Technology for Determining Time of Origin and Coordinates of Anomalous Seismic Processes

Telman Aliev[1], Ali Abbasov[2], Gambar Guluyev[3], Fahrad Pashayev[4],
Adalat Pashayev[5], Elkhan Sabziev[6], Ulkar Sattarova[7]
[1,3-7]Cybernetics Institute of ANAS, Baku, Azerbaijan
[2]The Ministry of Communications and Information Technologies of the Republic of Azerbaijan, Baku, Azerbaijan
[1]*telmancyber@rambler.ru*, [2]*ali@dcacs.ab.az*, [3]*scb_06@mail.ru*, [4]*farhad_pasha@mail.ru*,
[5]*adalat@kiber.az*, [6]*elkhan@kiber.az*, [7]*ulker.rzaeva@gmail.com*

***Abstract*— Analysis of seismic information received by means of acoustic sensors installed at the head of oil wells proved that when anomalous seismic processes (ASP) arise, seismic-acoustic waves spread in deep strata of the earth several tens of hours earlier than the expected earthquake is registered by ground seismic stations. Technology is offered for robust noise analysis of seismic-acoustic signals, as well as models and algorithms for determining the coordinates of ASP focus by means of stations built at suspended oil wells in 4 seismically active regions of Azerbaijan.**

***Keywords*— anomalous seismic processes; correlation functions; identification; monitoring; noise; robust estimates; coordinates; seismic-acoustic station**

I. Introduction

When an ASP enters its critical state, an earthquake occurs. Boundaries of the earthquake focus and magnitude cannot be determined with sufficient precision and depend on the structure and nature of the strain-stress distribution in rocks in the particular place. Rock deformation is uneven and transmits elastic waves. Volume of deformed rocks is an important factor determining strength of seismic impact and liberated energy. Each main burst is preceded by quite a long period of time of earthquake preparation. This period can last for from several hours to several days. The principle of building stations for robust noise monitoring of anomalous seismic processes (RNM ASP) has been offered for the purpose of monitoring of the beginning of time. The stations have been commissioned in four seismically active regions of Azerbaijan (Fig. 1) [1,2].

As Fig. 1 shows, those stations have the following geographical coordinates:

Baku (Qum Island):	40.310425°, 50.008392°
Siazan:	41.046217°, 49.172058°
Qoranboy:	40.609521°, 46.791458°
Shirvan:	39.933170°, 48.920745°

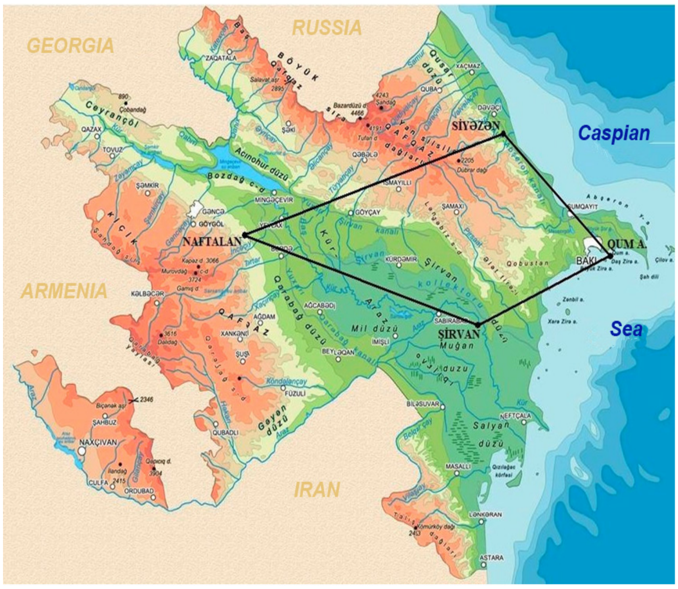

Figure 1. Location of RNM ASP stations in seismically active regions of Azerbaijan

Time span T_1 from the beginning point of preparation process to the moment when the critical state forms and an actual earthquake occurs can be regarded as ASP period. Experiments carried out at RNM ASP stations demonstrated that seismic-acoustic waves in that period spread in deep strata of the earth without reaching the upper strata, thereby not being registered by ground seismic stations. Meanwhile, they are direct precursors of earthquake preparation process. Regular ground stations register seismic oscillations much later, only when an earthquake occurs.

RNM ASP stations have been built for analysis of seismic-acoustic signals in ASP period and installed at the head of suspended oil wells. They receive noisy seismic-acoustic signals from deep strata of the earth (over 3-6 km) by means of hydrophones.

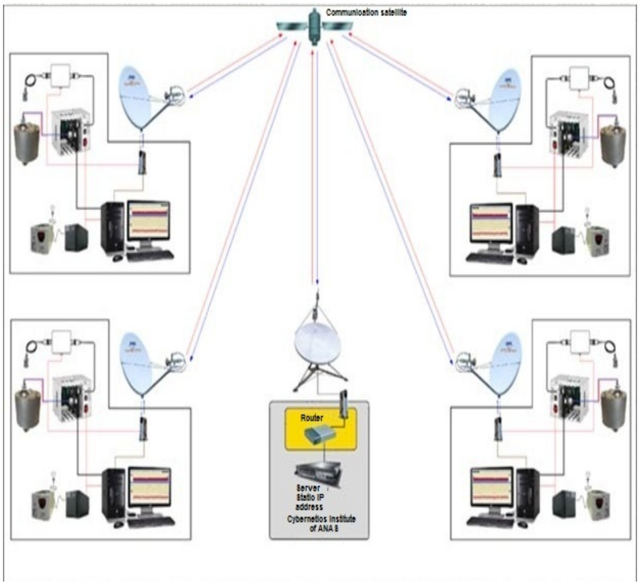

Figure 2. Seismic-acoustic monitoring system

Each station performs continuous monitoring of both seismic-acoustic and seismic signals (Fig. 2). Measuring and analysis results are sent from each station to the server of the seismic-acoustic monitoring center via a high speed radio channel with satellite communication. The seismic-acoustic monitoring center is located at the Cybernetics Institute. The system also can transfer received data to server of other monitoring centers.

Synchronous analysis of noise of seismic-acoustic signals from deep strata of the earth performed by means of the above-mentioned technologies confirmed that seismic-acoustic waves of ASP spread within a radius of 300-500 km dozens of hours earlier than seismic waves registered by ground seismic stations, which calls forth wide application of those technologies in seismology.

To carry out large-scale experiments on ASP monitoring, since 01.05.2010, as Fig. 1 shows, at Qum Island, in Shirvan, Siazan, Naftalan RNM ASP stations have been put to operation one by one.

Operating experience of RNM ASP stations and the obtained experimental data demonstrate that synchronous analysis of seismic-acoustic signals received from all four RNM ASP stations, with known stable average velocity of expansion of seismic processes in deep strata of the earth, create a possibility to determine coordinates of the focus and beginning of ASP origin.

However, operation of those stations has also showed that each of them allows indicating the process of origin of ASP, which precede an earthquake, within a radius of 300-500 km. On the other hand, their practical application in seismology first of all requires that they should allow one determining the coordinates and approximate time of an expected earthquake.

II. Problem Statement

Delayed registration of earthquakes by known types of standard ground seismic stations creates a grave problem for countries located in seismically active regions, which in its turn leads to serious casualties.

Therefore, development of new and more effective technologies and systems for monitoring of the beginning of origin of anomalous seismic processes is both of scientific and great practical interest [*Aliev, Guluyev et al. 2009, Aliev 2007*]. It is known that in many seismically active regions [*Sidorin* 1992; *Aliev 2007; Aliev, Abbasov et al. 2007; Aliev, Abbasov 2005; Aliev, Alizada et al. 2005; Aliev, Abbasov 2006 et al.; Aliev, Abbasov 2009 et al.*], the time of normal seismic state T_0 between occasional ASP varies within the range of several weeks or months. The period of time of origin and formation of ASP T_1 can last several hours or more. The period of time of the critical state T_2, when seismic waves reach the earth's surface and an earthquake occurs is estimated at minutes, after which a new period of rest T_0 begins. It is therefore appropriate to reduce the problem of monitoring and short-term earthquake prediction to provision of reliable indication of the start of the latent period of ASP origin T_1. The known existing systems and widely applied seismic stations are designated for registration of the start of period T_2. Unfortunately, their functions do not include reliable and adequate monitoring of the start of period T_1, which is one of the grave shortcomings of the modern systems and means of both control and monitoring of seismic processes, while indication of the start of period T_1 is the basic mission of monitoring systems.

Thereby, let us consider the matter in more detail. Assume that in the normal seismic state in the period of time T_0, the known classical conditions hold true for noisy seismic acoustic signals $g(i\Delta t) = X(i\Delta t) + \varepsilon(i\Delta t)$ received as the output of corresponding acoustic sensors, for instance, hydrophones, i.e. the equalities are true [*Aliev, Guluyev et al. 2009*]:

$$\omega_{T_0}\left[g(i\Delta t)\right] = \frac{1}{\sqrt{2\pi D_g}} e^{-\frac{(g(i\Delta t))^2}{2D_g}}, D_\varepsilon \approx 0,\ D_g \approx D_X;$$
$$R_{gg}(\mu) \approx R_{XX}(\mu); m_g \approx m_X; m_\varepsilon \approx 0;\ R_{X\varepsilon}(\mu = 0) \approx 0,$$
$$r_{X\varepsilon} \approx 0 \tag{1}$$

where $\omega_{T_0}\left[g(i\Delta t)\right]$ is $g(i\Delta t)$ signal distribution law; D_ε, D_X, D_g are the estimates of variance of the noise $\varepsilon(i\Delta t)$, the useful signal $X(i\Delta t)$ and the sum signal $g(i\Delta t)$ respectively; $R_{XX}(\mu)$, $R_{gg}(\mu)$ are the estimates of correlation functions of the useful signal $X(i\Delta t)$ and the sum signal $g(i\Delta t)$; m_ε, m_X, m_g are mathematical expectations of the noise $\varepsilon(i\Delta t)$, the useful signal and the sum signal; $R_{X\varepsilon}(\mu=0)$, $r_{X\varepsilon}$ are the cross-correlation function and the coefficient of correlation of the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$.

However, when the latent period of ASP origin T_1 begins, the condition (1) is violated, i.e. [*Aliev 2007; Aliev, Abbasov et al. 2007; Aliev, Abbasov 2005; Aliev, Alizada et al. 2005; Aliev, Abbasov 2006 et al.; Aliev, Abbasov 2009 et al.*]:

$$\omega_{T_0}[g(i\Delta t)] \neq \omega_{T_1}[g(i\Delta t)],\ D_\varepsilon \neq 0,\ D_g \neq D_X,$$
$$R_{gg}(\mu) \neq R_{xx}(\mu),\ m_g \neq m_x,\ R_{X\varepsilon}(\mu=0) \neq 0\ \ r_{X\varepsilon} \neq 0 \tag{2}$$

The period of the normal seismic state T_0 ends and the period of ASP origin T_1 begins. As a result, due to the violation of the equality (1), statistical estimates of the seismic-acoustic signal $g(i\Delta t)$ are determined with certain inaccuracy. Therefore, timely detection of the initial stage of ASP origin by means of conventional technologies is complicate in the period of time T_1 [*Aliev, Abbasov 2005; Aliev, Alizada et al. 2005; Aliev, Abbasov 2006 et al.*]. Meanwhile, the transition of ASP from the time span T_1 into the time span T_2 is registered reliably by means of analysis of seismic signals received at the outputs of seismic sensors. Standard seismic stations therefore register only the period of time T_2 of ASP reaching its critical state, when the earthquake occurs, which explains the delay in results of monitoring and short-term earthquake prediction with application of conventional technologies. Registration of ASP origin in the period of time T_1 therefore requires development of technology for analysis of the noise of seismic-acoustic signal as a carrier of diagnostic information about the moment when equalities (1) are violated.

The paper considers one of the alternative ways to solve those tasks.

Determining coordinates of the focus of ASP that precede an earthquake is an important problem of practical application of RNM ASP stations in seismology. Let us first consider the existing methods for calculation of earthquake focuses [6-7] based on seismic information obtained by means of the network of existing standard seismic stations.

It is known that in such cases, difference between the amounts of time it takes basic seismic waves P and S to reach ground seismic stations is used to determine the earthquake focus. P wave velocity is higher than S wave velocity. P wave velocity in homogeneous isotropic medium is determined from the expression

$$v_P = \sqrt{\frac{k + \frac{4}{3}\mu}{\rho}}$$

where k is volume coefficient, μ is shear modulus, ρ is density of the material penetrated by waves.

S wave velocity is calculated from the following expression:

$$v_S = \sqrt{\frac{\mu}{\rho}}$$

where μ is shear modulus, ρ is density of the material penetrated by waves.

The distance from the standard seismic station to the focus is found by multiply time difference by velocity difference:

$$S = \Delta T (v_p - v_s)$$

After the distance between the focus and different seismic stations has been determined, coordinates of the focus are found geometrically.

There are papers on determining coordinates of earthquake hypocenters and error analysis in determination of earthquake coordinates [8,9]. Unfortunately, it should be noted that in all known cases coordinates of focuses and hypocenters in seismic monitoring systems are determined after actual earthquakes.

However, as our experiments and operational experience of RNM ASP seismic-acoustic stations showed, application of the above-mentioned methods to determining the distance from stations to ASP focus is practically impossible. The present paper therefore considers one of possible solutions to the problem of determining the time of registration of ASP in RNM ASP stations and coordinates of ASP focus.

III. Robust Noise Technology of Monitoring of the Beginning of ASP Origin

It is known that in standard ground seismic stations, seismic signals are sampled at a frequency of 150-200 Hz. It is also known that to use noise of seismic-acoustic signal as a carrier of useful information, it has to be sampled at a much higher frequency [5, pp. 32-37]. Experiments at RNM ASP stations demonstrated that it is most appropriate to sample seismic-acoustic signals at a frequency $f = 2000$ Hz and higher. Considering that a seismic-acoustic signal is

$$g(i\Delta t) = X(i\Delta t) + \varepsilon(i\Delta t)$$

where $g(i\Delta t)$ is the noisy seismic-acoustic signal received from deep strata of the earth by means of suspended oil wells, $X(i\Delta t)$ is the useful signal, $\varepsilon(i\Delta t)$ is the noise, Δt is sampling interval and i is the sequence number of sampled readings.

In this case, sampling interval can be determined from the expression

$$\Delta t = \frac{1}{2000} = 0.0005\ s$$

Experimental researches carried out at RNM ASP stations demonstrated that when an ASP originates at the start of time T_1, the noise of seismic-acoustic signal becomes the basic carrier of information. The reason is that in the time T_0 in the normal state of seismic processes, the noise $\varepsilon(i\Delta t)$ emerges due to random external factors, which have no correlation with the useful signal. However, in the time T_1, when an ASP originates, the noise $\varepsilon(i\Delta t)$ forms due to the influence of the seismic processes related to its deviation from the normal state. Therefore, in the period of time T_1, correlation arises between the noisy signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ and the inequalities $R_{X\varepsilon}(\mu) \neq 0$, $r_{X\varepsilon} \neq 0$ take place.

Thereby, let us consider one of the alternative methods of approximate calculation of the indicated estimates. For that end, let us represent the known expression

$$D_g = R_{gg}(\mu = 0) = \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)g(i\Delta t) = \frac{1}{N}\sum_{i=1}^{N} g^2(i\Delta t) \tag{3}$$

as follows:

$$R_{gg}(\mu = 0) = \frac{1}{N}\sum_{i=1}^{N}\left[X(i\Delta t) + \varepsilon(i\Delta t)\right]^2 \tag{4}$$

It is obvious that by opening the brackets we will get the following

$$R_{gg}(\mu = 0) = \frac{1}{N}\sum_{i=1}^{N} X^2(i\Delta t) + \frac{1}{N}\sum_{i=1}^{N} 2\left[X(i\Delta t)\cdot\varepsilon(i\Delta t)\right] + \\ + \frac{1}{N}\sum_{i=1}^{N}\varepsilon^2(i\Delta t) \tag{5}$$

Assuming the following notations

$$\frac{1}{N}\sum_{i=1}^{N} 2\left[X(i\Delta t)\varepsilon(i\Delta t)\right] + \frac{1}{N}\sum_{i=1}^{N}\varepsilon^2(i\Delta t) = R_{X\varepsilon\varepsilon}(\mu = 0) \tag{6}$$

$$\frac{1}{N}\sum_{i=1}^{N} X^2(i\Delta t) = R_{XX}(\mu = 0) \tag{7}$$

$$\frac{1}{N}\sum_{i=1}^{N} 2\left[X(i\Delta t)\varepsilon(i\Delta t)\right] = 2R_{X\varepsilon}(\mu = 0) \tag{8}$$

$$\frac{1}{N}\sum_{i=1}^{N}\varepsilon^2(i\Delta t) = R_{\varepsilon\varepsilon}(\mu = 0) = D_\varepsilon \tag{9}$$

where $R_{X\varepsilon\varepsilon}(\mu = 0)$ is the estimate of noise correlation value, $R_{X\varepsilon}(\mu = 0)$ is the estimate of cross-correlation function between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$, $R_{\varepsilon\varepsilon}(\mu = 0) = D_\varepsilon$ is variance of noise $\varepsilon(i\Delta t)$, we get

$$R_{gg}(\mu = 0) = R_{XX}(\mu = 0) + 2R_{X\varepsilon}(\mu = 0) + R_{\varepsilon\varepsilon}(\mu = 0) \tag{10}$$

Thereby, the approximate estimate of noise correlation value $R_{X\varepsilon\varepsilon}(\mu = 0)$ and cross-correlation function between $R_{X\varepsilon}(\mu = 0)$ between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$ can be determined by means of the following expressions:

$$R_{X\varepsilon\varepsilon}(\mu = 0) = R_{gg}(\mu = 0) - R_{XX}(\mu = 0) \tag{11}$$

$$2R_{X\varepsilon}(\mu = 0) = R_{gg}(\mu = 0) - R_{XX}(\mu = 0) - R_{\varepsilon\varepsilon}(\mu = 0) \tag{12}$$

It is known [*Aliev* 2007] that that with the corresponding sampling interval Δt and with equality (1) being true, the following approximate equalities can be regarded as true:

$$\left.\begin{array}{l} R_{gg}(\mu = 1) \approx R_{XX}(\mu = 1) \\ R_{gg}(\mu = 2) \approx R_{XX}(\mu = 2) \\ R_{gg}(\mu = 3) \approx R_{XX}(\mu = 3) \end{array}\right\} \tag{13}$$

$$\left.\begin{array}{l} \Delta R_{gg}(\mu=1) = R_{gg}(\mu=0) - R_{gg}(\mu=1), \Delta R_{XX}(\mu=1) = R_{XX}(\mu=0) - R_{XX}(\mu=1) \\ \Delta R_{gg}(\mu=2) = R_{gg}(\mu=1) - R_{gg}(\mu=2) \approx R_{XX}(\mu=1) - R_{XX}(\mu=2) = \Delta R_{XX}(\mu=2) \\ \Delta R_{gg}(\mu=3) = R_{gg}(\mu=2) - R_{gg}(\mu=3) \approx R_{XX}(\mu=2) - R_{XX}(\mu=3) = \Delta R_{XX}(\mu=3) \end{array}\right\} \tag{14}$$

$$\left.\begin{array}{l}\Delta R_{gg}(\mu=2)\approx\Delta R_{XX}(\mu=2)\approx\Delta R_{XX}(\mu=1)\\ \Delta R_{gg}(\mu=3)\approx\Delta R_{XX}(\mu=3)\approx\Delta R_{XX}(\mu=2)\end{array}\right\} \qquad (15)$$

Under of equations (12)-(13), the following may be written

$$\left.\begin{array}{l}R_{XX}(\mu=0)=R_{XX}(\mu=1)+\Delta R_{XX}(\mu=1)\\ R_{XX}(\mu=0)\approx R_{XX}(\mu=1)+\Delta R_{XX}(\mu=2)\end{array}\right\} \qquad (16)$$

Taking into account expressions (10)-(14), the following may be written

$$\begin{array}{l}R_{XX}(\mu=0)\approx R_{XX}(\mu=1)+\Delta R_{XX}(\mu=1)\approx\\ \approx R_{gg}(\mu=1)+[R_{gg}(\mu=2)-R_{gg}(\mu=3)]\end{array} \qquad (17)$$

Expression (10) can therefore be represented as follows:

$$\begin{array}{l}R_{gg}(\mu=0)=R_{gg}(\mu=1)+[R_{gg}(\mu=2)-\\ -R_{gg}(\mu=3)]+2R_{X\varepsilon}(\mu=0)+R_{\varepsilon\varepsilon}(\mu=0)\end{array} \qquad (18)$$

Taking into account that $R_{\varepsilon\varepsilon}(\mu=0)$ is noise variance, expression (18) can be represented as follows:

$$R_{X\varepsilon}(\mu=0)\approx\frac{1}{2}\left[R_{gg}(\mu=0)-\left[R_{gg}(\mu=1)+\left(R_{gg}(\mu=2)-R_{gg}(\mu=3)\right)\right]-D_{\varepsilon}\right] \qquad (19)$$

The value of noise correlation $R_{X\varepsilon\varepsilon}(\mu=0)$ in this case can be determined by means of the following expression:

$$R_{X\varepsilon\varepsilon}(\mu=0)=\frac{1}{2}\left[R_{gg}(\mu=0)-\left[R_{gg}(\mu=1)+\left(R_{gg}(\mu=2)-R_{gg}(\mu=3)\right)\right]\right]=$$

$$=\frac{1}{2N}\sum_{i=1}^{N}\left[g(i\Delta t)g(i\Delta t)-\left[g(i\Delta t)g((i+1)\Delta t)+g(i\Delta t)g((i+2)\Delta t)-g(i\Delta t)g((i+3)\Delta t)\right]\right] \qquad (20)$$

It should be noted that the following expression can be used to calculate the estimate of noise variance in the absence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$

$$D_{\varepsilon}=\frac{1}{N}\sum_{i=1}^{N}\left[g(i\Delta t)g(i\Delta t)-2g(i\Delta t)g(i+2)\Delta t+g(i\Delta t)g(i+1)\Delta t\right]$$

. (21)

In the presence of correlation, however, it is inappropriate to use this formula for determination of the estimate of the noise variance D_{ε}. The technology of determination of the estimate of noise variance D_{ε} will therefore be considered in the following paragraphs.

In expressions (19), (20), readings of $g(i\Delta t)$, $g((i+1)\Delta t)$, $g((i+2)\Delta t)$, $g((i+3)\Delta t)$ are used to calculate the required estimates, similarly to the traditional algorithm. Formulas (19), (20) are therefore easily implemented in practice on widely used controllers and on personal computers. Naturally, after determination of the estimates of the noise variance D_{ε}, it will be also possible to calculate the coefficient of correlation $r_{X\varepsilon}$ between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$, if necessary.

It is clear that in the period of time T_0 in the monitoring of ASP origin, estimates of the noise correlation $R^{*}_{X\varepsilon\varepsilon}(\mu=0)$, cross-correlation function $R_{X\varepsilon}(\mu=0)$ and the coefficient of correlation $r_{X\varepsilon}$ between the useful signal and the noise of the acoustic signal received from deep strata of the earth will be close to zero due to the absence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$. It is also obvious that when an ASP originates in the period of time T_1, the value of noise correlation estimate $R_{X\varepsilon\varepsilon}(\mu=0)$ will increase sharply due to the emergence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$. Thus, the estimate $R_{X\varepsilon\varepsilon}(\mu=0)$ will be different from zero from the very start in the whole course of ASP, mirroring the presence of correlation.

IV. Technology of Determination of Estimates of Cross-Correlation Function and Coefficient of Correlation between the Useful Seismic Acoustic Signal and Its Noise

Let us now consider one of possible methods of determination of cross-correlation function $R_{X\varepsilon}(\mu=0)$ between the useful seismic acoustic signal $X(i\Delta t)$ and its noise $\varepsilon(i\Delta t)$ using the technology of calculation of estimates of relay correlation functions $R^{*}_{gg}(\mu=0)$. For that end, let us first assume the following notations:

$$\operatorname{sgn} g(i\Delta t)=\operatorname{sgn} x(i\Delta t)=\left\{\begin{array}{l}1\ at\ g(i\Delta t)\geq 0\\ 0\ at\ g(i\Delta t)<0\end{array}\right\} \qquad (22)$$

$$\left.\begin{array}{ll} \frac{1}{N}\sum_{i=1}^{N} Sgn\, g(i\Delta t)\cdot \varepsilon(i+\mu)\Delta t = 0 & at\ \mu = 0 \\ \frac{1}{N}\sum_{i=1}^{N} Sgn\, g(i\Delta t)\cdot \varepsilon(i+\mu)\Delta t \neq 0 & at\ \mu \neq 0 \\ \frac{1}{N}\sum_{i=1}^{N} \varepsilon(i\Delta t)\cdot \varepsilon(i\Delta t) \neq 0 & at\ \mu = 0 \\ \frac{1}{N}\sum_{i=1}^{N} \varepsilon(i\Delta t)\cdot \varepsilon(i+\mu) = 0 & at\ \mu \neq 0 \end{array}\right\} \quad (23)$$

The formula for determination of estimates of relay correlation functions $R^*_{gg}(\mu=0)$ in the presence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$ can be represented as follows:

$$R^*_{gg}(\mu=0) = \frac{1}{N}\sum_{i=1}^{N} \operatorname{sgn} g(i\Delta t) g(i\Delta t) =$$
$$= \frac{1}{N}\sum_{i=1}^{N} \operatorname{sgn} g(i\Delta t)\cdot[X(i\Delta t)+\varepsilon(i\Delta t)] =$$

$$= \frac{1}{N}\sum_{i=1}^{N} [[\operatorname{sgn} g(i\Delta t)\cdot X(i\Delta t)] + [\operatorname{sgn} g(i\Delta t)\cdot \varepsilon(i\Delta t)]] =$$

$$= \frac{1}{N}\sum_{i=1}^{N} \operatorname{sgn} g(i\Delta t) X(i\Delta t) + \frac{1}{N}\sum_{i=1}^{N} \operatorname{sgn} g(i\Delta t)\cdot \varepsilon(i\Delta t) =$$

$$= \frac{1}{N}\sum \operatorname{sgn} X(i\Delta t) X(i\Delta t) + \frac{1}{N}\sum_{1} \operatorname{sgn} X(i\Delta t)\varepsilon(i\Delta t) =$$
$$= R^*_{XX}(\mu=0) + R^*_{X\varepsilon}(\mu=0)$$

. (24)

It is known [*Aliev, Guluyev et al. 2009, Aliev 2007; Aliev, Abbasov et al. 2007; Aliev, Abbasov 2005*] that in the absence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$, with conditions (22), (23) taken into account, the following approximate equalities can be regarded as true for estimates of relay correlation function:

$$R^*_{gg}(\mu=0) - R^*_{gg}(\mu=1) \approx R^*_{gg}(\mu=1) - R^*_{gg}(\mu=2) \approx$$
$$\approx R^*_{gg}(\mu=2) - R^*_{gg}(\mu=3) \approx R^*_{gg}(\mu=3) - R^*_{gg}(\mu=4) \quad (25)$$

$$R^*_{XX}(\mu=0) - R^*_{XX}(\mu=1) \approx R^*_{XX}(\mu=1) - R^*_{XX}(\mu=2) \approx$$
$$\approx R^*_{XX}(\mu=2) - R^*_{XX}(\mu=3) \approx R^*_{XX}(\mu=3) - R_{XX}(\mu=4) \quad (26)$$

$$\Delta^* R_{gg}(\mu=0) \approx \Delta R^*_{gg}(\mu=1) \approx$$
$$\approx \Delta R^*_{gg}(\mu=2) \approx \Delta R^*_{gg}(\mu=3) \quad (27)$$

$$\Delta^* R_{XX}(\mu=0) = \Delta R^*_{XX}(\mu=1) \approx$$
$$\approx \Delta R_{XX}(\mu=1) \approx \Delta^* R_{XX}(\mu=2) \approx \Delta R^*_{XX}(\mu=3) \quad (28)$$

At the same time, when correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$ takes place, the following expressions can be regarded as true

$$\Delta R^*_{gg}(\mu=0) - \Delta R_{gg}(\mu=1) \neq$$
$$\neq \Delta R_{gg}(\mu=1) - \Delta R_{gg}(\mu=2) \quad (29)$$

$$\left.\begin{array}{l} \Delta R_{gg}(\mu=1) - \Delta R_{gg}(\mu=2) \approx \Delta R_{gg}(\mu=2) - \Delta R_{gg}(\mu=3) \approx \Delta R_{gg}(\mu=3) - \Delta R_{gg}(\mu=4) \approx 0 \\ \Delta R_{XX}(\mu=1) - \Delta R_{XX}(\mu=2) \approx \Delta R_{gg}(\mu=2) - \Delta R_{gg}(\mu=3) \approx \Delta R_{gg}(\mu=3) - \Delta R_{gg}(\mu=4) \approx 0 \end{array}\right\} \quad (30)$$

It follows from equality (24) that the estimate of relay correlation function $R^*_{X\varepsilon}(\mu=0)$ can be determined from the formula:

$$\Delta R^*_{gg}(\mu=0) \approx R^*_{XX}(\mu=0) + R^*_{X\varepsilon}(\mu=0) \quad (31)$$

$$R^*_{X\varepsilon}(0) \approx R_{gg}(\mu=0) - R_{XX}(\mu=0) \quad (32)$$

Therefore, to calculate $R^*_{X\varepsilon}(\mu=0)$ by means of the expression (32), $R_{XX}(\mu=0)$ must be calculated. Equalities (24)–(29) imply that the estimate $R^*_{XX}(\mu=0)$ can be calculated by means of the following expression

$$R^*_{XX}(\mu=0) \approx R^*_{XX}(\mu=1) + \Delta R^*_{XX}(\mu=1) \approx$$
$$\approx R^*_{gg}(\mu=1) + \Delta R^*_{gg}(\mu=1) \approx R^*_{gg}(\mu=1) +$$

$$+\left[R^*_{gg}(\mu=1) - R^*_{gg}(\mu=2)\right] = 2R^*_{gg}(\mu=1) - R^*_{gg}(\mu=2) \quad (33)$$

Thus, the expression (32) can be represented as follows:

$$R^*_{X\varepsilon}(\mu=0)=R^*_{gg}(\mu=0)-\left[2R^*_{gg}(\mu=1)-R^*_{gg}(\mu=2)\right]= \\ =R^*_{gg}(\mu=0)-2R^*_{gg}(\mu=1)+R^*_{gg}(\mu=1) \quad (34)$$

The expression for calculation of the estimate of relay cross-correlation function $R^*_{X\varepsilon}(\mu=0)$ between the useful seismic-acoustic signal $X(i\Delta t)$ and its noise $\varepsilon(i\Delta t)$ can therefore be written as follows:

$$R^*_{X\varepsilon}(\mu=0)\approx\frac{1}{N}\sum_{i=1}^{N}\left[\operatorname{sgn} g(i\Delta t)g(i\Delta t)- \right. \\ \left. -2\operatorname{sgn} g(i\Delta t)g((i+1)\Delta t)+\operatorname{sgn} g(i\Delta t)g((i+2)\Delta t)\right] \quad (35)$$

As was indicated above, in the presence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$, it is impossible to determine estimates of noise variance D_ε of the seismic acoustic signal $g(i\Delta t)$, using the expression (21). Accordingly, we should consider the possibility of determining it by means of estimates $R_{X\varepsilon\varepsilon}(\mu=0)$, $R^*_{X\varepsilon}(\mu=0)$ and estimates of differences $\Delta R_{gg}(\mu=0)$ and $\Delta R^*_{gg}(\mu=0)$ in more detail.

Taking into account the conditions (25) – (30) and equalities (33) – (35), the following can be written:

$$\left.\begin{array}{l} R^*_{X\varepsilon}(\mu=0)+\Delta R^*_{XX}(\mu=0)\approx\Delta R^*_{gg}(\mu=0) \\ R_{X\varepsilon}(\mu=0)+R_{\varepsilon\varepsilon}(\mu=0)+\Delta R_{XX}(\mu=0)\approx\Delta R_{gg}(\mu=0) \\ R_{X\varepsilon}(\mu=0)+R_{\varepsilon\varepsilon}(\mu=0)+\Delta R_{gg}(\mu=1)\approx\Delta R_{gg}(\mu=0) \end{array}\right\} \quad (36)$$

It is known [48] that the correlation between the estimates $R^*_{X\varepsilon}(\mu=0)$; $R^*_{XX}(\mu=1)$ and $R_{X\varepsilon}(\mu=0)$; $\Delta R_{XX}(\mu=1)$, as well as the correlation between the estimates $R^*_{X\varepsilon}(\mu=0)$; $\Delta R^*_{gg}(\mu=1)$ and $R_{X\varepsilon}(\mu=0)$; $\Delta R_{gg}(\mu=1)$, allow one to assume that the following approximate equalities are true:

$$\left.\begin{array}{l} \dfrac{R^*_{X\varepsilon}(\mu=0)}{\Delta R^*_{XX}(\mu=1)}\approx\dfrac{R_{X\varepsilon}(\mu=0)}{\Delta R_{XX}(\mu=1)} \\ \dfrac{R^*_{X\varepsilon}(\mu=0)}{\Delta R^*_{gg}(\mu=1)}\approx\dfrac{R_{X\varepsilon}(\mu=0)}{\Delta R_{gg}(\mu=1)} \end{array}\right\} \quad (37)$$

In this case, we obtain the following equality:

$$R_{X\varepsilon}(\mu=0)\Delta R^*_{gg}(\mu=1)\approx R^*_{X\varepsilon}(\mu=0)\Delta R_{gg}(\mu=1)$$

Thus, in the presence of correlation between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$, the estimate $R_{X\varepsilon}(0)$ can be determined from the formula:

$$R_{X\varepsilon}(\mu=0)\approx\frac{R^*_{X\varepsilon}(\mu=0)\cdot\Delta R_{gg}(\mu=1)}{\Delta R^*_{gg}(\mu=1)} \quad (38)$$

It is clear that after estimate $R_{X\varepsilon}(0)$ is determined, the estimate of noise variance D_ε can be determined both by means of the expression:

$$D_\varepsilon=R_{\varepsilon\varepsilon}(\mu=0)\approx\Delta R_{gg}(\mu=0)- \\ -\Delta R_{gg}(\mu=1)-R_{X\varepsilon}(\mu=0) \quad (39)$$

and by means of the expression:

$$D_\varepsilon=R_{X\varepsilon\varepsilon}(\mu=0)-R_{X\varepsilon}(\mu=0) \quad (40)$$

where $R_{X\varepsilon\varepsilon}$ is determined from the formula (20).

V. Models, Algorithms and Technologies for Determination of Coordinates of the Focus of ASP Origin

To determine the coordinates of the focus, synchronous analysis of seismic-acoustic signals received from all stations via satellite communication is performed at the server.

Estimates of characteristics of noise of seismic-acoustic signal are obtained every 5 seconds and used as source data for determination of coordinates of all four stations.

It is appropriate to select first the south-west station on the map of station locations. If we introduce a rectangular coordinate system and place its datum origin in the location point of the selected station, and direct axes Ox and Oy to the east and the north respectively and convert latitudes and longitudes of those stations to rectangular ones, they can be used in determination of the coordinates of the focus of ASP origin. In this case, if we assume that Qoranboy station is zero point, the other stations will have the following coordinates.

Qum Island	-0.299096°, 3.216934°
Siazan	0.436696°, 2.3806°
Qoranboy	0°, 0°
Shirvan	-0.676351°, 2.129287°

Thus, alongside with coordinates of those stations used as source data, the time of indication of change in characteristics of noise of seismic-acoustic signal $g(i\Delta t)$ by the mentioned stations is used to determine the coordinates of ASP focus.

It can be demonstrated that it is possible to determine the coordinates of the focus of seismic-acoustic signal by means of the time (moment) of indication of ASP at RNM ASP stations.

It is obvious that with velocity of seismic-acoustic signal of ASP being known [12.P.86] $(v \approx v_0 mps)$ and the time of its indication for each selected pair of stations being available, their registration time difference can be determined. Stated geometrically, for each pair of stations, set difference corresponds to the distance determined by means of a hyperboloid with focuses in the signal receiving points [11]. Determination of coordinates of ASP focus can therefore be reduced to determination of the intersection of those hyperboloids from corresponding expressions. Let us consider the matter in more detail.

Suppose that the source of a seismic-acoustic signal is located at point $A(x, y, z)$, where x, y, z are the coordinates to be determined. Let us assume that there are n quantity of signal receivers (stations) located at points $P_j(x_j, y_j, z_j)$, $j = 0,1,...,n$, and an acoustic signal reaches receiver j at moment T_j and v is the average velocity of signal $g(i\Delta t)$. For clarity sake, assume that $T_i \le T_j$ holds true for the pair $i < j$ under consideration.

It is clear that in this case, at $n = 04$, stations will have the following coordinates:

Qoranboy	$P_1(x_1, y_1, z_1) = P_1(0,\ 0,\ 0)$
Qum Island	$P_2(x_2, y_2, z_2) = P_2(-33.24,\ 357,\ 47.0)$
Siazan	$P_3(x_3, y_3, z_3) = P_3(48.53,\ 264.5,\ 0)$
Shirvan	$P_4(x_4, y_4, z_4) = P_4(-75,17,\ 236.61,\ 0)$

To determine coordinates x, y, z of ASP focus, the following equation system can be written, with $R_{i,j} = v \cdot (T_j - T_i)$:

$$\begin{aligned}&\sqrt{(x-x_j)^2 + (y-y_j)^2 + (z-z_j)^2} \cong \\ &\cong \sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2} + R_{ij}\end{aligned} \tag{41}$$

$$i, j \in \{1,2,...,n\}, \quad i < j$$

Symbol " $\cong$ " here indicates that equations (41) do not always hold precisely in real life, since seismic-acoustic signal does not spread along a straight line due to heterogeneity of rocks and its velocity is therefore not a constant value. Moreover, the source of ASP is located at a depth of more than 10 km and occupies quite a large area, which is why it should not be taken as one single point at determining the coordinates of ASP focus. These factors lead to incorrectness of solution of the problem under consideration. Thus, equation system (21) can be unstable despite quite reliable and adequate indication of ASP at RNM ASP stations. The problem under consideration can thereby prove to be incorrect in some cases and have no solution. To obtain an error-tolerant mathematical model, solution of this problem should be reduced to minimization of some functional that will allow one to determine stably coordinates of the focus of ASP origin with sufficient accuracy, using data received from seismic-acoustic stations. For this purpose, the following can be done.

Squaring equalities (21) twice and denoting $2g_{ij} = x_i^2 + y_i^2 + z_i^2 - x_j^2 - y_j^2 - z_j^2 + R_{ij}^2$, we will get the following equations&

$$\begin{aligned}&R_{ij}^2\left((x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2\right) - \\ &-\left(x\cdot(x_i - x_j) + y\cdot(y_i - y_j) + z\cdot(z_i - z_j) - g_{ij}\right)^2 \approx 0 \\ &\qquad i, j \in \{1,2,...,n\}, \quad i < j .\end{aligned}$$

Then, making up the sum of squares of left parts, we obtain the following functional:

$$\begin{aligned}&\Im(x,y,z) = \\ &= \sum_{i,j\in\{1,2,..,n\},\, i<j}^{n}\left(R_{ij}^2\left((x-x_i)^2+(y-y_i)^2+(z-z_i)^2\right)-\left(x\cdot(x_i-x_j)+y\cdot(y_i-y_j)+z\cdot(z_i-z_j)-g_{ij}\right)^2\right)^2\end{aligned} \tag{42}$$

It is obvious that functional $\Im(x, y, z)$ is positive (non-negative) and reaches its minimum $\Im(x, y, z) = 0$ only when all equations (21) hold strictly true. Determination of coordinates x, y, z in this case is therefore reduced to minimization of functional (42), i.e. $\Im(x, y, z) \to \min$.

Numerous methods are known for search of minimums of positive functionals. For instance, the minimum of functional $\Im(x, y, z)$ can be searched among stationary points that obey the equation system

$$\frac{\partial}{\partial x}\Im(x,y,z) = 0,\ \frac{\partial}{\partial y}\Im(x,y,z) = 0,\ \frac{\partial}{\partial y}\Im(x,y,z) = 0 \tag{43}$$

It should be noted that unlike original mathematical model (41), where $n = 3$ quantity of equations (i.e. 4 seismic-acoustic monitoring stations) are required for determination of coordinates x, y, z at setting source values with high accuracy, seemingly excessive quantity of equations (i.e. information from extra stations, e.g. $n \ge 4$) in model (42) can even improve the result, each new summand introducing a smoothening correction to functional (42). It is clear here that regardless of n, determination of coordinates of ASP focus is reduced to a system of three equations (42) with three unknown coordinates.

Expression (43) is obviously a system of algebraic equations of third order in x, y, z. In this case, most often used methods such as multidimensional alternative Newton's method [11, P.509] or gradient method [12, P.191] can be used for numerical determination of required coordinates. In the present paper, preference was given to the Fletcher–Reeves conjugate gradient method [11, P.292], which represents an iteration method of determining the extreme point of functional. Under this method, solution of the problem consists of the following sequential steps:

1. The starting point of iteration process is determined based on the time of indication of change in estimates $D_\varepsilon, R_{X\varepsilon\varepsilon}(\mu=0)$. For instance, according to the numbering, first two stations are situated closest to the focus of seismic-acoustic signal; a point located between $P_1(x_1, y_1, z_1)$ and $P_2(x_2, y_2, z_2)$ can be chosen as starting point $\left(x^k, y^k, z^k\right)$, $k=0$, i.e.

$$x^k = \frac{x_1+x_2}{2},\ y^k = \frac{y_1+y_2}{2},\ z^k = \frac{z_1+z_2}{2},\ k=0.$$

2. Determination of gradient $\nabla\Im(x,y,z) = \left(\frac{\partial\Im}{\partial x}, \frac{\partial\Im}{\partial y}, \frac{\partial\Im}{\partial z}\right)$ at point $\left(x^k, y^k, z^k\right)$, where partial derivatives of functional (42) are calculated from the following formulas:

$$\begin{aligned}
&\frac{\partial\Im}{\partial x}(x,y,z)= \\
&=4\sum_{i,j\in\{1,2,\dots,n\},i<j}^{n}\left(R_{ij}^2\left((x-x_i)^2+(y-y_i)^2+(z-z_i)^2\right)-\left(x\cdot(x_i-x_j)+y\cdot(y_i-y_j)+z\cdot(z_i-z_j)-g_{ij}\right)^2\right)\times \\
&\times\left(\left(R_{ij}^2+(x_i-x_j)^2\right)x+(x_i-x_j)\left(y\cdot(y_i-y_j)+z\cdot(z_i-z_j)-g_{ij}\right)\right) \\
&\frac{\partial\Im}{\partial y}(x,y,z)= \\
&=4\sum_{i,j\in\{1,2,\dots,n\},i<j}^{n}\left(R_{ij}^2\left((x-x_i)^2+(y-y_i)^2+(z-z_i)^2\right)-\left(x\cdot(x_i-x_j)+y\cdot(y_i-y_j)+z\cdot(z_i-z_j)-g_{ij}\right)^2\right)\times \\
&\times\left(\left(R_{ij}^2+(y_i-y_j)^2\right)y+(y_i-y_j)\left(x\cdot(x_i-x_j)+z\cdot(z_i-z_j)-g_{ij}\right)\right) \\
&\frac{\partial\Im}{\partial z}(x,y,z)= \\
&4\sum_{i,j\in\{1,2,\dots,n\},i<j}^{n}\left(R_{ij}^2\left((x-x_i)^2+(y-y_i)^2+(z-z_i)^2\right)-\left(x\cdot(x_i-x_j)+y\cdot(y_i-y_j)+z\cdot(z_i-z_j)-g_{ij}\right)^2\right)\times \\
&\times\left(\left(R_{ij}^2+(z_i-z_j)^2\right)z+(z_i-z_j)\left(x\cdot(x_i-x_j)+y\cdot(y_i-y_j)-g_{ij}\right)\right)
\end{aligned}$$

3. Calculation of vector $\mathbf{P}_k = \left(p_x^k, p_y^k, p_z^k\right)$ in accordance with the following rule:

$$\mathbf{P}_k = \begin{cases} -\nabla\Im(x^0, y^0, z^0), & k=0, \\ -\nabla\Im(x^k, y^k, z^k) + \dfrac{\left|\nabla\Im(x^k, y^k, z^k)\right|^2}{\left|\nabla\Im(x^{k-1}, y^{k-1}, z^{k-1})\right|^2}\mathbf{P}_{k-1}, & k\ge 1. \end{cases}$$

4. Selection of α_k (stride parameter) from the following formula:

$$\alpha_k = \arg\min_\alpha \Im(x^k+\alpha_k p_x^k, y^k+\alpha_k p_y^k, z^k+\alpha_k p_z^k),\quad k\ge 0$$

5. Calculation of the new approximation:

$$x^k = x^{k+1}+\alpha_{k-1}p_x^{k-1},\ y^k = y^{k+1}+\alpha_{k-1}p_y^{k-1},\ z^k = z^{k+1}+\alpha_{k-1}p_z^{k-1}$$

6. If $\left|\nabla\Im\left(x^{k+1}, y^{k+1}, z^{k+1}\right)\right| < \varepsilon$, ($k\ge 0$), where ε is the required accuracy of calculation, then point $\left(x^{k+1}, y^{k+1}, z^{k+1}\right)$ is the minimum point of functional $\Im(x,y,z)$. Otherwise, the process is continued from step 3.

Thus, required coordinates of ASP focus are determined, i.e. results of the original mathematical problem are obtained

$$\Im(x,y,z)\to\min$$

It should be noted that values x, y, z are the coordinates of the source in the Cartesian coordinate system. Physical interpretation of the obtained result shows that if the source of an anomalous seismic process is located at the point with coordinates x, y, z, then the time of signal reaching station i from the focus of ASP origin will be equal to Ti . It is obvious from the aforesaid that solving of this problem requires determination of T_i, T_j and their difference, i.e. $\left(T_i - T_j\right)$, as source data, i.e.

$$\Delta\tau_{\nu j} = \left(\tau_\nu - \tau_j\right)$$

Let us remark here that the problem was set and solved in the Cartesian coordinate system. In the geographical coordinate system, the westernmost station (if the latter is not the only one, then the southernmost of them) is the reference station. Geographical coordinates of the source can be calculated by carrying out an inverse transformation.

VI. TECHNOLOGY OF DETERMINING THE DIFFERENCE $\Delta\tau_{\nu j}$ BETWEEN REGISTRATION TIME INTERVALS OF DIFFERENT RNM ASP STATIONS

As follows from the previous paragraph, solving of this problem requires determining difference $\Delta\tau_{vj}$ between moments of registration of ASP origin by different RNM ASP stations as source data. Experimental researches carried out at those stations demonstrated that each of such stations allows registering ASP preceding earthquakes more than 10-15 hours before the beginning of earthquake within a radius of 300-500 km, which makes it possible to use those stations for monitoring of changes in the seismic situation in the controlled territory.

The diagram of the network of seismic-acoustic stations for robust noise monitoring of ASP (RNM ASP) is given in Fig. 1. Suspended oil wells are used as communication channels to receive information from deep (3-6 km) seismic processes. Installed at the heads of oil wells are acoustic sensors (hydrophones) and other auxiliary devices allowing one to determine estimates of noise $R_{X\varepsilon\varepsilon}(\mu=0), R_{X\varepsilon}(\mu=0), D_{\varepsilon}, R^{*}_{X\varepsilon}(\mu=0)$ as informative attributes. Received signals and informative attributes about ASP beginning are transmitted via satellite channel to the server of the monitoring center.

In the process of operation of the seismic-acoustic station, as was mentioned above, corresponding information is forwarded to the server of the monitoring center. At the beginning of ASP origin, current estimates of the signal received from hydrophones will be different from the estimates of normal seismic state by a quantity larger than the set threshold levels. Thus, information on the beginning of ASP is formed in the system in the beginning of time T_1, using the estimates of seismic-acoustic signals received at the output of hydrophone installed at the head of the steel bore of the well. At the same time, estimates obtained from the signals by standard ground stations only in the beginning of time T_2 (major seismic vibrations) are used to register the beginning of seismic vibrations. Corresponding information is sent to the server, where time difference between receiving of corresponding signals is found. Owing to this, ASP identification can be performed on the server by means of known recognition technologies, including neural network training, using results received from RNM ASP stations. It should be noted that determination of the coordinates of ASP focus requires creation of a network consisting of at least four such stations and their integration with standard seismic stations. For that end, another three stations were built in 2011 in addition to the station at Qum Island in the Caspian Sea: in the town of Shirvan in the south of the country, in the town of Siazan in the north and in the town of Naftalan in the west (Fig. 3j). Another station was built in the town of Neftchala on the southern coast of the Caspian Sea. A sixth station is projected to be built in the nearest future on the Turkish-Iranian border in the Nakhchivan Autonomous Republic.

With all four and more stations operating, results of analysis of seismic acoustic signals and ASP monitoring are sent from each station to the server of the monitoring center by means of all the proposed technologies at the moment of the transition from time span T_0 into time span T_1.

An experimental version of RNM ASP station was installed at the head of 3,500 m deep suspended oil well # 5 on 01.07.2010. The well is filled with water and for this reason, a BC 312 hydrophone is used as a sensor. Fig. 2a shows the structure of RNM ASP station. Fig. 2b shows the external appearance of RNM ASP station. A building was built afterwards to protect the station from the sun, wind and other external factors.

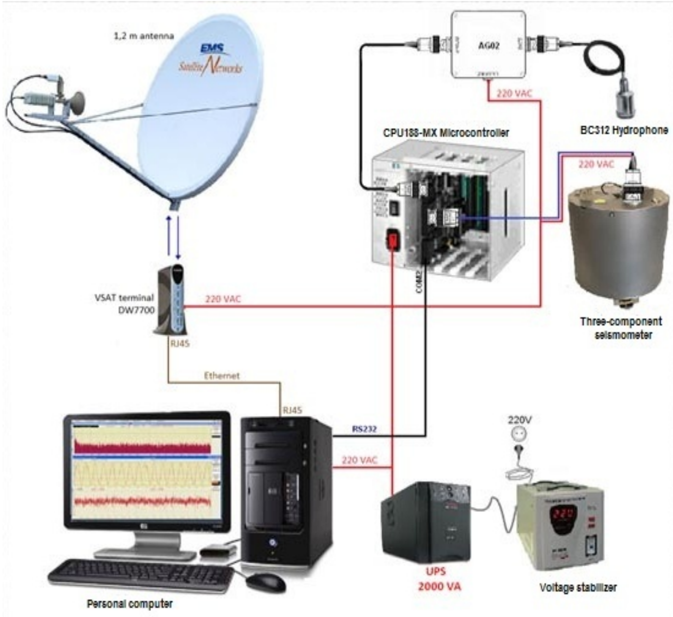

Figure 2a. Structure of RNM ASP station

Figure 2b. Appearance of the station after installation

The station includes the following equipment:

System unit of personal computer;

Fastwell Micro Pc controller;

GURALP LTD CMG 5T seismic accelerometer;

BC 321 hydrophone, made in Zelenograd;

Reinforcing and normalizing elements;

VSAT DW7700 terminal forming an Internet channel.

The following earthquakes have been registered by Azerbaijan seismic stations during the operation of the station from 01.07.2010 to 15.01.2011.

09.10.2010, town of Masally 00:58:11, M:3.5, d:12 км

11.10.2010, town of Shirvan, 22:50:23, M:3.9, d:37 км

17.10.2010, town of Imishli, 07:20:38, M:3.4, d:18 км

20.11.2010, Caspian Sea, 05:05:48-08:29:29, M:3.5, d: 50 km

25.11.2010, Baku, Sangachal, 09:15:21, M: 3.04, d: 36 km

Given below in the Fig. 3a, 3b, 3c, 3d, 3e are the results of monitoring of ASP preceding those earthquakes. The records show that the estimates of variance of noise of seismic acoustic signal received at the output of the hydrophone increase sharply over 5-10 hours before the earthquake.

Fig. 3f demonstrates records of the estimate of cross-correlation function $R_{x\varepsilon}(\mu)$ between the useful signal $R_{x\varepsilon}(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ related to the earthquakes in Azerbaijan (21.01.2011, 01:58:54), Georgia (23.01.2011, 07:51:23), Tajikistan (24.01.2011, 06:45:29) and on the border with Turkey, Armenia and Iran (3 earthquakes - 25.01.2011, 03:56:12, 04:02:32, 07:40:04). Lead of all charts over the beginning of the earthquake is 5-10 hours and more.

Fig. 3g gives the expanded record of the estimate of cross-correlation function during the earthquake in Georgia (near Kutaisi) on 23.01.2011, at 07:51:23. ASP was clearly registered 5-6 hours before the beginning of the earthquake.

On 23.10.2011, Azerbaijan seismic stations registered the earthquake with magnitude 5.6 that occurred at 16:00:25 in the east of Turkey, in the town of Van. Fig. 3h gives the record of cross-correlation function of the earthquake that entailed great human losses and destructions. All charts show Baku time.

Experiments showed that only estimates of characteristics of the noise $\varepsilon(i\Delta t)$ provide reliable and adequate registration of the beginning of origin of anomalous seismic processes.

Thus, the results of experiments carried out from 01.05.2010 to 20.02.2012 show that it is possible to perform earthquake monitoring by means of RNM ASP within a radius of over 300-500 km 10-20 hours before the earthquake. When spreading from earthquake focus, seismic-acoustic waves are reflected due to the resistance of some upper strata of the earth and change their direction. Considerable intensity of those waves allows them to travel to long distances.

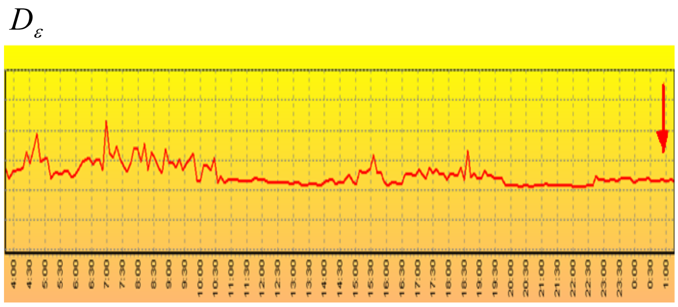

Figure 3a. 08.10.2010 Masally 00:58:11 M:3.5 d:12 km Noise variance

Start of ASP approximately at 04:30, 08.10.2010, earthquake at 00:58:11, 09.10.2010

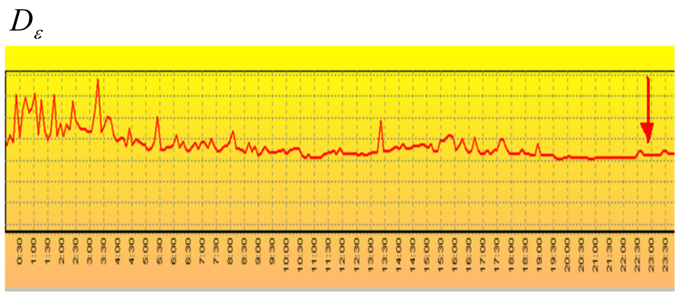

Figure 3b. 11.10.2010 Shirvan 22:50:23 M:3.9 d:37 km Noise variance

Start of ASP approximately at 00:30, 11.10.2010, earthquake at 22:50:23, 11.10.2010

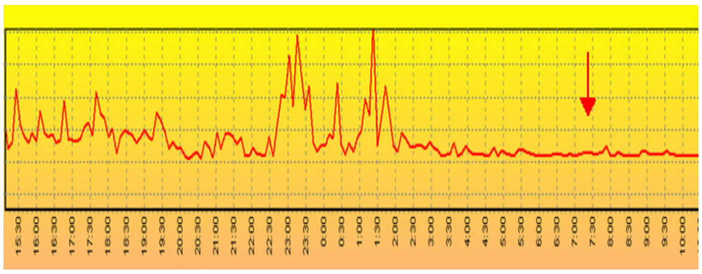

Figure 3c. 16-17.10.2010 Imishli 07:20:38 M:3.4 d:18 km. Noise variance

Start of ASP approximately at 15:30, 16.10.2010, earthquake at 07:20:38, 17.10.2010

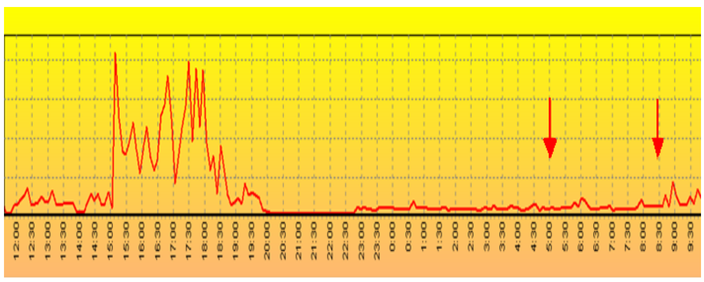

Figure 3d. 19-20.11.2010 At sea 05:05:48--08:29:29 20.11.2010 M:3.5 d: 50 km. Noise variance.

Start of ASP approximately at 12:20, 19.11.2010 г., two earthquakes at 05:05:48, 08:29:29 20.11.2010

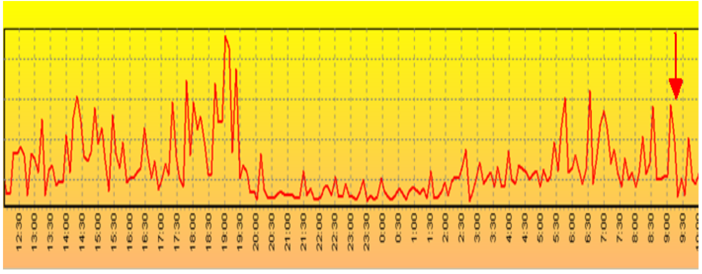

Figure 3e. 25.11.2010 Baku, Sangachal 09:15:21 M: 3.04 d: 36 km. Noise variance Start of ASP approximately at 12:10 24.11.2010, earthquake at 09:15:21 25.11.2010

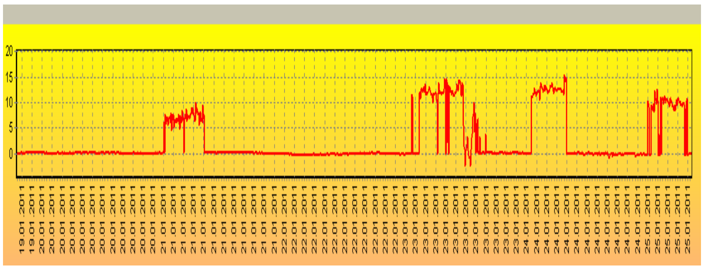

Figure 3f. In Azerbaijan (21.01.2011, 01:58:54), in Georgia (23.01.2011, 07:51:23.0), in Tajikistan (24.01.2011, 06:45:29.0) and on the border between Turkey and Iran (3 earthquakes 25. 01.2011, 03:56:12.; 04:02:32.; 07:40:04.)

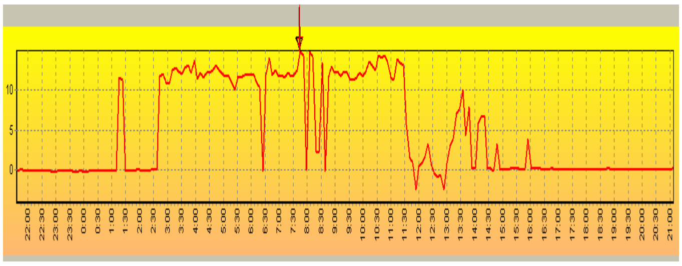

Figure 3g. 23.01.2011 Georgia, near Kutaisi 07:51:23 M: 4.5 d: 10 km Estimates of cross-correlation function

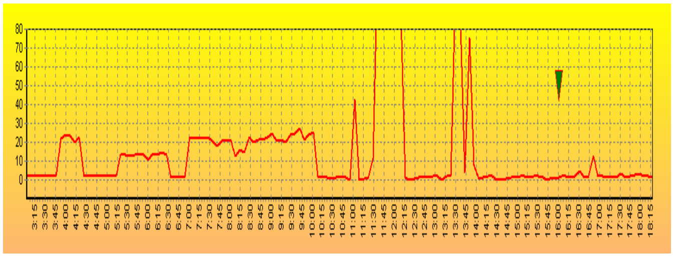

Figure 3h. 23.10.2011 East Turkey, Van 16:00:25 M: 5.6 Estimates of cross-correlation function

The given experimental research proved the expediency of construction and practical use of a network of RNM ASP stations. It also showed that, integration of RNM ASP stations with standard seismic stations will allow one to create robust intelligent systems in the future, which after a certain training period can be used for determining the coordinates and the magnitude of the expected earthquake.

The given diagrams of analysis of changes in noise characteristics of signal $g(i\Delta t)$ $R_{X\varepsilon}(\mu=0)$ show that they can be used as informative attributes to determine time of ASP registration at RNM ASP stations. For instance, Fig. 3 gives the record of the earthquake in East Turkey registered by means of estimate $R_{X\varepsilon}(\mu)$ at Shirvan RNM ASP station with the following parameters: time – 2012-04-04 09:41:41.0 UTC, coordinates – 38.84 N; 43.61 E, hypocenter depth – 2 km, magnitude – 4.5. 01:25:00 on 03.04.2012 can be regarded as the time of ASP registration at Shirvan RNM ASP station, which is over 24 hours earlier than the time of earthquake registration by ground seismic stations. Fig. 3j gives the expanded record of $R_{X\varepsilon}$ showing the initial stage of ASP origin.

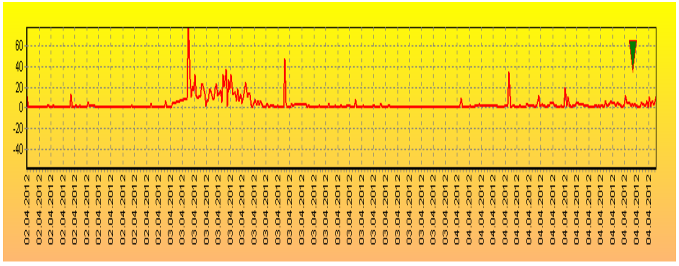

Figure 3i. Record of $R_{X\varepsilon}$ at Shirvan RNM ASP station for April 02-03-04, 2012

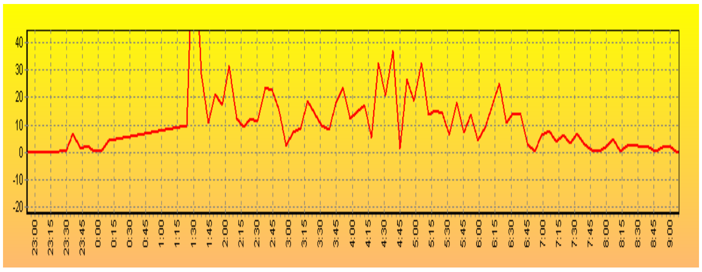

Figure 3j. Record of $R_{X\varepsilon}$ at Shirvan RNM ASP station for April 03, 2012

Fig. 3k gives the record of $R_{X\varepsilon}$ at Qum Island RNM ASP station for October 18, 2011, where 07:45:00 can be regarded as the starting point of ASP registration.

Fig. 3l gives the record of $R_{X\varepsilon}$ at Shirvan RNM ASP station for October 18, 2011, where 07:20:00 can be regarded as the starting point of ASP registration.

Both diagrams relate to ASP that preceded the earthquake in Georgia on 2011-10-18 at 23:26:29.0 UTC. ASP at both stations were registered 15 hours before the earthquake occurred.

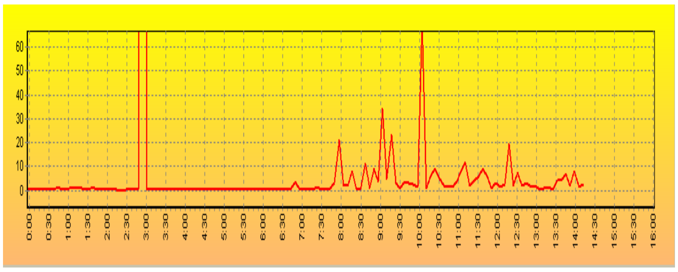

Figure 3k. Record of $R_{X\varepsilon}$ at Qum Island RNM ASP station for October 18, 2011

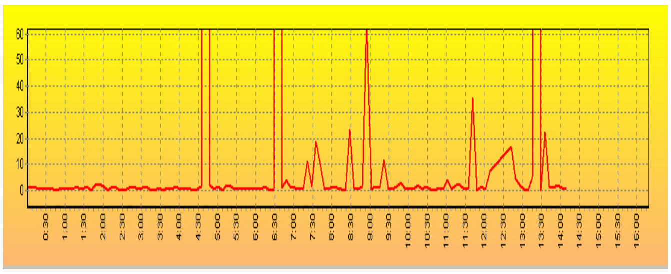

Figure 3l. Record of $R_{X\varepsilon}$ at Shirvan RNM ASP station for October 18, 2011

All the diagrams given above clearly show that ASP was registered at Shirvan RNM ASP Shirvan approximately 20-25 minutes earlier than at Qum Island RNM ASP station. This result agrees well with the value of acoustic signal velocity (40-50 m/s) in oil-and-gas bearing and sandy media [11].

Thus, according to the experimental results given above, one of possible ways to form source data for determination of the coordinates of ASP focus can be reduced to determination of the moment of indication of ASP beginning using records of characteristics of noise of seismic-acoustic signals $g_1(i\Delta t)$, $g_2(i\Delta t)$, $g_3(i\Delta t)$ and $g_4(i\Delta t)$ at corresponding RNM ASP stations, respective values $\Delta\tau_{vj}$ being easily determined from differences $\tau_v - \tau_j = \Delta\tau_{vj}$.

However, in this case, the time of ASP origin is registered with certain errors related to nonidentity of metorological characteristics of hydrophones installed at different RNM ASP stations. Such errors will naturally lead to inaccuracy in determination of sought-for coordinates. To eliminate those errors, therefore, the problem of determining this data can be reduced to the problem of determining the time shift between readings of seismic-acoustic signals $g_1(i\Delta t)$, $g_2(i\Delta t)$, $g_3(i\Delta t)$, $g_4(i\Delta t)$ received at the output of hydrophones installed at the heads of corresponding wells.

It is known that time shift $\Delta\tau = \mu_{\max}$ between two random correlated signals $g_1(i\Delta t)$ and $g_2(i\Delta t)$ is determined from the following expression.

$$R_{g_1g_2}(\mu) = \frac{1}{N}\sum_{i=1}^{N} g_1(i\Delta t)g_2(i+\mu)\Delta t \qquad (44)$$

This being the case, time $\Delta\tau_{v,j} = \mu_{\max}\Delta t$ is determined, when estimate $R_{g_1g_2}(\mu)$ assumes the maximum value. The advantage of this option is that precision of the estimate of time shift $\Delta\tau_{v,j} = \mu_{\max}\Delta t$ determined from expression (44) does not depend on identity of metrological characteristics of sensors, at the output of which signals $g_1(i\Delta t)$ and $g_2(i\Delta t)$ are received. Considering that precision of the sought-for coordinates x, y, z is first of all affected by source data inaccuracy $\Delta\tau_{vj}$, which consists of determined time shifts $\mu_{\max}\Delta t$, its determination from the following expression is also appropriate

$$R^{*}_{g_1g_2}(\mu) = \frac{1}{N}\sum_{i=1}^{N} g_1^2(i\Delta t)g_2^2(i+\mu)\Delta t \ , \qquad (45)$$

which will allow finding a more precise estimate $\Delta\tau_{vj}$. Experiments demonstrated that these expressions are more tolerant to the differences of metrological characteristics of RNM ASP sensors. It should also be noted that signals $g_1(i\Delta t)$ and $g_2(i\Delta t)$ registered by stations, which are over 100 km apart, are weakly correlated. In that case, the following formula should be used to determine the maximum time shift $\Delta\tau_{vj} = \mu_{\max}\Delta t$ between readings of $g_1(i\Delta t)$ and $g_2(i\Delta t)$:

$$R_{R_{X_{1\varepsilon}}R_{X_{2\varepsilon}}}(\mu) = \frac{1}{M}\sum_{i=1}^{M} R_{X_{1\varepsilon}}(i\Delta t)R_{X_{2\varepsilon}}(i+\mu)\Delta t \qquad (46)$$

where the required time shift $\Delta\tau_{vj} = \mu_{\max}\Delta t$ is determined between readings $R_{X_{1\varepsilon}}(i\Delta t)$ and $R_{X_{2\varepsilon}}(i+\mu)\Delta t$.

To sum up, the process of determination of difference in time $\Delta\tau_{vj} = \mu_{\max}\Delta t$ of ASP monitoring between different stations and calculation of the focus coordinates x, y, z described above can be carried out in the following order:

1) using the diagrams, determine empirically the starting moment τ_v of registration of the signal at the station that was the first to register ASP;

2) create files $g_1(i\Delta t)$, $g_1^2(i\Delta t)$, $R_{X_1\varepsilon}(\mu)$ etc. from readings of signal $g_1(i\Delta t)$ at the first station;
3) determine the stations that was the second, third and forth to register the ASP;
4) form files $g_2^2(i\Delta t)$, $g_3^2(i\Delta t)$, $g_4^2(i\Delta t)$, $R_{X_2\varepsilon}(\mu)$, $R_{X_3\varepsilon}(\mu)$, $R_{X_4\varepsilon}(\mu)$ from readings $g_2(i\Delta t)$, $g_3(i\Delta t)$, $g_4(i\Delta t)$;
5) determine estimate sets $R_{g_\nu g_j}(i\Delta t)$, $R^*_{g_\nu g_j}(i\Delta t)$, $R_{R_{X_\nu\varepsilon}R_{X_j\varepsilon}}(\mu)$ from expressions (44)–(46) and use them to determine time shifts $\Delta\tau_{\nu j}$;
6) determine index of time shifts $\mu\cdot\Delta t$ from the obtained estimates, when the estimate has the peak value among all the arrays μ_m, which eventually allows determining the difference of time interval $\Delta\tau_{\nu j}=(T_\nu-T_j)$ of ASP registration at stations ν and j respectively;
7) use the found time differences $\Delta\tau_{\nu j}=(T_\nu-T_j)$ as source data in model (43) to determine the coordinates (x,y,z).

In conclusion, let us note that to improve the reliability of results of monitoring of the beginning of ASP origin, the offered paper envisages several options for registration of ASP beginning. The following technologies are used during ASP monitoring to determine informative attributes.

1. Technology for determination of noise variance D_ε

$$D_\varepsilon=\frac{1}{N}\sum_{i=1}^{N}\left[g(i\Delta t)g(i\Delta t)-2g(i\Delta t)g(i+2)\Delta t+g(i\Delta t)g(i+1)\Delta t\right] \quad (47)$$

2. Technology for determination of noise correlation estimate $R_{X\varepsilon\varepsilon}(\mu=0)$

$$R_{X\varepsilon\varepsilon}(\mu=0)=\frac{1}{2N}\sum_{i=1}^{N}\left[g(i\Delta t)g(i\Delta t)-\left[g(i\Delta t)g((i+1)\Delta t)+g(i\Delta t)g((i+2)\Delta t)-g(i\Delta t)g((i+3)\Delta t)\right]\right] \quad (48)$$

3. Technology for determination of estimate of relay cross-correlation function between the useful signal and the noise

$$R^*_{X\varepsilon}(\mu=0)\approx\frac{1}{N}\sum_{i=1}^{N}\left[\operatorname{sgn}g(i\Delta t)g(i\Delta t)-2\operatorname{sgn}g(i\Delta t)g((i+1)\Delta t)+\operatorname{sgn}g(i\Delta t)g((i+2)\Delta t)\right] \quad (49)$$

4. Experimental research showed that presence of express extreme value of the estimate of cross-correlation function between signals $g_\nu(i\Delta t)$ and $g_j(i\Delta t)$ received from different combinations of RNM ASP stations is a reliable informative attribute of indication of the beginning of ASP origin. Given below are some technologies for solving of this problem.

$$R_{g_\nu g_j}(\mu_{\max})=\frac{1}{N}\sum_{i=1}^{N}g_\nu(i\Delta t)g_j(i+\mu)\Delta t \quad (50)$$

$$R^*_{g_\nu g_j}(\mu_{\max})=\frac{1}{N}\sum_{i=1}^{N}g_\nu^2(i\Delta t)g_j^2(i+\mu)\Delta t \quad (51)$$

$$R^*_{g_\nu g_j}(\mu_{\max})=\frac{1}{N}\sum_{i=1}^{N}g_\nu(i\Delta t)g_j^2(i\Delta t) \quad (52)$$

$$R^{**}_{g_\nu g_j}(\mu_{\max})=\frac{1}{N}\sum_{i=1}^{N}g_\nu^2(i\Delta t)g_j(i\Delta t) \quad (53)$$

Alongside with these estimates, application of the following technologies for determining express extreme value of cross-correlation functions is provided at the server of the network of stations:

$$R^*_{g_\nu g_j}(\mu_{\max})=\frac{1}{N}\sum_{i=1}^{N}\operatorname{sgn}g_\nu(i\Delta t)g_j(i\Delta t) \quad (54)$$

$$R^{**}_{g_\nu g_j}(\mu_{\max})=\frac{1}{N}\sum_{i=1}^{N}\operatorname{sgn}g_\nu(i\Delta t)g_j^2(i\Delta t) \quad (55)$$

Experiments showed that presence of express extreme value of estimates determined from expressions (50)-(55) is a reliable informative attribute of the beginning of ASP origin.

Thus, the readings of signals $g_1(i\Delta t)$, $g_2(i\Delta t)$, $g_3(i\Delta t)$, $g_4(i\Delta t)$, $g_5(i\Delta t)$ received from RNM ASP stations at Qum Island, in Shirvan, Siazan, Naftalan and Neftchala via satellite communication are transmitted to the server simultaneously. They are continuously analyzed with application of technologies (47)-(55) and informative attributes D_ε, $R_{X\varepsilon\varepsilon}(\mu=0)$, $R^*_{X\varepsilon}(\mu=0)$, $R_{g_\nu g_j}(\mu_{\max})$, $R^2_{g_\nu g_j}(\mu_{\max})$, $R'_{g_\nu g_j}(\mu_{\max})$, $R''_{g_\nu g_j}(\mu_{\max})$, $R^*_{g_\nu g_j}(\mu_{\max})$, $R^{**}_{g_\nu g_j}(\mu_{\max})$ are determined. When threshold value of each of those estimates is exceeded, information about possible ASP origin is formed at the server. After a certain amount of time, if values of estimates remain the same or grow, it is taken as an informative attribute of the beginning of ASP origin. If this is also the case with other informative attributes, it naturally increases reliability and adequacy of results of ASP monitoring.

Besides indication of the beginning of ASP origin, obtained informative attributes also bear information on the magnitude of an expected earthquake and the distance between the focus and RNM ASP stations. For instance, if all estimates $R_{g_\nu g_j}(\mu_{\max})$, $R^2_{g_\nu g_j}(\mu_{\max})$, $R'_{g_\nu g_j}(\mu_{\max})$, $R''_{g_\nu g_j}(\mu_{\max})$,

$R^{*}_{g_v g_j}(\mu_{\max})$, $R^{**}_{g_v g_j}(\mu_{\max})$ simultaneously have express extreme values, it means that the expected earthquake will have a high magnitude (over 5-6). On the other hand, if some of them have express extreme values and some do not, it will mean that a weak earthquake is to be expected. In such case, the focus will be located in the direction of the stations, at which those estimates were obtained. Difference in the value of estimate between maximal values of the specified informative attributes is related to difference of distances between the focus and corresponding stations.

Experiments also showed that the value of the estimate of cross-correlation function $R_{X\varepsilon}(\mu)$ between useful signal $X(i\Delta t)$ and noise $\varepsilon(i\Delta t)$ decreases as the distance from the earthquake focus grows. The value of the estimate of noise variance D_ε increases as the distance from the focus grows. Correlation $R_{X\varepsilon}(\mu)/R_{X\varepsilon\varepsilon}(\mu)$ decreases with distance and $D_\varepsilon / R_{X\varepsilon\varepsilon}$ increases. It is clear that knowing the coordinates of RNM ASP stations after coordinates of the focus of the expected earthquake have been determined, distance S_{st} between the stations and the focus can be easily calculated. After that, approximate value of minimal magnitude of the expected earthquake can be determined by means of the specified properties of estimates of noise analysis during origin of weak earthquakes, organizing training with application of neural networks. In the course of time and with quality training, accuracy of the magnitude of a predicted earthquake will improve.

On the basis of this approach, a computer imitation system has been created, in which 4 stations with the above-mentioned coordinates are located in the map of Azerbaijan. The expected point of ASP is selected by means of a mouse. Seismic-acoustic waves spread from that point in concentric circles. Each of the stations registers the time when the waves reaching them and the obtained time differences are written in a file in the order that corresponds to the numbering of the stations. The algorithm offered earlier is used to determine the coordinates of the imitated anomalous seismic process.

VII. CONCLUSION

The offered technology for determination of the starting moment of ASP by a network of RNM ASP stations, as well as the model and technologies for determination of ASP coordinates, calls forth wide application of those technologies in short-term earthquake prediction.

1. Results of the experiments at the seismic-acoustic station at Qum Island demonstrated that it is possible to detect the starting moment of ASP within a radius of more than 500 km several hours before the earthquake by means of estimates of noise variance, noise correlation value and cross-correlation functions between noises and useful signals. Another four stations were built for identification of coordinates and magnitude of earthquakes.

2. The results obtained from experimental data allow assuming that the time lead in registration of ASP origin by RNM ASP seismic-acoustic stations over standard seismic equipment is due to two factors.

First, seismic-acoustic waves that arise in the beginning of ASP origin do not reach the earth's surface due to frequency characteristics of certain upper strata, which leads to their horizontal spreading in deep strata as noise. Reaching steel pipes of the well at the depth of over 3-6 km, seismic-acoustic waves transform into acoustic signals and go to the surface at the velocity of sound, where they are detected by the hydrophone. At the same time, low frequency seismic waves from seismic processes are sensed at the surface in a certain amount of time, when the earthquake is already in progress, and are registered by seismic receivers of standard ground equipment much later. Second, application of robust noise technology allows one to analyze noises received from acoustic sensors and register anomalous seismic processes in the beginning of their origin. These two factors make it possible to indicate the time of the beginning of the coming earthquake based on the received seismic-acoustic information much earlier than it is done by stations of the seismic survey service.

3. Seismic-acoustic stations of ASP monitoring can also be used for monitoring of the latent period of volcano formation well before the eruption. Their use will also allow one to perform monitoring of testing of minor and major nuclear bombs and other experiments related to manufacture of military equipment on a regional basis. A network of such stations will make it possible to fully control such tests and various military maneuvers.

REFERENCES

[1] Ali Abbasov, Telman Aliyev, Akif Ali-zada, Gurban Yetirmishli, Gambar Guluyev, Fahrad Pashayev. Intellectual Seismoacoustic Telemetric Station. // The third international conference "Problems of cybernetics and informatics" Volume II September 6-8, 2010, Baku, Azerbaijan, pp. 83-85.

[2] Aliyev T.A., Ali-zada A.M., Yetirmishli G.D, Guluyev G.A., Pashayev F.G., Rzayev A.G. Intelligent Seismic-acoustic System for Monitoring of the beginning of Anomalous Seismic Processes. //Seismic Instruments, 2010, Vol 46, No. 1, pp. 27-41.

[3] T.A. Aliev, A.M. Abbasov, A.M. Alizade, G.D. Yetirmishli, G.A. Guluyev, F.G. Pashayev. "Results of experiments at the seismic-acoustic station at Qum Island" // Reports of the National Academy of Sciences of Azerbaijan, 2011, Vol. LXVII, №1 pp.19-31.

[4] Aliev T.A. Robust Technology with Analysis of Interference in Signal Processing, New York, Kluwer Academic/Plenum Publishers, 2003, 199 p.

[5] Aliev T. Digital noise monitoring of defect origin, London, Springer, 2007. 223 p.

[6] R. Van Zyl, and D. Newell, *"Locating The Epicenter of An Earthquake"/* CSTA – California Science Education Conference, October 23, 2011.

[7] Pujol, J. (2004). *"Earthquake location tutorial: a graphical approach and approximate epicentral locations techniques"*// Seism. Res. Lett. 75, no.1, pp. 63–74.

[8] M. Sambridge, and K. Ghallagher, *"Earthquake hypocenter location using genetic algorithms"*// Bulletin of the Seismological Society of America, Vol. 83, No. 5, October 1993, pp. 1467-1491.

[9] E.V. Deshcherevskaya, A.Ya. Sidorin "Estimation uncertainties of the earthquake coordinates at the Garm test area", in Russian) // Seismic Instruments. 2010. Vol.46, No 1, pp. 61-76.

[10] Aliev T.A., Abbasov A.M., Guluyev G.A., Rzayev A.H., Pashayev F.H. Positionally-binary and spectral indicators of microchanges in technical conditions of objects of the control. Automatic Control and Computer Sciences, Allerton Press, Inc., New York, No.3, 2009, pp. 156-165.

[11] Rudenko O.V. Giant nonlinearities in structurally inhomogeneous media and the fundamentals of nonlinear acoustic diagnostic techniques. // Physics–Uspekhi, 2006, vol. 176, No 1, pp. 77-95.

[12] Nerpin S.V., Chudnovski A.F. Soil Physics. M. "Nauka", 1967, 584 p.

[13] Pashayev A.B., Sabziyev E.N. Identification of coordinates of sources of acoustic signals. Materials of the Republican scientific conference "Modern problems of informatization, cybernetics and information technology", Baku, 2003, vol. 2, pp.58-60.

[14] Ilyin V.A., Pozniak E.G. Fundamentals of mathematical analysis. P.1, M.: Nauka, 1982, 616 p.

[15] Elster K.H., Reinhardt R., Schäuble M. and Donath G., An Introduction to Non-linear Programming. M.: Nauka, 1985, 264 p.

[16] Vasilyev F.P. Optimization methods. "Faktorial Press", 2002, 824 p.