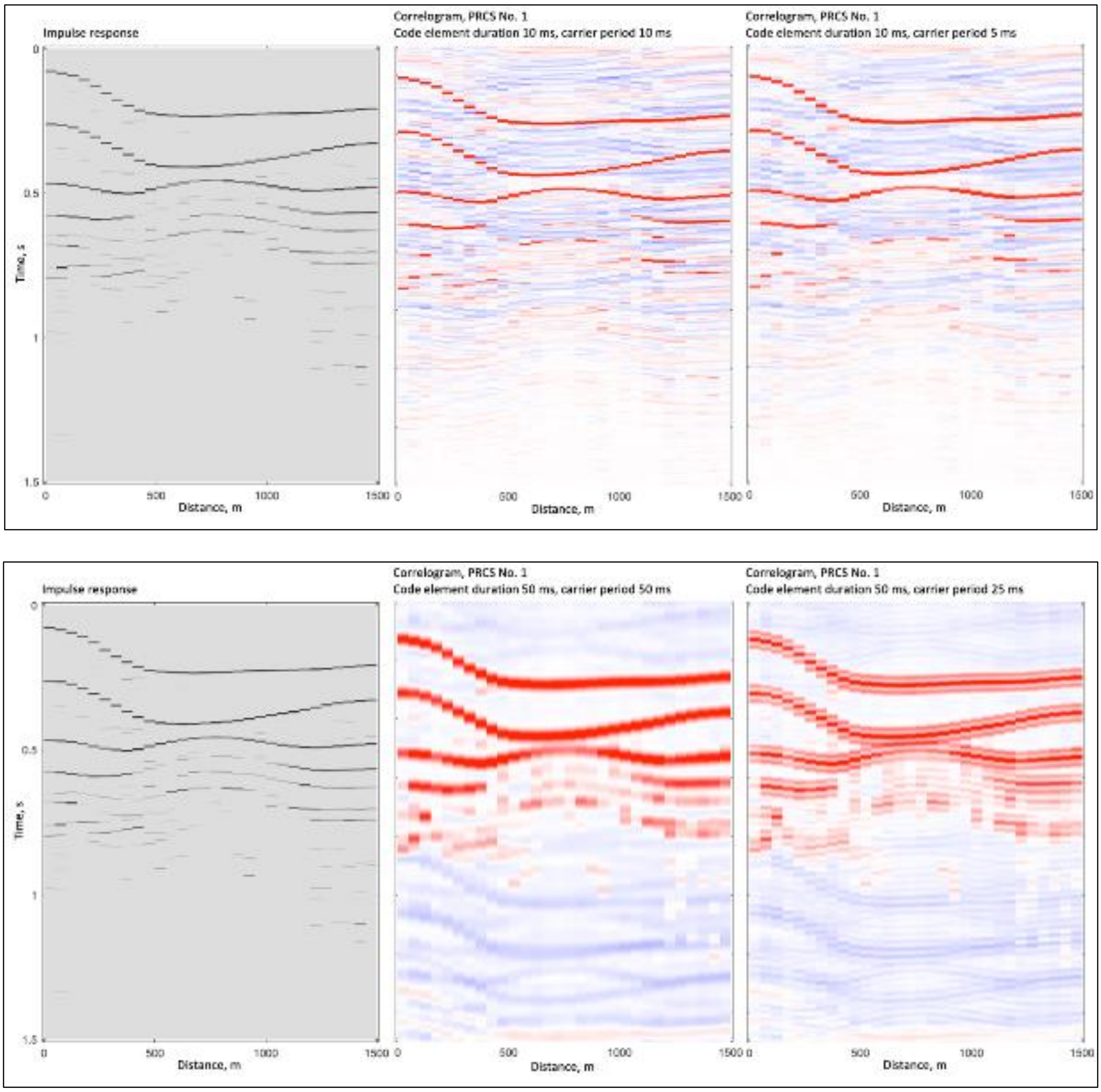

Figure 4 From left to right: the impulse response (reflection coefficients) and correlograms derived using the sweep signal based on PRCS No. 1 with different carrier periods. The top row corresponds to the PRCS element duration of 10 ms (total PRCS duration of approximately 0.7 s, with carrier periods of 10 ms and 5 ms). The bottom row corresponds to the 50-ms PRCS element (total PRCS duration of approximately 3 s, with carrier periods of 50 ms and 25 ms).

Fig. 6 demonstrates the detail of the recovered reflection images for the analyzed velocity model assuming single pulse at 400 Hz, single pulse at 30 Hz, and sweep signals with 10-ms PRCS elements. The resulting image obtained in the latter mode shows the best level of resolution for the upper three reflective boundaries. Meanwhile, weaker reflections corresponding to the 5th–7th reflective horizons are more distinctly visible on the correlograms for sweep signals with 50-ms elements (bottom row in Figs. 4 and 5).

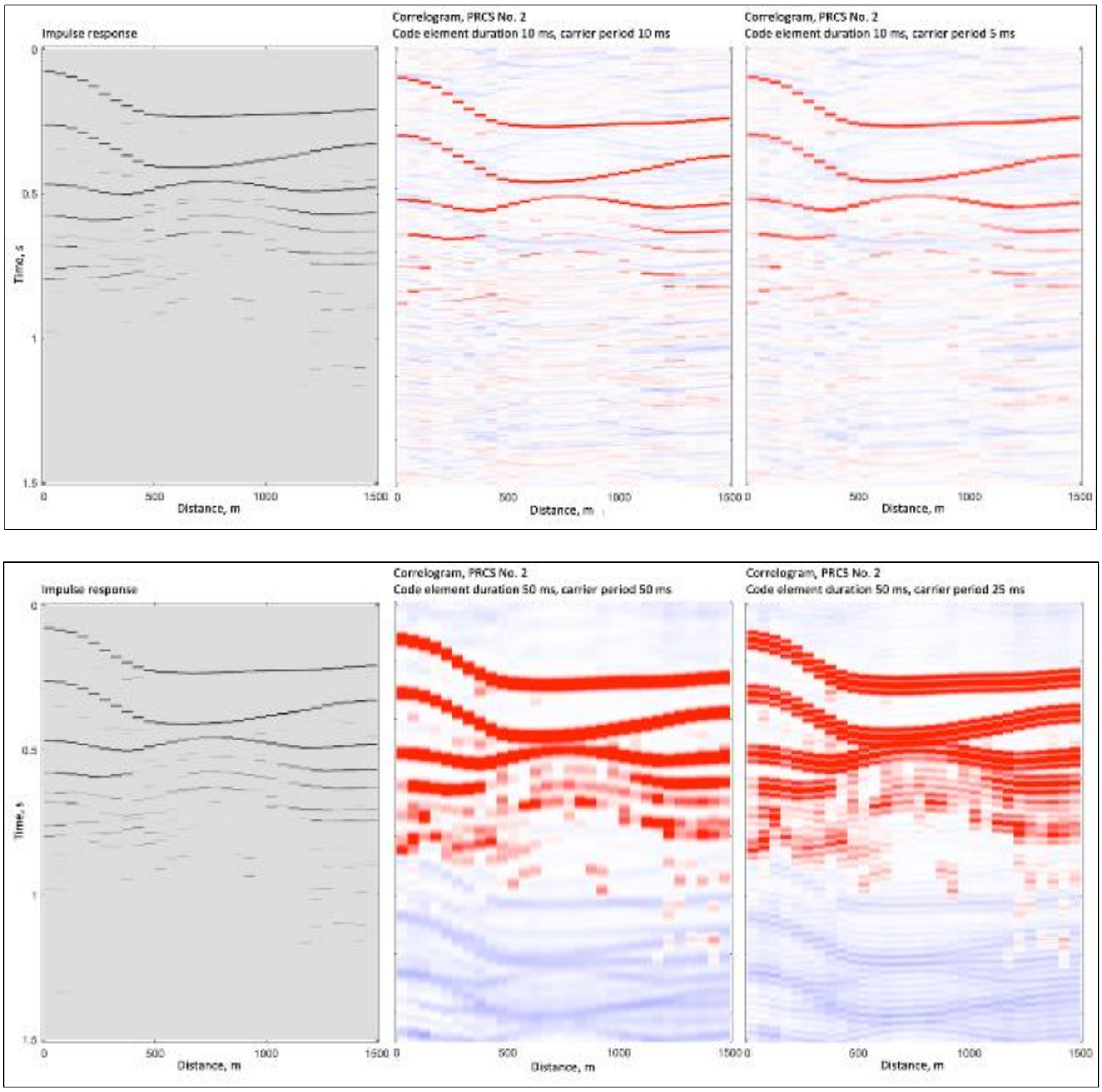

Figure 5 From left to right: the impulse response (reflection coefficients) and correlograms derived using the sweep signal based on PRCS No. 2 with different carrier periods. The top row corresponds to the PRCS element duration of 10 ms (total PRCS duration of approximately 1.5 s, with carrier periods of 10 ms and 5 ms). The bottom row corresponds to the 50-ms PRCS element (total PRCS duration of approximately 6.5 s, with carrier periods of 50 ms and 25 ms).

Thus, the results of the correlation processing of vibration seismic datasets simulated using pseudorandom sweep signals generally indicate the effectiveness of such signals in the seismic imaging applications. However, the accuracy of the reconstructed images varies significantly across the examined sweep signal variants, primarily depending on the duration of the PRCS element. An optimal outcome could likely be achieved by combining PRCS-based sweep signals with different parameters and subsequently gathering the resulting data available after correlation processing.

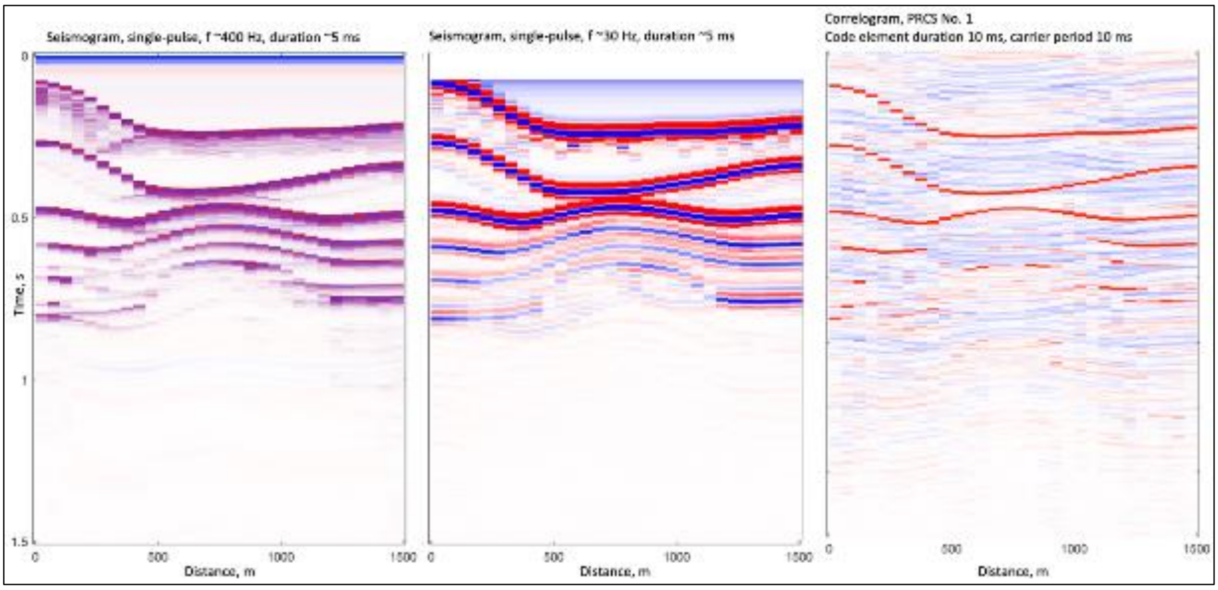

Figure 6 Comparison of seismic images simulated assuming single-pulse and sweep vibration modes for a zero-offset acquisition geometry. From left to right: a seismogram for a single wavelet-like pulse with a duration of approximately 5 ms (central frequency 400 Hz); a seismogram for a pulse of the same shape with a duration of approximately 50 ms (central frequency 30 Hz); a correlogram for a sweep signal based on PRCS No. 1, with a code element duration of 10 ms, a total duration of approximately 0.7 s, and a carrier period of 10 ms.

4. Conclusion

Using numerical full-wave modeling in a 2D velocity model of a multilayered anticline structure, a comparative analysis of synthetic vibroseismic datasets was conducted. The traces were simulated for a set of PRCS-based sweep signals differing in the number of elements and element duration as well as in carrier frequency. The results, presented as a series of correlograms, demonstrate the high resolution and clear delineation of reflections when using PRCS-based sweep signals.

Unlike physically unfeasible PRCS signals with rectangular impulses, which the we had examined in previous studies, the sweep signals presented in this work can be implemented in vibrational seismic systems. They exhibit sufficient efficiency in terms of resolution and signal-to-noise ratio.

The application of PRCS-based sweep signals expands the frequency range of seismic acquisition into higher frequencies, suppresses the influence of irregular noise waves, and thereby enhances resolution and investigation depth. Thus, both the theoretical analysis of PRCS application possibilities and the development of algorithmic, software, and hardware foundations for implementing this technology represent highly relevant directions for the advancement of geophysics.

The authors believe that despite potential challenges in implementing PRCS modes in vibrational seismic sources, this approach has considerable promise due to expected advantages that could drive the further development and improvement of vibrational seismic exploration technologies. It appears that with the optimal selection of PRCS parameters and spatial configuration of the acquisition system, significant advantages over systems using pulsed sources or frequency-modulated sweep signals can be achieved.

The findings of this study highlight the importance of developing seismic recording systems with an expanded frequency range. It is worth noting that this expansion should not only target higher frequencies but also lower frequencies, which are characteristic of PRCS (Fig. 3). This points to the need for advancements in seismic receivers and recording systems. Particularly promising are the use of molecular-electronic and fiber-optic sensors.

Compliance with ethical standards

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Disclosure of conflict of interest

The all authors declare no conflict of interest.

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