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# On a new automized technology for seismic source location*

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The automized technology of location of a different types of seismic sources – industrial explosions, vibrators, etc., – against the noise is proposed. The efficiency of the proposed approach is illustrated on a series of examples.

The location of different types of seismic sources – earthquakes, nuclear and industrial explosions – is one of the key problems in modern seismology.

It is based on the solution of the inverse problem of the reconstruction of parameters of a source (geographical coordinates, depth, power, the time in the epicenter) from the recording data of seismic signals with the use of a network of seismic stations or a seismic group (a set of seismographs). Thus, the problem of depression of a location error is one of important. Alongside with this problem there is another one – power rating of a source. But her this problem is not discussed.

Let us illustrate the urgency of the posed problem and the difficulty of its solution in relation to such a relevant problem as detection of nuclear explosions. The depression of the error of location allows us to essentially reduce the size of an inspection zone by the International forces of monitoring in regions of latent underground explosions. Thus, for example, an area of inspection of 1000 km – which is coordinated by the International convention – corresponds to the location error within the circle of radius 17 km. Reaching such levels of the location error in relation to small events with the help of a sparse regional seismic network of stations at recording distances exceeding 1000 km is currently problematic. At the same time there is a constant tendency of reaching further lower errors.

Widespread difficulties in the solution of the problem in question are associated with systematic anomalies of seismic waves travel times in Earth's crust and the upper mantle due to essential horizontal and vertical inhomogeneity of the Earth' structure. The indicated phenomenon is the cause of occurrence systematic errors of location of seismic sources. The currently accepted empirical approach to consideration of the factor of inhomogeneity is in the preliminary calibration of real seismic traces and MSSM stations with the help of seismic events with known site and time. At present as

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such events industrial explosions are used, the approaches, connected with the use of powerful seismic vibrators being developed [1]. Calibration allows us to define corrections to the regional medium model of propagations of seismic waves and, respectively, to their travel times.

Another difficulty in the solution of the problem under study is due to the presence of signals from events of different nature–earthquakes, industrial explosions, man-made noise. These sources are the background ones in relation to a useful event (in our example, to the nuclear explosion). It is sufficient to note, that the annual number of such events, recorded only by the seismic network Altai–Sayan region, is represented by denumerable sets.

In view of the above-said it is possible to distinguish the basic stages in the solution of the problem of location of a seismic source: its detection, identification, evaluation of arrival times of seismic waves, determination of parameters of an epicenter and the mapping on the digital geographical map.

Keeping in mind the influence of the background events and seismic noise there is a need in the automized technology of problem solution at the indicated stages. Such a technology is intended for the user to facilitate the routine work connected with data processing in conditions of continuous monitoring of events. In the present work some problems, associated with realization of this technology are considered.

The problem of automatic detection and determination of arrival times of seismic waves $t_p$, $t_s$ can be reduced to solution of the problem of the prompt detection of the time of disordering of a random sequence formed by discrete countings of the "background" noise and a useful seismogram $x_1, x_2, \ldots, x_M$. In view of the properties of noise instability and variability of characteristics seismograms, recorded from different kinds of seismovibrators, the detection and measurements are carried out in conditions of *a priori* uncertainty about parameters of seismic signals. Under these assumptions of primary importance is the task of the ensured detection of the time instants of disordering detection. One of the ways it of its solution is possible with the use of a variety of a sequential algorithm of the cumulative sums (ACS), which is based on approximation of fragments of pure noise and the waves $P$ and $S$ by models of autoregression of integrated sliding average (ARISV) [2]. In the case of a sequence of the Gauss random values $x_i$ the ACS has the form:

$$g_N = (g_{N-1} + \Delta g)^+, \quad g_0 = 0, \quad \Delta g_N = F(\Phi_1, \ldots, \Phi_p; \sigma_\epsilon^2), \tag{1}$$

$$\Delta g_N = \left[\frac{(1 - \sum_{i=1}^{p} \Phi_i)}{\sigma_\epsilon^2}\left(1 - \sum_{i=1}^{q} \phi_i\right)\right] \epsilon_N(m_0),$$

$$x_t = \Phi_1^{(i)} x_{t-1} + \ldots + \Phi_p^{(i)} x_{t-p} + \epsilon_t.$$

Here: $(g)^+ = \max(0, g)$; $\Phi_1, \ldots, \Phi_p$ are autoregression coefficients of order

$p$; $\phi_1, \ldots, \phi_q$ are coefficients of sliding average; $\epsilon_N$ is an independent Gauss random sequence; $\sigma_\epsilon^2$ is dispersion of random values of a series $x_i$. In this case the rule of a signal delivery about disordering is written down as:

$$t_p = \inf\{t : \ g_N > h\}, \tag{2}$$

where $h$ is a threshold level.

It is necessary to mark, that the procedure (1) has a recursive form, thanks to which can be realized in a real time scale. The accuracy of determination of the times of the wave arrival can be approximately described by a mean quadratic

$$\sigma^2 \approx \frac{\tau}{2\Delta f \cdot (A_{p,s}/\sigma_n)^2},$$

where $\tau, A_{p,s}$ are the duration and amplitude of $P$-waves and $S$-waves, $\Delta f$ is the frequency band occupied by them, $\sigma_n$ is a mean quadratic value of noise.

As is seen from the above ratio, the error of determination of of arrival times of waves can be decreased at the expense of extension of a frequency band and an increase of the ratio of amplitudes of waves to a seismic noise level. The latter is defined by a method of seismogram processing. Thus it is necessary to note that an attempt to increase the signal/noise ratio at the expense of narrow-band selection of waves results in narrowing the band $\Delta f$ and, respectively, in increasing the error $\sigma$.

The results of application of algorithms (1), (2) to the processing of explosive seismograms in combination with digital filtration algorithms are discussed below. Preliminary filtration is used for the rise of noise stability of the detection and estimation of parameters of seismic waves based on the consideration of their spectral distinctions. The algorithms are realized in the software package which is included in the program system of of seismic data processing "Astra" [3], developed in the MatLab system.

As an example, we consider the detection of waves and measurement of their arrival times in relation to two sequential explosions of power 4 and 12 tons with a delay between them equal to 52.843 s. Recording are made at a point located at distances of 230 and 240 km from sources. The initial recording of explosions in the frequency band 1–10 Hz are presented in the lower part of Figures 1–3.

Figure 1 shows in the graphic form the process of detection of wave arrival times on attaining a maximum of the cumulative sum (1), though, visually, the first arrival wave in the initial seismogram (the bottom of Figure 1a) is not detected. Similarly, in Figures 2, 3 the first arrival waves from both explosions, recorded on the components $z_2$, $z_3$, are detected. Two sequential maximums of the sum (1) define the wave arrival times from both explosions.

In Figure 4 the result of detection of the first arrival wave of the longitudinal wave $P$, recorded from a powerful chemical explosion at a distance

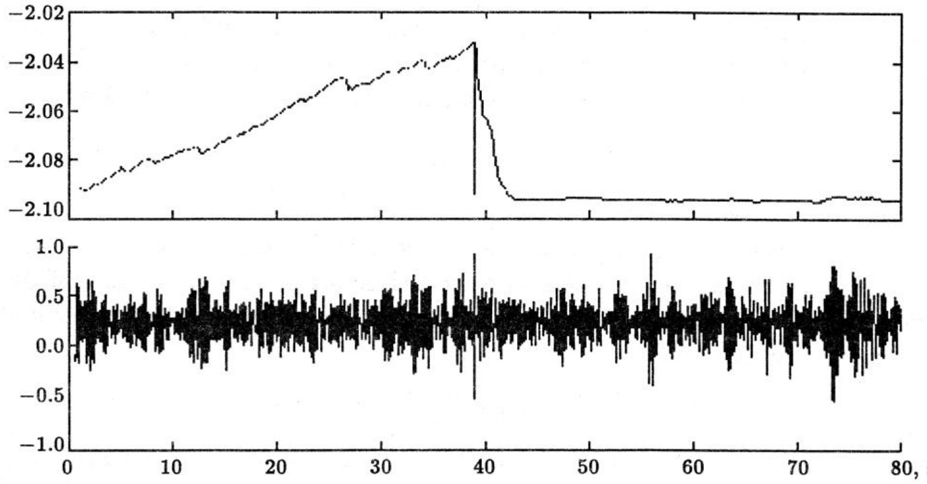


**Figure 1.** The form of the decision function a) of a combination of noise and signal, b) recorded from the explosion of power of 12 tons at a distance of 240 km; the beginning of the record corresponds to the moment of explosion

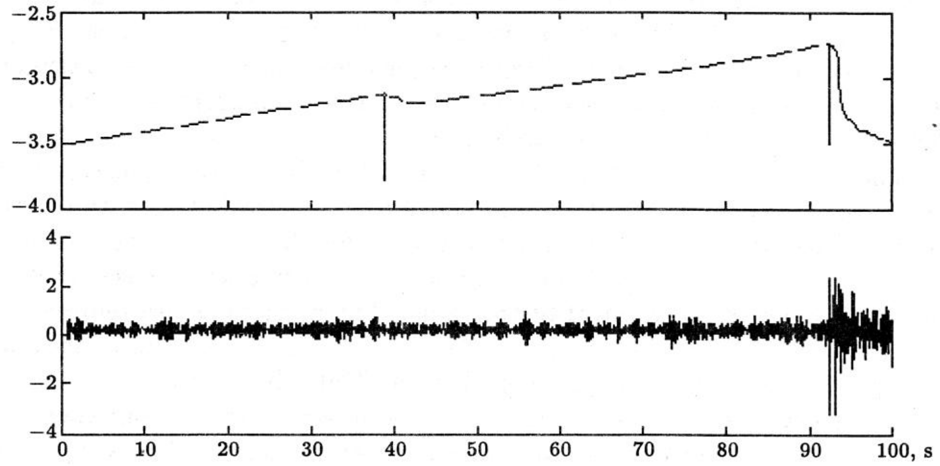


**Figure 2.** The form of the decision function a) of a combination of noise and signal, b) recorded on the component $z_2$ from two sequential explosions of power 4 and 12 tons at distances of 230 and 240 km; the beginning of the record corresponds to the moment of the 1st explosion

of 625 km is shown. At the bottom of the figure, the record of an explosion against the background of seismic noise, at the top – the diagram of the cumulative sum (1) are given. Its maximum corresponds to the arrival time of $P_n$-wave, equal to 86.64 s. The record is passed through a strip filter with a passband 1–10 Hz. The accuracy of evaluation of the arrival time was estimated by calibration travel times of waves for a given region and has made

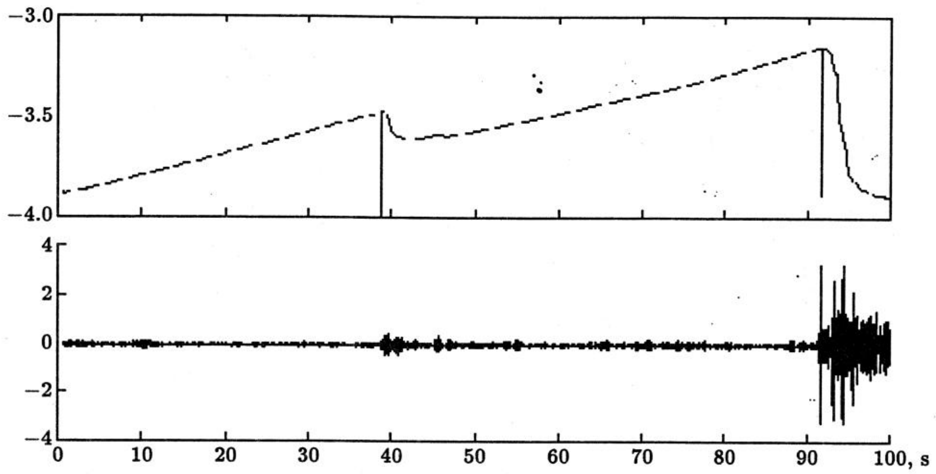


**Figure 3.** The form of the decision function a) of a combination of noise and signal, b) recorded on the component $z_3$ from two sequential explosions of power 4 and 12 tons at distances 230 and 240 km; the beginning of the record corresponds to the moment of the 1st explosion

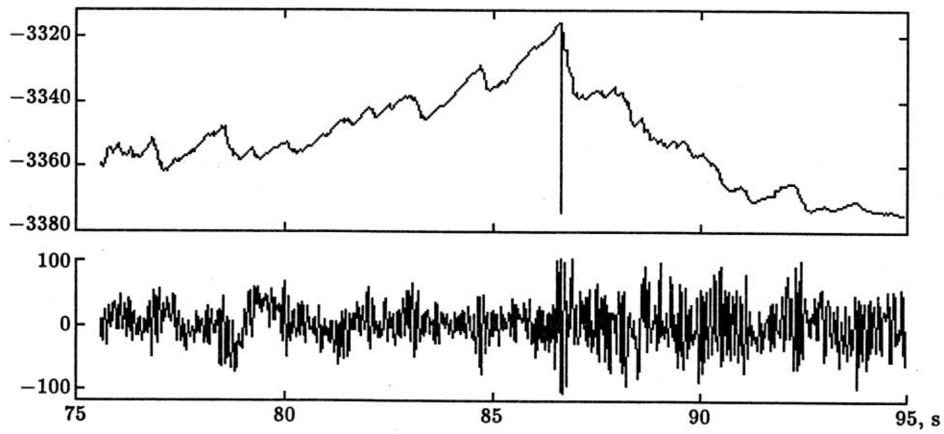


**Figure 4.** The form of the decision function a) of a combination of noise and signal b) recorded from the explosion "Omega-3" of power 100 tons at distances of 625 km; the beginning of the record corresponds to the moment of the explosion

0.6%. In a similar way, the arrival time of the transversel wave $S_n$ was estimated. The arrival times of the waves $T_p$, $T_s - T_p$, $T_s$ for a given explosion at a number of other observational points at distances 254, 284, 321, 530, 634 km from the explosive were assessed by the presented scheme. Based on the obtained estimations of the arrivals times of waves and with allowance of their velocities accepted for the Altai region, the epicenter coordinates of a seismic event were determined by the well-known method of cross bearings. As is known, for obtaining a unique solution we need data, as minimum,

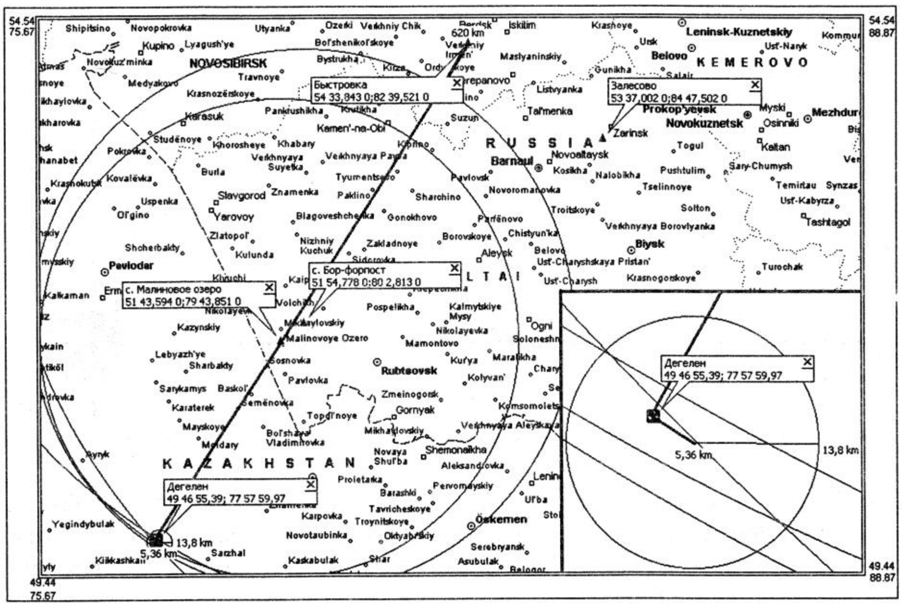


**Figure 5.** A map of the position of region of the explosion "Omega-3" and the recording stations

at three observational points. For the solution of this graphic task in the automatized mode, the program interface between the "Astra" system and the system of graphic mapping, realized on the basis of the GIS-platform Microsoft MapPoint2002 was developed.

A sequence of the process of mapping the results is the following. The results of preprocessing (in the form of estimations of source-receiver distances) from the system "Astra" are transferred to the database, with the use of the package MatLab – Database Toolbox. At the next step, the obtained data the access from the interpretation system to the data base is made out with Microsoft Jet drivers, the mapping of the calculated coordinates of a seismovibrator on a digital card is carried out through GIS a package Microsoft MapPoint. In Figure 5, an example of graphic reconstruction of the vibrosource coordinates, executed in relation to 100-ton chemical explosion "Omega-3", set off on the Semipalatinsk nuclear test site (Degelen) in 2000.

The source is reconstructed using the measurement data of wavetravel times at 4-th recording points marked with black triangles. The restored source should be localized on the line of intersection of circles of radii equal to the "source–receiver" distance. The latter is determined with the help of the calibration diagrams (hodographs of waves) from a difference of the times $(T_s - T_p)$ or by calculation of the product $V_p(T_s - T_p)$, where $V_p$ is $P$-wave velocity, selected for a given region. The error of determination of coordinates of the source is inside the circle, whose diameter is determined

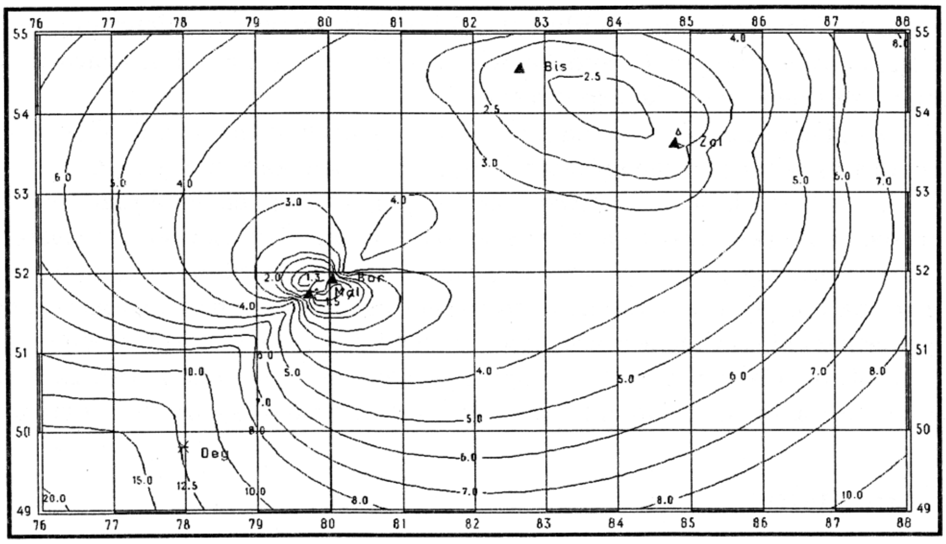


**Figure 6.** A map of isolines indicating to errors in determination of the epicenter position of the explosion "Omega-3" by the network of four stations ($v_p$ = 6.13 km/s, $v_s$ = 3.56 km/s, $\sigma T_p$ = 0.1 s, $\sigma T_s$ = 0.1 s)

by cross-points of the constructed circles. Geometrically, it is displayed in increased scale in the figure in the lower right angle. Here the true location of the explosion point in relation to the calculated location is shown. The ambiguity of evaluation of the source coordinates (about 13 km) is caused by unsuccessful layout in space of the recording points.

When solving the inverse problem of location the results of the program operation with detection and measurement of the arrivals times of $P$-waves and $S$-waves are transferred to the program intended for calculation of coordinates of a seismic source and time in the epicenter. The program is based on the algorithm of solution of the inverse problem by the nonlinear system of conditional equations:

$$T = \eta(X, \theta) + \epsilon,$$

where $T$, $\eta$, $\theta$, $\epsilon$ are, respectively, vectors of arrivals times of $P$- and $S$-waves at the network station, of estimated parameters and residuals, and $X$ is the matrix of coordinates of seismostations.

The applied techniques of solution of this problem are discussed in detail in [4]. The accuracy of definition of coordinates of seismic sources can be characterized by the isolines, corresponding to the given layout of seismic stations. Figure 6 presents an example of construction of such isolines for a network of stations, with whose help the explosion coordinates in Degelen (see Figure 5) were determined. The figure shows, that the error of determination of the explosion epicenter coordinates with the help of the indicated network of four stations is within 10–15 km with accuracy of determination of the arrivals times of $P$- and $S$-waves not exceeding $d = 0.1$ s, which is in good agreement with the experiment.

The given example is a sample of a poor choice of the layout of seismic stations as related to the epicentral zone. It is well seen in Figure 6.

The authors have the software for carrying out the optimal planning of seismic networks consisting of any amount number of stations as related to an arbitrarily given epi- or hypocentral zone, as well as for making of their analysis [4], where the modern methods of estimation of parameters of hypocenters of earthquakes are stated in good detail, as well as formulations of problems associated with the optimal planning of seismic networks and some criteria of the optimality of plans used in seismology are considered.

## Conclusion

The paper considers some aspects of making up a technology of location of different types of seismic sources. In this connection the main attention focuses on the development of algorithms and programs of automatization of processes of determination of characteristics of body waves, the evaluation with their use of parameters of a source in the seismic event epicenter. The problems of visualization of the processing results using the GIS-SYSTEM are considered. The reliability of distinguishing the events in seismograms and the accuracy of estimating their parameters are illustrated as applied to recording chemical explosions on the Semipalatinsk nuclear test site. The developed program represent separate fragments on the way to creation of the technology of location of a seismic source.

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