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Locating harmonic microseismic sources using phases of signals and spectral transformations

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Abstract. The paper presents the algorithm of locating harmonic microseismic signals using phases of the signals and spectral transformations. Different spectral transformations are considered and their properties required for the set problem solving are identified. The determination of the harmonic signals' location is exemplified using synthetic data.

1. Introduction

Usually geodynamic processes in a geological medium are the sources of seismic emission bearing information on the processes. One of the methods to study the seismicity is microseismic monitoring [1]. The important task of microseismic monitoring is locating seismic sources.

The way to locate the seismic sources depends on the signal/noise ratio. When the signal/noise is sufficiently high, it is possible to pick arrival times of waves of separate events in seismograms. In this case, the seismic sources can be located using the kinematic methods [2–4]. Such methods are applicable in downhole monitoring, i.e. when receivers are located in observation borehole [5, 6].

When the receivers are located on the surface (surface monitoring), the signal/noise ratio is usually low, and it is impossible to pick wave arrival times. For this reason, hypocenters of seismic events are located using semblance methods based upon stacking waves [7, 8]. Such methods include emission tomography [9]. This technique is based on determination of semblance measure for each point of space. To calculate semblance measure, signals from all receivers are summed with time delays that conform with travel times of wave from the chosen point of space. The semblance function can be calculated both in time and frequency domains [10, 11].

The studies [12–14] suggest locating the seismic sources using the time-reverse modeling. The method of time-reverse modeling works at low signal/noise ratios, which makes it applicable in surface monitoring. The method consists in propagating of wave field recorded by all receivers backward to space in the known velocity model of the medium. Seismic fields of the receivers interfere in space, and the energy focuses in the coordinates of the seismic source. A similar method is suggested in [12] where image resolution is improved by semblance-weighted deconvolution.

In [15] the problem of determination of microseismic event parameters is considered using the methods of statistical theory of random process parameters. This approach provides the opportunity to locate the seismic sources in case of high level of noise [16].

Another method of locating signals is called beamforming [17]: it is widely used in sonars, radars seismicity (seismic signal processing), radio astronomy and other areas. Beamforming acts as a spatial



filter which amplifies events from the wanted direction and suppresses events from the other directions [18]. There are two basic implementations of beamforming. The first implementation is based on calculation of phase shifts on receivers, compensation of seismic traces and their summation. It is similar to the above-mentioned calculation of semblance function. The other implementation is computation of cross-correlation matrix constructed using the receiver data [19]. This procedure also requires information on phases of receivers from the test point of space, which makes the algorithm commensurable with the seismic emission tomography by computational complexity. In the present-day seismics the cross-correlation beamforming is often used to study surface waves [20, 21].

This paper deals with locating harmonic sources [22]. Such sources can be observed, for instance in microseismic monitoring of rock ruptures filled with fluid [23, 24]. The algorithm proposed for the set problem solution is based on the phase information of signal and on using spectral transformations. The proposed approach differs from the above listed techniques and is convenient for locating microseismic sources by monitoring systems composed of groups of receivers arranged in lines.

2. Method of locating harmonic sources

Let us discuss implementation of the proposed approach. There are harmonic sources in a medium as well as a group of receivers arranged in line at equal distances. It is required to locate a source using this system.

The algorithm starts with a time–frequency representation of signal on each receiver. To solve this problem we will use spectral transform [25]. The classical approach is application of the Short-Time Fourier Transform (*STFT*):

$$S_n(\tau, f) = \int_{-\infty}^{+\infty} s_n(t) w(t - \tau) e^{-i2\pi ft} dt, \quad (1)$$

where $s_n(t)$ —signal on a j -th receiver; f —signal frequency; $w(t)$ —window function with a support in finite interval named the window width. A deficiency of the approach is finding the window width ensuring the best time–frequency resolution. This problem is suggested to be solved using other spectral transformations such as Stockwell transform (*ST*) or synchrosqueezing transform (*SST*). Let us discuss Stockwell transform [26] which is a special case of continuous wavelet transform (*CWT*):

$$S_n(t, f) = \int_{-\infty}^{+\infty} s_n(t) \frac{|f|}{\sqrt{2\pi}} e^{-\frac{(\tau-t)^2 f^2}{2}} e^{-i2\pi ft} dt. \quad (2)$$

The key advantage of (2) is automatic selection of window width depending on signal frequency. As frequency increases, the window width decreases, and, vice versa, with lower frequency, the window is wider, which finally leads to the high time–frequency resolution. *ST* is suitable for the analysis of both pulsed and long in time signals. On the other hand, in case of harmonic signals, the best time–frequency resolution can be ensured by *SST* [27]:

$$s(t) = \sum_{j=1}^J A_j(t) \cos(\theta_j(t)), \quad (3)$$

$s(t)$ is a signal; $A_j(t)$ is the signal amplitude; $k_j = \frac{1}{2\pi} \frac{d}{dt} \theta_j(t)$ is frequency of a j -th component of expansion; J is a number of the expansion components. Thus, implementation of *SST* consists in finding A_j and θ_j for expansion of (3) at each moment of time. When using *SST* as with *ST*, there is no need to select an optimal size for the window as this is done automatically. This property makes *ST* and *SST* preferable over the classical *STFT*. It is worthy of mentioning that all described transforms preserve signal phases, which is important for implementation of the proposed approach.

The next step is finding frequency of the source, plotting vector of phases on this frequency and applying additional spectral transformation of the phase vector to find the wave arrival direction. Let us analyze this step in more detail. Let a harmonic source emits at frequency f_0 at a time t_0 . Then,

having time–frequency representation of signal $S_m(t, f)$ on each receiver m , we can plot vector of phases:

$$\mathbf{g} = (S_1(t_0, f_0)/A_1 \quad S_2(t_0, f_0)/A_2 \quad \dots \quad S_N(t_0, f_0)/A_N), \quad (4)$$

where N is a number of receivers; $A_n = |S_n(t, f)|$, i.e. each value in the vector is normalized and we, for this reason, take into account only phase characteristics of the signal. Then, the vector \mathbf{g} is subjected to additional spectral transformation:

$$G(n, k) = F(\mathbf{g}(n)) \quad n=1 \dots N, \quad (5)$$

where F is some discrete spectral transform (*SFFT*, *ST* or *SST*); $G(n, k)$ is a space–frequency spectrogram; m is a number of component; k is a spatial frequency (wave number). In the resultant $G(n, k)$, by the spectrum peaks, the spatial frequency k of the incident wave is found. After that, the apparent velocity ($V_{app} = f / k$) and arrival direction ($\cos(\alpha) = V_{real} / V_{app}$) of wave are determined, where V_{real} is a wave velocity in the medium. In a homogeneous medium direction of arrival leads to the source. When a set of beams emergent from receivers at the found angles is plotted, the source location is found as their intersection. In a heterogeneous medium, the beams are constructed using information on the velocity structure of the medium in order to take into account refraction effects. The described algorithm can be presented as follows:

1. Time–frequency representation of signals on all receivers;
2. Finding frequency f_0 of the source;
3. Selection of time t_0 and plotting vector of phases \mathbf{g}
4. Space–frequency representation on phase information on receivers;
5. Finding spectrum peaks in the spatial spectrogram in order to determine the spatial frequency k and calculation of incidence angle of plane-wave signal.

This section describes the algorithm of locating a source by one-dimensional linear observation system. However, usually the surface microseismic monitoring uses three-dimensional systems. In this case the algorithm is employed if it is possible to distinguish groups of receivers arranged in line within the three-dimensional monitoring system.

3. Locating a source: Illustration

Let us consider a two-dimensional uniform linearly elastic medium (Figure 1a). Let a harmonic point source be in the medium at a point (1100, 500). Receivers are set at a spacing of 2 m along the straight line $y=0$. P-wave velocity in the medium is 2500 m/s.

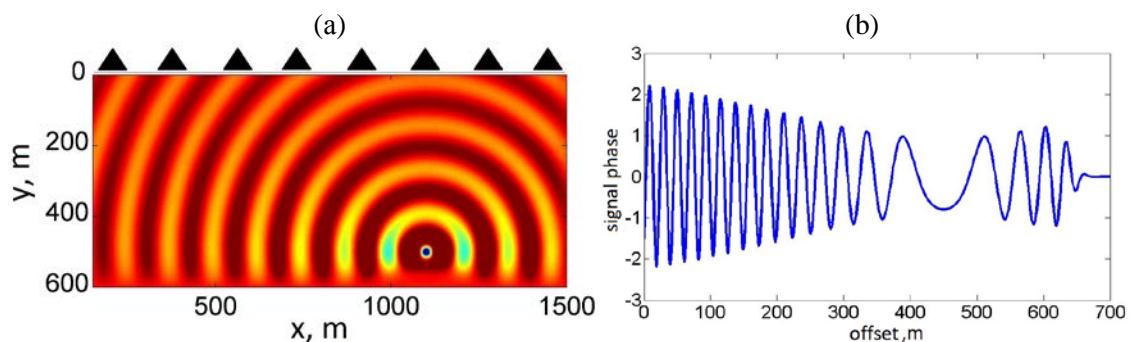


Figure 1. (a) Harmonic source and monitoring system; (b) phases of signal from the harmonic source at a certain time moment.

The synthetic seismograms are calculated using approaches proposed in [28, 29]. Then, we take *ST* of signals on each receiver and plot the vector of phases (4). By taking an argument (phase) of each element of the resultant vector we obtain a spatial signal. Figure 1b depicts such signal in the

considered example at the source frequency of 20 Hz. Later on, the vector of phases is subjected to additional spectral transformation (spectral transform of spatial signal). Figure 2 shows illustrations of various transforms of spatial signal for a source of 100 Hz. It is shown that the best frequency–space resolution is achieved using *SST* (Figure 2c). Under the same condition *ST* fails to detect low frequencies of the spatial signal. For this reason *ST* brings considerable errors of the source location. Numerical experiments show that with a suitable selected window width, the method *STFT* (Figure 2a) provides the accuracy of spatial signal frequencies' calculations as *SST*. At the same time *SST* is preferable as it enables more accurate distinguishing of signals from sources located at different spatial points owing to high space–frequency resolution.

Analysis of the obtained spectrograms reveals that, when the incidence angle of wave changes sign, spectrum peaks move from one part of the spectrum to another (from top to bottom and vice versa). This property has been used to recover the wave incidence angles. Relocation of the spectrum peaks in the spectrogram can be explained by the switch of the signal to the opposite phase. Thus, analysis of spatial spectrograms can be useful in solution of problems connected with locating of sources with different focus mechanisms [30].

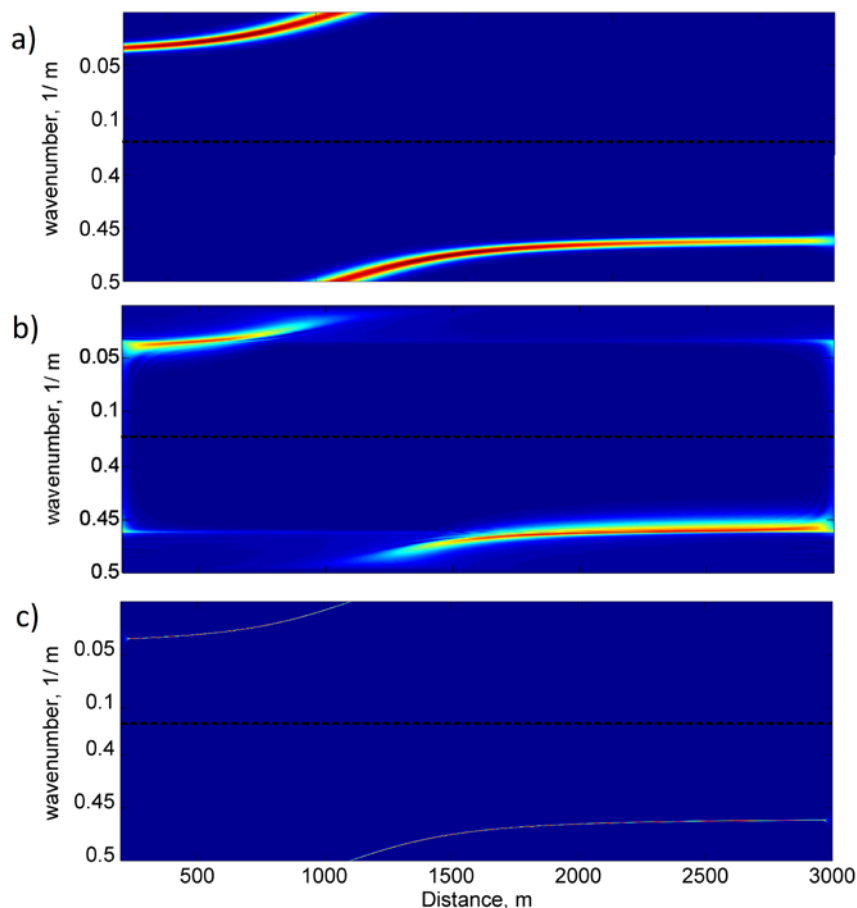


Figure 2. Spectrograms of spatial signal: (a) *STFT*; (b) *ST*; (c) *SST*.

The spatial frequency (wave number) of incident wave is found by detection of spectrum peaks in spectrogram (Figure 2). Thus, we have a wave number for each receiver. Then, the direction of wave arrival is calculated. In the homogeneous medium under consideration we locate a source by plotting a set of direct beams emitted from receivers at the found angles. The intersection point of the beams is the location of the source. Figure 3 shows examples of locating of harmonic sources with the frequencies of 10 and 50 Hz. Evidently, the proposed approach allows locating harmonic sources.

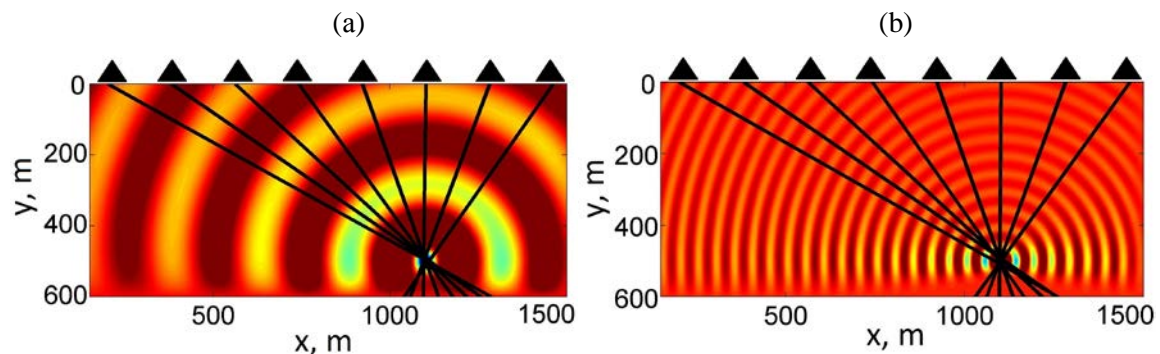


Figure 3. Locating a harmonic source using the proposed approach: (a) source frequency is 10 Hz; (b) source frequency is 50 Hz.

4. Conclusions

The paper has proposed the way to locate harmonic microseismic sources using spectral transformations and phase information of the signal. It has been shown that for the time–frequency representation of a signal, transforms ST and SST are preferable as against the classical $STFT$. The basic advantages consist in elimination of selecting the width of window and obtaining the best time–frequency resolution. Furthermore, it has been found that ST is inapplicable to space–frequency representation of signal. Using synthetic data, the author have demonstrated workability of the proposed algorithm. Based on the obtained results, it is possible to draw a conclusion that the use of various spectral transforms can improve efficiency of microseismic monitoring algorithms and assist in solving arising problems.

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