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ACCURACY OF EPICENTERS LOCATION OF SEISMIC EVENTS BASED ON “MIKHEVO” SMALL-APERTURE SEISMIC ARRAY DATA. DO ADDITIONAL SEISMIC STATIONS NEEDED?

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Abstract. The results of evaluating the accuracy of determining coordinates of the epicenters of seismic events that are registred by small-aperture array Mikhnevo are given. Quarry blasts located in the central part of the East European platform were used as a source of the events. With confident identification of seismic wave arrivals (signal to noise ratio ≥ 2), the small-aperture group independently provides high location accuracy and subsequent association of the event with the nearest quarry in coordinates. It is shown that the accuracy of the location strongly depends on the microseismic level, i.e. on signal to noise ratio. With a low signal to noise ratio (R≤2), the accuracy of the location decreases and in this case, the data received from the additional seismic stations can be useful.

Keywords: East-European craton, temporary seismic network, small-aperture seismic array, waveforms, seismic events.

Introduction

The main seismicity of the East European platform is associated with drilling-and-blasting operations in quarries during extraction of such minerals as limestones, dolomites, ferruginous quartzites, granites, etc. A unique base of waveforms (or wave “portraits”) was formed over 15 years since the creation of the Mikhnevo small-aperture seismic array. This base contains records of blasts carried out in more than 60 quarries operating in the central part of the platform. The waveforms of quarry blasts recorded by the stations of the Mikhnevo small-aperture seismic group remained unchanged for many years. The presence of such base allows to use the cross-correlation waveform method (CCWM) for the automatic identification of seismic events and their association with known quarries. The method is based on the calculation of the correlation coefficient between new records and waveforms available in the database from known events [*Adushkin et al.*, 2015; *Kitov et al.*, 2015].

Registration of events over the past three or four years showed the variability of waveforms from blasts in known quarries and their discrepancy with those stored in the database [*Nesterkina et al.*, 2018]. The main reason for the noted changes is the introduction of new technologies for drilling-and-blasting operations in quarries and the use of new explosives. These measures are aimed at reducing the seismic effect of blasting operations and improving the environmental situation at the quarry sites. However, a decrease in the seismic effect entails a decrease in the signal-to-noise ratio, defined as $R=A_s/A_m$, where A_s is an amplitude of the desired signal; A_m is the amplitude of the microseismic background, which inevitably leads to significant difficulties in registering events, calculating the coordinates of their epicenters and determining their nature. In this situation, a seismic group has increased registration capabilities compared to a single station, due to a higher signal-to-noise ratio on the stacked trace (theoretically, in $\sqrt{N}$, where N is the number of sensors in the group), becomes an effective, if not the only, tool for monitoring technogenic seismicity. The further application of the CCWM allows to unambiguously determine the nature of the event if its waveform is in the database. It was experimentally established that the software used in processing of the Mikhnevo small-aperture seismic array data makes it possible to determine the coordinates of the epicenters of local and regional events with an error of up to ±20 km at distances of about 500 km. The location accuracy is reduced if $R \leq 2$ or if, for technical reasons, not all recording channels of the group are working. In such cases, the error in determining the coordinates of the epicenter can reach 50 km, which entails a false association of the event with the quarry closest to the obtained coordinates or the assignment of the event to the category “nature is not established”. The traditional approach that involves data from other stations is practically unsuitable for the East European platform, since due to its aseismicity there is no network of seismic stations in its central part. The only sources of seismological information in the considered region are observations carried out at the Mikhnevo small-aperture seismic array and the Obninsk Central Seismological Observatory.

The experience of our observations shows that a number of quarry blasts in Kaluga, Vladimir, Moscow, and Tula regions are recorded only by stations of the Mikhnevo group [Nesterkina et al., 2018]. Natural questions arise - whether a small-aperture seismic array is capable of replacing a seismic network and whether the location accuracy of an event according to the data of one seismic array is sufficient for unambiguous identification of its nature. The possibility to find an answer appeared in 2017, when the Institute of Geosphere Dynamics RAS (IDG RAS) installed a temporary seismic network of three observation points equipped with broadband three-component seismic stations, as part of the study of the deep structure of the lithosphere in the central part of the East European platform. The stations of the temporary network, together with the stations of the Mikhnevo small-aperture seismic array, form an areal observation system with distances between registration points of about 100 km.

Registration of seismic events by stations of the Mikhnevo small-aperture array and determination of coordinates of epicenters

In its modern modification, the Mikhnevo small-aperture seismic array (hereinafter - the MHVAR array) consists of 15 stations located on an area of about 1.2 sq. km. Three stations - one short-period (vertical) and two broadband (three-component) - are located in the center of the group, in an adit at the depth of ~20 m; others - eight vertical and four three-component ones - are placed in sealed boxes distributed along three concentric circles at a depth of 1 m [*Sanina et al.,* 2012]. The *ELWIN* program developed at Kola Branch of GS RAS [*Asming*, 2004] is used to process the received data and locate the registered events.

The recordings of the MHVAR group stations can be complicated by rather strong noise associated with both atmospheric processes (the group is located in a forest) and with the agricultural activities of the population (a gardeners’ partnership is located at a distance of about 3 km from the group). In this regard, when processing seismic records, filtering is applied to isolate the desired signal. Filtering is selected taking into account the characteristics of the applied equipment and the most probable frequency of the desired signal. The use of a filter during the primary processing makes it possible to reliably distinguish *P*- and *S*-wave groups for events at regional distances of up to 3000 km. For more detailed processing, the bandpass filter is selected individually for each event. The azimuth to the signal source is determined, which in the presence of a clear first arrival of *P*-wave, is calculated from the delay times of the signal arrival at each sensor. In the absence of a clear first break, two procedures are used to determine the azimuth - – “*beam-forming*” (*B-F*) and *F-k* analysis. The *B-F* procedure assumes the summation of records from different sensors with shifts corresponding to certain values of the direction and velocity of the wave arrival, which leads to the maximization of the desired signal amplitude on the stacked trace; *F-k* analysis is an analogue to the *B-F* procedure in the frequency domain. The algorithm calculates the arriving plane wave azimuth and its apparent velocity for a user-specified fragment of the seismic array record [*Asming*, 2004].

Examples of records of two industrial blasts of different power, produced on 05.01.2015 (M = 2.1) and 28.12.2018 (M = 1.4) in Tula region at the Novogurovsky quarry, that is 60 km away from the MHVAR group, are shown in Fig. 1,2. All records are filtered in 1-10 Hz band; the measurement range of amplitudes in counts is indicated for each trace on the right (1 count – $7.45 \cdot 10^{-3}$ nm / s). The location results of the epicenters of the blasts are shown in the corresponding insets.

On the recordings of the blast on 05.01.2015 (see the upper fragment of Fig. 1), the arrivals of the *P*- and *S*- waves are clearly distinguished due to the high value of the signal-to-noise ratio (R>3); the azimuth was determined from the vertical channels in two ways - from the arrival time delays and using the *B-F* procedure. In both cases, the error was minimal - the discrepancy between the calculated and actual epicenter of the blast was less than 0.5 km. To determine the exact coordinates of the blast on, a temporary seismic station of the IDG RAS was additionally installed on the side of the quarry.

When R>3, the records of three channels are sufficient for confident event location using the *ELWIN* program, which is confirmed by the calculations of coordinates using channels C11, C12, C31 (see the lower fragment of Fig. 1). And in this case, the distance between the calculated epicenter of the blast and the actual one was less than 1 km. Note that if a signal-to-noise ratio is as in the considered example, then even with a minimum number of operating channels, the event epicenter is determined quite accurately from the data of a small-aperture seismic array.

The waveforms characteristic of the Novogurovsky quarry didn’t change for more than 10 years, which made it possible to identify blasts automatically using cross-correlation methods. However, in recent years, the power of blasts in this quarry noticeably decreased - the maximum magnitude of blasts in 2018 was 1.8; at the same time, the signal-to-noise ratio also decreased to R<2.

The waveforms of the blast of lower power, produced at the Novogurovsky quarry on 28.12.2018 (M = 1.4), are shown in Fig. 2. The arrival of the *P*-wave in the records is not clearly distinguished, the azimuth can be determined only using the *B-F* procedure; the error in determining the coordinates of the epicenter in this case was 5 km.

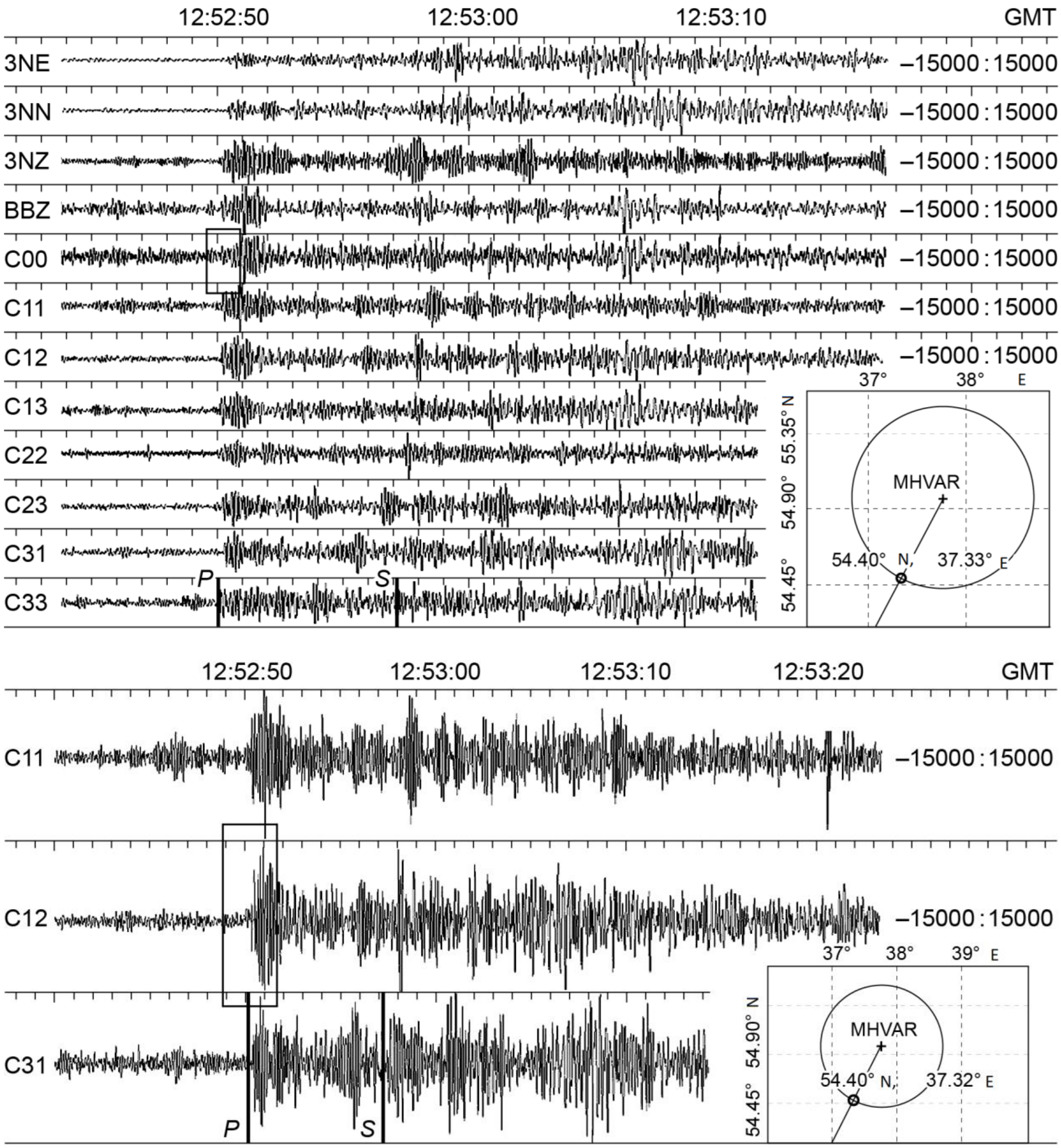

Fig. 1. Quarry "Novogurovsky". Wave forms of the blast on January 5, 2015 (M=2.1), recorded by stations of the MHVAR array. Number of each trace is indicated on the left. On the right is the range of amplitudes in counts (1 count – $7.45 \cdot 10^{-3}$ nm/s). All records are filtered in the 1–10 Hz band. The vertical segments mark the arrival of the P and S waves; rectangular contours – azimuth calculation windows using the *B-F* procedure. The lower fragment shows the location along three paths at R>3. The insets here and below show the results of the location of the epicenter of the blast

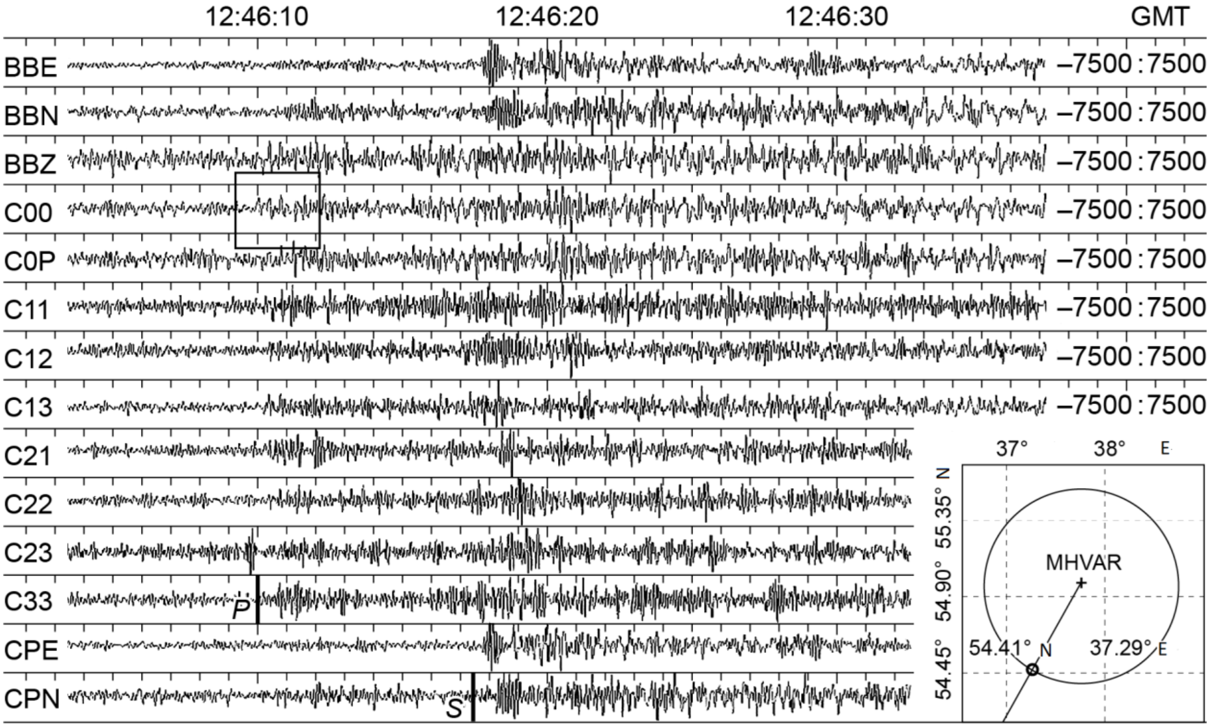

Fig. 2. Quarry "Novogurovsky". Wave forms of the blast of December 28, 2018 (*M*=1.4), recorded by the stations of the MHVAR array, and the results of the location of its epicenter. See comments in Fig. 1

In situations where the error in determining the coordinates of the event epicenter is significant, as in the case of the blast on 28.12.2018 (M = 1.4), they are specified using additional processing methods. For example, it is possible to create generalized waveforms applying to them a wavelet transform [*Sanina et al.*, 2016] and then using the waveform correlation method. A great help in determining the coordinates of the epicenter and identifying the source of the event can be provided by attracting data even from one seismic station located at a distance of several tens of kilometers from the group.

Temporary local seismic network of the Institute of Geosphere Dynamics RAS

The Institute of Geosphere Dynamics RAS installed three temporary seismic points, equipped with broadband three-component sensors as part of the study of the deep structure of the central part of the East European platform in 2017, and they are still continuously recording seismic events. The location of stations is due to the need to construct a sublatitudinal profile for the most complete study of the collision zone of the triple junction of megablocks in the central part of the platform [Structure…, 2006; Deep…, 2010].

Information about the hardware of the temporary network stations, their codes and coordinates are given in the table (hereinafter, when referring to the temporary network stations of the IDG RAS, their codes from the table are used).

Hardware and coordinates of the temporary network stations of the IDG RAS

Registration points	Station code	Coordinates		Sensors	Period, s
		° N	° E		
"Aleksandrovka"	ALX	54.89	35.01	Guralp CMG-6TD	30
"Shatura"	SHAT	55.21	39.97	RefTek 151-60	60

"Voskresensk"	VOSK	55.33	38.88	RefTek 151-60	60

An important condition for estimating the quality of installation of any seismic station is the study of the level of natural noises in the place of its location. In 1993 Peterson [1993] used data from a large number of stations located around the world to obtain the estimates of the parameters of noise spectral density as well as to establish the limits of their variations. For each station of the IDG RAS temporary network, estimates of the spectral noise density were performed based on the records obtained during the first month of registration. Intervals corresponding in time to earthquakes and man-made events were removed from continuous records during the analysis. The obtained curves of the noise spectral density (Fig. 3) lie within the limits established in the named work, which allows to speak about the confident registration of seismic events by the stations of the IDG RAS temporary network.

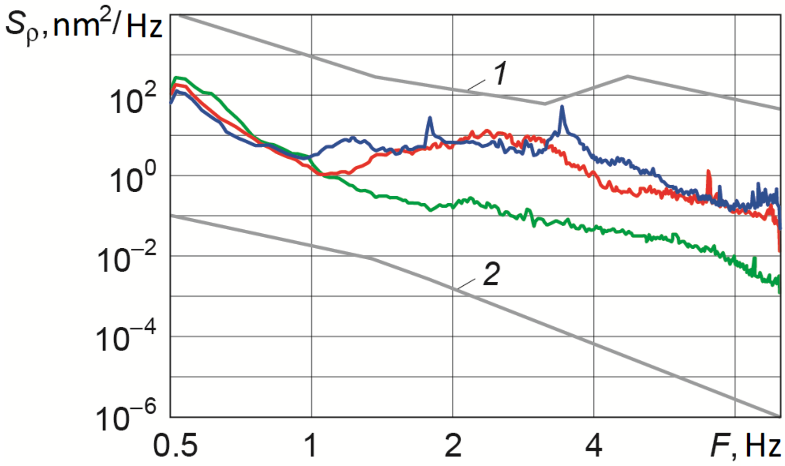

Fig. 3. The distribution of the spectral density of seismic noise obtained for stations of the temporary network of the IDG RAS according to observations for the first month of registration: ALX station (green curve), SHAT station (red), VOSK station (blue). The minimum (curve *1*) and maximum (curve *2*) permissible values of this parameter are shown

It follows from these estimates that the "quietest" is ALX station (green curve in Fig. 3), which is connected, apparently, with its installation in a specially organized Geophysical Observatory at the site of MSU "Aleksandrovka". At this station was recorded the maximum number of events in 2017–2019. The VOSK (blue curve) and SHAT (red curve) stations turned out to be "noisier".

It should be noted that a rather high noise level in 1.5–5 Hz band make difficulties for registration, complicating the location of events at local and regional distances, but does not affect the registration of teleseismic events. An example of registration of the same event by the MHVAR group and stations of the IDG RAS temporary network is shown in Fig. 4.

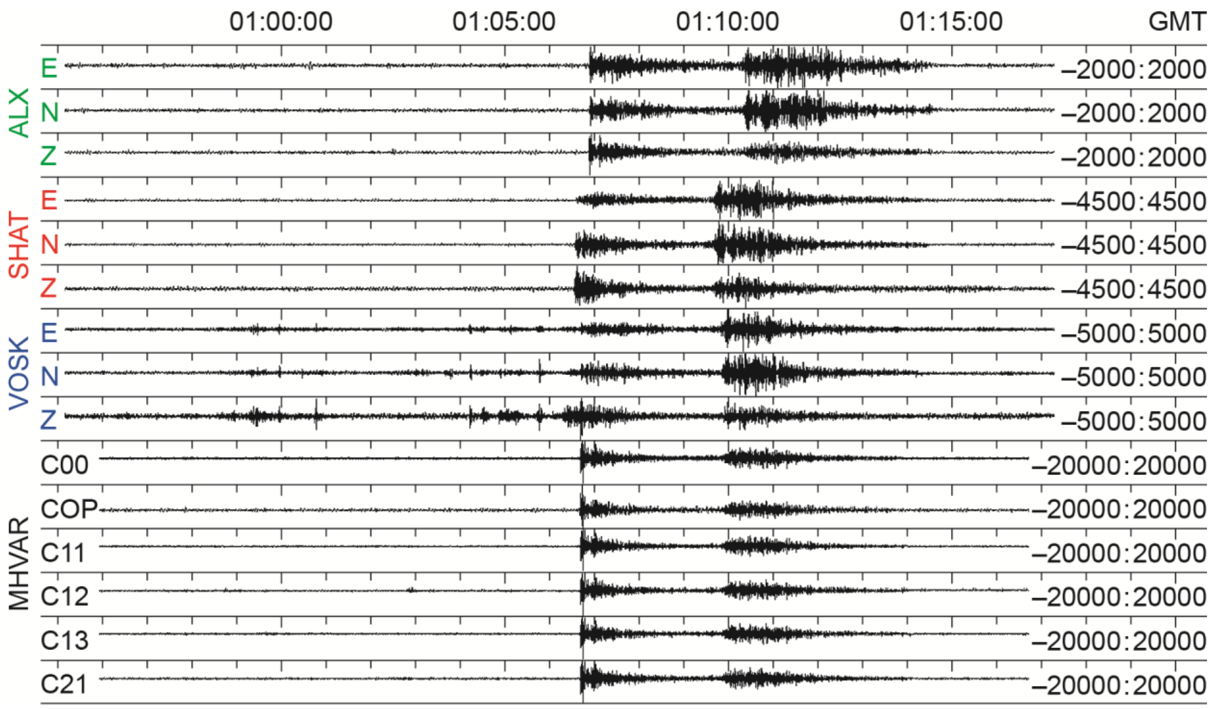

Fig. 4. Wave forms of the earthquake that occurred in Turkmenistan on January 7, 2018 (M=4.9). Records of the components E, N, Z at the stations of the temporary network of the IDG RAS and the records of the Z-component at stations of the MHVAR array are presented. The amplitudes are in counts and indicated on the right: for stations of the MHVAR array, 1 count – $7.45 \cdot 10^{-3}$ nm/s, for stations of the network, 1 count – 1.261 nm/s

The earthquake which records are given in Fig. 4, occurred on 07.01.2018 with the magnitude of 4.9 on the coast of the Caspian Sea in Turkmenistan near the city of Turkmenbashi; the hypocenter of the earthquake was at the depth of 10 km. It can be seen that the first arrivals of the *P*- and *S*-waves are distinguished quite confidently on the records of ALX and SHAT stations. The records of VOSK station contain significant industrial noise, which makes it very difficult to distinguish the *P*- and *S*-wave arrivals for event location.

Unfortunately, the noise level and industrial noise at the stations of the IDG RAS temporary network is very high. If under such conditions the first arrivals of waves from teleseismic earthquakes with M>5 are distinguished quite confidently, then it is often not possible to trace the arrivals of waves when registering events with M<3.

As an example, Fig. 5 shows the record of an explosion carried out on 24.01.2018 (M=2.8) in one of the largest quarry of the Mikhailovsky ore mining and dressing plant, located in the Kursk region.

The given records are filtered, and the first arrivals of *P*- and *S*-waves, registered by the stations of the MHVAR group and the ALX station of the IDG RAS temporary network, are confidently distinguished; at the other stations, it is practically impossible to distinguish the first arrivals.

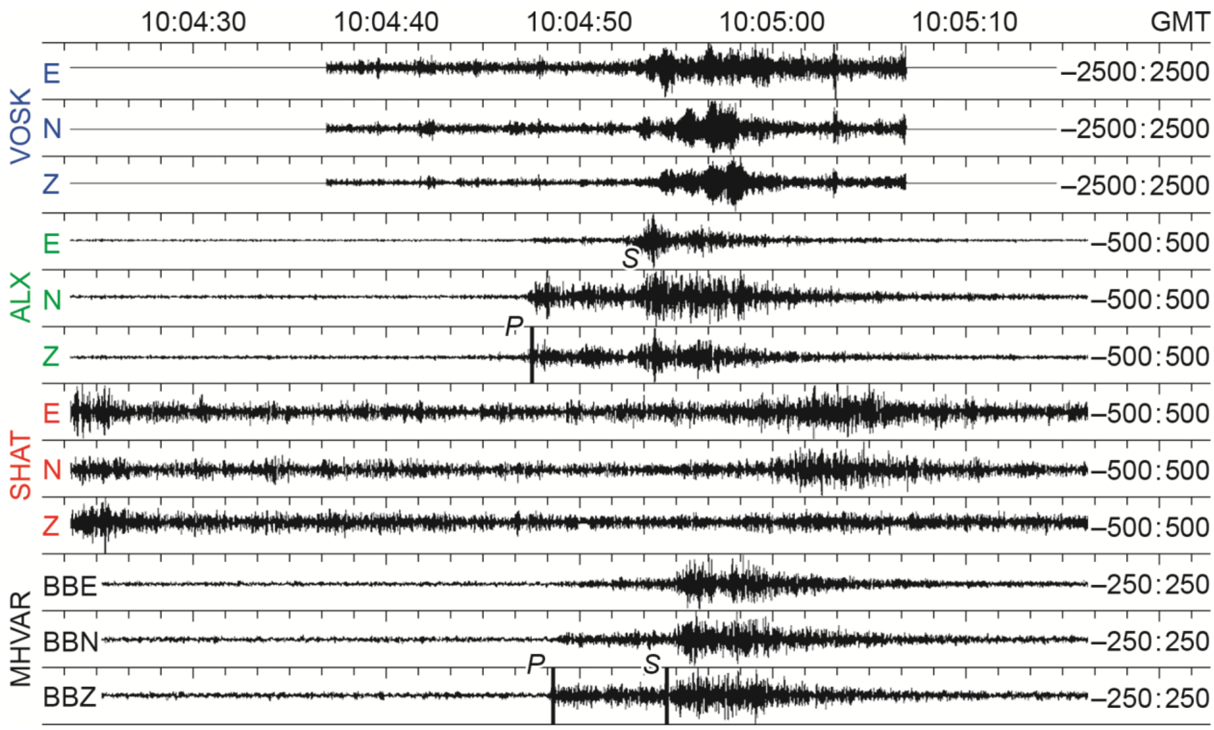

Fig. 5. Wave forms of the blast produced on January 24, 2018 (M=2.8) in the "Mikhailovsky" quarry, Kursk Region. On the records of stations of the MHVAR array and station ALX, the arrivals of P- and S-waves are marked. See comments in Fig. 4

Let us consider in more detail the registration results of seismic events in January 2018, when the stations of the MHVAR group recorded 195 seismic events, 66 of which were industrial explosions. The stations of the IDG RAS temporary network registered 71 events of different nature in the same period. Basically, these were earthquakes at teleseismic distances with M>4, nine events were earthquakes at regional distances of up to 3500 km with M>2.5, twenty were industrial explosions at epicentral distances of 50–500 km with magnitudes of 1.1–3.2, which were chosen to estimate the location accuracy of seismic events according to the MHVAR group data. It is important that these explosions were registered both by the stations of the MHVAR group and the stations of the IDG RAS temporary network.

At first, the coordinates of the epicenters of industrial explosions were determined only by the MHVAR group data, after which they were redefined using the data of the temporary network stations. Comparison of coordinates of the epicenters obtained only from the MHVAR group data and the coordinates "redefined" using the temporary network data showed that for 15 quarry blasts (75% of all considered) the discrepancy in the estimate did not exceed 1–2 km, i.e. the use of additional data did not lead to a significant improvement in the result. For five blasts, the maximum discrepancy in determining the coordinates reached 9 km. A detailed analysis of the recordings of the MHVAR group stations showed a significant noisiness (R<1.5).

As an example, below we consider the results of the location of industrial explosion epicenter produced on 23.01.2018 at 9:58:16 GMT at the Khomyakovo quarry in the Tula region. The quarry is 62 km away from the MHVAR group, 140 km away from the VOSK station, 180 km away from the ALX station and 182 km away from the SHAT station (Fig. 6). The waveforms used for joint processing are shown in Fig. 7, together with the results of the explosion epicenter location at the Khomyakovo quarry.

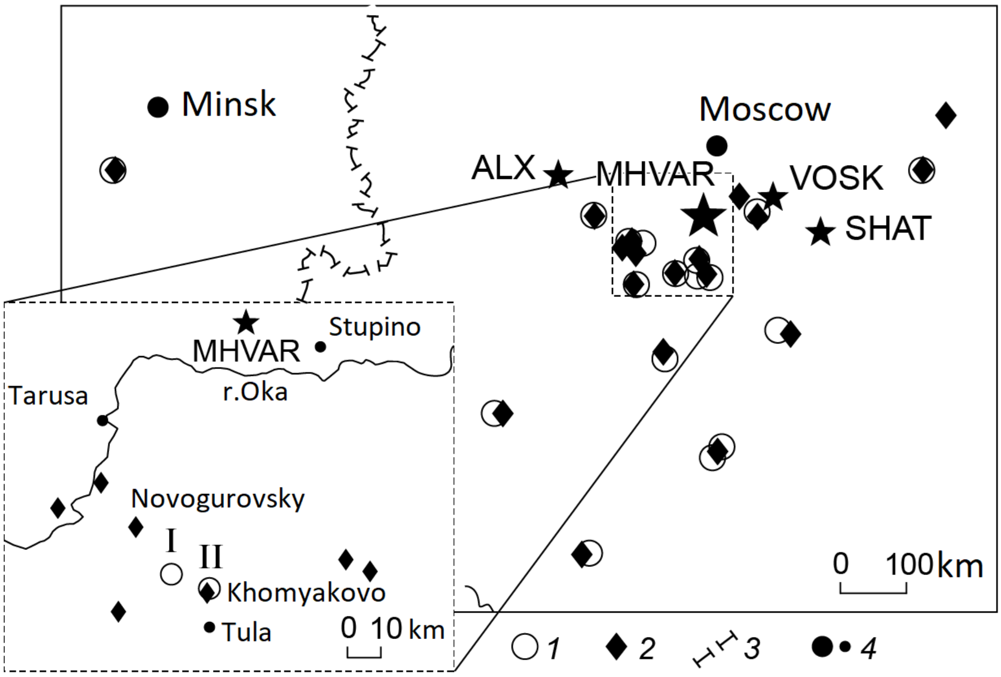

Fig. 6. Scheme The of the epicenters of industrial explosions recorded in January 2018 located by the stations of the Mikhnevo small-aperture array (MHVAR – large asterisk) and the temporary network of the IDG RAS (ALX, VOSK, SHAT – small asterisks): *1* – epicenters of blasts; *2* – quarries; *3* – the state border of the Russian Federation; *4* – settlements. The inset shows the results of the location of the epicenter of the event on January 23, 2018 only according to the MHVAR (I) data and with the use of ALX (II) station data

Initially, processing was carried out only on the records of the MHVAR group stations using the *B-F* procedure. Out of the existing 14 vertical channels, seven were excluded due to the high level of industrial noise in their recordings. Based on the processing results of the records of remaining channels, the epicenter coordinates of the considered blast were obtained – 54.36° N, 37.41° E. When they were compared with the known epicenter coordinates of the blast on 23.01.2018, the location error was 9 km (see inset in Fig. 6).

The record with the highest signal-to-noise ratio obtained at the ALX station was selected from the stations of the IDG RAS temporary network for joint processing with the records of the MHVAR group stations. The waveforms used for joint processing are shown in Fig. 7 together with the results of the joint epicenter location of the blast at the Khomyakovo quarry (inset).

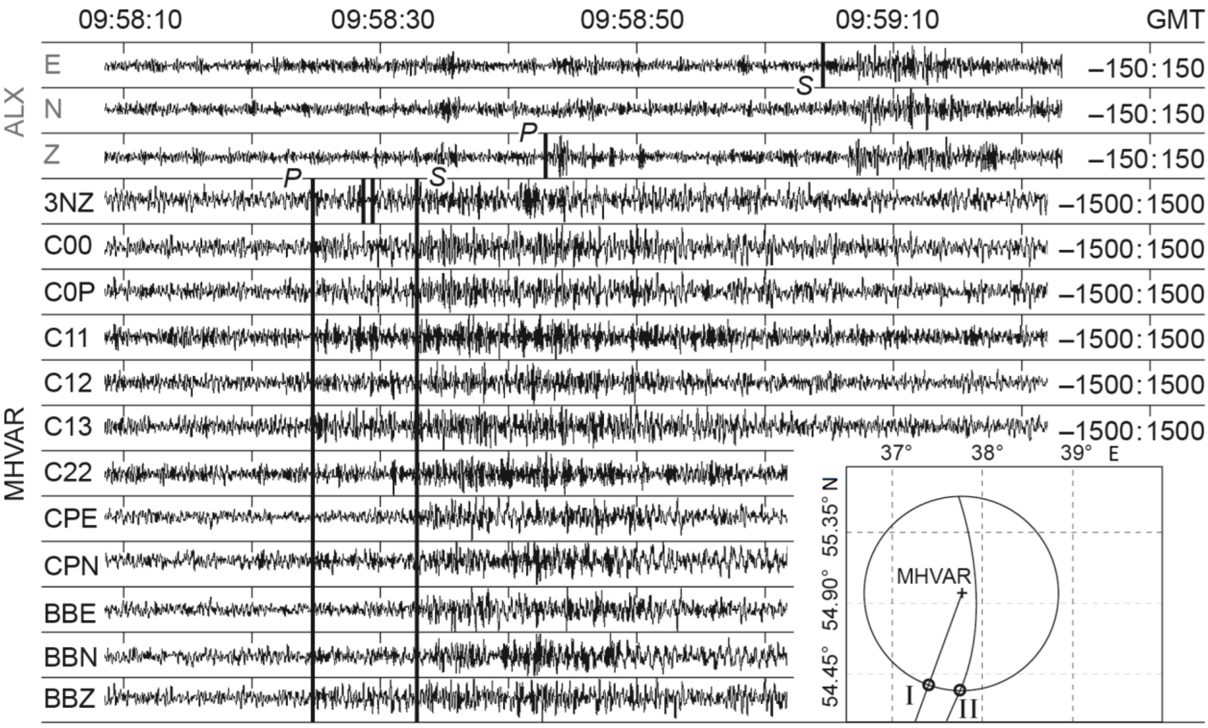

Fig. 7. Quarry "Khomyakovo". The waveforms of the blast on January 23, 2018 and the results of the location of its epicenter according to records of the ALX station and stations of the MHVAR array. For each record, the names of the channels are indicated on the left, the range of measurements of the amplitudes in counts on the right (for the MHVAR array 1 count – $7.45 \cdot 10^{-3}$ nm/s, the ALX station 1 count – 1.261 nm/s). The inset shows the results of the location of the epicenter of the event only according to the data of the MHVAR (I) array and with the use of ALX (II) station data

The coordinates 54.34° N, 37.62° E obtained from the results of joint location using the records of the MHVAR group stations and the station of the temporary network ALX are in good agreement with the coordinates provided by the administration of the Khomyakovo quarry - the calculated location error was only 1.5 km. The diagram shown in the inset to Fig. 6, clearly demonstrates that the processing of a small-aperture seismic array data, supplemented by records from only one station of the temporary network, made it possible to determine the event epicenter coordinates with higher accuracy.

Conclusions

The studies presented in this work convincingly demonstrate the effectiveness of using a small-aperture seismic array to monitor weak seismicity in the central part of the East European platform. Two aspects should be noted here.

1. In contrast to a single station, a small-aperture group usually registers a much larger number of events. When the waveforms of the registered events coincide with the wave "portraits" available in the database, the event is unambiguously identified.

2. With a confident identification of the arrivals of seismic waves ($R \geq 2$), the small-aperture group independently ensures high accuracy of the epicenter location and the subsequent association of the event with the closest quarry. As it was shown, the location accuracy largely depends on the level of microseismic noise (on the signal-to-noise ratio). With a low signal-to-noise ratio ($R \leq 2$), the location accuracy decreases, and in this case the data received

from the additional station can be useful. But this station must be installed on a special pedestal in an area with a low level of microseismic interference.

In our opinion, the further development of seismological observations in the most urbanized part of the East European platform should go along the path of improving the methods of processing seismic event registration data. For the small-aperture seismic array Mikhnevo, the solution to this problem should be the expansion of the base of waveforms with an increase in their duration, including the group of surface waves; creation of generalized wave "portraits", that take into account changes in the form of the recording; creation of a data bank of “characteristic” frequencies for each quarry; improving the cross-correlation waveform method, and the use of new methods for signal extraction.

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