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Abstract. The article provides a practical assessment of the effectiveness of the use of electrical prospecting equipment with pseudonoise sounding signals based on the results of field experiments with a new electrical prospecting measuring complex developed at the Scientific Station of the Russian Academy of Sciences. Two main sources of interference are considered, limiting the possibilities of effective use of pseudonoise signals in electrical prospecting equipment: "structural disturbances", manifested in the process of correlation processing of recorded signals and interference, the source of which is an industrial power network with a frequency of 50 Hz. Methods of reducing the influence of the above noises on the sounding curve obtained during data processing are considered using specially developed algorithms for eliminating "structural disturbances" and suppressing residual noise and interference.

1. Introduction

In the Research Station of the Russian Academy of Sciences (RS RAS) in Bishkek, work is being carried out to create new equipment, made on a modern element base, providing improved quality and efficiency of active electromagnetic monitoring of the earth's crust in the depth range from 100 m to 10 km [1]. The construction of the measuring equipment is based on the well-known method of sensing by the formation of a field in the near zone (SNF).

The main purpose of the work is to expand the capabilities of the electromagnetic monitoring system of the stress-strain state of the earth's crust, operating on the territory of the Bishkek Geodynamic Testing Area (BGTA), based on the electrical exploration method of sounding by the formation of a field in the far zone (SFF) and providing monitoring of the dynamic processes occurring in the crust at depths up to 20 km [2-4].

The advantage of the SNF method over the SFF method is that the separation between the source and the observation point can be significantly less than the investigated depth [5]. Due to the increased resolution of the SNF method, it is used for a more detailed study of the structure of the earth's crust. A distinctive feature of this method is the need to record signals in a very large dynamic range to achieve great sounding depths. "The more depth of research is needed, the later stages of formation need to be recorded. They correspond to an ever-lower level of the useful signal, therefore, for a real increase in depth, it is necessary to increase the power of the field sources and the sensitivity (noise immunity) of the measuring path" [6]. Based on the works [7-9], the authors carried out an estimated calculation of the dynamic range of the recorded signals for the territory of the BGTA [1]. Calculations have shown that for the range of sounding depths from 100 m to 10 km, the dynamic range of the recorded signals should be at least 200 dB. It is practically impossible to provide such a dynamic range of the recorded

signals only by improving the technical characteristics of the measuring equipment and using standard (known) algorithms for digital signal processing. To solve this problem, the RS RAS is developing a new technology for active electrical prospecting of the earth's crust using special sounding pseudonoise pulse trains with a large base. In this case, during the correlation processing of the received signal, complicated by the interference and noise uncorrelated with it, with the sounding signal, much greater suppression of noise and interference is provided than in the case of classical sounding by deterministic signals.

Mathematical modeling of measuring equipment has confirmed the possibility of effective use of pseudonoise signals (PNS) in electrical prospecting equipment. The results obtained showed that the use of PNS allows one to obtain a significant gain (by a factor of 100 or greater) in the output signal-to-noise ratio in comparison with traditional electrical prospecting systems due to the use of correlation signal processing [10]. The high level of suppression of interference and noise in the measuring system with PNS provides registration of very weak signals observed at long times of formation of the field, which makes it possible to measure the electrical parameters of the earth's crust in a wider range of depths at a reduced power of the sounding installation. To implement this idea, an experimental prototype of the measuring complex with pseudonoise signals (PNS EMC) was developed and manufactured, and work began in laboratory and field conditions with a manufactured sample to develop a new technology for sounding the earth's crust [1].

To confirm the results obtained on mathematical models, a series of field and laboratory experiments were carried out with a new measuring complex. In the course of the experimental work, important features of the use of PNS in electrical prospecting equipment were revealed.

2. Practical assessment of the effectiveness of the use of equipment with pseudonoise sounding signals

The method of sensing by the formation of a field in the near zone, used in the PNS EMC, imposes certain rules and restrictions when choosing a point on the earth's surface for conducting electromagnetic monitoring of the stress-strain state of the earth's crust. When choosing a measurement point, special attention is paid to the study of the level of interference and noise that limit the dynamic range of the recorded signals. In order to obtain statistical data on the spectral composition of interference and noise observed at various points on the earth's surface of the territory of the BGTA, special studies were carried out, described in [1]. Studies have shown that the main sources of interference are interference from an industrial power network with a frequency of 50 Hz. A number of field experiments were carried out to evaluate the efficiency of noise and interference suppression using correlation signal processing. The experiments were carried out at the "MGD" point located near the territory of the RS RAS. Due to the presence near powerful high-voltage power lines, this point is indicative for assessing the quality of measurements carried out using PNS EMC in the most unfavorable conditions.

In figure 1 shows an example of the recorded signal of the response of the medium to the effect of pseudonoise sounding pulses.
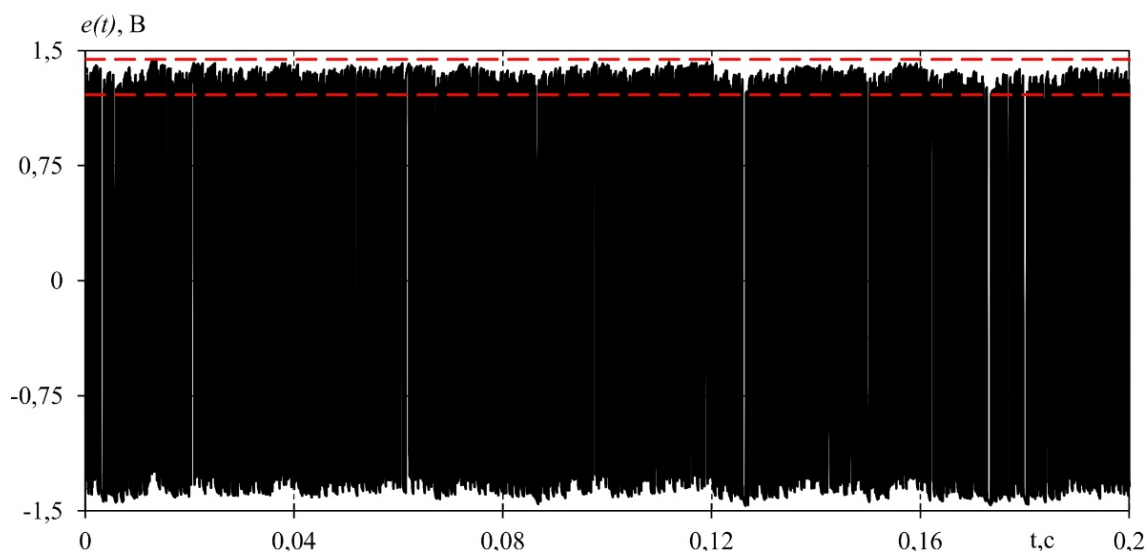
Figure 1. An example of the medium response signal to the probing action recorded at the "MGD" point.

The signal clearly shows periods of industrial noise with a frequency of 50 Hz (marked with red dotted lines). For an accurate assessment of the level of noise and interference, just before the sounding session, the registration of noise and interference was performed (figure 2-a). At the maximum amplitude of the recorded signal (from peak to peak) of about 3 V, the amplitude of noise and interference (A_n) recorded by the measuring channel was 32.625 mV (about 1% of the useful signal).

In figure 2-b, c shows the sections of the signal of the formation of the field in the region of small and large times obtained as a result of correlation processing and subsequent synchronous accumulation (200 accumulations) of the recorded signal. Against the background of the obtained curve of the formation of the field in the region of long times, impulse signals were detected, which were given the name "structural disturbances" since their temporal position is associated with the parameters and structure of the probing signals. As a rule, "structural disturbances" are pulses of different amplitudes located on the time axis of the field formation curve (figure 2-c). A distinctive feature of these noises is that their amplitude does not depend on the number of accumulations of periodically repeated cross-correlation functions obtained as a result of correlation processing of the registered signals. Mathematical modeling has shown that any static nonlinearities arising in the measuring path (including the process of converting signals by an analog-to-digital converter) are the cause of the appearance of "structural disturbances" [11, 12]. It is practically impossible to achieve a decrease in the nonlinear distortion coefficient of the measuring equipment to a level significantly less than 0.01% due to the lack of the necessary element base at the present time. Therefore, there remains one way to deal with "structural disturbances" - is to detect them on the field formation curve with subsequent removal.
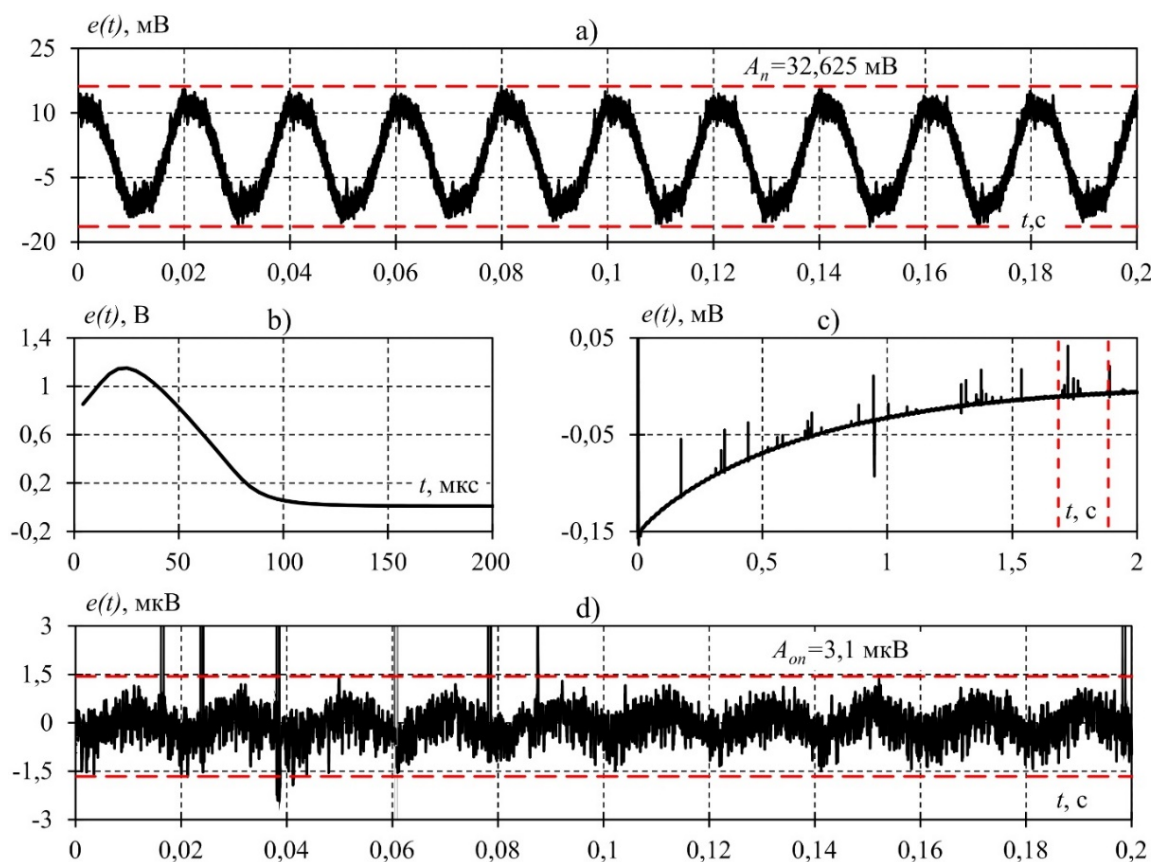
Figure 2. An example of signals recorded at the "MGD" point: noise recording - a); the signal of the formation of the field in the region of small - b) and large - c) times; the section of the signal of the field formation in the region of large times with the excluded low-frequency component - d).

On the curve of the formation of the field, not only "structural disturbances" is observed, but also residual tonal noise from the industrial AC power network, as well as other noises and interference of natural and artificial origin, the spectral components of which fall into the passband of the measuring channel (figure 2-d).

To estimate the amplitude of the noise and interference remaining after the correlation processing of the recorded signals, the signal section highlighted in figure 2-b with vertical dashed lines. After removing the low-frequency component from it (figure 2-d), the level of residual interference and noise (A_{on}), with the exception of "structural disturbances", decreased by a factor of 10524 (80 dB). Traditional synchronous accumulation allows you to get a gain by a factor of $\sqrt{200} \approx 14$.

3. Algorithms for Reducing the Level of Interference and Noise on the Formation Curve of the Field in the Long Time Domain

Despite the advantage of correlation processing in comparison with the traditional method of synchronous accumulation of recorded signals, the level of residual noise and interference is quite high, especially in the region of long times. To reduce their level, special algorithms have been developed for eliminating "structural disturbances" and suppressing residual noise and interference.

To solve the problem of reducing the influence of "structural disturbances" on the quality of the field formation curve, a special algorithm for eliminating "structural disturbances" was developed, based on a method for detecting signals by their energy, which allows to reliably (with a high probability) detect and eliminate "structural disturbances" appearing on the field formation curve obtained as a result of

correlation processing. To automatically search for the optimal threshold for detecting "structural disturbances", it is proposed to use a criterion based on the maximum approximation of the probability density distribution of residual interference and noise to the normal law, which makes it possible to automate the process of eliminating such interference as much as possible and thereby increase the speed of data processing in field work conditions. In figure 3 shows the result of the algorithm.
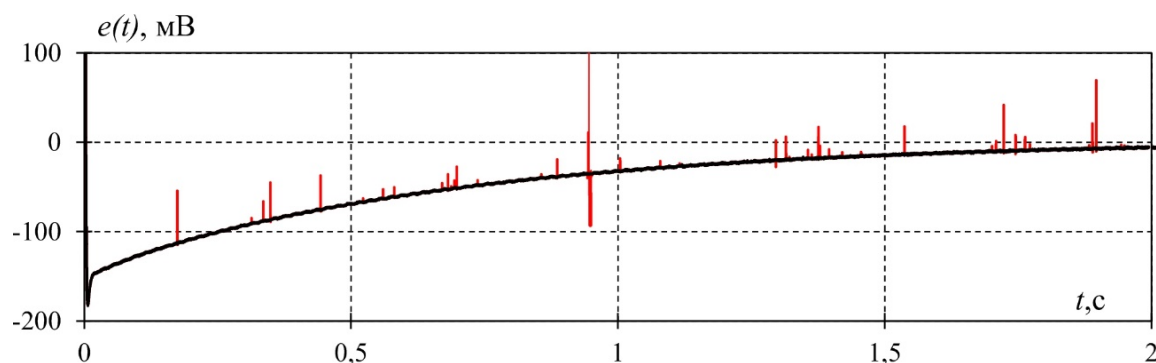

Figure 3. Segment of the field formation curve: red color - initial signal, black color - signal after elimination of "structural disturbances".

Application of the algorithm for removing "structural disturbances" in the processing of field data, allowed to eliminate almost all "structural disturbances" exceeding the level of residual noise and interference (figure 2-d). Standard digital signal filtering algorithms can be used to suppress remaining interference and noise

The suppression of the noise remaining on the sounding curve in the region of long times (starting from 20 ms and more) is provided using the median Dirichlet low-pass filter with a rectangular window. The frequency response of such a filter is described by the analytical expression

$$W_n(f) = \left| \frac{\sin^n(\pi \cdot f \cdot T_O)}{(\pi \cdot f \cdot T_O)^n} \right|,$$

where $n = 1, 2, 3, 4\ldots$ - filter order, T_0 - filter window length. With an increase in the filter order, on the one hand, the suppression of interference with frequencies above 50 Hz increases (by a factor of 5 - the first order, by a factor of 125 - the third order), on the other hand, the higher the filter order, the narrower its passband ($f_{cutoff} = 22$ Hz - the first order, $f_{cutoff} = 13$ Hz - third order). Narrowing the bandwidth with a large-order filter limits the acquisition of the field formation curve at short times. For the third-order Dirichlet filter, this boundary is defined as $t \geq 1 / (2 \cdot \pi \cdot f_{cutoff}) \geq 1 / (2 \cdot \pi \cdot 13) \approx 0.012$ s $= 12$ ms, which corresponds to the sounding depths determined by the inequality

$$h_E \geq \frac{1}{\sqrt{2}} \cdot \left(\frac{\rho_E \cdot t}{\pi \cdot \mu_0} \right)^{0,5} = 560 \text{ м},$$

where h_E is the effective sounding depth (thickness of the equivalent homogeneous skin layer); $\rho_E = 207$ Ohm·m is the average electrical resistivity of an equivalent homogeneous layer corresponding to the average electrical section of the earth's crust of the BGTA territory; μ_0 - magnetic constant (permeability) of vacuum.

In figure 4 shows the results of the stage-by-stage processing of the field formation curve obtained from the data of the field experiment at the "MGD" point.
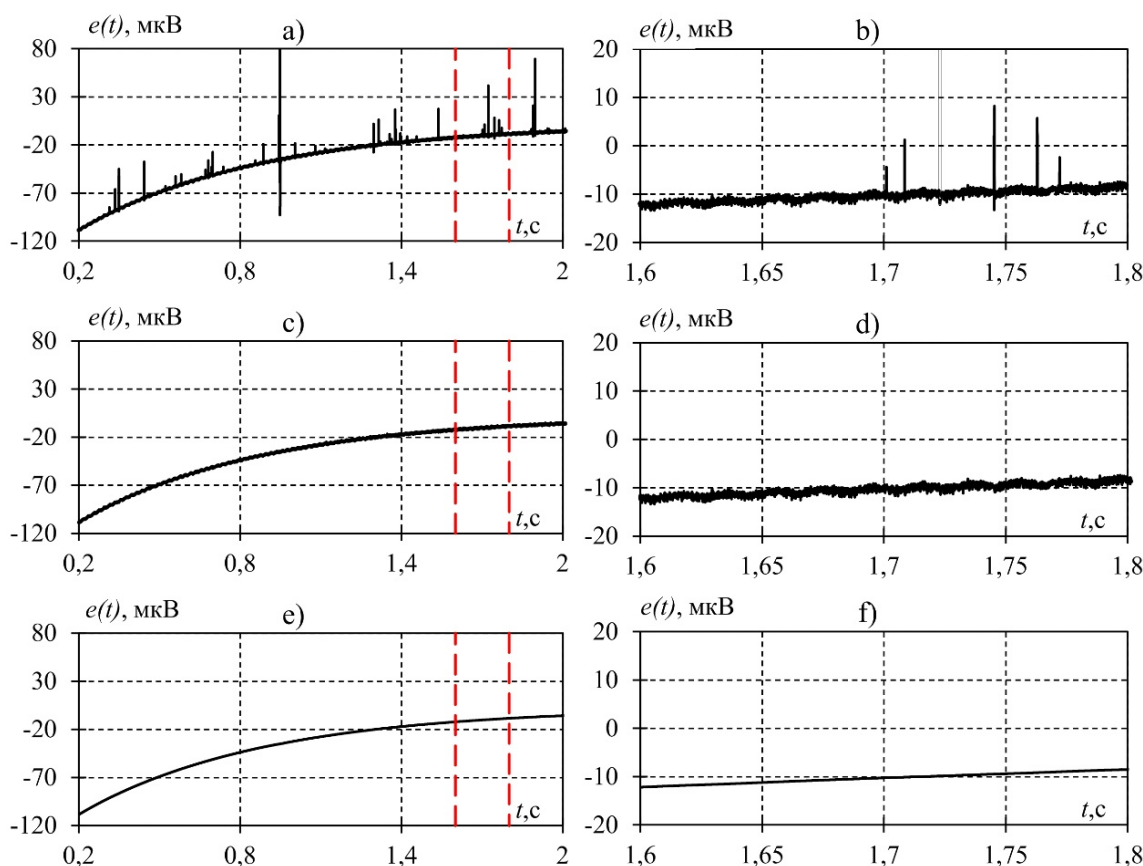
Figure 4. Result of data processing: a, b) sounding curve (accumulated correlation function) obtained after correlation processing of signals; c, d) sounding curve after removal of "structural disturbances"; e, f) sounding curve after additional processing with a third-order Dirichlet filter with $T_0 = 20$ ms.

As a result of processing in the signal $e(t)$ in the region of large times, all interference was almost completely eliminated. After such processing, only signal variations with frequencies below 13 Hz remain. It is possible that this signal also contains interference that is not associated with the sounding signal, for example, low-frequency signals determined by magnetotelluric currents induced in the earth's crust by processes occurring in the Earth's ionosphere. To isolate the regular component of the field formation signal determined by the probing signals, it is necessary to significantly increase the signal accumulation time during the probing experiments.

The dynamic range of the field formation signals recorded by the measuring complex was estimated according to the formula

$$D = 20 \, lg \left(\frac{e_{max}}{3\sigma} \right) = 180 \ \text{дБ},$$

where e_{max} is the initial signal value e(t); σ is the rms noise remaining after correlation processing and removal of "structural disturbances".

4. Conclusions

Field and laboratory experiments with PNS EMC showed that the main sources of interference that significantly limit the possibilities of effective use of PNS in electrical prospecting equipment are interference of two types: "structural disturbances", which manifests itself in the process of correlation

processing of registered signals and interference, the source of which is an industrial power network frequency of 50 Hz, the residual level of which, despite their significant suppression by means of synchronous accumulation and correlation processing of signals, is quite high, especially in the region of large times.

To reduce the influence of the above noises on the sounding curve obtained during data processing, special algorithms have been developed for eliminating "structural disturbances" and suppressing residual noise and interference.

The testing of algorithms on real field data showed a significant, by a factor of 100,000 (100 dB), a decrease in the level of interference and noise on the sounding curve (field formation) in the region of large times. Thus, additional processing of the field formation signal using algorithms significantly improved the signal-to-noise ratio at the output of the measuring complex and provided the registration of signals in a dynamic range of 180 dB. When choosing a measurement point with the absence of powerful high-voltage power lines near, a wider dynamic range of field formation signals can be obtained.

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