SPECTRUM MONITORING OF ELECTROMAGNETIC SIGNALS FROM ROCKS TO CONTROL GEODYNAMIC PROCESSES UNDER WORKING MINE CONDITIONS

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Abstract. The paper considers the techniques for continuous monitoring of samples and rocks destruction using the parameters of the measured electromagnetic signals which are generated in the destructive processes. The block diagram of the recorder is presented and the methods for processing of the measured electromagnetic signals to monitor and predict the geodynamic processes in rocks or the destruction of dielectric materials under electromagnetic interference. A phase modeling of the method to extract a useful signal from the background noise and electromagnetic interference has been implemented.

Keywords: electromagnetic signals, rocks, geodynamics, monitoring, spectrum analysis, event identification.

1. Introduction

Monitoring of the geomechanical state of a natural-technical system is essential for the safety of people and engineering facilities located in tectonically unstable areas. To efficiently determine the current state of an area and its geodynamic hazards, and to choose the proper way to control the massif state, it is promising to study the geodynamic and technology and nature related processes using the methods of mathematical and physical modeling, field geological and geophysical studies, deformation observations, electromagnetic and seismic monitoring [1–3].

In practice, a spatial-time analysis of microseismic area monitoring is primarily used to predict and prevent the formation of the environmentally fragile and geodynamically hazardous zones in the mine development areas. Two parameters that reflect time and space changes in the dynamic phenomena distribution are considered in [4, 5]: the time interval between seismic events and sampling fractal parameter for seismic events. Decrease of the time interval between the events of a certain energy class is considered to be the precursor of a powerful dynamic phenomenon. In addition, from the physical point of view, the value of the fractal distribution of seismic events of low power must correspond to the concentration of the seismic events in a small neighborhood of the future centre of a powerful dynamic phenomenon [4]. Unfortunately, the research in this field is complicated due to the specific conditions for observations and the presence of costly seismic stations that are not available in most working mines.

Another promising method to monitor changes in the stress-deformed state (SDS) of the rock mass and to predict geodynamic events, including those in a mine field, is the method based on dynamoelectric transformations in rocks and other dielectric structures, including structures that contain ferroelectrics and radioactive substances [1, 2, 6]. The development of the information system to monitor geodynamic events and other methods to control the geodynamic situation based on the research results on dynamoelectric transformations in rocks will significantly improve the accuracy of time and place predictions of these destructive phenomena.

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The research aims at the development of electromagnetic monitoring of changes in the rock SDS and control of geodynamic processes in working mines, as well as the processes of dielectric materials destruction.

2. Monitoring and control techniques

To develop the information system to monitor and to predict geodynamic events, the investigation of the EMS parameters and electromagnetic emission characteristics of the rocks in the Tashtagolsky mine (Kemerovo region) are being carried out at the depths up to 800 meters before and during the process of technological explosion with masses up to 300 tons, and during the process of rock mass relaxation after the explosion [6, 7]. Determination of the EMS parameters obtained in the changes of the rock SDS is of special interest [8–10]. It is possible to estimate the SDS of the controlled rock mass while examining the spatial structure of the electromagnetic field and the complex amplitude of its spectral components. It allows obtaining an additional indicator of a short-term earthquake prediction [2]. It should be noted that work in the mine is not performed during the technological explosion, and the level of electromagnetic interference is almost zero.

The scientists of Tomsk Polytechnic University (TPU) found out that the EMS frequency range of the rock mass from 1 to 100 kHz is the most informative [2, 6]. The need to ensure a long-term recording in digital signal spectrograms with high frequency resolution and in real time causes the problem in the low and medium frequency regions in EMS monitoring. This requires large amount of storage and energy resources that limit the portable device possibilities for actual measurements, particularly, when used in mining installations.

The scientists from TPU and the pilot plant "Smena" of Tomsk State University of Control Systems and Radioelectronics are involved in the development of the diagnostic facilities to monitor the state of rocks and to predict the geodynamic events in natural conditions. An autonomous frequency recorder of electromagnetic and acoustic signals of rocks was developed as a result of cooperative efforts [11, 12]. The recorder is developed on the basis of the modular principle. A digital signal processor (DSP) is the main element of the device to control the peripheral units and to perform mathematical calculations. The individual controllers are responsible for work with the user interface and supply system to logically divide the tasks. The purpose of each peripheral module is shown in Figure 1.

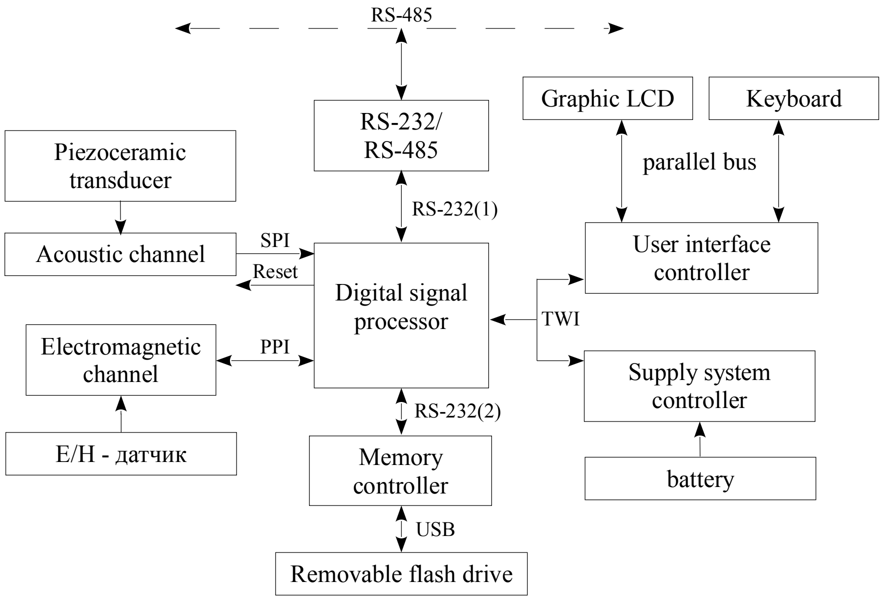

Figure 1. Block diagram of the recorder.

A keyboard and a graphic LCD are used for the information input and output in the initial processing. The device is powered by the battery to provide autonomous functioning of the complex for 3 days. RS-485 interface enables connection of several devices to the distributed network to analyze and provide connection during spatial processing of electromagnetic and acoustic signals.

The recorder is designed as a basic unit for receiving, mathematically processing and transmitting of data on electromagnetic and acoustic signals monitoring to the network. The acoustic signal recording provides the timing of the geodynamic events in the mine field. The main technical characteristics of the device are as follows: the frequency range of the signal analysis is from 1 to 100 kHz; the electromagnetic channel sensitivity is no less than 2 mV, and the acoustic channel sensitivity is no less than 5 mV; the dynamic range is no less than 60 dB; filtering is provided by Fast Fourier Transform (FFT); the refresh period of spectral characteristics is no less than16 ms; frequency step is no less than 1 kHz; 3 dB filter bands correspond to 3 kHz; rectangularity coefficient of 3 dB and 30 dB filters is 0.3; battery capacity is up to 16 A-hours**;** the autonomous work time of the unit is no less than 3 days; the mass of the unit with the battery is no more than 8 kg.

3. Simulation and mathematical processing

The device provides continuous recording of the electromagnetic emission with a sampling frequency of 1 MHz. In this regard, storage of the total amount of signals data with subsequent analysis in a laboratory or by a remote observer requires a portable autonomous device to possess a flash drive of an increased volume, a high data transmission rate to maintain communication in mines, and, in addition, it requires time consuming data processing. Therefore, to reduce the amount of information the device performs signal recording, real-time mathematical treatment (the window function, FFT, estimation of mathematical expectation and dispersion of a specified time interval) and stores the results in a removable flash drive. The operating algorithm for the mathematical block of the device is shown in Figure 2.

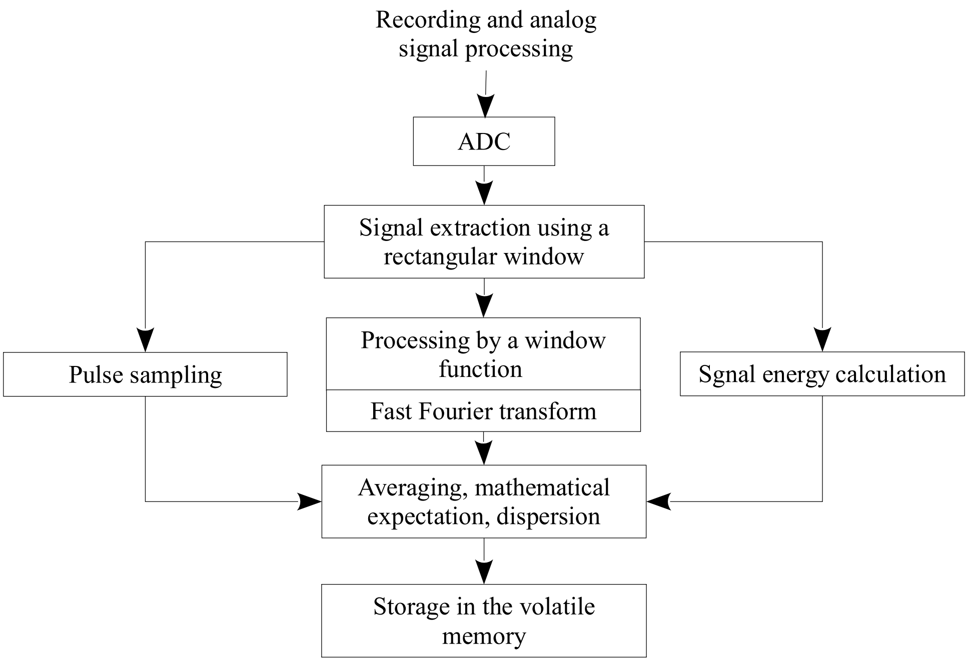

Figure 2. Algorithm for the mathematical block of the recorder.

To determine the system sensitivity at the stage of mathematical treatment of the signal is sufficiently relevant. Model this procedure. Assume that a useful signal with background noise caused by both imperfect device characteristics and continuous electromagnetic emission of the environment has been recorded. Therefore, identification is to be performed in the electromagnetic field of the event that in further analysis can appear to be the precursor of a geodynamic event.

For mathematical calculations, a useful sinusoidal signal emitted during rock crack propagation with an exponential rise and fall is chosen [13]. The dependence obtained by the authors in [13] was modified as where A_0 is the pulse amplitude; ω is pulse angular frequency ($\omega=2\pi f$); t_0 is entry of signal; τ_1, τ_2 are constants for rise time and fall time; T is the time for the pulse to reach its maximum amplitude. Here, τ_1 and τ_2 are substituted for the total time constant τ to independently control the rise time and fall time.

$$A = \begin{cases} A_0 \sin[\omega(t-t_0)]\left[1-\exp(\frac{-(t-t_0)}{\tau_1}\right], & t < T \\ A_0 \sin[\omega(t-t_0)]\left[1-\exp(\frac{-(T-t_0)}{\tau_1}\right]\exp(\frac{-(t-T)}{\tau_2}), & t \geq T \end{cases}, \quad (1)$$

Figure 3a shows a simulated waveform for the two signals assumed to be ideal upon geodynamic events. The signal parameters are as follows: the amplitude for both signals is of 2.5 relative units; the frequency is of 20 and 80 kHz (the frequencies are chosen to check the technique for upper and lower frequencies of the range under study); time constants τ_1 = 2 μs, τ_2 = 10 μs for the first signal and τ1 = 4 μs, τ2 = 30 μs for the second one; T – t_0 = 12 μs for the first signal, T – t_0 = 34 μs for the second one. This signal waveform is characteristic of the formation of the destructive zones in the mine fields.

Next, since the system and environment are not ideal, additive noise in the form of stationary white noise with amplitude smaller than that of the 10 dB original signal is set (Figure 3b). This white noise can be observed in all measurements of the EMS in the Tashtagolsky mine, including those performed in the down-time period. This is due to the natural redistribution of the rock mass SDS that occurs in the mine field after the technological explosion and mining of the ore body [6, 7]. In addition, noise in the form of a stationary sinusoidal EMS with an amplitude modulation and a frequency of 40 kHz with a carrier frequency of 3 kHz and amplitude equal to the original signal are set (Figure 3c). Superposition of the sinusoidal EMSs is caused by the electromechanical equipment in the mine that emits this type of noise (fans, drills, generators, motors, transformers, etc.). As a result of the complication performed for the recorded EMS (Fig. 3c), it is difficult to define what is the useful component of the signal providing information on the emergence of the destructive zone in the rock mass and its development over time, as well as on the geodynamic event which has already occurred. Therefore, for a remote observer, it is necessary to extract the original EMS to make the decision. For this purpose, the algorithm of the mathematical block of the recorder was used (Figure 2).

Pulse identification can be performed with different techniques, for example, signal level detection using the wavelet analysis corresponding to the model in [13]. As can be seen from Figure 3, the level detection will not identify the first pulse signal.

A more complicated approach using wavelet transform does not provide a uniform frequency resolution and is closely related to the signal waveform in the search model. That is, if the parameters of pulse signals (shape, length, rise time and fall time) may be different,
the approach based on convolution with the known model of the signal cannot be sufficiently universal. Other techniques to identify the signals against the background noise can be found in [14, 15], where signal identification against the background noise is reduced to the statistical analysis of stationary processes in terms of both the time and the spectral-time representations. This approach is most appropriate for the analysis of electromagnetic radiation of rocks and detection of deviations from stationarity in the form of pulse signal.

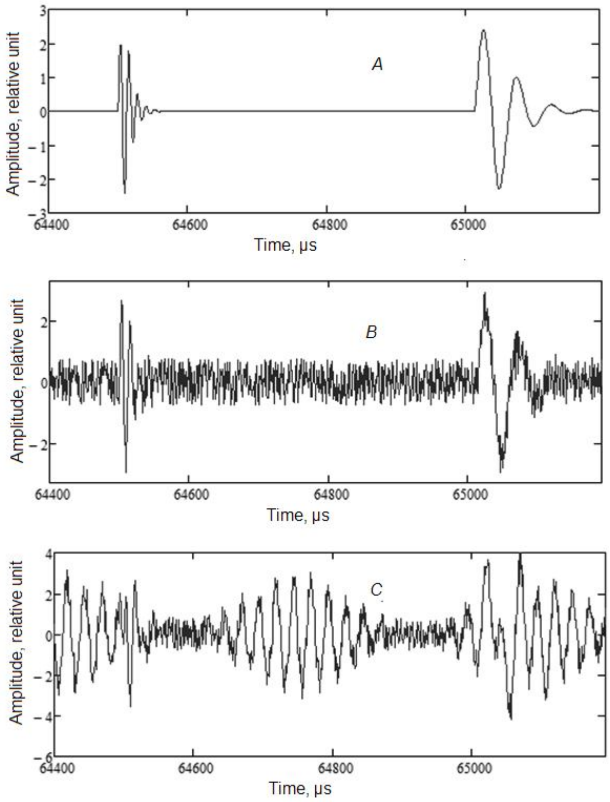

Figure 3. Informative electromagnetic signals of 20 kHz and 80 kHz (a); the same signals with white noise (b) white noise and sinusoidal electromagnetic interference (c).

As a result, the statistical analysis in the study was conducted using a fast Fourier transform (FFT) spectral-time decomposition of the total model signal shown in Figure 3. For the optimal relation between the analog filtering to identify the band with the frequency of 1–100 kHz and the compute capacity used for subsequent digital processing, the sampling rate was chosen equal to ~ 1 MHz. The width of the time window for FFT was ~ 1 ms (1024 samples), the frequency increment was 1 kHz. This relationship between frequency and time resolution is the most appropriate for spectral-time decomposition of the signal. Fast Fourier transform within a limited time interval may cause Gibbs effect, which can be minimized by processing the original signal with Kaiser Window with the coefficient of 9. Application of the window function, in contrast to the rectangle one, causes original signal losses, as processing reduces the amplitude of the signal near the edges of the time window. To eliminate these losses while calculating the spectral-time representation by means of the window function, fast Fourier transform is performed with the superposition of 50%, that is, 512 sample increment.

When considering the frequency-time representation of the signal, it is difficult to identify pulse signals against noise. The spectrum of the monophonic signal (Figure 3b) is illustrated in Figure 4, where the continuous line corresponds to the spectrum of the pulse signal with a frequency of 80 kHz over a time interval of 64–65 ms, and the dotted line is 20 kHz in the interval of 64.5 – 65.5 ms. Short duration of the pulse signals to be determined does not cause distinct maxima in the spectrum. The spectrum is strongly affected by the center frequency of 40 kHz with side harmonics, 3 kHz shifted from the center and by the bursts of white noise spectral components. Irregularity of the white noise spectrum is due to a small analysis time window.

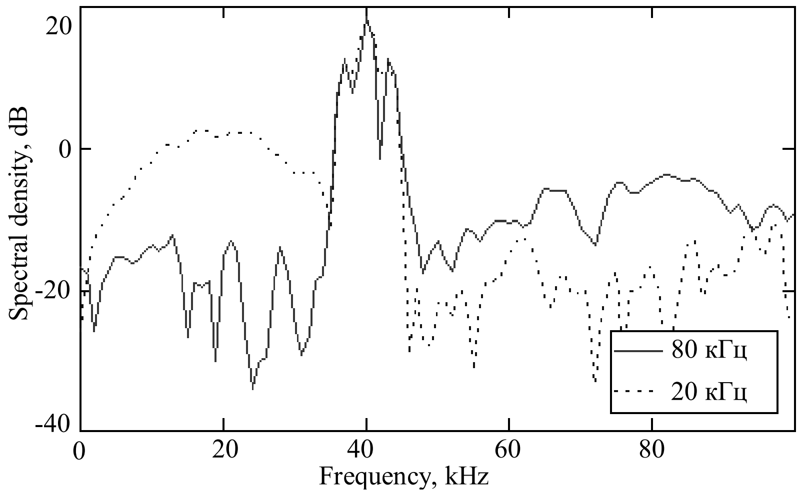

Figure 4. Amplitude spectra of the resultant signals to be determined.

To store the entire volume of the original data is difficult, and in addition, it may be not desirable, therefore, the recorder performs the spectral analysis and the calculated dependences on mathematical expectation (M_x), and the squared standard deviation (D_x) of the spectral amplitudes for each frequency component are stored in a removable media. The sample range to calculate M_x and D_x is set when starting the device. It can vary from 32 (accepted as the minimum calculation for D_x) to 1024 time windows being analyzed.

At the next simulation stage, statistical processing of spectral-time representation of the signal was performed. The time dependence for the squared standard deviation for spectral densities of the signal amplitudes was calculated by the expression [15]:

$$D(f,t) = \frac{\sum_{i=0}^{N-1}(x(f,t+\Delta t\cdot i) - \overline{x}(f,t..(t+\Delta t\cdot N)))^2}{N}, \quad (2)$$

where N is the value of the sequence of spectral densities to calculate the squared standard deviation n;
Δt is the minimum increment in the spectral-time representation;
$x(f,t+\Delta t\cdot i)$ is the spectral density at f frequency, at each increment in the time interval being calculated;
$\overline{x}(f,t..(t+\Delta t\cdot N))$ is mathematical expectation of the spectral density at f frequency, in the time interval from t to $(t+\Delta t\cdot N)$.

To perform calculation the simulated interval was divided into subintervals which consist of 32 samples (N = 32). The squared standard deviation of the spectral amplitude was calculated for each sub-interval by expression (2). Thus, the resulting volume of data on spectral-time representation was reduced by a factor of 32 times.

Figure 5 shows the dependence graph for the squared standard deviation (SD) of the signal amplitude spectral densities on frequency and time *D(f, t)*. Dark areas indicate large values of the square of the SD. The diagram in Figure 5 confirms that the event occurs after 64 ms from the beginning of the simulated interval.

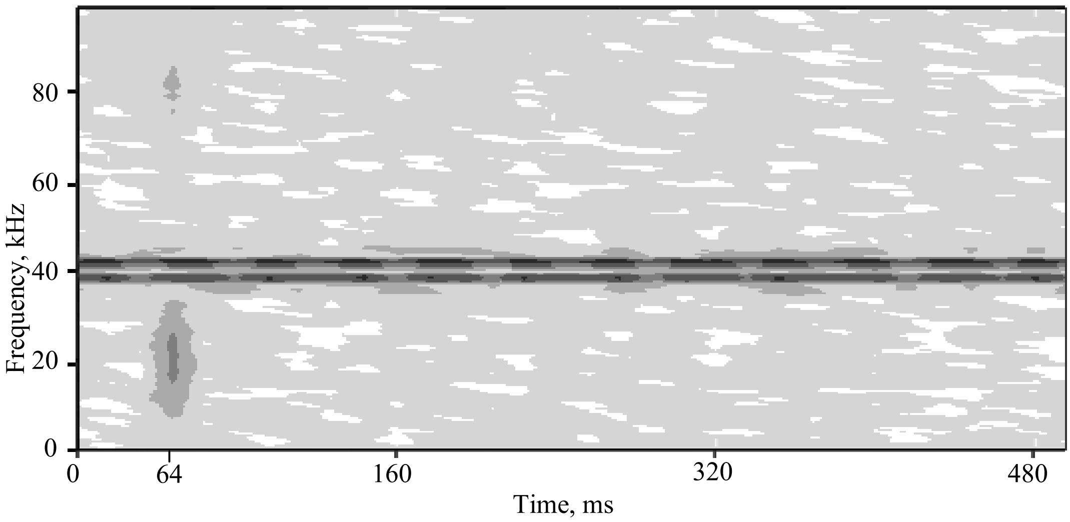

Figure 5. Time-and-frequency diagram of the squared standard deviation (SD) of the signal amplitude spectral densities *D(f, t).*

Two distinct noises can be observed at the frequencies of 37 kHz and 43 kHz. To filter the pulse signal from stationary noise, the degree of dispersion *D(f, t)* was evaluated for all spectral components by the squared SD in the investigated time interval of 500 ms. The values below a specific threshold proportional to SD are eliminated from the initial analyzed *D*(*f, t*) by the following expression:

$$D_1(f,t) = \begin{cases} D(f,t), & D(f,t) \geq k \cdot \sigma(f) \\ 0, & D(f,t) < k \cdot \sigma(f) \end{cases} \quad (3)$$

where *D(f, t)* is the initial squared standard deviation of the signal calculated by (2);
k is weight coefficient;
σ*(f)* is the standard deviation of the squared standard deviation for the spectral signal amplitudes calculated over the entire simulated time interval for each frequency component.

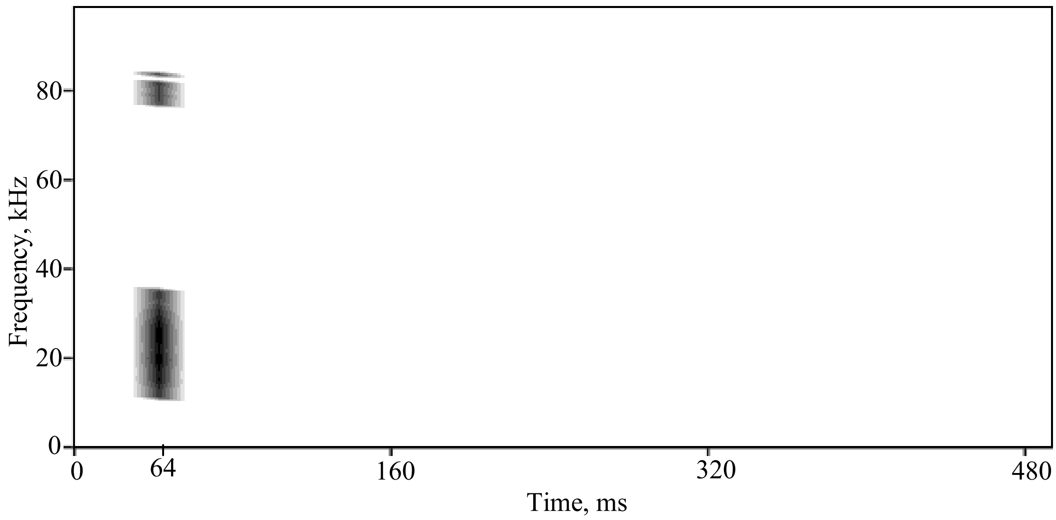

Figure 6. Identified parts of the pulse signal.

The data processed by expression (3) is shown in Figure 6. The weight coefficient k is 4.2 and it was chosen to ensure that the threshold value $k \cdot \sigma(f)$ is greater than the squared noise SD to obtain a "pure" characteristic.

The simulated SD was calculated over the entire time interval. But in processing of the measurement results within 2–3 days, this approach is not advisable as the background radiation intensity may vary with time. Therefore, in real time recording, the time interval for standard deviation estimation should be limited and chosen after preliminary evaluation of the environmental background radiation and in-situ calibration.

The weight factor to calculate the SD is chosen in the calibration process, in the time region free of signals caused by geodynamic events. Thus, the threshold $k \cdot \sigma(f)$ is expected to be of the value sufficient to exclude the stationary and quasi-stationary noise, and simultaneously to be most approximated to prevent filtering of the desired signal.

In simulation, the amplitude of the desired signal relative to the noise was chosen for the maximum probability of signal detection. Hence, for signals comparable to those in simulation with time parameters, the sensitivity of this processing method is about 10 dB.

Emission of pulse signals indicates deviation of the rock mass from the normal state. The analysis of the degree of deviation can be directly related to the prediction of a geodynamical event.

4. Conclusions

Thus, the paper presents a new type of a recorder to provide continuous recording of electromagnetic signals from rocks and dielectric materials in geodynamic processes, including those in the mine fields. This technique for processing the recorded electromagnetic signals may be used both to reduce the volume of the output data in continuous monitoring, and to obtain spectral-time images of electromagnetic pulses. The analysis of the data obtained in total processing of electromagnetic signals and noise showed that the most effective is standard deviation filtering of pulse signal to eliminate stationary noise. The analysis provides information on the development of destructive processes in the ore array or in the extended dielectric material destruction. The results obtained in processing the recorded electromagnetic signals from rocks can be used to transmit information in the network for remote monitoring. This sequence of data processing can be used successfully in the monitoring information network and for short-term prediction of geodynamic processes in underground and open pit mines.

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