Chapter 4. AUTOMATED LOCATION OF WEAK EVENT EPICENTERS BY THE MEDIUM SCANNING (EMISSION TOMOGRAPHY) METHOD

1. INTRODUCTION

As a rule, the inverse problem for determination of azimuths and epicenter distances of events based on seismic network data is resolved by analysis of arrival times of seismic phases at different sensors of the network. The conventional methods of 3-D location of seismic events require the preliminary procedure of the arrival times picking. The procedure of the determination of the arrival times is very delicate and may lead to multiple errors when one tries to perform it in the automatic mode. The automatic 3-D location of seismic events sources without preliminary determination of the arrival times of the seismic phases may be realized on the basis of a special autocorrelation procedure of the multichannel data processing. This approach is used in geophysics for mapping of underground structures radiating very weak coherent seismic signals being the components of a seismic noise or codas of earthquakes [Nikolaev et al.,1996, Thcebotareva et al.,1997]. This method of data processing is named the semblance analysis or the emission tomography method. The latter name reflects the sense of this method: as a result of the processing, the three-dimensional image of the medium is received where the brightness distribution shows a distribution of the active volumes within the structure. In other words we create a picture of the medium in terms of it's ability to generate the seismic energy.

2. APPLICATION OF THE EMISSION TOMOGRAPHY METHOD TO EVENT SOURCE LOCATION

The conventional version of the emission tomography method was successfully implemented for location of local earthquake sources with the help of small aperture arrays with an average inter-station distance 400 m and a distance between the array and the events about 10 km.[Thcebotareva, 1997c]. Nevertheless it is impossible to use this technique directly for location of events using the seismic networks due to breakdown of the spatial coherency of seismogram waveforms recorded by the stations with large inter-station distances. The effect of the waveforms decorrelation is especially significant in the regions with a complicated heterogeneous geological structure: for fractured and fault zones. Nevertheless it is known that correlation of the envelopes of the waveforms and some functionals (masks) of the waveforms are conserved even for large station separation. Hrnce, the emission tomography method can be used for event location provided that instead of the waveforms themselves their envelopes or some functionals are used as the input data. As the result of this approach a set of 2-D maps calculated for different depths is received where the event location is estimated as a maximum of the map values.

Briefly the idea of the location data processing algorithm consists in the following. Suppose that a small volume in the earth radiates a seismic signal. In the homogeneous medium the seismic wave field has the very simple structure: it is composed from spherical seismic waves. In a real medium the seismic front is distorted due to the lateral velocity variations, but a spatial signal coherence remains rather strong for sensor separation up to a distance of few kilometers. This fact can be used for the seismic source location. To extract the spatial coherent component of the seismic field and reconstruct the image of a weak seismic source we use a measure of the multichannel data coherency called Semblance [Taner at al., 1971, Nikolaev at al., 1986]. We use the formula for Semblance measure which differs from the traditional one [Taner at al, 1971] in a constant coefficient:

$$S = \frac{\sum_{j=1}^{T}\left[\sum_{i=1}^{K} f_{ij}(\tau_i)\right]^2}{\sum_{j=1}^{T}\sum_{i=1}^{K} f_{ij}^2(\tau_i)} \qquad (1)$$

where K is the number of network sensors; T is the time window length in samples, f_{ij} is the instantaneous amplitude of the j-th sample at the i-th recording site; τ_i is the time shift in the i-th channel corresponding to the propagation path of a hypothetical signal radiated from a focused grid point; the value $T=2B\delta t$, where B is a frequency band, δt is a sampling interval. For the homogeneous velocity model the sensor delays τ_i are calculated according to the formula:

$$\tau_i = r_i / V_0 \quad ,$$

where r_i is the distance between the i-th sensor and the point of scanning , V_0 is the average wave velocity. In the case of the layered 3-D heterogeneous velocity model we have

$$\tau_i = \sum_m \tau_i^m \, ,$$

where τ_i^m is the travel time along the seismic ray from the scanning point to the i-th sensor within the m-th layer.

By scanning the medium structure over a rectangular grid we derive maps of the spatial distribution of the Semblance values which characterize the emission properties of the medium. If there is no coherent components in the seismic noise and only an independent identically distributed Gaussian noise is present in every sensor, the Semblance has the asymptotically normal distribution, whose mean and variance are the functions of the number of the network sensors and a time window used for analysis [Nikolaev at al., 1991]:

$$\begin{cases} \langle S \rangle = 1 \\ \sigma_S^2 = \dfrac{2}{T} \end{cases} \qquad (2)$$

When a coherent signal generated by a seismic source is mixed with the noise wave field,. the Semblance values sharply increase for the grid points which are close to the source location i.e. a bright spot appears in the reconstructed image. The Semblance depends on the signal/noise ratio and the number of the seismic sensors. Let us assume for simplicity that identical signals are present in every channel, E_s and E_n are the signal and noise powers of the channels outputs. It is possible to verify that

$$<S>=(KE_s+E_n)/(E_s+E_n)=1+(K-1)E_s/(E_s+E_n) \qquad (3).$$

Where $<S>$ is the Semblance mean value. For a weak seismic signal

$$< S > \approx 1 + K\lambda \qquad (4)$$

where $\lambda = E_s/E_n$ is the signal /noise ratio. Formulas (3) and (4) show the physical sense of the Semblance measure: its value is the estimation of the ratio of the energy of the signal radiating from the scanning point to the total energy of the seismogram; $0 \le (< S > - 1) \le (K - 1)$. It means that we receive large values of the Semblance for scanning points that coincide with signal sources and small values of the Semblance for neighboring points, that is the Semblance map is the map of distribution of the seismic source intensity in the medium. Note in addition, that the confidence band for the Semblance estimate in the case of the coherent source absence is defined by the value of variance (2):

$$\delta_{\lambda=0} = 2\sigma = 2\sqrt{2/T}\ .$$

3. THREE COMPONENT EMISSION TOMOGRPHY

The implementation of three-component receivers allows to significantly improve the method of the emission tomography. Numerical simulation and analysis of real data have shown that the use of three-component data with an adapted version of the emission tomography algorithm essentially enhances the quality of the medium images: it is possible in this case to utilize the most portion of the energy of the appropriate types of the wave phases and to filter out the waves with different polarizations. In the three-component version instead of the f_{ij} in eq.(1) the projection of three-component particle motions at the direction of the selected type wave oscillations is used. It is made as for compressional P-wave as for two components (SV and SH) of shear wave regarded in the far-field zone of the ray initiated by the given source. In the simplest case the transition to the coordinates connected with the seismic ray is described by the formula: $\vec{f}_{ij} = \vec{a}_{ij}\hat{A}$, where $\vec{f}_{ij} = \left(f_{ij}^{P}, f_{ij}^{SV}, f_{ij}^{SH}\right)$ is the instantaneous data vector with the components corresponding to the seismic ray, $\vec{a}_{ij}$ is the data vector with the components in the vertical, NS and EW-directions, matrix $\hat{A}$ is equal

$$\hat{A} = \begin{bmatrix} \cos\theta_i & \sin\theta_i \sin\phi_i & \sin\theta_i \cos\phi_i \\ \sin\theta_i & -\cos\theta_i \sin\phi_i & -\cos\theta_i \sin\phi_i \\ 0 & -\cos\phi_i & \sin\phi_i \end{bmatrix},$$

where θ_i is the angle of incidence i.e the angle between the seismic ray direction and the vertical one at the point of i-sensor location, ϕ_i is the ray azimuth i.e. the angle between the projection of the seismic ray to the horizontal plane and the EW-direction.

Very often the seismic observations are carried out at the free surface where wave reflection and conversion are exist and strongly depend on the angle of incidence. Therefore, the real polarization of the body wave can in some cases appreciably deviates from one corresponding to the ray direction. In this case further improvement of the 3-component tomography results can be achieved by application of special frequency independent formulas suggested by D.Kennet that reflect influence of the ground surface.

While processing the three-component data one receive three 'beams', every one corresponds to the direction of polarization of the different body wave components. Algorithms based on correlation processing of these 'beams' give additional improvement in the signal/noise ratio for the images of seismic sources.

The emission tomography method can be directly used provided the well spatial coherency of the seismic signals exists over the array area. When data recorded by a seismic network are used, it is necessary to make the preliminary data processing with the purpose to replace the poorly correlated high-frequency waveforms to the high correlated low-frequency mask signals. One of such masks is provided by the STA/LTA detector, which is widely used in automatic signal detection.