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:

$$\tau_i = {}^{r_i}\!/_{V_0} \ ,$$

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]:

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

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

$$< S > \approx 1 + K\lambda \tag{4}$$

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.

4. TESTING OF SOURCE LOCATION EMISSION TOMOGRAPHY ALGORITHM USING SEISMOGRAMS FROM ISRAEL SEISMIC NETWORK

The main steps of the emission tomography algorithm used in our experiment are the following:

1. *Preliminary processing of the waveforms*. It consists of application of the channel mask-filter (STA/LTA filter or AR-model-depended filter) to receive the low-frequency masked signals from the high-frequency waveforms.
2. *Application of the scanning procedure*. It consists of calculation of the set of 2-D maps for different depths. Decision about the event source location is made when values of the Semblance are large then the confidence level for the «pure noise» seismogram. The largest value of the Semblance provides the source coordinates estimation.
3. *Definition of the origin time*. This can be realized by the Semblance measure calculation in the moving time window using estimated coordinates of the detected event. The largest value of the Semblance gives the origin time estimation.

The above algorithms were realized as a set of programs installed in the seismological program package SNDA. Programs were tested by numerical simulation and by application to the real data. The seismograms from local earthquakes recorded by the Israel seismic network were used for location of the seismic events sources. Table 1. contains the information about the earthquakes and stations used in the testing experiment. It includes the items: 1) data, 2) time, 3) ML-magnitude, 4) source location coordinates Xc and Yc (in Km) calculated by the routine procedure (provided by the Israel Seismic Network catalogue of local events), 5) source location coordinates Xs and Ys (in Km) calculated by the emission tomography procedure, 6) difference Dr (in Km) between the points of above locations, 7) number of the stations used for the tomography location. For calculation of the horizontal maps of the emission intensity we used the local orthogonal coordinate system with the center point with Latitude= 32.000 N, and Longitude= 35.500 E; axis Ox had the WE direction, axis Oy had the SN direction. The horizontal emission map for every event was calculated in 2601 points (51×51) over the rectangular grid, with inter-grid-points interval 5 km. During data processing we used the homogeneous velocity model with the velocity Vp=6.2 km/sec for P waves and velocity Vs=3.4 km/sec for S waves. These velocity values were well defined by the special study of the Israel regional velocity model on the basis of the Israel Seismic Network catalogue of local events.

Some illustrations of the testing results are given in Fig.1 and Fig.2. Fig.1,a shows an example of Israel network seismograms of event 1 from Table 1, Fig.1,b shows time series after application of the STA/LTA filter to these seismograms. Fig.2 demonstrates the results of location of the earthquake source with preliminary STA/LTA filtering: Fig.2,a shows the semblance map for the case where only P waves from the Fig.1. seismograms were used, Fig.2,b- where only S waves were used, Fig.2,c – where both P and S waves were used. The best contrast of the image was obtained at the depth 25 km, the maximum values of the brightness at the obtained horizontal maps are in the excellent agreement with the catalog source location, the error in location is approximately equal to the inter-grid-points distance.

As one can see from Table 1 the results of the epicenter location of all the earthquakes used in the testing experiment are in a good agreement with the catalog values. Only for 3 from 27 events the divergences of the locations by the conventional and emission tomography methods are as large as 11-15 km. For the other earthquakes the mean divergence in the locations is 5,2 km, that is this divergence is equal to the inter-grid distance.

Table 1. Information about earthquakes used in the testing experiment.

N	Data: year/ month/ day	Time: hour(h), minuts(m)	Magnitude ML	Xc km	Yc km	Xs km	Ys km	Dr km	Number of sens.
1	1987/10/07	15h14m	1.9	-22.512	74.436	-27.0	79.0	6.40	11
2	1988/02/24	15h37m	1.5	-23.300	79.500	-23.0	79.0	0.58	9
3	1988/03/03	13h15m	1.1	-22.681	82.421	-23.0	87.0	4.59	7
4	1988/08/06	14h49m	2.1	-33.565	79.014	-33.0	79.0	0.57	17
5	1990/08/11	22h14m	1.8	-8.132	109.459	-13.0	109.0	4.89	14
6	1990/08/21	06h21m	1.8	-32.645	73.576	-37.0	73.0	4.39	15
7	1990/09/04	16h43m	1.5	-43.502	100.790	-48.0	100.0	4.57	12
8	1990/09/16	09h41m	1.6	-48.525	106.692	-63.0	107.0	14.48	10
9	1990/11/17	07h29m	1.2	-21.545	87.853	-21.0	88.0	0.56	7
10	1990/11/20	00h01m	1.5	-25.737	60.692	-26.0	61.0	0.41	6
11	1990/12/21	15h24m	1.5	6.646	94.597	12.0	94.0	5.39	11
12	1991/01/09	02h30m	1.1	-21.360	86.632	-21.0	86.0	0.73	9
13	1991/01/26	17h46m	2.6	-21.266	86.743	-26.0	92.0	7.07	9
14	1991/01/26	19h02m	1.9	-19.109	87.848	-24.0	88.0	4.89	11
15	1991/01/27	03h05m	1.5	-16.483	89.617	-26.0	89.0	9.54	9
16	1991/02/12	08h32m	1.4	-2.996	95.039	-3.0	95.0	0.04	13
17	1991/02/25	06h33m	2.0	-18.215	64.446	-28.0	59.0	11.20	28
18	1991/04/05	18h07m	1.4	-43.042	120.308	-43.0	125.0	4.69	15
19	1991/04/07	17h17m	1.3	7.864	93.710	8.0	89.0	4.71	14
20	1991/04/15	01h20m	2.4	8.800	94.044	4.0	94.0	4.80	19
21	1991/04/15	05h03m	1.5	6.929	91.603	12.0	91.0	5.11	12
22	1991/04/16	06h37m	1.9	8.145	93.600	13.0	93.0	4.89	18
23	1991/04/27	07h13m	1.3	7.489	94.487	7.0	94.0	0.69	10
24	1991/05/01	14h35m	1.2	7.489	93.932	7.0	94.0	0.49	9
25	1991/05/01	20h46m	2.2	7.303	92.601	7.0	92.0	0.67	18
26	1991/05/03	22h06m	1.0	7.772	92.047	8.0	92.0	0.23	11
27	1991/05/16	02h49m	1.7	-48.460	119.890	-63.0	125.0	15.41	15

Figure captions for section 4.4

Fig.1,a Example of the Israel network seismograms for event 1 from Table 1.

Fig.1,b Time series after application of the STA/LTA filter to the seismograms from Fig.1,a.

Fig.2,a Semblance map for the case where only the P waves from the Fig.1,a seismograms are used.

Fig.2,b Semblance map for the case where only the S waves from the Fig.1,a seismograms are used.

Fig.2,a Semblance map for the case where both: the P and S-waves from the Fig.1,a seismograms are used.

5. INVESTIGATION OF EMISSION TOMOGRAPHY SOURCE LOCATION ACCURACY USING LOCAL EXPLOSIONS SEISMOGRAMS OF ISRAEL SEISMIC NETWORK

5.1. Introduction

To proceed to test programs of events location based on the method of emission tomography we used signals from local explosions recorded by Israel seismic network. Table 2. contains information about explosions used: data, time, magnitude, source coordinates (X_c and Y_c), provided by conventional location procedure based on seismic phases onset times, source coordinates by emission tomography location procedure (X_s and Y_s), deviation in event locations by the both methods (D_r), number of used network stations. For calculation of horizontal maps of emission power we used the local orthogonal coordinate system with the center in the point with Latitude 32.000 N, Longitude 35.500 E, axis OX is in the WE direction, axis OY is in the SN direction. The horizontal emission map for every event was calculated in 2601 points (51X51) over a rectangular grid, with inter grid points interval 5 km. For data processing we used the uniform model of medium with velocity V_p=6.2 km/sec for P waves and V_s=3.4 km/sec for S waves.

The deviation of explosion locations by the conventional and emission tomography methods is shown in the column (DR) of Table 2 (we will consider this deviation as the error of the tomography location method regarding the results of the conventional method as absolutely relyable). For 10 explosions used the mean value of the error is 12.9 km. The resolving power of the tomography location procedure used is defined by the length of diagonal of the grid square which is equal to 7 km. Therefore, the mean error of explosion location by the tomography method is in 1.8 times greater than the procedure resolving power equal 7 km. The mean error for location of explosions is appeared to be larger then the mean error for tomography location of earthquakes (described in section 4.4). In that experiment the mean value of the error for 27 earthquakes used was 8.6 km and after removing from consideration of 3 earthquakes with the largest deviation, we receive the mean error equal 5.3 km.

In the case of explosions we know in advance the depth of event because the hypocenter of explosion is always near the earth surface. This useful information improves accuracy of location. Nevertheless the set of destructive factors influenced on the results in the experiment with location of the explosions. The explosion seismograms are very noisy and sometimes it was possible to use only 15-20% of stations recorded the explosion. As consequence, network configuration relative to the event epicenter was not good for the most explosion: the epicenters of the explosions were out of a used sub-network areas; distances between explosion epicenters and center points of the sub-networks were large. These geometry peculiarities lead to increase of the location errors. Israel seismic network is not circular: it is very elongated in the north-south direction. This fact also increases the location error when explosion locates outside of the sub-network used in direction of the network elongation.

As explosion occur near the ground surface and network is also deployed on the surface, seismic rays which lay in the most upper part of the crust are used in location procedure. It is well known that the later is the most inhomogeneous. Large-scale near surface inhomogeneities and the surface relief disturb the ray-paths and lead to the deflection of seismic emission image maximums from real source positions.

The influence of different factors described above leads to increasing of the mean error of explosion location up to be in 1.8 times greater than the tomography location resolving accuracy. Nevertheless, this error is not too large and we can conclude that the programs of events location based on method of emission tomography permits to locate with a good accuracy both earthquakes and explosions.

Table 2.

N	**Data: year /month/day**	**Time: hour/min**	**Magnitude ML**	**Xc, km**	**Yc, km**	**Xs, km**	**Ys, km**	**Dr, km**	**Numb. of stations**
1	**1991/01/09**	**14h11m**	**2.2**	**-43.483**	**83.710**	**-45.**	**95.**	**11.4**	**21**
2	**1989/06/20**	**10h18m**	**2.6**	**-43.022**	**81.934**	**-42.**	**100.**	**18.1**	**21**
3	**1991/05/06**	**12h41m**	**1.8**	**3.836**	**101.028**	**-5.**	**100.**	**8.9**	**12**
4	**1990/08/28**	**14h24m**	**1.7**	**-19.587**	**83.191**	**-25.**	**85.**	**5.7**	**10**
5	**1991/05/08**	**13h04m**	**1.8**	**-43.676**	**82.491**	**-30**	**90.**	**15.6**	**21**
6	**1990/04/04**	**13h01m**	**2.4**	**-45.070**	**85.048**	**-58.**	**80.**	**13.9**	**22**
7	**1990/10/16**	**14h05m**	**2.2**	**-44.511**	**84.380**	**-44.**	**85.**	**0.8**	**15**
8	**1991/06/17**	**06h43m**	**1.6**	**6.081**	**-100.58**	**5.**	**125.**	**26.8**	**7**
9	**1991/03/19**	**14h02m**	**1.3**	**-43.483**	**83.710**	**-45.**	**101.**	**17.3**	**25**
10	**1991/08/12**	**13h03m**	**2.6**	**-42.459**	**82.154**	**-44**	**93.**	**10.9**	**7**

5.2. Investigation of influence of hypocenter depth on location accuracy

It should be emphasized that exact determination of the depth of an event source is very important thing for correct event location by the emission tomography method. When the seismic network is rather optimal from the point of view of side lobes and an event projection on the earth surface is located within the area of the network deploying the procedure provides a clear peak at the surface emission power map, location of the peak approximately the same as the real position of the deep event hypocenter. In practice often a network geometry is not so optimal; even when initial geometry is good we often have to remove part of station seismograms due to large noise, bad time shifts and so on. The typical case is when events occur out of the network area. This is also difficult case for good performing of the tomography location procedure.

In the case of a 'bad' network configuration or a 'bad' event position towards to the network the tomography location procedure provides on the surface map a peak which is very shifted from the correct event epicenter or even several peaks with approximately equal amplitudes. To investigate this effect simulation experiments for tomography location were made using the configuration of the Israel network. It was found that the peak shifts at the surface map can be equal to tens km.

Fig.1 shows the network configuration used for the simulation of tomography location. Event source was placed in the point (X=0 km, Y=0 km, Depth=30 km). Network seismograms after STA/LTA-detector preprocessing were simulated by rectangular 2-second length pulses with corresponding time shifts imposed to the modeled noise records. Fig.2 and Fig.3 show semblance maps for depths 0 km and 30 km respectively. On the earth surface the procedure provides 2 peaks with distance 30 km between them. Fig.4a shows variation of the maximum value with depth of semblance maps and Fig.4b shows migration of the largest peak position in the horizontal projection. The argument of the global maximum in Fig.4a allows to estimate the depth of the event source. As it is seen from Fig.4b the position of the largest peak for different depths moves in the horizontal plain around the position of the event source and has the large hit multiplicity. For the correct depth 30 km the procedure gives very clear and sharp peak (see Fig.3b) in the correct point (X=0 km, Y=0 km).

Fig.5-7 show the results of real data study using the earthquake which occured on 04.05.1991 in 18-07 . Fig.5 demonstrates the network configuration used for tomography location. Fig.6a and Fig.6b show respectively the variation with the depth of the maximum value of the emission maps and the migration of the largest map peak in the horizontal projection. The largest value corresponds to the depth=35 km, the peak position at this depth has coordinates X=-40 km, Y=120 km. The catalog information is: the source depth 17 km (±3 km), X=-43.04 km, Y=120.31 km. Like for simulation results described above the correct event epicenter position is the center of the area of the peak migration through the horizontal plane while depth changes from 0 to 60 km. Fig.7 demonstrates the semblance map calculated for the earth surface which has very many peaks. It is impossible to derive a conclusion on the event epicenter location based on this map. On the contrary the semblance map calculated for the depth 35 km, (depicted in Fig.8), has the single sharp peak with the position X=-40 km, Y=125 km which is very close to correct event epicenter: X=-43.04 km, Y=120.31 km.

The results of investigation made allow to design the following algorithm of accurate location of event epicenter. At the first step using approximately large inter grid step and large time windows in the STA/LTA-detector one founds position of the maximum of the horizontal semblance map calculated at the depth 0 km. At the second stage one put the center of horizontal maps to be calculated to the point of the found maximum, calculates a set of semblance maps for different depths and estimates the source depth by seeking of the global maximum of the maps. At the third step one gets the accurate estimate of the event source location by calculation of the horizontal semblance map for correct depth using a small inter grid step and short time windows in the STA/LTA-detector.

Figure captions for section 4.5

Fig.1. Network configuration used for simulation experiments.

Fig.2. Simulation results: semblance map for depth 0 km. The error of the event source location equal 30 km.

Fig.3. Simulation results: semblance map for depth 30 km. The event source location has no error.

Fig.4. Simulation results: (a) maximum values of horizontal semblance maps calculated for different depths in the range 0-60 km, (b) - projections of positions of semblance map maximums to the horizontal plane for different depths.

Fig.5. Sub-network configuration used for experiments with real event seismograms recorded by the Israel network.

Fig.6. Results of semblance map calculation for seismograms recorded by the Israel network:

(a)- maximum values of horizontal semblance maps calculated for different depths in the range 0-60 km,

(b) - projections of positions of semblance map maximums to the horizontal plane for different depths.

Fig.7. Semblance maps for seismograms recorded by the Israel network calculated for the depth 0 km. To derive the conclusion about event epicenter is almost impossible.

Fig.8. Semblance maps for seismograms recorded by the Israel network calculated for the depth 35 km. Location of the map peak is equal: X=-40 km, Y=125 km, that is very close to correct event epicenter: X=-43.04 km, Y=120.31 km.

References

1. Nikolaev, A.V.,Troitskiy, P.A. and Tchebotareva I.I., 1986. Lithospheric studies based on seismic noise. *Dokl. Akad.Nauk SSSR, v. 286, pp. 586-591 (in Russian)*

2. Nikolaev A.V., Troitskiy P.A., Tchebotareva I.J.,1991. Analysis of seismic holography. *Dep. VINITI, N18-B91, 52p.(in Russian).*

3. Taner, F. and Neidell, N.S., 1971. Semblance and other coherency measures for multichannel data. *Geophis., 36: 482-497*

4. Tchebotareva I.J., Nikolaev A.V., Sato H.,1997. Study of sources of seismic emission in the Earth's crust, Japan, northern Kanto. *Dokl. Akad. Nauk Russ, v.357, N.4, pp. 542-546 (in Russian).*