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Planning seismic networks in the Kemerovo region

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The present paper is a sequel to a series of publications [1–5] devoted to issues of planning and analysis of networks of seismic observations. To this series, one can refer [2, 4], in which the basic definitions and concepts of the theory of planning of seismic networks needed in this paper are briefly discussed.

Seismic observations in the Altai–Sayansk region, one of seismic-prone zones in Russia, are a part of the federal observations over natural and man-caused factors. The territory of the region in question makes more than $1.5 \cdot 10^6$ km^2 includes 13 subjects of the Russian Federation and three border areas of the neighboring countries: Kazakhstan, China, Mongolia. Annually, instruments record a few thousands of seismic events from which approximately for one thousand earthquakes and for one and a half thousand industrial explosions. Coordinates, origin time, and energy are determined for these events.

The quality of the information received depends on the instrumental equipment of points of observations, hardware and software of the center of gathering and processing data in Novosibirsk, as well as on the number and disposition of network stations.

The beginning of the 21st century became a starting point for the Altai–Sayansk region seismic network as concerns the work with the new instruments: in 2000, all the stations of the network became digital, equipped with Baikal-11 local product. Digital recording, as well as updating with new stations have demanded to estimate anew the capabilities of the network in terms of representativeness and the accuracy of definition of hypocenters parameters. The methods of estimating the quality of recording of seismic events (earthquakes, explosions, mountain blows, etc.) are stated in [1, 6–8] and have not undergone modifications as well as techniques of processing records of seismic events for obtaining parameters of hypocenters [9]. However, the new capabilities of the instruments have allowed one to essentially expand the territory representative recording the earthquakes of low-energy classes [3, 5, 10].

The objective of this research is planning of zonal network of seismic stations (NSS) which could provide the solution to the following tasks:

1. Seismic monitoring of a section of intensive man-caused impacts actions (on an example of the city of Kemerovo and adjoining territories) at a "weak seismicity" level, i.e., under the condition of the lower

limit of representativeness of seismic events not exceeding 4–5 energy classes.

2. Recognition of records of industrial explosions and earthquakes.
3. Estimation of a depth of the focus of seismic events independent of their nature.

The problem of planning is currently actual due to the seismic activation near to the towns of Osinniki (2005) and Polysaevo (2007). With a well-planned zonal network of observation, it would be possible to trace the previous history of the seismic activity, to calculate more reliably its nature, and to assess until very recently consequences at various scenarios of its development.

With allowance for the fact that Kuznetsk Basin according to the current maps of seismic zoning is attributed to 7–8-magnitude territories by the level of seismic activity, it is impossible to exclude a possibility of natural tectonic activity, along with the man-caused factors. With network capable of fixing even minor changes in seismic conditions, it is possible to exceed the detection, say, of foreshocks activity followed by a strong seismic event. In the case of a man-caused activity, it is apparently possible to correct the factors which have caused it in due time.

In this paper, the current regional sub-net, consisting of 7 stations, is optimally supplemented with the planned NSSs containing 15, 20, 25, 30, 35, 40, 45 stations. Seismic stations of the existing network are installed in Salair, Kemerovo, Mezhdurechensk, Berchikul, Tashtagol, Eltsovka, and Verkh-Baza (they are marked with black triangles in Figure 1).

Optimal addition is achieved within 44 stations in predetermined built-up areas (they are marked with grey triangles in Figure 1). Coordinates and names of these points are listed in Table 1. The planned stations occupy a comparatively small area of 54.09–56.20°N, 85.6–88.29°E.

The A-criterion is chosen as a criterion of optimal planning. According to it, the optimal plan has the least average variance of estimations of parameters or the least spur of a covariance matrix among all possible plans.

The ellipsoid of dispersion of parameters estimation set by such an optimal plan has the minimum sum of squares of lengths of axes and the least length of the diagonal of the rectangle described near to this ellipsoid.

As it was marked in [2], difficulties of estimating parameters of earthquakes hypocenters, as well as problems of planning seismic networks, consist in that the regression function is nonlinear according to estimated parameters. It is known [11] that in this case optimal plans are functions of estimated parameters of the hypocenters and as a result they are called locally-optimal, for example, locally A-optimal. The problem of their construction is essentially simplified, if it is possible to predetermine areas of

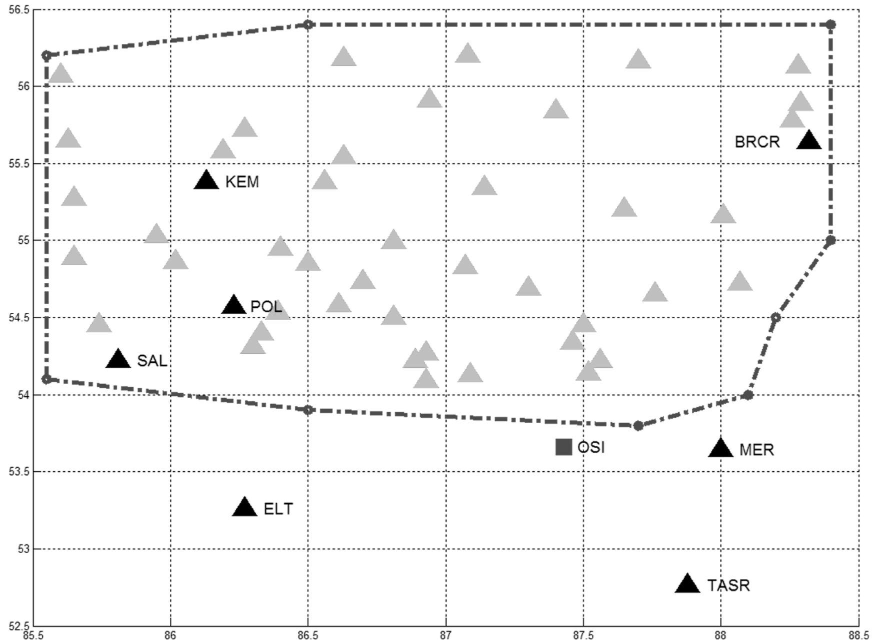

Figure 1. A map-scheme of the Kemerovo region with allocated epicentral area, regional and virtual seismic stations

Table 1. List of virtual stations of a zone network

54.09	86.93	Terentyevskoe	54.89	85.65	Promyshlennaya
54.13	87.09	Mal. Talda	54.95	86.40	Panfilovo
54.14	87.52	Krasnoznamenka	54.99	86.81	Krapivino
54.22	86.89	Sokolovo	55.03	85.95	Gorbunovka
54.22	87.56	Osinovoye	55.16	88.01	Pervomaysky
54.27	86.93	Kotino	55.20	87.65	Tsentralny
54.31	86.30	Tshertynsky	55.27	85.62	Topki
54.34	87.46	Ust-Narik	55.34	87.14	Bolshoy Shirokiy
54.40	86.33	Belovo	55.38	86.56	Kutshum
54.45	85.74	Novopesterevo	55.54	86.63	Blagoveschenka
54.45	87.50	Isaevo	55.58	86.19	Kurganovka
54.50	86.81	Novokhudyakovo	55.65	85.63	Kolmogorovo
54.53	86.39	Gramoteino	55.72	86.27	Barzas
54.57	86.23	Polisaevo	55.78	88.26	Tysul
54.58	86.61	Sartaki	55.84	87.40	Novoalekseevka
54.65	87.76	Pezas	55.89	88.29	Ust-Kolba
54.69	87.30	Bogdanovo	55.91	86.94	Krasniy Yar
54.72	88.07	Severniy	56.07	85.60	Tayga
54.73	86.70	Taradanova	56.13	88.28	Tyajin
54.83	87.07	Saltimakovo	56.16	87.70	Mariinsk
54.85	86.50	Berdyugino	56.18	86.63	Ijmorskaya
54.86	86.02	Protopopovo	56.20	87.08	Berikul

belonging of vectors of unknown parameters. This is valid for the majority of problems of seismology.

In the sequel, we seek for the minimax optimal plans [4, §4].

Owing to the influence of various factors among which it is possible to distinguish geological, geographical, and economical ones, *the NSS planning is in addition essentially discrete.* And, first of all, owing to an economical factor, the number of stations (points in a plan spectrum) is usually reduced to a minimum.

It is known in the theory of planning an experiment that *in such cases there is necessity to seek for exact optimal plans, i.e., plans that are optimal at a network of* n *stations with* n *given.* Finding of exact optimal (discrete) plans is a more difficult task than the search for the so-called continuous optimal plans. The problem becomes even more complicated because it is necessary to search for its own solution for every n [11].

For many problems of seismology planning, the NSS is within one of the statements described in [2, 4, p. 19].

In our case, we are within the limits of the following statement:

In a region there is a network of a certain number of seismic stations with additional instrumentation for a certain number of stations. From geological and geographical reasons within the region, a certain number of points for possible installation of this instrumentation is chosen. It is necessary to optimally supplement the existing network up to the specified number of stations for recording earthquakes from given focal zones.

The algorithm of the search for exact optimal plans at planning NSS uses ideas from [11] and we described it in [4, §4]. It consists in construction of a monotone decreasing converging sequence of values of the criterion function.

Applying the indicated algorithm, A-optimum additions of seven existing regional stations up to 15, 20, 25, 30, 35, 40, and 45 stations were obtained. For each of them, the detailed analysis consisting in construction of maps of energy representativeness of isolines, a confidence radius of an error of epicenters, and a confidence interval of an error in depth was carried out. The mean values over the whole above-considered area and over the chosen hypocentral zone for each network obtained were computed as well.

All the above-said allows us to choose for realization a network of a certain number of stations corresponding to available material capabilities.

A special attention is given to such an important parameter of a seismic event as a depth of the focus. The estimation of the focus depth is directly connected with designating of the nature of an event: in the case of massive determinations of depths of the focuses it is possible to divide the events into tectonic and man-caused once as a first approximation, since depths of excavations are well known and do not exceed a few first kilometers, but the bulk of tectonic earthquakes have large depths of the focuses.

Obtaining a large number of data will enable one—with the help of reference explosions with exactly known parameters (coordinates, time, depth)—to develop a statistically well-founded algorithm for recognition of explosions and earthquakes from the near-zone recordings in an area of overlapping the natural and technogenic events in depth.

The value of 0.05 s for the accuracy of recording arrival times and the value of 0.1 km/s for an error of speed of seismic waves velocity were chosen for all the planned stations.

Figure 2 shows the level of energy representativeness for the existing network of 7 stations and for planned networks of 15, 35, and 51 stations. The regional network of seven stations has the representativeness on the zone at the level of the 6th energy class and the planned networks are at levels of 5.1, 4.2, and 4, respectively. Figure 3 shows the level of confidence radius at the epicenter for networks of 7, 15, 35, and 51 stations. From these figures it is seen that its mean in the zone sharply decreases and is equal to 3.6, 1.7, 1, and 0.8 km, respectively. Figure 4 demonstrates pictures of a more abrupt decrease of the confidence interval in depth for the same set of networks of stations. Its mean is equal to 13, 2.6, 1.3, and 1 km, respectively.

The above-mentioned characteristics of the regional network and of all the planned networks are listed in Table 2 and a change of characteristics in the number of network stations is demonstrated with the diagrams shown in Figure 5.

All the planned zonal networks make possible to increase the accuracy of definition of coordinates and depth of seismic events to raise the representativeness of recording.

Table 2. The dependence of the means over the zone and the area from the number of stations in an optimal network

Number of stations in a network	The mean of the power class		The mean of the confidence radius of the epicenter		The mean of the confidence interval in depth	
	Zone	Area	Zone	Area	Zone	Area
7	6.14	6.00	3.623	3.398	13.033	11.996
15	5.11	5.31	1.707	1.924	2.554	3.940
20	4.79	5.11	1.373	1.654	1.881	3.369
25	4.52	4.93	1.188	1.485	1.646	3.112
30	4.33	4.78	1.067	1.343	1.400	2.890
35	4.24	4.76	0.970	1.298	1.311	2.850
40	4.13	4.64	0.906	1.178	1.184	2.671
45	4.06	4.60	0.848	1.117	1.088	2.588
51	4.00	4.56	0.791	1.062	1.021	2.508

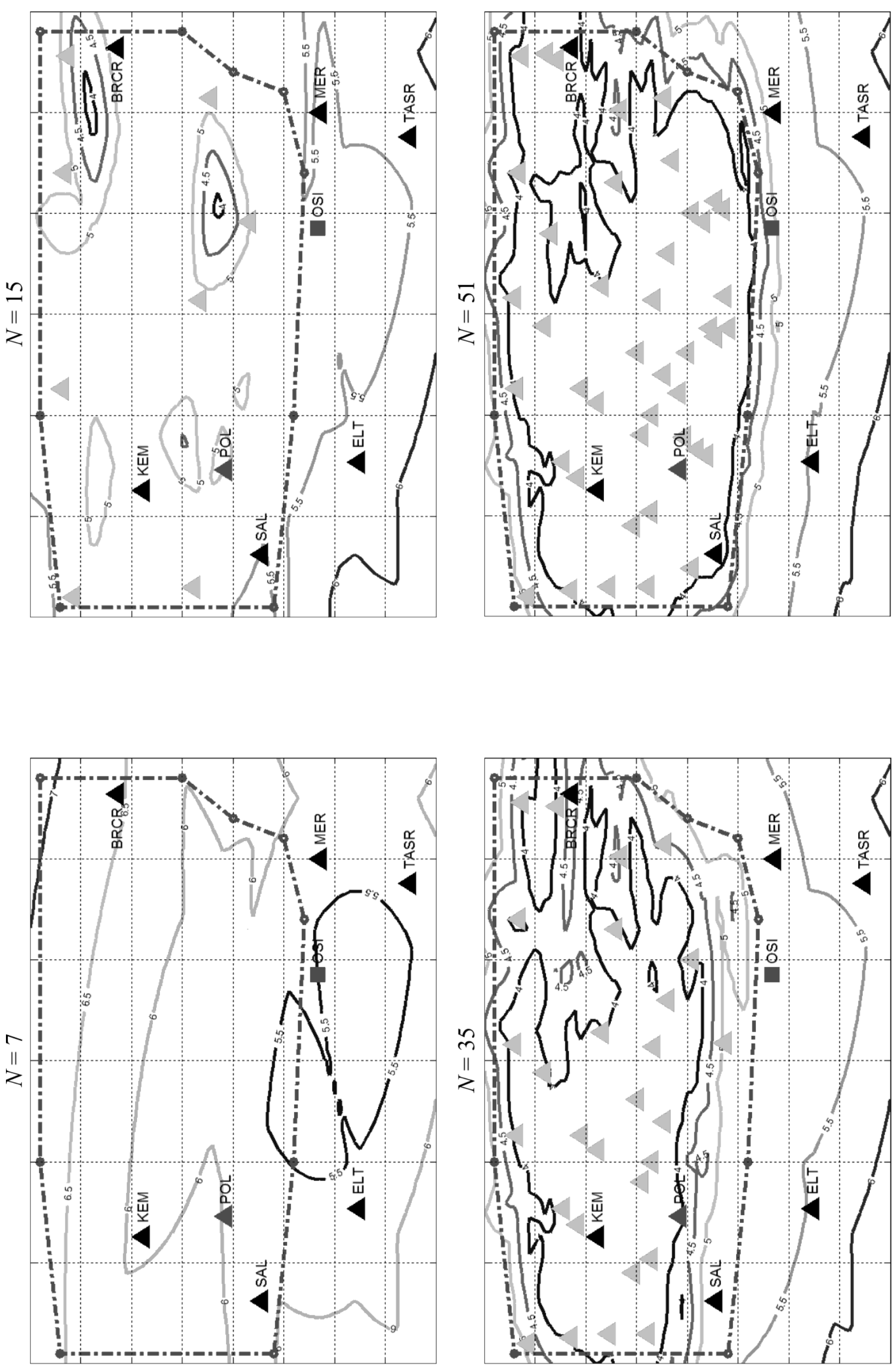

Figure 2. Maps of energy representativeness isolines for the network of N stations

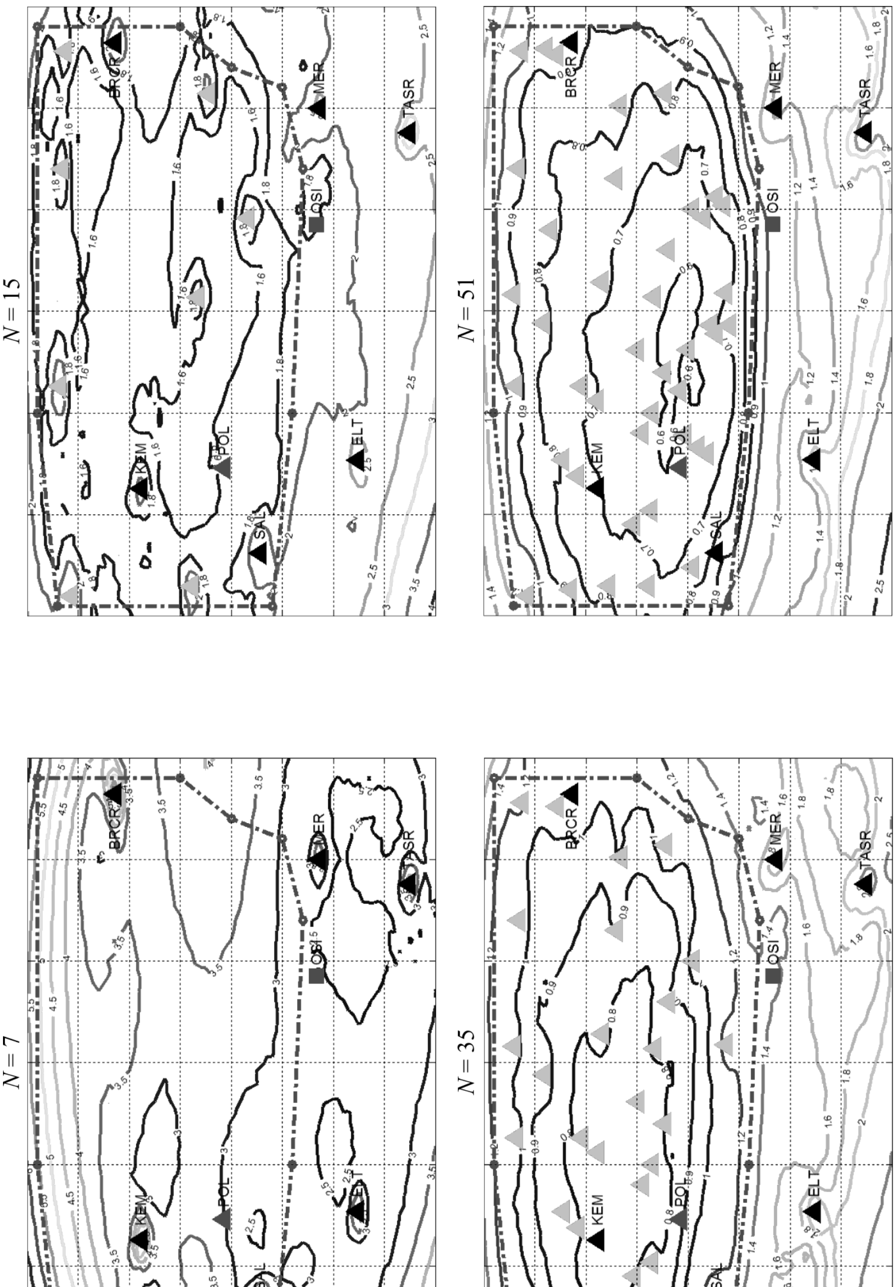

Figure 3. Maps of confidence radius of the epicenter isolines for the network of N stations

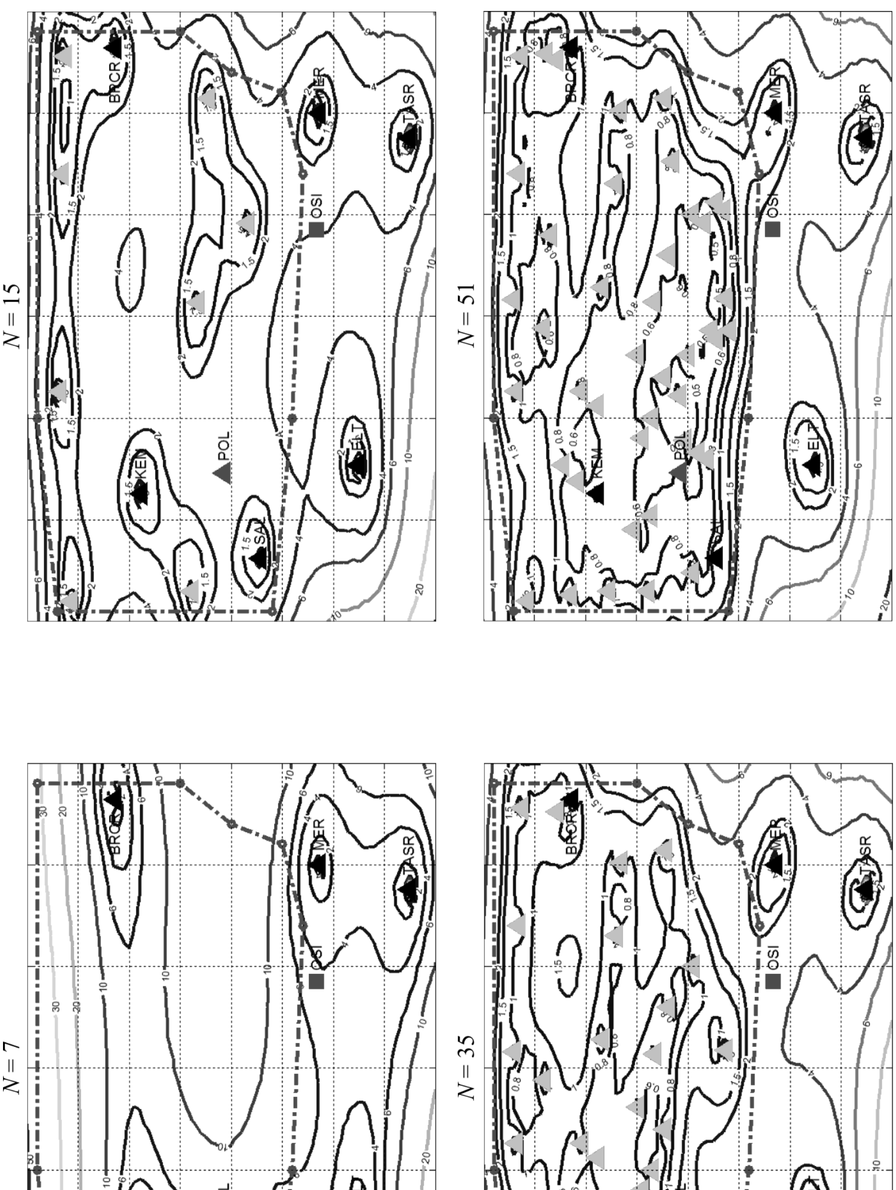

Figure 4. Maps of confidence interval in depth isolines for the network of N stations

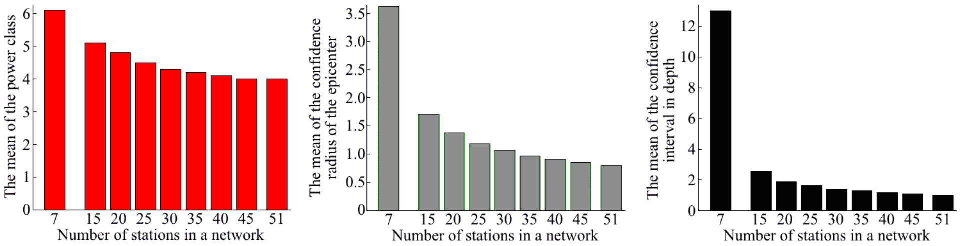

Figure 5. The dependence of means over the zone

Let us call the number of stations per unit of an area the "network density". Note that as radii of representative recording of low-energy classes make the first tens kilometers, a decrease of density the network results in the formation of spatial gaps in which the level of representativeness and the accuracy of definitions sharply decreases. Therefore, it is important that the network density in the planned networks be monotone increasing with an increase in the number of stations in a network.

Analyzing Figures 2–5 and Table 2, it is possible to make a conclusion that all the planned networks in all their parameters essentially surpass the regional network. Beginning with a network of 35 stations, their characteristics can provide a solution of the tasks stated.

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