Filtering of microseismic data based on information about signal phases

AV Azarov* and AS Serdyukov**

1Chinakal Institute of Mining, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
2Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia

E-mail: *antonazv@mail.ru; **aleksanderserdyukov@ya.ru

Abstract. Seismic data filtering algorithm has been developed. The proposed algorithm allows amplifying signals from the sources located inside a selected area of space. The paper presents a theory describing the principle of this algorithm. Testing on synthetic data showed that the proposed filtering method is capable to suppress signals from the sources located outside the selected area of space. On semi-synthetic data it was shown that the proposed filtering method allowed to suppress real noise and significantly increases the signal-to-noise ratio for the events located inside a selected area of space.

1. Introduction

Passive microseismic monitoring (MSM) is one of the methods for remote monitoring of mineral resource development [1]. The data collected during the process of MSM generally have a low signal-to-noise ratio.

Which is primarily caused by: 1) low energy of observed microseismic events; 2) mining equipment generating high-energy interference waves; 3) seismic receivers located at a distance from the monitoring area (which is of particular importance for ground-based monitoring systems applications). Given that a low signal-to-noise ratio can lead to incorrect operation of the MSM algorithms, noise suppression is of great importance in seismic processing and interpretation.

This paper presents a data filtering method that is capable to enhance signals from remote sources, i.e. located outside the certain observation area (i.e. 'region of interest (ROI)'). This method can be viewed as an extension to the method described in [2, 3] suggesting transforming the data to the $\tau-p$ domain based on characteristics that microseismic and noise show in this domain allowing to conduct signal-noise separation. Prior to transforming the data to the $\tau-p$ domain [2, 3] time delays proportional to the distance from the assumed location of the controlled seismic source to underground receiving stations (URS) are applied to each trace, so that microseismic events are well-focused about zero slowness (the inverse of the apparent velocity). At this, only values higher than a pre-set threshold are saved on the plane.

After applying inverse transform and introducing time-reverse delays, the seismogram should still contain signals from seismic sources located at the selected control point in space. The disadvantage of this method is its high computational complexity, since introducing time-delays and the inverse $\tau-p$ transformation must be conducted for each potential point in space. To solve this problem, we suggest pre-selecting controlled sources which will be located in the region of interest. The wavefield from
any potential source located inside ROI can be expressed as superposition of wavefields of the controlled source. Due to the transition to the frequency domain, the problem dimensionality is reduced, which allows using the orthogonal projection methods.

2. Projection filter
Let’s consider a seismic field that is generated by a set of sources:

\[ u_k(t) = \sum_j U_{kj}(t) + \mu_k(t), \]

where \( k = 1, \ldots, N \) is a receiver number; \( j \) is a source number; \( U_{kj}(t) \) is wavefield on the receiver \( k \) generating the source \( j \); \( \mu_k(t) \) is noise. Let’s perform the Fourier transform (FT) on the signal (1):

\[ \hat{u}_k(\omega) = \sum_j \hat{U}_{kj}(\omega) + \hat{\mu}_k(\omega). \]

The function \( \hat{U}_{kj}(\omega) \) in frequency domain can be written as:

\[ \hat{U}_{kj}(\omega) = A_{kj}(\omega) \exp(-i\omega\tau_{kj}), \]

where \( \tau_{kj} \) is traveltime from the source \( j \) to the receiver \( k \) (in this case, only primary arrivals of P-waves are considered); \( A_{kj} \) is the amplitude of signal.

Let’s consider a finite set of \( M \) controlled sources located inside AOI of the domain, and introduce a graph signal written as complex-valued vector in the \( N \)-dimensional frequency domain \( D \):

\[ v_j = \begin{pmatrix} A_{1j}(\omega) \exp(-i\omega\tau_{1j}) \\ A_{2j}(\omega) \exp(-i\omega\tau_{2j}) \\ \vdots \\ A_{kj}(\omega) \exp(-i\omega\tau_{kj}) \\ \vdots \\ A_{Mj}(\omega) \exp(-i\omega\tau_{Mj}) \end{pmatrix}, \]

where \( j \) is the number of controlled source; \( k \) is the number of receiver; \( A_{kj}(\omega) \) is the amplitude from the \( j \)-th source on the receiver \( k \).

The set of vectors \( S = [v_j] j = 1,...,M \) forms a linear subspace of solutions:

\[ V = \left\{ \sum_{n=1}^{M} \lambda_n v_n \mid v_n \in S, \lambda_n \in \mathbb{R} \right\}. \]

The data space is the sum of subspaces \( V \) and the orthogonal complement of \( V^\perp \):

\[ D = V \oplus V^\perp. \]

The principle of the proposed method is to evaluate the projection of the \( \hat{u}(\omega) = (\hat{u}_1(\omega), \ldots, \hat{u}_N(\omega))^T \) vector data onto the subspace \( V \). The orthogonal projection operator is set by the following matrix:

\[ P = A(A^T A)^{-1} A^T, \]
The proposed filtering procedure is implemented in three steps. In the first step, the Fourier transform (FT) is performed for each trace (the multi-dimensional graph Fourier transform):

$$u_t(t) \rightarrow \hat{u}_t(\omega).$$  \hspace{1cm} (8)

In the next step, a projector is used for each frequency to specify the frequency vector for frequency-domain data $$\hat{u}(\omega) = (\hat{u}_1(\omega), \ldots, \hat{u}_k(\omega), \ldots, \hat{u}_n(\omega))^T$$:

$$\hat{u}^F = P\hat{u}.$$  \hspace{1cm} (9)

As a final step, we perform an inverse Fourier transform over $$\hat{u}_k(\omega)$$, to obtain filtered traces, i.e. final filter operator in the time domain.

In the case of a small distance between the sources, the corresponding vectors (3) become almost linearly dependent, causing thereby a high conditionality number of matrix $$A$$ and, consequently, numerical instability of the $$A^TA$$ inversion procedure in formula (7). To solve this problem, we propose calculation of the pseudo inverse of a matrix $$A^TA$$.

3. Examples of synthetic data filtering

Consider a two-dimensional region that contains four explosive seismic sources (Figure 1). The medium is homogeneous with a P-wave velocity of 3000 m/s. Sources 1 and 2 are inside the AOI of space; sources 3 and 4 are located outside it. The Ricker wavelet with central frequency of 50 Hz is used as a source signature. A wavelet was emitted simultaneously from all four sources. The linear monitoring system is located on a straight line $$y = 0$$. The distance between the receivers is 20 m. The seismograms of synthetic microseismic events were calculated on the basis of elasticity equations solution using the approach discussed in [4, 5].

Figure 1. Model used for obtaining synthetic seismograms.

Synthetic seismograms (vertical displacement component) are shown in Figure 2a. Numbers near each waveform correspond to the numbering of sources in Figure 1. For construction of the projection operator (7) nine sources are selected within ROI (Figure 1). In this example, we assume that all sources are expansion center type and only the phase of signals are used, i.e. in formula (4), amplitudes $$A$$ were assumed to be 1. Thus, the solution space $$V$$ is stretched over a set of vectors $$S = \{v^j \mid j = 1, \ldots, 9\}$$, where $$v^j$$ is the phase vector generated by the $$j$$-th source. The filtering result is shown in Figure 2b.
Figure 2. Synthetic data filtering: (a) synthetic seismogram; (b) filtering result.

One can see that the data filtering entailed suppression of P-waves from sources located outside the ROI. Note that the amplitude of surface wave from the fourth source was subjected to lesser suppression (for a source-receiver offset of 900–1000 m), than at smaller offset values. The reason for this is that at higher offset values, the angle of the arrival (distribution of phases on the receivers) tends to be close (best-fit) to the arrival angles from surface waves generated by the controlled sources.

4. Filtering technique applications to semi-synthetic data

The standard approach for evaluation of filtering methods involves adding the statistical model-derived noise to the signal. In fact, this approach is not entirely appropriate, since it allows to test the filtering method’s capability to suppress real noise, which is often non-stationary and can correlate on different receivers. Let's consider experimental field data resulting from the microseismic monitoring of hydraulic fracturing operations at an oil field. Following [6], we present the seismic field record on each receiver as a real noise. The target time interval coincides with the fracking fluid injection operation. We assume that this data do not contain a desired signal, i.e. the one coming from the ROI.

Then, the recorded noise multiplied by a different coefficient is added to the synthetic signal. Figure 3a shows the system that was used for MSM of hydraulic fracturing operations. The surface monitoring system consisted of 42 irregularly spaced receivers (Figure 3a). Next, let's consider a way of obtaining a synthetic signal with some noise added to it. The records from perforation shots performed hydraulic fracturing operation were analyzed after bandpass filtering (Figure 3b). We enter a Cartesian coordinate system with the initial point that coincides with a wellhead.

Figure 3. (a) MSM system, location of the wellhead, orientation of perforation shot and offset source (top view); (b) perforation shot recorded after application of bandpass filtration.
In this coordinate system, the perforation-time was located at the point \( r = (x, y, z) = (-30, 20, 1260) \). Now consider a microseismic source that is from the epicenter of seismic event (perforation shot) by 80 m on the \( x \)-axis and 50 m on the \( y \)-axis, i.e. with coordinates \((-110, 70, 1260)\). For obtaining a synthetic signal from a given point, we introduce the time delays pertinent to the traces of perforation shots. The delays are defined as differences in P-wave travel times between the source located at the perforation point and the offset source. For calculation of the traveltime, we used a homogeneous medium with a velocity of 2400 m/s. By the analogy with the method discussed in [6], the resulting synthetic signal was added to the record of noise multiplied by different coefficients. The provided illustrations show the noise signal multiplication by 2 (Figure 4a) and by 5 (Figure 4c).

A cube with 200 m sides surrounding the perforation point served as the target region, in which the selected 16 target points are spaced at a distance of 50 m from each other within a 1260 m horizontal plane. Figures 4a and 4b show the results of semi-synthetic data filtering with added noise multiplied by multipliers 2 and 5, respectively. These illustrate the amplification of useful signal by the proposed technique.

**Figure 4.** Semisynthetic data and processing results: (a), (c) useful signal with different levels of added noise after bandpass filtering (a—noise multiplied by coefficient 2; c—by 5); (b), (d) filtered seismograms (by the proposed method), respectively.

5. Conclusions

The proposed method for microseismic data filtration, as surface-wave dispersion measurements obtained from active and passive data, is based on distributions of the phases of signals on the receivers. The application of synthetic data allows suppression of surface waves from sources located outside the region of interest, while semi-synthetic data can suppress real seismic noise, thereby significantly enhancing the signal-to-noise ratio.

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